Ethylene Storage near Midland, Michigan

by
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ABSTRACT

This paper describes the storage of ethylene gas in a multilayered salt section. The horizon used for gas storage is the Detroit River Series Salt zone of the Monroe Formation. The salt in this zone totals 92 feet and occurs in 7 separate layers in a 200 foot interval 4100 feet deep. Storage of gas in a multilayered salt section at this depth is unique.

The paper outlines the storage well program in five broad phases:

1. *Storage location site.*
2. *Establishment of cavern size.*
   Tightness of cavern.
   Capacity control and determination.
3. *Well construction.*
4. *Development procedures.*
5. *Storage operations.*

Each of the phases is discussed in some detail with presentation of test data and conclusions.

Some of the special problems encountered in this storage operation were:

1. *Precipitation of salts.*
   a. *Due to mixing different brines causing formation of calcium sulfate.*
   b. *Due to cooling a saturated brine from the well causing sodium chloride precipitation.*
2. *Gas leakage in control head and/or casing .*
3. *Formation of ethylene hydrates.*

The storage well has been in operation 3 years and has been essentially filled and emptied. Storage in the multilayered salt zone has been successful.

INTRODUCTION

Ethylene, a chemical intermediate, is produced in a plant that is distinctly separate from the consuming plants. This situation creates a need for storage.

This storage capacity should be substantial because of the turn around time required by the producing facilities and fluctuating demand by consuming plants.

When, in 1956, a need for additional storage capacity was established, both surface and sub-surface methods were evaluated. Studies concluded that storage of ethylene in a salt cavern would be more economical than other types of storage.

In the preliminary planning of this project, Dow was fortunate in obtaining both operating and technical assistance from the Gulf Oil Company and others that had been operating hydrocarbon storage wells.

We believe that storage in a multilayered salt zone that consists of relatively thin layers of salt which are distinctly separated by dolomite, limestone and anhydrite layers at a depth of 4200 feet is somewhat unique. The total thickness of salt is only 92 feet and the storage cavern would of necessity be of relatively large diameter. This cavern would also be essentially filled with large pieces of rock and debris.

At the Midland location, salt has been produced from the Detroit River Series of the upper Monroe formation for many years. This strata is of Devonian age and Paleozoic era. The salt occurs as distinct, pure, layers varying in thickness from 3 feet to over 20 feet. The salt strata are separated by massive competent layers of limestone, dolomite and anhydrite rocks. A total of 92 feet of salt is present in an interval of approximately 200 feet. The horizon tops at 4100 below ground surface in the Midland area. Overlaying the salt zones is a massive and structurally sound roof. The roof consists of dolomite and anhydrite rock layers within which little if any salt is interspersed. This is fortunate for in many areas salt is interspersed with the roof rocks. A typical cross section of this strata is shown in Figure 1.

Salt has also been produced from the massive Silurian salt beds that occur between 6000 and 8000 feet. A net salt thickness of 1500 feet is not uncommon in this zone.

The Detroit River Series salt zone was chosen for the storage operation because of its favorable capital and operating expenses as compared to the Silurian salt.

The methods of operation used and history of roof falls that occurred in solution mining of the Detroit River Salt series were evaluated and used extensively in designing the ethylene storage well.

Planning for the storage well involved or included these five broad phases:

1. Site location.
2. Cavern size.
   - Size determination.
   - Tightness of cavern.
3. Well construction.
4. Development procedures and phases.
5. Storage operations.

SITE LOCATION

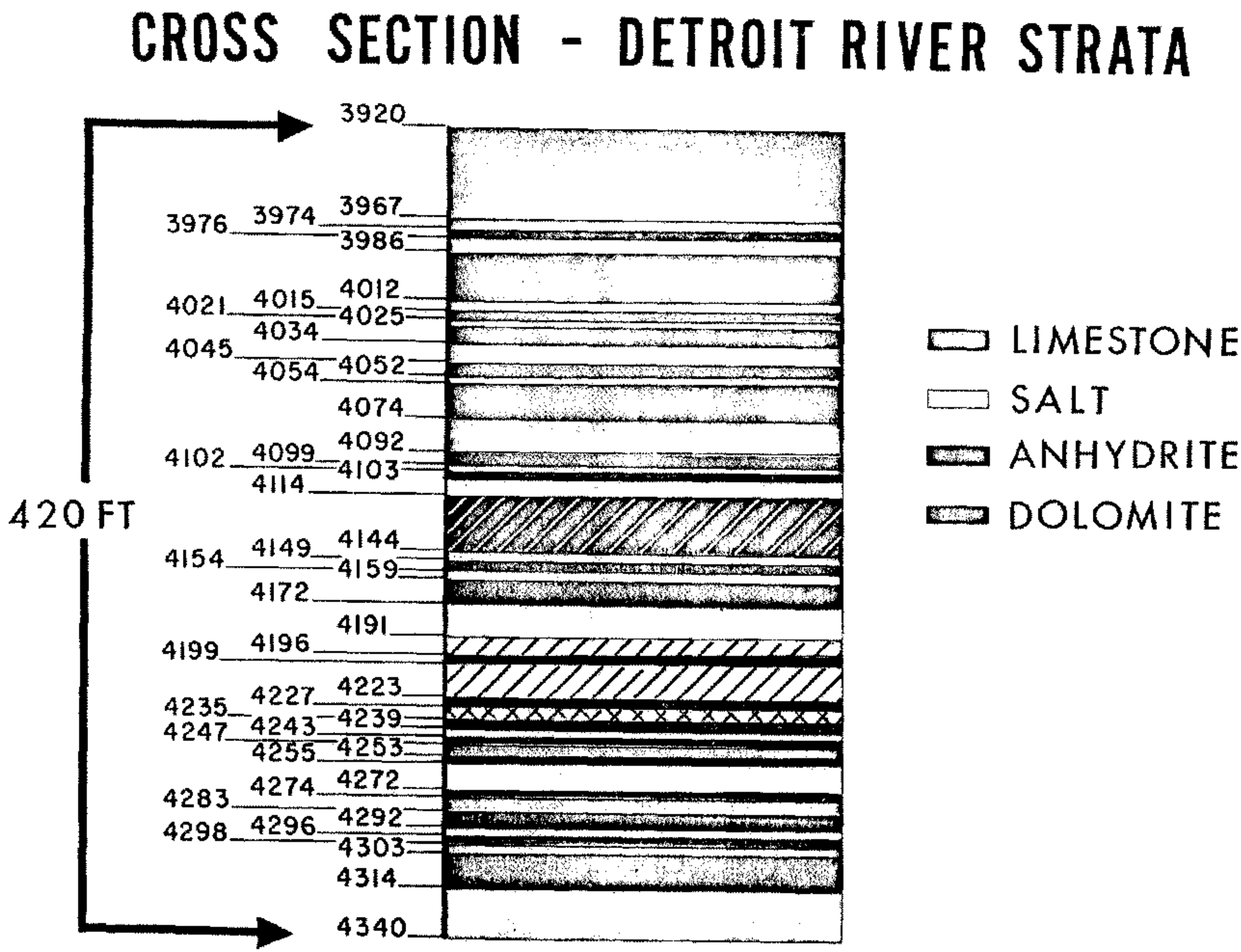
In establishing the location the two items that were considered most important were:

1. Safety.
   - Public
   - Plant
2. Salt thickness (net).

The storage area was planned to be large enough in acreage to provide for several storage wells. This area could eventually be a storage complex and by the nature of products handled would be considered a hazardous operation and should be remote from industrial plants and/or dwellings.

The sub-surface storage area is centered in an area of 360 acres that are approximately 5 miles north of the Midland plant and 1 mile north of the City Limits of Midland. This area is waste land unsuitable for farming and isolated from private dwellings.

Geological data indicated that approximately 90 feet of salt would be found in this area.


CROSS SECTION - DETROIT RIVER STRATA
420 FT
3920
3967
3974
3976
3986
4012
4015
4021
4025
4034
4045
4052
4054
4074
4092
4099
4102
4103
4114
4144
4149
4154
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4172
4191
4196
4199
4223
4227
4235
4239
4243
4247
4253
4255
4272
4274
4283
4292
4296
4298
4303
4314
4340
LIMESTONE
SALT
ANHYDRITE
DOLOMITE

Figure 1.

CAVERN SIZE

Cavern size and shape are of primary importance in designing a storage well. Capabilities of the production plant were important in size determination. How much excess capacity would be available for storage under normal consumption? How often would the production facilities require turn around? What would be the normal length of this shut down when all consumption would be supplied with ethylene from storage?

An important consideration was the question how large could the cavern be made and still avoid serious roof or ledge falls during the storage operations. When the cavern is filled with ethylene, the protruding layers would have less buoyancy and might fall. These falls could break the tubing. The cavern then would have to be emptied and reworked. There was also concern about the amount of ethylene that might be trapped under sections where the roof might fall or under ledges between salt layers.

Based on the history and sequence of rock falls in operating salt wells, the cavern size was established at 50, 000 tons of produced salt or approximately 830, 000 cubic feet.

Cavern Tightness -- A storage cavern must be tight and not have a significant loss of stored product. The cap rock and the interbedded layers of salt and rock must have low permeabilities. Therefore, the permeabilities of these rocks must be determined and computations made for expected product loss.

Tests conducted on a newly drilled but undeveloped salt production well indicated that the roof rocks and section were impermeable and that the chances of successful storage were good.

When the storage well was drilled, corings were taken through the vital roof section as well as through the entire salt section. Permeabilities, measured in millidarcies, were obtained from these core samples. The rate of loss of gas was calculated from the equation given in Figure 2. This gives the rate of flow through the dry cap rock. Corrections to account for moisture and pressure will substantially reduce the calculated loss. The loss in the ethylene storage well is expected to be not more than 0. 1% of the total material stored per year.

LOSS THROUGH ROOF OF STORAGE WELLS.....

$$Q = \frac{1.119 \times 10^{-4} A \left(P_1^2 - P_2^2\right)}{\bar{z}\, T\, \bar{\mu} \left(\sum \frac{L}{K}\right)}$$

Q = M SCF/DAY

A = ROOF AREA, SQUARE FEET

P_1 = GAS PRESSURE, PSIA

P_2 = PRESSURE ABOVE ROOF of CAVERN, PSIA

$\bar{Z}$ = AVERAGE GAS COMPRESSIBILITY

T = GAS TEMPERATURE, °R

$\bar{\mu}$ = AVERAGE GAS VISCOSITY, CP

L = THICKNESS of ROCK LAYER, FEET

K = PERMEABILITY of CAVERN ROCK, MILLIDARCYS

Figure 2.

Capacity Control and Determination -- Three methods were used for the control and evaluation of the completed cavern. See Figure 3.

1. Material balance
2. Decompression of brine and tightness test
3. Sonor or sound reflection measurements

METHODS OF SIZE DETERMINATION IN UNDERGROUND STORAGE CAVERNS.....

1 *MATERIAL BALANCE*

MEASURE QUANTITY AND COMPOSITION OF BRINE REMOVED

2 *DECOMPRESSION OF BRINE*

MEASURE AMOUNT OF BRINE DISPLACED BY INCREMENTAL DECOMPRESSION IN CAVERN.

3 *SONAR OR SOUND REFLECTION MEASUREMENTS*

CALCULATE DISTANCE FROM CENTER OF WELL TO WALLS BY MEASURING TIME NECESSARY FOR SOUND WAVES TO REFLECT BACK TO SOURCE.

Figure 3.

Material Balance -- Material or salt balance depends on measuring the amount of salt taken from the cavern. Flow rates and brine densities are all that are required. These can be easily and accurately obtained.

Decompression of Brine -- This method of measuring cavern volumes is dependent on the compressibility of brine solutions. The compressibilities are the fractional change in volume for a unit change in pressure. See Figure 4.

1. $C = \frac{1}{V} \frac{(\delta V_1)}{(\delta P)} V_2$

When pressure is released in any type of container not only does the fluid expand but the container also contracts due to the decreased stress applied to the walls of the container. Equation 2 states that the amount of fluid excluded from a vessel for an incremental change in pressure is the sum of the increase of the fluid plus the decrease in volume of the container:

2. $\frac{(\delta V_1)}{(\delta P)} V_2 + \frac{(\delta V_2)}{(\delta P)} V_1 = \frac{dV}{dP}$

It can be shown for cylinders with rigid ends that the change in volume per unit pressure change is:

$$3.\ \frac{(\delta V_2)\,V_1}{(\delta P)} = \frac{2Vr}{Y_e}$$

Where Y_e is Young's modulus of elasticity. Combining equations 1, 2 and 3 we get:

$$4.\ V_2 = \frac{(\ \ 1\ \ )}{(C + 2/Y_2)}\ \frac{\Delta V}{\delta P}$$

Since $Y_e = 8.5 \times 10^6$ psi for limestone, this amounts to a 10% correction for C. By measuring the volume of brine released (Δ V) corresponding to a decrease in pressure (Δ P), the volume of the cavern can be calculated. The changes here are measured as pressure differences of 100 to 200 psi and volume changes of 50 - 100 bbl. of brine. When the cavern was tested for volume, these tests were extended to check for cavern tightness.

VOLUME MEASUREMENT
BY BRINE DECOMPRESSION....

1. $$C = \frac{1}{V_2}\left(\frac{\delta V_1}{\delta P}\right)_{V_2}$$

2. $$\left(\frac{\delta V_1}{\delta P}\right)_{V_2} + \left(\frac{\delta V_2}{\delta P}\right)_{V_1} = \frac{dV}{dP}$$

3. $$\left(\frac{\delta V_2}{\delta P}\right)_{V_1} = \frac{2V_2}{ye}$$

4. $$V_2 = \frac{1}{(C+2/ye)}\ \frac{\Delta V}{\Delta P}$$

C = COMPRESSIBILITY OF BRINE PSI^{-1}
V_1 = VOLUME OF BRINE
V_2 = VOLUME OF CAVERN
ΔV = VOLUME OF BRINE — VOLUME OF CAVERN
P = PRESSURE
ye = YOUNG'S MODULUS OF ELASTICITY (8.5×10^6 PSI FOR LIMESTONE)

Figure 4.

Sonar Measurements -- When determining the volume and shape of a cavern with "sonar," the sound source and receiver are placed at various levels in the cavern. See Figure 5. The distance to the wall is obtained by measuring the time required for sound to travel to the wall and back to the source and then calculating the distance from the speed of sound in brine. At each depth a series of soundings are made since the cavern is not necessarily symmetrical.

Sonar works well in clean caverns. Obviously debris will look like the wall to sonar and open areas behind the debris will not be accounted for. In our well, sonar was successful in picking out the zones of solution and indicating where we had debris.

Material balance of the salt produced and that which is dissolved in the fluid filled cavern show the cavern is approximately 834,000 cu. ft. in volume and 110 feet in diameter. Pressure reduction tests were within 10% of the material balance computations.

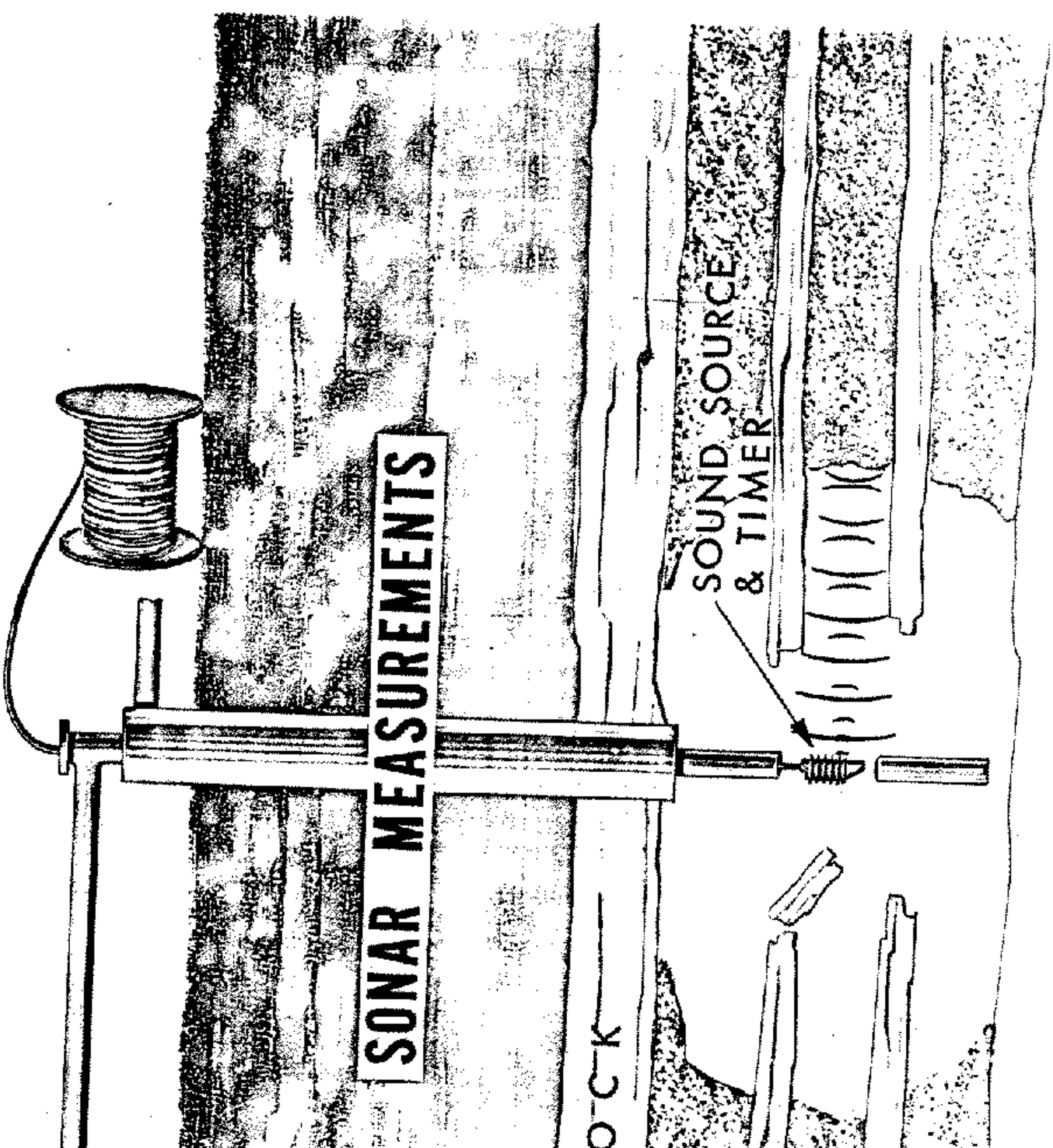


Figure 5.

WELL CONSTRUCTION

The storage well was drilled with rotary equipment. Figure 6 shows the salt column, casing program and hole size at completion.

A 17 1/2 inch hole was drilled from ground surface to approximately 1330 feet. 1326 feet of 13 3/8 inch O. D. - 54#, J-55, 8 RD. THD. casing was run and cemented with cement returns to the surface.

Then the well was drilled to 3840 using a 12 1/4 inch bit. The section from 3840 to 4345 was cored. After completion of coring, the well was reamed out to a 12 1/4 inch hole to T. D. of 4345. The 12 1/4 inch hole was taken to total depth because we felt there would be less chance for rock falls to catch and break the tubing and casing.

With the hole completed 4159 feet of 9 5/8 inch O. D. -43.5#, N-80, 8 RD. Thd. casing was run with a metal petal basket, float collar and centralizers. This string was cemented with a mix of cement, panseal, aquagel and latex cement. Latex cement was used at the bottom of the casing because of its low permeability. The top of this cement column is 650 feet from ground level. After the cement had set, the remaining cement in the pipe was drilled out and the hole cleaned out to 4340. A pressure test was performed on the hole as completed and is shown in Figure 7. Original hole was tight.

DEVELOPMENT PROCEDURES AND PHASES

For the storage well a cylindrical shape was desired. Development of the cavern was planned with this in mind.

In solution mining the layered Detroit River salt, both top and bottom injection of fresh water has been used. The penetration rate is greatest nearest the point where fresh water first contacts the salt. With top injection, the typical morning glory shape occurs and has the greatest development in the uppermost layers of salt with less and less dissolving in the lower zones. As development proceeds, the unsupported sections of rock become greater, finally reaching the point when rock falls occur. These rock falls would probably catch and break the tubing and necessitates emptying and cleaning out or redrilling the well.

Using bottom injection, the salt sections are developed more uniformly. Saturated production can be maintained at a higher rate with top than with bottom injection. See Figure 8.

In the solution mining process, a 7 inch casing was run inside the 9 5/8 inch and a 4 inch tubing string was run inside of the 7 inch. See Figure 6. The position of the 7 inch casing was changed during the phases of development as was the entry point of fresh water.

<u>Phase 1</u> -- During the first phase development the 7 inch - 23#, N-80, buttress thrd. casing string was set at 4246 and the 4 inch EUE-12 3/4#, J-55, tubing was set at 4330. The 7 inch and 4 inch strings were tapered having lighter weight and lower strength pipe on the bottom through the salt sections. A tapered string is insurance against rock falls breaking the tubing near the surface and piling up in the cavern. This left a total of 49 feet of salt below the 7 inch casing. Injection of fresh water was through the 7 inch and salt production up the 4 inch tubing (top injection). The developing rate was such that unsaturated brine was produced. Under this procedure the exposed salt would develop more uniformly. The salt produced during the development was disposed of by injecting into an existing disposal.

The first phase of development was completed at approximately 25,500 tons of salt.

Inspection at this time showed that the tubing string had broken off leaving approximately 60 feet of tubing in the partially completed cavern. The break occurred in the thin wall 4 inch (9 1/2# inch) that had been run on the bottom of the tubing and when the well was shut down to relocate the casing and tubing. This failure required a redrilling and clean out of the hole. The 7 inch string was removed and a cable tool rig was moved in to clean out the hole. When the hole had been cleaned out to original total depth, a sonar and regular caliper survey were run to determine the present cavern shape and dimensions.

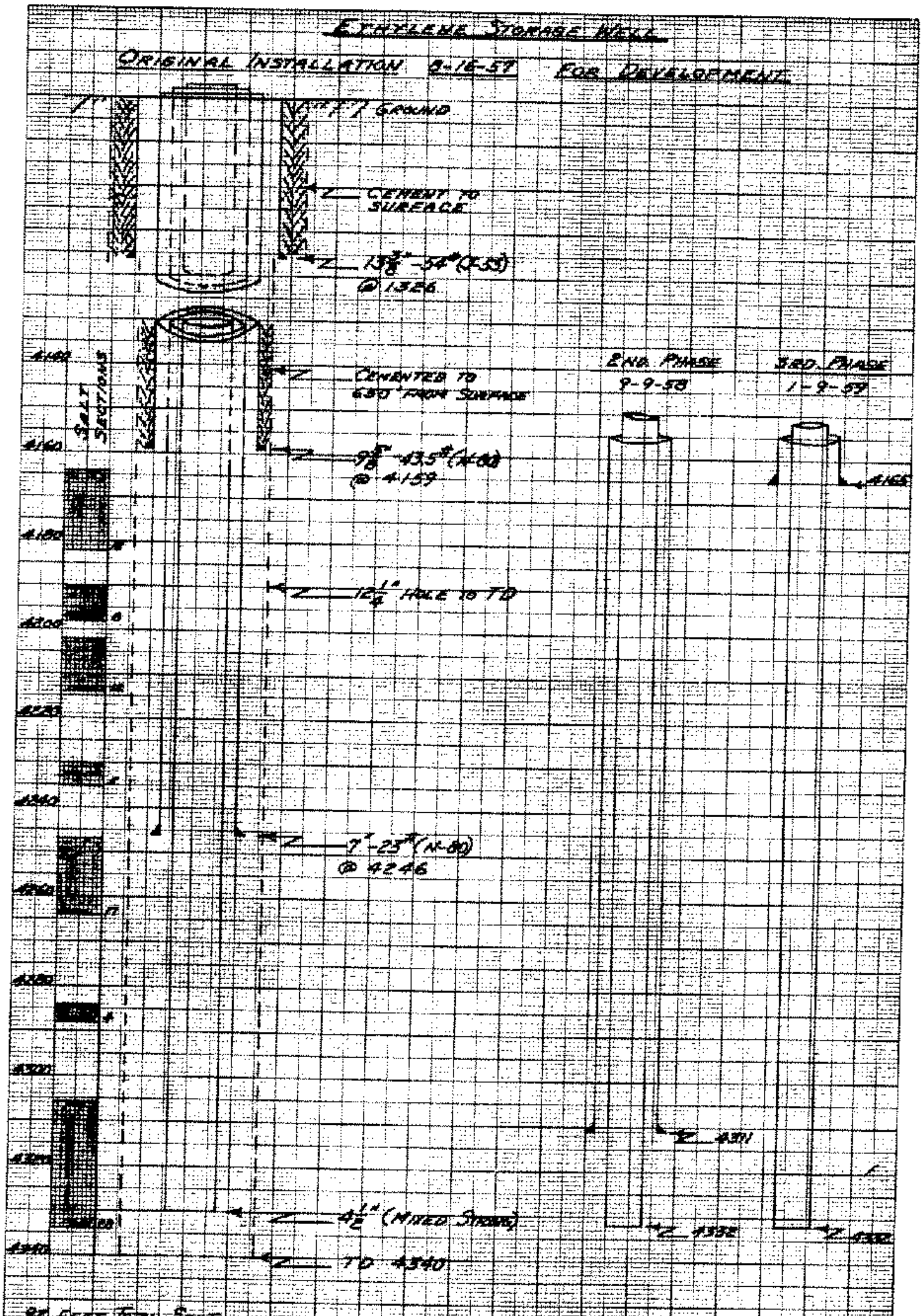
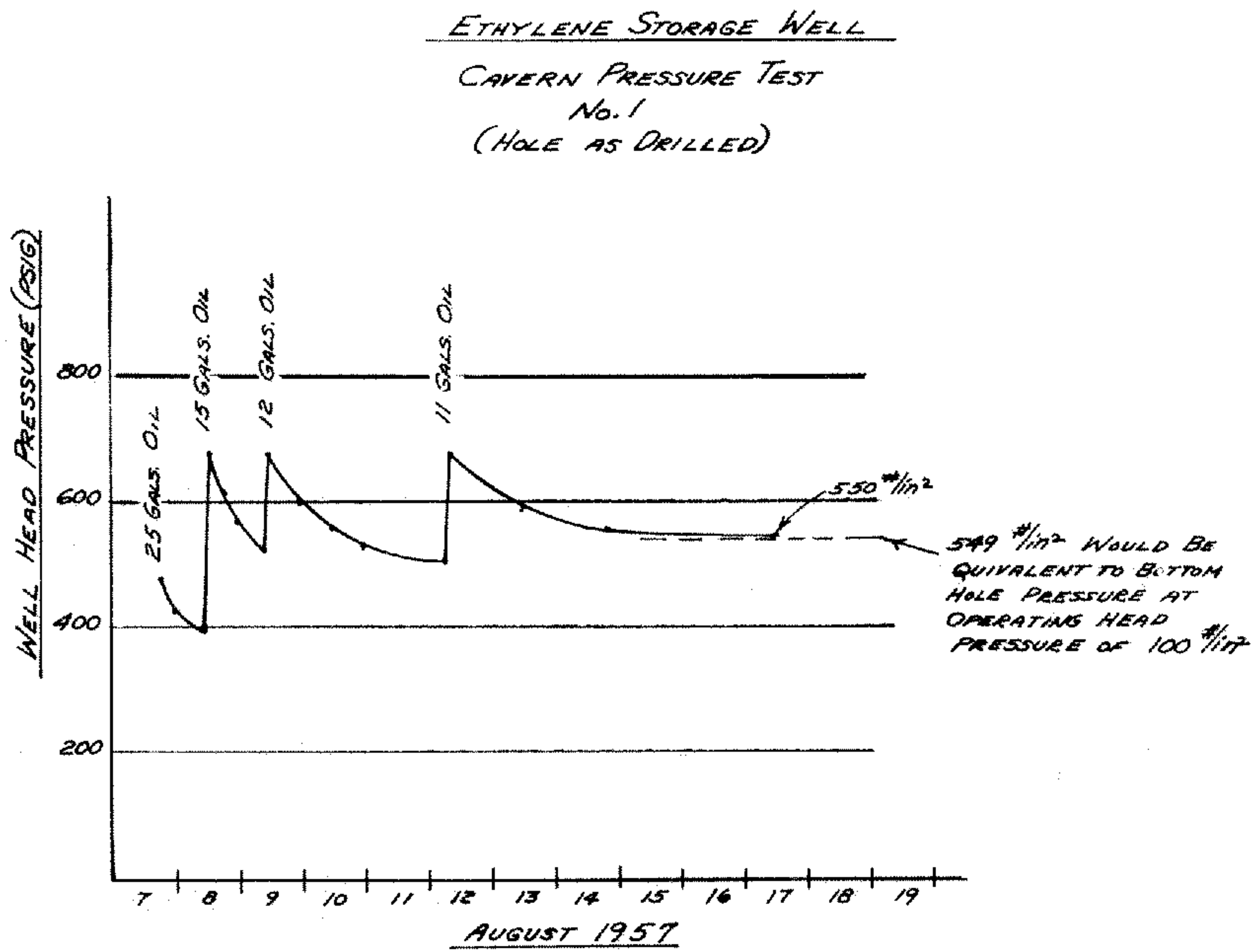

ETHYLENE STORAGE WELL
ORIGINAL INSTALLATION 8-16-57 FOR DEVELOPMENT
GROUND
CEMENT TO SURFACE
13 3/8" - 54# (J-55) @ 1326
CEMENTED TO 650' FROM SURFACE
SALT SECTIONS
2ND PHASE 9-9-58
3RD PHASE 1-9-59
9 5/8" - 43.5# (N-80) @ 4159
12 1/4" HOLE TO TD
7" - 23# (N-80) @ 4246
4 1/2" (MIXED STRING)
TD 4340
4311
4332
4165
92 FEET TOTAL SALT

Figure 6.


ETHYLENE STORAGE WELL
CAVERN PRESSURE TEST
No. 1
(HOLE AS DRILLED)
WELL HEAD PRESSURE (PSIG)
800
600
400
200
25 GALS. OIL
15 GALS. OIL
12 GALS. OIL
11 GALS. OIL
550 #/in²
549 #/in² WOULD BE QUIVALENT TO BOTTOM HOLE PRESSURE AT OPERATING HEAD PRESSURE OF 100 #/in²
7
8
9
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16
17
18
19
AUGUST 1957

Figure 7.

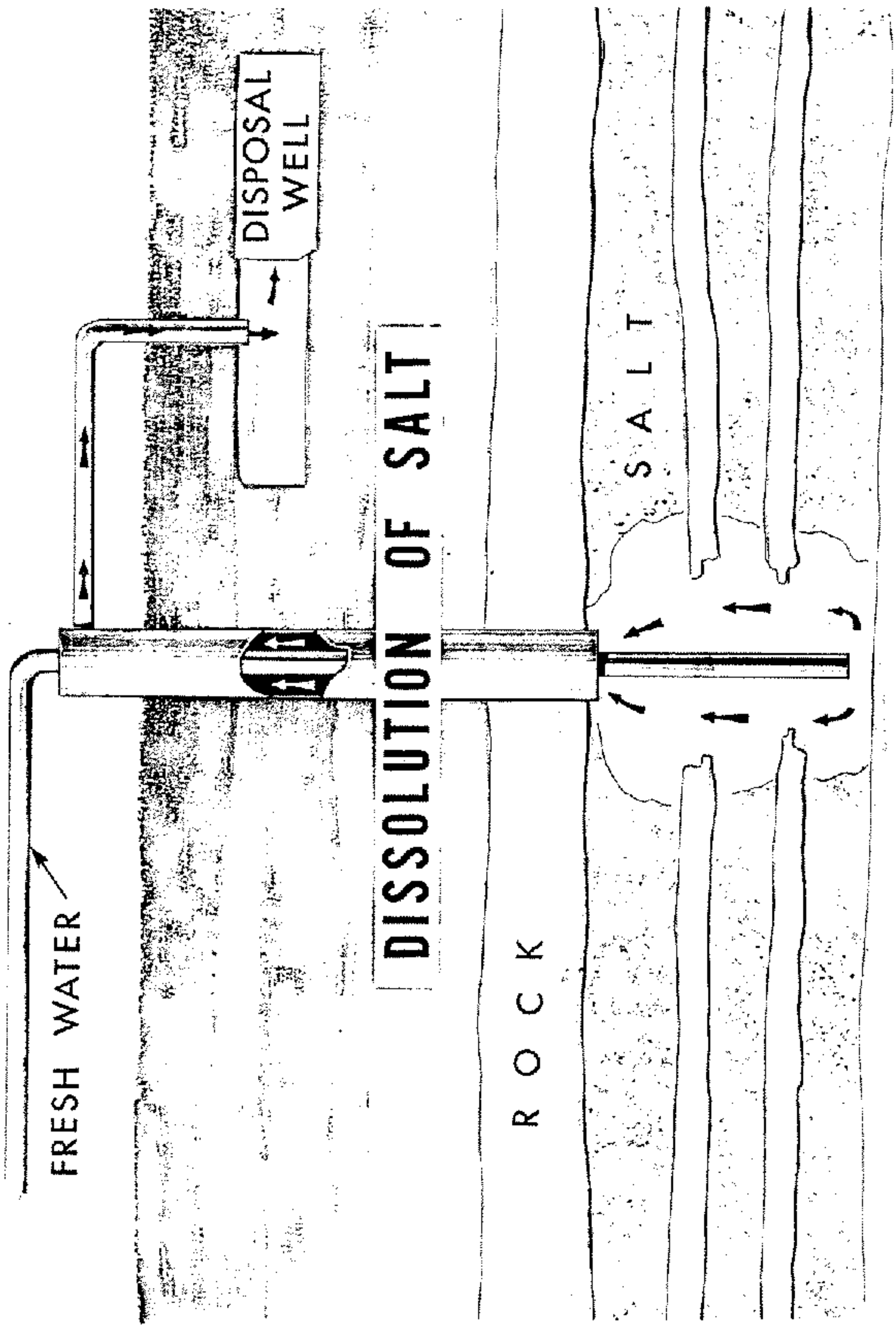

Figure 8.

Phase 2 -- For the second phase of development, the 7 inch casing was set at 4311 feet and the 4 inch tubing was reset to 4332 to mine the bottom 28 foot salt layer. At this point, a pressure test was made to test cavern tightness with the results shown on Figure 9. Test indicated a tight cavern.

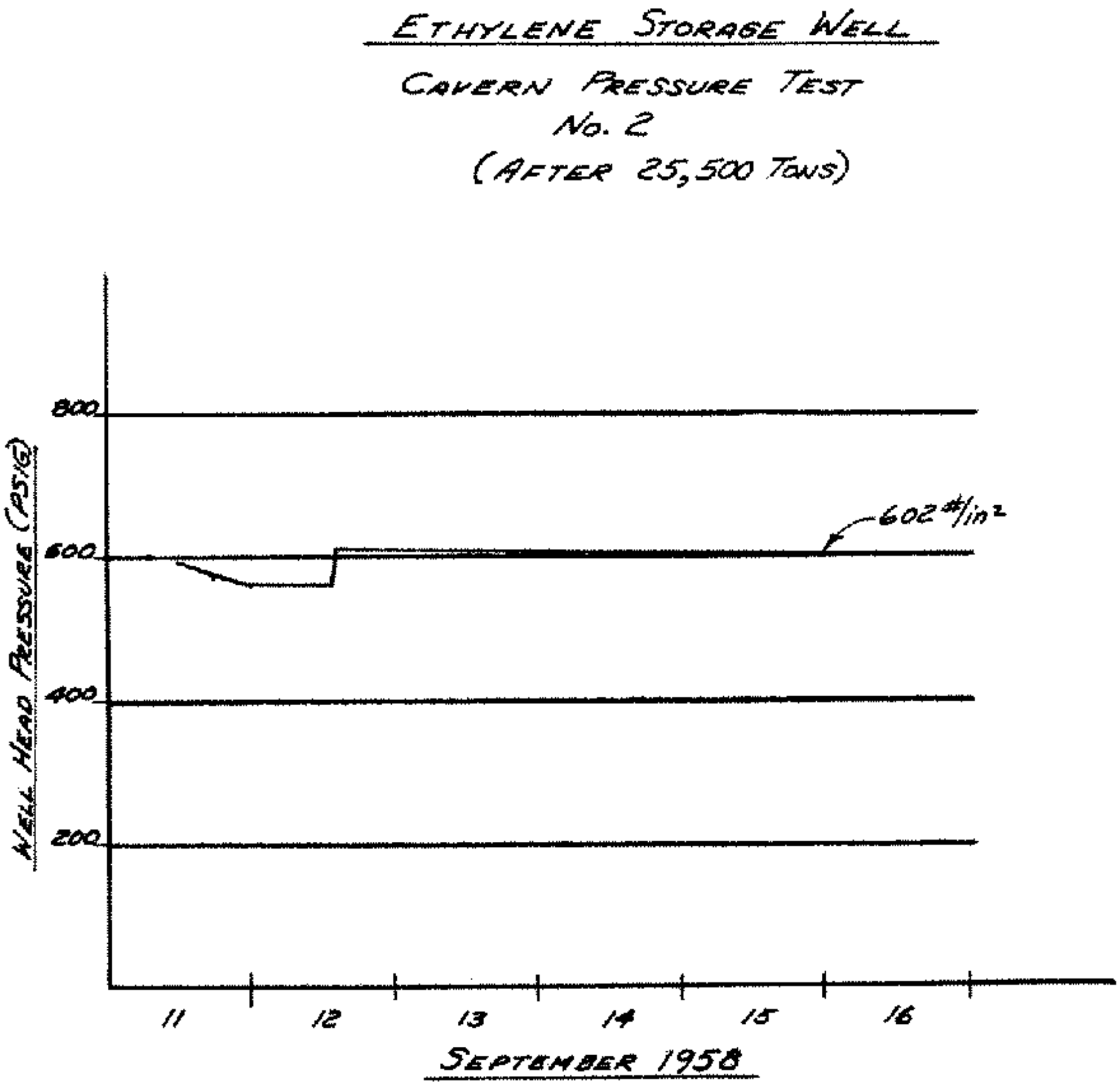

Figure 9.

During this phase fresh water was injected down the 4 inch tubing for a period of 2 months at which time the water was changed to top injection with salt solution coming up the 4 inch. The second phase produced a total of 10,950 tons. The total salt extracted at this time was 36,450 tons.

Phase 3 -- For the third and final phase, the 7 inch casing was set at 4165 feet near the top of the salt section and the tubing at 4332. Water injection was down the 4 inch or bottom injection. The final phase ended after a total of 50,200 tons of salt had been produced from the well. Another pressure test was performed to check on cavern tightness with the results as shown in Figure 10. Test again indicated a tight cavern.

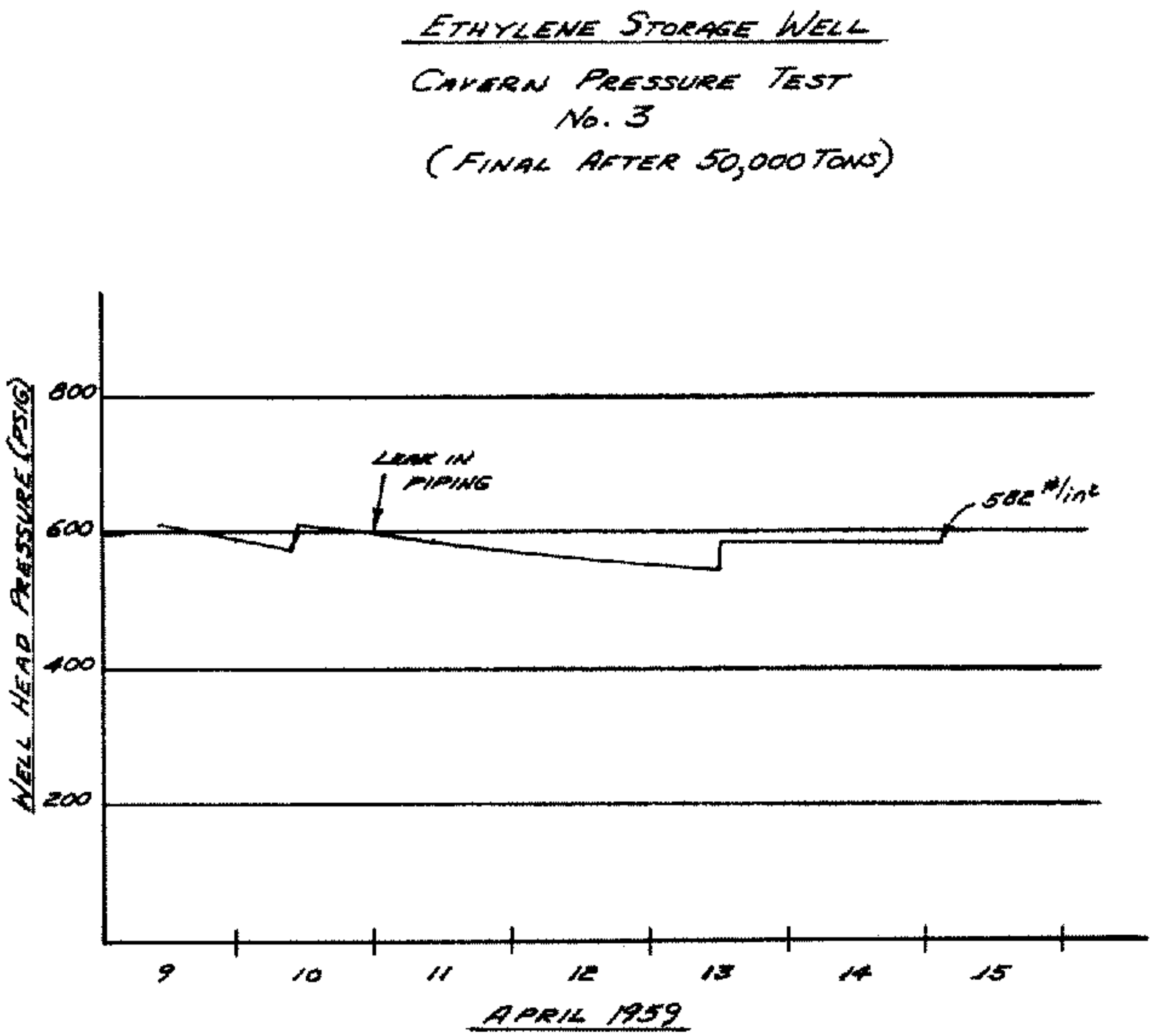

Figure 10.

Figure 11 is a plot of the cavern growth (tonnage of salt) plotted versus time with notes explaining injection cycles and casing and tubing settings. A final pressure reduction test to check size of cavern was performed with results as shown in Figure 12.

The 7 inch casing and 4 inch tubing were removed from the well and the cavern was calipered for zones having diameters of greater than 3 feet by using extended leg calipers. A series of 4 string shots was run, each covering a 20 foot section (4192 - 4212, 4227 - 4247, 4257 - 4277, 4292 - 4312) in an attempt to dislodge any ledge or debris that was about to fall. The string shot had little or no effect.

STORAGE OPERATIONS

Figure 13 shows the final installation of 7 inch casing and 4 inch tubing for ethylene storage. The 7 inch casing was set at 4327 and the 4 inch tubing at 4332. The bottom 1 1/2 feet of the 4 inch string is slotted to avoid complete closure if debris settled around the base of the tubing. The 7 inch casing was installed as a safety or tell-tale string to signal fill up of the storage cavern. When ethylene reaches the base of the 7 inch, it displaces the fluid in the 7 inch and actuates a pressure switch at the surface which in turn shuts down the ethylene compressing equipment.

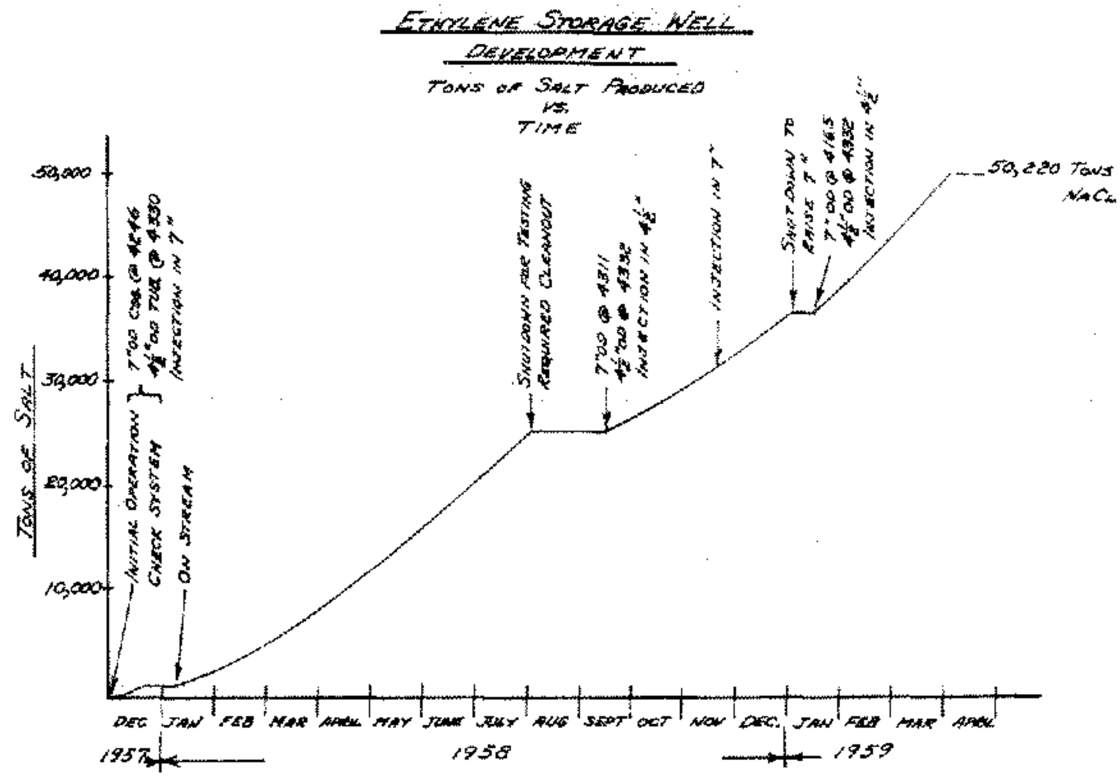

Figure 11.

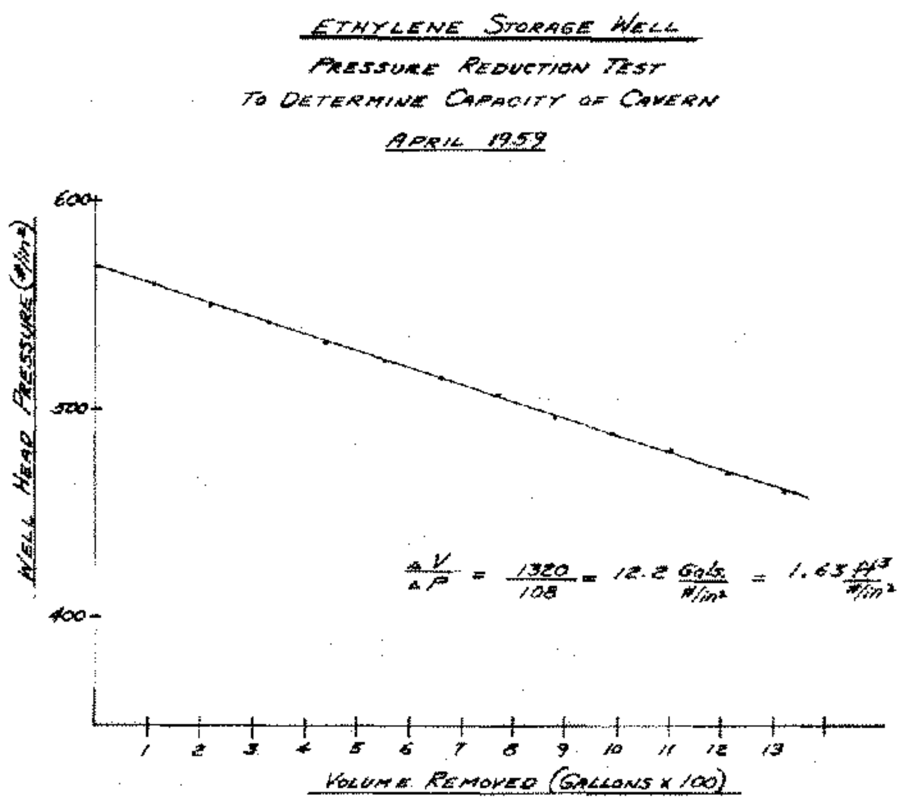

Figure 12.

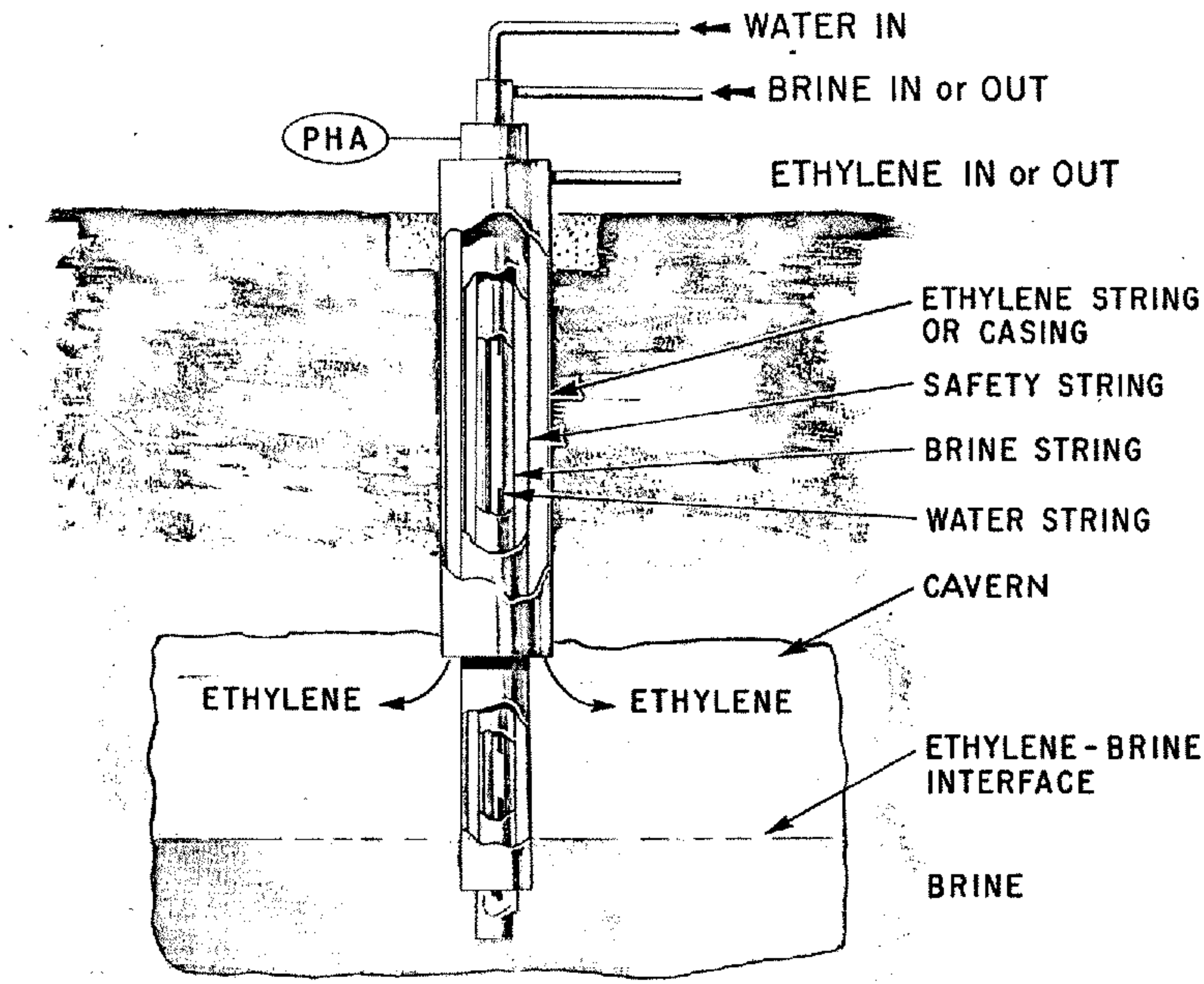
WATER IN
BRINE IN or OUT
PHA
ETHYLENE IN or OUT
ETHYLENE STRING OR CASING
SAFETY STRING
BRINE STRING
WATER STRING
CAVERN
ETHYLENE
ETHYLENE
ETHYLENE - BRINE INTERFACE
BRINE

Figure 13.

The Christmas tree used in this installation is a multiple head with an operating pressure rating of 3000# and tested to 6000#.

The ethylene storage facilities include the well itself plus above ground equipment, such as compressors, meter runs, various knockout drums, dehydration units and necessary instrumentation. See Figure 14.

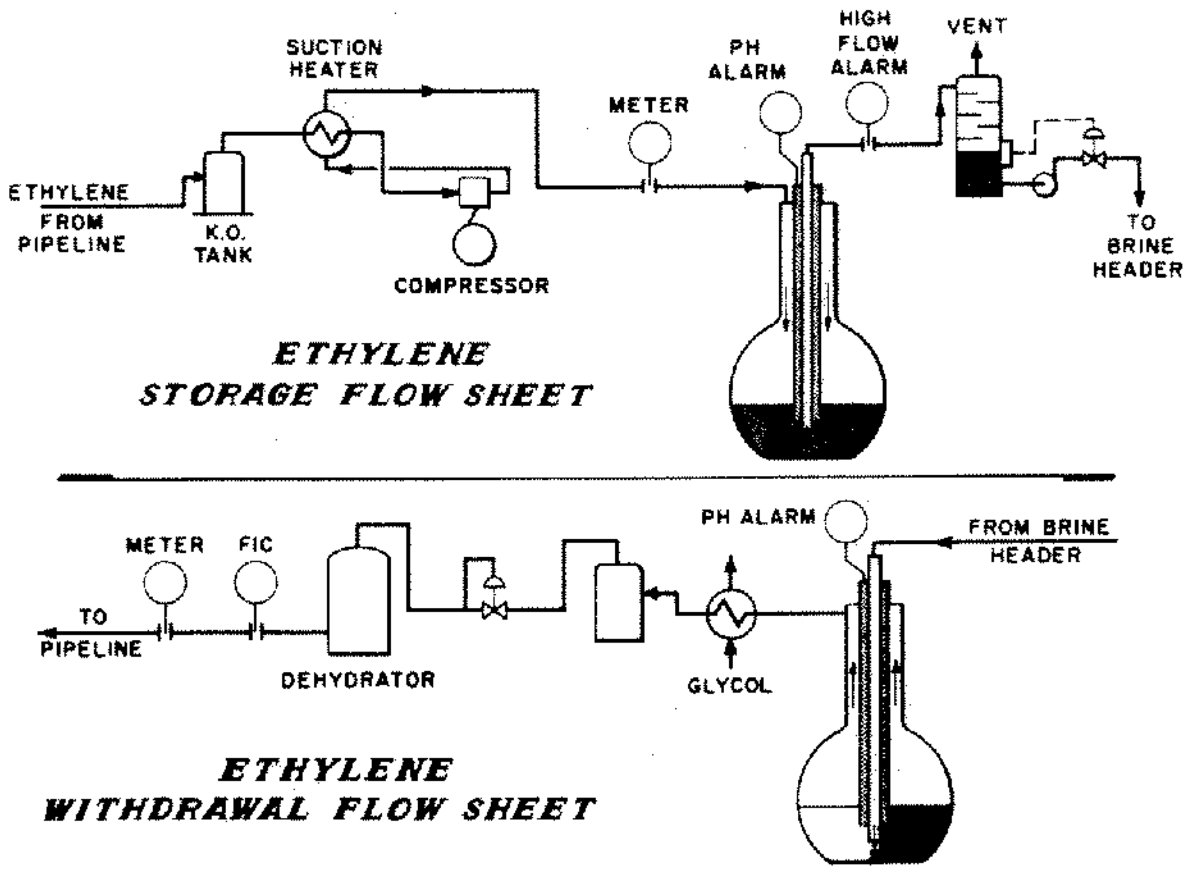

Figure 14.

The well operates unattended during the fill up cycle. During the withdrawal cycle and operator is in attendance continuously.

A. Filling cycle -- The ethylene flows from the main line to the well site, then through a knockout tank, suction heater, compressor meter run and then into storage well. Ethylene enters the 9 5/8 inch casing. As it enters the well it displaces brine from the cavern up the 4 inch tubing. The brine flowing out of the well is vented to remove any gases and is then pumped into a brine pipe line which is located near the storage site. The well floats on this brine line so that a brine pond is not required.

Bottom hole pressure is about 2400 psi., being equal to the pressure of the column of brine. The difference between the ethylene and brine pressures at the surface is equal to the difference in the static head of ethylene and brine. The ethylene pressure is approximately 1600 psi. and the brine pressure approximately 10 psi.

B. Withdrawal cycle -- During withdrawal ethylene flows from the 9 5/8 inch casing through a glycol heater, a knockout tank to remove liquid entrainment, pressure reduction from 1600 psi. to 1000 psi., through dehydrators to a metering station and then into the pipe line to the Midland plant.

Brine flows from the supply header into the 4 inch tubing to replace the ethylene in the cavern. The brine string floats on the brine header pressure.

SPECIAL PROBLEMS

Storage operations in the salt cavern have presented some special problems such as: (see Figure 15.)

1. Salt Precipitation.
   a. Gyping of the brine header and 4 inch tubing.
   b. Salt plugging the brine string.
2. Gas leakage in casing or well head equipment.
3. Formation of ethylene hydrates.

SPECIAL PROBLEMS....

- *SALT PRECIPITATION*

  A. DUE TO MIXING SEPARATE BRINES, CAUSING THE FORMATION OF CALCIUM SULPHATE OR GYPSUM.

  B. DUE TO COOLING A SATURATED BRINE FROM THE WELL CAUSING SODIUM CHLORIDE PRECIPITATION

- *FORMATION OF ETHYLENE HYDRATES*

Figure 15.

Gyping of the Brine Header -- When the salt cavern was completed, the brine remaining in the cavern was a saturated salt solution rich in sulfate. The brine that is used as the displacing fluid is a natural connate brine high in calcium and magnesium. When these two brines are mixed together calcium sulphate precipitates out of solution. During the first filling cycle, the brine leaving the well entered the supply header which contained the high Ca-Mg fluid and created serious plugging in this line.

This problem was solved by disposing of the salt brine in a disposal well as it was being displaced by the ethylene. Ethylene was removed from the well using the high calcium-magnesium brine.

The fluid used for displacement in salt cavern storage should be compatible with the fluid in the cavern. In future caverns we plan complete displacement of the salt brine before any storing with the natural (high Ca-Mg) brine upon which the system floats.

Salt Plugging of the Brine String -- We were aware that the cooling effect and pressure reduction on a saturated brine solution as it came up the tubing could cause sodium chloride precipitation. We also knew that we could control this by washing cycles or by installing a macaroni string, within the 4 inch tubing, for steady injection of fresh water. During operations the 4 inch tubing did become plugged with salt. The wash cycles required considerable operating expense. For these reasons, a macaroni string of 1 1/4 inch EUE tubing was run inside the 4 inch tubing. Brine leaving the cavern is now continuously diluted by water at the bottom of the 4 inch tubing which has prevented any salt precipitation.

Gas Leakage -- After filling operations began, a small gas leak developed and was believed to be in the 7 inch safety string. This, of course, could not be repaired unless the well was completely emptied of ethylene. To keep the 7 inch safety string functioning, the ethylene that accumulated at the top of the safety string was vented to the atmosphere every other day.

In October of 1961 the storage well was emptied and work started in an effort to locate a leak in the 7 inch casing.

The ethylene storage well is always considered hazardous and any work scheduled is carefully programmed before beginning. While working on the well the hole was constantly kept full of brine, air moving equipment was on hand, wind directions used to advantage, safety alarm equipment was installed and one safety man was on duty observing conditions at all times.

The 1 1/4 inch and 4 inch tubing strings were removed from the well. A set down packer was run on the bottom of the 4 inch tubing inside the 7 inch casing and set at various depths. At each of these settings the 9 5/8 inch ethylene string was pressured up and the 7 inch and 4 inch tubing were observed for leaks. This test indicated that there were no leaks in the 7 inch safety string.

A minor leak was found in the packing section of the Christmas tree. Plans are under way to repair this leak. In the storage of gas or hydrocarbons a metal to metal seal should be considered.

Formation of Ethylene Hydrates -- The 7 inch safety string was backflushed with fresh water once per month. Ground temperatures down to approximately 2000 feet are such that stable hydrates of ethylene and water can form.

The gas leaking into the safety string did form hydrates to the extent that the string was completely plugged off. This problem was solved by injecting warm brine down the 4 inch tubing melting the hydrates that had formed in the annular space.

The 7 inch safety string is now filled with diluted brine immediately after backwashing it with fresh water. The brine prevents the formation of hydrates.

SUMMARY

The ethylene storage well was placed in operation during 1959. In three years of operations it has been essentially full and emptied. Problems encountered in the operation have been successfully solved. Throughout the storage cycles it has proved to be a successful and economical method of storage.

REFERENCES

1. Katz and Cornell, "Flow of Natural Gas from Reservoirs."
2. Butz and Johnson, "Fundamentals of Underground Storage of Petroleum Fluids."