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Strategic Petroleum Reserve (SPR) Oil Storage Cavern Sulphur Mines 6 Certification Test and Analysis

Richard R. Beasley

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STRATEGIC PETROLEUM RESERVE (SPR)

OIL STORAGE CAVERN SULPHUR MINES 6 CERTIFICATION

TESTS AND ANALYSIS

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Abstract

Well leak tests and a cavern pressure test were conducted in June and July 1981 and indicated that oil leakage from the cavern is unlikely to exceed the DOE criterion if oil is stored at near atmospheric wellhead brine pressures and higher pressures are only used for short periods of oil fill and withdrawal. The data indicate that cavern structural failure during oil storage is unlikely and that there was no leakage from cavern 6 to the adjacent cavern 7. Because of the proximity of cavern 6 to cavern 7, it is recommended that a similar type of oil be stored in these two caverns.

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Introduction

Cavern 6 at the Sulphur Mines, Louisiana SPR oil storage site was certified for oil storage on February 3, 1978 (Ref. 1). The Dowell Sonar caliper survey taken December 29, 1977, and included in Ref 1, indicated a total cavern volume of 5.16 x 10^6 bbls.

The survey taken March 5, 1981 (Ref. 2) indicated a total cavern volume of 5.63 x 10^6 bbls. This volume increase was primarily a result of continued brining, prior to March 5, 1981, to get brine enrichment of PPG.

A well leak test in February and March 1981 (Ref. 3) indicated significant well leakage. Well workover actions to repair well and wellhead leaks were taken by TBC/DUCI and testing was restarted in June 1981 using test procedures (Ref. 4) which were developed in conjunction with the procedures and testing of West Hackberry cavern 6 (Ref. 5 and 6).

This report includes a general history of the cavern and a description of the certification testing, analyses, conclusions, and recommendations.

History

Wells 6X and 6Y were originally completed in 1955 as brine producing wells, and a sonar caliper survey conducted in October 1975 for PPG indicated a cavern volume 4.37×10^6 bbls (Ref. 1).

The site has a commercial history which dates back to 1868 when the Louisiana Petroleum and Coal Oil Company drilled the first oil exploration well. Subsequent exploration efforts discovered large deposits of high quality sulphur in the caprock. After several attempts to mine the sulphur conventionally, Herman Frasch invented a method to recover the sulphur using pressurized hot water. Approximately 9,400,000 tons of sulphur were removed from the caprock using the Frasch process. The removal of this vast amount of sulphur caused the overlying caprock to collapse causing subsidence at the surface. In addition to the sulphur industry, oil and gas have been produced by Union Texas Petroleum Company from the flanks of the dome. Pittsburgh Plate Glass (PPG) and Allied Chemical still have active brining operations in the dome. PPG produces brine from BSW 14 and BSW 15. Allied Chemical stores ethylene in BW 1 and BW 3 (Ref. 7).

In 1977 the DOE acquired approximately 640 acres for the SPR facilities at Sulphur Mines from Allied Chemical Corporation. During 1977, Gulf Interstate Engineering Company undertook certification studies for each of the acquired caverns. These were the 2-4-5 gallery and caverns 6 and 7. All were determined to be suitable for oil storage for five storage cycles (Ref. 1). Later, DOE determined that Sulphur Mines would only be utilized for one storage cycle. The storage potential in 1977 was approximately 24 million barrels (Ref 7). The cavern locations are illustrated in Figure 1.

A workover of well 6X by W-F&S in October and November 1979 included installation of the 7 5/8 in. production casing to a casing seat depth of 2505 ft. (Ref. 8). A workover of well 6Y by W-F&S in September and October 1979 included installation of the 7 in. production casing to a casing seat depth of 2500 ft. (Ref. 10). Reentry well 6Z was drilled by W-F&S in August and September 1979 (Ref. 12). The 10 3/4 inch hanging string was repositioned in July after the completion of the cavern tests (Ref. 13). The configurations of the three wells after cavern testing completion on July 6, 1981, and prior to the beginning of oil fill in mid July 1981 are shown in Figures 2, 3, and 4.

The certification testing was initiated in February 1981 by the injection of nitrogen into the three wells. This testing continued for about three weeks, and it was concluded that workovers were in order to reduce the indicated leak rate (Ref. 3). The well 6Y workover by TBC included setting plugs below the casing, conducting tests and taking corrective actions. The details of these workovers are available in Ref. 9, 11, and 13.

Certification testing was restarted with the injection of nitrogen into wells 6X and 6Z on June 2, 1981. The certification testing continued through July 7, 1981, when cavern pressure bleeddown was completed. Preliminary data reduction indicated acceptably low leak rates and no gross structural problems, and this information was forwarded to DOE on July 13, 1981 (Ref. 14).

Diagnostic Activities

There is no salt core and no side-wall-sample material available from Sulphur Mines site. Therefore, there are no material property or mineralogy data available for this site. All the cavern analyses will, therefore, use salt properties as derived from West Hackberry salt as published in Ref. 15.

Table 1 contains a listing of all available logs for the three wells. The BATS logs were run to assist in location of any high noise leak locations. The interface logs were run to locate the nitrogen/brine interface during well leak tests. The temperature logs in cavern 6 (Figure 5) indicate a 3°F temperature increase for a rate of 0.02°F/day. The brine samples taken 2/11/81 were analyzed and show 100% saturation at 68°F and over 99% saturation at the cavern brine temperature of 96°F. The analysis of these samples is included in Table 4.

Cavern sonar surveys were made and indicate the following volumes:

Date	Well	Volume, bbls
2/3/78 (Ref. 1)	6X	5.16×10^6
7/18/80 (Ref. 2)	6Y	5.16×10^6
3/5/81 (Ref. 2)	6Y	5.63×10^6

The latest sonar survey indicates a cavern shape as shown in Figure 6. The conclusion, reached in Ref. 16, that the upper waist section (2800 to 3090 ft.) may break off when the cavern is filled with oil, is still valid for the shape shown in Figure 6.

In an effort to estimate the space between cavern 6 and cavern 7, the following information was used:

1. Cavern 6 dimensions from Ref. 2.
2. Cavern 7 dimensions from Ref. 17.
3. Surface distance from well 6X to well 7A from coordinates in Ref. 8, Ref. 18, and data from the JDE survey completed 10/81.

4. Directional survey results from wells 6X and 7A taken from Ref. 1 and Ref. 18.

5. The range and azimuth from well 6Y at the cavern roof to well 6X pipe at the cavern roof, as seen during the sonar survey for Ref. 2 and obtained from Larry Vanmeter of Dowell.

This combination of data provides a nominal cavern separation of 75 ft. as shown in Figure 7. This 75 ft. separation is greater than previously indicated and would have a tolerance of ± 40 ft.

WELI LEAK TESTS IN FEBRUARY-MARCH 1982

A well leak and cavern pressure test of Sulphur Mines Cavern 6 was initiated on February 19, 1981, with injection of nitrogen into the annuli of wells 6X and 6Z and into the slick hole well 6Y to depths below the casing seats. While waiting for nitrogen temperature stabilization before pressurizing the cavern, it was noted that measured surface pressures indicated a large upward nitrogen-brine interface movement in well 6Y and significant movements in the other two wells. The interface movements were confirmed by density logs and a decision was made to abort the planned test, but to monitor interface movements for several days in an attempt to learn more about the leaks. A preliminary analysis of results obtained was presented in April 1981 (Ref. 3). DOE decided to workover well 6Y to find and repair the leaks.

A cement plug was set by TBC in well 6Y with the plug top at 2518 ft., and both nitrogen and brine leak tests were run by TBC. The details of the workover and the tests are included in Ref. 11, but they did not positively locate or repair any major leak. DOE decided to terminate the evaluation efforts and to proceed with the certification testing.

Well Leak Test and Cavern Pressure Test in June - July 1981

Following the well workover activities by TBC (Ref. 9, 11, 13) a well leak test was started on June 2, 1981, at 1000 hours using the procedures in Ref. 4. On some occasions it was necessary to allow minor deviations from the test procedures to achieve compatibility with equipment availability, schedules and other site activites.

The test sequence was: 1) well leak tests, and 2) cavern pressure tests at a 0.80 psi/ft gradient followed by 0.75 psi/ft gradient. It took 35 calendar days to complete and is summarized in Figure 8 and in Table 5. The total test pressure records are shown in Figures 9 through 13.

Well Leak Test

The well leak test ran from 6/2 through 6/15. The initial injection of nitrogen on 6/2 and 6/3 with the cavern at low pressure, the pressurization to 465 psia on 6/4, and the injection of nitrogen on 6/8 and 6/9 apparently resulted in reasonable temperature stability. The data from the interface logs and the calculated leak rates are shown in Table 6. The leak rate calculations are summarized in Appendix I.

The leak rate calculation requires knowledge of pressures, temperatures, interface depths, and borehole volumes in the zone of the nitrogen-brine interface. The interface depths are measured, the pressures are measured, and the nitrogen temperature is assumed to be constant. The borehole volumes are obtained from a combination of drilling history, caliper logs, if available, and weights of nitrogen put into the well. The nitrogen weights are obtained by using a load cell to weigh the Waukesha-Pierce Ind. liquid nitrogen tank during injection and using a density log to spot the interface as it passes a given depth. The borehole volume data are probably the most inaccurate of the inputs required for leak rate calculation.

Leak rates are a function of many variables including pressures, leaking fluids, flow path, and flow type. The pressures during the tests and during oil storage are described in Table 7, and it is apparent that the average oil pressure at the casing seat will be less than the nitrogen test pressure at the casing seat. This reduced pressure will result in a reduced leak rate. A review of the pressure drop equations (Ref. 19) indicates that for turbulent flow through rough wall passages, volumetric loss rates of crude oil could be as high as about one-third the volumetric loss rates of nitrogen at 100 atmospheres and 100°F. From this maximum, volumetric loss rates of crude oil decreases about two orders of magnitude for laminar flow (Ref. 6). At the maximum ratio of oil to nitrogen volumetric loss rate and the probable reduced casing seat pressure, the indicated oil leak rate from the wells is less than the DOE criterion of 100 bbls/yr for a cavern.

The pressure on the cavern at the end of the well leak test was increasing at a rate of 1.1 psi/day with an average brine pressure of 474 psia. This pressure increase will be compared with other test results and discussed in a later

section of this report. The pressure vs time plots are shown in Figures 14 through 21. The step in the nitrogen pressure curves, near hour 140 to 165 was the N2 interface reset on 6/8 and 6/9. The step in the pressure curves near hour 270 was caused by installation of new pressure probes. The step in the curves near hour 340 was the venting of nitrogen out of the wells.

Cavern Shut in at Maximum Allowable Pressure

After the nitrogen was removed from the wells, the cavern was pressurized to 715 psia (0.80 psi/ft) on 6/17. This test was continued until 6/26. The pressure on the cavern at the end of this test was decreasing at a rate of 1.0 psi/day with an average brine pressure of 695 psia. The pressure vs time plots are shown in Figures 22 through 26.

Cavern Shut in at Maximum Operating Pressure

After the completion of the maximum pressure test, the cavern pressure was bled down to 592 psia (0.75 psi/ft) on 6/26. This test was continued until 7/6. The pressure on the cavern at the end of this test was increasing at a rate of 1.0 psi/day with an average brine pressure of 608 psia. The pressure vs time plots are shown in Figures 27 through 30. The disturbance in the curves from hour 650 to hour 720 was caused by the low pressure test on cavern 7. This interaction will be discussed in a later section of this report. One other disturbance in the data is the temperature dependence of the pressure transducers.

Pressurization and Bleeddown

The cavern pressurization to 465 psia on 6/4 and to 715 psia on 6/17 used pump trucks and took brine from the site brine pond. On 6/4 the pumped brine was at 104°F and 87% saturated and was pumped into well 6Z. The total pumped with three trucks was 8424 bbls in five hours and the pressure rose from 60 to 465 psia. This pressurization gave an elasticity value of 20.8 bbl/psi. The pressure vs time curves are shown in Figures 31 and 32.

On 6/17 the pumped brine was at 118°F and 73% saturated and was pumped into well 6Z. The total pumped with two trucks was about 5660 bbls in 5.7 hours and the pressure rose from 450 psia to 714 psia on well 6X. This results in an elasticity value of 21.4 bbl/psi. The brine flow meter failed during part of the pumping; therefore, the total volume is extrapolated using pump truck data and some data from the flow meter. The pressure vs time curves are shown in Figures 33 and 34.

The cavern bleeddown to 592 psia on 6/26 and to 60 psia on 7/6-7/7 was accomplished without pumps, and the brine was put directly into the brine pond. On 6/26 the total brine removed was 1924 bbls in 1.7 hours and the pressure in well 6X went from 688 psia to 592 psia. This depressurization given an elasticity value of 20.0 bbl/psi hr. The pressure vs time curves are shown in Figures 35 through 37.

On 7/6-7/7 the total brine removed was 13861 bbls in 17.5 hours and the pressure went from 611 psia average to 50 psia average. The linear portion of this data was used to calculate an elasticity of 23.7 bbl/psi. The pressure vs time curves are shown in Figures 38 through 40.

The average system elasticity at a pressure change rate of about 1 psi/min is 21.5 bbl/psi for both pressurizing and bleeddown. This system elasticity is compared to the value of brine elasticity, using the values from Ref. 20 at 90°F, of:

2.1×10^{-6} bbl/bbl/psi x 5.63×10^{6} bbl = 11.8 bbl/psi which leaves 21.5 - 11.8 = 9.7 bbl/psi for a cavern (salt) elasticity.

Summary of Pressure Change Rate Results

The measured rates of wellhead brine pressure change at different cavern pressures are summarized as follows:

Pressure (psia)	Pressure Change Rate (psi/day)
695	-1.0
608	+1.0
474	+1.1

The parameters of brine temperature and brine salinity must be considered with the pressure change rate. Given a brine average temperature increase of 0.02°F/day and a nine day test, the brine volume would increase. This volume increase can be calculated using brine thermal expansion values from Ref. 20.

2.5×10^{-4} bbl/bbl/^{o}F x .02 x 5.63 x 10^{6} bbl = 28 bbl/day

The temperature increase of 0.02^{o}F/day will allow an average salt dissolution rate of:

0.00041 lb salt/lb H_2O x ^{o}F x 0.02^{o}F/day x 5.63 x 10^{6} bbl x 350.5 lb H_2O/bbl x 1/757 lb/bbl salt = 21 bbl salt/day

This disslutioning will cause the brine volume to increase by about 0.78 times the volume of dissolved salt at near saturation (Ref. 21):

0.78 x 21 = 16 bbl brine/day

Therefore, the brine volume increases by 28 + 16 = 44 bbl/day and the cavern volume increases by 21 bbl/day for a net volume change of plus 23 bbl/day. Using the value of 21.5 bbl/psi, which was developed earlier in the report, results in an expected 23/21.5 = 1.1 psi/day pressure increase in the cavern.

The decreasing pressure at the maximum allowable pressure and the trend of increasing pressure change with decreasing pressure is due to either salt creep, cavern leakage, or a combination of the two.

Salt creep, the time dependent flow of salt under stressed conditions, will cause volume changes of underground salt storage caverns. Changing volumes correspond to changing pressures, therefore, evaluation of salt creep is essential to the analysis of leak rate in terms of cavern pressure. Salt creep is a very complex and incompletely understood phenomenon. Finite element methods, as currently used for salt creep analyses of underground salt storage caverns, are generally considered to provide comparative relative results, but only order of magnitude results in an absolute sense for short times (~300 days). Factors affecting the accuracy of such analyses include; typical relatively large variations in measured values of salt properties which must be used in the analyses; differences between the behavior of laboratory specimens and the insitu salt; the dependence of creep on salt temperature to about the ninth power; and the time dependent and stress history dependent nature of creep. Unfortunately, order of magnitude creep analyses are inadequate for analysis of cavern pressures in terms of leak rate. It is thus generally concluded that complete analysis of pressure test results for SPR storage caverns, in terms of leak rates, are not possible with presently available methods of salt creep analysis. In-situ measurements are being made which will provide data to be incorporated into existing or new analytical

methods in ways to improve the reliability of creep calculations, possibly to the point where they would be useful to calculate actual leak rates from pressure tests. (Ref. 6).

The unknowns associated with creep and the data scatter of the three data points make detailed quantitative intepretation questionable. Some general conclusions are possible:

1. Cavern closure rate and leak rate are indistinguishable at this time. Therefore, pressure change rates are cavern closure rate minus leak rate. However, at operating pressures, the pressure increased indicating creep closure exceeded any loss due to a leak. Furthermore, early field data from creep experiments would indicate an expected pressure rise of about 1 psi/day.

2. Pressure change rate is higher with lower cavern pressure.

3. The pressure change rates of Sulphur Mines 6 are higher (more positive) than those of West Hackberry 6 (Ref. 6).

Relationships of Caverns 6 and 7 Pressures

The test procedures (Ref. 4) included the monitoring of cavern 7 pressure during the testing of cavern 6 primarily to verify the presence or absence of fluid flow between caverns. Cavern 7 well workovers were in progress until approximately 6/27 and therefore the only time that cavern 7 pressures were monitored was during cavern 6 pressurizations on 6/4 and 6/17. In both instances the pressure in cavern 7 was virtually constant. This gave no indication of a fluid leak but did indicate some manner of physical relationship.

When time in the cavern 7 workover schedule became available, it was decided to conduct the cavern 7 low pressure test as defined in Ref. 4. Cavern 6 was in the 0.75 psi/ft pressure test, thus conducting the cavern 7 low pressure test at 0.47 psi/ft would place maximum stress on the web between the caverns. The details of the low pressure test will be reported in Ref. 22, but a plot on the cavern 6 time base, is shown in Figures 41 and 42.

The effect of reducing the cavern 7 pressure can be seen in Figure 29 by the increase in curve slope at hour 648 and near hour 720. Cavern 7 was kept shut in and the downhole pressures monitored through the cavern 6 bleeddown on 7/6-7/7. The slope of the cavern 7 pressure curve changed from +10 psi/day prior to cavern 6 bleeddown, to +22 psi/day during the bleeddown.

One theory (there are probably several) that could explain the indicated cavern 6-7 pressure pressure relationship involves the assumption of a semi-rigid roof over caverns 6 and 7. An analogy would be a large semi-rigid structure (roof) on an elastic foundation and partially supported by two hydraulic jacks (caverns). As the load (pressure) is increased in one jack, the load (pressure) decreases in the other jack with an associated change in foundation (salt) loading. There has been no attempt to make a mathematical model of the cavern interaction, but this may be appropriate after the data from West Hackberry 6-7-8-9 (Ref. 6), Sulphur 6-7, and Sulphur 7-6 (Ref. 22) are compared.

Summary Discussion

Generally speaking, the most probable location of leakage from a cavern is from the wells, where the competent salt has been breached. However, there is a possibility of leakage from the cavern proper. If such leakage does exist, the probability is high that it will be to a nearby cavern or a nearby edge of dome. In the case of salt domes where extensive gas is present, a possible leakage path would be to caprock through a zone of gas bearing impurities in the salt.

The data from cavern 6 and 7 indicate no fluid communication between caverns and cavern 6 is about 383 ft. (Ref. 7) from the dome edge. Therefore, the most likely leakage path on cavern 6 would be around the well casing/cement/salt and up to caprock. The well test data indicates leaks in this area are less than 100 bbls/yr.

In addition to concerns regarding cavern leakage, a major concern is the structural integrity of the cavern. Sonar surveys indicate that the cavern has three salt ledges and that the maximum cavern diameter is over 550 ft. The sonar caliper has a definite beam width and, therefore, cannot "see" brine paths smaller than this beam width. For example, the leached lense at 2970 ft. shows a diameter of 530 ft. in Figure 6, but in fact this and other lenses may be significantly larger than indicated. The possibility exists that one or more of the three ledges may fall during or after oil fill, with the top ledge being the most likely to fall (Ref. 14 and Ref. 16). In addition, if a ledge falls, it may well cause lower ledge(s) to fall due to increased loading. We do not believe that these ledge falls would be likely to cause a cavern structural integrity problem, but would be likely to damage the brine string(s) in the cavern.

Structural analyses of the cavern using finite element model computer code "SANCHO" have indicated no structural problem except the potential for ledge falls. Efforts including field measurements at oil filled caverns are underway to attempt to validate the creep models. This data will allow prediction of cavern creep closure on the basis of theory and experimental data. These and other calculations on Sulphur Mines caverns will be limited due to lack of material properties data on Sulphur Mines salt.

Conclusions and Recommendations

Although all questions cannot be conclusively eliminated, cavern 6 appears to be suitable for one cycle of long term oil storage at normal pressure.

1. In general, the most probable location of a cavern leak is from the wells. Cavern well leaks measured during the June-July 1981 test indicate oil leaks from the wells during storage at near brine head pressures were well within the DOE leak rate criterion of 100 bbls/yr per cavern.

2. It was not possible to determine conclusively due to the indeterminate effect of creep closure that there was no cavern leakage in addition to that measured from the wells. The test did show that there was no fluid communication with cavern 7, the nearest cavern. The cavern is separated from the edge of the dome by about 380 feet, which is considered adequate under normal conditions.

3. It is also believed that serious structural failure of the cavern is unlikely during long term oil storage at brine head pressure, or during an accidental depressurization to oil head pressures. Analyses indicate the cavern is structurally adequate except for potential ledge falls during or after oil fill. The ledge falls should not result in any structural problems but may damage the hanging brine strings.

4. It is recommended that the cavern be evaluated for ledge falls and separation from cavern 7 each time oil is withdrawn to an interface depth of 3080 ft. or less.

5. It is recommended that cavern 6 and cavern 7 contain the same type of oil so that if a web failure occurs, the penalty will be minimized.

Sulphur Mines Cavern 6
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Table 1

List of Borehole Logs
Borehole Logs SM 6X

Date	Type of Log	Log Co.	Log Location
12/29/77	Sonar	Dowell	Ref. 1
1/3/78	CBL	McC	Ref. 1
1/3/78	Caliper	McC	Ref. 1
1/5/78	Direction	Sperry-Sun	Ref. 1
10/17/79	Caliper BLI = 3000	Sch	Ref. 8
10/25/79	Caliper BLI = 1840	Micro	Ref. 8
10/30/79	CBL	Sch	Ref. 8
11/1/79	Caliper BLI = 2550	Micro	Ref. 8
11/2/79	Collar	Micro	Ref. 8
2/12/81	Temp	GO	TBC
2/12/81	BATS	GO	TBC
2/19/81	Interface	Micro	TBC
2/25/81	Interface	Micor	TBC
6/2/81	Interface	Micro	TBC
6/5/81	Interface	Micro	TBC
6/8/81	Interface	Micro	TBC
6/11/81	Interface	Micro	TBC
6/15/81	Interface	Micro	TBC

Table 1 (Cont'd)

Borehole Logs SM 6Y

Date	Type of Log	Log Co.	Log Location
1/11/78	CBL	McC	Ref. 1
1/11/78	Caliper	McC	Ref. 1
9/27/79	Sonar	Dowell	Ref. 10
9/29/79	Caliper	Sch	Ref. 10
9/29/79	Caliper	Micro	Ref. 10
10/10/79	CBL	Sch	Ref. 10
10/12/79	Caliper	GO	Ref. 10
10/16/79	Formation test	Sch	Ref. 10
7/18/80	Sonar	Dowell	TBC
2/13/81	Temp	GO	TBC
2/13/81	BATS	GO	TBC
2/19/81	Interface	Micro	TBC
2/25/81	Interface	Micro	TBC
3/5/81	Sonar	Dowell	TBC
3/13/81	Interface	Micro	TBC
5/8/81	Interface	Micro	TBC
5/12/81	Interface	Micro	TBC
5/19/81	Interface	Micro	TBC
6/1/81	Caliper	GO	TBC
6/3/81	Interface	Micro	TBC
6/8/81	Interface	Micro	TBC
6/9/81	Interface	Micro	TBC
6/11/81	Interface	Micro	TBC
6/15/81	Interface	Micro	TBC
7/7/81	Temp.	GO	TBC

Table 1 (Cont'd)

Borehole Logs SM 6Z

Date	Type of Log	Log Co.	Log Location
8/21/79	ISF/Sonic	Sch	Ref. 12
8/22/79	BGT	Sch	Ref. 12
8/27/79	Directional	EMCO	Ref. 12
9/4/79	CDL	Sch	Ref. 12
9/6/79	BGT	Sch	Ref. 12
9/7/79	BGT	Sch	Ref. 12
9/16/79	CNL/CDL	Sch	REf. 12
9/16/79	CBL	Sch	Ref. 12
9/18/79	BGT	Sch	Ref. 12
9/24/79	CBL	Sch	Ref. 12
9/25/79	CDL	Sch	Ref. 12
9/27/79	Collar	GO	Ref. 12
2/13/81	Temp.	GO	TBC
2/13/81	BATS	GO	TBC
2/20/81	Density	Micro	TBC
2/20/81	Interface	Micro	TBC
2/20/81	Density	Micro	TBC
2/25/81	Density	Micro	TBC
3/21/81	Interface	Micro	TBC
3/16/81	Interface	Micro	TBC
4/9/81	Interface	Micro	TBC
6/2/81	Interface	Micro	TBC
6/9/81	Interface	Micro	TBC
6/11/81	Interface	Micro	TBC
6/15/81	Interface	Micro	TBC

Table 2

Comments on Logs

Well 6X	Comments
Sonar 12/29/77	Shows a cavern roof at about 2960 ft, a floor at 3400 ft., a volume of 5.16 x 10^6 bbls, and a shape with two ledges.
Gyro 1/5/78	Shows a relatively straight hole with a 9.4 ft deviation in a northwesterly direction at a depth of 2900 ft.
Caliper 10/17/79	Run prior to installing the 7 5/8" casing and shows relatively smooth 9.75 inch hole from 2590 to 2600 ft.
CBL 10/30/79	Shows a reasonably good bond on the 7 inch casing from about 630 ft. to 950 ft. and good bond from 950 ft. to 2500 ft.
Caliper 11/1/79	Shows bottom of casing at 2493 ft., a smooth hole to 2524 ft. with a diameter about 7 inches, a washout from 2524 ft. to 2530 ft., and then 7.5 inch hole to 2550 ft.
Temperature 2/12/81	Shows a maximum temperature of 150°F at 900 ft. and an average temperature of 120°F from 0 to 3000 ft. Final temp. was 96.1°F.
Density Interface	
6/2/81	Shows N_2 - Brine Interface 2600 ft.
6/8/81	Shows N_2 - Brine Interface 2230 ft. reset to 2605 ft.
6/11/81	Shows N_2 - Brine Interface 2596 ft. @ 0845
6/15/81	Shows N_2 - Brine Interface 2591 ft. @ 0950 Shows casing at 2502 ft.

Table 2 (Cont'd)

Well 6Y	Comments
Sonar 9/27/79	Shows a cavern roof at about 2911 ft., a floor at 3392 ft., a volume of 5.90 x 10^6 bbls, and a shape with three ledges.
CBL 10/10/79	Shows a good bond from 300 ft. to 2500 ft.
Temp. 2/13/81	Contains the note "not possible to scale" indicates a final temp. of 96.1^{C}F.
Sonar 3/5/81	Shows a cavern roof at about 2912 ft., a floor at 3390 ft., a volume of 5.63 x 10^6 bbls, and a shape with three ledges.
Caliper 6/1/81	Shows bottom of casing at 2498 ft., an irregular borehole with an estimated diameter of 7.87 inches to 2580 ft., and then hole goes beyond capiper maximum at 2584 ft. There are washout areas at 2500 ft., and at 2548 ft.
Density Interface 6/3/81	Shows N_2 - Brine Interface 2580 ft.
6/8/81	Shows N_2 - Brine Interface 2579 ft.
6/9/81	Shows N_2 - Brine Interface Reset 2579 ft.
6/11/81	Shows N_2 - Brine Interface 2570 ft. @ 1045
6/15/81	Shows N_2 - Brine Interface 2560 ft. @ 1120 Shows casing at 2502 ft.
Temp. 7/7/81	Shows a final temperature of 89.5^{O}F. The temperature in the borehole are about 10 F less than those on the 6X log of 2/12/81, therefore, we interpret a calibration error on either 2/81 or on 7/81. We assume a maximum of a 3°F temperature increase from 2/81 to 7/81.

Table 2 (Cont'd)

Well 6Z	Comments
CDL/GR 9/4/79	Shows top of salt at 1482 ft., a salt density of 2.05 to 2.16 g/cm^3 BLI = 1640 ft.
CDL/GR 9/16/79	Shows density of 2.05 to 2.16 above 2500 ft., shows two 5 ft. zones with density up to 2.34 g/cm^3 at 2505 and 2555 ft. GR is consistent and shows no high peaks that would indicate sylvite. BLI = 2600 ft.
CDL/GR 9/16/79	Shows density of 2.00 to 2.14 from 2600 to 2820 ft. and below 2845, a zone from 2820 to 2845 with a density maximum of 2.25 g/cm^3. GR shows no peaks. BLI = 2876 ft.
CBL 9/24/79	Show good bond from 400 ft. to about 2600 ft.
Caliper 9/18/79	Run prior to installation of production casing. BLI = 2600 ft.
Temp. 2/13/81	Contains the note "not possible to scale" indicates final temp. of 96.1^{o}F
Density Interface 6/2/81	Shows N_2 - Brine Interface 2695 ft.
6/9/81	Shows N_2 - Brine Interface Reset 2682 ft.
6/11/81	Shows N_2 - Brine Interface 2675 ft. @ 1205
6/15/81	Shows N_2 - Brine Interface 2653 ft. @ 0845 Shows Casing at 2574 ft.

Table 3

Abbreviations and Symbols

BATS	Noise Log
BSW	Brine Source Well
BW	Brine Well
bbl(s)	barrels (42 US gallons)
BH	Bradenhead Flange
BLI	Bottom of logged interval
CDL	Compensated density log
DOE	Department of Energy
DUCI	Dravo Utility Constructors, Inc.
GO	Gearhart (GO Wireline Co.)
GR	Gamma Ray Log
KB	Kelly Bushing on Drill Rig
LSU	Louisiana State University
PPG	Pittsburg Plate Glass Co.
PSIA	Pounds per Square inch Absolute
PSIG	Pounds per Square Inch Gauge
McC	McCullough (Baroid Petroleum Services)
MICRO	Micro Gage, Inc.
N_2	Nitrogen
Sch	Schlumberger Limited
SM	Sulphur Mines
SPR	Strategic Petroleum Reserve
STP	Standard Temperature and Pressure
TBC	Texas Brine Company
W-F&S	Williams Brothers Engineering Co. - Fenix & Scisson, Inc.
WP	Waukesha - Pierce, Ind. Nitrogen Services Div.

Table 4

Results of Analysis of SM Cavern 6
Brine Samples Taken 2/11/81

Materials Description

Brine in steel cylinders, some cylinders four feet long

SPR 102 = SM-6Y-3220
SPR 103 = SM-6Y-3270
SPR 104 = SM-6Y-3340
SPR 105 = SM-6Y-2950
SPR 106 = SM-6Y-3090
SPR 107 = SM-6Y-3030
SPR 108 = SM-6Y-3140
All collected 2/11/81

Work Requested

Density, Na, K, Ca, Cl, SO_4

Results

	All mg/mL						
	Na^+	K^+	Ca^{++}	Cl^-	$SO_4^=$	=	Density
SPR 102	120.	0.006	0.520	192.	1.38		1.20 @ 20.5°C
SPR 103	122.	0.010	0.468	194.	1.42		1.20 @ 21.0°C
SPR 104	121.	0.020	0.508	193.	1.38		1.20 @ 21.3°C
SPR 105	120.	0.010	0.500	192.	1.34		1.20 @ 21.2°C
SPR 106	121.	0.012	0.500	193	1.36		1.20 @ 21.9°C
SPR 107	120.	0.012	0.528	192.	1.36		1.20 @ 21.3°C
SPR 108	114.	0.010	0.504	192.	1.38		1.20 @ 21.4°C

Na^+ analyses appear to be 2 to 4% low (9% for SPR 108).

Based on Cl^- and density, all solutions were saturated as they were removed from their cylinders at room temperature. Each cylinder was rinsed with water and the rinse analyzed for the same elements. Total cations and anions recovered by rinse were about 1% of amount recovered directly and provide no evidence for large amounts of precipitated salt in the cylinders.

Table 5

Cavern 6 Test Chronology

Date and Day-of-year	Activity
6/2/81, 153	Data start at 1000 hrs. put N_2 in 6X and 6Z.
6/3, 154	Put N_2 in 6Y.
6/4, 155	Pressurized to 465 psia with pump trucks.
6/5 thru 6/7	Activities stopped due to weather.
6/8, 159	Reset interfaces on 6Y and 6X.
6/9, 160	Reset interface on 6Z and 6Y.
6/10, 161	Allow N_2 to stabilize.
6/11, 162	Ran interface logs in 6X, 6Y, 6Z. Test started.
6/12 thru 6/14	Conduct N_2 test, monitor pressures.
6/15, 166	Ran interface logs in 6Z, 6X, 6Y. Leak rates appear acceptable. Bled N_2 off.
6/16, 167	Wait on cavern 7 work.
6/17, 168	Pressurized to 715 psia with pump trucks.
6/18 thru 6/25	Monitor pressures.
6/26, 177	Bled pressure to 592 psia.
6/27 thru 6/28	Monitor pressures on Cavern 6.
6/29, 180	Started low pressure test on cavern 7. Monitored pressures on cavern 6.
6/30 thru 7/1	Monitor pressures on cavern 6. Continue low pressure test on cavern 7.
7/2, 183	Stopped low pressure test and shut in wells on cavern 7. Monitor pressures on cavern 6.
7/3 thru 7/5	Monitor pressures on cavern 6 and cavern 7.
7/6, 187	Started cavern 6 bleed.
7/7, 188	Completed cavern 6 bleed and removed all instruments from cavern 6 and cavern 7. Data stopped at hour 839, which is 35 days elapsed time.

TABLE 6

TABULATED RESULTS OF WELL LEAK TEST 6/2/81 THROUGH 6/15/81

Well	Date	I'Face Depth	Brine Press (1)	N2 Press.	Bore Volume Est. Ft^3/Ft Cal	N2	Avg	Test Hour	Calc. N2 Leak Rate bbl/yr (2)
6X	6/2	2600	39	1267	—			—	
	6/8	2605	447	1660	—			—	
	6/11	2596	450.	1661.8	—	.10	.10	215	
	6/15	2591	458.2	1657.8	—	.10	.10	312	0
6Y	6/3	2580	39	1270	—			—	
	6/9	2579	447	1647	—			—	
	6/11	2570	450.0	1649.5	.338	.40	.37	217	
	6/15	2560	458.2	1646.0	.338	.40	.37	313	12
6Z	6/2	2695	40	1291	—			—	
	6/9	2682	481	1554	—			—	
	6/11	2675	483.7	1702.3	—	.36	.36	218	
	6/15	2653	485.4	1705.1	—	.36	.36	311	85

(1) Well 6Y, brine pressure assumed to be equal to 6X brine

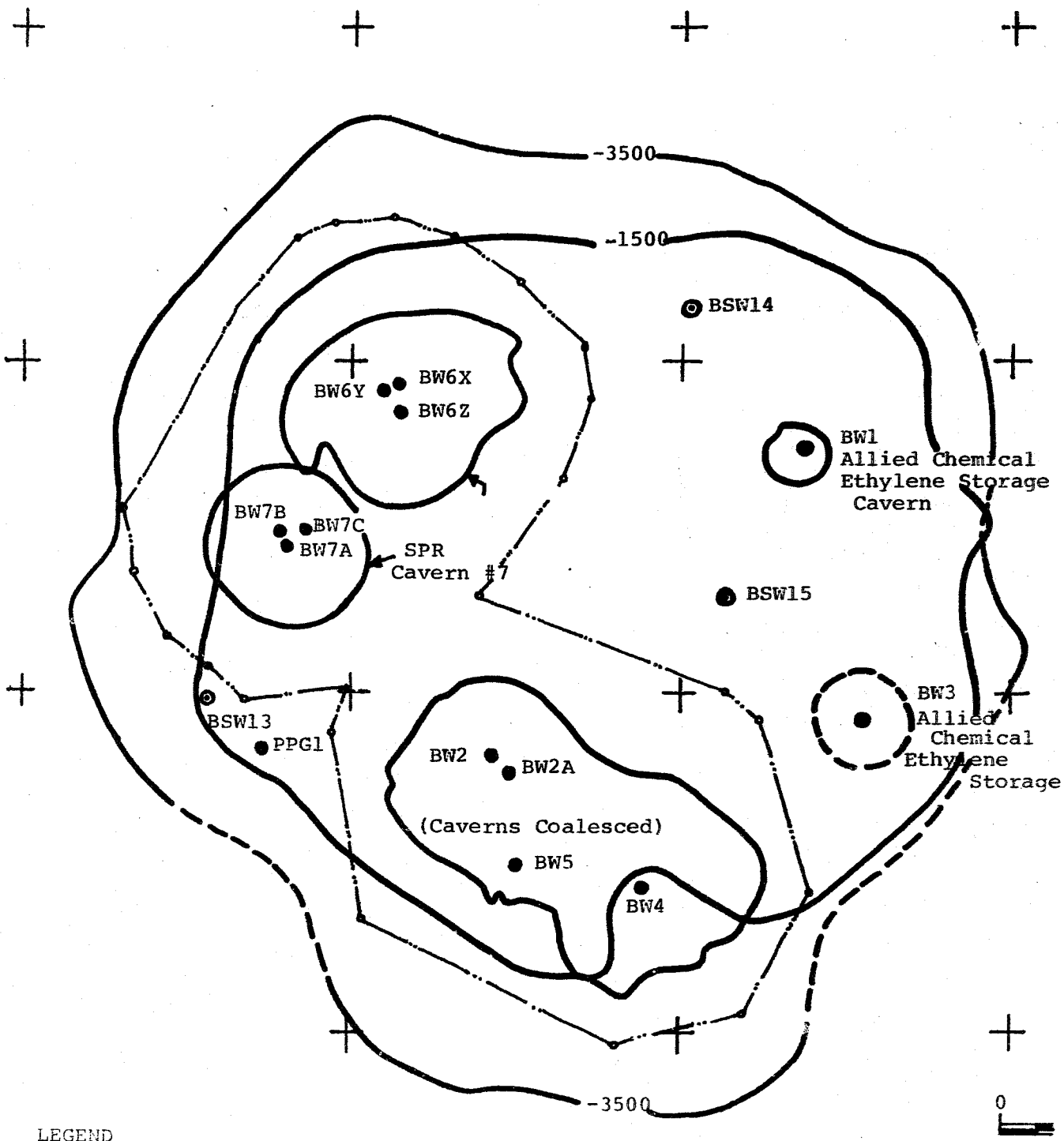
(2) Note that the change in pressure would cause the interface to move up about 8 ft. Calculations are included in Appendix I.

Table 7

Comparison Pressures at 2500 Ft. Depth

Condition	Casing Seat Fluid	Psia
Nitrogen test @ 0.70 psi/ft.	N_2	1750
Brine test @ 0.75 psi/ft.	Brine	1875
Brine test @ 0.80 psi/ft.	Brine	2000
Oil storage at zero brinehead with 0.52 psi/ft. brine	Oil	1300
Oil fill at maximum operating gradient of 0.75 psi/ft.	Oil	1875
Oil drawdown with 150 psi on the oil at the wellhead and 150 psi oil flow pressure drop in well with 0.37 psi/ft. oil	Oil	925

From Figure 6-6 of Ref. 7



LEGEND

- ● BW BRINE WELL
- ◎ BSW BRINE SOURCE WELL
- CAVERN EXTENT. BASED ON SONAR SURVEY
- SPR PROPERTY LINE

FIGURE 1

S. M. SITE

From Figure 5 of Ref. 8

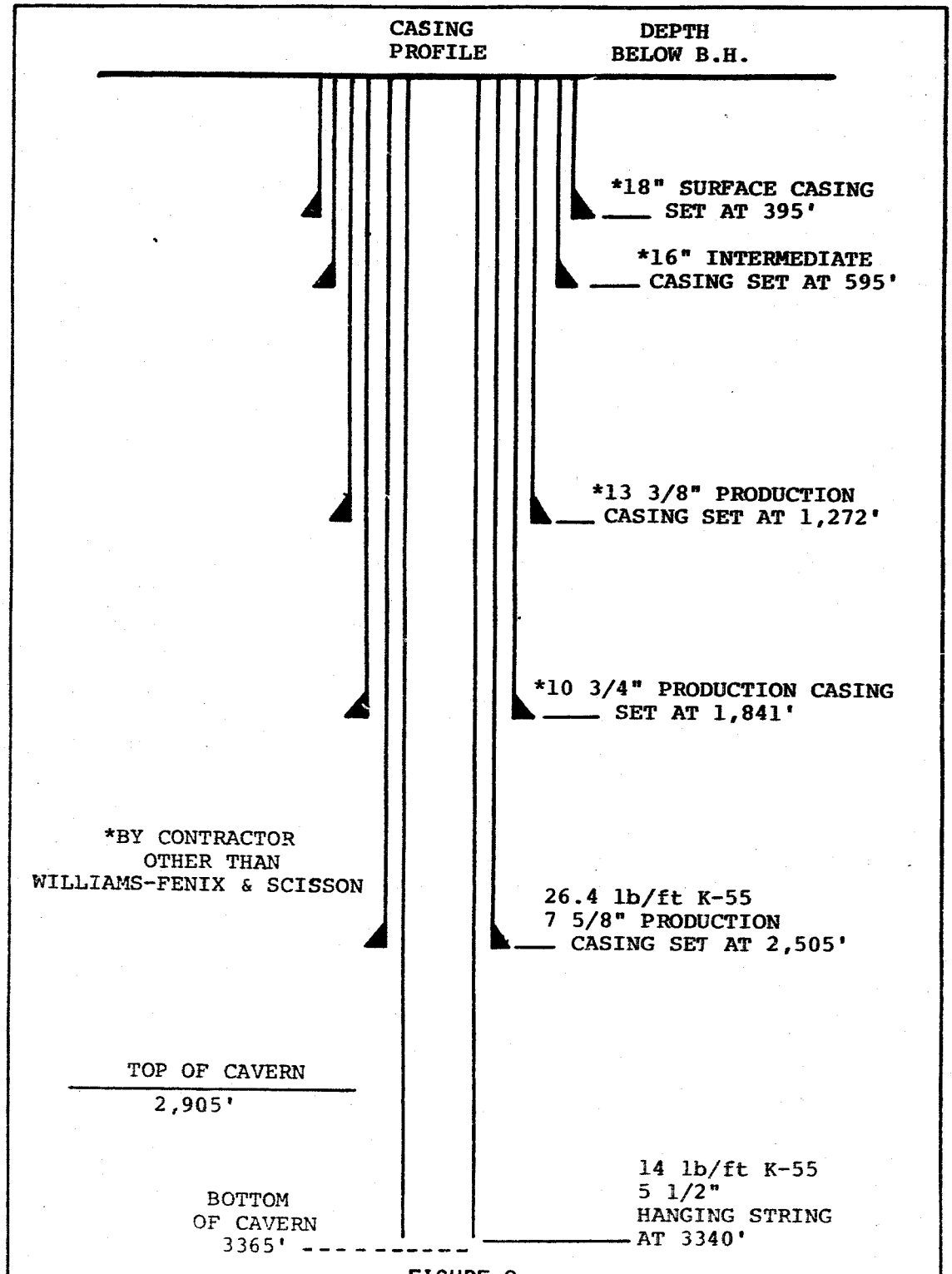


FIGURE 2
As-Built Casing Diagram SPR Well 6X (Workover) Sulphur Mines

FROM FIGURE 5 OF REF. 10

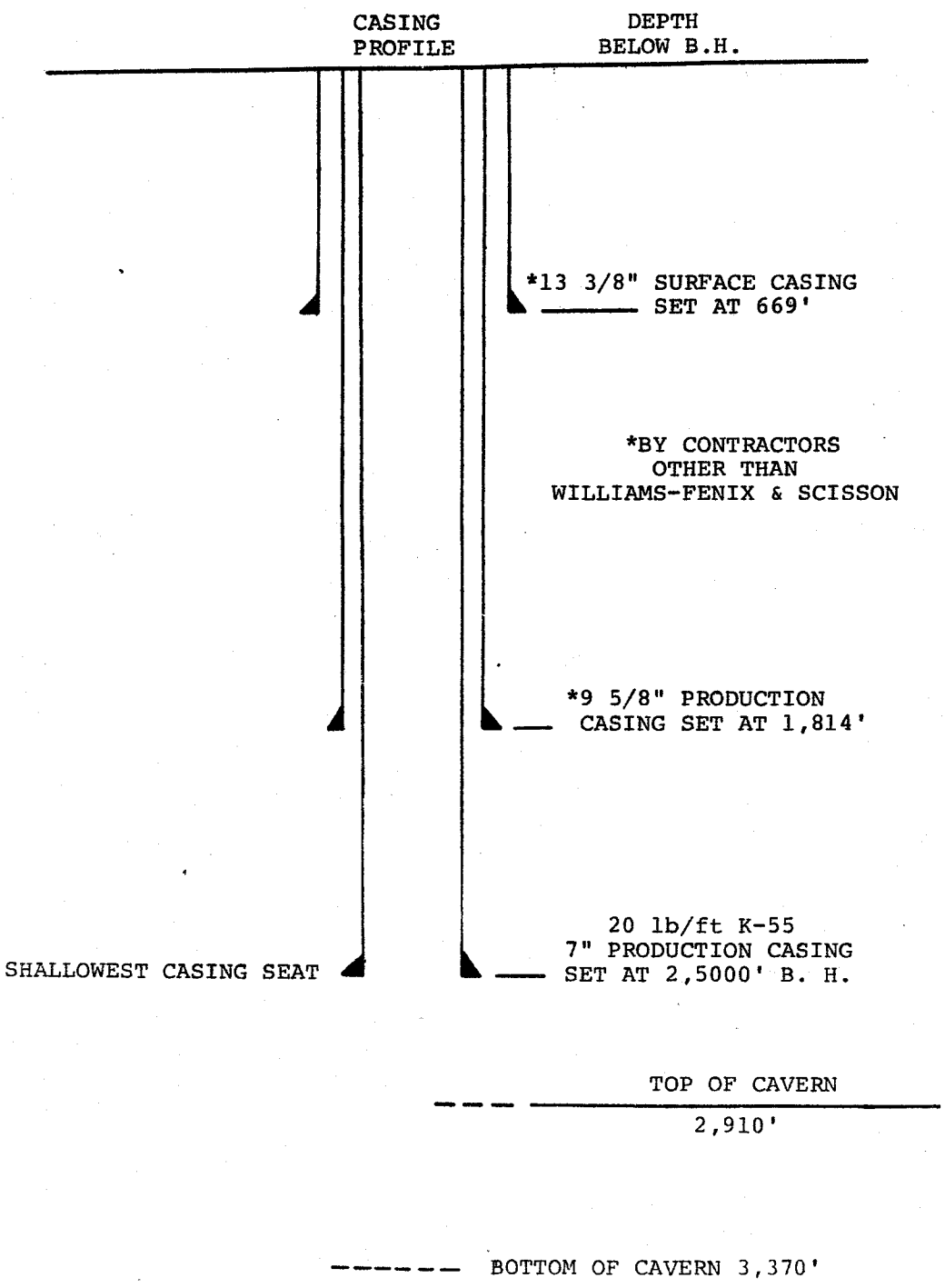


FIGURE 3. AS-BUILT CASING DIAGRAM
SPR 6Y (WORKOVER) SULPHUR MINES

FROM FIGURE 6 OF REF. 12

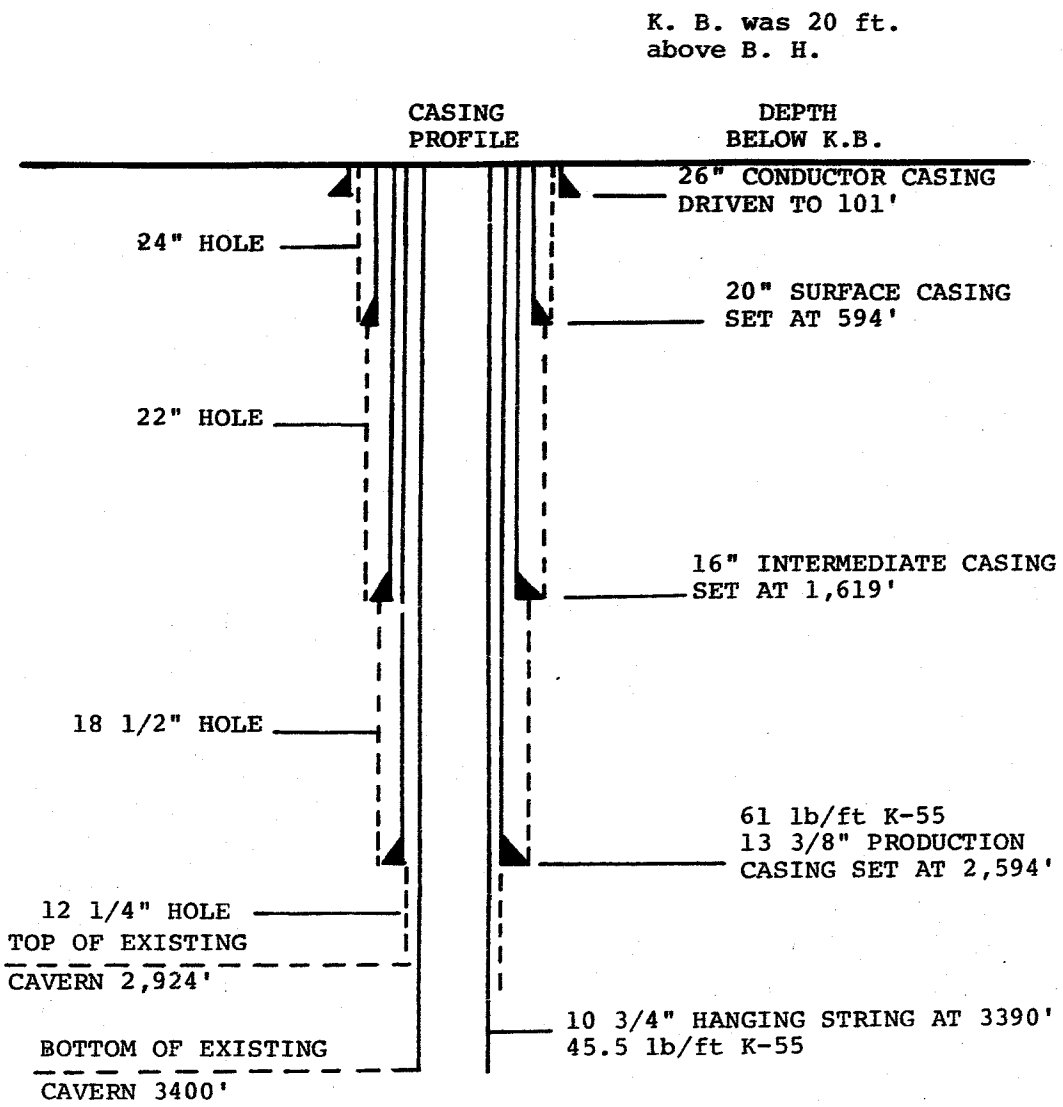


FIGURE 4

CASING DIAGRAM SPR RE 6Z SULPHUR MINES

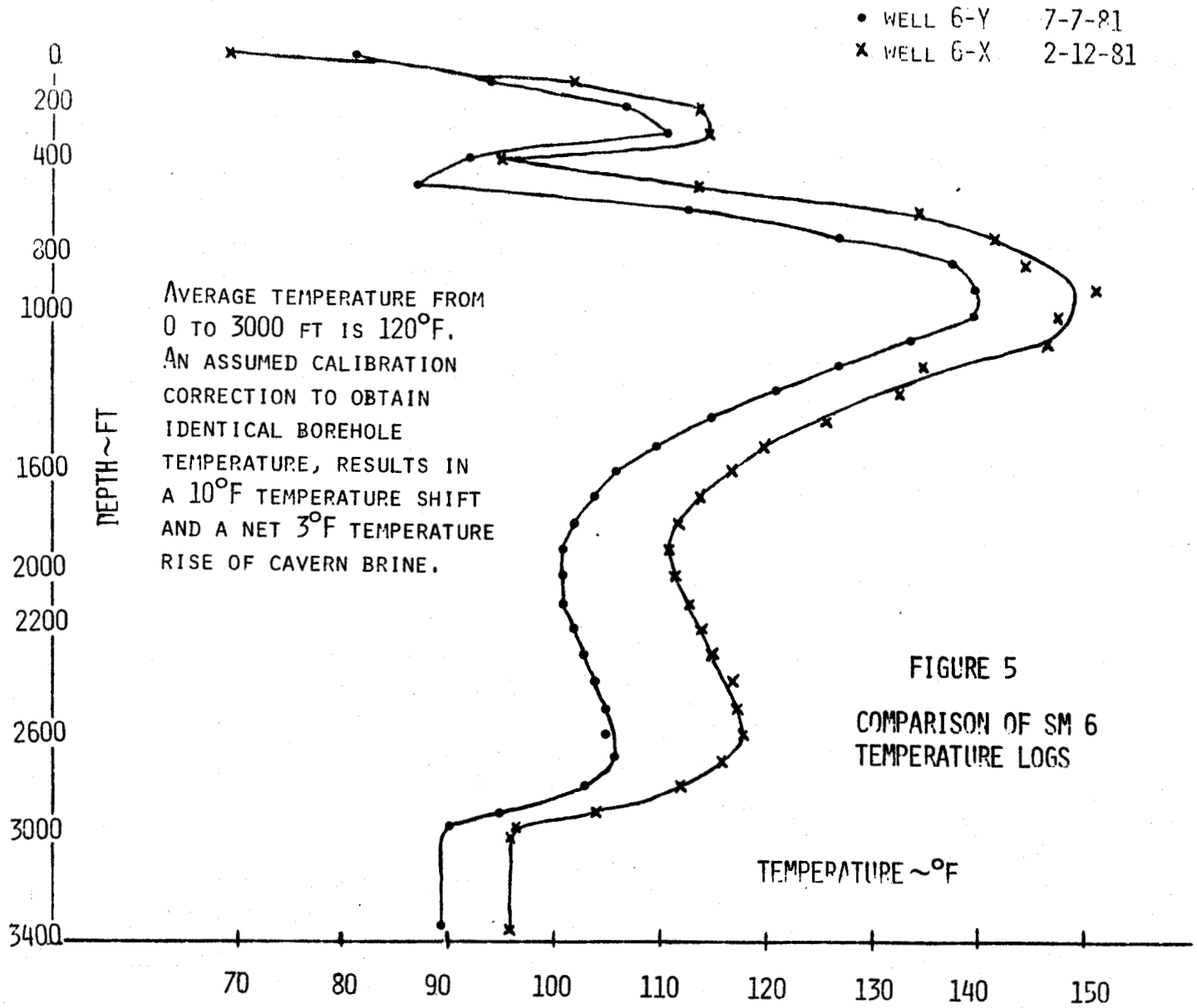


FIGURE 5

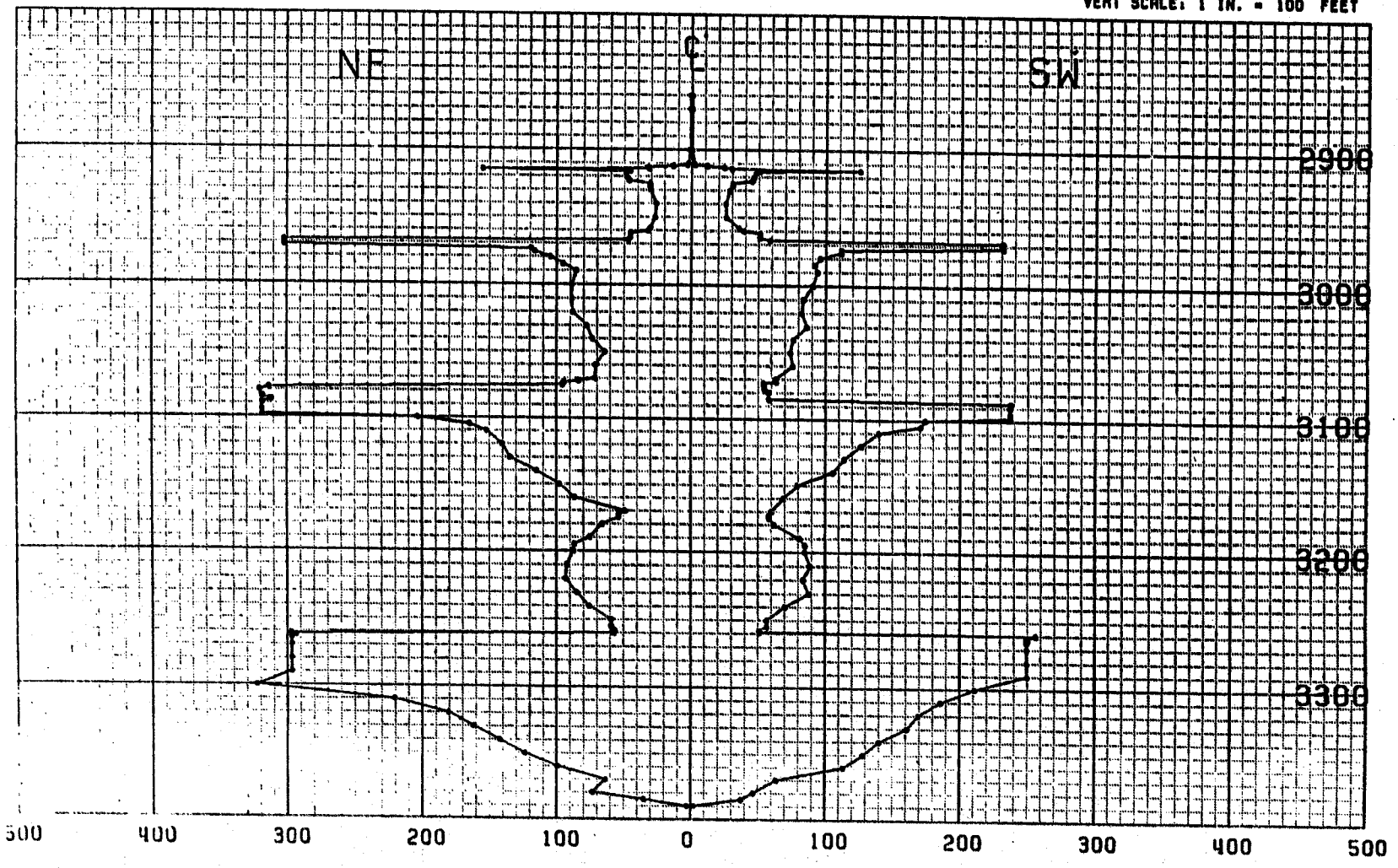
COMPARISON OF SM 6 TEMPERATURE LOGS

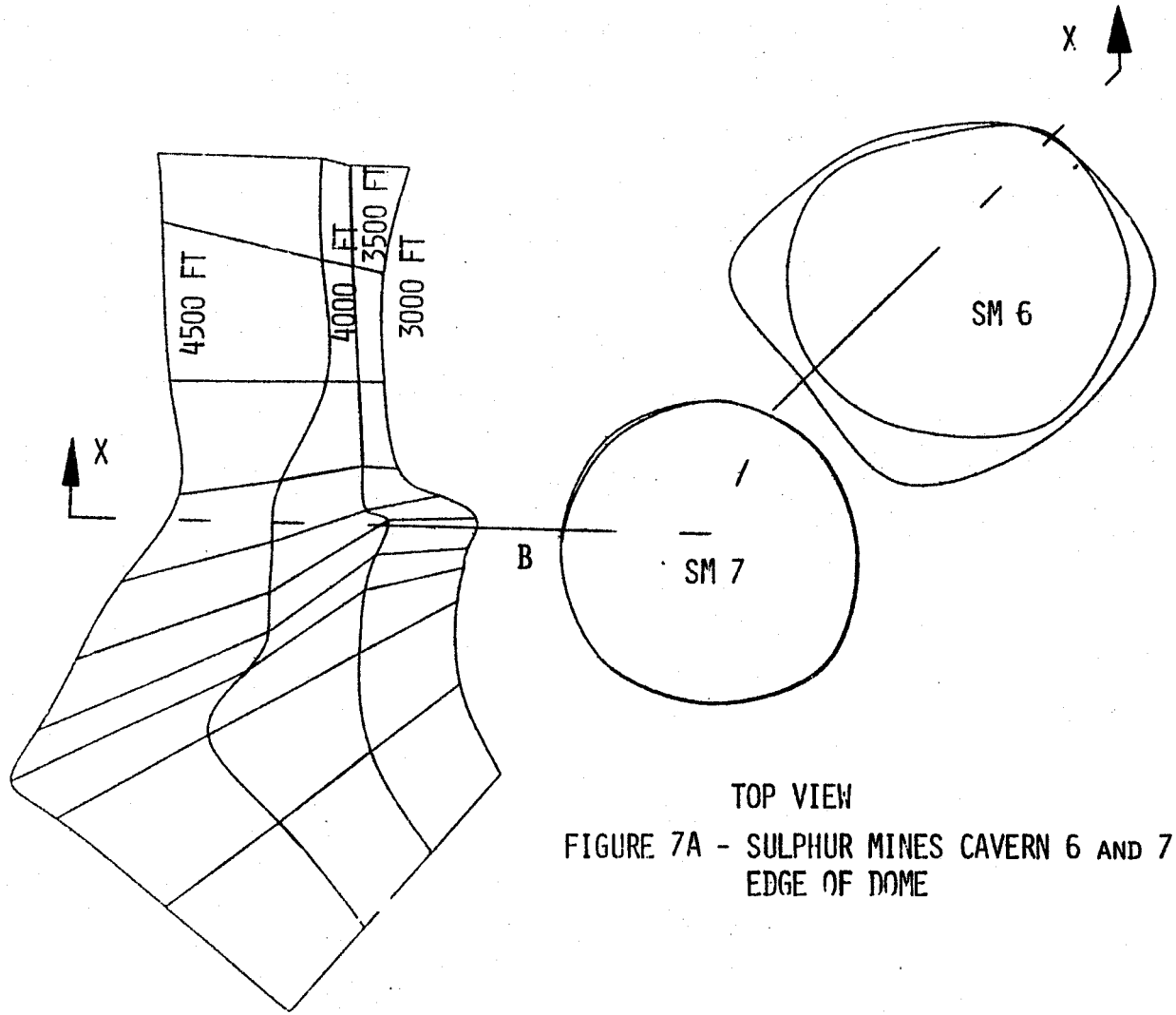
FIGURE 6

VERTICAL CROSS SECTION

FROM REFERENCE 2

TEXAS GULF CORPORATION (DOE)
SULPHUR MINES
WELL NO. 8-T
MARCH 5, 1981
HORZ SCALE: 1 IN. = 100 FEET
VERT SCALE: 1 IN. = 100 FEET





TOP VIEW

FIGURE 7A - SULPHUR MINES CAVERN 6 AND 7 WITH EDGE OF DOME

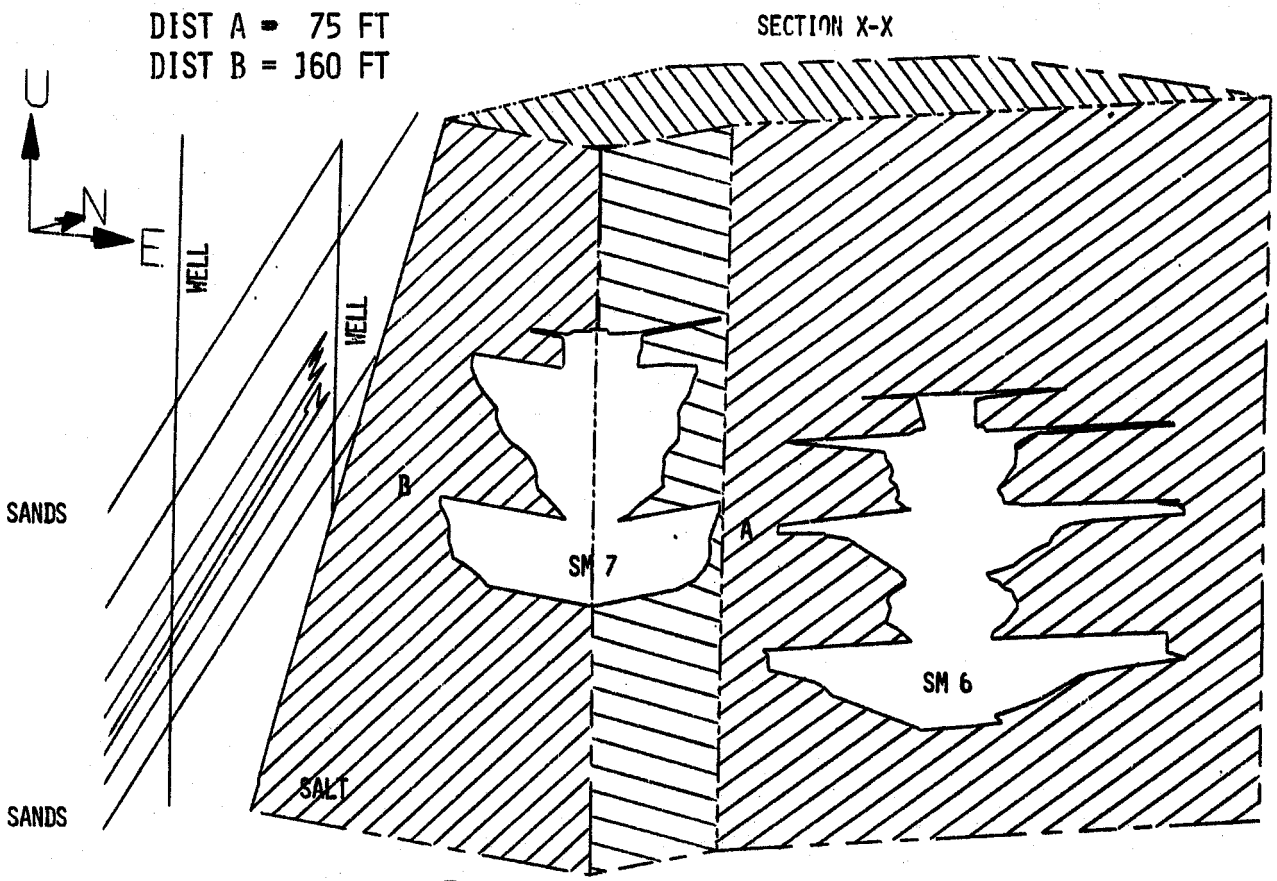
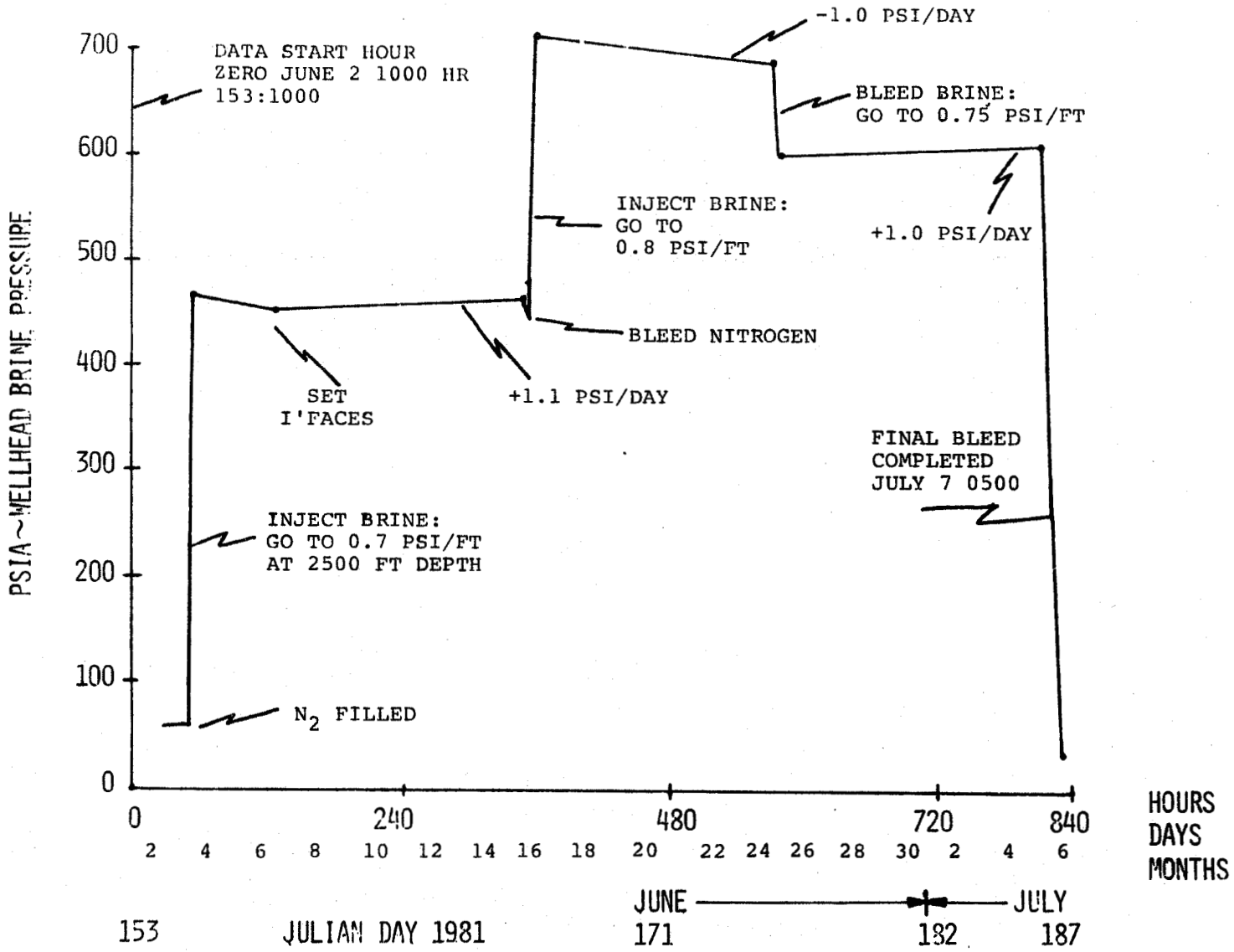


FIGURE 7B - SULPHUR MINES CAVERNS 6 AND 7 WITH EDGE OF DOME

FIGURE 8

SUMMARY OF S.M. CAVERN 6 TEST



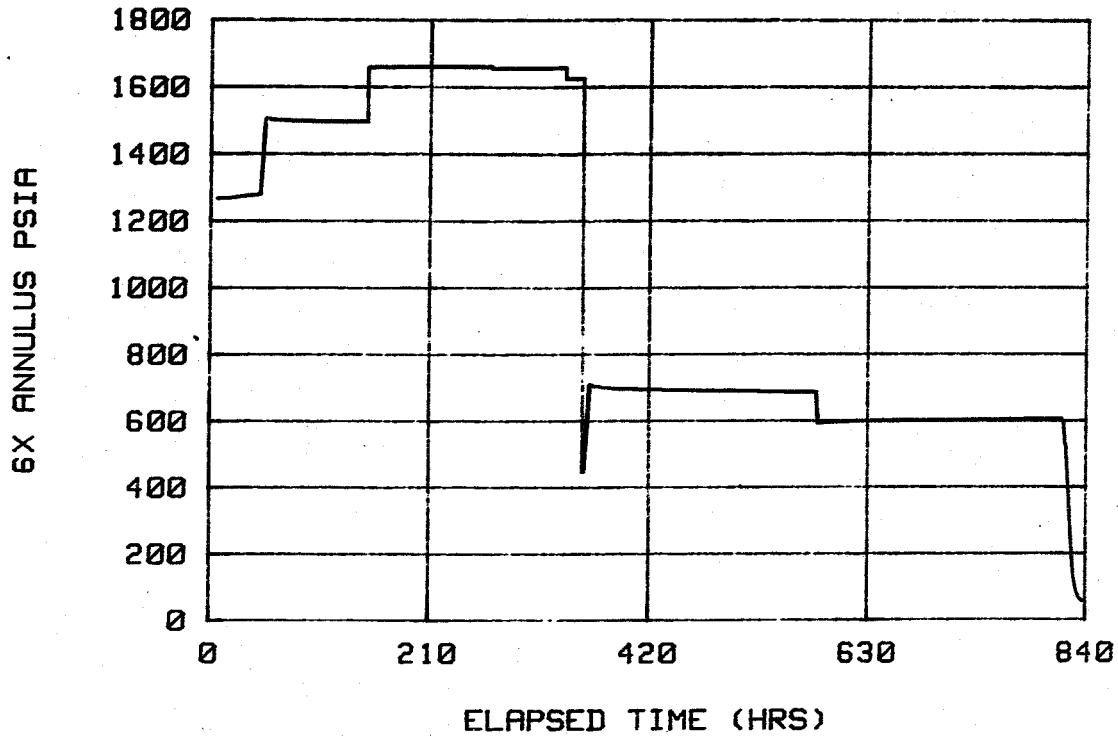


FIG 9 PRESS - TIME FOR TOTAL TEST

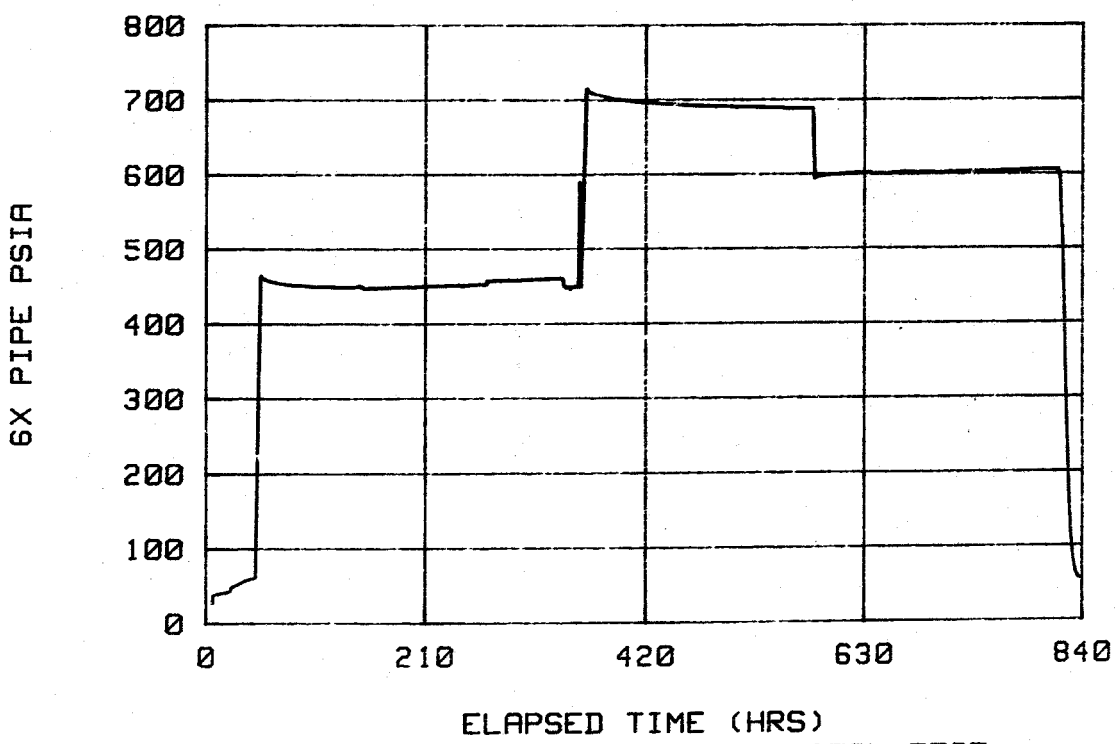


FIG 10 PRESS - TIME FOR TOTAL TEST

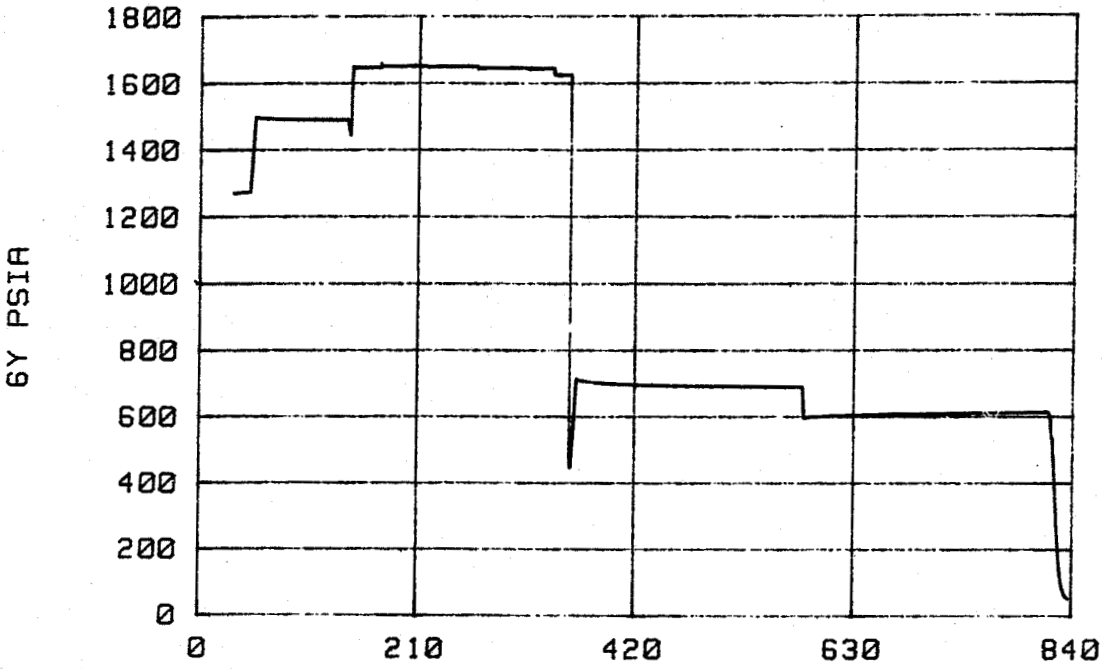


FIG 11 PRESS - TIME FOR TOTAL TEST

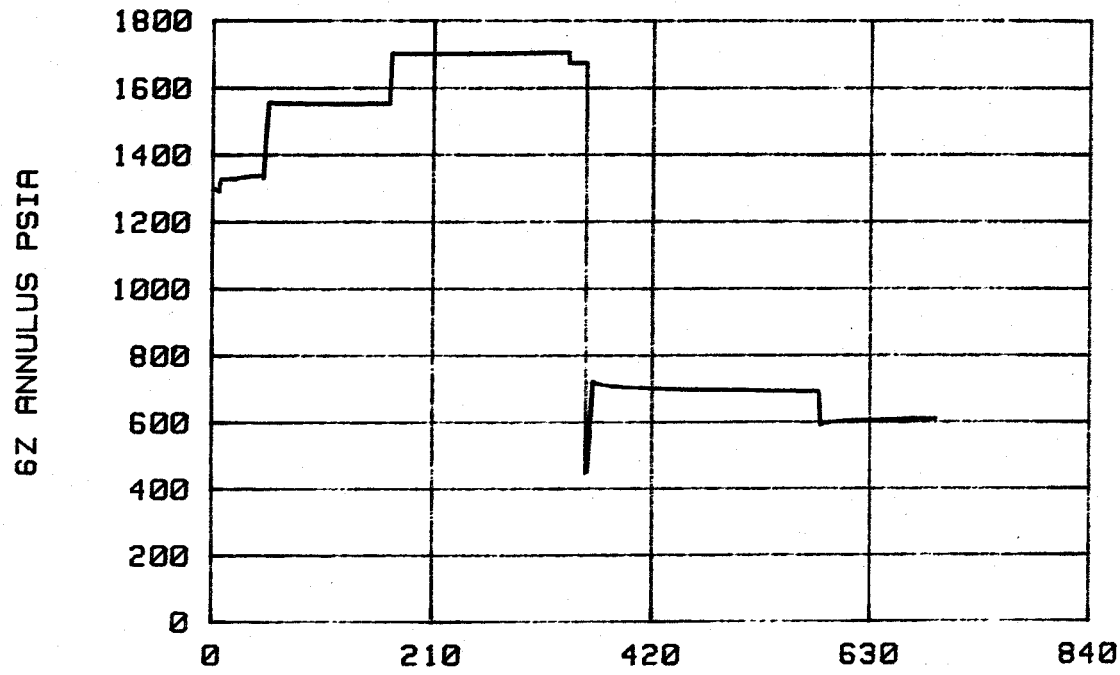


FIG 12 PRESS - TIME FOR TOTAL TEST

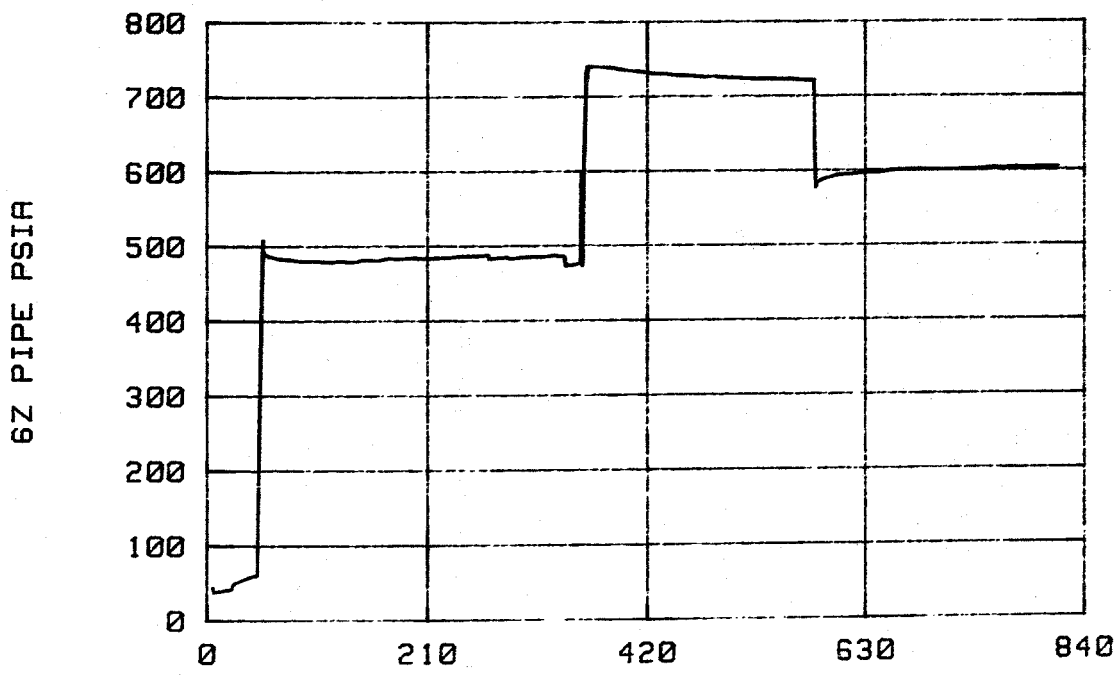


FIG 13 PRESS - TIME FOR TOTAL TEST

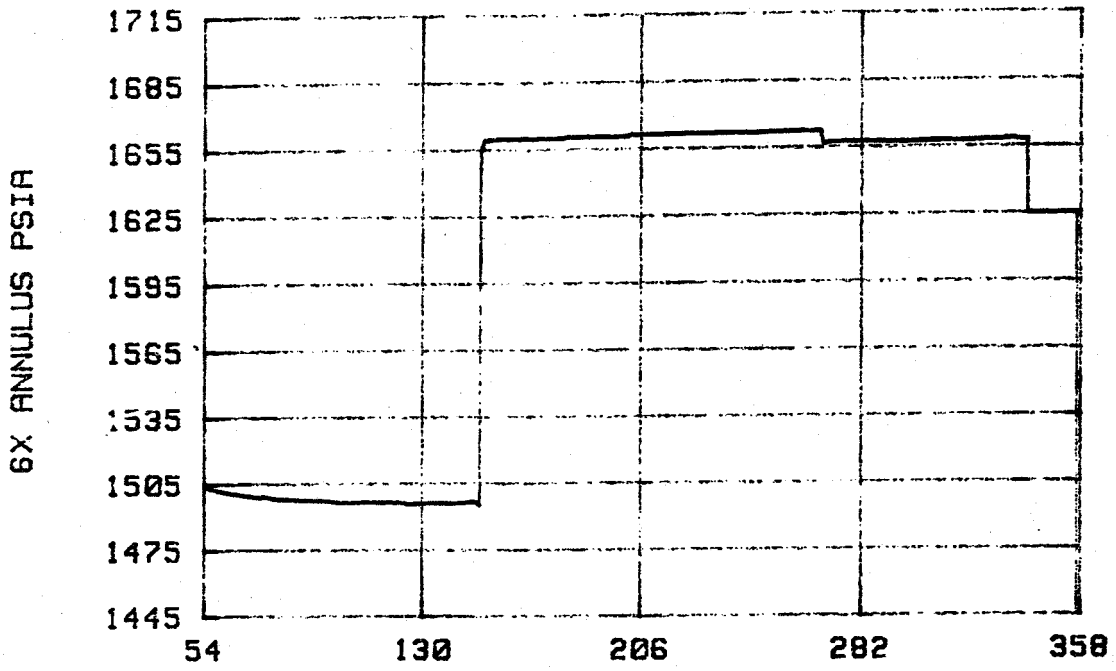


FIG 14 PRESS - TIME FOR WELL LEAK TEST

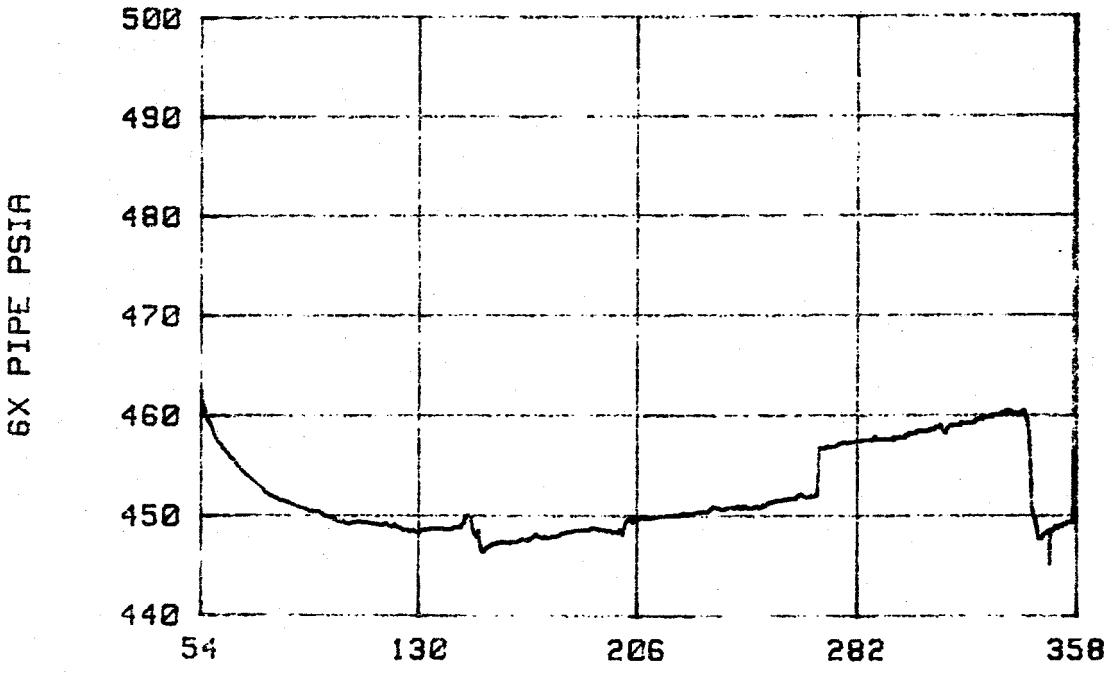


FIG 15 PRESS - TIME FOR WELL LEAK TEST

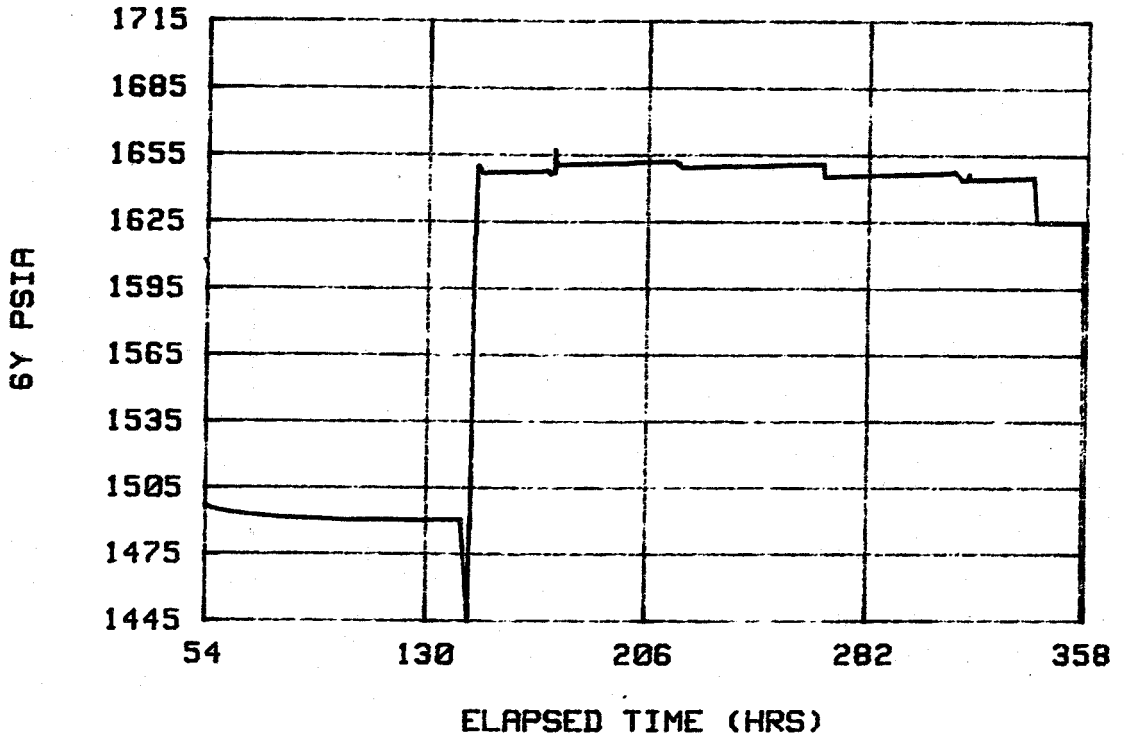


FIG 16 PRESS - TIME FOR WELL LEAK TEST

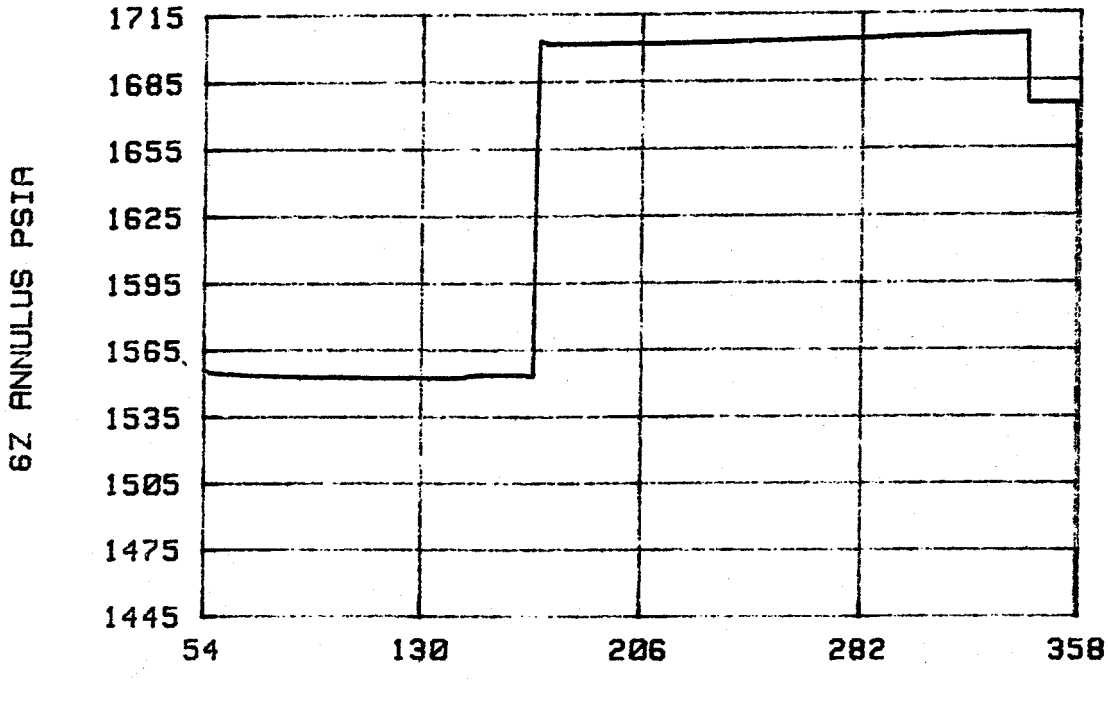


FIG 17 PRESS - TIME FOR WELL LEAK TEST

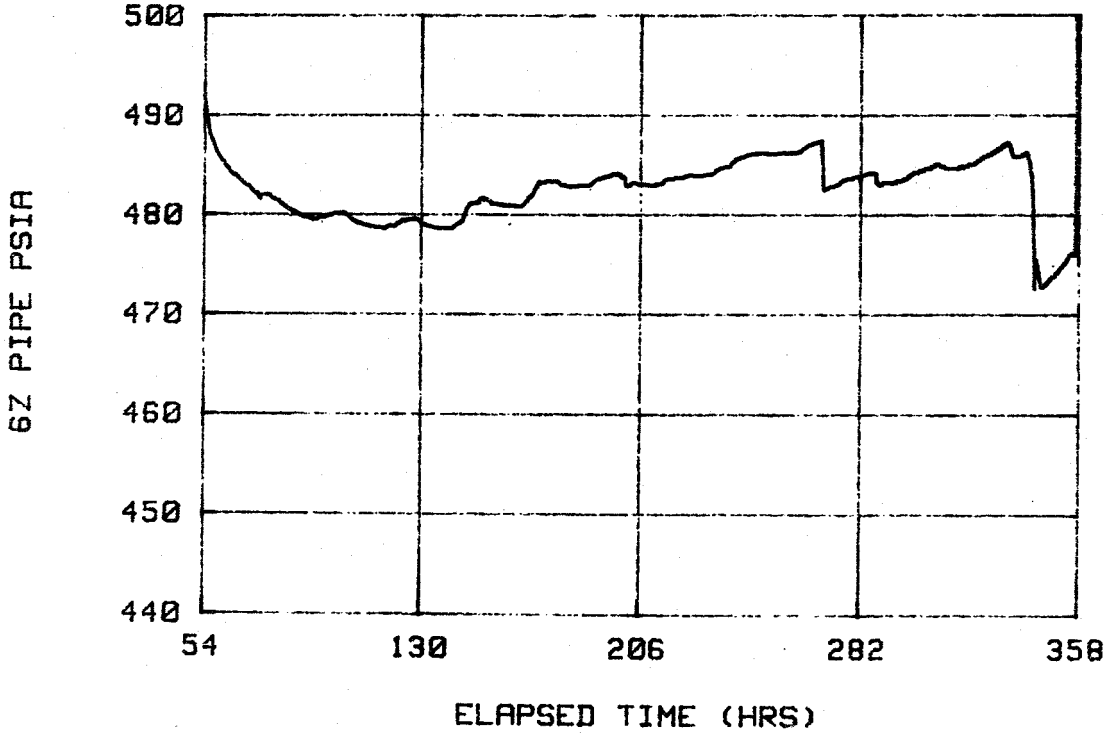


FIG 18 PRESS - TIME FOR WELL LEAK TEST

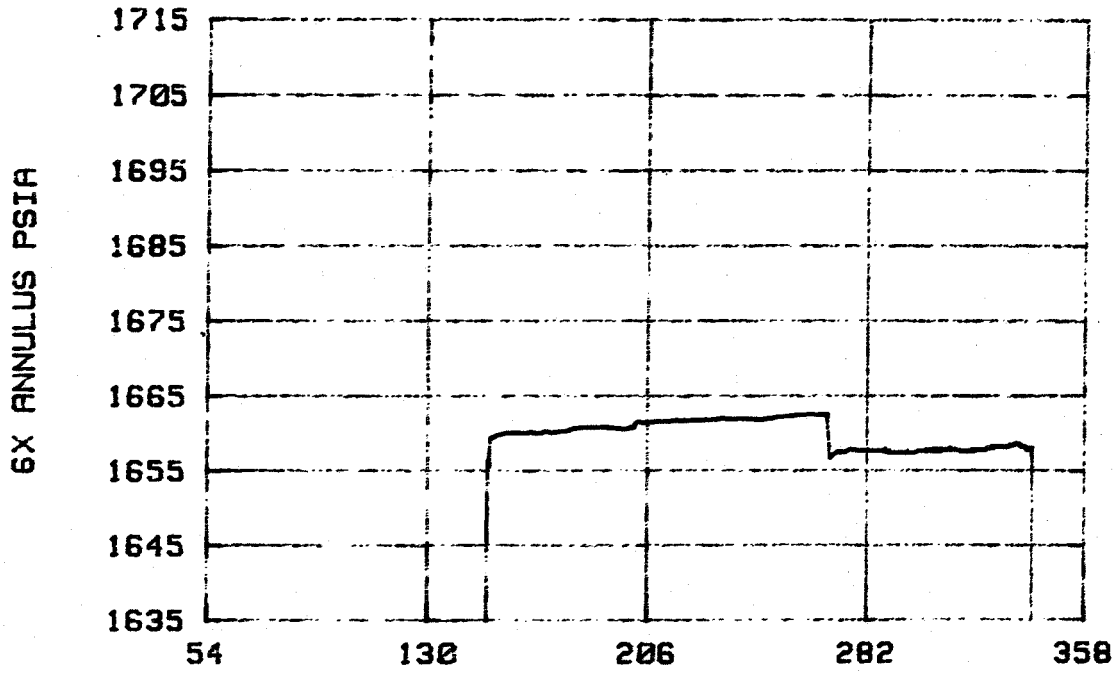


FIG 19 PRESS - TIME FOR WELL LEAK TEST

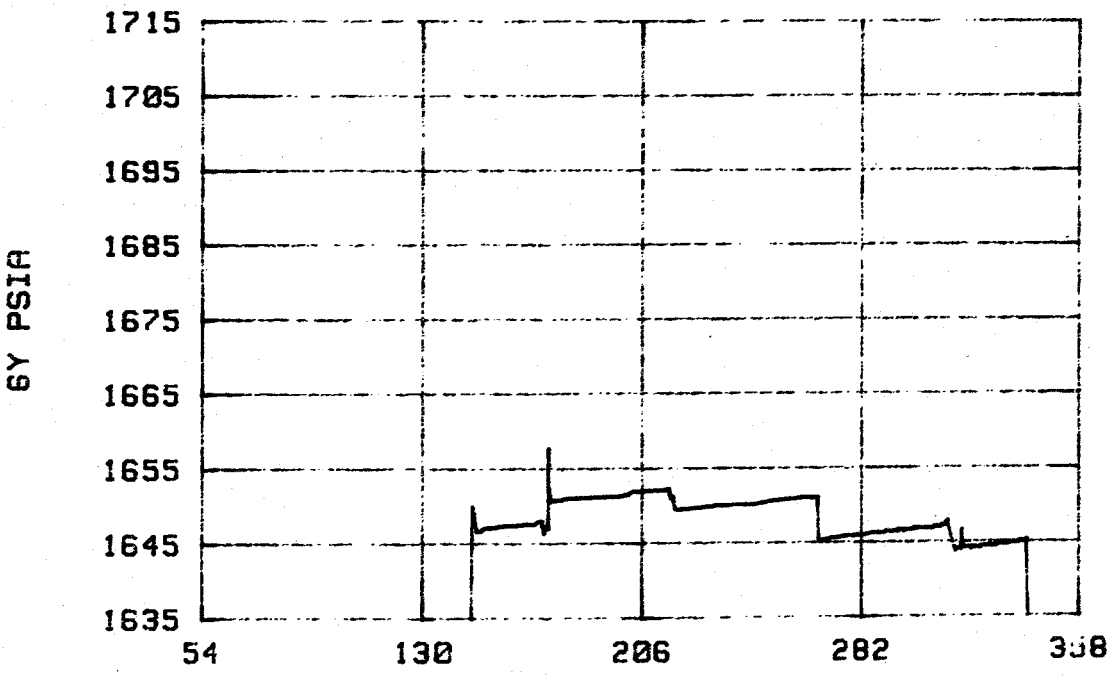


FIG 20 PRESS - TIME FOR WELL LEAK TEST

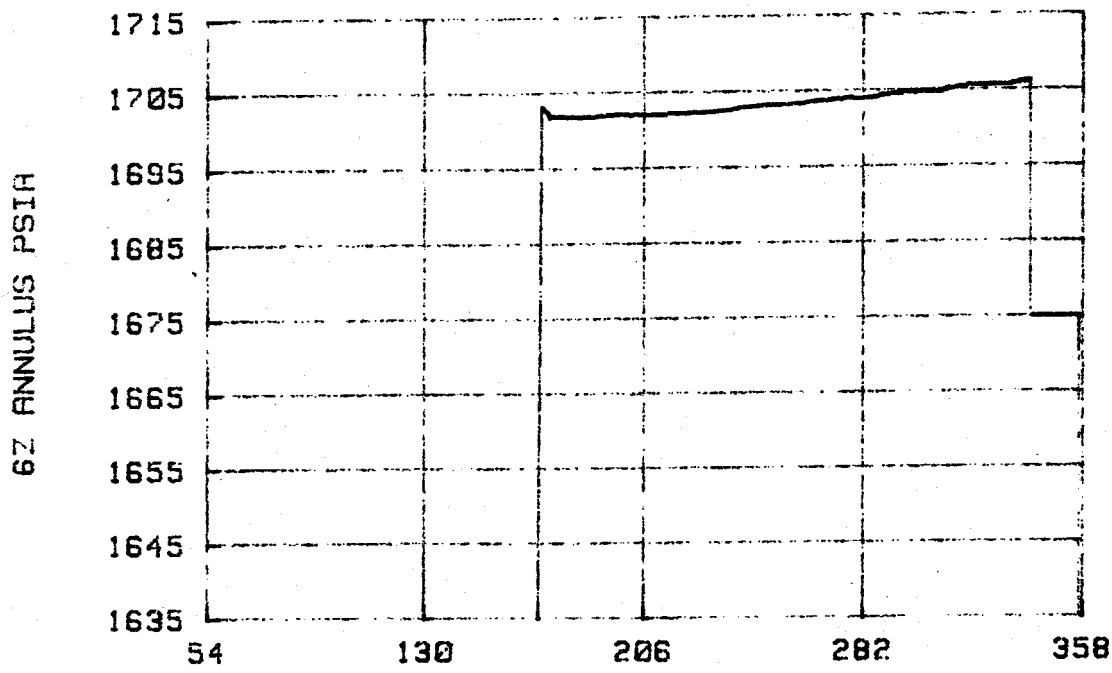


FIG 21 PRESS - TIME FOR WELL LEAK TEST

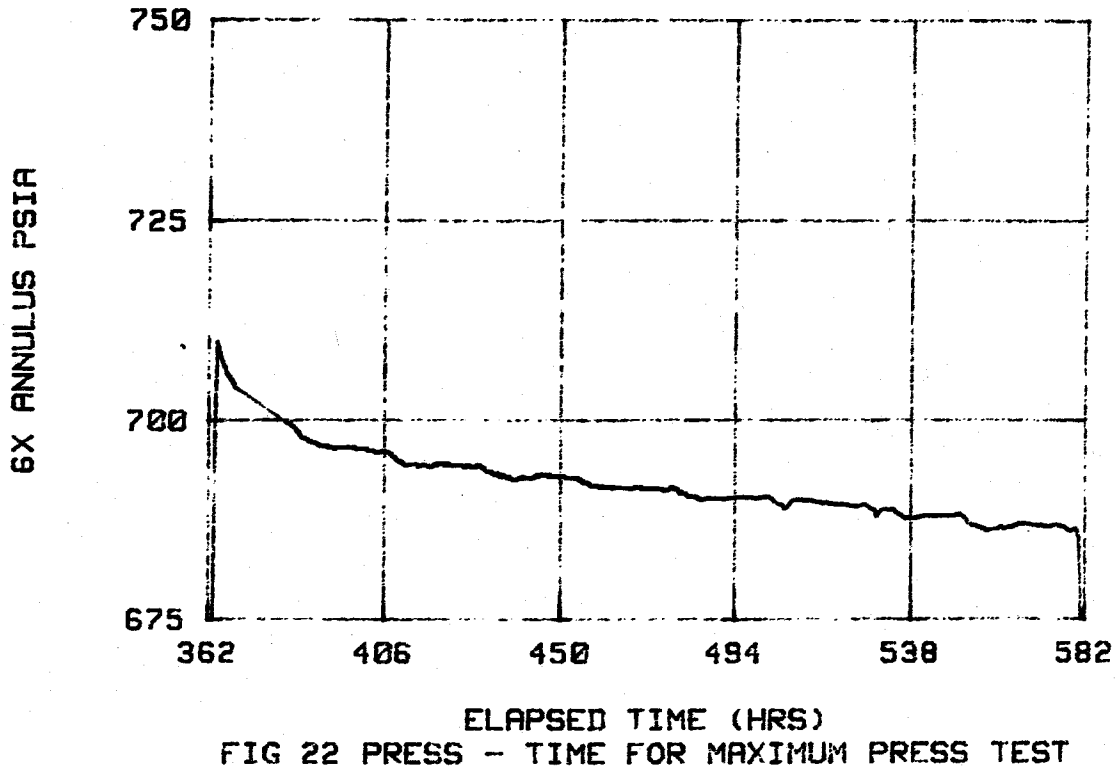


FIG 22 PRESS - TIME FOR MAXIMUM PRESS TEST

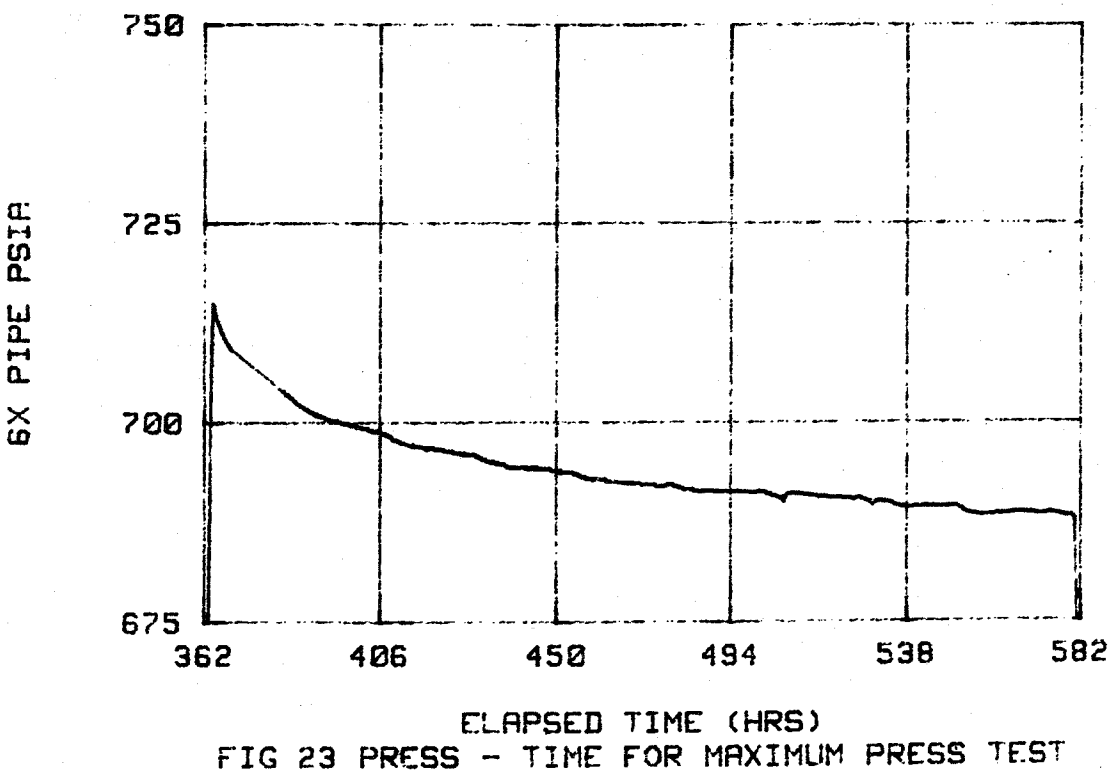


FIG 23 PRESS - TIME FOR MAXIMUM PRESS TEST

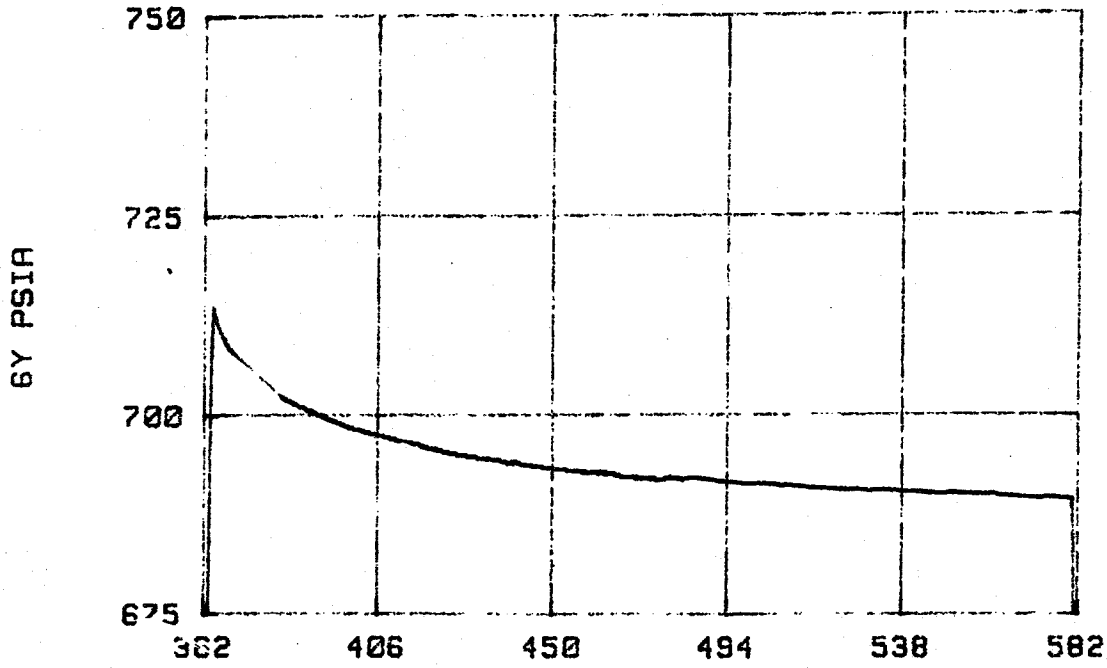


FIG 24 PRESS - TIME FOR MAXIMUM PRESS TEST

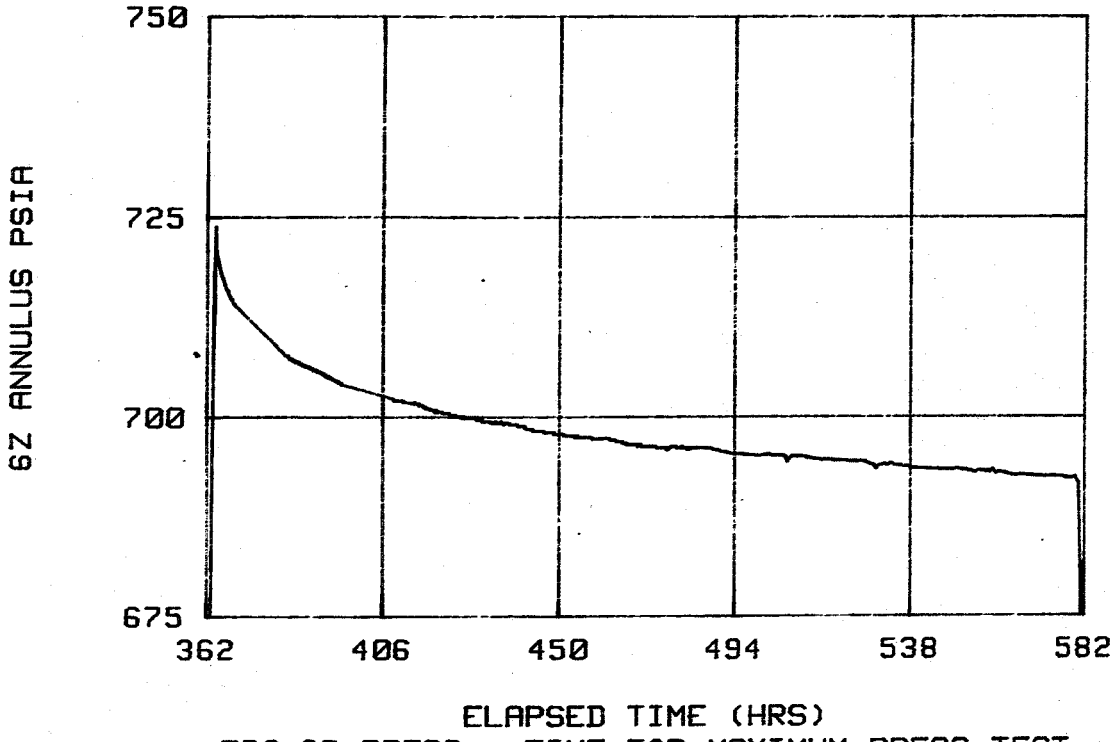


FIG 25 PRESS - TIME FOR MAXIMUM PRESS TEST

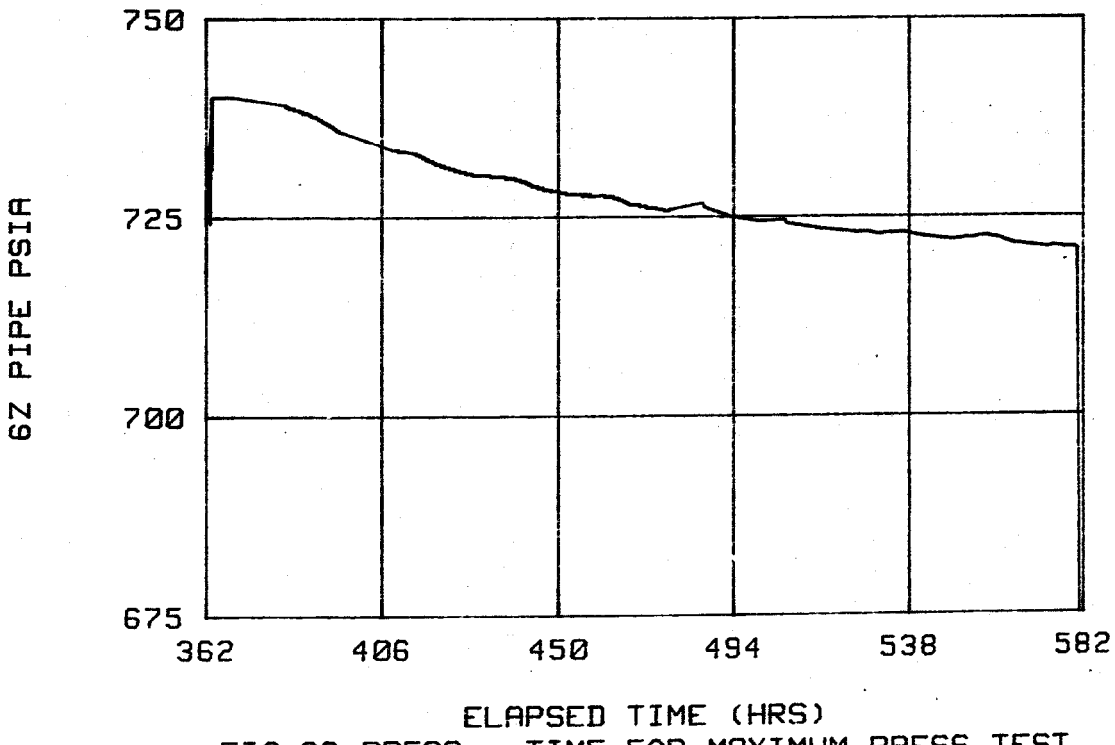


FIG 26 PRESS - TIME FOR MAXIMUM PRESS TEST

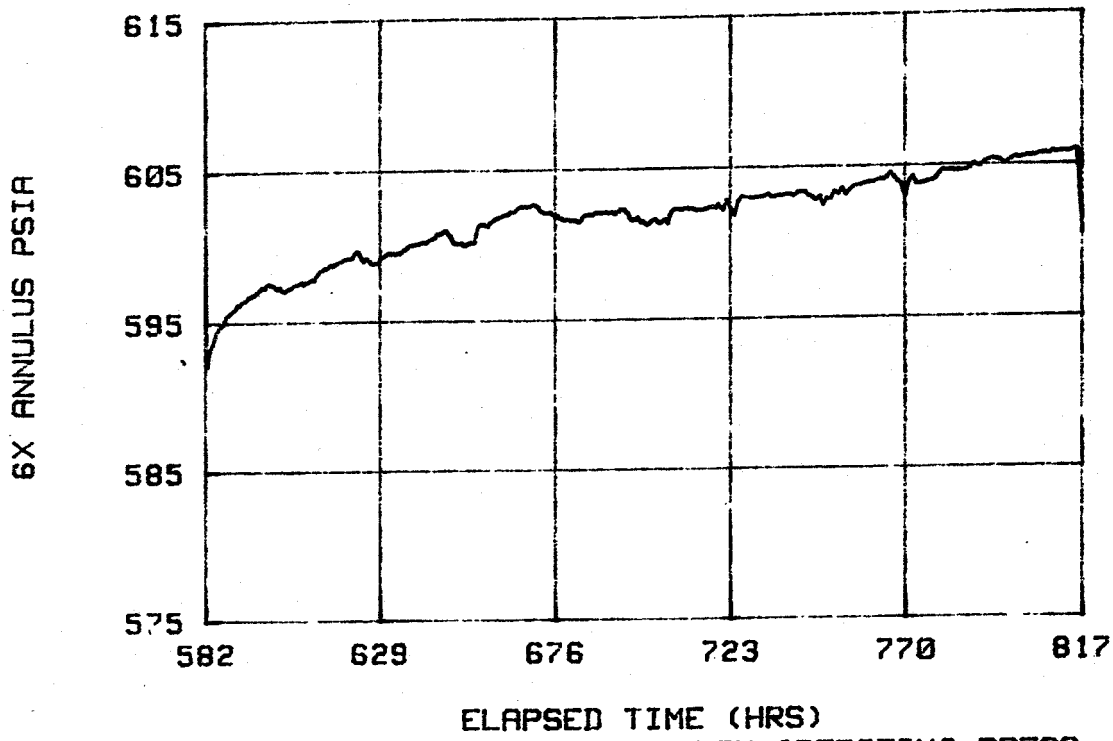


FIG 27 PRESS - TIME FOR MAX OPERATING PRESS

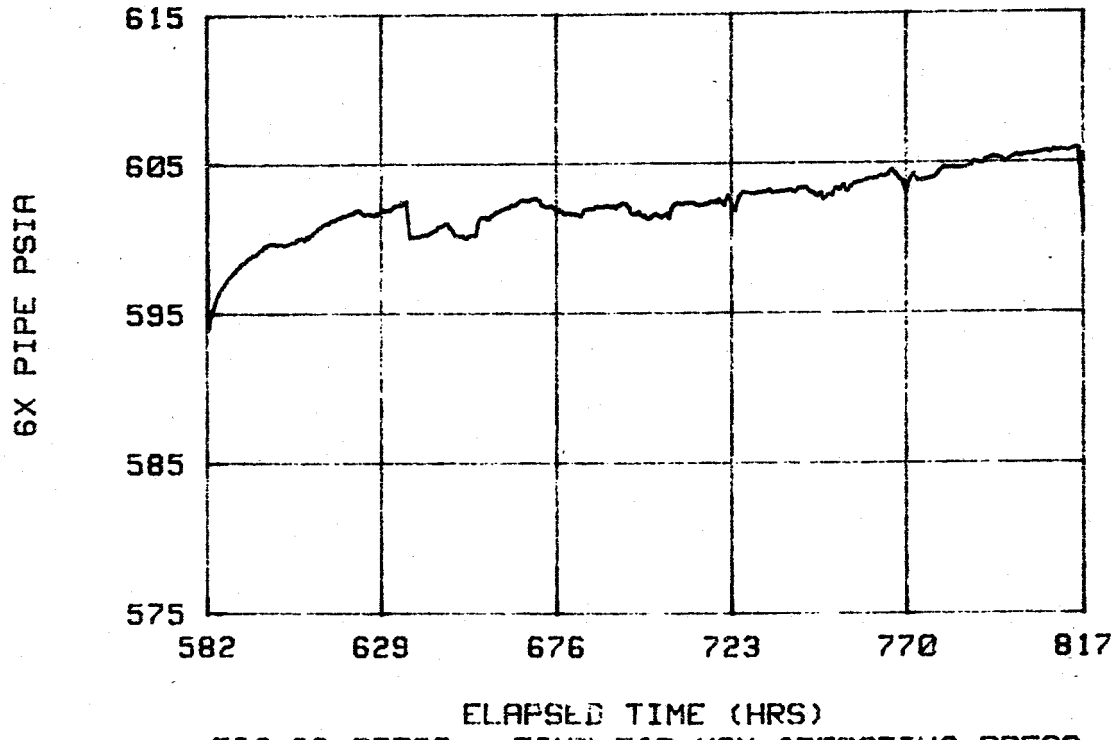


FIG 28 PRESS - TIME FOR MAX OPERATING PRESS

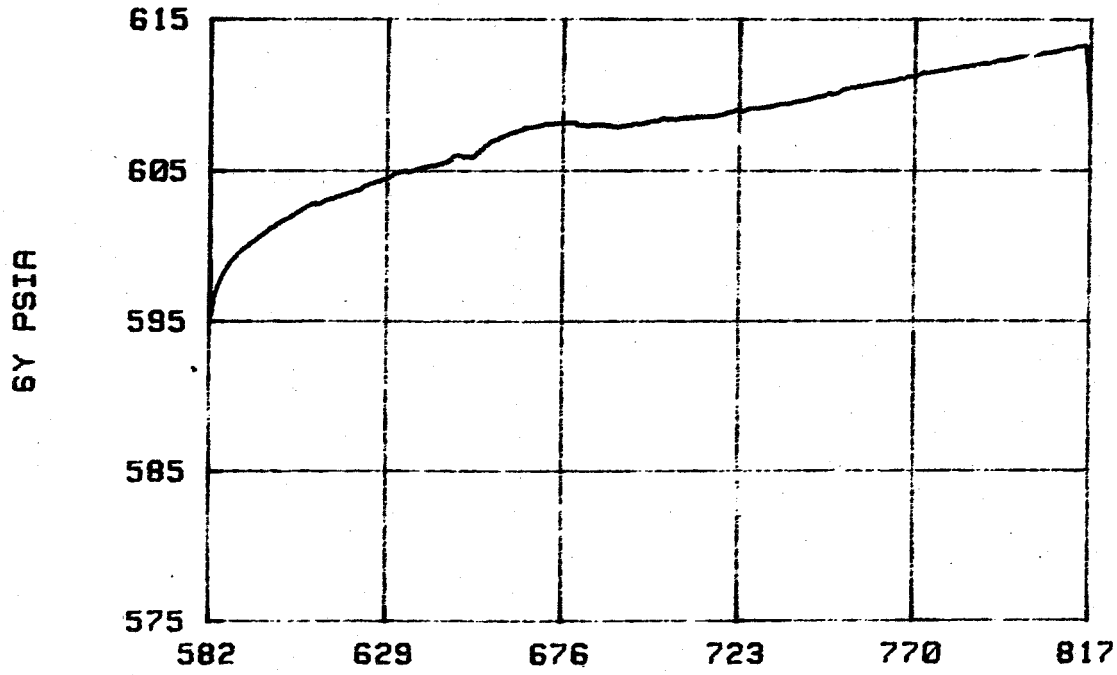


FIG 29 PRESS - TIME FOR MAX OPERATING PRESS

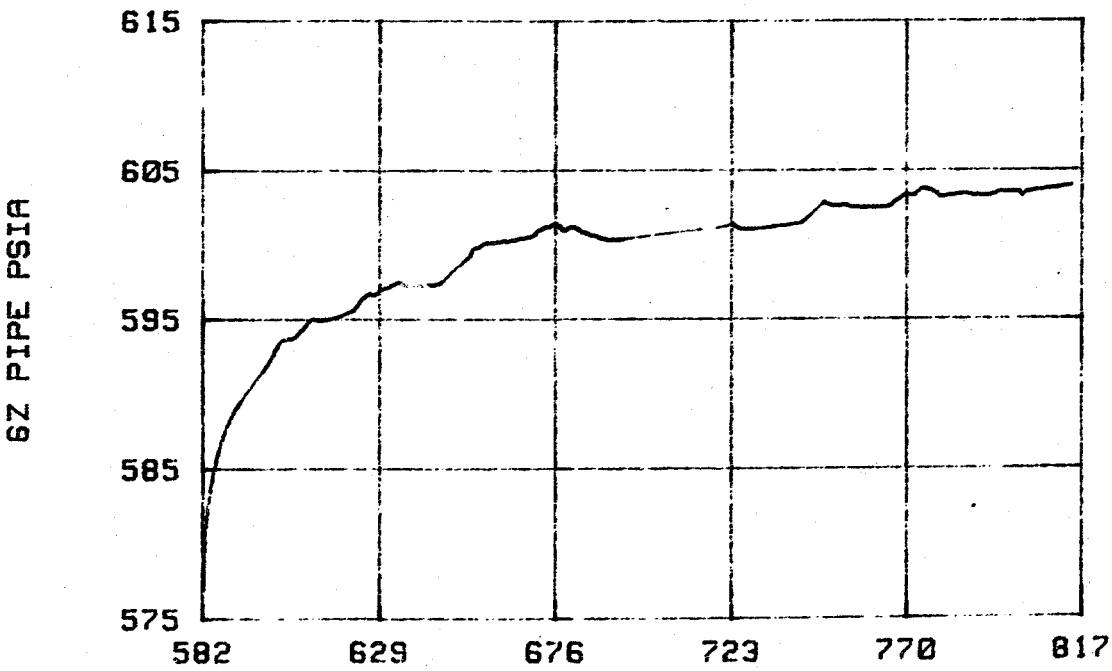


FIG 30 PRESS - TIME FOR MAX OPERATING PRESS

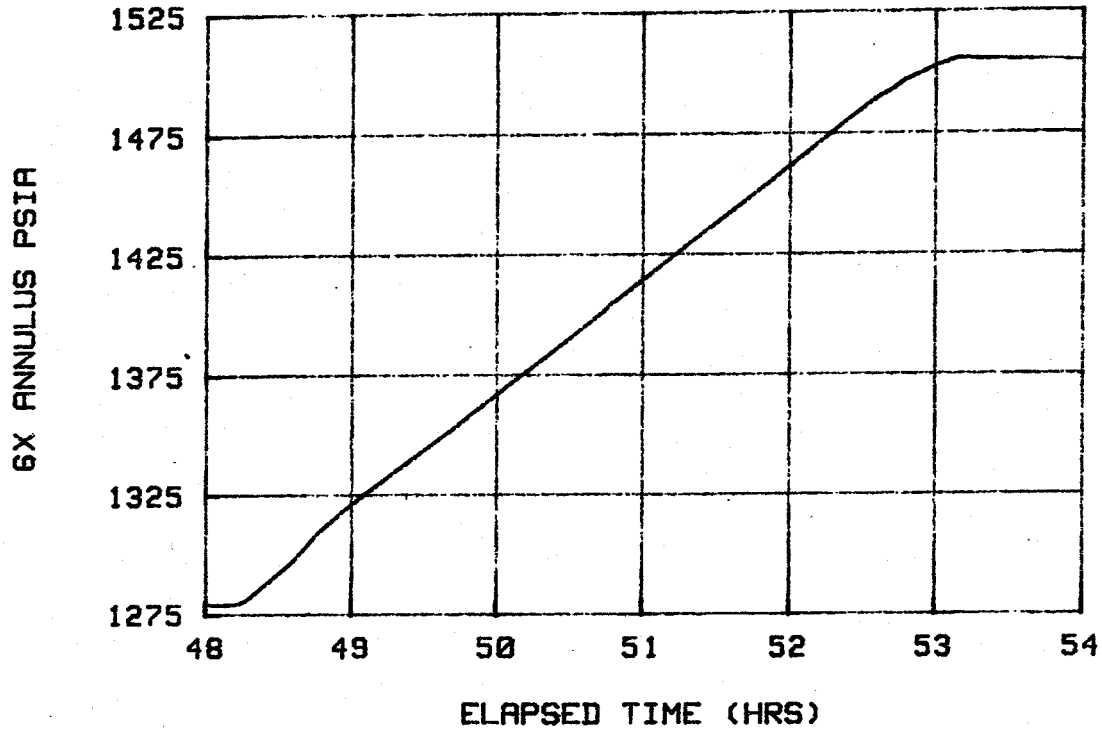


FIG 31 CAVERN PRESSURIZATION .52 - .7 PSI/FT

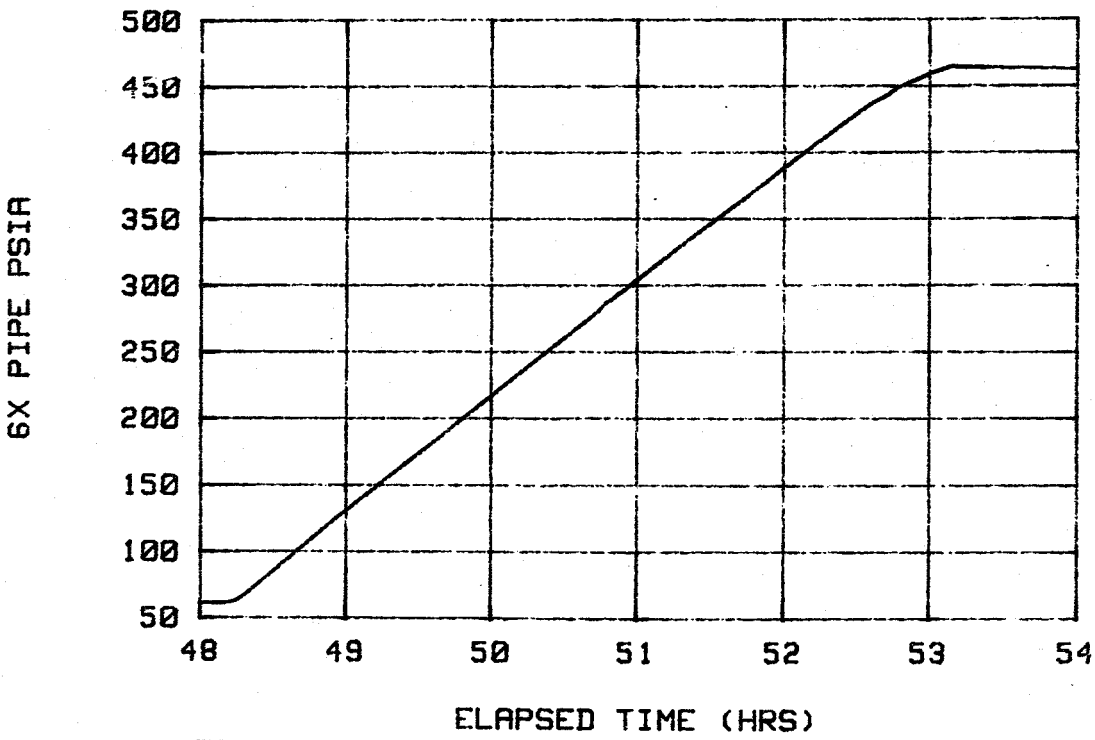


FIG 32 CAVERN PRESSURIZATION .52 - .7 PSI/FT

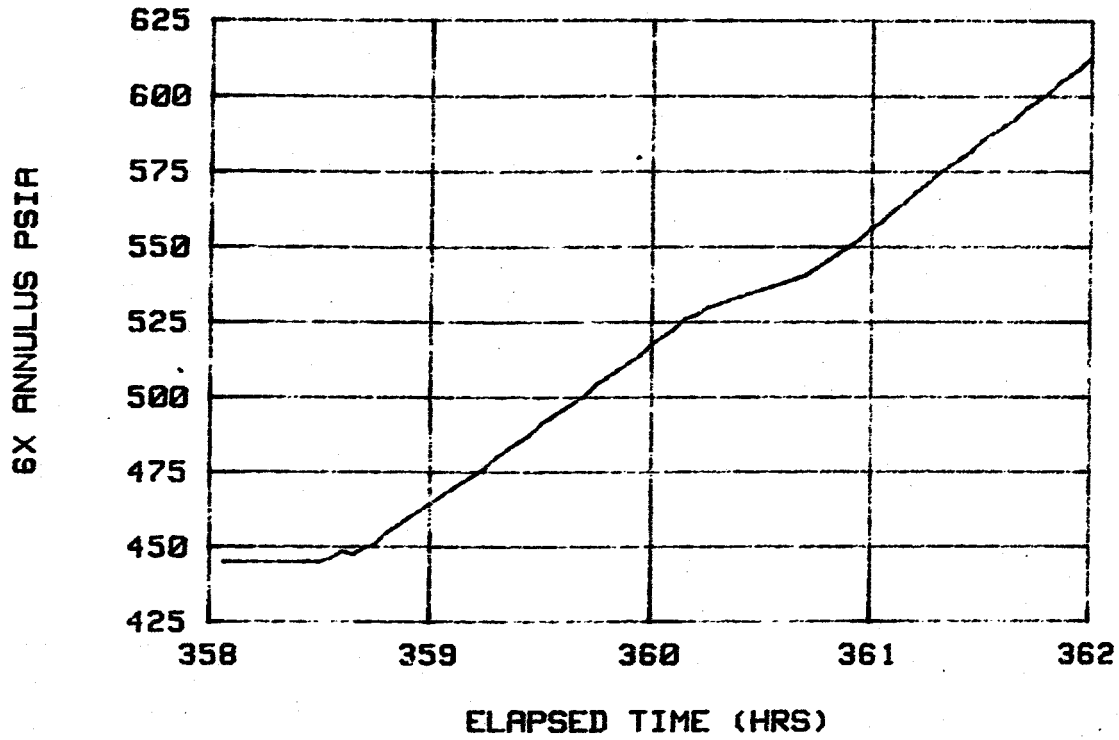


FIG 33 CAVERN PRESSURIZATION .7 - .8 PSI/FT

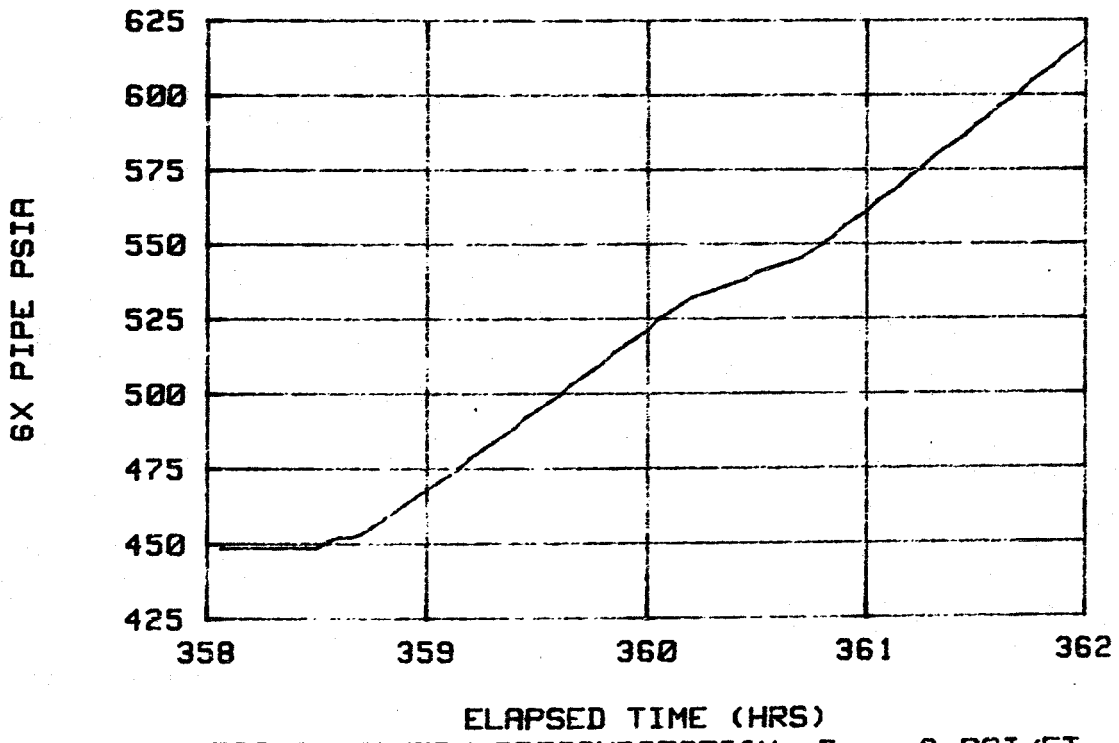


FIG 34 CAVERN PRESSURIZATION .7 - .8 PSI/FT

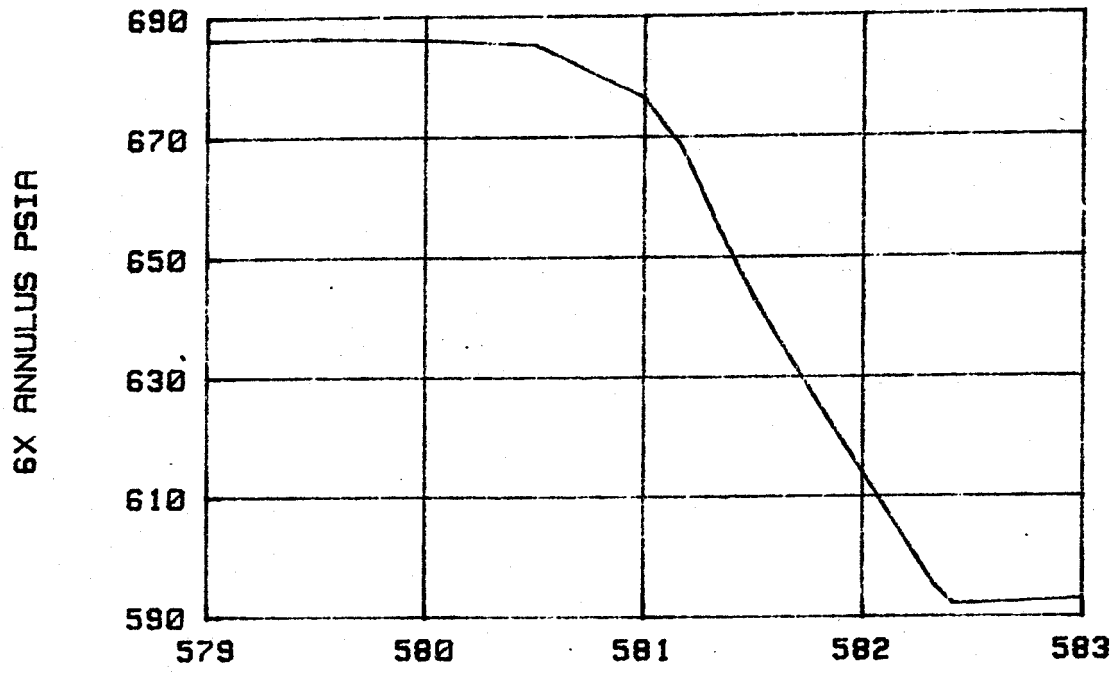


FIG 35 CAVERN BLEEDDOWN .8 - .75 PSI/FT

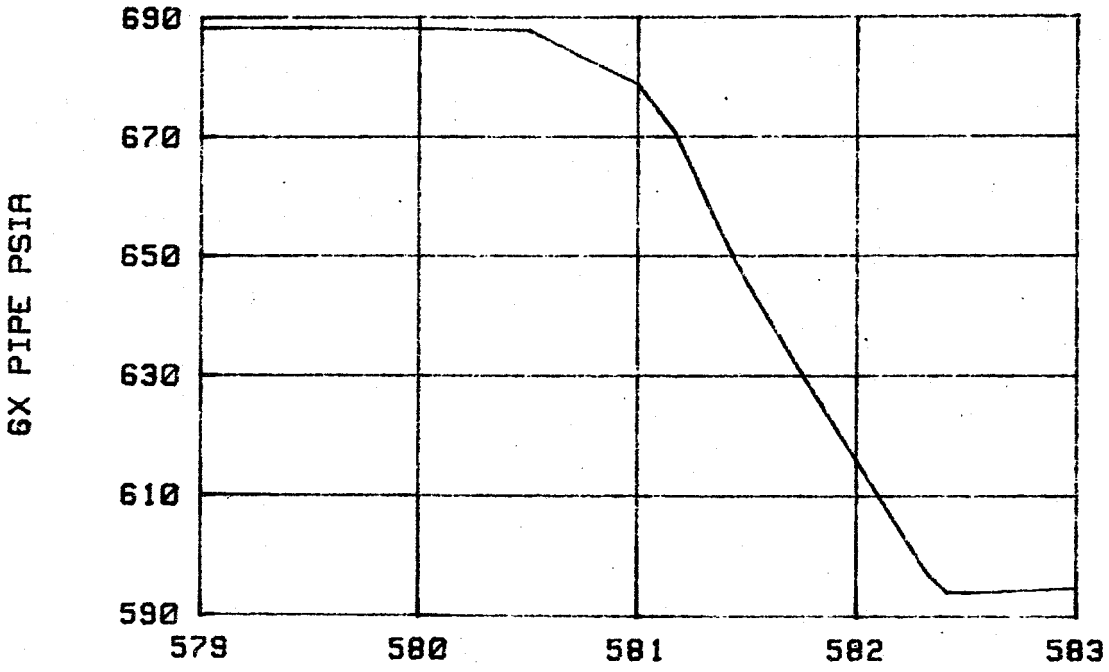


FIG 36 CAVERN BLEEDDOWN .8 - .75 PSI/FT

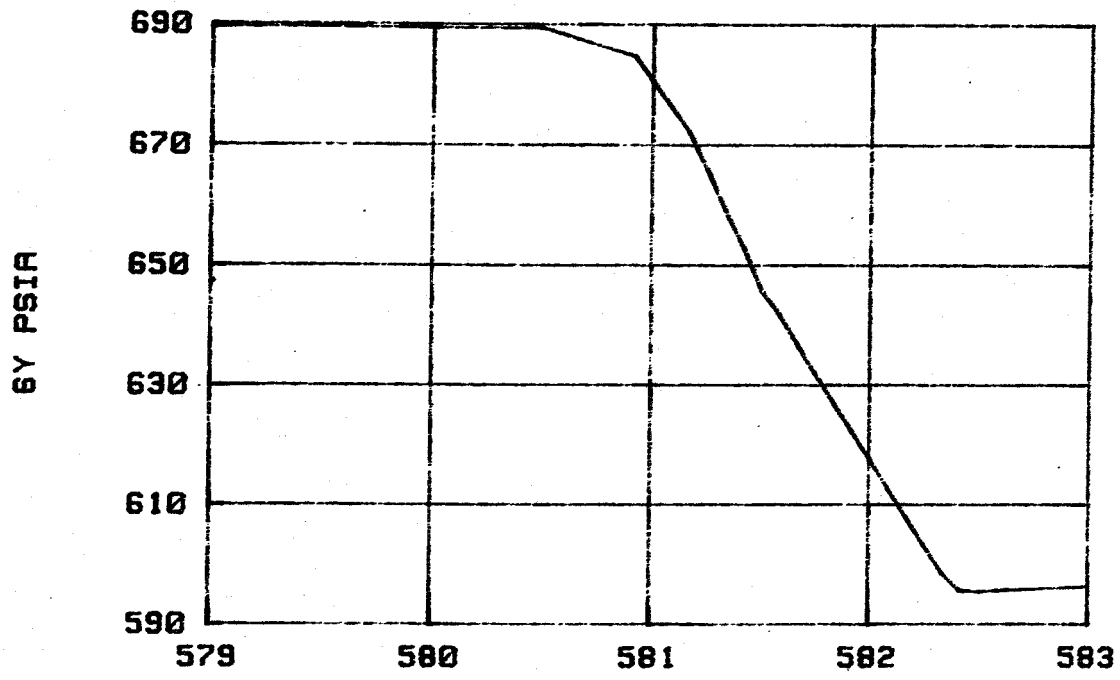
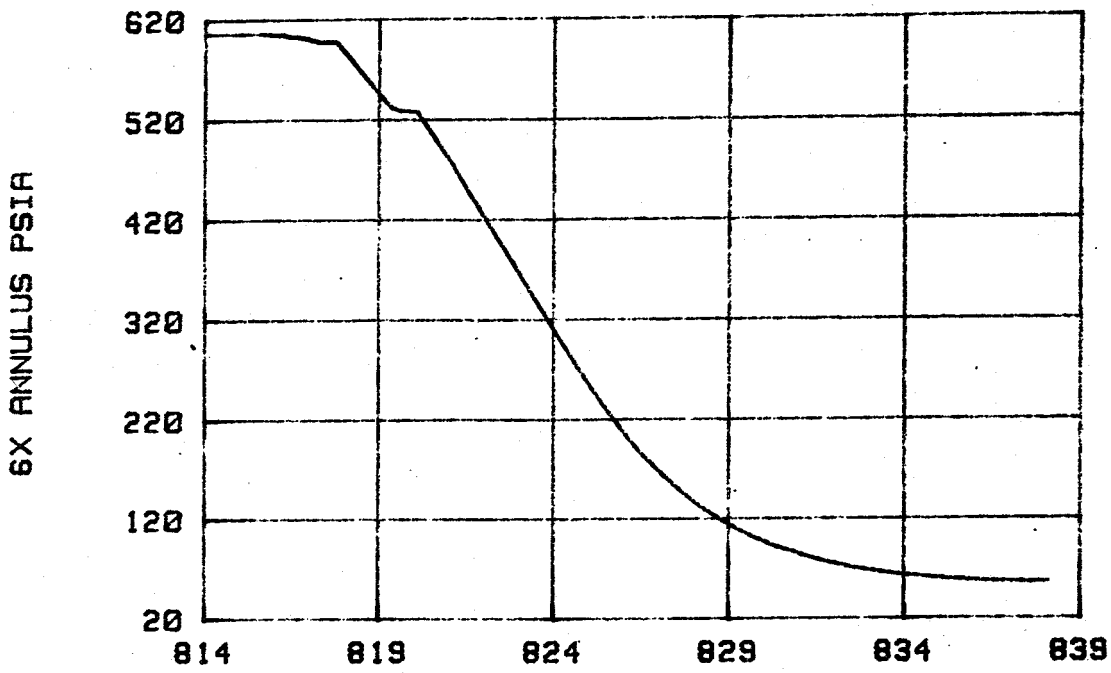
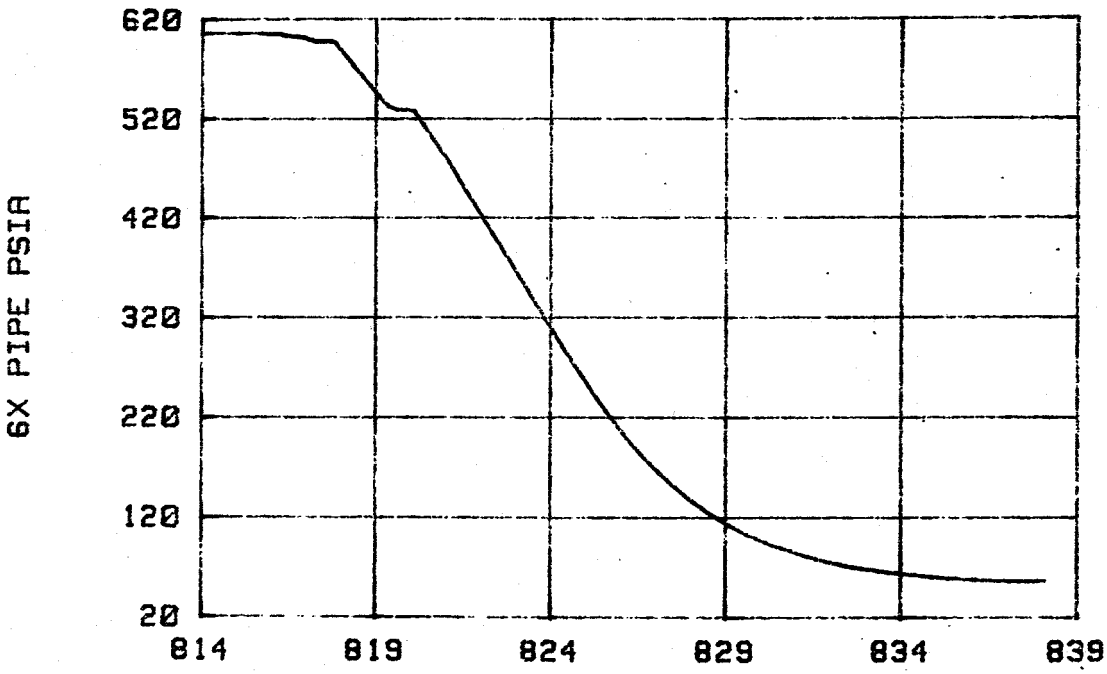


FIG 37 CAVERN BLEEDDOWN .8 - .75 PSI/FT



ELAPSED TIME (HRS)
FIG 38 CAVERN BLEEDDOWN .75 - .52 PSI/FT



ELAPSED TIME (HRS)
FIG 39 CAVERN BLEEDDOWN .75 - .52 PSI/FT

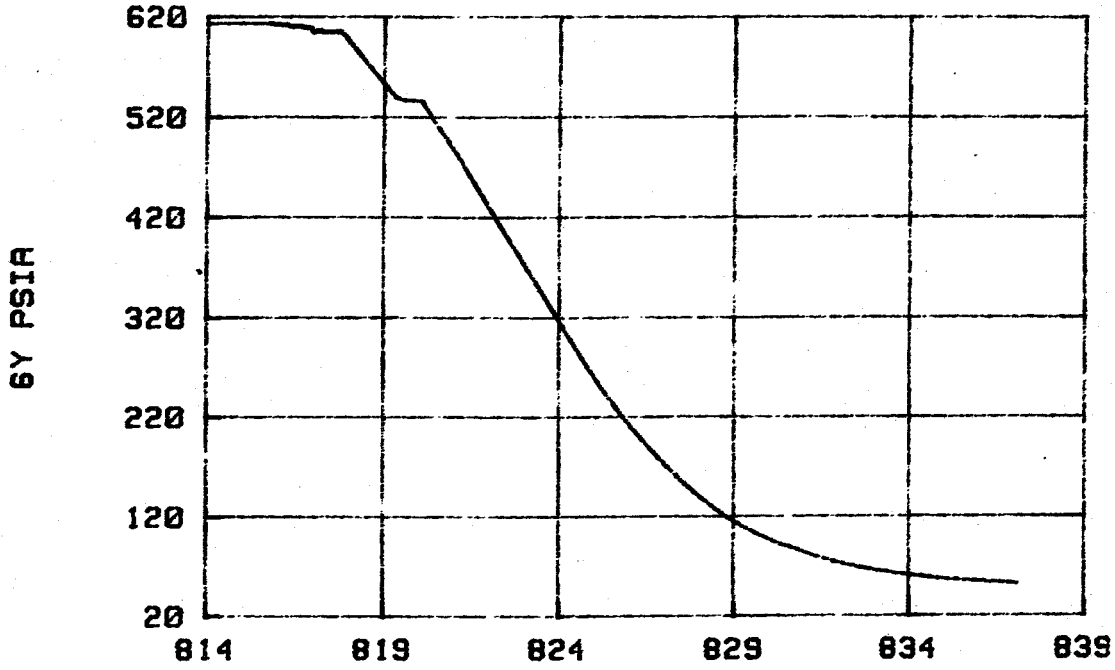


FIG 40 CAVERN BLEEDDOWN .75 - .52 PSI/FT

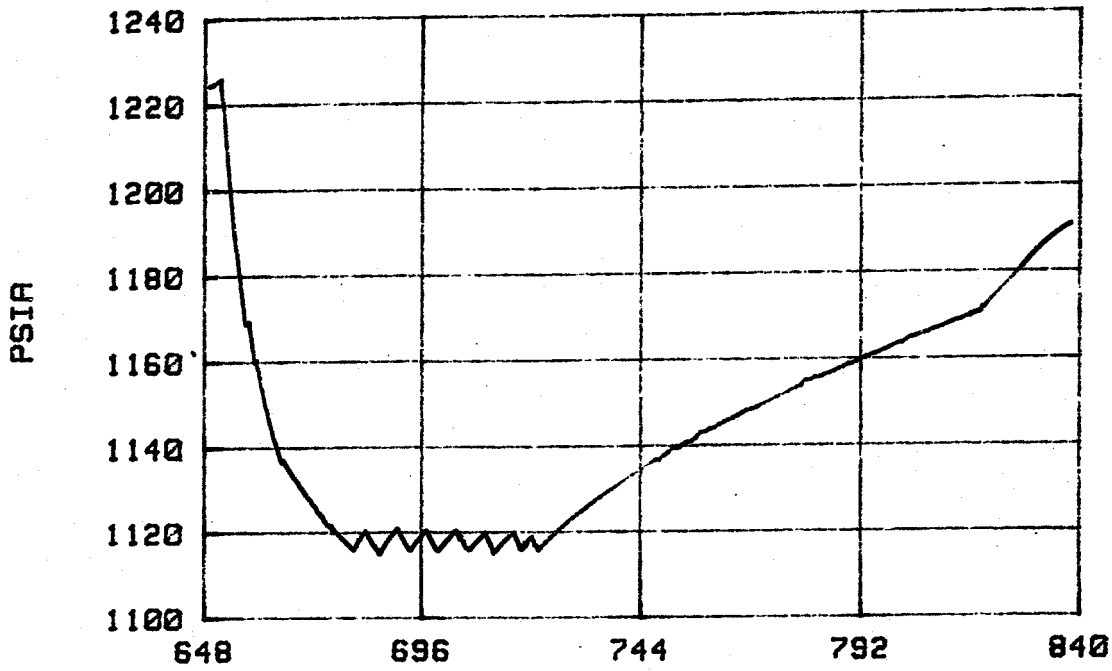


FIG 41 CAVERN 7 LOW PRESSURE TEST

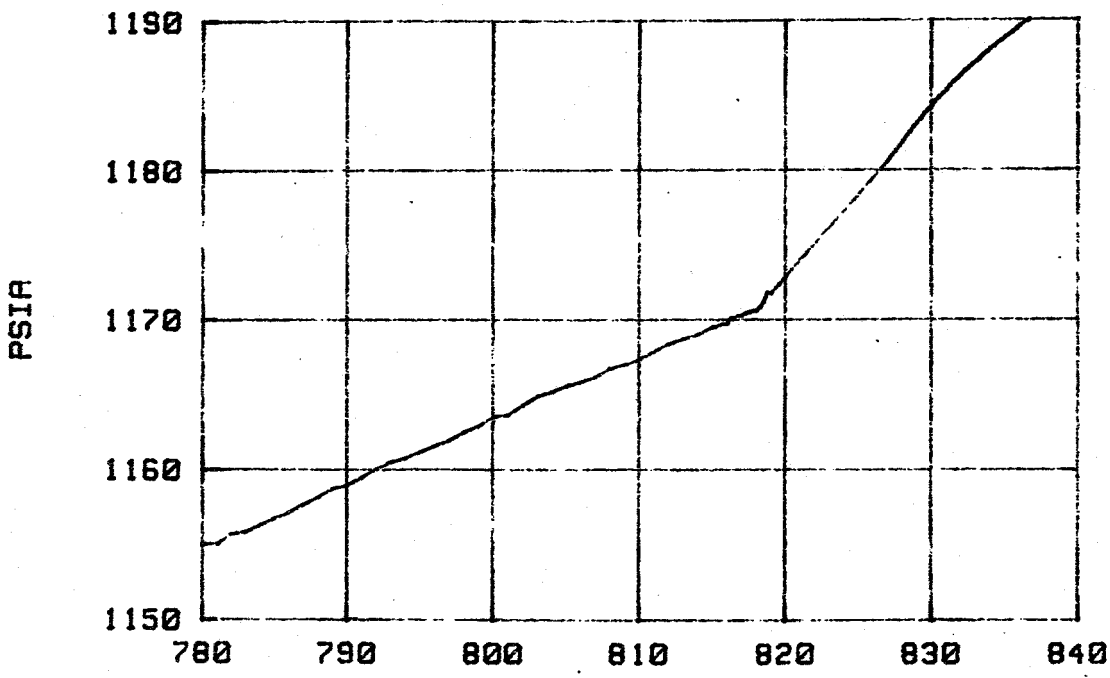


FIG 42 CAVERN 7 LOW PRESSURE TEST

Appendix I

Calculations Procedure for Hole Volume Using N2 Weights Well 6X

In Casing:

Depth Range selected = 2300 to 2500 ft.

N2 Weight = 10293 - 10061 = 232 lb.

N2 Vol. (STP) = 232 lb x 13.8 = 3201.6 Ft^3

Avg N2 pressure = pavg

pavg = (p + p x B)/2

p = Nitrogen pressure at the wellhead

d = Midpoint of depth range

The value (B) is to correct for the weight of the nitrogen column and is the value of the N2 pressure at the nitrogen-brine interface divided by the N2 pressure at the surface. This value is calculated from the equation:

B = 1 + 1/CRT where:

T = Nitrogen temperature (^{o}R)

R = Ideal gas constant (55.15877)

$$C = 1 - 1.3792533 \times 10^{-2} P + 4.9554999 \times 10^{-5} P^2 + 7.9147650 \times 10^{-5} PT - 2.7517031 \times 10^{-7} P^2T^2 - 1.1248659 \times 10^{-7} PT^2 + 3.9289709 \times 10^{-10} P^2 T^2$$

P = Nitrogen pressure (atmospheres) at the wellhead

$$pavg = [1600 + 1600 (1.00003050)^{2400}] /2 = 1723 \text{ psi}$$

N2 Volume in well = 3201.6 x 14.7/1723 = 27.3 ft^3

N2 volume per foot of casing = 27.3/200 ft. = .137 ft^3/ft

The Halliburton book gives 0.0999 ft^3/ft, for this casing, therefore, the N2 calculation indicates too much N2 by a factor of .137/.0999 = 1.37. Therefore, to get borehole volume from the N2 measurements (specific to each setup) the value must be divided by 1.37.

In open hole:

Depth range selected = 2575 to 2600 ft.

N2 weight = 9940-9908 = 32 lb

N2 Vol (STP) = 32 x 13.8 = 442 ft^3

Avg N2 pressure = pavg

$$pavg = [1660 + 1660\ (1.0000305)^{2587}\ ]/2 = 1728\ psi$$

N2 Volume in well = 442 x 14.7/1728 = 3.76 ft^3

Borehole Vol. = 3.76 ft^3/25 ft x 1/1.37 = .1 ft^3/ft

This value would result from a hole diameter of about 7 inches. The caliper log of 11/1/79 shows a 7.5 inch diameter above 2550, but there is no log in the final configuration at 2590 ft.

Appendix I (Cont'd)

Well 6Y

In casing:

Depth range selected = 2250 to 2450 ft

N2 weight = 10321-9777 = 544 lb

N2 Vol (STP) = 544 x 13.8 = 7507.2 ft^3 STP

Avg N2 press = pavg

pavg = $[1647 + 1647\ (1.00003051)^{2579}]/2$ = 1714 psi

N2 volume in well = 7507.2 x 14.7/1714 = 64.4 ft^3

N2 Volume per foot of casing = 64.4/200 ft. = .322 ft^3/ft.

The Haliburton book gives .2273 ft^3/ft, therefore the N2 calculation indictes too much N2 by a factor of .322/.2273 = 1.42.

In open hole:

Depth range selected = 2530 to 2580 ft

N2 weight = 10327-10085 = 242 lb

N2 Vol. (STP) = 242 x 13.8 = 3340 ft^3

Avg N2 pressure = pavg

pavg = $[1647 + 1647\ (1.00003051)^{2555}]/2$ = 1714 psi

N2 Volume in well = 3340 x 14.7/1714 = 28.6 ft^3

Borehole volume = 28.6/50 x 1.42 = .4 ft^3/ft

Appendix I (Cont'd)

Well 6Y

This is compared to the volume of .338 ft^3/ft for a 7 7/8" hole as estimated from the 6/1/81 caliper log. The assumed volume for leak calculated will be:

$V = (.338 + .4)/2 = .37\ ft^3/ft$

Appendix I (Cont'd)

Well 6Z

In casing:

Depth range = 2350 to 2550 ft.

N2 weight = 10985-10346 = 639 lb

N2 Vol. (STP) = 639 x 13.8 = 8818 ft^3

Avg N2 press = pavg

pavg = $[1554 + 1554\ (1.00003059)^{2450}]/2$ = 1614 psi

N2 Volume in well = 8818 x 14.7/1614 = 80.3 ft^3

N2 Volume per foot of casing = 80.3/200 ft = .402 ft^3/ft

The Haliburton book gives .224 ft^3/ft, therefore, the N2 calculation indicates too much N2 by a factor of .402/.224 = 1.79

In open hole:

Depth range = 2600 to 2680 ft

N2 weight = 10133-9717 = 416 lb

N2 Volume (STP) = 416 x 13.8 = 5741 ft^3

Avg N2 pressure = pavg

pavg = $[1554 + 1554\ (1.00003059)^{2640}]/2$ = 1619 psi

N2 volume in well = 5741 x 14.7/1619 = 52.13 ft^3

Borehole volume = 52.13/80 ft. x 1/1.79 = .364 ft^3/ft

This volume would indicate a borehole diameter of:

$$.364 = Pi\ (D^2 - 10.75^2)/4 \times 144$$

$$D = [(.364 \times 4 \times 144/Pi) + 10.75^2]^{.5} = 13.5$$ inch which is reasonably compatible with the stated use of a 12 1/4" drill bit from 2600 to 2924 per Ref. 12.

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