WATER CONTENT OF LIGHT NONHYDROCARBON GASES

Introduction In the chemical process industry it is often necessary to remove water from vapor or gaseous streams for several reasons:

1. to prevent the formation of hydrates in pipelines
2. to meet a water dew point requirement
3. to prevent corrosion in potentially condensing acid gas streams

Techniques for dehydrating natural gas or other gas streams such as ammonia synthesis gas typically include:

1. absorption using liquid desiccants
2. adsorption using solid desiccants
3. inhibition by injection of hydrate point depressants
4. dehydration by expansion refrigeration

In order to properly size the equipment or vessels involved in these processes, it is important to know the precise water content of the process gas stream.

For the determination of the saturation (dew point) water content of gases, the Engineering Data Book of the Gas Processors' Association (1) recommends Fig. 15-14 found on Page 15-10 of their 9th revised edition. This chart is based solely on natural gas systems after the work of McKetta and Wehe (2). The question immediately arises as to whether this chart might be applicable for light nonhydrocarbon gases such as hydrogen, nitrogen, CO and in particular to 3:1 hydrogen/nitrogen (ammonia syn gas). This application has a direct bearing in the sizing of ammonia plant dryers situated just upstream of the plant's cryogenic purification system.

This Study In this investigation we first perused the literature to see what data exists for the saturation water content of light nonhydrocarbon gases. We then performed a brief comparison of the reported water content for these gases with the corresponding values read from the McKetta-Wehe chart. The results of this comparison and a proposed generalized graphical correlation for the water content of light NHC gases are presented here. Finally, three examples are presented which illustrate the direct use of the proposed graphical correlation. The last illustration utilizes water content data read from our chart to size an ammonia plant dryer. This dryer employs a solid desiccant which adsorbs water from the process synthesis gas stream.

Available Data A brief search of the existing literature revealed the following data sources for the saturation water content of light nonhydrocarbon gases:

1. Bartlett (3) reports data for water vapor in hydrogen, nitrogen and 3:1 hydrogen/nitrogen at temperatures of 77, 100 and 122 deg. F for total system pressures up to 1000 atm.

2. Pollitzer and Strebel (4) report water content data for air, hydrogen and carbon dioxide at 122 and 158 deg. F and for pressures ranging between 10 and nearly 200 atm.

Table 1 provides a comprehensive listing of all of these data. The above authors originally reported water content as milligrams of water per liter of gas or mg/l. We converted these values to molar parts per million of water or PPMM. In the last three columns of the table we show the "ideal" water content defined simply as the ratio of the vapor pressure of water to the total pressure. In addition, the final column shows what we refer to as the water content ratio, WCR. The WCR is simply defined as the ratio of the actual water content to the ideal water content i.e. PPMM/PPMM-ideal. A sample calculation of the data reduction procedure used here is illustrated below.

Bartlett (3) reports a water content of 89.1 mg per liter of dry (H_2) gas at 100 atm and 122 deg. F with a gas phase compressibility factor of Z = 1.058. The conversion to PPMM is as follows:

$$gmoles\ dry\ gas = \frac{P}{Z\,RT} = \frac{100}{(1.058)(0.08206)(323.17)} = 3.5642$$

$$gmoles\ of\ H_2O = \frac{89.1}{(1000)(18.02)} = 0.004945$$

$$Then \qquad PPMM\ H_2O = \frac{0.004945}{3.5642} 10^6 = 1387.3$$

$$At\ 122\deg.F\ \ VP\,of\ \ water = 1.791\,psia$$

Therefore $$PPMM\ H_2O\ ideal\ = \frac{1.791}{(100)(14.696)}10^6 = 1218.7$$

Then $$Water\,Content\ \ Ratio, WCR\ = \frac{PPMM}{PPMM - ideal} = \frac{1387.3}{1218.7} = 1.138$$

Effective H_2 Critical Constants For the subsequent correlation work performed in this study, we required critical constants for the gases studied. Experimental PVT data for hydrogen do not obey the law of corresponding states. The configurational properties of very low molecular weight gases such as hydrogen and helium obey quantum rather than classical or statistical mechanics. Therefore, the properties of these gases cannot be correlated via the conventional corresponding states treatment using classical critical constants. Chueh and Prausnitz (5) have defined temperature-dependent effective critical constants with which the properties of quantum gases can be made to coincide with those for classical gases. They found these effective constants to depend on the molecular mass m and temperature T in a simple manner. They propose the following expressions for the effective critical temperature and effective critical pressure for hydrogen:

$$T_c\,(quantum\,gas) = \frac{T_c^o}{1+\dfrac{c_1}{mT}}, \deg.K \qquad (1)$$

$$P_c\,(quantum\,gas) = \frac{P_c^o}{1+\dfrac{c_2}{mT}},\ atm \qquad (2)$$

where c_1 = 21.8 deg. K

c_2 = 44.2 deg. K

Specifically, for hydrogen,

T_c^o = 43.6 deg. K; P_c^o = 20.2 atm; m = 2.02

Table 2 provides a listing of effective critical constants for hydrogen as a function of temperature over the range of 30 to 200 deg. F at 1 deg. F intervals. All of these data were generated directly from Equations 1 and 2 above.

Graphical Comparison at 122 deg. F Figure 1 is a plot of water content (PPMM) as a function of system pressure at 122 deg. F. The upper and lower solid curves represent values predicted from the GPA Engineering Data Book (1) and the ideal gas law respectively. The data points plotted here were taken from Table 1 for each of the nonhydrocarbon gases studied. The dashed curves represent the best visual fit through each set of data points. The various symbols associated with each system and the corresponding data source are listed on the plot as well.

The experimental data points generally lie between the two solid curves. Basically, we could justifiably draw a single line through all of the points below a pressure of 100 atm. Below about 30 atm, the GPA and ideal gas curves converge. At higher pressure levels, such as 200 atm and greater, the various systems display more of a spread. It appears that, in this higher pressure region, the water content decreases as the molecular weight of the nonhydrocarbon gas is decreased. For example at 200 atm, we read the following water contents from the curves of Figure 1.

Non HC Gas	Water Content, PPMM	Water Content Relative To The Ideal Gas Law
GPA (Nat. Gas)	1100	1.80
Nitrogen	998	1.64
3:1 H2/N2	850	1.39
Hydrogen	780	1.28
Ideal Gas Law Using VP of Water	610	1.00

The last column here shows the water content (WCR) relative to the ideal gas law prediction (Water VP/Pressure x 10^6).

As a final observation here in Figure 1, we see that a smooth curve drawn through the data points for the water content of CO_2 gas lies above the GPA curve (natural gas) . At 100 atm pressure, for example, we observe the following comparison:

System	Water Content, PPMM	Water Content Relative To The Ideal Gas Law
CO_2	3200	2.67
GPA (Nat. Gas)	1650	1.38
Ideal Gas Law	1200	1.00

Generalized Corres. States Correlation An attempt to graphically correlate the data of Table 1 within the framework of the Law of Corresponding States proved to be successful. Before we could this, however, it was necessary to compute the reduced temperature T_R and reduced pressure P_R for each data point listed. For the cases where air and ammonia syn gas were involved, we used the simple linear combining rules of Kay to compute the pseudo-critical properties of the gas mixtures on a dry basis. Individual component gas critical constants are listed below:

Comp.	T_c, deg. F	P_c, Psia	P_c, Atm
Oxygen	-181.1	737.1	50.16
Nitrogen	-232.4	493	33.55
Hydrogen		See Table 2	

If air is assumed to consist basically of 79 mole percent N_2/ 21 mole percent O_2, then the pseudo-critical constants are calculated to be,

$$P_{pc}\,(air) = (0.79)(493) + (0.21)(737.1) = 544.3\,Psia$$
$$T_{pc}\,(air) = (0.79)(-232.4) + (0.21)(-181.1) = -221.63 \text{ deg}.F$$

For ammonia syngas (3:1 H_2/N_2) at 122 deg. F:

From Table 2 we read P_c = 18.92 atm and T_c = -383.76 deg. F specifically for H_2. Therefore the pseudo-critical constants will be,

$$P_{pc} = (0.75)(18.92) + (0.25)(33.55) = 22.58 \; atm \; or \; 331.8\,psia$$
$$T_{pc} = (0.75)(-383.76) + (0.25)(-232.4) = -345.92 \text{ deg}.F$$

The reduced pressures and temperatures for each data point can then be simply computed via the expressions:

$$T_R = \frac{T}{T_c} \quad ; \quad P_R = \frac{P}{P_c} \qquad (3a,b)$$

$where\ T\ and\ T_c\ must\ be\ \exp ressed\ in\ absolute\ units\ (\deg.K\ or\ R)$

Table 1 also includes a listing of these reduced parameters for each data point. These parameters are the independent variables used in the correlation scheme described below.

By smoothing and cross plotting the entire data set listed in Table 1 we arrived at the more or less generalized graphical correlation shown in Figure 2. The correlation is expressed in a corresponding states format with WCR, the water content ratio, plotted as a function of the reduced pressure P_R with individual parametric curves of reduced temperature T_R. The correlation covers a range of T_R values between 2.5 and 7.5 and P_R values up to 50. Extrapolation beyond the bounds of these ranges is considered to be quite risky. The following three illustrations demonstrate direct application of Figure 2. The last illustration involves the actual design of a dryer employing a solid desiccant.

Illustration 1 Estimate the water content at saturation for a 3:1 molar mix of H_2 and N_2 at 122 deg. F and 600 atm.

At the bottom of page 5 we showed the calculation of the pseudo critical constants for this syn gas mixture at 122 deg. F. Therefore, the pseudo reduced parameters for the gas mixture are,

$$P_{PR} = \frac{600}{22.58} = 26.57 \quad ; \quad T_{PR} = \frac{122+459.7}{-345.92+459.7} = \frac{581.7}{113.78} = 5.11$$

If we enter these parameters on Figure 2, we read,

$$WCR = \frac{PPMM\ H_2O\ Actual}{PPMM\ H_2O\ Ideal} = 2.1$$

$$At\ 122\ \deg.F \quad VP\ for\ water = 1.791\,Psia$$

$$Therefore \qquad PPMM\ H_2O\,Ideal = \frac{1.791}{(14.696)(600)} x10^6 = 203.12$$

Now we can calculate the actual water content of this syn gas mixture.

$$PPMM\ H_2O\ \ Actual = (2.1)(203.12) = 427$$

Bartlett (3) reported an experimental value of 422 for this syn gas mixture at 122 deg. F and 600 atm.

<u>Illustration 2</u> What total pressure must a nitrogen gas stream be under in order to have a saturation water content of 680 PPMM at an operating temperature of 122 deg. F ?

For N_2 $P_c = 493$ psia and $T_c = -232.4$ deg. F

The reduced pressure and temperature of the gas are,

$$P_R = \frac{P}{493} \quad ; \quad T_R = \frac{122 + 459.7}{-232.4 + 459.7} = \frac{581.7}{227.3} = 2.56$$

where P, the system pressure in psia, is unknown. In order to employ Figure 2 for the solution here, we need to express the water content ratio WCR in terms of P also.

$$At\ 122\deg.F \quad VP\,of\ \ water = 1.791\,psia$$

$$Then \qquad PPMM\ of\ \ water\,(Ideal) = \frac{1.791}{P}x10^6 \ \ ; \ \ P\,in\,psia$$

$$And \qquad WCR = \frac{PPMM\ actual}{PPMM\ (Ideal)} = \frac{680}{\left(\frac{1.791}{P}\right)x10^6} = \frac{680\,P}{1.791x10^6}$$

The solution for P is done by performing a simple trial and error procedure. This procedure is shown in a tabular format below:

			$T_R = 2.56$	$P_c = 493$ psia	
Passumed		WCR	Fig. 2	$P_{calc} = P_R P_C$	
Atm	Psia	680 P/ 1.791x10^6	P_R	Psia	Atm
250	3674	1.395	3.6	1774.8	120.8
300	4409	1.674	6.1	3007	204.6
400	5878	2.232	12.	5916	402.6
500	7348	2.79	17.	8381	570.3
600	8818	3.348	22	10,846	738.
700	10,287	3.906	27.5	13,558	922.5

In Figure 3 we have plotted the calculated pressures P_{calc} against the assumed pressures $P_{assumed.}$ The resulting curve crosses the 45 degree line at P = 405 atm within the limits of reading accuracy. Therefore, in order for a nitrogen gas stream to be saturated with a water content of 680 PPMM at 122 deg. F, it must be subjected to a pressure of **405 atm**.

Illustration 3 We are asked to size a molecular sieve (adsorption) dryer for the following service: The gas is flowing at a rate of 64,500 lbmoles/hr. It consists of an ammonia plant synthesis gas (3:1 molar ratio of H_2 to N_2) and will enter the dryer saturated with water vapor at 122 deg. F and a total pressure of 200 atm.

The drying specifications and physical properties of the molecular sieve packing are listed below:

1. Water pickup or extent of adsorption is 9.0 lbs of water per 100 lbs of desiccant.

2. Desiccant density = 42 lbs/ cu ft.

3. Bed superficial gas velocity = 0.7 ft/sec.

4. Operating cycle time = 16 hours.

This gas mixture is initially at the same conditions of P, T and composition as that of the one treated in Illustration 1, and thus,

$$P_{pc} = 22.58 \text{ atm} \quad ; \quad T_{pc} = -345.92 \text{ deg. F}$$

Therefore $$P_{PR} = \frac{200}{22.58} = 8.86 \quad ; \quad T_{PR} = \frac{122+459.7}{-345.92+459.7} = 5.11$$

From Figure 2 we read a WCR value of 1.4

At 122 deg. F with a water VP of 1.791 psia we calculate the ideal water PPMM to be,

$$PPMM\ \ H_2O\ Ideal = \frac{1.791}{(14.696)(200)} x10^6 = 609.35$$

And then $$Actual\ PPMM\ \ H_2O = (1.4)(609.35) = 853.1$$

The water rate in the feed stream will be,

$$\left(853.1x10^{-6}\right)\left(64,500\,M/H\right) = 55\ lbmoles/Hr\ \ H_2O$$

$$Or \qquad = 991.5\,Lbs/Hr\ \ H_2O$$

The total weight of the molecular sieve desiccant is calculated as follows:

$$Lbs\ \ desiccant = \frac{Water\ \ adsorbed\ \ in\ \ a\ \ cycle}{Water\ \ pickup\ \ per\ \ lb\ \ of\ \ solid}$$

$$= \frac{\left(991.5\,lbs/Hr\right)\left(16\,Hrs\right)}{9/100} = 176,267\ \ lbs$$

$$Volume\ \ of\ \ desiccant = \frac{Wt.\ of\ \ desiccant}{Density\ \ of\ \ desiccant} = \frac{176,267}{42} = \ 4200\,cuft$$

Before we can determine the desiccant cross-sectional area, we need to first compute the gas volumetric flow rate.

At 122 deg. F and 200 atm, the compressibility factor of this syn gas is 1.112. Then the molecular weight and gas density are readily calculated.

$$Molecular\ \ weight = M = \left(0.75\right)\left(2\right) + \left(0.25\right)\left(28\right) = 8.5$$

$$Gas\ \ density\,(dry\,basis) = \frac{M\ P}{Z\ RT} = \frac{\left(8.5\right)\left(200\right)\left(14.696\right)}{\left(1.112\right)\left(10.731\right)\left(581.7\right)} = 3.6\,Lbs/Cu\,Ft$$

$$Volumetric\ \ gas\ \ rate = \frac{\left(64,500\right)\left(8.5\right)}{3.6} = 152,292\ \ Cu\,Ft/Hr$$

$$A_{CS} = \frac{Vol.Gas\,Flow\,Rate}{Superficial\ \ Gas\ \ Velocity} = \frac{152,292}{\left(3600\right)\left(0.7\right)} = 60.43\ \ Sq\,Ft$$

The desiccant will obviously be packed in the interior of the dryer in the shape of a right circular cylinder. Therefore,

$$A_{cs} = \frac{\pi}{4} d_i^2 \qquad ; \qquad V = A_{cs}\, L = \frac{\pi}{4} d_i^2\, L = Volume\ of\ \ desiccant$$

$$Dryer\ \ ID = d_i = \sqrt{\frac{4\, A_{cs}}{\pi}} = \sqrt{\frac{(4)(60.43)}{\pi}} = 8.8\ ft\ ;\ Use\ 9\ ft.$$

$$Lengh\ of\ \ desiccant\ in\ dryer = \frac{V}{A_{cs}} = \frac{4200}{60.43} = 70\ \ ft.$$

For actual design it would be best, in this case, to operate two dryers in series each with 35 ft of desiccant and inside diameter of 9 ft ($L/d_i = 3.9$).

The final question arising here is what would be the effect on the design if we used (Fig. 15-14) of the GPA Engineering Data Book (1) to determine the saturation water content of the dryer feed gas stream ? In Figure 1 we plotted the water content (PPMM) versus pressure generated from points read from the GPA Data Book Fig. 15-14 at 122 deg. F. At an operating dryer inlet pressure of 200 atm, we read a water content of 1100 PPMM. The inside diameter of the dryer is unaffected here because it only depends upon the total volumetric gas flow rate and superficial gas velocity which remain the same in any case. The determination of the length of the desiccant is dependent upon the total volume of desiccant which, in turn, depends directly upon the inlet water content. With all other properties held the same, the design length in this case would be,

$$L\left(Based\ \ on\ GPA\ chart\right) = \left(\frac{1100}{853.1}\right)(70) = (1.289)(70) = 90\ ft.$$

By using the GPA chart we calculate nearly a 30 percent higher length. Obviously, the GPA chart should not be used for this application because it is based solely on natural gas type systems. It provides a water content that is too high when applied to the ammonia syn gas mixture in this case. If the operating pressure is 40 atm (590 psia) or less, either the GPA chart or the Dalton's ideal gas law could be used for all practical purposes. This conclusion is quite clear upon inspection of Figure 1.

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List of References

1. Engineering Data Book, Gas Processors Association (GPA), Ninth Edition, (1972) Figure 15-14, Page 15-10.

2. McKetta, J.J. and Wehe, A.H., Petroleum Refiner (August 1958), Page 153.

3. Bartlett, E.P., Journal of the American Chemical Society, Vol. 49, (1927) Page 65.

4. Pollitzer and Strebel, Z. Physik Chem. Vol. 110, (1924), Page 768.

5. Prausnitz, J.M. and Chueh, P.L., "Computer Calculations for High-Pressure Vapor-Liquid Equilibria", Prentice-Hall, Inc. (1968).

Table 1

This spreadsheet provides a data reduction procedure for treating the water content of gases

Data of Pollitzer and Strebel

Inert Gas	Tc deg. F	Pc Psia	Oper. T deg. F	Oper. T deg. K	Oper. P Atm	Tr	Pr	mg/l water	Z	Pv/zRT gmoles gas	gmoles water	m.f. water	PPMM water	VP water Psia	Ideal PPMM Water	PPMM/ PPMM-ideal
CO2	87.9	1070.6	122	323.1667	84.2	1.0623	1.1558	363.8	0.535	5.93472	0.020189	0.003402	3401.791	1.791	1447.386	2.3503
	87.9	1070.6	122	323.1667	84.2	1.0623	1.1558	360.8	0.535	5.93472	0.020022	0.003374	3373.739	1.791	1447.386	2.3309
	87.9	1070.6	122	323.1667	84.2	1.0623	1.1558	368.3	0.535	5.93472	0.020438	0.003444	3443.87	1.791	1447.386	2.3794
	87.9	1070.6	122	323.1667	84.2	1.0623	1.1558	364.4	0.535	5.93472	0.020222	0.003407	3407.402	1.791	1447.386	2.3542
	87.9	1070.6	122	323.1667	84.2	1.0623	1.1558	361.6	0.535	5.93472	0.020067	0.003381	3381.22	1.791	1447.386	2.3361
	87.9	1070.6	122	323.1667	57.1	1.0623	0.7838	214.5	0.747	2.882421	0.011903	0.00413	4129.667	1.791	2134.324	1.9349
	87.9	1070.6	122	323.1667	54.2	1.0623	0.7440	189	0.757	2.699885	0.010488	0.003885	3884.738	1.791	2248.522	1.7277
	87.9	1070.6	122	323.1667	53.7	1.0623	0.7371	183.4	0.757	2.674979	0.010178	0.003805	3804.733	1.791	2269.458	1.6765
	87.9	1070.6	122	323.1667	53.7	1.0623	0.7371	179	0.757	2.674979	0.009933	0.003713	3713.453	1.791	2269.458	1.6363
	87.9	1070.6	122	323.1667	38.7	1.0623	0.5312	144.3	0.832	1.754	0.008008	0.004565	4565.433	1.791	3149.093	1.4498
	87.9	1070.6	122	323.1667	38.7	1.0623	0.5312	144.3	0.832	1.754	0.008008	0.004565	4565.433	1.791	3149.093	1.4498
H2	-383.76	278.03	122	323.1667	140.3	7.6600	7.4159	105	1.08	4.898644	0.005827	0.001189	1189.484	1.791	868.6379	1.3694
	-383.76	278.03	122	323.1667	134	7.6600	7.0829	101.5	1.075	4.700437	0.005633	0.001198	1198.321	1.791	909.4768	1.3176
	-383.76	278.03	122	323.1667	122.4	7.6600	6.4698	96.9	1.073	4.301537	0.005377	0.00125	1250.102	1.791	995.6691	1.2555
	-383.76	278.03	122	323.1667	105.1	7.6600	5.5553	93.8	1.062	3.731815	0.005205	0.001395	1394.851	1.791	1159.561	1.2029
	-383.76	278.03	122	323.1667	99.7	7.6600	5.2699	93.7	1.058	3.55346	0.0052	0.001463	1463.3	1.791	1222.366	1.1971
	-383.76	278.03	122	323.1667	93.4	7.6600	4.9369	92.8	1.055	3.338384	0.00515	0.001543	1542.612	1.791	1304.817	1.1822
	-383.76	278.03	122	323.1667	93.4	7.6600	4.9369	91.8	1.055	3.338384	0.005094	0.001526	1525.99	1.791	1304.817	1.1695
	-383.76	278.03	122	323.1667	77.4	7.6600	4.0912	88.7	1.045	2.792972	0.004922	0.001762	1762.391	1.791	1574.546	1.1193
	-383.76	278.03	122	323.1667	70.6	7.6600	3.7317	88.6	1.04	2.559843	0.004917	0.001921	1920.727	1.791	1726.203	1.1127
	-383.76	278.03	122	323.1667	56.6	7.6600	2.9917	83.5	1.032	2.068134	0.004634	0.002241	2240.542	1.791	2153.178	1.0406
	-383.76	278.03	122	323.1667	45	7.6600	2.3786	82.5	1.025	1.655505	0.004578	0.002765	2765.468	1.791	2708.22	1.0211
Air	-221.63	544.26	122	323.1667	192.3	2.4434	5.1924	122.9	1.044	6.945775	0.00682	0.000982	981.9206	1.791	633.7488	1.5494
	-221.63	544.26	122	323.1667	184.8	2.4434	4.9899	126.7	1.043	6.681279	0.007031	0.001052	1052.355	1.791	659.4691	1.5958
	-221.63	544.26	122	323.1667	167.4	2.4434	4.5201	122.5	1.033	6.110786	0.006798	0.001112	1112.46	1.791	728.0161	1.5281
	-221.63	544.26	122	323.1667	142.3	2.4434	3.8424	113.4	1.021	5.255585	0.006293	0.001197	1197.394	1.791	856.4294	1.3981
	-221.63	544.26	122	323.1667	133.1	2.4434	3.5939	111.4	1.010	4.969339	0.006182	0.001244	1244.033	1.791	915.6266	1.3587
	-221.63	544.26	122	323.1667	122.7	2.4434	3.3131	108.9	1.010	4.581051	0.006043	0.001319	1319.192	1.791	993.2347	1.3282
	-221.63	544.26	122	323.1667	119.5	2.4434	3.2267	107.5	1.005	4.483775	0.005966	0.00133	1330.485	1.791	1019.832	1.3046
	-221.63	544.26	122	323.1667	105.5	2.4434	2.8487	106	0.999	3.982253	0.005882	0.001477	1477.142	1.791	1155.165	1.2787
	-221.63	544.26	122	323.1667	98.7	2.4434	2.6651	105.4	0.998	3.72931	0.005849	0.001568	1568.402	1.791	1234.751	1.2702
	-221.63	544.26	122	323.1667	94.8	2.4434	2.5598	104.6	0.998	3.581952	0.005805	0.001621	1620.53	1.791	1285.547	1.2606
	-221.63	544.26	122	323.1667	79.6	2.4434	2.1493	97.6	0.992	3.025822	0.005416	0.00179	1789.995	1.791	1531.029	1.1691
	-221.63	544.26	122	323.1667	74.4	2.4434	2.0089	97.9	0.991	2.831009	0.005433	0.001919	1919.052	1.791	1638.036	1.1716
	-221.63	544.26	122	323.1667	12.7	2.4434	0.3429	84.6	1.000	0.478901	0.004695	0.009803	9803.247	1.791	9596.055	1.0216
	-221.63	544.26	122	323.1667	10.7	2.4434	0.2889	83.4	1.000	0.403483	0.004628	0.011471	11470.58	1.791	11389.71	1.0071
	-221.63	544.26	122	323.1667	9.9	2.4434	0.2673	84.3	1.000	0.373316	0.004678	0.012531	12531.29	1.791	12310.09	1.0180

Table 1 (cont.)

This spreadsheet provides a data reduction procedure for treating the water content of gases

Data of Pollitzer and Strebel

Inert Gas	Tc deg. F	Pc Psia	Oper. T deg. F	Oper. T deg. K	Oper. P Atm	Tr	Pr	mg/l water	Z	Pv/zRT gmoles gas	gmoles water	m.f. water	PPMM water	VP water Psia	Ideal PPMM Water	PPMM/ PPMM-ideal
CO2	87.9	1070.6	158	343.1667	50.3	1.1280	0.6905	381.1	0.822	2.172999	0.021149	0.009733	9732.504	4.523	6118.704	1.5906
	87.9	1070.6	158	343.1667	50.5	1.1280	0.6932	386.3	0.822	2.181639	0.021437	0.009826	9826.231	4.523	6094.472	1.6123
	87.9	1070.6	158	343.1667	50.3	1.1280	0.6905	383.2	0.822	2.172999	0.021265	0.009786	9786.134	4.523	6118.704	1.5994
	87.9	1070.6	158	343.1667	50.3	1.1280	0.6905	381.1	0.822	2.172999	0.021149	0.009733	9732.504	4.523	6118.704	1.5906
	87.9	1070.6	158	343.1667	50.3	1.1280	0.6905	385.3	0.822	2.172999	0.021382	0.00984	9839.764	4.523	6118.704	1.6081
	87.9	1070.6	158	343.1667	37.8	1.1280	0.5189	314.5	0.870	1.542893	0.017453	0.011312	11311.75	4.523	8142.085	1.3893
	87.9	1070.6	158	343.1667	37.8	1.1280	0.5189	313.3	0.870	1.542893	0.017386	0.011269	11268.59	4.523	8142.085	1.3840
	87.9	1070.6	158	343.1667	29.5	1.1280	0.4049	281.3	0.900	1.163973	0.01561	0.013411	13411.34	4.523	10432.91	1.2855
	87.9	1070.6	158	343.1667	29.5	1.1280	0.4049	283.6	0.900	1.163973	0.015738	0.013521	13520.99	4.523	10432.91	1.2960
H2	-383.61	279.07	158	343.1667	152.5	8.1180	8.0307	232.4	1.080	5.01429	0.012897	0.002572	2572.005	4.523	2018.169	1.2744
	-383.61	279.07	158	343.1667	148.2	8.1180	7.8043	228	1.075	4.895568	0.012653	0.002585	2584.502	4.523	2076.726	1.2445
	-383.61	279.07	158	343.1667	144.5	8.1180	7.6095	233.3	1.070	4.79565	0.012947	0.0027	2699.681	4.523	2129.902	1.2675
	-383.61	279.07	158	343.1667	138.2	8.1180	7.2777	224.2	1.070	4.586566	0.012442	0.002713	2712.646	4.523	2226.996	1.2181
	-383.61	279.07	158	343.1667	125.1	8.1180	6.5878	220.6	1.060	4.190973	0.012242	0.002921	2921.029	4.523	2460.198	1.1873
	-383.61	279.07	158	343.1667	112.9	8.1180	5.9454	214	1.050	3.818282	0.011876	0.00311	3110.219	4.523	2726.048	1.1409
	-383.61	279.07	158	343.1667	110.3	8.1180	5.8085	216	1.045	3.748199	0.011987	0.003198	3197.984	4.523	2790.307	1.1461
	-383.61	279.07	158	343.1667	107.9	8.1180	5.6821	212.3	1.040	3.68427	0.011781	0.003198	3197.744	4.523	2852.371	1.1211
	-383.61	279.07	158	343.1667	104.5	8.1180	5.5030	213.5	1.040	3.568177	0.011848	0.00332	3320.449	4.523	2945.175	1.1274
	-383.61	279.07	158	343.1667	85.6	8.1180	4.5077	212.2	1.030	2.951209	0.011776	0.00399	3990.163	4.523	3595.454	1.1098
	-383.61	279.07	158	343.1667	83.8	8.1180	4.4130	209.6	1.030	2.889151	0.011632	0.004026	4025.931	4.523	3672.683	1.0962
	-383.61	279.07	158	343.1667	65.0	8.1180	3.4229	208.1	1.020	2.262958	0.011548	0.005103	5103.178	4.523	4734.936	1.0778
	-383.61	279.07	158	343.1667	25.8	8.1180	1.3586	205.9	1.010	0.907114	0.011426	0.012596	12596.21	4.523	11929.1	1.0559
	-383.61	279.07	158	343.1667	23.9	8.1180	1.2586	205.3	1.000	0.848714	0.011393	0.013424	13423.72	4.523	12877.44	1.0424
	-383.61	279.07	158	343.1667	21.6	8.1180	1.1375	203.6	1.000	0.767038	0.011299	0.01473	14730.11	4.523	14248.65	1.0338
Air	-221.63	544.26	158	343.1667	154.2	2.5946	4.1637	272.2	1.031	5.311157	0.015105	0.002844	2844.096	4.523	1995.92	1.4250
	-221.63	544.26	158	343.1667	150	2.5946	4.0503	270.7	1.030	5.171511	0.015022	0.002905	2904.799	4.523	2051.805	1.4157
	-221.63	544.26	158	343.1667	147.5	2.5946	3.9828	270.5	1.028	5.095212	0.015011	0.002946	2946.118	4.523	2086.582	1.4119
	-221.63	544.26	158	343.1667	145	2.5946	3.9153	267.0	1.028	5.008853	0.014817	0.002958	2958.136	4.523	2122.557	1.3937
	-221.63	544.26	158	343.1667	124	2.5946	3.3482	260.1	1.014	4.342573	0.014434	0.003324	3323.827	4.523	2482.023	1.3392
	-221.63	544.26	158	343.1667	120	2.5946	3.2402	262.4	1.010	4.219133	0.014562	0.003451	3451.324	4.523	2564.757	1.3457
	-221.63	544.26	158	343.1667	91.5	2.5946	2.4707	245.5	1.002	3.242775	0.013624	0.004201	4201.264	4.523	3363.616	1.2490
	-221.63	544.26	158	343.1667	87.1	2.5946	2.3519	242.7	1.001	3.089922	0.013468	0.004359	4358.806	4.523	3533.534	1.2336
	-221.63	544.26	158	343.1667	80.5	2.5946	2.1736	246.0	1.000	2.858639	0.013651	0.004776	4775.524	4.523	3823.24	1.2491
	-221.63	544.26	158	343.1667	74.5	2.5946	2.0116	244.4	0.999	2.648221	0.013563	0.005121	5121.442	4.523	4131.152	1.2397
	-221.63	544.26	158	343.1667	72.0	2.5946	1.9441	240.1	0.998	2.561919	0.013324	0.005201	5200.822	4.523	4274.595	1.2167
	-221.63	544.26	158	343.1667	45.0	2.5946	1.2151	229.3	0.999	1.599596	0.012725	0.007955	7954.976	4.523	6839.352	1.1631
	-221.63	544.26	158	343.1667	42.4	2.5946	1.1449	224.7	0.999	1.507175	0.012469	0.008273	8273.41	4.523	7258.746	1.1398
	-221.63	544.26	158	343.1667	16.0	2.5946	0.4320	208.4	0.999	0.568745	0.011565	0.020334	20334.1	4.523	19235.68	1.0571
	-221.63	544.26	158	343.1667	14.5	2.5946	0.3915	207.0	0.999	0.515426	0.011487	0.022287	22286.9	4.523	21225.57	1.0500
	-221.63	544.26	158	343.1667	4.85	2.5946	0.1310	203.1	0.999	0.172401	0.011271	0.065376	65375.57	4.523	63457.9	1.0302
	-221.63	544.26	158	343.1667	4.35	2.5946	0.1175	201.9	0.999	0.154628	0.011204	0.072459	72459.34	4.523	70751.91	1.0241
	-221.63	544.26	158	343.1667	2.9	2.5946	0.0783	201.1	0.999	0.103085	0.01116	0.108258	108258.3	4.523	106127.9	1.0201

Table 1 (cont.)

This spreadsheet provides a data reduction procedure for treating the water content of gases

Data of Bartlett

Inert Gas	Tc deg. F	Pc Psia	Oper. T deg. F	Oper. T deg. K	Oper. P Atm	Tr	Pr	mg/l water	Z	Pv/zRT gmoles gas	gmoles water	m.f. water	PPMM water	VP water Psia	Ideal PPMM Water	PPMM/ PPMM-ideal
H2	-383.76	278.03	122	323.1667	100	7.6600	5.2858	89.1	1.058	3.564152	0.004945	0.001387	1387.288	1.791	1218.699	1.1383
	-383.76	278.03	122	323.1667	200	7.6600	10.5715	95.5	1.114	6.76997	0.0053	0.000783	782.8199	1.791	609.3495	1.2847
	-383.76	278.03	122	323.1667	400	7.6600	21.1430	101.8	1.230	12.263	0.005649	0.000461	460.6766	1.791	304.6747	1.5120
	-383.76	278.03	122	323.1667	600	7.6600	31.7146	108	1.360	16.63621	0.005993	0.00036	360.2589	1.791	203.1165	1.7737
	-383.76	278.03	122	323.1667	1000	7.6600	52.8576	118.7	1.600	23.56796	0.006587	0.000279	279.495	1.791	121.8699	2.2934
N2	-232.4	493	122	323.1667	100	2.5592	2.9809	105.4	1.009	3.737238	0.005849	0.001565	1565.075	1.791	1218.699	1.2842
	-232.4	493	122	323.1667	200	2.5592	5.9619	125.9	1.076	7.009058	0.006987	0.000997	996.8075	1.791	609.3495	1.6359
	-232.4	493	122	323.1667	400	2.5592	11.9237	148.3	1.240	12.16411	0.00823	0.000677	676.5597	1.791	304.6747	2.2206
	-232.4	493	122	323.1667	600	2.5592	17.8856	161.5	1.475	15.33915	0.008962	0.000584	584.274	1.791	203.1165	2.8765
	-232.4	493	122	323.1667	1000	2.5592	29.8093	170.3	1.950	19.33781	0.009451	0.000489	488.7115	1.791	121.8699	4.0101
3H2: 1N2	-345.92	331.8	122	323.1667	100	5.1125	4.4292	92.3	1.053	3.581076	0.005122	0.00143	1430.32	1.791	1218.699	1.1736
	-345.92	331.8	122	323.1667	200	5.1125	8.8583	103.3	1.112	6.782146	0.005733	0.000845	845.2368	1.791	609.3495	1.3871
	-345.92	331.8	122	323.1667	300	5.1125	13.2875	106.3	1.181	9.578848	0.005899	0.000616	615.8362	1.791	406.233	1.5160
	-345.92	331.8	122	323.1667	400	5.1125	17.7167	111.4	1.251	12.05715	0.006182	0.000513	512.7265	1.791	304.6747	1.6829
	-345.92	331.8	122	323.1667	600	5.1125	26.5750	123.2	1.398	16.18401	0.006837	0.000422	422.4447	1.791	203.1165	2.0798
	-345.92	331.8	122	323.1667	800	5.1125	35.4334	127.2	1.547	19.50031	0.007059	0.000362	361.9851	1.791	152.3374	2.3762
	-345.92	331.8	122	323.1667	1000	5.1125	44.2917	130.6	1.697	22.22082	0.007248	0.000326	326.1582	1.791	121.8699	2.6763
	-345.99	331.25	100	310.9444	200	4.9222	8.8731	56.5	1.115	7.029765	0.003135	0.000446	446.0185	0.9503	323.3193	1.3795
	-345.99	331.25	100	310.9444	400	4.9222	17.7461	62.9	1.258	12.46135	0.003491	0.00028	280.1114	0.9503	161.6596	1.7327
	-345.99	331.25	100	310.9444	600	4.9222	26.6192	69.3	1.411	16.66518	0.003846	0.000231	230.7642	0.9503	107.7731	2.1412
	-345.99	331.25	100	310.9444	1000	4.9222	44.3653	74.6	1.717	22.82524	0.00414	0.000181	181.3713	0.9503	64.66385	2.8048
	-346.07	330.7	77	298.1667	100	4.7232	4.4439	26.7	1.058	3.862991	0.001482	0.000384	383.5595	0.4596	312.7382	1.2265
	-346.07	330.7	77	298.1667	200	4.7232	8.8878	31.0	1.118	7.31135	0.00172	0.000235	235.2932	0.4596	156.3691	1.5047
	-346.07	330.7	77	298.1667	300	4.7232	13.3317	34.1	1.192	10.28619	0.001892	0.000184	183.9692	0.4596	104.2461	1.7648
	-346.07	330.7	77	298.1667	400	4.7232	17.7756	35.2	1.266	12.91325	0.001953	0.000151	151.2698	0.4596	78.18454	1.9348
	-346.07	330.7	77	298.1667	600	4.7232	26.6634	40.0	1.424	17.22069	0.00222	0.000129	128.9005	0.4596	52.12303	2.4730
	-346.07	330.7	77	298.1667	800	4.7232	35.5513	42.3	1.581	20.68081	0.002347	0.000114	113.5058	0.4596	39.09227	2.9035
	-346.07	330.7	77	298.1667	1000	4.7232	44.4391	44.2	1.738	23.51579	0.002453	0.000104	104.3057	0.4596	31.27382	3.3352

TABLE 2

HYDCRIT

T,F	T,R	TC,F	TC,R	PC,ATM
30	489.7	-384.2144	75.48558	18.69628
31	490.7	-384.2086	75.49146	18.69911
32	491.7	-384.2027	75.49731	18.70194
33	492.7	-384.1969	75.50313	18.70475
34	493.7	-384.1911	75.50893	18.70756
35	494.7	-384.1853	75.5147	18.71035
36	495.7	-384.1795	75.52046	18.71314
37	496.7	-384.1738	75.5262	18.71591
38	497.7	-384.1681	75.53191	18.71867
39	498.7	-384.1624	75.5376	18.72143
40	499.7	-384.1567	75.54327	18.72417
41	500.7	-384.1511	75.54891	18.7269
42	501.7	-384.1455	75.55453	18.72963
43	502.7	-384.1399	75.56013	18.73234
44	503.7	-384.1343	75.56572	18.73504
45	504.7	-384.1287	75.57128	18.73773
46	505.7	-384.1232	75.57682	18.74042
47	506.7	-384.1177	75.58234	18.74309
48	507.7	-384.1122	75.58784	18.74575
49	508.7	-384.1067	75.59331	18.7484
50	509.7	-384.1013	75.59877	18.75105
51	510.7	-384.0958	75.6042	18.75368
52	511.7	-384.0904	75.60962	18.75631
53	512.7	-384.085	75.61501	18.75892
54	513.7	-384.0796	75.62038	18.76153
55	514.7	-384.0743	75.62574	18.76412
56	515.7	-384.0689	75.63107	18.76671
57	516.7	-384.0636	75.63638	18.76929
58	517.7	-384.0583	75.64168	18.77185
59	518.7	-384.053	75.64696	18.77441
60	519.7	-384.0478	75.65221	18.77696
61	520.7	-384.0426	75.65744	18.7795
62	521.7	-384.0374	75.66266	18.78204
63	522.7	-384.0322	75.66786	18.78456
64	523.7	-384.027	75.67303	18.78707
65	524.7	-384.0218	75.67819	18.78958
66	525.7	-384.0167	75.68333	18.79207
67	526.7	-384.0116	75.68845	18.79456
68	527.7	-384.0064	75.69356	18.79704
69	528.7	-384.0014	75.69864	18.79951
70	529.7	-383.9963	75.70371	18.80197
71	530.7	-383.9913	75.70875	18.80442
72	531.7	-383.9862	75.71378	18.80687
73	532.7	-383.9812	75.71879	18.8093
74	533.7	-383.9762	75.72378	18.81173
75	534.7	-383.9713	75.72876	18.81415
76	535.7	-383.9663	75.73372	18.81656
77	536.7	-383.9614	75.73866	18.81896
78	537.7	-383.9565	75.74357	18.82135
79	538.7	-383.9515	75.74847	18.82374
80	539.7	-383.9467	75.75336	18.82611
81	540.7	-383.9418	75.75823	18.82848
82	541.7	-383.937	75.76308	18.83084
83	542.7	-383.9321	75.76791	18.83319
84	543.7	-383.9273	75.77273	18.83554
85	544.7	-383.9225	75.77753	18.83787
86	545.7	-383.9177	75.78231	18.8402
87	546.7	-383.9129	75.78707	18.84252
88	547.7	-383.9082	75.79182	18.84483
89	548.7	-383.9034	75.79655	18.84714
90	549.7	-383.8987	75.80127	18.84943
91	550.7	-383.894	75.80596	18.85172

TABLE 2 CONT. -

92	551.7	-383.8894	75.81065	18.854
93	552.7	-383.8847	75.81532	18.85628
94	553.7	-383.88	75.81996	18.85854
95	554.7	-383.8754	75.8246	18.8608
96	555.7	-383.8708	75.82922	18.86305
97	556.7	-383.8662	75.83382	18.86529
98	557.7	-383.8616	75.8384	18.86753
99	558.7	-383.8571	75.84296	18.86976
100	559.7	-383.8525	75.84753	18.87198
101	560.7	-383.848	75.85206	18.87419
102	561.7	-383.8434	75.85658	18.8764
103	562.7	-383.8389	75.86109	18.8786
104	563.7	-383.8344	75.86558	18.88079
105	564.7	-383.83	75.87006	18.88297
106	565.7	-383.8255	75.87452	18.88515
107	566.7	-383.821	75.87896	18.88732
108	567.7	-383.8166	75.88339	18.88948
109	568.7	-383.8122	75.8878	18.89163
110	569.7	-383.8078	75.8922	18.89378
111	570.7	-383.8034	75.89659	18.89592
112	571.7	-383.799	75.90096	18.89806
113	572.7	-383.7947	75.90532	18.90018
114	573.7	-383.7903	75.90966	18.9023
115	574.7	-383.786	75.91399	18.90442
116	575.7	-383.7817	75.9183	18.90652
117	576.7	-383.7774	75.9226	18.90862
118	577.7	-383.7731	75.92687	18.91072
119	578.7	-383.7689	75.93114	18.9128
120	579.7	-383.7646	75.9354	18.91488
121	580.7	-383.7604	75.93964	18.91695
122	581.7	-383.7561	75.94387	18.91902
123	582.7	-383.7519	75.94808	18.92108
124	583.7	-383.7477	75.95228	18.92313
125	584.7	-383.7436	75.95647	18.92518
126	585.7	-383.7394	75.96063	18.92722
127	586.7	-383.7352	75.96478	18.92925
128	587.7	-383.7311	75.96893	18.93128
129	588.7	-383.727	75.97306	18.9333
130	589.7	-383.7228	75.97717	18.93531
131	590.7	-383.7187	75.98128	18.93732
132	591.7	-383.7147	75.98537	18.93932
133	592.7	-383.7106	75.98944	18.94131
134	593.7	-383.7065	75.9935	18.9433
135	594.7	-383.7025	75.99755	18.94528
136	595.7	-383.6984	76.00159	18.94726
137	596.7	-383.6944	76.00562	18.94923
138	597.7	-383.6904	76.00962	18.95119
139	598.7	-383.6864	76.01362	18.95315
140	599.7	-383.6824	76.0176	18.9551
141	600.7	-383.6784	76.02157	18.95704
142	601.7	-383.6745	76.02553	18.95898
143	602.7	-383.6705	76.02947	18.96091
144	603.7	-383.6666	76.03341	18.96284
145	604.7	-383.6627	76.03733	18.96476
146	605.7	-383.6588	76.04124	18.96668
147	606.7	-383.6549	76.04513	18.96859
148	607.7	-383.651	76.04901	18.97049
149	608.7	-383.6471	76.05288	18.97239
150	609.7	-383.6433	76.05674	18.97428
151	610.7	-383.6394	76.06059	18.97616
152	611.7	-383.6356	76.06441	18.97804
153	612.7	-383.6318	76.06824	18.97992
154	613.7	-383.628	76.07205	18.98178

TABLE 2 CONT. -

155	614.7	-383.6242	76.07585	18.98365
156	615.7	-383.6204	76.07964	18.9855
157	616.7	-383.6166	76.0834	18.98735
158	617.7	-383.6129	76.08717	18.9892
159	618.7	-383.6091	76.09091	18.99104
160	619.7	-383.6053	76.09466	18.99287
161	620.7	-383.6016	76.09838	18.9947
162	621.7	-383.5979	76.1021	18.99653
163	622.7	-383.5942	76.1058	18.99834
164	623.7	-383.5905	76.10949	19.00016
165	624.7	-383.5869	76.11317	19.00196
166	625.7	-383.5832	76.11684	19.00377
167	626.7	-383.5795	76.1205	19.00556
168	627.7	-383.5759	76.12415	19.00735
169	628.7	-383.5722	76.12778	19.00914
170	629.7	-383.5686	76.1314	19.01092
171	630.7	-383.565	76.13501	19.01269
172	631.7	-383.5614	76.13862	19.01446
173	632.7	-383.5578	76.1422	19.01622
174	633.7	-383.5542	76.14578	19.01798
175	634.7	-383.5507	76.14935	19.01974
176	635.7	-383.5471	76.15292	19.02148
177	636.7	-383.5435	76.15646	19.02323
178	637.7	-383.54	76.15999	19.02497
179	638.7	-383.5365	76.16352	19.0267
180	639.7	-383.533	76.16704	19.02843
181	640.7	-383.5295	76.17054	19.03015
182	641.7	-383.526	76.17403	19.03187
183	642.7	-383.5225	76.17751	19.03358
184	643.7	-383.519	76.18099	19.03529
185	644.7	-383.5156	76.18445	19.03699
186	645.7	-383.5121	76.1879	19.03869
187	646.7	-383.5087	76.19134	19.04038
188	647.7	-383.5052	76.19477	19.04207
189	648.7	-383.5018	76.19819	19.04375
190	649.7	-383.4984	76.2016	19.04543
191	650.7	-383.495	76.205	19.0471
192	651.7	-383.4916	76.2084	19.04877
193	652.7	-383.4883	76.21177	19.05043
194	653.7	-383.4849	76.21514	19.05209
195	654.7	-383.4815	76.2185	19.05375
196	655.7	-383.4781	76.22186	19.0554
197	656.7	-383.4748	76.22519	19.05704
198	657.7	-383.4715	76.22852	19.05868
199	658.7	-383.4682	76.23184	19.06031
200	659.7	-383.4649	76.23515	19.06194

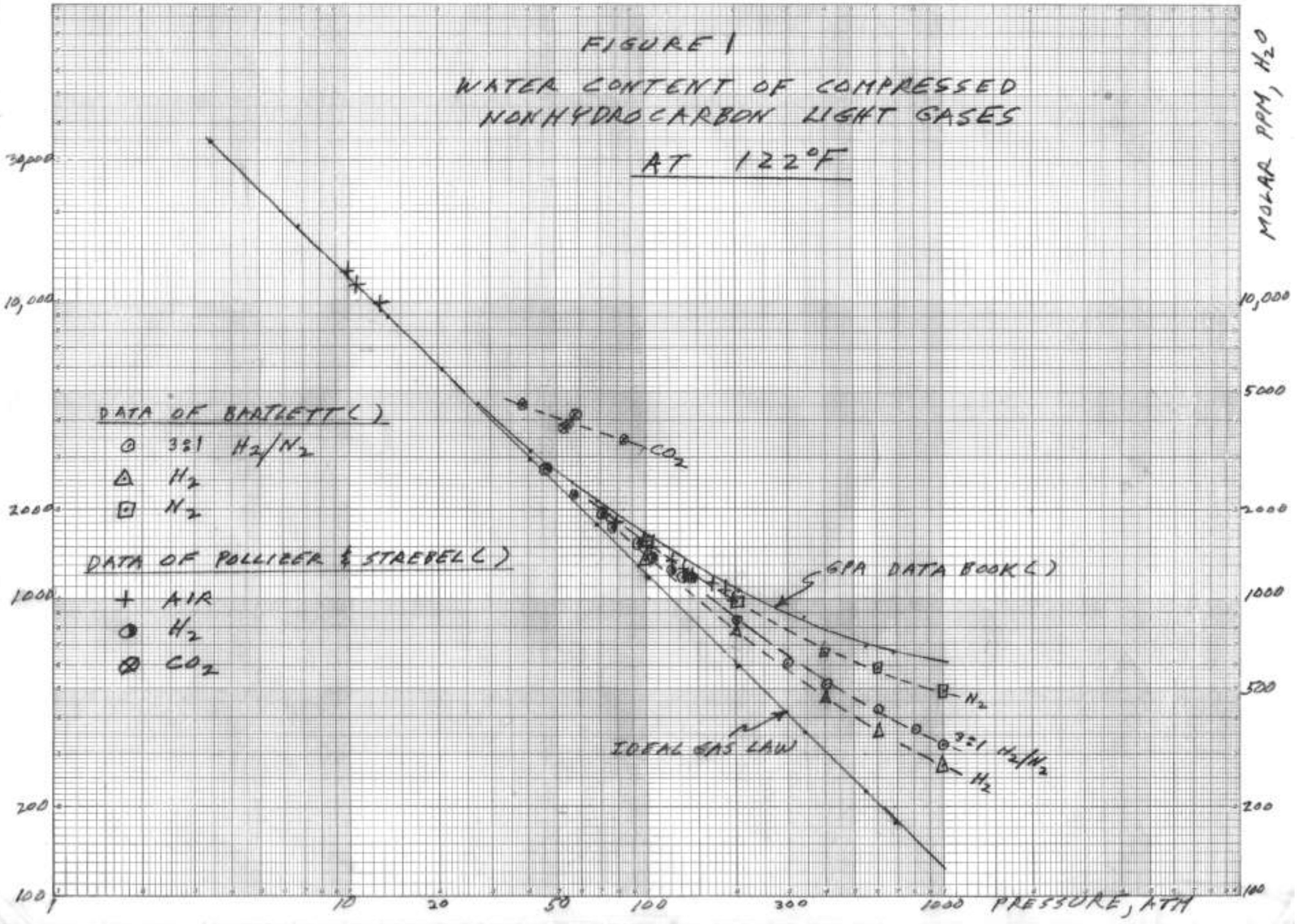


FIGURE 1

WATER CONTENT OF COMPRESSED NONHYDROCARBON LIGHT GASES

AT 122°F

CRK, 12-8-11.

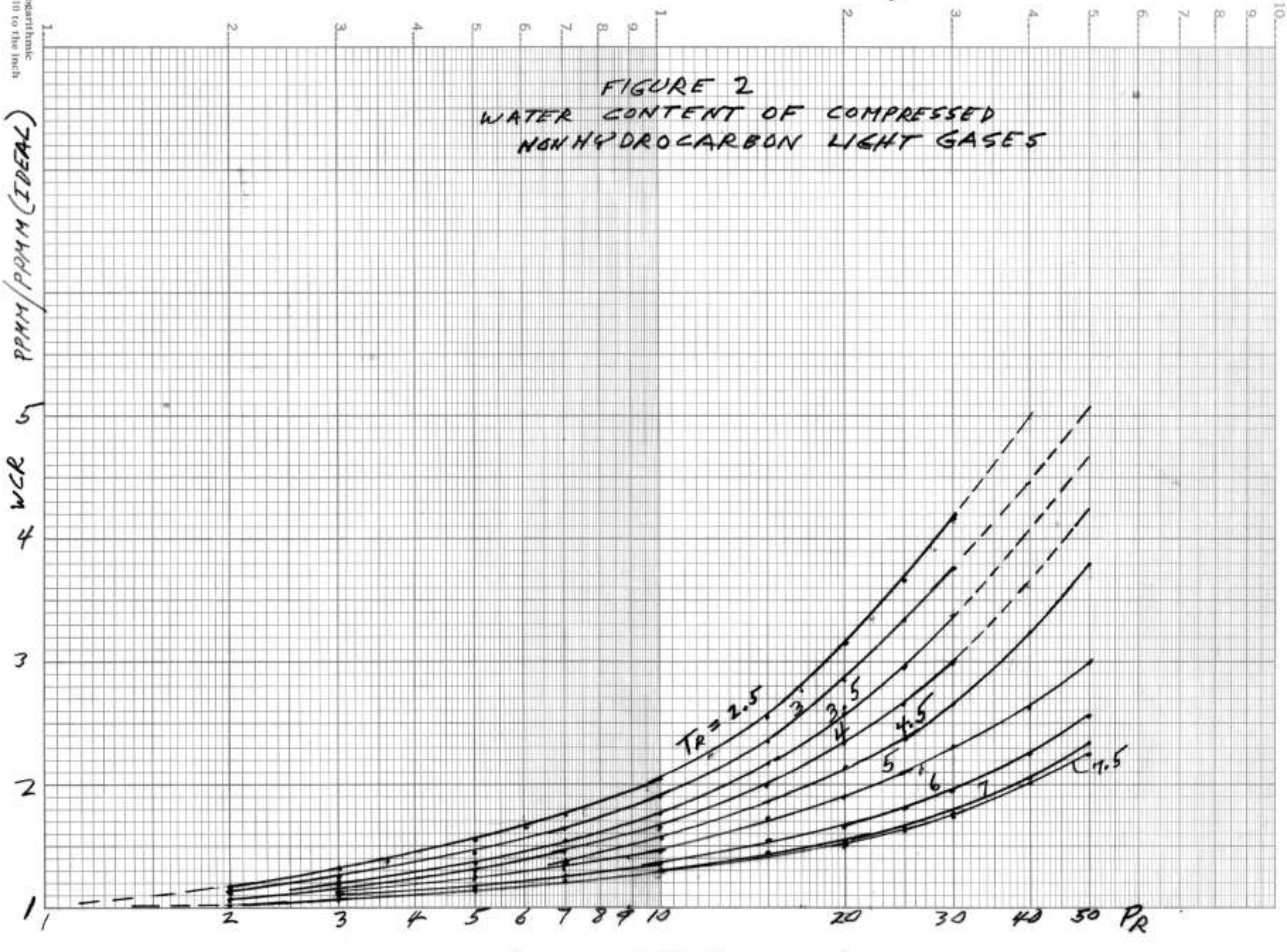
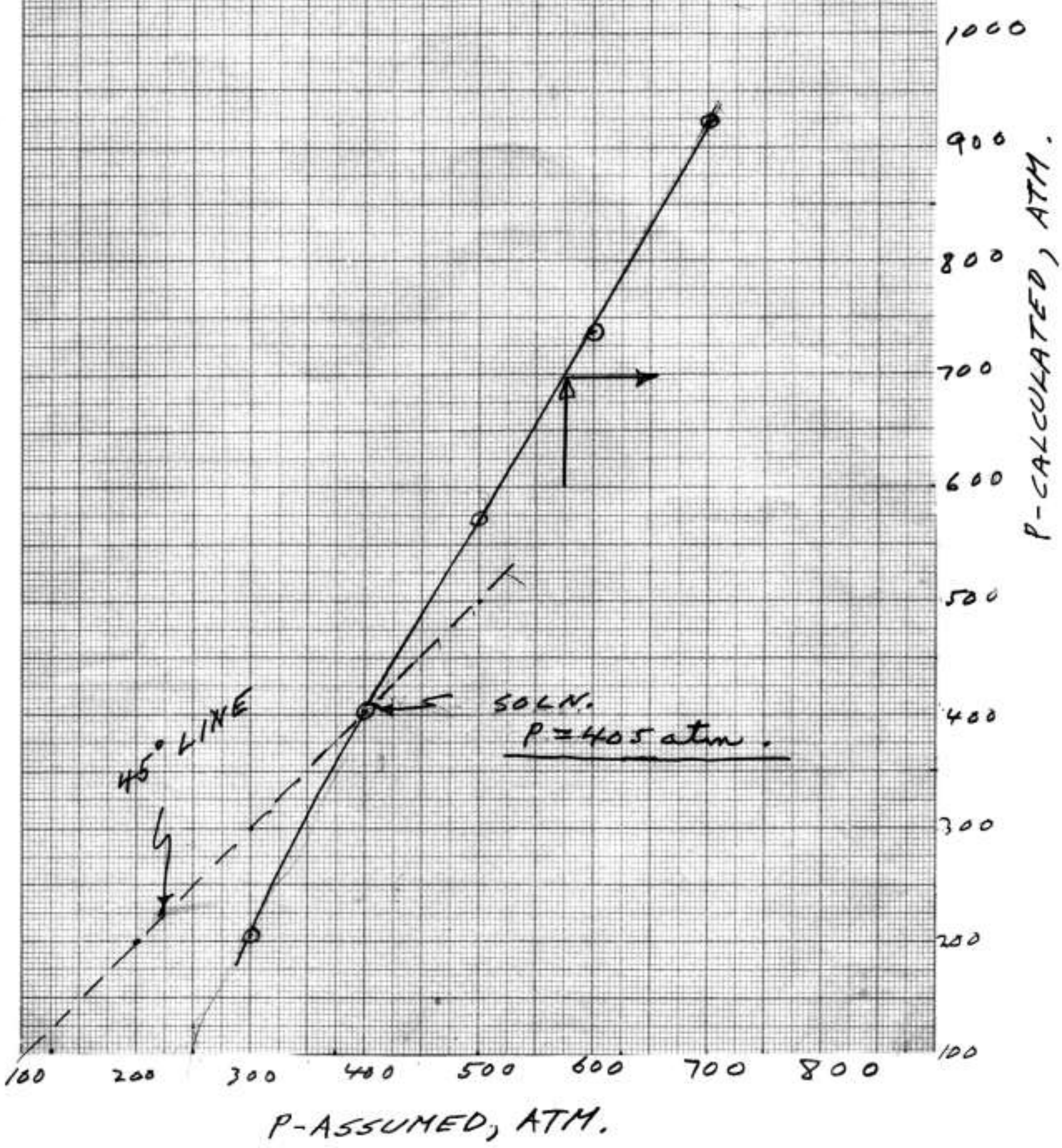


FIGURE 2
WATER CONTENT OF COMPRESSED
NONHYDROCARBON LIGHT GASES

CRK, 12-15-11.

FIGURE 3

GRAPHICAL ITERATIVE SOLUTION FOR ILLUSTRATION 2.



AUTHOR'S BACKGROUND

Dr. Charles R. Koppany is a retired chemical engineer formerly employed by C F Braun & Co/ Brown & Root, Inc. from 1965 to 1994. While at Braun he served in both the Research and Process Engineering departments. Dr. Koppany has also done part-time teaching in the Chemical Engineering Departments at Cal Poly University Pomona and the University of Southern California. He holds B.S., M.S. and PhD degrees in Chemical Engineering from the University of Southern California and is a registered professional engineer (Chemical) in the state of California.

crkoppany@aol.com