SIMPLIFIED METHOD FOR DETERMINING COMPRESSOR REQUIREMENTS FROM FIELD DATA

David J. Sager

In order to select a compressor, or calculate the performance of a compressor, certain design criteria must be known. This criteria is listed below:

1. Gas analysis. A gas analysis is preferred, but if one is not available, then the specific gravity or molecular weight, n value, critical pressure and critical temperature of the gas can be used.

2. Capacity. This is generally given in either MSCFD or MMSCFD (Thousand Standard Cubic Feet Per Day or Million Standard Cubic Feet Per Day) at a given base pressure and temperature. (Example: 14.65 PSIA & 60°F).

3. Inlet temperature. At the compressor inlet.

4. Inlet pressure. At the compressor inlet.

5. Discharge pressure. At the compressor outlet.

6. Elevation. At the compressor location.

Assuming values for the above design criteria, calculations can be made to either select a compressor, or calculate the performance of an existing compressor. For example, assume the following design criteria:

1. Gas analysis:

	Mol %
Methane	84.9%
Ethane	8.2%
Propane	2.5%
Iso-Butane	0.5%
Norm-Butane	1.2%
Peutane	0.5%
Hexanes +	0.5%
Nitrogen	1.2%
Carbon Dioxide	0.5%
	100.0%

2. Capacity = 2.0 MMSCFD (measured at 14.65 PSIA & 60°F).

3. Inlet temperature = 80°F

4. Inlet pressure = 240 PSIG

5. Discharge pressure = 1050 PSIG

6. Elevation = 2700 ft.

Based on the above C.O.S. (Conditions Of Service) we can determine the following values which are necessary to select a compressor, or calculate its performance.

A. Barometric pressure. The barometric pressure is determined by the elevation. This can be arrived at by using a formula, or an existing curve of which there are many. (See Exhibit A.) By using the attached curve (Exhibit A), it can be determined that the barometric pressure at 2700 ft. is 13.3 PSIA. It is necessary to know the barometric pressure because all compressor calculations are made using absolute values, whether it be pressure or temperature. Absolute pressures are gauge pressures plus the barometric pressure. In this case, the absolute inlet pressure (Ps) is; Ps = 240 PSIG +13.3 PSI = 253.3 PSIA; and the absolute discharge pressure (Pd) is Pd = 1050 PSIG +13.3 PSI = 1063.3 PSIA.

B. The ratio of compression. To determine the ratio of compression, the formula:

$Rc = \frac{Pd\ (PSIA)}{Ps\ (PSIA)}$ is used, where Rc is the ratio of compression, Pd is the absolute discharge pressure and Ps is the absolute inlet pressure. For our case the ratio of compression is:

$$Rc = \frac{1063.3\ (PSIA)}{253.3\ (PSIA)} = 4.20$$

C. The number of stages of compression required. The number of stages of compression required is normally determined by the discharge temperature of the compressor. This can be either the manufacturers' maximum allowable discharge temperature limit, or a specified limit, such as 300°F as in API - 11P.

Another determining factor of the number of stages required is the rod load or frame load rating of the compressor. In some cases you may not be exceeding the temperature limit, but you may be exceeding the allowable rod load limit of the compressor. By adding one more stage of compression you can reduce the rod load on the compressor. The calculations will follow.

Another determining factor for the number of stages is the volumetric efficiency of the cylinder. This comes into play mainly on propane applications because the low n value of propane allows a high ratio of compression without exceeding the discharge temperature limit, but this high ratio of compression causes a low volumetric efficiency and most manufacturers limit the V.E. to a minimum of 15%.

With all this, a good rule of thumb for the maximum number of ratios in a stage of compression is 4.0 to 4.5. Again, as long as the discharge temperature limit, the rod load limit, and the volumetric efficiency are not exceeded, then the ratio of compression in that stage is acceptable.

D. Discharge temperature. To determine the theoretical discharge temperature for a given ratio of compression, the following formula is used:

$$Td = Ts\ (Rc^{\frac{n-1}{n}})$$

Where Td is the absolute discharge temperature, Ts is the absolute inlet temperature and n is the ratio of specific heats of the gas. The absolute temperatures are in degrees Rankin, which is degrees Fahrenheit plus 460. n, or the ratio of specific heats is determined by the gas analysis or from the specific gravity. (See Exhibit B where the n value 1.267 was calculated basis the gas analysis, and then compared that to Exhibit C using a temperature of 60^{o}F which is what Exhibit B is based on.)

Using the value 1.267 for n, the discharge temperature for the Rc of 4.20, when Ts = 540 (80 + 460), is:

$$Td = 540\ (4.20^{\frac{.267}{1.267}}) = 731 - 460 = 271^{o}F$$

An easier way to determine the discharge temperature is to use a nomograph. (See Exhibit D.) To use the nomograph, you first find the ratio of compression on the right hand side. Go left to the n (k) value, then go vertically (up or down) to the inlet temperature. At the point where you intersect the inlet temperature curve, read left to the discharge temperature.

Seeing that the Td is 271^{o}F, we can do this compression in a single stage of compression, unless we find out later that we exceed the rod load or minimum V.E. limits of the compressor.

E. Estimate the compressor horsepower required. In order to estimate the compressor horsepower required to compress 2.0 MMSCFD from Ps = 253.3 PSIA to Pd = 1063.3 PSIA, the following formula can be used.

Compressor bhp = (22) (Rc per stage) (No. of stages) (MMSCFD) or,

Compressor bhp = (22) (4.20) (1) (2.0) = 184.8 bhp

This equation is close for gases with a specific gravity around 0.65, and stage compression ratios of 2.5.

A quick and easy method to determine the required compressor horsepower is to use the chart on Exhibit E. To use this chart, find the suction pressure in the left hand column and read across to the correct vertical discharge pressure column. This will give you the horsepower for each 1.0 MMSCFD of gas being compressed. Multiply this horsepower figure by the capacity (in MMSCFD) to determine the total horsepower required. Example, Ps = 250 PSIG and Pd = 1000 PSIG which gives 85 bhp/MMSCFD. Multiplying 85 bhp/MMSCFD times 2.0 MMSCFD gives a horsepower of 170.0 bhp. This compares with the 184.8 bhp calculated by the above formula.

F. Determine the required compressor displacement. To do this, we must convert the capacity from MMSCFD to acfm (actual cubic feet per minute at suction conditions). For this example it is at 250 PSIG and 80^{o}F.

The formula used for this conversion is:

$$acfm = \frac{SCFD}{1440} \times \frac{\text{Base Pressure (PSIA)}}{\text{Inlet Pressure (PSIA)}} \times \frac{\text{Inlet Temperature }(^{o}R)}{\text{Base Temperature }(^{o}R)}$$

$$acfm = \frac{2,000,000}{1440} \times \frac{14.65}{253.3} \times \frac{540}{520} = 83.4 \text{ cfm}$$

Once the acfm is known, the required displacement can be estimated by using the formula:

$$\text{Displacement (cfm)} = \frac{\text{acfm}}{\text{V.E.}} \text{ (Volumetric Efficiency)}$$

or

$$\text{Displacement (cfm)} = \frac{83.4}{0.61} = 136.7 \text{ cfm}$$

The V.E. of 0.61 was obtained by using Exhibit F. Exhibit F lets you pick the approximate V.E. basis the known ratio of compression and an estimated cylinder clearance. For estimating purposes, we use a cylinder clearance of 15%. By reading up vertically on the 15% clearance line to a ratio of compression of 4.20, and then left to the volumetric efficiency scale, we get a volumetric efficiency of 61.0%.

At this point it is advisable to stop and summarize what we have determined regarding the selection and performance of the compressor for given C.O.S. of:

1. Gas - n = 1.267
2. Capacity - 2.0 MMSCFD
3. Inlet temperature - 80°F
4. Inlet pressure - 250 PSIG
5. Discharge pressure - 1050 PSIG
6. Elevation - 2700 ft.

The following has been determined about the compressor selection and performance:

A. Barometric pressure - 13.3 PSIA

B. Rc - 4.20

C. Number of stages of compression - one

D. Theoretical discharge temperature - 271°F

E. Compressor brake horsepower - 184.8

F. Required cylinder displacement - 136.7 cfm

G. Volumetric efficiency - 61.0%

H. Required cylinder working pressure rating - 1050 PSIG minimum, as this is the required discharge pressure.

At this point it is necessary to mention that without some specific technical data from a compressor manufacturer, it is difficult to finish sizing this compressor. The minimum technical data required to complete this sizing is the horsepower and frame load rating of available frames, and the cylinder bores for these different frames with their corresponding working pressure ratings and inherent clearances.

Since Compressor Systems, Inc., who I am associated with, is a franchised distributor and packager of several different compressor lines, much technical data is available to us to accurately size and calculate performance on these different compressors. Also, being familiar with these different lines of compressors, it is possible for us to rule out several lines due to the horsepower and the high discharge pressure (1050 PSIG). The decision then on the compressor selection would be for either a balanced opposed compressor with one or two cylinders (dictated by displacement and working pressure rating), or a single-throw horizontal compressor. Generally, we would look at a single cylinder compressor first to see if it could handle the given conditions of services.

In this example, the single-throw horizontal compressor will be looked at.

Knowing that the Worthington HBGG compressor line has the following frames available:

Stroke (Ins.)	Piston Rod Dia. (Ins.)	Max. B.H.P.	Max. Frame Load (Lbs.)
5	1.375	39	5,500
7	1.625	66	9,000
9	1.750	100	14,000
11	2.000	170	18,000
13	2.500	220	25,000

it can be determined from the estimated bhp of 184.8 that the 13" stroke frame is required for this application.

From Exhibit G (dimension and specification page form Worthington's brochure entitled "Type HBGG Single-Horizontal Gas-Field Compressors") it can be seen that the closest bore size on the 13" frame to handle this application is the 6" bore which has a working pressure rating of 1250 PSIG, but a displacement of only 127.0 cfm. This size may work even though it is estimated that 136.7 cfm is required, and that is due to the actual inherent miminum clearance on this cylinder being only 9.0% and not 15% as used in the approximation done earlier.

Working a little differently now to see if the 6 X 13 HBGG size will work on this sample compressor application, the following steps will be taken:

1. Find V.E. basis actual cylinder clearance of 9.0%.
   From Exhibit F, reading up from 9.0% clearance to 4.20 ratios, and then to the left, the approximate V.E. is 74.-%.

2. Calculate compressor acfm knowing the cylinder displacement is 127.0 cfm and the V.E. is 74.0%.

   $$\text{Displacement (cfm)} = \frac{\text{acfm}}{\text{V.E.}}\text{, then}$$

   $$\text{acfm} = \text{Displacement (cfm) (V.E.)} = (127)\ (.74) = 94.0$$

3. Calculate MMSCFD to see if this compressor will handle the desired flow of 2.0 MMSCFD.
   Basis the formula:

$$acfm = \frac{SCFD}{1440} \times \frac{\text{Base Pressure (PSIA)}}{\text{Suction Pressure (PSIA)}} \times \frac{\text{Suction Temperature } (^{O}R)}{\text{Base Temperature } (^{O}R)}$$

then

$$94.0 = \frac{SCFD}{1440} \times \frac{14.65}{253.3} \times \frac{540}{520}$$

$$SCFD = \frac{(94.0)\ (1440)\ (253.3)\ (520)}{(14.65)\ (540)} = 2,253,707$$

4. Calculate compressor bhp basis actual flow of 2,253,707 SCFD. Using the formula:

   Compressor bhp = (22) (Ratios/Stage) (No. of stages) (MMSCFD)

   Compressor bhp = (22) (4.20) (1) (2.253) = 208.2

5. Calculate frame load to see that it is less than the maximum allowable.

Two additional pieces of information are required to make the frame load calculation. The two items are the area of the piston, and the cross-sectional area of the piston rod. From Exhibit H (Areas of Circles) it shows that the area of a 6" circle is 28.3 square inches, and the area of a 2.5" circle is 4.9 square inches. Having these two areas it is possible to use the formula:

F.L. compression = Area of Piston X Discharge Pressure (PSIA) - (Area of Piston-Area of Piston Rod) X Suction Pressure (PSIA)

F.L. compression = (28.3) (1063.3) - (28.3 - 4.9) (253.3) = 24,164 lbs.

F.L. tension = (Area of Piston-Area of Piston Rod) X Discharge Pressure (PSIA) - Area of Piston X Suction Pressure (PSIA)

F.L. tension = (28.3 - 4.9) (1063.3) - (28.3) (253.3) = 17,713 lbs.

Note: Both of these numbers should be positive to indicate that rod reversal is taking place. Havina a rod reversal indicates that proper lubrication is ocurring between the crosshead and cross-head pin.

Seeing that the frame load in both compression and tension is below 25,000 lbs. indicates that this compressor is acceptable for this particular application.

A check of this simplified sizing method is included as Exhibit I. The same conditions as were used in the sample problem were run on the Compressor Systems, Inc. computer, and the estimated performance from the computer is very encouraging for using this simplified method. The data fed into the computer was as follows:

1. Elevation.
2. Gas analysis.
3. Make of compressor.
4. Model of compressor.
5. Number of stages of compression.

6. Number of cylinders.

7. Cylinder diameter.

8. Cylinder clearance.

9. Suction temperature (^{O}F).

10. Suction pressure (PSIG).

11. Discharge pressure (PSIG).

A comparison of the computer calculated performance with the simplified version discussed above is shown below:

1. Barometric pressure (PSIA) was 13.296 from the computer vs. 13.3 (PSIA) from Exhibit A.

2. Discharge temperature (^{O}F) was 255.5 from the computer vs. 271 from the nomograph.

3. The compression ratio calculated by the computer was 4.1978 vs. 4.20 by hand.

4. The volumetric efficiency was 71.25% from the computer vs. 74.0% from Exhibit E.

5. Flow (capacity) was 2268 MSCFD or 2,268,000 SCFD vs. 2,253,707 which was calculated by the simplified method. (Note, C.S.I.'s computer program is based on using compressibility which is a relationship involving the critical temperature and pressure of the gas stream and this accounts for some of the difference between the computer calculation and the simplified version. For record purposes, the critical temperature used was 381^{O}R and the critical pressure was 670 PSIA.)

6. Total brake horsepower from the computer was 196.0 as compared to the 208.2 which was estimated from the simplified formula.

7. The computed compression and tension rod loads were 24,145 lbs. and 17,682 lbs., respectively. This compared to the estimated 24,164 lbs. and 17,713 lbs., respectively.

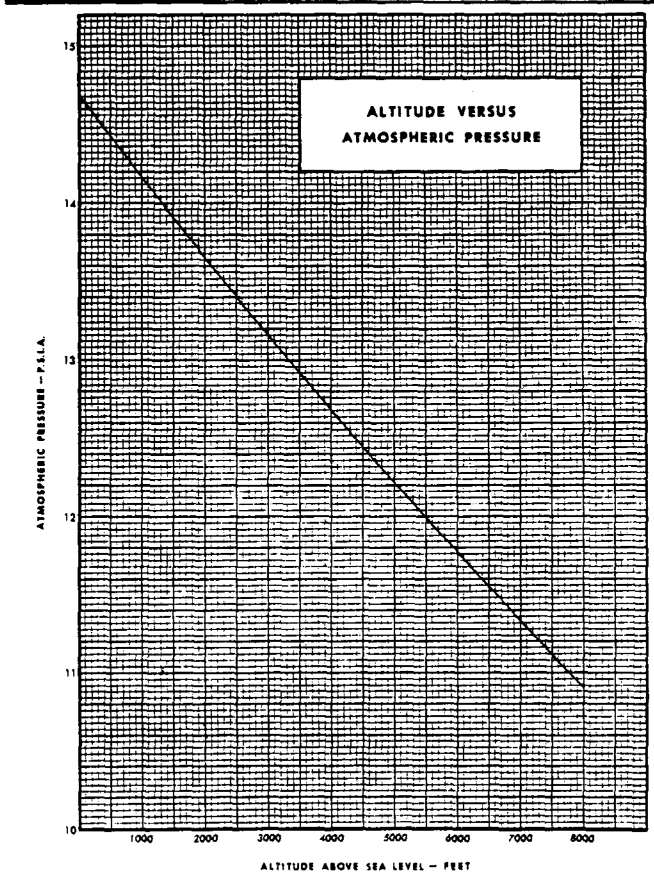
As can be seen by the above comparison, the simplified sizing/calculating method presented here is very reliable for predicting horsepower and displacement for individual well compressors. If enough data is known about a particular compressor, a good prediction of estimated performance can be made for any given set of conditions.

GENERAL DATA

GAS GATHERING COMPRESSORS

BAROMETRIC PRESSURE CURVE

EXHIBIT A



WORTHINGTON (COURTESY WORTHINGTON COMPRESSORS, INC.) Litho'd. in U.S.A.

EXHIBIT B

TYPICAL GAS ANALYSIS: 84.9% Methane, 8.2% Ethane 2.5% Propane, 0.5% Iso-Butane, 1.2% Norm. Butane, 0.5% Pentane, 0.5% Hexanes+, 1.2% Nitrogen and 0.5% Carbon Dioxide

GAS	FORMULA	% MOL.	MOL.WT.	MOL. # FRACT.	Cp/MOL.	Cp/MOL. FRACT.	TC	PART TC	PC	PART PC
Methane	CH_4	.849	16.042	13.62	8.435	7.16	344	292	673	571
Ethane	C_2H_6	.082	30.068	2.47	12.304	1.01	550	45	709	58
Propane	C_3H_8	.025	44.094	1.10	17.086	0.43	666	17	618	15
Iso-Butane	C_4H_{10}	.005	58.120	0.29	22.463	0.11	733	4	543	3
Norm. Butane	C_4H_{10}	.012	58.120	0.70	23.079	0.28	767	9	529	6
Pentane	C_5H_{12}	.005	72.146	0.36	28.671	0.14	847	4	485	2
Hexane	C_6H_{14}	.005	86.172	0.43	34.331	0.17	914	5	433	2
Heptane	C_7H_{16}		100.198		39.999		973		397	
Ethene	C_2H_4		28.052		10.127		510		749	
Propene	C_3H_6		42.078		15.190		657		668	
Butene	C_4H_8		56.104		20.648		751		619	
Pentene	C_5H_{10}		70.130		26.649		854		595	
Hexene	C_6H_{12}		84.156		30.296		931			
Water	H_2O		18.02		8.03		1165		3206	
Hydrogen	H_2		2.016		6.871		74		306	
Oxygen	O_2		32.000		7.002		279		730	
Nitrogen	N_2	.012	28.016	0.34	6.954	0.08	228	3	492	6
Carbon Monoxide	CO		28.010		6.956		242		514	
Carbon Dioxide	CO_2	.005	44.010	0.22	8.762	0.04	548	3	1073	5
Hyd. Sulfide	H_2S		34.076		8.655		672		1306	
Sulph. Dioxide	SO_2		64.060		9.417		775		1142	
Ammonia	NH_3		17.030		8.956		731		1657	
Argon	A		39.944		4.913		272		705	
Total		1.000	Mol.Wt. 19.53		Cp/Mol.= 9.420		Tc	382	Pc	668

Minus 1.986

Cv/Mol.= 7.434

$$\frac{Cp/Mol.}{Cv/Mol.} = \frac{9.420}{7.434} = 1.267 \text{ (n value)}$$

$$S.G. = \frac{19.53}{28.966} = 0.674$$

2.5% Propane, 0.5% Iso-Butane, 1.2% Norm. Butane,
0.5% Pentane, 0.5% Hexanes +, 1.2% Nitrogen, and 0.5% Carbon Dioxide

EXHIBIT B

GAS	FORMULA	% MOL.	MOL. WT.	MOL. # FRACT.	Cp/MOL.	Cp/MOL. FRACT.	TC	PART TC	PC	PART PC
Methane	CH_4	.849	16.042	13.62	8.435	7.16	344	292	673	571
Ethane	C_2H_6	.082	30.068	2.47	12.304	1.01	550	45	709	58
Propane	C_3H_8	.025	44.094	1.10	17.086	0.43	666	17	618	15
Iso-Butane	C_4H_{10}	.012	58.120	0.29	22.463	0.11	733	4	543	3
Norm. Butane	C_4H_{10}	.005	58.120	0.70	23.079	0.28	767	9	529	6
Pentane	C_5H_{12}	.005	72.146	0.36	28.671	0.14	847	4	485	2
Hexane	C_6H_{14}		86.172	0.43	34.331	0.17	914	5	433	2
Heptane	C_7H_{16}		100.198		39.999		973		397	
Ethene	C_2H_4		28.052		10.127		510		749	
Propene	C_3H_6		42.078		15.190		657		668	
Butene	C_4H_8		56.104		20.646		751		619	
Pentene	C_4H_{10}		70.130		26.649		854		595	
Hexene	C_6H_{12}		84.156		30.296		931			
Water	H_2O		18.02		8.03		1165		3206	
Hydrogen	H_2		2.016		6.871		74		306	
Oxygen	O_2		32.000		7.002		279		730	
Nitrogen	N_2	.012	28.016	0.34	6.954	0.08	228	3	492	6
Carbon Monoxide	CO	.005	28.010		6.958		242		514	
Carbon Dioxide	CO_2		44.010	0.22	8.762	0.04	548	3	1073	5
Hyd. Sulfide	H_2S		34.076		8.655		672		1306	
Sulph. Dioxide	SO_2		64.060		9.417		775		1142	
Ammonia	NH_3		17.030		8.856		731		1657	
Argon	A		39.944		4.913		272		705	
TOTAL		1.000	Mol. Wt.	19.53	Cp/Mol. = 9.420		Tc	382	Pc	668

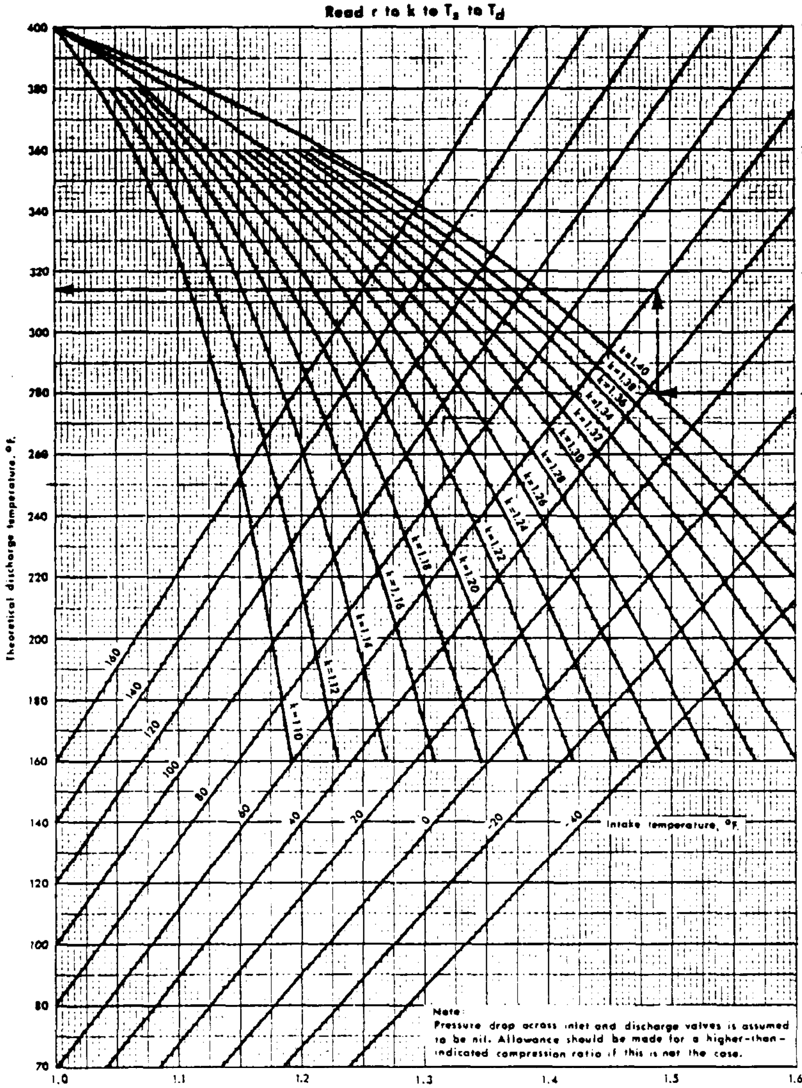
Cp/Mol. = 9.420
Minus 1.986
Cv/Mol. = 7.434

$$\frac{\text{Cp/Mol.}}{\text{Cv/Mol.}} = \frac{9.420}{7.434} = 1.267 \text{ (n value)}$$

$$\text{S.G.} = \frac{19.53}{28.966} = 0.674$$

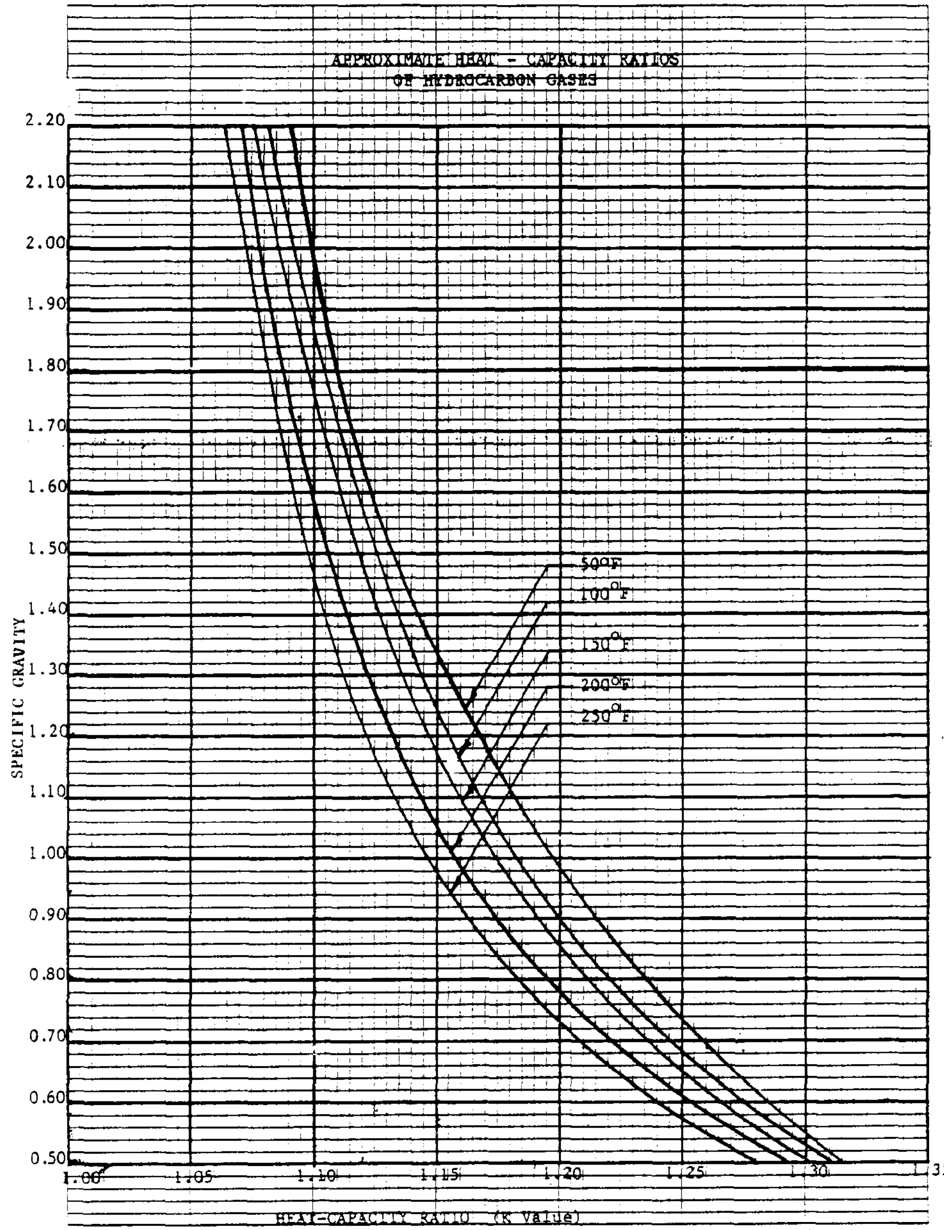
EXHIBIT D

FIG. 4-6
Theoretical discharge temperatures
Single-stage compression
Read r to k to T_s to T_d



(TAKEN FROM THE NGPSA ENGINEERING DATA BOOK)

EXHIBIT C



Estimated BHP To Compress Natural Gas

DISCHARGE PRESSURE PSIG

SUCTION PRESSURE PSIG

	25	50	75	100	150	200	350	500	600	750	800	900	1000	1250	1500	1750	2000	2500	3000	4000	4500	6500
0	65	100	130	145	170	190	235	250	280	275	280	290	300	315	330	345	350					
10	35	65	85	105	130	145	185	215	230	235	240	250	255	275	290	300	310	320	330	350	360	390
25		40	55	70	95	120	150	175	185	205	210	220	230	240	255	265	275	285	295	320	330	370
50			25	40	70	80	120	140	155	170	175	180	190	205	215	220	245	255	265	280	285	325
75				20	45	55	95	120	130	145	150	155	165	180	195	205	215	225	235	260	270	300
100					30	45	75	100	115	130	135	140	145	160	170	180	195	205	215	235	245	275
150						20	55	75	85	105	110	115	120	135	150	160	165	175	185	210	220	260
200							40	60	70	80	85	95	100	115	125	140	150	165	175	195	205	240
250							25	45	55	65	70	80	85	105	115	125	135	145	160	180	190	225
300							20	35	45	55	60	70	75	80	85	100	120	130	140	160	170	205
350								25	35	50	55	60	65	75	90	100	110	120	130	150	160	195
400								20	30	40	45	50	55	70	80	90	105	110	120	140	150	185
450								15	20	30	35	40	50	60	70	80	100	105	115	130	140	175
500									15	30	35	40	45	55	60	75	95	100	110	125	135	165
550									15	25	30	35	40	50	55	70	90	95	110	125	130	160
600										20	25	30	35	45	55	65	85	90	100	115	125	155
750											15	20	25	35	40	55	75	80	90	105	115	140
1000														20	30	40	50	60	70	90	105	125
1250															25	30	40	50	60	75	90	110
1500																20	30	35	50	65	75	90
1750																	20	30	40	55	65	80
2000																		20	35	45	55	70
3000																				20	35	50
4000																					20	30

THREE-STAGE

TWO-STAGE

SINGLE-STAGE

COMPRESSOR SYSTEMS INC.
HOME OFFICE
P.O. DRAWER "A" A.T.S.
MIDLAND, TEXAS 79701
915/563-1170
TWX: 910-895-5349

(1) MMSCFD @ 14.7 PSI & 60°F
(2) Not Corrected for Compressibility
(3) N = 1.26

EXHIBIT E

COMPRESSOR HORSEPOWER SELECTION CHART

DISCHARGE PRESSURE (PSIG) (BRAKE HORSEPOWER PER MILLION CU. FT.)

SUCTION PRESSURE (PSIG)

	25	50	75	100	125	150	175	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200
0	65	99	128	144	156	168	178	187	203	218	233																	
10	35	63	85	104	121	131	140	149	163	175	186	196	205	214	223	231												
20		43	62	78	92	106	118	128	139	151	160	170	178	186	193	199	206	212	218	225								
30		29	47	62	74	85	96	107	123	133	143	152	159	167	173	179	185	191	196	201	206	211	216	221	226	230		
40			36	50	61	72	81	90	107	121	130	138	145	152	158	164	170	175	180	185	190	194	198	202	206	210	214	218
50			26	41	52	61	70	78	93	106	119	127	134	141	147	153	158	163	168	173	177	181	185	189	193	196	200	203
60				32	44	53	61	69	83	95	108	118	125	131	137	143	148	153	158	162	166	170	174	178	182	185	188	192
70				25	37	46	54	61	74	86	97	109	117	123	129	135	140	145	149	153	157	161	165	169	172	176	179	182
80					30	40	47	54	67	78	89	98	109	117	122	127	132	137	142	146	150	153	157	161	164	167	171	174
90					24	34	42	49	61	72	81	91	100	109	116	121	126	131	135	139	143	147	150	154	157	160	163	166
100						28	37	44	55	66	75	84	92	100	109	116	120	125	129	133	137	141	144	148	151	154	157	160
125							25	32	44	54	63	71	78	85	92	99	106	113	117	121	124	128	131	134	137	140	143	146
150								22	35	45	53	60	67	74	80	86	92	98	103	110	114	118	121	124	127	130	133	135
175									27	37	45	52	57	60	71	76	82	87	92	97	102	107	112	115	118	121	123	126
200										30	38	45	52	58	63	68	73	78	83	88	92	96	101	105	110	113	116	119
250											26	33	40	46	51	56	60	65	69	73	77	81	85	88	92	95	99	102
300												23	30	36	41	46	50	54	58	62	66	69	73	76	79	83	86	89
350													21	27	33	38	42	46	50	53	57	60	63	67	70	73	75	78
400															25	30	35	39	43	46	50	53	56	59	60	64	67	70
450																23	28	32	36	40	43	46	49	52	55	58	60	63
500																	22	26	30	34	38	41	44	46	49	52	54	57
550																		20	25	29	32	36	39	41	44	46	49	51
600																				23	27	30	34	37	39	42	44	46
650																					22	26	29	32	35	38	40	42
700																						22	25	28	30	33	36	38
750																							20	24	27	29	32	34

THREE STAGE

TWO STAGE

SINGLE STAGE

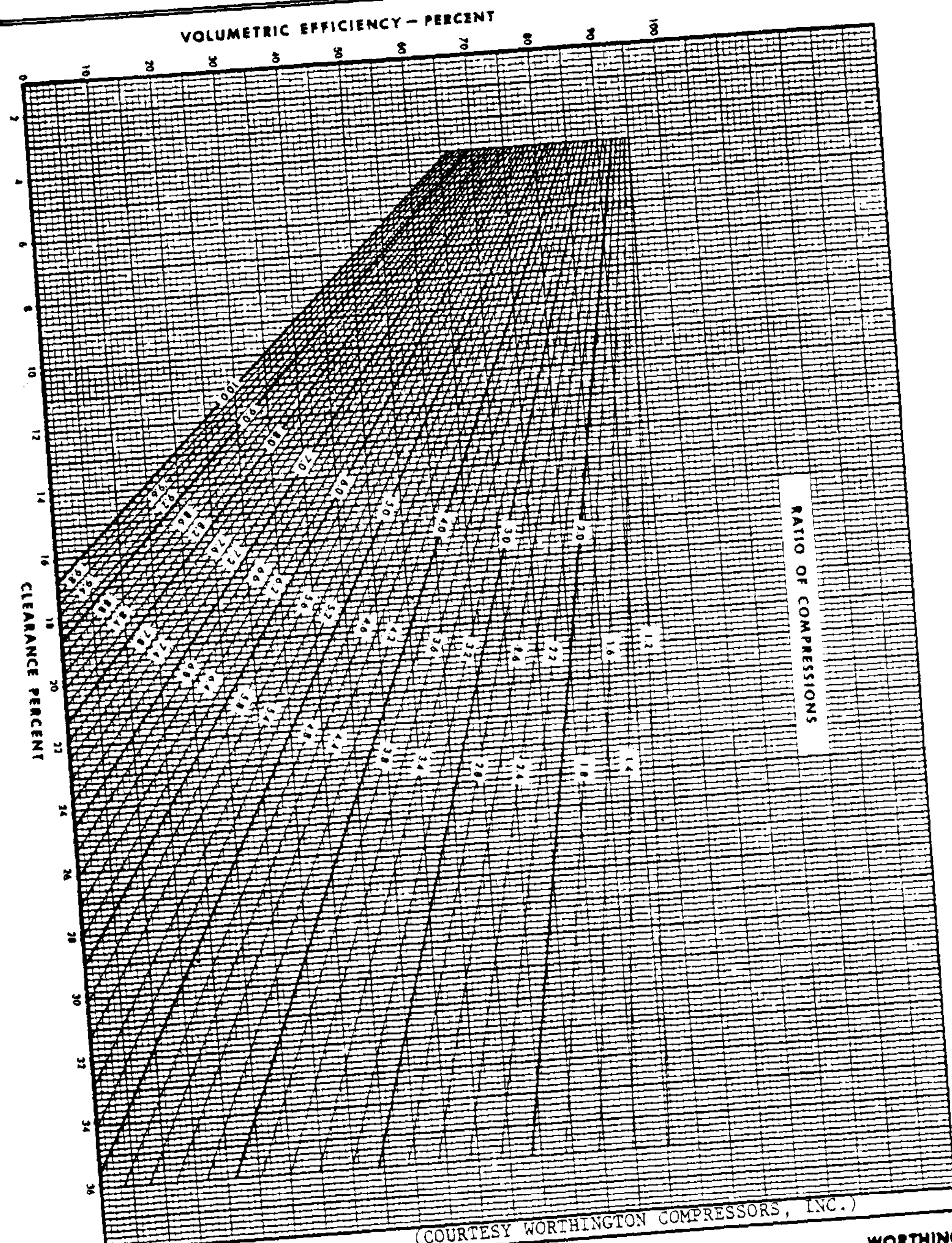
EXHIBIT E

EXHIBIT F

GAS GATHERING COMPRESSORS

CURVE OF CLEARANCE VS VOLUMETRIC EFFICIENCY

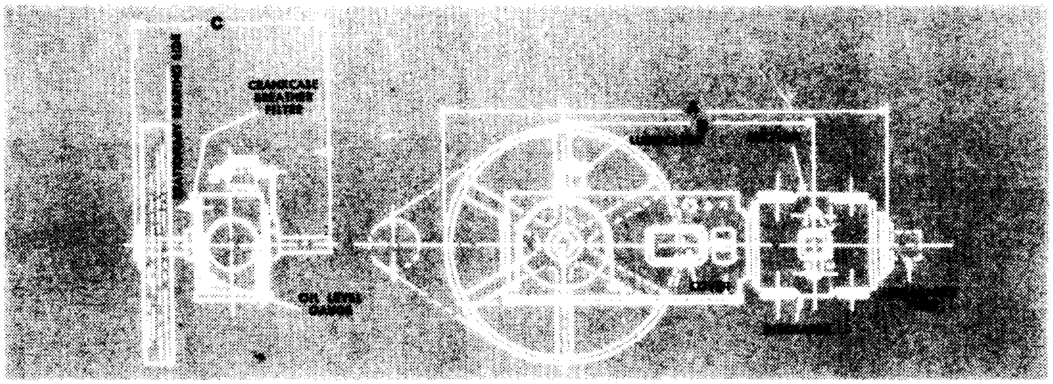
GENERAL DATA



(COURTESY WORTHINGTON COMPRESSORS, INC.)

WORTHINGTON

EXHIBIT G



Dimensions and specifications

Size, inches	Piston displacement, cfm	Max. working press., psi	Rpm	Approx. weight, lbs.	Gas pipe, inches	Appproximate overall dimensions A	B	C
2½ x 5	16.3	1500	675	1275	1½	6′-5¾″	4′-1¼″	1′-10″
3⅛ x 5	27.0	1350	675	1300	1½	6′-5¾″	4′-1¼″	1′-10″
3½ x 5	34.7	1350	675	1340	1½	6′-6 1/16″	4′-1¼″	1′-10″
4 x 5	46.2	1350	675	1390	2	6′-7⅛″	4′-2¼″	1′-10″
5 x 5	73.8	1200	675	2135	3	6′-8½″	4′-1⅝″	1′-10″
6 x 5	108.0	300	675	1815	3	6′-5¾″	4′-0⅝″	1′-10″
3⅛ x 7	27.6	1500	514	1610	1½	7′-3¾″	4′-8¼″	2′-7½″
4 x 7	48.0	1500	514	1700	2	7′-5⅛″	4′-9¼″	2′-7½″
5 x 7	77.4	1200	514	2445	3	7′-6½″	4′-8⅝″	2′-7½″
5½ x 7	94.6	1250	514	2670	3	8′-1 1/16″	5′-1⅜″	2′-7½″
6¼ x 7	123.0	1250	514	2670	3	8′-1 1/16″	5′-1⅜″	2′-7½″
8 x 7	205.0	300	514	2220	3	7′-1⅜″	4′-4⅞″	2′-7½″
3⅛ x 9	30.3	1500	450	2610	1½	7′-9 9/16″	4′-10 1/16″	3′-3″
4 x 9	53.3	1500	450	2700	2	7′-10 15/16″	4′-11 1/16″	3′-3″
4¾ x 9	77.4	1000	450	3250	3	8′-0⅛″	4′-10½″	3′-3″
5½ x 9	106.0	1250	450	3670	3	8′-4 9/16″	5′-0⅞″	3′-3″
6¼ x 9	138.0	1250	450	3670	3	8′-4 3/16″	5′-0⅞″	3′-3″
7¼ x 9	188.0	800	450	4320	4	8′-4 3/16″	4′-11⅝″	3′-3″
8 x 9	230.0	300	450	3220	3	7′-7¼″	4′-6¾″	3′-3″
9 x 9	293.0	550	450	4140	5	8′-1½″	4′-10¼″	3′-3″
10 x 9	363.0	150	450	3750	5	7′-11⅝″	4′-8⅞″	3′-3″
4½ x 11	73.0	1500	400	5180	2½	10′-0¾″	6′-2⅞″	3′-7″
5¼ x 11	102.0	1400	400	5000	3	9′-6″	5′-11½″	3′-7″
6 x 11	136.0	1250	400	5230	3	9′-9¾″	6′-0⅞″	3′-7″
6½ x 11	161.0	800	400	5830	4	9′-8 9/16″	5′-10¾″	3′-7″
7¼ x 11	202.0	800	400	5830	4	9′-8 9/16″	5′-10¾″	3′-7″
8 x 11	248.0	800	400	5830	4	9′-8 9/16″	5′-10¾″	3′-7″
9 x 11	316.0	550	400	5650	5	9′-5″	5′-9⅜″	3′-7″
9½ x 11	353.0	550	400	5650	5	9′-5″	5′-9⅜″	3′-7″
10½ x 11	433.0	550	400	5650	5	9′-5″	5′-9⅜″	3′-7″
12 x 11	568.0	350	400	6230	6	9′-8″	5′-11″	3′-7″
14 x 11	776.0	150	400	6580	8	9′-10 7/16″	6′-0¾″	3′-7″
5 x 13	84.5	1500	327	6500	2½	10′-7½″	6′-9⅞″	4′-5⅛″
6 x 13	127.0	1250	327	6550	3	10′-4½″	6′-7⅞″	4′-5⅛″
7 x 13	177.0	900	327	7040	4	10′-4⅞″	6′-4⅞″	4′-5⅛″
8¼ x 13	251.0	550	327	7160	5	10′-3⅛″	6′-5¾″	4′-5⅛″
9¼ x 13	319.0	550	327	7160	5	10′-3⅛″	6′-5¾″	4′-5⅛″
11 x 13	455.0	350	327	7500	6	10′-3″	6′-6″	4′-5⅛″
12 x 13	544.0	350	327	7500	6	10′-3″	6′-6″	4′-5⅛″
14 x 13	745.0	150	327	7950	8	10′-6⅝″	6′-7¾″	4′-5⅛″
17 x 13	1105.0	100	327	8100	8	10′-4⅜″	6′-6½″	4′-5⅛″

Areas of Circles

Diameters in Inches and Areas in Square Inches

Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area	Dia.	Area
1/8	.012272	1/2	44.1787	7/8	173.782	1/2	471.436	1/4	1209.95
1/4	.049087	5/8	45.6636	15	176.715	3/4	481.107	1/2	1225.42
3/8	.110447	3/4	47.1731	1/8	179.673	25	490.875	3/4	1240.98
1/2	.19635	7/8	48.7071	1/4	182.655	1/4	500.742	40	1256.64
5/8	.306796	8	50.2656	3/8	185.661	1/2	510.706	1/4	1272.39
3/4	.441787	1/8	51.8487	1/2	188.692	3/4	520.769	1/2	1288.25
7/8	.601322	1/4	53.4563	5/8	191.748	26	530.93	3/4	1304.20
1	.7854	3/8	55.0884	3/4	194.828	1/4	541.19	41	1320.25
1/8	.99402	1/2	56.7451	7/8	197.933	1/2	551.547	1/4	1336.40
1/4	1.2272	5/8	58.4264	16	201.062	3/4	562.003	1/2	1352.65
3/8	1.4849	3/4	60.1322	1/8	204.216	27	572.557	3/4	1369.00
1/2	1.7671	7/8	61.8625	1/4	207.395	1/4	583.207	42	1385.45
5/8	2.0739	9	63.6174	3/8	210.598	1/2	593.959	1/4	1401.99
3/4	2.4053	1/8	65.3968	1/2	213.825	3/4	604.807	1/2	1418.63
7/8	2.7612	1/4	67.2008	5/8	217.077	28	615.754	3/4	1435.37
2	3.1416	3/8	69.0293	3/4	220.354	1/4	626.798	43	1452.2
1/8	3.5466	1/2	70.8823	7/8	223.655	1/2	637.941	1/4	1469.14
1/4	3.9761	5/8	72.7599	17	226.981	3/4	649.182	1/2	1486.17
3/8	4.4301	3/4	74.6621	1/8	230.331	29	660.521	3/4	1503.3
1/2	4.9087	7/8	76.5888	1/4	233.706	1/4	671.959	44	1520.53
5/8	5.4119	10	78.54	3/8	237.105	1/2	683.494	1/4	1537.86
3/4	5.9396	1/8	80.5158	1/2	240.529	3/4	695.128	1/2	1555.29
7/8	6.4918	1/4	82.5161	5/8	243.977	30	706.86	3/4	1572.81
3	7.0686	3/8	84.5409	3/4	247.45	1/4	718.69	45	1590.43
1/8	7.6699	1/2	86.5903	7/8	250.948	1/2	730.618	1/4	1608.16
1/4	8.2958	5/8	88.6643	18	254.47	3/4	742.645	1/2	1625.97
3/8	8.9462	3/4	90.7628	1/8	258.016	31	754.769	3/4	1643.89
1/2	9.6211	7/8	92.8858	1/4	261.587	1/4	766.992	46	1661.91
5/8	10.3206	11	95.0334	3/8	265.183	1/2	779.313	1/4	1680.02
3/4	11.0447	1/8	97.2055	1/2	268.803	3/4	791.732	1/2	1698.23
7/8	11.7933	1/4	99.4022	5/8	272.448	32	804.25	3/4	1716.54
4	12.5664	3/8	101.6234	3/4	276.117	1/4	816.865	47	1734.95
1/8	13.3641	1/2	103.8691	7/8	279.811	1/2	829.579	1/4	1753.45
1/4	14.1863	5/8	106.1394	19	283.529	3/4	842.391	1/2	1772.06
3/8	15.033	3/4	108.4343	1/8	287.272	33	855.301	3/4	1790.76
1/2	15.9043	7/8	110.7537	1/4	291.04	1/4	868.309	48	1809.56
5/8	16.8002	12	113.098	3/8	294.832	1/2	881.415	1/4	1828.46
3/4	17.7206	1/8	115.466	1/2	298.648	3/4	894.62	1/2	1847.46
7/8	18.6655	1/4	117.859	5/8	302.489	34	907.922	3/4	1866.55
5	19.635	3/8	120.277	3/4	306.355	1/4	921.323	49	1885.75
1/8	20.629	1/2	122.719	7/8	310.245	1/2	934.822	1/4	1905.04
1/4	21.6476	5/8	125.185	20	314.16	3/4	948.42	1/2	1924.43
3/8	22.6907	3/4	127.677	1/4	322.063	35	962.115	3/4	1943.91
1/2	23.7583	7/8	130.192	1/2	330.064	1/4	975.909	50	1963.5
5/8	24.8505	13	132.733	3/4	338.164	1/2	989.9	1/4	1983.18
3/4	25.9673	1/8	135.297	21	346.361	3/4	1003.79	1/2	2002.97
7/8	27.1086	1/4	137.887	1/4	354.657	36	1017.878	3/4	2022.85
6	28.2744	3/8	140.501	1/2	363.051	1/4	1032.065	51	2042.83
1/8	29.4648	1/2	143.139	3/4	371.543	1/2	1046.349	1/4	2062.9
1/4	30.6797	5/8	145.802	22	380.134	3/4	1060.732	1/2	2083.08
3/8	31.9191	3/4	148.49	1/4	388.822	37	1075.213	3/4	2103.35
1/2	33.1831	7/8	151.202	1/2	397.609	1/4	1089.792	52	2123.72
5/8	34.4717	14	153.938	3/4	406.494	1/2	1104.469	1/4	2144.19
3/4	35.7848	1/8	156.7	23	415.477	3/4	1119.244	1/2	2164.76
7/8	37.1224	1/4	159.485	1/4	424.558	38	1134.118	3/4	2185.42
7	38.4846	3/8	162.296	1/2	433.737	1/4	1149.089	53	2206.19
1/8	39.8713	1/2	165.13	3/4	443.015	1/2	1164.159	1/4	2227.05
1/4	41.2826	5/8	167.99	24	452.39	3/4	1179.327	1/2	2246.01
3/8	42.7184	3/4	170.874	1/4	461.864	39	1194.593	3/4	2269.07

EXHIBIT H

ELEVATION................FT 2700
ATMOSPHERIC PRESSURE...PSIA 13.296
SPECIFIC GRAVITY (AIR=1)... 0.674
N-VALUE (CP/CV)............ 1.244

******COMPRESSOR DATA******

MAKE...... WORTHINGTON
MODEL..... HBGG13
STAGE NO.................. 1
NUMBER OF CYLINDERS........ 1
CYLINDER DIAMETER.........IN 6.000
STROKE....................IN 13.000
RPM........................ 327
ROD DIAMETER..............IN 2.500
DISPLACEMENT.............CFM 127.038

CONDITIONS OF SERVICE

SUCTION PRESSURE.......PSIG 240.000
SUCTION TEMPERATURE.......F 80
DISCHARGE PRESSURE.....PSIG 1050.000

********PERFORMANCE********

SUCTION PRESSURE.......PSIA 253.296
DISCHARGE PRESSURE.....PSIA 1063.296
DISCHARGE TEMPERATURE.....F 255.512
COMPRESSION RATIO.......... 4.1978
AVERAGE CLEARANCE.........% 8.950
VOLUMETRIC EFFICIENCY...... 0.7125
CAPACITY...............MCFD 2268
BRAKE HORSEPOWER PER STAGE. 196
TOTAL BRAKE HORSEPOWER..... 196
ROD LOAD - COMPRESSION-LBS. 24145
ROD LOAD - TENSION-LBS..... 17682

EXHIBIT I