A REVIEW OF OPERATIONS AT THE TWOFREDS FIELD CO_2 INJECTION PROJECT

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ABSTRACT

The emphasis of this paper is on what has been accomplished and how it has been accomplished. It is a matter of public record that from the time carbon dioxide was first injected at the tail end of a waterflood operation eleven years ago until now the production from Twofreds Field has increased from less than 180 bopd, to over 920 bopd, with the associated recovery of over 2.5 MMbbls of tertiary oil.

The story that hasn't been told is exactly how this has been accomplished; what equipment is involved in the handling, processing, transportation, injection, and gathering of CO_2 and the problems encountered throughout the system in dealing with this corrosive and compressible material.

With introductory remarks as to the general nature of carbon dioxide, its unusual properties and how they relate to oilfield equipment and handling, this paper addresses equipment design, operation and maintenance from the source through the processing plant, through compressors and down the line, through injection facilities into the reservoir and finally to the recycling stage.

INTRODUCTION

Twofreds (Delaware) Field is located at the intersection of Loving, Ward, and Reeves Counties, Texas (Figure No. 1). The field was discovered in 1957 and produces from an upper member of the Bell Canyon formation, Permian in age, better known as the Delaware Sand. Basic reservoir data is shown in Figure No. 2.

The Twofreds Field was nearing depletion under waterflood operations when RGS (Transpetco Inc.) of Shreveport approached Houston Pipe Line Company of Houston with an idea. A schematic of this idea is illustrated in Figure No. 3, a system sketch of the project which ultimately evolved. Upon recognizing the significance and importance of RGS's proposal, Houston Pipe Line approved the project and turned it over to a sister subsidiary, HNG Fossil Fuels Company, to operate. RGS invited Murphy Oil USA to join in their half of the program and Arco, one of the original owners of the field, elected to participate as the newly formed group bought up the working interest. Thus the participants in the venture became HNG Fossil Fuels Company (49.3%), Murphy Oil USA, Inc. (37.0%), RGS (12.3%) and Arco Oil & Gas (1.4%).

Basically the project involves 1) taking CO_2-rich natural gas from the Ellenburger formation, 2) processing this gas at Intratex Gas Company's Mi Vida Plant, 3) compressing the stripped-off CO_2 for transmission at Twofreds, 4) injecting the CO_2 into the reservoir, and 5) recovering oil and gathering the CO_2-rich produced gas for recycle through the plant. While not part of the original plan, a significant expansion of the project in 1980 involved the installation of an exhaust gas plant to generate "push" gas which would follow the CO_2 in certain portions of the reservoir.

The implementation of this basic idea has proven to be successful. Since beginning the project in 1974, field production has been re-established and oil that would otherwise have been left in the ground has been recovered. As shown in Figure No. 4, oil production in 1984 averaged 922 bopd where the previous year claimed only 883 bopd and the year before that only 848 bopd.

That is what has been accomplished. How it has been accomplished is the subject of this paper. What is the general nature of carbon dioxide, what equipment is involved in its handling, processing, transportation, injection and gathering? What special precautions must be taken when designing, operating and maintaining the equipment necessary for such a project? And what problems have been encountered? These are the questions that will be addressed as we work our way through the system sketched in Figure No. 3.

DISCUSSION

Origin of Carbon Dioxide

The carbon dioxide used at Twofreds Field comes from natural gas wells producing primarily from the Ellenburger formation. There have been numerous theories put forth to explain the occurrence of CO_2 in underground formations. In the Proceedings of the 31st Annual Meeting of the SPSC, Arco[1], in discussing field operations at their Sheep Mountain CO_2 Unit, leaned toward the igneous emanation theory which is based on the fact that carbon dioxide is a common accessory of igneous activity. Carbon itself does occur in igneous and metamorphic rocks in both elemental form (graphite and diamond) and in the form of carbonate (apatite and scapolite). And various gaseous forms of carbon (CO_2, CO and CH_4) can be obtained by heating igneous or metamorphic rocks. The relative amounts of each form are determined by the following equilibrium reactions:

$$H_2 + CO_2 \rightleftarrows CO + H_2O$$
$$CO + 3H_2 \rightleftarrows CH_4 + H_2O$$

The position of equilibrium depends on the oxidation state of the magma; CO_2 would be the predominant gas in oxidizing environments (high H_2O) and CH_4 would predominate in reducing enviornments (high H_2). The actual emanation of CO_2 from igneous rocks results from substitution in various solid-solution series of minerals, for example between end members of the apatite group; carbonate-apatite and hydroxylapatite:

$$Ca_{10}(PO_4)(CO_3)H_2O \rightleftarrows 2Ca_5(PO_4)_3(OH) + CO_2$$

Some metamorphic rocks can also yield CO_2 when heated in the presence of silicious fluids, as in the scapolite-plagioclase reaction:

$$Ca_4\,[Al_2Si_2O_8]_3(CO_3) + SiO_2 \rightleftarrows 3CaAl_2Si_2O_8 + CaSiO_3 + CO_2$$

While this is certainly a working theory, the actual volumes of CO_2 produced from igneous rocks are typically small amounts and could not account for the massive volumes of CO_2 found in the Ellenburger.

Another theory, one invoked by Shell[2] to explain the origin of CO_2 at their McElmo Dome Unit, is contact metamorphism. This is a well documented phenomenon. The general equilibrium equations that result in CO_2 gas involve the production of forsterite from dolomite, and wollastonite from calcite:

$$2CaMg(CO_3)_2 + SiO_2 \leftrightarrows Mg_2SiO_4 + 2CaCO_3 + 2CO_2$$
$$CaCO_3 + SiO_3 \leftrightarrows CaSiO_3 + CO_2$$

The forward reactions are endothermic and would thus be favored by high temperatures.

While promoting yet another theory, that of CO_2 charged meteoric waters infiltrating the exposed Ellenburger formation during Pennsylvanian time, Holmquest[3] presented data which also supports the theory of contact metamorphism originating along the contact of the Ellenburger with the igneous and metamorphic rocks of the Diablo platform, Marathon uplift, and Ouachita folded belt areas. Specifically, he maps the increasing percentage of CO_2 in the Ellenburger as these features are approached.

This mechanism, which yields massive volumes of CO_2, appears to be the best of the many working hypotheses for the Ellenburger. In his excellent article on the genesis of subsurface CO_2, Farmer[4] also concurs that most CO_2 found in appreciable large accumulations originated via contact metamorphism.

Now that we've accounted for the presence of CO_2 in our Twofreds system diagram, and before taking it through the plant, it would be helpful to review briefly some of the characteristics of this unusual gas.

Physical and Thermodynamic Properties of Carbon Dioxide

At atmospheric conditions, CO_2 is a colorless, non-toxic gas with a slight biting odor. It weighs about 1.5 as much as air. Figure No. 5 tabulates the important physical properties. If CO_2 gas at atmospheric conditions is isothermally compressed, it will become a saturated vapor at about 750 psia with a density of around 9.9 lb/cubic ft. Continued isothermal compression will increase the density to approximately 54 lb/cu ft at which point the CO_2 will be a saturated liquid. Had we taken our atmospheric CO_2 and isobarically cooled it, it would have become solid at about -110°F.

The critical temperature for CO_2 is 87.8°F. The gas cannot be liquified above this temperature no matter how much it is compressed. Thus 87.8°F is the highest temperature at which liquid CO_2 can exist. The critical pressure of CO_2, or that pressure at which CO_2 will begin to liquify at 87.8°F, is 1069.4 psia.

The lower limit of temperature at which CO_2 can exist as a liquid is -69.9°F. The triple point is at this temperature and a pressure of 75.1 psia. At these conditions CO_2 may coexist as either solid, liquid, or gas.

CO_2 is a very compressible gas. As shown in Figure No. 6, deviation from ideal behavior can reach as low as a 0.27 z-factor at 100°F and 1500 psi.

There are practical ramifications to the recognition of these interesting properties. We'll refer back to them later. It is important to the design of processing, compressing and transporting facilities to insure that no unwanted phase changes occur in pipelines or vessels.

Armed now with an understanding of the nature of CO_2, let's enter the gas processing plant along with the CO_2 and observe its behavior.

Processing of Carbon Dioxide

Ellenburger gas in the Mi Vida area generally contains about 50 mole % CO_2 with 1/2% H_2S and 1/2% N_2. The first step in the processing of this gas is to remove the H_2S. At the Mi Vida plant this is accomplished by the use of molecular sieves.

Upon entering the mole sieve unit at 813 psia and 120°F (Figure No. 7), the gas first passes through a knock-out vessel and a couple of heat exchangers before reaching the sieves. After being stripped of its H_2S content, the gas leaves the unit through a filter separator at 773 psia and 89°F into the Flour solvent unit (Figure No. 8).

Cooling off through three more exchangers, the gas enters the contactor at 764 psia and 45°F. The absorbant used at Mi Vida is propylene carbonate, a selective solvent with excellent solubility characteristics to CO_2. After flashing through three stages of vaporization, passing through several more exchanger systems and an expansion turbine, the CO_2 stream, now 96% pure, leaves the unit at about 19 psia and 64°F. Impurities include a small percent of the original N_2 fraction and minor amounts of methane and heavier hydrocarbons.

This gas stream is then intercepted on its way to the vent stack and routed to the Twofreds compressor station.

Compression of Carbon Dioxide

The Twofreds compressor station is located directly behind the Mi Vida gas processing plant and takes CO_2 at the vent stack. The station consists of seven Ingersoll-Rand reciprocating compressors, five of which are driven by 1000 hp turbo-charged Waukesha L7042G's and serve a primary compression role, and two of which are driven by 750 hp naturally-aspirated Waukesha L7042G's and serve as booster compression.

This 6500 hp station can move 15 MMcfd of CO_2 from 2.5 psig to 1800 psig. Primary compression is paralleled 3-stage 4-throw and the boost is 1-stage 2-throw.

Normal lubricants are used throughout the system. The compressor externals (pistons, packing glands, cross-slides, etc.) use Exxon TK460. Exxon GLX is used for both the driver and compressor crankcases, rods, sleeves, and other internals. The only special requirement for handling CO_2 in the compressor has been the replacement of O-rings in the valves with aluminum disks. The station is equipped with automatic shut-downs for high and low suction pressure, high discharge temperature, low oil pressure, vibration, and high oil and water temperatures. The gas entering the station is dry (actually measured at zero lb/MMcf water content) and an inlet scrubber with a paper-type filter insures against passage of particulate matter. The only liquid carry-over from the plant has been minor amounts of propylene carbonate, and these are irregular occurrences. The discharge scrubber has a cotton sock filter which absorbs just a minor amount of lubricator oil.

Every compressor station experiences start-up problems. Valve failures, misalignment, problems with sand, welding slag, etc. is just part of normal debugging. HNG was spared these headaches by virtue of our lease-purchase agreement with Ingersoll-Rand. Station start-up was in February of 1974 and IR managed the facility until January of 1977, at which time HNG personnel took over operations.

The biggest problem ever to occur at the compressor station was in March of 1975. The system had been operational for a year. Mi Vida Plant experienced an emergency shut down. Pure methane gas (at about 2-1/2 psi) began moving toward the vent stack, preventing the activation of the low-suction automatic shut down. As pressure decreased, the butterfly valve in the vent stack failed, allowing air to be sucked back through the stack into the system along with the methane. This explosive mixture made it through the primaries, but upon reaching sufficient temperature in coolers, ripped off the butt plates, and backed into the cylinders. Over $500,000 damage was incurred.

Since taking over operations in January of 1977, the biggest problem we've had has been related to timing chains on an eccentric gear. On one occasion the result was a bent cam shaft which necessitated center-line boring.

A typical operations report (Figure No. 9) would show the CO_2 moving through the four stages of compression from 60°F and 17.8 psia to 120°F and 1,424 psia. Interstage cooling accounts for the moderated temperatures.

As shown on the Pressure-Enthalpy Diagram (Figure No. 10), each Mcf of CO_2 would be reduced to 6.28 cubic feet and its density would increase from 0.145 lb/cu ft to 22.7 lb/cu ft. The CO_2 has moved from the superheated-vapor region into a supercritical state. The highly compressible nature of CO_2 as compared to an ideal gas or nitrogen begins to show up at these elevated pressures. This is illustrated in Figure No. 11.

Transmission of Carbon Dioxide

The compressed CO_2 travels approximately 8 miles from the compressor station to the Twofreds distribution system. The pipe itself is 8.625" O.D. API 5-2 Grade "B" seamless. Wall thickness is 1/2", coated with Koppers hi-melt enamel type TGF-4 coating. The line was taped before being strung out and laid in an 18" ditch. Maximum allowable working pressure is 2160 psig in the 3050 psig test line. Flanges, valves and fittings are 900# ANSI. Scrubbers and filters are located on both ends.

The line is cathodically protected externally and since the CO_2 is dry (virtually zero water content), internal corrosion is not a problem. There are no crack arrestors and the line has been in service since 1974 without failure.

The Mi Vida-Twofreds transmission was designed to be supercritical (>1200 psi) rather than low pressure (<700 psi) or liquid. This is mainly to take advantage of the benefits of single phase flow, avoid the needless cost of refrigeration and insulation, and achieve a lower energy loss per mile.

Actual pressure loss in the transmission varies from 20-40 psi depending on rate, and the temperature drops 20-30 degrees depending on ambient conditions. Having reached the field, the CO_2 is delivered to the injectors through the field distribution system.

Injection of Carbon Dioxide

Once received, the CO_2 is distributed and injected through 24 wells (there are also 12 exhaust gas injectors). The gas is still dry so there are no corrosion problems, and teflon gaskets and taping are used instead of rubber or hydrocarbon based doping.

Each injector is equipped with EDI pressure and rate controllers which allow operational control to conform to requirements determined by the reservoir engineering studies.

Daily rates, temperatures, and pressures are recorded in the field and transmitted to Houston for review via an IBM PC network. In spite of typically poor voice quality on the microwave telephone lines, the use of Microcom Networking Protocol has delivered error-free transfer of data in both directions.

While it is beyond the scope of this paper to discuss the actual mechanisms and chemistry at work in the reservoir undergoing CO_2 flooding, it should be pointed out here the purpose of using exhaust gas as a "pusher". Attempts were made to follow CO_2 injection with water. These efforts turned out to be unsuccessful in that on a a reservoir basis, injection volumes couldn't keep up with withdrawals. After a survey of other possible pusher-type injectants, exhaust gas, which is mostly nitrogen, was chosen as the most economical alternative. Because of its low viscosity and resulting high mobility, it must be alternated with water to minimize viscous fingering in the reservoir. With the mobility ratio problem under control, it can be shown (recall from the discussion of thermodynamic properties that CO_2 is highly compressible) that one favorable attribute of exhaust gas is that it occupies a much greater volume than CO_2 at reservoir conditions. Just as an example, at original reservoir conditions of 2385 psi and 104^{o}F, it would take 2,389 cubic feet of pure CO_2 to occupy one reservoir barrel as opposed to only requiring 723 cubic feet of pure N_2.

Production

There are 45 producing wells at Twofreds Field. They all produce varying amounts of CO_2 but the CO_2 is invariably wet. Corrosion is a potentially big problem which requires a comprehensive program.

Our current corrosion prevention program utilizes Brakesol's C-76, an oil soluble blend of a dimertrimer acid and imidazoline developed for severe CO_2 environments. Pumping wells are treated on a weekly basis and flowing wells on a bi-monthly basis.

The pumping wells are truck-treated with 3 gallons of C-76 and 2 gallons of a phosponic acid scale inhibitor GS-1200 and flushed with 2 to 10 barrels of oxygen-free fresh water, depending on the well to get chemical to bottom.

The flowing wells are treated every 60 days for corrosion and paraffin inhibition. This is done with a hot oiler using the following procedure:

1) pump 4 bbl hot diesel
2) pump 110 gal Brake Sol paraffin chemical P-99
3) pump 5 bbl pad of produced crude
4) pump 27 1/2 gal corrosion inhibitor C-76
5 displace the C-76 to bottom with hot produced crude
6) shut in 4 hr then return to production

The wells are monitored by the use of iron counts and double coupons, one on the flowline and one on casing - each isolated from the other. Coupons are changed every 60 days and iron counts are taken every 30 days to insure that corrosion is kept at a minimum.

This particular program has been in effect since June of 1980, and has proven to be very effective. There have been no corrosion-related failures since January of 1981.

In addition to our basic corrosion prevention program, each well is hot watered each month. There are two purposes for this treatment. Firstly, the Delaware formation water is high in chlorides and solids. By pumping hot fresh water down the casing and up the tubing, the system is kept free of salt rings and bridges. The second purpose is to remove paraffin from casing, tubing and flow lines allowing better filming for the corrosion inhibitors. Five gallons of C-71 corrosion inhibitor are mixed with each 75 barrels of fresh water. This gives added protection to the downhhole casing, tubing, and rods. This program was initiated in 1978 and has also proven to be effective.

Emulsion breakers are being injected into each of the five satellite batteries on the Twofreds lease. We are currently using Nalco Chemical Ul-Sep 4492 emulsion breaker. This chemical is injected into the test separators to insure accurate oil and water readings on the daily tests, and is also injected downstream of the fluid transfer pumps. This downstream injection takes advantage of the pump agitation to help dissipate the chemical throughout the entire fluid stream.

At the central battery the fluid passes through a free water knock-out which dumps the stripped water into disposal tanks. The oil flows from the knock-out into the chem-electric. Here, Nalco 914, a paraffin control chemical, is injected. This prevents bottom buildup and keeps the LACT unit probe from developing a film which might incorrectly indicate a high BS&W content in the oil. The oil is sold at 1/10% BS&W content.

All produced gas is gathered to the field compressor and routed back to the Mi Vida Plant, ending our cycle.

CONCLUSION

Twofreds Field was on the tail end of a waterflood operation when a few forward-thinking companies implemented an idea which was, basically, to utilize existing and available resources and equipment, couple it with understanding of the nature of CO_2 and the effects it would have on an oil reservoir, and carry out an oil recovery project which has proved over the years to be extremely successful.

The cycle through which CO_2 passes in this project involves a complex integration of processing, compressor, transmission, and production technologies. Potential problems in each phase of the cycle can be avoided by careful design, monitoring, and operation of the equipment involved.

REFERENCES

1. Huff, R, and Tracey, T: "Update on Operations of the Sheep Mountain CO_2 Unit," Paper presented at SPSC 31st Annual Meeting, April, 1984.

2. Shell Oil Company, Mid Continent Division: "New Fizz for an Old Field," Informational Brochure, 1982.

3. Holmquest, H.J.: "Deep Pays in Delaware and Val Verde Basins," in Fluids in Subsurface Environments, AAPG Memoir 4, p. 257-279, 1965.

4. Farmer, R.E. : "Genesis of Subsurface Carbon Dioxide," in Fluids in Subsurface Environments, AAPG Memoir 4, p. 378-385, 1965.

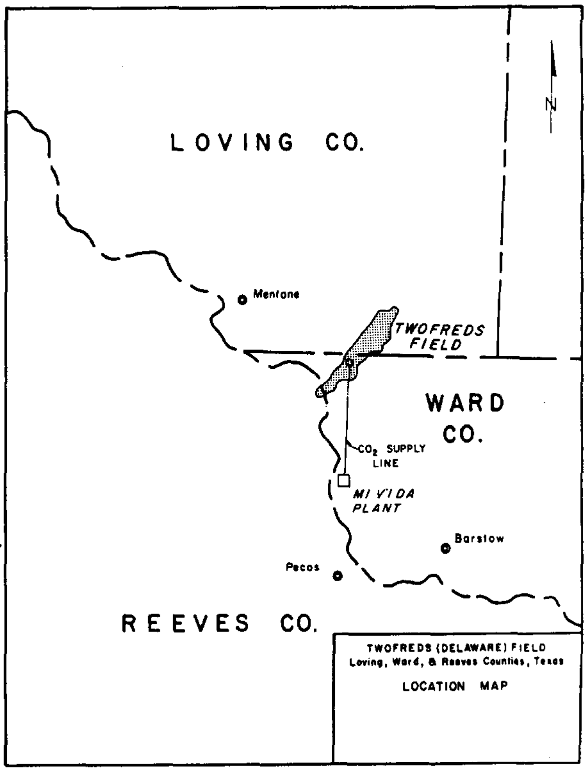

Figure 1 - Twofreds (Delaware) field

OOIP WITHIN UNIT AREA, MMBBLS	51.1
AVERAGE DEPTH, FT.	4820
NET PAY, FT.	18
AVERAGE POROSITY, %	20.3
AVERAGE PERMEABILITY, MD	33.1
RESERVOIR TEMPERATURE, ^{O}F	104
AVERAGE WATER SATURATION, %	43
ORIGINAL RESERVOIR PRESSURE, PSI	2385
ORIGINAL GOR, CF/B	441
FORMATION VOLUME FACTOR	1.179
OIL VISCOSITY & RESERVOIR TEMP., CP	1.467

Figure 2 - Basic reservoir data

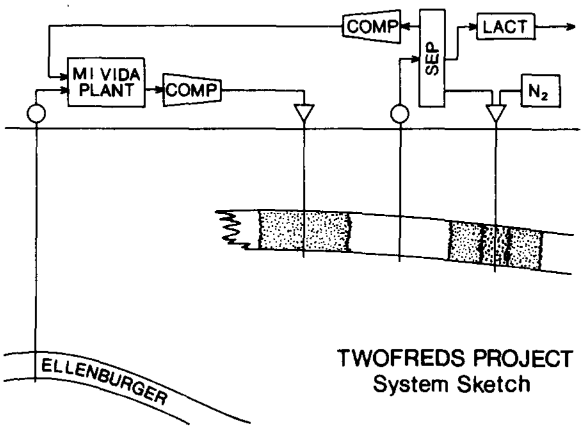

Figure 3 - System sketch

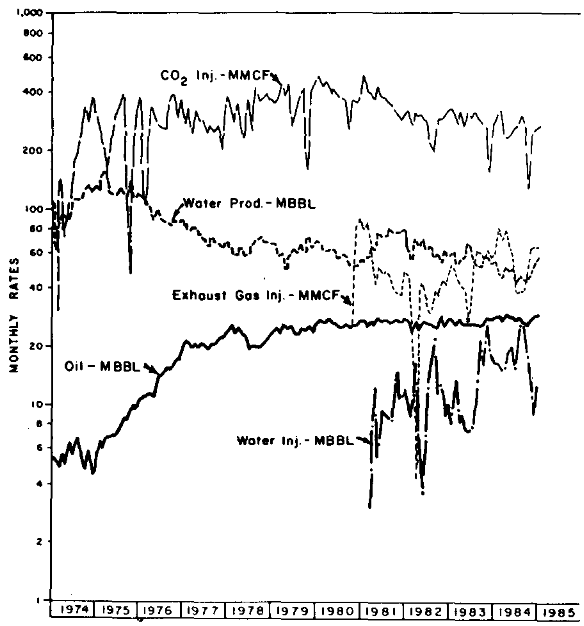

Figure 4 - Total field production history

PHYSICAL PROPERTIES OF CARBON DIOXIDE

PROPERTY	VALUE
Formula	CO_2
Molecular Weight	44.01
Appearance	Colorless, Odorless Gas Colorless Liquid, or White Opaque Solid (Dry Ice)
Density Solid (Dry Ice)	97.5189 lb./ft^3 @ -109.3^{o}F
Density Liquid	63.69 lb./ft^3 @ 0^{o}F
Density Gas	0.1234 lb./ft^3 @ 32^{o}F
Melting Point	-69.9^{o}F, 75.1 PSIA
Boiling Point	-109.3^{o}F, (Sublimes)
Triple Point	-69.9^{o}F, 75.1 PSIA
Critical Temperature	87.8^o
Critical Pressure	1069.4 PSIA
Critical Density	28.9519 lb./ft^3
Specific Heat Gas	0.1989 BTU/lb^{o}F (60^{o}F)
Specific Heat Liquid	0.53 BTU/lb^{o}F (60^{o}F)
Ratio of Heat Capacities	1.3
Latent Heat of Fusion (Triple Point)	85 BTU/lb (69.9^{o}F)
Latent Heat of Vaporization (Liquiflow)	122 BTU/lb (0^{o}F)
Latent Heat of Sublimation (Dry Ice)	246 BTU/lb (110^{o}F)
Viscosity Gas	0.015 Centipoises (32^{o}F)
Viscosity Liquid	0.14 Centipoises (0^{o}F)
Thermal Conductivity Gas	0.0085 BTU ft/ft^2^{o}F. Hr. (32^{o}F)
Thermal Conductivity Liquid	0.11 BTU ft/ft^2^{o}F. Hr. (0^{o}F)
Surface Tension (Liquid)	8.23 Dynes/cm (0^{o}F)
Solubility in H_2O	1.79 ft^3 CO_2 Gas/ft^3 H_2O (32^{o}F)

Figure 5

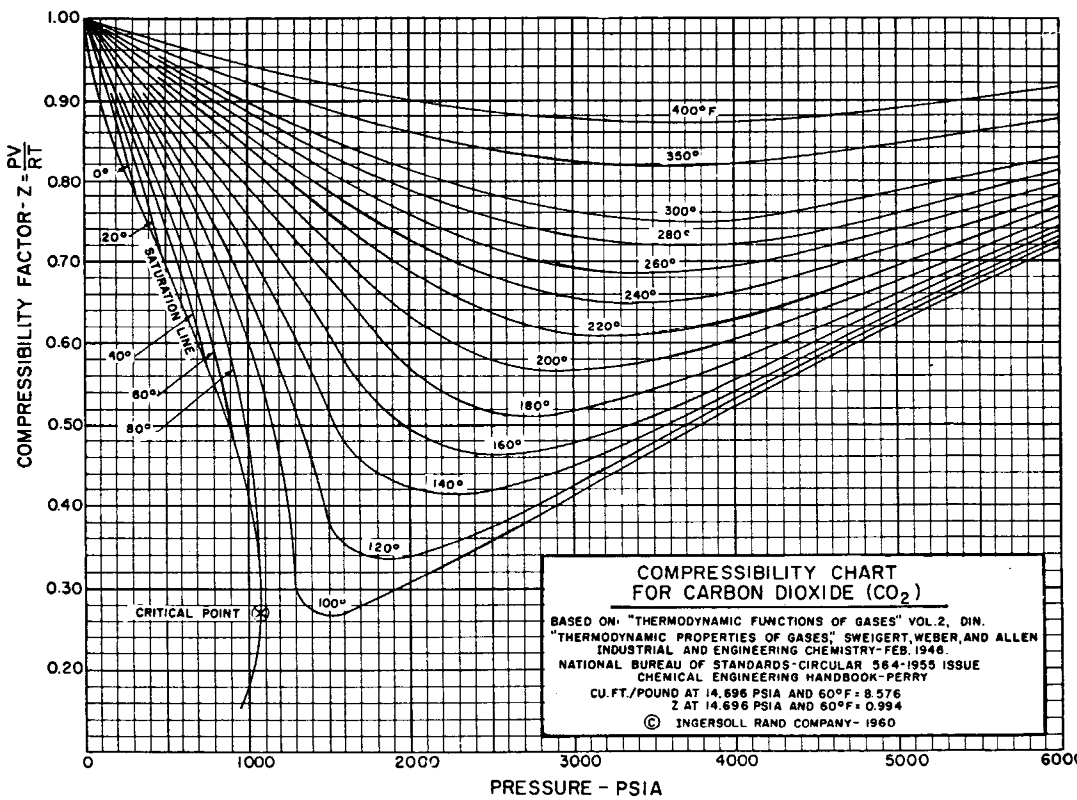

Figure 6

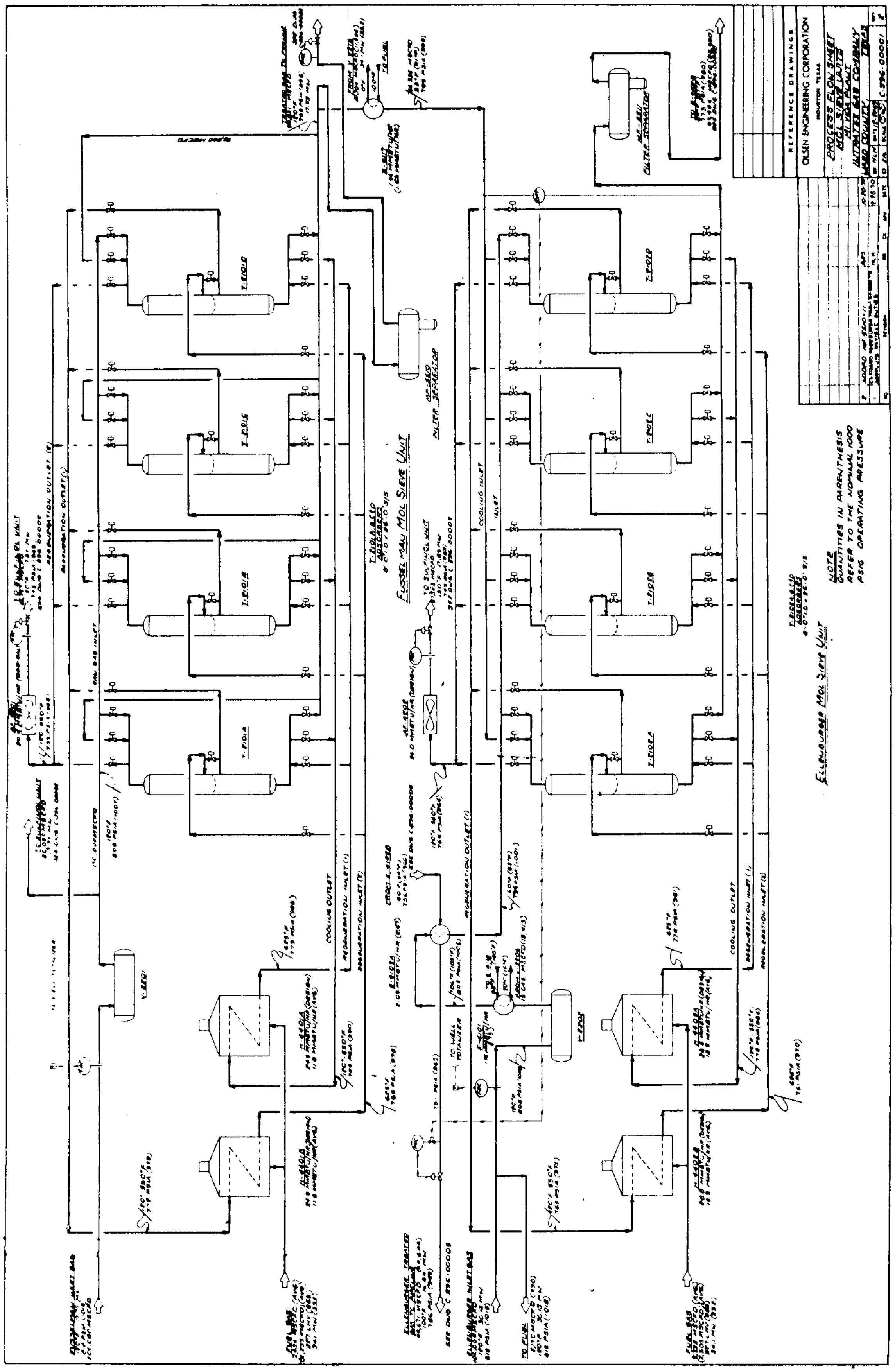
Fussel Man Mol Sieve Unit
Ellenburger Mol Sieve Unit
Olsen Engineering Corporation
Houston Texas
Process Flow Sheet
Note
Quantities in parenthesis refer to the nominal 1000 psig operating pressure

Figure 7

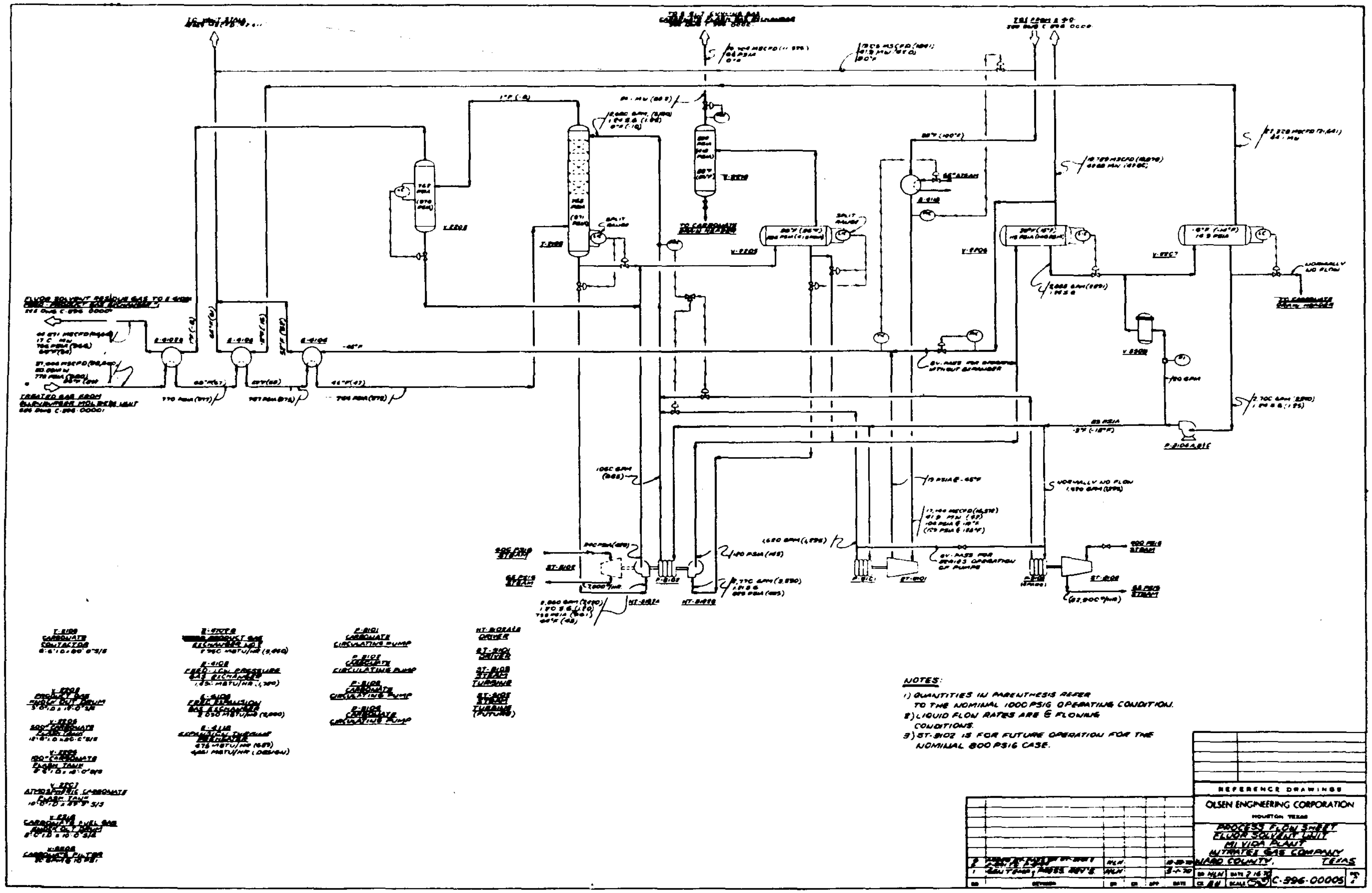
NOTES:
1) QUANTITIES IN PARENTHESIS REFER TO THE NOMINAL 1000 PSIG OPERATING CONDITION.
2) LIQUID FLOW RATES ARE @ FLOWING CONDITIONS.
3) ST-8102 IS FOR FUTURE OPERATION FOR THE NOMINAL 800 PSIG CASE.
REFERENCE DRAWINGS
OLSEN ENGINEERING CORPORATION
PROCESS FLOW SHEET
FLUOR SOLVENT UNIT
MI VIDA PLANT
WARD COUNTY, TEXAS
C-596-00005

Figure 8

COMPRESSOR OPERATIONS REPORT

	SUCTION °F	SUCTION PSIA	DISCHARGE °F	DISCHARGE PSIA
1st Stage	60	17.8	289	55.7
2nd Stage	76	51.5	266	239
3rd Stage	80	221	240	665
Booster	85	615	230	1,540
To Pipeline			120	1,424

Figure 9

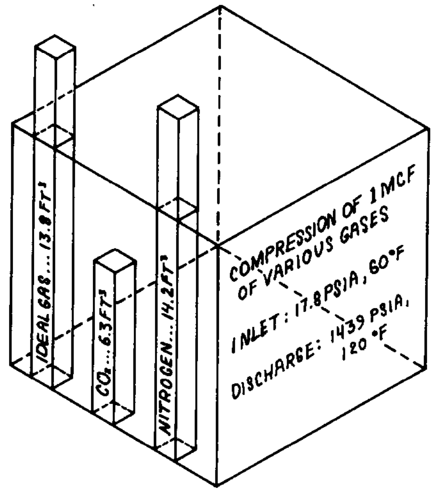

Figure 11

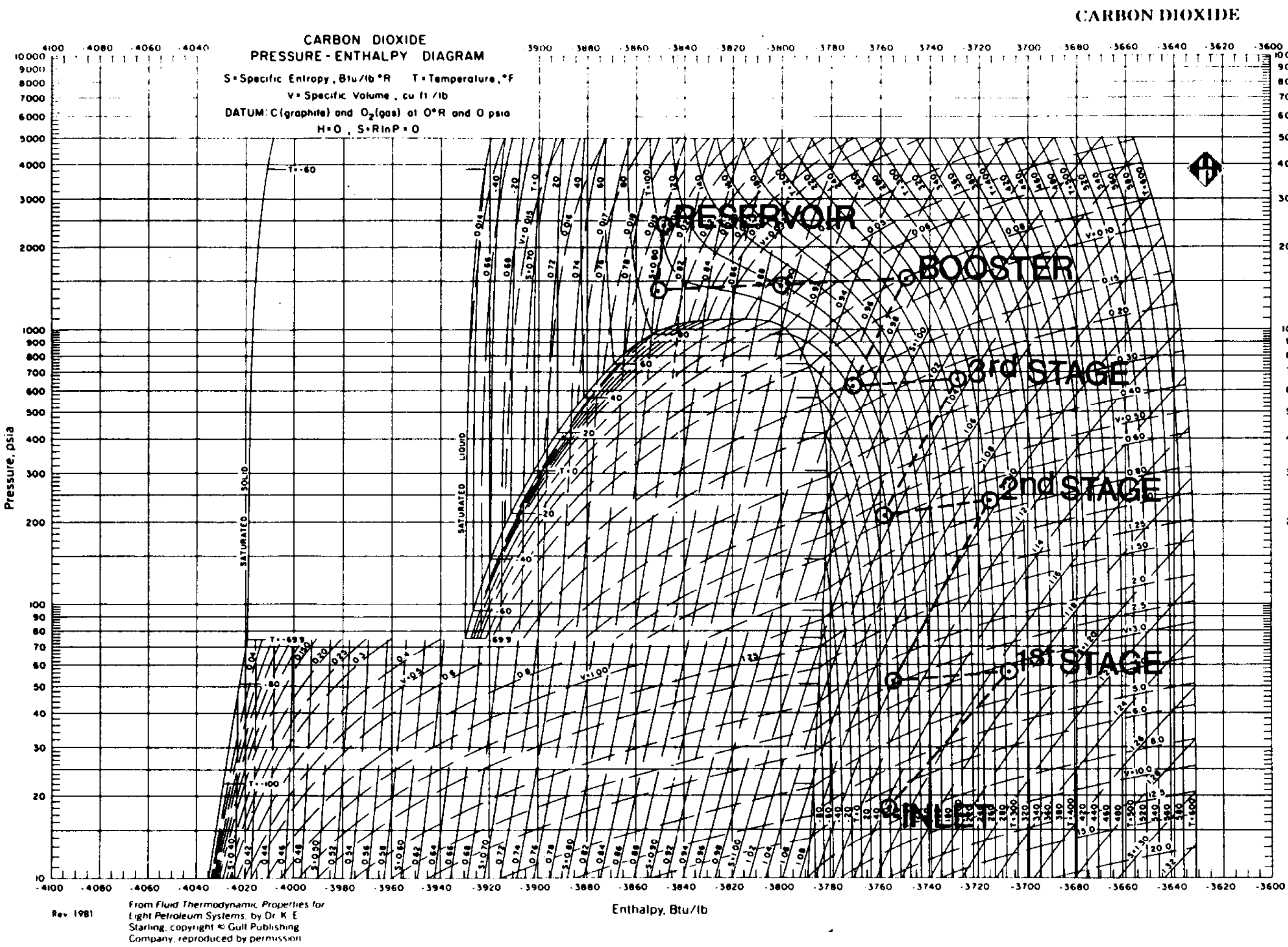

Figure 10