PHYSICAL AND CHEMICAL PERFORMANCES OF FIBERGLASS TUBULARS IN SUPER CRITICAL APPLICATION OF CO_2

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I. Abstract

Long term chemical and physical performance of aliphatic amine cured fiberglass Tubulars in high pressure super critical application of CO_2 in both cyclic and static conditions have been investigated. No physical or chemical degradation was detected at the selected test condition of 2300 PSI and 120°F of carbon dioxide in cyclic or static conditions. Further analysis suggests a slow rate of CO_2 penetration into the amine cured epoxy laminate. The failure mechanism model developed and presented here suggest a predictable failure based on stress due to pressure and temperature. The verification of the model presented paves the way for major simplification and cost reduction potentials in future construction and extension of a CO_2 WAG Piping Systems.

II. Introduction

Carbon Dioxide (CO_2) injection is being used commercially to produce oil that normally would be unrecoverable. CO_2 is injected in the super critical state at a surface pressure of about 1500 to 2500 PSI. "CO_2 is an efficient injectant because it dissolves readily in both oil and water, with CO_2 solubility increasing with increasing pressure. The dissolution of CO_2 in oil increases or swells the crude volume and decreases the crude viscosity, which results in a more mobile oil bank and improved sweep efficiency.", (Reference 1).

Generally, in order to prevent channeling and maximize flood profitability, implementation of water alternating gas (WAG) injection becomes necessary. The CO_2 WAG systems increases corrosion concerns drastically due to formation of carbonic acid and the contamination of produced water used for re-injection for metallic tubulars.

With a proper selection of raw materials, outstanding results have been achieved in the past 25 years using fiberglass tubulars in low pressure or low concentration applications of CO_2 to combat corrosion problems. However, a few initial set backs in the early 80's, due to improper raw material selections, connection integrity, misapplication, or pure mishandling of the product, kept the usage of FRP Tubulars to a few selected projects for high pressure CO_2 WAG Systems. The information presented here is intended to provide a reliable and predictable failure mechanism to facilitate selection and operation limitation of FRP Tubulars for a trouble free corrosion controlled high pressure CO_2 WAG Piping System.

III. Performance Requirements

A. Chemical Performance - From a chemical resistance stand point, selection of raw materials, especially the solvent resistance and cross link density of the matrix materials, have a direct impact on the functionality of fiberglass tubulars in super critical applications of CO_2.

The three raw materials employed in manufacturing of fiberglass tubulars are epoxy, glass and a curing agent. The epoxy contributes mainly to the strength, temperature and chemical resistance of the finished products. The glass provides high strength and load carrying capabilities. The curing agent cross links and converts the epoxy to a solid, which in turn protects and encapsulates the glass from chemical attack. It also plays a major role in chemical and heat resistance of the systems. Formation of carbonic acid, which results from reaction of carbon dioxide and water, has been cited as the failure mechanism on some FRP Tubulars. In fact, carbonic acid is a very weak acid, almost 500,000 times weaker than sulfuric acid for a given concentration, and the effect of it on fiberglass tubulars is negligible. CO_2 at super critical stages acts as a solvent, and with increasing pressure the permeation of CO_2 increases drastically (Reference 2).

Therefore, solvent resistance and chemical suitability of FRP Tubulars are of the same concern and needs prime consideration. In Table #1, qualitative summary of FRP laminate performance with selected curing agents are presented.

B. Connection Performance - A novel application of risk based engineering design concepts to the make-up and connection reliability of 8 round tubulars was developed for the American Petroleum Institute (API) in the laboratories of the Center for Frontier Engineering Research (C-FER) (Reference 3)). In this study, the number of specimens were repeatedly made up and subjected to combined axial load, internal gas pressure (nitrogen gas) and thermal loading. The resulting leakage and damage was analyzed using probabalistic techniques to obtain a quantative bases for assessing the risk of leakage and mechanical damage. The finding is summarized as follows:

- The threshold leakage pressure of 8 round FRP connections is a direct function of average thread contact stress.

- The probability of leakage and damage for any make up method at all levels of make up and internal pressure can be assessed using contact stress phenomena (Figure 1 and Figure 2).

- Turn Base Method developed, "Dry Hand Tight; DHT", showed it to be at least twice as accurate compared to the torque based make-up procedure.

- Thread quality and type strongly affects both leakage and damage probabilities.

- The role of thread compound as a major variable in the sealing mechanism (type of carrier, amount and size distribution of the Teflon particle, and type of Teflon particle), make-up torque response and connections resistance to gauling damage has been established.

C. Physical Performance - The few engineering and research attempts to quantify and understand the failure mechanism and life expectancy of FRP Tubulars in a high pressure CO_2 environment has been, at best, inconclusive. Generally, this research concentrated on resin systems alone, and at pressures or temperatures far exceeding the reality of WAG operating conditions. This, in turn, casted even further doubt about wide usage of these products. The goal of this project was to provide a reliable and predictable failure mechanism to facilitate selection and operation limitations of FRP Tubulars in high pressure CO_2 WAG Systems.

IV. Physical Performance Evaluation

A. Test Program - To evaluate the worst case operational parameters, maximum operating pressure (MOP) and maximum operating temperature (MOT), were established in consultation and cooperation of knowledgeable oil company personnel. Testing equipment was designed to subject and monitor samples at the required pressures and temperatures. Table 2 summarizes the test program used to evaluate the effect of super critical application of CO_2 on 2" 2500 PSI aliphatic amine cured epoxy piping systems.

B. Test Methods and Sample Preparation - The program was designed to answer critical questions concerning the operation and reliability of piping system in actual conditions. The testing was as follows:

- Maximum Operating Pressure (MOP) = 2300 PSI.
  Maximum Operating Temperature (MOT) = 120°F.

- Sample #1, 2, 3, 4, 5 and 6 were cycled from salt water to CO_2 5 times a week. The effect of duration and number of cycles (WAG) was evaluated by removing sample #1 from the test loop after one month, sample #2 after 2 months, #3 after 3 months, up to sample #6 after 6 months of cyclic operation. Therefore, sample #1 only saw one month of cycling and sample #6 saw 6 months of cycling (salt water to CO_2).

- Sample #7, 8 and 9 were cycled once a week, once a month and once every 3 months for a total period of 6 full months for a better clarification of cycle and duration of a WAG operation.

- Sample #10 and 11 were tested in Static condition with sample #10 being tested in salt water only and sample #11 in CO_2 only.

- Sample #12 is a control sample. This sample was stored in the test chamber, but was not exposed to any pressure.

C. <u>Test Results</u> - After 6 months of both cyclic and static testing, all 12 samples were removed from the test chambers. A six inch section was cut out of each of the 12 specimens for further physical evaluation and the rest were rethreaded and strain gaged in hoop and axial direction for preparation for destructive evaluations. The results can be summarized as follows:

- All samples were visually inspected, on both the inside and the outside of the pipe body. No visual signs, chemical or physical, of degradation at 2300 PSI and 120°F of CO_2 in cyclic or static condition were detected in any of the 12 samples.

- Visual inspection was repeated, on both the inside and the outside of the pipes after the specimens were immersed in dye penetrant. No visual signs of micro cracking or delamination was detected in any of the 12 samples.

- Each sample was evaluated for degree of cure by DSC, differential scanning colorimetry. The average glass transition temperature was found to be 108.5°C with a minimum value of 101°C and a maximum of 118°C.

- Each sample was evaluated and gaged for wall thickness, OD's, layering sequence and glass percentage and was found to be within the design parameters of the products (Figure 3).

- The proportional elastic limits (PEL) of the products (Figure 11), defined as deviation from linearity in a stress and strain response, was evaluated in hydro testing of each sample. The average values of PEL was at 3824 PSI with a standard deviation of 250 PSI for all 12 samples, including the control samples (Figure 4).

- The ultimate weep pressure of all the samples averaged around 8458 PSI with a standard deviation of 557 PSI (Figure 4). It was noticed that samples 1 through 6 (cycled once a week), showed a lower statistical value for weep pressures (average = 8020 PSI, standard deviation = 244 PSI) (Figure 3) than the sample 7 through 12 (average = 8895 PSI, standard deviation = 244 PSI).

- The variation in stress vs. strain response are minimal among all specimens, including the control sample. This is an indication of unaffected modulus of elasticity and absence of any chemical degradations (Figure 5).

V. Development of a Failure Mechanism Model -

A. Model Objective - Due to the unusual shape and size of CO_2 molecules, an in depth understanding of the CO_2 permeation into a composite structure is necessary. This task was broken into the following:

Is there any permeation by CO_2 at super critical stages into the composite structure?

- If No: No further action was needed.
- If Yes: Does this permeation cause any chemical degradation?
- If Yes: The epoxy systems employed in the structure needs modification.
- If No: Is there any physical degradation?
- If Yes: It suggests that the operating stresses induced by pressure or temperature are above the systems functional limits.
- If No: What is the stress limitation? (Pressure and temperature relationships)

B. Development of the Novel Method to Find The Stress Limitation

1. Test Method and Sample Preparation - Even though satisfactory test results were obtained at this point (no chemical or physical effect in cyclic or static condition in super critical application of CO_2, 2300 PSI, 120°F, in aliphatic amine cured FRP tubulars), the knowledge gained was limited to specific conditions. Further study into the CO_2 properties revealed important facts, which helped to devise the following method. As depicted in Figure 9, it is assumed there is permeation of CO_2 into the laminate structure, and it is collecting in microvoids, which naturally occurs in filament wound laminate. After a period of time the internal pressure of the voids will reach the test pressure. From the carbon dioxide pressure enthalpy diagram (Figure 10), CO_2 at 120°F with a pressure of 2300 PSI has a specific volume of .0215 ft^3/lbs. At this specific volume and

200°F, the internal pressure will reach almost 5000 PSI. With this knowledge, the 6" sample saved from each of the 12 test specimens were cut to 5 series and each series was numbered from 1 to 12. Next, each series was inserted in a preheated oven at specified temperature for 3 hours. Then each series was independently visually inspected and delamination was evaluated by rating from 0 to 10, 0 being no effect and 10 showing maximum effect.

2. Test Results -

120°F Exposure: No visual sign of damage or delaminations detected at 120°F (Figure 6).

150°F Exposure: No visual sign of damage or delaminations detected at 150°F (Figure 6).

175°F Exposure: Sample #6 (6 months daily cycle) shows whitening and delamination. This delamination is contained within the first layer. Sample #5 and #7 show some whitening, but no delamination. Sample #10 (6 month static CO_2) shows 2 or 3 spots of small delamination (⅛" radius) (Figure 6).

200°F Exposure: Samples of up to 3 months of daily cyclic exposure showed no evidence of delamination. Two or three very small delamination spots are evident on Sample #4 and get worse until Sample #6, which shows almost uniform delamination of the first layer. The weekly, monthly and 3 month cycle sample at 200°F all show spotty delamination contained within the first layer. Sample #10 (6 month static CO_2) shows as severe delaminations as Sample #6 (6 month CO_2 daily cyclic) (Figure 6).

250°F Exposure: As it is shown in Figure 6, all the samples, except Sample #1 (one month daily cyclic), Sample #11 (salt water sample) and Sample #12 (the control sample) show some delamination. The effect is similar to the sample exposed at 200°F, but more severe delaminations are present.

The failure mechanism model presented here suggest delamination due to internal stresses generated by CO_2 entrapped in the Microvoids present in the laminate. Delamination increases with the number of CO_2 cycles at or above 175°F. This effect gets progressively worse as the temperature increases (Figure 6 & 7). Delamination of the 1st and 2nd layer also increases with temperature in static CO_2 application. However, the effect is much less pronounced than the cyclic effect until 200°F and matches or surpasses the cyclic effect at 250°F (Figure 7 & 8). The model presented here predicts that CO_2 at temperatures around 165 -175°F, will generate enough internal stresses in the CO_2 filled voids in the laminate to exceed the interlaminar shear stress between the layers. The internal pressure generated at these temperatures are around 3800 to 4000 PSI, which is in close proximity to the pressure at PEL (Proportional Elastic Limits) of the laminates (Figure 12).

C. Verification of the Model - The failure mechanism model was further investigated by pressurizing additional samples of 2" 2500 PSI product in static CO_2 condition at 120°F. Four samples were pressurized from 2300 to 4700 PSI using carbon dioxide giving a specific volume of .0215 ft^3/lbs. After 4½ months of testing, the samples were rapidly de-pressurized. The analysis of the samples, as shown in Figure 13, verifies the previous results showing that only after reaching a differential pressure in the microvoids filled with CO_2 of equal or greater than interlaminar shear stress, delamination will occur.

It is believed that by regulating the de-pressurization of the samples, the CO_2 permeation is reversible and the delamination can be controlled.

VI. Field Performance Evaluation

As a minimum, 46 strings of 2⅞" 2500 PSI down hole tubing were used in a $C0_2$ WAG system in Rangly, Colorado. Figure 14 depicts the injection history of Well Fee 51, plus the results of a Destructive Test performed on 3 separate joints retrieved from this well.

As it can be seen, the weep pressure and the proportional elastic limits of the samples are quite consistent and meet or exceed the published catalog values. A visual inspection evaluation of these samples shows no degradation or delamination on the inside or the outside of the product.

VII. Potential Application

It is believed that the results of this research project can have profound implications in future use and application of composite material in a gas environment. As a minimum, the following can be identified:

- An effective and precise test procedure can be developed using the method suggested here for screening and selecting raw material for permeation evaluation in gaseous application.

- Major simplification and cost reduction potentials exist in future construction and extension of a CO_2 WAG piping systems by combining the water and CO_2 lines. It is believed that the permeation theory presented here is identical for epoxy lined steel. In fact, this presents a major challenge for epoxy lined steel piping systems since the adhesion of epoxy to steel pipes is much less than the adhesion between layers of fiber glass to each other.

- Set limits on operational parameters to insure longevity of non metallic materials and coating.

VIII. Conclusion

A. The penetration rate and the effects of CO_2 on the laminate are a function of cross link density of the resin systems. As the cross link density is larger, the penetration rate is less (Reference 1).

B. Connection design and sealability of the systems at high pressure and temperature/gas applications need prime consideration (Reference 2).

C. No visual sign of degradation due to chemical attack at 2300 PSI and 120°F of CO_2 in cyclic or static condition is detected in the Aliphatic Amine cured tubulars tested.

D. The variation in stress versus strain responses are minimal among the samples tested which indicates unaffected modules of elasticity. This also indicated the absence of any chemical degradation (Figure 5).

E. The failure mechanism model presented here suggests a delamination caused by internal stress generated by CO_2 entrapped in the microvoids present in the laminate. (The verification of the model is also presented.)

F. The model predicts that CO_2 at higher temperatures will generate enough internal stresses in the CO_2 filled Microvoids in the laminate to exceed interlaminate shear stress between the layers (peel strength), therefore causing delamination.

G. The delamination of the 1st layer increases with increased number of CO_2 cycles, at or above 175°F: This effect get progressively worse as the temperature increases (Table 4) beyond 175°F (Figure 6,7 & 8).

H. Delamination of the 1st layer increases with temperature increases in static CO_2 application. The effect is much less pronounced than the cyclic effect until 200°F and matches or surpasses the cyclic effect at 250°F. No visual effect what so ever was detected at 150°F and below (Figure 7 & 8).

I. The model suggests slow CO_2 penetration into aliphatic amine cured epoxy laminates. (After 6 months of cyclic and static tests, maximum penetration is estimated at less than .016".) This suggests that at normal operating conditions there is not a significant effect on the laminate.

J. Three samples of 2⅞" 2500 PSI down hole tubing in actual WAG system at Rangely Colorado in 6500 ft deep wells, operated at maximum pressure 2100 and maximum temperature of 160°F shows no sign of micro crack, or delamination. Also, the ultimate pressure after 6 years of service (3 years of WAG) is above the published values for the new, untested pipe.

K. The evaluation method presented here can be used to develop an effective and precise test procedure for screening and selection of raw material for permeation evaluation in gaseous application.

L. Major simplification and cost reduction potential in future construction and extension of a CO_2 WAG system is achievable by combining CO_2 and water injection line into one system.

IX. Further Research Needs

The clear indication of CO_2 permeation needs further investigation at least in the following area:

A. Development of a master curve relating the effect of temperature and permeation effect on interlaminar shear stress.

B. Development of a deeper understanding of permeation effect caused by CO_2 concentration in a gas mixture (is the CO_2 partial pressure in the gas mixture the main culprit?).

X. **Acknowledgements** - Fiber Glass Systems, Inc. expresses thanks and acknowledges the in-depth technical contributions and encouragements of Oxy USA, Midland Division, Exxon USA, Amoco Corporation, and Chevron U.S.A.. Also, the author wishes to express his thanks to Mr. Louis Rodriguez for his dedication and contribution to this project.

XI. References

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2. G. Hossein Arian, Fiberglass Systems Inc., "Chemical Resistance and Curing Agents in Fiberglass Reinforced Oilfield Tubulars", corrosion 90, paper 429.

3. Dan Shute, Center for Frontier Engineering Research (C-FER), "Development of Make-Up Procedure for Fiberglass Tubing", abridged final report for American Petroleum Institute (API), April 1992.

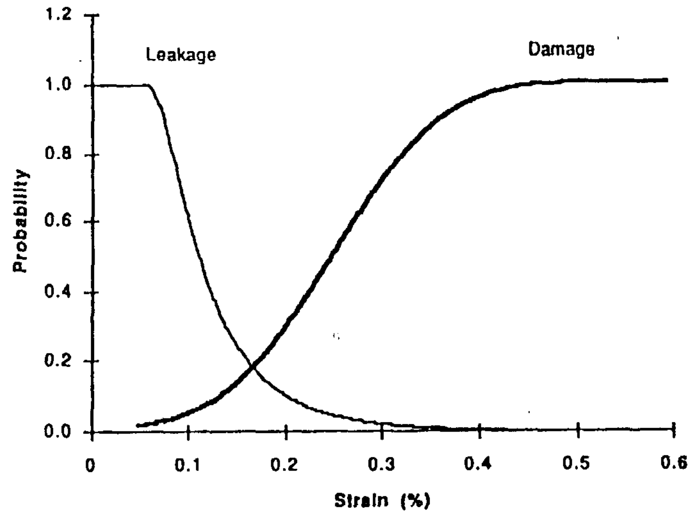
Table 1
Qualitative Summary of FRP Laminate Performance
With Selected Curing Agents

	Curing Agents		
	Aliphatic	**Aromatic**	**Anhydrides**
Glass Transition Temp Degrees Celsius	115 - 125	140 - 160	115 - 145
Maximum Operating Temp Degrees Fahrenheit	200	220	150
Cross Link Density	High	Medium	Low
Adhesion to Glass	Best	Good-Best	Good-Best
Physical Properties	Best	Good-Best	Good-Best
Cure Sensitivity	Low	Medium-High	Medium-High
Chemical Resistance:			
In Base	Best	Best	Good
In Solvent	Best	Good-Best	Fair
In Acid	Fair	Fair-Good	Best

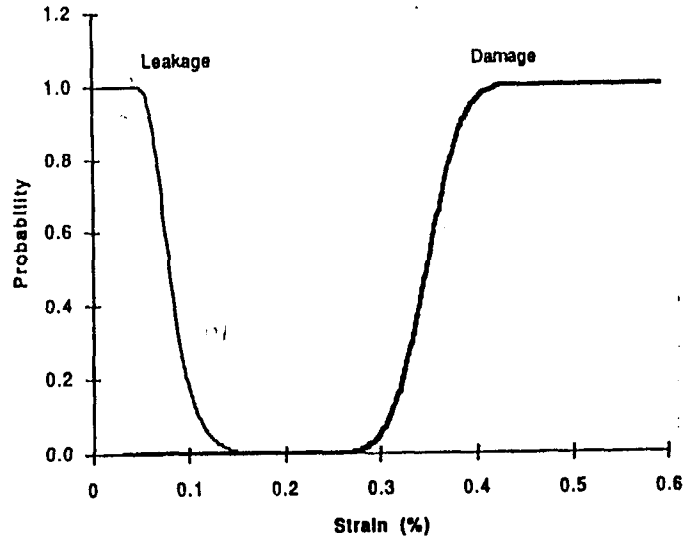
Table 2
Summary of Test Program
2" 2500 PSI Line Pipe

Size	Test Temperature	Test Pressure	Test Condition Steady	Test Condition Cyclic	Test Environment	Test Duration Hours	Number Of Cycle	Comments & Sample #
2"	110-120°F	2300	—	5 Times A Week	* Salt Water/ CO_2	720	20	1 Month #1
2"	110-120°F	2300	—	5 Times A Week	* Salt Water/ CO_2	1440	40	2 Months #2
2"	110-120°F	2300	—	5 Times A Week	* Salt Water/ CO_2	2160	60	3 Months #3
2"	110-120°F	2300	—	5 Times A Week	* Salt Water/ CO_2	2880	80	4 Months #4
2"	110-120°F	2300	—	5 Times A Week	* Salt Water/ CO_2	3600	100	5 Months #5
2"	110-120°F	2300	—	5 Times A Week	* Salt Water/ CO_2	4320	120	6 Months #6
2"	110-120°F	2300	—	Once A Week	* Salt Water/ CO_2	4320	26	6 Months #7
2"	110-120°F	2300	—	Once A Month	* Salt Water/ CO_2	4320	6	6 Months #8
2"	110-120°F	2300	—	Once In 3 Months	* Salt Water/ CO_2	4320	2	6 Months #9
2"	110-120°F	2300	✓	—	CO_2	4320	0	6 Months #10
2"	110-120°F	2300	✓	—	Salt Water	4320	0	6 Months #11
2"	110-120°F	00	✓	—	Salt Water	4320	0	Control Sample #12

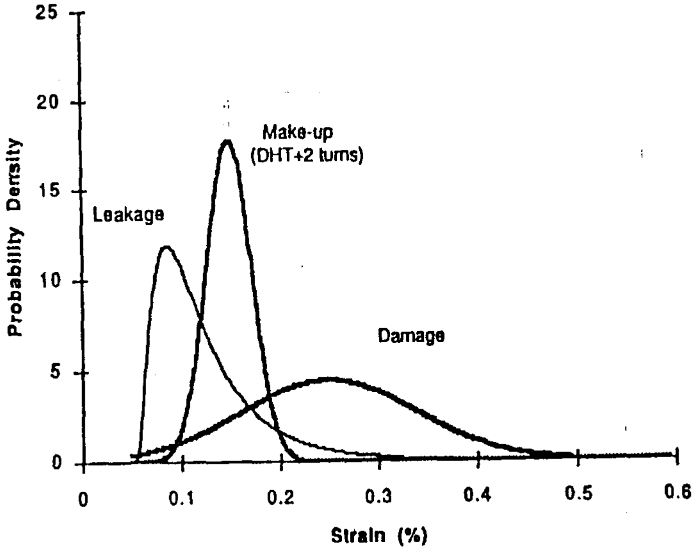
* Cycles from salt water to CO_2 and vise versa.



(a) Set #1 Connection failure behaviour.



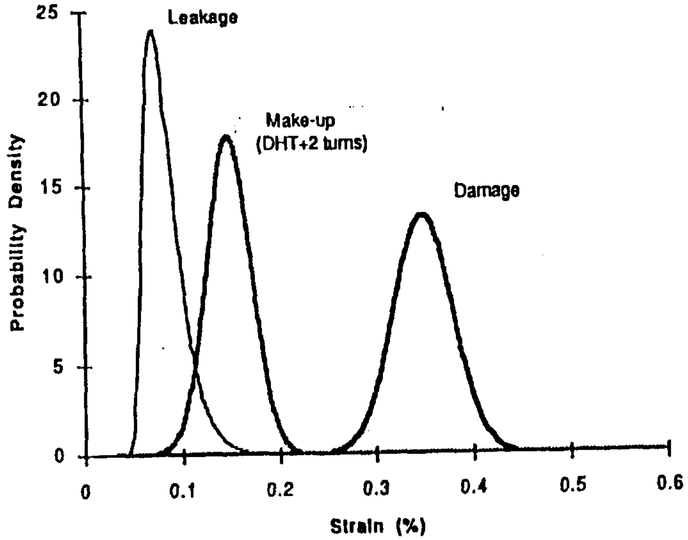
(a) Set #2 Connection failure behaviour.



(b) set #1 Probability density functions

Figure 15 Probabilistic description of Set #1 connection behavior

Figure 1

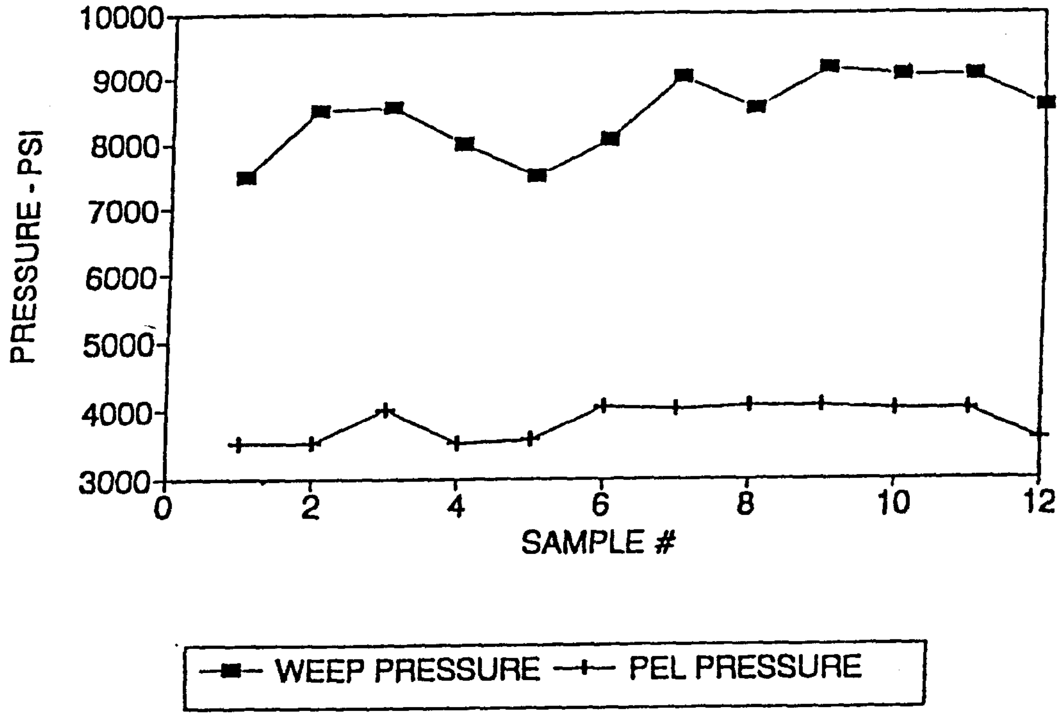


(b) set 32 Probability density functions.

Figure 16 Probabilistic description of Set #2 connection behavior.

Figure 2

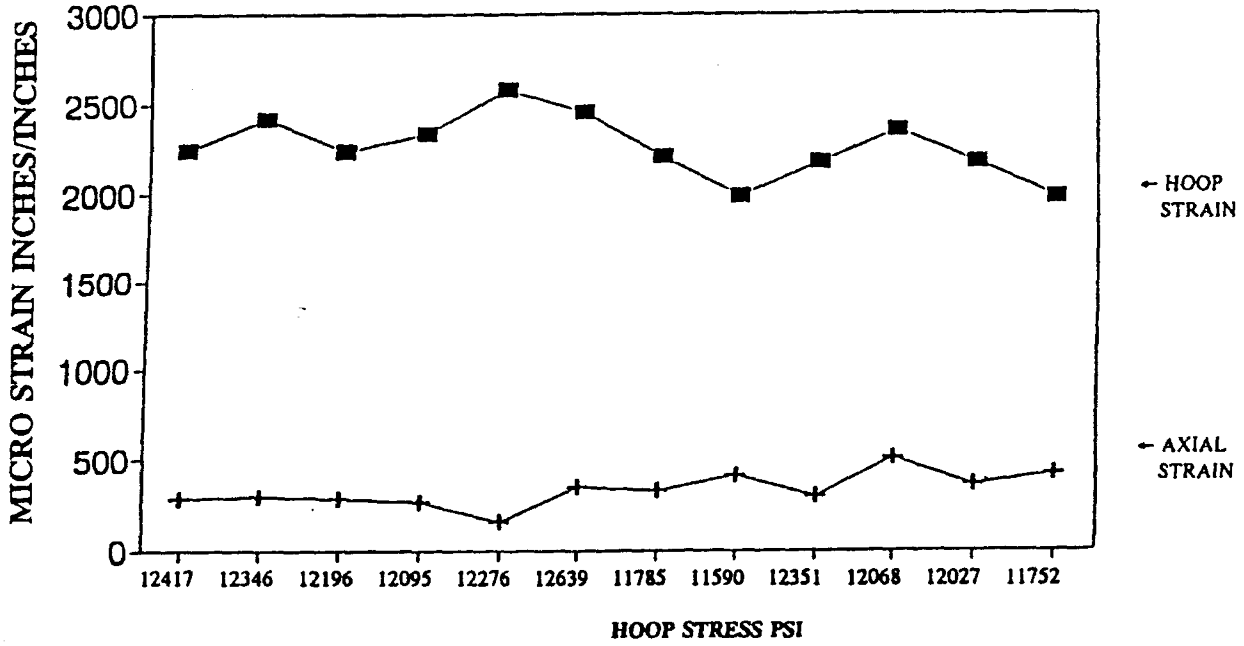
WEEP AND PEL, AFTER 6 MONTHS
TEST COND: 2300 PSI, 120°F, CO_2/H_2O



Sample Number	Test Environment	Mode Steady	Mode Cyclic	Test Time Hour	Number of Cycles	CO^2 Exposure Hour	Density Lb/ Cubic Ft	Glass %	Tg Degree	WEEP PSI	PEL PSI
1	H_2O/CO_2		Y	720	20	360	124	77	111	7500	3508
2	H_2O/CO_2		Y	1440	40	720	125	78	108	8500	3504
3	H_2O/CO_2		Y	2160	60	1080	126	79	118	8565	4014
4	H_2O/CO_2		Y	2880	80	1440	126	79	114	8000	3510
5	H_2O/CO_2		Y	3600	100	1800	124	78	107	7500	3571
6	H_2O/CO_2		Y	4320	120	2160	125	78	103	8060	4045
7	H_2O/CO_2		Y	4320	26	2160	125	78	107	9018	4012
8	H_2O/CO_2		Y	4320	6	2160	125	78	111	8545	4074
9	H_2O/CO_2		Y	4320	2	2160	125	78	101	9153	4069
10	CO_2	Y		4320	1	4320	125	78	106	9034	4008
11	H_2O	Y		4320	1	0	125	78	111	9058	4019
12	Control	Y		4320	1	0	125	78	105	8565	3557

Figure 3

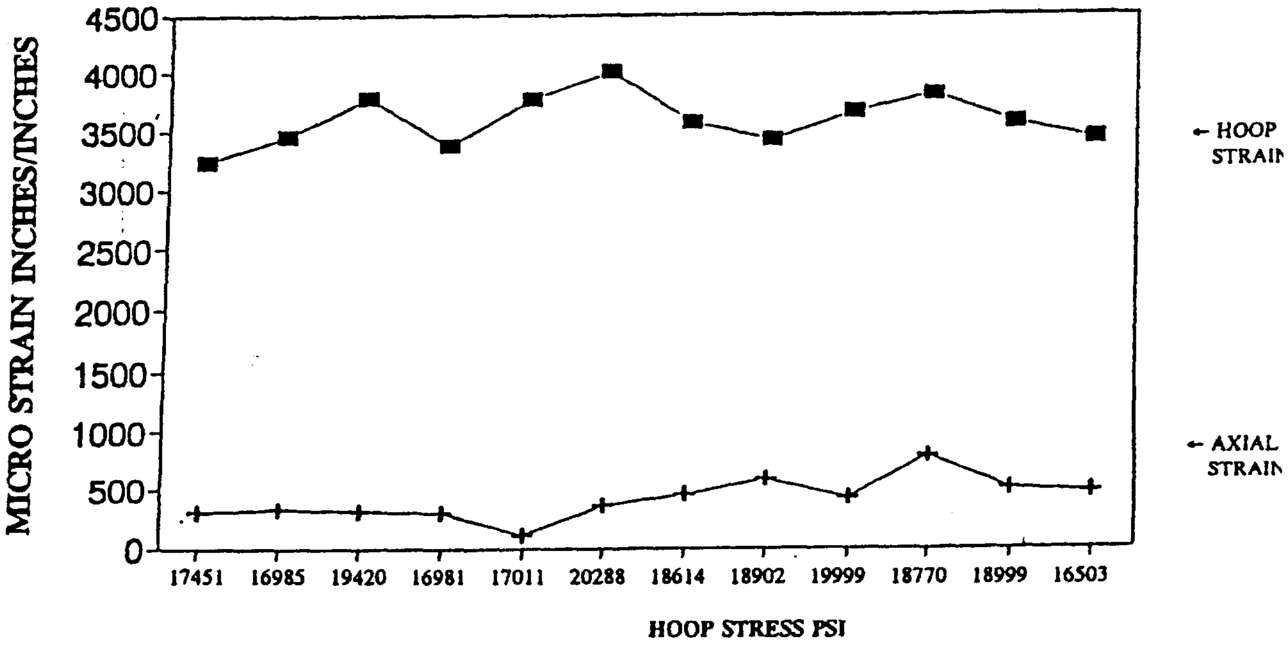
STRESS AND STRAIN AT 2500 PSI
TEST COND: 2300 PSI, 120°F, CO_2/H_2O



Sample Number	ID Inches	OD Inches	RATING Pressure	RATING Hoop	RATING Axial	RATING Stress	PEL Pressure	PEL Hoop	PEL Axial	PEL Stress	WEEP Pressure
1	1.92	2.35	2496	2242	285	12417	3508	3240	307	17451	7500
2	1.92	2.36	2547	2412	297	12346	3504	3458	323	16985	8500
3	1.92	2.36	2521	2237	289	12196	4014	3785	312	19420	8565
4	1.92	2.36	2500	2325	264	12095	3510	3388	296	16981	8000
5	1.92	2.37	2577	2576	161	12276	3571	3769	101	17011	7500
6	1.92	2.35	2520	2452	350	12639	4045	4005	360	20288	8060
7	1.92	2.39	2540	2208	332	11785	4012	3576	456	18614	9018
8	1.92	2.39	2498	1989	413	11590	4074	3423	581	18902	8545
9	1.92	2.36	2513	2182	305	12351	4069	3664	422	19999	9153
10	1.92	2.38	2577	2356	512	12068	4008	3814	783	18770	9034
11	1.92	2.38	2544	2176	367	12027	4019	3580	511	18999	9058
12	1.92	2.39	2533	1977	422	11752	3557	3437	471	16503	8565
AVG	1.92	2.37	2530	2261	333	12128	3824	3594	410.2	18326	8458
STD	---	0.01	26.70	169.1	85.86	293.22	250.1	210.1	164.1	1236.1	557.1

Figure 4

STRESS AND STRAIN AT PEL
TEST COND: 2300 PSI, 120°F, CO_2/H_2O

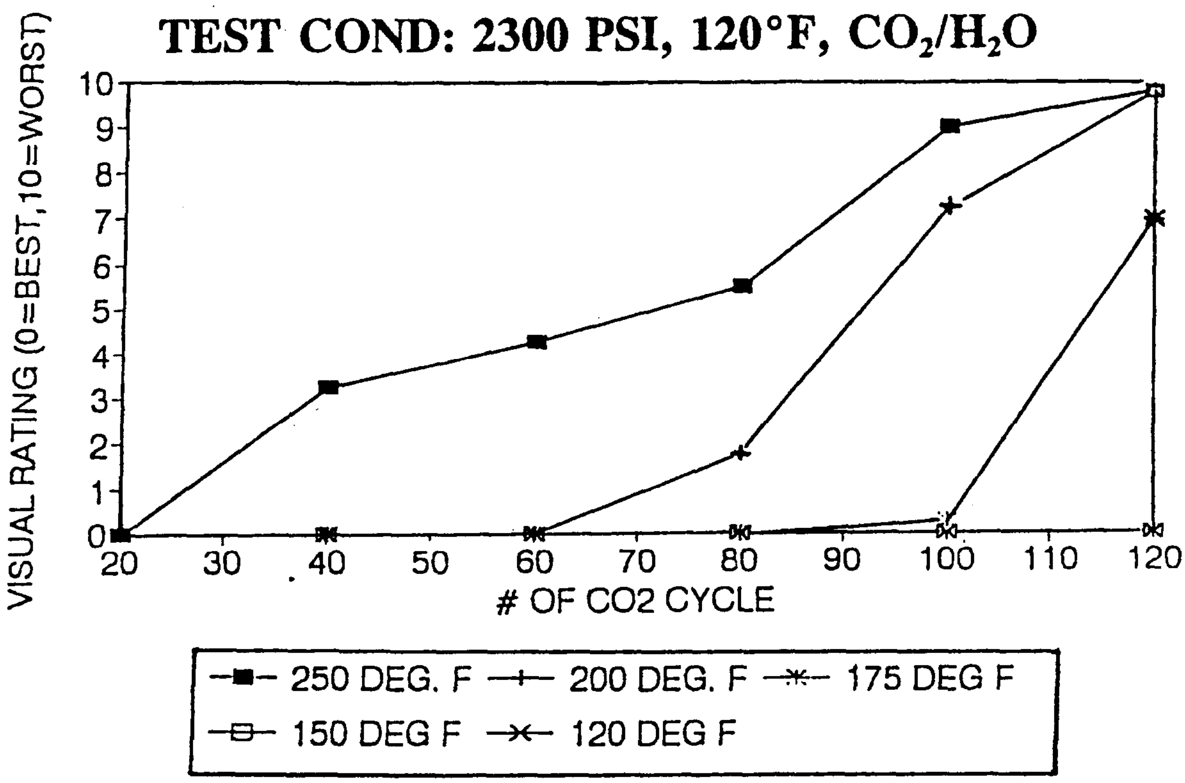


Sample Number	ID Inches	OD Inches	RATING Pressure	RATING Hoop	RATING Axial	RATING Stress	PEL Pressure	PEL Hoop	PEL Axial	PEL Stress	WEEP Pressure
1	1.92	2.35	2496	2242	285	12417	3508	3240	307	17451	7500
2	1.92	2.36	2547	2412	297	12346	3504	3458	323	16985	8500
3	1.92	2.36	2521	2237	289	12196	4014	3785	312	19420	8565
4	1.92	2.36	2500	2325	264	12095	3510	3388	296	16981	8000
5	1.92	2.37	2577	2576	161	12276	3571	3769	101	17011	7500
6	1.92	2.35	2520	2452	350	12639	4045	4005	360	20288	8060
7	1.92	2.39	2540	2208	332	11785	4012	3576	456	18614	9018
8	1.92	2.39	2498	1989	413	11590	4074	3423	581	18902	8545
9	1.92	2.36	2513	2182	305	12351	4069	3664	422	19999	9153
10	1.92	2.38	2577	2356	512	12068	4008	3814	783	18770	9034
11	1.92	2.38	2544	2176	367	12027	4019	3580	511	18999	9058
12	1.92	2.39	2533	1977	422	11752	3557	3437	471	16503	8565
AVG	1.92	2.37	2530	2261	333	12128	3824	3594	410.2	18326	8458
STD	---	0.01	26.70	169.1	85.86	293.22	250.1	210.1	164.1	1236.1	557.1

Figure 5

EFFECT OF TEMPERATURE AND NUMBER OF CYCLE

TEST COND: 2300 PSI, 120°F, CO_2/H_2O

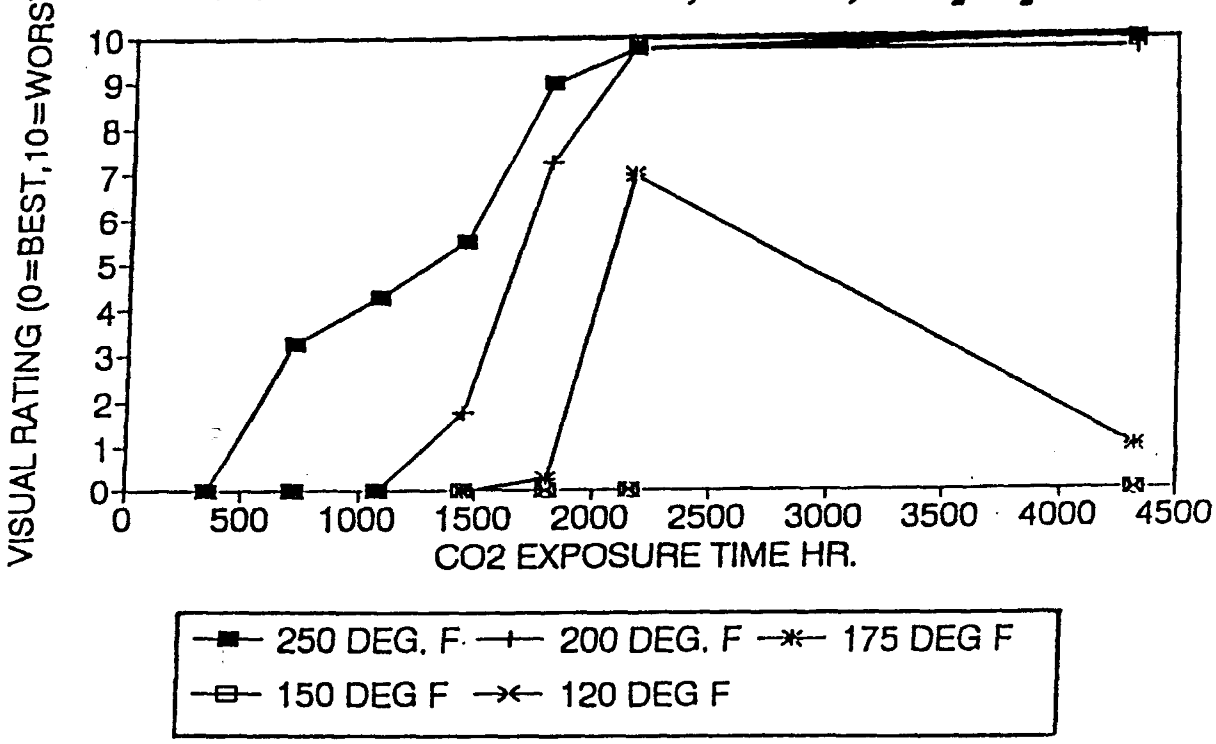


Sample Number	Test Environment	MODE Steady	MODE Cyclic	Test Time Hour	Number Of Cycle	CO_2 Exposure Hour	VISUAL 0 = Best 10 = Worst 120	150	175	200	250
1	H_2O/CO_2		Y	720	20	360	0	0	0	0	0
2	H_2O/CO_2		Y	1440	40	720	0	0	0	0	3.25
3	H_2O/CO_2		Y	2160	60	1080	0	0	0	0	4.25
4	H_2O/CO_2		Y	2880	80	1440	0	0	0	1.75	5.5
5	H_2O/CO_2		Y	3600	100	1800	0	0	0.25	7.25	9
6	H_2O/CO_2		Y	4320	120	2160	0	0	7	9.75	9.75
7	H_2O/CO_2		Y	4320	26	2160	0	0	0.25	7.5	8.25
8	H_2O/CO_2		Y	4320	6	2160	0	0	0	7.75	8.25
9	H_2O/CO_2		Y	4320	2	2160	0	0	0	6.75	7.25
10	CO_2	Y		4320	1	4320	0	0	1	9.75	10
11	H_2O	Y		4320	1	0	0	0	0	0	0
12	CONTROL	Y		4320	1	0	0	0	0	0	0

Figure 6

EFFECT OF TIME & TEMPERATURE

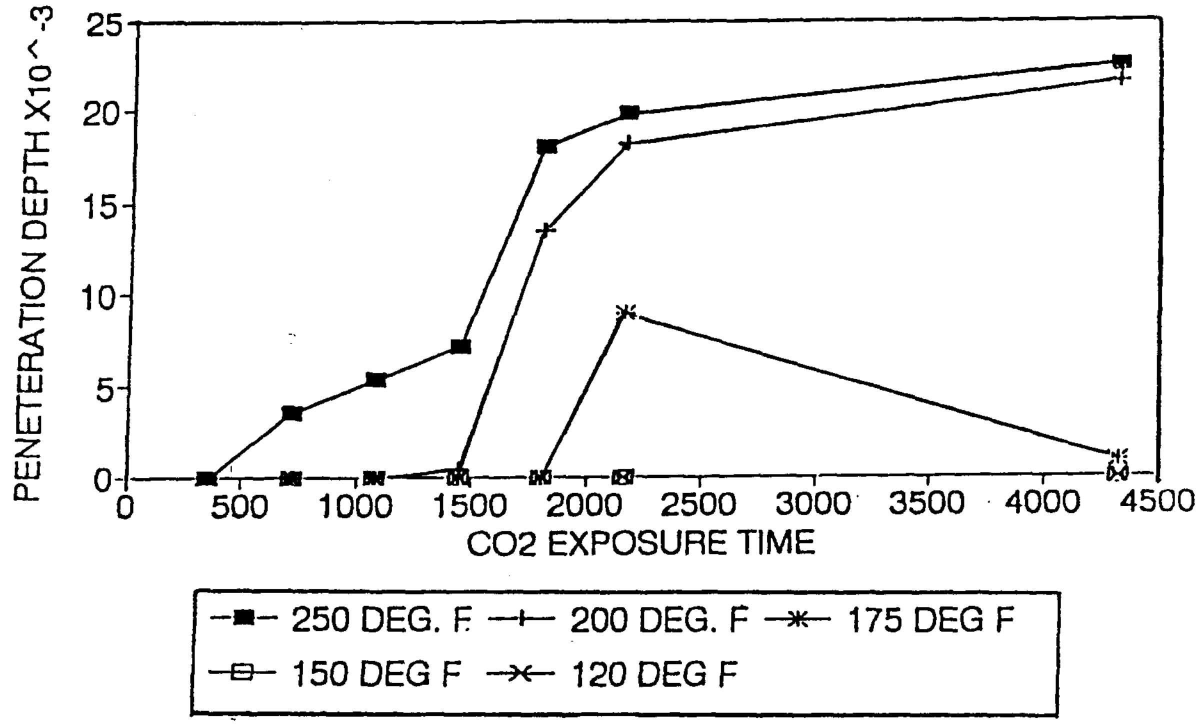
TEST COND: 2300 PSI, 120°F, CO_2/H_2O



Sample Number	Test Environment	MODE Steady	MODE Cyclic	Test Time Hour	Number Of Cycle	CO_2 Exposure Hour	VISUAL 0 = Best 10 = Worst 120	150	175	200	250
1	H_2O/CO_2		Y	720	20	360	0	0	0	0	0
2	H_2O/CO_2		Y	1440	40	720	0	0	0	0	3.25
3	H_2O/CO_2		Y	2160	60	1080	0	0	0	0	4.25
4	H_2O/CO_2		Y	2880	80	1440	0	0	0	1.75	5.5
5	H_2O/CO_2		Y	3600	100	1800	0	0	0.25	7.25	9
6	H_2O/CO_2		Y	4320	120	2160	0	0	7	9.75	9.75
7	H_2O/CO_2		Y	4320	26	2160	0	0	0.25	7.5	8.25
8	H_2O/CO_2		Y	4320	6	2160	0	0	0	7.75	8.25
9	H_2O/CO_2		Y	4320	2	2160	0	0	0	6.75	7.25
10	CO_2	Y		4320	1	4320	0	0	1	9.75	10
11	H_2O	Y		4320	1	0	0	0	0	0	0
12	CONTROL	Y		4320	1	0	0	0	0	0	0

Figure 7

CO_2 PENETRATION DEPTH 10 ^ -3
TEST COND: 2300 PSI, 120°F, CO_2/H_2O



Sample Number	Test Environment	MODE Steady	MODE Cyclic	Test Time Hour	Number Of Cycle	CO_2 Exposure Hour	CO_2 PENETRATION, 10 ^ -3: 120	150	175	200	250
1	H_2O/CO_2		Y	720	20	360	0	0	0	0	0
2	H_2O/CO_2		Y	1440	40	720	0	0	0	0	3.6
3	H_2O/CO_2		Y	2160	60	1080	0	0	0	0	5.4
4	H_2O/CO_2		Y	2880	80	1440	0	0	0	0.45	7.2
5	H_2O/CO_2		Y	3600	100	1800	0	0	0	18	13.5
6	H_2O/CO_2		Y	4320	120	2160	0	0	9	19.8	18.9
7	H_2O/CO_2		Y	4320	26	2160	0	0	0	17.1	16.2
8	H_2O/CO_2		Y	4320	6	2160	0	0	0	16.2	17.1
9	H_2O/CO_2		Y	4320	2	2160	0	0	0	14.4	14.4
10	CO_2	Y		4320	1	4320	0	0	0.9	21.6	22.5
11	H_2O	Y		4320	1	0	0	0	0	0	0
12	CONTROL	Y		4320	1	0	0	0	0	0	0

Figure 8

CO_2 PENETRATION FAILURE MECHANISM IN FRP TUBULARS

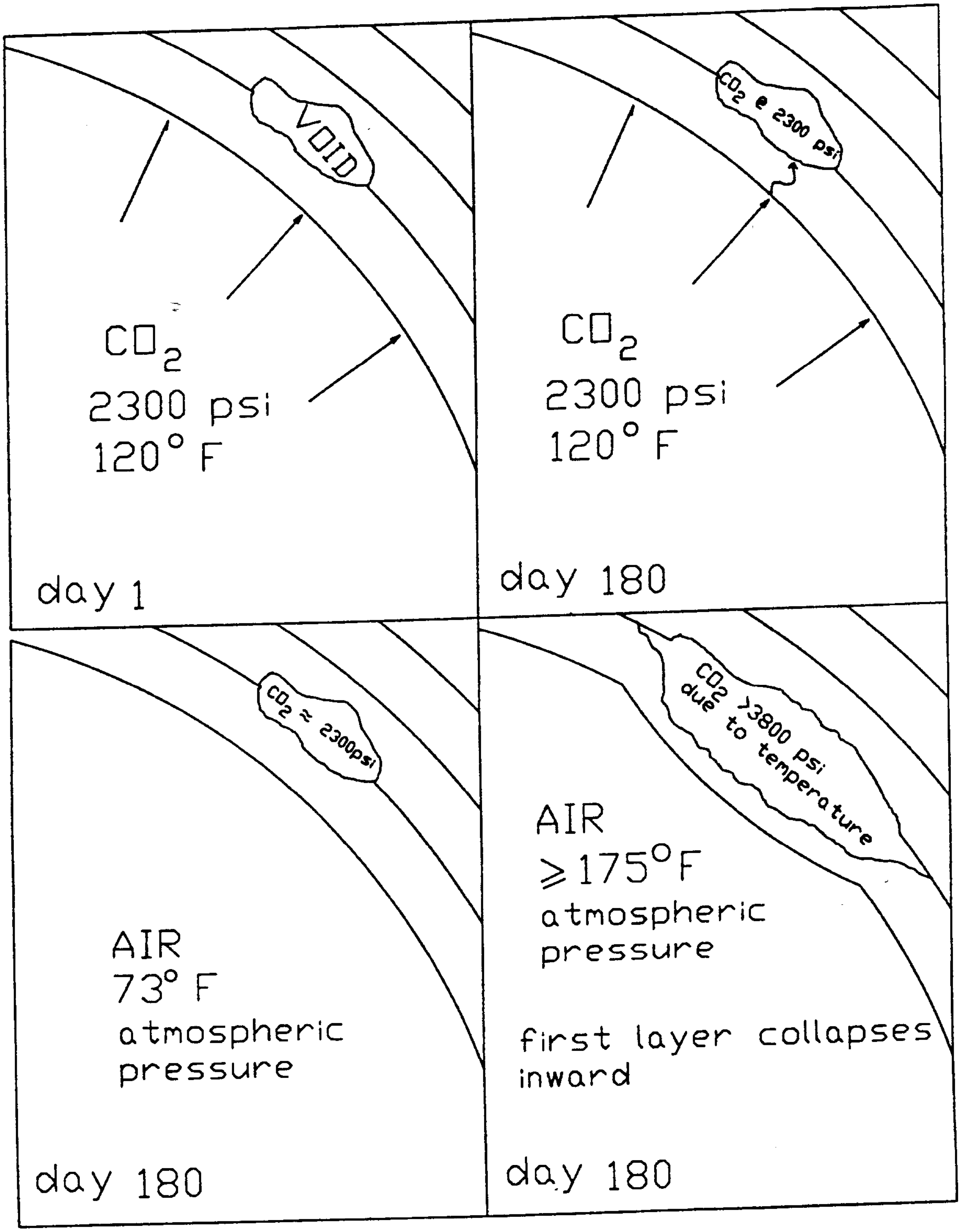


Figure 9

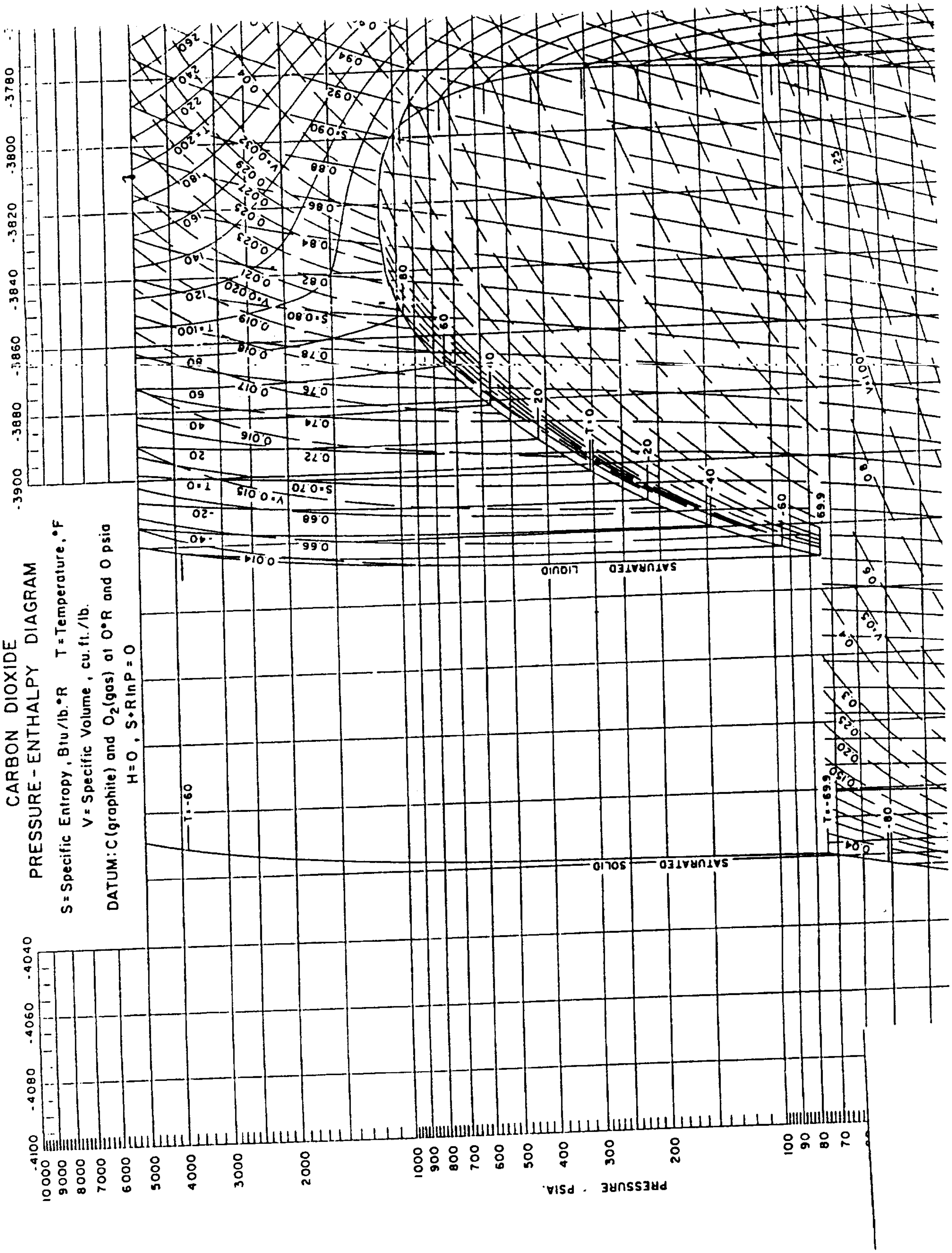

CARBON DIOXIDE
PRESSURE - ENTHALPY DIAGRAM
S = Specific Entropy, Btu/lb.°R T = Temperature, °F
V = Specific Volume, cu. ft./lb.
DATUM: C(graphite) and O2(gas) at 0°R and 0 psia
H = 0 , S + R ln P = 0
PRESSURE - PSIA.
SATURATED LIQUID
SATURATED SOLID

Figure 10

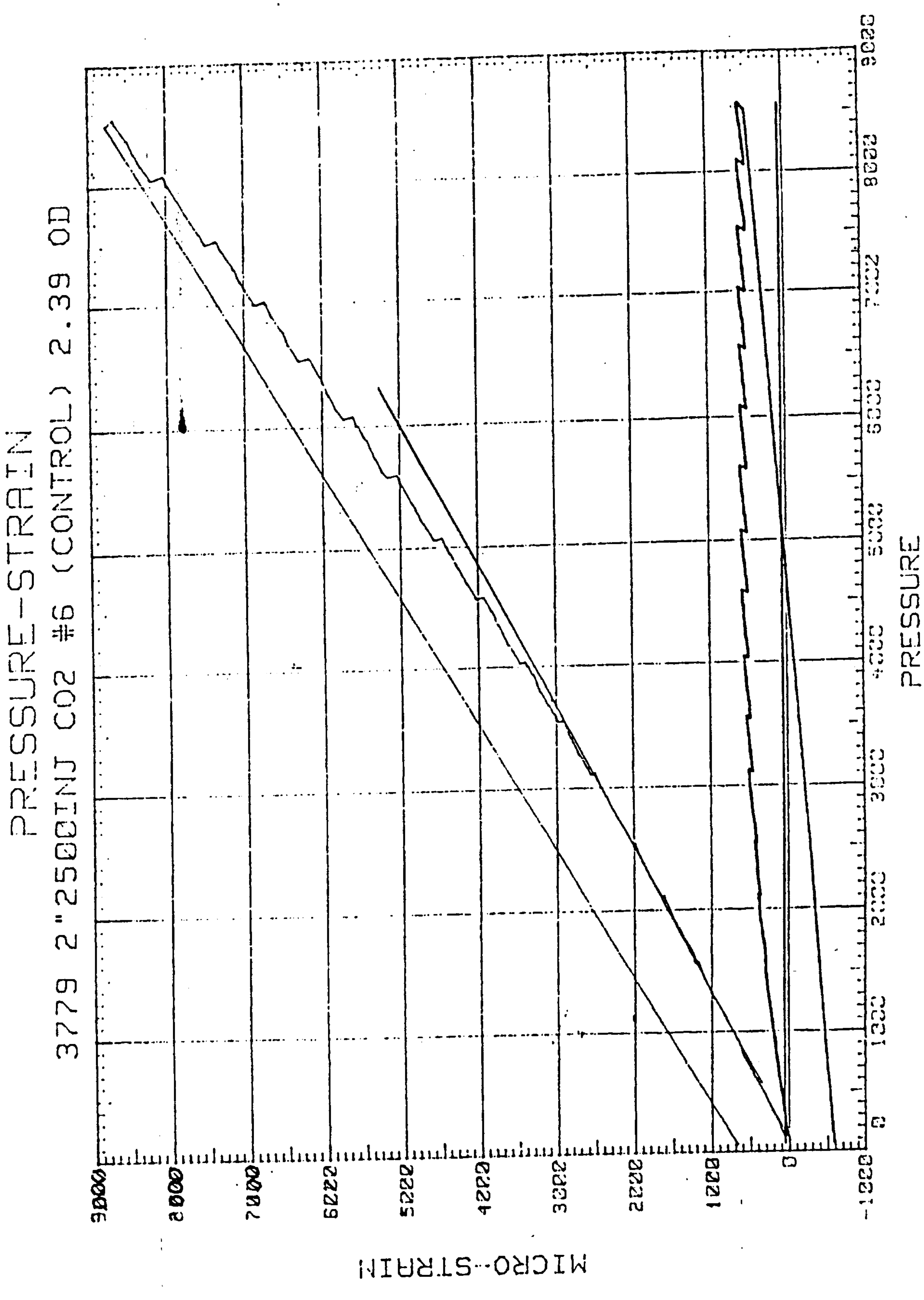

PRESSURE-STRAIN
3779 2"2500INJ CO2 #6 (CONTROL) 2.39 OD
PRESSURE
MICRO-STRAIN

Figure 11

TEMP.& PRESSURE RESPONSE/ CO2
STAR 2" 2500 , 3824 PSI PEL

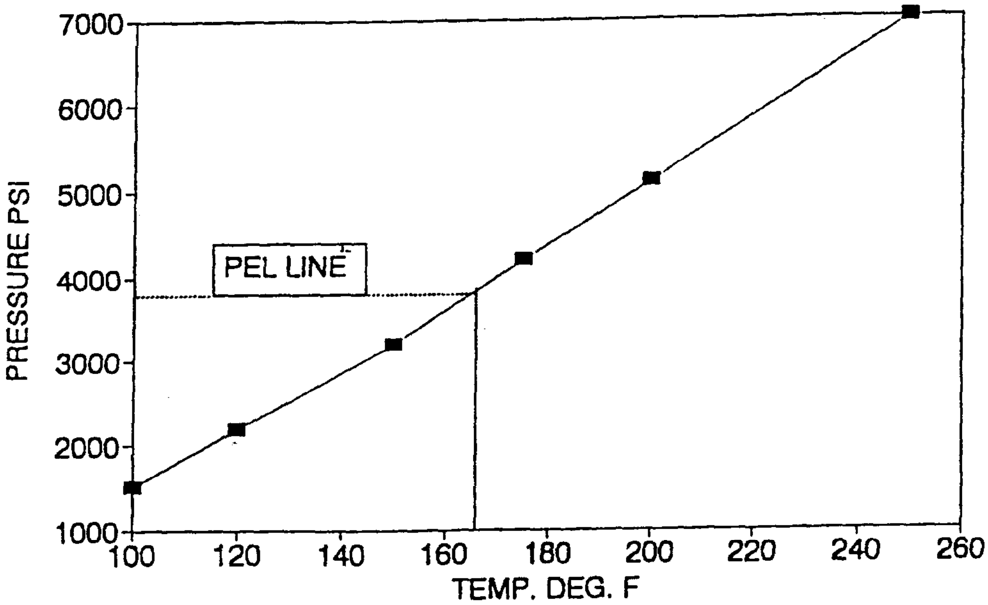
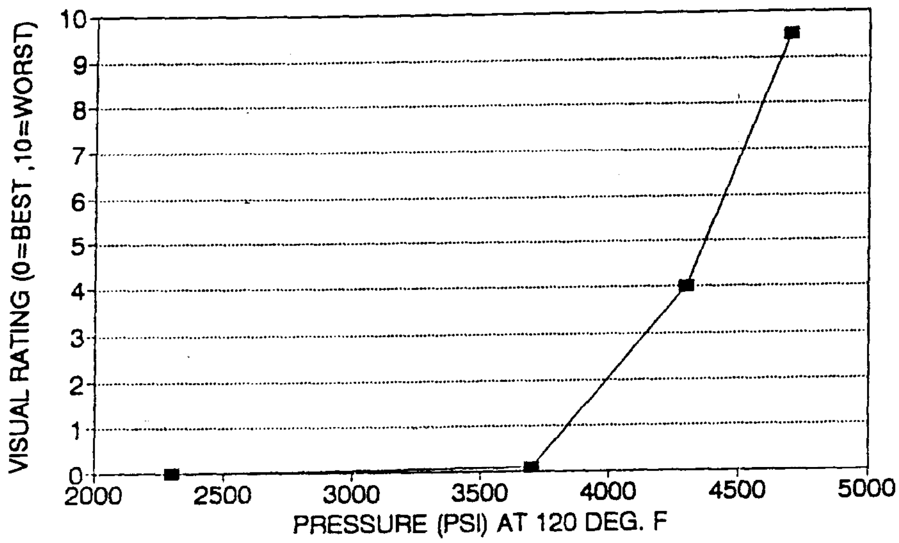


Figure 12

VERIFICATION MODEL
CRITICAL PRESSURE AT INTERLAMINAR SHEAR



Sample Number	Test Environment	MODE Steady	MODE Cyclic	Test Time Hour	Number Of Cycle	CO_2 Exposure Hour	Internal Pressure	Hoop Stress	Visual Rating 0=Best 10=Worst 120
1	CO_2	Y		3240	1	3240	2300	10771	0
2	CO_2	Y		3240	1	3240	3800	17795	0.1
3	CO_2	Y		3240	1	3240	4300	20137	4.0
4	CO_2	Y		3240	1	3240	4700	22010	9.5

Figure 13

Field Performance Evaluation

Rangly Colorado

Product:	2⅞" 2500 PSI Down Hole Tubing
Location:	Rangly Colorado
Installation Date:	1985
Well Condition:	Depth - Approximately 6,000 ft. Type - CO_2 WAG Injection
Surface Injection Pressure:	(H_2O) 1380 to 1860 PSI (CO_2) 1325 to 2100 PSI
Surface Injection Temperature:	(H_2O) 130 to 150°F (CO_2) 45 to 70°F
Bottom Hole Temperature:	160°F
CO_2 Exposure Time:	11 Cycles, Total of 455 days

Sample Number	Test Environment	Mode Steady	Mode Cyclic	Test Time Hour	Number of Cycles	CO^3 Exposure Hour	Density Lb/ Cubic Ft	Glass %	Tg Degree	WEEP PSI	PEL PSI
1	H_2O/CO_2 T# 3575		Y	39,264	11	10,920	116	70	118	5900	3574
2	H_2O/CO_2 T# 3576		Y	39,264	11	10,920	116	70	110	5850	3750
3	H_2O/CO_2 T# 3577		Y	39,264	11	10,920	115	69	104	5200	3800

Figure 14