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Technical Report

REACTOR FUEL WASTE DISPOSAL PROJECT
PRESSURE-TEMPERATURE EFFECT ON SALT CAVITIES AND
SURVEY OF LIQUIFIED PETROLEUM GAS STORAGE

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REACTOR FUEL STORAGE PROBLEM

RESEARCH CONCEPTS FOR STORING WASTE

PREFACE

The development of storage techniques for safe disposal of atomic reactor fuel wastes is one ultimate goal of the Atomic Energy Commission. Past experience in the storage of liquefied petroleum gases in salt domes has shown that a very good possibility exists in that medium. The purpose of the following work is to evaluate the practicability of utilizing salt dome cavities for disposal of atomic reactor wastes. A literature survey is included in the appendix of all previous experience in storing various materials. Actual model studies of miniature salt cavities were conducted.

The author wishes to express his appreciation to Dr. F. W. Jessen for his immediate supervision throughout this study, to the Atomic Energy Commission, particularly Dr. J. Leiberman, Sanitary Engineer of the Commission Staff, for making this study possible, to Dr. E. F. Gloyna, Project Director, for his supervision of the over-all project, to Dr. H. H. Power and Dr. G. W. Crawford for their constructive comments, to Mr. Shosei Serata for his many helpful suggestions, to Dr. Robert Schechter, Dr. K. A. Kobe, Dr. William R. Muehlberger, and others who offered helpful suggestions.

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ABSTRACT

It is deemed feasible to store atomic reactor fuel wastes in a salt dome cavity to a depth where the differential in pressure between the soil over-burden pressure and pressure of the fluid inside the cavity does not exceed 3000 psi, and the temperature is less than 400°F. Tests at pressure increments of 1000 psi were conducted on a 2" cylindrical cavity contained in a 6" long by 6" cylindrical salt core. Tests indicate that the cavity exhibited complete stability under pressures up to 3000 psi and temperatures to 300°F. At temperature ranges of 100° to 400°F. and with pressures to 5000 psi continuous deformation of the cavity resulted.

Initial movement of the salt was observed at all pressures. This was evidenced by vertical deformation and cavity size reduction. However, it was noted that a point of structural equilibrium was reached at lower temperatures when the pressure did not exceed 5000 psi.

A study of the literature reveals that the most common type of cavity utilized in liquefied petroleum gas storage is either cylindrical or ellipsoidal. A few are pear or inverted cone shaped. There has been no indication of leakage for cavities when pressure tested for as long as 72 hours. This indicates that the salt mass is not permeable under conditions of prevailing underground temperature and pressure. However,

salt specimens tested under atmospheric pressure and temperature exhibited permeabilities of .1 to .2 millidarcys.

The cost of completing underground storage cavities in salt masses is expected to be approximately \$1.05 per barrel of storage space.

SUMMARY AND CONCLUSIONS

(1) It is deemed feasible to store reactor fuel wastes in washed out cavities of salt domes for limited depths and controllable temperatures. For maximum cooling, temperature considerations indicate that the cavity should be completely filled. However, from a structural standpoint the inevitable initial creep would indicate that only a partial filling of the cavity would be desirable. A complete filling of the cavity would be safe if proper surface pressure relief facilities were provided.

(2) The differential between overburden pressure and the empty cavity should not exceed 3000 psi. For overburden pressure gradients ranging between 1.00 psi/ft and 0.75 psi/ft, this would correspond to depths of 3000 feet and 4000 feet respectively for completely empty cavities.

(3) It has been shown experimentally that a salt cavity under simulated high over-burden pressures will completely close as a result of plastic flow. This is a function of both temperature and pressure.

(4) A salt cavity under constant pressure and temperature will reach structural equilibrium. This was shown experimentally and by theoretical calculations. This particular set of experiments showed structural equilibrium to be evident at the following maximum conditions:

<u>Temperature, °F</u>	<u>Pressure, psi</u>	<u>Per Cent Cavity Closure</u>
90	4000 - 5000	7.5 - 10
300°F	4000	9
400°F	3000	14

Reactor fuel waste storage should be safe in salt cavities at depths less than 3000 feet and temperatures less than 300-400°F.

(5) Salt upon being removed from a mine and prepared for testing will exhibit some permeability under atmospheric pressure and temperature. The testing of actual cavities under the earth's over-burden pressure and the earth's normal temperature show that no permeability of salt exists in place.

(6) The average cost to complete an average sized cavity in a salt dome is \$1.05 per barrel of storage space.

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INTRODUCTION

The purpose of this investigation was to determine the effect of the earth's over-burden pressure and temperature on a salt cavity. A very limited investigation of salt permeability under atmospheric pressure and temperature was conducted. Also, a complete literature study was made of liquefied petroleum gas storage.

This particular report is one of several covering the over-all problem of storing reactor fuel wastes in salt dome and/or salt beds, performed at The University of Texas. The list of reports includes:

- (1) "Development of Design Principle for Disposal of Reactor Fuel Waste into Underground Salt Cavities," January 1, 1959.
- (2) "The Geology of Salt Domes," January 1, 1959.
- (3) "Thermal Considerations in the Storage of Reactor Fuel Waste in Salt Formations" (In preparation).

Numerous references will be made to these correlative studies. A few of the problems covered in these reports are: (1) radiation effect, (2) chemical effect, (3) time effect, (4) stress distribution, (5) geological study, (6) creep, (7) thermal heat effect, (8) structural stability, (9) permeability, (10) a complete literature survey of previous work in liquefied petroleum storage, and (11) cost of developing solution cavities. This report will cover only items 8, 9, 10, and 11.

Figure 1 shows something of the over-all nature and location of salt domes.

Items number 10 and 11 are in a supplemental report which is included in the appendix and gives an over-all picture of Liquefied Petroleum Gas storage as utilized in the petroleum industry today. Included with this report is a condensed resume of answers to questionnaires concerning LPG (Liquefied Petroleum Gas) storage (Table 2).

For experimental study a cylindrical cavity was chosen for analysis since it was deemed suitable for reactor fuel waste disposal. This particular cavity shape, allowing for irregularities, can be easily leached out of salt domes in field operations. (107)

Each individual experiment is discussed in some detail, and all results are presented in graphical form.

The problem of accurately determining the stresses which exist in rocks in the earth's crust is indeed a complex one. Theoretical studies have differed widely in many of the basic assumptions about the physical properties of the rock itself. Some solutions of problems in underground stress analysis assume that rock is elastic, homogeneous, and isotropic in character; others assume that rock possesses plastic, viscous, elastico-viscous properties, or a combination thereof. Experimental evidence has shown that salt possesses plastic, viscous and elasticoviscous properties. (12)

PRIMARY SALINE DEPOSITS IN THE UNITED STATES

FIG. 1. MAP OF GULF COAST PROVINCE SALT DOMES

FIG. 2. CROSS-SECTION SHOWING THE RELATIONSHIP OF THE STRATA WITH SALT DOMES OF THE GULF COAST PROVINCE

FIG. 3. DETAILED SECTION THROUGH A SALT DOME SHOWING THE RELATIONSHIP OF THE STRATA WITH SALT DOMES OF THE GULF COAST PROVINCE

LOCATION AND NATURE OF SALT DOMES & BEDS

SALT MINE

FLOW MEASUREMENTS AT GRAND SALINE

TEST STATION

EFFECTS OF SALT FLOWAGE

TEST STATION

GRAND SALINE SALT DOME

FIG. 1. LOCATION AND NATURE OF SALT DOMES.

Related work on this project has shown that salt becomes more plastic with temperature.⁽⁸⁶⁾ Figures 2, 3, and 4 show salt test specimens subjected to compressive tests at room temperature wherein eventual rupture occurred. Figure 5 shows a cylindrical salt specimen that was subjected to a confining pressure and temperatures of 300°F and 570°F. Plastic flow occurred without rupture. Figure 6 shows plastic deformation of a salt test specimen by uniaxial compression at a temperature of 770°F.

The present work involves experiments designed to show the effects of temperature and pressures on salt cavities. Figures 9, 10, and 11 show the results obtainable under certain conditions of pressure and temperature. Figures 7 and 8 illustrate the equipment used.

FIG. 2. SALT COMPRESSION TEST
(ROOM TEMP.)

FIG. 3. SALT COMPRESSION TEST
(ROOM TEMP.)

FIG. 4. SALT COMPRESSION TEST
(ROOM TEMP.)

FIG. 5. CRYSTAL FROM GRAND SALINE SALT
MINE TESTED WITH CONFINING PRESSURE
OF 14,500 PSI AT 300°F AND 570°F.
(LEFT, ORIGINAL ; MIDDLE, 300°F ;
RIGHT, 570°F).

FIG. 6. PLASTIC DEFORMATION OF SPECIMEN BY UNIAXIAL COMPRESSION AT 770°F.

FIG. 7. 400,000 POUND TEST APPARATUS FOR MEASURING CREEP RATES IN CYLINDRICAL CAVITY.

FIG. 8. CYLINDRICAL CAVITY TEST APPARATUS.

FIG. 9. CLOSURES RESULTING FROM CREEP IN CYLINDRICAL SALT CAVITY. (6" O.D X 2" I.D.)

FIG. 10. PARTIALLY CLOSED CYLINDRICAL CAVITY.

FIG. 11. THE 98% CAVITY CLOSURE.

APPARATUS AND PROCEDURE

For the purpose of approaching underground storage conditions as nearly as possible, the following factors were considered:

1. Control of pressure and temperatures
2. Measurement of temperature gradients throughout salt mass
3. Measurement of structural stability of salt cavities.

In order to obtain triaxial pressure on the salt cavity without resorting to the application of fluid pressure directly on the salt mass, a system was designed whereby the same effect could be produced through axial loading only. By cutting a core to close dimensions to fit a steel test cylinder, and applying axial pressure, a lateral pressure was obtained. This equipment is shown in Figures 12, 13, and 14. A steel cylinder was made from an AISI Type 347 (SAE 30347 or AMS-5646) stainless steel alloy. This high chrome nickel steel (17-19% Cr, 9-13% Ni) was selected because it offered high strength at relatively high temperatures.

A core, having only a slightly smaller outside diameter than the inside diameter of the test cylinder, was cut from a block of salt and prepared for testing. Pressure was applied by means of the top piston such that over-burden pressure was simulated. Strain gage measurements on the outside of the

FIG. 12. CUTAWAY VIEW OF TEST CYLINDER.

FIG.13. CROSS SECTION OF TEST CYLINDER.

FIG. 14. SCHEMATIC DIAGRAM OF ASSEMBLY FOR MODEL SALT CAVITY TEST.

steel cylinder verified the lateral pressure effective on the salt core.

It was found impossible to cut a core so perfect that it would be an exact fit in the 6" I.D. steel cylinder. However, an excellent core was cut with the saw shown in Figure 15. Approximately five-thousandths inch taper resulted on the salt core over its entire length. This was caused primarily by the accumulation of powdered salt cuttings wearing on the salt core. A salt-saturated cement slurry, which left a thin film of cement in all void spaces, was used to fill in between the salt core and the steel cylinder to assure a perfect fit. Actually the core fit so closely that three small $1/16$ " deep grooves were cut the entire length of the core to allow cement to travel from top to bottom, and assuring complete covering of the core and elimination of all voids between the core and steel cylinder. A piston with $3/1000$ inches clearance was fitted on top of the main cylinder so that upon downward movement the salt or cement would not have a tendency to flow by the piston. The same close fit was utilized in the center hole through which the $3/4$ " pipe carrying the thermocouple leads and heating element wire was fitted.

Thermometer wells, $3/64$ inch diameter, were drilled in the side of the cylindrical wall and in the center of the bottom plate.

Cutting the Salt Core

Cutting a smooth 6 inch O.D. salt core presented a rather difficult problem. An attempt to find some company with experience in cutting salt cores was not successful. The method for cutting granite by feeding abrasive materials underneath a smooth-edged circular saw also was unsuccessful. So much heat was developed that eventual fusing of the salt to the saw occurred.

To insure greater cutting accuracy and control, a core barrel saw was designed and constructed. See Figure 15.

The salt specimens were obtained from the Grand Saline Mine, Figure 16. The large specimens were sawed by cross-cut saw (Figure 17) and eventually cut with the core barrel saw as indicated in Figure 18.

The features of the high speed salt core saw were a thin wall, and sharp teeth. The main body was made from brass and the teeth made from high alloy steel. This saw proved highly successful and cut some 15-6" O.D. by 7" long salt cores. However, approximately 20 hours are required to cut a good core. Heating of the saw was troublesome since no liquid could be used for cooling for fear of damage to or change of the salt characteristics. The cutting procedure was discontinued at intervals to allow cooling of the core and saw. Corrosion of surrounding equipment caused abandonment of the use of air.

It was also desirable to have parallel surfaces on each end of the core which would be perpendicular to the cylindrical core. A miter box assured perpendicular cuts with a regular wood hand-saw.

SALT CORE AND
CORE BARREL SAW

CORING
OPERATION

CAVITY AND
HOLE FOR CEMENT

FIG. 15. DETAILS OF CUTTING DEVICE
AND SPECIMEN.

FIG 16 MINE OPERATION AT 700 FT
BELOW SURFACE IN GRAND
SALINE SALT DOME IN EAST
TEXAS

FIG 17 USING CROSS-CUT SAW TO CUT
LARGE SALT BLOCK FROM GRAND
SALINE MINE.

FIG 18 CUTTING 6" OD SALT CORES

FIG 19. SALT CORES, CORE BARREL,
HEATING ELEMENT, AND NON-
ASSEMBLED TEST CYLINDER

Preparing the Salt Core for Testing

A 2" diameter cylindrical cavity, 4" in depth, was cut in the center of the 6" core by means of a high speed circular metal hole saw.

To duplicate underground conditions for cement and pipe, 3/4" O.D. by 5/8" I.D. steel pipe was set to the top of the cavity and cemented in place. Numerous failures occurred in attempting to set the pipe with paper, rubber, and other types of packers. Difficulty was experienced in attempting to keep the small pipe (hereinafter referred to as casing) centered so that it would fit in the large test cylinder. The packer itself would slide down the walls thereby leaving a smaller sized cavity than originally planned. This was finally solved by cutting a 2-1/4" hole down to the top of the cavity. The 1/8" shoulder on the top of the cavity served as a seat for the stainless steel packer. A 5/8" hole in the center allowed full opening for the 5/8" I.D. x 3/4" O.D. casing. Drilling a 3/4" hole only 1/4" deep left a shoulder for the casing. This 2-1/4" shoulder on the salt along with the 3/4" shoulder of the packer made the loading of the test cylinder somewhat less difficult.

Detailed Procedure for Loading the Test Cylinder with a Salt Core

The procedure for loading the salt core in the test cylinder prior to the actual test proved to be very time consuming and complex. Figures 7, 8 and 19 show photographs of the test cylinder in the non-assembled and assembled conditions. Figures 12,

13, and 14 show the assembled apparatus, a cross-sectional view, and a cut-away view of the test equipment.

The following step-wise procedure was followed in loading the test cylinder with a 6" outside diameter by a 6-1/2" to 7" long salt core:

(1) The entire outside surface of the core was covered with a thin film of epoxy resin to protect it from vapors, and to prevent entry of water from the cement.

(2) An attempt was made to place strain gages in the inside of the cavity, but it was found to be extremely difficult. Once the gages were in place there was no means of holding them in position long enough to assure a good bond.

A device made similar to a balloon was made for keeping pressure on the gages long enough to assure a proper bond. By using 100 psig air pressure inside the balloon, which in turn acted against the strain gages, a good bond was achieved. Figure 22 shows strain gage leads coming out of the cavity. Inside mounted strain gages eventually were abandoned in favor of mercury displacement to measure reduction of volume of the cavity.

(3) The strain gages were covered with a ceramic material to assure impermeability against mercury. This entire procedure was abandoned on later experiments since it was found that once deformation took place the ceramic materials would crack, expose the gages and leads to mercury, and short out the gages.

(4) An insulated thermocouple was installed in the bottom of the cavity and adjacent to the wall of the cavity. The terminal of this thermocouple was installed $1/4$ " into the salt. This arrangement gave a direct reading of the temperature at the cavity walls.

(5) The heating element was then placed inside the cavity. Accurate volume measurements were taken of the cavity with and without the heating element in place. Figures 12 and 13 show the heating element in position. This inside heating element was abandoned after 3 tests and the complete system heated from the outside. This was accomplished by wrapping flexible coiled type heating elements around the outside of the test cylinder.

(6) The small casing ($3/4$ " O.D. x $5/8$ " I.D. pipe) was then attached to the metal packer ($2-1/4$ " O.D. x $1/4$ " thick with the $3/4$ " I.D. centered hole) by a ceramic cement (Sauereisen of cement) at this point.

(7) The packer and casing was then placed in position on top of the $2-1/4$ " shoulder at the top of the cavity. To prevent loss of water from cement into the cavity, the packer was cemented to the walls with a ceramic cement. Because of extremely close tolerances the casing had to be centered exactly. A template, designed so that the pipe could be centered in the salt core which in turn was centered in the test cylinder, allowed the pipe to be cemented in place. This procedure proved to be necessary in that earlier experiments revealed some water in the cavity.

(8) The next step was to cement the core assembly in the large steel cylinder. First, all metal parts in contact with salt were coated with a thin film of paraffin from a solution of paraffin in kerosene, so that the cement would not adhere to the metal parts. Removal of the salt core upon completion of tests was facilitated thus. A salt-saturated 50% cement slurry was used for cementing.

Cement was poured into the bottom of the empty steel test cylinder. It was necessary to have cement on both top and bottom of the core to smooth out all irregularities resulting from cutting the core. The salt core with the casing in place was then placed in the steel cylinder on top of the cement. The salt core was rotated back and forth while exerting a downward pressure. This action was continued until cement came to the top from around the core, thus assuring a perfect fit of the salt core in the steel cylinder. Cement was then poured around the casing with enough additional cement to fill any irregularities on top of the core.

(9) The top, movable piston was then placed in position on top of the salt core with approximately 1/2 inch of the casing protruding out the top of the piston. All necessary leads (thermocouple, etc.) were routed out through the 3/4" casing.

(10) The 50 ml burette was then placed in position. On the initial experiments the leads were all sealed at the top and flexible plastic tubing was connected to the burette. This

method was troublesome and unsatisfactory so the 3/4" casing itself was threaded and a stainless steel pipe connection made between the 3/4" casing and the burette (Figures 12, 13 and 14).

(11) The thermocouples were then placed in position.

(12) The completed test cylinder was placed in the materials testing machine. A slotted plate provided an outlet for all leads.

(13) A small load (100 lbs.) then was applied to the test cylinder. At this time a dial gage was installed to measure the downward movement of the salt with increased load.

(14) Strain gages were installed and thermocouples connected.

(15) If heat was to be applied internally to the cavity or externally to the cylinder it was applied at this time, and maintained until equilibrium conditions were reached.

(16) Loads were applied in equal increments until a maximum of 400,000 lbs approximately was reached. Strain gage, dial gage, thermocouple, and mercury volume displacement readings were taken at each successive increase in load.

(17) On some tests the maximum of 400,000 lbs was maintained for several days to observe creep characteristics.

(18) Upon completion of a test it was necessary to remove the salt core without destroying it so that visual observations could be made. In the first test the core was dissolved with fresh water. Since it was deemed imperative to examine the cavity and core intact an unloading arrangement was devised.

The top and bottom were removed from the test cylinder, and the core was pressed out with a 12" long x 9-5/8" piece of N-80 casing. This method proved very satisfactory in recovering the core intact; however, it was impossible to prevent some horizontal fracturing, as noted in Figure 11.

Heating Elements

A 1000 watt heating element to fit inside the 2" long by 2" diameter cavity was designed. This element was 1" x 1-1/2" overall and allowed sufficient space for the mercury used to measure cavity size changes with increased pressures and temperatures. The first element was made from nichrome wire, 20 gage, 0.652 ohms resistance per foot. Approximately 9 feet of this wire was used in successive layers. Each layer of wire in turn was insulated with a ceramic binder capable of withstanding approximately 3000°F. Since the element had to be immersed in mercury, it was rendered impermeable by heating to 200°F for 24 hours. The leads also had to be protected. These leads were copper, encased in an inconel sheath, and insulated from each other and the sheath by a filling of aluminum oxide. However, numerous difficulties were encountered in the use of this heating element as the ceramic insulator became brittle and trouble arose from mercury "shorting out" the element. Furthermore, the inside layers of nichrome wire, being so well insulated, became over-heated and burned out.

A commercial heating element (Chromalox "Redhead" Electric Cartridge Heater) was located, but was used in only one experiment.

This particular element was completely enclosed in a stainless steel sheath while the leads were enclosed in a 1/4" stainless steel tube. It necessitated a three inch long cavity which did not conform to all other experiments. It worked very well but was crushed.

The most successful temperature control was accomplished by heating the entire steel cylinder. A combination of six heating elements which when combined had a capacity of 4000 watts were wrapped around the cylinder. Variable voltage control provided good control of any desired temperature. Once the coiled elements were in place on the 9" O.D. steel cylinder, a 13" I.D. metal sheath was placed around the cylinder. This gave 2" of space between the steel cylinder and the metal sheath which was packed with insulating material. Asbestos insulated leads were used near the test cylinder. Thermocouple measurements were taken inside the cavity, on the edge of the cavity, and at the bottom of the cavity. The insulation proved good enough such that a uniform constant temperature was maintained throughout the salt mass.

DISCUSSION OF RESULTS

Each individual experiment is discussed in some detail because various failures and mishaps throw some light on the data obtained.

The results of all tests are shown graphically and by photograph in Figures 20-42 (inclusive).

Experiment #1

The first experiment was conducted at 80°F. The core was 6" diameter by 7-4/32" in length having a cavity 2" in diameter by 2-1/8" in length. Two SR-4 strain gages were placed on the cavity walls.

The purpose of this test was to check cavity stability at room temperature (80°F) and at a maximum loading of 400,000 lbs. (15918 psi at critical area). See Figure 39. For a test time of approximately one hour and with a maximum loading of 400,000 lbs, the cavity showed a diametral deformation of 6.3%. The strain gages mounted on the outside of the steel cylinder proved to be of poor quality and indicated that strain gages of better quality should be baked in place. This was done for the next experiment.

Since the method for removal of the cores was not devised until Experiment #2 was completed, no pictures of cut-away salt sections are available for Experiment #1. However, Figure 21

FIG. 20. SALT CORE REMOVED FROM TEST CYLINDER AFTER COMPLETION OF TEST. (HORIZONTAL FRACTURE LINE INDICATES POST SAWING OF CORE).

FIG. 21. EXP. NO.1 - TOP VIEW OF SALT CORE IN TEST CYLINDER. (SALT CUT AWAY DOWN TO TOP OF CAVITY).

FIG. 22. EXP. NO.2 - SALT CORE SEPARATED AT TOP OF CAVITY. (STRAIN GAGE LEADS AND PLASTIC PACKER SHOWN).

FIG. 23. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (BLACK LINES INDICATE ORIGINAL CAVITY SIZE).

FIG. 24. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (HEATING ELEMENT IN POSITION).

FIG. 25. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (BLACK LINES INDICATE ORIGINAL CAVITY SIZE).

FIG. 26. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (BLACK LINES INDICATE ORIGINAL CAVITY SIZE).

FIG. 27. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED.

FIG. 28. HORIZONTAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (100% CAVITY CLOSURE).

FIG. 29. HORIZONTAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (64% CAVITY CLOSURE).

FIG.30. VERTICAL DEFORMATION OF SALT CORE.

FIG.31. SALT CAVITY VOLUME CHANGE.

FIG.32. VERTICAL DEFORMATION OF SALT CORE.

FIG.33. SALT CAVITY VOLUME CHANGE.

FIG.34. VERTICAL DEFORMATION OF SALT CORE.

FIG.35. SALT CAVITY VOLUME CHANGE.

FIG. 36. VERTICAL DEFORMATION OF SALT CORE.

FIG. 37. SALT CAVITY VOLUME CHANGE.

FIG. 38. VERTICAL DEFORMATION OF SALT CORE.

FIG. 39. STRESS AREA.

FIG. 40. SALT CAVITY VOLUME CHANGE.

FIG. 41. VERTICAL DEFORMATION OF SALT CORE.

FIG. 42. SALT CAVITY VOLUME CHANGE.

FIG. 26. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (BLACK LINES INDICATE ORIGINAL CAVITY SIZE).

FIG. 27. VERTICAL CUT THROUGH SALT CORE AFTER TEST COMPLETED.

FIG. 28. HORIZONTAL CUT THROUGH SALT CORE AFTER TEST COMPLETED. (100% CAVITY CLOSURE).

FIG. 29. HORIZONTAL CUT THROUGH SALT CORE AFTER TEST COMPLETED (64% CAVITY CLOSURE)

FIG. 30. VERTICAL DEFORMATION OF SALT CORE.

FIG. 31. SALT CAVITY VOLUME CHANGE.

FIG. 32. VERTICAL DEFORMATION OF SALT CORE.

FIG. 33. SALT CAVITY VOLUME CHANGE.

FIG. 34. VERTICAL DEFORMATION OF SALT CORE.

FIG. 35. SALT CAVITY VOLUME CHANGE.

FIG. 36. VERTICAL DEFORMATION OF SALT CORE

FIG. 37. SALT CAVITY VOLUME CHANGE.

FIG. 38. VERTICAL DEFORMATION OF SALT CORE.

FIG. 39. STRESS AREA.

FIG. 40. SALT CAVITY VOLUME CHANGE.

FIG. 41. VERTICAL DEFORMATION OF SALT CORE.

FIG. 42. SALT CAVITY VOLUME CHANGE.

FIG. 43. VERTICAL DEFORMATION OF SALT CORE.

FIG. 44. SALT CAVITY VOLUME CHANGE.

FIG. 45. VERTICAL DEFORMATION OF SALT CORE.

FIG. 46. SALT CAVITY VOLUME CHANGE.

shows a top view of the cavity itself. The salt around the edges of this cavity was cut away by a circular saw until the cavity was uncovered. The salt core was still in place in the test cylinder when this picture was taken.

Experiment #2

The purpose of this test was to determine cavity stability and creep at 80°F and at a maximum loading of 400,000 lbs. for a prolonged period of time.

The salt core on test number 2 had the following dimensions:

Length of core	6-1/2"
Diameter of core	6"
Diameter of cavity	2"
Length of cavity	2"
Original volume of cavity with packer in place . . .	83.6 ml.

Strain gages were originally placed inside the cavity. The inside of the cavity was coated with a resinous compound (Hysol) to prevent any water from entering the cavity. The original volume of 83.6 ml is less than the calculated volume for a 2" cylindrical cavity 2" in diameter (calculated volume = 103 ml) because of the strain gages and coating component. The strain gages failed immediately from exposure to the mercury. The test was continued for 146 hours at 80°F. Excellent results were obtained. See Figures 30 and 31. The mercury measuring system failed after 57 hours, but enough information was obtained to permit an extrapolation of the curve as seen in Figure 31.

A very peculiar thing occurred in the latter part of the experiment in that water began to come out of the cavity along with the mercury. Water originally present in the cavity would have been displaced by the mercury in the original loading, and hence must have been water loss from the cement that was originally lost into the salt, and subsequently squeezed out under the extremely high pressures. Figures 22 and 23 show photographs of the salt core after test completion.

Experiment #3

The purpose of this test was to determine cavity stability and creep at a higher temperature and a maximum stress of 15,918 psi.

The salt core used in this experiment had the following dimensions:

Length of core	6-1/2"
Diameter of core	6"
Cavity size	2" x 2"
Depth from top to cavity . .	2-1/4"
Vol. of cavity without heating element	88 ml
Vol. of cavity with heating element	65 ml

An attempt was made to conduct this test at a higher temperature of 400°F. However, a portion of the heating element was "short-circuited" so the test was completed at 100°F.

This is an important test temperature since it approximates the average temperature expected at approximately 3000 feet underground. Compressive strength of salt is approximately 3000 psi, and would be present at approximately 3000 feet.

The cavity was filled with mercury and mercury volume displacement readings were taken. A dial gage reading (indicating salt movement) was also taken on this test along with temperature and strain gage measurements.

The results of this test show that 52 cc of mercury were displaced in 8 hours and 15 min representing 59% cavity closure. During the first hour after an initial loading of 40,000 lbs. the pressure was raised by 25,000 lb. increments to a total of 400,000 lbs.

Figures 32 and 33 show plotted results of this test. Figure 24 shows a cut-away of the salt core after test completion.

Figure #4

The purpose of this test was to determine cavity stability and creep at higher temperatures. Because of heating element failure the test was conducted at 90°F and at a maximum loading of 400,000 lb (15,918 psi).

The salt core in this test had the following dimensions:

Volume of cavity with
heating element 88 ml

Volume of cavity without
heating element 107.5 ml

Length of core 6-1/2"
 Length of cavity 2-1/4"
 Depth to top of cavity 2

Experiment #4 was at first attempted with the nichrome-ceramic heating element on the inside of the cavity. However, after the cavity reached a temperature of 140°F the ceramic coating cracked, allowing the mercury to "short out" the element. The cement around the casing (3/4" by 5/8" pipe) was then drilled out, the casing and packer removed and the heating element examined. This test was completed at 90°F. The results of this test are noted in Figures 34 and 35. The percent cavity closure is shown to be 97%. Figure 25 shows a photograph of a vertical cut of the completed test specimen.

Experiment #5

The purpose of this test was to determine cavity stability and creep at a temperature of 90°F and at successive pressure increments of 1000 psi. This was done in an attempt to determine the maximum safe pressure loading.

The salt core in this experiment had the following dimensions:

Length of core 6-1/2"
 Diameter of core 6"
 Diameter of cavity 2"
 Length of cavity 2"

Depth to top of cavity 2-1/4"

Original volume of cavity . . . 100 ml

Each pressure loading was then maintained constant for a period long enough to establish structural equilibrium of the cavity. This was observed by noting a leveling off of both mercury volume displacement and vertical deformation.

Figure 38 indicates the salt cavity volume change for different pressure loadings. It should be noted from the graph that the first appreciable and continued mercury volume displacement occurred at 6000 psi, with a small change continuing to occur after a loading of 3000 psi.

Figure 40 shows this same experiment and indicates a continual increasing of the slope (increased mercury displacement) as pressure loadings are increased. This particular curve clearly illustrates that a levelling off fails to occur after a pressure loading of 5000 psi.

Figure 36 of Exp. 5 shows vertical deformation of the salt core. Decreased cavity volume checks very well with the mercury displacement measurements. A constant value was reached for pressure loadings up to and including 4000 psi. For loadings above 4000 psi, the vertical movement indicated continual deformation.

Figure 37 also shows vertical deformation for increased pressure loadings again showing that above 4000 psi continuous deformation would result. Figure 26 shows a photograph of a vertical cut of the salt core after test completion.

Experiment #6

The purpose of this test was to determine cavity stability and creep at a temperature of 200°F and a loading of 200,960 lbs. (8000 psi).

The test core of experiment #6 had the following dimensions:

Length of core	6-3/4"
Diameter of core	6"
Diameter of cavity	2"
Length of cavity	3-1/4"
Original volume of cavity with heating element	145 ml
Original volume less heating element	173.4 ml

On this particular test, the temperature measured 1/4" deep into the side of the cavity was recorded and maintained at 200°F. The temperature at the outer edge of the salt was recorded and maintained at 175°F (Figure 41).

Heat was supplied by an inside mounted heater approximately 3" long (commercial type). The cavity was made longer to incorporate the heating element. This particular cavity had a volume of 173.4 ml compared to approximately 100 ml for cavities of the previous experiments. Although the heating element was enclosed in a stainless steel sheath it was destroyed at the end of the test by salt movement. Fortunately approximately fifty hours elapsed before this occurred. As may be noted from Figure 47, very little additional cavity closure occurred in this test at 200°F as compared to the test at 90°F.

Figures 41 and 42 show the vertical deformation of the salt core and volume displacement respectively. Figure 27 is a photograph of the salt core after test completion.

Experiment #7

The purpose of this test was to determine cavity stability and creep at a temperature of 400°F and at successive pressure increments of 1000 psi up to a maximum pressure of 8000 psi. Pressure was applied in 1000 psi increments in order to evaluate the maximum safe loading.

The salt core of experiment #7 had the following dimensions:

Length of core	6-5/8"
Diameter of core	6"
Diameter of cavity	2"
Length of cavity	2"
Original cavity volume	100 ml

On this test, the heat was applied from the outside of the steel test cylinder.

In order to establish the pressure at which rapid cavity closure would occur, stresses up to 8000 psi in 1000 psi increments were applied and held constant for approximately forty-eight hours. Figures 43 and 44 show the results of this test. An appreciable change occurred between 3000 psi and 4000 psi as noted by both cavity closure and vertical deformation. It should also be noted that at 15,918 psi, the cavity closed

completely in approximately 30 hours after application of this stress. However, from Figure 42 it is noted that the vertical deformation of the salt core did not stop as soon as the cavity had closed completely. This was explained as soon as the core was examined after the test. Salt had flowed up the 3/4" casing. This, of course, accounted for the continued vertical deformation even though the cavity was completely closed. Figure 28 is a photograph of the salt core after test completion. Decided movement of the salt at 400°F occurred at pressures greater than 3000 psi. Structural equilibrium was obtained at pressure loadings less than 3000 psi.

Experiment #8

The purpose of this test was to determine cavity stability and creep at a temperature of 300°F and at successive pressure increments of 1000 psi up to a maximum pressure of 8000 psi. Each pressure loading was held constant for approximately forty-eight hours.

The test core on experiment #8 had the following dimensions:

Length of core	6-3/4"
Diameter of core	6"
Diameter of cavity	2"
Length of cavity	2"
Original cavity volume	100 ml

On this test the heat was applied from the outside as in experiment #7. Again, in order to establish a safe pressure

differential across the cavity, pressures were increased in 1000 psi increments. The temperature was maintained constant at 300°F. Figures 45 and 46 show the results of this test. The cavity exhibited good stability through pressure loadings of 4000 psi. An immediate increase in cavity closure was noted at 5000 psi. This in turn was verified by continued vertical deformation. Figure 29 is a photograph showing the salt core after test completion.

General Discussion

Figure 47 shows the cavity closure vs time for six experiments. Experiments #2 and #4 are shown for a maximum possible machine loading of 15,918 psi at 80°F and 90°F respectively. Those two experiments after approximately 60 hours show the cavities to reach the same rate of closure. It should be noted that the graph shows the fractional part of cavity closed at each time interval rather than the actual rate of closure.

The two lower curves (Figure 47) for experiments #5 and #6 show cavity closure for the same loading of 8000 psi but for temperatures of 90°F and 200°F respectively. As expected, the cavity at 200°F shows a greater percentage closure.

A temperature of 200°F would be expected between 5500 and 6500 feet according to the geothermal gradients given by Earl A. Nichols.⁽⁷¹⁾ However, there have been instances where abnormally high temperatures have been found in salt domes.

FIG. 47. CAVITY CLOSURE.

FIG. 48. CAVITY CLOSURE V.S. PRESSURE.

In tests conducted at 400°F, and later at 300°F, complete cavity closure occurred for an 8000 psi loading at 400°F in approximately 30 hours. This compares to a 50% closure for 8000 psi at 300°F, a 24% closure for 8000 psi at 200°F, and a 20% closure for 8000 psi at 90°F.

Figure 48 shows a plot of cavity closure vs pressure for temperatures of 90°F, 200°F, 300°F, and 400°F. All points were taken after a loading time of 72 hours. In some instances these points were taken from curves extrapolated to the time of 72 hours. A decided increase in cavity volume closure occurred at 3000 psi and 400°F, 4000 psi and 300°F, 5000 psi and 90°F-200°F. Temperature then becomes a very influential factor above 300°F. This was as anticipated since the lower temperature ranges (up to 300°F) are not expected to appreciably alter the strength characteristics of salt masses. This should point out that temperatures from the earth's geothermal gradient will not be significant in altering the strength of cavities above depths of 6000 feet.

Table 1 shows a summary of all tests with per cent cavity closure and vertical salt core deformation given at the end of 25, 50, and 100 hours. The 100 hour figures are extrapolated values for most of the tests.

The so-called critical areas (area of 6" salt core minus area of 2" cavity) has been used in computing the stress shown in the various curves (Figure 39). For a maximum machine loading of 400,000 lbs. this stress was calculated to be 15,918 psi.

TABLE I
SUMMARY TABLE OF RESULTS

EX P No.	TIME HRS	TEMP °F	ORIGINAL CAVITY VOL, ML.	STRESS PSI	PERCENT CAVITY CLOSURE	VERTICAL DEFORMATION OF SALT CORE in/in
2	50	80	83.6	15918	78	.0480
2	100	80	83.6	15918	85*	.0515
2	150	80	83.6	15918	-	.0530
3	8	100	88	15918	59	.0470
4	50	90	107.5	15918	74	.0530
4	100	90	107.5	15918	85	.0570
4	150	90	107.5	15918	91	.0595
4	200	90	107.5	15918	96	.0620
5	50	90	100	1000	1*	.0055*
5	100	90	100	1000	1*	.0055*
5	25	90	100	2000	3.2	.0112
5	50	90	100	2000	3.2*	.0112*
5	100	90	100	2000	3.2*	.0112*
5	25	90	100	3000	4.9	.0142
5	50	90	100	3000	5.1	.0144
5	100	90	100	3000	5.1*	.0144*
5	25	90	100	4000	6.7	.0168
5	50	90	100	4000	7.1	.0172
5	100	90	100	4000	7.5	.0175
5	25	90	100	5000	8.9	.0190
5	50	90	100	5000	9.3	.0195
5	100	90	100	5000	10*	.0205*

*INDICATES EXTRAPOLATED VALUES

TABLE I - Cont'd
SUMMARY TABLE OF RESULTS

EX P No.	TIME HRS	TEMP °F	ORIGINAL CAVITY VOL, ML.	STRESS PSI	PERCENT CAVITY CLOSURE	VERTICAL DEFORMATION OF SALT CORE in/in
5	25	90	100	6000	11.5	.0219
5	50	90	100	6000	12.6	.0225
5	100	90	100	6000	14.9*	.0240*
5	25	90	100	7000	15.4	.0247
5	50	90	100	7000	16.6	.0254
5	100	90	100	7000	19.2*	.0267*
5	25	90	100	8000	22.4	.0282
5	50	90	100	8000	25.5	.0295
5	100	90	100	8000	31.8*	.0319*
6	25	200	173.4	8000	24.8	.0432
6	50	200	173.4	8000	30.6	.0540
8	25	300	100	1000	2	.0108
8	50	300	100	1000	2	.0108
8	100	300	100	1000	2*	.0108*
8	25	300	100	2000	5	.0148
8	50	300	100	2000	5	.0148
8	100	300	100	2000	5*	.0148*
8	25	300	100	3000	7	.0170
8	50	300	100	3000	7	.0170
8	100	300	100	3000	7*	.0170*
8	25	300	100	4000	9	.0192
8	50	300	100	4000	9	.0192
8	100	300	100	4000	9*	.0192*

*INDICATES EXTRAPOLATED VALUES

TABLE I - Cont'd

SUMMARY TABLE OF RESULTS

EX P No.	TIME HRS.	TEMP °F	ORIGINAL CAVITY VOL, ML.	STRESS PSI	PERCENT CAVITY CLOSURE	VERTICAL DEFORMATION OF SALT CORE in/in
8	25	300	100	5000	14	.0235
8	50	300	100	5000	16	.0256
8	100	300	100	5000	19*	.0270*
8	25	300	100	6000	22	.0289
8	50	300	100	6000	24	.0292
8	100	300	100	6000	28*	.0310*
8	25	300	100	7000	31	.0339
8	50	300	100	7000	36	.0357
8	100	300	100	7000	45*	.0395*
8	25	300	100	8000	48	.0445
8	50	300	100	8000	55	.0482
8	100	300	100	8000	68.5*	.0565
7	25	400	100	1000	5	.0140
7	50	400	100	1000	5	.0140
7	100	400	100	1000	5*	.0140*
7	25	400	100	2000	9	.0194
7	50	400	100	2000	9	.0194
7	100	400	100	2000	9*	.0194*
7	25	400	100	3000	14	.0239
7	50	400	100	3000	14	.0239
7	100	400	100	3000	14*	.0239*

*INDICATES EXTRAPOLATED VALUES

TABLE I - Cont'd

SUMMARY TABLE OF RESULTS

EX P No.	TIME HRS.	TEMP °F	ORIGINAL CAVITY VOL, ML.	STRESS PSI	PERCENT CAVITY CLOSURE	VERTICAL DEFORMATION OF SALT CORE in/in
7	25	400	100	4000	23	.0295
7	50	400	100	4000	28	.0313
7	100	400	100	4000	36*	.0350*
7	25	400	100	6000	45	.0432
7	50	400	100	6000	51	.0462
7	100	400	100	6000	63*	.0525*
7	25	400	100	8000	98	.0645
7	50	400	100	8000	100	.0730
7	100	400	100	8000	100*	.0850*

*INDICATES EXTRAPOLATED VALUES

From strain gages located on the outside of the cylinder the stress distribution on the salt core was calculated. This is shown in Figure 49. Full acknowledgement is hereby given to Dr. Shosei Serata and Dr. E. F. Gloyne for the discussion concerning Figure 49 and the various derived equations.⁽⁸⁶⁾ As may be seen in Figure 14 an axial loading was applied to the top of the salt specimen. Since the salt core fit so closely a lateral pressure was produced by the reaction of the steel cylinder against the lateral expansion of the salt. The stress distribution around the cavity was calculated from the axial and lateral pressures applied. From the measured strain on the outside of the cylinder, Σ_t , the lateral pressure was calculated from the following equation:

$$\Sigma_t = \frac{-1}{E(w^2 - 1)} \left[-P_i \left\{ (1 - \nu) + \frac{b^2}{r^2} (1 + \nu) \right\} \right. \\ \left. + p_o \left\{ (1 - \nu)w + \frac{b^2}{r^2} (1 + \nu) \right\} \right] + \frac{-\nu \sigma_2}{E}$$

where:

w = ratio of outside diameter to the inside diameter of the steel cylinder

Σ_t = tangential strain obtained by SR-4 strain gage on the outside of the steel cylinder

P_o = pressure acting outside of the steel cylinder = 0

σ_2 = axial stress in the steel cylinder = 0

r = radius at which the strain is measured = b

P_i = confining pressure on the salt

ν = Poisson's ratio

FIG. 49. STRESS DISTRIBUTION AND REDUCTION OF RADIUS IN PROCESS OF CREEP CLOSURE OF CYLINDRICAL CAVITY.

Pi may be determined from:

$$P_i = \frac{E(w^2 - 1)}{2} \Sigma_t$$

For a tangential strain, Σ_t , of 730×10^{-6} the confining pressure on the salt, P_i , was calculated to be 13,700 psi. Several calculations with varying assumptions then were made. If the salt was considered to be elastic the maximum differential stress calculated a value of 31,000 psi. This curve is shown on Figure 49. The assumption was then made that the salt was deforming plastically and the stress distribution calculated again. This curve is also shown on Figure 49 and shows a maximum differential stress of 13,000 psi. This is still a greater stress than salt can withstand. This excess of differential stress is the driving force of the creep closure, until stress is reduced to the point at which the salt can withstand creep. This stress reduction is established by reducing cavity volume. This process of establishing a structural equilibrium is, in principle, the same as that for the development of a plastic zone.

The differential stress allowable in the salt around a cylindrical cavity is obtained from the relation:

$$\sigma_t - \sigma_r = -\frac{2}{\sqrt{3}} \sigma_o = -1.15 \sigma_o$$

σ_o = absolute value of the yielding strength
of salt (assuming salt ductile)

Therefore the salt will creep into the cavity until the differential stress reaches $1.15 \sigma_o$.

The relation between the strain reading outside of the steel cylinder, Σ_t , and the final radius of the reduced cavity, a' , can be obtained by equating P_i to σ_r at $r = b$ as:

$$-P_i - \frac{2}{\sqrt{3}} \sigma_o \ln \frac{b}{a'} = - \frac{E(w^2 - 1)}{2} \Sigma_t$$

$$- \frac{\sqrt{3}}{2\sigma_o} \left\{ -P_i + \frac{E(w^2 - 1)}{2} \right\}$$

P_i = internal pressure of the salt cavity

b = outside diameter of the salt

E = Young's modulus at the steel cylinder

w = ratio of the outside diameter to the inside diameter of the steel cylinder.

The radius of the reduced cavity, a' , can be calculated from strain gage data.

In Figure 49 the reduced diameters of the cavity are shown at equilibrium with assigned σ_o values of 10,000 psi, 6000 psi, and 3000 psi.

For a pressure loading of $P_z = 15,918$ psi a completely sealed cavity would reduce to the a' (radius) labeled for each case before reaching structural equilibrium. For example if the salt exhibited a strength equivalent to $\sigma_o = 3000$ psi, then the cavity would be almost completely closed. For an assigned $\sigma_o = 10,800$ psi, no closure would result, and approximately 60% closure results for an assigned $\sigma_o = 6000$ psi.

It should be noted, however, that complete cavity closure occurred at a stress loading of 8000 psi at 400°F after approximately 30 hours. This indicates that the preceding theoretical calculations do not strictly apply to the experiments performed. The theoretical calculations are for a perfect cylinder having no outlet. From experiment #7 it is noted that salt actually flowed out the cavity into the 3/4" casing after complete cavity closure had resulted.

PERMEABILITY TESTS

Salt samples as removed from the Grand Saline Mine (Figure 16) exhibited numerous fractures indicating possible permeability (ability to transmit fluids). The unit of permeability is the darcy. A material having a permeability of one darcy will permit the flow of a homogeneous (one phase) fluid of one centipoise viscosity through a cross-sectional area of one square centimeter at the rate of one cubic centimeter per second for a pressure gradient of one atmosphere per centimeter in the direction of flow.

It was decided to run a permeability test on a representative sample. At first, this was attempted on small one inch square by one inch long samples. Several tests were run utilizing a rubber seal and the Fancher type core holder. Both nitrogen and air were used for these permeability tests. However, extreme difficulty was experienced in attempting to maintain a seal on the outside of the small salt core by the rubber enclosure. Small irregularities in the salt allowed the by-passing of some air or nitrogen. However, it was felt that several tests were successful, and permeabilities of 1.2, 1.35, 1.10, and .95 millidarcys respectively were found.

Since the preceding test represented a very small specimen, a larger specimen (12.70 cm in length by 4.57 cm square) was also tested. This large specimen was mounted in a lucite cylinder. The salt itself was held in position and sealed by a thermal setting epoxy resin (Hysol). See Figures 50, 51, and 52. Each end was tapped for copper tube connections. The permeability was checked with both nitrogen and kerosene. The kerosene was colored with a red dye such that the possible path of any moving fluid could be followed. The permeability in this instance was found to be 0.331 millidarcys with kerosene and 1.09 millidarcys using nitrogen. The 1.09 md. obtained using nitrogen was the true or liquid permeability. In other words, a plot of apparent permeability versus the reciprocal of the mean pressure gave a value of 1.09 millidarcys at infinite mean pressure. This was obtained by extending the straight line plot to zero for the reciprocal of the mean pressure.

All permeabilities were calculated from Darcy's equation of linear flow:

$$Q_m = \frac{K A \Delta P}{\mu L}$$

Q_m = mean flow rate, cc/sec

A = cross-sectional area of core, cm^2

FIG. 50. ASSEMBLED PERMEABILITY
TEST EQUIPMENT.

FIG. 51. SALT CORE CONTAINED IN
LUCITE HOLDER.

FIG. 52. SALT CORE CONTAINED IN
LUCITE HOLDER.

ΔP = difference in upstream and downstream pressure, atmospheres

μ = viscosity of fluid, centipoise

L = length of core, cm

In all cases some 6 or 7 different flow rates and pressures were taken.

The flow rate divided by the area ($\frac{Q_m}{A}$) was then plotted against the pressure drop divided by the length ($\frac{\Delta P}{L}$). The best straight line was drawn through these points. The slope of the line multiplied by the viscosity gave the answer in millidarcys. In other words $K = \mu \left(\frac{Q_m/A}{\Delta P/L} \right)$.

These particular samples exhibited some permeability. Considerable time was spent in core examination in an attempt to determine whether or not there had been a possibility of damage to the sample. This particular sample had been brought from the Grand Saline Mine in a large block. It had then been sawed out to a smaller block and later reduced to its final test size. Certainly none of the salt crystals showed any permeability. The red colored kerosene showed the fluid followed along the fracture or cleavage planes.

From all field tests on underground storage cavities there is no evidence that permeability exists under pressure. This is one phase of this project which warrants further extensive investigation. It is the author's opinion that little or no permeability exists under actual underground conditions. From Table II, "Condensed Questionnaire Tabulation," in the Appendix

it is noted that no leaks have been noted in cavities when fluid pressure was held at the surface. Some of these pressure tests were maintained for as long as 72 hours with no drop in pressure. If salt under actual over-burden pressure and earth temperature had any permeability, certainly a drop in pressure should have occurred in 72 hours. It is also known that salt mines in Germany have been excavated to within 30 feet of hydrocarbon gases and yet no gas was ever detected in the shaft. An oral check with various oil companies confirmed that salt after being brought to the surface exhibited some permeability--ranging from less than one millidarcy to 5 millidarcys in some instances.

It is evident from these tests that permeability tests should be conducted under pressure and temperature conditions, and should be done in any continuation of the over-all project.

A P P E N D I X

LITERATURE SURVEY

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INTRODUCTION

In compiling all available information on the feasibility of storing atomic reactor wastes in washed out salt domes, a complete literature survey on the storage of liquefied petroleum gases has been conducted. The following types of storage have been used for liquefied petroleum gas (LPG) products:

1. Above ground tanks
2. Dissolved cavity in salt domes
3. Dissolved cavity in salt beds
4. Excavated chambers
5. Abandoned mines
6. Natural caverns
7. Quarries
8. Permeable reservoirs
9. Clay pits

A breakdown of the storage facilities as listed by the National Petroleum Council is as follows: (65)

Salt Domes	35.8%
Salt Beds	39.3%
Mined Lime	0.1%
Mined Shale	2.6%
Mined Chalk	0.5%
Abandoned Oil and Gas Wells	16.3%
Water Sands	1.9%
Abandoned Rock Quarry with Floating Roof	<u>3.5%</u>
Total	100.0%

It should be noted that 75% of the total storage of LPG products is in salt domes and salt beds.

This report is limited to a consideration of salt domes for the storage of atomic reactor fuel wastes. From the entire preceding listed groups of possible storage, the salt dome

seems to offer the best possibility. In domes the salt mass can be expected to be relatively free of water insoluble materials. Sulphur is sometimes found on the flanks of salt domes, but not in the main salt mass itself. The salt mass, in making its original extrusion toward the surface, may have picked up some sand and other insoluble materials. This may be particularly true for over-hanging salt domes. Sand has been reported in salt domes of the over-hanging type. For this reason the entire salt mass should be cored during drilling operations. Reference should be made to the section on "Drilling Operations--Coring" and to the geological report concerning this same project for a more detailed analysis of salt domes, possible impurities, etc.

SELECTION OF THE DOME

Several items must be considered before the final selection of a suitable dome is made. They can be listed as follows:

A. Transportation

Many of the domes are located such that transportation problems will be encountered. If the reactor fuel wastes are to be transported by rail, a railroad must be within a reasonable distance from the dome selected. If the reactor fuel waste is not transferred to trucks from the railroad, then suitable piping facilities must be provided, or a rail spur must be built to get the wastes to the site.

Domes located in marsh lands will offer expensive transportation problems. However, it is likely that such areas will not be inhabited, and will offer greater desirability from a safety standpoint.

B. Geology

This topic has been covered in detail in the geological report, but the following factors should be emphasized.

1. Boundary Conditions--The dome itself must be defined as to shape. It may be possible that this information is available from oil companies operating in the area. If oil is being produced from the flanks of these domes then electric logs and possibly structure maps should be available. If this information is not available, it is possible that the dome can

be defined from seismic data. Of course the drilling and coring of some wells on the flanks of the domes may be needed to define the domal structure.

2. Depth--From strength tests it has been determined that the maximum depth is approximately 3000 feet. This assumes the rock over-burden pressure to be 1.0 psi per foot, and that temperature of 300°F will not be exceeded. Since the cavity must always be emptied of liquid before the injection of any reactor fuel wastes, the unfortunate circumstance of always having an empty cavity to contend with will exist. If the cavity could be left full of fluid, then a greater depth would be feasible. In some areas the over-burden pressure can be expected to be as low as 0.75 psi per foot and the depth limitation can be extended to 4000 feet. If some liquid can be placed in the hole, and subsequently displaced with the reactor wastes, then the depth limitation can be extended since the cavity will be full of liquid at all times.

C. Availability

Once the decision has been made to use salt domes for the storage of atomic reactor fuel wastes, it will then be necessary to secure property leases on suitably deemed known domes. Since the major oil companies in the United States are utilizing these domes for the storage of liquefied petroleum products, the availability of these domes can be expected to be somewhat difficult. However, the domes located in

inaccessible spots should be available. The property in question could be leased similar to the handling of oil and gas leases or possibly bought outright.

D. Power Source

It would be wise to examine the nearness of electric power to the site. It is almost a certainty that electric power will be needed to run the down-the-hole pump to empty the cavity of brine water before the injection of atomic reactor fuel wastes. The pump used in pumping wash water could also conveniently be an electrical centrifugal pump.

ACQUISITION OF PROPERTY

The acquisition of leases and/or fee property can be expected to be on a competitive basis. The underground storage of liquefied petroleum gases is becoming increasingly popular. Although several storage cavities may be incorporated in any one dome, it is believed that it would not be good practice to attempt the storage of liquefied petroleum gases and atomic reactor fuel wastes in the same dome even though they could be stored in separate cavities. Therefore, the leasing or buying of property would be limited to areas not utilized by the petroleum industry.

WELL LOCATION

At the present time, it is believed that a long cylindrical shaped cavity of small diameter will be the most desirable for reactor fuel waste storage. The long cylindrical cavity will afford the most area exposed per unit volume of waste, and thereby offer the best heat conductance. Since many of these domes may be over a mile in diameter, it is very probable that several cavities can be created in one dome.

From the paper, "Formation Strength Considerations in Salt Cavern Construction and Operation," by D. F. Johns, Shell Oil Company, the following information is given regarding cavity spacing in an individual dome:

For a unidirectional or hydrostatic stress field, the stress concentration produced around single openings is negligible at a distance of one diameter from the boundary of the opening.

If this statement is accepted, it will be useful in determining the spacing for more than one cavity in any one dome. Of course, this distance must be checked for adequate heat conductance, and some additional distance should be allowed for a safety factor.

Of course, the wells must be located so that they will not be too close to the flank of the dome, since the likelihood of any possible insolubles will be nearer to the flank. By coring all wells, the presence of any insolubles will be definitely established. All surface obstacles will have to be removed in order to insure the correct location of the well itself.

WASH WATER

The normal procedure for creating a cavity in salt is to utilize a wash water which is pumped into the well. The leaching action of the water creates the cavity in the salt. The problem of furnishing wash water then becomes a necessity for every salt cavity created. Wash water may be of the following types:

1. Fresh
2. Sea
3. Produced Salt Water
4. Plant Disposal Water

Fresh water is the most desirable of the previously mentioned waters, but in some instances it can be expensive or not available. However, on the Gulf Coast of Texas and Louisiana where a large number of the salt domes are located, ample fresh water should be available. If a lake, river, stream, or fresh water well is not in the immediate vicinity, water may be piped to the well location. It should be kept in mind that water pump rates of from 200-800 bbls/hr may be necessary. Actually, in some areas the wash rates have been curtailed because of limited availability of fresh water. This has been particularly true in some areas of West Texas.

Another source of wash water that should be considered is sea water. Since a great number of the salt domes are located along coastal areas and possibly in the Gulf itself, the use of sea water should be considered for wash water.

Sea water contains approximately 35,000 parts per million. A saturated brine at normal temperatures contains 260,000 ppm of sodium chloride.

Another source of wash water in some areas will be field disposal water that has been produced from oil wells, separated from the oil, and made ready for disposal to a pit or disposal well. Such water may contain 50,000-150,000 ppm of dissolved salts. In the event that fresh water or sea water is not available, then field disposal water may have to be considered for use as wash water.

DISPOSAL OF SATURATED RETURN WATER USED IN WASHING SALT DOME STORAGE CAVITIES

Before the beginning of any cavity excavation by washing with water, serious consideration must be given to the means of disposing of the saturated or partially saturated return wash water. This water cannot be pumped into lakes, rivers, streams, or onto the land itself because of its detrimental action.

There are at least three feasible methods available for the disposal of the salt-saturated wash water. These include: (1) injection into porous or cavernous subsurface formations; (2) evaporation in earthen pits; and (3) batch dumping or pipelining of the water into the Gulf of Mexico. Each method has advantages and disadvantages, and deciding the most practical and economical method may depend more on the locality of the salt dome than any other factor.

A more detailed analysis of the preceding methods is:

Subsurface Injection: In areas where relatively shallow salt-water sand or cavernous formations exist below the fresh water table, the injection of the return water into these beds is quite convenient and feasible. The chief limitations to this method of disposal lie in the capacity of the bed and its depth. However, since highly cavernous formations are usually associated with cap rocks of salt domes, it is entirely possible that the return water may be injected into such a

zone. Some consideration should be given to the idea of setting an additional casing string on the cavity well itself and injection of the return water down the annular space. Also additional disposal wells, where necessary, could be drilled to suitable formations adjacent to the cavity being washed. Serious treating problems may arise if the water is injected into sandstone formations because of plugging of the sand face. However, this may be overcome by backwashing the well, acidizing, fracturing, or by some other means.

Evaporation Pits: The limitations of this type of disposal system are immediately evident. For pits that are not to be lined with asphalt, the surface terrain must be suitable to the creation of pits which will not allow the salt water to seep out over the area or into the streams or fresh water aquifers. Also, quite a large pit volume is usually necessary for an adequate storage capacity. This method must be restricted to use in the more arid regions since the disposal depends on evaporation. It is quite doubtful that this method of disposal could be used when washing storage cavities in domes along the Gulf Coast. However, where applicable, this method is probably the most economical type of disposal.

The following procedure should serve as a guide in the construction of an asphalt lined pit. (113)

- (1) Perform the necessary clearing and excavation.
- (2) Prepare the storage pit surface. This involves compacting, grading and rolling until the pit base levels do not exceed a tolerance of $1/2$ ", and the pit surface is dry and firm.

- (3) Prime the pit with a coat of medium curing cut-back asphalt.
- (4) Apply a coat of catalytic asphalt sufficient to provide a membrane lining of 3/8" minimum thickness.
- (5) The membrane lining should then be covered with earth of not less than 6" in depth to secure the lining and prevent damage from wave action.

Disposal into the Gulf: For the disposal of the return water used for washing cavities in salt domes within 5-10 miles of the Gulf of Mexico or its inlets or in domes under the continental shelf, dumping the water into the Gulf is probably the most practical and economical method available. Certainly no other method is worth consideration for domes lying under the continental shelf. Of course, the economies of this method for inshore domes would depend entirely upon the distance to the Gulf and the terrain covered by the disposal line.

Conclusion: Many factors control the selection of the method of disposal. It is doubtful that any economic generalizations could be made on the relative merits of any method. Rather, each case must be examined independently, and the disposal method chosen on the basis of the considerations listed herein.

DRILLING OPERATIONS

The drilling operations include everything from moving the drilling rig onto location until washing procedures are ready to begin.

A. Drilling Rig

The drilling rig required to drill the original hole, set casing, and perform other normal operations will vary as to specifications depending upon the depth to be drilled. For contract rigs the costs will normally be on a footage basis until the top of the salt cap is reached. A footage contract, including cost per foot, coring, logging, etc. will vary depending upon the locality. Day rates most likely will prevail after reaching the cap, since lost circulation and other troubles are not uncommon. A day rate basis of \$500-\$750 per day may be anticipated.

B. Roads

Provisions must be made for adequate roads to reach the well location. Precautions must be made for unfavorable weather conditions. Temporary board roads may be used originally until the cavity has been tested and proved suitable for storage. At that time suitable permanent roads should be constructed.

C. Water

Once the rig has been set up on location provisions must be made to secure water for mixing mud, cement, etc. Since

wash water must be provided for leaching the cavity this water can also be used for mixing mud, etc.

D. Drilling Fluid

To overcome the effects of the three contaminants most likely to be encountered by the mud, (1) Cement, (2) Anhydrite, and (3) Salt, one of the four following treatments should suffice. (63)

- (1) For muds having had only minor alkaline tannate or phosphate treatment, the use of sodium bicarbonate is the most economical method.
- (2) For cement contaminated muds with a pH above 9.5, soda ash or sodium carbonate is regularly used.
- (3) If phosphates are commonly used as dispersing agents, they may be used to treat cement. Sodium acid pyrophosphate or sodium tetrphosphate may be used.
- (4) For alkaline tannate muds the use of quebracho is effective.

The cap-rock immediately above the salt mass is normally anhydrite. The two best methods for treating anhydrite contamination are: (63)

- (1) Caustic-Quebracho, Bentonite and Driscose, and
- (2) Caustic-Quebracho, lime and Driscose or starch.

Immediately beneath the anhydrite cap the salt mass itself will be encountered. The salt concentration of the mud will immediately become too high to be handled as a fresh water system. Special salt-water clays of the Florida Fullers' earth type can be used. The usual practice is to discard about one-half of the old mud, add salt to saturation, and then add the necessary salt-water clay and starch to give the proper

viscosity. In some instances the salt may be penetrated with saturated water alone. Excessive hole enlargement results if fresh water mud is used. Failure of the drill pipe is enhanced because of greater vibration in the enlarged hole.

E. Casing and Bit Program

Reference should be made to Table II, "Condensed Questionnaire Tabulation," for typical casing and hole sized used for LPG storage projects. Provision should be made to assure a final completion string of at least 7" casing. This will allow ample clearance for the use of 4-1/2" drill pipe for wash pipe and will give sufficient clearance for unavoidable fishing jobs. If lost circulation zones are known or can be accurately predicted the casing program should account for these zones. Some recommended casing and bit programs for a dome on the Gulf Coast are as follows:

<u>Conductor String</u>		<u>Surface String</u>		<u>Intermediate String</u>		<u>Oil String (Completion)</u>	
<u>Bit Size</u>	<u>Casing Size</u>	<u>Bit Size</u>	<u>Casing Size</u>	<u>Bit Size</u>	<u>Casing Size</u>	<u>Bit Size</u>	<u>Casing Size</u>
36	30	24	20	15	10-3/4	9-5/8	7
30	24	20	16	15	10-3/4	9-7/8	7

All of these and possibly another intermediate string may or may not be necessary. It is entirely possible in some areas to run only surface casing and the completion string.

1. Conductor String--In many areas where the surface soils are very loose and unconsolidated or in a swamp marsh, the use of conductor pipe is necessary to stabilize the cellar floor and restrain the hole walls to a depth where the walls will be self-supporting. Depending upon surface soil conditions these strings may vary from one thirty-foot joint to several hundred feet.

2. Surface String--In most states the setting of surface casing is required by law. The primary purpose is to seal off fresh water sands. The required depth will vary from a few hundred feet to several thousand feet depending on water bearing zones. The surface string provides a foundation and support for the well-head connections and supports all additional strings run in the well. The connection or junction between the well-head and the surface string must be rigid and strong because of the high compressive stresses placed upon it. The surface string also offers the first connection for blow-out preventers and in turn gives control for high-pressure sands encountered at a lower depth.

3. Intermediate String--The intermediate string is also commonly known as a "protector string." Intermediate strings serve various purposes, but in the case of salt domes, they generally become a necessity to seal zones of lost circulation. In the vicinity of the anhydrite cap, usually encountered above salt domes, very porous zones may be present. These zones are

so porous that drilling fluid is lost and circulation to the surface becomes impossible. In many instances lost circulation material and cement squeeze jobs will not remedy the situation, and therefore, the setting of an intermediate casing string is necessary. If two or more of these zones are encountered then two or more intermediate strings may be required.

4. Completion String--The final string of casing normally set in most oil wells is more commonly referred to as the "oil string." It serves as a receiver for all-down-the-hole equipment such as tubing, packers, pumps, etc. In the case of salt domes the completion string is generally set several hundred feet into the salt. This string then serves as the top of the cavity itself. Therefore, it must be deep enough into the salt to assure that leakage will not occur from an upward migration.

F. Cements

In cementing the various casing strings, a variety of cements have been utilized for strings used in connection with LPG storage. It is deemed advisable to cement all strings all the way to the surface. This will be an additional precaution to eliminate any possibility of leaks. Cement behind the pipes will also serve as additional protection in the event of corrosive fluids.

Reference is made to Table II, "Condensed Questionnaire Tabulation," showing the various types of cements that have been used.

<u>Type</u>	<u>Number of Companies</u>	<u>Remarks</u>
Salt Saturated Slurry	14	(In some cases used only in contact with salt)
Pozmix (made by Halliburton Oil Well Cementing Co.)	2	
Regular Common Cement Slurry	15	
Regular Common Cement w/Gel.	1	(Various percentages of gel used)
Resin	4	(Spotted around bottom)
Sulfate Resistant Cement Slurry	1	
Calcium Chloride Gel	1	

G. Detection of the Salt Cap

For a planned drilling program to proceed smoothly the salt cap (usually anhydrite) should be detected immediately upon entry by the drilling bit. Detection may be by one of the following methods:

1. Sample Returns--By making a continued check on the return of bit cuttings picked up from the mud return line, the anhydrite can be found in the cuttings. If it is suspected that drilling is proceeding in the immediate vicinity of the salt cap, a few feet should be drilled, the drilling stopped, cuttings

circulated to the surface. By checking mud velocities in the hole, the time of return of the cuttings can be calculated.

2. Coring--Since it is deemed advisable to core all the salt section, the coring can be started early enough to include all the salt cap. In this manner the salt cap will be picked up immediately upon examination of the cores. On a project of this nature coring the entire section from approximately 200 feet of the formation above the cap-rock to the desired depth in the massive salt is imperative. The core size should be at least 3-1/2" in diameter with a 6-1/8" diameter bit and the ratio of the core diameter to the bit diameter should be as large as possible.⁽³²⁾ It will always be wise from a recovery standpoint to cut as large a diameter core as possible. A double barrel tube should be used so that the core will be retained in the inner barrel. A diamond bit will do an excellent job and is to be preferred, though good results have been obtained also with roller cutters and drag type bits.

3. Well Logging--Once the cap has been drilled and drilling is proceeding into the salt, the cap may be pin-pointed by the use of one of numerous types of electric well logging instruments.

Every well should be logged at least once and possibly with several types of logs. The various logs will aid in determining the position of the salt cap, and may be helpful in detecting stringers or insoluble layers that might exist in the salt mass.

The log best adapted for the distinction between salt and anhydrite is the Short Interval Velocity Log.⁽¹⁰⁰⁾

WASHING OPERATIONS

In order to reduce costs during washing operations the large drilling rig used to drill the original hole, set casing and tubing should be replaced by a small workover unit. This small unit does not necessarily have to be on the job at all times, but need only be used to re-position the tubing or liners.

This small unit must be capable of handling the wash tubing, the floating liner, and must be capable of picking up 3000 feet of 7"-32 lb/ft casing or $(3000)(32) = 96,000$ lbs. Once the floating liner is in place and the wash tubing on bottom, the small unit will be required to pick up the wash tubing and the floating string.

This will occur at various time intervals depending upon the leaching rate. It is very probable that if several cavities in the same vicinity are being washed, one portable work-over unit will be able to serve all of them.

A. Washing Procedures

Numerous procedures have been utilized for the washing of salt cavities.

1. Top-hole Method

a. One Wash String (Reverse Circulation): Reference should be made to Figure 53, for the following discussion of this type of washing procedure. This method is sometimes

FIG. 53. TOP-HOLE METHOD.

FIG. 54. ONE WASH STRING-BOTTOM HOLE METHOD.

FIG. 55. COMBINATION TRUMP-BLANK, WASH PIPE AND LINER RE-POSITIONING METHOD.

referred to as the top injection method. One wash string is utilized; the wash water is injected down the tubing-casing annulus and returned through the tubing. Tubing previously has been run to the bottom of the hole, or it may be lowered at intervals as desired. This method of washing tends to result in an inverted cone shaped cavity. This method is not considered desirable for washing cavities for reactor fuel waste storage. It offers the disadvantages of an undesirable shape and the possibility of washing out behind the casing seat.

b. One Wash String (Normal Circulation): Again the so-called top injection is utilized. Refer to Figure 53. In this method of washing, the wash water is injected down the tubing and the wash water is returned through the tubing-annular space. This method is not considered suitable for reactor waste storage since it also offers the disadvantages of giving an undesirable shape and washing out behind the casing seat. It is believed that a pan-cake shaped cavity results from this method of washing.

2. Bottom-Hole Method--In the bottom-hole method the wash pipe is run to bottom and wash water is introduced into the cavity at the bottom of the hole. See Figure 54. Washing is continued without moving the tubing. Washing by this method has a tendency to develop a bell-shaped cavity. This method also fails to offer a desired shape for reactor waste storage, and some wash out behind the casing seat may result.

3. U-Tube Method--Another method of washing salt cavities sometimes employed is the utilization of two separate wells. However, this method is generally resorted to only after a conventional method has failed because of a stuck wash pipe, stuck drill pipe, etc. By drilling an off-set well, communication is established between the two wells and the wash water is then injected down one well with the return brine water coming out the other well.

4. Combination Trump-Blanket, Wash Pipe and Liner Repositioning Method--The Trump-Blanket Method used in combination with previously mentioned washing procedures is considered to be the best available method used today. Reference is made to Figure 55 for a sketch of this method. This method incorporates an additional wash string. For purpose of explanation it will be beneficial to assign pipe sizes to the various strings. Assume that the last string (completion string of casing) is 13-3/8" casing set 300 feet into the salt mass. To assure no possibility of washing out behind this casing seat assume that a string of 7" (floating string, not cemented) is run to 200 feet below the casing seat of the 13-3/8" pipe. The wash string (4-1/2" drill pipe having a 30 ft perforated section on bottom) is then run to the bottom of the hole which in turn will be the bottom of the cavity. A hydrocarbon "blanket" (kerosene, butane, propane, etc.) is then injected between the 13-3/8" and the 7" pipe. This blanket must extend

below the 13-3/8" casing seat and preferably to within a few feet of the end of the 7" pipe to insure better cavity shape control. Because of its lower density the blanket liquid will remain above the wash water and brine.

Washing is conducted by injecting water down the 4-1/2" drill pipe through the perforations onto the salt and return through the 7" casing - 4-1/2" drill pipe annular space. The hydrocarbon blanket will prevent the water from reaching the casing seat. The 4-1/2" drill pipe is then raised in intervals of approximately 60 feet and washing progresses at each successive interval. Cavity shape and control are obtained by starting from bottom with both strings (spaced at the proper interval) and raising both at successive intervals up the hole. This procedure gives a cylindrical shaped cavity, considered most desirable for the storage of atomic reactor fuel wastes.

5. Combination Trump-Blanket Bottom-Hole Liner Positioning Method--In this method the bore hole is drilled all the way to the bottom. A liner or floating string (preferably 7" casing) is run to a fairly high position in relation to total depth. The wash tubing is run to bottom and left on bottom until washing is completed. A hydrocarbon blanket is always maintained at the end of the liner. Three variables control the cavity development: (1) normal circulation and reverse circulation, (2) positioning of the liner, and (3) location of the bottom of the protective blanket.

In utilizing this method the liner itself is moved upward as washing progresses, but the tubing remains in its initial position at bottom. Open-end tubing will be effective in this instance. It will be necessary to pull tubing every time the liner is to be moved unless the cat-head is capable of picking up the tubing string. Therefore, the positioning of the liner should be accurately studied to minimize the number of times the tubing must be pulled. However, for this procedure the work-over unit need only be utilized when the liner needs to be moved since several days will be spent in washing at each successive interval. A sonic caliper check will be necessary at intervals to determine how often the liner and/or hydrocarbon blanket must be moved.

Field experience has indicated that a roughly cylindrical cavity will be developed from the preceding washing method. However, there are so many variables involved that experience and caliper checks are the only reasonable criteria to be used in cavity shaped development. (104)

B. Wash Water Pumps

Drilling rigs are equipped with pumps for circulating mud. However, since these pumps are generally piston operated positive displacement type pumps, and extreme pulsations and vibrations occur, their use is not recommended. Pulsations aggravate the already present possibility of whipping off the tubing string. If this type of pump is to be used,

pulsation dampners should be installed before the washing procedure begins.

Centrifugal pumps are highly recommended because of the discharge of water at constant rate and pressure. A typical centrifugal pump 200 HP, 4", 7 stage, 7000-9000 bbls/day at 800 psi discharge will do the job successfully. The pump can be skid mounted for moving from one job to another.

C. Cavity Size

In setting up and conducting a washing procedure a means of determining the cavity size must be available. This means that the volume of input and output water should be checked along with the specific gravity of each. From the weight of salt removed and the density of the same, the volume of the cavity is determined readily. Refer to the Appendix to Figure 58 showing "Total Solids, ppm vs Specific Gravity of Water," Figure 56 showing "Resistivity, ohm-meters vs concentration, ppm (micrograms NaCl in water per gram of solution) and Figure 57 showing "Titration Curves for Determination of sodium Chloride and Chloride Content." These curves will assist in making cavity size calculations. In each case the volume of salt in cubic feet can be determined easily. It seems that the most commonly accepted industry procedure for determining cavity size has been a measurement of the specific gravity which in turn allows immediate cavity volume calculations.

For example, assume that a fresh water is being used for wash water and that the effluent brine is 50,000 barrels. Also assume that the wash rate has been controlled to maintain an average specific gravity of 1.10. From Figure 58, a brine of S.G. 1.10 contains 144,000 ppm NaCl. The number of barrels of NaCl per barrel of brine is $\frac{(144,000)(2.59 \times 10^{-6})(1.10)}{5.61}$ = .073 bbls salt/bbl of brine. The total bbls of salt in 50,000 bbls of brine is equal to $(50,000)(.073) = 3650$ bbls of salt. From the International Critical Tables 3:79 it is found that the shrinkage due to solution of NaCl in water is 0.9825. The amount of fresh water in the system is then $(50,000 - 3650)/.9825 = 46,350/.9825 = 47,200$ bbls of fresh water. The volume of the cavity must be the 3650 bbls accounted for plus the salt in the brine in the cavity or is equal to $3650 + x$. The per cent salt in solution for a S.G. = 1.10 is 7.3%. Therefore the following relation must hold true.

$$\frac{x}{3650 + x} (100) = 7.3$$

$x = 287$ bbls salt in cavern
brine solution.

Total cavity volume = $3650 + 287 = 3937$ bbls.

For a pump rate of 1500 bbl/hr a pumping time of 34 hours would be required.

D. Determining Final Cavity Size and Shape

Recently a method has been devised for determining the actual cavity shape and size. This sonar instrument has proven

to be very satisfactory in operation and gives a means of checking the exact cavity shape and size. This device is recommended to detect any abnormalities in shape and size that have occurred during washing. A plastic model may be made of the cavity.

E. Pipe Used in Washing Procedure

From experience in the field it has been found that 2" (2-3/8" O.D.) or 2-1/2" (2-7/8" O.D.) tubing has given some trouble while washing. It has parted in some instances. It is now fairly common procedure to use 4-1/2" Drill Pipe for the wash string since it offers greater stability. The pipe itself is either bull-plugged (closed on the end) or closed by a so-called orange-peel (end pointed and welded closed). The orange-peel is preferred since the bull-plug offers an enlarged shoulder which increases the possibility of stuck wash pipe. The wash pipe itself is then perforated above for any desired distance.

It seems that no set pattern has been followed previously in deciding the size and number of perforations to be used. Open-end tubing is used in many instances. Since it would seem desirable to direct the wash water to a specified interval, the combined area of the perforated or slotted section must not exceed the area of the pipe itself. In this manner the wash water can be directed at the same velocity through the entire interval. One immediate objection to this

restricted interval would be the possible plugging of the perforations if reverse circulation is started. Another procedure to prevent "whipping" of the tubing has been to add weight to the end of the tubing string. However, if this weight is in the form of enlarged sections such as drill collars, it will increase the possibility of stuck drill pipe.

F. Wash Water

Refer to the section previously discussed for information on wash water to be used in leaching operations.

G. Specific Gravity Measurements

1. Gravitimeter--Since it is imperative that accurate size measurements be maintained, the use of a gravitimeter is necessary.

2. Specific Gravity Balance--A specific gravity balance can be set up in the field for determining specific gravities.

3. Salometer--This particular device measures the percent saturation of the brine.

H. Water Measurement

Water measurement (both input wash water and out-put brine) is necessary so that cavity size determinations can be made. Reference is made to Table II of the Appendix for a tabulation of various types of measuring devices. Several companies meter both input and output water and some meter only input water. It is deemed advisable to meter both input

and output water. In this manner one metering device serves as a check on the other. Since cavity size is of extreme importance in reactor fuel waste storage, the use of a metering device on both input and output lines adds additional safety to cavity size calculations. The metering devices available include (1) Stock Tank, (2) Weir, (3) Fluid Meter, and (4) Orifice Meter.

Any of the preceding methods of water volume measurement should be adequate. If stock tanks are to be used, two will be required since one must be filling while the other is being emptied. Additional labor will be required in this case to switch tanks and keep a close tabulation of the number of tanks used. A weir, in turn, also will require closer supervision to obtain a correct average reading.

An orifice meter with a recording chart gives a continuous record of the fluid rate. A positive displacement fluid meter would seem to be the most accurate and less troublesome since it is insensitive to rate and records progressively the number of barrels of fluid passed.

An ideal situation would be to use on both input and output lines an orifice meter in conjunction with a fluid meter. In this manner a record of the rate along with total fluid could always be obtained.

I. Pump Rates

The controlling factor for determining the necessary pump rate in the injection of wash water is the cavity shape. If

the washing procedure utilizing the combination trump-blanket bottom-hole method is used, the circulation of wash water must be at such a rate as to prevent the return water becoming 100 per cent saturated. A very slow circulation rate will result in saturated brine before the injected water reaches the top of the cavity. It is then obvious that most of the salt removal will occur below the point of saturation. If this occurs before the water enters the liner-casing annular space then the cavity will have a progressively smaller diameter towards the top. Reverse circulation should off-set these effects.

If a rapid circulation rate is used, the returning water will be less highly saturated and a more even distribution of salt removal will result. It is difficult to predict the exact pump rate needed for each well, but per cent saturation can be checked against pump rate for each job as washing progresses. Field experience has indicated that pump rates as high as 1500 bbl/HR (1050 gal/min) may be necessary to maintain an under-saturated brine. (109)

In some areas the availability of wash water may be the controlling factor in pump rates. If the pump rate is controlled by a limited water supply, this factor must be considered in cavity control development. More reverse circulation will be necessary in order to maintain a cylindrical shaped cavity.

J. Troubles Encountered and Solutions

1. Whipping Off of Wash String--One trouble that is ever present is the possibility of whipping off the wash string. During washing operations it has been found that the tubing has whipped off at the top of the cavity. It is believed that this is caused by the high velocity of fluid moving the tubing around in the cavity similar to a fire hose left free to whip around. Various attempts have been made to solve this problem. One attempt has been to run several feet of pipe below a perforated or slotted wash interval. This pipe, extending into the small bore hole, stabilizes the entire string. However, this has proven to be unsatisfactory in that insolubles settle around the pipe and stuck wash pipe has resulted.

Further stabilization has been attempted by welding fins on the bottom of the wash pipe itself so that a closer fit between the pipe and hole would occur.⁽¹⁵⁾ This idea was also abandoned when stuck pipe resulted. Slower pump rates have been used successfully, but the slow rates are sometimes undesirable in cavity control development. The adding of weight to the end of the tubing string has proved successful. The utilization of heavier drill pipe for wash pipe has proved to be most successful and least troublesome. Pump rates can be maintained at the desired velocity. The drill pipe itself incorporates enough additional weight to give the required stabilization.

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2. Wash-Out of Formation Behind the Completion Casing String.--A common source of trouble is washing out the formation behind the completion casing string. Of course, this is a very undesirable situation since a bad leak may result in the cavity itself. However, such action is controlled when the Trump-Blanket method of washing is utilized. The hydrocarbon blanket protects the casing seat if it is properly positioned and maintained.

3. Plugging of the Wash Strings and Well-Heads.--The plugging of the wash string and well-head with insolubles is not uncommon in washing operations. However, most difficulty has occurred in washing salt beds. It is not believed that this trouble will be severe in washing salt domes since insolubles in excess of 2-5% are not likely to be present. If this trouble does occur, it possibly can be remedied by reversing the circulation of wash water or in severe cases the wash pipe must be pulled.

TESTING PROCEDURES

In order to insure that no leaks are present a planned testing procedure must be followed. As noted in Table II, variable testing intervals have been used, and some of the companies applied only a final test after the cavity was completed. This final test is the only one required by the Natural Gasoline Association of America "Tentative Standards for the Underground Storage of Liquefied Petroleum Gas." Refer to the Appendix for a reproduced copy of these standards. These standards also state that the test shall be deemed successful if the shut-in pressure remains constant for one hour after the fluid has reached equilibrium in the hole.

It is common practice in the drilling of any well to test the casing after each string is set.

Since the leakage of any atomic reactor fuel wastes is very critical, the following testing procedure is recommended:

1. Place an internal hydrostatic test on each casing string. This test should be applied after the cement has set.
2. Once the washing of the cavity has started a hydrostatic test should be placed on the cavity for each 5000 bbls additional volume washed. The test pressure, equivalent to that obtainable with a gradient of .75 psi per foot of depth, should be held for 12 hours.

3. Once the cavity has been completed it should be pressure tested for at least 72 hours, holding a surface pressure as indicated previously.

Of course, it will be evident if any leaks or possible permeable zones have been encountered. The surface pressure on the final test should be recorded on a pressure recorder so that any drop in pressure can be detected. Any drop of pressure will indicate an unfavorable storage cavity for atomic reactor fuel wastes, even though LPG products are sometimes stored where small drops in pressure have occurred. Pressure drops are not to be expected in the homogeneous mass of a salt dome.

The Christmas tree and related connections should also be pressure tested after installation. In particular, the ring gasket joints should be properly tested and checked.

REMOVAL OF BRINE

Once the washing procedure has been completed and before the injection of any waste material into the cavity, the brine must be removed from the cavity. This means that the cavity must be emptied of brine. Brine can be removed by several different types of artificial lift now commonly utilized in the oil fields. These methods consist of (1) centrifugal submergible pump, (2) sucker rod or beam type pump, and (3) gas lift and (4) hydraulic pumps.

If electricity is available, the submergible centrifugal pump is considered to be the best suited for the job. These pumps are available on a rental basis.

Figure 59 shows a typical installation of a Reda pump to empty a salt cavity. Figure 60 shows possible pump selections for emptying a 500,000 bbl cavity.

If gas pressure is available, gas lift would probably be the next most economical method for removing the brine. However, some difficulty would result in trying to completely empty the cavity. The hydraulic system which utilizes a power oil to operate a positive displacement type pump could be used, but involves running two tubing strings.

The sucker rod or beam type pump would do an adequate job, but the time involved would be longer. If electricity or high pressure gas is not available, this method would be satisfactory.

FIG.59. PUMP INSTALLATION TO EMPTY CAVITY OF SALT BRINE.

FIG.60. PUMP SELECTION TO EMPTY CAVITY.

SAFETY FACTORS

The Natural Gasoline Association of America has set up tentative safety standards for the underground storage of liquefied petroleum gas. A copy of these standards is reproduced in this report. Certainly extreme safety must be exercised in the handling of atomic reactor fuel wastes. In addition to the safety standards set up by the NGAA, additional precautions must be taken in handling radioactive products. The entire well-head area should be fenced in completely and locked.

ECONOMIC FACTORS

There are many variables which will determine the total cost of completing an underground storage project. These include:

1. Land
2. Roads and fences
3. Salt water disposal problems
4. Depth of cavity
5. Size of cavity
6. Nature of overlying material
7. Troubles encountered
8. Drilling rates
9. Availability of wash water
10. Pump costs
11. Work-over unit costs
12. Casing program and cementing costs
13. Surface connections
14. Staking location
15. Drilling mud
16. Logging
17. Sonar check of exact cavity shape and size
18. Cleaning up the location and location damages
19. Other miscellaneous items.

The following cost figures are given for projects completed for LPG storage. Billue⁽⁹⁾ gives the following costs effective in 1952:

<u>Cavity Size, Barrels</u>	<u>Cost Per Barrel of Storage</u>
10,000 - 50,000	\$2.00
50,000 - 100,000	\$1.50 - \$1.25
100,000 - 500,000	\$1.00 - \$.50
500,000 - 1,000,000	\$.50 - \$.25

C. V. Kroeger gives the following cost figures for completing a salt cavity in Upton County, Texas:⁽⁴⁸⁾

Drilling and casing	\$13,500.00
Water circulation	8,800.00
Injection equipment	<u>6,800.00</u>
TOTAL	\$29,100.00

Since this was a 60,000 barrel capacity storage project the cost was approximately \$.50 per barrel.

F. Matheny gives the following cost figures for storage projects located in the Permian salt beds of West Texas as compared to a salt dome near the Mississippi River:⁽⁵⁸⁾

<u>Location</u>	<u>Size, Barrels</u>	<u>Cost Per Barrel</u>
West Texas	100,000	\$.50
Mississippi River	500,000	\$.15

A decided difference of \$.35 per barrel of storage space is noted. The difference in size accounts for a portion of

this difference, but the difference in availability of wash water also accounts for a portion of the \$.35. Therefore, the locality of the salt dome will be an important factor in determining final costs.

Costs varying from \$.47 to \$2.00 per barrel of storage capacity are cited by Reidel⁽⁸²⁾ and Wilson⁽¹¹²⁾ for cavities of 100,000 to 900,000 barrels and at depths of 2000 to 4000 feet.

Wilson estimates the cost per barrel of storage for four wells having a total capacity of 900,000 barrels to be \$.4773.⁽¹¹²⁾

Table II in the Appendix shows cost figures submitted by various operators of L.P.G. storage projects. The average cost for salt dome storage is \$1.05 per barrel compared to \$1.04 per barrel for salt bed storage. These figures vary from \$.26 to \$2.59 per barrel.

The National Petroleum Council⁽⁶⁵⁾ estimates that one-half to one billion barrel storage cavities can be developed for \$.25 per barrel.

From the preceding cost figures it is evident that each case will have to be examined independently before the proposed cost analysis can be completed.

TABLE II
CONDENSED QUESTIONNAIRE TABULATION

SALT DOMES												
COMPANY NO.	NO. SALT BED	NO. SALT DOMES	STRUCTURE		LOCATION	GROUND LEVEL ELEV.	DEPTH TO TOP OF SALT DOME	NO. OF CAVITY PER DOME	FREQUENCY DURING WASHING	TESTING PROCEDURE		
			GEOLOGICAL AGE	FORMATION DESCRIPTION						FINAL SURF. TEST PRESS	DURATION OF FINAL TEST	LEAKS PSI/HR
1.		1	Permian	Dome	Jefferson County	47'	2000 - 2100'	4	Beginning and end	1400	24	None
2.		1		Stratton Ridge Dome	Brazoria County	18'	1330'	4	Beginning and end	1000	24	None
3.	Omit	1		Dome	Jefferson County	40'	1690'	1	"	750	12	None
4.												
5.		1	Permian	Dome	Harris	70'	1360'	2	-	500	24	0
6.		1	Permian	Dome	Chambers	80'	1380'	6	Ea. 50,000 bbls.	500	24	0
7.		1	Permian	Dome	Liberty Co.		700'	6	Not regular	500	1-3 hrs.	0
8.		1	Permian	Dome	Hardin Co.	45'	1000'	4	Once after each	.8 psi/ft	24	0
9.		1	Pre-cretaceous	Dome	Brazoria	70'	1400'	3	csg string & end			
10.		4		Dome	Hattiesburg, Mississippi	-	1650'	-	Ea. 100,000 bbls.	700	72	5 psi/hr
									Tested prior to storage			-
11.		1	-	Dome	Tyler, Texas	-	1500'	-	"	"	"	"
12.		1	-	Dome	Mont Belview, Texas	-	1900'	-	"	"	"	"
13.		1	-	Dome	Arcadia, La.	-	1450'	-	"	"	"	"
SALT BEDS												
1.	1		Permian	Evaporite Bed	Lea Co., New Mex.	3801	2215	2	End only	500	24	0
2.	1		Permian	Anhydrite & Salt-sedimentary	Scurry Co.	2409	750	5	End only	300	?	0
3.	1		Permian	Salt Bed	Howard Co.	2300	900	6	End only	400	4	0
4.	1		Permian	Salt Bed	Scurry Co.	2375	818	-	-	-	-	-
5.	1		Salado	Salt Section	Reagan Co.	2532	1291	1	Continuous	600	24	0
6.	1		Permian	Bed	Hutchison Co., Texas	2800	1300	11	Ea. 100,000 bbls. of cavity	500	72	5 psi/hr
7.	1		Permian	Bed	Kingman Co. Kansas	1440	900	3	Ea. 100,000 bbls of cavity	400	72	5 psi/hr
8.	1		Triassic	Bed	Scurry Co.	2400'	1030	3	Each 5,000 bbls	500	1	(Were able to pump in 500 psi)
9.	1		Triassic	Bed	Scurry Co.	2400'	1030	4	" " "	200	1	None
10.	1		Permian	Bed	Andrews Co.	3145	1280	1	-	660	240	.21 psi/hr
11.	1		Permian	Bed	Andrews Co.	3147	1240	1	-	720	6	-
12.	1		Permian	Salado Bed	Yoakum Co.	3560	2285	-	Each 10,000 bbls.	300	24	0
13.	1		Permian	" "	Yoakum Co.	3560	2295	-	" " "	300	24	0
14.	1		Permian	" "	Ector Co.	3311	1530	-	Each 100,000 bbls	-	-	-
15.	1		Devorian	Salt Bed	Kent Co., Michigan	630	3788	3	NGAA TEST	-	NGAA TEST	-
16.	1		Permian	Salt Bed	Reno Co.	1558	600	10	" "	-	"	-
17.	1		Permian	" "	Gray Co.	3265	2059	3	" "	-	"	-
18.	1		Permian	" "	Winkler Co. Texas	2900	1160	1	Every 25,000 bbls.	500	24	10 psi/hr
19.	1		Permian	" "	"	2900	1247	1	2 times	500	24	"
20.	1		Permian	" "	"	2900	2017	1	" "	500	24	"
21.	1		Permian	" "	Andrews Co.	3316	1800	1	None	-	-	-
22.	1		Permian	" "	"	3340	1650	1	"	-	-	-
23.	1		Permian	" "	"	3340	1650	1	"	-	-	-

TABLE II
CONDENSED QUESTIONNAIRE TABULATION

COMPANY NO.	SIZE OF HOLE			SECTIONS CORED	DEPTH INTO SALT BEFORE WASHING	SALT WASHING PROCEDURE							
	SURFACE	INTERMEDIATE	COMPLETION			TRUMP BLANKET	METHOD TOP-HOLE	BOTTOM HOLE	CONTROL OF CAVITY SHAPE	WATER USED	PUMP RATE BBL/HR	OPTIMUM RATE BBL/HR	S.G. OF BRINE OPTIMUM RATE
1.	25"	17.5"	12.25"	Cap & 3 50' sections salt	1000' in 3 600' in 1 1700'	-	Special Using - 2 brine string		Revers washing	Fresh Field Salt Fresh	400	420	1.2
2.				All	1900'	-	Protective casing hung at 3 diff. levels	2/3 revers 1/3 normal		-	550	550	1.195
3.	30" - 90'	17-1/2 - 1700	12-1/4- 2000										
4. Omit	24" - 556'	24	8-3/4	Check	2600'	Yes	Liver & Blanket			yes	800	800	1.193
5.	32	24	8-3/4	Samples	2100'	Yes	& revise wash			yes	800	800	1.193
6.	32	24	8-3/4	Samples	1675'		Yes	None		yes	800	800	1.19
7.	23	17-1/2	12-1/4	Coring Top Cap	200' (?)	Yes	Used special liner and inner tubing string - start with progressive circulation from bottom			yes & some oil field brine	500	500+	1.19
8.	22 & 15	12-1/4	8-3/4	Bottom Cap, All Salt			Hydrocarbon blanket	Reverse & conventional		Yes	600	-	1.18
9.	26"	17-1/2"	12-1/4"	Cup rock & lost circle (cored all zone at crest of cap salt) 80'			Use of 2 conc. strings of tubing - proper positioning of string						
10.	-	-	-				"						
11.	-	-	-				"						
12.	-	-	-				"						
13.	-	-	-				"						
SALT BEDS													
1.	13-3/8	9-5/8	8-5/8	Elec. log & cone	550"	No	No	Yes	No	Yes	215	215	1.204
2.	12-1/4	8-3/4	-	Caliper survey off-set well	T.D. (1250')	Yes	-	Yes	No	Yes	Availability of fresh water		95% sat
3.	15"	None	9-7/8"	Core all	300'	Yes	No	No	No	Yes	125	100	1.19
4.	12-1/2"	-	8-5/8"	Samples	400	No	No	Yes	Reverse washing	Yes	500	500	1.1-1.2
5.	13-3/8"	-	9-5/8"	Sample returns Used All salt	280'	No	No	Yes	Reverse washing	Yes	115	150	1.18
6.	24"	17-1/4"	12-1/4"	Sample returns coring & electric lgs. (Cored all salt)	250'	Yes	No	No	Reverse & Conventional	Yes	250	250	1.10
7.	17-1/4"	-	12-1/4"	"	" 150'	Yes	No	No	"	Yes	250	250	1.10
8.	9-7/8"	-	7-5/8"	Sample All returns Salt	600	Yes	No	No	-	Yes	250	70	?
9.	20"	13-3/4"	9-7/8"	" None	600	Yes	No	No	-	Yes	?	60	1.13
10.	17-1/2	11	7-7/8	" No coring	1110	No	No	Yes	None	Yes	129	120	1.2
11.	17-1/2	11"	11"	" "	1150	No	No	Yes	None	Yes	129	120	1.2
12.	17-1/4"	11"	7-7/8	Log All salt	650	No	No	Yes	By circle	Yes	275	150-300	1.15
13.	17-1/4"	11"	7-7/8	Log None	480	No	No	Yes	Rate & bottom hole	Yes	275	150-300	1.15
14.	17-1/2"	12-1/4" - 11"	7-7/8	-7-3/4 Coring Cap rock & salt	560	No	No	Yes		Yes	275	150-300	1.15
15.	13	9	7	" All salt	254	No	No	Yes	None	Yes	280	280	1.15
16.	15	-	12	" " "	200	No	No	Yes	None	Yes	285	285	1.15
17.	13-3/4	-	8-3/4	" " "	148	No	No	Yes	None	Yes	250	250	1.145
18.	17-1/2	12-1/4	8-5/8	Returns -	590		Yes	Yes	Reverse Washing	Yes	180	350	1.07
19.	17-1/2	12-1/4	8-5/8	" -	173			Yes	LP blanket	Yes	180	350	
20.	22	12-1/4	8-5/8	Coring -	139			Yes	" "	Yes	180	350	
21.	26	-	17-1/2	Elec. log None	480	No	No	Yes	None	Yes	225	-	1.2
22.	26	-	17-1/2	" "	730	No	No	Yes	None	Yes	190	-	"
23.	26	-	17-1/2	" "	730	No	No	Yes	None	Yes	180	-	"

TABLE II
CONDENSED QUESTIONNAIRE TABULATION

COMPANY NO.	DETERMINING CAVITY CAPACITY MEASUREMENT					CAVITY DESCRIPTION			T R O U B L E S				
	INPUT WATER	OUT-PUT BRINE	S.G. MEASURE WHILE WASHING	SONIC DEVICE	OTHERS	CAPACITY	SHAPE	MAX. DIAMETER	WASHOUT BEHIND CAMP CAVITY STRING	WHIP OFF TBG STRING	STUCK DRILL PIPE IN CAP	LOST CIRCULATION	CORROSION
1.	Fluid meter	None	Yes	Yes	Measure product in hole & check product with photon log.	(150,000 to 210,000)	Inverted bowling pin	1-50' to 1-62.5'	No, used condensate blanket	Yes, too much wt on tubing	Yes	Yes	No
2.	Orifice meter	Venture Meter				500,000	Saucer - 1 cylinder rest	400'				Yes, convert lost circle materials	
3.	"	None	Yes	Plan to	None	200,000	Cylindrical	20-25' (est)	No, used oil blanket	None	No	Yes, lost all materials	
4.	Omit												
5.	Fluid meter	Fluid meter	Yes	Yes		2-500,000	Pear	?	No	No	No	Yes set csg.	No
6.	"	"	Yes	Yes		6-250 - 300,000	Cyl & Cone	80'	No	No	No	Yes set lever	No
7.	Orifice meter	None	Yes	Yes	Elec logs	250,000	Pear	Unknown	Used kerosene blanket	No	No	Yes	No
8.	Fluid meter	None	Yes	Unsatisfactory	Measure LPG in	3-100,000	"	75'	Diesel oil blanket	No	No	Yes set csg in cap	No
9.	Meter	Meter	Yes	Yes		1-160,000	Irregular	100'	Yes, used propane blanket	No	No	Yes cemented multiple stage	No
10.						200,000	Cylinder						
11.						500,000	Pear	-	-	-	-	-	-
12.						31,000,000	"	-	-	-	-	-	-
13.						9,000,060	"	-	-	-	-	-	-
SALT BEDS													
1.	Orifice meter	Fluid meter	X	No		43,000	Pear	103'	Kerosene blanket	No	No	No	No
2.	Fluid Meter	Fluid meter	X	No		50,000							
3.	Orifice meter	Orifice meter	X	No		101,440	bbls. (4) bell	-	-	-	Pasted tubing 60' off bottom	No	No
4.	Fluid meter	Fluid meter	X	No	Measured by vol of LPG stored	0,000	Pear	-	No	Yes, induced circulation rate	No	No	No
5.	Orifice meter	Orifice meter	X	No	None	150,000	Irreg. Pear	-	-	Tubing pasted by shale fall in drilled twin - U-tubed wells			No
6.	Meter	Meter	X	Yes	None	42,471	Pear	-	No	Used 4-1/2" drill pipe for washing		Yes set csg	-
7.	Meter	Meter	X	Yes	"	100,000	to Cyl.	250'	Yes, used propane blanket	-	-	-	-
8.	Fluid meter	Fluid meter	X	No	"	250,000	to Cyl.	100'	"	-	-	-	-
9.	Fluid meter	Fluid meter	X	No	None	75,000	to Cyl.	100'	"	-	-	-	-
10.	"	"	X	No	"	100,000			"	No	No	No	No
11.	"	"	X	No	"	70,000	Unknown	?	"	Yes, used larger tubing	No	No	No
12.	Orifice meter	Orifice meter	X	No	Measure LPG in after completion	31,000	Pear	72'	No		No	No	No
13.	"	"	X	No	"	99,671	Pear	100'	No		No	No	No
14.	"	"	X	No	"	92,547	"	100'	No		No	No	No
15.	"	"	X	No	"	200,000	"	150'	No		No	No	Yes
16.	"	"	X	No	"	200,000	"	150'	"		"	"	Yes
17.	"	"	X	No	"	200,000	"	-	"		"	"	Yes
18.	Fluid meter	None	X	No	"	163,000	Irreg.	-	"		"	"	No
19.	"	"	X	No	"	450,150	"	-	"		"	"	No
20.	"	"	X	No	"	173,000	"	-	"		"	"	No
21.	Orifice meter	None	X	No	"	150,000	Hour glass	-	"		"	"	"
22.	"	"	X	No	"	110,000	Pear	-	"		"	"	"
23.	"	"	X	No	"	75,000	"	-	Yes, use blanket	"	"	"	Minor
						66,400	"	-	"	"	"	"	"
						6,800	"	-	"	"	"	"	"
						50,000	"	-	"	"	"	"	"

TABLE II
CONDENSED QUESTIONNAIRE TABULATION

COMPANY No.	SIZE & LENGTH PIPE			COMPLETION PROCEDURES					POSITION OF FINAL COMPLETION STRING RELATION TO SALT DOME				OVERALL COST PER BBL OF STORAGE CAPACITY	MOST DESIRABLE SHAPE	STRUCTURALLY STRONGEST SHAPE
	SURFACE	INTERMEDIATE	COMPLETION	WASH	TUBING	SALT SAT	REGULAR	OTHER	AMOUNT	DIST	ABOVE CAP	DEPTH INTO SALT			
1.	20"-1155'	13-3/8-2118	9-5/8"-2914		5-1/2-3825	Yes		?	Circl.to surface	No		800'-900'	\$1.29	Inverted bowling pin	Inverted bowling pin
2.	20"-100'	13-3/8-1100'	9-5/8-1900	7"-2850	4-1/2-3000	Yes - in contact w/salt									
3.	26"-90' 26"-556'	13-3/8-1697'	9-5/8-1998'			Pozmix w/few gals resin cement above shoe			Circl. to surface	No		No	\$1.00	Cylindrical	Cylindrical
4. Omit															
5.	24"-100'	18-5/8-850'	9-5/8-1750'		4-1/2-4000	Yes				No		350'	-	Cyl. & cone	Cyl. & cone
6.	24"-100'	18-5/8-875	9-5/8-1650'		4-1/2-3500	Yes		Resin	Circl. to surface	No		350'	-	Cyl. & cone	Cyl. & cone
7.	24"-104'	20"-273'	13-3/8-885'	10-3/4"-1120'	7"-2331'	Yes		Resin		No		500"	-	Pear	Pear
8.	16"-800'	13-3/8-1200	9-5/8-1500'	7"-2800'	4-1/2-2900'	Yes	None		Varied	No		250'	\$1.00	Pear cyl.	Pear cyl.
9.	20"-700'	13-3/8-1700'	8-5/8-1770'		4-1/2"-2280	Salt diacet, sulfate resistant cement slurry w/low temp resin cement spot around bottom				No		350'	\$1.00	Pear	Pear
10.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11.	-	-	-	-	-	-	Common	-	-	-	-	-	-	-	-
12.	-	-	-	-	-	-	Common	-	-	-	-	-	-	-	-
13.	-	-	-	-	-	-	Common	-	-	-	-	-	-	-	-
SALT BEDS															
1.	13-3/8-331'	9-5/8-2246	7"-2349		3-1/2"-2713'	Yes	-		Circl. to surface	-		143'	\$2.59	Pear	Pear
2.	9-5/8-750'				4"-2'-4" off bottom 7" perf lines 60' up in 9-5/8 to T.D.				"	(Yes top)		None	\$1.70	Bell	Bell
3.	12-3/4-100'	None	8-5/8-926'	5-1/2-950'	2-3/8-1125'	Yes			"	No		25'	\$1.25	Pear	Pear
4.	8-5/8-1240'						Common	-	"	-		4'	\$.38	Pear	Pear
5.	13-3/8-669'	7-5/8-1291'			4-1/2" drill pipe 1350'				"	Set to top of cap	None	\$1.31 (Surface & storage facilities)		Pear	Pear
6.	13-3/8-1450'		8-5/8-1500'		4-1/2-1600'	(Pozmix cement Slurry calcium chloride gel cement slurry)			"			200'	\$1.00	Pear	Pear
7.	13-3/8-850'		8-5/8-950'		4-1/2-1000'				"			50'	\$1.00	"	"
8.	-	-	7-5/8-635		4-1/2-1210'	No	Yes w/4% gal			Top of cap	No		\$.40	"	"
9.	16"-400'	10-3/4"-1005'	7"-1035'		3-1/2-1200'	Yes	Pozmix			No		400'	\$1.00	"	"
10.	12-3/4-355'	8-5/8-1240'	7"-438 set at 1587		5"-1066 2"-2377 4"-599'	Yes	-		535 sx	No		295'	\$1.85	"	"
11.	12-3/4-361'	8-5/8-1656'			5"-1709 2-1/2-2385	Yes	-		650 sx	No		415'	\$1.85	"	"
12.	13-3/8-60'	8-5/8-2220			5-1/2-2600	No	Reg. heat		Circl. to surface	10' above in)		-	\$.40	Inverted carrot	spherical
13.	13-3/8-60'	8-5/8-2310			5-1/2-2650	No	Reg. heat		"	anhydrite)		25'	\$.40	or ellipsoidal (long	
14.	13-3/8-25'	8-5/8-1520			4-1/2-800'	No	Reg. heat		"	cap)		-	\$.70	axel vertical)	
15.	16"-173'	10-3/4-697	7"-3788		3"-4042	No	Portland		"			250'	\$2.00	Pear	Pear
16.	13"-220'	-	9-5/8-600'		3"-800	No	"		"	-		200'	\$.80	"	"
17.	9-5/8-568	-	7"-2059		3"-2189	No	"		"	-		130'	\$.50	"	"
18.	13-3/8-300'	10-3/4-1160'	7"-1247		5"-1430	Yes	"		"	No		3'	\$.275	"	"
19.	13-3/8-300'	10-3/4-1247	7"-1319		5"-1386	Yes	"		"	No		4'	\$.260	"	"
20.	18"-300'	-	9-5/8-2047		5"-2174	Yes	"		"	No		4'	\$.678	"	"
21.	20"-239	10-3/4-1993"	7"-2092		4-1/2"D.P. -2240	NO	Regular		"	No		292'	\$1.25	"	"
22.	20"-206'	10-3/4-1800"	7"-1976		" -2382	No	Regular		"	No		326'	\$1.25	"	"
23.	20"-198'	80' of 13-3/8"	7"-1979		" -2373	No	"		"	No		329'	\$1.25	"	"

NGAA TENTATIVE STANDARDS FOR
THE UNDERGROUND STORAGE OF
LIQUEFIED PETROLEUM GAS

F O R E W O R D

The Natural Gasoline Association of America has been preparing liquefied petroleum gas test methods, specifications and plant procedures for 22 years, having begun its activities in this field in 1930.

As a result of the recent trend toward the use of underground storage wells (usually washed out of salt) and underground storage caverns (usually mined out of suitable shale or limestone formations) for the bulk storage of liquid petroleum products, particularly LP-Gases, it seemed proper that the Natural Gasoline Association of America should, because of member company experience in this new activity, develop certain basic safety standards for the construction, testing and fitting of these underground LP-Gas storage installations.

It is to be understood that since geological formations may and do vary widely, good engineering may dictate certain modifications of these standards.

Adopted as tentative standards,
August 1952, as amended March 17,
1954, by the Natural Gasoline
Association of America, 422 Kennedy
Building, Tulsa 3, Oklahoma.

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DIVISION I

LP-GAS UNDERGROUND STORAGE WELLS

1.1 Location of LP-Gas Underground Storage Wells

(a) LP-Gas underground storage wells shall be located a minimum distance of 100 feet from nearest line of adjoining property which may be build upon - measured from the wellhead (christmas tree).

(b) Care and precaution shall be exercised to prevent any unplanned communication of well with any existing cavern or mine.

1.2 Construction of LP-Gas Underground Storage Wells

(a) LP-Gas underground storage wells shall be drilled and completed in accordance with the rules, regulations or practice pertaining to oil or gas wells of comparable depth applicable to the same area in which they are located. In case no state regulations exist, reference should be made to rules and regulations adopted by other gas or oil producing state regulatory bodies, such as Texas Railroad Commission. It is recommended that where practical the casing be cemented from bottom to top; however, in every case the casing shall be cemented through the cased salt section and at least 200 feet into the overburden.

1.3 Wellhead, Valves and Fittings

(a) The christmas tree (wellhead fittings) shall be of steel.

(b) The valves shall be flanged valves and shall have an ASA primary service pressure rating of not less than 300 psig (Series 30).

(c) If the stored LP-Gas is to be withdrawn by pumping, the tubing equipment, such as stuffing boxes, oil savers, flow tees and other fittings, shall have a working pressure of not less than 250 psig.

(d) The casing valves and fittings shall have a minimum ASA pressure rating in accordance with the following table:

Tubing Length	Steel Valves ASA Rating	Steel Casing Heads and Steel Tubing		API Flange Series No.
		Heads* API psig Working Pressure		
0 - 1500'	300	720		300
1501 - 2000'	400	960		400
2001 - 3000'	600	960		400
3001 - 5000'	900	2,000		600
5001 - 7500'	1,500	3,000		900

*This table will apply to steel valves if API ratings are used.

1.4 Maximum Design Pressure of LP-Gas Underground Storage Well

(a) The maximum design and operating pressure of an LP-Gas underground storage well shall not exceed one psig per foot of overburden, e.g., if well ceiling is 500 feet below the surface, the maximum design and operating pressure would not exceed 500 psig. In no case shall the minimum depth of overburden be less than 350 feet. The geological character of the overburden may further limit the permissible operating pressure.

1.5 Vapor Pressure* Limitation on LP-Gas to be Stored

(a) The vapor pressure of the LP-Gas to be stored shall not exceed the maximum design and operating pressure of the LP-Gas underground storage well. The vapor pressure shall be determined at the maximum well temperature.

1.6 Pressure Test of Completed LP-Gas Underground Storage Well

(a) Upon completion of an LP-Gas underground storage well and prior to LP-Gas injection for storage, a hydrostatic test shall be applied. The test pressure, measured at the casing head, shall be equivalent to the vapor pressure of the material (vapor pressure at the storage temperature) to be stored plus one-hundred psig.

(b) The test shall be deemed successful if the shut-in pressure remains constant for one hour after fluid in hole has reached equilibrium.

1.7 Protection of Christmas Tree (Wellhead) Fittings

(a) The christmas tree shall be protected from mechanical damage.

1.8 Withdrawal of LP-Gas from Underground Storage Well

(a) These wells may use (but not be limited to) either water displacement or pumping methods to withdraw or recover the LP-Gas.

DIVISION II

LP-GAS UNDERGROUND STORAGE CAVERNS (Mined or Natural)

2.1 Location of LP-Gas Underground Storage Caverns

(a) LP-Gas underground storage caverns shall be located a minimum distance of 100 feet from line of adjoining property

*As determined by NGAA LPG Vapor Pressure Test.

which may be built upon - measured from christmas tree (fittings atop cavern shaft).

(b) Cavern extremities shall be located a minimum distance of 50 feet from line of adjoining property which may be built upon.

(c) Care and precaution shall be exercised to prevent any unplanned communication of cavern with any existing cavern or mine.

2.2 Maximum Design Pressure of LP-Gas Underground Storage Cavern

(a) The maximum design and operating pressure of an LP-Gas underground storage cavern shall not exceed one psig per foot of overburden, e.g., if cavern ceiling is 200 feet below the surface, the maximum design and operation pressure would not exceed 200 psig. The geological character of the overburden may further limit the permissible operating pressure.

2.3 Vapor Pressure Limitation on LP-Gas to be Stored

(a) The vapor pressure of the LP-Gas to be stored shall not exceed the maximum design and operating pressure of the LP-Gas underground storage cavern. The vapor pressure shall be determined at the maximum cavern temperature. Experience has shown this temperature to be in the neighborhood of 58 - 65 F.

2.4 Cavern Valves, Piping and Fittings

(a) The valves, piping and fittings shall be of steel and shall be suitable for a minimum working pressure of 250 psig.

2.5 Pressure Test of Completed LP-Gas Underground Storage Cavern

(a) Upon completion of an LP-Gas underground storage cavern and prior to LP-Gas injection for storage, an air or vapor test of 100 psig shall be applied.

(b) The test shall be deemed successful if the shut-in pressure remains constant for twelve hours after reaching equilibrium.

2.6 Protection of Christmas Tree Fittings (Atop Cavern Shaft Head)

(a) The christmas tree shall be protected from mechanical damage.

2.7 Withdrawal of LP-Gas from Underground Storage Cavern

(a) These caverns may use (but not be limited to) either gas displacement or pumping methods to withdraw or recover the LP-Gas.

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