T H E U N I V E R S I T Y O F M I C H I G A N

COLLEGE OF ENGINEERING
Department of Chemical and Metallurgical Engineering

Final Report

PIPELINE CALCULATIONS FOR GAS-LIQUID SYSTEMS

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ORA Project 06922

supported by:

AMERICAN NATURAL GAS SERVICE COMPANY
COLUMBIA GAS SYSTEM SERVICE COMPANY
NATURAL GAS PIPELINE COMPANY OF AMERICA

administered through:

OFFICE OF RESEARCH ADMINISTRATION   ANN ARBOR

August 1965

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SUMMARY AND CONCLUSIONS

This study has considered the transporting of light hydrocarbon liquids by dissolving them in high pressure natural gases. The presence of the higher molecular weight material increases the deviation of the gas mixture from ideal gas behavior and increases the gas density in the pipeline but with only minor viscosity increases. Thus, the addition of liquids like propane to natural gases increases the flow capacity of the line and thereby reduces the cost of transportation.

A computer program was written to solve the pipeline flow equation, to calculate the horsepower of compression of the gas, and to determine the cost of building and operating the line. This program was capable of finding the minimum cost of transportation for a given pipe strength, line diameter, gas composition, and flow rate.

The phase relationships for gas-liquid systems were studied. The minimum pressure to maintain the mixtures in a single phase was found for various systems of natural gases and light hydrocarbon liquids. The pipeline pressure was always maintained at pressures above this minimum value in the design calculations.

The transportation costs were calculated for natural gas and nine mixtures containing condensable liquids for a series of conditions. The parameters studied were

Composition and corresponding minimum pressure	
Steel strength:	65,000 and 100,000 psi
Pipe diameter:	16, 24, and 30 inch
Pressure:	700 to some 3600 psia
Flow rate:	200-1500 million cu. ft./day.

The important factors used in the study and the costs of transportation of the mixtures (single phase) in cents/100 miles/Mcf are given in Tables 5, 6A, and 6B, attached.

It was found that the transportation cost decreased with increasing flow rate, increasing pressure level to some 2500 psia, and increasing molecular weight of the gas mixture up to gravities of about 0.9. The costs of transporting propane, butane, and condensates are in the range of 8 to 15 cents per barrel per 1000 miles. The cost of separating the condensates from the natural gas at the market terminal has not been included in these figures. Costs for specific mixtures are attached in Table 9. The above costs for hauling liquids in large quantities appear to be from 35-50% of the tariff for product pipelines.

The study indicates that further work is justified in considering the transportation of light hydrocarbons in large quantities along with natural gas in long distance pipelines.

TABLE 5

Economic and Other Factors Used in Study

Length of line (L_t) 1000 miles
Flowing temperature (T_f) 60°F
Pipe strength (S) 65,000 psi and 100,000 psi
Pipe diameter (OD) 16 inch, 24 inch and 30 inch (OD)
Pipe roughness EE = 250 micro-inches
Bend Index 200° per mile
Longitudinal joint factor for pipe (E) 1.0
Pipe design factor (F) 0.72
Compressor efficiency, EFF, 80%
Pipe cost (Y) 65,000 psi strength, \$265 per ton
100,000 psi strength, \$384 per ton
Cost of laying pipe (N) \$1200 per inch OD per mile
Communication system cost (H) \$3000 per mile
Compression station cost (X_1 + X) \$270,000 + \$165 per horsepower
Cost of fuel (CF) 20 cents/Mcf
Fuel consumption (FHPHR) 8.7×10^{-3} Mcf per horsepower - hour
Cost of labor and maintenance for pipeline (CLML) \$850/mile/yr
Cost of labor and maintenance for compressor stations (CLMS) \$19/hp/yr
Gas loss (LG) = 0.005 fraction of flow at 20 cents/Mcf
Administration expenses (AD) $\frac{1}{3650}$ cents/100 miles/Mcf
Annual investment charge, 15% per year
Line assumed to flow at 100% capacity 365 days/yr

TABLE 6A

Cost of Transporting Fluids
cents/100 miles/Mcf

Based on 1000 mile pipeline, 65,000 psi steel

Mixture	16" diameter Min. Cost cents /100 miles /Mcf	16" Pipe Thick-ness in.	16" Flow Rate MMcf /day	16" Min. Press. psia	24" diameter Min. Cost cents /100 miles /Mcf	24" Pipe Thick-ness in.	24" Flow Rate MMcf /day	24" Min. Press. psia	30" diameter Min. Cost cents /100 miles /Mcf	30" Pipe Thick-ness in.	30" Flow Rate MMcf /day	30" Min. Press. psia	Mol. wt.
Natural Gas	1.99	.19	150	700	1.37	.29	400	700	1.16	.36	600	700	17.39
	1.61	.31	250	1100	1.17	.39	600	1100	.997	.445	900	1100	
	1.45	.376	300	1560	1.06	.516	800	1560	.904	.585	1200	1560	
	1.338	.477	400	2100	.994	.626	900	2100	.858	.754	1500	2100	
10% Propane	1.984	.194	150	700	1.374	.273	400	700	1.148	.356	800	700	20.06
	1.581	.304	250	1100	1.148	.404	600	1100	.979	.443	900	1100	
20% Propane	1.329	.389	350	1560	.972	.502	800	1560	.833	.592	1300	1560	22.73
	1.27	.447	400	1960	.938	.590	900	1960	.807	.708	1500	1960	
30% Propane	1.23	.39	400	1540	.893	.505	900	1540	.765	.60	1500	1540	25.4
	1.20	.437	400	1940	.877	.598	1000	1940	.761	.696	1500	1940	
5% Propane and	1.388	.404	350	1600	1.017	.514	800	1600	.873	.609	1300	1600	20.76
5% Butane	1.32	.458	400	2000	.977	.633	1000	2000	.84	.724	1500	2000	
5% Butane	1.509	.365	300	1300	1.104	.46	700	1300	.942	.525	1100	1300	19.42
	1.39	.416	350	1700	1.02	.53	800	1700	.88	.627	1300	1700	
10% Butane	1.338	.455	400	1880	.982	.58	900	1880	.846	.701	1500	1880	21.47
	1.308	.514	450	2280	.97	.707	1100	2280	.846	.806	1500	2280	
15% Butane	1.293	.453	400	2000	.953	.632	1000	2000	.82	.725	1500	2000	23.51
	1.30	.515	400	2400	.957	.731	1100	2400	.877	.853	1500	2400	
Kurata S-2	1.343	.555	400	2660	.985	.787	1100	2660	.941	.909	1500	2660	24.96
	1.383	.642	450	3060	1.034	.890	1100	3060	1.018	1.037	1300	3060	
Kurata S-4	1.353	.579	450	2630	.9937	.789	1100	2630	.8875	.926	1500	2630	29.15
	1.443	.649	450	3030	1.070	.896	1100	3030	1.03	1.036	1300	3030	

TABLE 6B

Cost of Transporting Fluids
cents/100 miles/Mcf

Based on 1000 mile pipeline, 100,000 psi steel

Mixture	16" diameter Min. Cost cents /100 miles /Mcf	16" Pipe Thick-ness in.	16" Flow Rate MMcf /day	16" Min. Press. psia	24" diameter Min. Cost cents /100 miles /Mcf	24" Pipe Thick-ness in.	24" Flow Rate MMcf /day	24" Min. Press. psia	30" diameter Min. Cost cents /100 miles /Mcf	30" Pipe Thick-ness in.	30" Flow Rate MMcf /day	30" Min. Press. psia	Mol. wt.
Natural Gas	1.56	.191	250	1100	1.12	.261	600	1100	.96	.281	900	1100	17.39
	1.36	.264	350	1560	1.00	.327	800	1560	.86	.377	1200	1560	
	1.26	.306	400	2100	.94	.402	900	2100	.82	.479	1400	2100	
10% Propane	1.93	.124	150	700	1.32	.189	400	700	1.11	.234	700	700	20.06
	1.52	.186	250	1100	1.10	.259	600	1100	.94	.308	1000	1100	
20% Propane	1.26	.251	350	1560	.92	.322	800	1560	.79	.391	1400	1560	22.73
	1.20	.287	400	1960	.88	.395	1000	1960	.74	.467	1600	1960	
5% Propane and	1.32	.260	350	1600	.97	.332	800	1600	.831	.403	1400	1600	20.8
5% Butane	1.25	.297	400	2000	.92	.402	1000	2000	.802	.460	1400	2000	
10% Butane	1.26	.292	400	1880	.93	.373	900	1880	.80	.447	1500	1880	21.47
	1.22	.331	450	2280	.91	.450	1100	2280	<.80	.510	>1500	2280	
Kurata S-2	1.24	.371	450	2660	.92	.504	1100	2660	.81	.610	1700	2660	24.96
	1.28	.406	450	3060	.96	.590	1300	3060	<.90	.680	>1500	3060	
Kurata S-4	1.26	.371	450	2630	.93	.504	1100	2630	<.84	.596	>1500	2630	29.15
	1.33	.409	450	3030	.99	.572	1100	3030	<.91	.680	>1500	3030	

TABLE 9

Cost of Hauling Liquids

Composition	Dia.	Min. Press. psia	Cost Cents/1000 miles/Mcf Mixture	Cost Cents/1000 miles/Mcf Gas	Total Rate MMcf /day	Gas Rate MMcf /day	Liq. Rate 1000 bbls /day	Cost Mixture $1000 /day	Gas Cost $1000 /day	Liq. Cost $1000 /day	Cents/bbl /1000 miles
65,000 psi steel											
30% Propane	24	1540 2100	8.93	9.94	900	616	189	80.4	65.6	14.8	7.8
20% Propane	24	1960 2100	9.38	9.94	900	704	131	84.4	70.0	14.4	11.0
5% Butane	24	1300	11.04	11.04	700	650	37.8	77.4	71.8	5.6	14.8
S-2	24	2660 2100	9.85	9.94	1100	934	143	108.3	92.9	15.4	10.8
100,000 psi steel											
10% Propane	24	1100 1560	11.0	11.2	600	528	48.1	66.0	59.1	6.9	14.3
20% Propane	24	1560 1560	9.2	10.0	800	625	116	73.6	62.5	11.1	9.6
S-2	24	2660	9.2	9.6	1100	934	144	101	89.1	11.1	7.7
S-4	24	2630	9.3	9.6	1100	860	206	102.3	82.5	19.8	9.6

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PIPELINE CALCULATIONS FOR GAS-LIQUID SYSTEMS

Introduction

The purpose of this project is to investigate the economics of carrying liquids along with natural gases in a single phase in high pressure pipelines. To carry out the investigation, the physical properties of the gas-liquid mixtures, pipeline flow calculations, compression calculations, and economical factors are combined into a single relationship. This relationship was programmed for the computer to permit a quick evaluation of the parameters over a wide range of conditions.

The basis of the study is the fact that liquefiable hydrocarbons when added to natural gas increase the density of the system, both because of the increased molecular weight of the mixture and also because the compressibility factor is lower for the mixture due to its lower pseudocritical temperature. At the same time, the increased molecular weight of the mixture does not increase the viscosity of the gas significantly. This combination of properties was thought to be such that the cost of transporting gases containing propane, butane, and raw natural gasoline could be less than for natural gas itself. To carry out the study, it is necessary to determine the conditions at which various systems are in a single phase. The density in the form of the compressibility factor and the viscosity are needed for such systems at the pressures and temperatures of the pipelines.

The pipeline flow calculations for this study are based on the American Gas Association Institute of Gas Technology report[1]. It was deemed necessary to ascertain that the procedure was the equivalent of Weymouth's equation with Moody friction factors[2], and this was found to be true for the "partially turbulent case" adopted.

In any comparative study, it is necessary to establish a standard. After several trials, it appeared best to compare the cost of transporting natural gas a distance of 1000 miles with included liquids dissolved in a single phase fluid with the cost of transporting the gas alone. For each mixture and pipe diameter, the cheapest transportation cost was sought before comparing the two costs. From these two costs, one can find the cost of hauling the normally liquid constituent and compare it with liquid pipeline rates.

The various phases of the study will be described in turn starting with the phase behavior of gas-liquid systems.

Phase Behavior of Hydrocarbon Systems

Mixtures of natural gas and light hydrocarbons may be transported as a single phase provided the proper temperatures and pressures are maintained. For pipelines buried in the ground, the temperature range is limited to from about 30-150°F or from ground temperature to the compressor outlet temperature. The objective of this study is to find the pressures suitable for pipeline transportation over which gas-liquid mixtures will remain in single phase at temperatures of 40-100°F. As will be illustrated in a general discussion of phase behavior, there are two pressure regions at which mixtures such as methane and propane will remain in single phase. The first is the low pressure region wherein increased pressure causes condensation of liquid to occur. The second region--that of interest in this study--is the high pressure region where two phases occur upon lowering the pressure. The latter is sometimes referred to as the retrograde region since phase changes occur due to an opposite change in pressure to that normally found at low pressure. This behavior will be made clear in a general discussion of the behavior of mixtures.

Behavior of a Binary Mixture

Figure 1 shows the behavior of a binary system such as methane-propane. The curve AC_1 is the vapor pressure curve of methane and HC_3 is the vapor pressure curve of propane. At pressures above $AC_1C_2C_3$, all mixtures of methane and propane are in a single phase. Diagram BDC_2EFG represents the border curve between the single phase region outside and the two phase region inside for a specific mixture of 80% methane and 20% propane (molal basis). The areas of interest in the single phase region are pressures above the curves DC_2EF or any pressure at temperatures above F. The problem is to find a convenient way of calculating the single phase region for any mixtures of known composition at pipeline temperatures.

Although Figure 1 shows the behavior of only one mixture of methane and propane, the two phase region for all mixtures lies within the area of $AC_1C_2C_3H$ and outside this region all mixtures are in single phase. Figures 2a and 2b show quantitatively the location of the border curves for the methane-propane system. It may be seen that the various mixtures are similar in behavior and so only the 80% methane mixture will be discussed. When viewed from the interest of pipeline flow at $40\text{-}100^{\circ}F$, one needs to consider a series of mixtures of increasing propane content. Figures 3a and 3b give experimental data for the methane-butane system.

Studies were made by the writer on phase behavior of hydrocarbon systems in glass windowed cells some 25-30 years ago[2,3,4]. Consider the behavior of mixture A, Figure 1. At the temperature and pressure of I, it is in a single phase. Upon dropping the pressure isothermally to D, it remains in single phase until reaching pressure D at which pressure bubbles of vapor appear. The curve BDC_2 is the bubble point curve for mixture A. Further pressure reductions below D cause various percentages of vapor to form as indicated qualitatively on Figure 1. For quantitative percentages of liquid, see Kurata phase diagrams in this report.

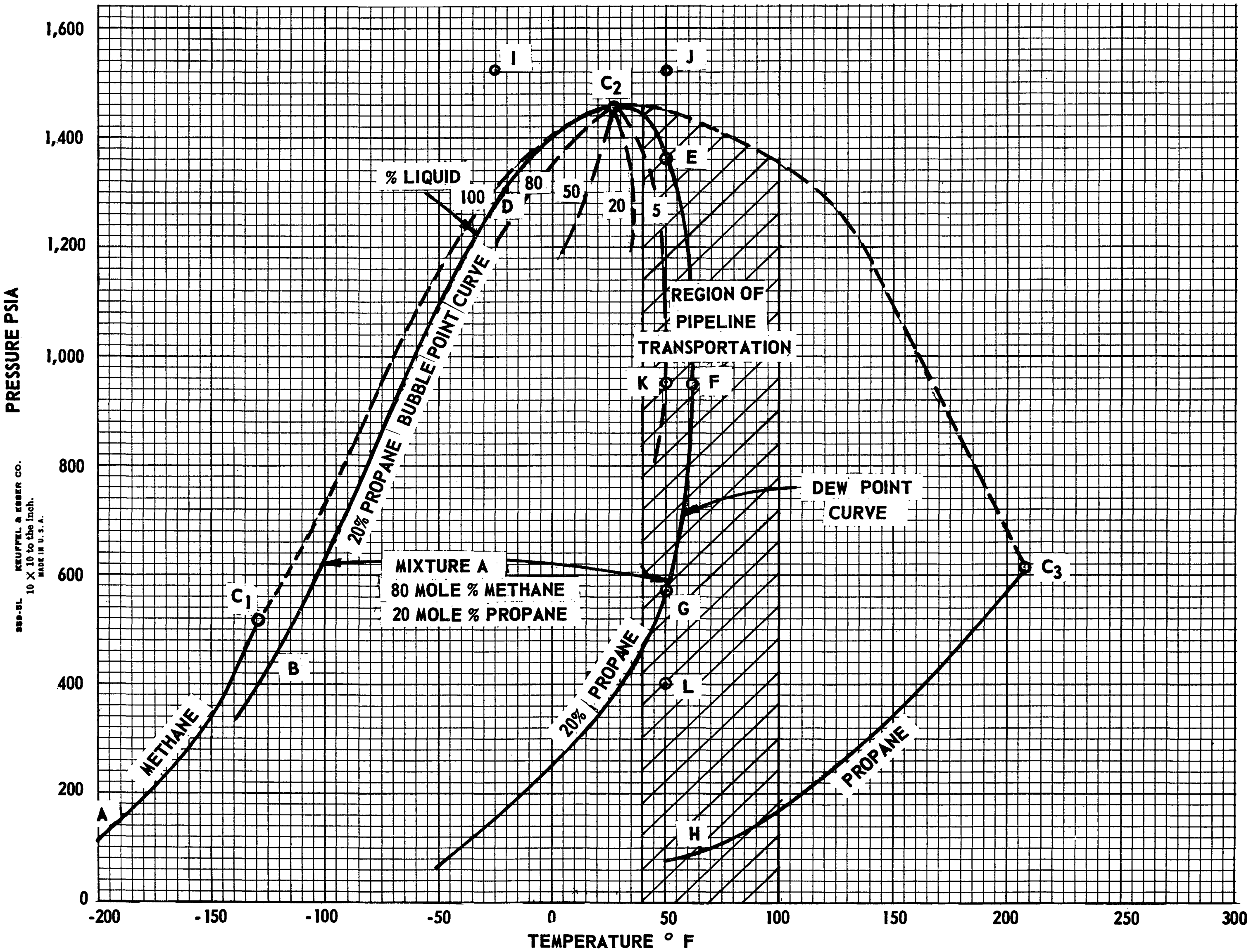

Figure 1. Illustration of Phase Behavior for Binary System of Methane-Propane

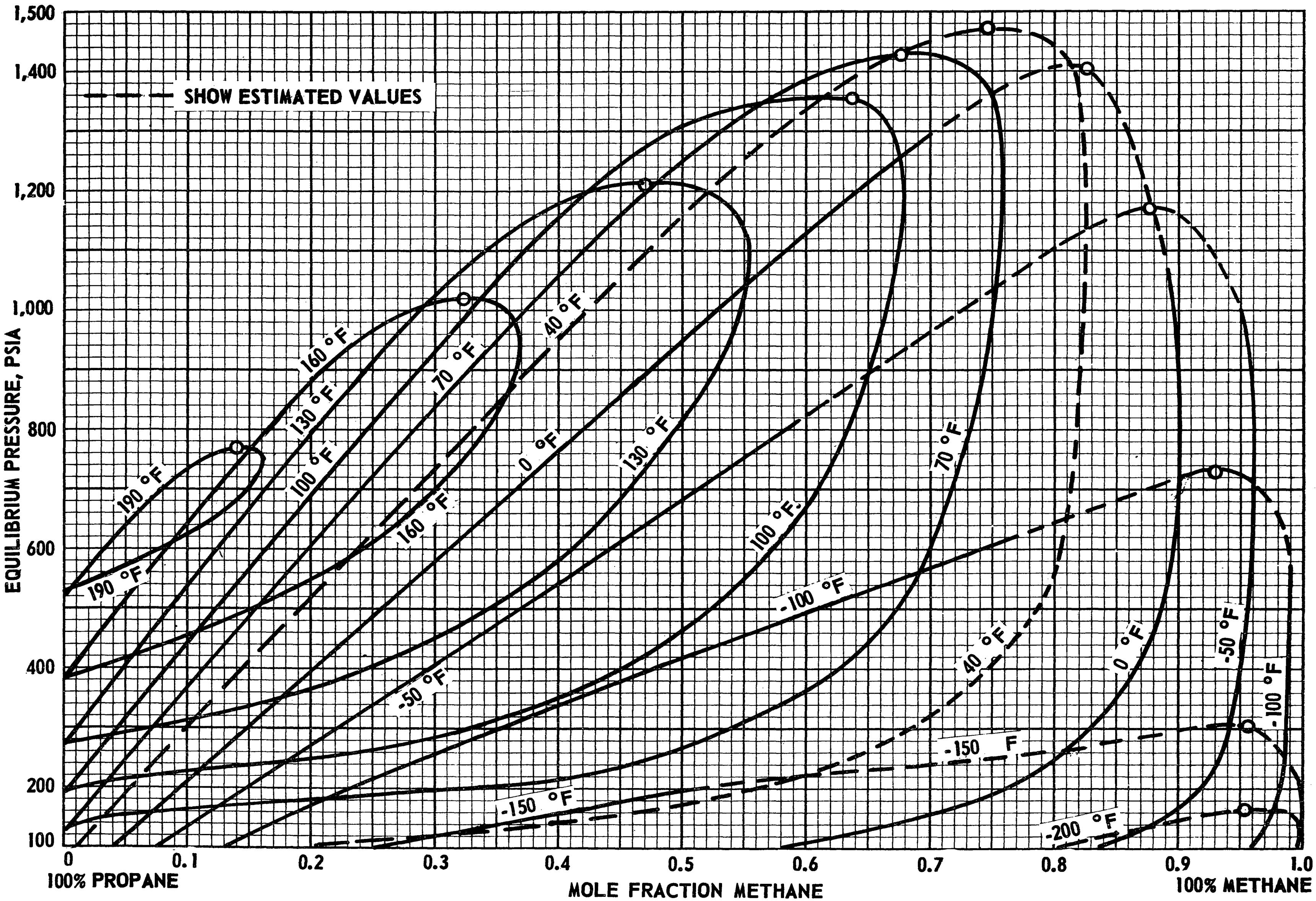

Figure 2a. Bubble and Dew Point Curves for Methane-Propane System.

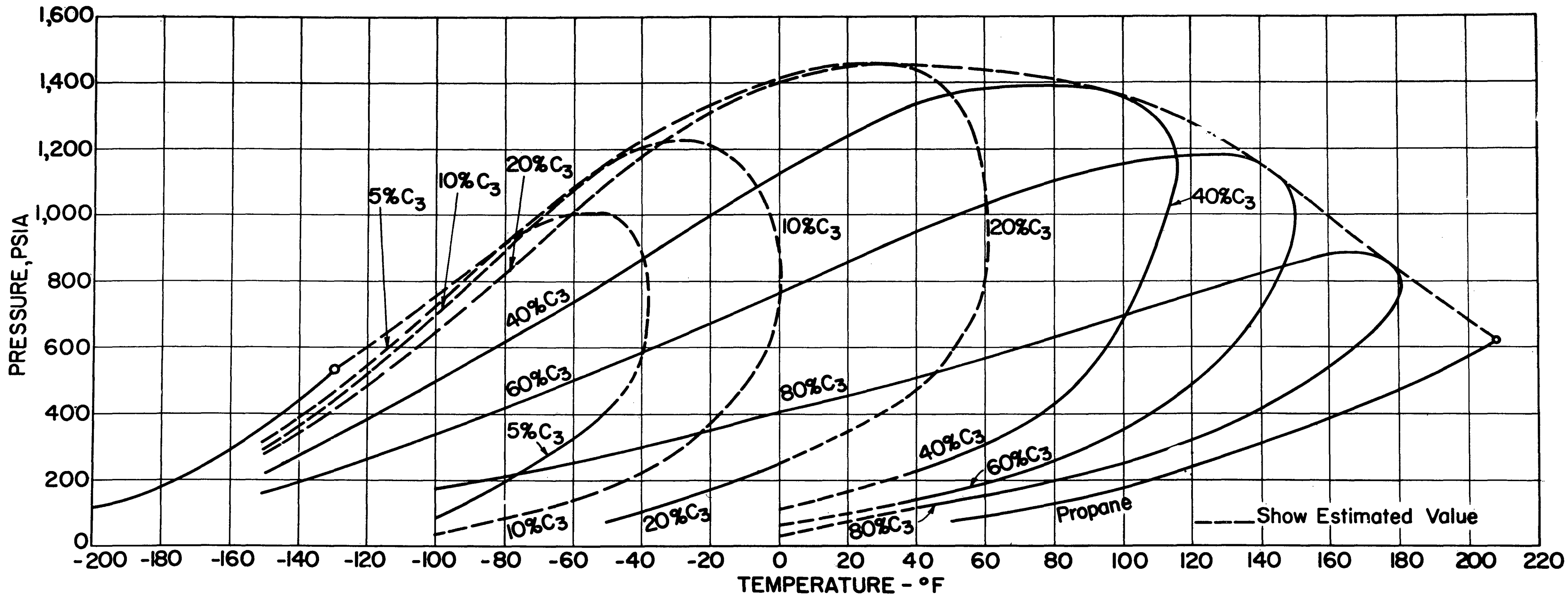

Figure 2b. Phase Behavior of Methane-Propane System

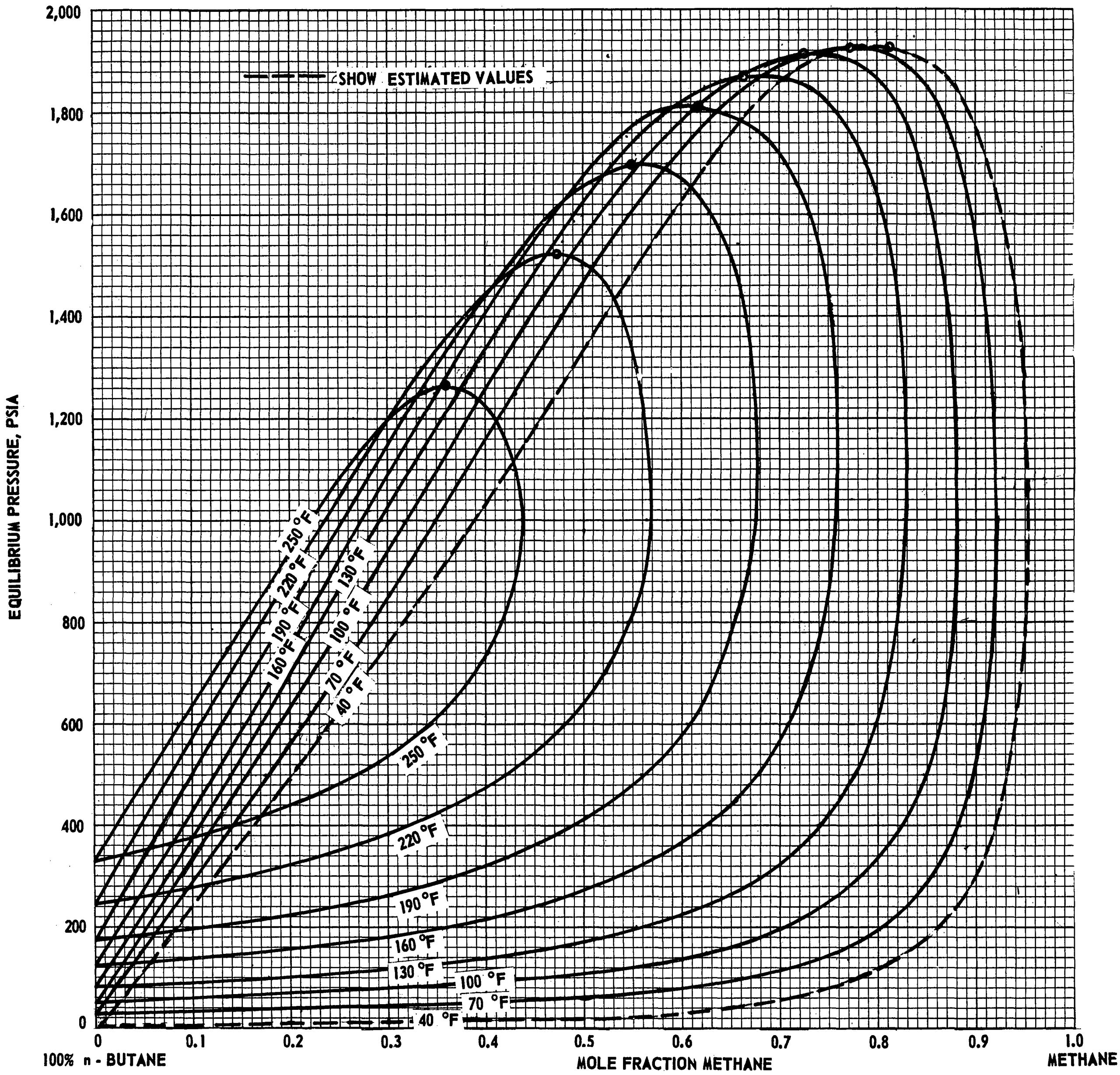

Figure 3a. Bubble and Dew Point Curves for Methane-n-Butane System

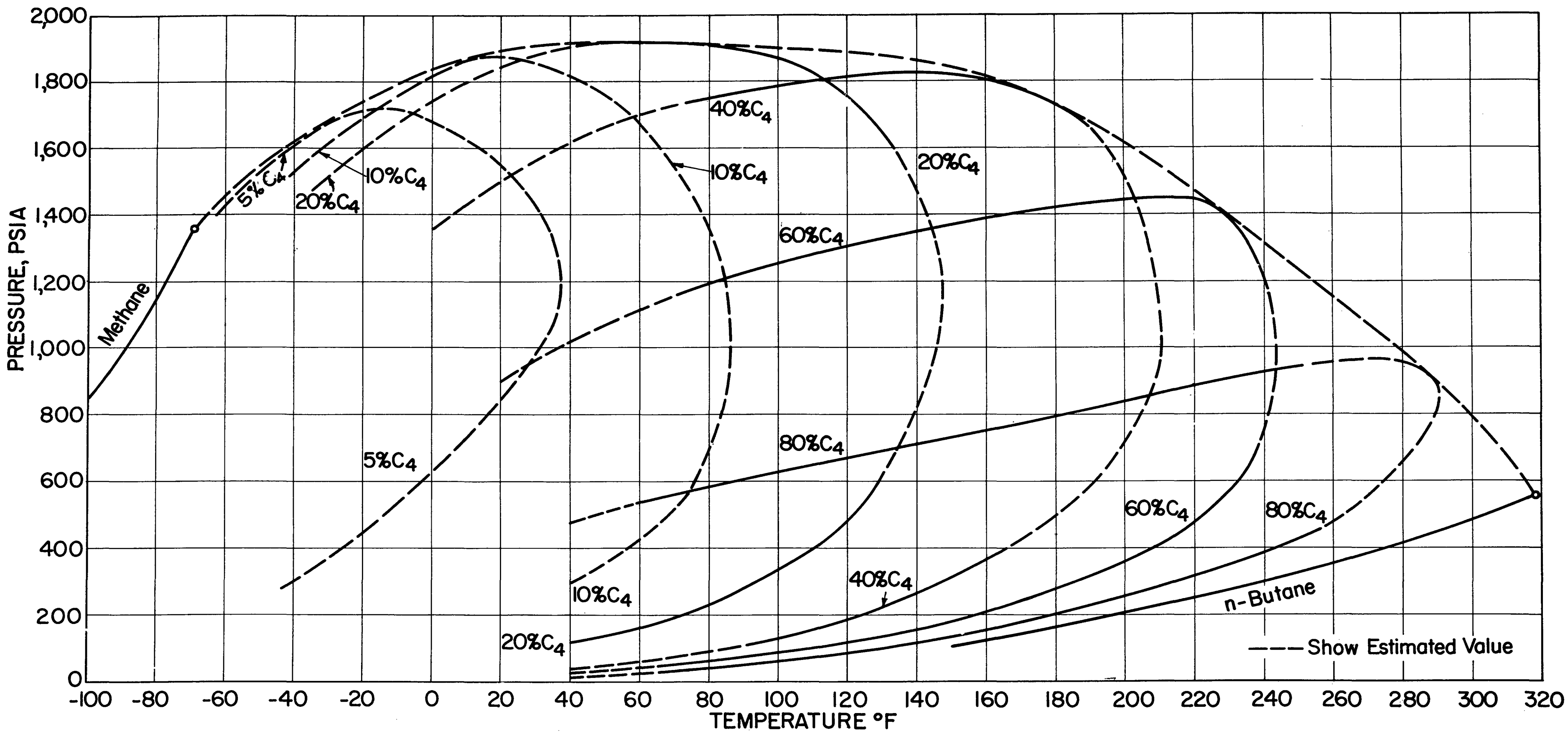

Figure 3b. Phase Behavior of Methane-n-Butane System

Mixture A at J is in a single phase and upon dropping the pressure to E, droplets of liquid or dew form beginning at pressure E. The curve C_2EF is the dew point curve for mixture A, sometimes known as the upper or retrograde dew point curve. As the pressure is dropped below E, liquid forms reaching its maximum volume at K. Further pressure reductions below K cause the liquid to vaporize. When the pressure reaches G, all of the liquid has vaporized and point G is the lower or normal dew point. When compressing the mixture from L to G, dew forms in the manner usual for pipelines.

Should one have selected a single pressure just above C_2 and allowed the pressure to drop, it would have been observed that at C_2 the mixture would change from a single phase to about 50% by volume liquid and 50% vapor. Point C_2 is the critical temperature and pressure for mixture A; it is the convergence of the bubble point, dew point, and various percentage liquid lines.

Region of Interest for Pipeline Flow

Any mixture of natural gas and liquid hydrocarbons has a phase diagram generally similar to mixture A. Figure 4 is presented to relate the region of interest relative to the phase behavior of a mixture. In the past, pipelines have been operated at temperatures above C of Figure 4 to keep the gas in a single phase. A mixture carefully stripped of heavy hydrocarbons, pentanes and heavier, can carry a considerable amount of liquefiable propane or butane at temperatures of $40^{\circ}F$ and above. For these mixtures whose maximum two phase temperature (cricondentherm point C of Figure 4) lies below the pipeline temperature, the currently used procedures may be followed in that there is no lower or higher limit of pressure which will cause condensation.

This study proposes to handle in pipelines those mixtures for which point C is within or above the pipeline temperature range of $40\text{-}100^{\circ}F$. Therefore, it will be necessary for such

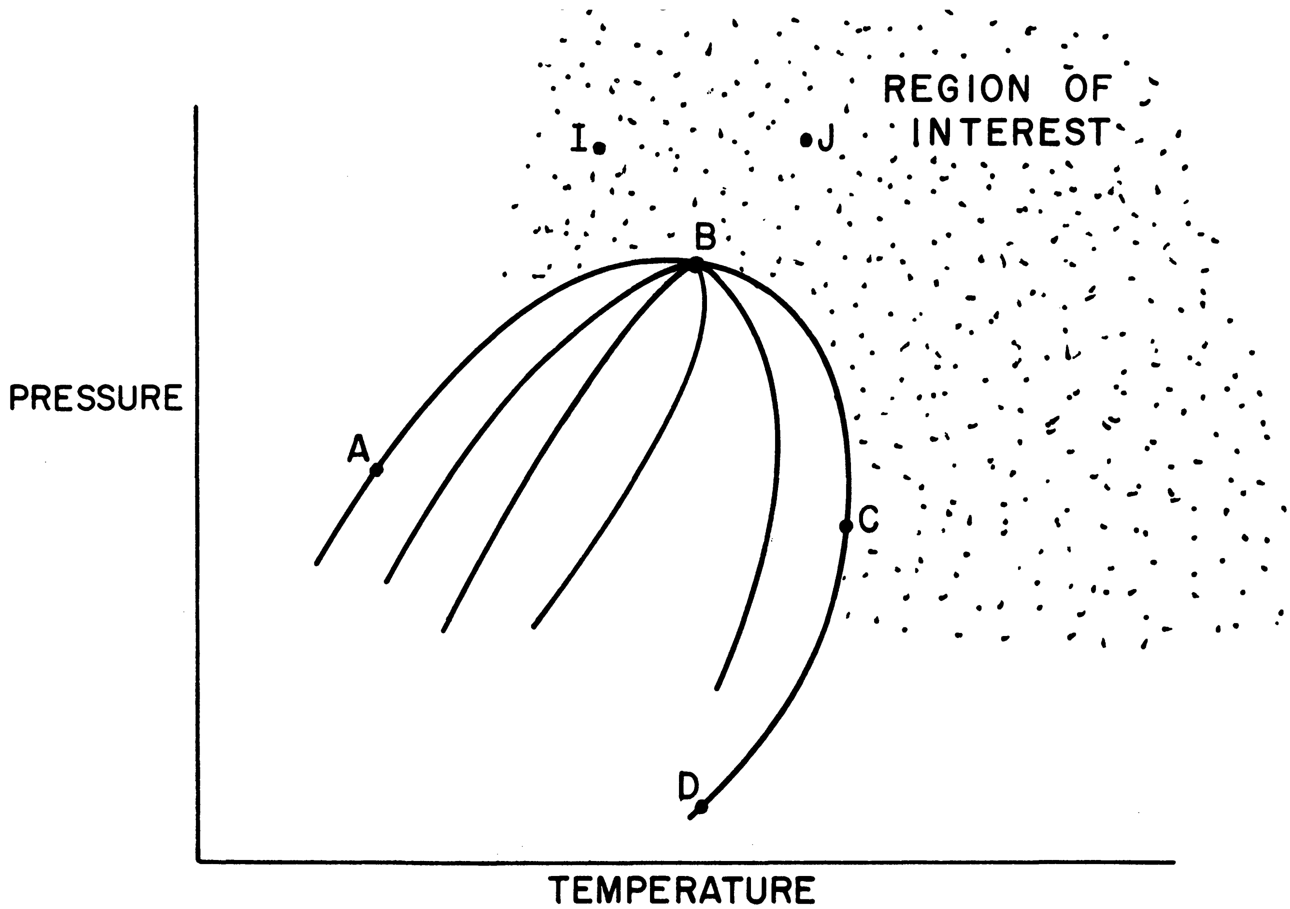

Figure 4. Region of Interest for Pipeline Transportation of Gas-Liquid Systems

mixtures to limit the lower pressure at which they may be transported to the conditions corresponding to pressures of ABC of Figure 4. It would seem that the procedure desired is a way of finding the maximum pressure in the temperature range of pipeline flow used here as 40-100^{o}F at which two phases occur. This maximum two phase pressure will then become the minimum pipeline pressure for single phase operation. Thus for methane-propane mixtures, the minimum pressure in pipelines for mixtures rich in propane, one can use the critical loci, curve $C_1C_2C_3$ of Figure 1. The plan is to use a minimum pressure in the pipeline 100 psi above the single phase pressure to give some degree of safety.

It does not matter with respect to phase behavior whether the mixture is at condition I or J on Figure 1. For pipeline transportation, it can move over a temperature range including crossing the critical at these pressures and remain in single phase. It is true that the densities of the mixtures in this region are high compared to present values in gas pipelines, and that the density changes rapidly with both temperature and pressure. It is believed that centrifugal compressors should be considered for such fluids in that they are as much like a liquid as a gas.

The terms liquid and gas become relatively useless when describing single phase fluids in the region of I and J in Figures 1 and 4. Fluid at I might be called a "compressed liquid", but the nature of the liquid at D, Figure 1, is so unusual, i.e., density, compressibility, etc., that use of the term "liquid" may be misleading. Likewise, application of the term "gas" to fluid at J would not be meaningful. The description of these single phase fluids can be made only by indicating their density and compressibility.

Mixtures Considered in Study

The liquids which need transportation are propane, butanes, natural gasolines or condensates, and crude oil. Initially, it was intended to consider transporting all of these liquids. However, pipeline calculations have been made only for propane, butanes, natural gasoline, and propane-butane mixtures. Table 1 lists the mixtures which have been studied.

One consideration is the volume of liquids which a pipeline can handle for various concentrations. When vaporized, propane represents 35.8 cubic feet at 60°F and 1 atmosphere per gallon and n-butane 30.77 cubic feet per gallon. A pipeline with a 500 million cubic feet per day capacity will carry 1,580,000 gallons (37,700 bbls) of propane per day at a concentration of 10 mole % propane. These quantities of liquids are large. The State of Louisiana in 1964 produced a total of 350,000 bbls per day of all natural gas liquids, while Texas produced 750,000 bbls per day. The barrels condensate per million cubic feet of gas included all the propane as listed in Table 1.

Figure 5 is a plot of barrels of liquid per day versus quantity of gas with lines for various mixtures of gas and liquids. It is helpful in arriving at the quantities of liquid being considered for various concentrations and gas flow rates. This figure does not include the propane present in the natural gas as condensate.

Permissible Pressures

For each mixture on Table 1, one needs to know the minimum pressure permitted when transporting the fluid in a single phase. For a 0.6 gravity natural gas and the 10% propane-90% natural gas mixture, the 40°F minimum pipeline temperature is above the liquefaction temperature at any pressure. For such mixtures, the minimum pressure put in Table 1 is 600 psia, but this is an arbitrary value to make the lowest pipeline pressure at 700 psia the minimum permitted pressure plus 100 psia safety factor used for all mixtures to avoid condensation in liquid rich mixtures.

For those mixtures which form two phases at the lowest contemplated pipeline temperature, used here as 40°F, one needs

TABLE 1

Compositions and Properties of Mixtures

	1 Natural Gas	2 Gas 90% Propane 10%	3 Gas 80% Propane 20%	4 Gas 70% Propane 30%	5 Gas 90% 5% Propane 5% Butane	6 Gas 95% Butane 5%	7 Gas 90% Butane 10%	8 Gas 85% Butane 15%	9 Mixture S-2 (Kurata)	10 Mixture S-4 (Kurata)
				Mole Percentage Composition						
methane	.927	.8343	.7416	.6499	.8343	.88115	.8343	.78795	.78800	.72800
ethane	.05	.0450	.0400	.0350	.0450	.04700	.0450	.04250	.05900	.05460
propane	.023	.1207	.2184	.3161	.0707	.02185	.0207	.01955	.03146	.03020
i butane					.0200	.02000	.0400	.06000	.01064	.01228
n-butane					.0300	.03000	.0600	.09000	.01596	.01842
pentanes									.04250	.06880
hexanes									.02525	.04382
heptanes+									.02140	.03750
N_2									.00579	.00538
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00000	.99900
mol. wt.	17.39	20.06	22.73	25.4	20.76	19.42	21.47	23.51	24.96	29.15
gravity	0.600	0.692	0.778	0.875	0.716	0.671	0.742	0.811	0.861	1.005
bbls condensate per million cu. ft.	15.30	80.25	145.6	210.2	86.7	54.2	93.9	131.6	130.5	187.6
Limiting single phase pressure 40-100 ^{o}F psia	600	600	1460	1440	1500 (est)	1200	1780	1900	2560	2530
Pseudo T_c, ^{o}R	361	391.5	421.5	453	396	381	400	420	426	460.5
P_c, psia	673.6	668	661	667	663	667	660	654	649	634

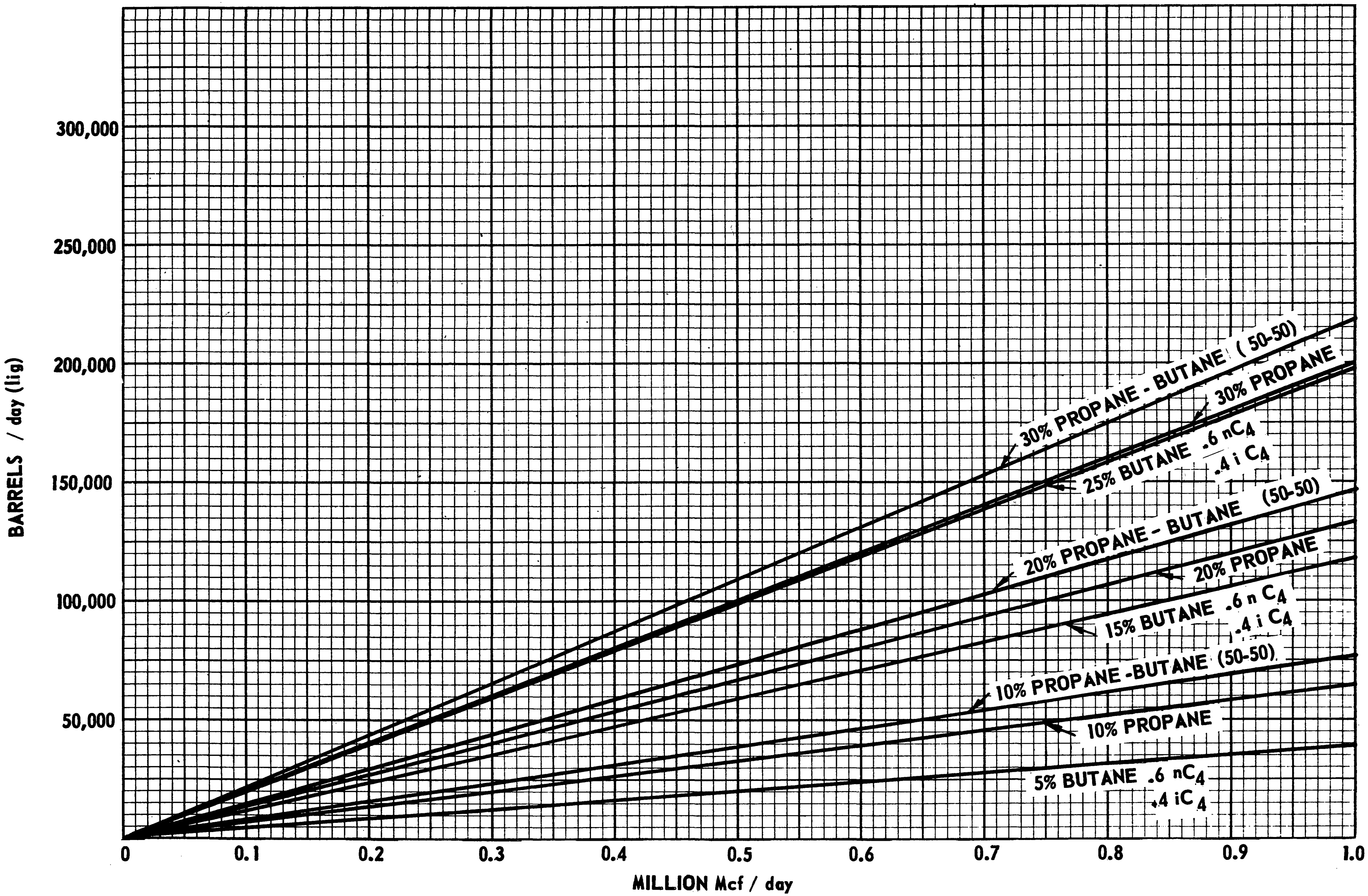

Figure 5. Relationship of Barrels of Liquid Per Day as a Function of Quantity of Gas as Mixture

the upper dew point pressure or bubble point pressure should the critical temperature be above 40°F. Calculation of the dew or bubble point pressure could be made for various mixtures using equilibrium constants[2]. However, in this region, the convergence pressure for the equilibrium constants is very sensitive to composition and machine computation with an established program such as the NGPA and Oklahoma State University are devising would be needed. However, even such a program cannot be trusted at critical conditions. A rather fruitless study was made of a correlation of the single phase pressures with molal average boiling point and molecular weight for the mixtures under consideration. From the lack of correlation found in this study, it was decided to rely on experimental phase data with minor adjustments for the mixtures shown in Table 1. References to experimental data for specific systems are given in Table 2.

For the natural gas, it was decided to use a 0.6 gravity gas with the composition shown on Table 1. The compositions for streams 2-8 are given on the table after adding the indicated amount of liquids. For the last mixtures, 9 and 10, the compositions are those used for determining the phase behavior.

It should be noted that the mixtures in Table 1 are not the pure methane-propane and methane-butane systems, but have intermediate constituents present in the natural gas.

The differences in the behavior of mixtures 2, 3 and 4 as compared to the methane-propane mixtures should be considered. Figure 6 shows the critical loci of the methane-propane-pentane system. From the figure, it is observed that adding an intermediate constituent, propane, lowers the critical pressure for any methane-pentane system. In like manner, ethane will lower not only the critical pressure at a given temperature but also the bubble and dew point curves for a specific mixture. Reference can be made to the methane-ethane-propane systems of Price and Kobayashi, shown in the Handbook, p. 579[2]. At 1100 psia and 50°F, ethane at 3% does not reduce the propane content of a dew point gas. At 800 and 1000 psia and 50°F, the propane content is 1 or 2% less for a dew point whem some 5% of ethane is added to the methane-propane system.

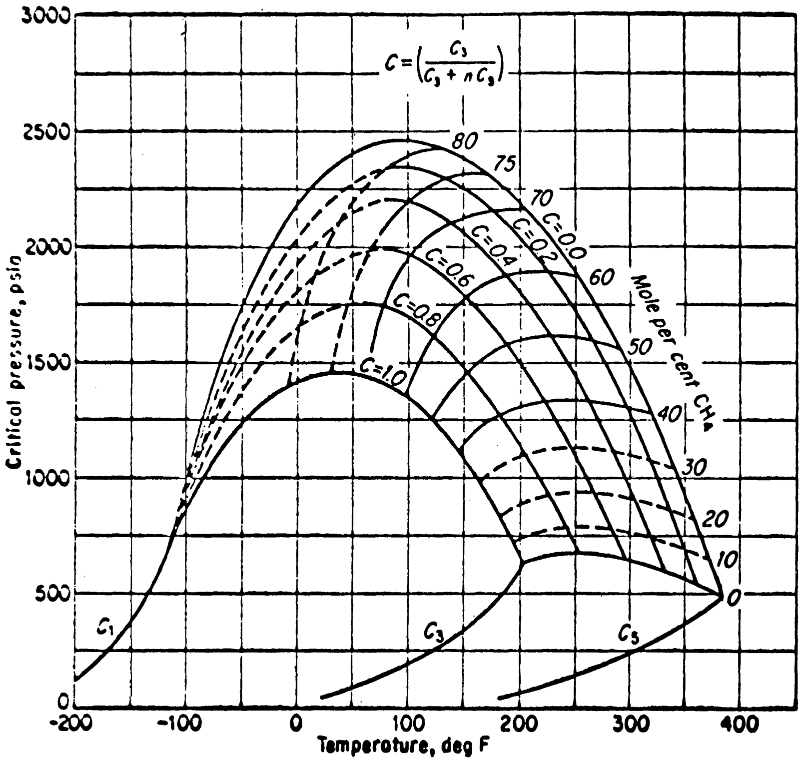

Figure 6. Critical Loci of Methane-Propane-Pentane System

TABLE 2

Phase Behavior Data Sources for Light Hydrocarbon Systems

System	Temp. (°F)	Two Phase Press. Range (psia)	Reference
Methane-Ethane	0 40	300-900 500-900	5
Methane-Propane	40 100 160	511-1469 180-1355 380-890	6
Methane-n-Butane	70 100 160	819-1924 339-1904 435-1810	7
Methane-Isobutane	100 160	100-1680 150-1400	8
Methane-n-Pentane	100 160	313-2443 720-2300	9
Methane-Propane-n-Pentane	100 160	1350-2375 700-2150	10 11
Methane-Ethane-Propane	0 50	100-1300 100-1200	12
Ethane-Propane	0 50	100-400 100-200	12
Propane-n-Butane	160	55-172	13
Methane-Butane-Decane	100-460 160 100-460 40	400-10,000 400-5000 200-10,000 1000-4000	14 15 16
Gas Condensates	0-200	600-2700	4

It may be concluded that the differences in minimum pipeline pressures selected from binary systems are not in error enough to influence the cost of pipeline transportation significantly. Dr. Fred Kurata measured for his doctorate thesis[4] gas-natural gasoline mixtures for which the phase behavior are of interest. Two of these mixtures S-2 and S-4 were selected for this study. Figures 7 to 8 give the phase diagrams from the thesis. At 40°F, mixture S-2 is below the critical temperature of 55°F. In this case, a higher pressure is required to hold the mixture in a single phase at 100°F than at 40°F. Mixture S-4 has the full pipeline temperature range below its critical temperature of 109°F.

The phase diagrams for nine other mixtures studied by Kurata are given in Appendix D along with the compositions. To obtain the critical points for other mixtures, the method of Kurata[4,2] is suggested since it is based on natural gas-liquid systems.

The minimum pressure listed on Table 1 is either the 600 psia when no phase changes occur, or the highest bubble or dew point value found over the temperature range of 40-100°F. As indicated previously, the ethane in the natural gas was neglected. Likewise, the propane in the gas was neglected in finding the single phase pressure for mixtures 6, 7, and 8.

Initially, it was intended to use butanes as 40 mole % isobutane and 60 mole % normal butane. The composition is indicated in this manner on Table 1 and was used in finding pseudocritical conditions for viscosity and density to be discussed later. Otherwise, the phase behavior is based on methane-n-butane properties. Isobutane generally would provide some safety factor. The 5% propane-5% butane, mixture No. 5, has not been measured experimentally. The value given is an estimate.

The Density of Single Phase Hydrocarbon Fluids

The method of expressing the density for natural gases is the gas law, including a compressibility factor (Z)

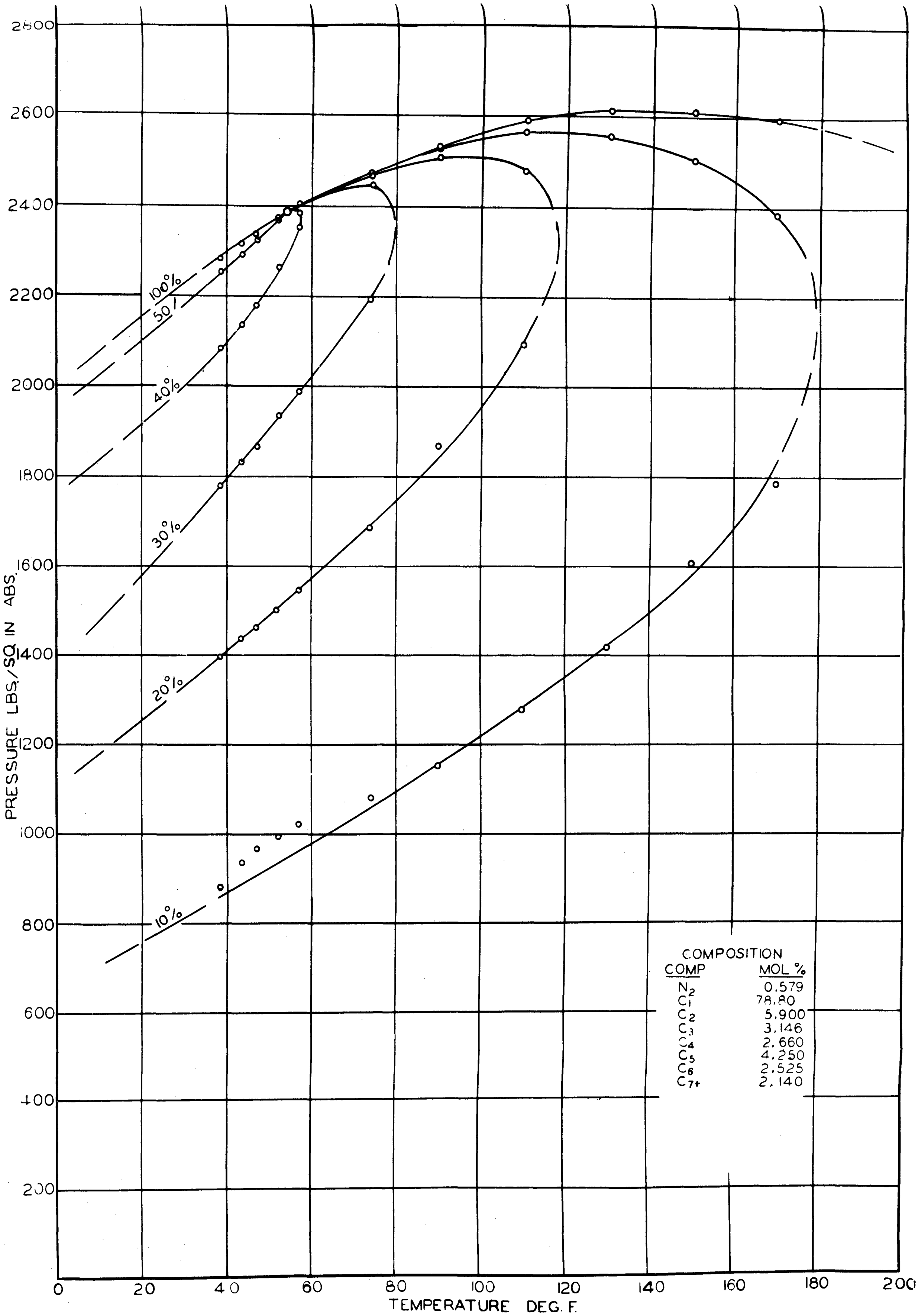

Figure 7. Phase Diagram for Mixture S-2 (Kurata)[28]

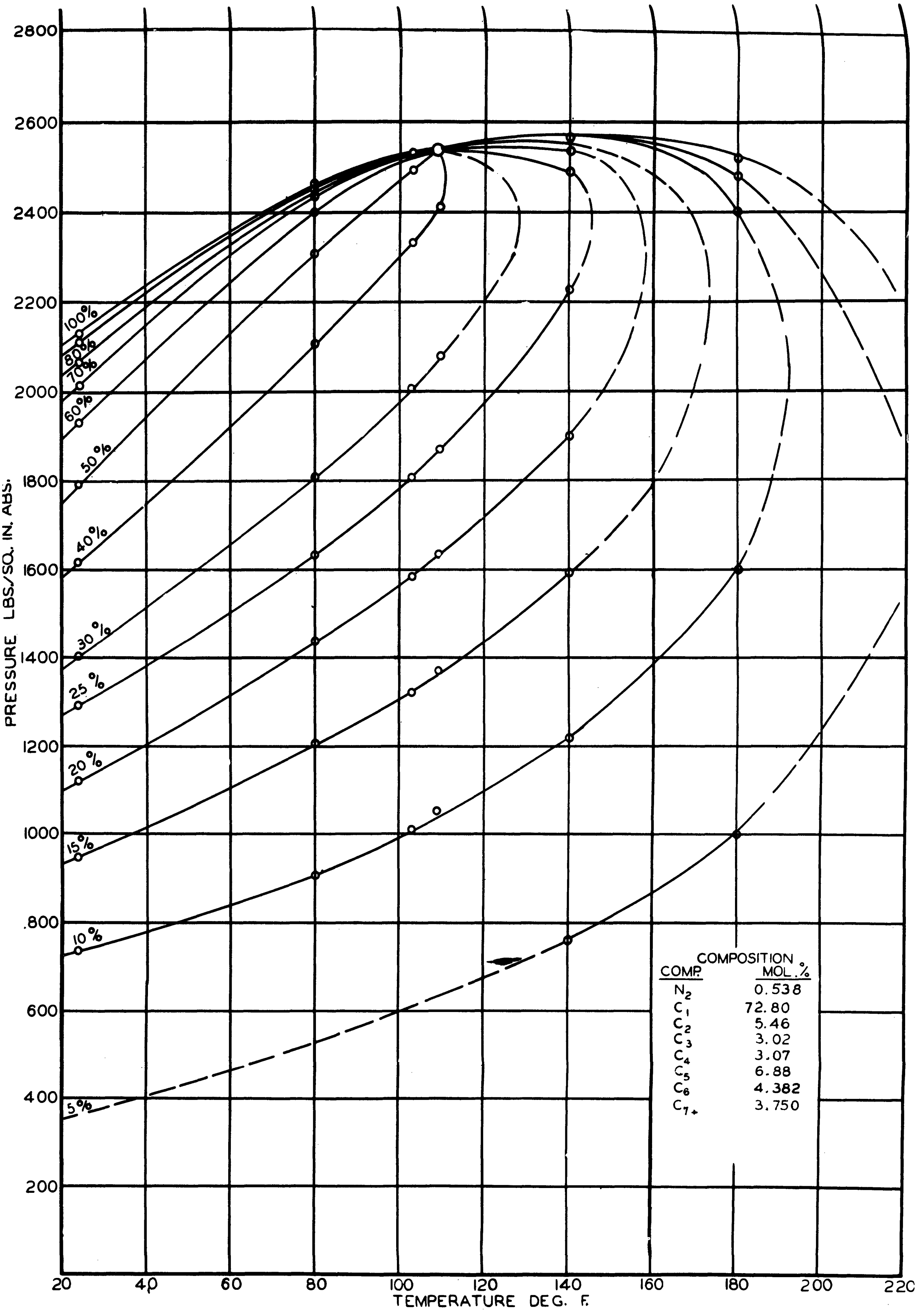

Figure 8. Phase Diagram for Mixture S-4 (Kurata)[28]

$$PV = ZnRT$$

where P = pressure, psia

V = volume, cu. ft./lb. mole

Z = compressibility factor

n = number of pound moles

R = gas constant, 10.73 for these units

T = ^{o}Rankine, ^{o}F + 460.

A generalized chart of compressibiliity factor versus reduced pressure (pressure over critical pressure) and lines of reduced temperature (absolute temperature over critical temperature) has been devised for natural gases, Figure 4-16, p. 106[2]. This chart has been put in form for computing by Sarem[17] and is generally satisfactory, excepting for values of the compressibility factor below 0.50 where errors can become large. At reduced temperatures of 1.15 and below and at pressures of 600 to 2000 psia, the correlation is not reliable.

A program (ZFAC) has been prepared using Sarem's method to give the compressibility factor for any temperature and pressure when the gas composition is known. Should the composition be represented only by the gas gravity (G), the program uses the pseudocriticals corresponding to the published relationship of these values with G.

The subroutine for computing Z at any temperature (Tr 1.05-2.95) and pressure (Pr 0.1-14.95) requires the composition of the gas or its gravity. The critical properties and molecular weight of N_2, CO_2, CH_4-C_7H_{16}, iC_4H_{10}, and iC_5H_{12} are already in the program. Three added constituents may be specified along with their T_c, P_c and molecular weights. Initially, the mole fractions of all constituents and properties of the three added constituents are set at zero.

This subroutine is incorporated into the pipeline flow program, and it provides the Z when called upon. An example of the use of this program for predicting Z's is given in Appendix F, along with a comparison of computer values with those read from the chart.

The AGA supercompressibility factors were not used in this study, and presumably would be an alternate way of expressing density.

For mixtures S-2 and S-4, the thesis[4] gives the saturated densities with only a nominal precision. Figure 9 shows the measured saturated densities along with values at 3000 and 4000 psia calculated from the compressibility chart.

Viscosity

The pipeline flow formula requires the viscosity of the fluid as a function of temperature and pressure. In general, for simplified cases a constant flowing temperature will be used in the pipeline. Therefore, it is more appropriate to say that the viscosity is needed as a function of pressure at a given temperature ($60^{\circ}F$) and for a given composition.

The viscosity of methane, some natural gases, and of the methane-butane and methane-propane system have been determined. These viscosities also have been correlated as a function of reduced temperature and pressure with a reasonable degree of success[18,19]. Table 3 lists the sources of data which are of interest. Figure 10 gives the reported methane-propane viscosities.

It was decided to use the correlation of Bicher and Katz for the viscosity of the fluids. Figures 11 and 12 give the correlation based on reduced temperature, reduced pressure, and molecular weight. The work of Carr et al[19] indicated that Bicher's data had some inaccuracies over some ranges of pressure, since Bicher apparently had some turbulence in his rolling ball viscosimeter. The correlation of Carr et al probably would have been better but would have been more difficult to use. In view of the indirect effect of viscosity on the friction factor, the work of Bicher seemed satisfactory.

The viscosity correlations as shown in Figures 11 and 12 were programmed by submitting the points on the curves as data

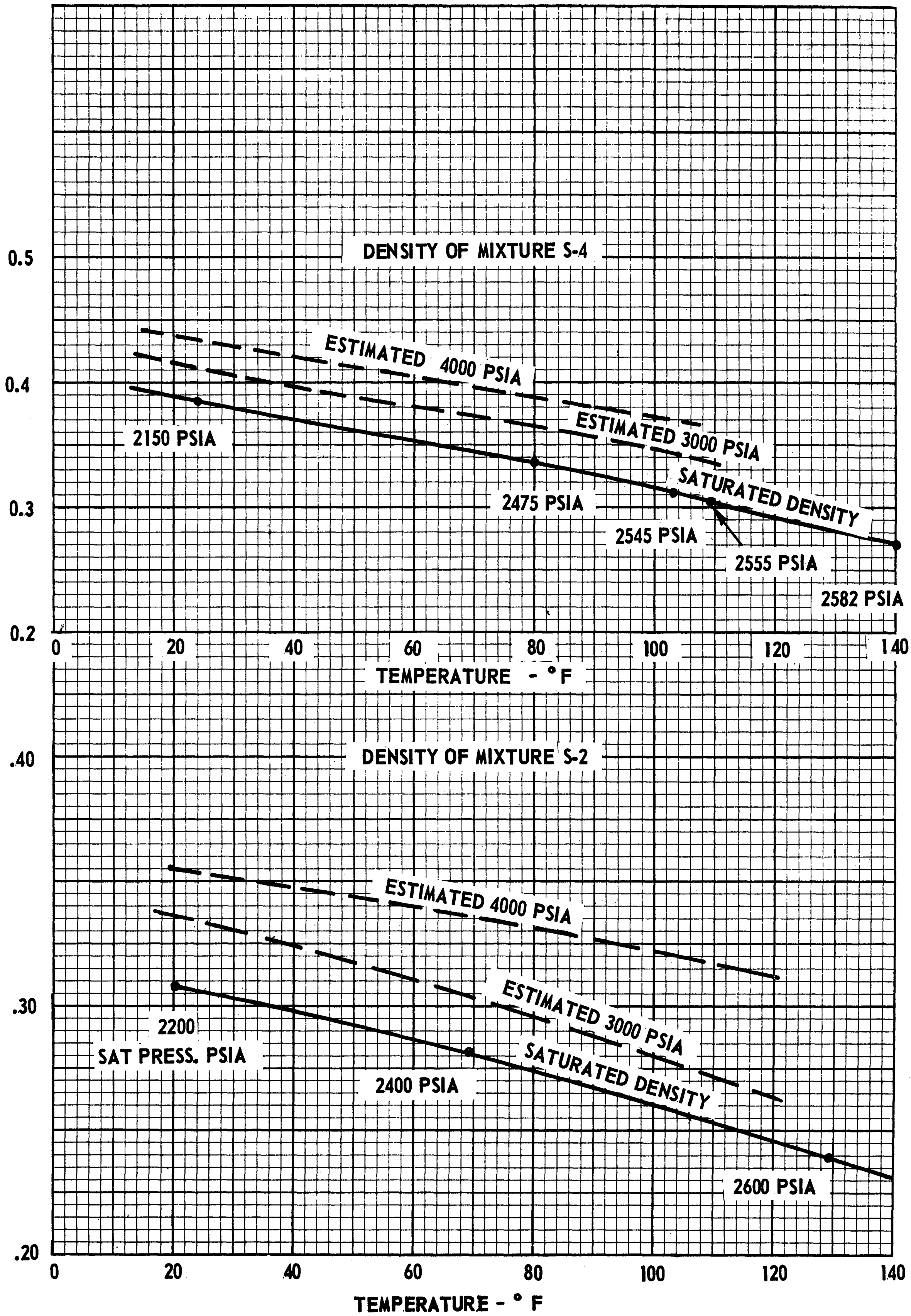

Figure 9. Density of Gas S-Natural Gasoline Mixture (S-2 and S-4)

TABLE 3

Viscosity Data

System	Temp. (^{o}F)	Pressure (psia)	Source
Methane	0-150	14.7-4000	18,21
Methane-Propane	0-150	14.7-4000	18
Propane	0-150	14.7-4000	18,22
Methane-n-Butane	70-160	14.7-4000	23
Ethane	59-150	100-4000	22
Pentane	77-150	100-3000	24
Natural Gases		100-4000	21

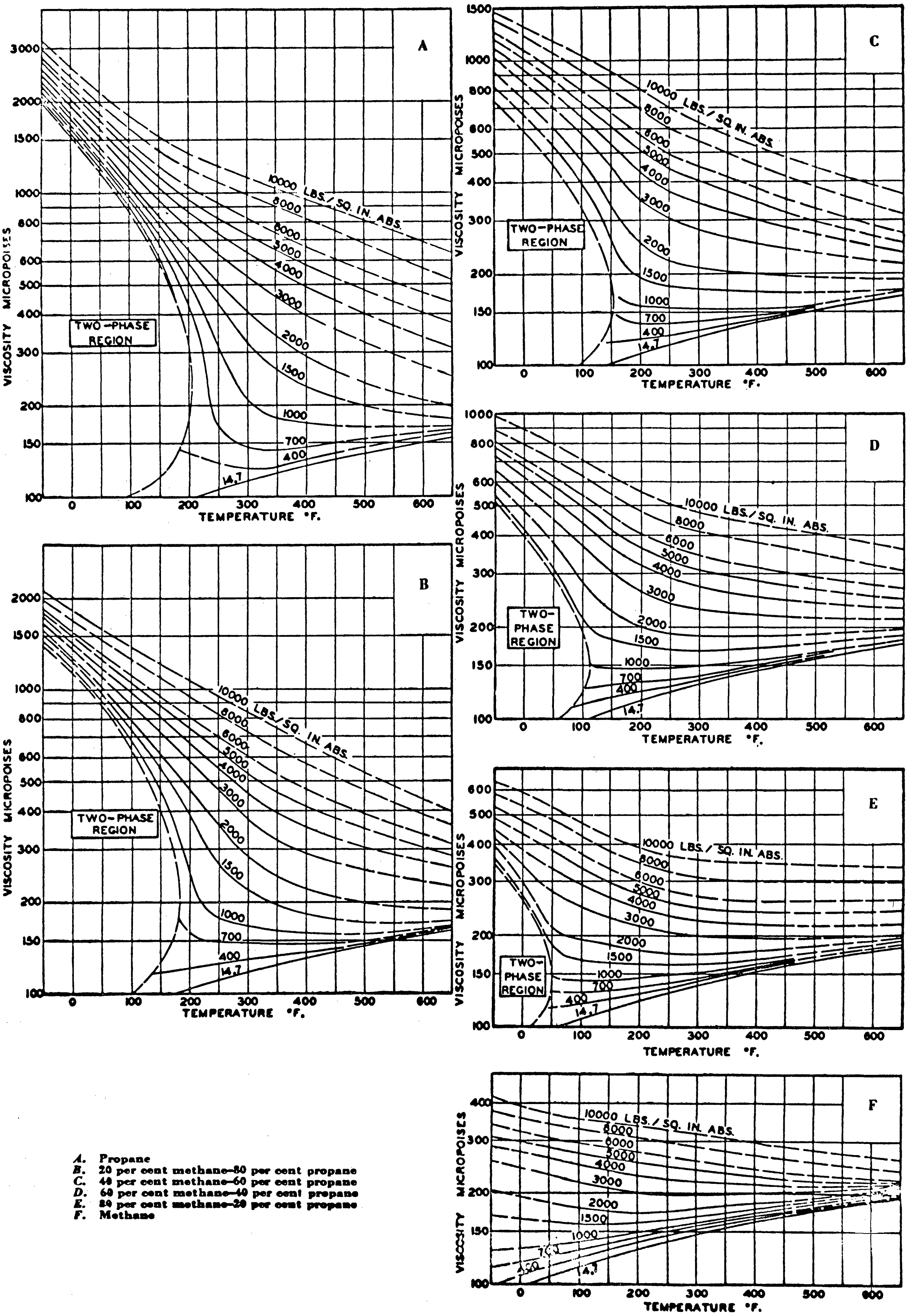

Figure 10. Viscosity of Propane, Methane and Mixtures

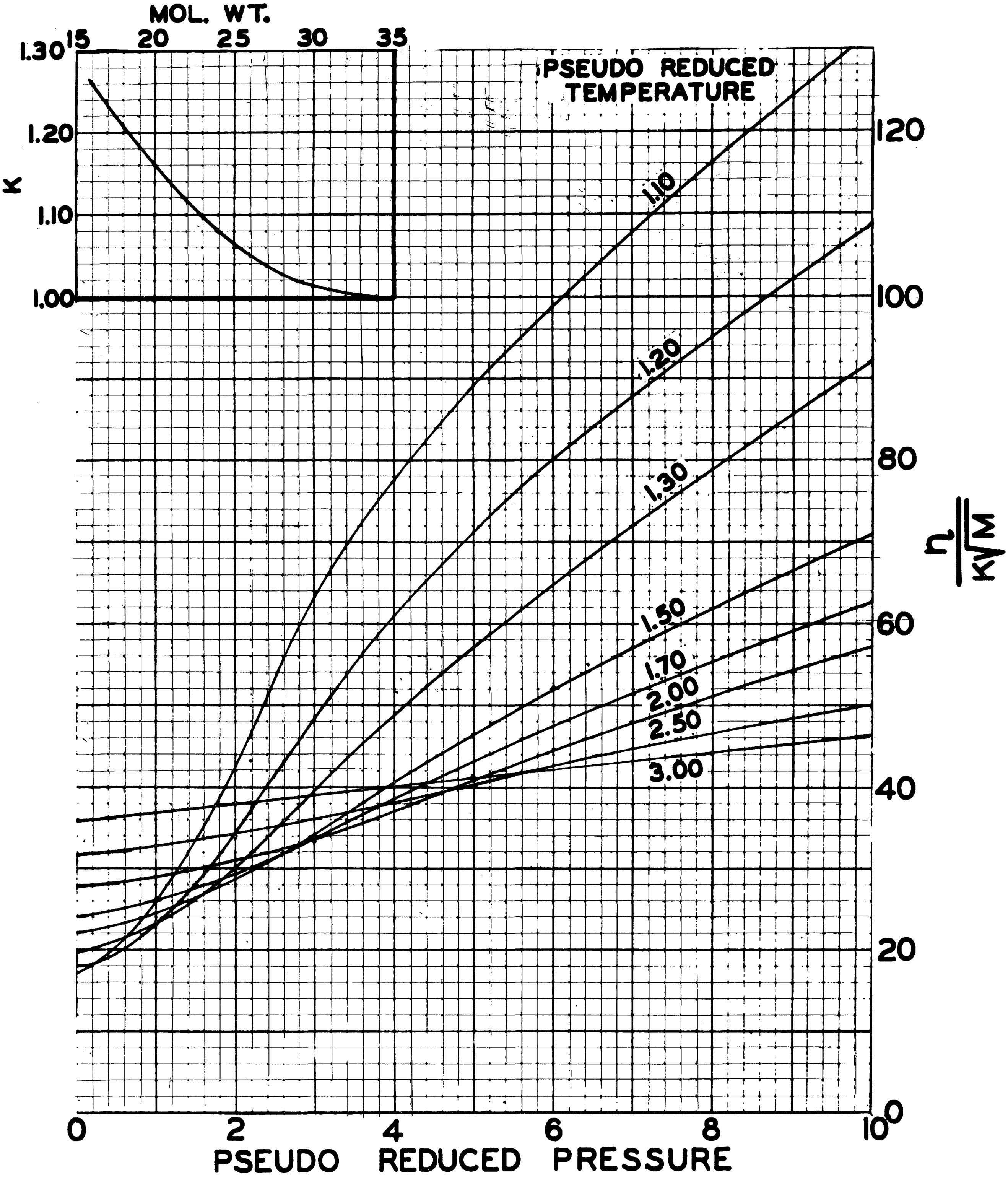

Figure 11. Viscosity of Paraffin Hydrocarbons (Correlation) at High Reduced Temperatures

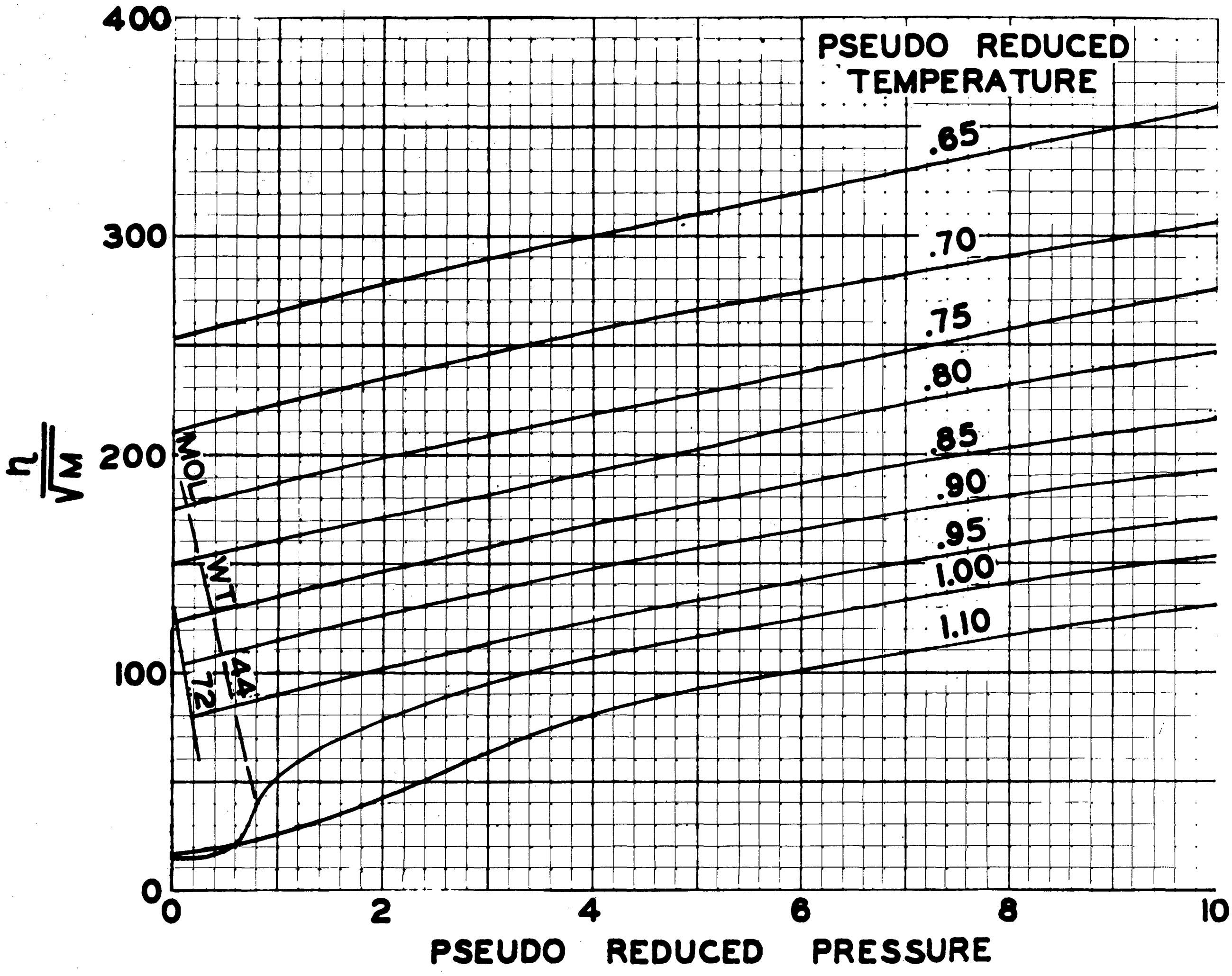

Figure 12. Viscosity of Paraffin Hydrocarbons at Low Reduced Temperatures

and providing an interpolation procedure. Appendix G lists the viscosity data used by the computer.

Pipeline Flow Calculations

Upon discussing with the Advisory Committee the appropriate equation for making pipeline calculations, a copy of the report "Computation of Flow and Natural Gas Transmission Lines" by the Institute of Gas Technology with A. E. Uhl and Committee NB13 as the author (1964) was supplied to the project[1]. It was agreed that this method of computing pipeline flow would be satisfactory from the standpoint of the sponsor companies. Therefore, an effort was made to see how this formulation of pipeline flow fitted into the usual Moody friction factor concept for flow of fluids in pipes. If possible, the flow formulas used in the report would be used but with an understanding of the friction factor which the procedure follows.

It was found that the partially turbulent flow calculation procedure was that of using the Moody friction factors with a roughness corresponding to smooth pipe. Added factors for degrees of bending and pipeline flow efficiency are included. Otherwise, the procedure is exactly that which would be used in the normal Weymouth type equation which employs the Moody friction factor. In the fully turbulent case, a further simplification is made in the report which does not appear necessary in this project. Accordingly, the pipeline flow formula is presented in the manner which is believed to be compatible with the IGT report and the flow calculations with which the writer is already familiar.

Flow Formula

It is proposed to calculate flow in natural gas transmission lines by the following equation[1]:

$$Q_b = 77.5\, F_{tb}\, F_{pb}\, F_{gr}\, F_{tf}\, F_{pv}\, F_d\, F_t\, F_f\, F_{fe} \left(\frac{P_1^2 - P_2^2}{L} \right)^{0.5} \qquad (1)$$

where Q_b = gas flow rate - cu. ft./day at P_b and T_b

P = pressure - psia
P_1 = inlet pressure
P_2 = outlet pressure

L = total length of pipe between compressor stations excluding any equivalent length due to bends in pipe since such is included in F_f. Equivalent length due to valves, gates, etc. are to be included.
L = L_t/NOS, miles
L_t = total length of line, miles
NOS = number of stations

F_{tb} = base temperature factor $\frac{T_b}{520}$. A base temperature factor of 60°F will be used. $F_{tb} = 1.0$ (2)

F_{pb} = base pressure factor $\frac{14.73}{P_b}$. A base pressure of 14.73 will be used.

$$F_{pb} = 1.0 \tag{3}$$

F_{gr} = gas gravity factor = $\sqrt{\frac{0.6}{G}}$ (4)

G = molecular weight/29.0

F_{tf} = flowing temperature factor = $\sqrt{\frac{520}{T_f}}$ (5)

T_f = flowing temperature - °R

F_{pv} = supercompressibility factor = $\sqrt{\frac{1}{Z}}$ (6)

F_d = line diameter factor = $D^{2.5}$

D = inside diameter of the pipe in inches (7)

F_t = transmission factor = $\frac{1}{\sqrt{f_F}} = \frac{2}{\sqrt{f_M}}$ (8)

f_F = fanning friction factor (9)

f_M = Moody friction factor

F_f = drag factor = function (Bend Index). Graph of F_f versus Bend Index is as shown in Figure 13 (reproduced from Figure IV-1, p. 56, IGT report, 1964). (10)

F_{fe} = flow efficiency factor. Normally use $F_{fe} = 1.0$ unless there are data on cleanliness, etc. to reduce the value. (11)

For the above restrictions the equation reduces to

$$Q_b = 77.5\ F_{gr}\ F_{tf}\ F_{pv}\ F_d\ F_t\ F_f \left(\frac{P_1^2 - P_2^2}{L}\right)^{0.5} \tag{12}$$

Calculation of Supercompressibility Factor

In evaluating F_{pv}, a pressure and temperature are needed. The pressure to be used is the $P_{average}$ (P_{avg}) defined as follows:

$$P_{avg} = \frac{2}{3}\left[P_1 + P_2 - \frac{P_1 P_2}{P_1 + P_2}\right] \tag{13}$$

Calculation of Moody Friction Factor and Transmission Factor (F_t)

The Moody friction factor has been plotted against Reynolds number with lines of constant wall roughness (Moody, 7-25), (Katz, Figure 7-3, p. 303)[2]. The Reynolds number for a gas flowing in pipe is given by the following equation:

$$Re = 4.775 \times 10^{-4} \left(\frac{Q_b}{\mu}\right)\left(\frac{G}{D}\right)\left(\frac{P_b}{T_b}\right) \tag{14}$$

where Re = Reynolds number, dimensionless

Q_b = gas flow - cu. ft./day at P_b and T_b

μ = fluid viscosity - $\frac{\text{lb}}{\text{ft sec}}$

D = inside diameter of pipe - inches

P_b = base pressure = psia

T_b = base temperature - $^{\circ}R$

For P_b = 14.73 psia and T_b = 520°R of this report

$$Re = 1.3526 \times 10^{-5} \frac{Q_b G}{D} \tag{15}$$

The friction factor will be found for a pipe roughness of 250 micro-inches. Colebrook's relationship, Handbook[2], p. 302, for evaluating the Moody friction factor in the form used by the AGA becomes

$$F_t = \frac{2}{\sqrt{f_M}} = 4 \log \frac{D}{EE^*} + 2.28 - 4 \log \left(1 + 9.34 \frac{D/EE}{Re \sqrt{f_M}}\right) \tag{16}$$

Drag Factor (F_f)

This factor is taken from Figure 13 corresponding to 200 degrees of bends per mile for plastic lined pipe and becomes 0.936.

Work of Compression

In obtaining the work of compression, one solves the basic flow equation which for horizontal flow and neglecting kinetic energy changes become[2] (p.315, Equation (7-66))

$$A = \int_{P_1}^{P_2} VdP \tag{17}$$

where A = work of compression
V = volume
P = pressure

During compression, the temperature rises and the relationship between volume and pressure is dependent upon the thermodynamic properties of the fluid, the heat transferred from the fluid during compression, and the flow inefficiencies which occur in the compressor.

It has been customary to employ the ideal gas relationship for adiabatic and reversible compression in finding the relationship

*Where EE = pipe roughness, inches

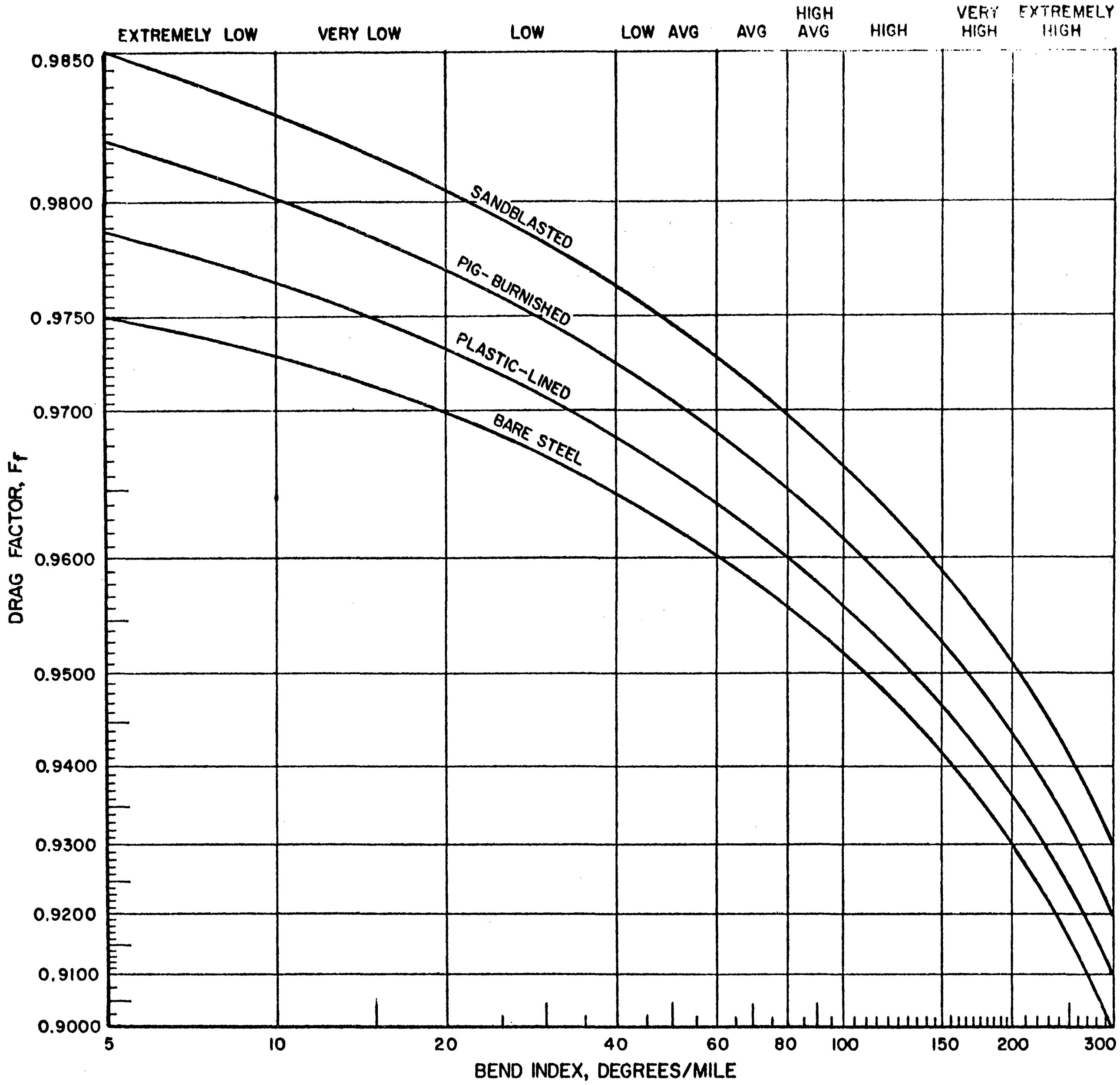

Fig. IV-1.-DRAG FACTOR AS A FUNCTION OF PIPE TYPE AND BEND INDEX
(For typical lines constructed of 40-foot pipe joints welded in the field, and involving a valve setting approximately every 10 miles)

Fig. 13. Reproduced from Reference 1, Uhl *et al.*

between V and P, namely

$$PV^k = P_1 V_1^k = \text{constant} \tag{18}$$

where k = ratio of specific heats, C_p/C_v.

When using this relationship between P and V and still retaining the units of ft. lbs./lb. for A, one obtains

$$A = \frac{k}{k - 1} \frac{53.241\ T_f}{G} \left[\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} - 1 \right] \tag{19}$$

G = gas gravity, molecular weight/29.0

T_f = inlet temperature, $^{\circ}R$

Subscript 1 refers to the outlet pressure of the compressor or maximum pressure in the pipeline.

Subscript 2 refers to the inlet pressure to the compressor or minimum pressure in the pipeline.

Retaining the ideal gas relationship but converting units of A to horsepower per million cubic feet of Gas (14.73 psia and $60^{\circ}F$) per day, one obtains

$$A = 0.088 \ \frac{k\ T_1}{k - 1} \left[\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} - 1 \right] \tag{20}$$

The question arises as to the most suitable method of converting this formula based on ideal gases to one which will handle actual gases, knowing that the deviation from ideal gases can be of a considerable magnitude. Also, at what temperature should the value of k be evaluated?

One way to evaluate the work is to invoke a parallel equation for work of compression based on enthalpy increase during adiabatic reversible compression. Equation (7-79), p. 316 of Reference 2 with units of A given above shows the equation to be

$$A = 0.0432\ \Delta H \tag{21}$$

where ΔH is increase in enthalpy during pressure rise along a constant entropy line.

Enthalpy - Entropy diagrams have been prepared for natural gases at various gas gravities, such as 0.6, 0.7, 0.8, 0.9, and 1.0. By use of such charts and selected conditions, one can obtain the work of compression.

Three methods for correcting the deviation of the gas from ideal conditions have been used in modifying Equation (20). None of these equations are exact; they are expected to find the same result as integrating the VdP term with the actual volume used at each P. This would require multiplying each ideal volume by the Z which corresponds not only to the pressure involved but to the temperature to which the gas has risen at each increment of pressure rise. The three versions are

$$A_1 = 0.0854 \left(\frac{k}{k-1}\right) \frac{T_f Z_2}{EFF} \left[\left(\frac{P_1}{P_2}\right)^{\frac{k-1}{k}} - 1\right] \frac{14.73}{14.65} \tag{22}$$

where $\frac{14.73}{14.65}$ is a conversion of the constant to correspond to 14.73 as P_b.

Z_2 = compressibility factor corresponding to inlet conditions.

EFF = compressor efficiency, taken as 0.80 for centrifugal compressors.

$\frac{P_1}{P_2}$ = compression ratio.

T_f = inlet gas temperature, ^oR.

k = ratio of specific heat at constant pressure to that at constant volume.

This equation was recommended by the Natural Gas Pipeline Company of America.

$$A_2 = 0.0853 \left(\frac{k}{k - 1}\right) \frac{T_f}{EFF} \left[\left(\frac{P_1}{P_2}\right)^{\frac{(k - 1)^Z}{k}} - 1 \right] \frac{14.73}{14.65} \qquad (23)$$

The equation is from the Handbook[2], p. 316.

$$A_3 = \frac{44.64}{EFF} \left(\frac{T_f}{520}\right) \left(\frac{k}{k - 1}\right) \left(\frac{Z_1 + Z_2}{2}\right) \left[\left(\frac{P_1}{P_2}\right)^{\frac{k - 1}{k}} - 1 \right] \qquad (24)$$

This equation was supplied by the Columbia Gas System Service Corporation.

From this study, see Table 4, it was agreed to use Equation (22) for computing the work of compression. The equation uses the compressibility factor at the entrance to the compressors as a direct factor on the ideal gas quantity.

Economics of Single Phase Pipeline Flow for Mixtures of Natural Gas and Liquid Hydrocarbons

The purpose of this study is to devise a method of calculation for predicting the conditions at which natural gas and liquid hydrocarbons may be combined as a single phase system and transported economically in pipelines. It is known that the light hydrocarbons can be maintained in single phase with natural gases under specified temperatures and pressures. The ability to carry such light hydrocarbons over long distances along with natural gas may become economical if pressures higher than those normally used in pipelines are available. The use of higher strength steels would be advantageous in this connection. This survey proposes to set up a master economic program of pipeline flow in which the prime variables are investigated systematically to find the minimum cost of transportation.

During the course of the study, three programs have been written for the economic calculations. At the time the first

TABLE 4

Comparison of Work of Compression Calculations

Inlet at 1500 psia, $60^{\circ}F$ ($520^{\circ}R$)

$k(= \frac{C_p}{C_v})$ at Inlet Conditions

		A_{chart}				A_1	A_2	A_3	T_1	
$\frac{P_1}{P_2}$	EFF 100 %	95	90	85	80	Z_2, factor	Z_2, exponent	$\left(\frac{Z_2 + Z_1^*}{2}\right)$	ideal $^{\circ}R$	chart $^{\circ}R$
Gas Gravity = 0.6										
1.35	12.3	12.9	13.7	14.6	15.4	12.6	12.25	13.2	553	560
1.45	14.0	14.7	15.6	16.6	17.5	15.85	15.25	16.8	564	568
1.55	16.2	17.0	18.0	19.3	19.0	18.8	18.05	20.0	570	580
Gas Gravity = 0.8										
1.35	10.6	13.3	11.2	11.8	12.5	13.3	10.4	12.5	548	553
1.45	13.4	16.8	15.2	13.8	15.8	14.9	11.85	16.0	555	563
1.55	14.9	15.7	16.5	17.6	18.6	17.8	14.1	19.3	563	572
Gas Gravity = 1.0										
1.35	6.7	7.1	7.4	7.9	8.4	8.65	5.59	9.9	544	531
1.45	7.25	7.6	8.0	8.5	9.1	10.85	6.88	12.87	550	533
1.55	7.85	8.25	8.7	9.25	9.8	12.9	8.12	15.6	555	537

*Z_1 refers to value taken at T_1, "chart". NOTE: Subscript 2 refers to inlet to compressor and subscript 1 to outlet.

progress report was written, the calculations were directed toward finding the size of pipe and number of compression stations to give the minimum cost for a fixed flow rate, composition and strength of pipe. It included a Lagrangian method of undetermined multiplier to predict the compression ratio for the minimum cost before proceeding to calculate the minimum cost. The maximum pressure in the pipeline was fixed.

The second method fixed the composition, pipe strength, diameter of the pipe, and maximum pressure in the pipeline as 1.65 times the minimum permissible pressure for the composition.

The third method--which is the one used in reporting the results herein--fixes

Composition
Minimum pipeline pressure
Strength of steel
Pipe diameter.

For a series of flow rates, the cost of transporting gas is found for an increasing number of compression stations (decreasing compression ratio) until the cheapest cost is found for that flow rate. The flow rate is increased in increments, and the procedure is repeated until the cost increases over the previous minimum. Calculations are made for 16, 24, and 30 inch OD pipelines.

The economic computer program has been devised to compute the cost of transporting a thousand cubic feet (Mcf) of natural gas 100 miles when using a pipeline 1000 miles long. The cost includes both amortization of the investment and operating expenses.

The basic calculations made fix the following items:

a. Composition
b. Strength of steel
c. Pipe diameter
d. Flow rate

e. Number of compressor stations

f. Minimum pressure or inlet pressure to compressors (P_2).

For a given case, the pressure drop between stations is computed by Equation (12), and then the horsepower is computed by Equation (22). For this particular case, the cost of transportation can be found.

The pipeline investment is obtained by finding the tons of steel and laying cost. The pipe wall thickness is calculated by Equation (A1) using the maximum pressure calculated in connection with pipeline flow. From the wall thickness, diameter, and cost per ton of steel, the pipeline and communication system investment is computed (IINVL).

$$\text{IINVL} = (\text{YW} + \text{N} \times \text{OD} + \text{H}) \frac{10^7}{\text{QB}} \tag{25}$$

Y = \$/ton of steel

W = tons of steel per mile (see Appendix A)

N = cost of laying pipe, \$/mile/in. OD = \$1200

OD = outside diameter of pipe in inches

H = cost of communication system, \$/mile = \$3000

QB = cubic feet of gas flowing per day

IINVL = cents/100 miles/Mcf/day.

The station investment (IINVS) is obtained from

$$\text{IINVS} = \left[\text{X} + \frac{\text{X}_1 10^6}{\text{A} \times \text{QB}} \right] 10 \frac{\text{A}}{\text{L}} \tag{26}$$

IINVS = cents/100 miles/Mcf/day

X_1 = fixed station cost = \$270,000

X = cost per horsepower = \$165

A = horsepower per station per million cubic feet per day

NOS = number of stations for 1000 mile line, $\frac{L_t}{L}$

L_t = total length of pipeline, miles (used as 1000)

L = length of line between stations, miles

QB = flow rate in cubic feet per day.

The transportation charge due to investment is taken as 15% per year. Therefore the cost of transportation due to investment when flowing gas 365 days per year becomes

$$CMMAM = \left[IINVL + IINVS\right] \frac{0.15}{365} \tag{27}$$

CMMAM = transportation charge or cost due to investment in cents/100 miles/Mcf transported.

The operating charges are computed as follows by adding the fuel cost, compressor operating charge, the gas loss, the line maintenance, and the administration expense:

$$\begin{aligned} CMMOP = & \left[(FHPHR)\ 24 \times 365 \times CF + CLMS\right]\ 10\ \frac{A}{L}\ \frac{FOOP}{365} \\ & + \left[LG \times GASCST \times \frac{10^3}{LT} + \frac{CLML \times 10^6}{QB \times 365}\right]\ 10 + \frac{AD^*}{3650} \end{aligned} \tag{28}$$

CMMOP = transportation cost for operations in cents/100 miles /Mcf

FHPHR = Mcf per horsepower - hour = 8.7×10^{-3}

A = horsepower per station per million cubic feet per day

QB = flow rate of gas, cubic feet per day

CF = fuel cost for compressors, $0.20/Mcf

CLMS = maintenance charge of stations, $/hp/yr = $19

FOOP = fraction of time in operation = 1.0

NOS = number of stations, used as $\frac{1000}{L}$

GASCST = charge for gas lost, $/Mcf, used as $0.20 = CF

LG = gas loss in passing through line, fraction, used as 0.005

LT = total length of line = 1000 miles

CLML = labor and maintenance cost for line, $/mile/yr, used as $850

AD = administration expenses, $/mile/yr/MMcf/day.

The total cost of transportation then becomes the cost due to investment plus that due to operations.

$$CY = CMMAM + CMMOP \tag{29}$$

CY = cents/100 miles/Mcf.

---

*After all calculations had been made, it was found that the correct expression should have been AD/36.5.

TABLE 5

Economic and Other Factors Used in Study

Length of line (L_t) 1000 miles
Flowing temperature (T_f) 60°F
Pipe strength (S) 65,000 psi and 100,000 psi
Pipe diameter (OD) 16 inch, 24 inch and 30 inch (OD)
Pipe roughness EE = 250 micro-inches
Bend Index 200° per mile
Longitudinal joint factor for pipe (E) 1.0
Pipe design factor (F) 0.72
Compressor efficiency, EFF, 80%
Pipe cost (Y) 65,000 psi strength, $265 per ton
100,000 psi strength, $384 per ton
Cost of laying pipe (N) $1200 per inch OD per mile
Communication system cost (H) $3000 per mile
Compression station cost (X_1 + X) $270,000 + $165 per horsepower
Cost of fuel (CF) 20 cents/Mcf
Fuel consumption (FHPHR) 8.7 $\times 10^{-3}$ Mcf per horsepower - hour
Cost of labor and maintenance for pipeline (CLML) $850/mile/yr
Cost of labor and maintenance for compressor stations (CLMS) $19/hp/yr
Gas loss (LG) = 0.005 fraction of flow at 20 cents/Mcf
Administration expenses (AD) $\frac{1}{3650}$ cents/100 miles/Mcf
Annual investment charge, 15% per year
Line assumed to flow at 100% capacity 365 days/yr

Calculation of Transportation Costs

With the computer program given in Appendix B, the costs of transporting the 10 mixtures given in Table 1 were computed as shown by example in Appendix C. For each mixture, the minimum single phase pressure was determined as listed in Table 1. To this pressure, 100 psi was added to find the minimum pipeline pressure. Calculations were made for this minimum pipeline pressure and for a pressure 400 psi higher.

The variables used in addition to pressure when surveying the cost of transporting the various mixtures were

Pipe strength
Pipe diameter
Number of stations in 1000 miles
Flow rate.

For each composition, strength of steel, minimum pressure, and pipe diameter, a series of calculations are made with increasing number of stations at each of a series of flow rates. As shown on Figure 14, for a fixed composition, strength of steel, pipe diameter, and minimum pipeline pressure, the cost is found at each of a series of flow rates for an increasing number of compression stations until the cost goes through a minimum value. Figure 14 is for the 80% natural gas-20% propane mixture. The starting minimum number or compressor stations is set by including it as data in the computer program, and the costs are calculated for it and the next larger number of stations in sequence until the cost rises. At this point, the flow is incremented, and the procedure is repeated as long as the minimum cost decreases for the new flow rate.

The minimum cost at each flow rate of Figure 14 is plotted versus flow rate on Figure 15. All three pipe sizes are included on this one plot. As would be expected, the larger pipe sizes give lower costs of transportation. Figure 15 for the 80% natural

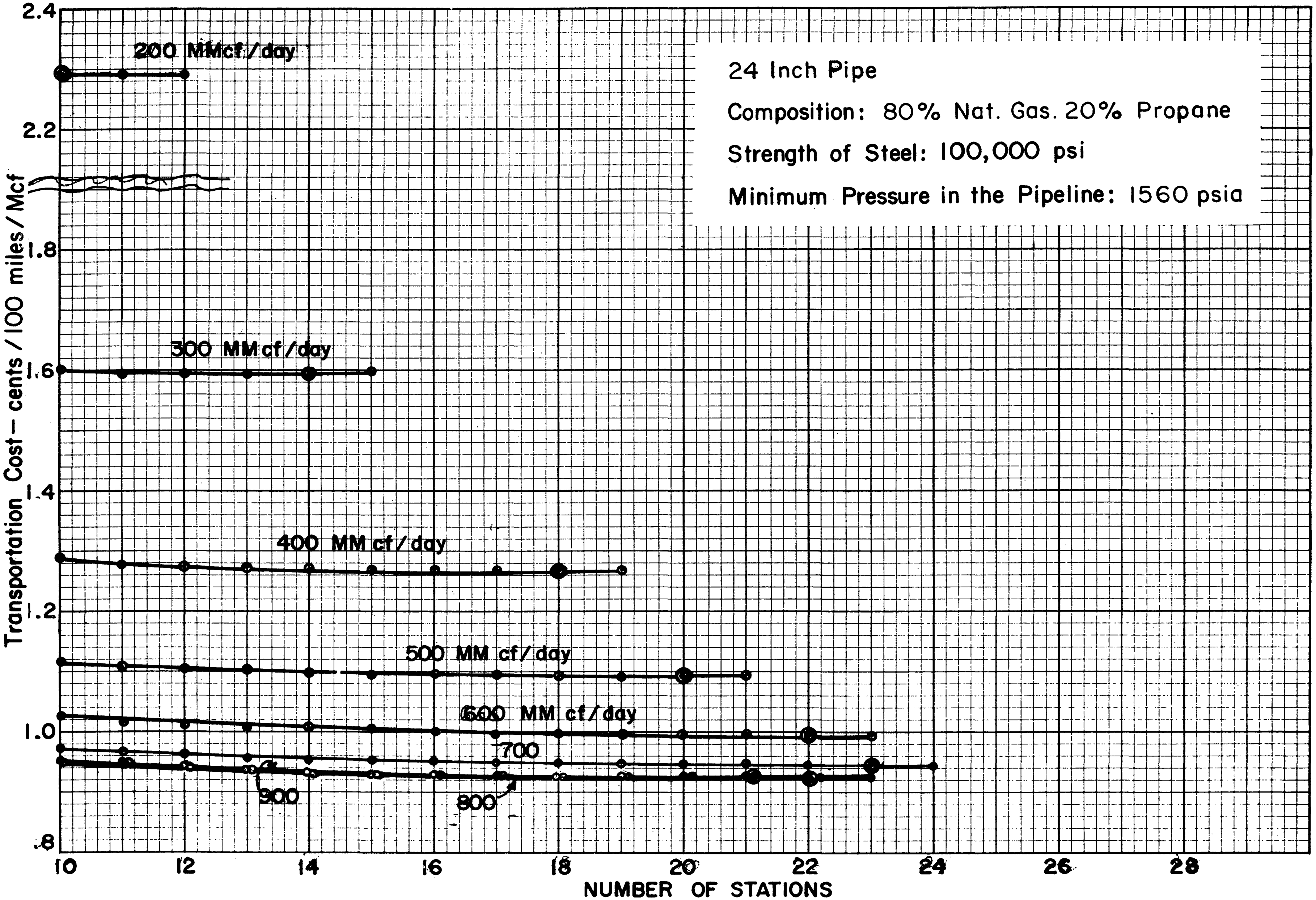

Figure 14. Cost of Transporting Gas as a Function of Number of Stations

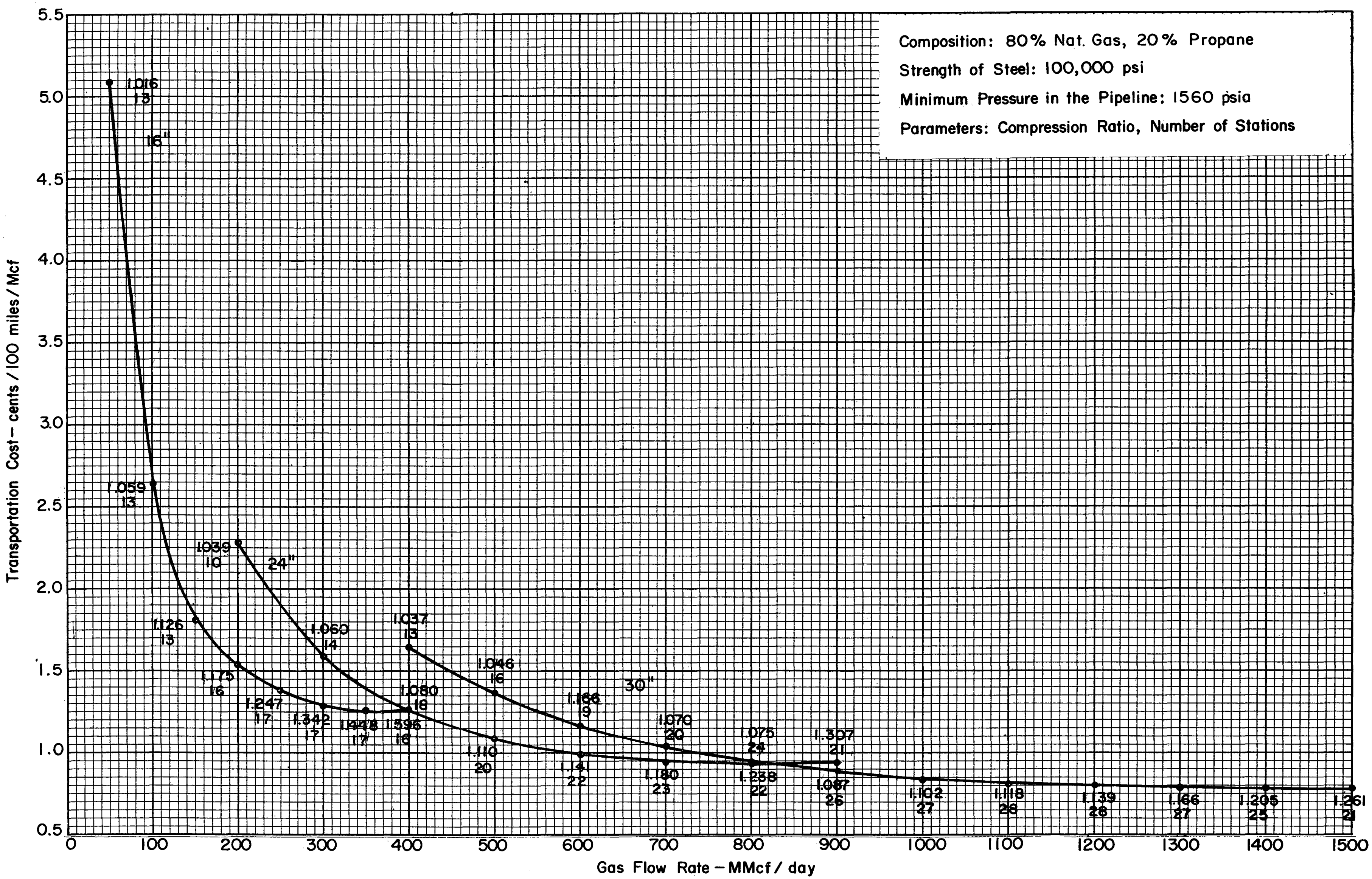

Figure 15. Cost of Transporting Gas as a Function of Flow Rate, 80% Natural Gas—20% Propane

gas-20% propane with 100,000 psi steel is included in the report. The remainder of these plots is included as Appendix E.

The original calculations for the 65,000 psi steel cases were based on $228 per ton rather than the $265 agreed upon as the proper cost. Rather than redoing the entire calculations, a program was written to compute only the new cost based on the horsepower per million cubic feet, pipe thickness, number of stations, and flow rate already determined. These computations were made for the 65,000 psi cases using five different number of stations adjacent to the minimum point previously found.

The 100,000 psi steel cases were run correctly as shown in the example print-out in Appendix B.

The minimum cost for each case is listed on Table 6, 66 values for the 65,000 psi steel and 45 values for the 100,000 psi steel since only 7 compositions were run in the latter case.

These costs for transporting various streams composed of natural gas and condensates are used to predict the cost of transporting the liquid portion of the gas stream.

The strength of the steel is a variable in the computer program, but only the 65,000 psi steel at $265 per ton and the 100,000 psi steel at $384 per ton were investigated. At these prices, the lines designed to use 100,000 psi steel gave cheaper transportation costs than the 65,000 psi steel.

The flow rate is a key variable in determining the cost of transporting the mixtures. Figure 16 is a plot of cost of transportation versus flow rate, with an identification of the pipe diameter and minimum pipeline pressure all for the 100,000 psi steel. The relationship is much as one would expect, a decreasing cost with higher flow rate.

The effect of pressure on the cost of transportation is indicated on Figures 17 and 18; the flow rate is identified for each point, all for the 100,000 psi steel. It is difficult to separate flow rate and pressure, but it appears that the cost of transportation decreases with pressure up to about 2500-3000

TABLE 6A

Cost of Transporting Fluids
cents/100 miles/Mcf

Based on 1000 mile pipeline, 65,000 psi steel

Mixture	16" diameter Min. Cost cents /100 miles /Mcf	16" Pipe Thickness in.	16" Flow Rate MMcf /day	16" Min. Press. psia	24" diameter Min. Cost cents /100 miles /Mcf	24" Pipe Thickness in.	24" Flow Rate MMcf /day	24" Min. Press. psia	30" diameter Min. Cost cents /100 miles /Mcf	30" Pipe Thickness in.	30" Flow Rate MMcf /day	30" Min. Press. psia	Mol. wt.
Natural Gas	1.99	.19	150	700	1.37	.29	400	700	1.16	.36	600	700	17.39
	1.61	.31	250	1100	1.17	.39	600	1100	.997	.445	900	1100	
	1.45	.376	300	1560	1.06	.516	800	1560	.904	.585	1200	1560	
	1.338	.477	400	2100	.994	.626	900	2100	.858	.754	1500	2100	
10% Propane	1.984	.194	150	700	1.374	.273	400	700	1.148	.356	800	700	20.06
	1.581	.304	250	1100	1.148	.404	600	1100	.979	.443	900	1100	
20% Propane	1.329	.389	350	1560	.972	.502	800	1560	.833	.592	1300	1560	22.73
	1.27	.447	400	1960	.938	.590	900	1960	.807	.708	1500	1960	
30% Propane	1.23	.39	400	1540	.893	.505	900	1540	.765	.60	1500	1540	25.4
	1.20	.437	400	1940	.877	.598	1000	1940	.761	.696	1500	1940	
5% Propane and 5% Butane	1.388	.404	350	1600	1.017	.514	800	1600	.873	.609	1300	1600	20.76
	1.32	.458	400	2000	.977	.633	1000	2000	.84	.724	1500	2000	
5% Butane	1.509	.365	300	1300	1.104	.46	700	1300	.942	.525	1100	1300	19.42
	1.39	.416	350	1700	1.02	.53	800	1700	.88	.627	1300	1700	
10% Butane	1.338	.455	400	1880	.982	.58	900	1880	.846	.701	1500	1880	21.47
	1.308	.514	450	2280	.97	.707	1100	2280	.846	.806	1500	2280	
15% Butane	1.293	.453	400	2000	.953	.632	1000	2000	.82	.725	1500	2000	23.51
	1.30	.515	400	2400	.957	.731	1100	2400	.877	.853	1500	2400	
Kurata S-2	1.343	.555	400	2660	.985	.787	1100	2660	.941	.909	1500	2660	24.96
	1.383	.642	450	3060	1.034	.890	1100	3060	1.018	1.037	1300	3060	
Kurata S-4	1.353	.579	450	2630	.9937	.789	1100	2630	.8875	.926	1500	2630	29.15
	1.443	.649	450	3030	1.070	.896	1100	3030	1.03	1.036	1300	3030	

TABLE 6B

<u>Cost of Transporting Fluids</u>
<u>cents/100 miles/Mcf</u>

Based on 1000 mile pipeline, 100,000 psi steel

Mixture	16" diameter Min. Cost cents /100 miles /Mcf	16" Pipe Thick-ness in.	16" Flow Rate MMcf /day	16" Min. Press. psia	24" diameter Min. Cost cents /100 miles /Mcf	24" Pipe Thick-ness in.	24" Flow Rate MMcf /day	24" Min. Press. psia	30" diameter Min. Cost cents /100 miles /Mcf	30" Pipe Thick-ness in.	30" Flow Rate MMcf /day	30" Min. Press. psia	Mol. wt.
Natural Gas	1.56	.191	250	1100	1.12	.261	600	1100	.96	.281	900	1100	17.39
	1.36	.264	350	1560	1.00	.327	800	1560	.86	.377	1200	1560	
	1.26	.306	400	2100	.94	.402	900	2100	.82	.479	1400	2100	
10% Propane	1.93	.124	150	700	1.32	.189	400	700	1.11	.234	700	700	20.06
	1.52	.186	250	1100	1.10	.259	600	1100	.94	.308	1000	1100	
20% Propane	1.26	.251	350	1560	.92	.322	800	1560	.79	.391	1400	1560	22.73
	1.20	.287	400	1960	.88	.395	1000	1960	.74	.467	1600	1960	
5% Propane and 5% Butane	1.32	.260	350	1600	.97	.332	800	1600	.831	.403	1400	1600	20.8
	1.25	.297	400	2000	.92	.402	1000	2000	.802	.460	1400	2000	
10% Butane	1.26	.292	400	1880	.93	.373	900	1880	.80	.447	1500	1880	21.47
	1.22	.331	450	2280	.91	.450	1100	2280	<.80	.510	>1500	2280	
Kurata S-2	1.24	.371	450	2660	.92	.504	1100	2660	.81	.610	1700	2660	24.96
	1.28	.406	450	3060	.96	.590	1300	3060	<.90	.680	>1500	3060	
Kurata S-4	1.26	.371	450	2630	.93	.504	1100	2630	<.84	.596	>1500	2630	29.15
	1.33	.409	450	3030	.99	.572	1100	3030	<.91	.680	>1500	3030	

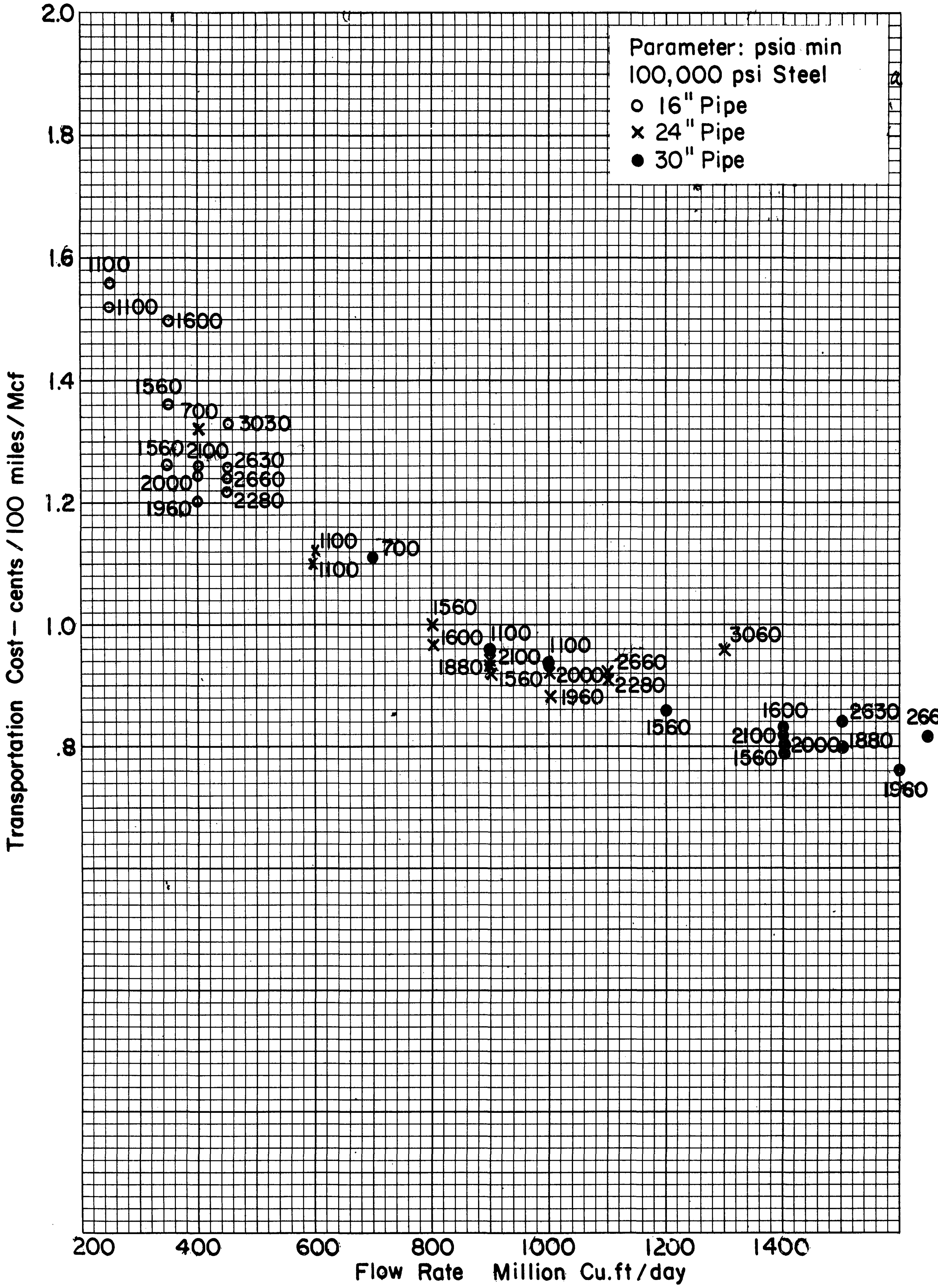

Figure 16. Effect of Flow Rate on Cost

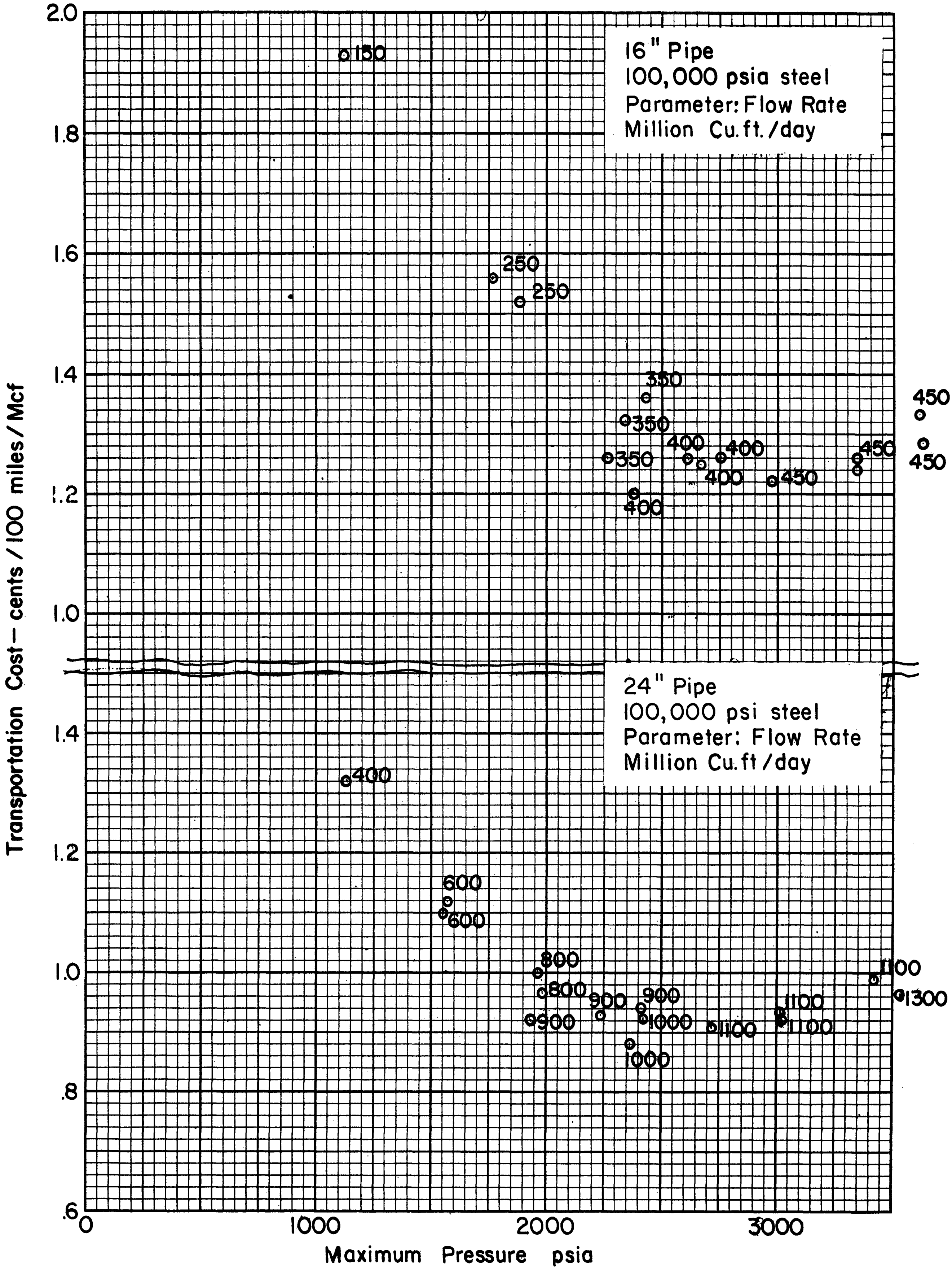

Figure 17. Effect of Pressure on Cost of Transportation

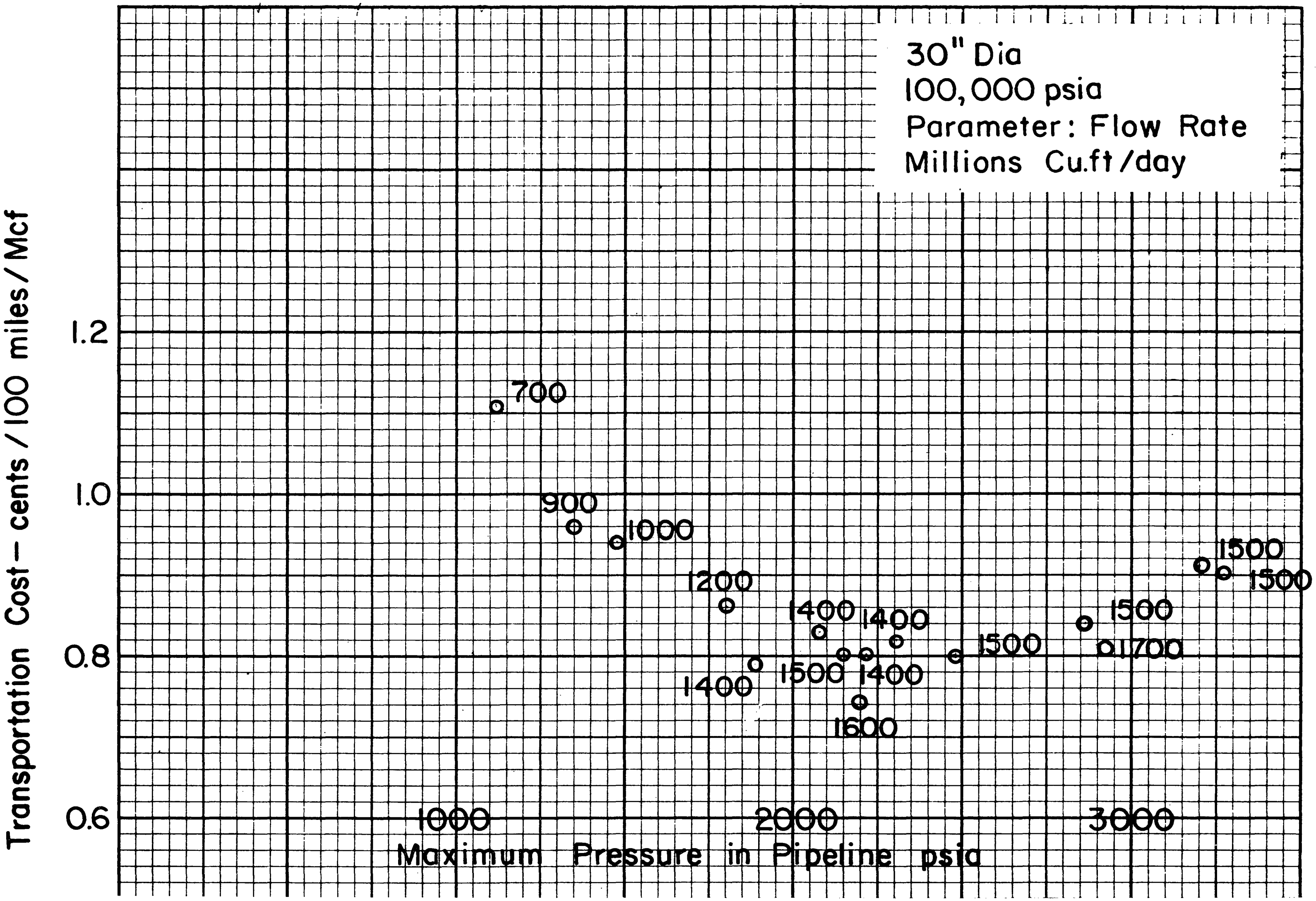

Figure 18. Effect of Pressure on Cost of Transportation

psia. It should be noted that the maximum pipeline pressure is plotted on these figures. The maximum pressure was found by multiplying the minimum pressures in Table 6 by the compression ratio listed on Figure 15. A similar plot using minimum pressures for the 65,000 psi steel with the incorrect cost of steel as distributed in the progress report gave a similar impression.

The effect of molecular weight on cost is given on Figures 19 and 20. Again, it is difficult to be sure the effect of flow rate is not obscuring the independent effect of molecular weight. Generally, increases in molecular weight are accompanied by a decrease in cost. That is, the addition of propane or butane gives a lower overall cost of transportation per unit of fluid. The higher molecular weights represented by the Kurata mixtures give rising costs, but they could be influenced by the unusually high operating pressure needed to keep the mixtures in single phase.

Effect of Temperature

These calculations have all been made at 60°F. The nature of the compressibility factors is such that there would be less effect on the density by adding higher molecular weight hydrocarbons at higher temperatures and greater effect on density at lower temperatures. Thus, the effect of increased pipeline capacity observed in winter when the temperatures are lower would be accentuated for gases carrying condensates.

Cost of Hauling Liquids

The objective is to find the cost of transporting the liquid constituent. To do this, it appears logical to set some cost for transporting the gas alone. Then it is necessary to set some total flow rate and divide the composition into the gas portion and the liquid portion. By knowing the transportation cost of the mixture and that of the gas alone, one can find the cost of transporting the liquid.

One method of proceeding is to use a standard cost for transporting gas. The value of 1.1 cents/Mcf/100 miles or

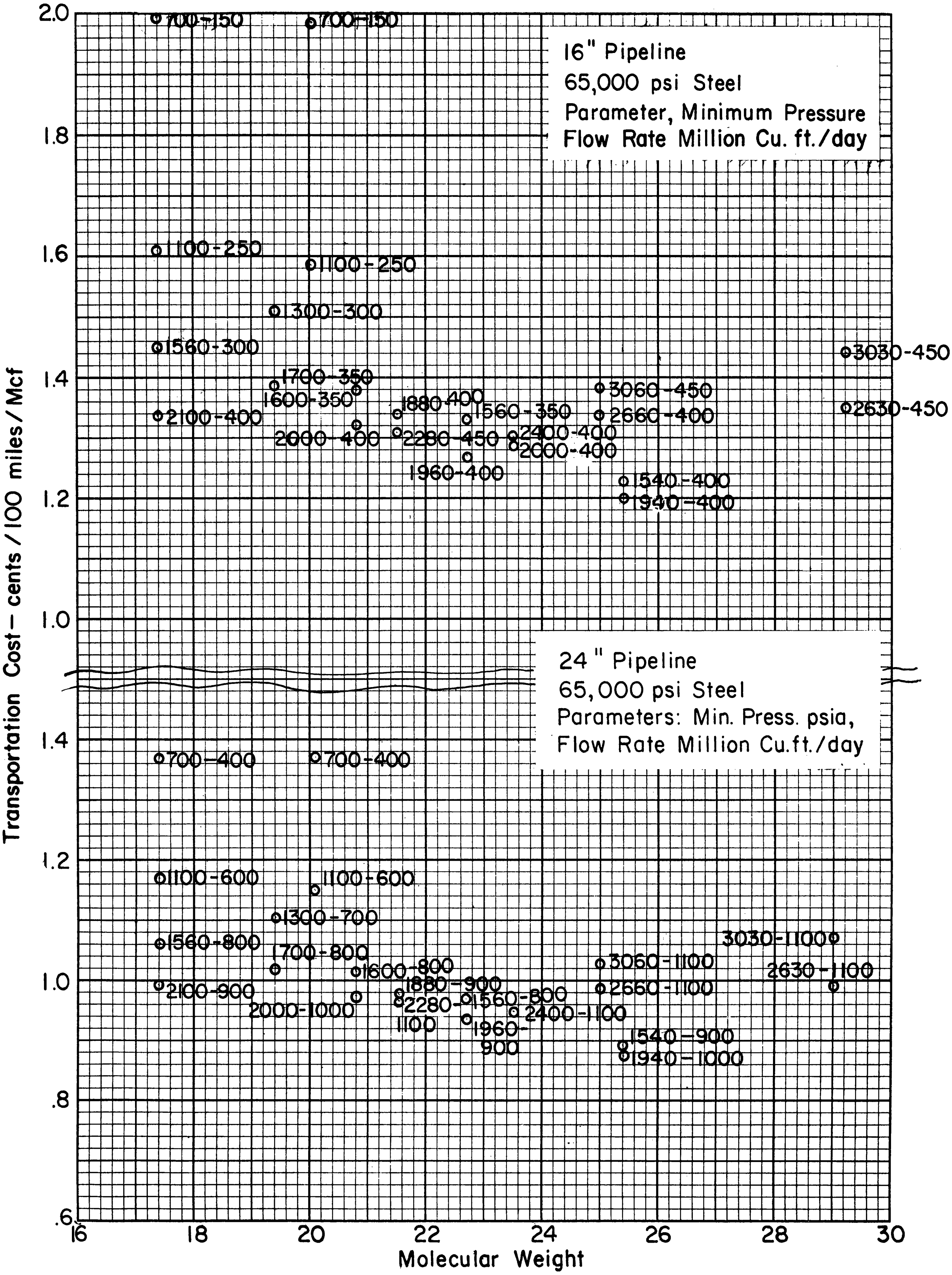

Figure 19. Effect of Molecular Weight on Cost of Transportation (65,000 psi steel)

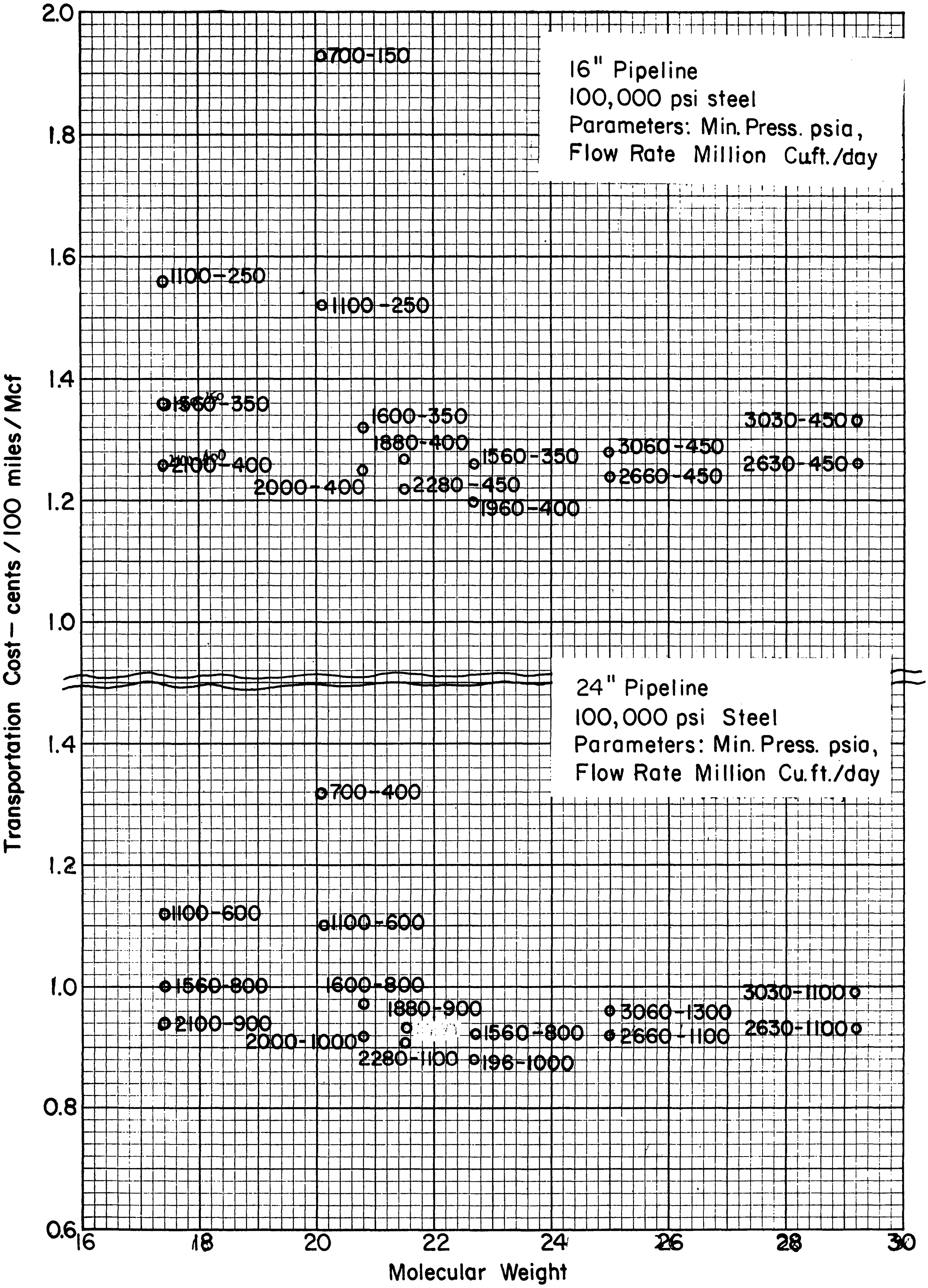

Figure 20. Effect of Molecular Weight on Cost of Transportation (100,000 psi steel)

11 cents/Mcf/100 miles is used as the best value at 500-600 million cu. ft./day and is the minimum value considered. At a flow rate of 900 million cu. ft./day, the cost of transporting gas is down to 0.95 cents/Mcf/100 miles.

Table 7 gives two example calculations of the cost of hauling liquids. The propane cost of 13.4 cents per barrel per 1000 miles for Case I is considerably below that of Colonial Pipeline Company tariff for products shown in Table 8, but of course there is some cost of separating the liquids from the gas at terminal. Case II is for condensate where the mixture costs more to haul than does natural gas because a 16" line is used. Here, the condensate is still cheaper than product pipeline tariffs.

In examining Tables 6A and 6B, one can find for 24" or 30" diameter pipelines several cases where the flow rates are the same for gas and for specific mixtures. Taking such pairs of conditions, the cost of hauling liquids is computed for several mixtures on Table 9. These calculations show very favorable rates for transporting liquids when extremely large quantities are involved. These results are ample justification for further pursuit of these concepts for hauling liquids, including investigation of separation costs.

Conclusions

1. The addition of the light hydrocarbons propane, butane, and condensates to natural gas flowing in pipelines increases the total flow capacity of the line and reduces the cost of transportation.

2. The pressures required to keep these liquids in single phase are above present pipeline pressures, but not high enough to increase the cost of transporting the gas mixtures.

3. The cost of hauling liquids, dissolved in natural gas without consideration of separation costs, is some 35-50% of the tariffs posted by the Colonial Pipeline Company for liquid products

4. A slight advantage was found for using 100,000 psi steel at $384 per ton over 65,000 psi steel at $265 per ton.

5. Operating pressures up to some 2500 psi in pipelines appear to decrease the cost of transporting single phase natural gas liquid mixtures.

6. This study should be a sufficient basis for further consideration of transporting liquid along with natural gas, whenever large quantities of liquid need to be transported over long distances.

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TABLE 7

Calculation of Cost of Transporting Liquids in Gas Pipeline for 1000 Miles

Case I 20% Propane-80% Natural Gas

65,000 psi steel
24 inch pipe
Minimum pressure 1960 psia
Flow rate 900 million cu. ft./day
(131,000 bbls/day propane)
Cost of transportation = 0.938 cents/100 miles/Mcf
Using a cost for natural gas of 0.95 cents/100 miles/Mcf (9.5 cents/1000 miles) and dividing stream into $0.7816 \times 900{,}000 = 704{,}000$ Mcf of gas and 131,000 bbls

$\left(0.2184 \times \frac{900{,}000{,}000}{35.8 \times 42}\right)$ of propane.

Cost per day for 900 million at $0.938 \times \frac{10}{100} = \$84{,}500$

Cost per day for 704,000 Mcf at $0.95 \times \frac{10}{100} = 66{,}900$

$\$17{,}600$

In this case the propane is hauled 1000 miles for

$\frac{17{,}600 \times 100}{131{,}000} = 13.4$ cents/bbl.

Case II Kurata S-4 Gas Condensate

100,000 psi steel
Cost of hauling 1.26 cents/Mcf/100 miles
Flow rate 450 million cu. ft./day
16 inch pipe
Minimum pressure 2630 psia
84,300 bbls condensate/day
352 million cubic feet of natural gas

Cost of hauling mixture 1000 miles $450{,}000 \times 1.26 \times \frac{10}{100} = \$56{,}700$

Cost of hauling natural gas $352{,}000 \times 1.1 \times \frac{10}{100} = 38{,}700$

$\$18{,}000$

The cost of hauling the condensate is $\frac{18{,}000 \times 100}{84{,}300}$ = 21.4 cents/bbls/1000 miles.

TABLE 8

Published Tariff for Product Transportation by Colonial Pipeline Company

Entrance to Pipeline	Exit from Pipeline	Estimated Miles	Cost cents /bbl	Cents /bbl 1000 miles
Beaumont (Texas)	Philadelphia (Pa.)	1380	31.75	23.0
Lake Charles (Louisiana)	Philadelphia (Pa.)	1320	31.25	23.7
Pasadena (Texas)	Philadelphia (Pa.)	1450	33.50	23.01
Beaumont (Texas)	Chattanooga (Hamilton County)	860	24.65	28.7
Beaumont (Texas)	Knoxville (Tenn.)	960	25.75	26.8
Beaumont (Texas)	Nashville-Davidson (Davidson County)	990	26.05	26.3

TABLE 9

Cost of Hauling Liquids

Composition	Dia.	Min. Press. psia	Cost Cents/1000 miles/Mcf Mixture	Cost Cents/1000 miles/Mcf Gas	Total Rate MMcf /day	Gas Rate MMcf /day	Liq. Rate 1000 bbls /day	Cost Mixture $1000 /day	Gas Cost $1000 /day	Liq. Cost $1000 /day	Cents/bbl /1000 miles
65,000 psi steel											
30% Propane	24	1540 2100	8.93	9.94	900	616	189	80.4	65.6	14.8	7.8
20% Propane	24	1960 2100	9.38	9.94	900	704	131	84.4	70.0	14.4	11.0
5% Butane	24	1300	11.04	11.04	700	650	37.8	77.4	71.8	5.6	14.8
S-2	24	2660 2100	9.85	9.94	1100	934	143	108.3	92.9	15.4	10.8
100,000 psi steel											
10% Propane	24	1100 1560	11.0	11.2	600	528	48.1	66.0	59.1	6.9	14.3
20% Propane	24	1560 1560	9.2	10.0	800	625	116	73.6	62.5	11.1	9.6
S-2	24	2660	9.2	9.6	1100	934	144	101	89.1	11.1	7.7
S-4	24	2630	9.3	9.6	1100	860	206	102.3	82.5	19.8	9.6

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APPENDIX A

FORMULA FOR COST OF PIPE

The thickness of the pipe can be calculated by the following formula (Eqn. 841.1, ASME code B31.8, 1963)[25]

$$THK = \frac{(P_1)(OD)}{(2S)(F)(E)} \qquad \text{(A-1)}$$

The cost of pipe is given by

$$YW = Y \times 5280 \times \frac{\pi(OD^2 - (OD-2THK))^2}{4 \times 144} \times \frac{62.4 \times 7.86}{2000} \qquad \text{(A-2)}$$

$$= 7.08\ (OD^2 - (OD + 4\overline{THK}^2 - 2(OD)(2THK))(Y)$$

$$YW = 28.2\ THK(OD-THK)(Y) \qquad \text{(A-3)}$$

Y = Cost of pipe material, \$/ton
OD = Outside diameter of pipe, in.
ID = Inside diameter of pipe, in.
P_1 = Maximum pressure in pipe, psig
ρ_s = Density of steel 490, lb/ft^3
S = Minimum specified yield strength of steel, psi
F = Construction type design factor as given in Table 841.11, ASME code B31.8, 1963 (Ref. 25) (taken as 0.72)
E = Longitudinal joint factor as given in Table 831.12, ASME code (taken as 1.0)
T = Temperature derating factor for project (taken as 1.0)
YW = Cost of pipe, \$/mile

APPENDIX B

COMPUTER PROGRAM AND NOMENCLATURE

The computer program written in MAD solves in sequence the flow equation for pressure drop in the pipeline, the horsepower requirement for compression of the gas, and economical equations for obtaining the cost of transportation of the gas. Table B-1 is a print-out of the program as used in the pipeline flow calculations reported herein. It is the third program developed. The program was written to make it as general as possible and not all of the possible cases have been used in the example problem. The hand calculation follows in Appendix C. The nomenclature follows the program.

It is believed that a reading of the program along with the nomenclature will provide an understanding of the calculations. Some explanations are given where they are thought to be necessary.

The program reads all the data. It stores the information about the composition and initializes all the counters for diameter of the pipe, the strength of steel, minimimum specified flow rate, maximum pressure in the pipeline and the initial number of stations. The diameter of the pipe and the strength of steel are fixed parameters. A provision is made to allow for different initial and final flow rates, and number of stations. The initial flow rate corresponding to the diameter selected is read in as data. The switch (COMPSW) is turned "on" or "off" by making its values 1 or 0. By having it off the program computes the composition of the gas based on addition of propane and butane in barrels/day. If the switch is "on" the program expects the compositions of gas specified as part of the data.

The next step is to compute the pseudo critical properties of the mixture and the molecular weight. The program allows for N_2, CO_2, and methane to heptanes in the mixture. The gas gravity is computed by dividing the molecular weight of the mixture by 29, the molecular weight of the air. From gas gravity the gas gravity factor is computed.

The next step is to have the machine know what the minimum pressure in the pipeline is going to be. If this pressure is already known then the value of MMWT should be set higher than the molecular weight of the mixture. As we do not expect any mixture to exceed a molecular weight of 40, this number can be safely used. The program also has provisions for computing the minimum pressure as a function of the molecular weight at 40° or 60°F. In order for the computer to calculate the minimum pressure the value of MMWT should be set less than the expected molecular weight. In case nothing is read in the data for MMWT, it will be taken as zero making it safe automatically. This feature was put in the program when a correlation of minimum pressure with molecular weight was being developed. Whenever the interpolation is required as in the calculation of viscosity, compressibility factor and ratio of specific heats, the program makes use of subroutine TAB. A comment "unsuccessful interpolation" is printed whenever some error in interpolation occurs. The TAB subroutine follows the program.

The maximum pressure in the pipeline is computed by adding 100 psia to the minimum pressure (for safety when handling condensate) and multiplying by the assumed compression ratio. The initial value for the starting number of stations is furnished as input data.

The length between the compressor stations is computed. The thickness of the pipe, the inside diameter of the pipe and the line diameter factor are computed. Since both the maximum and the minimum pressure in the pipeline are known the average pressure is computed. From this value the reduced pressure is calculated; the reduced temperature is computed from the temperature of the line supplied as part of the data.

Based on the reduced temperature and pressure the compressibility factor of the single phase fluid is computed by Sarem's[17] method. A separate subroutine (ZFAC) has been prepared for this purpose, Appendix F.

The compressibility factor calculation by Sarem's method is good only when reduced temperature is greater than 1.1. The program has the facility to compute compressibility factors for reduced temperatures less than 1.1 provided the experimental data is available. In the case of the methane-propane system the data has been obtained from Sage and Lacey[6]. The data are stored as a two-dimensional array. Multiple interpolation with the help of subroutine TAB has been used to obtain Z values at any reduced temperature and pressure. At any stage if there is any difficulty in obtaining interpolation a comment is printed out indicating that effect. At the same time based on molecular weight and the reduced temperature and pressure, the viscosity of the mixture is computed by the method of Bicher and Katz.[18] The points on the curves of the viscosity correlation are supplied as part of the data in this program and interpolation techniques are used (see Appendix G).

In order to compute the transmission factor (F_t) the value for the Moody friction factor must be known. The Moody friction factor chart is well satisfied by Colebrook's relationship[2] as given by Eq. (16) both in the fully turbulent region and in the transition zone. If the value for FTB is set as 1, it indicates fully turbulent region, and if the value is zero it is taken as the transition region. In most of our calculations we are in the transition region. Therefore, the value of FTB has been set as zero. The Moody friction factor requires a trial and error calculation and therefore it has been prepared as an external function and named FNGFRI. This external function computes the value of transmission factor ($= 2/\sqrt{FM}$) directly.

Since the gas gravity factor, temperature flowing factor, supercompressibility factor, transmission factor, drag factor (read from Fig. 13 and fed as part of the data), flow efficiency factor (known by experience) and line diameter factor are known the program is ready to calculate the pressure drop. The compression ratio is computed using the minimum pressure, P2, and the pressure drop. If the difference between the assumed and calculated values of the compression ratio is greater than 1%, the calculated compression ratio is taken as the assumed value and the calculation repeated until there is agreement within 1%.

Based on this compression ratio, the new maximum pressure in the pipeline, new thickness of the pipe and new internal diameter of the pipe are calculated. A new flow rate is also computed. This will be automatically within 1% of the flow rate for which the entire calculations are based.

Once the compression ratio is fixed the horsepower required is computed with the help of Eq. (22). A new value of compressibility factor based on inlet conditions at the compressor is computed and used in the formula.

At this stage the program is ready to compute all the costs required. The operating cost,ammortization cost, initial line and station investment are computed based on the flow rate existing in the line at that particular section of the line. The fuel consumed at each station is subtracted from the flow rate existing in the line.*

When the calculations are completed for the minimum flow rate and number of stations, the number of stations is incremented by one and the calculations repeated until the transportation cost increases for that flow rate. The minimum cost is stored separately for each flow rate. The flow rate is increased in appropriate increments (set in data) until the minimum cost corresponding to each flow rate starts rising. The absolute minimum cost corresponding to a certain diameter of the line and flow rate is stored separately and is printed out at the end when all the calculations pertaining to that line have been completed.

For each flow rate the program makes a plot of transportation cost (sum of operating cost and ammortization cost) as a function of number of stations. Upon completion of the calculations for each diameter of the line it also makes a plot of the minimum cost of transportation as a function of flow rate. These plots are very handy for a quick survey of the answers obtained.

It may be pointed out that any information fed to the computer in one set of data remains unaltered even when that set of data has been processed and a new set is getting processed unless and until those values get changed in the program or are changed by the new set of data. As an example if the composition of propane is 0.05% for one mixture and is zero for the other mixture, then it will be necessary to make the value of the composition of the propane as 0, otherwise it will be counted as 0.05.

---

*The initial line and station investment and the transportation cost are based on the average value of gas flowing which amounts to saying that the cost of the fuel should include a transportation cost to the station at which it is used.

Explanation of the Input Data

The computer program was written to be very flexible in processing data for various types of conditions. This flexibility is controlled by various control variables which are defined in the nomenclature to make the understanding and use of the program simpler. A brief description of the input variables are given below with a detailed account of how to use the control variables. Reference may be made to Table B-3 for an example print-out of the input data.

KCP, MWT1

These represent the points taken from a graph of $K(C_p/C_v)$ as a function of molecular weight. For any value of molecular weight of the mixture the subroutine TAB finds the corresponding value of K.

PP, VFM, VFM1, COM1, MP

These are used to calculate the specific volume and then the compressibility factor at any pressure between 200 and 5000 psia and any temperature between 40 to 100°F for methane-propane system and having reduced temperature less than 1.1. PP represents the array for the pressure, VFM the specific volumes at 40°F starting at 0.2 mole fraction methane to 0.9 mole fraction methane. Similarly VFM1 represents the specific volumes at 100°F. COM1 specifies the mole fraction methane. MP represents the number of pressures used which in turn become the number of columns in the two-dimensional array of VFM and VFM1.

V, V1, PRD, NP, MT, KS

These are used to calculate the viscosity at any reduced temperature, pressure and molecular weight for the mixtures under study. V represents the points taken from curves starting at reduced temperature of 3 to the ones at 0.65. V1 represents the array for reduced temperatures. PRD gives the array for reduced pressures, and NP for the number of reduced pressures. MT and KS represent the graph of KI (correction factor for viscosity) as a function of molecular weight.

TN2, TCO2, ..., TNC6H4, PN2, PCO2, ..., PNC6H4, MN2, MCO2, ... MNC6H4

These are data for the critical temperatures and pressures and the molecular weights for N_2, CO_2, CH_4, C_6H_{14}, iC_4H_{10}, and iC_5H_{12}.

SR1, SR2, ..., SR6, Y

These represent the strength of steels and their corresponding costs in \$/ton. In case only one strength of steel is to be processed set SR2 to SR6 as zero.

BUTI, DBUT, BUTF AND PROPI, DPROP, PROPF

If information is desired for the addition of butane and/or propane to the gas in barrels/day the variables above may be used. These variables represent the quantity of butane or propane added in barrels/day. The initial and final values will be set as zero in case there is no addition as barrels/day. DBUT and DPROP are the incremental additions of butane and propane used in the iteration if a series of calculations are desired. Additions are normally added by specifying the desired values of the gas composition.

NOSF

This represents the maximum value for the number of stations. Depending on what is considered a minimum length between compressor stations, the value of NOSF should be set.

CRI AND DCR

These represent the initial value for the compression ratio. If the maximum allowable compression ratio (CRMAX) has been set as 1.65 CRI may be set as 1.2. DCR allows for changes in CRI during the processing of the data, but normally it should be set as zero.

COMPSW

If we have mixture of known composition and no additional propane or butane (PROPI, BUTI) is added then this should be set as 1. Otherwise it may be set as zero.

QBI, DQB, QBF

These represent the initial, incremental, and final flow rates for the flow rate iteration loop. Judgment should be used in setting up these values. QBF may be set higher than normally expected as the program is going to stop increasing the flow rate once the cost starts increasing.

MMWT

Normally we should set its value greater than the expected molecular weight. In case we have data for the minimum pressure as a function of molecular weight at 40° or 60°F then MMWT may be set as zero.

OD11, OD12, OD13

These represent the outside diameters of the pipe chosen for investigation. In case we went to process only one diameter, OD11 should be set equal to the desired diameter and OD12 and OD13 should be set as zero.

CRMAX

This represents the maximum allowable compression ratio.

NN

This represents the minimum number of stations which will be processed irrespective of whether the minimum cost has occurred or not. This is usually set at 5.

FFF

Minimum number of flow rates which will be processed. If only one flow rate is to be processed set FF equal to 1. Normally FF should be set as 3 since if the second flow rate gives a higher cost than the first, the program will set the flow rate one step less than the first flow rate and process that condition. It will repeat the process until it finds a suitable flow rate. This helps set the initial flow rate when poor judgment is used in selecting it.

FF

This is a drag factor. Its value is read from the graph of drag factor as a function of bend index.

NST1, NST2, DQB2, DQB4, QBMX, QBMX2

In certain mixtures it will be wasteful to process the costs starting from the same number of stations for all the flow rates. To avoid this, the program has the facility to change the initial value for the number of stations and the flow rate increment. NST1 and DQB2 represent the initial number of stations and the incremental flow rate to be used when the flow rate becomes equal to QBMX. Similarly NST2 and DQB4 represent the initial number of stations and the incremental flow rate when the flow rate becomes equal to QBMX2. QBMX2 should be set higher than QBMX. In case no change is needed then their values should be set higher than the expected final flow rates (QBF1, QBF12, QBF13).

Three external functions available from the Computer Library of The University of Michigan Computing Center were used in the program. They were TAB, SETPLT, and ZERO. A brief description of how to use the external functions is included.

TABLE B-1

PRINT-OUT OF COMPUTER PROGRAM FOR COST OF TRANSPORTING GAS IN CENTS/100 MILES/Mcf

```
$COMPILE MAD, EXECUTE , DUMP ,PRINT OBJECT , PUNCH OBJECT       PIPE2                 011724   07/12/65     2 .4  9.4 AM

MAD (01 MAY 1965 VERSION) PROGRAM LISTING ... ... ...

            DIMENSION  NOSS(40), CYN(40)   , NOSTA(40)                                *001
            DIMENSION  KCP(30), MWT1(30)   ,QBFL(30), CY3(30)    ,CY61(30)            *002
            INTEGER  NOS12, NOS13 , NOSTA  , NN, FFF   , NST1, NST2                   *003
            DIMENSION  PP(50), VFM(330, DIM1),VFM1(300, DIM1), CUM1(25)               *004
            INTEGER  CP, MP ,MMN , KKKK , NO                                          *005
            VECTOR VALUES  DIM1= 2, 1, 0                                              *006
            DIMENSION DI(60),   Y(30)   ,   OD1(30)    , MW(60), VP(60), VP1(60)      *007
            INTEGER  I, J, II, JJ, III, JJJ, KK , OF ,ND,XX,YY                        *008
            INTEGER  LL ,       TT, MM , NOS, NOSI,DNOS,NOSF,ODT                      *009
            INTEGER  Q, BU    , FTB , NOST   , COMPSW, ZSW                            *010
            INTEGER  T, TG, NP, MF                                                    *011
            DIMENSION V1(40), V(400, DIM), MT(20),KS(20), PRD(20)                     *012
            VECTOR VALUES DIM= 2,1, 0                                                 *013
            ZERO.( FN2, FCO2, FCH4, FC2H6, FC3H8, FIC4H0, FNC4H0,                     *014
          1       FIC5H2, FNC5H2, FNC6H4, FX, FY, FZ,TX, TY, TZ, PX, PY,              *014
          2 PZ, MX, MY, MZ  )                                                         *014
            ZERO.(     FNC7H6)                                                        *015
START       PRINT COMMENT  $1       PIPELINE CALCULATIONS $                           *016
            READ AND PRINT DATA                                                       *017
            DIM1(2)= MP                                                               *018
            DIM(2)= NP                                                                *019
            FCH4S=FCH4                                                                *020
            FC2H6S=  FC2H6                                                            *021
            FC3H8S=  FC3H8                                                            *022
            FIC4HS=  FIC4H0                                                           *023
            FNC4HS=  FNC4H0                                                           *024
            KK=0                                                                      *025
            KKK=0                                                                     *026
            KKKK= 0                                                                   *027
            IINV1= 1.E36                                                              *028
            CY1= 1.E36                                                                *029
            III=0                                                                     *030
            THROUGH S14, FOR VALUES OF OD= OD11, OD12, OD13                           *031
            WHENEVER  OD .E. 0.,   TRANSFER TO  S14                                   *032            01
            PRINT COMMENT $0       NEW DIAMETER OF PIPE$                              *033            01
            PRINT RESULTS OD                                                          *034            01
            III=III+1                                                                 *035            01
            WHENEVER OD .E. OD12                                                      *036            01
            QBI= QB12                                                                 *037      01    01
            QBF1= QBF12                                                               *038      01    01
            NOSI= NOS12                                                               *039      01    01
            END OF CONDITIONAL                                                        *040      01    01
            WHENEVER OD .E. OD13                                                      *041            01
            QBI= QB13                                                                 *042      01    01
            QBF1= QBF13                                                               *043      01    01
            NOSI= NOS13                                                               *044      01    01
            END OF CONDITIONAL                                                        *045      01    01
            JJJ= 0                                                                    *046            01
            THROUGH  S1, FORVALUES OF S= SR1, SR2, SR3, SR4, SR5, SR6                 *047            01
            ST4 =S                                                                    *048            02
            WHENEVER S.E. 0., TRANSFER TO   S1                                        *049            02
            PRINT COMMENT $0   NEW STRENGTH OF STEEL$                                 *050            02
            PRINT RESULTS  S                                                          *051            02
```

TABLE B-1 (Continued)

```
          KK= 0                                                              02
          KKK= 0                                                             02
          KKKK= 0                                                            02
          JJJ= JJJ+1                                                         02
Q01       Q= 0                                                               02
          THROUGH S3, FOR QB= QBI, DQB, QB.G. QBF1                           02
          PRINT COMMENT  $0        NEW FLOW RATE AND COMPOSITION $           03
          QBS= QB                                                            03
          Q= Q+1                                                             03
          WHENEVER   Q.E. 1, TRANSFER TO QBFLW                               03
          WHENEVER  NOSI.L. 4                                                03
          NOSI= 4                                                        01  03
          TRANSFER TO  QBFLW                                             01  03
          END OF CONDITIONAL                                             01  03
          NOSI=  NOSTA(Q-1)                                                  03
QBFLW     QBFL(Q)= QB                                                        03
          WHENEVER  QB.G. QBMX                                               03
          NOSI=  NST1                                                    01  03
          DQB=  DQB2                                                     01  03
          END OF CONDITIONAL                                             01  03
          WHENEVER  QB.G. QBMX2                                              03
          NOSI=  NST2                                                    01  03
          DQB=  DQB4                                                     01  03
          END OF CONDITIONAL                                             01  03
          BU= 0                                                              03
          THROUGH S3, FOR BUT= BUTI, DBUT, BUT.G. BUTF                       03
          BU= BU+1                                                           04
          I=0                                                                04
          THROUGH S3, FOR PROP= PROPI, DPROP, PROP.G. PRCPF                  04
          I= I+1                                                             05

         NEW GAS FLOW RATE AND COMPOSITION OF MIXTURE

          WHENEVER COMPSW .E. 1, TRANSFER TO S11                             05
          QB= QBS                                                            05
          FCH4= FCH4S                                                        05
          FC2H6= FC2H6S                                                      05
          FC3H8= FC3H8S                                                      05
          FIC4HO= FIC4HS                                                     05
          FNC4HO= FNC4HS                                                     05
          PRPFD= PROP* 5.61*PRPRHO*62.4* 379.* 14.7/(44.09* 14.73)           05
          IBUTFD= 0.3* BUT* IBUTRH* 379.* 14.7*62.4*5.61/(58.12*14.73)       05
          NBUTFD= 0.7* BUT* NBUTRH* 379.* 14.7*62.4*5.61/(58.12*14.73)       05
          QBF= QB+ PRPFD + IBUTFD+ NBUTFD                                    05
          FCH4= FCH4* QB/ QBF                                                05
          FC2H6= FC2H6* QB/ QBF                                              05
          FC3H8=(FC3H8  * QB+ PRPFD   )/ QBF                                 05
          FIC4HO =  IBUTFD/QBF                                               05
          FNC4HO= NBUTFD /QBF                                                05
          QB= QBF                                                            05
S11       QBF= QB                                                            05
          NATGAS= FX                                                         05
          PRINT RESULTS NATGAS,       FC3H8,FIC4HO, FNC4HO, QBF              05
          PRINT RESULTS FCH4, FC2H6, FNC5H2, FNC6H4, FNC7H6, FN2             05

         CALCULATION OF PSEUDO CRITICAL TEMPERATURE, PRESSURE
         AND MOLECULAR WEIGHT

          PSUM=  FX*PX+ FY*PY + FZ*PZ                                        05
          TSUM=  FX*TX+ FY*TY + FZ*TZ                                        05
```

TABLE B-1 (Continued)

```
           MSUM=  FX*MX+ FY*MY + FZ*MZ                                          *105          05
           TC= TSUM+ FN2*TN2+ FCO2* TCO2+  FCH4* TCH4+ FC2H6* TC2H6+            *106          05
         1 FC3H8* TC3H8+ FIC4HO*TIC4HO+ FNC4HO* TNC4HO+ FIC5H2*TIC5H2          *106
         2 + FNC5H2* TNC5H2+ FNC6H4* TNC6H4                                    *106
           PC= PSUM+ FN2*PN2+ FCO2* PCO2+  FCH4* PCH4+ FC2H6* PC2H6+            *107          05
         1 FC3H8* PC3H8+ FIC4HO*PIC4HO+ FNC4HO* PNC4HO+ FIC5H2*PIC5H2          *107
         2 + FNC5H2* PNC5H2+ FNC6H4* PNC6H4                                    *107
           MWT=MSUM+ FN2*MN2+ FCO2* MCO2+  FCH4* MCH4+ FC2H6* MC2H6+           *108          05
         1 FC3H8*MC3H8+ FIC4HO*MIC4HO+FNC4HO*MNC4HO+FIC5H2*MIC5H2              *108
         2 +FNC5H2*MNC5H2+FNC6H4*MNC6H4                                        *108
           TC= TC+ FNC7H6* TNC7H6                                               *109          05
           PC= PC+ FNC7H6* PNC7H6                                               *110          05
           MWT= MWT + FNC7H6*  MNC7H6                                           *111          05
           G=MWT/29.                                                            *112          05
           PRINT RESULTSQB,TC,PC,G,MWT                                          *113          05
           WHENEVER MWT.L.MMWT, TRANSFER TO GO                                  *114          05
           WHENEVER TF.E.500.                                                   *115          05
           PMIN=TAB.(MWT,MW(1),VP(1),1,1,2,MF,SW)                               *116     01   05
           END OF CONDITIONAL                                                   *117     01   05
           WHENEVER TF.E.520.                                                   *118          05
           PMIN=TAB.(MWT,MW(1),VP1(1),1,1,2,MF,SW)                              *119     01   05
           END OF CONDITIONAL                                                   *120     01   05
           WHENEVER SW.E.2., PRINT COMMENT $0 UNSUCCESSFUL INTERPOLATION$       *121          05
GO         FGR=SQRT.(0.6/G)                                                     *122          05
           FTF=SQRT.(520./TF)                                                   *123          05
           K= TAB.(MWT, MWT1(1), KCP(1), 1, 1, 2, 12, SW)                       *124          05
           WHENEVER  SW.E. 2., PRINT COMMENT $0    INTERPOLATION UNSUCESSFUL$   *125          05
           J=0                                                                  *126          05
           CR= CRI                                                              *127          05
           CR4= CR                                                              *128          05
           CR3= CR                                                              *129          05
           J=J+1                                                                *130          05
           II=0                                                                 *131          05
           THROUGH  S12,FOR VALUES OF P1= (PMIN+100.)*CR                        *132          05
           II=II+1                                                              *133          06
           P22= P1/CR                                                           *134          06
           THROUGH  S10, FOR  NOS= NOSI, DNOS, NOS.G. NOSF                      *135          06
LLT        PRINT COMMENT $0  NEW N. O. S.     $                                 *136          07
           NO= 0                                                                *137          07
           L=  LT/ NOS                                                          *138          07
PP2        P2=P1/CR                                                             *139          07
           NO= NO+1                                                             *140          07
           THK=P1*OD/(2.*F*E*S)                                                 *141          07
           D= OD- 2.*THK                                                        *142          07
           FD= C.P. 2.5                                                         *143          07
           WHENEVER P2 .L. PMIN+90.,  TRANSFER TO S12                           *144          07
           PAVG=2.*(P1+P2-P1*P2/(P1+P2))/3.                                     *145          07
           TR= TF/TC                                                            *146          07
           PR= PAVG/PC                                                          *147          07
           WHENEVER  TR .L.  1.1                                                *148          07
ZRTE       THROUGH BETA, FOR CP=1, 1, CP.G. 7                                   *149     01   07
           WHENEVER  FCH4  .L.  COM1(CP)                                        *150     01   08
           VOL1= TAB.(PAVG, PP(1), VFM(CP-1,1 ),1,1,2, MP, SW)                  *151     02   08
           VOL2= TAB.(PAVG, PP(1), VFM(CP  ,1 ),1,1,2, MP, SW)                  *152     02   08
           WHENEVER SW .E. 2., PRINT COMMENT $0   INTERPOLATION UNSUCCESSFUL$   *153     02   08
           TRANSFER TO  OUT                                                     *154     02   08
           END OF CONDITIONAL                                                   *155     02   08
BETA       CONTINUE                                                             *156     01   08
OUT        VOL= VOL1+  (VOL2- VOL1)*(FCH4 - COM1(CP-1) )/(COM1(CP)              *157     01   07
         1   -COM1(CP-1))                                                       *157
```

TABLE B-1 (Continued)

```
        Z1= VOL* PAVG/( 10.73* TF)                                          *158   01   07
        PRINT RESULTS  VOL, VOL1, VOL2  ,Z1                                 *159   01   07
        THROUGH GAMA, FOR CP=1, 1, CP.G. 7                                  *160   01   07
        WHENEVER  FCH4  .L.  COM1(CP)                                       *161   01   08
        VOL3= TAB.(PAVG, PP(1),VFM1(CP-1,1 ),1,1,2, MP, SW)                 *162   02   08
        VOL4= TAB.(PAVG, PP(1),VFM1(CP  ,1 ),1,1,2, MP, SW)                 *163   02   08
        WHENEVER SW .E. 2., PRINT COMMENT $C   INTERPOLATICN UNSUCCESSFUL$  *164   02   08
        TRANSFER TO  OUT1                                                   *165   02   08
        END CF CONDITIONAL                                                  *166   02   08
GAMA    CONTINUE                                                            *167   01   08
CUT1    VOL5=VOL3+  (VOL4- VOL3)*(FCH4 - COM1(CP-1) )/(CCM1(CP)             *168   01   07
      1   -COM1(CP-1))                                                      *168
        Z2= VOL5*PAVG/( 10.73* TF)                                          *169   01   07
        PRINT RESULTS  VOL5, VOL3, VOL4, Z2                                 *170   01   07
        Z= (Z2-Z1)* (TF-500.)/(560.-500.)  + Z1                             *171   01   07
        PRINT RESULTS   Z                                                   *172   01   07
        WHENEVER ZSW .E. 1, TRANSFER TO  AHP.                               *173   01   07
        TRANSFER TO  FPVS                                                   *174   01   07
        END OF CONDITIONAL                                                  *175   01   07
        ZFAC.(TF,PAVG,TC,PC,G,Z)                                            *176        07
FPVS    FPV=SQRT.(1./Z)                                                     *177        07
        THROUGH TEES,FORT=1,1,T.G.TG                                        *178        07
        WHENEVER TR.GE. V1(T)                                               *179        08
        T= T-1                                                              *180   01   08
        VISKM1= TAB.(PR,PRD(1),V(T,1),1,1,1,NP,SW)                          *181   01   08
        VISKM2= TAB.(PR,PRD(1), V(T+1,1),1,1,1,NP,SW)                       *182   01   08
        VISKM=((V1(T)-TR)/(V1(T)-V1(T+1)))*(VISKM2-VISKM1)+VISKM1           *183   01   08
        KI=TAB.(MWT,MT(1),KS(1),1,1,2,MF,SW)                                *184   01   08
        WHENEVER SW.E.2., PRINT COMMENT $4 UNSUCCESSFUL INTERPOLATION       *185   01   08
      1 $                                                                   *185
        WHENEVER  TR.L. 1., KI= 1.                                          *186   01   08
        MU= KI*SQRT.(MWT)*VISKM*6.7197E-8                                   *187   01   08
        TRANSFER TO XP                                                      *188   01   08
        END OF CONDITIONAL                                                  *189   01   08
TEES    CONTINUE                                                            *190        08
XP      FTB=0                                                               *191        07
        FNGFRI.(FTB,D,EE,QB,G,MU,FT)                                        *192        07
K67     K6=  77.5*FGR*FTF*FPV*FT*FF*FFE*FD                                  *193        07
        P1=  SQRT. (P2*P2+ QB*QB*L/(K6*K6))                                 *194        07
        CR= P1/P2                                                           *195        07
        PRINT RESULTS P1, P2, K6, CR4                                       *196        07
        WHENEVER  .ABS. (CR4-CR)/CR .G. .01                                 *197        07
        WHENEVER NO.G. 6    .OR.  CR.G. CRMAX                               *198   01   07
        NOS= NOS+1                                                          *199   02   07
        L= LT/NOS                                                           *200   02   07
        WHENEVER  L.L. 20., TRANSFER TO S3                                  *201   02   07
        CR= CRI                                                             *202   02   07
        CR4= CR                                                             *203   02   07
        P2= P22                                                             *204   02   07
        P1= P2*CR                                                           *205   02   07
        TRANSFER TO LLT                                                     *206   02   07
        END OF CONDITIONAL                                                  *207   02   07
        WHENEVER CR-CR4 .G. 3.           .OR. NO.G. 10, TRANSFER TO S9      *208   01   07
        CR4= CR                                                             *209   01   07
        TRANSFER TO  PP2                                                    *210   01   07
        END OF CONDITIONAL                                                  *211   01   07
        THK= P1* OD/ (2.* F*E* S)                                           *212        07
        D=  OD- 2.*THK                                                      *213        07
        FD= 'D.P. 2.5                                                       *214        07
        DELTP=   SQRT.((P1*P1- P2*P2)/L)                                    *215        07
```

TABLE B-1 (Continued)

```
               QB3=  77.5* FGR* FTF* FPV* FT* FF* FFE* FD* DELTP             *216        07
               QB= QB3                                                       *217        07

              CALCULATION OF HORSEPOWER OF COMPRESSOR

               CRPW= (K-1.)/K                                                *218        07
               P20=  P2                                                      *219        07
               WHENEVER  TR .L. 1.1                                          *22         07
               ZSW =1                                                        *221    01  07
               PAVG= P2                                                      *222    01  07
               TRANSFER TO   ZRTE                                            *223    01  07
               END OF CONDITIONAL                                            *224    01  07
               ZFAC.  (TF, P2  , TC, PC, G, Z)                               *225        07
AHP            A=(.0854*K*TF*Z*(CR.P.CRPW-1.)/(EFF*(K-1)) )*14.73/14.65      *226        07
               ZSW =0                                                        *227        07
               P2= P20)                                                      *228        07
               PRINT RESULTS CR,A,Z,      K, NOS, L, LT, PAVG                *229        07

              COSTS

YWT            YW=28.2*(D+THK)*THK*Y(JJJ)                                    *230        07
               CMMOP=0.                                                      *231        07
               CMMAM=0.                                                      *232        07
               IINVL= 0.                                                     *233        07
               IINVS= 0.                                                     *234        07
               THROUGH S7, FOR NOST=1,1,NOST.G.NOS                           *235        07
               CMMOP1=((365.*24.*FHPHR*CF+CLMS)*A*FOOP/(L*365.)              *236        08
             1 +(LG*GASCST*1E3/LT+CLML*1.E6/(QB*365.))                       *236
             1 )*10.+AD/3650.                                                *236
               CMMAM1=(((YW+N*OD+H)*B*1.E6/QB+ALPHA*(X+X1*1.E6/(A*           *237        08
             1 QB))*A/L)*FOOP/365.)*10.                                      *237
               IINVL1=                                                       *238        08
             1       (YW+N*OD+H)/(QB/1.E7)                                   *238
               IINVS1=                                                       *239        08
             1       (X+X1*1.E6/(A*QB))*10.*A/L                              *239
               LSG=(24.*FHPHR*A*QB*1.E-3+(LG*QB)/NOS)                        *240        08
               QB=QB-LSG                                                     *241        08
               CMMOP=CMMOP+CMMOP1                                            *242        08
               CMMAM=CMMAM+ CMMAM1                                           *243        08
               IINVS= IINVS+ IINVS1                                          *244        08
               IINVL= IINVL+ IINVL1                                          *245        08
S7             CONTINUE                                                      *246        08
               CMMOP=CMMOP/NOS                                               *247        07
               CMMAM=CMMAM/NOS                                               *248        07
               CY=CMMOP+CMMAM                                                *249        07
               IINVS= IINVS/NOS                                              *250        07
               IINVL= IINVL/NOS                                              *251        07
               IINV=IINVL+IINVS                                              *252        07
               PRINT RESULTS P1, PAVG, CR, S, OD, D, QB, QB3                 *253        07
               PRINT RESULTS IINVL,IINVS,CMMOP,CMMAM                         *254        07
               PRINT RESULTS IINV,CY,THK,YW                                  *255        07
               TINV=IINV *QB3*1.E-7*LT                                       *256        07
               TOPCST=CY*QB3*1.E-7*LT                                        *257        07
               PRINT RESULTS  TOPCST, TINV, A, Z                             *258        07
               PRINT RESULTS  P2, TR, PR, FT                                 *259        07
               KK=KK+1                                                       *260        07
               NOSS(KK)= NOS                                                 *261        07
               CYN(KK)= CY                                                   *262        07
               WHENEVER KK.E.1                                               *263        07
               CY1=CY                                                        *264    01  07
```

TABLE B-1 (Continued)

```
NOSTA(Q)=  NOS                                              *265    01   07
TRANSFER TO INN                                             *266    01   07
END OF CUNDITIONAL                                          *267    01   07
WHENEVER CY1.GE.CY                                          *268         07
IINV1=IINV                                                  *269    01   07
CY1=CY                                                      *270    01   07
CY3(Q)=  CY1                                                *271    01   07
PROP2=PROP                                                  *272    01   07
CR2=CR                                                      *273    01   07
P12=P1                                                      *274    01   07
NOS2=NOS                                                    *275    01   07
BUT2=BUT                                                    *276    01   07
OD4=OD                                                      *277    01   07
D2=D                                                        *278    01   07
ST2=S                                                       *279    01   07
QB4= QB                                                     *280    01   07
QBF4=  QB3                                                  *281    01   07
TINV2 = TINV                                                *282    01   07
TPCST2= TOPCST                                              *283    01   07
WHENEVER NOS.E. NOSF, TRANSFER TO MNOS                      *284    01   07
WHENEVER  KK.E. 1, TRANSFER TO  S1C                         *285    01   07
OTHERWISE                                                   *286    01   07
WHENEVER KK.L. NN,TRANSFER TO S1C                           *287    01   07
PRINT COMMENT $0  MINIMUM COST AT THE END OF N. C. S.  $    *288    01   07
PRINT RESULTS  QB4, QBF4  , FNC4HO, FIC4HO                  *289    01   07
PRINT RESULTS NATGAS, FC3H8, CR2, P12, NOS2, ST2, OD4, D2   *290    01   07
PRINT RESULTS FCH4, FC2H6, FNC5H2, FNC6H4, FNC7H6, FN2      *291    01   07
PRINT RESULTS  IINV1, CY1, TPCST2, TINV2                    *292    01   07
PRINT COMMENT  $1     PLOT OF TRANSPORTATION COST VS NOS$   *293    01   07
PRINT RESULTS  OD, S, P2,  QBF4                             *294    01   07
SETPLT.(1, NOSS(1), CYN(1 ), KK, $*$, 33, LABEL)            *295    01   07
PRINT COMMENT $0               NUMBER OF STATICNS$          *296    01   07
KKK= KKK+1                                                  *297    01   07
WHENEVER  KKK .E. 1                                         *298    01   07
IINV6= IINV1                                                *299    02   07
CY6= CY1                                                    *300    02   07
CY61(Q)= CY3(Q)                                             *301    02   07
PROP6= PROP2                                                *302    02   07
CR6= CR2                                                    *303    02   07
P16= P12                                                    *304    02   07
NOS6=        NOS2                                           *305    02   07
BUT6= BUT2                                                  *306    02   07
OD6= OD4                                                    *307    02   07
D6=  D2                                                     *308    02   07
ST6= ST2                                                    *309    02   07
QB6=  QB4                                                   *310    02   07
QBF6=  QB3                                                  *311    02   07
TINV6=  TINV2                                               *312    02   07
TPCST6=  TPCST2                                             *313    02   07
KK= 0                                                       *314    02   07
TRANSFER TO  S12                                            *315    02   07
END CF CONDITIONAL                                          *316    02   07
WHENEVER  CY6 .GE. CY1                                      *317    01   07
TRANSFER TO  MMN2                                           *318    02   07
OTHERWISE                                                   *319    02   07
KK= 0                                                       *320    02   07
CY61(Q)= CY3(Q)                                             *321    02   07
TRANSFER TO  S9                                             *322    02   07
END OF CONDITIONAL                                          *323    02   07
END OF CONDITIONAL                                          *324    01   07
```

TABLE B-1 (Continued)

```
 S10      QB= QBFL(Q)                                                   *325       07
 S12      QB = QBFL(Q)                                                  *326       06
 KM       KKKK= KKKK+1                                                  *327       05
          KK= 0                                                         *328       05
          QB= QBFL(Q)                                                   *329       05
          WHENEVER KKKK.E. 1                                            *330       05
          CY8= CY6                                                      *331    01 05
          TRANSFER TO  S3                                               *332    01 05
          END OF CONDITIONAL                                            *333    01 05
          WHENEVER CY6.G. CY8                                           *334       05
          TRANSFER TO S9                                                *335    01 05
          OTHERWISE                                                     *336    01 05
          CY8= CY6                                                      *337    01 05
          END OF CONDITIONAL                                            *338    01 05
S3        CONTINUE                                                      *339       05
 S9       CONTINUE                                                      *340       02
          WHENEVER  Q. L. FFF                                           *341       02
          QBI= QBI-DQB                                                  *342    01 02
          TRANSFER TO  Q01                                              *343    01 02
          END OF CONDITIONAL                                            *344    01 02
          PRINT COMMENT $6 MINIMUM INITIAL INVESTMENT(CENTS/100 MILES/M *345       02
        1 INVESTMENT(DOLLARS)  $                                        *345
          PRINT COMMENT $0 TOTAL OPERATING COST(DOLLARS/DAY) AND TOTAL  *346       02
        1 CF/DAY) AND TRANSPORTATION COST(CENTS/100 MILES/MCF) $        *346
          PRINT RESULTS  QB6, QBF6 , FNC4H0, FIC4H0                     *347       02
          PRINT RESULTS NATGAS, FC3H8, CR6, P16, NOS6, ST6, OD6, D6     *348       02
          PRINT RESULTS FCH4, FC2H6, FNC5H2, FNC6H4, FNC7H6, FN2        *349       02
          PRINT RESULTS  IINV6, CY6, TPCST6, TINV6                      *350       02
          WHENEVER Q.L. 3, TRANSFER TO S2                               *351       02
          PRINT COMMENT $1  PLOT OF TRANSPORTATION COST VS FLOW FLOW RA *352       02
        1 TE     $                                                      *352
          PRINT RESULTS  OD, S, P2                                      *353       02
          SETPLT.(1, QBFL(1), CY61(1),Q, $*$, 33, LABEL)                *354       02
          PRINT COMMENT $0                  FLOW RATE, CUBIC FEET/DAY$  *355       02
S2        CONTINUE                                                      *356       02
          ZERO.(QB6, QBF6, CR6, P16, NOS6, ST6, OD6, D6, IINV6,         *357       02
        1  CY6, TPCST6, TINV6  )                                        *357
          KK= 0                                                         *358       02
          KKK= 0                                                        *359       02
          KKKK= 0                                                       *360       02
          CR= CR3+ DCR                                                  *361       02
S1        CONTINUE                                                      *362       02
          S=ST4                                                         *363       01
 S14      CONTINUE                                                      *364       01
          VECTOR VALUES LABEL =$  TR. COST(CENTS/100 MILES/MCF)  $      *365
          TRANSFER TO START                                             *366
          END OF PROGRAM                                                *367
```

TAB 1/20/62

SINGLE TABLE INTERPOLATION

PURPOSE GIVEN THE VALUE OF AN INDEPENDENT ARGUMENT X, PERFORM A KTH ORDER INTERPOLATION ON A TABLE OF (X(I),Y(I)) VALUES FOR THE CORRESPONDING DEPENDENT ARGUMENT Y.

CALLING SEQUENCES

```
     MAD        Y = TAB.(X,XT,YT,M1,M2,K,N,SW)
     FORTRAN    Y = TAB(X,XT,YT,M1,M2,K,N,SW)
     UMAP       CALL     TAB
                PAR      X
                PAR      XT
                PAR      YT
                PAR      M1
                PAR      M2
                PAR      K
                PAR      N
                PAR      SW
                NORMAL RETURN - Y IN THE ACCUMULATOR
```

ARGUMENTS

- X INDEPENDENT FLOATING POINT ARGUMENT X FOR WHICH THE CORRESPONDING VALUE Y IS DESIRED.
- XT NAME OF THE FIRST ENTRY IN THE TABLE OF FLOATING POINT INDEPENDENT VARIABLES, X(I).
- YT NAME OF THE FIRST ENTRY IN THE TABLE OF FLOATING POINT DEPENDENT VARIABLES, Y(I).
- M1 INTEGRAL NUMBER OF STORAGE LOCATION STEPS BETWEEN EACH ENTRY OF THE INDEPENDENT VARIABLE TABLE. NORMALLY M1 = 1 WHEN THE VARIABLES ARE STORED IN SEQUENTIAL LOCATIONS.
- M2 INTEGRAL NUMBER OF LOCATIONS BETWEEN EACH ENTRY OF THE DEPENDENT VARIABLE TABLE. NORMALLY M2 = 1.
- K INTEGRAL ORDER OF INTERPOLATION DESIRED, K .LE. 5.
- N INTEGRAL NUMBER OF ENTRIES IN THE INDEPENDENT VARIABLE TABLE (NUMBER OF PAIRS (X(I),Y(I))).
- SW FLOATING POINT COMPUTATION SWITCH
  - SW = 1.0 NORMAL RETURN, INTERPOLATION SUCCESSFUL.
  - SW = 2.0 AC OR MQ OVERFLOW OR UNDERFLOW OR DIVIDE CHECK - - ERROR RETURN.
- Y FLOATING POINT DEPENDENT VARIABLE, THE INTERPOLATED VALUE FOR THE INDEPENDENT VARIABLE X.

CODING INFORMATION

STORAGE REQUIRED

```
   TAB         307
   ERASABLE     22
```

SETPLT
USTPLT
1/20/62

SET UP FOR PLOT SUBROUTINE
(IT MAKES PLOT PAINLESS)

PURPOSE -- THIS SUBROUTINE IS DESIGNED TO BE USED WITH THE PLOT SUBROUTINE (WHICH IS ON LIBRARY TAPE). THE PLOT SUBROUTINE PRODUCES GRAPHS OF THE QUANTITIES GIVEN IT BY THE USER. (FOR A DETAILED EXPLANATION,SEE THE PLOT WRITEUP) IT IS A POWERFUL AND VERSATILE TOOL, BUT IS, AS A RESULT, RATHER COMPLICATED AND CLUMSY TO USE. IT REQUIRES THAT THE USER MAKE 4 ENTRIES TO THE SUBROUTINE WITH A TOTAL OF 16 ARGUMENTS, AND IN ORDER TO DETERMINE THE VALUES FOR THESE ARGUMENTS (SUCH AS THE NUMBER OF HORIZONTAL LINES, NUMBER OF SPACES BETWEEN HORIZONTAL LINES, ETC.) THE USER MUST DO CONSIDERABLE PRECALCULATION. THE USER MUST ALSO KNOW THE RANGE OF ANSWERS IN ADVANCE SO HE CAN SET THE MAXIMUM AND MINIMUM VALUES FOR THE ABSCISSA AND FOR THE ORDINATE. THIS IS ALL WORK THAT CAN BE DONE BY THE COMPUTER, AND SETPLT IS A SUBROUTINE THAT DOES IT.

FEATURES -- SETPLT INSPECTS THE DATA TO BE PLOTTED, CALCULATES THE ARGUMENTS, AND THEN EXECUTES PLOT SUCH THAT - -

1. ALL POINTS TO BE PLOTTED LIE IN THE RANGE OF THE GRAPH.
2. GRIDWORK IS SQUARE.
3. NUMERIC LABELS ON ABSCISSA AND ORDINATE GRID LINES ARE ''NICE'' VALUES.
4. GRAPH IS APPROXIMATELY SQUARE.
5. IF THE POINTS TO BE PLOTTED HAVE ABSCISSA AND/OR ORDINATE VALUES WHOSE MAGNITUDE IS GREATER THAN 10.P.7, THE NUMERIC LABELS TO THE GRID LINES ARE MODIFIED BY A SCALE FACTOR, AND A HEADING IS PRINTED OUT INFORMING THE USER OF THE SIZE OF THE SCALE FACTOR.
6. IF THE SIZE OF THE GRAPH IS INDETERMINATE IN EITHER THE Y(VERTICAL) AND/OR THE X(HORIZONTAL) DIRECTION (IE. A HORIZONTAL OR VERTICAL LINE, OR A POINT), AN APPROPRIATE COMMENT IS PRINTED OUT AND THE MAXIMUM AND MINIMUM VALUES OF THE APPROPRIATE AXES ARE ADJUSTED SO THAT THE VALUES MAY BE GRAPHED.

RESTRICTIONS-- ALL POINTS (X,Y) WHICH ARE TO BE PLOTTED MUST BE OBTAINED AND STORED IN TABLES BEFORE EXECUTING SETPLT.

CALLING SEQUENCES -- THERE ARE TWO CALLING SEQUENCES AVAILABLE, A REGULAR AND AN ALTERNATE ONE.

REGULAR CALLING SEQUENCE -- USER EXECUTES ONLY SETPLT (OR USTPLT). USER DOES NOT EXECUTE PLOT.

```
MAD-      EXECUTE SETPLT.(L,XLOC,YLOC,NUM,BCD,NCHAR,LABEL)
FORTRAN-  CALL SETPLT(L,XLOC,YLOC,NUM,BCD,NCHAR,NHABCD...)
UMAP-     CALL    USTPLT
          PAR     L
           .       .
           .       .
           .       .
          PAR     LABEL

          OR ANY EQUIVALENT UMAP SUBROUTINE CALL
```

```
     ALTERNATE CALLING SEQUENCE -- THIS IS FOR USERS WHO WANT TO USE ''OMIT'' TO
     CHANGE THE GRAPH BEFORE IT IS PRINTED, WHO WANT TO PRINT MORE THAN ONE COPY
     OF THE GRAPH, WHO WANT TO USE DIFFERENT PLOTTING CHARACTERS FOR DIFFERENT
     PARTS OF THE DATA, OR, IN GENERAL, WHO WANT TO TAKE ADVANTAGE OF SOME OF
     THE SPECIAL FEATURES OF PLOT ( FOR DETAILS ON THESE SPECIAL FEATURES, SEE
     THE PLOT WRITEUP)  WHEN USING THIS ALTERNATE CALLING SEQUENCE, USER
     EXECUTES SETPLT, AND THEN MUST EXECUTE PLOT3 AND PLOT4 (OR FPLOT4) HIMSELF.

          MAD-     EXECUTE SETPLT.(L,XLOC,YLOC,NUM)
          FORTRAN- CALL SETPLT(L,XLOC,YLOC,NUM)
          UMAP-    (FOR THIS ALTERNATE CALLING SEQUENCE EITHER THE NAME SETPLT
                   OR USTPLT MAY BE USED)
                   CALL     USTPLT,L,XLOC,YLOC,NUM
                   OR EQUIVALENT SUBROUTINE CALL

ARGUMENTS --
     L      =NONZERO IF MAX GRAPH LENGTH IS TO BE ONE PAGE
            =ZERO OTHERWISE. (IN THIS CASE , LENGTH .LE. 2 PAGES)
     XLOC   =LOCATION OF FIRST VALUE OF X OR POINTS (X,Y) TO BE PLOTTED
             (IN TABLE OF X VALUES)
     YLOC   =LOCATION OF FIRST VALUE OF Y OF POINTS (X,Y) TO BE PLOTTED
             (IN TABLE OF Y VALUES)
             (THESE TWO TABLES MUST BE STORED BACKWARDS IN STORAGE, AS MAD AND
             FORTRAN DO.  THE VALUES OF X AND Y STORED IN THESE MUST BE FLOATING'
             POINT VALUES)
     NUM    =NUMBER OF POINTS TO BE PLOTTED (EITHER MAD,UMAP,OR FORTRAN INTEGER)
     BCD    =LEFT-ADJUSTED BCD(HOLLERITH) PLOTTING CHARACTER.
     NCHAR  =NUMBER OF BCD CHARACTERS (INCLUDING BLANKS) IN THE LABEL ARRAY.
     LABEL  =NAME OF ARRAY CONTAINING THE STRING OF BCD CHARACTERS TO BE PRINTED
             AT LEFT EDGE OF OUTPUT PAGE (LABEL FOR ORDINATE).  MUST BE STORED
             BACKWARD WHEN USING MAD (USING VECTOR VALUES STATEMENT), OR
             FORWARD WHEN USING UMAP (USING BCD OR BCI BLOCK).
             MUST BE STORED 6 CHARACTERS TO THE WORD (C6).
     NHABCD... FOR FORTRAN USERS, THE STRING OF CHARACTERS FOR THE ORDINATE
             LABEL APPEARS DIRECTLY IN THE CALLING SEQUENCE. THE N PRECEEDING THE
             H (SPECIFYING THE HOLLERITH STRING) SHOULD BE THE SAME AS THE VALUE
             OF NCHAR.

EXAMPLES--  SEE NEXT PAGE

CODING INFORMATION--
     STORAGE USED                              SUBROUTINES USED
          SETPLT     701                            .PRINT
          ERASABLE  1750,IF L=NONZERO               PLOT1
                    4064,IF L=ZERO                  PLOT2
                     (FIRST 25 LOCATIONS            PLOT3
                     OF ERASABLE ARE                PLOT4
                     NOT USED)                      FPLOT4
                                                    ELOG
     STORAGE REQUIRED                               .01301
          SETPLT     701
          ERASABLE  4064
```

SAMPLE PROBLEM
THIS PROBLEM IS THE FIRST EXAMPLE PROBLEM AT THE END OF THE PLOT WRITEUP, REWRITTEN TO USE SETPLT. IT IS SUGGESTED THAT THE READER COMPARE THEM. BOTH MAD AND FORTRAN VERSIONS ARE GIVEN.

```
$COMPILE MAD, PUNCH OBJECT                                        PLMAD000
          R
          R PROGRAM TO ILLUSTRATE PLOTTING MULTIPLE POINTS WITH MAD
          R
           DIMENSION X(100), Y(100)
           INTEGER N
FIRST      READ FORMAT ENTR, N
           READ FORMAT DATA, X(1)...X(N)
           READ FORMAT DATA, Y(1)...Y(N)
           PRINT FORMAT TITLE
           EXECUTE SETPLT.(1,X(1),Y(1),N,$*$,32,ORD)
           PRINT FORMAT ABS
           TRANSFER TO FIRST
          R
          R FORMAT STATEMENTS
          R
           VECTOR VALUES ENTR = $I10*$
           VECTOR VALUES DATA =$7F10.4*$
           VECTOR VALUES TITLE =$1H1,S54,15HPLOT OF X VS Y   /1H *$
           VECTOR VALUES ABS = $1H0,S55,14HTHE ABSCISSA X *$
           VECTOR VALUES ORD =$                     THE ORDINATE Y $
           END OF PROGRAM
$DATA
```

```
$COMPILE FORTRAN, PRINT OBJECT, PUNCH OBJECT                      PLFTR000
C
C     PROGRAM TO ILLUSTRATE PLOTTING MULTIPLE POINTS WITH FORTRAN
C
      DIMENSION X(100),Y(100)
    1 READ INPUT TAPE 7,100, N
      READ INPUT TAPE 7,101,(X(I), I=1,N)
      READ INPUT TAPE 7,101,(Y(I), I=1,N)
      WRITE OUTPUT TAPE 6,102
      CALL SETPLT(1,X(1),Y(1),N,1H*,32,32H                  THE ORDINATE
     X Y )
      WRITE OUTPUT TAPE 6,103
      GO TO 1
C
C     FORMAT STATEMENTS
C
  100 FORMAT (I10)
  101 FORMAT (7F10.9)
  102 FORMAT (1H1,54(1H ),15HPLOT OF X VS Y   /1H )
  103 FORMAT (1H0,55(1H ),14HTHE ABSCISSA X )
$ DATA
```

TABLE B-1 (Concluded)

ZERO - SPRAY

STORE CONSTANT

```
PURPOSE   ZERO    STORES ZERO
          SPRAY   STORES ARBITRARY CONSTANT.

CALLING SEQUENCES
     MAD        EXECUTE ZERO.(L1,L2,.....,LN)
     UMAP       CALL    ZERO
                L1
                L2
                .
                .
                .
                LN

ARGUMENTS
     THE  LI  ARE STANDARD ARGUMENT LIST ELEMENTS OF THE FORM
          MAD A...D OR A
          UMAP  BLK     A,,D    OR    PAR     A
     SPRAY IS CALLED EXACTLY AS ZERO EXCEPT THAT THE FIRST ARGUMENT
     IS A SINGLE CONSTANT (IN MAD) OR THE LOCATION OF A SINGLE CONSTANT
     (IN UMAP) WHICH IS TO BE STORED INSTEAD OF ZERO.

PROGRAMMING INFORMATION
     LOCATIONS REQUIRED
        ZERO - SPRAY      34
        ERASABLE           0
```

TABLE B-2

NOMENCLATURE FOR COMPUTER PROGRAM AND FORMULATIONS

Symbol	Designation	Units
AD	Administration expenses	\$/mile/year/MMcf/day
ALPHA (α)	Fixed charges on compression, fraction	none
A	Brake horsepower	hp/MMcf/day at 60°F and 14.73 psia
B	Fixed charges on pipe, fraction of investment	none
BU	Counter for butane addition	none
BUT2	Butane condensate at minimum cost for each flow rate	bbl/day
BUT6	Butane condensate at minimum cost for the line	bbl/day
BUTF	Final value of butane condensate	bbl/day
BUTI	Initial value of butane condensate	bbl/day
BUT	Butane condensate	bbl/day
CF	Fuel Cost	\$/Mcf at 60°F and 14.73 psia
CLML	Cost of labor and maintenance for line	\$/mile/yr
CLMS	Cost of labor and maintenance for stations	\$/hp/yr
CMMAM	Average amortization costs of pipeline	cents/100 miles/Mcf
CMMAM1	Amortization cost at each station	cents/100 miles/Mcf
CMMOP	Average operating costs of pipeline	cents/100 miles/Mcf
CMMOP1	Operating cost at each station	cents/100 miles/Mcf
COM1	Fraction methane (used when the TR is less than 1.1 for methane-propane system)	none
COMPSW	Switch for either having program determine the composition of the mixture ("off" i.e. = 0) or when the composition is already specified ("on" i.e. = 1)	none
CP	Used as counter for COM1	none
CR	Compression ratio, P_1/P_2	none
CR2	Compression ratio corresponding to minimum yearly transportation cost for certain flow rate	none
CR3	Storage for initial value of compression ratio	none

TABLE B-2 (Continued)

Symbol	Designation	Units
CR4	Storage for initial value of compression ratio	none
CR6	Compression ratio corresponding to minimum yearly transportation cost for certain diameter of pipe	none
CRI	Initial falue for compression ratio	none
CRMAX	Maximum value for compression ratio	none
CRPW	(K-1)/K	none
CY	Total transportation cost	cents/100 miles/Mcf
CY1	Minimum yearly transportation cost for certain flow rate	cents/100 miles/Mcf
CY3	Minimum yearly transportation cost for certain flow rate	cents/100 miles/Mcf
CY61	Minimum yearly transportation cost for certain diameter of pipe	cents/100 miles/Mcf
CY6	Minimum yearly transportation cost for certain diameter of pipe	cents/100 miles/Mcf
CY8	Storage for CY6	cents/100 miles/Mcf
CYN	Total transportation cost—used for plotting CY vs. NOS	cents/100 miles/Mcf
D2	Inside diameter of the pipe corresponding to minimum transportation cost for certain flow rate	in.
D6	Inside diameter of the pipe corresponding to minimum transportation cost for certain diameter of the pipe	in.
DBUT	Increment to butane condensate	bbl/day
DCR	Increment in compression ratio	none
DELTP	$\sqrt{P_1^2 - P_2^2/L}$	--
D	Inside diameter of pipe	in.
DNOS	Increment to number of stations	none
DPROP	Increment to propane addition	bbl/day
DQB2	Increment to flow rate when it exceeds QBMX	ft^3/day
DQB4	Increment to flow rate when it exceeds QBMX2	ft^3/day
DQB	Increment to flow rate	ft^3/day
EE	Pipe roughness	in.
EFF	Efficiency of compressor stations	none
E	Longitudinal joint factor	none
FC2H6	Mole fraction C_2H_6	none
FC2H6S	Storage for FC_2H_6	none

TABLE B-2 (Continued)

Symbol	Designation	Units
FC3H8	Mole fraction C_3H_8	none
FC3H8S	Storage for FC_3H8	none
FCH4	Mole fraction CH_4	none
FCH4S	Storage for FCH_4	none
FCO2	Mole fraction CO_2	none
FD	Line diameter factor	in.$^{2.5}$
FFE	Flow efficiency factor	none
FF	Drag factor	none
FFF	Number for processing minimum number of flow rates for one diameter of pipe. Ordinarily FFF = 1	none
FGR	Gas gravity factor	none
FHPHR	Fuel use	Mcf/hp hr
FIC4HO	Mole fraction IC_4H_{10}	none
FIC4HS	Storage for $FICH_4$	none
FIC5H2	Mole fraction IC_5H_{12}	none
FM	Moody friction factor	none
FN2	Mole fraction N_2	none
FNC4HO	Mole fraction nC_4H_{10}	none
FNC4HS	Storage for $FNCH_4$	none
FNC5H2	Mole fraction nC_5H_{12}	none
FNC6H4	Mole fraction nC_6H_{14}	none
FNC7H6	Fraction normal heptane	none
FOOP	Fraction of year in operation	none
FPV	Supercompressibility factor	none
F	Pipeline design factor (average = 0.72)	none
FTB	Switch for fully turbulent (1) and transition zone (0). Set FTB = 1 when fully turbulent and FTB = 0 when otherwise	none
FTF	Flowing temperature factor	none
FT	Transmission factor	none
FX	Mole fraction unknown component X, e.g., natural gas	none
FY	Mole fraction unknown component Y, e.g., natural gas	none

TABLE B-2 (Continued)

Symbol	Designation	Units
FZ	Mole fraction unknown component Z, e.g., natural gas	none
GASCST	Cost of gas	\$/Mcf at 14.73 psia and 60°F
G	Gas gravity	none
H	Communication cost	\$/mile
IBUTFD	Isobutane condensate (gas added)	ft^3/day
IBUTRH	Density of isobutane (liquid)	g/cc
III	Counter for outside diameter	none
I	Counter for compositions	none
IINV1	Minimum initial investment at each station	cents/100 miles/Mcf/day
IINV6	Minimum average initial investment of pipeline corresponding to certain diameter of line	cents/100 miles/Mcf/day
IINVL	Average initial investment for the pipeline	cents/100 miles/Mcf/day
IINVL1	Initial investment for the pipeline	cents/100 miles/Mcf/day
IINVS	Initial investment for stations	cents/100 miles/Mcf/day
IINVS1	Initial investment for stations	cents/100 miles/Mcf/day
IINV	Total initial investment for line and stations	cents/100 miles/Mcf/day
II	Counter for various maximum pressures in the pipe (P_1)	none
JJJ	Counter for stresses in pipe	none
J	Counter for compression ratio	none
K6	77.5 x FGR x FTF x FPV x FT x FF x FFE x FD	none
K	Ratio of heat capacity at constant pressure to constant volume	none
KCP	Used for correlation of ratio of specific heats (C_p/C_v) as a function of molecular weight	none
KI	Correction factor to viscosity as a function of molecular weight	none
KKKK	Counter used for keeping track of flow rate and the minimum transportation cost	none
KKK	Counter used for keeping track of flow rate	none
KK	Counter for keeping track of NOS	none
KS	Used as KI for correlation of KI as a function of molecular weight	none
LG	Loss of gas in pipeline, fraction	none

TABLE B-2 (Continued)

Symbol	Designation	Units
L	Length between compression stations	miles
LT	Total length of pipeline	miles
MC2H6	Molecular weight C_2H_6	lb/lb mole
MC3H8	Molecular weight C_3H_8	lb/lb mole
MCH4	Molecular weight CH_4	lb/lb mole
MCO2	Molecular weight CO_2	lb/lb mole
MF	Number of points used in correlation of KI as a function of molecular weight	none
MIC4HO	Molecular weight iC_4H_{10}	lb/lb mole
MIC5H2	Molecular weight iC_5H_{12}	lb/lb mole
MMWT	For molecular weight comparison. If PMIN is known set MMWT greater than predicted molecular weight of the mixture, e.g., say 40. If PMIN is to be determined at 40° or 60°F from correlation of PMIN as a function of molecular weight, set PMIN = 0	lb/lb mole
MN2	Molecular weight N_2	lb/lb mole
MNC4HO	Molecular weight NC_4H_{10}	lb/lb mole
MNC5H2	Molecular weight NC_5H_{12}	lb/lb mole
MNC6H4	Molecular weight NC_6H_{14}	lb/lb mole
MNC7H6	Molecular weight of normal heptane	lb/lb mole
MP	Number of points used in correlation of volume as a function of pressure for determining Z	none
MSUM	Sum of molecular weight for X,Y,Z	--
MT	Used as molecular weight array in correlation of KI as a function of molecular weight	lb/lb mole
MU	Viscosity of gas	lb/ft sec
MW	Used as molecular weight array in correlation of equilibrium pressure as a function of molecular weight	lb/lb mole
MWT	Molecular weight of mixture	lb/lb mole
MWT1	Used as molecular weight array in correlation of $K(C_p/C_v)$ as a function of molecular weight	lb/lb mole

TABLE B-2 (Continued)

Symbol	Designation	Units
MX	Molecular weight of X	lb/lb mole
MY	Molecular weight of Y	lb/lb mole
MZ	Molecular weight of Z	lb/lb mole
NATGAS	Fraction of natural gas	none
NBUTFD	Normal butane condensate (gas added)	ft^3/day
NBUTRH	Density of normal butane (liquid)	g/cc
NN	The minimum number for which the number of stations will be processed irrespective of where the minimum cost lies. For example see case of natural gas at 65,000 psi and 16 in. pipeline	none
NO	Counter for number of trials involved in checking of compression ratio	none
NOS12	Number of stations to start computation when OD = OD12	none
NOS13	Number of stations to start computation when OD = OD13	none
NOS	Number of stations	none
NOSI	Initial value for number of stations	none
NOSF	Final value for number of stations	none
NOS2	Number of stations for minimum yearly transportation cost for certain flow rate	none
NOS6	Number of stations corresponding to minimum transportation cost for certain diameter of the line	none
NOSS	Array (NOS) used for plot of cost as a function of number of stations	none
NOSTA	Storage for starting number of stations	none
NOST	Used for iteration of number of stations	none
N	Pipe laying cost as function of diameter	$/in. diam/mile
NP	Number of points used for correlation of viscosity as a function of reduced pressure and temperature	none
NST1	Number of stations when flow rate is greater than QBMX	none
NST2	Number of stations when flow rate is greater than QBMX2	none
OD	Outside diameter of pipe	in.
OD11	First value in the iteration loop of the outside diameter of the pipe	in.

TABLE B-2 (Continued)

Symbol	Designation	Units
OD12	Second value in the iteration loop of the outside diameter of the pipe	in.
OD13	Third value in the iteration loop of the outside diameter of the pipe	in.
OD4	Outside diameter of the pipe giving minimum transportation cost for certain flow rate	in.
OD6	Outside diameter of the pipe giving minimum transportation cost for certain diameter of the line	in.
P12	Maximum line pressure corresponding to minimum yearly transportation cost at certain flow rate	psia
P16	Maximum pressure in the pipeline corresponding to minimum transportation cost for certain diameter of the line	psia
P20	Pressure at end of line section (minimum)—minimum pressure in the pipeline	psia
P22	Pressure at end of line section (minimum)	psia
P1	Maximum line pressure	psia
P2	Pressure at end of line section (minimum)	psia
PAVG	Average flowing pressure	psia
PC2H6	Critical pressure for C_2H_6	psia
PC3H8	Critical pressure for C_3H_8	psia
PCH4	Critical pressure for CH_4	psia
PCO2	Critical pressure for CO_2	psia
PIC4HO	Critical pressure for iC_4H_{10}	psia
PMIN	Maximum point on bubble or dew point curve for a mixture in the temperature range of interest	psia
PNC4HO	Critical pressure for nC_4H_{10}	psia
PIC5H2	Critical pressure for iC_5H_{12}	psia
PNC5H2	Critical pressure for nC_5H_{12}	psia
PNC6H4	Critical pressure for iC_6H_{14}	psia
PNC7H6	Critical pressure for normal heptane	psia
PN2	Critical pressure for N_2	psia
PP	Array corresponding to pressure in correlation of volume as a function of pressure	psia

TABLE B-2 (Continued)

Symbol	Designation	Units
PRD	Array corresponding to reduced pressure in correlation of viscosity as a function of reduced pressure	none
PC	Critical pressure of mixture	psia
PROP	Quantity of propane added	bbl/day
PROPI	Initial value to quantity of propane	bbl/day
PROPF	Final value to quantity of propane added	bbl/day
PROP2	Quantity of added propane giving minimum yearly transportation cost	bbl/day
PROP6	Quantity of propane added corresponding to the minimum transportation cost	bbl/day
PRPFD	Quantity of propane added (gas)	ft^3/day
PRPRHO	Density of propane (liquid)	g/cc
PR	Reduced pressure	none
PSUM	Sum of critical pressures corresponding to constituents X,Y,Z	psia
PX	Critical pressure for X	psia
PY	Critical pressure for Y	psia
PZ	Critical pressure for Z	psia
Q	Counter for variation of flow rate	none
QB	Gas flow rate for natural gas at the entrance	ft^3/day at 14.73 and 60°F
QB12	Starting flow rate for OD12 (second diameter)	ft^3/day
QB13	Starting flow rate for OD13 (third diameter)	ft^3/day
QB3	The flow rate for which the cost has been computed	ft^3/day
QB4	Minimum cost corresponding to certain flow rate	ft^3/day
QB6	Minimum cost corresponding to certain diameter of the line	ft^3/day
QBF	Total gas flow rate after propane or butane addition. Whenever there is no addition QB = QBF	ft^3/day at 14.73 and 60°F
QBF12	Final flow rate corresponding to OD12 (second diameter of the pipe)	ft^3/day
QBF13	Final flow rate corresponding to OD13 (third flow rate)	ft^3/day
QBF1	Final flow rate	ft^3/day
QBF6	Flow rate corresponding to the minimum transportation cost	ft^3/day

TABLE B-2 (Continued)

Symbol	Designation	Units
QBFL	Array used for plotting minimum transportation cost (CY61) as a function of flow rate	ft^3/day
QBI	Starting flow rate	ft^3/day
QBMX	Flow rate at which the starting value for the number of stations can be changed (variable name NST1)	ft^3/day
QBMX2	Flow rate at which the starting value for the number of stations can be changed (variable name NST2). QBMX2 should be higher than QBMX.	ft^3/day
QBS	Storage for QB (flow rate)	ft^3/day
SR1	First strength of steel	psi
SR2	Second strength of steel. Set at zero when only one strength of steel is to be processed.	psi
SR3	Third strength of steel. Set at zero when only one strength of steel is to be processed.	psi
SR4	Fourth strength of steel. Set at zero when only one strength of steel is to be processed.	psi
SR5	Fifth strength of steel. Set at zero when only one strength of steel is to be processed.	psi
SR6	Sixth strength of steel. Set at zero when only one strength of steel is to be processed.	psi
ST4	Strength of steel corresponding to the minimum transportation cost for a certain flow rate	psi
ST6	Strength of steel corresponding to the minimum transportation cost for certain diameter of the line	psi
SW	Switch for interpolation. SW = 1, correct interpolation. SW = 2, incorrect interpolation.	psi
S	Stress in pipe	psia
ST2	Stress in pipe corresponding to minimum yearly transportation cost	psia
TC	Critical temperature of mixture	°R or °K
TF	Flowing temperature of mixture	°R or °K
TN2	Critical temperature of N_2	°R or °K
TCH4	Critical temperature of methane	°R or °K

TABLE B-2 (Continued)

Symbol	Designation	Units
TG	Number of reduced temperatures for which the viscosity correlation is available (Figs. 11 and 12)	°R or °K
TC02	Critical temperature of CO_2	°R or °K
TC2H6	Critical temperature of C_2H_6	°R or °K
TC3H8	Critical temperature of C_3H_8	°R or °K
TIC4HO	Critical temperature of iC_4H_{10}	°R or °K
TINV2	Minimum total investment corresponding to certain flow rate	cents/100 miles/Mcf/day
TINV6	Minimum total investment corresponding to certain diameter of the line	cents/100 miles/Mcf/day
TINV	Total investment. Sum of initial investments due to line and stations	cents/100 miles/Mcf/day
TN2	Critical temperature of nitrogen	°R
TNC4HO	Critical temperature of nC_4H_{10}	°R or °K
TIC5H2	Critical temperature of iC_5H_{12}	°R or °K
TNC5H2	Critical temperature of nC_5H_{12}	°R or °K
TNC7H6	Critical temperature of normal heptane	°R
TOPCST	Total transportation cost for operation	$/day
TPCST2	Total transportation cost for operation corresponding to certain flow rate	$/day
TPCST6	Total transportation cost for operation corresponding to certain diameter of the line	$/day
TR	Reduced temperature	°R
T	Counter corresponding to reduced temperatures for viscosity correlation (Figs. 11 and 12)	none
TNC6H4	Critical temperature of nC_6H_{14}	°R or °K
TX	Critical temperature of X	°R or °K
TY	Critical temperature of Y	°R or °K
TX	Critical temperature of Z	°R or °K
TSUM	Sum of critical temperature corresponding to X,Y,Z above	°R or °K
THK	Thickness of pipe	in.

TABLE B-2 (Concluded)

Symbol	Designation	Units
V1	Array corresponding to reduced temperature in the correlation of viscosity as a function of molecular weight, TR, and TP (Figs. 11 and 12)	--
VFM1	Array corresponding to volume as a function of pressure used for multiple interpolation for a temperature of 100°F	--
VFM	Array corresponding to volume as a function of pressure used for multiple interpolation for a temperature of 40°F	--
VISKM1	Viscosity/(KI x $\sqrt{\text{molecular weight}}$) used for multiple interpolation	--
VISKM2	Viscosity/(KI x $\sqrt{\text{molecular weight}}$) used for multiple interpolation	--
VISKM	Viscosity/(KI x $\sqrt{\text{molecular weight}}$) used for multiple interpolation	--
VOL1	Volume used for multiple interpolation	ft^3
VOL2	Volume used for multiple interpolation	ft^3
VOL3	Volume used for multiple interpolation	ft^3
VOL4	Volume used for multiple interpolation	ft^3
VOL5	Volume used for multiple interpolation	ft^3
VOL	Volume used for multiple interpolation	ft^3
VP	Array used for maximum point on the dew point, bubble point curve at 40°F (pressure as a function of molecular weight)	psia
VP1	Array used for maximum point on the dew point, bubble point curve at 60°F (pressure as a function of molecular weight)	psia
V	Array corresponding to viscosity as a function of molecular weight, reduced temperature, and pressure	psia
X	Cost of compressor horsepower	$/hp
X1	Fixed cost of compressor horsepower	$/hp
Y	Cost of pipe	$/ton
YW	Cost of pipe	$/mile
Z	Compressibility factor	none
Z1	Compressibility factor at 40°F for TR less than 1.1 and corresponding to methane-propane system	none
Z2	Compressibility factor at 100°F for TR less than 1.1 and corresponding to methane-propane system	none
ZSW	Switch used for skipping over computation of viscosity and trial and error calculation for the compression ratio	none

TABLE B-3

PRINT-OUT OF DATA AND COMPUTED RESULTS OF SAMPLE PROBLEM

(80% natural gas, 20% propane at 1560 psia minimum pressure, 100,000 psi steel, 24 in. dia line, 600 million cu ft/day flow rate)

```
PIPELINE CALCULATIONS

KCP(1)=  1.06, 1.08, 1.1, 1.12, 1.14, 1.16, 1.18, 1.2, 1.22, 1.24,

 1.26, 1.28

MWT1(1)= 78.4, 60.3, 49.3, 41.7, 36.2, 31.8, 28.3, 25.2, 22.7

 20.5, 18.5, 16.7

 MP= 17

PP(1)=  200., 400., 600., 800., 1000., 1250., 1500., 1750., 2000.,

2250., 2500., 2750., 3000., 3500., 4000., 4500., 5000.

          VFM(1)=  8.37, 2.23, 1.287, 1.262, 1.26, 1.212, 1.241,

 1.238, 1.227, 1.217, 1.213, 1.206,1.198, 1.184, 1.174, 1.164, 1.154,

13.06, 5.26, 1.917, 1.25, 1.251, 1.208, 1.219, 1.213, 1.201, 1.192,

 1.182, 1.173, 1.153, 1.142, 1.125, 1.111, 1.096,

 17.77, 5.63, 2.963, 1.809, 1.266, 1.236, 1.215, 1.2, 1.185,

 1.174, 1.162, 1.153, 1.142, 1.125, 1.111, 1.096, 1.084,

22.42, 7.32, 4.,  2.577, 1.74, 1.289, 1.234, 1.203, 1.185, 1.167,

 1.15, 1.139, 1.123, 1.1, 1.083, 1.068, 1.054,

24.14, 9.02, 5.04, 3.34, 2.341, 1.559, 1.317, 1.258, 1.222, 1.186,

 1.162, 1.142, 1.12, 1.091, 1.067, 1.046, 1.029,

 24.40, 10.71, 6.23, 4.11, 2.941, 2.02, 1.525, 1.402, 1.311, 1.252,

 1.205, 1.167, 1.138, 1.045, 1.06, 1.033, 1.01,
```

TABLE B-3 (Continued)

```
24.75, 11.71, 7.11, 4.87, 3.54, 2.49, 1.868, 1.632, 1.459

1.353, 1.27, 1.214, 1.173, 1.109, 1.062, 1.027, 0.9974

VFM1(1)=  24.86, 7.26, 3.5,  1.465, 1.442, 1.414, 1.389, 1.366,

1.353, 1.338, 1.325, 1.313, 1.303, 1.283, 1.266, 1.25, 1.236,

25.8, 9.2,  4.59, 2.5, 1.482, 1.431, 1.399, 1.364, 1.345, 1.326,

1.31, 1.292, 1.279, 1.255, 1.234, 1.217, 1.202,

26.61, 9.75, 5.6, 3.54, 2.42, 1.533, 1.456, 1.401, 1.363, 1.333, 1.307,

1.286, 1.266, 1.235, 1.213, 1.191, 1.173,

27.29, 12.11, 6.45, 4.32, 3.09, 2.21, 1.615, 1.497, 1.424, 1.373,

1.3333, 1.3, 1.273, 1.23, 1.197, 1.17, 1.147,

27.88, 12.81, 7.71, 5.,   3.67, 2.63, 1.946, 1.704, 1.55, 1.453, 1.388,

1.34, 1.301, 1.241, 1.198, 1.162, 1.134,

28.38, 13.33, 8.29, 5.78, 4.28, 3.06, 2.445, 2.033, 1.767, 1.594,

1.494, 1.415, 1.356,  1.268, 1.208, 1.161, 1.125,

28.8, 13.75, 8.73, 6.24, 4.75, 3.6, 2.861, 2.366, 2.039, 1.811,

1.652, 1.531, 1.441, 1.317, 1.234, 1.172, 1.127

COM1(1)= 0.2, .3, .4, .5, .6, .7, .8, .9

         V(1)= 36.9, 38.,39.1,40.,41.1,42.1,43.2,44.1,45.4,46.1,

          32.4,34.1,36.,38.1,40.,42.3,44.8,46.4,48.2,50.,

          29.,31.,33.9,37.,40.8,44.2,48.,51.,54.1,57.,
```

TABLE B-3 (Continued)

```
  26.,29.2,34.,38.3,43.2,47.8,51.8,55.2,59.,62.3,
  24.2,29.,34.1,40.2,46.2,52.,57.,62.,66.3,70.8,
  23.,30.,39.8,48.8,57.2,64.8,72.,79.,85.9,92.,
  23.,34.,48.1,60.6,71.3,80.,87.8,95.1,102.1,108.3,
 26.,42.2,63.,77.8,89.,98.4,108.,116.,124.1,130.3
  52.,78.,95.,101.6,116.,124.,132.,140.,148.,152. ,
 90., 102., 113., 123., 132., 142., 151., 159., 163., 171.,
 115., 126., 139., 149., 156., 163., 172., 180., 186., 192.,
 135., 147., 158., 168., 178., 186., 195., 202., 210., 215.,
 160., 170., 181., 192., 202., 212., 222., 231., 240., 248.,
 186., 200., 210., 219., 228., 238., 247., 256., 265., 273.,
 222., 233., 246., 256., 265., 273., 282., 290., 300., 305.,
 265., 278., 290., 300., 310, 320., 330., 340., 350., 360.
MW(1)= 22.74,28.1, 33.38
VP1(1)= 1400., 1340., 1050.
MF= 3        , TG= 16
            V1(1)= 3., 2.5, 2., 1.7, 1.5, 1.3, 1.2, 1.1, 1. ,
            .95, .90, .85, .75, .7, .65
            MT(1)=15., 18., 21., 24., 27., 30., 33., 35.
            KS(1)= 1.3, 1.205,1.14, 1.08, 1.04, 1.008, 1.004, 1.
```

TABLE B-3 (Continued)

```
PRD(1)= 1., 2., 3., 4., 5., 6., 7., 8., 9., 10.

NP=10

TN2= 226.9, TCO2= 277.9, TCH4 = 343.3, TC2H6 = 549.8, TC3H8 = 666.

TIC4HO = 734.7, TNC4HO = 765.3, TIC5H2 = 829.8, TNC5H2= 845.6

TNC6H4 = 914.1

PN2= 492. , PCO2= 730. , PCH4 = 673.1, PC2H6 = 708.3, PC3H8 = 617.4

PIC4HO = 529.1, PNC4HO = 550.7, PIC5H2 = 483. , PNC5H2= 489.5

PNC6H4 = 439.7

MN2= 28.02, MCO2= 32. , MCH4 = 16.04, MC2H6 = 30.07, MC3H8 = 44.09

MIC4HO = 58.12, MNC4HO = 58.12, MIC5H2 = 72.15, MNC5H2= 72.15

MNC6H4 = 84.16

SR1= 65.E3,SR2=1.E5, SR3= 0., SR4= 0., SR5= 0., SR6= 0.

Y(1)= 228., 254., 265., 384., 467., 535.

 Y (1)= 254., 384., 0., 0., 0., 0.

FF= .936, FFE= 1.,          F= .72, E= 1.0 ,     EFF= 0.8

      X= 165., N=1200., H= 3000., ALPHA= .15, CF= 0.2, CLML= 850.

CLMS=19., LG= 0.005, B= 0.15,            FHPHR= 8.7E-3, FCCP=1.

PRPRHO= 0.51, IBUTRH= 0.563, NBUTRH= 0.583, BUTI= 0., DBLT= 1.E4

 BUTF= 0., EE= 250.E-6

GASCOST= 0.20 , X1=2.7E5  , AD= 1.
```

TABLE B-3 (Continued)

```
          LT= 1000.

NOSI= 6, DNOS= 1,  NOSF=  25

 CRI= 1.4 ,  DCR= .1

 TF= 520.,  COMPSW=1

PROPI= 0.  , DPROP=2E4, PROPF= 0.

         QBI=3.0E8, DQB=0.5E8, QBFI= 6.E8

QBI= 1.5E8, QB12= 4.0E8,QB13= 5.0E8

NOSI= 7 ,  NOS12=    6, NOS13= 6

 QBF12= 1.6E9,   QBF13=  1.7 E9

PMIN= 600. ,  MMWT= 30.

 OD11= 16., OD12= 24., OD13= 30.

 CRMAX=  1.65,    NN=   5,

CRI= 1.2

SR1= 65.E3,

SR2= 1.E5   , Y(2)= 384.

TNC7H6=972.36  , PNC7H6= 397.71  ,    MNC7H6=  100.2

 MMWT= 30.

NOSF= 35

  NOS12=  10,  NOS13=  14

FF= .936    , FFF= 3
```

TABLE B-3 (Continued)

```
QBMX=  5.E9  , QBMX2=  5.E9

DQB2=    2.E8,    DQB4=  3.E8

 DQB2= 1.E8,  DQB4=   2.E8

   SR1=  65.E3, Y(1)= 265., SR2= 1.E5, Y(2)= 384.

SR1=  1.E5,  Y(1)=  384.

FFF= 1 , NN= 5

SR2= 0.

 DQB2= 1.E8,  DQB4=   2.E8

FX= 0.8, MX= 17.387, TX=  361.05, PX= 673.58, FC3H8=  0.2

 PMIN=  1460.

OD11= 24., OD12=0. , OD13= 0.

NOSI= 18

  QBI= 6.0E8,  DQB=1.0E8,    QBF1=   6.0E8    *  End of Input Data Print-out
--------------------------------------------------------------------------------
NEW DIAMETER OF PIPE                                Start Of Output Print-out
        OD =      24.000000
NEW STRENGTH OF STEEL
           S =  1.000000E 05
 NEW FLOW RATE AND COMPOSITION
    NATGAS =       .800000,        FC3H8 =       .200000,        FIC4HO =       .000000,       FNC4HC =       .000000
       QBF =  6.000000E 08
      FCH4 =       .000000,        FC2H6 =       .000000,        FNC5H2 =       .000000,       FNC6H4 =       .000000
    FNC7H6 =       .000000,          FN2 =       .000000
        QB =  6.000000E 08,           TC =    422.039993,            PC =    662.343987,            G =       .783710
       MWT =      22.727600
```

TABLE B-3 (Continued)

NEW N. O. S.

P1 =	1826.218842,	P2 =	1559.999985,	K6 =	4.710186E 06,	CR4 =	1.200000
P1 =	1825.626022,	P2 =	1559.999985,	K6 =	4.715852E 06,	CR4 =	1.170653
CR =	1.170273,	A =	5.260765,	Z =	.591005,	K =	1.219763
NOS =	18,	L =	55.555555,	LT =	1000.000000,	PAVG =	1696.597672
P1 =	1825.626022,	PAVG =	1696.597672,	CR =	1.170273,	S =	1.000000E 05
OD =	24.000000,	D =	23.391458,	QB =	5.853216E 08,	QB3 =	6.000127E 08
IINVL =	1852.817642,	IINVS =	238.198824,	CMMOP =	.138381,	CMMAM =	.859322
IINV =	2091.016449,	CY =	.997703,	THK =	.304271,	YW =	7.807482E 04
TOPCST =	5.986341E 04,	TINV =	1.254636E 08,	A =	5.260765,	Z =	.591005
P2 =	1559.999985,	TR =	1.232111,	PR =	2.561505,	FT =	21.451289

NEW N. O. S.

P1 =	1812.609360,	P2 =	1559.999985,	K6 =	4.715923E 06,	CR4 =	1.170653
CR =	1.161929,	A =	5.018107,	Z =	.591005,	K =	1.219763
NOS =	19,	L =	52.631579,	LT =	1000.000000,	PAVG =	1696.286377
P1 =	1812.609360,	PAVG =	1696.286377,	CR =	1.161929,	S =	1.000000E 05
OD =	24.000000,	D =	23.395797,	QB =	5.855017E 08,	QB3 =	6.002783E 08
IINVL =	1842.919586,	IINVS =	243.795176,	CMMOP =	.138977,	CMMAM =	.857554
IINV =	2086.714752,	CY =	.996531,	THK =	.302102,	YW =	7.752524E 04
TOPCST =	5.981961E 04,	TINV =	1.252610E 08,	A =	5.018107,	Z =	.591005
P2 =	1559.999985,	TR =	1.232111,	PR =	2.561035,	FT =	21.451382

NEW N. O. S.

P1 =	1800.674896,	P2 =	1559.999985,	K6 =	4.717453E 06,	CR4 =	1.170653
P1 =	1800.544296,	P2 =	1559.999985,	K6 =	4.718825E 06,	CR4 =	1.154279
CR =	1.154195,	A =	4.791913,	Z =	.591005,	K =	1.219763
NOS =	20,	L =	50.000000,	LT =	1000.000000,	PAVG =	1683.210083
P1 =	1800.544296,	PAVG =	1683.210083,	CR =	1.154195,	S =	1.000000E 05
OD =	24.000000,	D =	23.399818,	QB =	5.851730E 08,	QB3 =	6.000028E 08
IINVL =	1835.323303,	IINVS =	249.211349,	CMMOP =	.139462,	CMMAM =	.856658
IINV =	2084.534637,	CY =	.996120,	THK =	.300091,	YW =	7.701575E 04

TABLE B-3 (Continued)

	TOPCST = 5.976749E 04,	TINV = 1.250727E 08,	A = 4.791913,	Z = .591005
	P2 = 1559.999985,	TR = 1.232111,	PR = 2.541293,	FT = 21.455258
NEW N. O. S.				
	P1 = 1789.821671,	P2 = 1559.999985,	K6 = 4.718840E 06,	CR4 = 1.154279
	CR = 1.147322,	A = 4.589842,	Z = .591005,	K = 1.219763
	NOS = 21,	L = 47.619047,	LT = 1000.000000,	PAVG = 1683.141785
	P1 = 1789.821671,	PAVG = 1683.141785,	CR = 1.147322,	S = 1.000000E 05
	OD = 24.000000,	D = 23.403393,	QB = 5.853270E 08,	QB3 = 6.002291E 08
	IINVL = 1827.149841,	IINVS = 254.642143,	CMMOP = .139965,	CMMAM = .855531
	IINV = 2081.791962,	CY = .995496,	THK = .298304,	YW = 7.656288E 04
	TOPCST = 5.975257E 04,	TINV = 1.249552E 08,	A = 4.589842,	Z = .591005
	P2 = 1559.999985,	TR = 1.232111,	PR = 2.541190,	FT = 21.455278
NEW N. O. S.				
	P1 = 1779.913513,	P2 = 1560.000000,	K6 = 4.720047E 06,	CR4 = 1.154279
	P1 = 1779.817871,	P2 = 1560.000000,	K6 = 4.721141E 06,	CR4 = 1.140970
	CR = 1.140909,	A = 4.400415,	Z = .591005,	K = 1.219763
	NOS = 22,	L = 45.454545,	LT = 1000.000000,	PAVG = 1672.370087
	P1 = 1779.817871,	PAVG = 1672.370087,	CR = 1.140909,	S = 1.000000E 05
	OD = 24.000000,	D = 23.406727,	QB = 5.850543E 08,	QB3 = 6.000020E 08
	IINVL = 1820.839523,	IINVS = 259.936623,	CMMOP = .140379,	CMMAM = .855113
	IINV = 2080.776123,	CY = .995493,	THK = .296636,	YW = 7.614030E 04
	TOPCST = 5.972975E 04,	TINV = 1.248470E 08,	A = 4.400415,	Z = .591005
	P2 = 1560.000000,	TR = 1.232111,	PR = 2.524927,	FT = 21.458480
NEW N. O. S.				
	P1 = 1770.827179,	P2 = 1560.000000,	K6 = 4.721152E 06,	CR4 = 1.140970
	CR = 1.135146,	A = 4.229429,	Z = .591005,	K = 1.219763
	NOS = 23,	L = 43.478261,	LT = 1000.000000,	PAVG = 1672.320221
	P1 = 1770.827179,	PAVG = 1672.320221,	CR = 1.135146,	S = 1.000000E 05
	OD = 24.000000,	D = 23.40972[illegible]	QB = 5.851828E 08,	QB3 = 6.001921E 08
	IINVL = 1813.987427,	IINVS = 265.237309,	CMMOP = .140808,	CMMAM = .854476

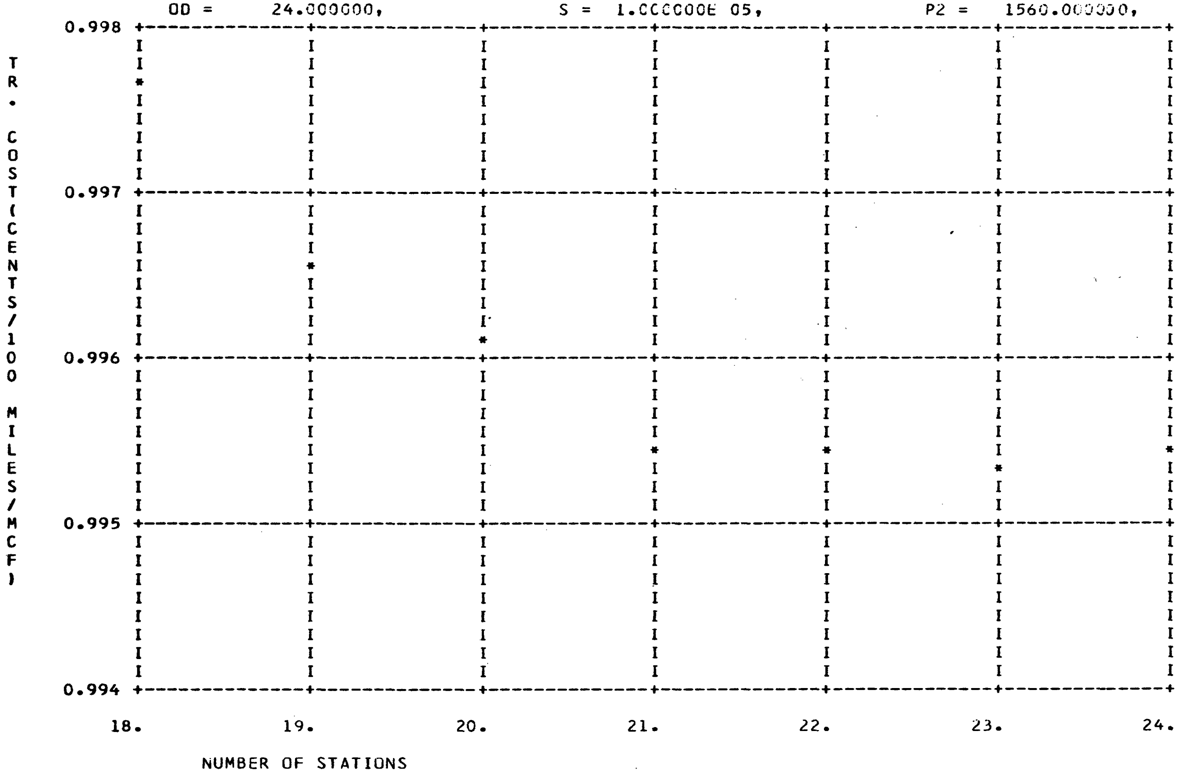
TABLE B-3 (Continued)

```
     IINV =   2079.224731,         CY =        .995284,        THK =        .295138,         YW =  7.576047E 04
   TOPCST =  5.973616E 04,       TINV =  1.247934E 08,          A =       4.229429,          Z =        .591005
       P2 =   1560.000000,         TR =       1.232111,         PR =       2.524852,         FT =      21.458495
NEW N. C. S.
       P1 =   1762.467392,         P2 =    1560.000000,         K6 =  4.722127E 06,        CR4 =       1.140970
       CR =      1.129787,          A =       4.069802,          Z =        .591005,          K =       1.219763
      NOS =            24,          L =      41.666667,         LT =    1000.000000,       PAVG =    1667.637665
       P1 =   1762.467392,       PAVG =    1667.637665,         CR =       1.129787,          S =  1.000000E 05
       OD =     24.000000,          D =      23.412511,         QB =  5.851211E 08,        QB3 =  6.001785E 08
    IINVL =   1808.184784,      IINVS =     270.457474,      CMMOP =        .141185,      CMMAX =        .854237
     IINV =   2078.642242,         CY =        .995422,        THK =        .293745,         YW =  7.540725E 04
   TOPCST =  5.974308E 04,       TINV =  1.247556E 08,          A =       4.069802,          Z =        .591005
       P2 =   1560.000000,         TR =       1.232111,         PR =       2.517782,         FT =      21.459890
MINIMUM COST AT THE END OF N. O. S.
      QB4 =  5.851828E 08,       QBF4 =  6.001921E 08,     FNC4H6 =        .000000,     FIC4H6 =        .000000
   NATGAS =       .800000,       FC3H8 =        .200000,        CR2 =       1.135146,        P12 =    1770.827179
     NOS2 =     23.000000,        ST2 =  1.000000E 05,        OD4 =      24.000000,         O2 =      23.409724
     FCH4 =       .000000,      FC2H6 =        .000000,     FNC5H2 =        .000000,     FNC6H4 =        .000000
   FNC7H6 =       .000000,        FN2 =        .000000
    IINV1 =   2079.224731,        CY1 =        .995284,     TPCST2 =  5.973616E 04,      TINV2 =  1.247934E 08
```

TABLE B-3 (Concluded)

PLCT OF TRANSPORTATION COST VS NOS

OD = 24.000000, S = 1.CCCCOOE 05, P2 = 1560.000000, QBF4 = 6.001921E 08



MINIMUM INITIAL INVESTMENT(CENTS/100 MILES/MINVESTMENT(DOLLARS)

TOTAL OPERATING COST(DOLLARS/DAY) AND TOTAL CF/DAY) AND TRANSPCRTATION COST(CENTS/100 MILES/MCF)

QB6 =	5.851828E 08,	QBF6 =	6.001785E 08,	FNC4H0 =	.000000,	FIC4HC =	.000000
NATGAS =	.800000,	FC3H8 =	.200000,	CR6 =	1.135146,	P16 =	1770.827179
NOS6 =	23.000000,	ST6 =	1.CCCOOOE 05,	OD6 =	24.000000,	D6 =	23.409724
FCH4 =	.CCOOCO,	FC2H6 =	.CCOOCO,	FNC5H2 =	.000000,	FNC6H4 =	.000000
FNC7H6 =	.CCCCCC,	FN2 =	.C00000				
IINV6 =	2079.224731,	CY6 =	.995284,	TPCST6 =	5.973616E 04,	TINV6 =	1.247934E 08

APPENDIX C

EXAMPLE HAND CALCULATION

ILLUSTRATIVE EXAMPLE PROBLEM BY HAND CALCULATION

Problem

Compute the minimum cost of the pipeline system and cost of transporting 600 million cu ft per day of a mixture of 80% natural gas and 20% propane (molal basis) over a distance of 1000 miles at 60°F through 24-in. OD pipe having a strength of 100,000 psi. Select the minimum pressure as 100 psi above the dew point at 60°F. This is the first of a series of calculations to be done on the computer at increasing flow rates to find the minimum cost of some optimum flow rate. The number of compressor stations is a variable in this calculation and will include one more and one less station than the optimum.

Solution

MINIMUM PRESSURE

The minimum pressure for 80% natural gas and 20% propane in the range 40° to 100°F is 1460 psia and therefore the minimum pressure in the pipeline is set at 1560 psia. This information is given in the program as data.

HORSEPOWER AND MAXIMUM LINE PRESSURE

By use of the flow equation (Eq. 12) the pressure drop in the line is computed to obtain the maximum pressure in the line. From the inlet and outlet pressures the horsepower will be computed. The steps solving the flow equation are given.

1. Calculation of Gas Gravity Factor (FGR)

The molecular weight of the gas from Table 1 is 17.4.

$$\text{Molecular Weight} = 0.8 \times 17.4 + 0.2 \times 44.09 = 22.73\ (22.728^*) \qquad \text{(C-1)}$$

*The values in parentheses are those on the computer print-out for this example.

$$\text{Gas gravity, } G = \frac{22.73}{29.0} = 0.784\ (0.7837) \tag{C-2}$$

$$FGR = \sqrt{\frac{0.6}{0.784}} = \underline{\underline{0.874}} \tag{C-3}$$

<u>Temperature flowing factor</u> (<u>FTF</u>)

$$FTF = \sqrt{\frac{TF}{520}} = 1 \tag{C-4}$$

2. Trial and Error Calculations for Compression Ratio

From computer results we know that optimum value for number of stations is 22. So we shall make computations for 21 stations. NOS = 21 (including the one at the entrance).

$$\text{Let assumed compression ratio be } = 1.16 \tag{C-5}$$

$$\text{Maximum pressure in pipeline } P_1 = 1.16 \times 1560 = 1810 \text{ psia} \tag{C-6}$$

3. Length Between Compressor Stations

$$L = \frac{1000}{21} = 47.6\ (47.62) \text{ miles} \tag{C-7}$$

4. Thickness and ID of the Pipe

$$THK = \frac{P_1 x OD}{2xFxExS} = \frac{1810x24}{2x0.72x1x100{,}000} = 0.301 \text{ in.} \tag{C-8}$$

$$D(ID) = 24 - 2 \times 0.301 = 23.398 \text{ in.} \tag{C-9}$$

$$FD = \text{Line diameter factor} = D^{2.5} = 23.398^{2.5} = 2620 \text{ in.}^{2.5} \tag{C-10}$$

5. Average Pressure

$$\text{PAVG} - \frac{2}{3}\left(\text{P1} + \text{P2} - \frac{\text{P1P2}}{\text{P1+P2}}\right)$$

$$= \left(1810 + 1560 - \frac{1810 \text{x} 1560}{1810+1560}\right)$$

$$= \frac{2}{3}(2532) \quad = \quad 1690 \text{ psia} \qquad \text{(C11)}$$

6. Calculation of Compressibility Factor (Z) and FPV

This is calculated by Sarem's method using Lagrange polynomials which fit best the compressibility factor chart. A subroutine ZFAC has been prepared which calculates Z based on TR and PR, the reduced temperature and pressure, respectively.

Pseudo Critical Properties

$$\text{TC} = 0.8 \text{ x } 364.7 + 0.2 \text{ x } 666 = 424°\text{R } (422) \qquad \text{(C-12)}$$

$$\text{PC} = 0.8 \text{ x } 673.6 + 0.2 \text{ x } 617.4 = 662.4 \text{ psia } (662.3) \qquad \text{(C-13)}$$

$$\text{TR} = \frac{520}{424} = 1.23 \ (1.232) \qquad \text{(C-14)}$$

$$\text{PR} = \frac{1810}{662.4} = 2.73 \qquad \text{(C-15)}$$

$$\text{Z} = 0.58 \qquad \text{(C-16)}$$

$$\text{FPV} = \sqrt{\frac{1}{\text{Z}}} = \sqrt{\frac{1}{0.58}} = 1.315 \qquad \text{(C-16a)}$$

7. Calculation of Viscosity (Bicher and Katz Method)

$$\left.\begin{aligned} \text{TR} &= 1.23 \\ \text{PR} &= 2.73 \end{aligned}\right] \text{ Eqs. (C-14), (C-15) above}$$

Molecular weight (MWT) = 22.73

Fig. 11,

$$KI = 1.1 \tag{C-17}$$

and

$$\frac{VISKM}{KIx\sqrt{MWT}} = 5.18 \quad \text{or} \quad VISKM = 51.8 \times 1.1 \times \sqrt{22.73}$$

$$= 272 \text{ micropoises}$$

$$MU = VISKM = 272 \times 6.72 \times 10^{-8}$$

$$= 1.825 \times 10^{-5} \text{ lb/ft sec} \tag{C-18}$$

8. Calculation of Transmission Factor (FT)

$$FT = \frac{2}{\sqrt{FM}} \tag{C-19}$$

where FM = Moody friction factor

$$RE = \frac{D\rho v}{\mu} = 1.3526 \times 10^{-5} \frac{QBxG}{DxMU} \tag{C-20}$$

from Eqs. (C-2), (C-9), and (C-18)

$$= 1.3526 \times 600 \times 10^{6} \times \frac{0.784}{23.4x1.825}$$

$$= 1.49 \times 10^{7} \tag{C-21}$$

$$\frac{2}{\sqrt{FM}} = 4 \log \frac{D}{EE} + 2.28 - 4 \log \left(1 + 9.34 \frac{D/EE}{RE\sqrt{FM}}\right)$$

Let $\frac{2}{\sqrt{FM}} = 21.45$

Is

$$21.45 \equiv 4 \log \frac{23.4}{250\text{x}10^{-6}} + 2.28 - 4 \log \left(1 + 9.34 \frac{\frac{23.4\text{x}21.45}{250\text{x}10^{-6}}}{1.49\text{x}10^{7}\text{x}2}\right)$$

$$= 4 \text{ x } 4.974 + 2.28 - 4 \log (1 + 6.3 \text{ x } 10^{-1})$$

$$= 22.17 - 0.82 = 21.35$$

$$\therefore \frac{2}{\sqrt{FM}} = 21.40 \qquad \text{(C-22)}$$

9. Drag Factor (FF)

It was agreed to use a bend index of 200°/mile, plastic lined pipe (Fig. 13)

$$FF = 0.936 \qquad \text{(C-23)}$$

10. Checking for Assumed Compression Ratio

Let

$$K6 = 77.5 \text{ x } FGR \text{ x } FTF \text{ x } FPV \text{ x } FT \text{ x } FF \text{ x } FFE \text{ x } FD$$

From Eqs. (C-3), (C-4), (C-10), (C-16a), (C-22), (C-23)

$$K6 = 77.5 \text{ x } 0.874 \text{ x } 1 \text{ x } 1.34 \text{ x } 21.4 \text{ x } 0.936 \text{ x } 1 \text{ x } 2620$$

$$K6 = 4.76 \text{ x } 10^{6}$$

$$P1 = \sqrt{P2^2 + \frac{QB^2 xL}{(K6)^2}}$$

$$= \sqrt{1560^2 + (600 \text{ x } 10^6)^2} \text{ x } \frac{47.6}{(4.76\ 10^6)^2}$$

$$= 1790 \ (1790) \text{ psia}$$

$$CR = \frac{P1}{P2} = \frac{1790}{1560} = 1.147$$

Second Trial for Compression Ratio

Therefore let us assume CR as 1.147. Repeating steps 2-10 we have

$$P1 = 1.147 \times 1560 = 1790 \text{ psia}$$

$$THK = \frac{P1xOD}{2xFxExS} = \frac{1790x24}{2x0.72x1x100{,}000} = 0.298 \text{ in. } (0.298)$$

$$D = 24 - 2 \times 0.298 = 23.40 \text{ in. } (23.403)$$

$$FD = 23.403^{2.5} = 26.25 \text{ in.}^{2.5}$$

$$\text{Average pressure} = PAVG = \frac{2}{3}\left(1790 + 1560 - \frac{1790x1560}{1790+1560}\right)$$

$$= 1677 \text{ psia } (1678)$$

$$TR = 1.23\ (1.232)$$

$$PR = \frac{1677}{662.4} = 2.53\ (2.533)$$

$$Z = 0.565$$

$$FPV = \sqrt{\frac{1}{0.565}} = 1.33$$

$$\frac{VISKM}{KI\sqrt{MWT}} = 39.3 \quad \text{or} \quad VISKM = 39.3 \times 1.1 \times \sqrt{22.73}$$

$$= 206 \text{ micropoises}$$

$$MU = 206 \times 6.72 \times 10^{-8} = 1.39 \times 10^{-5} \text{ lb/ft sec}$$

$$RE = \frac{D\rho v}{\mu} = 1.3526 \times 10^{-5}\,\frac{QBxG}{DxMU}$$

$$= 1.3526 \times 10^{-5} \times 600 \times 10^{6} \times \frac{0.784}{23.4x1.39x10^{-5}}$$

$$= 1.96 \times 10^{7}$$

$$\frac{2}{\sqrt{FM}} = 4 \log \frac{D}{EE} + 2.28 - 4 \log \left(1 + 9.34 \frac{D/EE}{RE\sqrt{FM}}\right)$$

Let $\frac{2}{\sqrt{FM}} = 21.45$

$$\frac{2}{\sqrt{FM}} = 4 \log \frac{23.4}{250x10^{-6}} + 2.28 - 4 \log \left(1 + 9.34 \underbrace{\frac{\frac{23.4x21.45}{250x10^{-6}}}{1.96x10^{7}x2}}_{0.48}\right)$$

$$= 4 \times 4.97 + 2.28 - 4 \times 0.17$$

$$= 21.49$$

Verification from Moody Friction Factor Chart

$$EE/D = \frac{250x10^{-6}}{23.4} = 10.7 \times 10^{-6} = 0.0000107$$

$$FM = 0.0086$$

$$\frac{2}{\sqrt{FM}} = \frac{2}{9.22x10^{-1}} = 21.6$$

$$K_6 = 77.5 \times FGR \times FTF \times FPV \times FT \times FF \times FFE \times FD$$

$$= 77.5 \times 0.874 \times 1 \times 1.33 \times 21.46 \times 0.936 \times 1 \times 2625$$

$$= 4.77 \times 10^{6}$$

$$P1 = \sqrt{P2^2 + \frac{QB^2L}{K_6^2}}$$

$$= \sqrt{1560^2 + (600 \times 10^6)^2 \times \frac{47.6}{(4.77x10^6)^2}}$$

$$= 1790 \text{ psia}$$

$$CR = \frac{P1}{P2} = \frac{1790}{1560} = \underline{\underline{1.147}} \text{ which checks}$$

Calculation of Horsepower of Compressor

Using Equation (22) to obtain the horsepower per station

$$A = \frac{0.0854 \times K \times TF \times Z^{*}(CR^{\frac{K-1}{K}} - 1)}{(K-1) \times EFF} \frac{14.73}{14.65}$$

*Z is based on inlet conditions.

$$PR = \frac{1560}{662.4} = 2.353$$

$$TR = 1.232$$

$$Z = 0.575 \ (0.591)$$

$$\text{Molecular weight} = 22.73$$

Using chart in NGSMA, p. 27 (1957) to find K

$$K = \frac{C_p}{C_v} = 1.22 \ (1.22)$$

$$\text{Horsepower } A = \frac{0.0854 \times 1.22 \times 520 \times 0.575 \times \left(1.147^{\frac{1.22-1}{1.22}} - 1\right)}{0.22 \times 0.8} \times \frac{14.73}{14.65}$$

$$= 4.48 \ (4.588) \text{ hp/MMcf/day}$$

Cost of Pipeline and Compression Stations

From Eqn. (A-3) the cost of the pipeline in dollars per mile (YW) is computed

$$YW = 28.2 \times (D + THK) \times THK \times Y$$

$$= 28.2 \times (23.4 + 0.298) \times 0.298 \times 384$$

$$= 7.65 \times 10^4 \ (7.656 \times 10^4) \ \$/\text{mile}$$

The Initial Investment in Pipeline (IINVL)

$$IINVL = (YW + N \times OD + H) \times \frac{10^7}{QB}$$

$$= (7.65 \times 10^4 + 1200 \times 24 + 3000) \times \frac{10^7}{600\text{x}10^6}$$

$$= 1805\ (1827^*)\ \text{cents/100 miles/Mcf/day}$$

Note: *This value takes into account the adjustment in quantity of gas flowing through the pipeline due to fuel consumption at each station. This is the reason for the discrepancy in the two values. This also occurs in the costs stated below.

Initial Investment for Stations (IINVS)

The initial investment for stations in given by Eq. (26)

$$\text{IINVS} = \left(X + \frac{X1\text{x}10^6}{\text{AxQB}}\right) \times \frac{A}{LT} \times NOS \times 10$$

$$= \frac{10(X)(A)(NOS)}{LT} + \frac{(X1)(10^7)\ (NOS)}{(QB)(LT)}$$

$$= \frac{(10)(165)(4.48)(21)}{1000} + \frac{270{,}000 \times 10^7 \times 21}{600 \times 10^6 \times 1000}$$

$$= 155.2 + 94.4 = 249.6\ (254.3)\ \text{cents/100 miles/Mcf/day}$$

Operating Cost (CMMOP)

The operating cost is given by Eq. (28)

$$\text{CMMOP} = ((365 \times 24 \times FHPHR \times CF + CLMS) \times \frac{A \times NOS \times FOOP}{365 \times LT}$$

$$+ LG \times GASCST \times \frac{10^3}{LT} + \frac{CLML \times 10^6}{QB \times 365}\Big) \times 10 + \frac{AD}{3650}$$

$$= ((\overbrace{365 \times 24 \times 8.7 \times 10^{-3} \times 0.20 + 19}^{15.2}) \frac{4.48 \times 21 \times 1}{365 \times 1000}$$

$$+ 0.005 \times 0.20 \times \frac{10^3}{1000} + \frac{850 \times 10^6}{600 \times 10^6 \times 365}\Big) \times 10 + \frac{1}{3650}$$

$$= (35.2 \times 2.58 \times 10^{-4} + 0.001 + 3.88 \times 10^{-3}) \times 10 + \frac{1}{3650}$$

$$= (0.00882 + 0.001 + 0.00388) \times 10 + \frac{1}{3650}{}^{*}$$

$$= 0.1395\ (0.139965)\ \text{cents/100 miles/Mcf.}$$

Amortization Cost

The amortization cost is based on paying 15% of investment per year, Eq. (27).

$$CMMAM = \left(\left(\left(YW + N \times OD + H\right) \times \frac{B \times 10^6}{QB}\right)\right.$$

$$\left. + ALPHA \times \left(X + \frac{X1 \times 10^6}{A \times QB}\right)\left(\frac{A \times NOS}{LT}\right)\right)\frac{(FOOP)}{(365)} \times 10$$

$$= \left(\left(7.65 \times 10^4 + 1200 \times 24 + 3000\right) \frac{(0.15) \times 10^6}{600 \times 10^6}\right.$$

$$\left. + 0.15 \left(165 + \frac{270{,}000 \times 10^6}{4.48 \times 600 \times 10^6}\right)\left(\frac{4.48 \times 21}{1000}\right)\right) \times \frac{1 \times 10}{365}$$

$$= (27.1 + 3.75) \times \frac{10}{365}$$

$$= 0.845\ (0.8555^*)\ \text{cents/100 miles/Mcf}$$

*See note at the end of the Initial Investment on Pipeline.

Fuel Consumption at the Compressor Stations (LSG)

This is needed to obtain the pipe line delivery.

$$LSG = (24 \times FHPHR \times A \times QB \times 10^{-3}) \times NOS + LG \times QB$$

$$= 24 \times 8.7 \times 10^{-3} \times 4.48 \times 600 \times 10^{+6} \times 10^{-3} \times 21 + 0.005 \times 600 \times 10^6$$

$$= (11.75 + 3) \times 10^6 = 14.75 \times 10^6\ ft^3/day$$

*As indicated earlier, this should be AD/36.5. For this example the cost of transporting gas, CY, would be raised about 3% by the correction.

Quantity of gas, at the exit

$= (600 - 14.75) \times 10^6$

$= \underline{585.25 \times 10^6}$ ($\underline{585}.33 \times 10^6$) ft^3/day

CY $=$ CMMAM + CMMOP $= 0.845 + 0.1395 = \underline{\underline{0.9845}}$ (0.9955) cents/100 miles/Mcf

IINV $=$ IINVL + IINVS $= 1805 + 250 = 2075$ cents/100 miles/Mcf

In reviewing the method of finding amortization and operating cost, the full 600 million cu ft of gas are used even though only 585.25 million are sold. The computer program finds costs by using the actual flow in each segment, and therefore is based on an average pipeline delivery somewhere between 600 and 585 million cu ft.

Total Investment (TINV) $=$ IINV x QB x 10^{-7} x LT

$= 2075 \times 600 \times 10^6 \times 10^{-7} \times 1000$

$= 1.245 \times 10^8$ (1.250×10^8) dollars/day

Total Operating Cost (TOPCST) $=$ CY x QB x 10^{-7} x LT

$= 0.9845 \times 600 \times 10^{+6} \times 10^{-7} \times 1000$

$=$ 59,070 (59,730) dollars/day

APPENDIX D

PHASE DIAGRAMS DETERMINED BY KURATA FOR MIXTURES NOT STUDIED IN THIS REPORT

These diagrams, reproduced from the Ph.D. thesis of Fred Kurata at The University of Michigan in 1941, under the direction of Professor Donald L. Katz, represent the experimentally determined phase diagrams. The compositions of the mixtures are listed on the diagrams.

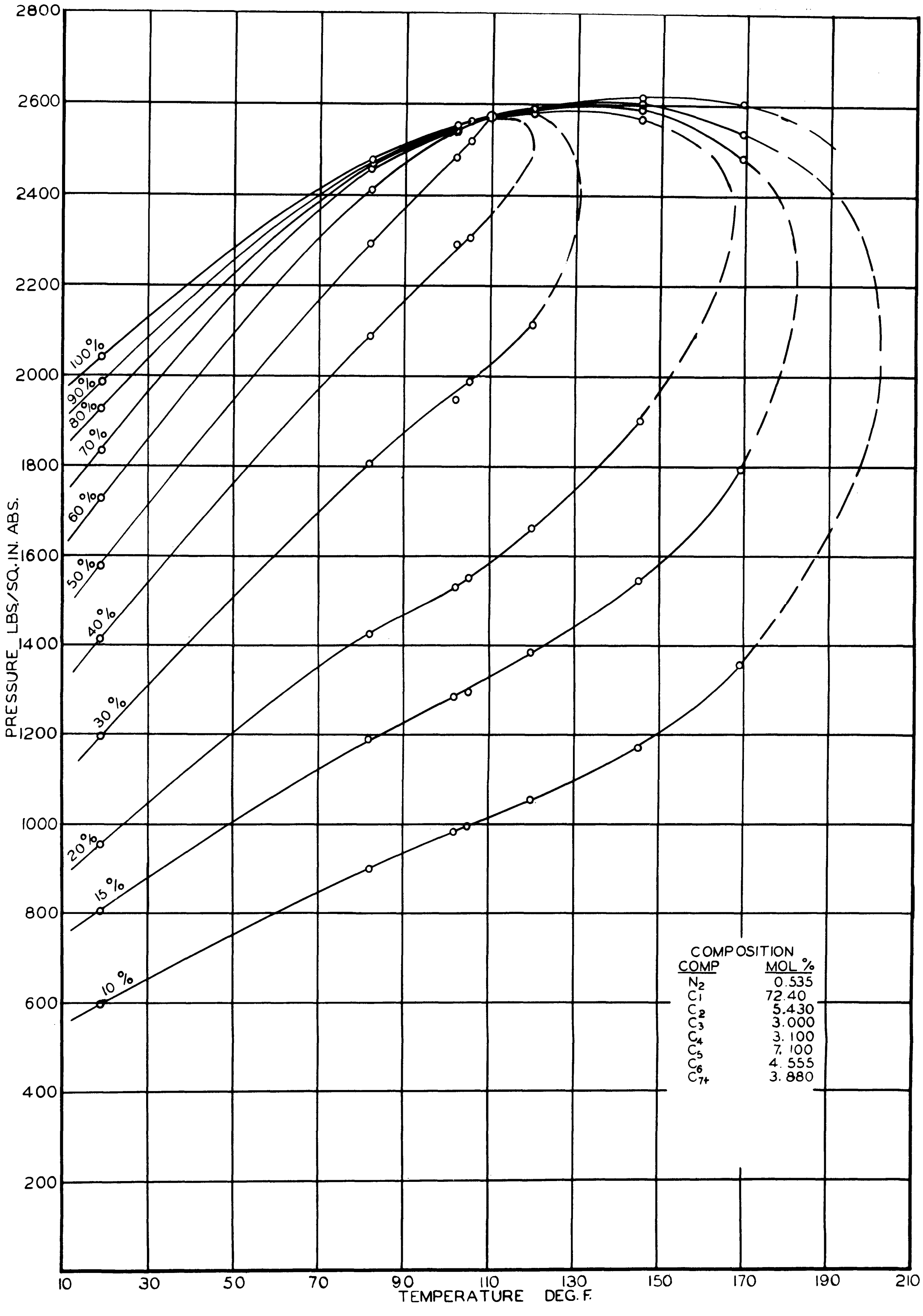


Fig. D-1. Phase diagram for mixture S-3.

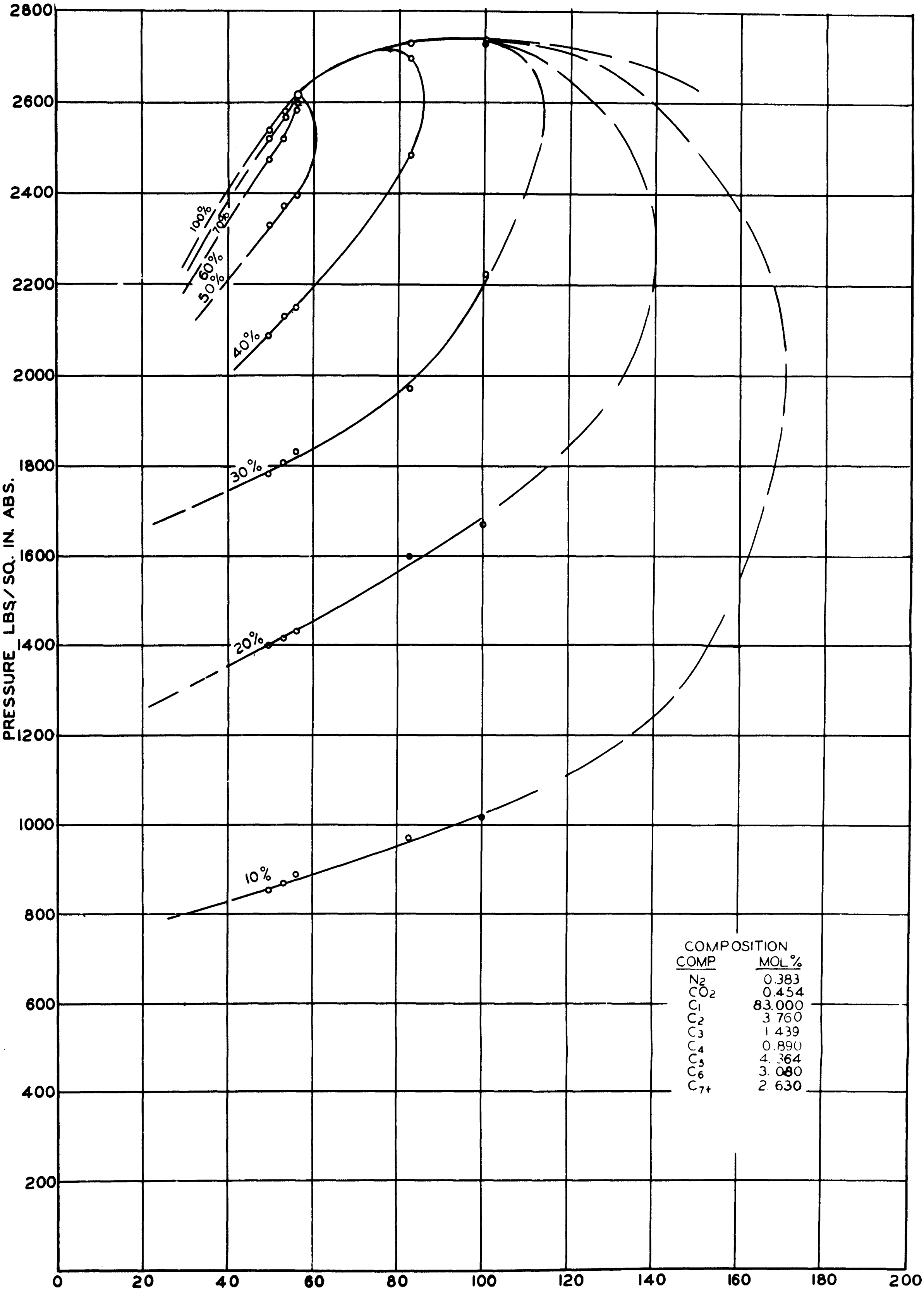


Fig. D-2. Phase diagram for mixture T-1.

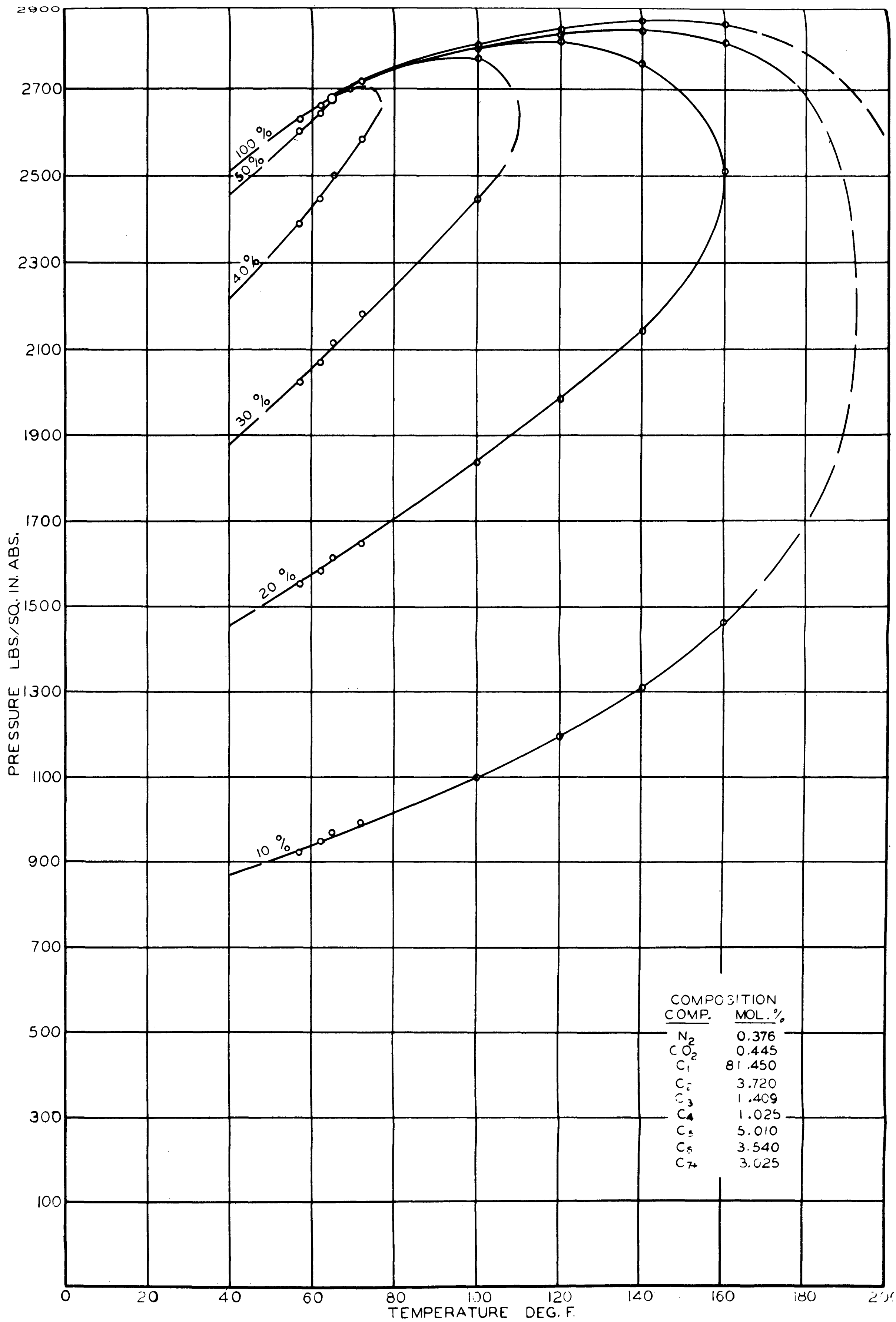


Fig. D-3. Phase diagram for mixture T-3.

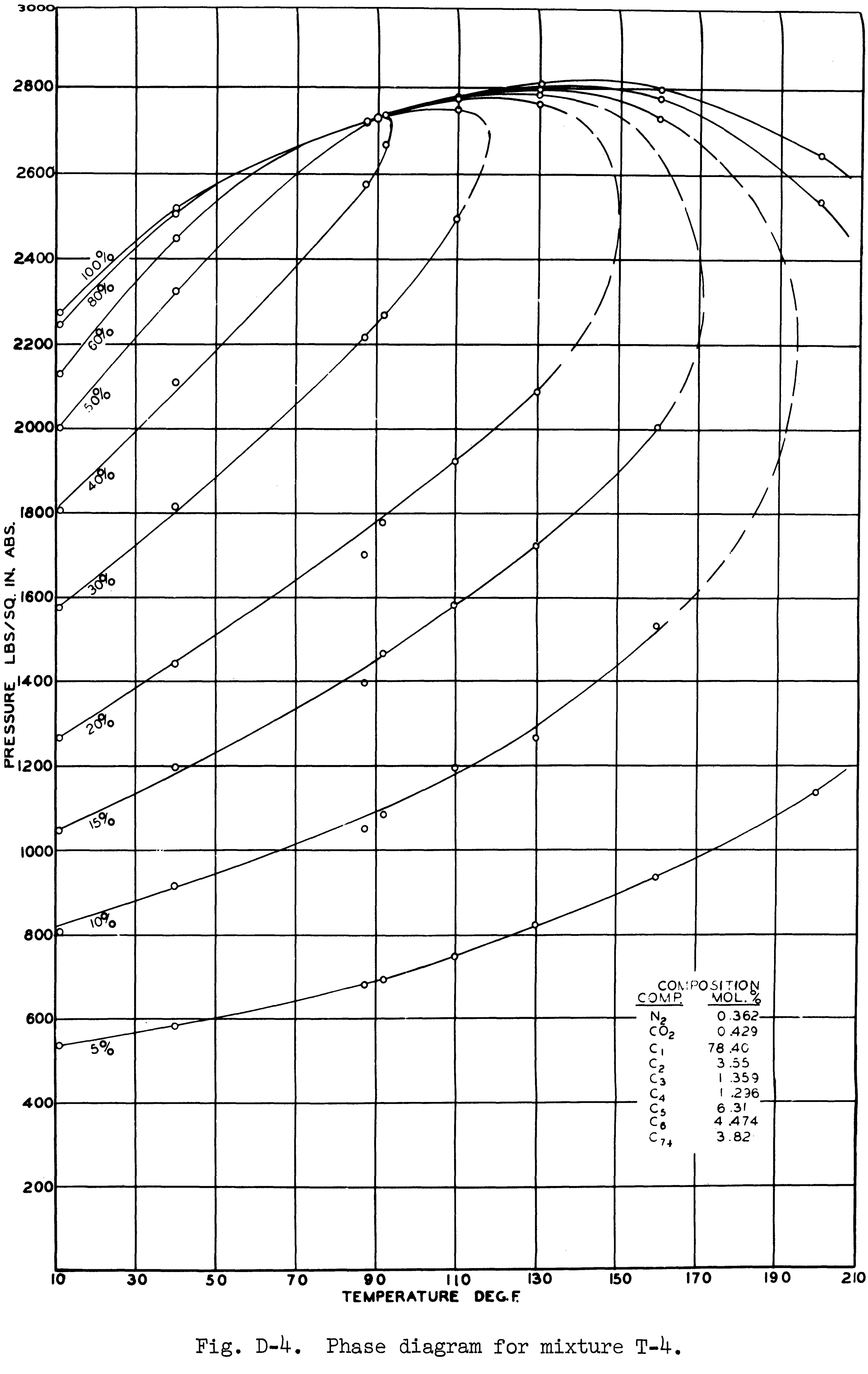


Fig. D-4. Phase diagram for mixture T-4.

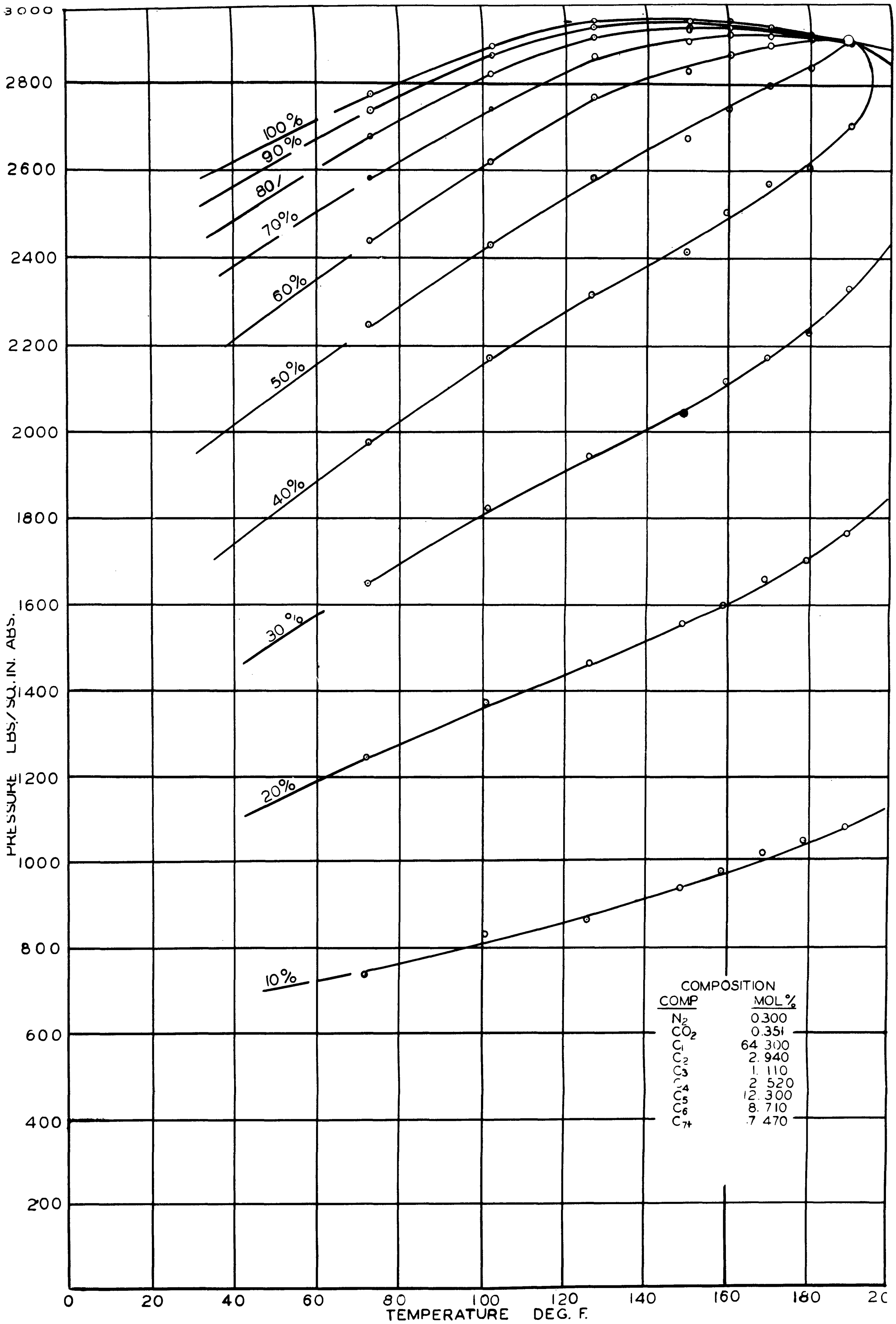


Fig. D-5. Phase diagram for mixture T-5.

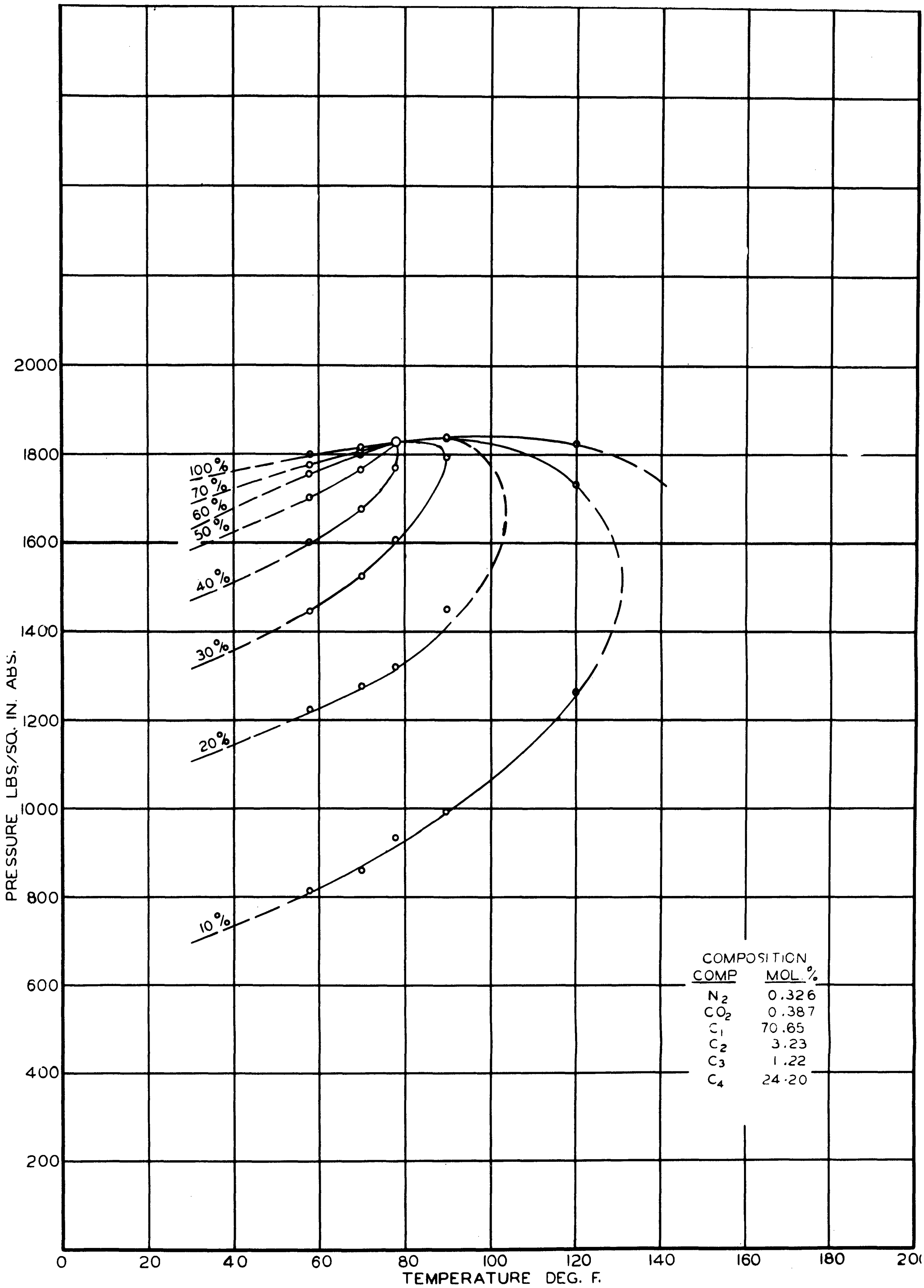


Fig. D-6. Phase diagram for mixture B-1.

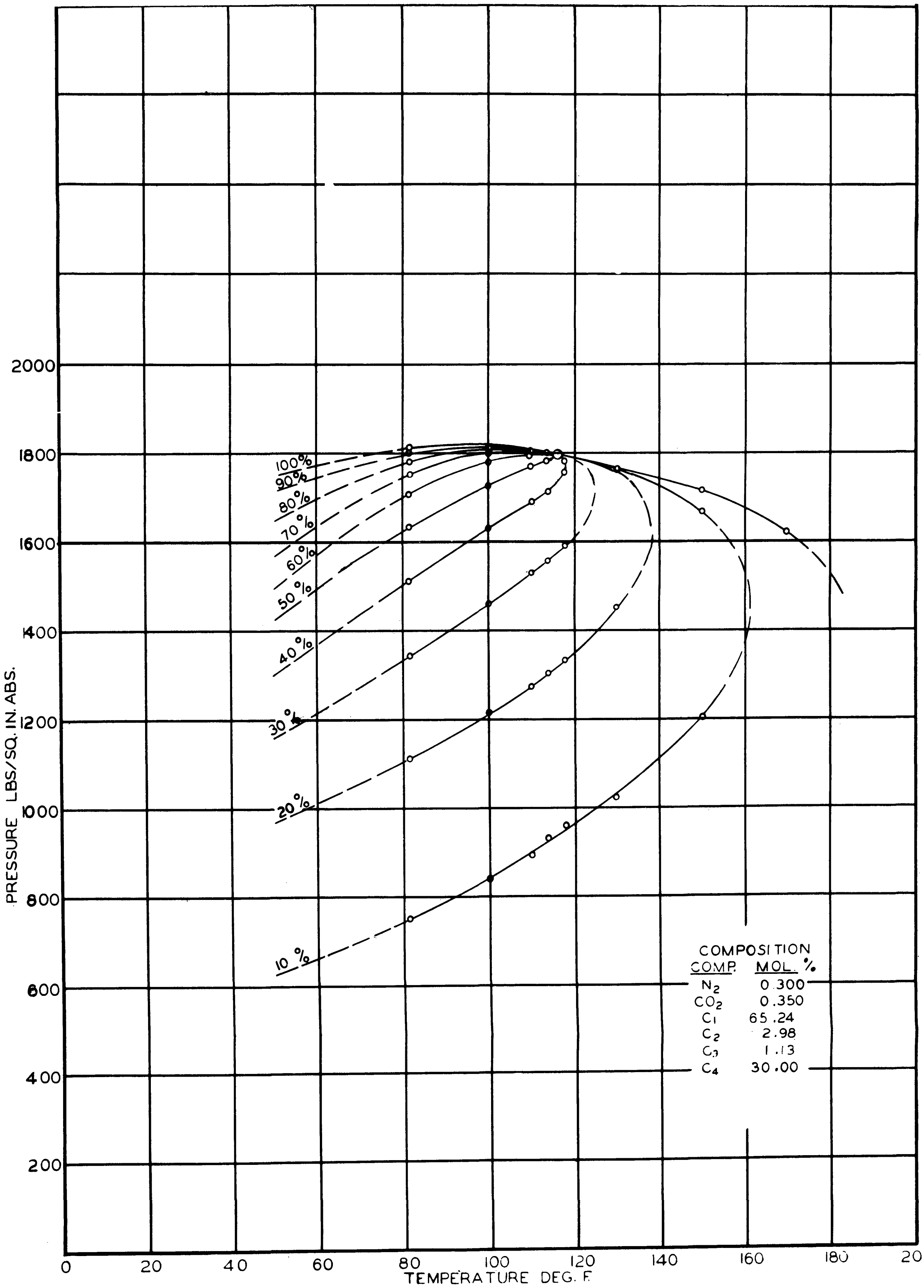


Fig. D-7. Phase diagram for mixture B-2.

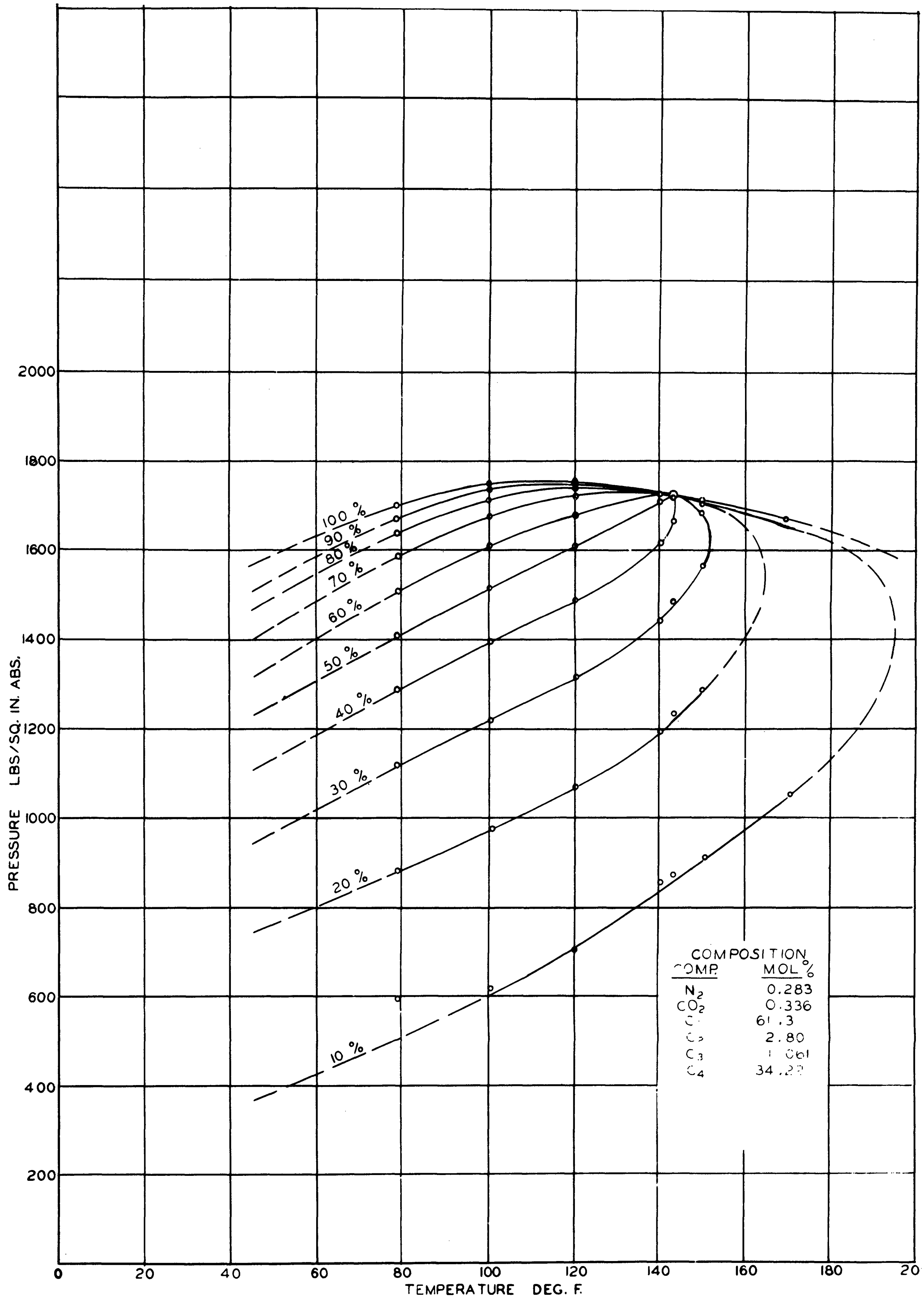


Fig. D-8. Phase diagram for mixture B-3.

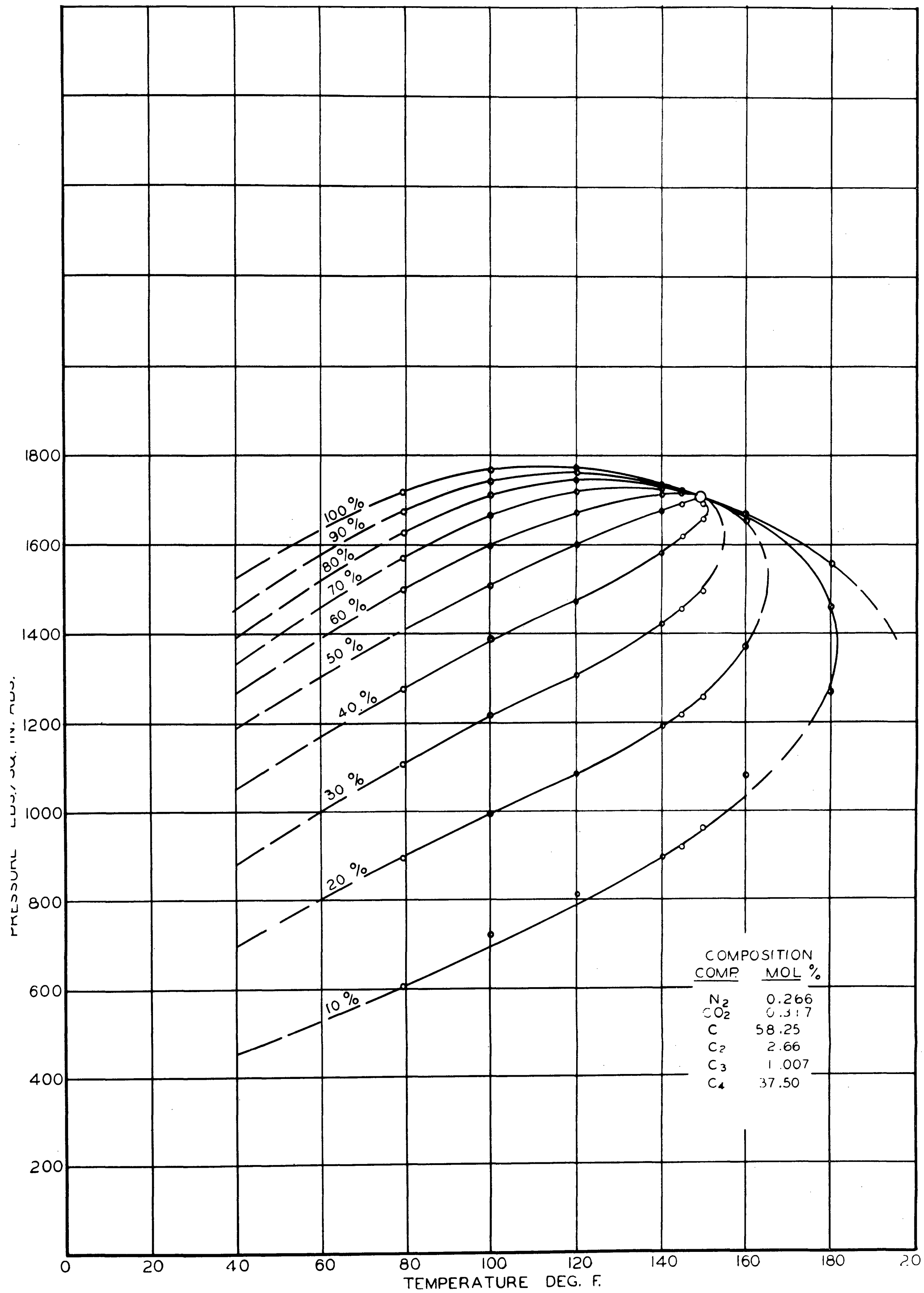


Fig. D-9. Phase diagram for mixture B-4.

APPENDIX E

CHARTS GIVING RESULTS OF ECONOMIC CALCULATIONS

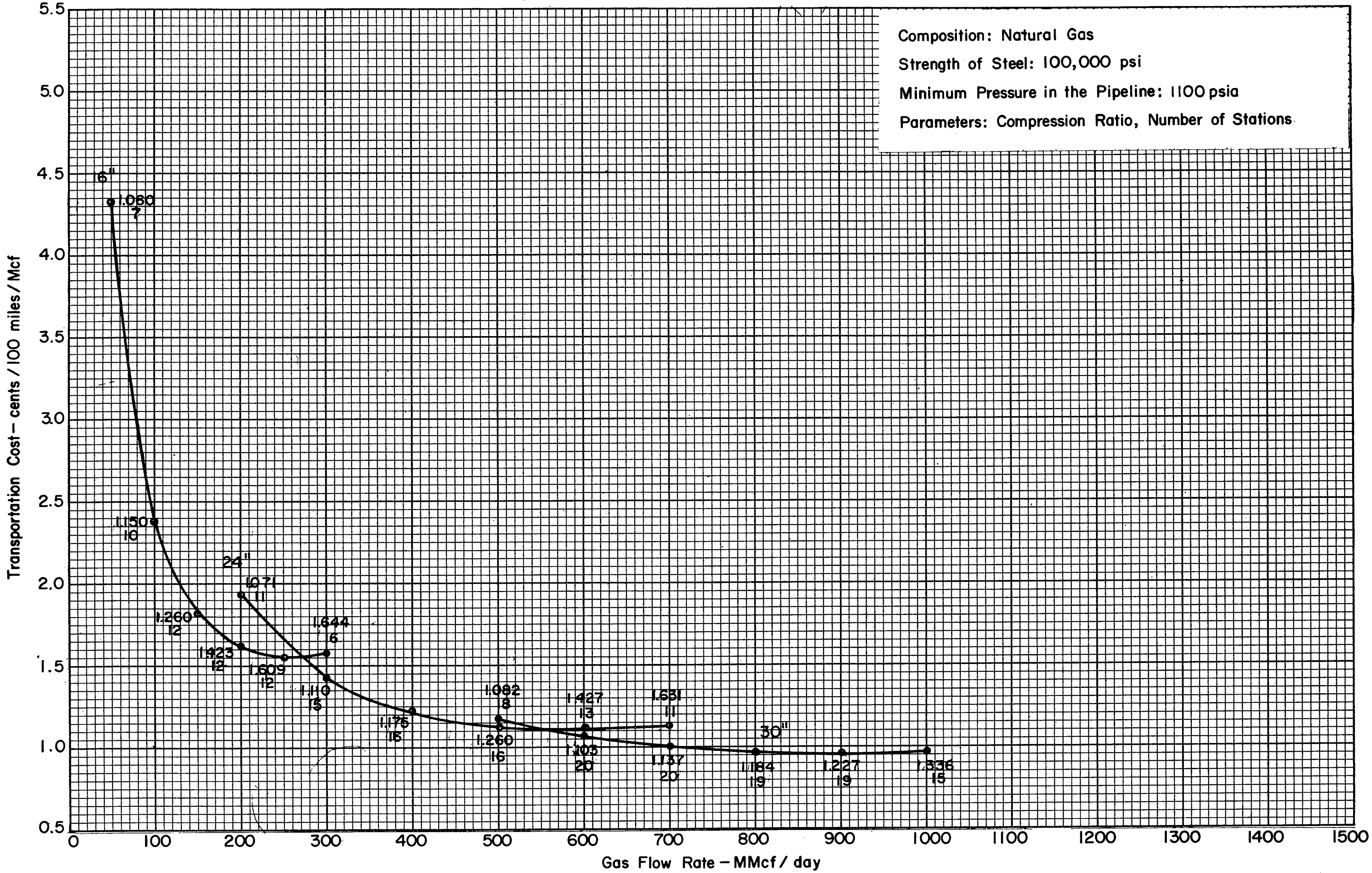


Figure 15E-1. Cost of Transportation versus Flow Rate

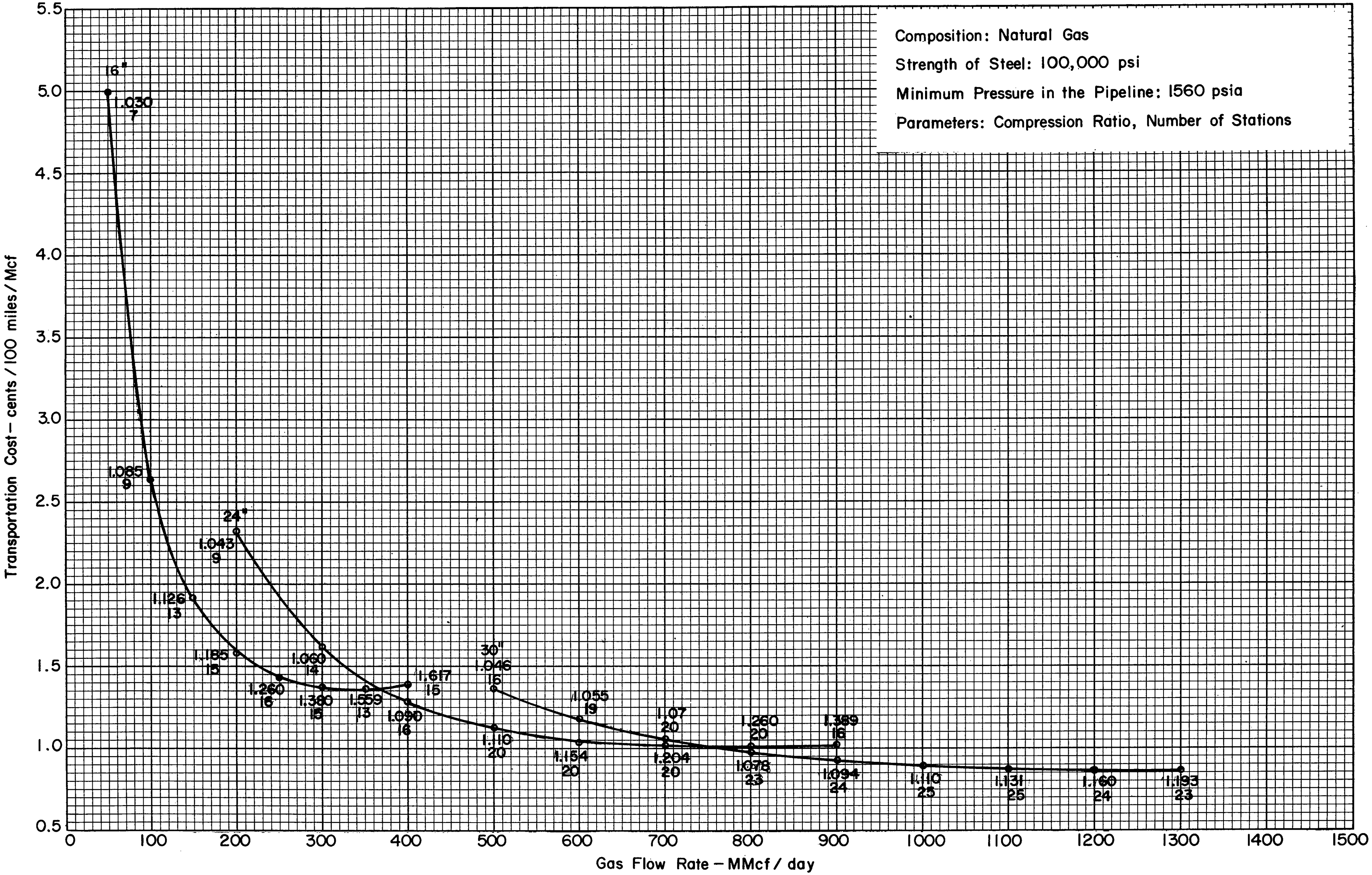


Figure 15E-2. Cost of Transportation versus Flow Rate

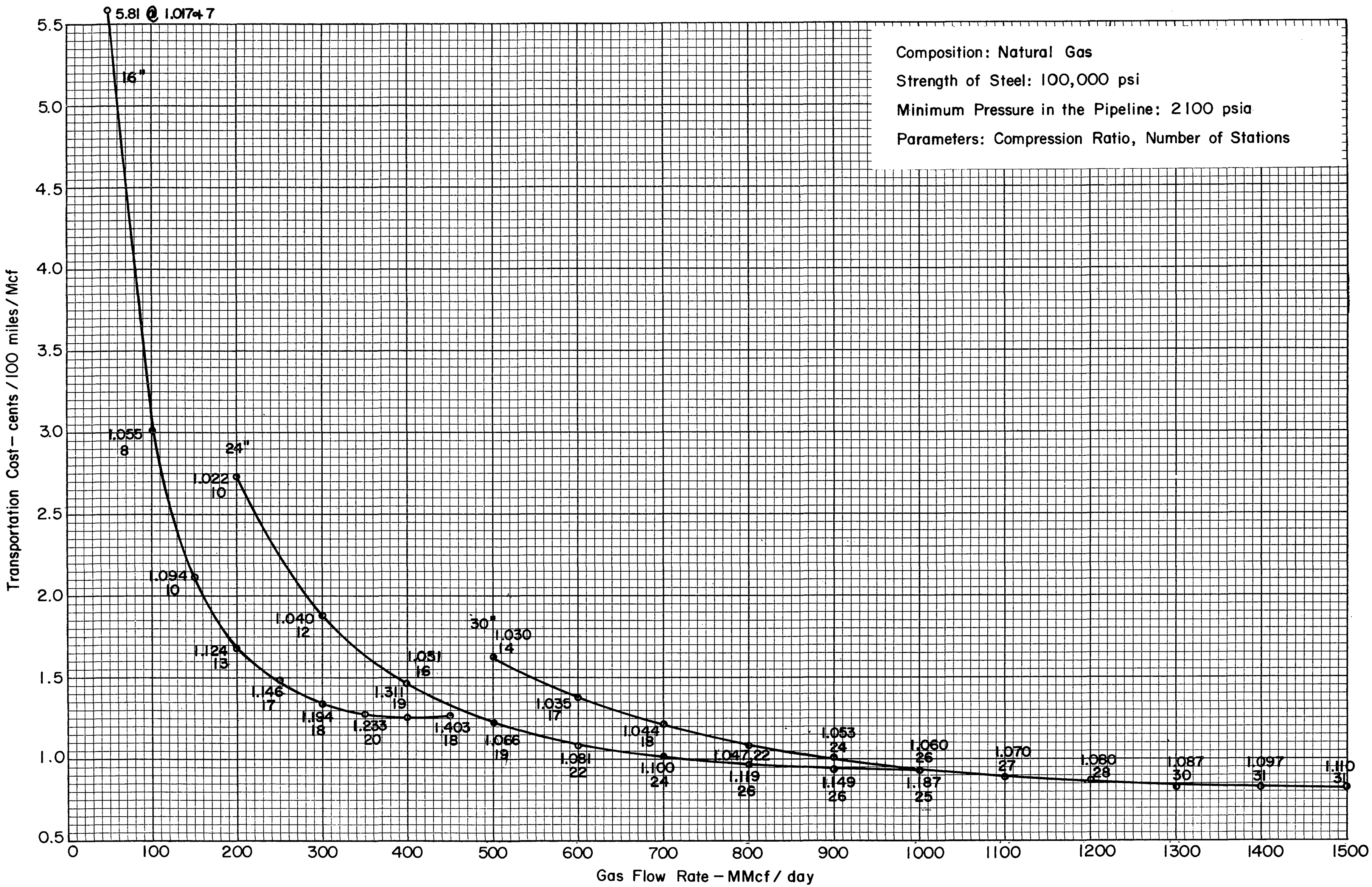


Figure 15E-3. Cost of Transportation versus Flow Rate

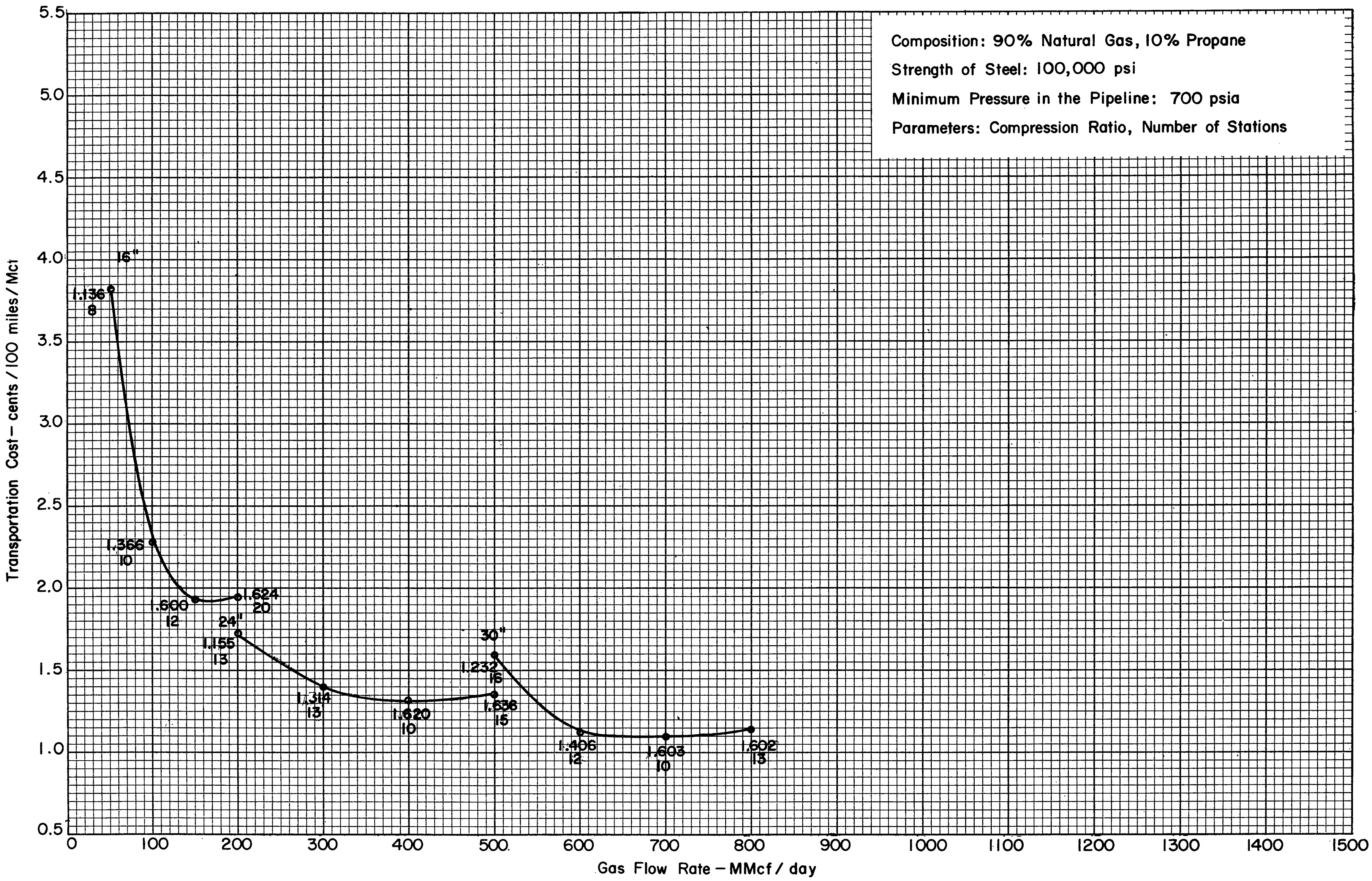


Figure 15E-4. Cost of Transportation versus Flow Rate

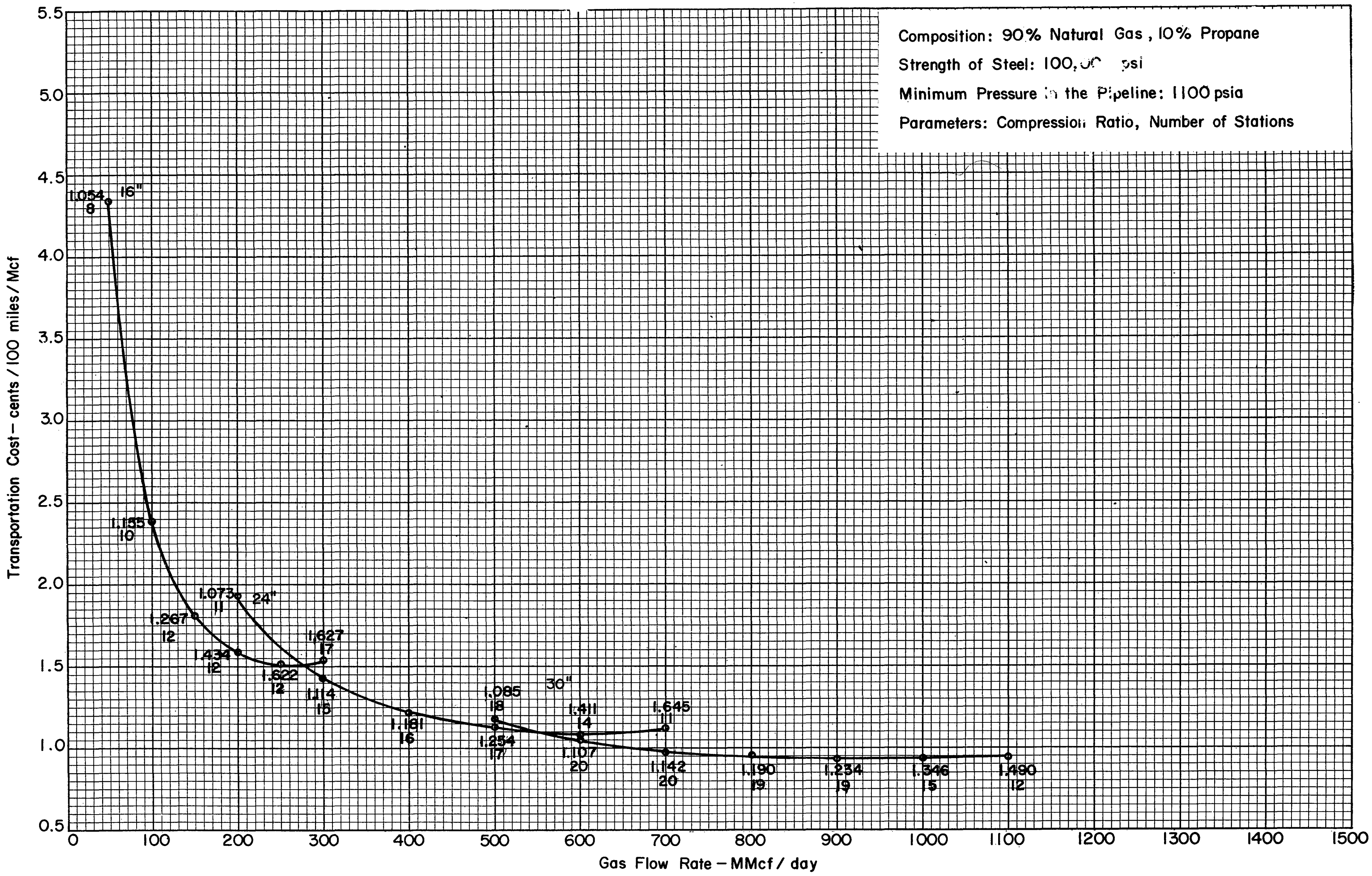


Figure 15E-5. Cost of Transportation versus Flow Rate

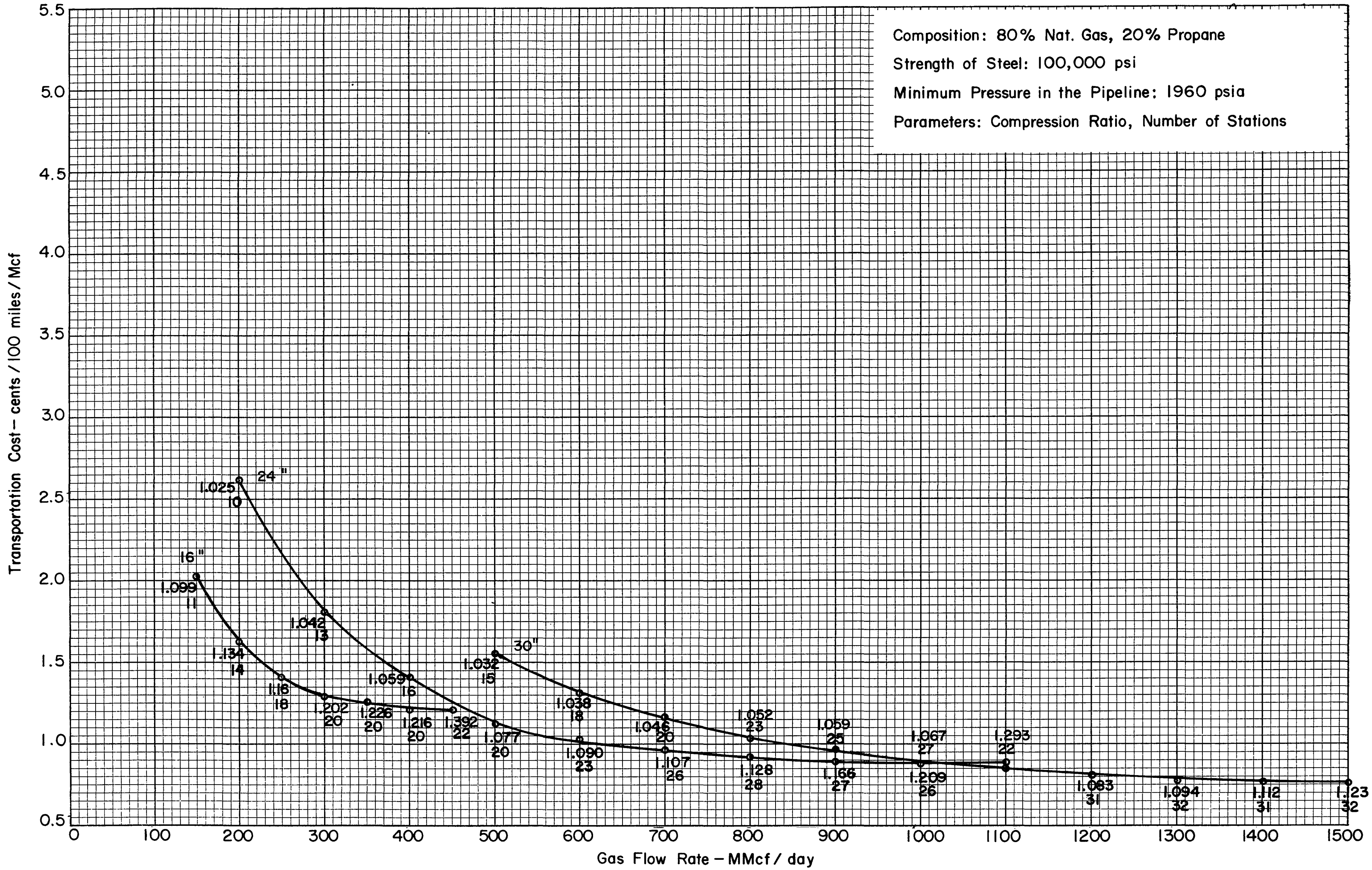


Figure 15E-6. Cost of Transportation versus Flow Rate

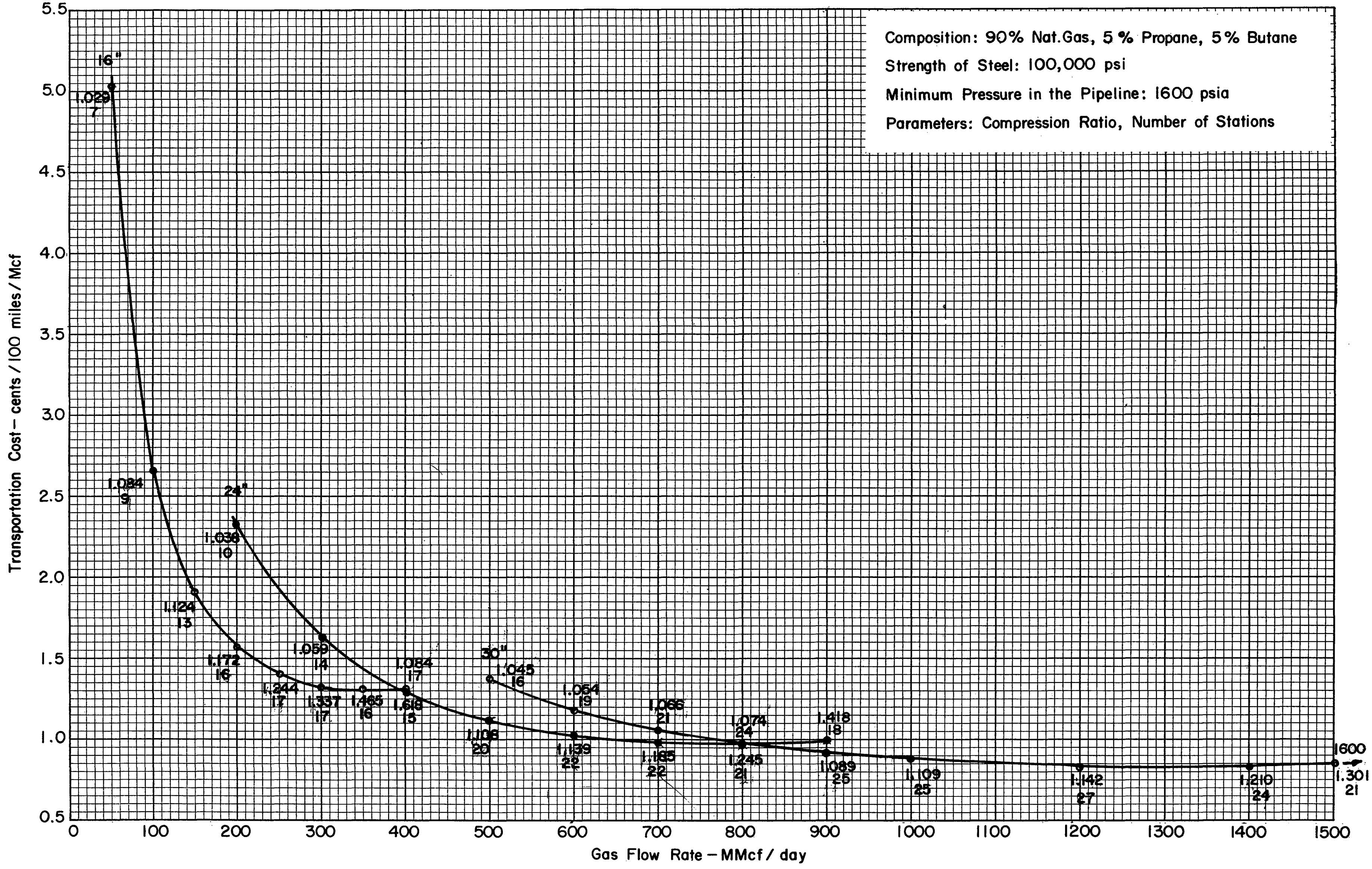


Figure 15E-7. Cost of Transportation versus Flow Rate

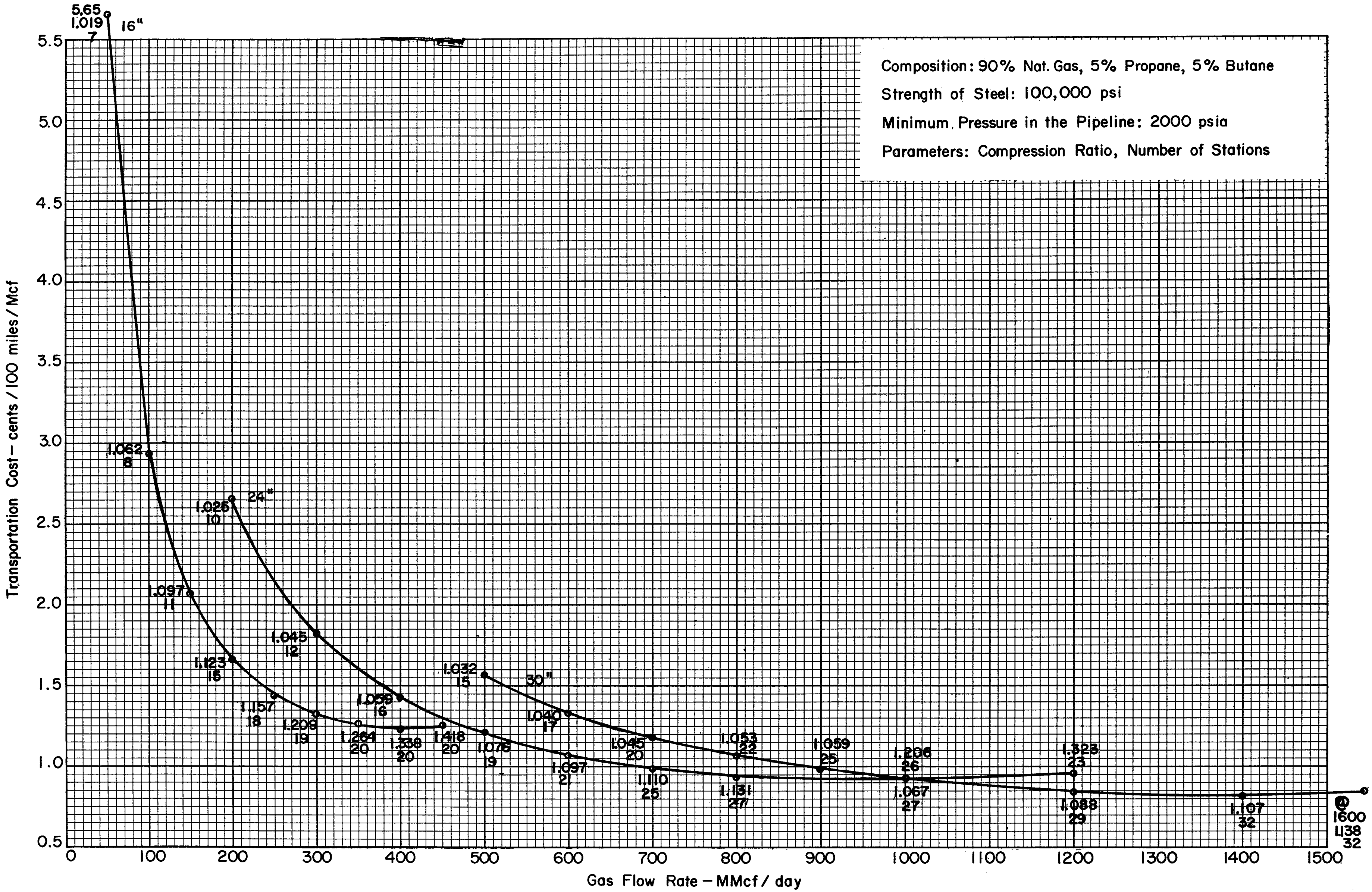


Figure 15E-8. Cost of Transportation versus Flow Rate

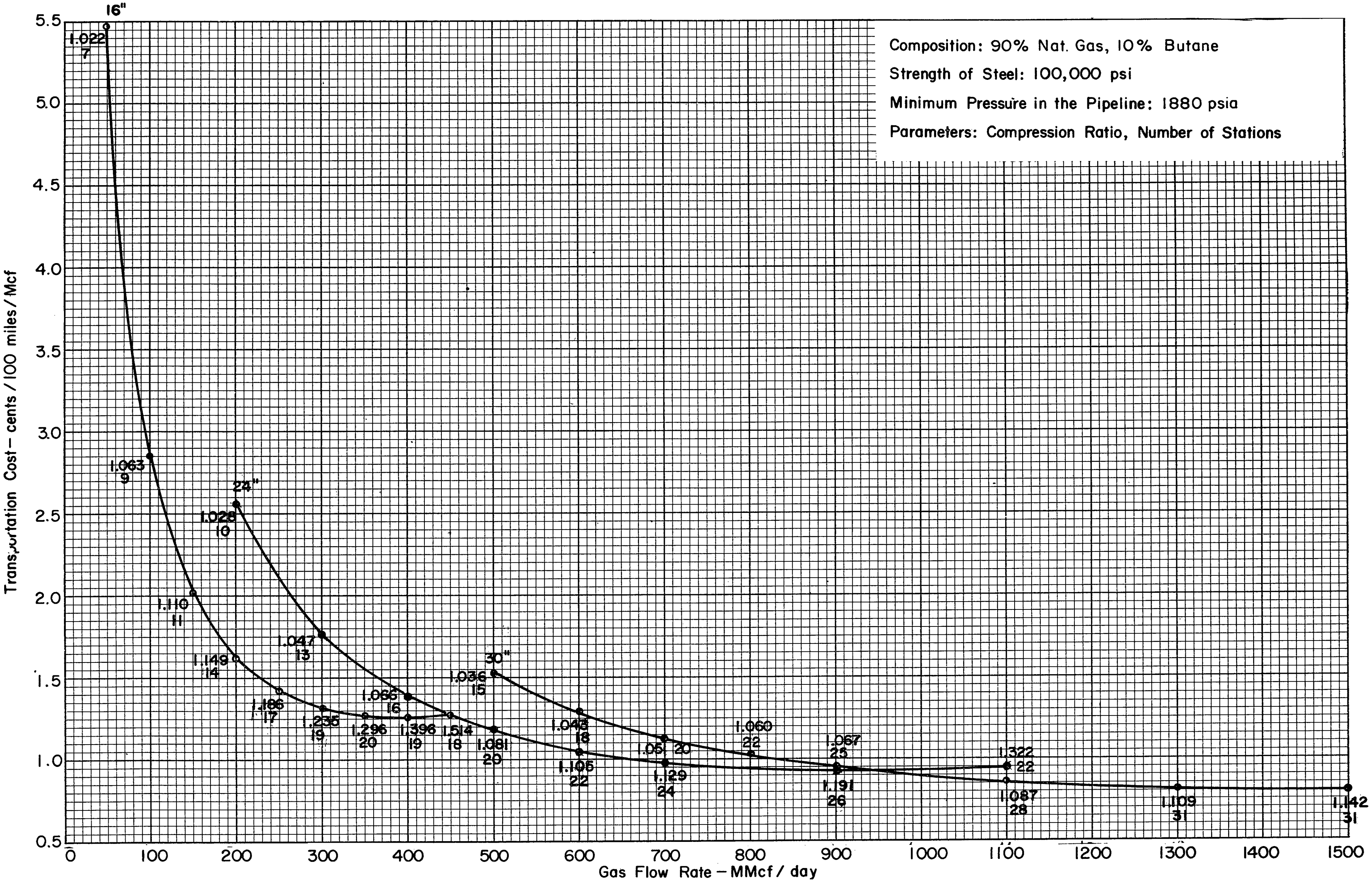


Figure 15E-9. Cost of Transportation versus Flow Rate

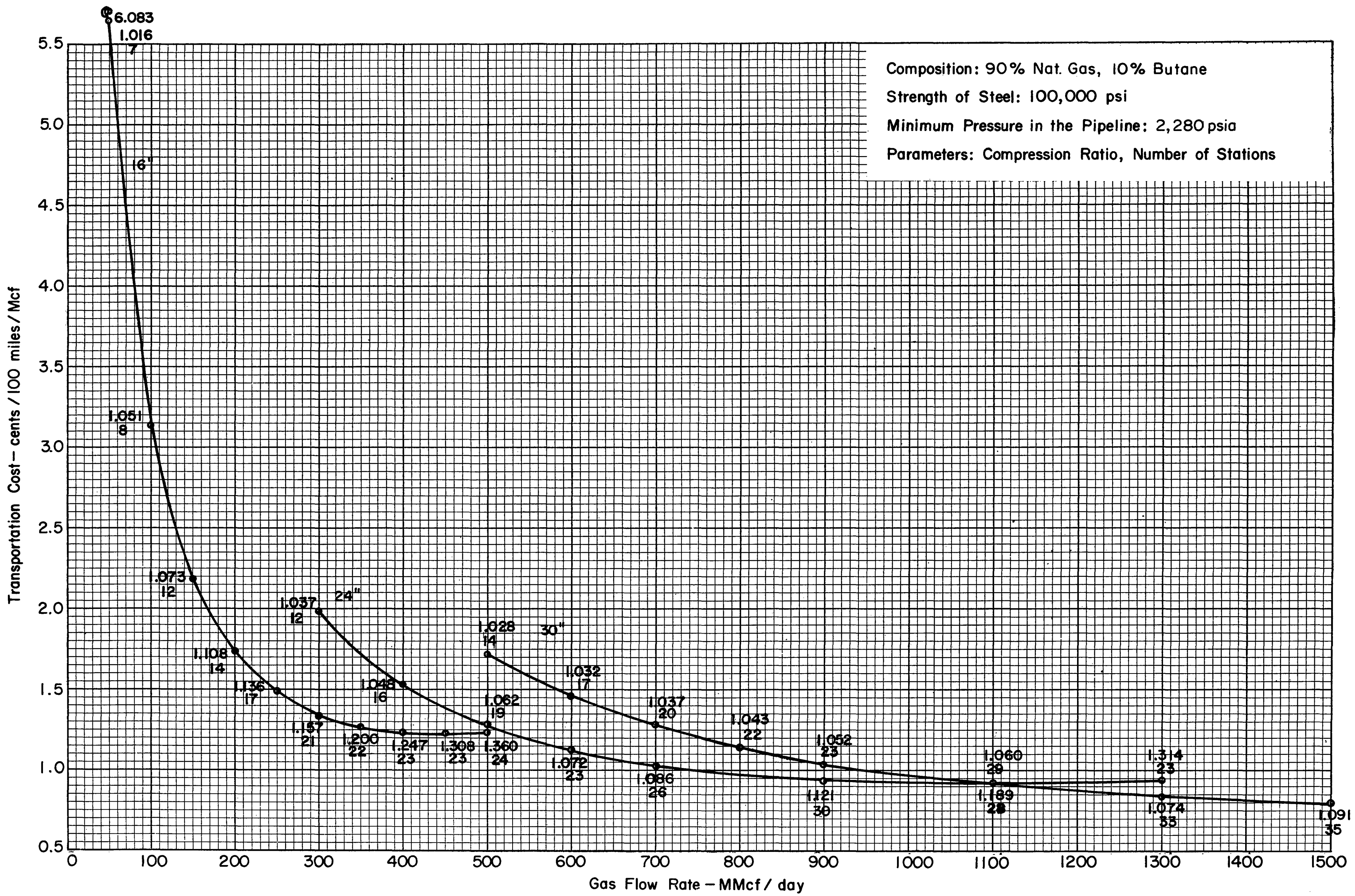


Figure 15E-10. Cost of Transportation versus Flow Rate

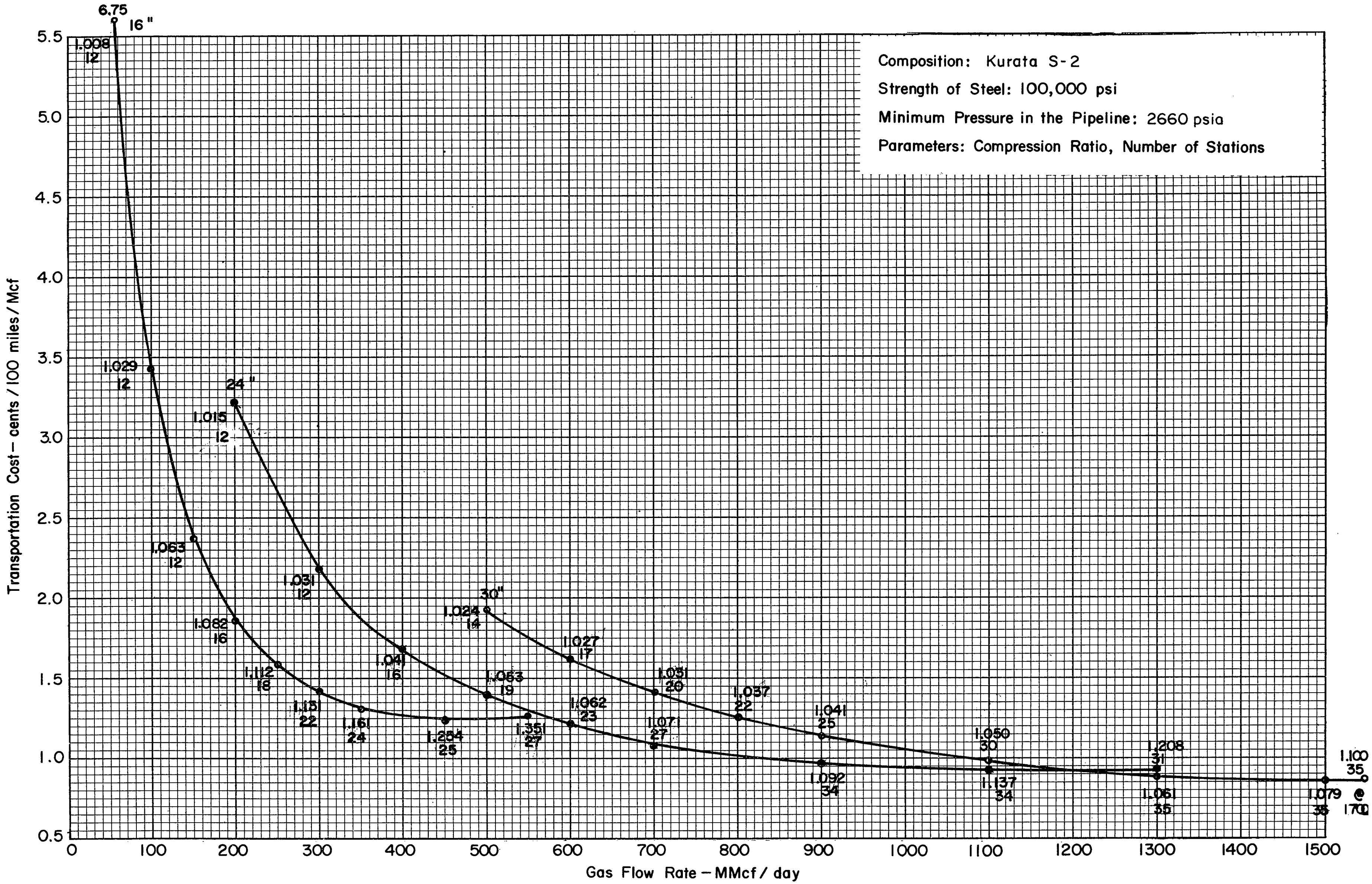


Figure 15E-11. Cost of Transportation versus Flow Rate

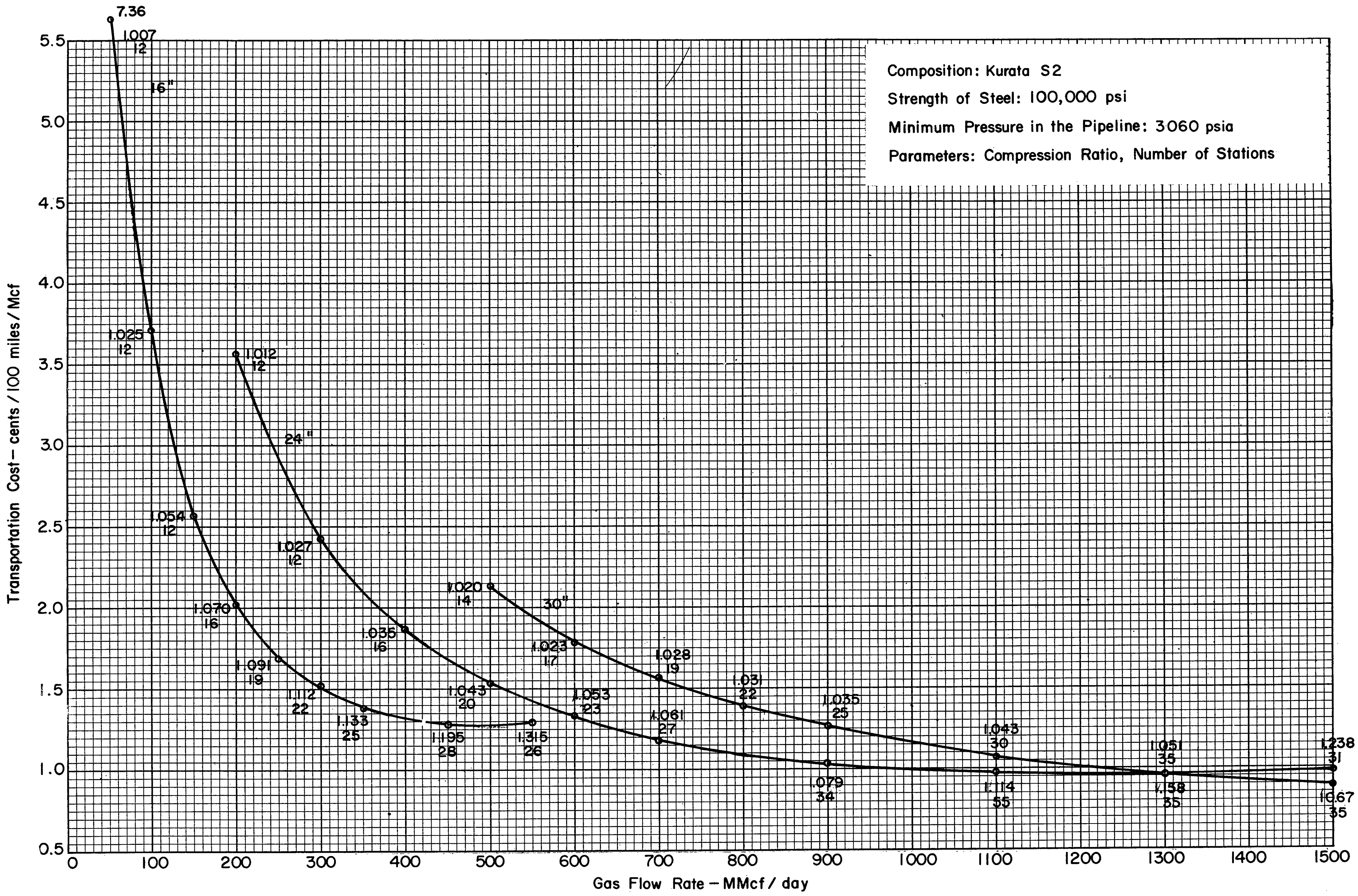


Figure 15E-12. Cost of Transportation versus Flow Rate

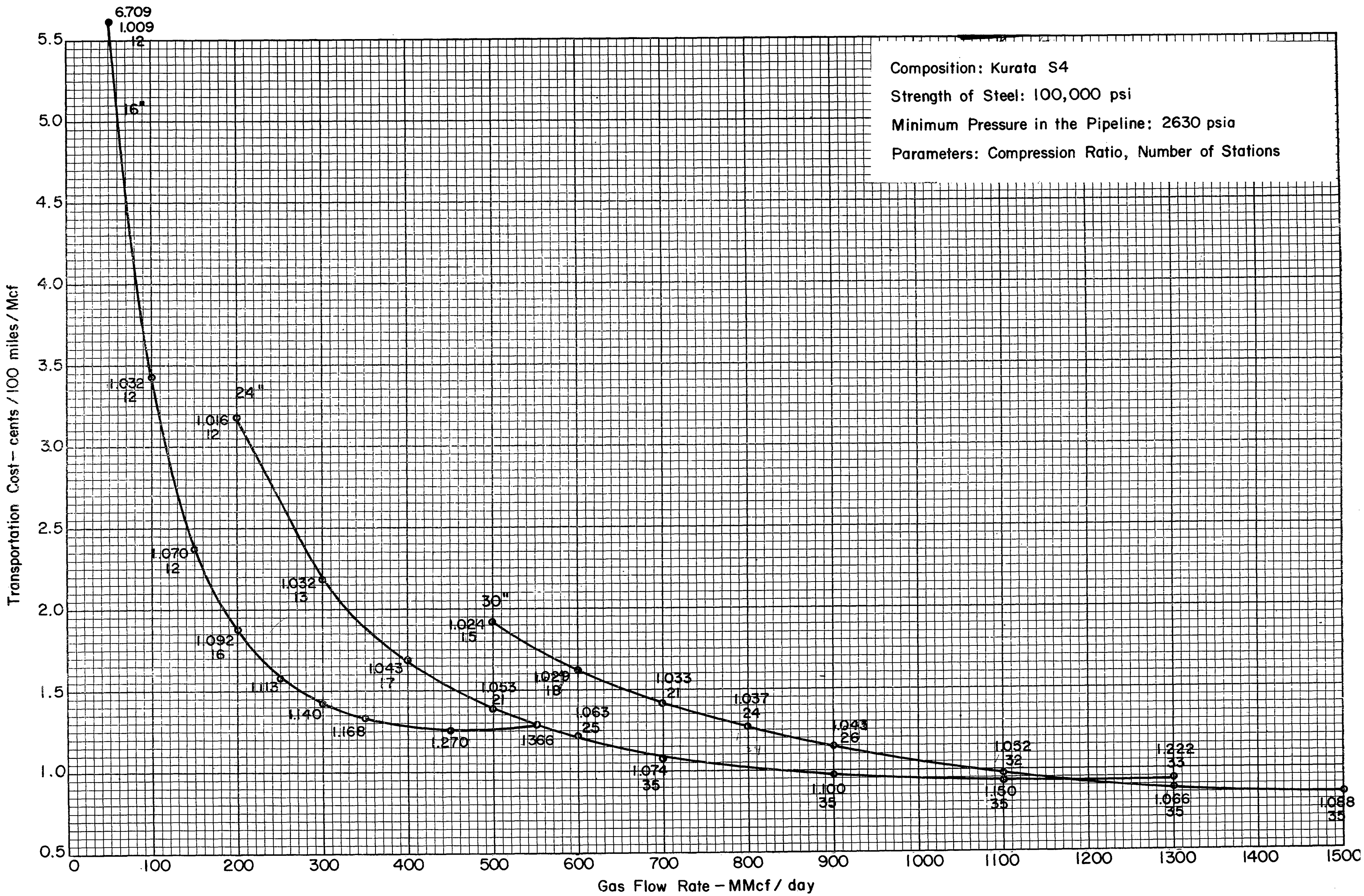


Figure 15E-13. Cost of Transportation versus Flow Rate

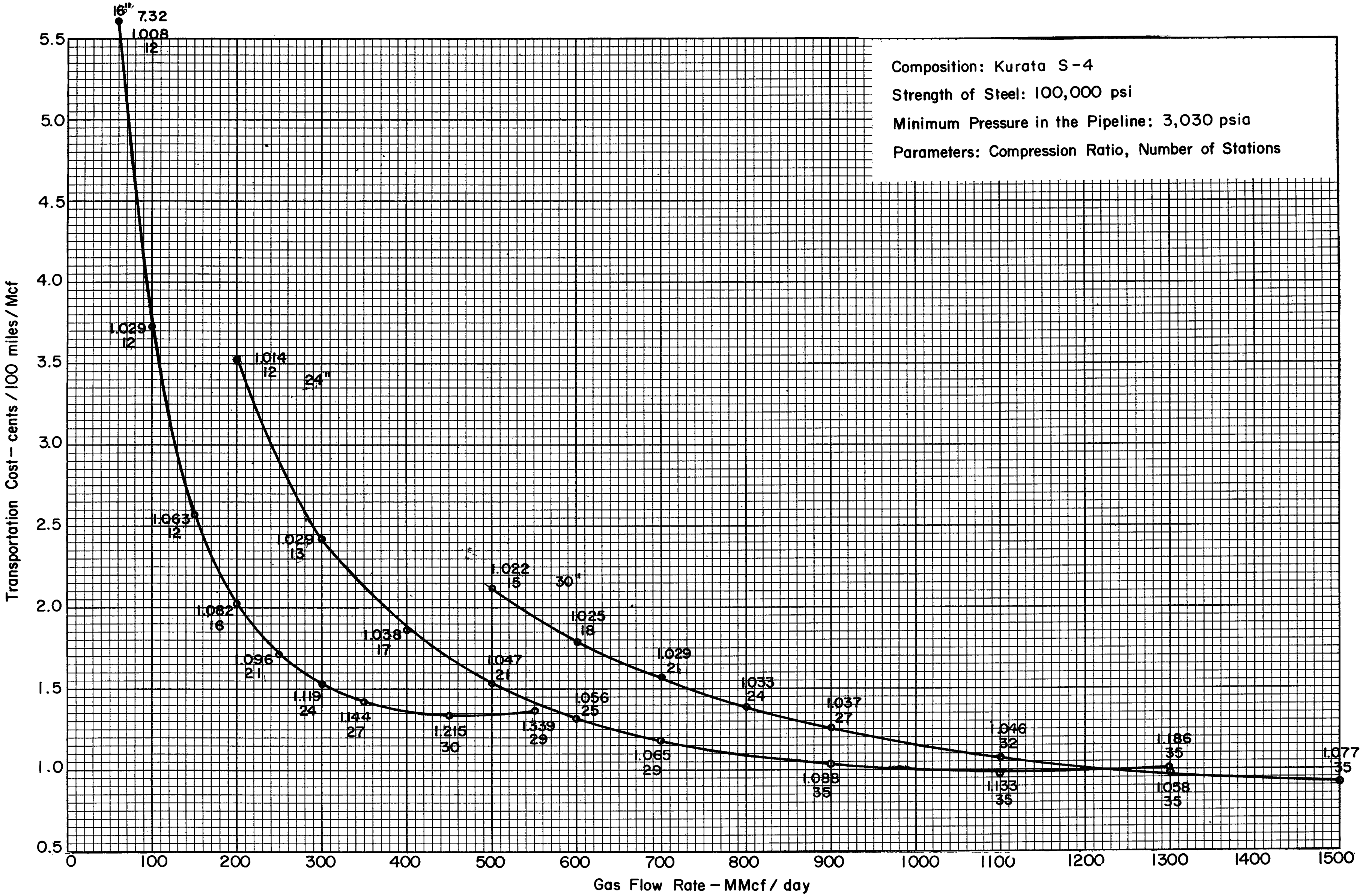


Figure 15E-14. Cost of Transportation versus Flow Rate

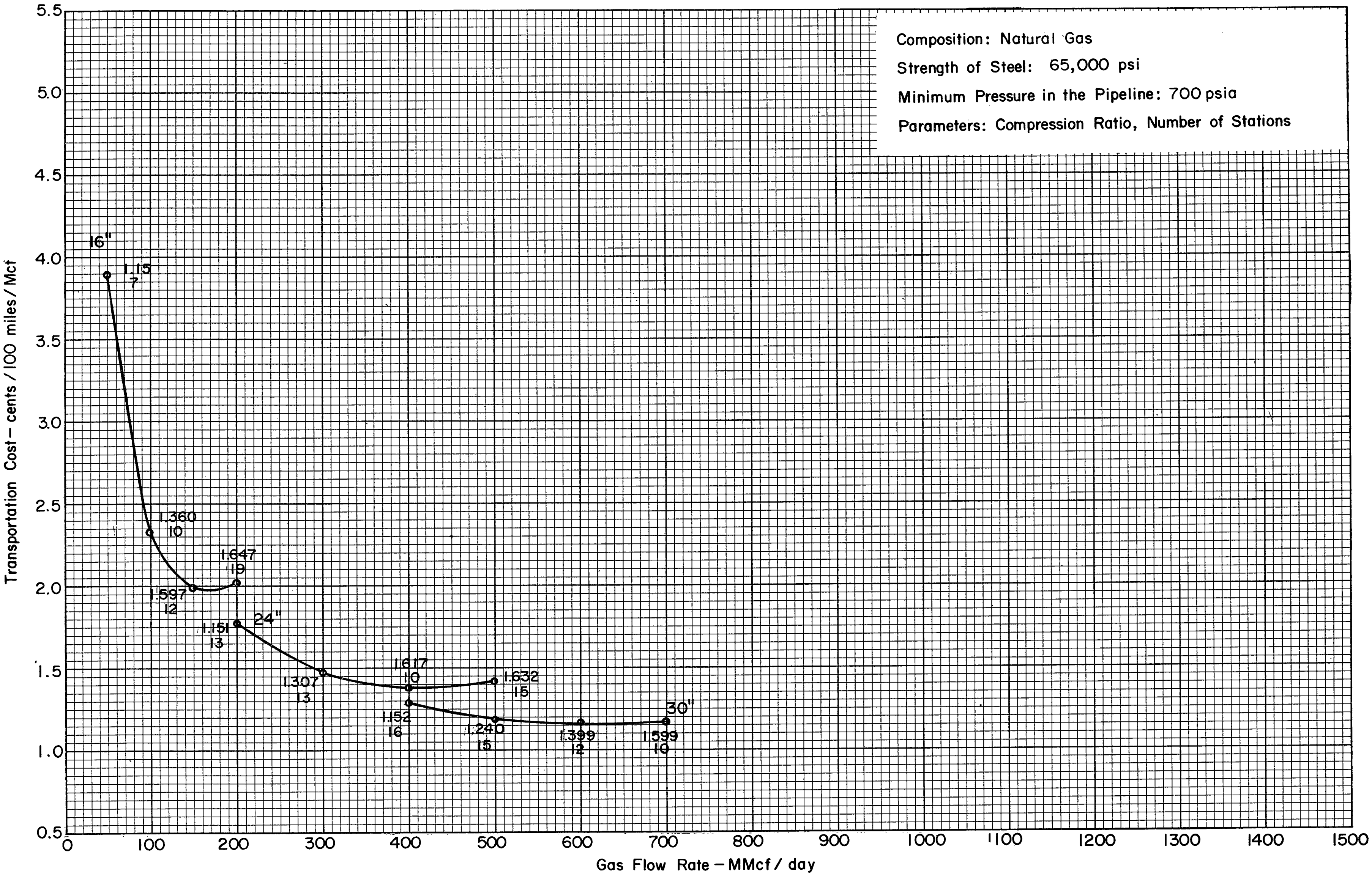


Figure 15E-15. Cost of Transportation versus Flow Rate

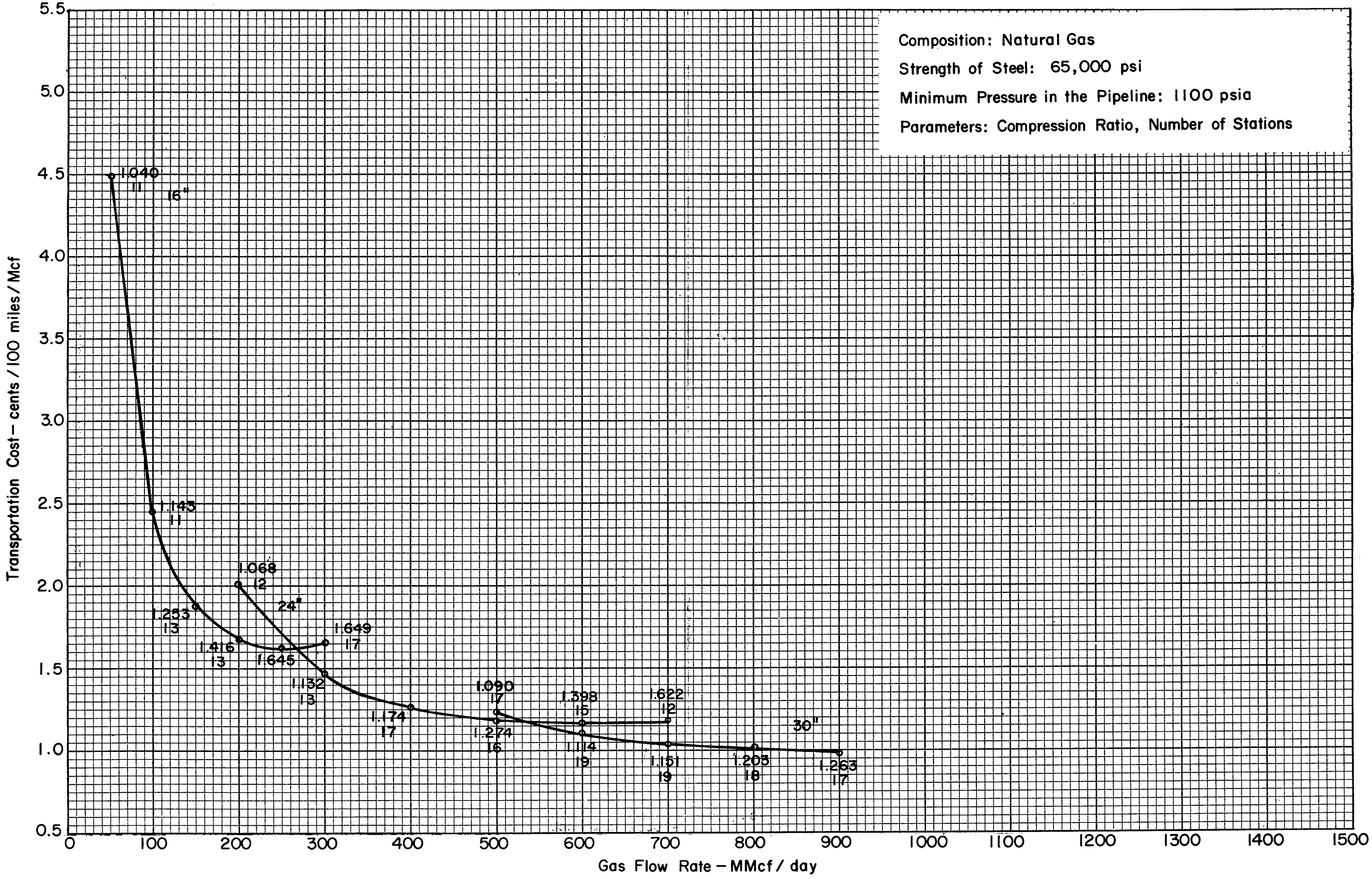


Figure 15E-16. Cost of Transportation versus Flow Rate

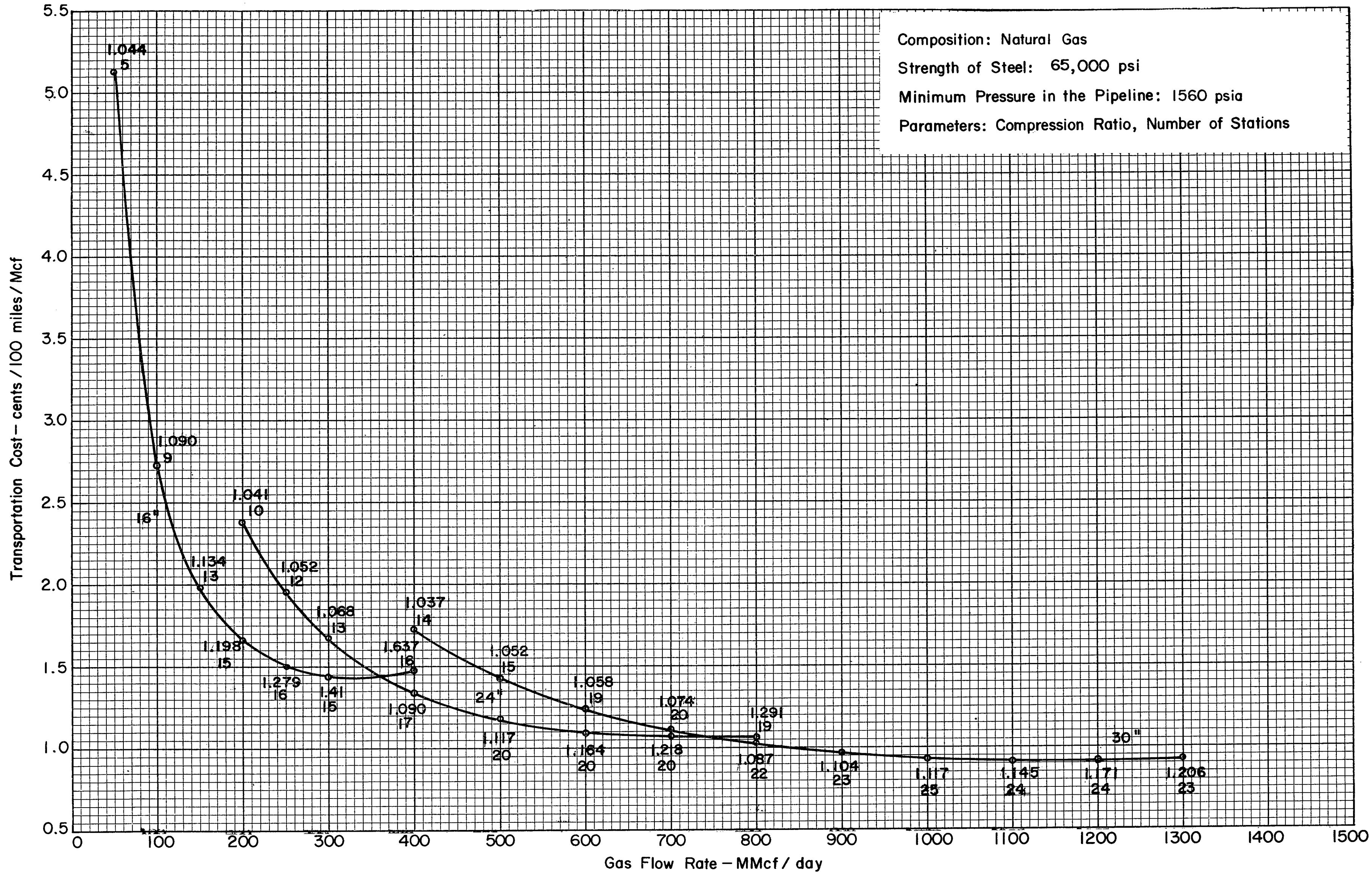


Figure 15E-17. Cost of Transportation versus Flow Rate

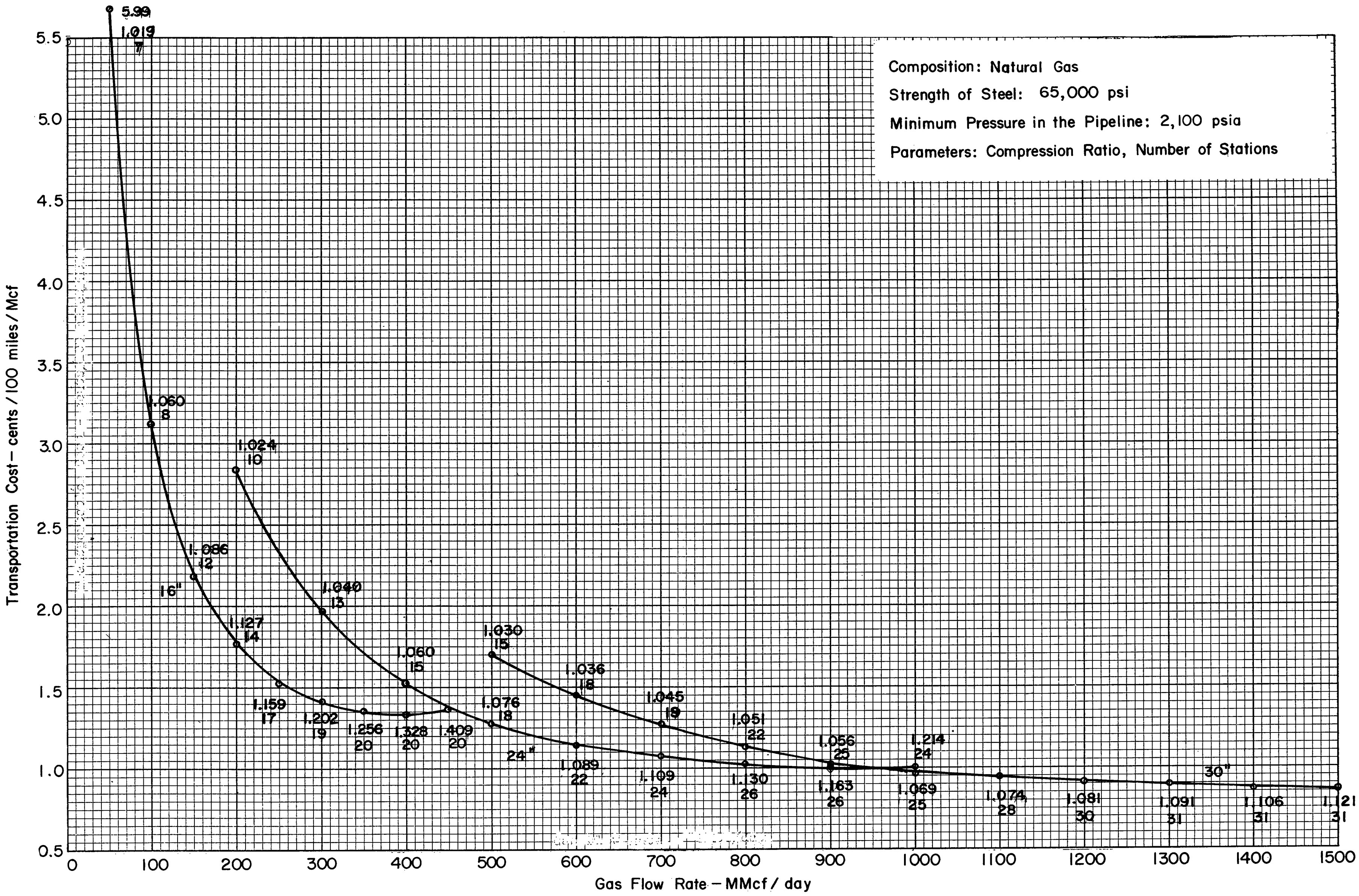


Figure 15E-18. Cost of Transportation versus Flow Rate

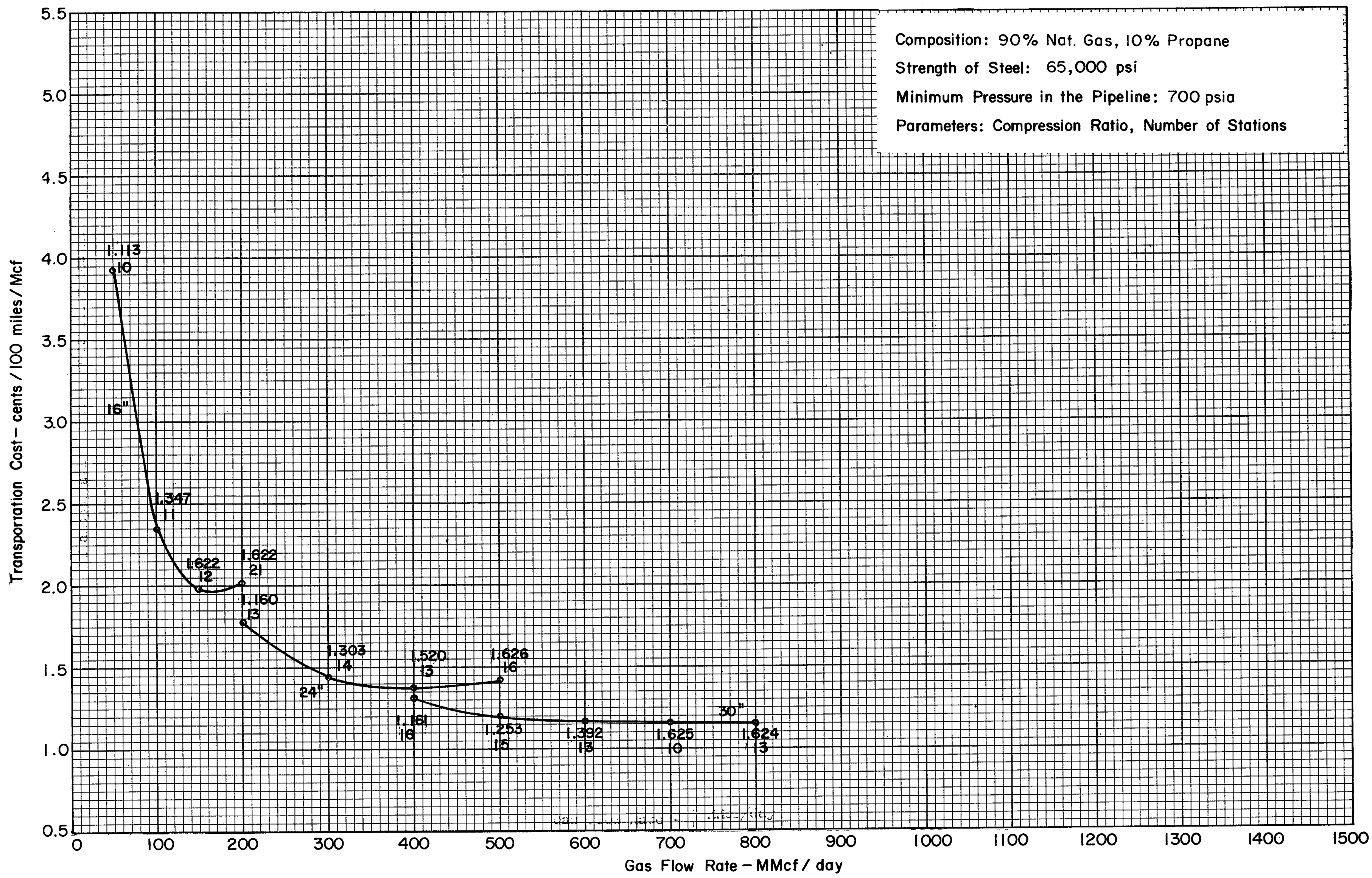


Figure 15E-19. Cost of Transportation versus Flow Rate

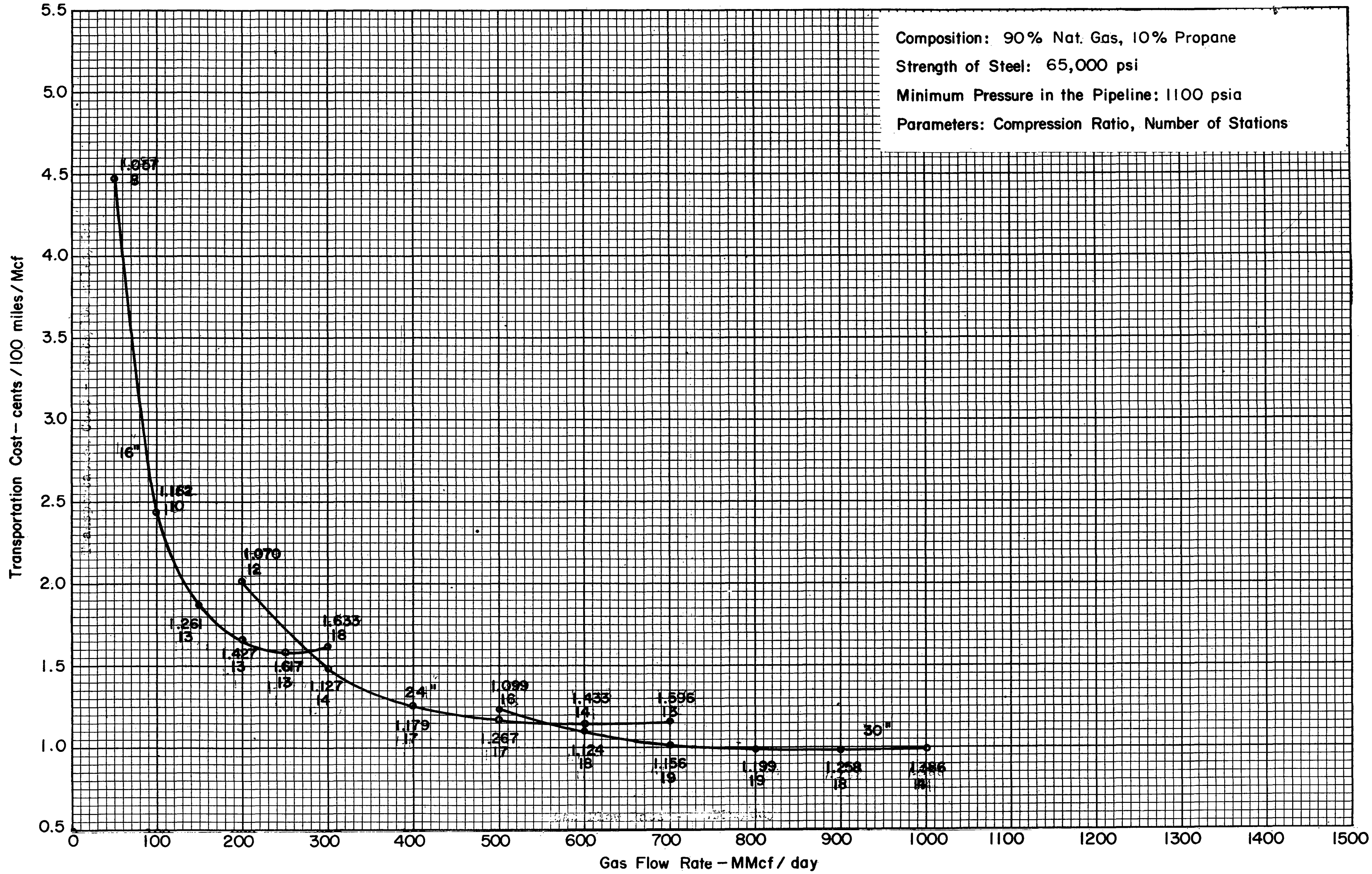


Figure 15E-20. Cost of Transportation versus Flow Rate

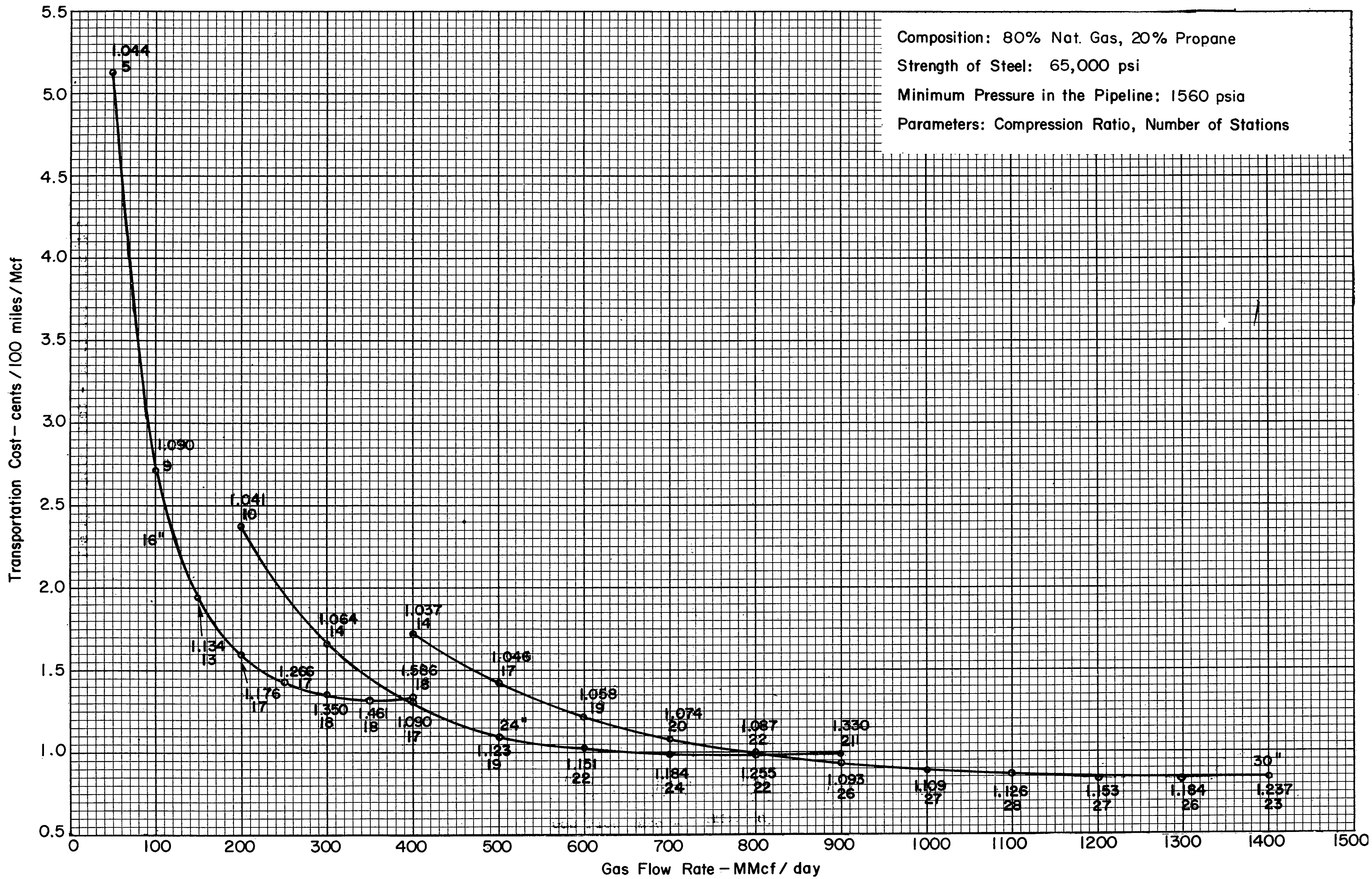


Figure 15E-21. Cost of Transportation versus Flow Rate

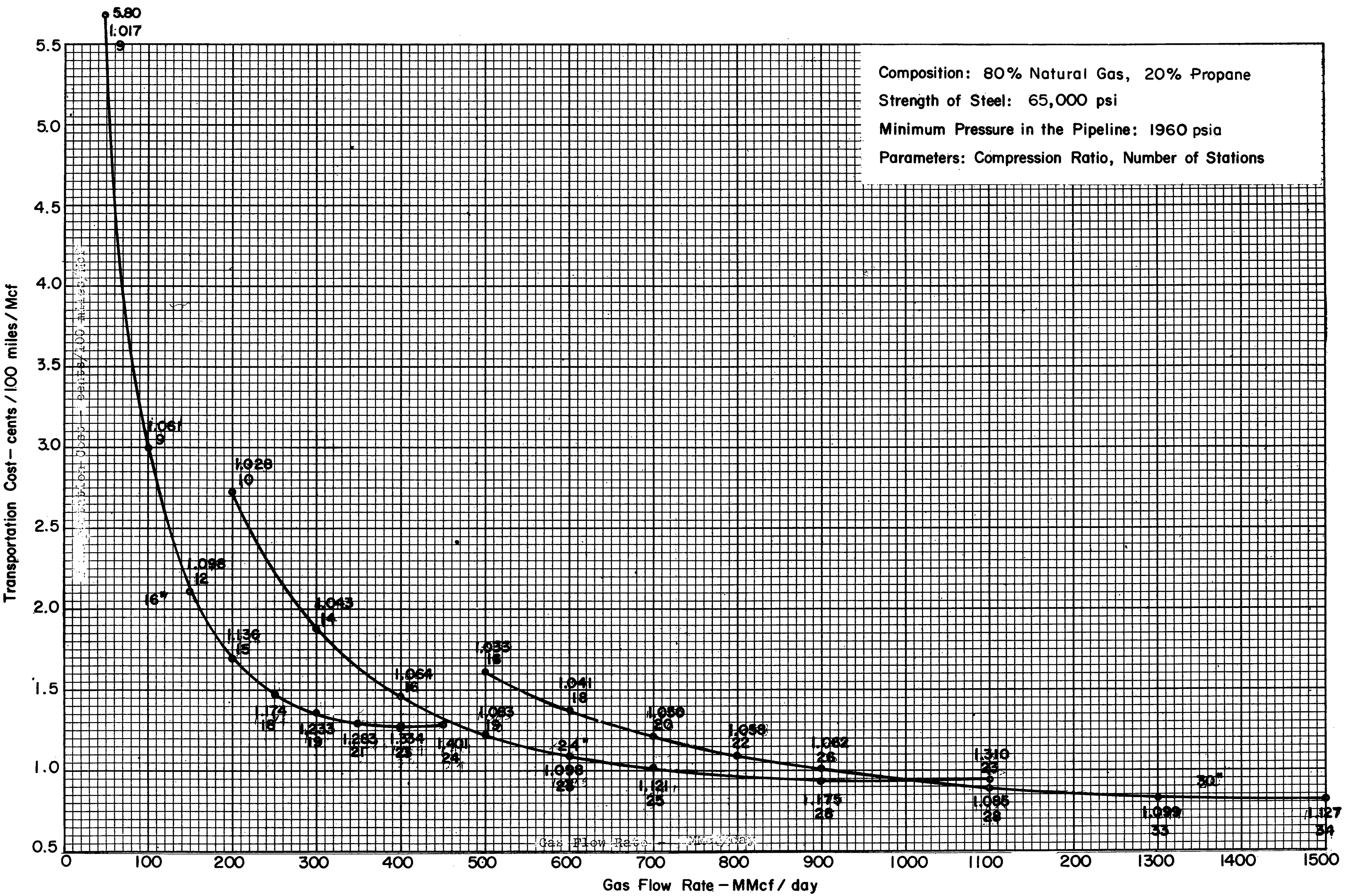


Figure 15E-22. Cost of Transportation versus Flow Rate

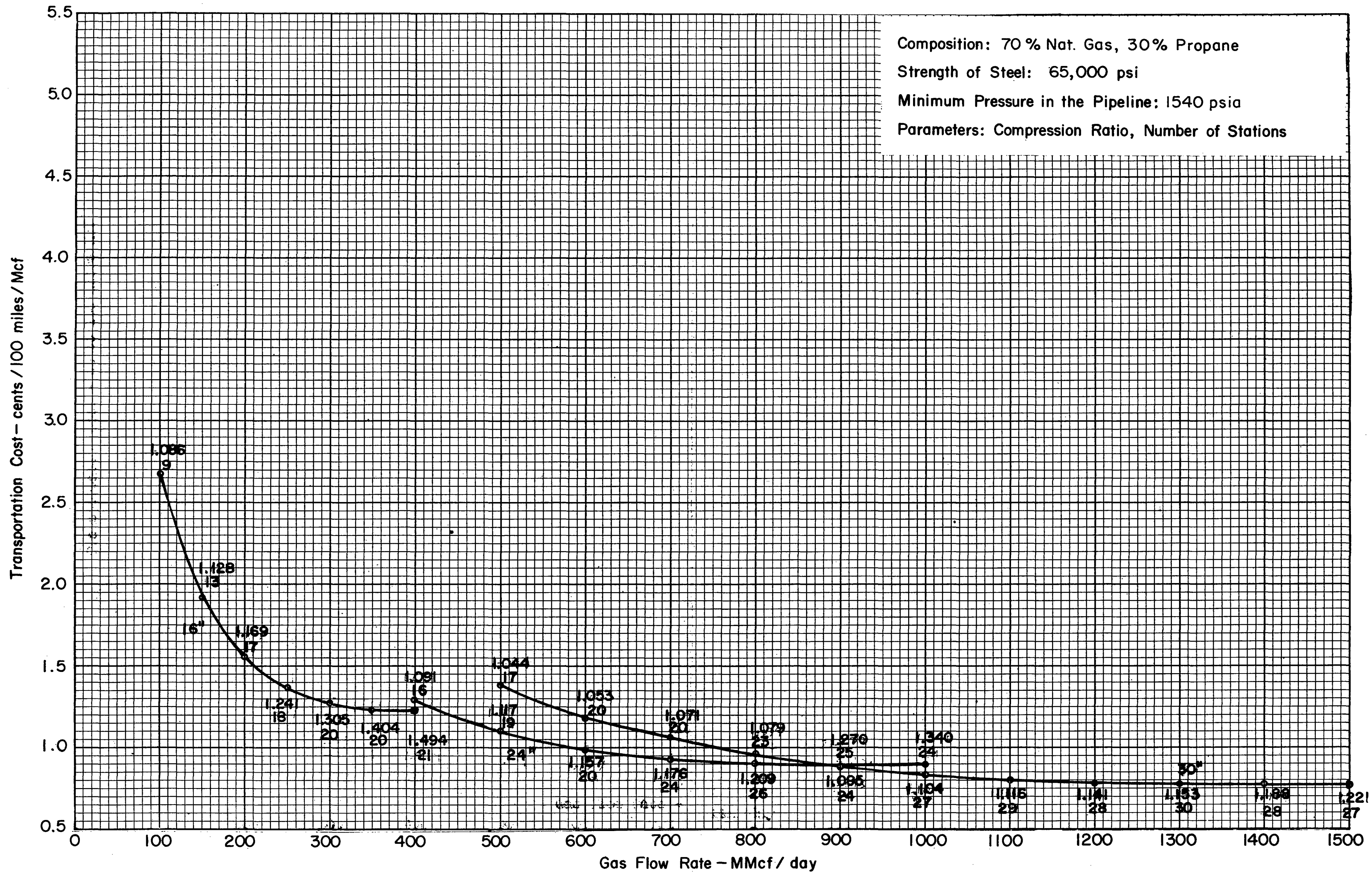


Figure 15E-23. Cost of Transportation versus Flow Rate

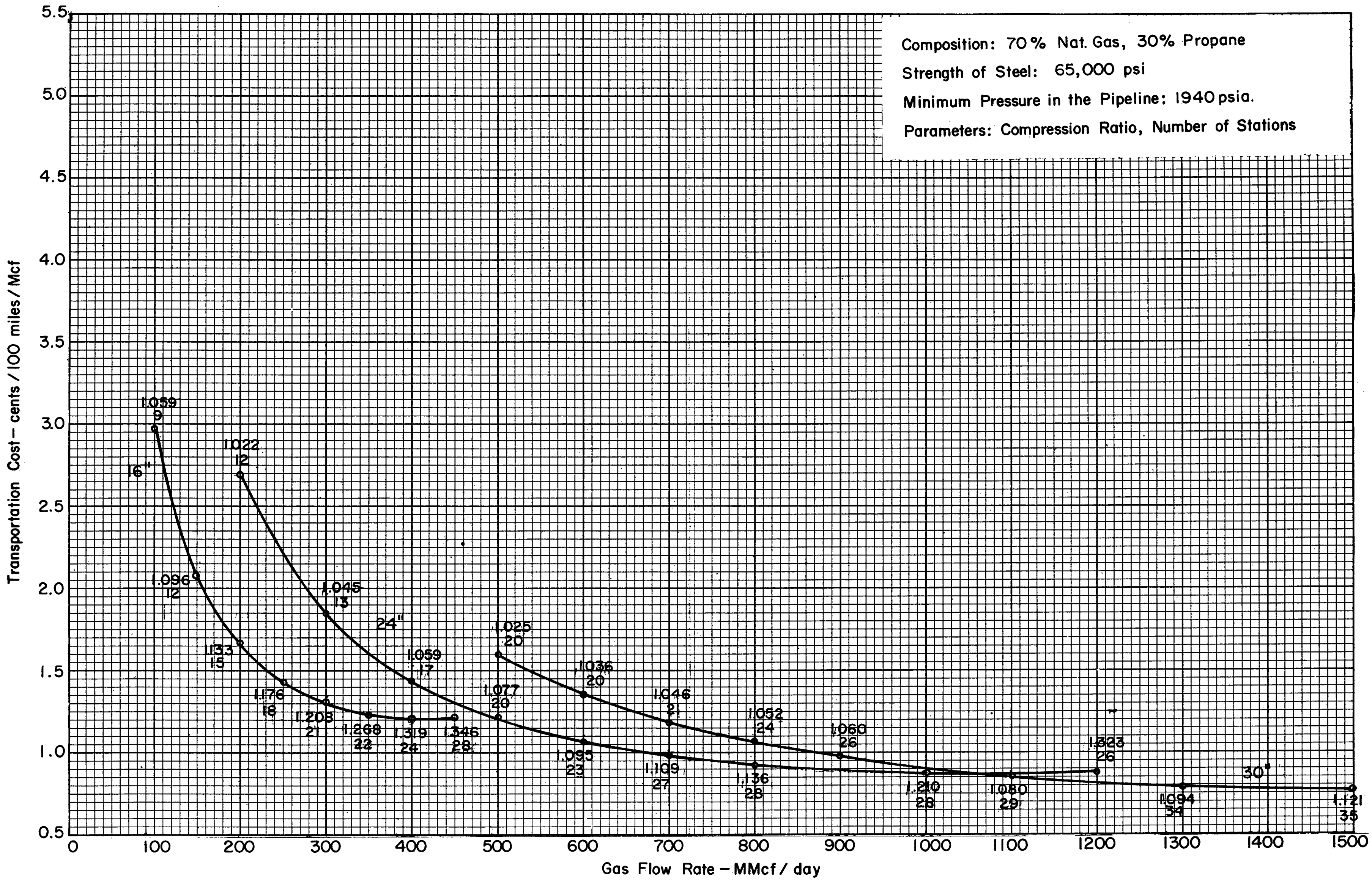


Figure 15E-24. Cost of Transportation versus Flow Rate

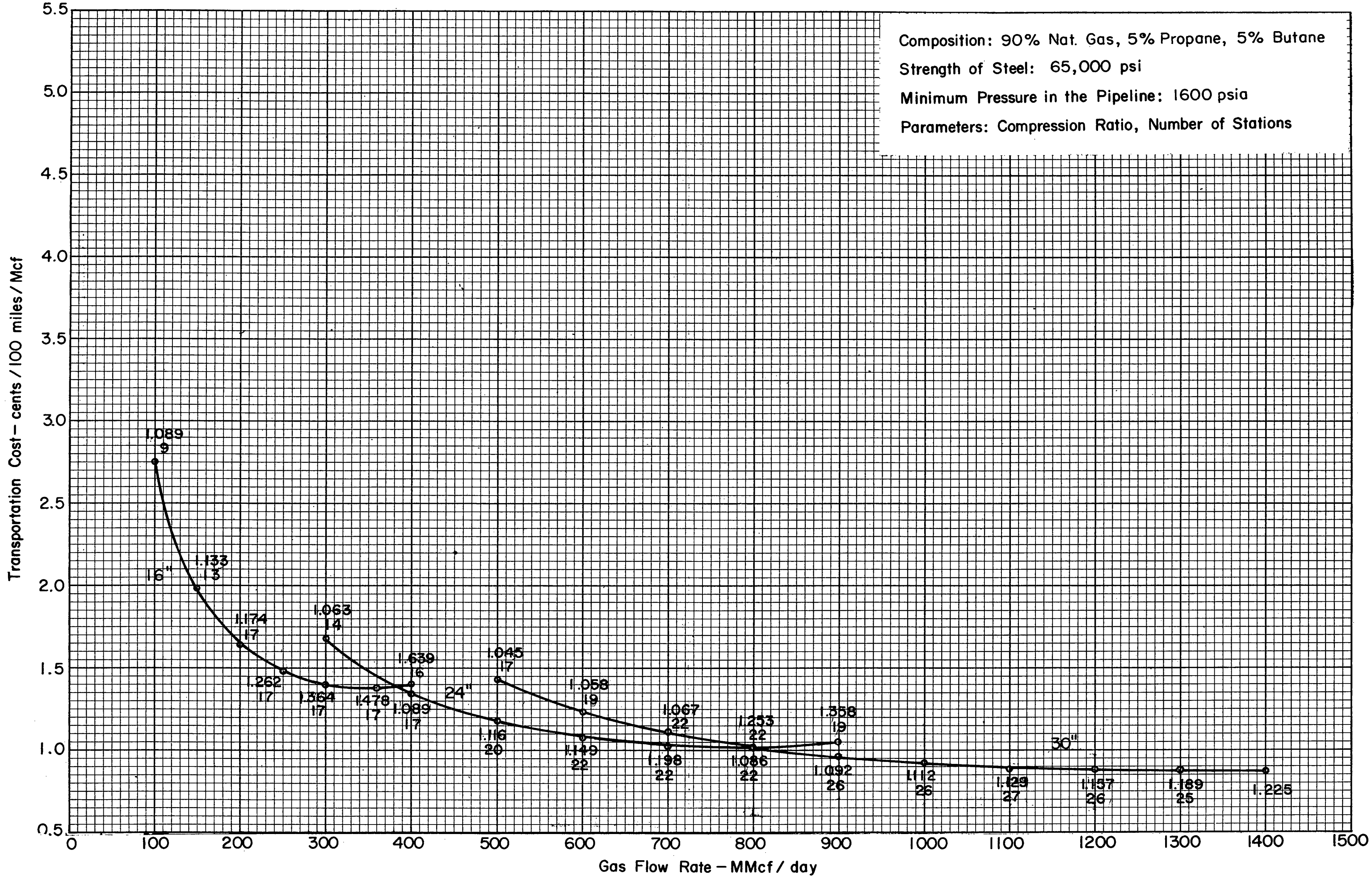


Figure 15E-25. Cost of Transportation versus Flow Rate

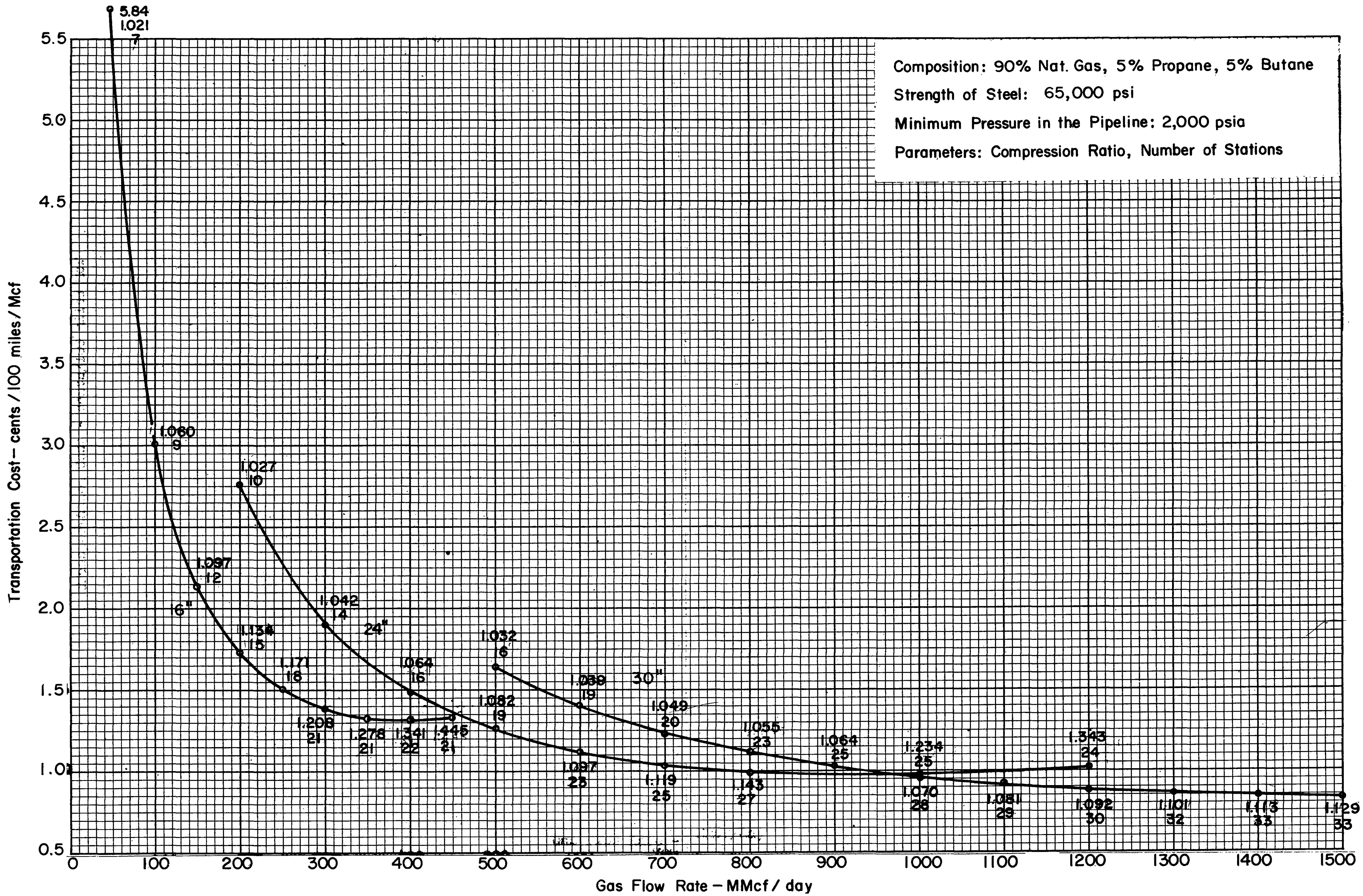


Figure 15E-26. Cost of Transportation versus Flow Rate

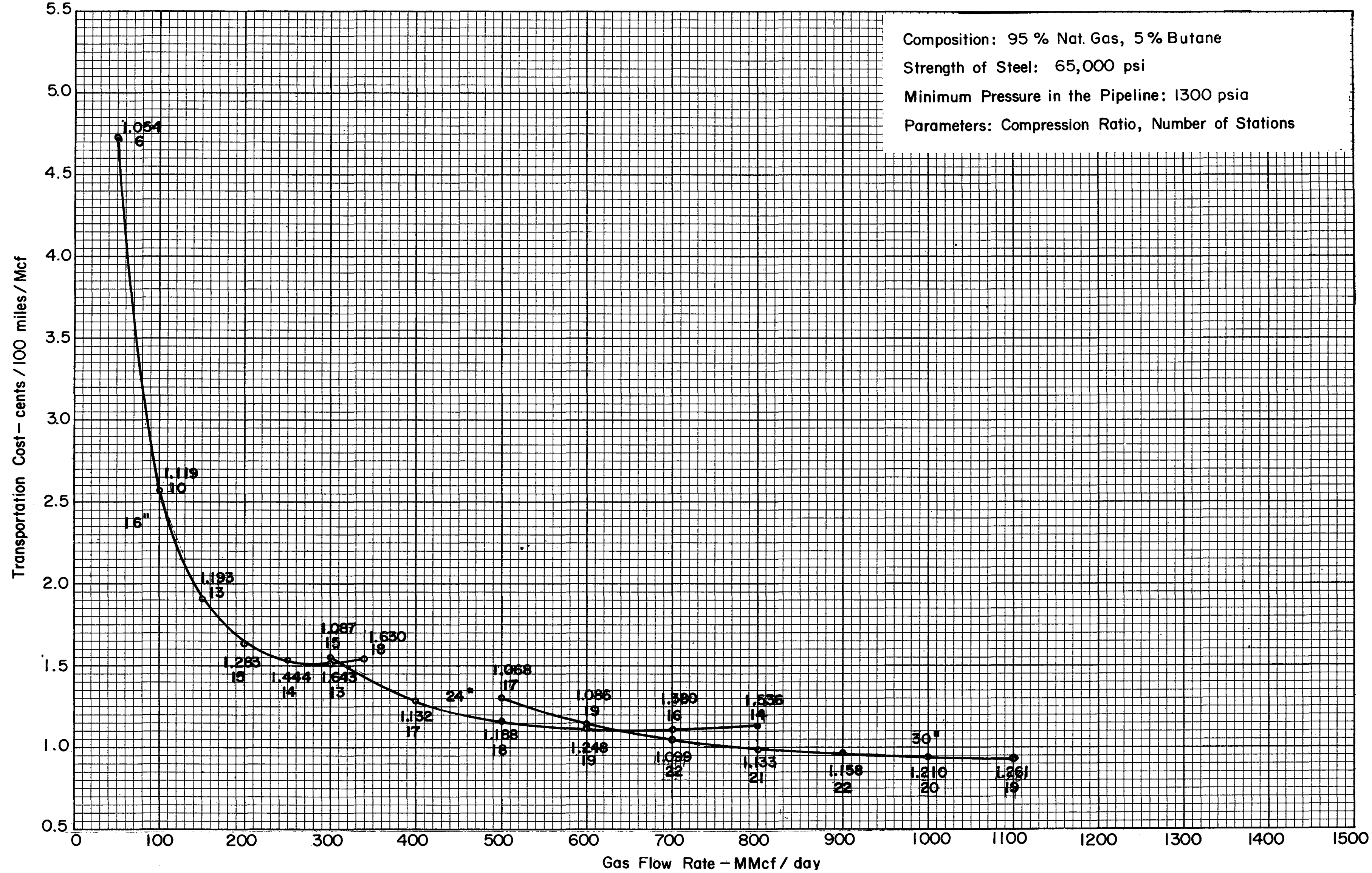


Figure 15E-27. Cost of Transportation versus Flow Rate

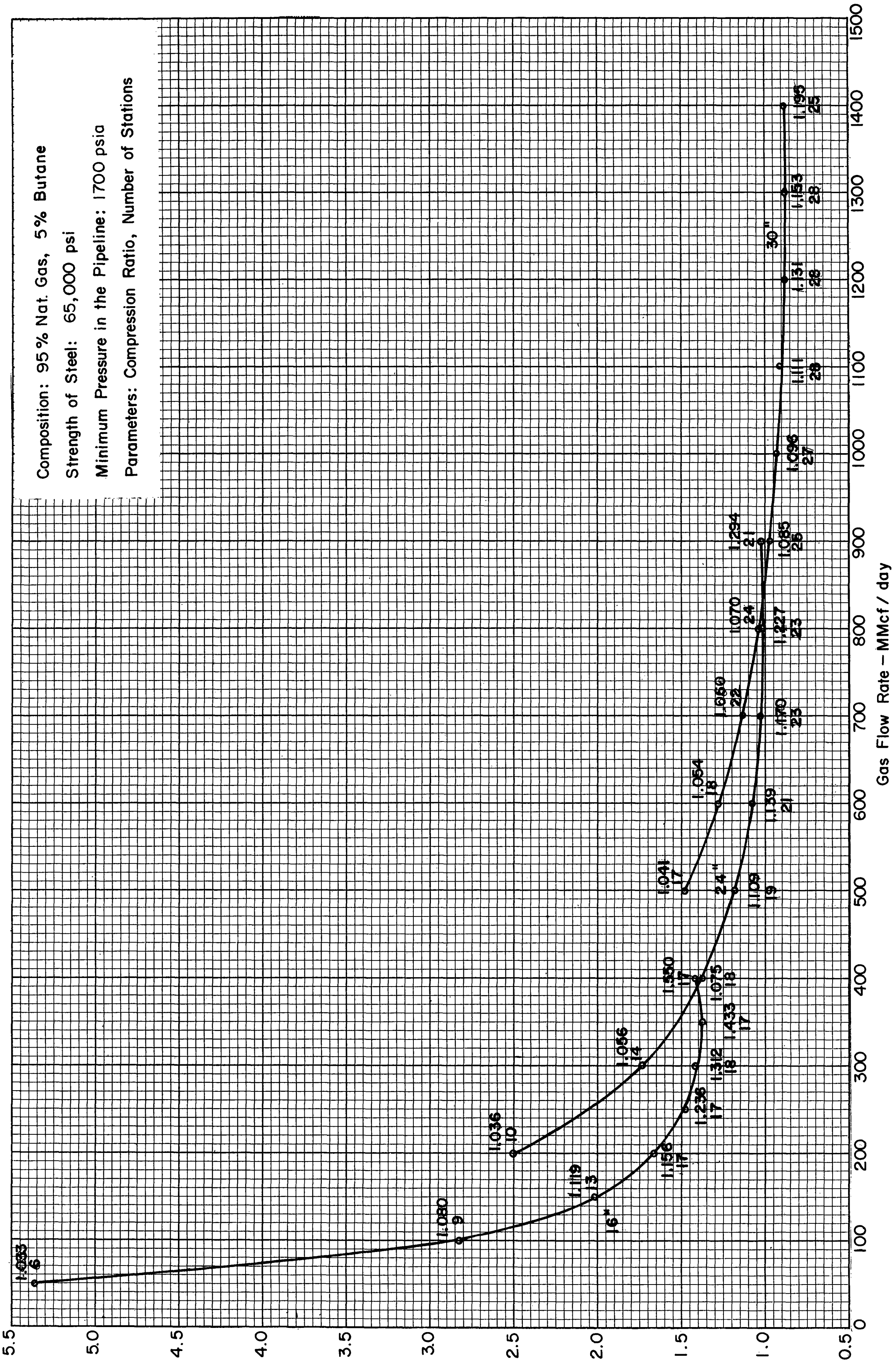


Figure 15E-28. Cost of Transportation versus Flow Rate

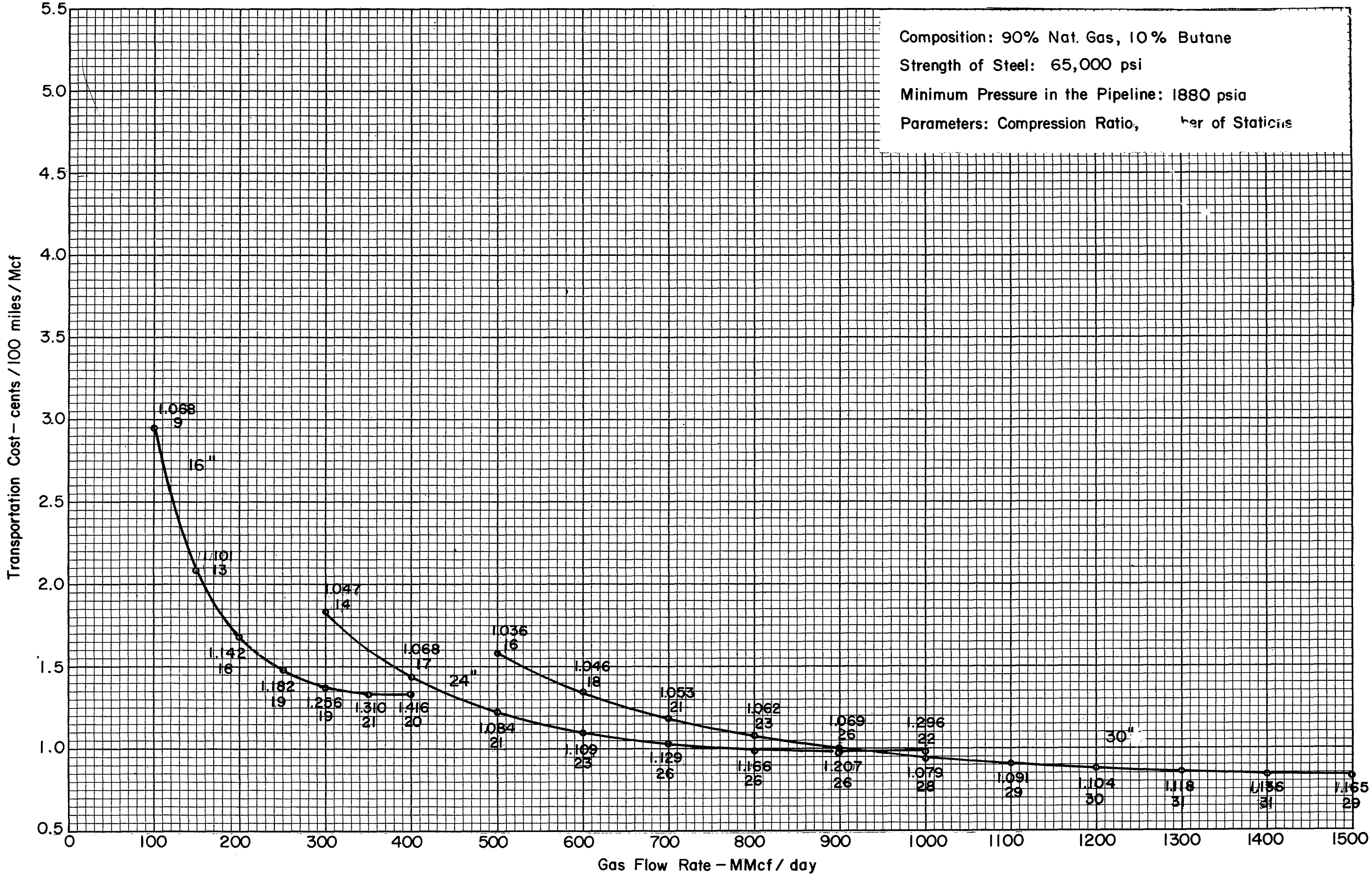


Figure 15E-29. Cost of Transportation versus Flow Rate

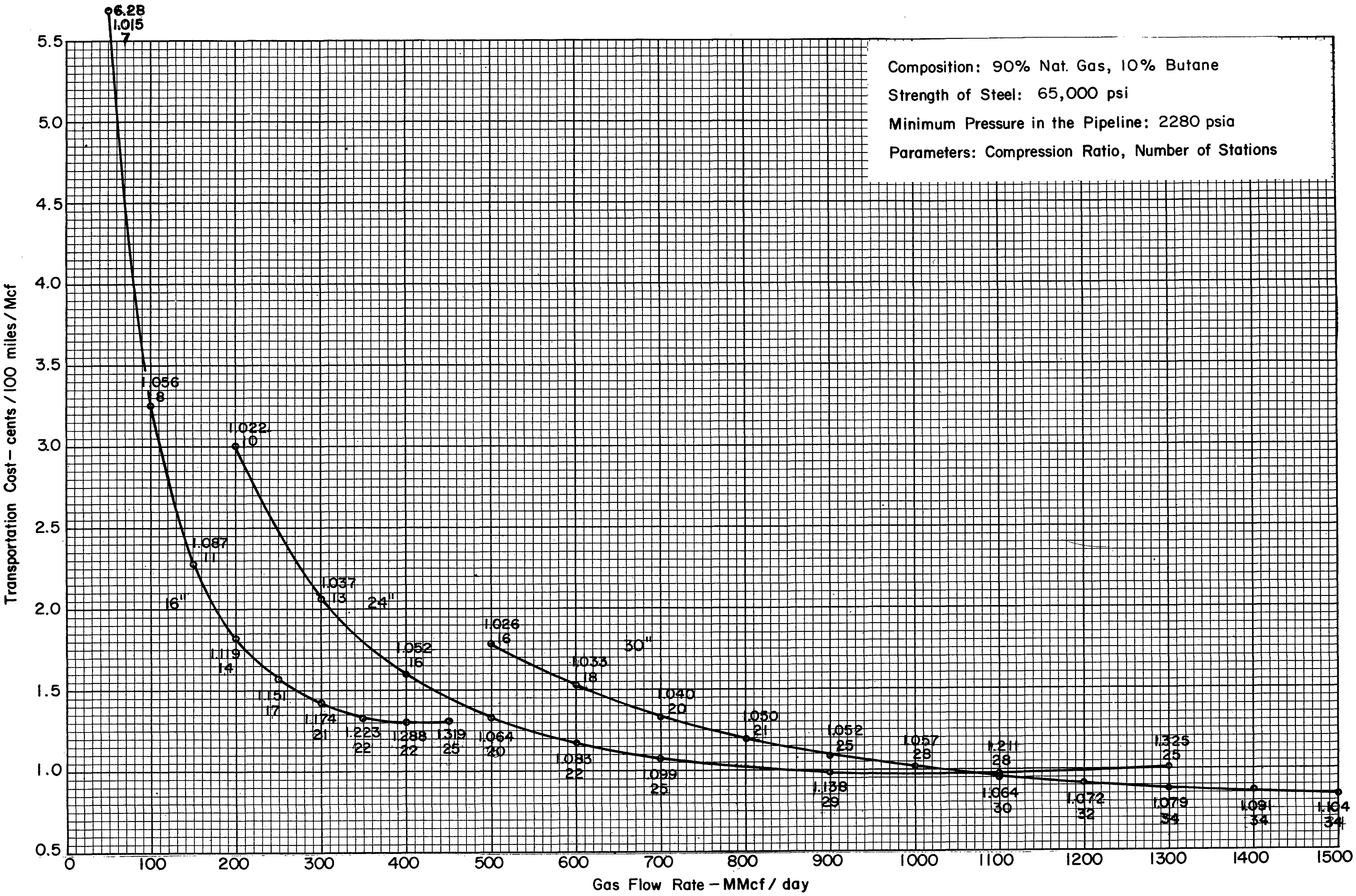


Figure 15E-30. Cost of Transportation versus Flow Rate

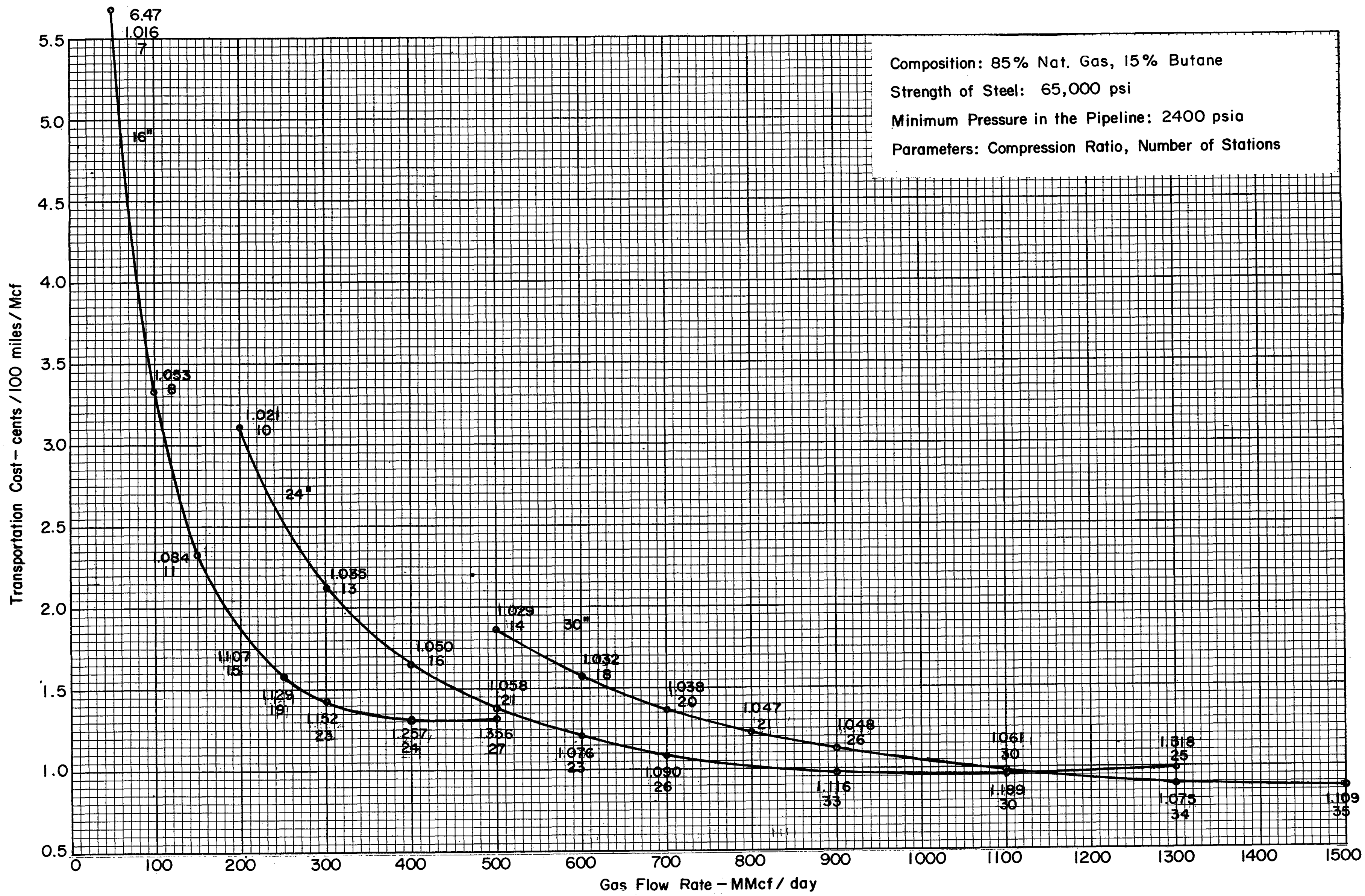


Figure 15E-31. Cost of Transportation versus Flow Rate

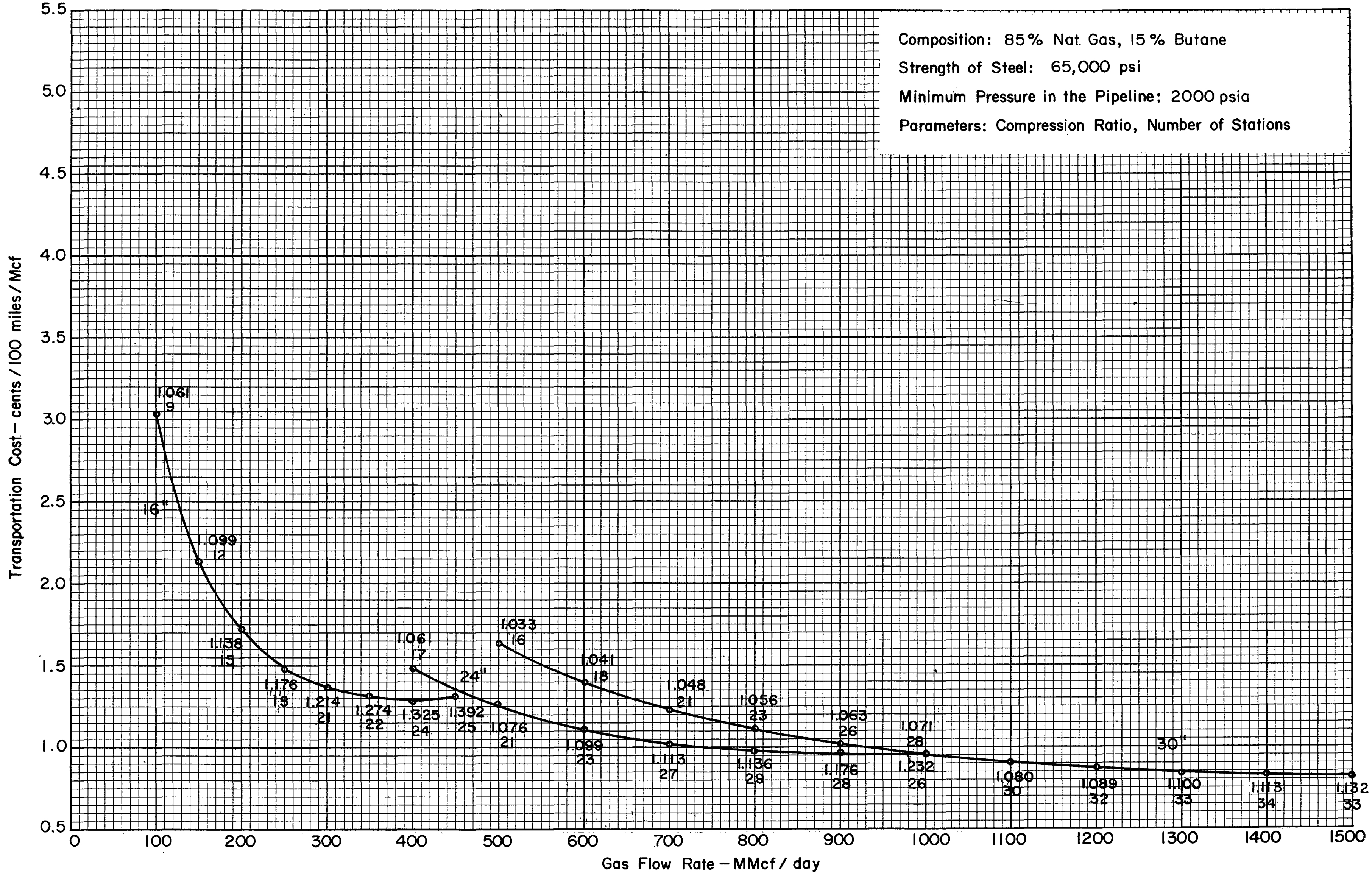


Figure 15E-32. Cost of Transportation versus Flow Rate

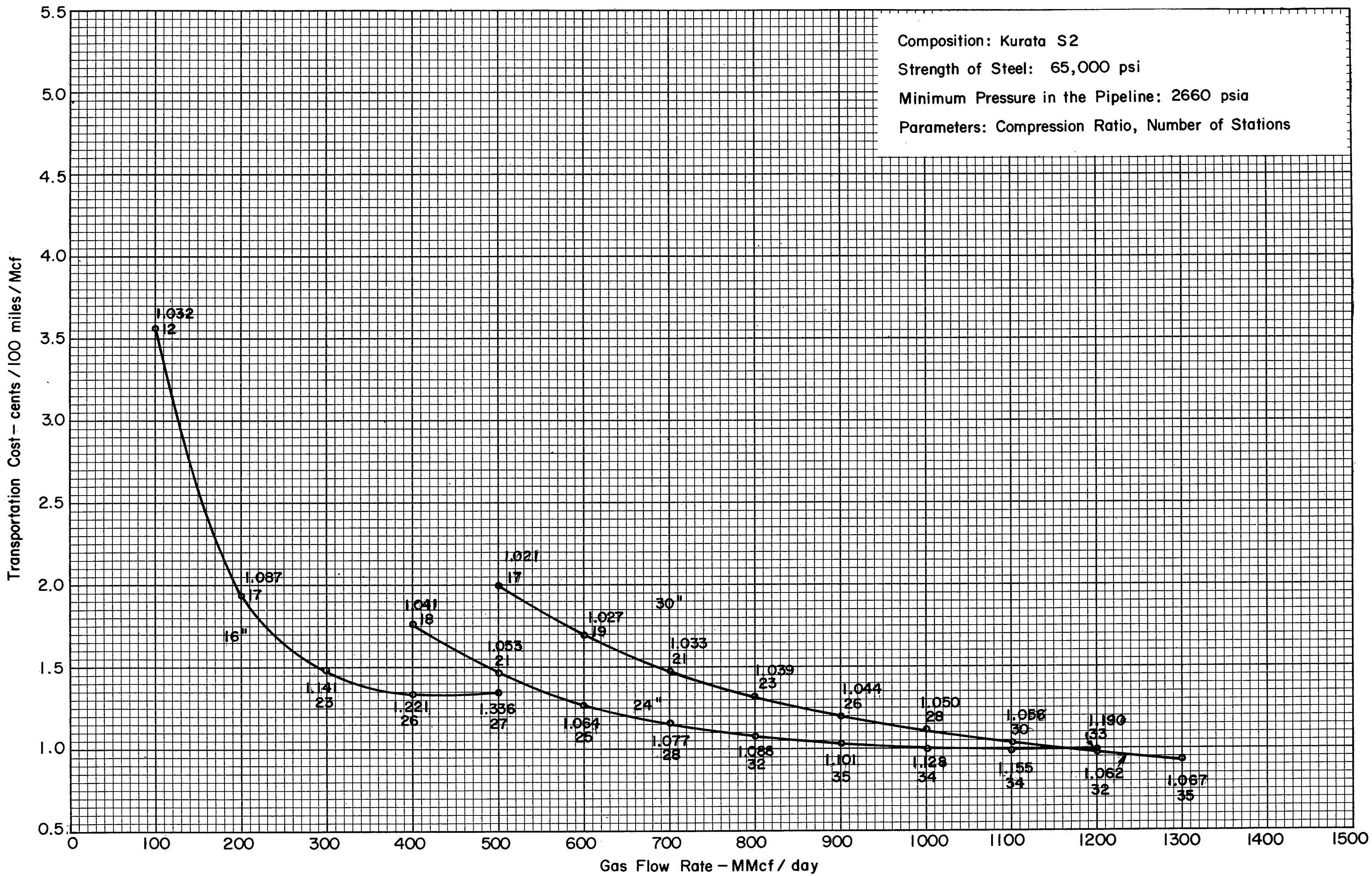


Figure 15E-33. Cost of Transportation versus Flow Rate

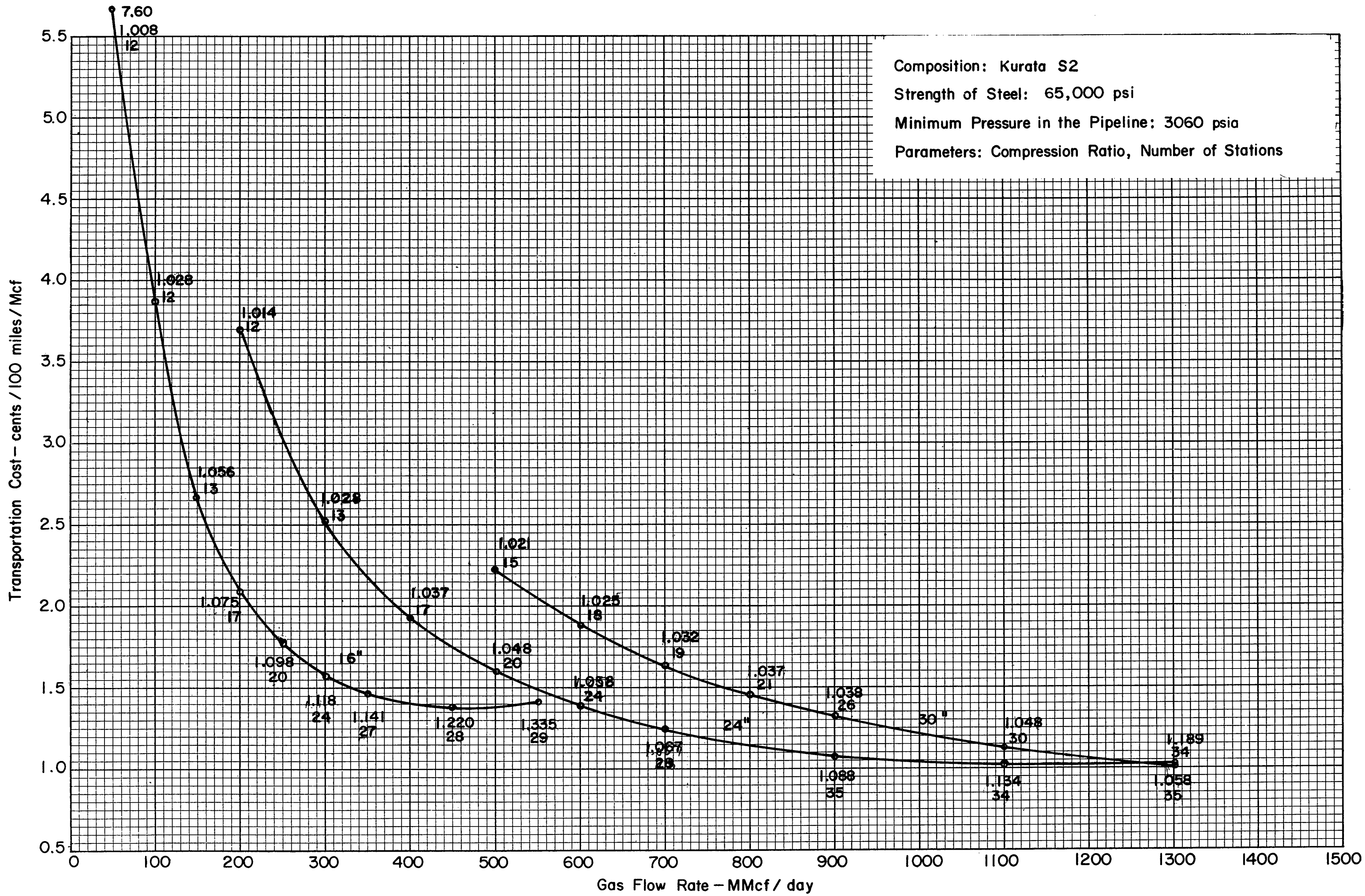


Figure 15E-34. Cost of Transportation versus Flow Rate

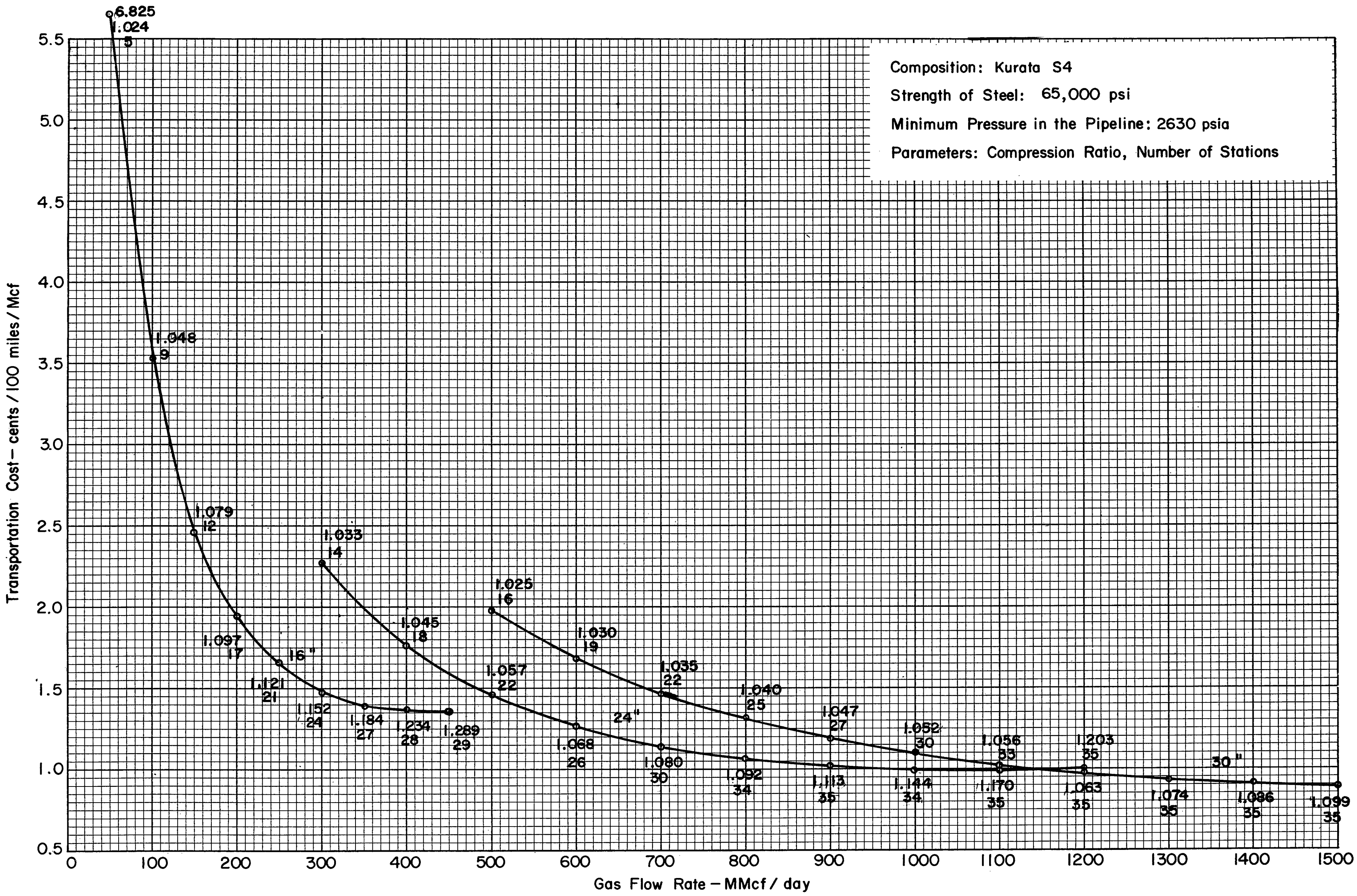


Figure 15E-35. Cost of Transportation versus Flow Rate

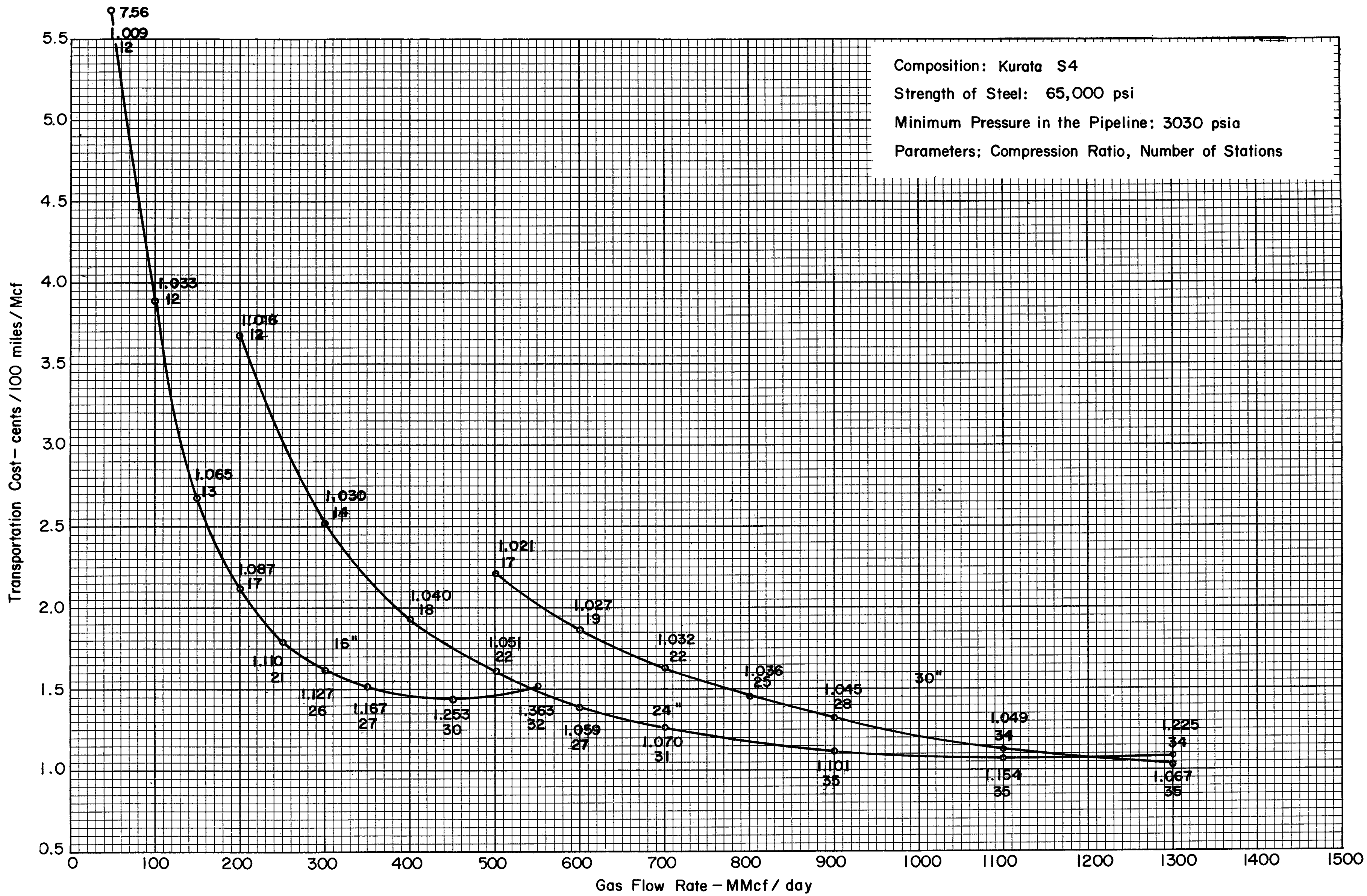


Figure 15E-36. Cost of Transportation versus Flow Rate

APPENDIX F

EXAMPLES OF SAREM'S METHOD FOR COMPUTING COMPRESSIBILITY FACTOR

Z'FAC

Example of the Use of Subroutine ZFAC

```
        TEST PROGRAM FOR SUBROUTINE ZFAC
        THIS PROGRAM CAN ACCEPT MIXTURES CONTAINING NITROGEN,
        METHANE TO N-HEXANE AND THREE ADDITIONAL COMPONENTS
        WITH KNOWN TC, PC, AND MOL. WT.
         ZERO.( FN2, FCO2, FCH4, FC2H6, FC3H8, FIC4H0, FNC4H0,            *001
       1       FIC5H2, FNC5H2, FNC6H4, FX, FY, FZ,TX, TY, TZ, PX, PY,     *001
       2 PZ, MX, MY, MZ  )                                                *001
         PRINT FORMAT TITLE                                               *002
         VECTOR VALUES TITLE= $1H1, T10, H*TEMP.*, T25, H*PRES.*, T40, H*TC*, T  *003
       1  52, H*PC*, T64, H*Z, CALCULATED*, T86, H*FROM Z CHART*, T10     *003
       2  6, H*G*  /*$                                                    *003
START    READ DATA                                                        *004
         PSUM=  FX*PX+ FY*PY + FZ*PZ                                      *005
         TSUM=  FX*TX+ FY*TY + FZ*TZ                                      *006
         MSUM=  FX*MX+ FY*MY + FZ*MZ                                      *007
         TC= TSUM+ FN2*TN2+ FCO2* TCO2+  FCH4* TCH4+ FC2H6* TC2H6+        *008
       1  FC3H8* TC3H8+ FIC4H0*TIC4H0+ FNC4H0* TNC4H0+ FIC5H2*TIC5H2      *008
       2  + FNC5H2* TNC5H2+ FNC6H4* TNC6H4                                *008
         PC= PSUM+ FN2*PN2+ FCO2* PCO2+  FCH4* PCH4+ FC2H6* PC2H6+        *009
       1  FC3H8* PC3H8+ FIC4H0*PIC4H0+ FNC4H0* PNC4H0+ FIC5H2*PIC5H2      *009
       2  + FNC5H2* PNC5H2+ FNC6H4* PNC6H4                                *009
         MWT=MSUM+ FN2*MN2+ FCO2* MCO2+  FCH4* MCH4+ FC2H6* MC2H6+        *010
       1  FC3H8* MC3H8+ FIC4H0*MIC4H0+ FNC4H0* MNC4H0+ FIC5H2*MIC5H2      *010
       2  + FNC5H2* MNC5H2+ FNC6H4* MNC6H4                                *010
         G= MWT/ 29.                                                      *011
         ZFAC.(T, P, TC, PC, G, Z)                                        *012
         PRINT FORMAT RESULT, T, P, TC, PC, Z, Z1  , G                    *013
         VECTOR VALUES RESULT= $1H ,T6, F10.2,T21,F10.2,T36,F10.2,T48,F10.2,T62,  *014
       1  F7.4, T84,WF7.4 , T104, F7.4*$                                  *014
         TRANSFER TO START                                                *015
         END OF PROGRAM                                                   *016
```

```
CALL .ATION OF COMPRESSIBILITY FACTOR(Z) BY US' OF
LEGENDRE POLYNOMIALS.
REF. SAREM, OIL AND GAS JOURNAL, SEP. 18, 1961, PAGE 118.
 EXTERNAL FUNCTION  (T, P, TC, PC,G, Z)          ZFAC Subroutine              *001
 ENTRY TO  ZFAC.                                                              *002
 DIMENSION           PM(10), PN(10)                                           *003
 INTEGER M,N                                                                  *004
 DIMENSION  A((0 ... 5)*(0 ... 5))                                            *005
 VECTOR VALUES  A(1)  =   2.1433504, 0.33123524, 0.10572871,                  *006
1 -0.052184 40,0.019703980, -0.00530959, 0.083176184,                         *006
2  -0.13403614, -0.050393654, 0.044312146, -0.026383354,                      *006
3  0.0089178330, -0.021467042,0.066880961, 0.0050924798                       *006
4 , -0.019329465, 0.019262143, -0.010894821, -0.00087140318                   *006
5 ,-0.027174261, 0.010551336, 0.0058972516, -0.01153539, 0                    *006
6  .009559389, 0.0042846283, 0.0088512291, -0.0073181933,                     *006
8    0.0015366676, 0.0042910089, -0.0060114017, -0.0016595343,                *006
9 -0.002152 929, 0.0026959963, -0.0028326809,- 0.00081302526,                 *006
1 0.0031175170                                                                *006
 WHENEVER TC .L. 0.01                                                         *007
 TC= G*100./0.32 + 171                                                        *008
 PC=  -G*25./ 0.545 + 699.7                                                   *009
 END OF CONDITIONAL                                                           *010
 PR= P/PC                                                                     *011
 TR= T/TC                                                                     *012
 X= (2.*PR-15.)/14.8                                                          *013
 Y= (2.*TR-4.)/ 1.9                                                           *014
 PM(0)= 0.7071068                                                             *015
 PN(0)= PM(0)                                                                 *016
 PM(1)= 1.224745*X                                                            *017
 PM(2)= 0.7905695 *(3.*X*X-1.)                                                *018
 PN(2)= 0.7905695 *(3.*Y*Y-1.)                                                *019
 PM(3)= 0.9354145*(5.*X.P. 3. -3.*X)                                          *020
 PN(3)= 0.9354145*(5.*Y.P. 3. -3.*Y)                                          *021
 PM(4)= 0.265165*(35.*X.P. 4.- 30.*X*X+3.)                                    *022
 PN(4)= 0.265165*(35.*Y.P. 4.- 30.*Y*Y+3.)                                    *023
 PM(5)= 0.293151*(63. *X.P. 5.- 70.*X.P. 3.+ 15.*X)                           *024
 PN(5)= 0.293151*(63. *Y.P. 5.- 70.*Y.P. 3.+ 15.*Y)                           *025
 PN(1)= 1.224745*Y                                                            *026
 Z=0.                                                                         *027
 THROUGH  ZLOOP, FOR N=0,1, N.G. 5                                            *028
 THROUGH  ZLOOP, FOR M=0,1, M.G. 5                                            *029
 Z= Z+ A(N,M)* PM(M)*PN(N)                                                    *030
ZLOOP  CONTINUE                                                               *031
 FUNCTION RETURN                                                              *032
 END OF FUNCTION                                                              *033
```

Computer Output

TEMP.	PRES.	TC	PC	Z, CALCULATED	FROM Z CHART	G
480.00	1000.00	378.43	669.68	.7267	.7280	.6534
480.00	1400.00	378.43	669.68	.6453	.6350	.6534
480.00	1800.00	378.43	669.68	.6181	.6000	.6534
480.00	2200.00	378.43	669.68	.6175	.6030	.6534
480.00	2600.00	378.43	669.68	.6369	.6320	.6534
480.00	3000.00	378.43	669.68	.6708	.6720	.6534
500.00	1000.00	378.43	669.68	.7515	.7720	.6534
500.00	1400.00	378.43	669.68	.6948	.6900	.6534
500.00	1800.00	378.43	669.68	.6663	.6450	.6534
500.00	2200.00	378.43	669.68	.6655	.6400	.6534
500.00	2600.00	378.43	669.68	.6726	.6580	.6534
500.00	3000.00	378.43	669.68	.6986	.6880	.6534
520.00	1000.00	378.43	669.68	.7886	.8020	.6534
520.00	1400.00	378.43	669.68	.7369	.7390	.6534
520.00	1800.00	378.43	669.68	.7084	.7000	.6534
520.00	2200.00	378.43	669.68	.6993	.6850	.6534
520.00	2600.00	378.43	669.68	.7063	.6950	.6534
520.00	3000.00	378.43	669.68	.7261	.7200	.6534
540.00	1000.00	378.43	669.68	.8193	.8300	.6534
540.00	1400.00	378.43	669.68	.7726	.7780	.6534
540.00	1800.00	378.43	669.68	.7451	.7350	.6534
540.00	2200.00	378.43	669.68	.7343	.7230	.6534
540.00	2600.00	378.43	669.68	.7377	.7270	.6534
540.00	3000.00	378.43	669.68	.7530	.7460	.6534

* ALL INPUT DATA HAVE BEEN PROCESSED.
AT LOC 16127

Z-factor equation developed for use in digital computers

Only 36 coefficients need be stored to permit a digital computer to generate Z factors. Capacity of small computers is not taxed, and mean deviation is as low as 0.004

BY A. M. SAREM

... research engineer in the production research department of Sinclair Research, Inc. He joined Sinclair in 1954 and since that time has done research in the field of fluid flow in porous media and phase behavior of hydrocarbons and associated fluids. He holds BS and MS degrees from University of Tulsa where he has also done postgraduate work in mathematics.

NATURAL-GAS and reservoir-engineering calculations involving the compressibility factor Z can best be handled in a computer program if the Z factors can be generated internally by a digital computer.

An accurate method of getting Z factors from a computer by use of a 20-by-20 input table was recently developed by Gray and Sims.[1] But for small and medium-sized computers the memory storage needed for this table lookup method seriously limits the scope of related programs. What is needed is a method that will supply the Z factors without using much storage capacity in a small computer.

The solution. To solve this problem, an equation requiring storage of only 36 coefficients was fitted to a chart in which Z was expressed as a function of p_r and T_r. Two sets of Legendre polynomials were used and the coefficients were found by the method of least squares.

Accuracy of such an approximation depends on the degree of the polynomials and the magnitude of the intervals chosen for fitting, among other things. For convenience and desired accuracy, the compressibility chart was tabulated at intervals of 0.1 on p_r and T_r for values of p_r between 0.1 and 14.9, and values of T_r between 1.05 and 2.95. Polynomials up to fifth degree were used.

The general equation is:

$$Z = \sum_{m=0}^{5} \sum_{n=0}^{5} A_{nm} P_m(x)\, P_n(y)$$

Where:

$$x = \frac{2p_r - 15}{14.8}$$

$$y = \frac{2T_r - 4}{1.9}$$

P_m, P_n are Legendre polynomials of degree m and n, respectively.

$$A_{nm} = \frac{\int_x \int_y Z(x,y)\, P_m(x)\, P_n(y)\, dy\,dx}{\int_x \int_y P_m^2(x)\, P_n^2(y)\, dy\,dx}$$

Expressions for the Legendre polynomials of degree 0-5 are given in Table 1. Calculated coefficients, obtained by numerical integration from the Z factor chart, are listed in Table 2.

TABLE 1 — LEGENDRE POLYNOMIALS OF DEGREE 0-5

$P_0(x) = 0.7071068$
$P_1(x) = 1.224745x$
$P_2(x) = 0.7905695\,(3x^2 - 1)$
$P_3(x) = 0.9354145\,(5x^3 - 3x)$
$P_4(x) = 0.265165\,(35x^4 - 30x^2 + 3)$
$P_5(x) = 0.293151\,(63x^5 - 70x^3 + 15x)$

Mean deviation between Z factors calculated by the method shown here and those appearing in the original chart was found to be acceptable. On the boundaries of the chart, where T_r = 1.05 and 2.95, and p_r = 0.1 and 14.9, 53 points showed a mean deviation of 0.013. For 300 points scattered uniformly throughout the chart, mean deviation was found to be 0.004.

References

1. Gray, E. H., and Simms, H. L., "Z Factor Determination in Digital Computers": The Oil and Gas Journal, July 20, 1959, p. 80.
2. Poettman, F. H., and Carpenter, P. G., "The Multiphase Flow of Gas, Oil, and Water Through Vertical Flow Strings with Application to the Design of Gas-Lift Installations": API Drilling & Production Practices, (1952), p. 257.
3. Brown, G. G., Katz, D. L., Oberfell, G. G., Alden, R. G., "Natural Gasoline and the Volatile Hydrocarbons": Section One Sponsored by NGAA, Tulsa, (1948), p. 38.

TABLE 2—VALUES OF THE COEFFICIENTS, A_{mn}

	m=0	m=1	m=2	m=3	m=4	m=5
n=0	2.1433504	0.083176184	−0.021467042	−0.00087140318	0.0042846283	−0.0016595343
n=1	0.33123524	−0.13403614	0.066880961	−0.027174261	0.0088512291	−0.0021520929
n=2	0.10572871	−0.050393654	0.0050924798	0.010551336	−0.0073181933	0.0026959963
n=3	−0.052184040	0.044312146	−0.019329465	0.0058972516	0.0015366676	−0.0028326809
n=4	0.019703980	−0.026383354	0.019262143	−0.01153539	0.0042910089	−0.00081302526
n=5	−0.0053095900	0.0089178330	−0.010894821	0.009559389	−0.0060114017	0.0031175170

APPENDIX G

VISCOSITY DATA USED TO REPRESENT CORRELATION

The points on the curves of Figs. 11 and 12 are listed in matrix form for interpolation by TAB to obtain viscosity at any reduced temperature, pressure, and molecular weight.

```
V(1)= 36.9, 38.,39.1,40.,41.1,42.1,43.2,44.1,45.4,46.1,
 32.4,34.1,36.,38.1,40.,42.3,44.8,46.4,48.2,50.,
  29.,31.,33.9,37.,40.8,44.2,48.,51.,54.1,57.,
   26.,29.2,34.,38.3,43.2,47.8,51.8,55.2,59.,62.3,
  24.2,29.,34.1,40.2,46.2,52.,57.,62.,66.3,70.8,
  23.,30.,39.8,48.8,57.2,64.8,72.,79.,85.9,92.,
  23.,34.,48.1,60.6,71.3,80.,87.8,95.1,102.1,108.3,
26.,42.2,63.,77.8,89.,98.4,108.,116.,124.1,130.3
  52.,78.,95.,101.6,116.,124.,132.,140.,148.,152. ,
90., 102., 113., 123., 132., 142., 151., 159., 163., 171.,
115., 126., 139., 149., 156., 163., 172., 180., 186., 192.,
135., 147., 158., 168., 178., 186., 195., 202., 210., 215.,
160., 170., 181., 192., 202., 212., 222., 231., 240., 248.,
186., 200., 210., 219., 228., 238., 247., 256., 265., 273.,
222., 233., 246., 256., 265., 273., 282., 290., 300., 305.,
265., 278., 290., 300., 310, 320., 330., 340., 350., 360.
V1(1)= 3., 2.5, 2., 1.7, 1.5, 1.3, 1.2, 1.1, 1. ,
.95, .90, .85, .75, .7, .65
MT(1)=15., 18., 21., 24., 27., 30., 33., 35.
KS(1)= 1.3, 1.205,1.14, 1.08, 1.04, 1.008, 1.004, 1.
NP=10        PRD(1)= 1., 2., 3., 4., 5., 6., 7., 8., 9., 10.
```

APPENDIX H

DATA FOR COMPRESSIBILITY FACTOR OF METHANE-PROPANE SYSTEM IN MATRIX FORM

```
 PP(1)=  200., 400., 600., 800., 1000., 1250., 1500., 1750., 2000.,
 2250., 2500., 2750., 3000., 3500., 4000., 4500., 5000.
          VFM(1)=  8.37, 2.23, 1.287, 1.262, 1.26, 1.212, 1.241,
 1.238, 1.227, 1.217, 1.213, 1.206,1.198, 1.184, 1.174, 1.164, 1.154,
13.06, 5.26, 1.917, 1.25, 1.251, 1.208, 1.219, 1.213, 1.201, 1.192,
 1.182, 1.173, 1.153, 1.142, 1.125, 1.111, 1.096,
 17.77, 5.63, 2.963, 1.809, 1.266, 1.236, 1.215, 1.2, 1.185,
 1.174, 1.162, 1.153, 1.142, 1.125, 1.111, 1.096, 1.084,
22.42, 7.32, 4.,  2.577, 1.74, 1.289, 1.234, 1.203, 1.185, 1.167,
 1.15, 1.139, 1.123, 1.1, 1.083, 1.068, 1.054,
24.14, 9.02, 5.04, 3.34, 2.341, 1.559, 1.317, 1.258, 1.222, 1.186,
 1.162, 1.142, 1.12, 1.091, 1.067, 1.046, 1.029,
 24.40, 10.71, 6.23, 4.11, 2.941, 2.02, 1.525, 1.402, 1.311, 1.252,
 1.205, 1.167, 1.138, 1.045, 1.06, 1.033, 1.01,
 24.75, 11.71, 7.11, 4.87, 3.54, 2.49, 1.868, 1.632, 1.459
 1.353, 1.27, 1.214, 1.173, 1.109, 1.062, 1.027, 0.9974
 VFM1(1)=  24.86, 7.26, 3.5,  1.465, 1.442, 1.414, 1.389, 1.366,
 1.353, 1.338, 1.325, 1.313, 1.303, 1.283, 1.266, 1.25, 1.236,
 25.8, 9.2,  4.59, 2.5, 1.482, 1.431, 1.399, 1.364, 1.345, 1.326,
 1.31, 1.292, 1.279, 1.255, 1.234, 1.217, 1.202,
 26.61, 9.75, 5.6, 3.54, 2.42, 1.533, 1.456, 1.401, 1.363, 1.333, 1.307,
 1.286, 1.266, 1.235, 1.213, 1.191, 1.173,
 27.29, 12.11, 6.45, 4.32, 3.09, 2.21, 1.615, 1.497, 1.424, 1.373,
 1.3333, 1.3, 1.273, 1.23, 1.197, 1.17, 1.147,
 27.88, 12.81, 7.71, 5.,   3.67, 2.63, 1.946, 1.704, 1.55, 1.453, 1.388,
 1.34, 1.301, 1.241, 1.198, 1.162, 1.134,
 28.38, 13.33, 8.29, 5.78, 4.28, 3.06, 2.445, 2.033, 1.767, 1.594,
 1.494, 1.415, 1.356,  1.268, 1.208, 1.161, 1.125,
 28.8, 13.75, 8.73, 6.24, 4.75, 3.6, 2.861, 2.366, 2.039, 1.811,
 1.652, 1.531, 1.441, 1.317, 1.234, 1.172, 1.127
 COM1(1)= 0.2, .3, .4, .5, .6, .7, .8, .9
```

APPENDIX I

SUBROUTINE FNGFRI FOR CALCULATION OF MOODY FRICTION FACTOR BY COLEBROOK RELATIONSHIP

EXPLANATION OF THE EXTERNAL FUNCTION FNGFRI

This external function solves by trial and error for the Moody friction factor using Colebrook relationship. It is good for both fully turbulent flow and for the flow in the transition zone. Explanation of its usage is as follows:

FNGFRI (FTB, D, EE, QB, G, MV, FT)

FTB = Set FTB = 1 for fully turbulent flow
= 0 for transition zone

D = Inside diameter of the pipe, in.

EE = Pipe roughness, in.

QB = Gas flow rate, ft^3/day

G = Gas gravity (mol wt/29.0)

MV = Viscosity of the mixture, lb/ft/sec

FT = $2/\sqrt{FM}$

FM = Moody friction factor

```
$COMPILE MAD, EXECUTE, DUMP ,PRINT OBJECT                    FNGFR
          RSUBROUTINE FOR FANNING FRICTION FACTOR(1/SQRT(F))
          RFOR FULLY TURBULANT SET FTB = 1.0, OTHERWISE SET IT ANYTHING
          RFT= 1/ SQRT(F) = 2/SQRT(FM)
          RREF. KATZ HANDBOOK EQUATION 7-23, PAGE 302
          R
           EXTERNAL FUNCTION  (FTB, D,        EE, QB, G, MU, FT)
           E'O  FNGFRI.
           INTEGER  FTB
           FT= 4.* LOG10.(D/EE)+2.28
           FT2 = FT
           W'R  FTB .E. 1 , T'O  FB
           RE=  1.3526E-5* QB*G/(MU*D)
 LOOP      FT1= FT2-4. *LOG10.(1.+ 4.67*D* FT/(EE*RE)  )
           W'R  .ABS. (FT1-FT)/FT  .L. .001
           T'O  FB
           O'E
           FT= FT1
           T'O  LOOP
           E'L
 FB        F'N
           E'N
```