UPDATE ON OPERATIONS OF THE SHEEP MOUNTAIN CO_2 UNIT

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ABSTRACT

ARCO Oil and Gas Company started producing the nation's first large-scale natural carbon dioxide (CO_2) reservoir on January 31, 1983, from the Sheep Mountain Unit located in Huerfano County, Colorado. With the installation of a 330 MMCFD capacity pipeline, completed in January 1983, this CO_2 has become an important source for future enhanced recovery projects in the West Texas area.

This paper describes the Sheep Mountain reservoir, including a geological history, and the current theories for CO_2 creation and migration in the Dakota and Entrada formations. A comparison of CO_2 fluid properties to hydrocarbon fluid properties is presented, followed by a discussion of the producing characteristics of the wells and the conditioning processes employed before the CO_2 is placed in the pipeline. An account of the problems encountered since start up and the resulting or proposed solutions is also included.

INTRODUCTION

The Sheep Mountain CO_2 Project started in 1972. Following the leasing of land, the formation of two development units (Sheep Mountain Unit and Dike Mountain Unit), and the drilling of sixteen delineation wells, full-scale development of the Sheep Mountain Unit was begun in 1981. Five drill sites were constructed within the Unit (Figure 1), each containing CO_2 gas processing facilities capable of heating, dehydrating, and compressing 60-80 MMCFD, depending on pipeline conditions and locations within the Unit. Fourteen development wells were directionally drilled off of Drill Sites #1, 2 and 3 in 1981 and 1982. Drill Sites #4 and #5 will be developed in 1984 to provide sufficient well capacity for a projected demand of 300-330 MMCFD by January 1, 1985.

GEOLOGY

The Sheep Mountain CO_2 reservoir consists of two distinct carbon dioxide bearing zones, within two different thrust plates. The Sheep Mountain Plate underlies the Sheep Mountain Unit, while the Abeyta Creek Plate underlies the Dike Mountain Unit. (The Abeyta Creek Plate is excluded from this discussion.)

The upper horizon within the Sheep Mountain Plate, the Dakota formation, is divided into two members, the lower member being made up of medium-grained sands and pebble conglomerates (typical of a fluvial environment), and the upper member being made up of fine-to-medium grained sands (typical of a beach and near-shore environment). The Dakota formation ranges in thickness from 125 to 250 ft and in permeability from 20 to 4000 md. The lower horizon, the Entrada sandstone, is separated from the Dakota by a 100 to 200 foot section of the Morrison formation. The Entrada formation is made up of fine-to-medium grained sands. Depositional environment of the Entrada is assumed to be fluvial. It ranges in thickness from 60 to 90 ft and in permeability from 10 to 250 md. Cements in both sandstones tend to be siliceous, with much lesser amounts of carbonate and clay cements. Figure 2 is a typical log section of the Sheep Mountain reservoir.

The structure of the Sheep Mountain reservoir is very complex. Tectonic activity associated with the formation of the present-day Rocky Mountains, which occurred from late Cretaceous through the Eocene periods, created several thrust faults through the Paleozoic, Mesozoic, and Tertiary sections, along with the two aforementioned thrust plates. Associated with the tectonics was significant igneous activity. Several igneous dikes and sills are present throughout the Sheep Mountain Field, with most of them occurring above the CO_2 productive horizons. Some metamorphized altered sections within the Dakota and Entrada have been observed, with one well having the Entrada section totally replaced with an igneous intrusion.

Shown in Figures 3 and 4 is the current structural interpretation of the Dakota and Entrada reservoirs. All faults shown are assumed to be sealing, both within and on the periphery of the structure. Therefore, faults seal both formations on the eastern and southern borders. An aquifer contains the reservoirs on the remaining western and northern edges. At this time, it is believed that the aquifer is of limited extent and will provide no support for future pressure maintenance.

There are several theories attempting to explain the presence of the carbon dioxide trapped in the Sheep Mountain reservoir. The first, and least attractive, is that the CO_2 is a by product of combusted hydrocarbons which were in place before the igneous activity. If this were true, there would be more evidence than has been found of residue products from this combustion process. Another theory is that the carbon dioxide was formed by the thermal reaction of carbonates at depth. However, the Dakota and Entrada reservoirs are sandstones and contain a very low quantity of carbonate material. Another idea is that the carbon dioxide is an igneous emanation from carbonatite. Carbonatite is an intrusive carbonate rock associated with alkaline igneous intrusive activity. Samples of this mineral have been found in the Sheep Mountain area. It is theorized that as this igneous material passed through and around the present day reservoirs, carbon dioxide, along with much smaller amounts of other gases, was released.

CHARACTERISTICS OF CARBON DIOXIDE

The composition of the gas produced at Sheep Mountain ranges from 95 to 98% CO_2 with the remaining components being nitrogen, methane, and a few heavier hydrocarbons. This results in a critical pressure (P_c) of approximately 1059 psia and a critical temperature (T_c) of 82°F. (This compares to critical properties for 100% methane of Pc = 668 psia and Tc = -116.7°F.) Under normal operating conditions, the produced CO_2 from Sheep Mountain will be below its critical conditions, resulting in two-phase flow and higher hydrate temperatures.

Figure 5 is a pressure-enthalpy diagram for 100% CO_2. (It should be noted that this Figure adheres to work done by V. V. Altunin and M. P. Vukalovich which supports the proposal that the boundary between phases above the critical point follows a constant volume line curving upward to the right.) At the average Sheep Mountain reservoir temperature of 127°F, the CO_2 in place will always be in the gaseous phase. However, as this gas is produced through the completion, up the tubing, and into the conditioning plants, pressure and temperature are reduced, and the CO_2 enters the two-phase region. It has also been predicted that two-phase flow is possible within the reservoir near the wellbore in lower permeability areas, as the conductive heat from the reservoir has been estimated to be small compared to the convective cooling from the polytropic expansion. (The ratio of convective heat flux from the expansion to conductive heat flux from surrounding beds, under typical flow conditions 50 feet from the wellbore, is approximately 380.) Another unique characteristic of the CO_2 wells at Sheep Mountain is that at static wellbore conditions, a column of liquid CO_2 is formed within the tubing, whereby gaseous CO_2 is below and above it. Figure 6 illustrates this phenomenon. Care must be taken to handle these liquid slugs when wells are opened for initial flow. In addition, at initial reservoir conditions, the gas is saturated with water. The possibility of carbon dioxide hydrates is very real, at a temperature of 55°F, for all of the producing wells.

Because of the unique properties of CO_2 as compared to hydrocarbon gas as described above, along with its known corrosive nature when associated with water, special considerations have been made in producing and processing this gas at Sheep Mountain. These considerations will be discussed in the next two sections of this paper.

PRODUCTION OF CARBON DIOXIDE AT SHEEP MOUNTAIN

Based on the pay thicknesses and permeabilities found at Sheep Mountain, it is not surprising that the producing wells have very high deliverabilities. Figures 7 and 8 illustrate the flowing capacity of Wells #2-22-A and #1-15-C, respectively, constructed from actual flow data. It should be noted that these wells are not the most productive in the field, as #2-22-A, a Dakota well, has a pay thickness of 200 ft. and an average permeability to gas of 220 md, while #1-15-C, an Entrada well, has a pay thickness of 55 ft. and an average gas permeability of 20 md.

Pressure transient analysis has been very useful in evaluating the Sheep Mountain reservoir. When applying these analysis techniques to CO_2 production, it is obviously important to use the viscosity and compressibility properties of CO_2 as opposed to those of hydrocarbon gas, especially when using real gas pseudo pressure m(p) in the analyses. (m(p), which is twice the integral of $P/\mu z$, is used to take care of the variance of gas viscosity and density with pressure.) In-situ permeability values differ enough from core data that we can assume that 1) slippage factors for CO_2 are quite different than for air, and 2) pressure and temperature are very important in measuring permeability to carbon dioxide gas. From these transient flow tests, we have also been able to gain interesting information about skin damage in Sheep Mountain wells. We have been able to separate out the various skin values contributing to the apparent skin, whereby the following values have been estimated in various wells from the pressure transient tests analyzed to date:

s_a = apparent skin = 0 to +18.0
s_w = skin due to slanted wellbore = -2.6 to 0
s_p = skin due to perforation geometry = 0 to +2.0
s_t = skin due to non-Darcy flow = 0 to +2.0
s_f = skin due to liquid blockage = 0 to +14.0

One of our major concerns is the skin damage due to liquid blockage (s_f) which is probably drilling mud filtrate. In one particular well, we observed this skin to be as high as +18.0. But in a test six years later, it had been reduced to +3.6, indicating that this liquid blockage has dissipated over time. We need to have a more exact estimate for this dissipation time period. Also, as mentioned earlier, there is the possibility of liquid CO_2 forming near the wellbore in lower permeability producers, which could reduce the relative permeability to CO_2. We are planning to run extensive liquid/gas relative permeability tests on Sheep Mountain core samples in order to evaluate the potential damage of liquid blockage in a CO_2 reservoir.

Production from the Dakota and Entrada reservoirs cannot be commingled because of State of Colorado rules. All completions are single completions (dual wells would be impractical due to the high deviations), perforated with four deep penetrating shots per foot throughout the productive intervals, which are identified by gas effect crossover on the FDC/CNL open-hole logs. The optimization of perforation density has been studied using inflow performance calculations, indicating that the potential increase in rate from increasing the shot densities from 4 SPF is not justifiable due to the high productivity of these wells, and more importantly, due to tubing limitations. Through increased shot densities and hydraulic fracturing, there is potential for significantly increasing productivity of wells on Drill Sites #4 and #5. This is because of their lower permeability and, therefore, lower deliverabilities.

Tubing hydraulics calculations for Sheep Mountain wells are very complex due to the two-phase flow conditions. The ARCO Oil and Gas Plano Research Department has put together a flowing wellbore simulation model specifically designed for carbon dioxide production. It predicts wellbore pressures, temperatures, liquid mass fractions, fluid hydraulics, and heat transfer. It also gives information on hydrate formation and gas/liquid loading. The model's predictions compare favorably with actual flowing pressure and temperature data, coming within ±2% at relatively low flow rates and ±10% at the higher flow rates. All recently completed Sheep Mountain wells have 4-1/2-in. internally plastic-coated tubing with a packer, modified for CO_2 service, set 50 to 100 ft. above the completion interval. Figure 9 shows typical tubing curves for the two surface operating pressures of 750 psig and 350 psig, along with reservoir inflow performance curves for permeability thickness products (kh) of 55,000 md-ft and 1,000 md-ft, respectively.

Current pipeline demand of 80 MMCFD, as of December 1, 1983, can be met with the operation of one drill site. Drill Sites #1, 2, and 3 have all taken turns in meeting this demand. As production is steadily increased to an estimated peak rate of 300 MMCFD by early 1985, more drill sites will be operating simultaneously. The development drilling of Drill Sites #4 and #5 will help provide the needed well capacity. Bottom-hole static reservoir pressures are being taken semiannually to monitor the reservoir's depletion and to enable material balance estimates of gas reserves.

CONDITIONING OF CARBON DIOXIDE AT SHEEP MOUNTAIN

Drill Sites #1, #2, and #3 each have the capability to handle high capacity wells (from the highly permeable Dakota formation) at 750 psig FTP and low capacity wells (from the relatively less permeable Entrada formation) at 350 psig FTP with a drill site capacity of 80 MMSCFPD (Figure 10). Drill Sites #4 and #5 are designed to handle a flowing pressure of only 350 psig from the less permeable parts of both the Dakota and Entrada with a capacity of 60 MMSCFD (Figure 11). Due to the corrosive nature of wet CO_2, the processing facilities from the wellhead through dehydration were constructed with stainless steel. (For price comparison, schedule 80 carbon steel pipe is $2.82/ft, while 2-in. schedule 80 stainless steel pipe is $29.80/ft.)

The CO_2 production first enters the plant at a minimum temperature of 55°F. Sufficient heat is added through 5 MMBTU/hour individual wellstream heaters to vaporize all liquid CO_2 in order to prevent hydrate formation and liquid CO_2 dropout when the gas flows through a choke valve, a venturi meter, and into a production header.

The gas is dehydrated by a triethelyene glycol (TEG) 12-tray contactor. This dehydrated low-pressure CO_2 (30 MMSCFPD) is compressed (one stage) from 350 psig to 750 psig, cooled by a glycol/water system and combined with 50 MMCFPD dehydrated high pressure CO_2 gas (750 psig). The combined stream is then compressed to 1500 psig (design 2,000 psig), cooled with glycol/water heat exchange, metered and sent by pipeline to the central metering station. Drill Sites #1, #2, and #3 each contain a 6000 BHP electric-motor driven two-stage reciprocating compressor. Drill Sites #4 and #5 each have a 7000 BHP compressor.

A vapor recovery system has been installed at each drill site making them virtually free from any emissions. Vapors from the TEG dehydrators, production separators, and suction scrubbers are compressed and reintroduced ahead of the low pressure TEG contactor.

PROCESSING PROBLEMS AND RECOMMENDATIONS

One of the first problems encountered during pre-start up testing was leaking of all eight TEG contactor chimney trays. The chimney trays separate the TEG portion of the contactor from the scrubber section. Poor welding on these stainless steel trays caused the steel to crack at the welds. A major rework of the chimney trays has been done. Another minor problem in the dehydration system was that hydrocarbons in the CO_2 stream caused TEG to foam. The foaming caused a high dew point in the CO_2 stream and a large loss of TEG. A silicone based defoamer was used to correct the problem.

Extremely high wear on compressor rods was noticed shortly after start up. Five of the six second-stage compressor rods had to be replaced. Lubricating oil that met all manufacturers specifications was used; however, it did not perform in the compression of CO_2. A highly fortified petroleum-based lubricating oil with additives such as anti-scuff, water displacant, metal wetters, and corrosion inhibitors is now being used successfully. The compressors also experienced a large number of compressor valve failures following start up. Some of these failures were caused by sand, welding slag, etc. Since the valve failures continued after start up, the compressor manufacturer has designed new valve assemblies which are performing satisfactorily at present.

Elastomer seal failures have occurred throughout the field at wellhead caps, block valves, compressor unloader valves, and pig trap launcher caps. The elastomer compound of EPDM per Y267 formulation is now being used in O-Ring replacements.

SUMMARY

The mystery of where natural carbon dioxide comes from may never be solved, but there are no secrets to producing and conditioning CO_2 once it has been found. Special considerations must be made for its critical properties, which are quite different from hydrocarbon gas. Two-phase flow is probable under most operating pressures and temperatures, along with increased chances of hydrate problems. Due to the corrosive nature of CO_2 with the presence of water, expensive materials must be used to prevent failures.

The Sheep Mountain reservoir has performed as well, if not better than expected. The start up and continued operations have gone smoothly, with the exception of the problems discussed above, and some computer-control software difficulties. The conditioning plants are operating as designed. No problems are foreseen in meeting projected pipeline demands as the Sheep Mountain Project continues to be a major source of CO_2 for West Texas enhanced recovery operations.

ACKNOWLEDGEMENTS

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3. "Thermophysical Properties of Carbon Dioxide", Vukalovich, M. P. and Altunin, V. V., Collet's Publishers, London (1968).

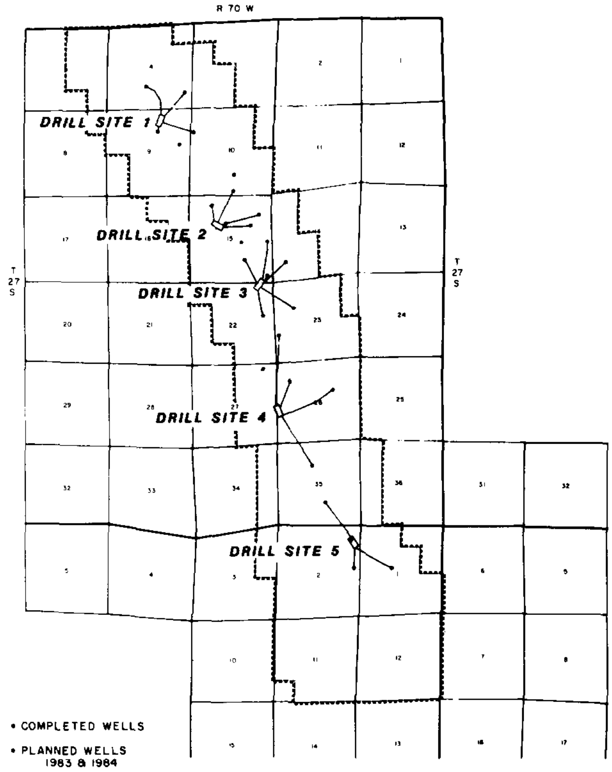

Figure 1 - Sheep Mountain Unit drill site locations

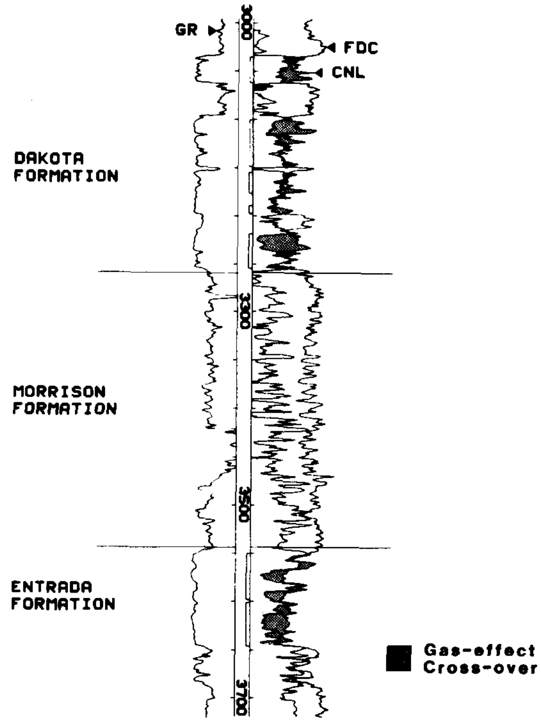

Figure 2 - Type log - Sheep Mountain reservoirs

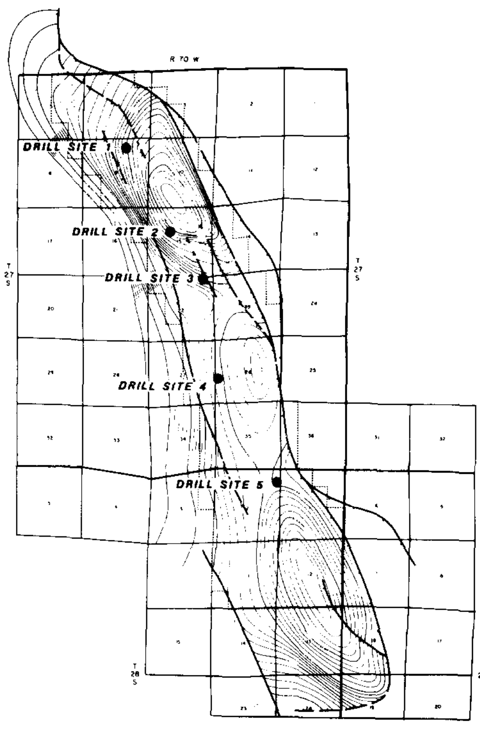

Figure 3 - Sheep Mountain Unit, Dakota Structure

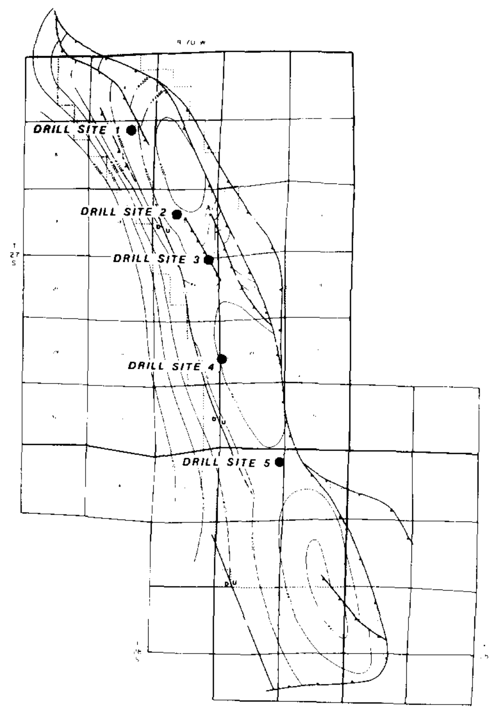

Figure 4 - Sheep Mountain Unit, Entrada Structure

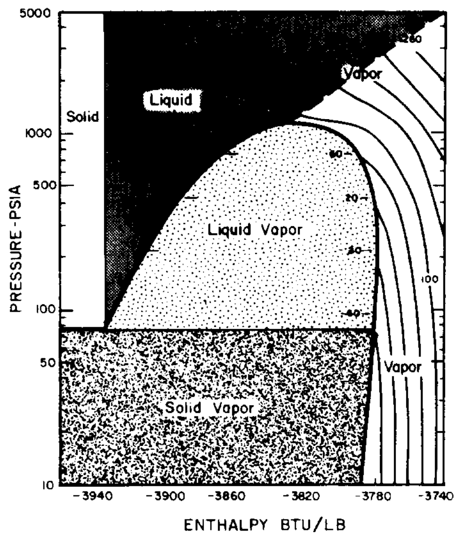

Figure 5 - CO_2 Pressure - Enthalpy Diagram

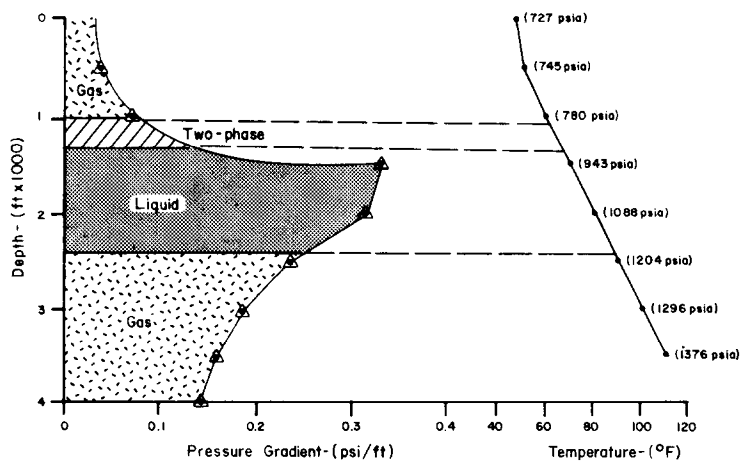

Figure 6 - Correlation of pressure, temperature and pressure gradient in a static wellbore to illustrate phase changes vs. depth

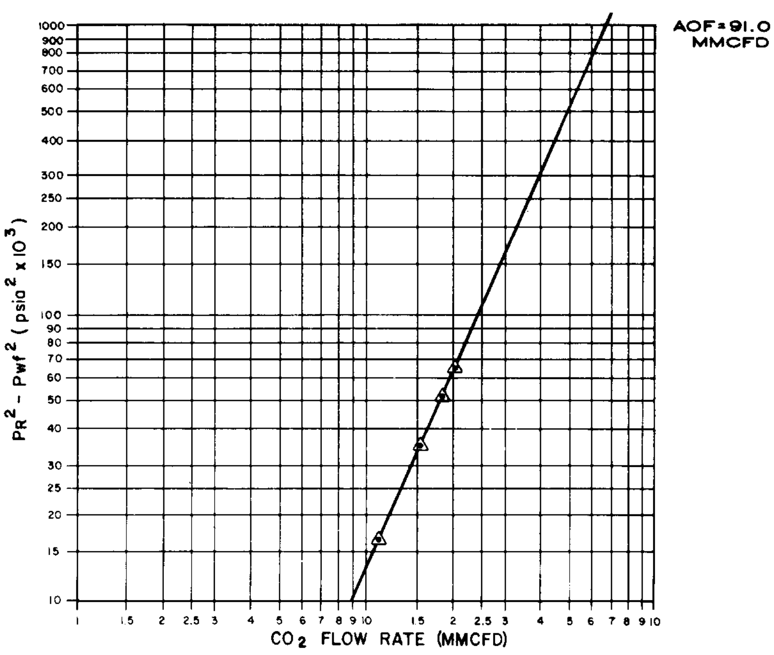

Figure 7 - Deliverability of SMU No. 2-22-A (PR= 1470 psia)

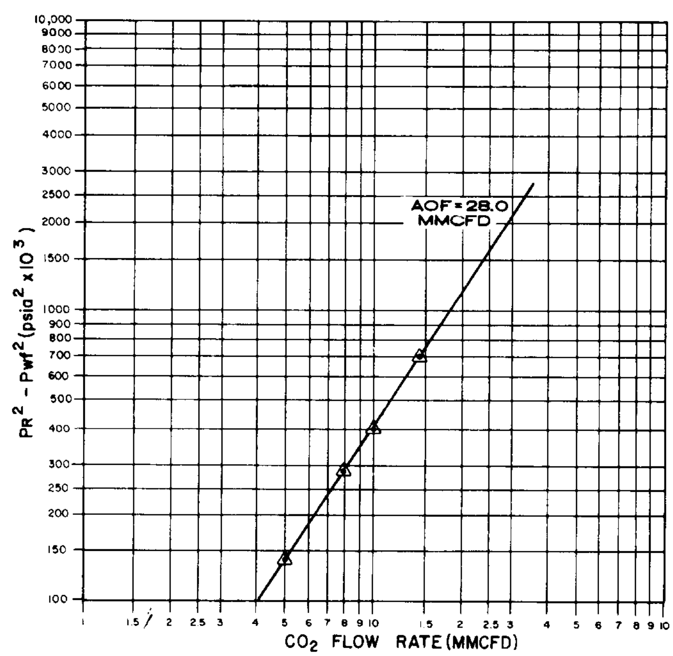

Figure 8 - Deliverability of SMU No. 1-15-C (PR= 1397 psia)

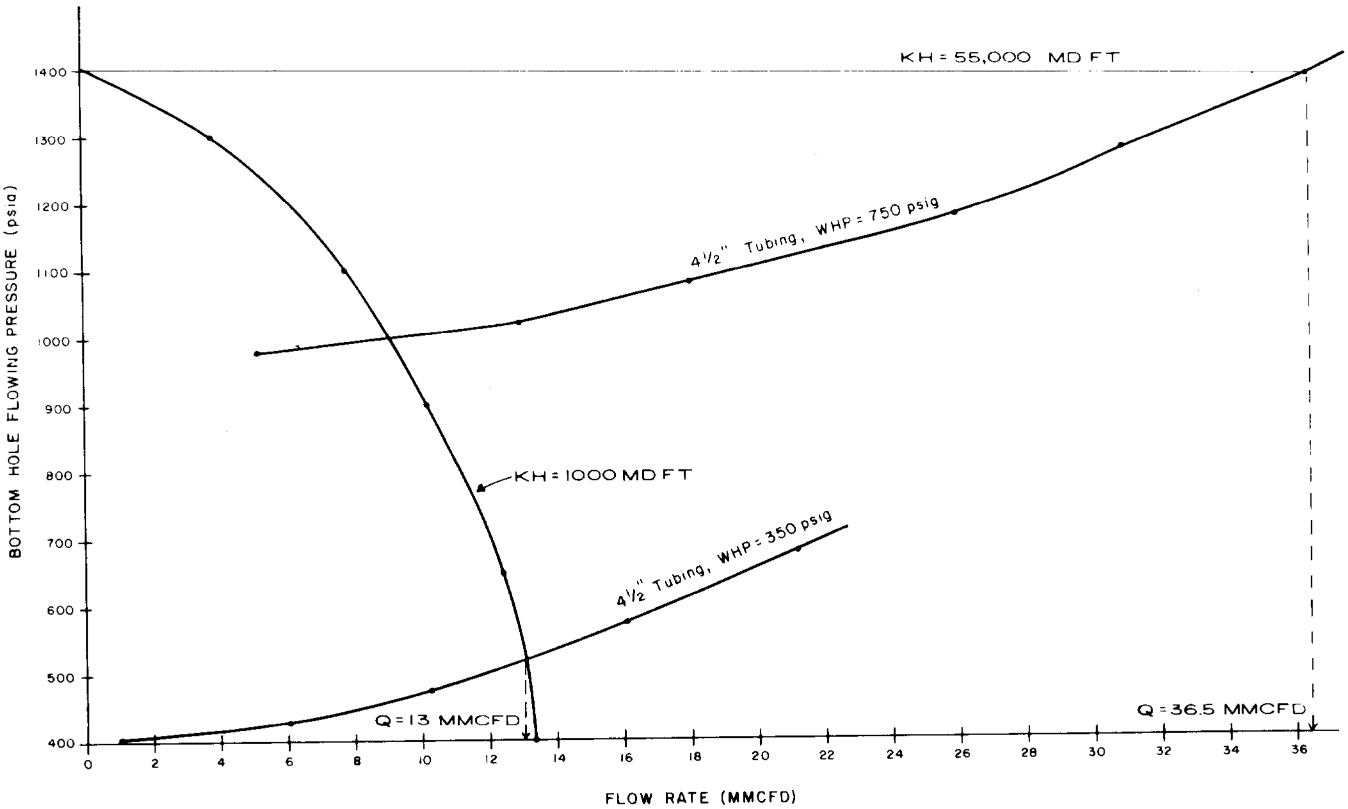

Figure 9 - IPR and tubing curves for typical Sheep Mountain wells

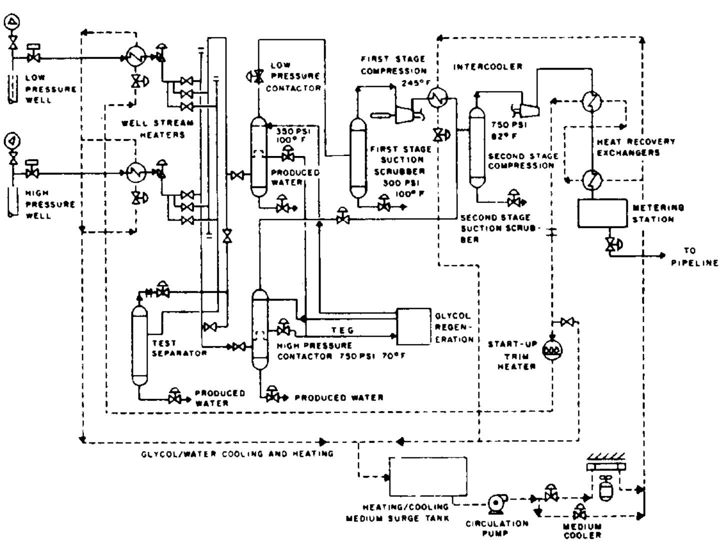

Figure 10 - Process flow, Sheep Mountain CO_2 facilities - drill sites No. 1, 2, and 3

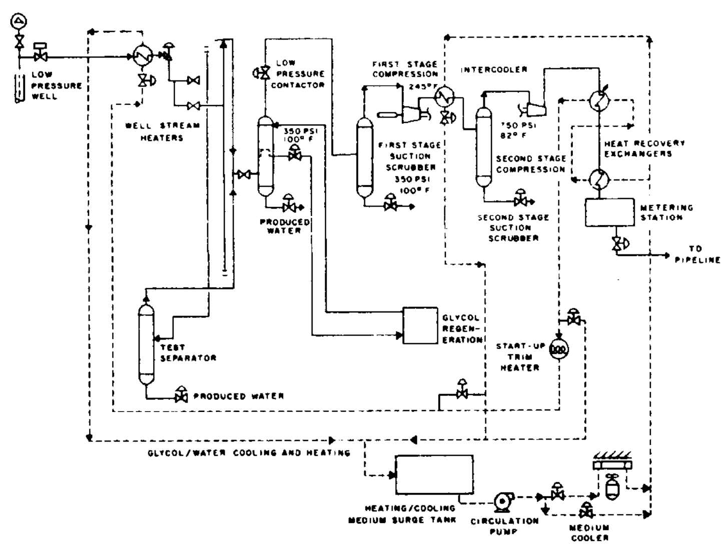

Figure 11 - Process flow, Sheep Mountain CO_2 facilities - drill sites No. 4 and 5