The Compression and Transmission of Illuminating Gas

A Thesis Read at the July, 1905, Meeting of the Pacific Coast Gas Association.

Some Economics in High Pressure Gas Transmission

A Thesis Read at the September, 1906, Meeting of the Pacific Coast Gas Association.

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THE COMPRESSION AND TRANSMISSION OF ILLUMINATING GAS.

The subject of illuminating gas compression is almost a new one, and the nature of the gas is so entirely different from that of air that we are obliged to consider the question mainly from the theoretical standpoint, backed up by a few indicator cards, which have been furnished us by gas compressors. But you may be assured that all of the data given herewith is eminently practical, because there has been eliminated all of the small variables that are important from a chemical standpoint, but which the advancing piston of a compressor cylinder takes little heed of.

We are not concerned about the candle power or the commercial utility of a gas, but simply with its weight and composition, and what may happen to it after it leaves the compressor cylinder is not the province of this paper.

All gases are sponge-like in that they hold various vapors from water vapor to carbon vapors, which they lose to a more or less extent when the sponge is squeezed as in the act of compressing in a cylinder, and what is squeezed out and how much of it is not essential to our discussion, and lies better in the realm of the technical gas engineer.

We have assumed, however, that inasmuch as when we compress a gas the temperature rises in a fixed ratio to the pressures, that there is no direct tendency for a gas to change its physical condition in the compressing cylinder, for an added temperature gives an added capacity for saturation, and this probably increases in about the same ratio as the volume diminishes during compression. So that for commercial purposes we can not be far wrong in assuming the physical condition of the gases as constant during the range of pressures that will be ordinarily met.

All phenomena of compression and expansion of gases is intimately associated with temperature; in fact, the power to compress any gas adiabatically in foot-pounds is simply the difference in temperature between the gas before and after compression, multiplied by its weight in pounds, by its specific heat, and then by Joules' equivalent to convert heat units to foot-pounds. Expressed algebraically, this equation is:

$L = J\ W\ C_p\ (T - T_0)$ where

J is Joules' equivalent $= 772$.

$W =$ the weight in pounds avoirdupois to be compressed.

C_p is the specific heat of the gas at constant pressure.

T_0 is the initial absolute temperature.

T is the final absolute temperature.

L is the work expressed in foot-pounds.

This is the general equation for the compression of any gas adiabatically.

In glancing at this equation, the first stumbling block we strike is C_p, the specific heat of the gas at constant pressure, and this must be first determined. After that we must discover some means of finding T, the final temperature.

To anticipate a little, it may be stated here that these temperatures are all functions of the ratio of the specific heats of gas at constant pressure, and at constant volume.

It is then our first duty to understand about these two specific heats and to know how to determine them for any gas, and the rest is simple.

The specific heat of any substance is the amount of heat one pound of that substance will absorb to raise its temperature 1° Fah., the specific heat of water being 1.

When a gas is heated two different results may be obtained, depending upon whether the gas is allowed to expand and increase its volume when heated, the pressure remaining constant, or whether the air is confined, the volume remaining constant, and the pressure increased. The amount of heat to raise the temperature of a gas 1° under these two conditions is different.

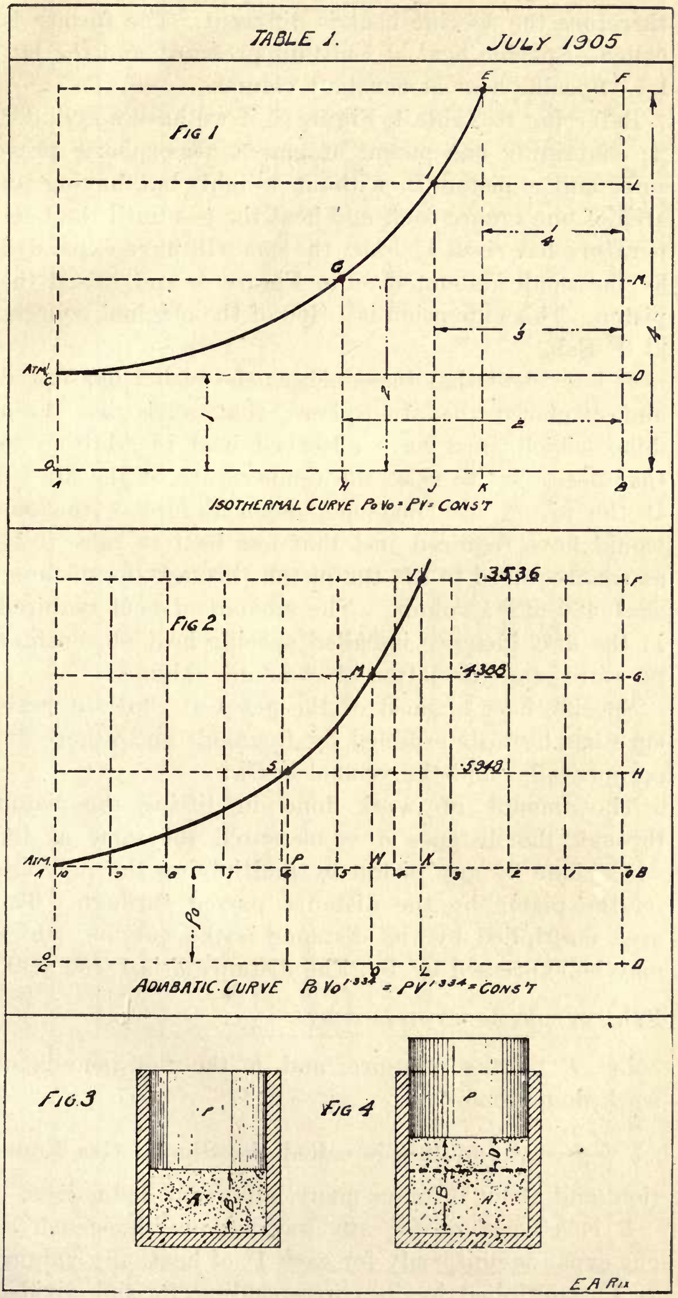
TABLE 1.
JULY 1905
FIG 1
ISOTHERMAL CURVE PoVo = PV = CONS'T
FIG 2
.3536
.4388
.5949
ADIABATIC CURVE PoVo 1.334 = PV 1.334 = CONS'T
FIG 3
FIG 4
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therefore the specific heat is different. The former is called—Specific heat at constant pressure, and the latter—Specific heat at constant volume.

Referring to Table 1, Figure 3, if we have a cylinder *A,* containing one pound of gas at atmospheric pressure, and a piston *P,* without weight, but having an area of one square foot, and heat the gas until the temperature has risen 1° Fah., the gas will have expanded by the small amount *d* as in Figure 4, and raised the piston. This expansion is 1/460 of the original volume, at 0° Fah.

It is evident that inasmuch as the piston has raised and displaced the atmosphere, that work has been done, which must have absorbed heat in addition to that necessary to raise the temperature of the air 1°. If the piston was fastened, as in Figure 3, the gas would have required just that less heat to raise it 1° as was required to lift the piston through the distance $d=1/460$ of its volume. The amount of heat required in the first instance is called specific heat at constant pressure, and the latter at constant volume.

Specific heat of most of the gases at constant pressure has been determined by Regnault and others experimentally, and the symbol is C_p.

The amount of work done in lifting the piston through the distance *d* is measured the same as the work done by any piston by multiplying the pressure on the piston by the distance passed through. The area multiplied by the distance is the volume, which may be expressed by *V.* The distance *d* is 1/460 at 0° Fah., or may be expressed by $\frac{1}{T}$.

Let *P* be the pressure, and *R* the foot-pounds of work done, then

$\frac{VP}{T}=R$ and this is called the Simple Gas Equation, and about it hangs many important deductions.

R is a constant for any gas, because inasmuch as gas expands uniformly for each 1° of heat, any volume as V_1 multiplied by its corresponding P_1 and divided

TABLE 2 — CRUDE OIL GAS MANUFACTURED AT OAKLAND CAL BY CALIFORNIA GAS AND ELECTRIC COR — JUNE 1905

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32° FAH	C_p	PERCENT OF VOLUME X WEIGHT PER CU. FT	PERCENT OF VOLUME X WEIGHT PER CU. FT X C_p	
C_2H_4	7	·0780922	·404	·54664	220842	$\frac{V_o P_o}{T_o} = R = \frac{144 \times \frac{1}{.0323577} \times 14.7}{492}$
CH_4	28·3	044668	·5929	1·26390	749350	
H	51 9	005594	3·409	29032	·989700	$R = \frac{30.30 \times 144 \times 14.7}{492} = 133.2$
CO	5	·0780922	·2479	·39045	·096793	
CO_2	3	·122760	·217	·36828	·079167	$C_v = C_p - \frac{R}{J} = ·6884 - \frac{133.2}{772} =$
N	4 8	·078371	·2438	·37618	·091711	$= ·6884 - ·1725 = ·5159$
O		·098180	·21751			
	100·00			3·23577	2·227563	$\frac{C_p = ·6884}{C_v = ·5159} = 1334 = Y$
				= ·0323577	·022275 ÷	
				PER CUBIC FOOT.	·0323577	$\frac{Y}{Y-1} = 4 \quad \frac{Y-1}{Y} = ·2504$
					·6884 = C_p	$\mathcal{L} = 8467\left(\frac{T}{T_o} - 1\right)$ FOOT POUNDS

NOTE — SPEC GRAV 402 OBSERVED. SPEC GRAV ·4008 CALCULATED

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by its corresponding temperature T_1 will equal R, or to put it algebraically,

$$\frac{V P}{T}=\frac{V_1 P_1}{T_1}=\frac{V'' P''}{T''}=R=\text{Constant}$$

R being always in foot-pounds, if we divide it by Joules' equivalent 772, which is, as you know, the amount of foot-pounds equal to 1 heat unit, and which is always denoted by J, we shall have the amount of heat units that were converted into work to raise the piston, and this amount of heat, we know, must be the difference between the specific heat at the constant pressure and the specific heat at constant volume, or,

$$\frac{R}{J}=C_p-C_v$$

from which we have

$$C_v=C_p-\frac{R}{J}$$

an equation from which the specific heat at constant volume may be determined for any gas within the limits of its stability, and certainly within the commercial pressures you are likely to encounter.

For a perfect gas, these specific heats are practically constant; that is, they are not affected by pressure or temperature, but so far hydrogen and air appear to be nearer than any other gases. CO and CO_2, which are inferior components of illuminating gas, as it is now made, show the greatest deviation, but not enough to render their vagaries of moment in the consideration of the power question, consequently all the following data have been calculated on the basis of the simple gas law.

$$\frac{PV}{T}=R=\text{Constant.}$$

As an example showing how to calculate the specific heat at constant volume, let us take $C_2\ H_4$. This gas have been calculated on the basis of the simple gas law. values ascribed to Regnault in the references we have at hand.

Upon applying the simple gas equation to the Reg-

TABLE 3. CRUDE OIL GAS MANUFACTURED AT FRESNO CAL. BY CALIFORNIA GAS AND ELECTRIC COR JUNE 1905

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32° FAH	C_p	PERCENT OF VOLUME X WEIGHT PER CU FT	PERCENT OF VOLUME X WEIGHT PER CU FT X C_p	
C_2H_4	5	·0780922	·404	·39046	·157745	$\frac{V_o P_o}{T_o} = R = \frac{144 \times \frac{1}{.028453} \times 14.7}{492}$
CH_4	29·7	·044668	·5929	1·32640	·786420	
H	55·4	·005594	3·409	·30968	1·055700	$R = \frac{35.146 \times 144 \times 14.7}{492} = 151$
CO	5	·0780922	·2479	·39045	·096793	
CO_2	1	·1227603	·217	·12276	·026577	$C_v = C_p - \frac{R}{J} = \cdot 7724 - \frac{151}{772} = \cdot 7724$
N	3·9	·078371	·24380	·30564	·074515	$- \cdot 1956 = \cdot 5768.$
O		·089180	·21751			
	100 00			2·84539	2·19775	$\frac{C_p = \cdot 7724}{C_v = \cdot 5768} = 1.339 = \gamma$
				= ·028453	·0219775 ÷	
				PER CUBIC FOOT.	·028453 =	$\frac{\gamma - 1}{\gamma} = \cdot 253 \quad \frac{\gamma}{\gamma - 1} = 3.95$
					·7724 = C_p	$\mathcal{L} = 8361\left(\frac{T}{T_o} - 1\right)$ FOOT LBS.

NOTE ÷ SPEC. GRAV ·353 OBSERVED.– SPEC GRAV ·3524 CALCULATED

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nault value there was a large discrepancy, and it will be interesting no doubt to make the calculations here, and thus make them serve the double purpose of showing how to determine the specific heat at constant volume and to point out the error.

Regnault gives the C_p of $C_2 H_4$ to be .404, and C_v to be .173. The weight per cubic foot to be .0780922, or 12.8 cubic feet in one pound at 32° Fah.

If, now, one pound, or 12.8 cubic feet, be heated to 1° Fah. and allowed to expand, the simple gas equation

$$\frac{P V}{T^{o}} = R \text{ will give at } 32°$$

$$\frac{14.7 \times 144 \times 12.8}{492} = \mathrm{R} = 55.$$

Fifty-five foot-pounds of work has been performed by the gas in expanding against the atmosphere; to convert this into heat units we divide by Joules' equivalent, 772.

$$\frac{55}{772} = .07124 \text{ units of heat.}$$

Inasmuch as

$$C_v = C_p - \frac{R}{J} \text{ and } \frac{R}{J} = .07124$$

we have $C_v = .404 - .07124 = .3327$, instead of .173 as determined by Regnault. The ratio between the two specific heats forms the basis for all the calculations for the relations between pressure, volume, and temperature in compressing gas, and that is why we must be particular about these specific heat factors.

$\frac{C_p}{C_v} = \gamma$ (gamma), which we shall discuss further on, and which is brought in now simply as additional proof about the figures which we have just obtained for $C_2 H_4$.

For $C_2 H_4$, using Regnault's values, we have

$$\gamma = \frac{.404}{.173} = 2.33$$

for our values

TABLE 4. CRUDE OIL GAS MANUFACTURED AT HAPPY VALLEY CAL. BY CALIFORNIA GAS AND ELECTRIC COR JUNE 1905.

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32° FAH.	C_p	PERCENT OF VOLUME X WEIGHT PER CU. FT.	PERCENT OF VOLUME X WEIGHT PER CU. FT. X C_p	
C_2H_4	10·3	·0780922	·404	·80435	·324957	$\frac{V_0 P_0}{T_0} = R = \frac{144 \times .0374492 \times 14.7}{492}$
CH_4	26	·044668	·5929	1·16136	·688530	
H	46	·005594	3·409	·25732	·877210	$R = \frac{26.70 \times 144 \times 14.7}{492} = 114.8$
CO	6	·0780922	·2479	·46855	·116150	
CO_2	3	·1227603	·217	·36828	·079167	$C_v = C_p - \frac{R}{J} = .6015 - \frac{114.8}{772}$
N	8·4	·078371	·24980	·65831	·160840	$= .6015 - .1487 = .4528$
O	·3	·089180	·21751	·02675	·005818	
	100·00			3·74492	2·252672	$\frac{C_p = .6015}{C_v = .4528} = 1.328 = \gamma$
				= ·0374492	·0225267	
				PER CUBIC FOOT	÷ ·0374492	$\frac{\gamma - 1}{\gamma} = .247 \quad \frac{\gamma}{\gamma - 1} = 4.054$
					= ·6015 = C_p	
NOTE	SPEC GRAV ·464 CALCULTION					$L = 8573\left(\frac{T}{T_0} - 1\right)$ FOOT LBS

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$$y = \frac{.404}{.3327} = 1.214.$$

In reading a new book by Travers on the study of gases (page 275), he gives some very interesting calculations to show the limiting values of $\frac{C_p}{C_v}$ or y.

His conclusions are that for a monoatomic gas within the limits of the simple gas equation $\frac{PV}{T^o} = R$, the values of $\frac{C_p}{C_v}$ can never exceed 1.667, and the value for a diatomic gas should range about 1.4 and the polyatomic gases still less, until we reach the value of 1, where, of course, there should be no expansion work at all when heat was applied.

We can see, therefore, that the value $\frac{C_p}{C_v}$ of 2.33 from Regnault's values is an impossibility, the maximum possible value being only 1.667, and $C_2\ H_4$ being the polyatomic gas, its value would be less than 1.4, all of which indicates that our figures $\frac{C_p}{C_v} = 1.214$ are approximately correct.

It will now be necessary to apply our understanding of these principles and try and determine the values of the specific heats for illuminating gas. There seems to be plenty of data about the specific heat at constant pressure for gas mixtures, but nothing about the specific heat at constant volume.

Reference is now made to the Tables 2, 3, 4, 5, 6, 7, and 8, which show the composition and heat properties of seven different gases and the methods employed in determining the weights, specific gravities, and specific heats.

Column 1 is the chemical symbol for the different components.

Column 2 is the percentage by volume of the different components.

Column 3 gives reliable weights per cubic foot.

TABLE 5 CARBURETTED WATER GAS PURIFIED SAN FRANCISCO. GAS CO NORTH BEACH DEC 14TH 1897

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32° FAH	C_p	PERCENT OF VOLUME X WEIGHT PER CU. FT	PERCENT OF VOLUME X WEIGHT PER CU. FT X C_p	
C_2H_4	9·2	·0780922	·404	·72842	·29427	$\frac{V_0 P_0}{T_0} = R = \frac{144 \times \frac{1}{.04671} \times 14{\cdot}7}{492}$
CH_4	22·2	·044668	·5929	·99145	·58780	
H	35·1	·005594	3·409	·19610	·66850	$R = \frac{21{\cdot}4 \times 144 \times 14{\cdot}7}{492} = 92{\cdot}02$
CO	25·2	·0780922	·2479	1·96786	·48781	
CO_2	3	·1227603	·217	·36810	·07987	$C_v = C_p - \frac{R}{J} = {\cdot}47 - \frac{92{\cdot}02}{772}$
N	4·9	·078371	·24380	·38367	·09352	$= {\cdot}47 - {\cdot}1192 = {\cdot}3508$
O	·4	·089180	·21751	·03564	·00772	
	100·00			4·67124	2·21949	$\frac{C_p = {\cdot}47}{C_v = {\cdot}3508} = 1{\cdot}34 = Y$
				·04671	·0221949	
				PER CUBIC FOOT	÷ ·04671	$\frac{Y-1}{Y} = {\cdot}254 \quad \frac{Y}{Y-1} = 3{\cdot}97$
					= ·47 = C_p	
NOTE SPEC GRAV ·578 AT 32°						$\mathcal{L} = 8403\left(\frac{T}{T_0} - 1\right)$ FOOT LBS

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TABLE 6 COAL GAS MANUFACTURED AT HUDSON MASS. ANALYZED BY STATE INSPECTOR OF GAS

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32° FAH	C_p	PERCENT OF VOLUME X WEIGHT PER CU. FT.	PERCENT OF VOLUME X WEIGHT PER CU FT X C_p	
C_2H_4	5.91	.0780922	.404	.46151	.18644	$\frac{V_0 P_0}{T_0} = R = \frac{144 \times \frac{1}{.03292} \times 14.7}{492}$
CH_4	37.91	.044668	.5929	1.69306	1.00377	
H	45.52	.005594	3.409	.25463	.86793	$R = \frac{30.4 \times 144 \times 14.7}{492} = 130.72$
CO	5.60	.0780922	.2479	.43730	.10840	
CO_2	1.07	.1227603	.217	.13128	.02847	$C_v = C_p - \frac{R}{J} = .683 - \frac{130.72}{772} =$
N	3.84	.078371	.24380	.30094	.07118	$= .683 - .1693 = .5137$
O	.15	.089180	.21751	.01337	.00290	
	100.00			3.29209	2.24909	$\frac{C_p = .683}{C_v = .5137} = 1.33 = Y$
				= .03292	.02249	
				PER CUBIC FOOT	÷ .03292	$\frac{Y-1}{Y} = .248 \qquad \frac{Y}{Y-1} = 4$
					= .683 = C_p	
NOTE SPEC. GRAV .408						$\mathcal{L} = 8467\left(\frac{T}{T_0} - 1\right)$: FOOT LBS

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TABLE 7 CALIFORNIA. NATURAL GAS SUISUN CAL. DEC 20TH 1901

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32° FAH	C_p	PERCENT OF VOLUME X WEIGHT PER CU. FT	PERCENT OF VOLUME X WEIGHT PER CU. FT X C_p	
C_2H_4	0	·0780922	·404	·00000	0000	$\frac{V_o P_o}{T_o} = R = \frac{144 \times \frac{1}{.04566} \times 14.7}{492}$
CH_4	92·58	·044668	·5929	4·11530	2·4403	
H	2·18	·005594	3·409	·01219	·0415	$R = \frac{21.9 \times 144 \times 14.7}{492} = 94.17$
CO	0	·0780922	·2479	·0000	0000	
CO_2	·6	·1227603	·217	·07362	·01597	$C_v = C_p - \frac{R}{J} = .5664 - \frac{94.17}{772}$
N	4·44	·078371	·24380	·34796	·08481	$= .5664 - .122 = .4444$
O	·2	·089180	·21751	·01783	·00387	
	100·00			4·56690	2·58645	$\frac{C_p = .5664}{C_v = .4444} = 1.28 = Y$
				= ·04566	·025864	
				PER CUBIC FOOT	÷ ·04566 =	$\frac{Y-1}{Y} = .219 \qquad \frac{Y}{Y-1} = 4.41$
					·5664 = C_p	

NOTE SPEC. GRAV ·566 CALCULATED

$$\mathcal{L} = 9335\left(\frac{T}{T_o} - 1\right) \text{ FOOT LBS.}$$

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TABLE 8 — AVERAGE NATURAL GAS. — KENT PAGE 649 — 1895

1	2	3	4	5	6	7
SYMBOL	PERCENT OF VOLUME	WEIGHT PER CUBIC FOOT 32°FAH	C_p	PERCENT OF VOLUME X WEIGHT PER CU.FT.	PERCENT OF VOLUME X WEIGHT PER CU.FT. X C_p	
C_2H_4	.31	·0780922	404	·02421	·00978	$\frac{V_0 P_0}{T_0} = R = \frac{144 \times \frac{1}{.045786} \times 14.7}{492}$
CH_4	92·6	·044668	·5929	4·13551	2·45190	
H	2·18	·005594	3·409	·01219	·04155	$R = \frac{21.84 \times 144 \times 14.7}{492} = 93.96$
CO	.50	·0780922	·2479	·03904	·00977	
CO_2	26	·1227603	·217	·05642	·01223	$C_v = C_p - \frac{R}{J} = .57 - \frac{93.96}{772} =$
N	3·61	·078371	·24380	·28091	·06848	$= .57 - .122 = .448$
O	·34	·089180	·21751	·03032	·00659	
	99·80			4·57860	2·60030	$\frac{C_p = .57}{C_v = .448} = 1.272 = Y$
				= ·045786	·026003	
				PER CUBIC FOOT	÷ ·04578	$\frac{Y-1}{Y} = .214 \quad \frac{Y}{Y-1} = 4.67$
					= ·57 = C_p	

$$\mathcal{L} = 9885\left(\frac{T}{T_0} - 1\right) = 5100 \text{ Foot Pounds}$$

NOTE - HAVE FIGURED 100% INSTEAD OF 99·80% AS ABOVE.

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TABLE 9.	PROPERTIES OF ILLUMINATING GASES												32° FAH			JUNE 1905.
LOCATION OF WORKS	COMPOSITION BY VOLUME							WEIGHT PER CU FT.	SPEC GRAV.	C_p	C_v	γ	$\frac{\gamma}{\gamma-1}$	$\frac{\gamma-1}{\gamma}$	R	£ FOOT POUND.
	C_2H_4	CH_4	H	CO	CO_2	N	O									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
FRESNO	5	29.7	55.4	5	1	3.9	0	028453	·3524	·7724	·5768	1·339	3·95	·253	151	$8361\left(\frac{T}{T_0}-1\right)$
OAKLAND	7	28·3	51·9	5	3	48	0	·0323577	·4008	·6884	·5159	1·334	4·	·25	133·2	$8467\left(\frac{T}{T_0}-1\right)$
HAPPY VALLEY	10.3	26	46	6	3	8·4	3	·0374492	·464	·6015	·4528	1·328	4·05	·247	114·8	$3573\left(\frac{T}{T_0}-1\right)$
NATURAL GAS.																
AVERAGE NATURAL GAS	·31	92·6	2·18	·5	·26	3·61	·34	·045786	·567	·57	·4182	1·272	4·67	·214	93·96	$9885\left(\frac{T}{T_0}-1\right)$
CAL NATURAL GAS SUISUN CAL DEC 20TH. 04	0	92·58	2·18	0	·6	4·44	·2	·04566	·566	·5664	·4444	1·28	4·41	·219	94·17	$9335\left(\frac{T}{T_0}-1\right)$
COAL GAS																
HUDSON MASS. ANALYZED BY STATE INSPECTOR.	5·91	37·91	45·52	5·6	1·07	3·84	·15	·03292	·403	·683	·5137	1·33	4·	·248	130·7	$8467\left(\frac{T}{T_0}-1\right)$
CARBURETTED WATER GAS PURIFIED																
NORTH BEACH DEC 14 TH. 1897.	9·2	22·2	35·1	25·2	3·	4·9	·4	·04671	·578	·47	·3503	1·34	3·97	·254	92·02	$8403\left(\frac{T}{T_0}-1\right)$ E.A. RIX.

Column 4 gives the specific heat of each component gas as determined by Regnault and others.

Column 5 gives the product of the different percentages of the component gases and their weights per cubic foot, or Column 2 multiplied by Column 3. The total sum divided by 100 gives the weight of the gas per cubic foot.

Column 6 gives the product of Column 4 and Column 5 for specific heat, being a weight function. We must, in order to get the specific heat of the compound gas, take into consideration not only the percentages of the component parts, but the weights as well, and also the specific heat of each component. The sum of the products in column divided by 100, and then by the weight of one cubic foot of the compound gas, will give the specific heat at constant pressure C_p.

Column 7 gives the calculations to find the specific heat at constant volume and also R and $\frac{C_p}{C_v}$ or y for each gas, and also various factors of y which we will find useful later.

Table 9 concentrates Tables 2 to 8, so that we may study them easier.

You will note that our results cover quite a field, taking in California fuel oil gas, Massachusetts coal gas, Indiana natural gas, California natural gas, and California carburetted water gas, and after carefully studying their heat and power properties, as shown in Table 9, we have selected the fuel oil gas made in Oakland as having the best average properties for the purposes we have in view, and particularly as fuel oil gas is the one you will probably have most to deal with.

We may therefore consider our subject as having for a basis a gas with the following properties at 32° Fah.:

Weight per cubic foot, .0323577.

Cubic foot in one pound avoirdupois, 30.98.

Specific gravity, .4008.

C_p =.6884.

C_v =.5159.

$y=1.334.$

$\frac{y-1}{y}=.25.$

$\frac{y}{y-1}=4.$

$R=133.2.$

$L=8467\left(\frac{T}{T^{o}}-1\right)$

A cubic foot of gas varies in weight according to the altitude or pressure, and also according to the temperatures. The law of this variation is expressed as follows:

Having given the weight of a gas for any temperature, or any pressure, then the weight at any other temperature or pressure will be as the ratio of absolute temperature or pressure, or

$W'=W\frac{T}{T^{o}}$ or $W\frac{P}{P^{o}}$ where

W=known weight.

T^{o} and P^{o} the known temperature or pressure and W' the desired weight.

For example:—Our standard gas weights at sea level, or 14.7 pounds absolute pressure, and 32° Fah., .03235 pounds per cubic foot; at 20 pounds gauge, or 34.17 pounds absolute, a cubic foot would weigh .03235 $\times\frac{34.17}{14.7}=.03235\times 2.36=.076346$ pounds, and at 60° Fah., instead of 32° Fah., this cubic foot would weigh $.076346\times\frac{520}{460}=.0819$ pounds, 460 being the absolute temperature of $O°$ and 520° the absolute temperature of 60° Fah.=460° +60°=520°.

Altitudes are nothing more or less than pressures less than sea level, and are treated just the same as pressures above the normal atmospheric.

Thus at 5225 feet the absolute pressure is 12.044, consequently gas at this altitude would weigh $\frac{12.044}{14.7}$ times the weight at sea level.

For your convenience it may be well to add here that when the barometric pressure is known, the atmospheric pressure is found by multiplying the barometric pressure by .4908, or $P^0 = B \times .4908$.

For example.—When the barometer is 29.92 the atmospheric pressure is 29.92 × .4908, or 14.7, the normal sea-level pressure.

To find the atmospheric pressure when the altitude in feet is given, we have

$$P^o = 14.72 - \frac{57000\,N - N^2}{100,000,000} \text{ in which}$$

N = altitude in feet.

For example.—To find the atmospheric pressure at 10,000 feet we have

$$P^o = 14.72 \; \frac{57,000 \times 10,000 - (10,000)^2}{100,000,000} \text{ or}$$

$P^o = 14.72 - 4.7 = 10.02$, the atmospheric pressure required.

The foregoing rules will be all that is necessary to calculate all variations of weights due to pressure, altitude, or temperature, and relative volumes follow exactly the same laws as relative weights.

For convenience in many calculations Table 10 is given herewith, showing the pressure ratios, or $\frac{P}{P^0}$ for every pound from 1 to 110, and the volumes ratios will be inversely as the pressure ratios and consequently the reciprocal of the figures on the table.

This might be called a table showing also the rates of isothermal compression or expansion or Marriotte's law, the general formula for which is:

$P^0\ V^0 = P\ V$ = Constant, or in other words, the product of any pressure by its volume is always equal to the product of any other pressure by its volume, and this rule will be found useful in determining the contents of receivers, etc. It must always be remembered that in using these rules all temperatures must be alike, or corrections made according to the rules just given.

PRESSURE RATIOS	JULY 1905		TABLE 10		
Gauge	$\frac{p}{po}$	Gauge	$\frac{p}{po}$	Gauge	$\frac{p}{po}$
1	1·068027	38	3·585026	75	6·102025
2	1·136054	39	3·653053	76	6·170052
3	1·204081	40	3·721080	77	6·238079
4	1·272108	41	3·789107	78	6·306106
5	1·340135	42	3·857134	79	6·374133
6	1·408162	43	3·925161	80	6·442160
7	1·476189	44	3·993188	81	6·510187
8	1·544216	45	4·061215	82	6·578134
9	1·612243	46	4·129242	83	6·646241
10	1·680270	47	4·197269	84	6·714268
11	1·748297	48	4·265296	85	6·782295
12	1·816324	49	4·333328	86	6·850322
13	1·884351	50	4·401350	87	6·918349
14	1·962378	51	4·469377	88	6·986376
15	2·020405	52	4·537404	89	7·054403
16	2·088432	53	4·605431	90	7·122430
17	2·156459	54	4·673458	91	7·190457
18	2·224486	55	4·741485	92	7·258484
19	2·292513	56	4·809512	93	7·326511
20	2·360540	57	4·877539	94	7·394538
21	2·428567	58	4·945566	95	7·462535
22	2·496594	59	5·013593	96	7·530592
23	2·564621	60	5·081620	97	7·599619
24	2·632648	61	5·149647	98	7·66646
25	2·700675	62	5·217674	99	7·734673
26	2·768602	63	6·285701	100	7·802700
27	2·836729	64	5·353728	101	7·870727
28	2·904756	65	5·421755	102	7·938754
29	2·972783	66	5·489782	103	8·006781
30	3·040810	67	5·557809	104	8·074980
31	3·108837	68	5·625836	105	8·142835
32	3·176864	69	5·693863	106	8·210862
33	3·244891	70	5·761890	107	8·278889
34	3·312918	71	5·829917	108	8·346916
35	3·380945	72	5·897944	109	8·414943
36	3·448972	73	5·965971	110	8·482970
37	3·516999	74	6·033998		

E. A. RIX.

ISOTHERMAL COMPRESSION.

There are two methods of compressing any gas.

First.—Where the temperature remains unchanged during compression. This is called isothermal compression and is the ideal method never realized in practice.

Second.—Adiabatic compression, which is the kind we meet in practice where the heat developed by compression expands the air being compressed until it follows a different law from Marriotte.

While isothermal compression is not practical, it is necessary to know about it and how to make the calculations concerning it.

We have found that the volume ratios are inversely as the absolute pressure ratios in isothermal compression. Consequently if the pressure ratios are 1, 2, 3, and 4, the corresponding volumes will be 1, ½, ⅓, ¼. To show this graphically, refer to Table 1, Figure 1.

Let $A\ B$ be the line of 0 pressure or the perfect-vacuum line. $C\ D$ the intake line and we erect pressures ordinates $G\ H = 2 \times D\ B$ at a point H equal to ½, $A\ B$ and $I\ J = 3 \times B\ D$ at a point $J = ⅓\ A\ B$ and $E\ K = 4 \times B\ D$ at a point $K = ¼$ of $A\ B$ counting all volumes from $F\ B$ or the end of the piston stroke.

If we join the points $C\ G\ I\ E$ in a curved line, it will be the isothermal or logarithmic curve and it will be noted that the area

$$E\ F\ B\ K = 4 \times \tfrac{1}{4} = 1$$
$$I\ L\ B\ J = 3 \times \tfrac{1}{3} = 1.$$
$$G\ M\ B\ H = 2 \times \tfrac{1}{2} = 1$$
$$C\ D\ B\ A = 1 \times 1 \text{ or } 1$$

As found before, $P^{o}\ V^{o} = P'\ V' =$ Constant, and the figure represents the ideal indicator card for isothermal compression for four compressions, counting from 0, and the above method will always be proper to lay out an isothermal curve, no matter what the intake pressure may be.

To find the work of compression and delivery isothermally

$P^0\ V^0$ hyp. log. $\frac{P}{P^0}$ in foot-pounds in which

P^0 = Initial pressure absolute.
V^0 = Initial volume.
P = Final pressure.
L = Work required.

In all our calculations V^0 will be taken as one cubic foot.

For example:—How many foot-pounds of work are required to compress 1 cubic foot of gas at sea level to eighty pounds gauge pressure?

For sea level P^0 per square foot $= 14.7 \times 144 = 2116.8$ pounds. Then

$$L = 2116.8 \text{ hyp. log. } \frac{P}{P^0}$$

Consulting Table 10, we find

$\frac{P}{P^0}$ for 80 pounds gauge=6.442 the hyperbolic logarithm of which is 1.863.

Substituting, we have

$L = 2116.8 \times 1.863 = 3943$ foot-pounds.

If a table of hyperbolic logarithms is not at hand, it would be well to remember that hyp. log. = common log. $\times$ 2.3026.

The $H\ P$ required for above work will be $\frac{3945}{33000} =$ .1195 $H\ P$.

To find the $M\ E\ P$ of isothermal compression,

$M\ E\ P = P^0$ hyp. log. $\frac{P}{P^0}$ using the quantities in the previous example we have $M\ E\ P = 14.7 \times 1.863 = 27.38$ pounds. We know that $H\ P = \frac{M\ E\ P \times V}{33000}$ and for one cubic foot $V = 1 \times 144$. Consequently, using the last example,

$H\ P = \frac{27.38 \times 1 \times 144}{33000} = .1195$, the same result as before. $\frac{1 \times 144}{33000} = .00436$. Consequently a short and convenient formula would be for isothermal compression $H\ P = .00436 \times M\ E\ P$.

It will be noted that none of the physical properties of gases enter into the above equations, consequently we must conclude that it takes the same power to compress one cubic foot of any gas isothermally to the same pressure, provided the ratios of pressures are the same.

ADIABATIC COMPRESSION.

We have before stated that isothermal compression is ideal, and not realized in practice. All of the work expended in compressing a gas is converted into heat instantly, and this increases both the temperature and the volume of the gas during compression, so that, instead of having a relation between pressure and volume ($P_0\ V_0 = P\ V =$ Constant), such as we found in isothermal compression, we now have a relation $P_0\ V_0^y = P\ V^y =$ Constant, or in other words, the gamma powers of each volume, multiplied by its corresponding pressure, is Constant. This is the equation of the Adiabatic curve. y is the same that we found to be the ratio between the specific heat at constant pressure and that at constant volume. This relation can perhaps be fastened a little easier in the mind by remembering that the equation of the isothermal curve represents the law of Marriotte and the equation of the adiabatic curve represents the Exponential law of Marriotte.

Inasmuch as the power to compress a gas is measured practically by the indicator diagram, and this in turn is compared to the adiabatic curve which is theoretical curve of compression, and inasmuch as we depend upon the value of y to construct this curve, it will be at once seen why we were so particular to discover the relation $\frac{C^p}{C^v} = y$. Now if $P_0\ V_0^y = P\ V^y$ and from the simple gas equation $\frac{V^o P^o}{T^o} = \frac{V P}{T} = R$, by combining these we have all the adiabatic relations between volume pressure and temperature as follows:

$$\frac{P}{P^o} = \left(\frac{V^o}{V}\right)^y = \left(\frac{T}{T_o}\right)^{\frac{y}{y-1}}$$

$$\frac{V}{V_o} = \left(\frac{P^o}{P}\right)^{\frac{1}{y}} = \left(\frac{T^o}{T}\right)^{\frac{1}{y-1}}$$

$$\frac{T}{T^o} = \left(\frac{V^o}{V}\right)^{\frac{y-1}{y}} = \left(\frac{P}{P^o}\right)^{\frac{y-1}{y}}$$

It will always be necessary to use the above formulas in making calculations for pressures, temperatures, and volumes, or for power to compress any gas which varies far enough from the standard we have selected to make it necessary, but there is no doubt that for all practical purposes, at least for the present, Table 11, which is calculated for our standard gas, will give the proper values for rapidly and easily calculating any problems connected with compressing illuminating gas.

All reference to expansion is purposely omitted, because gas will probably never be used for expansion work in an engine as air is used.

Assuming that all may not be familiar with just how to arrive at the results as indicated in Table 11, let us take a ratio of $\frac{P}{P^o} = 2$ corresponding to 14.7 pounds gauge pressure and discover what are the values of $\frac{V}{V^o}$ and $\frac{T}{T^o}$. We have $\frac{V}{V^o}\left(\frac{P^o}{P}\right)^{\frac{1}{y}}$ y we have already decided from our standard gas to be 1.334.

Therefore, $\frac{1}{y} = \frac{1}{1.334} = .749$ $\frac{V}{V^o} = \left(\frac{P^o}{P}\right)^{.749}$ or since

$\frac{P^o}{P} = ½$ or .5 we have

$\frac{V}{V^o} = .5^{.749}$ or

$\text{Log.} \frac{V}{V^o} = \log .5 \times .749.$

Log. .5 = 1.6989 × .749 = 1.77447 = log. $\frac{V}{V^o}$ giving value of $\frac{V}{V^o} = .5949$ and $\frac{V^o}{V}$ will be reciprocal of $\frac{V}{V^o}$ or 1.681.

To find the ratio of temperature for this same rate of compression, we have $\frac{T}{T^o} = \left(\frac{P}{P^o}\right)^{\frac{y-1}{y}}$ $\frac{y-1}{y} = .25.$

Hence:

$\text{Log.} \frac{T}{T^o} = .25 \log. \frac{P}{P^o}$

$\text{Log.} \frac{P}{P^o} = .301 \times .25 = .07525 = \text{Log.} \frac{T}{T^o}$

$\frac{T}{T^o} = .1892.$

T = 520 × 1.1892 = 618° absolute or 158° Fah. if $T^o = 60°$ Fah. We have then

$\frac{P}{P^o} = 2 \quad \frac{V^o}{V} = 1.681 \quad \frac{V}{V^o} = .5949.$

$\frac{T}{T^o} = 1.1892 \quad T = 158°$

Air under the same conditions gives

$\frac{P}{P^o} = 2 \quad \frac{V^o}{V} = 1.6349 \quad \frac{V}{V^o} = .6117.$

$\frac{T}{T^o} = 1.2226 \quad T = 175°$ Fah.

These examples will serve to show how this Table 11 was calculated. A few examples will show its use.

Problem.—To find the final temperature due to adiabatic compression.

Opposite $\frac{P}{P^o}$ and under the headline $\frac{T}{T^o}$ will be found the ratio of absolute temperatures.

Example.—What is the final temperature due to 14.7 pounds gauge pressure at sea level and 60° Fah.?

TABLE II. ADIABATIC TABLE FOR GAS JULY 1905					
$\frac{p}{p_0}$	$\frac{T}{T_0}$		$\frac{T}{T_0}-1$	$\frac{V}{V_0}$	
	NUMBER	DIFF.		NUMBER	DIFF.
1·2	1·0466	412	·0466	·8063	300
1·4	1·0878	369	·0878	·7763	733
1·6	1·1247	336	·1247	·7030	594
1·8	1·1583	309	·1583	·6436	488
2·	1·1892	287	·1892	·5948	410
2·2	1·2179	268	·2179	·5538	352
2·4	1·2447	251	·2447	·5186	301
2·6	1·2698	268	·2698	·4885	264
2·8	1·2966	195	·2966	·4621	233
3·	1·3161	214	·3161	·4388	207
3·2	1·3375	204	·3375	·4181	186
3·4	1·3579	195	·3579	·3995	168
3·6	1·3774	188	·3774	·3827	152
3·8	1·3962	180	·3962	·3675	139
4·	1·4142	173	·4142	·3536	126
4·2	1·4315	168	·4315	·3410	117
4·4	1·4483	162	·4483	·3293	108
4·6	1·4645	157	·4645	·3185	99
4·8	1·4802	152	·4802	·3086	94
5·	1·4954	697	·4954	·2992	383
6	1·5651	615	·5651	·2609	284
7	1·6266	552	·6266	·2325	222
8	1·6818	503	·6818	·2103	177
9	1·7321	462	·7321	·1926	147
10	1·7783		·7783	·1779	E.A.Rix

$\frac{P}{P_0} = \frac{29.4}{14.7} = 2.$ Then $\frac{T}{T^o} = 1.1892$, or $520 \times 1.1892 =$ 618° abs. or 158° Fah.

If the initial temperature has been 100° then $560 \times 1.1892 = 666°$ abs. or 206° Fah.

It is readily noted from this that the higher the initial temperature, the higher the final temperature, and it will also be noted that while there is a difference of 40° between the initial temperature, there is a difference of 48° between the final temperatures; a difference of 8°.

Inasmuch as the temperature developed during compression is at the expense of power, it is evident that it takes more power to compress the same weight of gas at 100° Fah. than at 60° Fah. to the same pressure, all other conditions being similar.

It is an axiom, therefore, that the cost of power for compressing gas will be the least when the initial temperature is the lowest, and it will be shown, later on, that cooling before compression will effect a considerable saving, if the gas to be compressed is drawn from the holder exposed to the sun, provided, of course, that cooling water may be had at a small expenditure of power.

Problem.—To find the volume immediately after compression.

Consult Table 11, and under the heading $\frac{V}{V^o}$ and opposite the pressure ratio $\frac{P}{P^o}$ the proper value will be found; and it must always be remembered that these values of temperature and volumes assume no radiation of heat whatever, for when the heat generated by compression has radiated the temperatures and volumes are as calculated isothermally.

Please note that $\frac{V}{V^o}$ is measured from the end of the stroke. The difference given in Table 11 will enable greater or lesser values of $\frac{P}{P^o}$ to be conveniently determined by simple rules of proportion.

From this table the adiabatic curve can be readily drawn.

Refer to Table 1, Figure 2.

Let *A B* be the intake line and *C D* the line of 0 pressure, these lines representing the piston stroke. Divide *A B* into a decimal scale; beginning at *B* erect *F D* at the end of the stroke and divide it into equal values of *B D*. *B D* may be the value at sea level or at an altitude or it may be any intake pressure whatever; these rules will always apply. These values of *B D* may be subdivided into five parts, where special accuracy is required, and their values will also be found in Table 11.

D H representing a ratio of $\frac{P}{P^o} = 2$, the corresponding value of $\frac{V}{V^o}$ will be found in Table 11 to be .5948, and laying off the value the point *S* will be found.

Similarly at *G* representing $\frac{P}{P^o} = 3$ we find $\frac{V}{V^o} =$ .4388, and laying this off we find that the point M. And then *F* representing $\frac{P}{P^o} = 4$ has a value for $\frac{V}{V^o}$ of .3536, and we lay off this value and find point *J*. Joining the point *J M S A* we develop the adiabatic curve, and the shape of this curve will depend upon the length of the card, the value of $\frac{C_p}{C_v}$ or y. The equation of the curve is $P\,V^y = P'\,V'^y$ or referring to the diagram.

$$M\,O \times (M\,G)^y = J\,L \times (J\,F)^y$$

Problem.—To determine the power to compress a gas adiabatically.

All that precedes this subject has been necessary to its proper understanding, and while possibly the various symbols are well remembered, it will probably be better to group them together, so that they may be readily referred to.

P^0 is always the lesser absolute pressure, and consequently the intake pressure in compression. We shall take this as 14.7 at sea level, for the 4-inch water pressure of the gas will not fill the cylinder at any greater than atmospheric pressure. P is the final absolute pressure.

T^0 is the initial absolute pressure, and unless otherwise specified is taken at 60° Fah. or 520° absolute, that temperature being the probable temperature of the gas mains.

T is the final absolute temperature.

V^0 is the volume at P^0.

V is the volume at P.

P' V' T' are intermediate pressures, temperatures, and volumes.

L is the work expressed in foot-pounds.

H P is horsepower.

M E P is mean effective pressure, which is always gauge pressure.

W is the weight of a unit volume or one cubic foot of our standard gas at 60° Fah. and at sea level, with an absolute pressure of 14.7 lbs. per square inch, or 2116.8 pounds per square foot, and equals .03063 pounds avoirdupois.

J is Joules' equivalent taken at 772 foot-pounds.

C^p is the specific heat at constant pressure = .6884.

C^v is the specific heat at constant volume = .5159.

$$y \text{ is } \frac{C^p}{C^v} = 1.334.$$

$$\frac{y}{y-1} = 4. \quad \frac{y-1}{y} = .25 \quad \frac{1}{y} = .75$$

$J\ C^p = 772 \times .6844 = 531.45$ foot-pounds.

This value is Joules' equivalent for 1 lb. of gas at constant pressure.

$J\ W\ C^p = 531.45 \times .03063 = 16.28$ foot-pounds = Joules' equivalent for 1 cubic foot of gas.

$$J\ W\ C^p\ T^0 = 16.28 \times 520 = 8465 \text{ foot-pounds.}$$

$$\frac{y}{y-1} \times P^o V^o = 4 \times 144 \times 1 \times 14.7 = 8465$$

foot-pounds = the intrinsic energy of 1 cubic foot of gas at 60° Fah. and atmospheric pressure at sea level; or to reduce those values of foot-pounds to horsepower, we have

$$J\ W\ C^p\ T^o = \frac{8465}{33000} = .2564\ H\ P$$

$$\frac{y}{y-1}\ P^o\ V^o = \frac{8465}{33000} = .2564\ H\ P$$

All of these foregoing quantities are constants to be used in determining the power to compress gas, and as we have said before, are all based on a quantity of 1 cubic foot of our standard gas at sea level and 60° Fah.

We mentioned at the beginning of this paper that the power to compress any gas adiabatically might be expressed by the general formula

$L = J\ W\ C^p\ (T—T^o)$, or to put it in another form,

$$L = J\ W\ C^p\ T^o \left(\frac{T}{T^o} — 1\right)$$

You now at once recognize the prefix $J\ W\ C^p\ T^o$ as the one for which we have found a value of 8465 foot-pounds. Therefore, for our standard gas we have

$L = 8465 \left(\frac{T}{T^o} — 1\right)$ which is a practical formula.

You also recognize that $\frac{T}{T^o}$ is all you need solve, and these values are all given in Table 11 for the various values of $\frac{P}{P^o}$. We can now understand our first problem.

How many foot-pounds are necessary to compress 1 cubic foot of our standard gas to 14.7 pounds gauge pressure?

$\frac{P}{P^o} = \frac{294}{14.7} = 2.$ Consulting Table 11 we find $\frac{T}{T^o} — 1 = .1892$ and $8465 \times .1892 = 1601.57$ foot-pounds, and the same method may be applied for all pressures.

If we use the value of $J\ W\ C^p\ T^o$ in horsepower, we have $H\ P = .2564\left(\frac{T}{T^o} - 1\right)$ a perfectly practical formula for 1 cubic foot of our standard gas at 60° Fah. and at sea level.

Our previous example would then be rendered:

$L = .2564 \times .1892 = .0485$ horsepower for 1 cubic foot compressed to 14.7 lbs. gauge. At 80 lbs. gauge pressure.

$\frac{P}{P^o} = 6.442$ and $\frac{T}{T^o} = 1.593.$

$H\ P = .2564 \times .593 = .1520$ horsepower per cubic foot, or 15.20 H P per 100.

MEAN EFFECTIVE PRESSURES.

It will be found that inasmuch as we learn from an indicator what our gas compressor is doing, and inasmuch as $M\ E\ P$ pressures are quickly determined by a planimeter from an indicator card, that to become familiar with what the $M\ E\ P$ should be and compare it with what the compressor is doing is the best practical way of dealing with the subject.

We found that

$$L = J\ W\ C^p\ T^o\left(\frac{T}{T^o} - 1\right)$$ and that.

$$J\ W\ C^p\ T^o = \frac{y}{y-1} P^o\ V^o,$$ therefore

$$L = \frac{y}{y-1} P^o\ V^o\left(\frac{T}{T^o} - 1\right)$$

L must always equal $M\ E\ P \times V^o$, we have

$$M\ E\ P \times V^o = \frac{y}{y-1} P^o\ V^o\left(\frac{T}{T^o} - 1\right)$$ or

$$M\ E\ P = \frac{y}{y-1}\ P^o\left(\frac{T}{T^o} - 1\right)$$ and since

$\frac{y}{y-1} = 4$, we have for our standard gas

$$M\ E\ P = 4\ P^o\left(\frac{T}{T^o} - 1\right)$$

Take 80 lbs. gauge pressure.

$\frac{T}{T^0} - 1 = .593$ as determined in a former example by Table 11.

$P^0 = 14.7$.

$M\ E\ P = 4 \times .593 \times 14.7 = 34.86$ lbs. per sq. in.

For our standard gas for one cubic foot at sea level

$$M\ E\ P = 4 \times 14.7 \left(\frac{T}{T^0} - 1\right) = 58.8 \left(\frac{T}{T^0} - 1\right)$$

$$H\ P = \frac{144 \times 1 \times M\ E\ P}{33000} = .00436 \times M\ E\ P, \text{ or}$$

$$H\ P = .00436 \times 58.8 \left(\frac{T}{T^0} - 1\right) = .2564 \left(\frac{T}{T^0} - 1\right)$$

the same result we obtained in a former example.

INITIAL TEMPERATURES.

The general expression for the work of compression being

$$L = \frac{y}{y-1} P^0\ V^0 \left(\frac{T}{T^0} - 1\right)$$

it is evident that so long as $\frac{T}{T^0}$ remains constant, the power to compress one cubic foot of the same gas is constant, but inasmuch as the temperature of the mains is practically constant and about 60° Fah., if our initial temperature from the holder should happen for any reason to be 100° Fah., as it was entering the compressor, it is evident that the compressor must make an extra number of revolutions to deliver a fixed quantity into the mains at 60° Fah. than it would if the mains were the same temperature as the gas in the holder, and the ratio would be as the absolute temperatures or $\frac{560}{520}$, or 8 per cent additional. In a plant where 250 horsepower is used in compressing the gas, this would mean a saving of 20 horsepower. By passing the gas through a cooler before it reached the compressor would correct the loss. Inasmuch as little water is required for this, and the water is in no wise impaired for other purposes, that this cooling could always be done. *Vice versa,* if the temperature of the holder was lower than the mains, as in winter, there would be a corresponding gain and some of the otherwise lost heat of compression would be utilized in expanding the gas to a temperature corresponding to the main. In the long run, the gain might balance the loss, if no cooling were done, but it seems a business proposition to save where possible, especially where it costs little or nothing.

TWO STAGE COMPRESSION.

If we consider the general equation for the work performed in compressing any gas, adiabatically

$$L = J\ W\ C^p\ (T - T^0)$$

we note that the only variable is T, the final temperature, if our initial temperature remains the same. In other words, the difference between the initial and final temperature determines always the power expended in a compressor, just as it does the power given out by any heat engine. It is evident, then, that the lower we keep the final temperature the less power it takes. Water-jacketing the cylinders accomplishes but little, probably from 3 to 5 per cent, for the reason that gases being such poor heat conductors that, while they are rapidly drawn in and pushed out of the compressing cylinder, there is not time for the heat to radiate through the cylinder walls, and only the portion immediately in contact with the cool cylinder walls suffers any reduction of temperature. The water jacket keeps the cylinder walls cool so that lubrication is effective and is valuable for that reason principally.

Practically speaking, the compression is adiabatic, or even greater because the pressure in the cylinder is always greater than the receiver on account of the work expended in forcing the gas through the valve openings, and this extra heat generated overruns the adiabatic temperature corresponding to the receiver pressure.

The water jacket being ineffective, the device of stage compression was inaugurated, where, after the gas was compressed to a portion of the final pressure in a cylinder, it was discharged into an intercooler, its temperature reduced to the initial and then compressed by a smaller cylinder to the final pressure. The work was found to be a minimum when the final temperature of each stage was the same.

If we represent the initial pressure by P^0 and the final by P', and volumes and temperatures similarly, we shall have, using our general formula for work expended,

$$L = \frac{y}{y-1} P^0 V^0 \left(\frac{T}{T^0} - 1\right) \text{ for first stage and}$$

$$L' = \frac{y}{y-1} P V \left(\frac{T'}{T} - 1\right) \text{ for second stage.}$$

We know that before compression $P^0 V^0$ must equal $P V$, consequently if L is desired to equal L', we must have

$$\left(\frac{T}{T^0} - 1\right) = \left(\frac{T'}{T} - 1\right) \text{ or}$$

$$\frac{T}{T^0} = \frac{T'}{T}$$

$$\frac{T}{T^0} = \left(\frac{P}{P^0}\right)^{\frac{y-1}{y}}$$

$$\frac{T'}{T} = \left(\frac{P'}{P}\right)^{\frac{y-1}{y}}, \text{ or reducing}$$

$$\frac{P}{P^0} = \frac{P'}{P} \text{ or } P^2 = P^0 P' \text{ or } P = \sqrt{P^0 P'}$$

In other words, to make the work in two stages equal, and to have the work a minimum, P, the intermediate pressure, must be a mean proportional between the initial and the final pressure, the volumes and the piston areas must follow the same law, since we naturally make the strokes alike.

For an example, let us take 80 pounds final gauge pressure:

$P = \sqrt{P^0 P'}$ or $\sqrt{14.7 \times 94.7} = 37.31$ absolute or 22.61 gauge pressure. This makes

$$\frac{P}{P^o} = \frac{37.31}{14.7} = 2.54, \text{ and}$$

$$\frac{P'}{P} = \frac{94.7}{37.31} = 2.54$$

and inasmuch as these pressure ratios are the same, the work expended on each stage will be the same and the piston ratio will be 2.54 also.

We found for the standard gas that

$$H\ P = .2564 \left(\frac{T}{T^o} - 1\right)$$

Referring to Table 11, we find when

$$\frac{P}{P^o} = 2.54, \text{ that } \frac{T}{T^o} = 1.2624.$$

Then $H\ P = .2564 \times .2624 = .06727$ for each stage and for both stages, $2 \times .06727 = .13454\ H\ P$.

It will be remembered that we calculated the single stage *H P* for 80 lbs. in a former example as .1520. We have then 13.45 *H P* per 100 cu. ft. two stage against 15.20 *H P* single stage, a saving of 13 per cent in power.

If the maintaining of a low temperature is any advantage in gas compression, we have a temperature of 366° Fah. in the single stage compression against 195° Fah. in the two stage, a remarkable difference. Suppose now that we have a cylinder having an area of 100 sq. inches, when we compress to 80 lbs. the maximum strain is 8000 lbs., if the compressor is single stage and 4522 lbs. if the compressor is a tandem two stage, a remarkable difference, tending to show that we can build the two stage compressor very much lighter for the same work.

Another point in favor of the two stage compressor, it has a greater volumetric efficiency. A piston never delivers from a cylinder an amount of gas equal to its displacement, because clearance spaces are filled with gas at the discharge pressure, which expands in the return stroke of the piston and occupies more or less space according to the ratio of compression and the amount of clearance. The greater the temperature of compression, the hotter the piston and heads and

TABLE 12 — LOSS OF PRESSURE CAUSED BY FRICTION OF COMPRESSED GAS IN PIPES — JULY 1905 — E. A. RIX

$P_1^2 - P_2^2$ = DIFFERENCE IN SQUARES OF INITIAL AND FINAL ABSOLUTE PRESSURE, PER 100 FEET OF PIPE

Equivilant Volume in Cu. Ft. of Free Air per Min. Passing through Pipe.	Size of Pipe: 1	1¼	1½	2	2½	3	3½	4	5	6	7	8	9	10	12	14	16	18	20
50	90	28.52	12.	2.88															
75	201	59.10	27.72	6.30															
100	360	118.2	47.4	11.28	3.69														
150	810	265.8	106.8	25.32	8.28	3.30													
200	1440	472.8	189.6	45.0	14.76	5.94	1.62	1.44											
250	2250	738.	286.4	70.2	23.10	9.24	4.26	2.16											
300	3240	1062	426.6	100.8	33.24	13.32	6.18	3.18											
400	5760	1890	757.8	180.	58.98	23.70	10.92	5.64	1.86										
500	9000	2952	1186.8	282	92.4	37.2	17.10	8.76	2.88										
600	12960	4260	1707.	405	132.6	53.4	24.6	12.6	4.14										
800		7440	3042.	720	236.4	92.4	43.8	22.5	7.38	2.96									
1000		11760	4740	1128	369.	148.2	68.4	35.04	11.52	4.62	1.65								
1500		26400	10680	2532	828.	333.	153.	79.2	25.92	10.44	4.80								
2000			18960	4500	1476	594	273.	140.4	46.2	18.54	8.52	4.38							
3000			42600	10080	3324	1332	618.	315.6	103.8	41.07	19.26	9.90	5.49						
4000				18000	5898	2370	1092	562.2	184.5	74.4	34.2	17.58	9.72	5.76					
5000				28200	9300	3708	1710	876	288.	115.8	53.4	27.42	15.24	9.0	3.62				
6000				40800	13380	5340	2460	1260	414.6	166.8	76.8	39.6	21.9	12.96	5.22				
8000					23760	9480	4380	2250	738.	296.4	136.8	70.2	39.3	23.10	9.24	4.26			
10000					57200	14760	6840	3510	1152	462.6	213.6	109.8	61.08	36.	14.46	6.72	3.42		
15000						33000	15300	7908	2592	1044	480.6	247.2	136.8	81.	32.46	15.0	7.74	4.26	
20000						58800	27300	14100	4614	1854	855.	438.6	243.6	144.	57.90	26.7	13.8	7.62	4.5
25000							42600	21900	7200	2970	1320.	678.	381.	225.	90	42.	21.6	11.88	7.02
30000								31800	10380	4170	1920	990.	552.	324	130.2	60	30.9	17.1	10.08
35000								43200	14100	5700	2640	1350	750	441.	177.	82.2	42.0	23.4	13.8
40000								56100	18420	7440	3420	1770	978	576.	231.6	106.8	54.9	30.3	18.0
50000									28800	11580	5340	2760	1524	900	361.8	168.	85.8	47.7	28.2
60000									42600	16680	7680	3960	2196	1296	522.	248.4	123.	68.4	40.2
80000										29700	13680	7080	3900	2370	924	429	219	122.4	72.0
100000										46260	21360	11040	6120	3600	1452	672	343.	190.2	112.8

TABLE 13. PRESSURES AND SQUARES OF PRESSURES. JULY 1905

Gauge Pressure	Absolute Pressure	Sq. of Absolute Pressure	Gauge Pressure	Absolute Pressure	Sq. of Absolute Pressure	Gauge Pressure	Absolute Pressure	Sq. of Absolute Pressure	Gauge Pressure	Absolute Pressure	Sq. of Absolute Pressure
0	14.7	216									
2	16.7	279									
4	18.7	350									
6	20.7	428									
8	22.7	515									
10	24.7	610	56	70.7	4998	105	119.7	14328	240	254.7	64855
12	26.7	713	58	72.7	5285	110	124.7	15550	250	264.7	70055
14	28.7	824	60	74.7	5580	115	129.7	16822	260	274.7	75450
16	30.7	942	62	76.7	5883	120	134.7	18144	270	284.7	81050
18	32.7	1069	64	78.7	6194	125	139.7	19516	280	294.7	86845
20	34.7	1204	66	80.7	6512	130	144.7	20938	290	304.7	92840
22	36.7	1347	68	82.7	6839	135	149.7	22410	300	314.7	99040
24	38.7	1498	70	84.7	7174	140	154.7	23932	325	339.7	115400
26	40.7	1656	72	86.7	7517	145	159.7	25504	350	364.7	132940
28	42.7	1823	74	88.7	7868	150	164.7	27125	375	389.7	151850
30	44.7	1998	76	90.7	8226	155	169.7	28790	400	414.7	191950
32	46.7	2180	78	92.7	8593	160	174.7	30500	425	439.7	193300
34	48.7	2372	80	94.7	8968	165	179.7	32290	450	464.7	215925
36	50.7	2570	82	96.7	9351	170	184.7	34100	475	489.7	239790
38	52.7	2777	84	98.7	9742	175	189.7	35980	500	514.7	264900
40	54.7	2992	86	100.7	10140	180	194.7	37905	550	564.7	318900
42	56.7	3215	88	102.7	10547	185	199.7	39875	600	614.7	378900
44	58.7	3446	90	104.7	10962	190	204.7	41900	650	684.7	441800
46	60.7	3684	92	106.7	11385	195	209.7	43970	700	714.7	510800
48	62.7	3931	94	108.7	11810	200	214.7	46090	750	764.7	584800
50	64.7	4186	96	110.7	12254	210	224.7	50490	800	814.7	663750
52	66.7	4449	98	112.7	12701	220	234.7	55060	900	914.7	836700
54	68.7	4720	100	114.7	13156	230	244.7	59860	1000	1014.7	1029650

valves get, and the less weight of gas enters the cylinder on account of the clearance expansion. There are other losses which need not be mentioned here, but these two are sufficient to make the volumetric efficiency of single stage compressors at 80 lbs. average about 75 per cent.

It will be readily seen that the initial cylinder of a two-stage machine at 80 lbs. will have its clearance losses divided by 2.54, because that will be the relative ratio of pressures and the temperature losses in proportion to

$\frac{195}{366}$ because that is the absolute temperature ratio.

These combined will make the average two-stage compressor good for 90 per cent volumetric efficiency—in other words, 15 per cent better than a single stage. One can, therefore, afford to pay at least 15 per cent more for a two-stage machine than for a single-stage machine, the intake cylinders being the same size, and this extra 15 per cent will nearly, or sometimes quite, pay for the difference in price.

It is evident from the calculations we have made that the efficiency of a two-stage machine over the single stage increases directly as the pressure ratios increase, and inasmuch as altitude increases pressure ratios, it is evident that the higher the altitude the more urgent becomes the necessity for using the two-stage machines, and at altitudes above 3000 feet it is practically imperative.

Theoretically, an infinite number of stages would give isothermal compression, but practically the losses involved in driving the gas through too many cylinders and valves would offset this gain, and we can consider that two stages will probably be the limit for all ordinary purposes.

ALTITUDE COMPRESSION.

We found that it took the same power to compress one cubic foot of gas at any temperature to the same final pressure, provided the initial pressures were the same, and it naturally followed that it took more power to compress the same weight at higher temperatures, because there would be a larger volume and the piston would have to make more strokes.

Altitude acts like an increase of temperature in lessening the density of a gas, but it introduces another element, viz., change of initial pressure, so that as we reach higher altitudes the pressure ratio is constantly increasing, which means, of course, that the temperature of compression is increasing and more work per unit of gas weight is being done, but the weight is constantly decreasing as we ascend, and the combination of these results is that while it takes less work to discharge any given cylinder full of gas at an altitude, the increased number of strokes necessary to compress a weight equivalent to a given sea level volume is considerably greater.

Table 17. July, 1905

Altitude.	$\frac{P}{P^o}$	$\frac{Y}{Y-1}$	P^o	V^o	$\frac{T}{T^o}-1$	Foot-pounds to compress one cubic foot	Equivalent to produce same compressed gas at altitude	Initial pressure.....	Gauge press........
Sea level..	6.44	4	14.7	1×144	.593	5020	5020	14.7	80
10,000 ft..	9.47	4	10.	1×144	.753	4337	6375	10.	80

$T = 390°$ Fah. at sea level.
$T = 450°$ Fah. at 10,000 feet altitude.

Table 17, shows a comparison between compressing gas at a sea level and at 10,000 feet altitude single stage compression. The columns 3 to 6, inclusive, comprise the components of the general formula for compressing gas, and it is interesting to note the variable quantities. It will be seen that while one cubic foot of the altitude gas requires less power, the increased volume necessary to produce a common result makes it require 25 per cent more power.

It will also be noted that the final temperature is quite high in comparison to sea level compression, which speaks loudly for two-stage compression.

FLOW OF GAS IN PIPES.

After reading the report of the committee on "The Flow of Gas in Pipes," for the Ohio Gas Light Association, as published in the *American Gas Light Journal,* April 24, 1905, the general impression would be that the formulas were not sufficiently reliable to be of great service, because there was a variation in the results of a given problem of from 1 to 200 per cent. It would seem, however, that six formulas out of the nine do not vary 15 per cent, and the three most frequently used do not vary 2½ per cent.

If we should accept the largest of these three, called the Pittsburg formula, we would probably not be far wrong, and particularly as the results do not differ greatly from those obtained by using Cox's computer, and I am informed by those who have used the computer that it is perfectly safe.

Again, the variation in the areas of those pipe sizes most likely to be used are much more considerable than the variations of any of the six formulas above referred to. Thus, taking the commercial sizes of pipe from 1″ to 6″, the average variation between the areas of each size is 35 per cent.

If we therefore make a practice of using the pipe that is the nearest size larger than our calculations, we shall have an ample safety factor.

For air we have been using a formula developed by Mr. J. E. Johnson, Jr., and published in the *American Machinist* July 27, 1899.

$$P'^2 - P''^2 = \frac{.0006\ Q^2\ L}{d^5}$$

P' = absolute initial pressure.
P'' = absolute final pressure.
Q = free air equivalent in cubic feet per minute.
L = length of pipe in feet.
d = diameter on pipe in inches.

Practical results from this formula show that it is a little too liberal, and that $P'^2 - P''^2 = \frac{.00005\, Q^2\, L}{d^5}$ would be nearer the results.

The Pittsburg gas formula reduces to the same value when the proper substitutes are made for the relative specific gravities of gas and air.

Inasmuch as the specific gravity of gas is always referred to air as 1, it seems right that our gas formula should refer to air and a co-efficient used for each gas.

The velocity of different gases through a pipe varies inversely as the square root of their densities, or what amounts to the same thing, their specific gravities or weights compared to air, then the velocities will vary as

$$\sqrt{\frac{G}{I}} \text{ or } \sqrt{G}$$

Where G is the specific gravity of gas.

Prefixing this to our original equation, we have in general, for any gas,

$$P'^2 - P''^2 = .0005\sqrt{G} \times \frac{Q^2\, L}{d^5}$$

Or

$$Q = \frac{44.72}{\sqrt[4]{G}} \sqrt{\frac{P'^2 - P''^2 \times d^5}{L}}$$

Inasmuch as certainly for some considerable time crude oil gas will be most extensively used by members of this Association, let us substitute in the above formula the value of the largest probable specific gravity, viz., .49, and we have $\sqrt{.49} = .7$ and

$$P'^2 - P'' = .00035\, \frac{Q^2\, L}{d^5} \qquad (A)$$

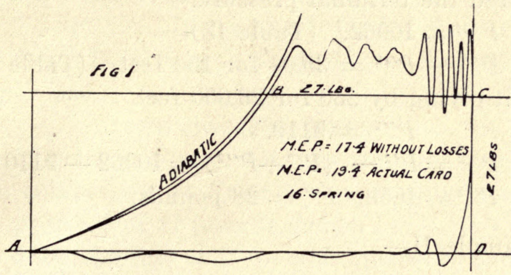
Or

$$Q = 53.45 \sqrt{\frac{P'^2 - P''^2 \times d^5}{L}}$$

Q is in cubic feet per minute rather than per hour, because all compressors are so rated.

Table 12 gives values of $P'^2 - P''^2$ for 100 feet of various sized pipes and quantities will be found convenient for figuring gas flows in pipes. The values are calculated from equation (A).

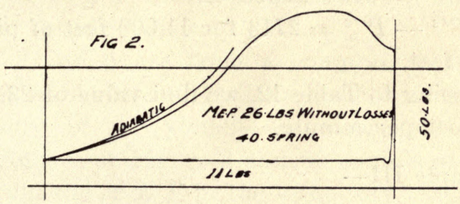
TABLE 14 INDICATOR CARDS FROM GAS COMPRESSORS. JULY 1905



$$M.E.P. = \frac{\gamma}{\gamma - 1}\ p_o \left(\frac{T}{T_o} - 1\right)$$

$= 3.95 \times 14.7 \times .3028 = 77.58$ ADIABATIC

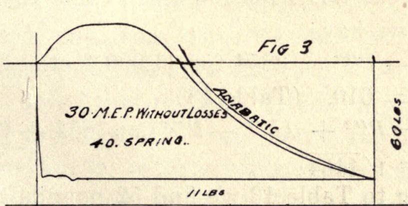
CRUDE OIL GAS FRESNO. CAL.



$$M.E.P. = \frac{\gamma}{\gamma - 1}\ p_o \left(\frac{T}{T_o} - 1\right)$$

$= 4.76 \times 25.7 \times .219 = 26.30$ ADIABATIC

NATURAL GAS. ANDERSON IND



$$M.E.R. = \frac{\gamma}{\gamma - 1}\ p_o \left(\frac{T}{T_o} - 1\right)$$

$= 4.67 \times 25.7 \times .257 = 30.85$ ADIABATIC

NATURAL GAS ANDERSON IND

E.A. RIX.

Example I—

1000 cubic feet per minute of gas at 90 pounds gauge pressure is discharging into a 4″ pipe 26,000 feet long. Required the terminal pressure.

$P'^2 = 10962.$ (Table 13)

$P'^2 - P''^2 = 35.04$ for 100 feet. (Table 12)

Multiplying by 260 for 26,000 feet

$P'^2 - P''^2 = 9110.$

$P''^2 = P'^2 - (P'^2 - P''^2) = 10962 - 9110 = 1852.$

$P''^2 = 1852.$ $P'' = 28$ pounds.

Example II—

A pipe line 3″ diameter and 11,000 feet long. Required to find the quantity of gas that will be delivered at a terminal pressure of 1 pound, the initial pressure being 40 pounds.

$P'^2 = 2992.$ (Table 13)

$P''^2 = 279$ (Table 13)

$P'^2 - P''^2 = 2713$ for 11,000 feet of pipe or 24.6 for 100 feet.

Referring to Table 12, we find value of 23.70 for 420 cubic feet per minute.

Example III—

A pipe line is 11,000 feet long and 4″ diameter. The equivalent of 1000 cubic feet is wanted at the end of the line at 10 pounds pressure. What must be the initial pressure?

$P'^2 - P''^2 = 35.04$ for 100 feet (Table 12). Multiplying by 110 we have

$P'^2 - P''^2 = 3854$ for 11,000 feet.

$P''^2 = 610.$ (Table 13)

$P'^2 = P''^2 + (P'^2 - P''^2) = 3854 + 610 = 4464.$

$P' = \sqrt{4464}.$

Referring to Table 13 we find 52 pounds gauge pressure to be the initial pressure.

Example IV—

The equivalent of 200 cubic feet per minute is to be put through a pipe 53,000 feet long. The initial pressure is 20 pounds. The final pressure must be 6 pounds. What will be the size of the pipe?

$P'^2 = 1204$. (Table 13)

$P''^2 = 428$. (Table 13)

$P'^2 - P''^2 = 776$ for 53,000 feet of pipe or 1.464 per 100 feet. Referring to Table 12, we find 4″ to be the proper size.

SOME CORROBORATIONS.

Table 15 gives at Figure 1 a card from the gas cylinder of a compressor at Fresno, compressing crude oil gas at a pressure of 27 pounds gauge.

If we draw the line of 27 pounds' pressure and take the *M E P* with a planimeter, following the curve *A B* and the straight lines *B C* — *C D* and *A B*, we shall have the *M E P* of a perfect card following the actual compression line. This *M E P* we find to be 17.4 pounds, using the y which we found for Fresno gas, the adiabatic *M E P* for 27 pounds = 17.58, making a good check on our values.

Figures 2 and 3 are from a compressor pumping natural gas at Anderson, Indiana, each having an intake pressure of 11 pounds—drawing lines of 50 pounds' pressure at Figure 2 and 60 pounds at Figure 3, and taking the *M E P* in the same way that we did in Figure 1, we find that the *M E P* for Figure 2 is 26 pounds, and for Figure 3, 30 pounds.

Using the value of y which we developed for natural gas and calculating the adiabatic *M E P*, we find they are 26.30 and 30.85 pounds, respectively, a very satisfactory check, and from these we may fairly conclude that our theories and formulas are reasonable.

It will be noted that the line of the compressor curve is very near the adiabatic, even though the compressors were making but 60 to 70 revolutions per minute. An air card would show at least double the separating space.

This would appear to show that the jackets were doing but very little good, and possibly because illuminating gas may be a much poorer conductor of heat than air.

TABLE 9 GAUGE PRESSURES, PRESSURE RATIOS, FINAL TEMPERATURES, VOLUME RATIOS, MEAN EFFECTIVE PRESSURE AND BRAKE HORSE POWERS FOR ILLUMINATING GAS AT SEA LEVEL AND 60° FAH. JULY 1905

SINGLE STAGE.

Gauge Pressure	$\frac{P}{P_o}$	$\frac{T}{T_o}-1$	Final Temperature T.	Adiabatic M.E.P.	Practical M.E.P. at Commercial Piston Speeds	Brake H.P. to Compress 100 Cu Ft at Sea Level & 60° Fah	$\frac{V}{V_o}$
3.00	1.2	.0466	84°	2.74	3.014	1.514	.8063
5.90	1.4	.0878	106°	5.16	5.676	2.85	.7763
8.9	1.6	.1247	125°	7.33	8.063	4.05	.7030
11.8	1.8	.1583	142°	9.30	10.23	5.14	.6436
14.7	2.	.1892	158°	11.17	12.22	6.15	.5948
17.7	2.2	.2179	173°	12.81	14.09	7.08	.5538
20.8	2.4	.2447	187°	14.38	15.82	7.95	.5186
23.6	2.6	.2698	200°	15.86	17.45	8.76	.4485
26.5	2.8	.2966	214°	17.46	19.31	9.63	.4621
29.4	3.	.3161	224°	18.58	20.44	10.27	.4388
32.4	3.2	.3375	238°	19.84	21.82	10.96	.4181
35.3	3.4	.3579	246°	21.04	23.15	11.63	.3995
38.3	3.6	.3774	256°	22.20	24.42	12.26	.3827
41.2	3.8	.3962	266°	23.29	25.62	12.87	.3675
44.1	4	.4142	275°	24.35	26.79	13.46	.3536
47.1	4.2	.4315	284°	25.37	27.91	14.00	.3410
50.	4.4	.4483	293°	26.25	28.87	14.56	.3293
53.	4.6	.4645	301°	27.31	30.04	15.10	.3185
55.9	4.8	.4802	310	28.22	31.04	15.60	.3080
58.8	5.	.4954	317	29.12	32.03	16.10	.2992
73.5	6.	.5651	354	33.22	36.54	18.36	.2609
88.2	7.	.6266	386	36.80	40.40	20.36	.3225
102.9	8.	.6818	424	40.04	44.04	22.15	.2103
117.6	9.	.7321	441	43.14	47.45	23.80	.1926
132.3	10.	.7783	446	45.85	50.43	25.28	.1779

PRACTICAL M.E.P. = ADIABATIC M.E.P. + 10%

BRAKE HORSE POWER PER 100 CU FT = + 26.5 %

FORMULA $H.P. = 32.5\left(\frac{T}{T_o}-1\right)$ FOR STANDARD GAS AT SEA LEVEL AND 60° FAH

E. A. RIX.

The line of compression comes so near the adiabatic that we may well call the compression adiabatic for safety in our calculations—but while the *M E P* adiabatic for any pressure represents the greatest possible power required to compress a gas, a still greater power must be applied—for example look at the Fresno card, Figure 1, Table 14—the area above the 27-pounds line represents work done in overcoming the inertia of the outlet valves in pushing the gas into the main, and this area will be greater or less depending upon the valve area and the size of the discharge openings and the piston speed. It will also be noted that there is an area representing suction work below the line *A D*, notwithstanding that the gas has a 4″ water pressure at holder. This probably indicates that the pipes from the holder to the compressor are too small.

Now, if we run a planimeter over the actual area of the card, we find that the real *M E P* is 19.4, or about 10 per cent greater than the adiabatic, and this agrees quite well with ordinary air practice, where a safe rule for single-stage work is to take the *M E P* at 10 per cent above the adiabatic and the two-stage *M E P* the same as the adiabatic. Slow speed, well-constructed compressors will do somewhat better, but it is well to calculate on the average type.

Now, for brake power to be delivered to a gas compressor, we have to allow a mechanical efficiency of the compressor at not to exceed 85 per cent, so that this 15 per cent loss combined with the 10 per cent loss in the cylinder points to the fact that we should add 26½ per cent to the adiabatic *H P* for the brake power required.

The steam-engine cards on the Fresno compressor show an *M E P* reduced to the size of the air cylinder of 20.75 pounds, or 20 per cent higher than the adiabatic air *M E P*, but this compressor had a Meyer cut-off, which helped its economy considerably.

Referring to Table 9, column 17, gives the formula for computing the power to compress one cubic foot of the gas at sea level and 60° Fah. If the calculation be made it will be noted that it takes practically the same power to compress one cubic foot of any of these gases, consequently Table 19 may be used generally.

In conclusion your attention is called to Table 19, which contains in convenient form the results which we have obtained, and which it is hoped you will find very helpful in considering thermodynamic questions regarding the standard illuminating gas made from crude oil.

SOME ECONOMICS IN HIGH PRESSURE GAS TRANSMISSION.

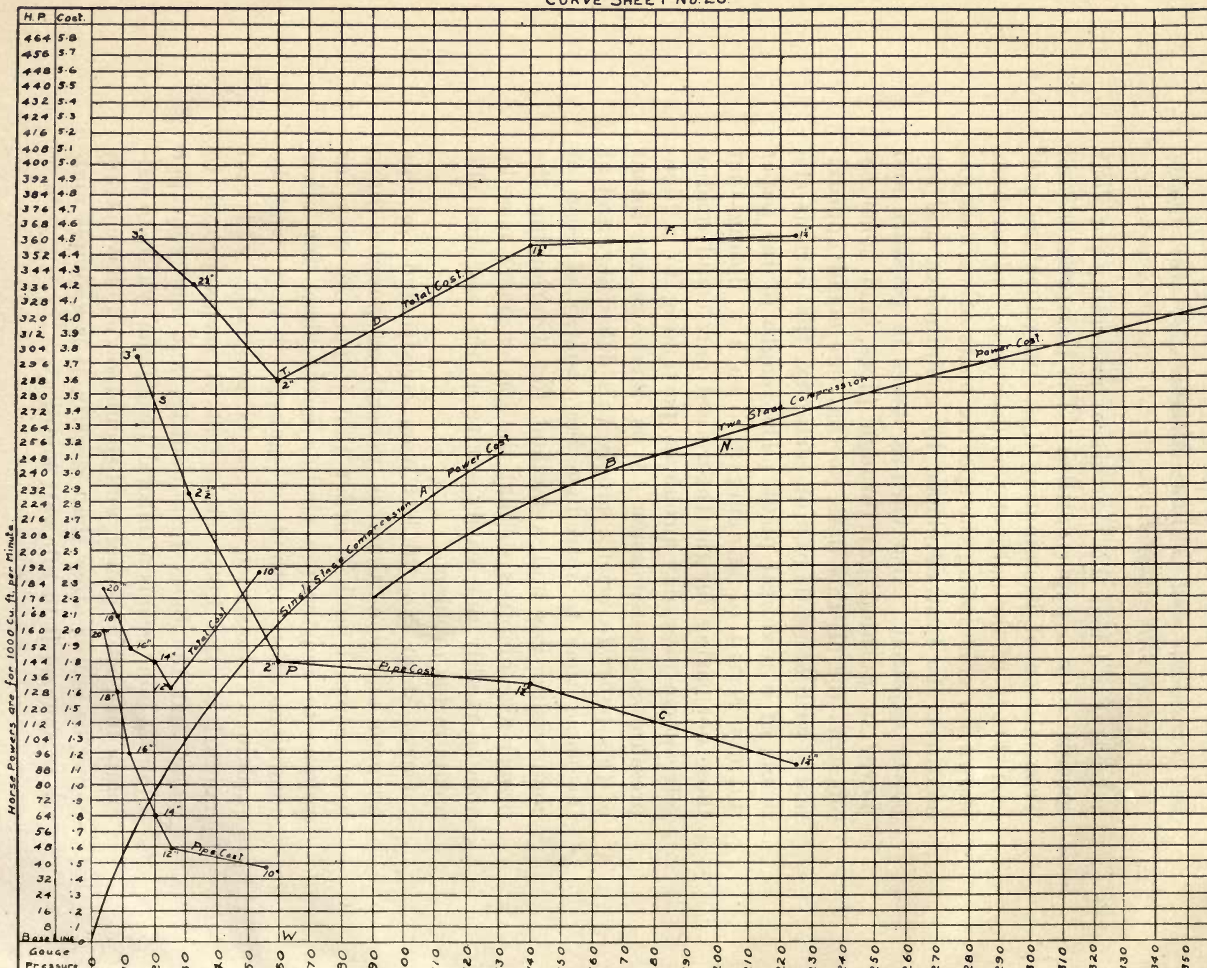
By EDWARD A. RIX.

Mr. President and Fellow Members of the Pacific Coast Gas Association.

Last year I had the pleasure of presenting for your consideration a paper entitled "The Compression and Transmission of Illuminating Gas," in which the general theory of the subject was discussed, and methods shown for calculating the specific heats of various gas mixtures, the heat developed by compression, and the power required. Also various losses in pressure and power in pushing gas through pipes, and some coefficients for all this data, so that one could approximate, with some degree of certainty, the various elements of a practical plant. The length of the paper did not permit of bringing it to such a closing that those not caring for the theoretical part could readily solve some everyday problems pertaining to a high-pressure gas transmission. It is, therefore, the intent of this paper to briefly supply this deficiency, and at the same time to introduce the element of cost of compressing gas and a method for determining the proper size of pipes so that the gas engineer may be able to readily and easily arrive at the essential elements in his problem.

Curve sheet No. 20 has been constructed for this purpose and conditions as general as possible have been assumed, and in order that it may be easy for anyone to construct a similar curve sheet for other conditions, the method of making it may well be explained. Inasmuch as gas is generally sold and handled by the 1,000 cubic feet, it seems proper to make that the basis for quantity, and one cent per kilowatt hour seems a natural base from which to calculate the cost of power, and should anyone have steam power or power other than electric, it is a simple matter to convert it to kilowatt hours.

CURVE SHEET No. 20



—LEGEND—

COST OF COMPRESSING 1,000 CU. FT. OF GAS
Power Cost
1-Cent per K.W. Hour.

1-Cent per K.W. Hour = ¾ cent per H.P. Hour
1-H.P. Hour = 60 × 33000 = 1,980,000 ft lbs for ¾ cent
1-Cent would then produce 2,640,000 foot lbs.
8 H.P. = 264,000 ft. lbs.
Then every 8 H.P. would cost $\frac{1}{10}$ cent.

PIPE COST FORMULA PER 1000 CU. FT GAS

10,000,000 cu. ft. per year = A
10,000 ft of pipe = B
1 cent per ft. cost
Then C = $\frac{1}{10}$ cent per 1000 Cu. ft. gas and for quantity = Q. and length of pipe = $\mathcal{L}$ and price of pipe p in cents we have

$$C = \frac{\mathcal{L}A}{BQ} \times \frac{p}{10}$$

LOSS OF PRESSURE IN PIPES

$$P_1^2 - P_2^2 = \frac{.00035 \times Q^2 \mathcal{L}}{d^5}$$

P_1^2 = Initial absolute pressure
P_2^2 = Final " "
Q = Quantity Cu. Ft. per Min
$\mathcal{L}$ = Length in feet.
d = Diameter in inches
and

$$P_1^2 = (P_1^2 - P_2^2) + P_2^2$$

Edward A. Ri-
Sept. 1906

If a kilowatt hour costs one cent, a horsepower will cost practically three-quarters of a cent, one horsepower hour=60x33,000 or 1,980,000 foot pounds for three quarters of a cent, one cent would therefore produce $\frac{1,980,000}{.75}$=2,640,000 foot pounds.

Eight horsepower equals 264,000 foot pounds, consequently every 8 horsepower will cost 1-10 of a cent per minute. This gives us the basis for our curve, for if we lay out our sheet in equal divisions of any size and call each one along the vertical line 8 horsepower, we can also make each division represent 1-10 of a cent, and each horizontal division we can conveniently call 10 pounds.

If you will now refer to Table 19, the last table which I read at our last meeting, it will be possible to construct the curve, remembering that the table is constructed for 100 cubic feet per minute, the horsepower therein contained must be multiplied by 10, for the 1000 feet capacity we are now considering.

Take, for example, 50 pounds gauge pressure, the brake horse-power required for 100 cubic feet is 14.56, and for 1000 would be 145.6. Where the vertical line indicating 50 pounds meets the horizontal line drawn from 145 horse-power will be a point on the curve. Similarly other points can be made, and joining the points together, we shall have a cost and power curve combined which will be very useful in our calculation.

I have constructed two of these curves, A and B. A is the curve of single stage compression and B for two-stage compression. Single stage is rarely used beyond 100 pounds pressure, nor two stage below 90 pounds pressure. You will note quite a difference in favor of two-stage compression. For example, at 100 pounds pressure it costs 2.35 cents per 1000 for two-stage and 2.75 cents for single-stage. In even a small plant using 50,000,000 feet per year, the difference would be $200 per annum, which is well worth saving.

The two-stage curve may be readily constructed from the single-stage curve by remembering that the intermediate absolute pressure between the stages is a mean proportional between the initial and final absolute pressure, and, inasmuch as it takes the same power for each stage, if we double the power required for the first stage we shall have the desired results, thus the intermediate gauge pressure for 200 pounds pressure will be 41 pounds. We note from the single-stage curve that 41 pounds requires 128 horse-power, consequently twice this is 256 horse-power, which, laid out on our curve sheet on the 200-pound vertical line, will give us the point N on the two-stage curve, and so on for other points to complete the curve.

It must be understood that the horse-powers are for 1000 cubic feet per minute, and the cost will be per 1000, and if you wish to eliminate the element of time just multiply the horse-power by 33,000 and the result will be the foot pounds to compress 1000 cubic feet of gas, and independent of time.

If power costs more or less than 1 cent per kilowatt hour, or the quantity to be compressed is greater or less than 1000 cubic feet per minute, the results may be read from the curve by simply using a corresponding proportion, for example:

The curve shows that 1000 cubic feet can be compressed to 20 pounds gauge pressure at the cost of 1 cent, it follows, therefore, that 2000 cubic feet can be compressed to 20 pounds for 2 cents, or if power costs 2 cents per kilowatt hour instead of 1 cent, then only one-half the quantity can be compressed for 1 cent, or double the quantity if power costs but ½ a cent a kilowatt hour. This method of proportion, however, does not apply to the matter of pressure, for you will note that while a cost of 1 cent gives 20 pounds pressure, a cost of 2 cents gives 58 pounds pressure, and a cost of ½ a cent gives only 8 pounds pressure. In other words, it costs just as much to compress gas from 0 to 8 pounds as it does from 8 to 20 pounds, and just as much to compress from 0 to 20 pounds as from 20 to 58 pounds. It would be well right here to consider this fact, for it has a great bearing on high-pressure transmission.

If it was found, for example, that it was costing 1 cent per 1000 to deliver gas through a certain pipe at 20 pounds pressure, and it became necessary to double the pressure in order to supply an increased demand, the gas company might consider it inadvisable because it might double the cost. Consulting the curve, it will be seen that the cost for compressing at 40 pounds pressure is only 1.6 cents per 1000 cubic feet instead of 2 cents, as may be imagined, and this fact might justify the increased pressure, and the higher the pressure the more the seeming disproportion.

From the curve take a geometrical progression of gauge pressure, 5-10-20-40-80-160-320, and we note the corresponding costs of compression for 1000 cubic feet to be, in cents, .3-.575-1.00-1.6-2.4-3.-3.9, in other words, while the pressure from 5 to 320 has increased sixty-four times, the cost of compression has increased but thirteen times.

It must not, however, be hastily inferred that because of this decreasing power ratio that it is economical to compress at high pressure, because it may not be so and depends upon the amount of gas to be pumped, for while the rate for 1000 may be small and make no material difference where a small quantity is pumped, with a large quantity the total amount of the yearly cost of pumping may exceed so materially the interest and depreciation on a larger pipe using a lower pressure that the latter installation will be deemed preferable.

The question of whether a large pipe and small pressure, or a small pipe and high pressure shall be used is simply a matter of equating the relative costs of pumping, together with the interest and depreciation on the plant, and, with the curve given herewith, it may be easily determined, and it is to show how to make this determination quite accurately and simple that I have written this paper. It has seemed to me that the cost of attendance, buildings, laying out pipe, etc., for any one problem may be neglected, for while it is an item of cost, it will be practically the same for whatever pipe you may select. We can then make our comparison, using the market cost of pipe and the cost of power only, to which may be added the other costs after the size of the pipe is determined, in order to give the total cost per 1000 for handling the gas.

The power and cost curves, as constructed, can be called "Standard" and white prints made from it, and upon these white prints the pipe curves laid out, as will be shown, and this same white print can be used in all cases. Let us then take two examples, one for small quantity and one for large quantity, and before starting at it let us make a general standard formula, which will simplify many of the calculations.

No plant will pump less than 10,000,000 cubic feet per year, which is about 1200 per hour, or at a less distance than 10,000 feet, consequently take for a basis:

10,000,000 feet per year $=a$
10,000 feet of pipe $=b$
1 cent per foot cost of pipe
10% per annum interest and depreciation on the pipe.

Then equating these quantities we will find that the pipe cost C for 1000 cubic feet of gas will be 1/10 of a cent.

For any other quantity Q, and length of pipe L, and price of pipe P, we shall have:

$$\text{Pipe cost per 1000 } C=\frac{La}{bQ}\times\frac{P}{10}$$

Example 1—50,000,000 cubic feet per year, or 6000 per hour, 50,000 feet of pipe, and power to cost ½ cent per kilowatt hour, substituting in our formula

$$C=\frac{La}{bQ}\times\frac{P}{10} \text{ we have } C=\frac{50,000\times 10,000,000}{10,000\times 50,000,000}\times\frac{P}{10}=\frac{P}{10}$$

That is to say that whatever size pipe we select the pipe cost per 1000 cubic feet of gas will be 1/10 the market cost of pipe per foot.

Taking the market prices of to-day, then if we should use:

1¼ pipe, cost per 1000 cubic feet, equals........ .559
1½ pipe, cost per 1000 cubic feet, equals........ .67
2 pipe, cost per 1000 cubic feet, equals........ .894
2½ pipe, cost per 1000 cubic feet, equals........1.429
3 pipe, cost per 1000 cubic feet, equals........1.875

Having thus blocked out the matter of pipe, we must find what pressure it is necessary to use to pump the gas through these various sized pipes, assuming always that the terminal pressure shall be one pound gauge.

You will remember that we developed a formula in my paper, read last year, which may be used here with accuracy.

$$P_1^2 - P_2^2 = \frac{.00035 \times Q^2 L}{d^5} \text{ where } P_1^2 - P_2^2$$

is the difference between the squares of the initial and final absolute pressures.

Q is the quantity of gas in cubic feet per minute.

L is the length of pipe, in feet.

D is the pipe diameter, in inches.

Substituing in this equation the elements in our problem, we have:

$$P_1^2 - P_2^2 = \frac{35 \times 100 \times 100 \times 50,000}{100,000 \times d} \text{ or } P_1^2 - P_2^2 = \frac{175,000}{d^5}$$

Then $P_1^2 \times P_2^2$ equals for

1¼ pipe 57,370
1½ pipe 23,000
2 pipe 5,500
2½ pipe 1,800
3 pipe 700

P_2 being our final pressure 1lb. or 15.7 lbs. absolute makes $P_2^2 = 246$, and remembering that $P_1^2 - P_2^2 = (P_1^2 - P_1^2 + P_1^2$

we have

1¼	pipe	P_2^2	absolute	=57,616	then	P_1	gauge	=225 lbs.
1½	"	"	"	=23,246	"	"	"	=140 "
2	"	"	"	= 5,746	"	"	"	= 61 "
2½	"	"	"	= 2,046	"	"	"	= 31 "
3	"	"	"	= 946	"	"	"	= 16 "

Now we are ready to put all this on our curve sheet in order that we may have a graphic representation of the situation. The power cost curve is on a basis of 1 cent per kilowatt hour; if, therefore, we plot any other costs on this standard sheet, they must be increased or diminished by the ratio the actual power cost bears to the standard power cost of 1 cent per kilowatt. Our problem calls for a power cost of ½ cent per kilowatt hour, consequently we must plot in our pipe costs at double their real amount, for the standard power cost curve is double the cost stated in our problem. Take, then, the 2-inch pipe. We have found the pipe cost to be .894, which, multiplied by 2, equals 1.798, and the initial pressure required is 61 pounds. If then we lay off the point P on the 61 pounds pressure ordinate and opposite the cost Line 1.798 or 1.8, we shall have the two-inch pipe established, and similarly we can establish the other points, and joining them by lines we have a pipe cost curve S. C., which shows the cost of pipe per 1000 cubic feet of gas for all sizes from 1¼ to 3 inch. It is evident that the total cost of pumping the gas is the pipe cost plus the power cost, consequently if we add the pipe cost curve to the power cost curve, we shall have a curve of total cost. Take the 2-inch pipe once more, and with dividers measure off the distance W. P., the cost of the pipe line, and add it to the line W. Y., which is the power cost, and we have the point T., as the result of the addition. Do the same for the other sizes of pipe, join these points by lines, and we have the curve D. F. as the final result, showing the combined power and pipe cost per 1000 cubic feet of gas for all the sizes of pipe under consideration.

It is evident at a glance that the 2-inch pipe shows the least cost, consequently the solution of our problem is 2-inch pipe at 60-pound initial pressure. Total cost per 1000 3.6 cents on a basis of 1 cent per kilowatt hour, but as our power costs ½ a cent per kilowatt hour, the total cost is 1.8 cents per 1000 cubic feet of gas.

The graphical method is very satisfactory, for one can see at a glance the relations between the various elements, for example: You will note that it cost practically the same to pump this gas through a $1\frac{1}{4}$-inch pipe at 225 pounds pressure or a $1\frac{1}{2}$-inch pipe at 140 pounds pressure or the 3-inch pipe at 16 pounds pressure, which is interesting.

PROBLEM TWO.

Take 5000 cubic feet per minute, 300,000 per hour or 2,500,000,000 per year, through the same length pipe as in our former problem, and at the same power cost per kilowatt hour. The pipe being the same length and the quantity fifty times greater. We will have $\frac{P}{500}$ for pipe cost per 1000 where we had $\frac{P}{10}$ formerly, and taking pipe casing prices up to 12 inches, which was the largest I could get, and assuming them above that size simply for illustration, we find the following prices per 1000 feet of gas for these pipes:

10 inch equals .25 cent per 1000 cubic feet of gas.
12 inch equals .30 cent per 1000 cubic feet of gas.
14 inch equals .40 cent per 1000 cubic feet of gas.
16 inch equals .60 cent per 1000 cubic feet of gas.
18 inch equals .80 cent per 1000 cubic feet of gas.
20 inch equals 1.00 cent per 1000 cubic feet of gas.

and the respective pressures necessary to force the gas through these pipes to be:

10 inch equals 53 pounds.
12 inch equals 26 pounds.
14 inch equals 20 pounds.
16 inch equals 12 pounds.
18 inch equals 8 pounds.
20 inch equals 4 pounds.

Multiply the pipe cost by 2 and transferring those quantities to our curve sheet, precisely as we did in the other problem, we have a pipe curve, E, showing the pipe cost per 1000 cubic feet, and adding this to the power curve, we have the final result in the curve F, which shows this rather surprising fact, that the 12-inch pipe is the best, and that it will carry this gas at 26 pounds pressure, and at a cost of 8/10 of a cent per 1000 for power and pipe.

The curve shows also that the gas can be put through the 10-inch pipe at 53 pounds pressure at the same cost as through the 20-inch pipe at 4 pounds pressure. I believe this graphical method will be of service to you, particularly as these curve sheets can be filed away and always used for quick reference, for the eye can take in the whole relative situation at a glance. I believe this method of handling the subject removes it from the realm of speculation, and makes an orderly comparison of power and pipes possible, to the end that an adequate selection can be made.

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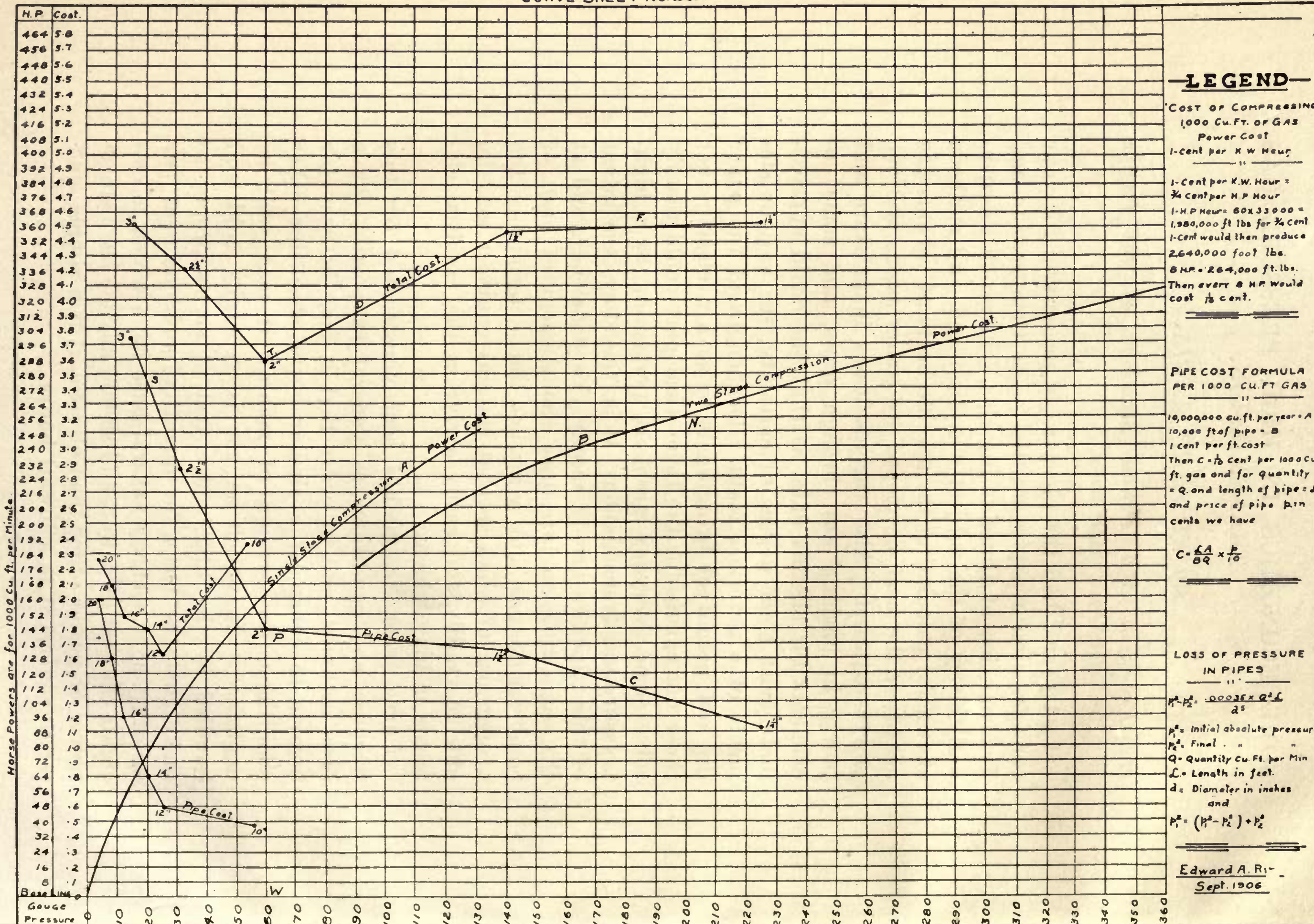

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Eight horsepower equals 264,000 foot pounds, consequently every 8 horsepower will cost 1-10 of a cent per minute. This gives us the basis for our curve, for if we lay out our sheet in equal divisions of any size and call each one along the vertical line 8 horsepower, we can also make each division represent 1-10 of a cent, and each horizontal division we can conveniently call 10 pounds.

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2½	"	"	"	= 2,046	"	"	"	= 31 "
3	"	"	"	= 946	"	"	"	= 16 "

Now we are ready to put all this on our curve sheet in order that we may have a graphic representation of the situation. The power cost curve is on a basis of 1 cent per kilowatt hour; if, therefore, we plot any other costs on this standard sheet, they must be increased or diminished by the ratio the actual power cost bears to the standard power cost of 1 cent per kilowatt. Our problem calls for a power cost of ½ cent per kilowatt hour, consequently we must plot in our pipe costs at double their real amount, for the standard power cost curve is double the cost stated in our problem. Take, then, the 2-inch pipe. We have found the pipe cost to be .894, which, multiplied by 2, equals 1.798, and the initial pressure required is 61 pounds. If then we lay off the point P on the 61 pounds pressure ordinate and opposite the cost Line 1.798 or 1.8, we shall have the two-inch pipe established, and similarly we can establish the other points, and joining them by lines we have a pipe cost curve S. C., which shows the cost of pipe per 1000 cubic feet of gas for all sizes from 1¼ to 3 inch. It is evident that the total cost of pumping the gas is the pipe cost plus the power cost, consequently if we add the pipe cost curve to the power cost curve, we shall have a curve of total cost. Take the 2-inch pipe once more, and with dividers measure off the distance W. P., the cost of the pipe line, and add it to the line W. Y., which is the power cost, and we have the point T., as the result of the addition. Do the same for the other sizes of pipe, join these points by lines, and we have the curve D. F. as the final result, showing the combined power and pipe cost per 1000 cubic feet of gas for all the sizes of pipe under consideration.

It is evident at a glance that the 2-inch pipe shows the least cost, consequently the solution of our problem is 2-inch pipe at 60-pound initial pressure. Total cost per 1000 3.6 cents on a basis of 1 cent per kilowatt hour, but as our power costs ½ a cent per kilowatt hour, the total cost is 1.8 cents per 1000 cubic feet of gas.

The graphical method is very satisfactory, for one can see at a glance the relations between the various elements, for example: You will note that it cost practically the same to pump this gas through a $1\frac{1}{4}$-inch pipe at 225 pounds pressure or a $1\frac{1}{2}$-inch pipe at 140 pounds pressure or the 3-inch pipe at 16 pounds pressure, which is interesting.

PROBLEM TWO.

Take 5000 cubic feet per minute, 300,000 per hour or 2,500,000,000 per year, through the same length pipe as in our former problem, and at the same power cost per kilowatt hour. The pipe being the same length and the quantity fifty times greater. We will have $\frac{P}{500}$ for pipe cost per 1000 where we had $\frac{P}{10}$ formerly, and taking pipe casing prices up to 12 inches, which was the largest I could get, and assuming them above that size simply for illustration, we find the following prices per 1000 feet of gas for these pipes:

10 inch equals .25 cent per 1000 cubic feet of gas.
12 inch equals .30 cent per 1000 cubic feet of gas.
14 inch equals .40 cent per 1000 cubic feet of gas.
16 inch equals .60 cent per 1000 cubic feet of gas.
18 inch equals .80 cent per 1000 cubic feet of gas.
20 inch equals 1.00 cent per 1000 cubic feet of gas.

and the respective pressures necessary to force the gas through these pipes to be:

10 inch equals 53 pounds.	16 inch equals 12 pounds.
12 inch equals 26 pounds.	18 inch equals 8 pounds.
14 inch equals 20 pounds.	20 inch equals 4 pounds.

Multiply the pipe cost by 2 and transferring those quantities to our curve sheet, precisely as we did in the other problem, we have a pipe curve, E, showing the pipe cost per 1000 cubic feet, and adding this to the power curve, we have the final result in the curve F, which shows this rather surprising fact, that the 12-inch pipe is the best, and that it will carry this gas at 26 pounds pressure, and at a cost of 8/10 of a cent per 1000 for power and pipe.

The curve shows also that the gas can be put through the 10-inch pipe at 53 pounds pressure at the same cost as through the 20-inch pipe at 4 pounds pressure. I believe this graphical method will be of service to you, particularly as these curve sheets can be filed away and always used for quick reference, for the eye can take in the whole relative situation at a glance. I believe this method of handling the subject removes it from the realm of speculation, and makes an orderly comparison of power and pipes possible, to the end that an adequate selection can be made.