DESIGN AND CONSTRUCTION OF SHEEP MOUNTAIN CO_2 PIPELINE

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INTRODUCTION

Exploration for natural gas in the Sheep Mountain area, located approximately 28 miles northwest of Walsenburg, Colorado, was begun in early 1972. The first two wells completed produced CO_2 instead of natural gas. ARCO Oil and Gas Company purchased the leases from the original lease holders in 1974 and continued development of the field. The boundaries of the Sheep Mountain Unit were finalized in 1981, and the Unit now consists of approximately 9,000 acres. (See Figure 1.)

As a result of this purchase, the Company began making studies and plans on how to produce and deliver the CO_2 to various oil fields to be used for enhanced oil recovery (EOR) of the oil remaining in place. It was felt that as much as 25% of the remaining oil in place could be recovered using CO_2 for tertiary miscible flooding.

The production facilities for CO_2 recovery are very similar to those used in the production and recovery of natural gas; therefore, the design and construction of the production facilities were not considered to be a major problem.

Since CO_2 can be transported by different methods, the Company had to select the most economical method for delivery of the CO_2 to the oil fields selected for EOR. Based on the volumes needed for EOR and the production capabilities within the Unit, the Company decided to use a pipeline for the transportation of the 330 MMSCFD that would be produced within the Unit.

DESIGN OF THE PIPELINE SYSTEM

Once the decision was made to transport the CO_2 by pipeline, it was necessary to finalize the selection of exactly which oil fields would be used for this method of EOR. The Wasson (San Andres) and Seminole (San Andres) fields located in Yoakum and Gaines Counties, Texas were selected as the termination points for the pipeline. Delivery to these fields would require a pipeline approximately 408 miles long.

Basically, the Sheep Mountain CO_2 Pipeline is similar to any other high-pressure hydrocarbon pipeline. The original design flow rate for the pipeline was to be 330 MMSCFD, requiring a pipeline 20 inches in diameter. Later on in the project, the design was changed to add more CO_2 from the Bravo Dome area in New Mexico. (See Figure 2.) The final flow rate for the last 225 miles of the pipeline was increased to 500 MMSCFD which required a 24-in. pipeline.

The characteristics of CO_2 are such that to transport this amount of CO_2 per day, the CO_2 must be kept above its critical pressure at all points in the line. This will insure that the CO_2 remains in a single dense vapor stage. (See Figure 3.)

The Sheep Mountain fluid consists of about 97+ mol % CO_2, with about 3 mol % hydrocarbons and nitrogen. Densities vary from a low of 23.8 lb/ft^3 at 1,320 psia and 107°F to a high of 61.9 lb/ft^3 at 2,860 psia and 34°F. The compressibility of the Sheep Mountain CO_2 mix varies from a low of 0.15 to high of 0.40.

The pipeline begins at an elevation of about 8,800 ft at the Sheep Mountain Unit, drops to 6,300 ft. in southern Colorado before rising to 8,500 ft. where it crosses into New Mexico, and finally drops to approximately 3,300 ft. at the Seminole terminal. (See Figure 2.) The maximum pressures at any given point along the pipeline vary from a high of 2,860 psia to a low of 1,200 psia. (See Figure 4 for a plot of maximum possible pressures along the line.) Because of the differences in elevations and the varying densities of the CO_2 along the pipeline, the pressure at the pipeline's delivery point is greater than the pressure at the point of origin. At one point along the pipeline (Milepost 143), the pressure becomes high enough under certain flow conditions to necessitate the installation of a pressure control station. This station was designed to reduce downstream pressure and thus insure safety of the pipeline while simultaneously maintaining a back pressure of at least 1,200 psia.

Certain basic criteria were established for design of the pipeline to insure the most economical system. These criteria were:

1. The pressure in the pipeline would not be allowed to fall below 1,200 psia, thus maintaining single phase flow.

2. The CO_2 would be dehydrated so as to be noncorrosive, allowing the use of carbon steel pipe (less than 200 ppm of water).

3. The final delivery pressure would be approximately 2,000 psia to permit direct injection of the CO_2 into the oil fields.

4. Any CO_2 transported in the line would be at least 96% pure.

As in the design of any pipeline, hydraulic calculations were necessary to predict pressure drops and flow rates for sizing the line. Such calculations are especially important where long distances and large elevation differentials are involved.

In the pipeline design, CO_2 is injected into the mainline pipeline from the production facilities in Colorado at a temperature of approximately 110°F. and a pressure of 1,600 psia. CO_2 from the Bravo Dome area enters the pipeline at MP 183 at approximately 2,200 psia. All compression of the CO_2 is done at the production facilities for the design flow rates. As the fluid is transported to its destination, it approaches a temperature slightly less than that of the ground or sink surrounding it. This phenomenon alone accounts for a 60% to 70% increase in fluid density and produces a marked change in the hydraulic characteristics of the fluid. Physically, for a given mass flow rate, as the density increases the volumetric rate decreases; this produces lower velocities in the pipeline and associated lower friction pressure losses. Therefore, simulating hydraulic conditions using long segments of pipeline cannot accurately predict line pressures, since these nonlinear fluctuations in hydraulic characteristics cannot be accounted for with such a model. Computer programs were developed to simulate CO_2 flow in this high-relief pipeline system. The Sheep Mountain CO_2 Pipeline was divided into segments short enough to permit the linearization of physical properties over each segment, and hydraulic calculations were made by the computer in a sequential manner from segment to segment.

Since the hydraulic characteristics of CO_2 are sensitive to temperature changes, variations in the temperature of the fluid had to be predicted and accounted for. This was accomplished by a simple energy balance, using the thermodynamic characteristics of our CO_2 mix. Generally, the equation had to compensate for the isentropic expansion of the fluid, the exchange of energy to (or from) the surrounding sink and the change of potential energy to pressure due to elevation differentials.

Friction loss calculations for the Sheep Mountain CO_2 Pipeline were made for each segment using the Darcy-Weisbach general flow equation.

The routing of the Sheep Mountain CO_2 Pipeline produced large elevation differentials along the length of the line as described earlier. Comprehensive analyses were made to determine line pressure requirements for standard operating (dynamic) and emergency shutdown (static) situations. With an incompressible fluid, static hydraulic calculations are not difficult to make. CO_2, however, is highly compressible, and has a density equal to or greater than most incompressible hydrocarbons. In the static analyses, the line was segmented, and the same equations were used as with the flowing cases. In a shutdown from a standard operating condition, the line's total mass fill was assumed to be the same as the operating case from which the shutdown occurred. The ground temperature and the operating temperature profile (prior to shutdown) were used for every case to predict static pressures. Generally, the profiles with the highest temperature produced the highest static pressures when mass fill remained constant.

Due to the high compressibility of CO_2, the adiabatic bulk modulus of CO_2 is low relative to an incompressible fluid. For this reason, surges due to the closing of mainline block valves were negligible and had no effect on the design of the system. Since booster stations were not a part of the design, surges due to the shutdown of boosters were not addressed in great detail.

Once the hydraulic calculations had been completed and the line had been sized, the pipe material was selected. The northern portion of the line (183 miles) is 20-in. OD with wall thicknesses varying from 0.438 in. to 0.625 in. The southern portion of the line (225 miles) is 24-in. OD with wall thicknesses varying from 0.562 in. to 0.750 in. The line pipe is API5LX-70 DSAW high yield strength with high impact toughness characteristics to resist crack propagation. The Charpy Impact Values are greater than 50 ft-lbs at 0°F, and the carbon equivalent is less than 0.40% by weight. The precrack drop weight tear tests (PC-DWTT) average greater than 1,450 ft-lbs/in^2.

The Sheep Mountain CO_2 Pipeline is not a common carrier and therefore does not fall under the jurisdiction of the ICC. Also, the design requirements did not fall under any of the applicable design codes (DOT 195, ASME/ANSI B31.8 and B31.4). Regardless of these facts, the Company decided that the design would meet the most stringent requirements of each of the codes, in case the line came under federal jurisdiction at a future date. This decision resulted in the pipeline and associated facilities being designed to an ANSI 1500 rating.
Metering of the CO_2 is accomplished using turbine meters which were selected because of their accuracy. Three meters were installed at each metering site, with two meters being active and one as a spare. A ballistic type meter prover is incorporated at each meter station so that the meters can be proved in-line at flowing conditions.

The final design of the Sheep Mountain CO_2 Pipeline included an origin meter station located within the Sheep Mountain Unit, a pressure control station located at MP 143, an injection metering station at Bravo Dome (MP 183), a delivery meter station located at the Wasson Field in Denver City, Texas, a meter station at the Seminole Field, Texas, eight scraper launcher/receiver stations at various points along the pipeline route, and mainline block valves approximately every 20 miles along the route.

Pipeline operations are conducted from a single operations control center. A computer-based control system provides operator interface to intelligent Remote Terminal Units (RTU's) for Supervisory Control and Data Acquisition. Communications to these RTU's are via leased telephone lines.

CONSTRUCTION

Construction on the pipeline started in mid-April of 1982 and was essentially complete in late January, 1983. The construction of the pipeline was accomplished using one construction spread for the 20-inch portion of the pipeline (183 miles) and one spread for the 24-inch portion (225 miles). The Origin Meter Station (OMS), Gladstone Pressure Reduction Station (PRS) and the Bravo Dome Meter Station were installed by one contractor and the Lingo, Denver City, and Seminole stations were installed by a second contractor.

Special welding procedures were developed for welding on the X-70 pipe due to the chemical composition of the pipe as well as its high strength. The pipe was preheated to 250°-300°F before welding and was kept heated to this temperature during welding. The pipeline was constructed to API Standard 1104.

The main problems encountered during construction were related to the terrain through which the pipeline was laid. The Sheep Mountain area and the Johnson Mesa area were very steep and rocky, which made construction progress slow. The Canadian River crossing created a slowdown in construction because of high water; this obstacle was overcome by constructing diversion dams and installing the pipeline in two sections.

The southernmost portion of the pipeline passed through the oil and gas fields around Denver City, Texas and Seminole, Texas. Due to the many pipelines that already existed in that area, the pipe installed there was laid in relatively short sections.

Once the pipeline was in place, it was necessary to hydrostatically test the pipeline to insure its integrity. These tests were conducted in segments, due to the limited availability of water supplies and also to allow some of the tests to be conducted before construction was completed. The test pressures varied from 2200 psig to 3800 psig along the pipeline, but the stresses in the pipe never exceeded 98% of its minimum yield strength (See Fig. 5). In the tests, each pipeline segment, after having been filled with water, was allowed to stabilize for a period of 48 hours. It was then held under test pressure for a period of eight hours. The pressure change during the test period varied from 40 to 100 psi; this variation was due to temperature changes along the pipeline.

After the hydrostatic tests were completed, the water was removed from the pipeline. The pipeline was then dehydrated to a -40°F dew point, after which it was sealed off with a positive pressure, to await filling with CO_2.

CONCLUSION

Present plans call for the pipeline to be filled with CO_2 by mid-March, 1983, and to deliver approximately 50 MMSCFD to the Seminole Meter Station. Total deliveries are planned to increase to the maximum flow rate of 500 MMSCFD during 1984.

ACKNOWLEDGEMENTS

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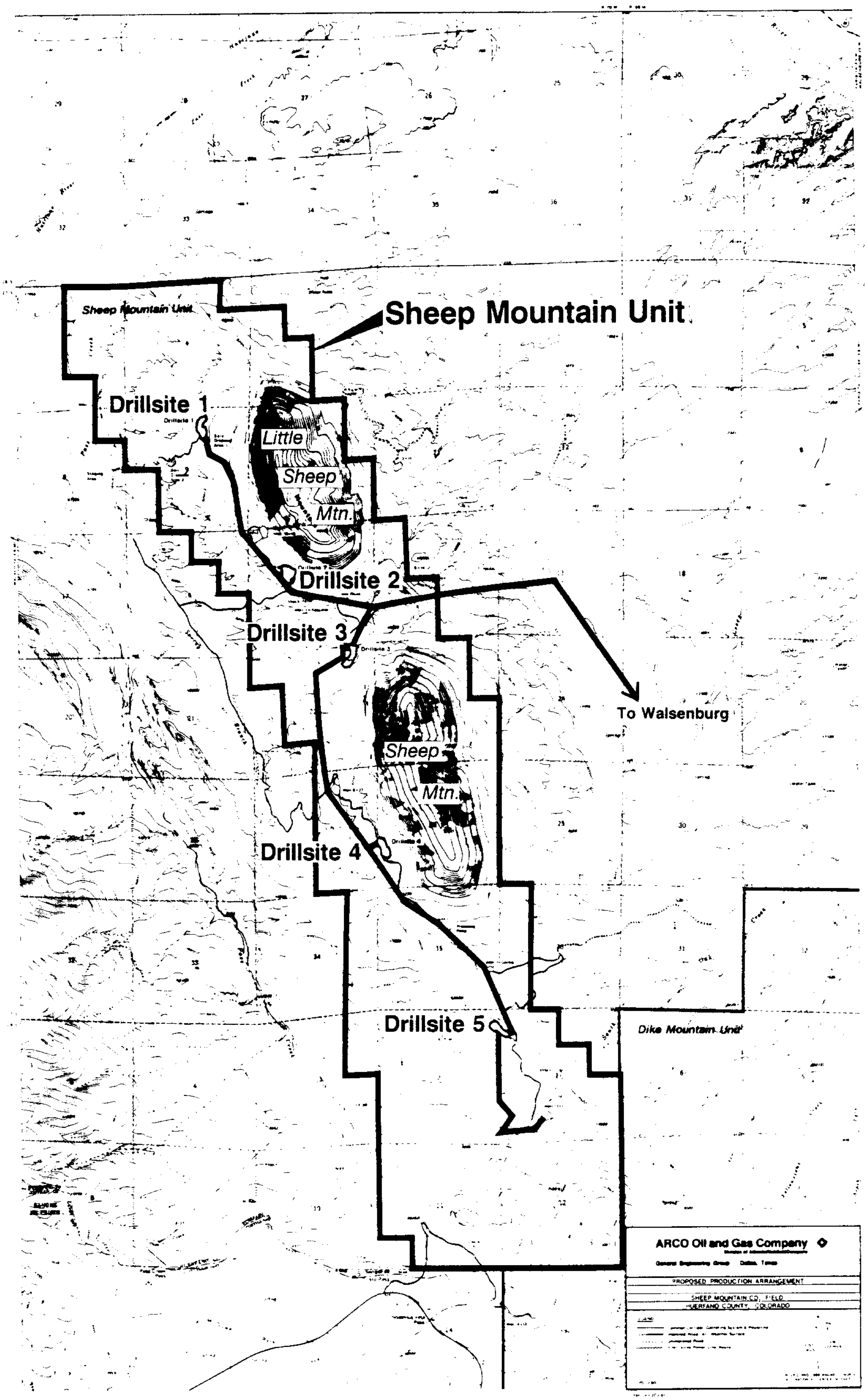
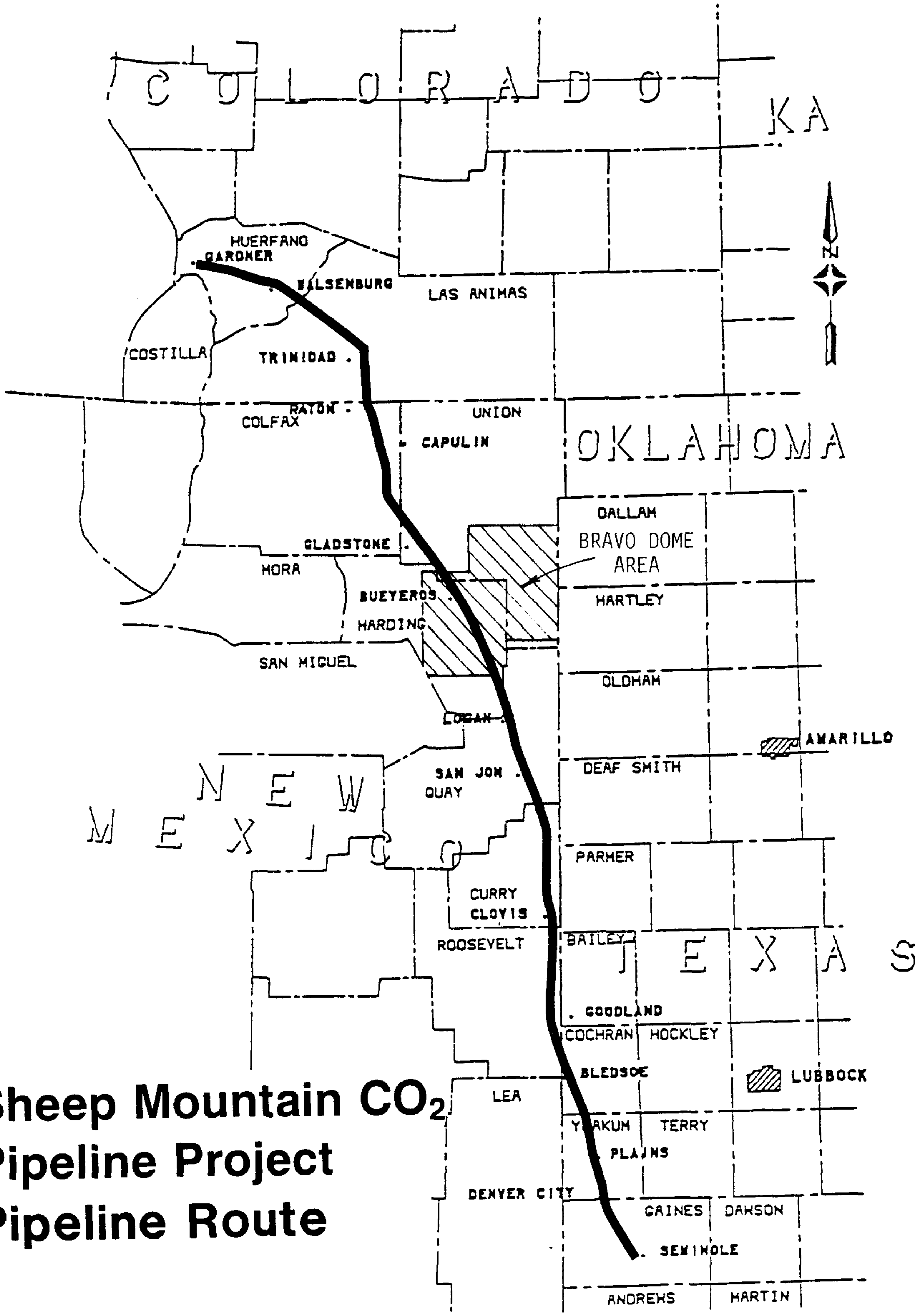


Sheep Mountain Unit
Sheep Mountain Unit
Drillsite 1
Little
Sheep
Mtn.
Drillsite 2
Drillsite 3
To Walsenburg
Sheep
Mtn.
Drillsite 4
Drillsite 5
Dike Mountain Unit
ARCO Oil and Gas Company
PROPOSED PRODUCTION ARRANGEMENT
SHEEP MOUNTAIN CO2 FIELD
HUERFANO COUNTY, COLORADO

FIGURE 1



Sheep Mountain CO_2 Pipeline Project Pipeline Route

FIGURE 2

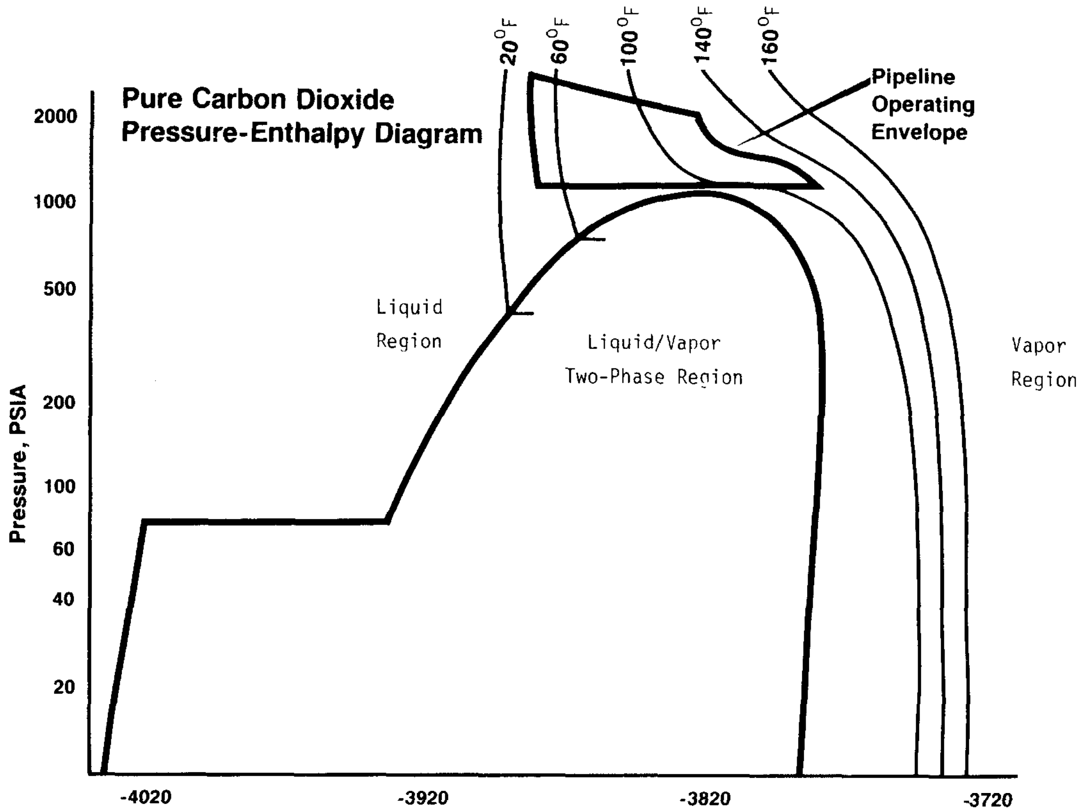


FIGURE 3

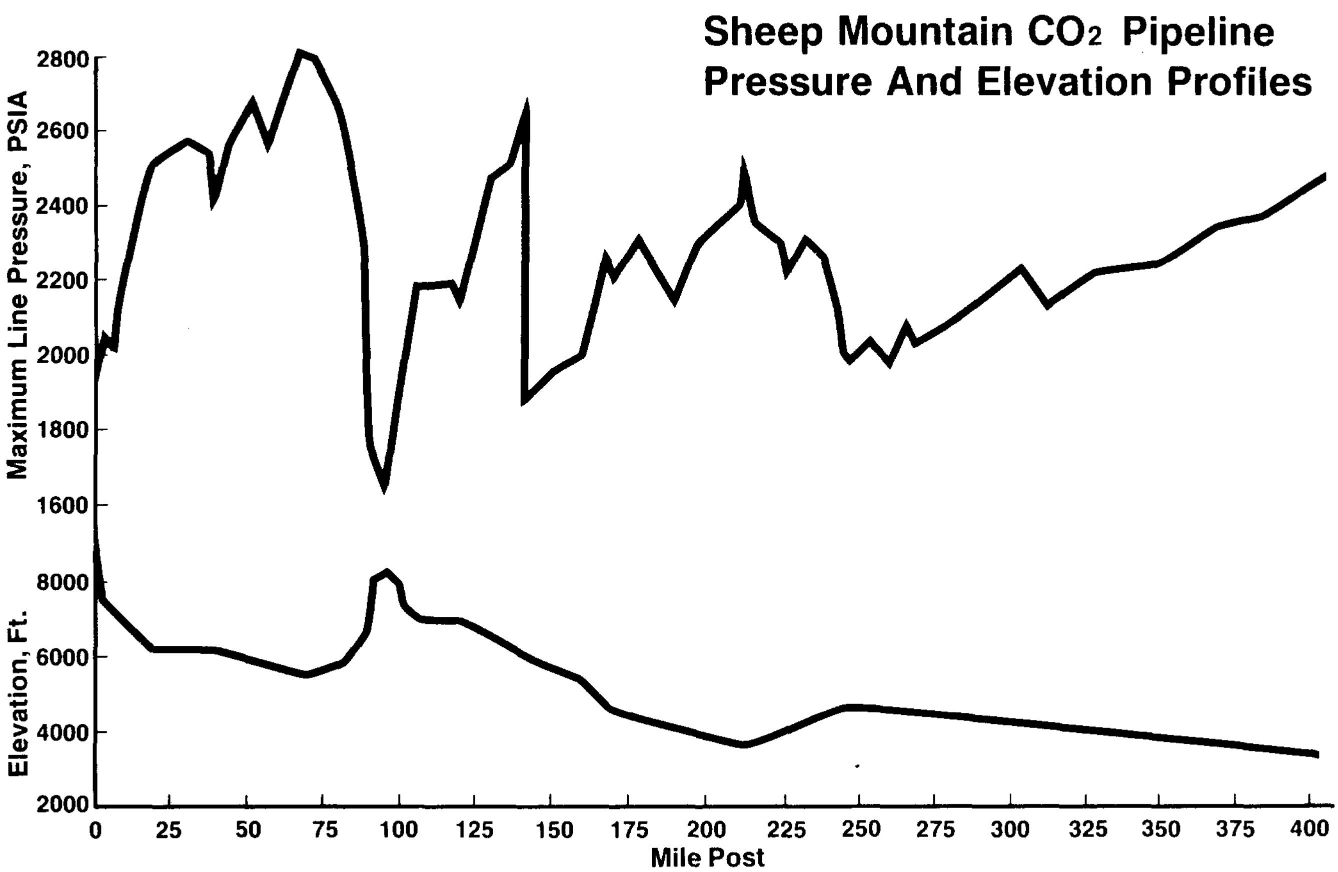


FIGURE 4

SHEEP MOUNTAIN CO_2 PIPELINE HYDROSTATIC TEST PLAN PROFILES

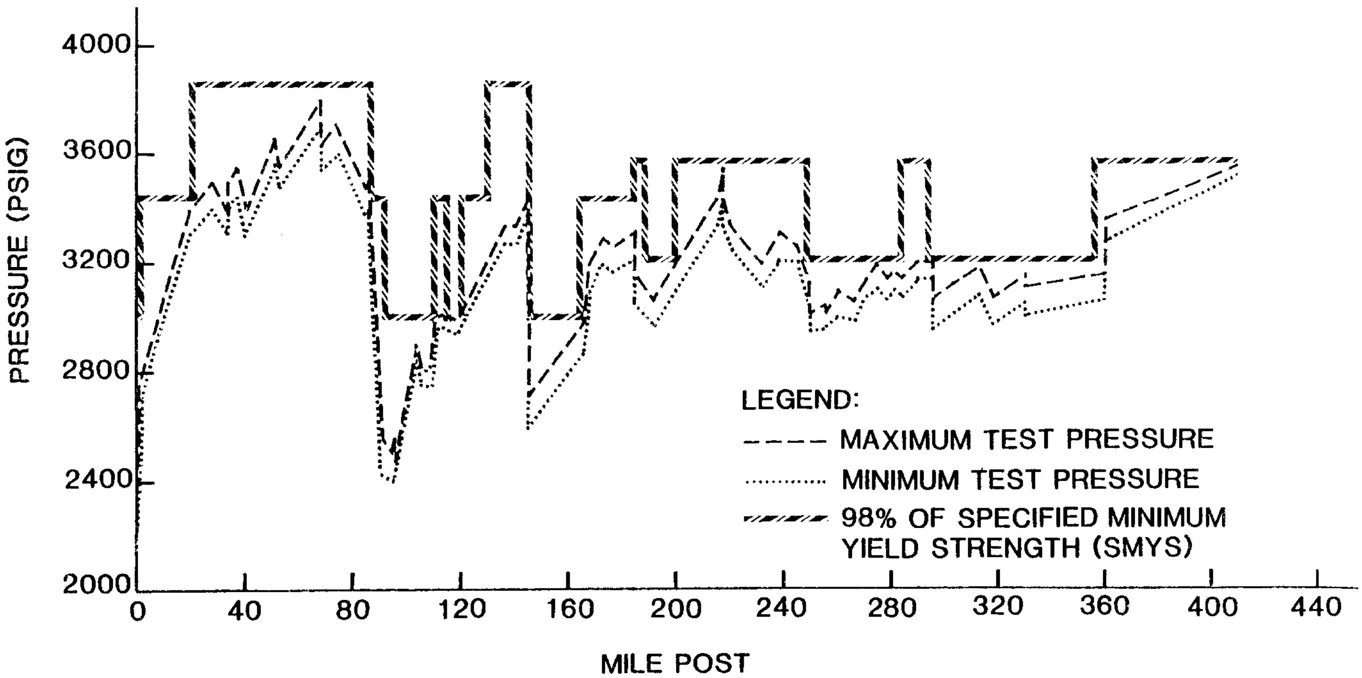


FIGURE 5