THE DIRECT DETERMINATION OF THE ENTHALPY OF FLUIDS UNDER PRESSURE

by

Alan Edward Mather

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1967

Doctoral Committee:

Professor Donald L. Katz, Chairman
Professor Joseph J. Martin
Professor John E. Powers
Professor Edgar F. Westrum, Jr.
Professor G. Brymer Williams

ACKNOWLEDGEMENTS

The author wishes to express his appreciation for the assistance of many people during the course of this research:

To Professor D. L. Katz for his advice and encouragement during the supervision of the work.

To Professor J. E. Powers who was closely involved with this research, for his help, understanding, and encouragement.

To Professors J. J. Martin, E. F. Westrum, Jr., and G. B. Williams, for serving on the doctoral committee.

To J. C. Golba and V. F. Yesavage who contributed greatly to this work by assisting in all phases of the enthalpy project.

To N. W. Prodany for many helpful discussions, some of which involved the present research.

To E. A. Manker and D. T. Mage, who introduced me to the enthalpy project.

To E. R. Freedman, J. C. Golba, Jr., and P. Bandyopadhyay for assistance in reduction of data, I.J.S. Sehgal for preparation of figures and comparison of methods of prediction, and J. R. Gwozdz for calculations in the design of the calorimeter.

To members of the ORA Instrument Shop, particularly E. Rupke, Supervisor, who made the shop services available whenever they were needed, and H. Senecal, who fabricated the isothermal throttling calorimeter and made suggestions which contributed much to its success.

To members of the staff of the Chemical and Metallurgical Engineering Department in particular C. Bolen, D. Connell, and F. Drogosz for their help in the mechanical and analytical problems which arose.

The author is also indebted to the following organizations:

To the Natural Gas Processors Association for continued support of the research and for provision of fellowships.

To the Continental Oil Company for a fellowship.

To the American Petroleum Institute for support of Mr. Golba.

To the Southern California Gas Company for the supply of the methane used in this work.

To the Dow Chemical Company for the gift of a large quantity of Styrofoam.

To the National Bureau of Standards for the calibration of thermocouples and standard cells.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES - (Cont.)

LIST OF FIGURES - (Cont.)

NOMENCLATURE

a, b, c	Constants in B-W-R equation of state
A_o, B_o, C_o	Constants in B-W-R equation of state
A, B, C, D	Flow meter calibration constants
B	Second virial coefficient in volume expansion
B'	Second virial coefficient in pressure expansion
C	Third virial coefficient in volume expansion
C'	Third virial coefficient in pressure expansion
f	Fugacity
$\bar{f}$	Fugacity in a solution
F	Mass flow rate
$\underline{H}$	Specific enthalpy
$\bar{H}$	Partial molal enthalpy
$\Delta\underline{H}vap$	Enthalpy change on vaporization
P	Pressure
P_c	Critical pressure
P_r	Reduced pressure, P/P_c
ΔP	Pressure drop
$\dot{Q}$	Rate of transfer of heat
R	Gas constant
T	Temperature
T_c	Critical temperature
T_r	Reduced temperature, T/T_c
$\underline{V}$	Specific volume

$\dot{W}$	Rate of transfer of work
x	Composition
Z	Compressibility factor, $P\underline{V}/RT$
α	Constant in B-W-R equation of state
γ	Constant in B-W-R equation of state
δ	Constant in modified B-W-R equation of state
ε	Percentage error
μ	Joule-Thomson coefficient
μ	Viscosity
ρ	Density
ϕ	Isothermal throttling coefficient
ω	Acentric factor

Subscripts

c	Critical property
$\underline{H}$	Constant enthalpy
i	Component in mixture
mix	Mixture property
P	Constant pressure
T	Constant temperature
1	Initial state
2	Final state
11,22	Pure component interaction
12	Mixture interactions between 1 and 2

Superscripts

E	Excess property
o	Zero-pressure property

ABSTRACT

Accurate values of enthalpy are directly useful in design but they are also needed to test theories of fluids, to improve methods of prediction, and to derive other thermodynamic properties. The purposes of this work were:

1) To modify the existing recycle system and isobaric flow calorimeter to allow measurements under conditions different from those for which the equipment was originally designed.
2) To obtain accurate data on the effect of temperature on enthalpy for mixtures of methane with propane and with nitrogen.
3) To design, construct, and test a device for the direct measurement of the effect of pressure on enthalpy.

The flow calorimeter recycle system was modified by the installation of a Corblin diaphragm compressor to prevent contact of the gas mixture with the compressor oil. A second six-junction calibrated thermopile was installed in the isobaric calorimeter as a check on the original thermopile. The new thermopile is calibrated up to +150°C thus allowing accurate measurements to higher temperatures. Other modifications were made to the recycle system to increase the ease of operation.

The facility was used to obtain isobaric data on the effect of temperature on enthalpy for mixtures of 11.7 mole percent propane in methane, 28 mole percent propane in methane, and 43.4 mole

percent nitrogen in methane. These experimental data covered the liquid, two-phase, and gaseous regions at temperatures from -240°F to +130°F at pressures from 250 to 2000 psia. With supplemental data on the effect of pressure on enthalpy from the literature, pressure - enthalpy - temperature diagrams and skeleton enthalpy tables for these mixtures were prepared.

Detailed consideration of the various means of measuring the effect of pressure on enthalpy led to the choice of an isothermal throttling calorimeter. In common with several other throttling calorimeters, a capillary tube is used to cause the pressure drop and electrical energy is added to make the expansion essentially isothermal. However, an innovation in this design is the heater, an insulated resistance wire which passes axially through the capillary. The pressure drop across the calorimeter is measured by a differential pressure balance and any temperature difference between the inlet and outlet is sensed by calibrated duplicate six-junction thermopiles.

Measurements of the effect of pressure on enthalpy were made with nitrogen as a test gas at -147°F, 33°F, and 201°F at pressures from 2000 psia to 100 psia. The data are in agreement with values from the literature; however, the literature values disagree among themselves by up to 4 percent. Measurements were made on a mixture of 5.2 mole percent propane in methane at temperatures of -147°F, -27°F, 92°F, and 200°F. At the highest isotherm, measurements were made in two different capillary coils to test the effect of flow rate. The data from the two coils agreed with a maximum deviation of ±1 percent.

Isobaric measurements were also made on the 5.2 mole percent propane in methane mixture to extend the data of Manker from 80°F to 250°F. A skeleton enthalpy table and an enthalpy diagram for this mixture covering the range -280°F to + 300°F at pressures up to 2000 psia was constructed which is based almost entirely on direct experimental determinations.

THE DIRECT DETERMINATION OF THE ENTHALPY OF FLUIDS UNDER PRESSURE

INTRODUCTION

A knowledge of the enthalpy behavior of a fluid is necessary for the rational design of processes involving the transfer of heat and work. In the past, the data used in design were obtained principally from P-V-T data, either directly using thermodynamic relations or indirectly using an equation of state. The process of generating enthalpies from compressibility data involves differentation with attendent loss in accuracy of at least one order of magnitude. In a region where the derivatives are changing rapidly, such as the critical region, the error may be very large. For this reason, it is desirable to have enthalpies which were measured directly; because of the time involved and the expense of obtaining such data, few have been published. It is, of course, impossible to obtain data for all the materials of interest over wide ranges of pressures and temperature; however, experimental data on selected materials and mixtures are useful not only in themselves, but also for derivation of other thermodynamic properties.

The goal of this work was to obtain data on the isobaric effect of temperature on enthalpy for mixtures of methane with propane and with nitrogen, and to develop, fabricate, and test a device for the measurement of the effect of pressure upon enthalpy. Section I presents the pertinent thermodynamic relations, reviews the recent literature on enthalpy data and methods of prediction, and presents a listing of previous work on the two binary systems studied in this work.

Section II considers the isobaric effect of temperature on enthalpy, describes modifications to the equipment used and presents data for nitrogen, a mixture of methane and nitrogen and three mixtures of propane and methane. Section III considers the isothermal effect of pressure on enthalpy, reviews previous work of this type and describes the calorimeter developed in the course of this work. The experimental results obtained are compared with other direct measurements, with Joule-Thomson data, and with values derived from compressibility data. The construction of skeleton enthalpy tables and pressure - enthalpy - temperature diagrams for the mixtures is discussed in Section IV along with comparisons of some of the results of this work with data from the literature.

SECTION I - PRELIMINARY CONSIDERATIONS

In this section, the thermodynamic relations which will be required are presented, a review of recent experimental enthalpy data is given and the methods of prediction of the enthalpy of mixtures are considered briefly with emphasis on those methods which will be used later in comparison with the experimental data. A review of all experimental data on the two binary systems studied in this work, methane - propane and methane - nitrogen, is also presented.

Thermodynamic Relations

The first law of thermodynamics, applied to a flow calorimeter with negligible potential and kinetic energy effects is:

$$\left[\underline{H}_{T_2,P_2} - \underline{H}_{T_1,P_1}\right]_x = \frac{\dot{Q} - \dot{W}}{F} \tag{1}$$

where $\dot{Q}$ is the rate of heat leak, $\dot{W}$ is the rate of electrical energy transfer, and F is the mass flow rate. Flow calorimeters may be designed for various modes of operation. In the isobaric mode, the pressure difference P_2-P_1 is made small and the fluid is heated to change its temperature. Equation (1) becomes:

$$\left[\underline{H}_{T_2} - \underline{H}_{T_1}\right]_{P_1,x} = \frac{-\dot{W}}{F} - \int_{P_1}^{P_2} \left(\frac{\partial \underline{H}}{\partial P}\right)_T dP \Bigg]_{T_1} \tag{2}$$

where the integral term is the correction for the small pressure drop and $\dot{Q}$ is assumed to be negligible. In the isenthalpic mode, no energy is added to the system and the heat leak is made negligible. For this case Equation (1) reduces to

$$\left[\underline{H}_{T_2,P_2} - \underline{H}_{T_1,P_1}\right]_x = 0 \qquad (3)$$

In a flow calorimeter operated in the isothermal mode, a pressure drop is imposed on the fluid, and electrical energy is added to return the outlet temperature to that of the inlet. It is possible to utilize this scheme only when the Joule-Thomson coefficient is positive, i.e. when the fluid cools upon expansion. For an isothermal expansion, Equation (1) reduces to:

$$\left[\underline{H}_{P_2} - \underline{H}_{P_1}\right]_{T_1,x} = \frac{-\dot{W}}{F} - \int_{T_1}^{T_2} C_p \, dT\Big|_{P_2} \qquad (4)$$

where $\dot{Q}$ is assumed negligible and the integral corrects for any mismatch between the inlet and outlet temperatures.

In the two-phase region, Equation (1) can be used to determine the enthalpy change on vaporization. For a binary mixture, it is possible to define an infinite number of paths across the two-phase region, but only the isobaric and isothermal paths are of general interest and the enthalpy changes are obtained from Equations (2) and (4).

The relations presented above involve integral changes in enthalpy. These integral data in a single-phase region may be interpreted to yield the derivative enthalpy properties: the heat capacity, the Joule-Thomson coefficient, μ, and the isothermal throttling coefficient, ϕ. Thus

$$C_p \equiv \left(\frac{\partial \underline{H}}{\partial T}\right)_P = \lim_{\Delta T \to 0} \left[\frac{(\underline{H}_{T_2} - \underline{H}_{T_1})_{P_1,x}}{T_2 - T_1}\right] \qquad (5)$$

and

$$\mu \equiv \left(\frac{\partial T}{\partial P}\right)_{\underline{H}} = \lim_{\Delta P \to 0} \left[\frac{T_2 - T_1}{P_2 - P_1}\right]_{\underline{H},x} \qquad (6)$$

and

$$\phi \equiv \left(\frac{\partial \underline{H}}{\partial P}\right)_T = \lim_{\Delta P \to 0} \left[\frac{(\underline{H}_{P_2} - \underline{H}_{P_1})_{T_1,x}}{(P_2 - P_1)}\right] \qquad (7)$$

These three derivatives are related by the mathematical identity:

$$\phi = -\mu C_p \qquad (8)$$

The isothermal throttling coefficient, ϕ, can be expressed in terms of volume, temperature, and pressure as:

$$\phi = \underline{V} - T \left(\frac{\partial \underline{V}}{\partial T}\right)_P \qquad (9)$$

thus allowing this coefficient to be obtained from compressibility data or an equation of state. It is instructive to consider the zero-pressure limit of ϕ.

The virial expansion, which is an open form of an equation of state, is a power series in density:

$$\frac{P\underline{V}}{RT} = 1 + \frac{B}{\underline{V}} + \frac{C}{\underline{V}^2} + \text{---} \qquad (10)$$

The terms B, C, --- are known as the second, third, --- virial coefficients and they are related by the statistical theory of imperfect gases to the interactions of molecules in pairs, triplets, etc.

A similar power series is an expansion in pressure:

$$\frac{P\underline{V}}{RT} = 1 + B'P + C'P^2 + \text{---} \qquad (11)$$

The coefficients of the two series are related by:

$$B' = B/RT \qquad (12)$$

$$C' = (C-B^2) \,/\, (RT)^2 \qquad (13)$$

Using equations (9), (11), (12) and (13), ϕ can be expressed as:

$$\phi = -T^2 \left[\frac{d}{dT}\left(\frac{B}{T}\right) + P \frac{d}{dT}\left(\frac{C}{T}\right) + \text{---} \right] \qquad (14)$$

The zero-pressure value of ϕ is finite and depends only on B:

$$\phi^o = B - T\left(\frac{dB}{dT}\right) \qquad (15)$$

Experimental values of ϕ^o can be used to derive changes in B upon integration of Equation (15) or they can be compared with values of ϕ^o calculated from virial coefficients obtained from other types of experiments. For binary mixtures, B is of the form:

$$B_{mix} = x_1^2 B_{11} + 2x_1x_2 B_{12} + x_2^2 B_{22} \qquad (16)$$

where B_{11} and B_{22} are the pure component second virial coefficients and B_{12} is the interaction virial coefficient. It follows that the derivative of B_{mix} is:

$$\frac{dB_{mix}}{dT} = x_1^2 \left(\frac{dB_{11}}{dT}\right) + 2x_1x_2 \left(\frac{dB_{12}}{dT}\right) + x_2^2 \left(\frac{dB_{22}}{dT}\right) \qquad (17)$$

The enthalpy change on mixing can be determined in a flow calorimeter by mixing two pure gases in a chamber and adding electrical energy to equalize the inlet and outlet temperatures. The first law of thermodynamics for this calorimeter reduces to:

$$\left[\underline{H}_{mix}\right]_{T_2,P_2} - \left[x_1\underline{H}_1 - x_2\underline{H}_2\right]_{T_1,P_1} = \frac{\dot{Q} - \dot{W}}{F} \qquad (18)$$

Corrections can be made for the differences in pressure and temperature between the inlet and outlet and the excess enthalpy or heat of mixing can be determined by:

$$\underline{H}^E = \left[\underline{H}_{mix} - x_1\,\underline{H}_1 - x_2\,\underline{H}_2\right]_{P,T} \qquad (19)$$

Review of Experimental Data

All of the thermal properties mentioned above have been measured experimentally with most data being obtained on pure components. Reviews of data have been presented by Masi[128] and Barieau[5]. A review of Joule-Thomson data was made by Johnston and White[93], while Potter[148] has considered both Joule-Thomson and isothermal throttling coefficient data. Table I presents a listing of the experimental determinations of thermal properties under pressure, supplementing that of Mage[120]. Emphasis has been placed on mixture data and, in general, references to pure component data are included only if they did not appear in earlier reviews. Although an increased amount of enthalpy data has become available, the need for more data to test methods of prediction and improve correlations remains.

TABLE I

RECENT REFERENCES TO EXPERIMENTAL THERMAL DATA ON FLUIDS UNDER PRESSURE

Constant Pressure Heat Capacity Data

Year	System	Authors	Reference
1956	Methanol, benzene Methanol-benzene Methanol-hexane Methanol-benzene-hexane	McCracken and Smith	115
1960	Carbon dioxide	Koppel and Smith	105
1960	Ethanol, benzene, n-Pentane, Ethanol-benzene, Ethanol-n-pentane	Storvick and Smith	178
1962	1-Propanol, ethyl ether, isopropyl ether, acetone, methyl ethyl ketone	Eubank and Smith	54
1963	Methane	Jones *et al.*	95
1963	Nitrogen	Mage *et al.*	119
1963	Natural gas, methane	Hujsak, Froning, and Goddin	88
1963	Air, nitrogen, methane-nitrogen	Jenkins and Berwaldt	92
1963	1-Propanol-benzene	Costa and Smith	34
1964	Methane-propane	Manker *et al.*	122

Year	System	Authors	References
1965	Carbon dioxide	Vukalovich, Altunin, and Gureev	191
1965	Methane-ethane-propane-nitrogen	Nathan	136
1965	Heavy water	Stepanov and Mursalov	175
1965	Methane, nitrogen	Sahgal *et al.*	166
1966	Methane-propane, methane-nitrogen	Mather *et al.*	130
1966	Water	Sirota and Grishkov	171
1966	Helium-nitrogen	Mage and Katz	121
1966	Methane, nitrogen, methane-hydrogen	Wiener	193
1967	Natural gas	Wilson and Barton	196
1967	Methane-propane	Mather *et al.*	131
1967	Propane-isopentane	Lenoir	112
1967	Natural gas	Laverman and Selcukoglu	111
1967	Hydrogen	Medvedev, Dedikov, and Astrov	134

Latent Heat Data

1951	Carbon dioxide-ethylene	Barnard *et al.*	6
1960	n-Pentane	Kozicki and Sage	106
1960	n-Octane	McKay and Sage	116
1961	Methane	Hestermans and White	78
1961	Cyclohexane	Kozicki and Sage	107
1962	1-Butene	Kozicki, Cuffel, and Sage	108

Year	System	Authors	References
1963	Methane	Jones *et al.*	95
1963	Nitrogen	Mage *et al.*	119
1963	1-Pentene	Cuffel, Kozicki, and Sage	37
1963	n-Decane	Couch, Kozicki, and Sage	35
1963	n-Butanol-benzene	Shannon, Gustafson and O'Neill	169
1963	t-Butanol-benzene, t-Butanol-water	Shannon and O'Neill	170
1964	Methane-propane	Manker	123
1964	n-Hexane	Huisman and Sage	86
1964	trans-2-Butene	Huisman and Sage	87
1965	n-Butane-n-Decane	Houseman and Sage	83
1967	Methane-ethylene	Tully and Edmister	187
1967	Propane	Helgeson and Sage	76

Joule-Thomson Data

1933	Helium-air	Roebuck and Osterberg	156
1934	Petroleum naphtha, n-pentane	Pattee and Brown	143
1938	Helium-nitrogen	Roebuck and Osterberg	158
1939	Methane-ethane	Budenholzer, Sage and Lacey	21
1940	Methane-n-Butane	Budenholzer, Sage and Lacey	22
1940	Helium-argon	Roebuck and Osterberg	159
1942	Methane-propane	Budenholzer *et al.*	23
1943	Natural gas	Sage, Botkin, and Lacey	164

Year	System	Authors	References
1959	Carbon dioxide-propylene	Sahgal	165
1959	Nitrogen-argon, nitrogen-hydrogen, argon-oxygen	Koeppe	103
1960	Nitrogen, methane, ethane, methane-ethane, methane-propane, ethane-nitrogen	Head	75
1962	Nitrogen	Potter and Levy	149
1964	Nitrogen-ethane	Stockett and Wenzel	177
1964	Nitrogen, methane, nitrogen-methane-ethane	Ahlert	1
1965	Methane-hydrogen, ethylene-hydrogen	Ayber	4
1966	Neon	Gladun	71

Isothermal Throttling Data

Year	System	Authors	References
1940	Benzene-n-heptane	Parekh	142
1955	Carbon dioxide-ethylene Carbon dioxide-nitrous oxide Nitrous oxide-ethylene Nitrous oxide-nitrogen	Charnley *et al.*	27
1957	Argon-nitrogen	Ishkin and Rogovaya	90
1965	Propane-benzene	Yarborough and Edmister	199
1966	Methane-propane	Dillard	41
1966	Nitrogen-hydrogen	Bolshakov *et al.*	17
1967	Steam	Stribolt and Lydersen	180
1967	Methane-hydrogen	Gelperin *et al.*	67
1967	Methane-nitrogen	Bolshakov *et al.*	18

Year	System	Authors	References
	Heat of Mixing Data		
1962	Hydrogen-nitrogen	Beenakker and Coremans	8
1965	Hydrogen-nitrogen, hydrogen-argon, nitrogen-argon-methane-hydrogen, argon-methane	Beenakker *et al.*	9
1967	Hydrogen-nitrogen, hydrogen-argon, nitrogen-argon, hydrogen-nitrogen-argon	Knoester, Taconis, and Beenakker	102
1967	Hydrogen-methane, helium-methane, methane-nitrogen, methane-argon, helium-argon	Van Eijnsbergen and Beenakker	189

Methods of Prediction of Enthalpies of Mixtures

In most engineering problems, enthalpies must be generated from correlations and prediction methods. The number of systems of interest is so large and the rate of production of experimental enthalpy data so small because of the time and effort involved that it is unlikely that experimental data are available for the problem under consideration. The ideal solution would be the calculation of thermodynamic properties, including enthalpy, from a knowledge of the interactions between molecules. At present this can only be done for relatively simple molecular models, but increasing efforts are being made in this area. For example, Hermsen and Prausnitz[77] and Eckert, Renon, and Prausnitz[46] have calculated excess functions for binary liquid mixtures of hydrocarbons at low pressure which are in agreement with experimental values. Osborne[140] has also presented a method for the prediction of liquid mixture enthalpies from a molecular model for liquid mixing. Limited comparisons were in agreement with experimental data. A combination of the hard-sphere and Lennard-Jones potentials was used by Orentlicher and Prausnitz[139] to obtain a three parameter equation for the density and energy of dense fluids. The parameters evaluated from pure component density and enthalpy were found to predict enthalpies for simple fluid mixtures within about 4 percent.

Despite this recent trend toward more fundamental methods of prediction, empirical or semi-empirical methods will continue to be used, especially since they may be applicable over a wider range of conditions than the theoretical methods. A detailed investigation of various prediction methods will not be given here, but the main classes of methods will be considered and methods will be compared with experimental data later. Hobson and Weber[80,81] have reviewed prediction methods, and Reid and Sherwood[154] have recommended various correlations. A recent review of the types of mixture prediction methods was made by Nathan[137]. The main groups into which the methods can be divided are:

1. Pure Component
2. Equivalent component
3. Corresponding states
4. Fugacity relationships
5. Equations of state

1. Pure Components

The assumption of zero heat of mixing allows the enthalpy of a mixture to be calculated from the sum of the enthalpies of the pure components present. This method may give good results at moderate pressures and relatively high temperatures, for chemically similar compounds such as hydrocarbons in a homologous series. Charts for the pure component enthalpies are given by Maxwell[133], Peters[145] and Scheibel and Jenny[167]. Difficulty arises in using these charts when the pure component does not exist in the phase that it is in the mixture (i.e. a liquid above, or a vapor below the critical temperature of the component). Peters has derived auxiliary curves for estimation of partial enthalpies under those conditions and Maxwell used an extension of the vapor pressure curve for the partial enthalpy of a low-boiling component in a liquid mixture.

2. Equivalent Component Concept for Mixtures

Several methods have been proposed which consider the mixture to be a hypothetical pure component and correlate enthalpies on the basis of a parameter such as molal average boiling point, mixture molecular weight, or mixture specific gravity. The assumption is made that a mixture and a pure component with the same correlative parameter exhibit the same enthalpy behavior. Scheibel and Jenny[167] and Canjar and Peterka[24] have presented correlations of this type for hydrocarbons.

3. Corresponding States

The principle of corresponding states was first applied to the correlation of P-V-T data, but the extension to enthalpies using the integrated form of Equation (9) follows directly. Among the earliest correlations of this type are those of Cope,Lewis and Weber[33] and Edmister[47].

Later work on generalized correlations has employed a third parameter to improve the agreement with experimental data. Lydersen, Greenkorn, and Hougen[114] used the compressibility factor at the critical point, z_c, while Curl and Pitzer[38] employed the acentric factor ω, which is related to the shape of the reduced vapor pressure curve.

In applying these correlations to mixtures it is necessary to obtain values for the critical temperature, T_c, the critical pressure, P_c, and the third parameter of the mixture. In most cases, recourse is made to rules which allow the mixture critical properties to be calculated from those of the pure components. For example, the values for a number of correlations are obtained by the linear mixing rules suggested by Kay[96], but non-linear mixing rules have been proposed by Pitzer and Hultgren[147] and Prausnitz and Gunn[150].

4. Enthalpies from Fugacities

The effect of temperature on the fugacity of a component in a mixture is given by:

$$\left(\frac{\partial \ln \bar{f}_i}{\partial T}\right)_{P,x} = \frac{H_i^o - \bar{H}_i}{RT^2} \tag{20}$$

and if a relation for the fugacities is known, the partial molal enthalpy $\bar{H}_i$ can be calculated. The disadvantage of this method is that any error in the expression for fugacity (which is derived from P-V-T and vapor-liquid equilibrium data) is magnified in the differentiation. The advantage claimed for this method is that the enthalpies obtained are consistent with the vapor-liquid equilibrium data, a point of importance in multicomponent mixtures. The chief proponents of this method have been Edmister and coworkers.[50,53]

5. Equations of State

The enthalpy of many substances is known in the ideal gas state from spectroscopic calculations and direct experimental determinations at low pressures. Rossini[161] has tabulated values for many hydrocarbons and simple gases. With the effect of temperature on enthalpy known at zero pressure, the effect of pressure on enthalpy can be obtained from Equation (9) if an equation of state is used to represent the P-V-T behavior of the substance.

A large number of equations of state have been proposed, but only a few have been used for extensive calculations of enthalpies. Martin[127] has recently reviewed equations of state primarily from the standpoint of representation of the P-V-T surface of a substance. Relatively simple equations like the Redlich-Kwong[153] equation have been used for enthalpy prediction and the recent modification by Wilson[195] is claimed to improve the accuracy of such predictions. More complex equations such as the Benedict-Webb-Rubin[10] and Martin-Hou[125] equations have also been used to predict thermodynamic properties, including enthalpy. Values of the enthalpy of CO_2 in the critical region have been calculated from the Martin-Hou equation[126] which agree within a few percent with the experimental enthalpy data of Koppel and Smith[105].

A problem arises in the extension of equation of state calculations to mixtures since the constants for particular mixtures are not available and usually must be calculated from empirical mixing rules utilizing the constants of the pure components. The virial equation is one of the few equations for which the composition dependence of the constants is known exactly. This equation is restricted to vapors since the power series relation tends to diverge at densities approaching those of liquids.

6. Special Considerations for Latent Heats

Many of the methods described above can be used for latent heat prediction, but some have been specifically developed for this purpose. Strickland-Constable[181] has presented the rigorous equations for calculation of the enthalpy change of vaporization of a binary mixture at constant pressure and at constant temperature from the properties of the phases. Only the isothermal change can be calculated from P-V-T data; the isobaric change requires a knowledge of the heat capacities of the two phases. For most mixtures the data are not extensive enough for accurate calculations and few have been attempted.

Edmister[49] has derived a simple approximate expression for the isobaric latent heat which requires only a knowledge of the phase behavior and ideal gas enthalpies. Stevens and Thodos[176] have fit the tables of Lydersen-Greenkorn-Hougen[114] for the saturated liquid and vapor envelopes and applied the resulting equations to mixtures using pseudocritical properties calculated by Kay's rule.

A listing of commonly-used methods of prediction is given in Table II, along with the region of applicability and the type of the correlation. Most of these methods are applicable only to non-polar materials and many are specifically for hydrocarbons.

Comparisons of various prediction methods with experimental data have appeared in a number of recent articles. Wiener[194] and Findlay, Mora, and Jacoby[62] compared some of the data of this work with various correlations. More extensive comparisons with other published data as well as the data of this work are made by Sehgal *et al*[168]. General conclusions that can be drawn from these comparisons is that no method of prediction is suitable in the region of the critical point or in the two-phase region, but that a number of methods are satisfactory in the liquid and gaseous regions.

TABLE II

METHODS OF PREDICTION OF ENTHALPIES OF MIXTURES

Method	Application of Correlation		Author	Reference
3	Tr 0.8 to 2.5	Pr < 5.5	Edmister	47
2,3	0 to 600° F.	< 10,000 psia	Holcomb and Brown	82
1,2	-100 to 800° F.	< 1000 psia	Scheibel and Jenny	167
1	-260 to 400° F.	< 600 psia	Peters	145
1	-200 to 700° F.	< 2200 psia	Maxwell	133
4	-100 to 400° F.	< 600 psia	Canjar and Edmister	25
2,4	-100 to 300° F.	< 3500 psia	Papadopoulos *et al.*	141
3,4	Tr 0.6 to 2	Pr 0.2 to 1	Edmister and Canjar	48
4	Isobaric integral heat of vaporization		Edmister	49
3	Tr 0.5 to 15	Pr < 30	Lydersen *et al.*	114
2	-200 to 500° F.	< 1500 psia	Canjar and Peterka	24

TABLE II (Cont.)

Method	Application of Correlation		Author	Reference
3	Tr 0.8 to 4	Pr < 9	Curl and Pitzer	38
5	Virial equation of state		Brewer and Geist	19
3	Saturated liquid and vapor enthalpies		Stevens and Thodos	176
5	Virial equation of state		Tooke and Hays	184
5	Redlich-Kwong equation of State		Edmister, Thompson and Yarborough	51
3	100 to 460° F.	200 to 2000 psia	Edmister and Yarborough	52
4	Saturated liquid and vapor enthalpies		Edmister, Persyn and Erbar	50
4	Saturated liquid and vapor enthalpies		Erbar, Persyn and Edmister	53
3	Tr 0.5 to 30	Pr < 30	Yen and Alexander	200
5	Modified Redlich-Kwong equation of state		Wilson	195
5	Modified B-W-R equation of state		Barner and Schreiner	7
3	Tr 0.5 to 4	Pr < 10	NGPSA	138
3	Tr 0.4 to 60	Pr < 100	Yen	201

1 Pure Component

2 Equivalent Component

3 Corresponding states

4 Partial enthalpies from fugacity

5 Equation of state

The Methane - Propane System

Both of the pure components of this system have been extensively studied and compilations of the thermodynamic properties of methane and propane are presented by Tester[183] and Kuloor *et al.*[110] Some enthalpy determinations made since these compilations were published include the work of Jones,[94] Sahgal *et al.*[166] and Colwell, Gill, and Morrison[32] for methane and Yarborough[198] and Helgeson and Sage[76] for propane.

Fewer data exist on the properties of methane-propane mixtures, but they include volumetric, phase equilibrium, Joule-Thomson and heat capacity measurements.

Compressibility Data

Sage, Lacey, and Schaafsma[163] measured the density of mixtures of methane and propane at temperatures between 20° and 90°C at pressures from 10 to 200 atmospheres. The compositions of the coexisting phases were also determined in this temperature range. A later investigation by Reamer, Sage, and Lacey[152] extended the earlier work to pressures up to 10,000 psia for temperatures between 40° and 460°F and increased the accuracy of values in the range covered by the older work. Again both volumetric and phase behavior were studied.

Phase Equilibria

Other studies of the phase behavior of the methane-propane system besides the work of Sage and co-workers have been published. Frolich *et al.*[65] determined the solubility of methane in propane at 25°C at pressures up to 90 atmospheres. Data in the low temperature region from -176° to 32°F were obtained by Akers, Burns, and Fairchild[2]. These data have appreciable scatter and the later work of Price and Kobayashi[151] from 50° down to -200°F is to be preferred. A few data points of the solubility of methane in propane from 92° to 128°K are given by Cheung and Wang[28] in a study of hydrocarbon solvents at low temperatures. Above 90°F Roof and Baron[160] report serious disagreement (as much as 50 psi) between the critical locus determined by Reamer, Sage and Lacey[152] and their visual observations. However, their values differ by 18 psi at 110°F from the value determined by Rutherford[162] in the same laboratory.

Thermal Data

Joule-Thomson coefficients for three mixtures of methane and propane have been determined by Budenholzer *et al.*[23] at pressures up to 1500 psia in the temperature interval between 70° and 310°F. Head[75] measured Joule-Thomson coefficients for a mixture of 51.1 mole percent propane in methane at pressures up to 40 atmospheres between 260° and 360°K. Attempts were made to obtain data in the two-phase region but surging flow through the throttle valve led Head to estimate the accuracy of the two-phase results as ± 10 percent.

Cutler and Morrison[39] have measured the vapor pressures and heat capacities of liquid mixtures of methane and propane and heat of vaporization of methane from the mixtures in the temperature range 90° to 110°K. This work is quite valuable since it gives the heat of mixing of methane-propane mixtures directly over the entire range of compositions.

Dillard *et al.*[42] present data of the isothermal effect of pressure on enthalpy for methane and two mixtures of methane and propane in the range 90° to 200°F at pressures up to 2000 psia. The data for methane and a nominal 5 percent propane in methane mixture appeared in the thesis of Dillard[41].

Manker[123] obtained isobaric data on a nominal 5 percent propane in methane mixture at temperatures from -245° to 87°F at pressures from 250 to 2000 psia. Approximate Joule-Thomson coefficients were obtained at 60°F at pressures up to 2000 psia. A preliminary report of this work has been published[122].

Some of the results of this thesis have been presented in publications prior to this report. Some data and preliminary enthalpy diagrams for the nominal 12 percent propane in methane[129,130] and 28 percent propane in methane[131] mixtures have been published.

Other experimental data of the methane-propane system are presented in Table III.

TABLE III

EXPERIMENTAL INVESTIGATIONS ON THE METHANE - PROPANE SYSTEM

Property	Temperature (^oF)	Pressure (psia)	Year	Author	Reference
P-V-T-x, V-L	68 to 194	147 to 2840	1934	Sage, Lacey, and Schaafsma	163
P-V-T-x, V-L	40 to 460	200 to 10,000	1950	Reamer, Sage, Lacey	152
V-L	77	1320	1931	Frolich *et al.*	65
V-L	-176 to 32	50 to 1450	1954	Akers, Burns and Fairchild	2
V-L	-200 to 50	100 to 1300	1959	Price and Kobayashi	151
V-L	110	950 to 1268	1962	Rutherford	162
V-L	-295 to -229	0.2 to 24	1964	Cheung and Wang	28
V-L	89 to 181	823 to 1323	1967	Roof and Baron	160
Joule-Thomson	70 to 310	0 to 1500	1942	Budenholzer *et al.*	23
Joule-Thomson	10 to 190	25 to 590	1960	Head	75
$C_p, \Delta\underline{H}_{vap}$	-242 to 80	250 to 2000	1964	Manker	123
$C_p, \Delta\underline{H}_{vap}$	-298 to 262	< 14.7	1965	Cutler and Morrison	39
$\Delta\underline{H}_T$	90 to 200	0 to 2000	1966	Dillard	41
			1966	Dillard *et al.*	42
Viscosity	68 to 482	14.7	1931	Trautz and Sorg	186

TABLE III (Cont.)

Property	Temperature	Pressure	Year	Author	Reference
Viscosity	77 to 437	400 to 5000	1943	Bicher and Katz	12
Viscosity	40 to 280	100 to 8000	1966	Giddings, Kao and Kobayashi	68
Viscosity, density	-239 to 70	100 to 5000	1967	Huang, Swift and Kurata	84
Thermal Conductivity	122 to 302	14.7	1960	Smith, Durbin, and Kobayashi	172
Surface Tension	5 to 194	40 to 1500	1943	Weinaug and Katz	192

The Methane-Nitrogen System

A number of compilations of the thermodynamic properties of the pure components of this system are available. References for methane are given in the section on the methane-propane system and recent tabulations for nitrogen include those of Din[43] and Strobridge[182]. Enthalpy measurements on nitrogen since these works were compiled include the work of Mage *et al.*[119] and those of Sahgal *et al.*[166] Other references to recent enthalpy data on nitrogen are given in Table I.

The thermodynamic properties of mixtures containing 10 to 30 mole percent nitrogen in methane have been calculated by Bloomer *et al.*[16] from volumetric data and ideal gas heat capacities. Joule-Thomson coefficients for mixtures of methane and nitrogen were calculated from P-V-T data by Perry and Herrmann[144] and heats of mixing for liquid mixtures have been calculated from volumetric and phase behavior data by Knapp[101]. Few direct enthalpy measurements have been made on methane-nitrogen mixtures, but extensive phase equilibria and volumetric data are available. Table IV lists the experimental investigations which have been made on this system.

TABLE IV

EXPERIMENTAL INVESTIGATIONS ON THE METHANE-NITROGEN SYSTEM

Property	Temperature (°F)	Pressure (psia)	Year	Author	Reference
P-V-T-x	32 to 392	425 to 4800	1928	Keyes and Burks	99
P-V-T-x	32 to 392	1470 to 10,300	1941	Kritschewsky and Levchenko	109
P-V-T-x	-280 to 200	0 to 1500	1955	Bloomer *et al.*	16
V-L	-303 to -268	14.7	1919	McTaggart and Edwards	117
V-L	-298 to -220	12 to 337	1939	Torocheshnikov and Levius	185
V-L	-266	147	1939	Steckel and Zinn	174
V-L	-293	< 14.7	1943	Vellinger and Pons	190
V-L	-202 to -148	225 to 688	1951	Kelley and Lipscomb	97
V-L	-295 to -119	9 to 685	1952	Bloomer and Parent	14
V-L	-280 to -150	20 to 650	1953	Cines *et al.*	29
V-L	-313 to -175	29 to 230	1957	Fastovsky and Petrovsky	59
V-L	-295 to -236	< 82	1964	Cheung and Wang	28
V-L	-295	< 4	1966	Sprow and Prausnitz	173
V-L	-309 to -296	< 4	1967	Fuks and Bellemans	66
V^E	-329 to -298	< 14.7	1959	Blagoi	13
S-L	-345 to -298	< 14.7	1939	Fedorova	61

TABLE IV (Cont.)

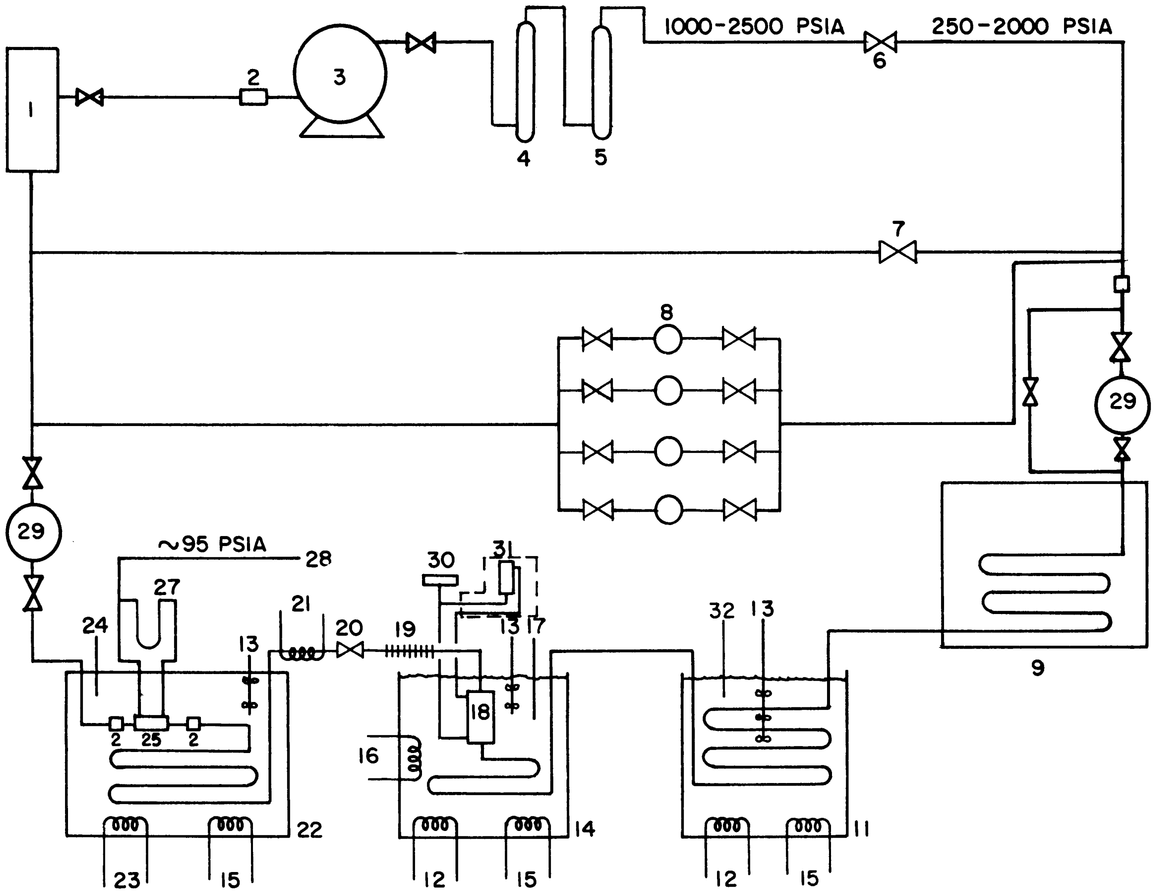
Property	Temperature (^{o}F)	Pressure (psia)	Year		Reference
S-L	-332 to -317	< 14.7	1941	Fastovsky and Krestinsky	58
Cp	-207 to 69	300	1963	Jenkins and Berwaldt	92
Cp	-224 to -186	125 to 350	1966	Kohne, Anderson, Miller	104
ϕ	-148 to 32	0 to 735	1967	Bolshakov *et al.*	18
H^E	-97 to 68	190 to 1610	1966	Van Eijnsbergen	188

SECTION II - THE ISOBARIC EFFECT OF TEMPERATURE ON ENTHALPY

Enthalpy data were obtained on binary mixtures of methane with propane and with nitrogen using the isobaric flow calorimeter designed by Faulkner[60]. This calorimeter is part of a recycle system, the evolution of which can be traced in the theses of Faulkner, Jones[94], Mage[120] and Manker[123]. The recycle system serves to bring the fluid under investigation to desired conditions of temperature and pressure for measurements.

Experimental Equipment

A schematic diagram of the flow system is shown in Figure 1. The fluid is compressed to a pressure higher than that at which measurements are to be made and is passed through two large filters (4,5) to remove any oil or water in the gas. The fluid is throttled to the approximate measuring pressure and a portion throttled again (7) back to the compressor intake. The compressor is a constant volume machine and therefore the flow rate through the calorimeter section is varied by regulation of the amount of this bypass stream. The fluid passing through the calorimeter section is cooled in the dry ice bath (9) if the desired measurement temperature is below about -100° F. Further cooling is accomplished in the heat exchange bath (11) which contains coils through which liquid nitrogen is passed. The fluid is brought to within a few degrees of the desired temperature in this bath and passes to the calorimeter bath (14). In the calorimeter bath the fluid is brought to bath temperature by passing through 100 feet of 3/16" O.D. copper coil before entering the isobaric flow calorimeter (18). Here electrical energy is added



LEGEND

1. Compressor intake buffer tank
2. Micron filter
3. Corblin Diaphragm Compressor, 4 SCFM
4. Oil removal unit (fiberglass)
5. Water removal unit (anhydrous calcium sulfate)
6. Metering valves
7. Calorimeter by-pass metering valves
8. Gas storage tanks
9. Dry ice cooler
11. Low temperature cooling bath
12. Liquid nitrogen cooling
13. Stirrer
14. Low temperature measuring bath
15. Controlled heat input
16. Nickel resistance-sensor for heat input controller
17. Platinum thermometer
18. Calorimeter
19. Finned tubing
20. Calorimeter metering valves
21. Line heater
22. Metering bath
23. Water cooling
24. Thermometer
25. Flowmeter (Meriam)
27. U-tube and water manometer
28. Lead to 180" mercury manometer
29. Buffer tank
30. Pressure balance
31. High pressure mercury manometer
32. Resistance thermometer for bath controller

Figure 1. Flow Diagram of the Apparatus

and the resulting temperature rise measured. Measurements are made of the inlet pressure to the calorimeter, the pressure drop across the calorimeter and the temperature of the calorimeter bath. After leaving the calorimeter the fluid is brought back to room temperature before throttling to 80 psig (Valve 20). The gas is then passed to the flow meter bath (22) where the flow rate is measured by a calibrated Meriam flow meter (25). After leaving the flow meter bath the gas passes through several buffer tanks before returning to the intake of the compressor. The pressure level of the measurements is changed by adjustment of the amount of gas in the storage tanks (8) relative to the amount in the recycle system.

A major revision to the system made before the start of this work was the replacement of the oil-lubricated compressor previously employed, with an A2CCV50/250 Corblin diaphragm compressor with remote heads (3). This compressor removes the source of oil which had caused composition variations because of the different solubilities of the components of the mixture in the compressor oil. The remote heads allow operation at fluid temperatures up to 300° F without expensive hydraulic oils. A photograph of this compressor is shown in Figure 2.

Measuring Instruments

A detailed description of the measuring instruments has been given by Jones[94] and only changes from that work are given here. The important measurements are:

1. The temperature rise in the calorimeter. This is measured by duplicate six-junction copper-constantan thermopiles which were calibrated at the oxygen and nitrogen points and compared with a

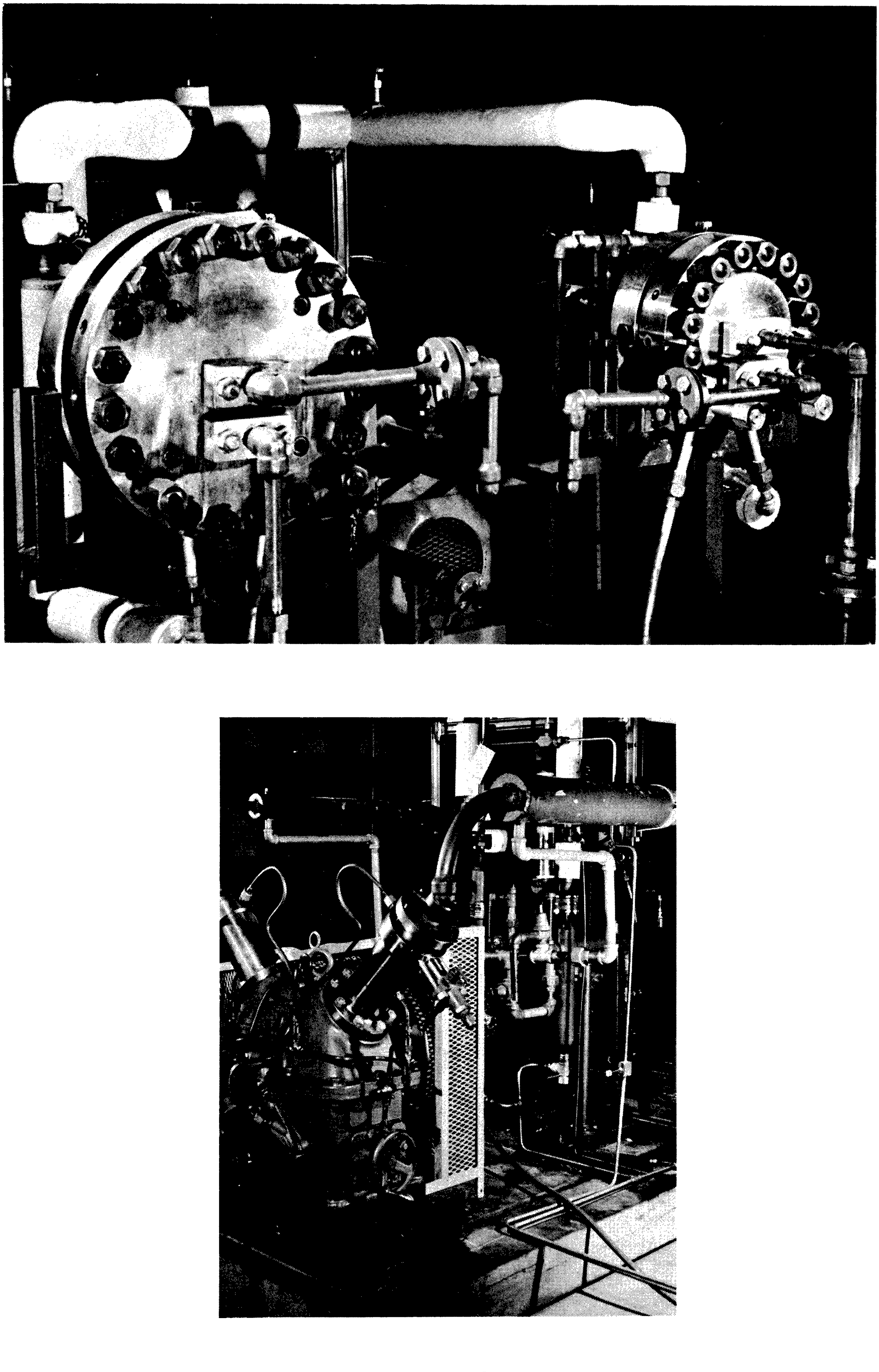


Figure 2. Corblin Diaphragm Compressor

platinum thermometer at 20° C intervals by the National Bureau of Standards. In previous work only one thermopile was used (G25691T) which was calibrated from -196° to 0° C. The second thermopile added before this work was begun (G-32321) is calibrated from -196° to +150° C and the calibration data are given in Table XXXIV of Appendix B. The accuracy of the temperature rise measurement is about ± 0.2%.

2. The temperature of the calorimeter bath, which is assumed to be the inlet temperature to the calorimeter, is measured using a platinum resistance thermometer. The calibration constants are given by Jones[94].

3. The electrical energy input to the calorimeter supplied by a DC power supply is measured by a K-3 potentiometer using standard resistors to scale the voltages to the range of the potentiometer. The circuitry and the calibration data for the potentiometer and standard resistors are given by Jones[94]. The accuracy of the electrical energy determination is ± 0.05%.

4. The mass flow rate of gas is determined from the measurement of the pressure drop across the laminar flow element together with the temperature and pressure at the element. These data are used to solve the calibration equation:

$$\frac{\rho \, \Delta P}{F\mu} = B + A\left(\frac{F}{\mu}\right) + C\left(\frac{F}{\mu}\right)^2 + D\left(\frac{F}{\mu}\right)^3 \qquad (21)$$

for the mass flow rate, F. The calibration constants A,B,C,D are obtained from a least squares fit of calibration data obtained by direct weighing. The calibration equipment and procedure are described by Jones[94]. A comparison between values determined by direct weighing (recalibration) in the third set of calibration data with values calculated from Equation (21) using constants determined from the previous two calibration sets is given in Table V. These data were obtained on the nominal 5 mole percent propane in methane mixture.

TABLE V

COMPARISON OF MASS FLOW RATES DETERMINED BY DIRECT WEIGHING (RECALIBRATION) WITH VALUES CALCULATED FROM EARLIER CALIBRATION CURVE

Run	Recalibration lb/min	Calculated lb/min	Percent Deviation
31	.06930	.06937	-0.10
32	.06921	.06923	-0.03
33	.10518	.10522	-0.04
34	.10511	.10516	-0.05
35	.15961	.15943	+0.11
36	.15960	.15938	+0.14
37	.20027	.19981	+0.23
38	.19999	.19957	+0.21
39	.22448	.22379	+0.31
310	.22359	.22303	+0.25

It can be seen that the maximum deviation is 0.31 percent while the absolute average deviation is 0.15 percent. The accuracy of the mass flow rate determination is believed to be about ± 0.2%.

5. The pressure at the inlet to the calorimeter was measured

with a calibrated Heise gauge during measurements on the nominal 12 and 28 percent propane in methane and nominal 43 percent nitrogen in methane mixtures. The calibration of this gauge is given in Table XXXV of Appendix B. The accuracy of the gauge is 0.1 percent of full scale.

In the work on the nominal 5 mole percent propane in methane mixture a calibrated dead weight gauge was used to measure the inlet pressure to the calorimeter. The calibration data for this gauge are given in Table XXXVI of Appendix B and can be seen to be accurate to 0.03 percent.

6. The pressure drop across the isobaric calorimeter is measured with a 40-inch high pressure mercury manometer. The accuracy of this measurement is ± 0.1 inches of mercury which does not introduce appreciable error since the correction term for the pressure drop, which is calculated from the B-W-R equation of state, is rarely one percent of the total energy input.

Procedure for Isobaric Measurements

The fluid being studied is brought to the desired state of pressure and temperature with the recycle system shown in Figure 1 and passed into the isobaric calorimeter at a desired flow rate. Electrical energy is added at a rate which results in the desired fluid temperature at the calorimeter outlet. The temperature rise is monitored until it reaches a constant value indicating attainment of steady state. This period is usually 3/4 to 1 hour, and at this point the values of the variables are recorded.

Materials Used

The source and purity of the gases used in this work are given in Table VI. The gases were used without further purification.

TABLE VI

MATERIALS

Component	Supplier	Purity
Methane	Southern California Gas Co.	99.7%
Propane	Phillips Petroleum Co.	99.9%
Nitrogen	Liquid Carbonic Corp.	99.95%

Experimental Data On The Methane - Propane System

Isobaric enthalpy determinations were made on three mixtures of methane and propane, of nominal composition 5, 12, and 28 mole percent propane.

Nominal 5 Percent Propane in Methane Mixture

Isobaric data for this mixture were obtained at temperatures from 80° F. to 257°F. at pressures from 500 to 2000 psia. This mixture was previously studied by Manker[123] at temperatures from -245°F. to 87°F. at pressures from 250 to 2000 psia. The range of the present experiments is shown in Figure 3, where dashed lines indicate the experimental determinations of Manker.

Initial experiments were made using the mixture of Manker, which had been stored in cylinders since his work. This gas was analyzed chromatographically to be 5.2 mole percent propane. After about half the data runs on this mixture had been made, additional gas was required to replace losses. The final mixture did not match the initial mixture exactly and was analyzed to be 5.1 mole percent propane in methane. Impurities were determined by mass spectrometer analyses and the composition of the nominal 5 percent mixture is given in Table VII.

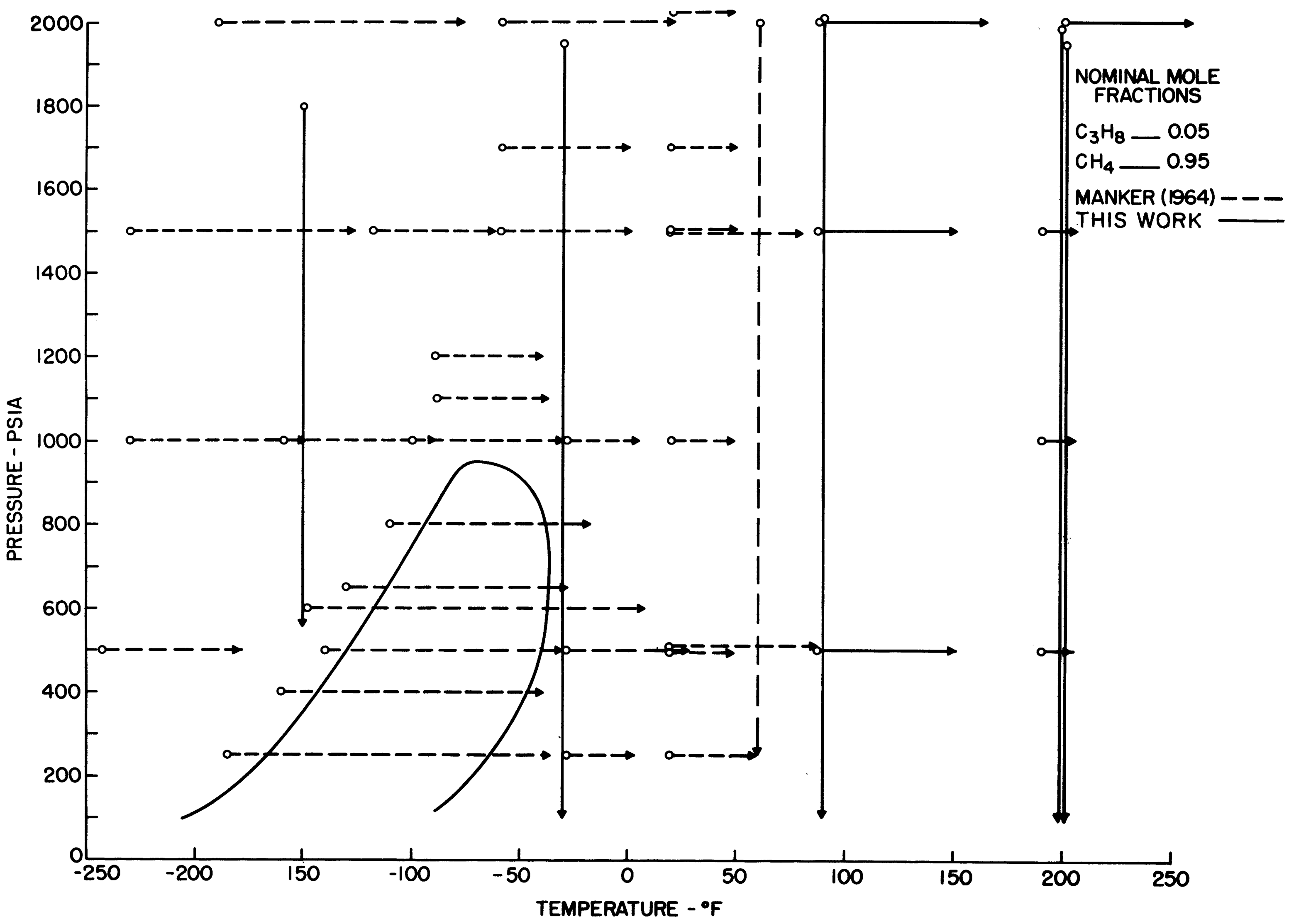


Figure 3. Range of Experimental Measurements on the Nominal 5 Percent Mixture

TABLE VII

COMPOSITION OF NOMINAL 5 PERCENT MIXTURE

	Mole Fraction
Methane	0.9463 *
Propane	0.051 ± .001
Carbon Dioxide	0.0003
Ethane Nitrogen	} 0.0013
Oxygen/Argon	0.0001
	1.0000

* by difference

The flow meter was calibrated three times in the course of the experimental work on this mixture. All three calibration sets are in good agreement and a cubic equation fits the 34 calibration points within 0.17 percent. The calibration data are given in Table XXXVII of Appendix B and the data are plotted on Figure 47.

The experimental data converted to units used in this work, psia, °F, pounds mass and Btu, are presented in Table XLIII of Appendix D.

The experimental enthalpy data were plotted as mean heat capacity versus temperature to obtain point values of heat capacity as shown in Figure 4. The data are seen to blend smoothly into the results of Manker at lower temperatures and into the results of calculations using the B-W-R equation of state at higher temperatures. Although Manker tabulated C_p up to 100°F, most of his data end about 60°F and the values up to 100°F are extrapolations. Figure 4 shows that the extrapolated values of Manker are low. The same behavior was found at other pressures, the extrapolated values being too low in all cases. The table

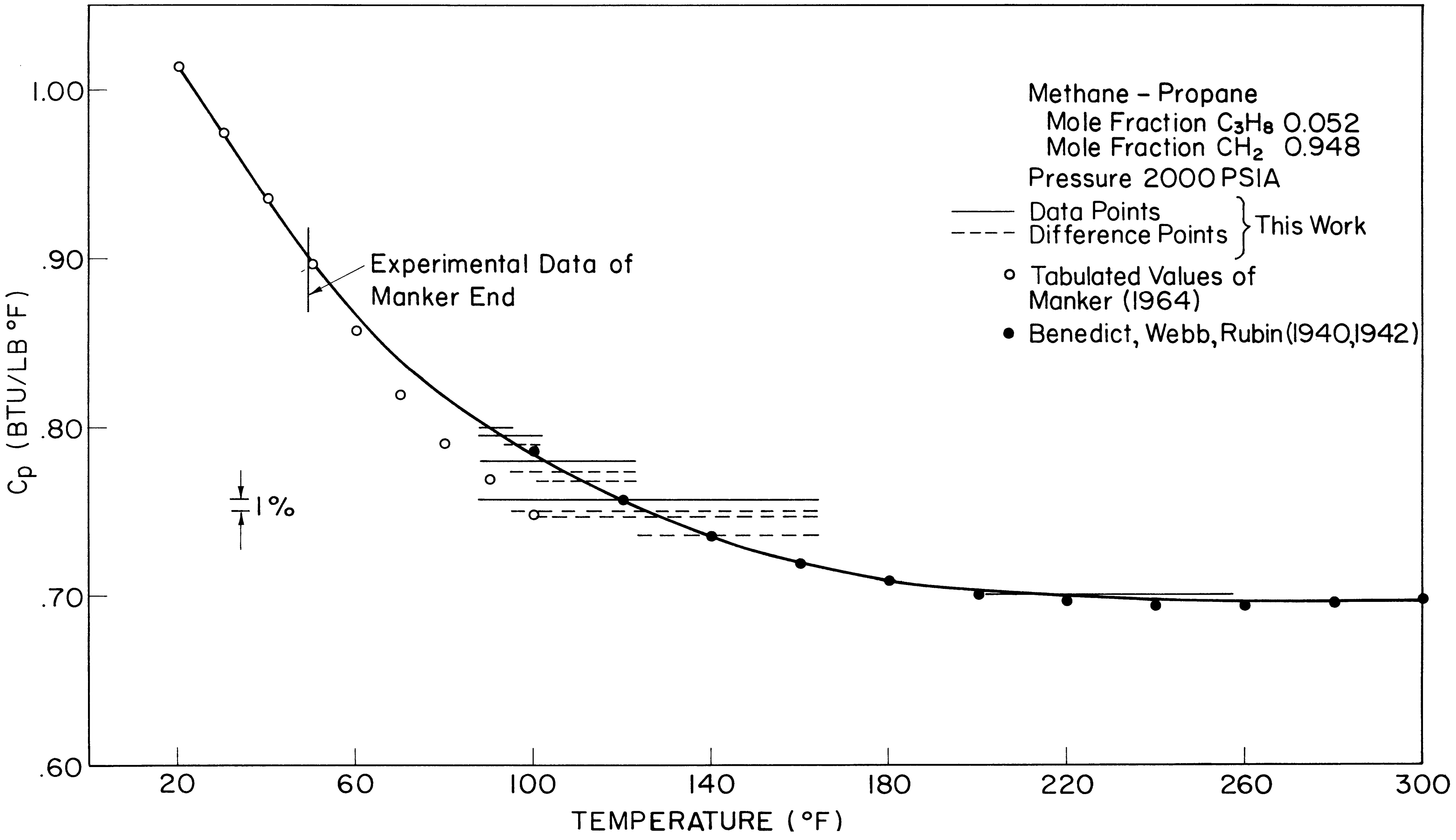


Figure 4. Blending of Experimental Heat Capacities with Values Calculated from B-W-R Equation of State

of heat capacities for this mixture presented by Manker has been revised and extended to 300°F. The values are listed in Table VIII with entries in italics indicating interpolation or extrapolation of experimental data.

Experimental values of the heat capacity at 200°F are plotted as a function of pressure in Figure 5. Below 1500 psia the results are linear in pressure and the value at zero pressure obtained by linear extrapolation agrees within 0.1 percent with the point calculated for the mixture from the ideal gas values for methane and propane of Rossini[161].

Nominal 12 Percent Propane in Methane Mixture

Isobaric determinations in this mixture cover the liquid, two-phase, and gaseous regions at temperatures from -240°F to 140°F at pressures from 250 to 2000 psia. The location of the experimental data is shown in Figure 6.

Chronologically, this mixture was the first to be studied and many problems arose in the experimental work. The Corblin diaphragm compressor high pressure diaphragms failed at irregular intervals much shorter than the 500 to 1000 hours service life claimed by the manufacturer. In one case, the high pressure diaphragms failed 8 hours after replacement. The continual dismantling of the compressor heads led to the loss of mixture and it appears that the system gas was never thoroughly mixed for the early experiments. Another problem was encountered in the calibration of the flow meter. The pipe dope used to join the threaded connections on the flowmeter was found to have entered the element causing shifts in the flow meter calibration. As a result of these problems, the preliminary data presented on this mixture[129] are believed

TABLE VIII

TABULATED VALUES OF ISOBARIC HEAT CAPACITIES FOR THE NOMINAL 5 PERCENT MIXTURE

C_p (Btu/lb - °F)

Temperature	Pressure, psia								
°F	0	250	500	750	1000	1200	1500	1700	2000
-280	0.460	0.740	0.742	0.747	0.749	0.751	0.753	0.753	0.752
-270	0.460	0.746	0.749	0.752	0.754	0.755	0.756	0.755	0.752
-260	0.461	0.753	0.757	0.758	0.759	0.760	0.759	0.757	0.753
-250	0.462	0.763	0.764	0.765	0.764	0.764	0.763	0.760	0.755
-240	0.462	0.773	0.772	0.772	0.770	0.769	0.767	0.764	0.758
-230	0.463	0.787	0.782	0.780	0.776	0.774	0.771	0.767	0.761
-220	0.463	0.801	0.795	0.789	0.784	0.781	0.775	0.772	0.766
-210	0.464	0.818	0.809	0.801	0.793	0.788	0.781	0.776	0.772
-200	0.464	0.838	0.826	0.814	0.803	0.796	0.787	0.783	0.778
-190	0.465	0.862	0.844	0.830	0.816	0.806	0.796	0.790	0.785
-180	0.466	0.888	0.866	0.847	0.831	0.820	0.808	0.802	0.793
-170	0.466	0.927	0.894	0.871	0.849	0.837	0.824	0.812	0.803
-160	0.467		0.928	0.897	0.872	0.859	0.842	0.832	0.815
-150	0.468		0.972	0.936	0.901	0.889	0.862	0.847	0.827
-140	0.469		1.037	0.981	0.938	0.922	0.884	0.867	0.842
-130	0.470		1.182	1.041	0.986	0.958	0.908	0.887	0.858
-120	0.471			1.127	1.051	1.003	0.937	0.910	0.876
-110	0.472			1.268	1.155	1.062	0.976	0.944	0.897
-100	0.473				1.330	1.144	1.026	0.982	0.921
- 90	0.474				1.618	1.292	1.087	1.027	0.950
- 80	0.475				2.281	1.499	1.159	1.080	0.983
- 71.8					2.513				
- 70	0.477				2.467	1.725	1.257	1.128	1.018
- 60	0.478				1.930	1.849	1.357	1.188	1.054
- 59.6						1.849			
- 50	0.480	0.557			1.470	1.723	1.414	1.245	1.087
- 44.6							1.426		
- 40	0.482	0.550	0.645		1.223	1.470	1.421	1.280	1.116
- 36.2								1.283	
- 30	0.484	0.544	0.632	0.773	1.066	1.229	1.367	1.275	1.137
- 25									1.140
- 20	0.487	0.539	0.620	0.747	0.949	1.073	1.269	1.234	1.138
- 10	0.489	0.536	0.609	0.717	0.871	0.986	1.164	1.176	1.121
0	0.491	0.534	0.600	0.690	0.817	0.936	1.069	1.118	1.090
10	0.494	0.534	0.593	0.674	0.777	0.868	0.990	1.054	1.054
20	0.497	0.535	0.588	0.658	0.746	0.820	0.929	0.993	1.014
30	0.500	0.536	0.583	0.646	0.721	0.789	0.881	0.939	0.974
40	0.503	0.537	0.581	0.635	0.703	0.760	0.840	0.899	0.935
50	0.506	0.537	0.579	0.629	0.689	0.734	0.806	0.863	0.896
60	0.509	0.538	0.578	0.625	0.677	0.719	0.779	0.815	0.865
70	0.512	0.540	0.577	0.621	0.668	0.706	0.759	0.792	0.840
80	0.516	0.543	0.577	0.618	0.660	0.694	0.743	0.774	0.818
90	0.519	0.546	0.577	0.615	0.653	0.684	0.730	0.758	0.799
100	0.523	0.548	0.578	0.612	0.647	0.676	0.718	0.744	0.783
110	0.527	0.551	0.579	0.609	0.642	0.669	0.709	0.733	0.769
120	0.531	0.554	0.580	0.608	0.638	0.663	0.700	0.723	0.757
130	0.535	0.558	0.582	0.607	0.635	0.659	0.693	0.714	0.745
140	0.539	0.561	0.584	0.608	0.633	0.655	0.687	0.707	0.735
150	0.543	0.564	0.586	0.608	0.632	0.652	0.682	0.700	0.727
160	0.547	0.567	0.588	0.609	0.631	0.650	0.678	0.695	0.719
170	0.552	0.571	0.590	0.610	0.630	0.648	0.674	0.690	0.713
180	0.556	0.574	0.593	0.612	0.631	0.647	0.672	0.687	0.708
190	0.560	0.578	0.596	0.614	0.632	0.647	0.670	0.684	0.704
200	0.565	0.582	0.599	0.616	0.633	0.647	0.668	0.681	0.701
210	0.570	0.586	0.602	0.618	0.634	0.647	0.667	0.680	0.699
220	0.574	0.590	0.606	0.621	0.636	0.648	0.667	0.679	0.697
230	0.579	0.594	0.609	0.623	0.638	0.649	0.667	0.678	0.696
240	0.584	0.598	0.612	0.626	0.640	0.651	0.668	0.679	0.695
250	0.588	0.602	0.616	0.629	0.643	0.653	0.669	0.679	0.695
260	0.593	0.606	0.619	0.632	0.645	0.655	0.670	0.680	0.695
270	0.598	0.611	0.623	0.635	0.647	0.657	0.672	0.681	0.696
280	0.603	0.614	0.626	0.638	0.650	0.660	0.674	0.683	0.696
290	0.608	0.619	0.630	0.641	0.653	0.663	0.677	0.685	0.696
300	0.613	0.623	0.634	0.644	0.655	0.665	0.680	0.688	0.697

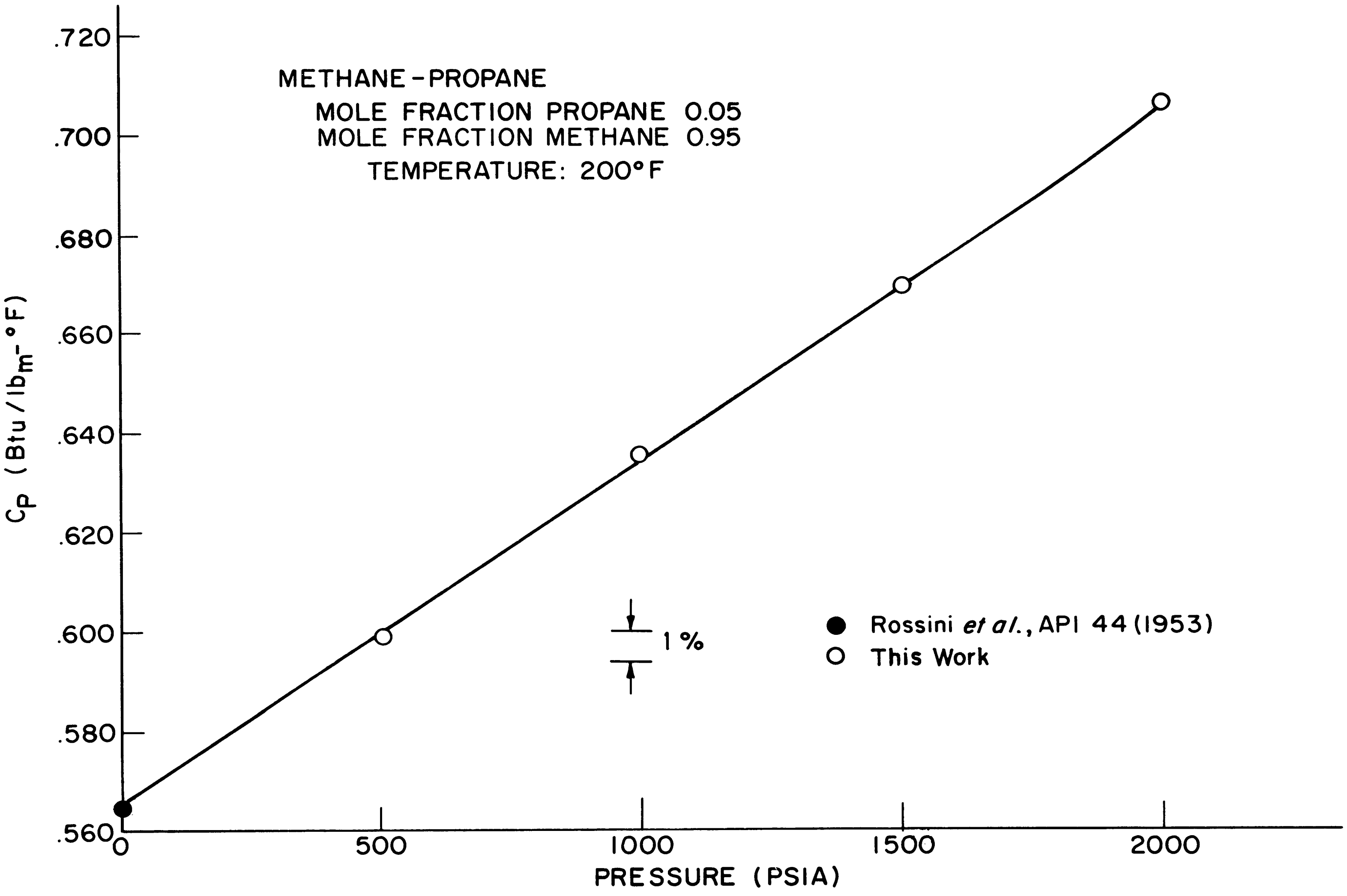


Figure 5. The Heat Capacity of the Nominal 5 Percent Mixture as a Function of Pressure

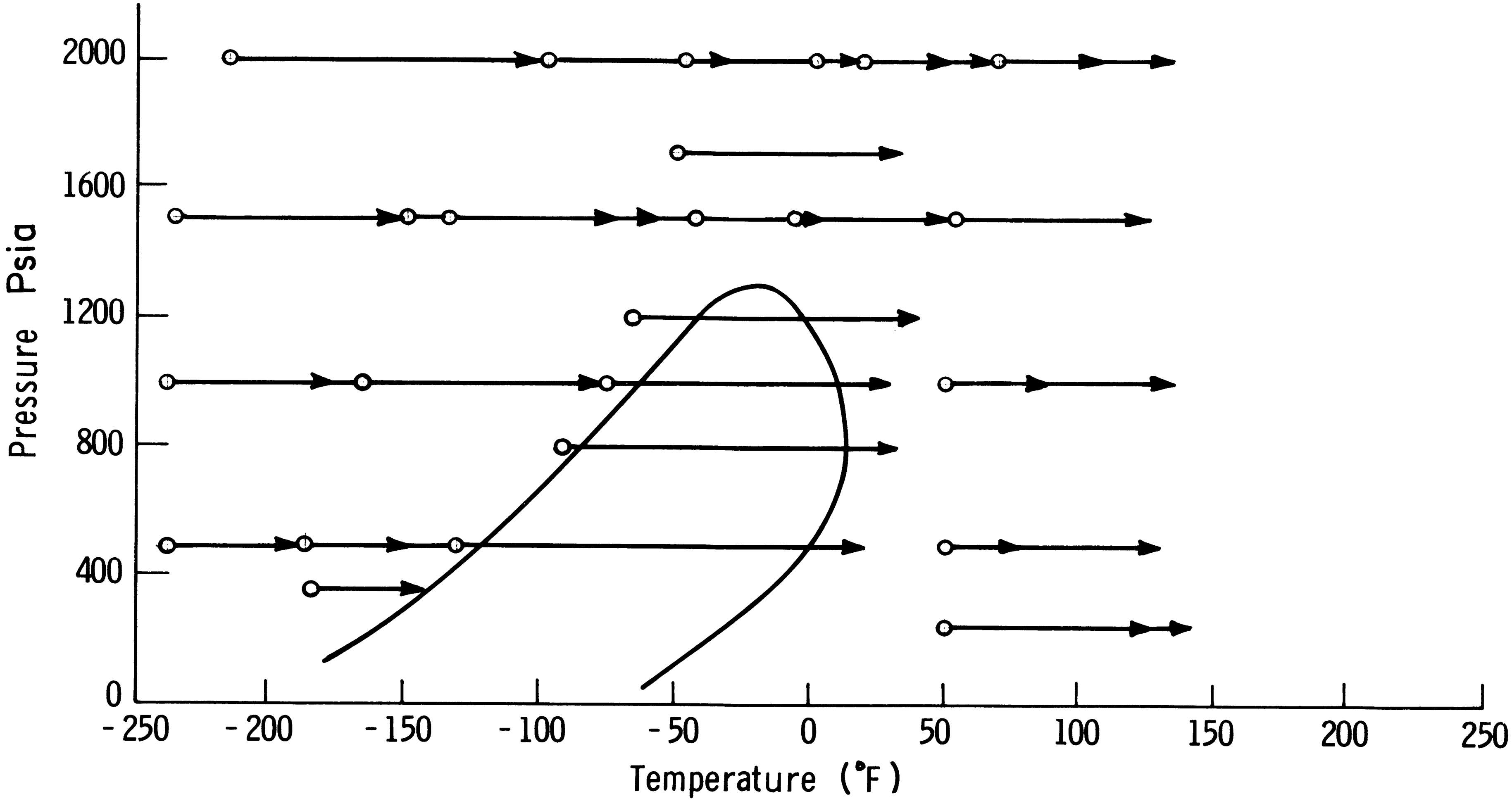


Figure 6. Range of Experimental Measurements on the Nominal 12 Percent Mixture

to be in error.

In May 1965 the system gas was completely remixed until a stable composition was attained. The joints connecting the flow meter to the system were either silver soldered or replaced by compression fittings to remove the source of contamination to the flow meter and the flow element was cleaned ultrasonically. The flow meter was calibrated and the enthalpy determinations reported here were made. A record of the composition during the course of the experimental work is presented in Figure 7. Although some variation is noted, there is no indication of a change in average composition with time. A sample of the nominal 12 percent propane mixture was independently analyzed at the Continental Oil Company in Ponca City, Oklahoma and at the Phillips Petroleum Company, Bartlesville, Oklahoma. The same sample was analyzed with the gas chromatograph of the laboratory and the mass spectrometer at the University of Michigan. A comparison of the results is presented in Table IX.

TABLE IX

COMPARISON OF ANALYSES OF NOMINAL 12 PERCENT MIXTURE

	Chromatograph			Mass Spectrometer
	Phillips	Conoco[1]	U of M	U of M
O_2/Ar	----	----	0.01	----
N_2	0.09	0.09	0.13	0.13
C_2H_6	0.07	0.07		
CO_2	0.05	----	0.03	----
CH_4	88.07	88.38	88.12	88.02
C_3H_8	11.72	11.46	11.71	11.85 ± 0.37

[1] Gas Processing Group

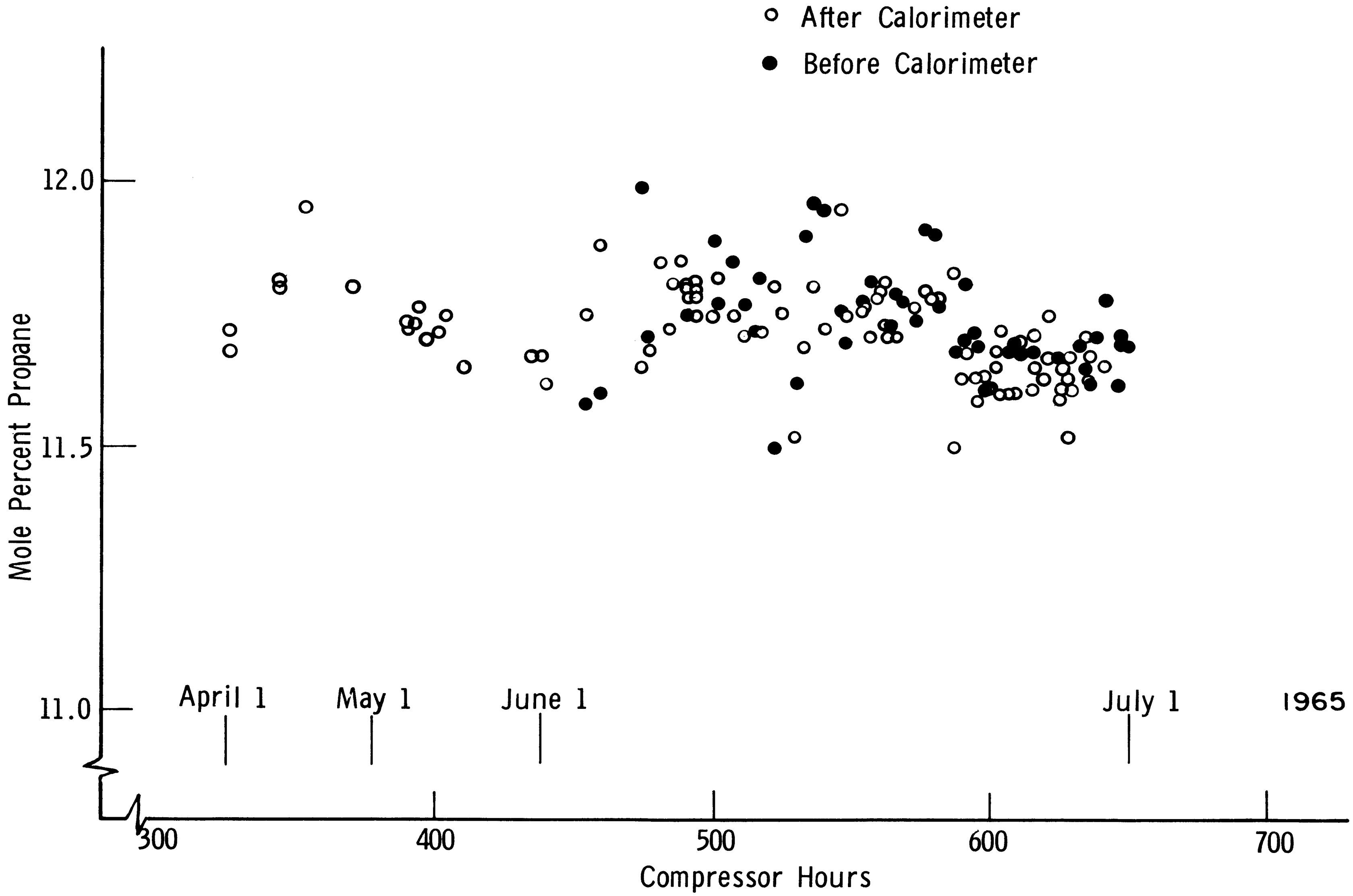


Figure 7. Composition of the Nominal 12 Percent Mixture as a Function of Time

The three chromatographic analyses are seen to be in good agreement and the mass spectrometer value in agreement within its limits of error. Consideration of the numerous analyses and the independent checks led to the selection of the composition shown in Table X for the nominal 12 percent mixture.

TABLE X

COMPOSITION OF NOMINAL 12 PERCENT MIXTURE

	Mole Fraction
Methane	0.8812 *
Propane	0.117 ± .001
Carbon Dioxide	0.0003
Ethane Nitrogen	0.0013
Oxygen/Argon	0.0001
	1.0000

* by difference

The flow meter was recalibrated twice during the course of the experimental work reported here. The recalibrations are in good agreement with the calibration of May 1965 and a cubic equation fits all 34 calibration points with an average deviation of 0.15 percent. The calibration data are given in Table XXXVIII of Appendix B and are plotted in Figure 48.

The experimental data for this mixture are presented in Table XLIV of Appendix D. Isobaric heat capacities were derived from the experimental enthalpy data and are presented in Table XI. Again entries in italic type represent interpolated or extrapolated values.

Enthalpy data in the two-phase region were interpreted to yield

TABLE XI

TABULATED VALUES OF ISOBARIC HEAT CAPACITIES FOR THE NOMINAL 12 PERCENT MIXTURE

C_p (Btu/lb °F)

Temperature	Pressure psia				
°F	0	500	1000	1500	2000
-280	0.423	*0.677*	*0.706*		
-270	0.424	*0.686*	*0.708*		
-260	0.425	*0.697*	*0.712*	*0.704*	
-250	0.427	*0.707*	*0.716*	*0.709*	
-240	0.428	0.718	0.720	*0.715*	*0.723*
-230	0.429	0.728	0.727	0.720	*0.726*
-220	0.430	0.740	0.732	0.027	*0.729*
-210	0.431	0.751	0.739	0.730	0.733
-200	0.432	0.762	0.747	0.735	0.738
-190	0.434	0.774	0.758	0.741	0.742
-180	0.435	0.789	0.771	0.748	0.747
-170	0.436	0.805	0.788	0.755	0.752
-160	0.437	0.825	0.808	0.765	0.758
-150	0.438	0.850	0.834	0.777	0.764
-140	0.440	0.887	0.865	0.790	0.771
-130	0.441	0.942	0.903	0.807	0.780
-120	0.443	1.034	0.947	0.827	0.790
-110	0.444		1.000	0.851	0.806
-100	0.446		1.060	0.880	0.825
- 90	0.448		1.134	0.916	0.846

TABLE XI - (Cont.)

Temperature	Pressure psia				
°F	0	500	1000	1500	2000
- 80	0.450		1.237	0.962	0.872
- 70	0.452		1.500	1.018	0.900
- 60	0.454			1.083	0.932
- 50	0.456			1.161	0.963
- 40	0.459			1.247	0.993
- 30	0.461			1.300	1.022
- 24				1.313	
- 20	0.464			1.309	1.051
- 10	0.467	1.059	1.493	1.271	1.068
0	0.470	0.890	1.106	1.224	1.075
2					1.076
10	0.473	0.784	0.985	1.167	1.068
20	0.476	0.713	0.896	1.099	1.047
30	0.479	0.662	0.828	1.030	1.022
40	0.483	0.623	0.776	0.965	0.994
50	0.486	0.594	0.736	0.910	0.964
60	0.490	0.572	0.707	0.863	0.934
70	0.494	0.570	0.691	0.824	0.904
80	0.498	0.551	0.679	0.793	0.878
90	0.502	0.546	0.668	0.770	0.853
100	0.506	0.544	*0.659*	0.752	0.828
110	0.510	0.548	*0.652*	0.736	0.809

TABLE XI - (Cont.)

Temperature °F	Pressure psia 0	 500	 1000	 1500	 2000
120	0.514	0.554	0.646	0.723	0.791
130	0.518	0.560	0.641	0.712	0.775
140	0.523	0.568	0.637	0.705	0.762
150	0.527	0.575	0.634	0.697	0.750
160	0.532	0.577	0.632	0.690	0.740
170	0.537	0.580	0.630	0.684	0.731
180	0.541	0.582	0.630	0.680	0.724
190	0.546	0.585	0.629	0.676	0.718
200	0.551	0.588	0.630	0.673	0.713
210	0.556	0.591	0.630	0.671	0.708
220	0.561	0.594	0.631	0.670	0.705
230	0.565	0.597	0.633	0.669	0.702
240	0.570	0.601	0.634	0.669	0.700
250	0.575	0.605	0.636	0.669	0.698
260	0.580	0.608	0.639	0.669	0.697
270	0.586	0.612	0.641	0.670	0.697
280	0.591	0.616	0.643	0.671	0.697
290	0.596	0.620	0.646	0.673	0.697
300	0.601	0.624	0.649	0.674	0.697

values of the integral isobaric heat of vaporization. The inlet temperature for such traverses was always in the liquid region. From this base successive additions of electrical energy were made to obtain data in the liquid, two-phase, and vapor regions. A plot of the enthalpy change versus temperature such as Figure 8 was prepared and values of the bubble and dew points as well as the integral isobaric heat of vaporization obtained. The results are presented in Table XII.

TABLE XII

HEATS OF VAPORIZATION OF NOMINAL 12 PERCENT MIXTURE

Pressure (psia)	Bubble Point (^{o}F)	Dew Point (^{o}F)	ΔH_{vap} (Btu/lb)
500	-123.4	3.3	200.3
800	- 89.2	10.0	156.7
1000	- 65.9	10.7	114.5

Nominal 28 Percent Propane in Methane Mixture

Isobaric enthalpy determinations on this mixture were made in the single and two-phase regions in the temperature range -240^{o}F to 140^{o}F at pressures from 250 to 2000 psia. The range of individual runs is indicated by the horizontal lines in Figure 9.

The composition of the circulating gas misture was analysed during the course of the experiments with the chromatograph and a record of the analyses is shown in Figure 10. There does not appear to be a significant deviation from the average composition selected for this mixture given in Table XIII.

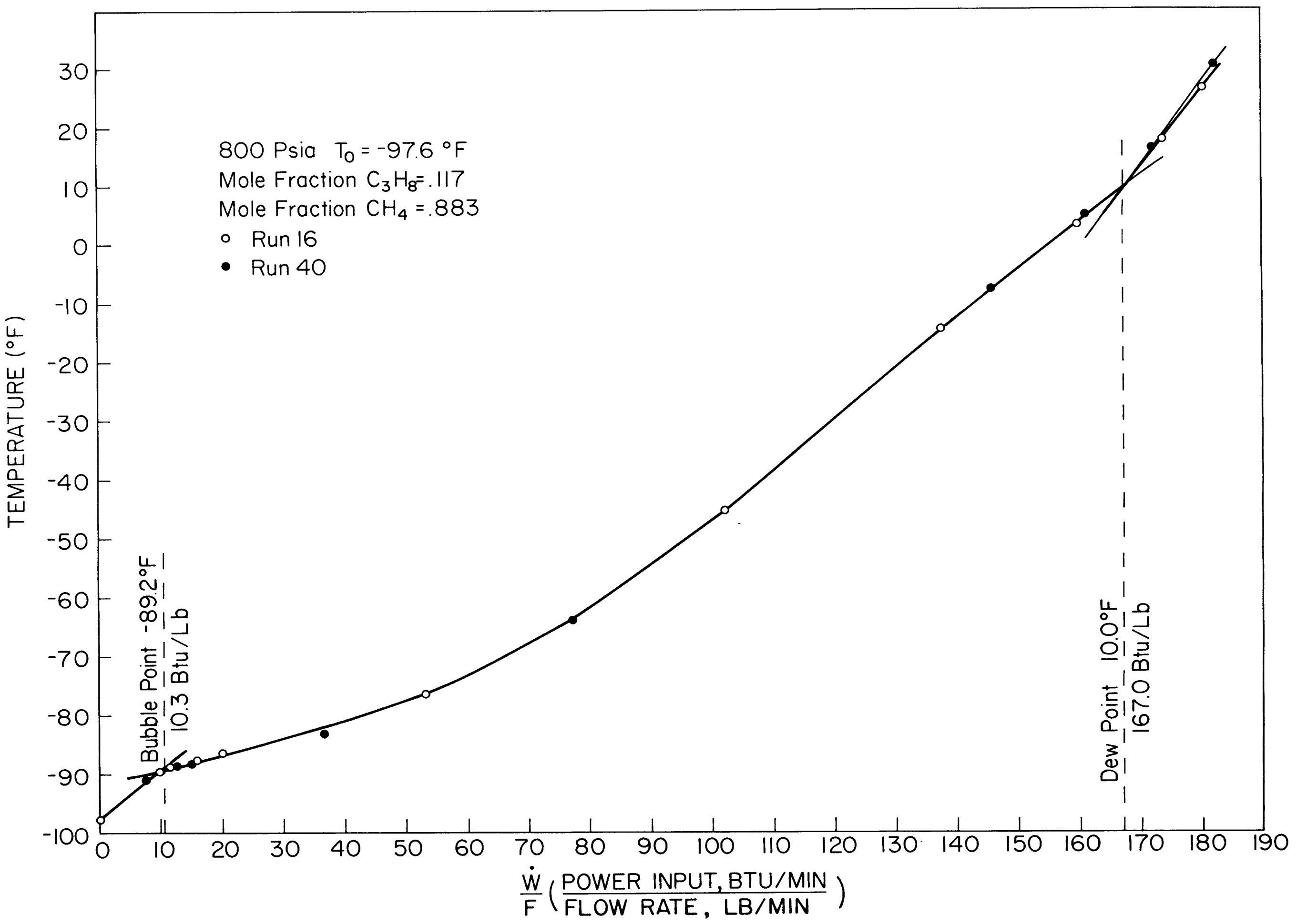


Figure 8. Enthalpy Traverse of the Two-Phase Region

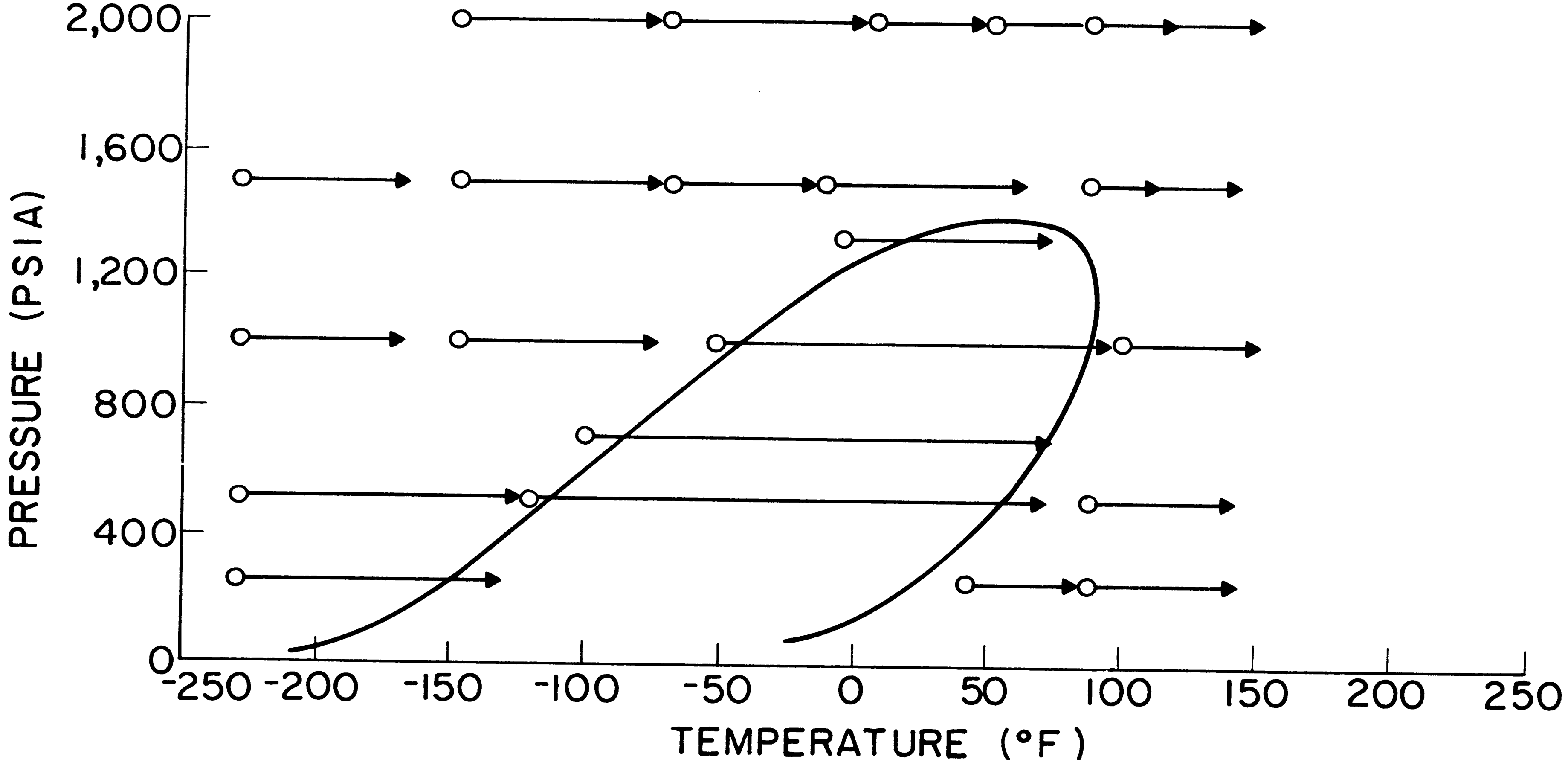


Figure 9. Range of Experimental Measurements on the Nominal 28 Percent Mixture

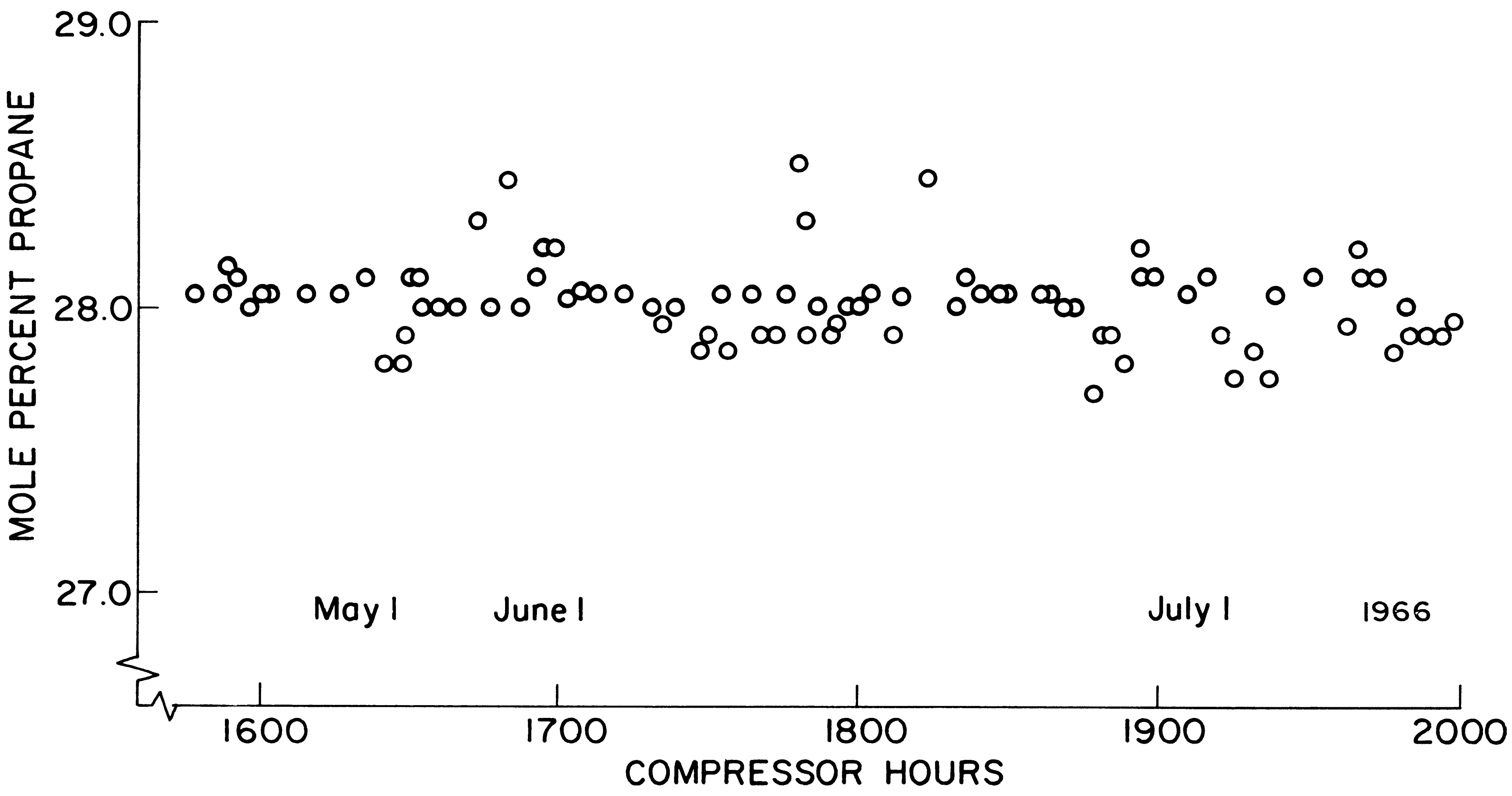


Figure 10. Composition of the Nominal 28 Percent Mixture as a Function of Time

TABLE XIII

OMPOSITION OF NOMINAL 28 PERCENT MIXTURE

	Mole Fraction
Methane	0.7181 *
Propane	0.280 ± .001
Carbon Dioxide	0.0003
Ethane	0.0005
Nitrogen	0.0010
Oxygen/Argon	0.0001
	1.0000

* by difference

In order to ensure the accuracy of the results, it is standard practice to calibrate the flowmeter with the mixture under study before any runs are made and after every 10 runs are complete. Unfortunately the remarkable success in calibration experienced with all the other mixtures was not achieved when working with the mixture of 28 mole percent propane in methane. Ten complete sets of calibration runs were made. The results of the calibration runs are summarized in Figure 11.

Calibration Sets 10 and 80 are believed to be in error as the result of oil in the flowmeter and/or water in the manometer leads. Ignoring these results but taking all other sets into account yields a calibration curve which fits all calibration points with an average deviation of one percent. Individual sets are fit with the straight lines on Figure 11 with average deviations not exceeding 0.25 percent. Therefore an attempt was made to match individual calibrations with experimental runs on a chronological basis.

No reliable calibration is available for interpretation of Runs 1

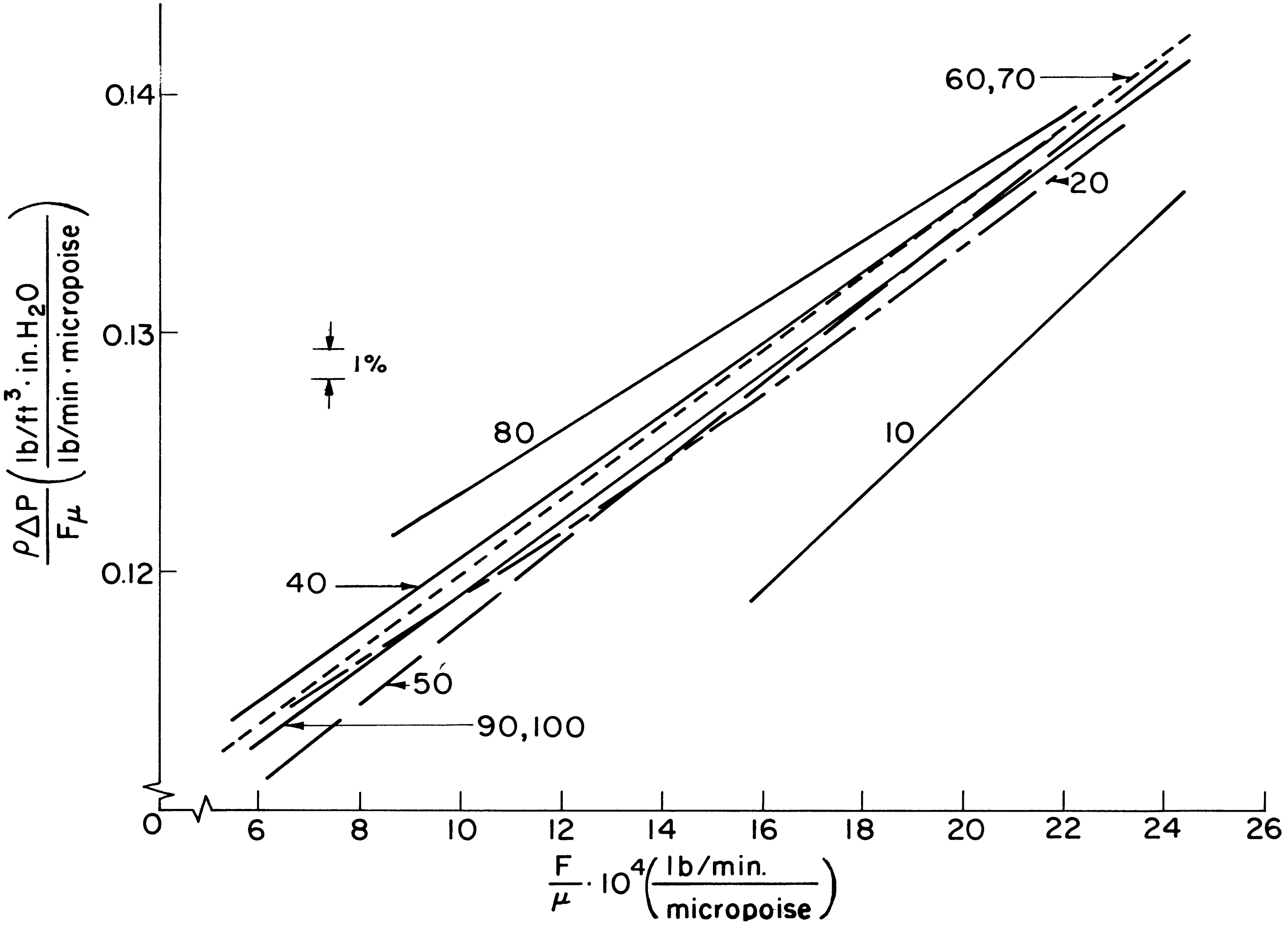


Figure 11. Flow Meter Calibrations with Nominal 28 Percent Mixture

through 19. Flow rates for Runs 20 and 21 were calculated from Calibration Set 40, and for Runs 23 and 24, Calibration Set 50 was employed. Runs 25 through 28 used Calibration Set 60 while the remaining Runs 30 through 48 used combined Sets 60 and 70. The last three runs, 49-51, used combined Sets 90 and 100. The error introduced by this procedure is believed to be considerally less than one percent in the point value of heat capacity, C_p, obtained from these data.

The experimental data for this mixture are presented in Table XLV of Appendix D.

Values of heat capacity derived from the experimental enthalpy data are given in Table XIV. The enthalpy traverses across the two-phase region were used to obtain values of the bubble and dew points and the isobaric heat of vaporization. These results are presented in Table XV. The values of the dew points at 500 and 700 psia may be in error because few data points were obtained in the region of the saturated vapor envelope.

TABLE XV

HEATS OF VAPORIZATION OF NOMINAL 28 PERCENT MIXTURE

Pressure (psia)	Bubble Point ($^{\circ}$F)	Dew Point ($^{\circ}$F)	ΔH_{vap} (Btu/lb)
500	-110.5	~59	226.5
700	- 82.3	~72	202.5
1000	- 46.0	79.3	155.3

TABLE XIV

TABULATED VALUES OF ISOBARIC HEAT CAPACITIES FOR THE NOMINAL 28 PERCENT MIXTURE

C_p (Btu/lb - °F)

Temperature	Pressure, psia				
°F	0	500	1000	1500	2000
-280	0.355	*0.625*	*0.621*	*0.623*	
-270	0.357	*0.627*	*0.623*	*0.624*	
-260	0.359	*0.629*	*0.625*	*0.625*	
-250	0.362	*0.631*	*0.628*	*0.626*	
-240	0.364	*0.633*	*0.630*	*0.628*	
-230	0.366	0.636	0.633	*0.630*	
-220	0.369	0.640	0.636	0.633	*0.630*
-210	0.371	0.644	0.639	0.635	*0.632*
-200	0.373	0.648	0.643	0.637	*0.634*
-190	0.375	0.654	0.648	0.641	*0.637*
-180	0.378	0.660	0.653	0.646	*0.641*
-170	0.380	0.667	0.659	0.650	*0.644*
-160	0.382	0.675	0.666	0.656	*0.649*
-150	0.384	0.684	0.673	0.662	0.654
-140	0.386	0.695	0.681	0.669	0.660
-130	0.389	0.709	0.691	0.678	0.666
-120	0.391	0.725	0.702	0.688	0.673
-110	0.394	0.747	0.715	0.698	0.680
-100	0.396		0.730	0.708	0.688
- 90	0.399		0.748	0.718	0.697

TABLE XIV - (Cont.)

Temperature	Pressure, psia				
°F	0	500	1000	1500	2000
- 80	0.402		0.770	0.732	0.708
- 70	0.405		0.798	0.749	0.720
- 60	0.409		0.834	0.770	0.733
- 50	0.412		0.880	0.794	0.748
- 40	0.415			0.823	0.764
- 30	0.419			0.854	0.783
- 20	0.423			0.893	0.803
- 10	0.427			0.938	0.824
0	0.430			0.986	0.846
10	0.434			1.040	0.868
20	0.438			1.093	0.890
30	0.443			1.126	0.913
40	0.447			1.135	0.935
50	0.451	0.637		1.128	0.952
60	0.455	0.616		1.110	0.961
65					0.961
70	0.460	0.600		1.082	0.960
80	0.464	0.588		1.034	0.955
90	0.469	0.579	0.795	0.984	0.944
100	0.474	0.572	0.754	0.934	0.924
110	0.479	0.569	0.726	0.889	0.904
120	0.484	0.567	0.706	0.854	0.885

TABLE XIV - (Cont.)

Temperature °F	Pressure, psia 0	 500	 1000	 1500	 2000
130	0.489	0.566	0.689	0.823	0.867
140	0.494	0.566	0.677	0.797	0.849
150	0.499	*0.566*	*0.668*	0.776	*0.833*
160	0.504	*0.567*	*0.660*	*0.759*	*0.817*
170	0.509	*0.569*	*0.654*	*0.744*	*0.803*
180	0.514	*0.571*	*0.649*	*0.732*	*0.789*
190	0.519	*0.573*	*0.646*	*0.721*	*0.777*
200	0.525	*0.576*	*0.643*	*0.713*	*0.766*
210	0.530	*0.578*	*0.641*	*0.705*	*0.756*
220	0.535	*0.581*	*0.639*	*0.700*	*0.747*
230	0.541	*0.585*	*0.638*	*0.695*	*0.740*
240	0.546	*0.588*	*0.638*	*0.691*	*0.734*
250	0.551	*0.591*	*0.638*	*0.687*	*0.729*
260	0.557	*0.594*	*0.639*	*0.684*	*0.724*
270	0.562	*0.597*	*0.639*	*0.683*	*0.720*
280	0.567	*0.601*	*0.640*	*0.682*	*0.717*
290	0.573	*0.604*	*0.642*	*0.682*	*0.715*
300	0.578	*0.609*	*0.644*	*0.681*	*0.713*

Experimental Data on Nominal 43 Percent Nitrogen in Methane Mixture

Isobaric enthalpy determinations of this mixture were obtained in the liquid, two-phase, and gaseous regions at temperatures from -240°F. to 140°F. at pressures from 250 to 2000 psia. The locations of the experimental determinations are shown in Figure 12.

Accurate determination of the composition of this mixture proved to be a problem. Initial analyses made with the chromatograph and the mass spectrometer at The University of Michigan are compared in Table XVI with independent analyses of the same sample (chromatograph standard) by the Continental Oil Company and the Phillips Petroleum Company in 1965.

TABLE XVI

COMPARISON OF ANALYSES OF THE METHANE-NITROGEN MIXTURE (1965)

	Chromatograph			Mass Spectrometer
	Phillips	Conoco[1]	U of M	U of M
O_2/Ar	-	-	0.02	-
N_2	44.32	44.31	43.10	43.40
C_2H_6	0.05	0.04	0.05	-
CO_2	0.03	-	-	-
CH_4	55.60	55.65	56.83	56.60
C_3H_8	0.0	0.0	-	-

[1] Gas Processing Group

The agreement was less than desired and a chromatographic analysis based on comparison with four mixtures prepared by weight in

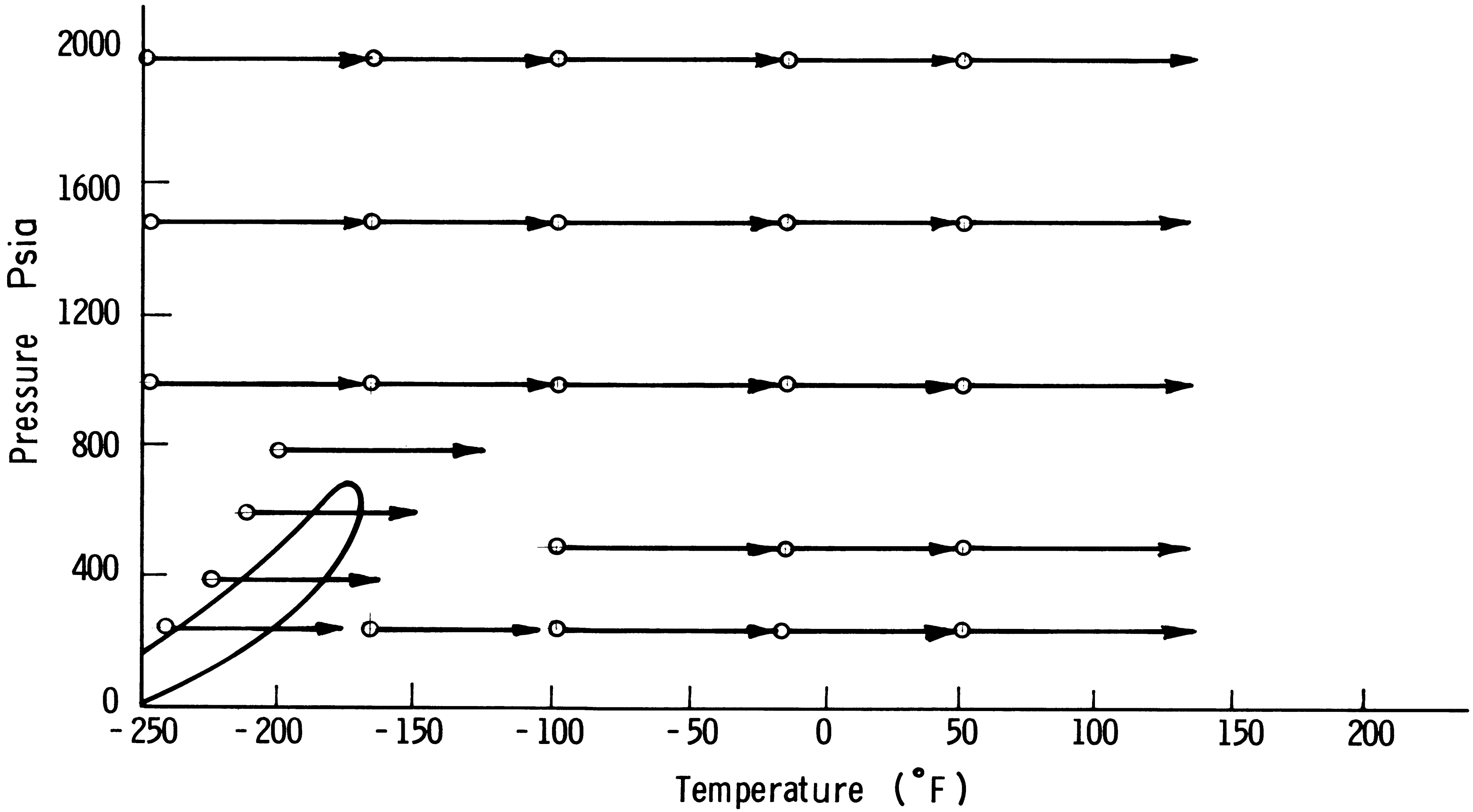


Figure 12. Range of Experimental Measurements on the Nominal 43 Percent Mixture

small sample bombs gave 43.3 mole percent nitrogen in the mixture. To resolve this discrepancy, another three mixtures were prepared by weight using ultra-high purity methane and analyzed along with the mixture on another molecular sieve column. The result was 43.4 mole percent nitrogen. Another reanalysis of the sample by mass spectrometer at this time gave 43.2 mole percent nitrogen, so Continental Oil Company was requested to reanalyze this sample. The results of analyses obtained in 1967 are shown in Table XVII.

TABLE XVII

COMPARISON OF ANALYSES OF THE METHANE-NITROGEN MIXTURE (1967)

	Chromatograph			Mass Spectrometer
	Conoco[1]	Conoco[2]	U of M	U of M
O_2/Ar	----	----	0.01	----
N_2	44.31	42.69	43.42	43.20
C_2H6	0.05	0.05	0.05	----
CO_2	0.02	0.03	----	----
CH_4	55.61	57.23	56.52	56.80
C_3H_8	0.01	----	----	----

[1] Gas Processing Group.

[2] Analytical Group.

It appears that the discrepancy between the independent analyses and the analyses of this mixture at the University of Michigan has still not been resolved. A record of the composition during the experimental measurements (obtained by comparison with the chromatograph standard taken as 43.3 mole percent nitrogen) is shown in Figure 13. From a consideration of the numerous analyses and checks, the composition of

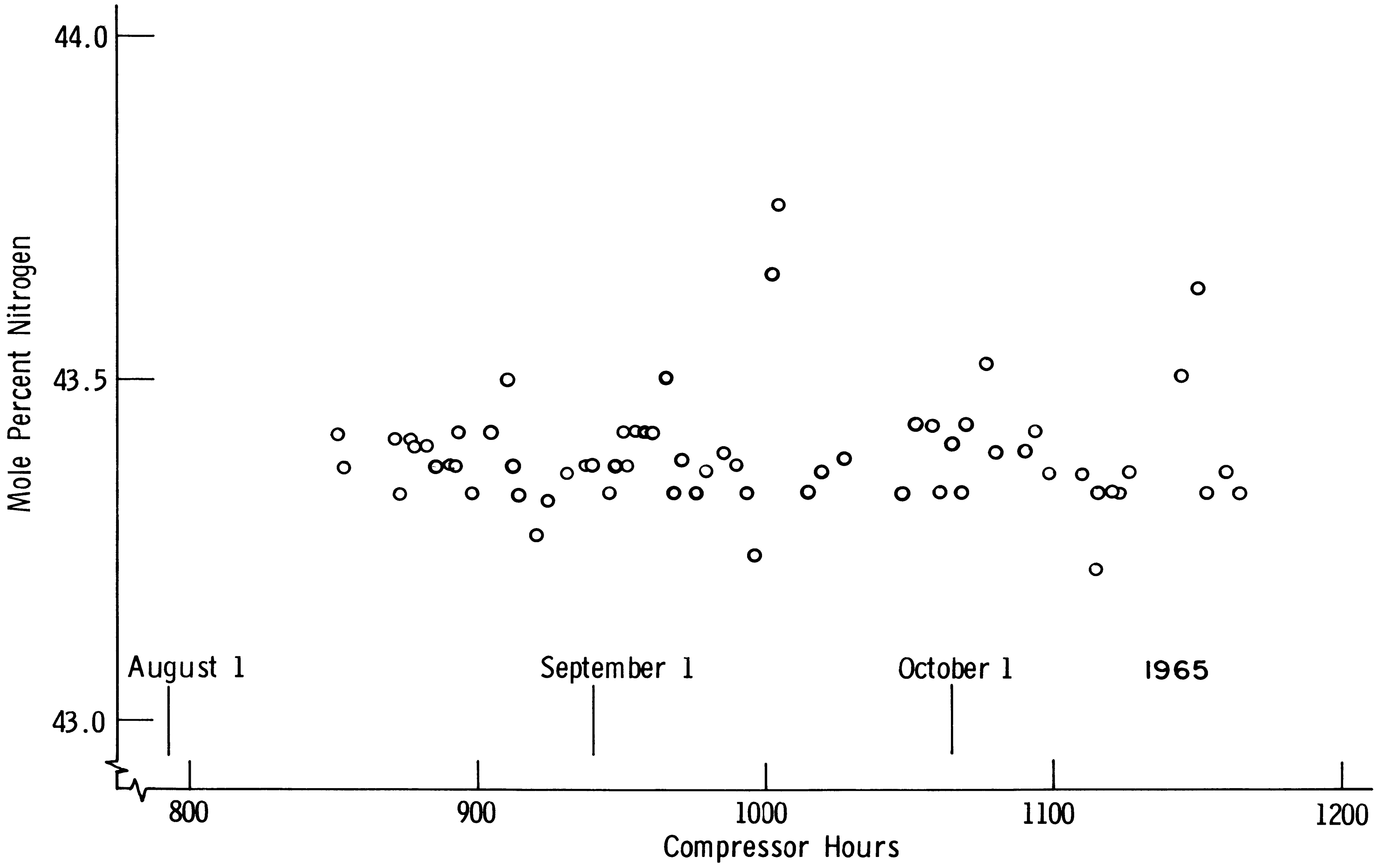


Figure 13. Composition of the Nominal 43 Percent Mixture as a Function of Time

the methane-nitrogen mixture was taken to be that given in Table XVIII.

TABLE XVIII

COMPOSITION OF NOMINAL 43 PERCENT MIXTURE

	Mole Fraction
Methane	.5652 *
Propane	-----
Carbon Dioxide	.0002
Ethane	.0005
Nitrogen	.434
Oxygen/Argon	.0001
	1.0000

* by difference

Three sets of calibration runs were obtained on the flow meter during the course of the experiments on this mixture. The average deviation of the 30 calibration points from the cubic equation fit to them was 0.13 percent. The calibration data are given in Table XXXIX of Appendix B and are plotted in Figure 49.

The experimental data for this mixture are presented in Table XLVI of Appendix D. Isobaric heat capacities derived from the experimental data are tabulated in Table XIX. As with the other mixtures the experimental data were extrapolated from the lowest experimental temperature down to -280°F. The heat capacities at highest experimental temperatures were blended into calculations of Cp made with the B-W-R equation of state up to 300°F. A plot of the heat capacity at 1500 psia as a function of temperature is shown in Figure 14. The data are presented as solid bars and the enthalpy differences obtained from the basic data having

TABLE XIX

TABULATED VALUES OF ISOBARIC HEAT CAPACITIES FOR THE NOMINAL 43 PERCENT MIXTURE

C_p (Btu/lb - °F)

Temperature	Pressure, psia					
°F	0	250	500	1000	1500	2000
-280	0.354			*0.550*	*0.597*	*0.588*
-270	0.354			*0.573*	*0.606*	*0.596*
-260	0.354			*0.597*	*0.615*	*0.604*
-250	0.354			*0.621*	*0.624*	*0.612*
-240	0.354			0.647	0.636	0.621
-230	0.354			0.673	0.647	0.630
-220	0.354			0.700	0.661	0.640
-210	0.354			0.728	0.676	0.650
-200	0.354			0.761	0.693	0.661
-190	0.354			0.806	0.715	0.673
-180	0.354			0.872	0.746	0.687
-170	0.354			0.992	0.784	0.705
-160	0.355	0.450		1.274	0.836	0.731
-150	0.355	0.435		1.406	0.900	0.756
-143				1.413		
-140	0.355	0.424		1.411	0.953	0.779
-130	0.355	0.416		1.370	0.985	0.800
-128					0.986	
-120	0.355	0.410		1.080	0.973	0.813

TABLE XIX - (Cont.)

Temperature	Pressure, psia					
°F	0	250	500	1000	1500	2000
-110	0.355	0.406		0.870	0.954	0.818
-100	0.356	0.403	0.472	0.733	0.901	0.813
- 90	0.356	0.400	0.461	0.657	0.833	0.792
- 80	0.356	0.397	0.450	0.607	0.765	0.766
- 70	0.357	0.395	0.437	0.572	0.706	0.739
- 60	0.357	0.393	0.431	0.544	0.663	0.712
- 50	0.358	0.391	0.423	0.524	0.627	0.683
- 40	0.358	0.389	0.418	0.508	0.594	0.654
- 30	0.359	0.387	0.415	0.495	0.569	0.627
- 20	0.359	0.386	0.412	0.484	0.550	0.602
- 10	0.360	0.384	0.410	0.474	0.538	0.581
0	0.361	0.383	0.408	0.466	0.527	0.562
10	0.362	0.382	0.406	0.459	0.517	0.547
20	0.363	0.383	0.405	0.453	0.506	0.534
30	0.364	0.383	0.404	0.448	0.496	0.523
40	0.365	0.384	0.402	0.443	0.487	0.514
50	0.366	0.384	0.401	0.439	0.477	0.505
60	0.367	0.385	0.400	0.435	0.469	0.498
70	0.369	0.385	0.400	0.431	0.463	0.491
80	0.370	0.386	0.399	0.428	0.458	0.484
90	0.371	0.386	0.400	0.426	0.454	0.478
100	0.373	0.387	0.400	0.424	0.451	0.473

TABLE XIX - (Cont.)

Temperature	Pressure, psia					
°F	0	250	500	1000	1500	2000
110	0.374	0.387	0.400	0.423	0.449	0.470
120	0.376	0.388	0.400	0.422	0.446	0.467
130	0.378	0.389	0.400	0.422	0.444	0.464
140	0.379	0.389	0.400	0.421	0.442	0.461
150	0.381	0.391	0.400	0.421	0.440	0.458
160	0.383	0.392	0.401	0.421	0.439	0.456
170	0.384	0.393	0.402	0.421	0.438	0.455
180	0.386	0.395	0.403	0.421	0.438	0.453
190	0.388	0.396	0.404	0.421	0.437	0.452
200	0.390	0.398	0.406	0.421	0.437	0.451
210	0.392	0.399	0.407	0.422	0.437	0.450
220	0.394	0.401	0.408	0.423	0.437	0.450
230	0.396	0.403	0.410	0.423	0.437	0.449
240	0.398	0.404	0.411	0.424	0.437	0.449
250	0.400	0.406	0.413	0.425	0.438	0.449
260	0.402	0.408	0.414	0.427	0.438	0.449
270	0.404	0.410	0.416	0.428	0.439	0.450
280	0.406	0.412	0.417	0.429	0.440	0.450
290	0.408	0.414	0.419	0.430	0.441	0.450
300	0.410	0.416	0.421	0.432	0.442	0.451

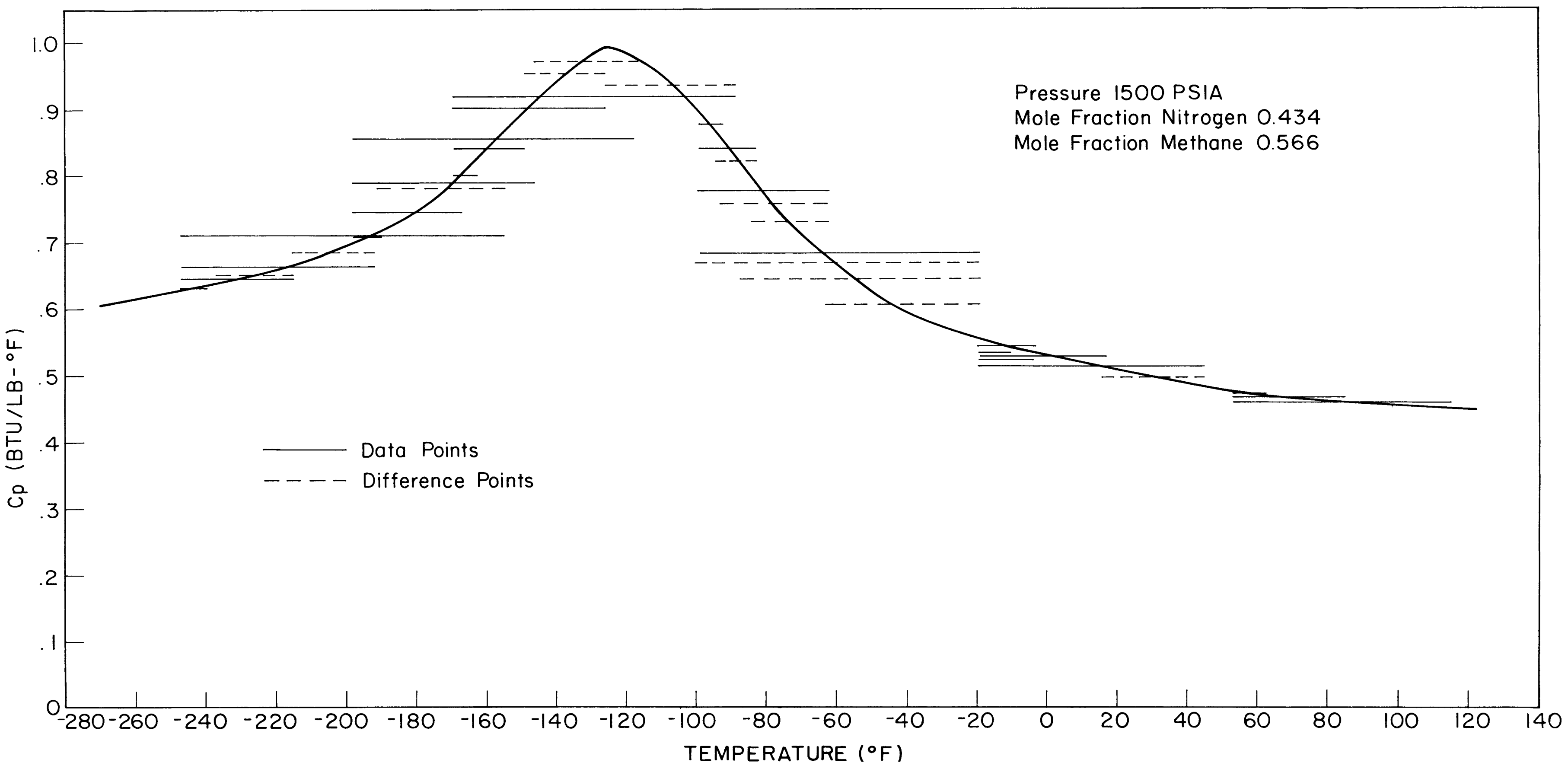


Figure 14. Heat Capacity of the Nominal 43 Percent Mixture at 1500 psia

the same initial temperature are shown as broken lines. The use of difference points facilitates the drawing of the equal-area curve to obtain point values of heat capacity. In this example the location of the maximum in heat capacity is determined using the differenced data. This maximum in heat capacity is characteristic of data obtained at pressures above the critical pressure and Manker[123] used the locus of these maxima to estimate the critical point of a mixture.

The three enthalpy traverses across the two-phase region yielded the values of the bubble points, dew points, and latent heats of vaporization at constant pressure given in Table XX.

TABLE XX

HEATS OF VAPORIZATION OF NOMINAL 43 PERCENT MIXTURE

Pressure (psia)	Bubble Point (^{o}F)	Dew Point (^{o}F)	ΔH_{vap} (Btu/lb)
250	-231.0	-190.7	120.2
400	-208.0	-176.1	98.9
600	-183.1	-157.3	71.3

Experimental Data on Nitrogen to Evaluate Heat Leak

In the reduction of all the isobaric data using Equation (2) the assumption is made that the calorimeter is adiabatic, that is, the heat leak Q is assumed to be negligible. This assumption is based on the results of extensive tests of vacuum level, guard heater mismatch and rate of conduction in the calorimeter conducted by Manker[123]. He concluded that the heat leak error was under 0.02 percent, much smaller than the estimated accuracy of the enthalpy measurements.

Montgomery and DeVries[135] have established that the heat leak is zero if the heat capacity determined by the calorimeter is independent of the flow rate. With each of the mixtures studied with the isobaric calorimeter, one run was made to test this assumption. The plots of heat capacity versus 1/F are shown in Figures 15 and 16 for the mixtures. While the heat capacity appears to be independent of the flow rate within the precision of the measurements (± 0.2 percent), lines indicating heat leak can easily be drawn through the data. A disturbing feature is the fact that the sign of the heat leak (slope of the line) appears to vary from one run to another.

The latent heat of vaporization data obtained on the nominal 28 percent mixture raised doubts that the heat leak could be neglected. In the construction of a preliminary enthalpy diagram for this mixture[131] the latent heats at 500 and 700 psia appeared to be high by 5 to 6 percent. These enthalpy traverses across the two-phase region involved temperature rises of up to 170°F and the assumption of adiabatic conditions with very large temperature differences had not been checked. Nitrogen was selected as the test gas because large temperature rises could be obtained without overloading the DC power supply.

Isobaric enthalpy data were obtained from the inlet conditions of -196°F at 1000 psia with temperature rises of 24, 45, 85, 158, and 229°F at various flow rates. The experimental data are presented in Table XLVII of Appendix D. Plots made of the mean heat capacity as a function of reciprocal flow rate to establish the magnitude of the heat leak are shown in Figure 17. The precision of these data is poorer than normal and the range of flow rates is smaller than desirable. However, estimates of the heat leak were made using the equation:

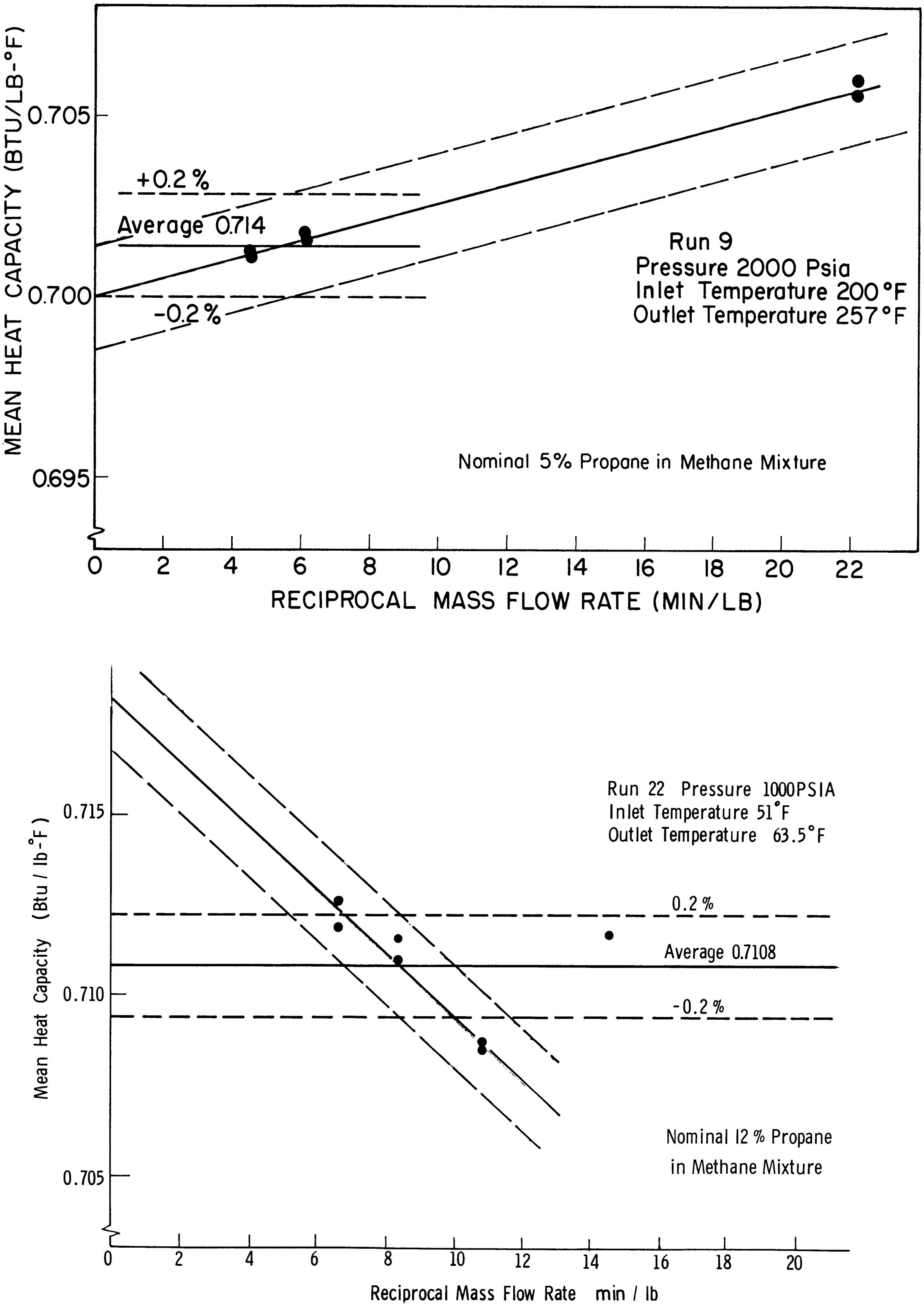
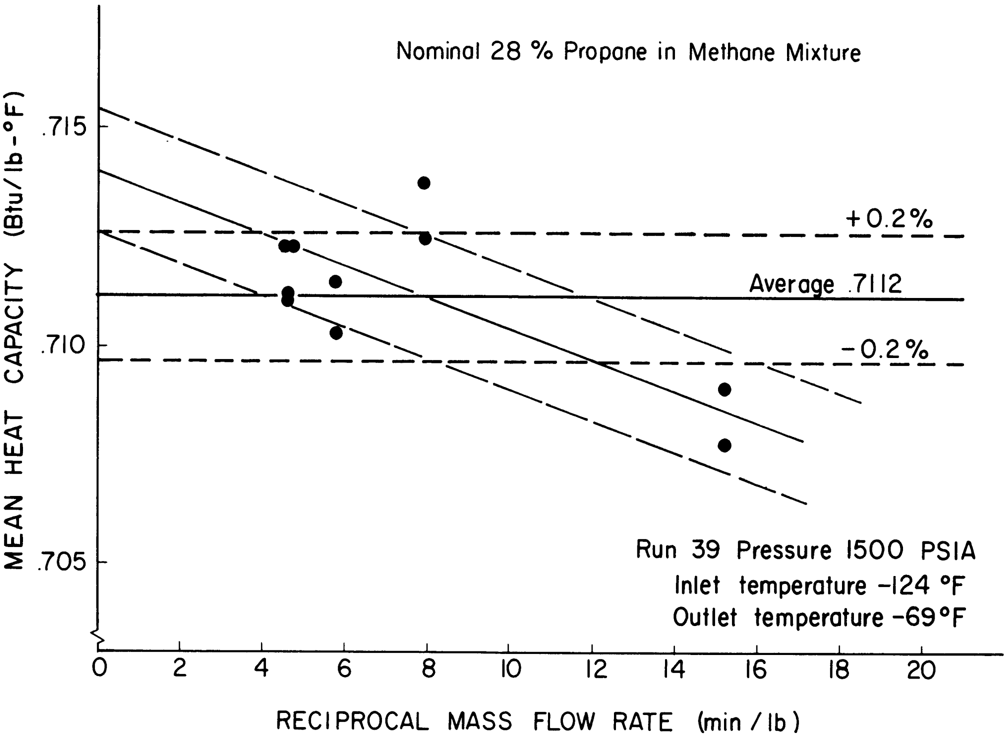


Figure 15. Heat Capacity as a Function of Reciprocal Flow Rate for Nominal 5 and 12 Percent Mixtures



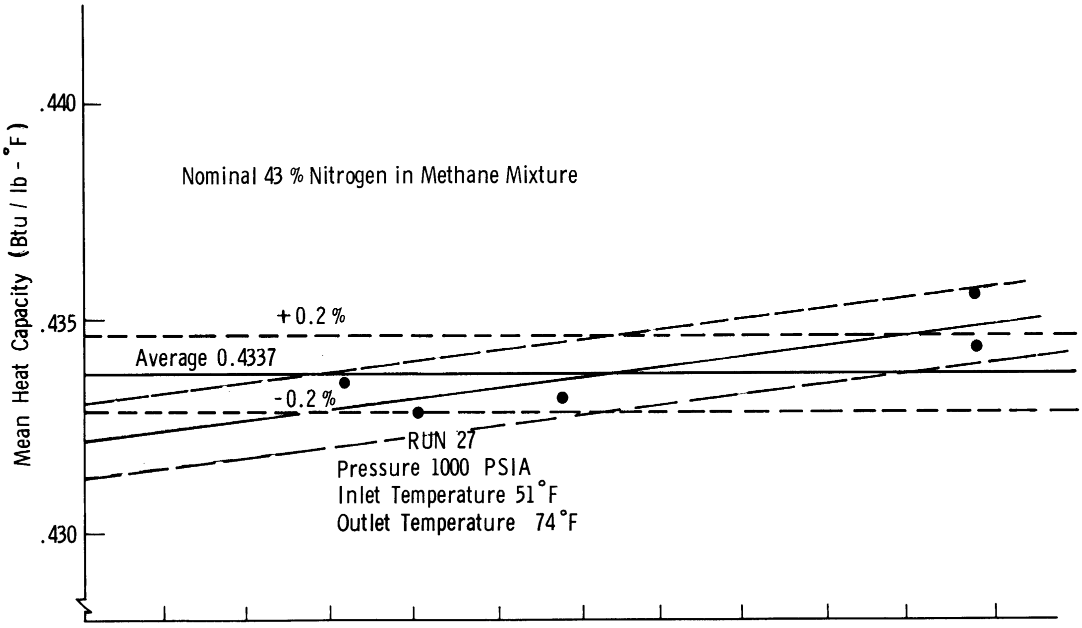


Figure 16. Heat Capacity as a Function of Reciprocal Flow Rate for Nominal 28 and 43 Percent Mixtures

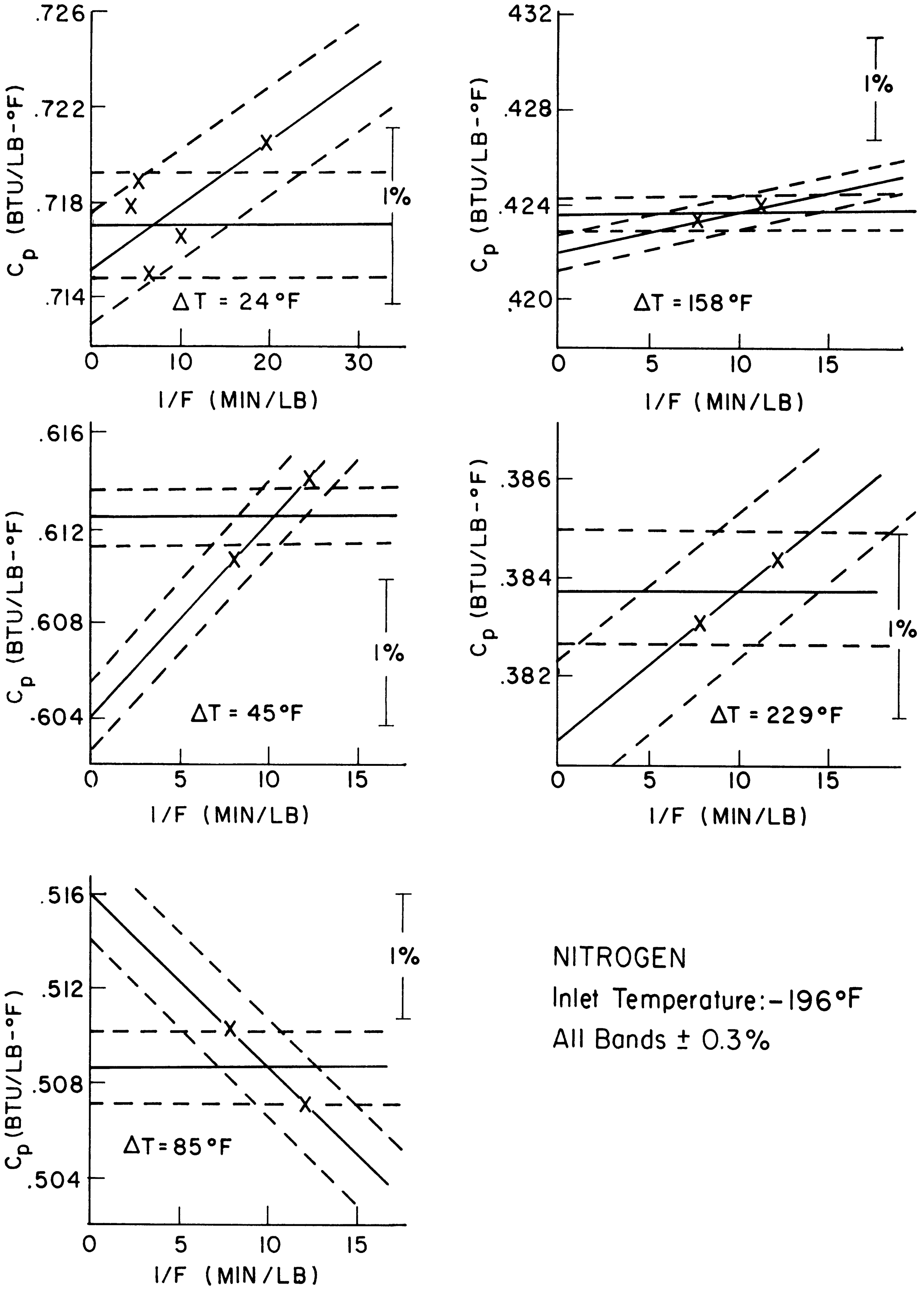


Figure 17. Heat Capacity as a Function of Reciprocal Flow Rate for Nitrogen

$$\overline{C}_p = C_p^{\infty} - \frac{\dot{Q}}{F\Delta T} \qquad (22)$$

where $\overline{C}_p$ is the mean heat capacity calculated from Equation (2) and C_p^{∞} is the intercept on the ordinate at infinite flow rate. The estimates are plotted in Figure 18 as a function of the temperature rise across the calorimeter. Also included on this plot are values taken from Figures 15 and 16 for the mixtures. There appears to be no direct correlation and it is concluded that heat leak effects are less than one percent even with temperature rises of 200°F.

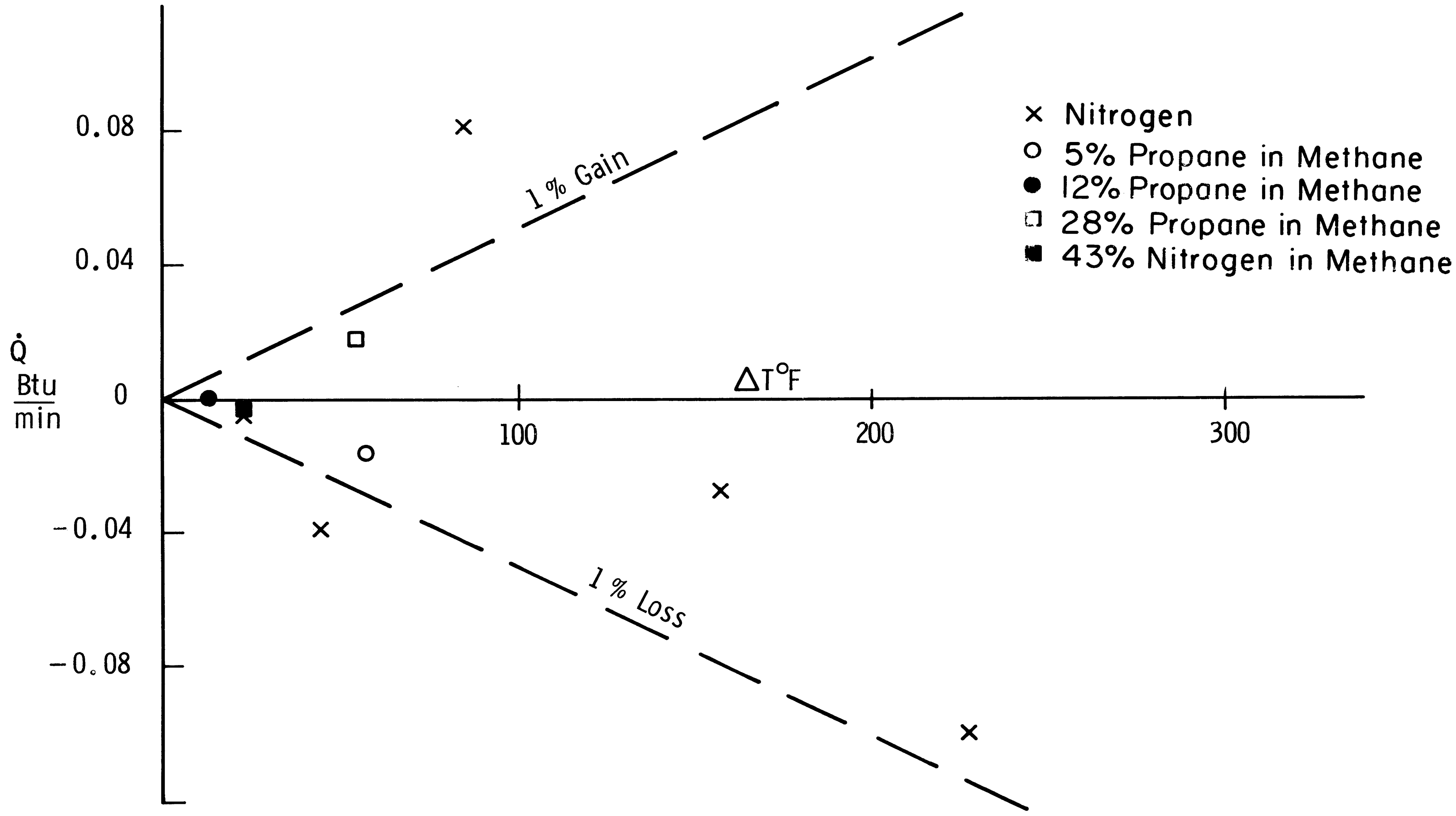


Figure 18. Apparent Heat Leak as a Function of Temperature Rise Across the Calorimeter

SECTION III-THE ISOTHERMAL EFFECT OF PRESSURE ON ENTHALPY

Previous work employing isothermal throttling calorimeters is reviewed and the design of a new throttling calorimeter is discussed here. The new calorimeter was used to obtain data on nitrogen and a nominal 5 percent propane in methane mixture. These data are compared with other direct measurements, Joule-Thomson data, and calculated values from correlations and compressibility data.

Background in Isothermal Throttling Calorimetry

All methods for measuring the isothermal effect of pressure on enthalpy involve some means for the production of a pressure drop and a source of energy to compensate for the cooling effect resulting from the pressure drop. Hence, the methods are suitable only where ϕ is negative and no isothermal calorimeters have been designed to abstract energy if the fluid warms on expansion. The porous plug method of Joule-Thomson measurements is well-known, and Buckingham[20] first proposed the measurement of the isothermal throttling coefficient by embedding a heating coil in the plug of an ordinary Joule-Thomson experiment. However, no devices utilizing this method have been used for isothermal throttling measurements. The throttling devices which have been used are the capillary, the valve throttle and the orifice.

Keyes and Collins[100] described an apparatus consisting of a platinum capillary which caused the pressure drop and also served as the resistance heater. Some data on carbon dioxide and ammonia were obtained at low pressures and room temperature. In later models, [Collins and Keyes[30,31]], a heating element consisting of resistance wire supported upon pyrex tubes was inserted into a short length of tubing. Substantially all the flow resistance of the calorimeter was caused by the heater. Measurements were made on steam and on nitrogen at low pressures (inlet pressure less than

3 atm.) and both μ and ϕ were determined.

Independently, in Germany, Eucken, Clusius, and Berger[55] reported a different apparatus for determining ϕ. A throttle valve was used to cause the pressure drop and the gas, after expansion, was passed over heating wires to bring the outlet temperature back to that of the inlet. The first measurements were made with air as the test gas.

A second throttle valve, which unlike the first could be adjusted without dismantling, was used by Eucken and Berger[56] for measurements on methane at temperatures from 165° to 293°K at pressures up to 100 atm. Measurements of the latent heat of vaporization were attempted but two-phase flow through the valve resulted in instability and no results could be obtained. Three measurements of the integral isothermal throttle effect of methane ($\Delta p \sim 30 - 50$ atm) above the critical were made to aid in the preparation of the enthalpy-pressure-temperature diagram[57]. Another throttle, similar to that of Keyes and Collins[100], consisting of a nickel-silver capillary was used to obtain data for carbon dioxide at 0°C. For unspecified reasons, no measurements with this capillary coil were made on methane.

Gusak[74] employing a copy of the Eucken device obtained data for nitrogen between 115° and 292° K at pressures from 60 to 200 atm.

The Russian workers, Ishkin and Kaganer[89] employing essentially the same apparatus as Gusak[74] obtained data on air and nitrogen at pressures up to 50 atm. at temperatures from -183° to +30°C. Data were obtained at closely spaced intervals in the critical region. The results were used to prepare enthalpy diagrams for air and for nitrogen. Later experiments were made on argon and mixtures of argon and nitrogen by Ishkin and Rogovaya[90].

Recently other Russian workers, using an improved throttle valve, have published results on mixtures of nitrogen and hydrogen (Bolshakov et al.[17]), methane and hydrogen (Gelperin et al.[67]), and methane with nitrogen[18].

A throttling valve was used by Charnley, Isles, and Townley[26] for measurements on nitrogen, ethylene, carbon dioxide, and nitrous oxide. The pressure drop was a few atmospheres and absolute pressures up to 50 atm. at temperatures between 0° and 45°C were used. The range was restricted by the use of plastic materials of construction. Using this apparatus, Charnley, Rowlinson, Sutton and Townley[27] made measurements on the binary mixtures carbon dioxide + nitrous oxide, carbon dioxide + ethylene, nitrous oxide + ethylene, and nitrous oxide + nitrogen. Interaction virial coefficients were derived from the zero-pressure data for the mixtures.

Francis, McGlashan, and Wormald[63] describe an apparatus operating below atmospheric pressure designed to obtain all three of the partial derivatives in Equation (8), but results were presented only for ϕ of benzene from 60° to 130°C.

Andersen[3] used an orifice to cause the pressure drop, followed by a heater to bring the gas back to the inlet temperature. The apparatus was designed to operate up to 4 atm. at temperatures between 0° and 30°C and values were obtained for air in this region.

Stribolt and Lydersen[180] made measurements on steam using a removable orifice to cause the pressure drop and the gas was passed over a heater to bring the outlet temperature back to that of the inlet.

Except for the three measurements of Eucken and Berger[57] all the data described above can be called differential values of ϕ, since the pressure drop was only a few atmospheres and the values of ϕ were easily obtained from the values of $(\Delta \underline{H}/\Delta P)_T$. Gilliland and Lukes[69] constructed a device for the measurement of the integral isothermal throttling effect, the enthalpy departure from the ideal gas state.

The throttle was a stainless steel capillary which also served as the resistance element, as in the Keyes and Collins[100] design. Capillaries of different lengths were used to obtain different pressure drops. Inlet pressures ranged up to 2800 psia while the outlet pressure was always near atmospheric. The equipment was later used to study n-pentane, n-heptane, and isooctane as well as mixtures of benzene and n-heptane by Parekh[142]. Only the pure component results were published by Gilliland and Parekh[70].

Yarborough[198] constructed a calorimeter similar to that used by Gilliland and Lukes[69]. Data were obtained on propane, benzene, and three mixtures of propane and benzene with inlet pressures up to 1000 psia in the temperature range 200 to 400°F. The results are reported in a paper by Yarborough and Edmister[199]. This calorimeter was used by Dillard[41] to study methane and a mixture of methane in propane at inlet pressures up to 2000 psia at temperatures of 90, 150 and 200°F.

The calorimeter designed by Dolan[44] consists of a capillary coil to cause the pressure drop and the heat required is determined from the difference in the amount of energy expended in heating the bath of boiling Freon surrounding the coil and the amount of energy abstracted in the Freon evaporated. Data were obtained with nitrogen at 74.5°F at inlet pressures up to 1500 psia.

Design of Isothermal Throttling Calorimeter

The first requirement in the design of the present calorimeter was that it operate over a wide range of temperatures, from -250° F. to 300° F. and at any pressure in this temperature range from 100 to 2000 psia. Type 304 stainless steel was selected as the material of construction because of its strength at low temperatures and the possibility of experimental work with corrosive fluids.

The instability of two-phase flow through a valve caused by alternate slugs of liquid and vapor prevents accurate thermodynamic measurements so the use of a throttling valve was abandoned since the design was to allow for the possibility of measuring isothermal enthalpy changes across the two-phase region.

An orifice also tends to be unstable in two-phase flow and the high velocity at the throat must be dissipated before accurate temperature measurements can be made. Heat leakage resulting from the difference in temperature between the walls and the jet may be significant unless elaborate precautions are taken to isolate the throttle from the surroundings.

A capillary was considered to be the best configuration for the throttle because the expansion is smooth and if energy is added to the fluid during expansion, the process will be almost isothermal. It should be noted that it is not necessary for the expansion to be isothermal; since enthalpy is a point function, the change in enthalpy between the inlet and outlet is determined only by the conditions at these points and does not depend upon the path of the fluid. However, by making the path as nearly isothermal as possible, heat leakage from the surroundings to the system is minimized.

The disadvantage of a capillary throttle is that it is not possible to vary flow rate and pressure drop independently. In this present design this is offset somewhat by making the capillary removable so various combinations of pressure drop and flow rate may be obtained.

Some earlier designs using a capillary as a throttle also used the capillary itself as a resistance heater. The relatively large flow rates in the recycle system into which the isothermal calorimeter was to be installed required the use of reasonably large diameter capillaries.

These capillaries have a low electrical resistance and require large currents to dissipate the energy input. In low temperature calorimetry, it is desirable to make power input leads as small as possible to minimize conduction from the surroundings, but with currents of the order of 10 amperes, large leads must be used to minimize lead losses.

The heater of the present calorimeter is an insulated Nichrome wire which passes inside the capillary for its entire length. The Nichrome wire is grounded at the outlet of the capillary and a copper power lead is connected to the heater wire at the inlet to the capillary. The combination of heater wire size and capillary size allows different pressure drop-power input relations. With this arrangement, currents were kept below one ampere.

The calorimeter developed here is designed for operation over a wide range of conditions and can be used in the liquid, two-phase, or gaseous regions. It can be used with relatively small pressure drops to measure ϕ or with large pressure drops to obtain integral values of the enthalpy change with pressure. The incorporation of the heater inside the flow resistance minimizes the temperature gradients in the system thus reducing the possibility of heat leaks.

Description of Calorimeter

The isothermal throttling calorimeter is part of the recycle system described earlier under isobaric measurements. Both isothermal and isobaric calorimeters are located in a constant temperature bath controlled to about 0.1° F. Four packless valves with stainless steel bellows located within the bath make it possible to operate either calorimeter with only minor adjustments. The isothermal throttling calorimeter is shown in Figure 19. The fluid enters the upper portion of the calorimeter vacuum jacket from the constant temperature bath. Here the pressure tap (9) and thermowell (1)

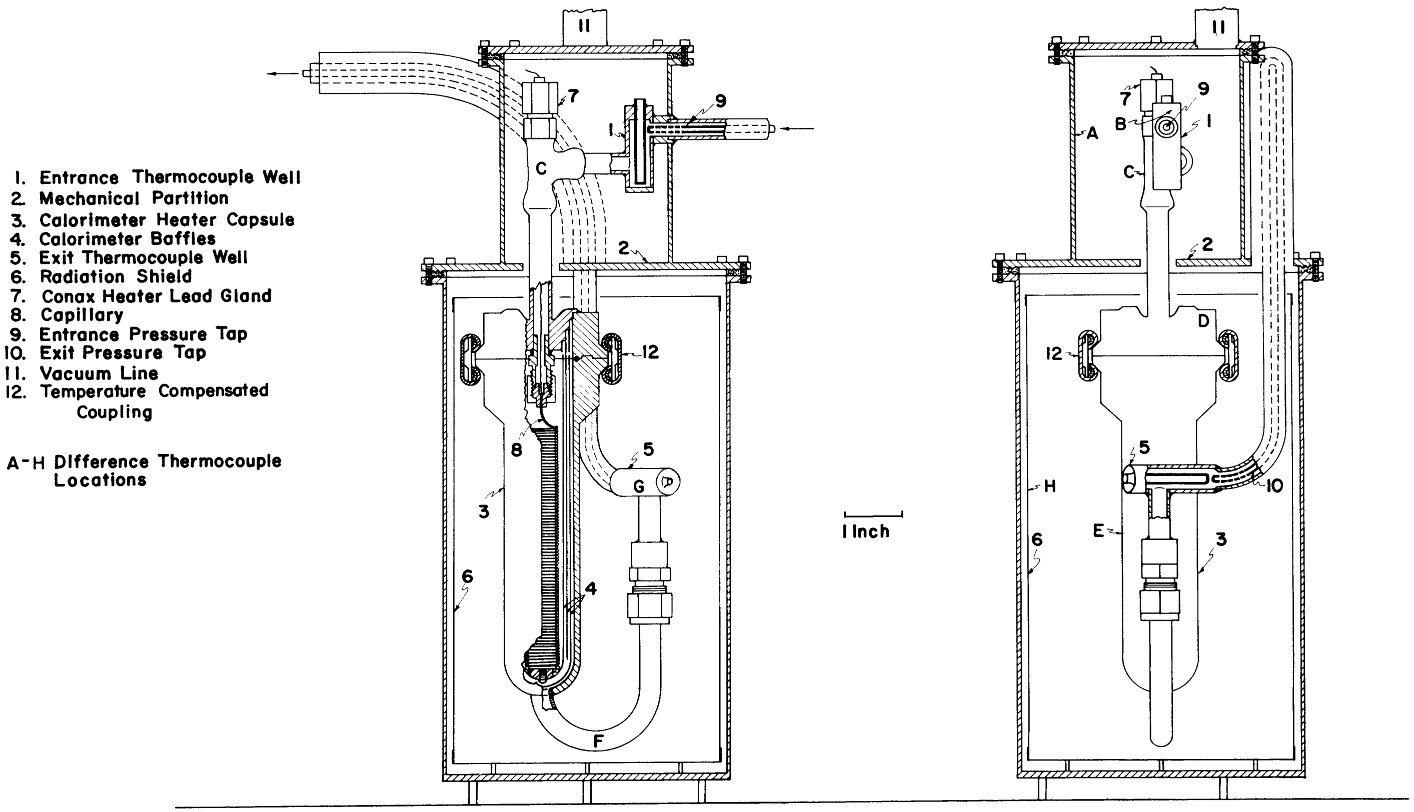


Figure 19. Isothermal Throttling Calorimeter

serve to measure the inlet conditions of the fluid before it passes to the throttle chamber (3). Inside the chamber is a removable capillary coil (8) which causes the pressure drop in the fluid. In this work, three different capillary sizes were employed of 16 BWG, 17 BWG, and 19 BWG hypodermic tubing, all about 10 feet in length. The nominal ID of these capillaries is .047, .042, and .027 inches respectively.

The chamber closure is a temperature compensated coupling (12) using a stainless steel O-ring. Although this closure was initially successful, the seal was found to leak after it had been opened and closed a number of times. It was necessary to use 1 mil Mylar gaskets on both sides of the O-ring for subsequent experiments to obtain a seal.

To offset the cooling effect as the pressure drops, electrical energy is added to the flowing fluid by the insulated Nichrome resistance wire (36 B&S, nominal .005" O.D.) inside the capillary.

The lead wire for this heater is brought from the vacuum jacket into the pressure capsule through a Conax gland (7), which uses a Teflon sealant. The other end of the heater wire is soldered to the low pressure end of the capillary to ground it electrically. The fluid jetting from the capillary is passed back and forth through three copper baffles (4) to reduce kinetic energy effects and smooth out temperature fluctuations before passing to the exit thermowell (5) and the exit pressure tap (10). The line in which the fluid leaves the calorimeter is enclosed by a vacuum tube for a distance of three feet after leaving the calorimeter to minimize heat conduction back from the surroundings.

Other efforts were made to reduce heat transfer to the surroundings. A radiation shield (6) completely encloses the calorimeter capsule. The lead wires to the heater are brought into contact with the vacuum jacket to eliminate heat transfer in the leads. The thermocouple lead wires are wrapped around a massive copper thermal equalization block before passing to the thermowells and the outlet thermopile leads are bonded to the outlet line with Apiezon grease. The entire jacket is evacuated to 1 to 5 microns through the vacuum line (11), which is bent under the surface of the bath fluid so that the contents of the upper portion of the calorimeter do not see a surface at temperature different from that of the bath. Single-junction copper-Constantan difference thermocouples are attached to the skin of the calorimeter at various points (A through H in Figure 19) to indicate the temperature profile along the calorimeter.

Measuring Instruments

1. The inlet pressure to the calorimeter is measured with the dead weight gauge used for some of the isobaric experiments.

2. The pressure drop across the calorimeter is measured by the differential pressure balance of Roebuck[155]. Leather packings were originally used as the seal on the piston of this instrument. Difficulties in operation led to the replacement of the leather with an O-ring seal using Viton O-rings. The piston in this device was replaced by Manker and the conversion of the mass on the piston to pressure drop in psi was given as 19.998 psi/lb. mass. The pressure is transmitted from the calorimeter fluid to the oil in the pressure measuring system by means of the Ruska differential pressure indicator for the inlet pressure and through a mercury U-leg for the outlet pressure. The level of mercury in the U-leg is sensed by electrical phobes sealed into each leg.

Although the Roebuck pressure balance is accurate to about 0.1 to 0.2 percent, the imbalance in the mercury U-leg could be as much as 0.5 inches because of the position of the electrical probes. It was found that the sensitivity of the pressure measuring system was about 0.05 lb mass on the pressure balance or about 1 psi. This limited the lower pressure drop measurements to an accuracy of about 1 percent.

3. The electrical energy is supplied to the heater by the DC power supply used for isobaric experiments. Essentially the same circuitry (standard resistors, potentiometer) is used to determine the power input to the calorimeter as in the isobaric experiments.

4. The flow rate of fluid is determined by the laminar flow meter as in the isobaric experiments.

5. Any temperature difference between the entrance and exit thermowells is sensed by duplicate six-junction copper-Constantan differential thermopiles using the K-3 potentiometer. The thermopiles were calibrated by the National Bureau of Standards and the results are given in Table XXXIV of Appendix B. Thermopile A was fabricated from 40 AWG copper wire and 36 AWG Constantan wire, while both copper and Constantan wires of thermopile C were 40 AWG.

6. The inlet temperature to the calorimeter is assumed to be the temperature of the calorimeter bath, which is measured by the platinum resistance thermometer as in the isobaric experiments.

The basic measurements affecting the accuracy of the isothermal enthalpy data obtained in this work are the power input to the calorimeter, the flow rate of fluid and the pressure drop across the calorimeter. The estimated errors for those measurements and the most probable error of the enthalpy measurements are listed in Table XXI.

TABLE XXI

ACCURACY OF ISOTHERMAL MEASUREMENTS

	Low ΔP	High ΔP
Power Input	0.05%	0.05%
Pressure Drop Across Calorimeter	1.0 %	0.3 %
Flow Rate	0.2 %	0.2 %
$\sqrt{\sum_i \varepsilon_i^2}$	1.02%	0.37%

Procedure for Isothermal Measurements

Using the recycle system, the fluid is brought to the desired conditions of pressure and temperature at the inlet to the calorimeter. A pressure drop of 100 to 300 psi is obtained by adjustment of the flow rate of fluid through the calorimeter section. The voltage supplied to the calorimeter heater wire is adjusted manually until the temperature difference between the inlet and outlet, sensed by the differential thermopiles is less than 5 microvolts (about 0.05° F). When steady state is reached, as indicated by the constancy of the pressure drop and the temperature difference across the calorimeter, the values of the variables are recorded. The time of approach to steady state is of the order of one hour.

Experimental Results with Nitrogen

Nitrogen was selected as the test gas because of the large amount of data for this element which are available for comparison. Data in both the isothermal and isenthalpic modes were obtained over about 100 psi pressure drops at three temperature levels, -147.1°F, +32.6°F, and +201.3°F using the 17 BWG capillary coil. The location of the experimental runs is shown

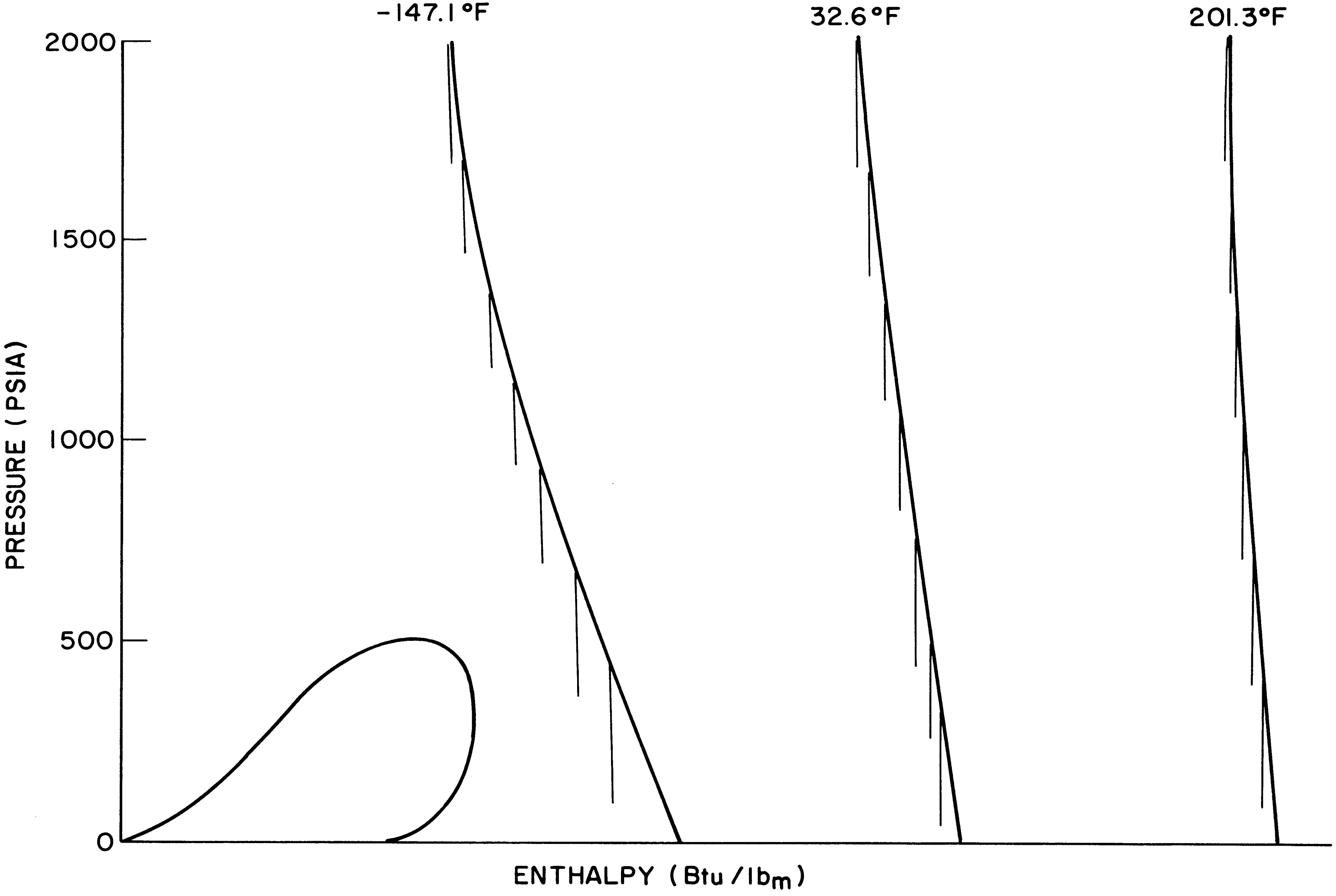


Figure 20. Range of Experimental Measurements on Nitrogen

in Figure 20 and extend from 100 to 2000 psia. The data are given in Tables XLVIII and XLIX of Appendix D.

Three sets of calibration runs on the flow meter were made in the course of the experiments on nitrogen. The cubic equation fits all 26 calibration points with an average deviation of 0.22 percent. The calibration data are given in Table XL of Appendix B and are plotted as Figure 50.

Analysis of Results with Nitrogen

The isenthalpic (Joule-Thomson) data obtained on nitrogen are plotted in Figure 21 for the three initial temperatures. Note that the horizontal bars representing the experimental data appear in pairs because the two six-junction thermopiles indicated significantly different values of the temperature drop across the calorimeter. This was not the case during isothermal operation nor has it been the case in experiments with the isobaric calorimeter. The difference in thermopile readings was interpreted to be the result of heat transfer (combined radiation and conduction) from the calorimeter bath to the pressure capsule. Heat transfer occurs because the pressure capsule attains the temperature of the outlet fluid which is lower than that of the bath. This is shown by the temperature change recorded during an isenthalpic run by the difference thermocouples attached to the skin of the calorimeter which are given in Table XXII. The radiation shield is seen to attain a temperature between that of the bath and that of the calorimeter pressure capsule. More radiation shields would reduce heat transfer but an analysis of heat transfer with increasing number of shields shows that the incremental reduction in heat transfer of shields after the first few is slight.

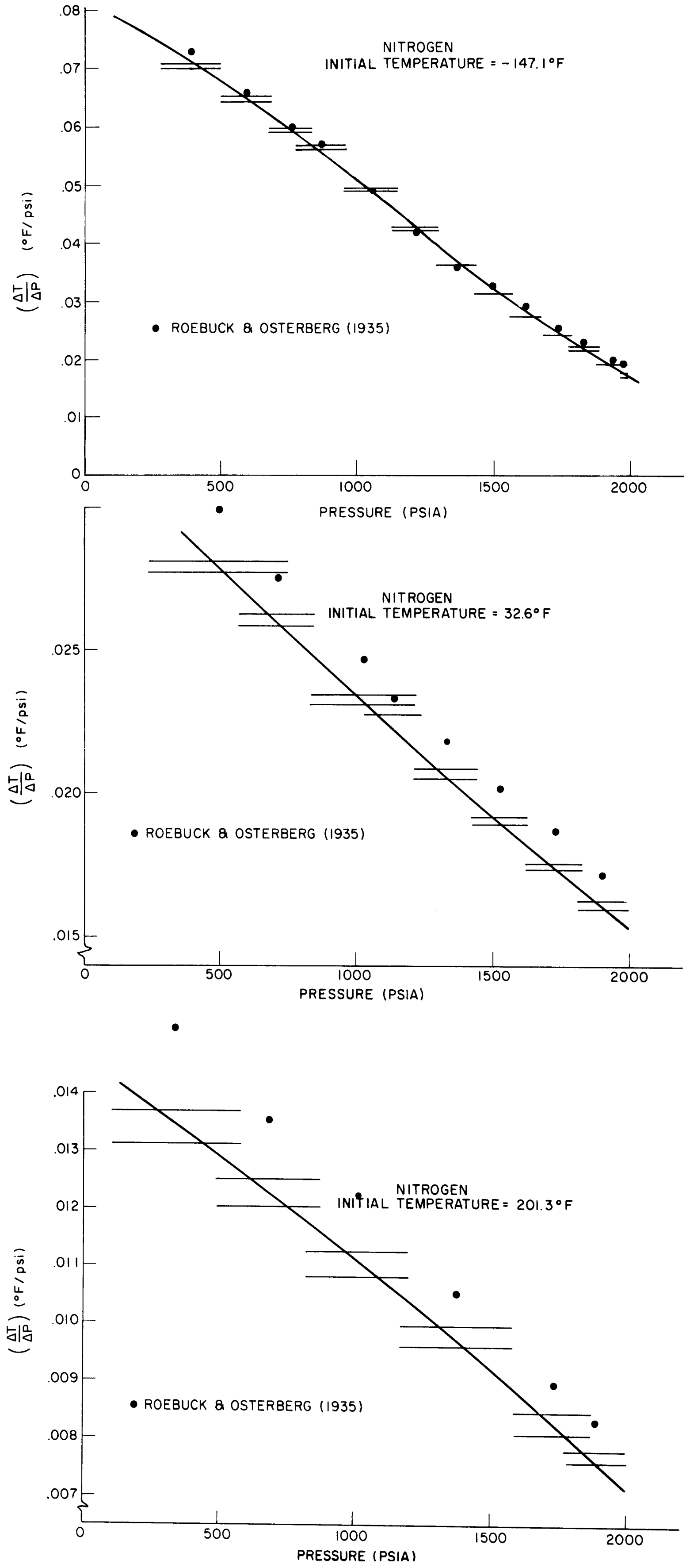


Figure 21. Isenthalpic (Joule-Thomson) Data on Nitrogen

TABLE XXII

COMPARISON OF DIFFERENCE THERMOCOUPLE READINGS

Thermocouple Pair	Location	Thermocouple Output (microvolts)	
		Isenthalpic Run	Isothermal Run
A-B	Inlet Thermowell	+ 0.5	-0.8
A-C	Inlet Tee	+ 0.7	-0.4
A-D	Top of Heater Capsule	-175.2	0.0
A-E	Middle of Heater Capsule	-184.5	-0.1
A-F	Bottom of Heater Capsule	-195.0	-0.5
A-G	Outlet Thermowell	-195.3	-0.6
A-H	Radiation Shield	- 49.6	-1.0

The isenthalpic data are compared with the corrected results of Roebuck & Osterberg[157] in Figure 21. The present results were obtained at constant inlet temperatures as shown in Figure 22 for the measurements at -147.1°F. Hence the smooth curves drawn on Figure 21 trace the locus of points of increasingly lower temperatures at lower pressures. The data are not in good agreement with those of Roebuck and Osterberg except at the lowest temperature where radiation is less significant.

From these observations, it was concluded that the isothermal throttling calorimeter is not suitable for isenthalpic determinations unless the fluid warms upon expansion. In this case it would be possible to heat the radiation shield to the temperature of the exit fluid.

The isothermal data for nitrogen at the three temperatures are plotted as a function of pressure in Figures 23 through 25. An equal-area curve is passed through the bars to obtain point values of ϕ. The data bars indicate

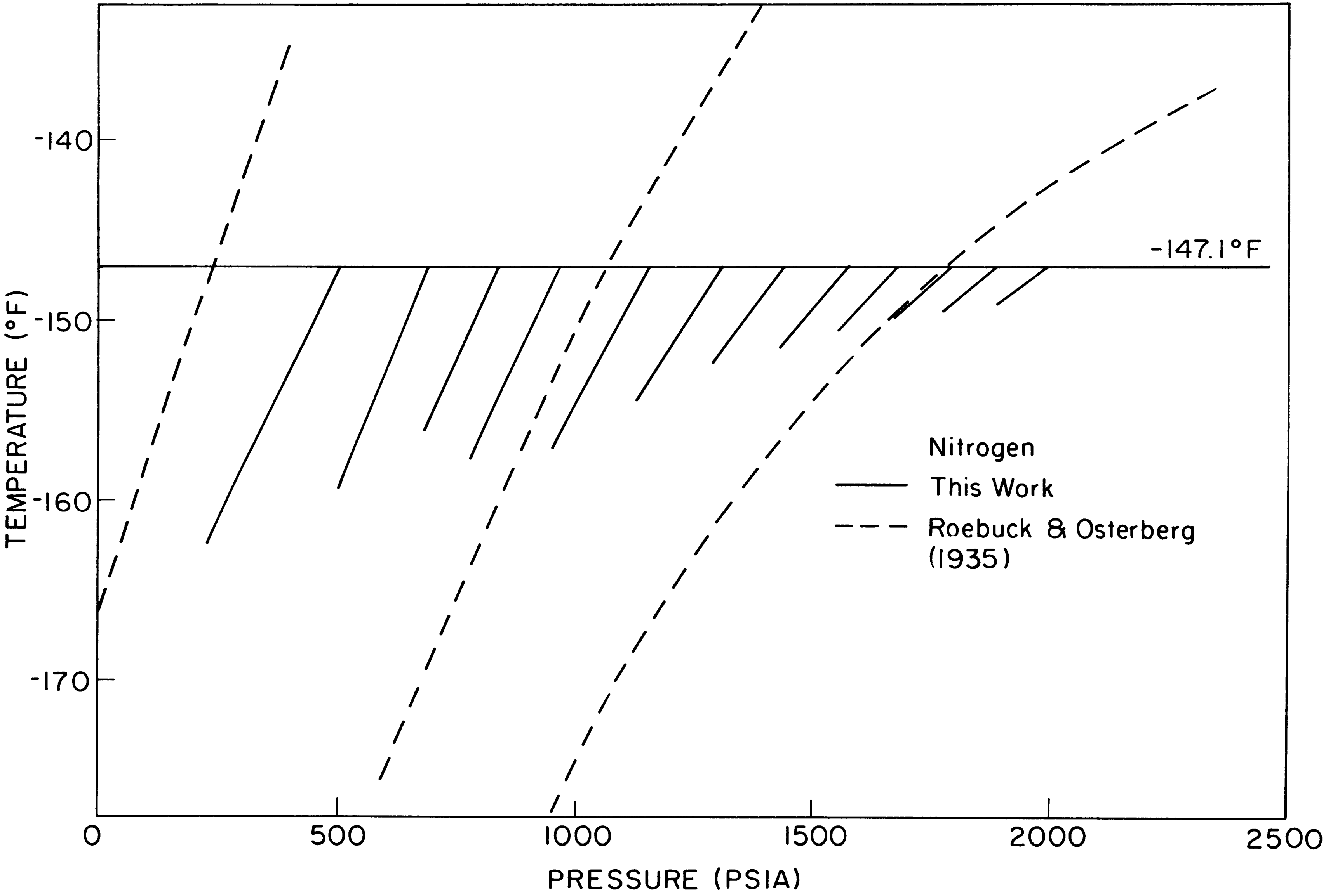


Figure 22. Comparison of the Types of Joule-Thomson Experiments

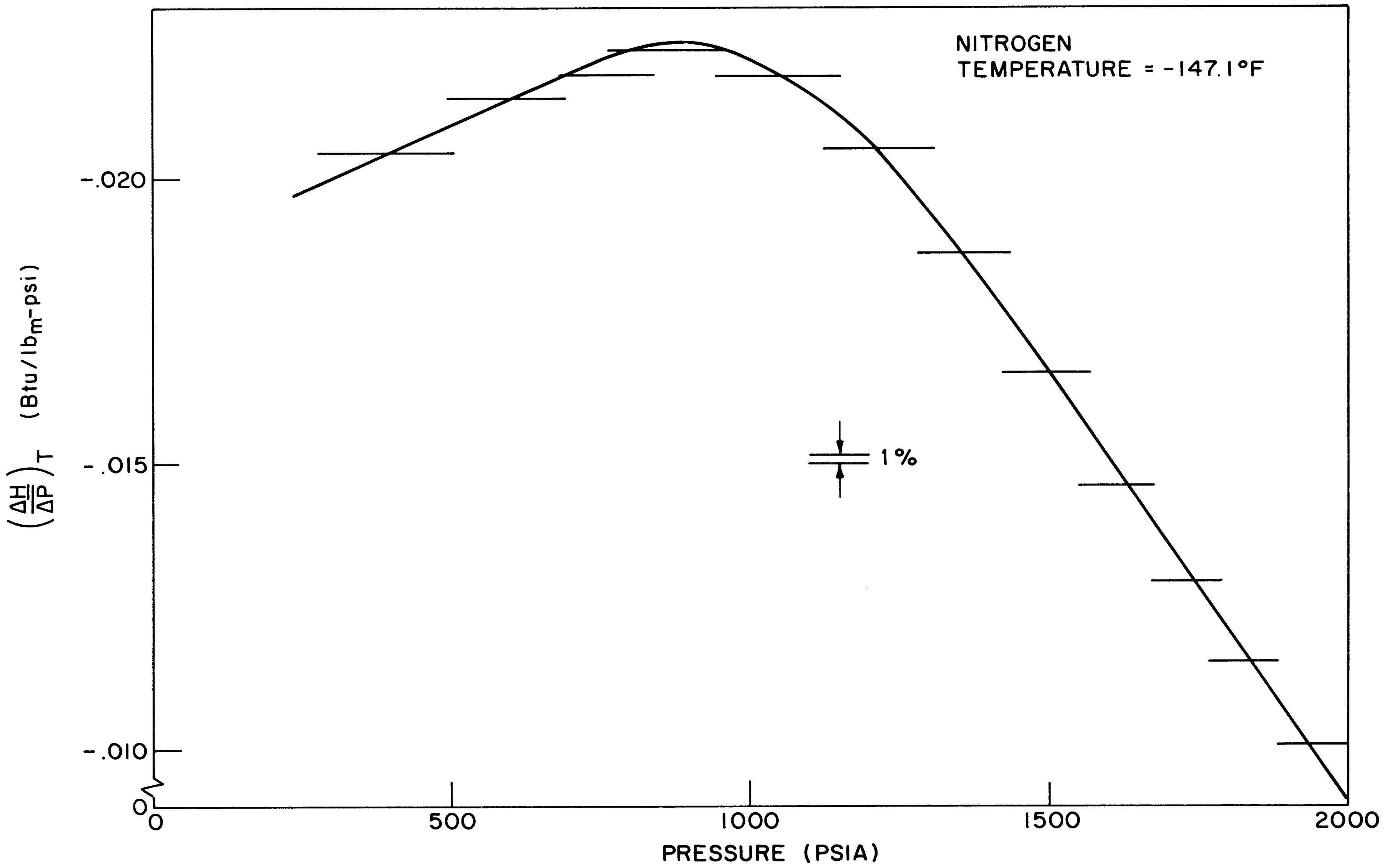


Figure 23. Isothermal Data on Nitrogen at -147.1° F

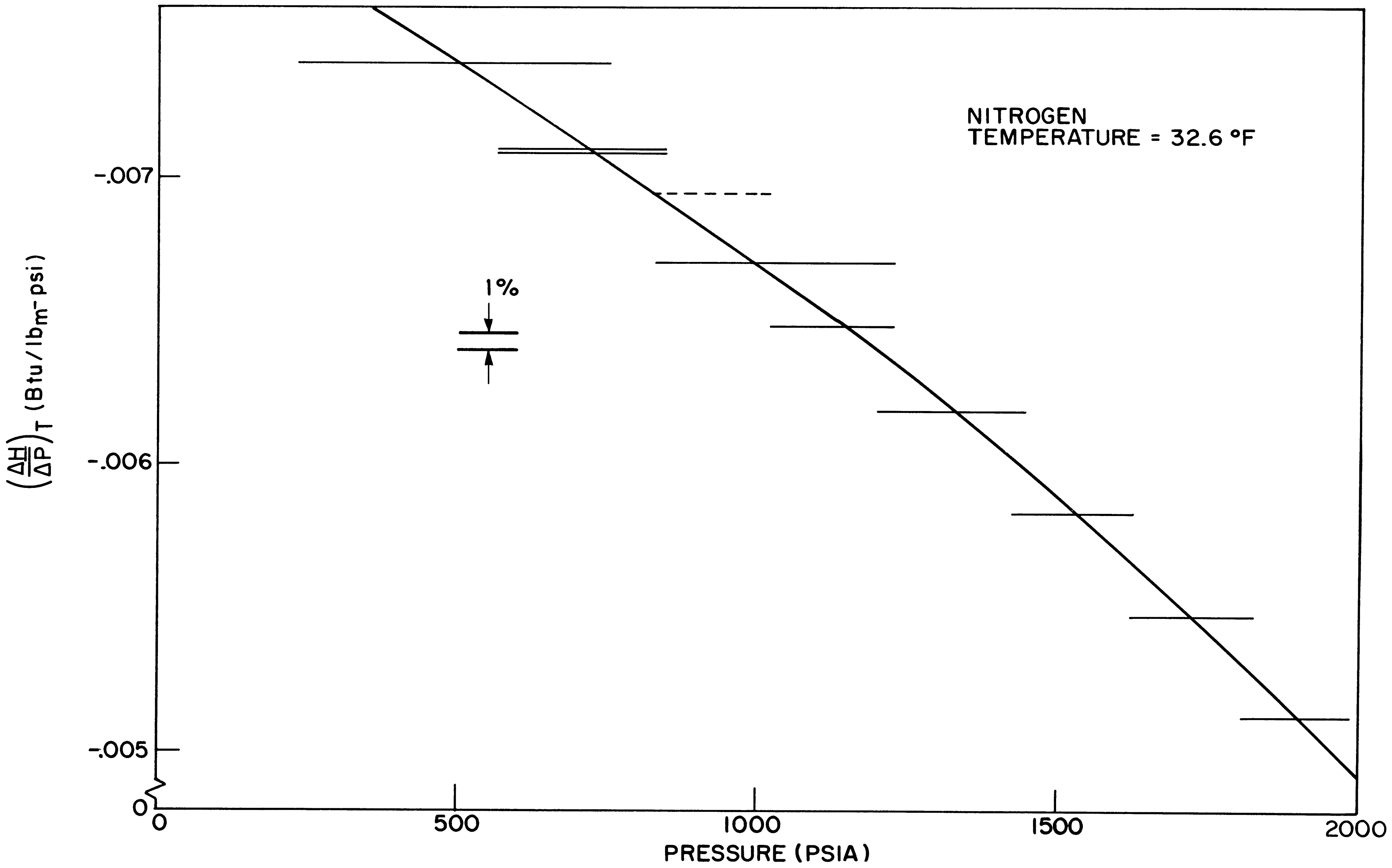


Figure 24. Isothermal Data on Nitrogen at 32.6° F

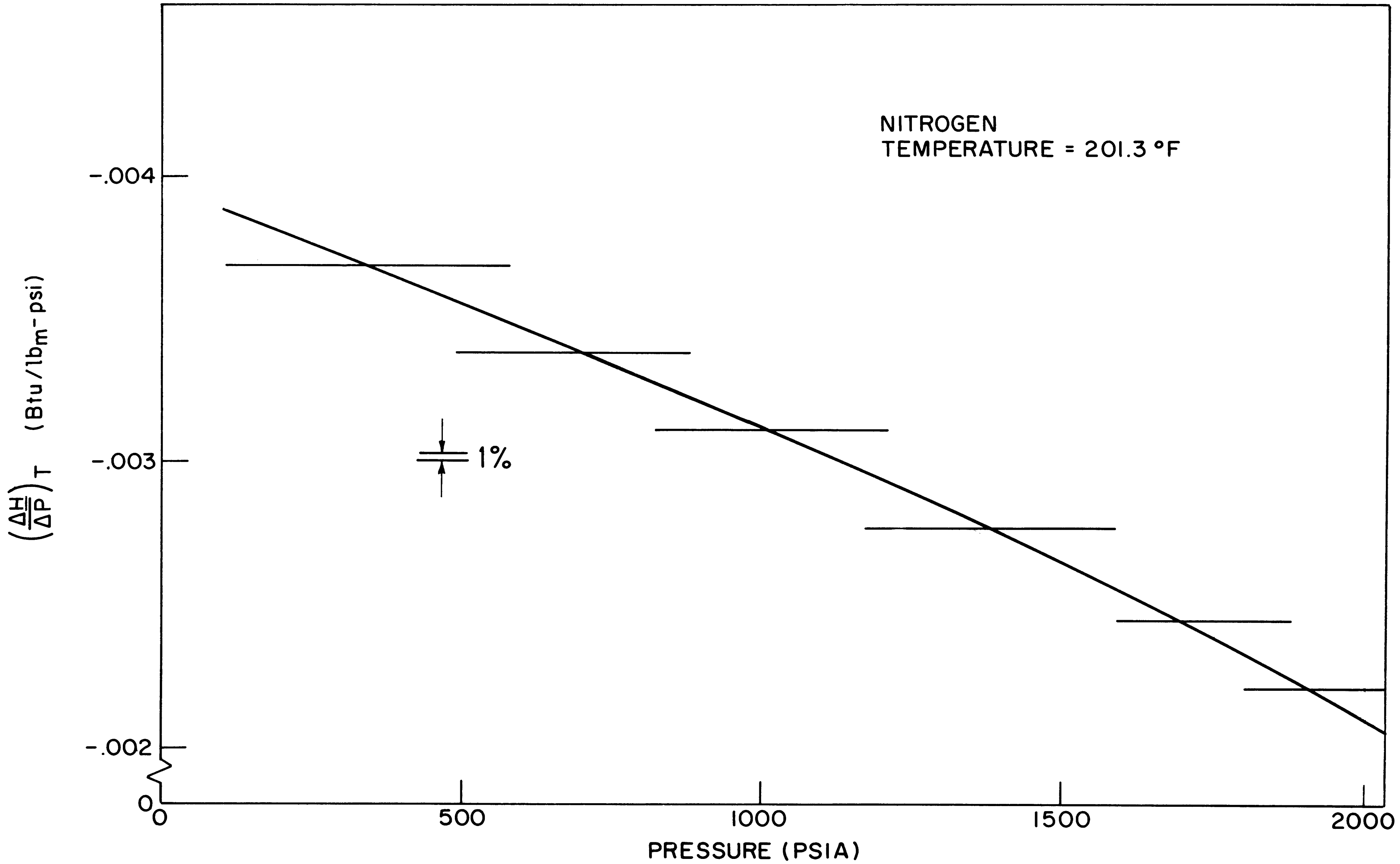


Figure 25. Isothermal Data on Nitrogen at 201.3° F

a precision of about ± 1/2 percent and a band of this size is drawn on Figure 26 for comparison with other experimental data. The data of Ishkin and Kaganer[89] are believed to be high by as much as 5 percent [see Bolshakov et al.[17]]. Values of ϕ calculated from the Joule-Thomson data of Roebuck & Osterberg[157] combined with the heat capacities of Jones[94] at the lower temperatures and those of Mackey & Krase[118] at the highest temperature are also plotted. The present data appear to be somewhat lower than other experimental values.

Values of ϕ can be calculated from an equation of state using Equation (9). The Benedict-Webb-Rubin equation is frequently used for calculation of thermodynamic properties. For nitrogen, two sets of constants for this equation are available, the earlier set of Stotler & Benedict[179] and the recent values of Crain & Sonntag[36]. Bloomer and Rao[15] modified the B-W-R equation of state by the addition of two more constants to represent the low temperature volumetric data with greater accuracy. The equations used to calculate thermodynamic properties from these equations of state are presented in Appendix C. The results of equation of state calculations are compared with the experimental band in Figure 27. None of the equations represent the experimental band accurately at all temperatures over the range of pressure.

A number of tabulations contain values of enthalpy for nitrogen, which usually have been derived from volumetric data. The tabulated values of enthalpy were differenced to give values of ϕ for comparison with the experimental data.

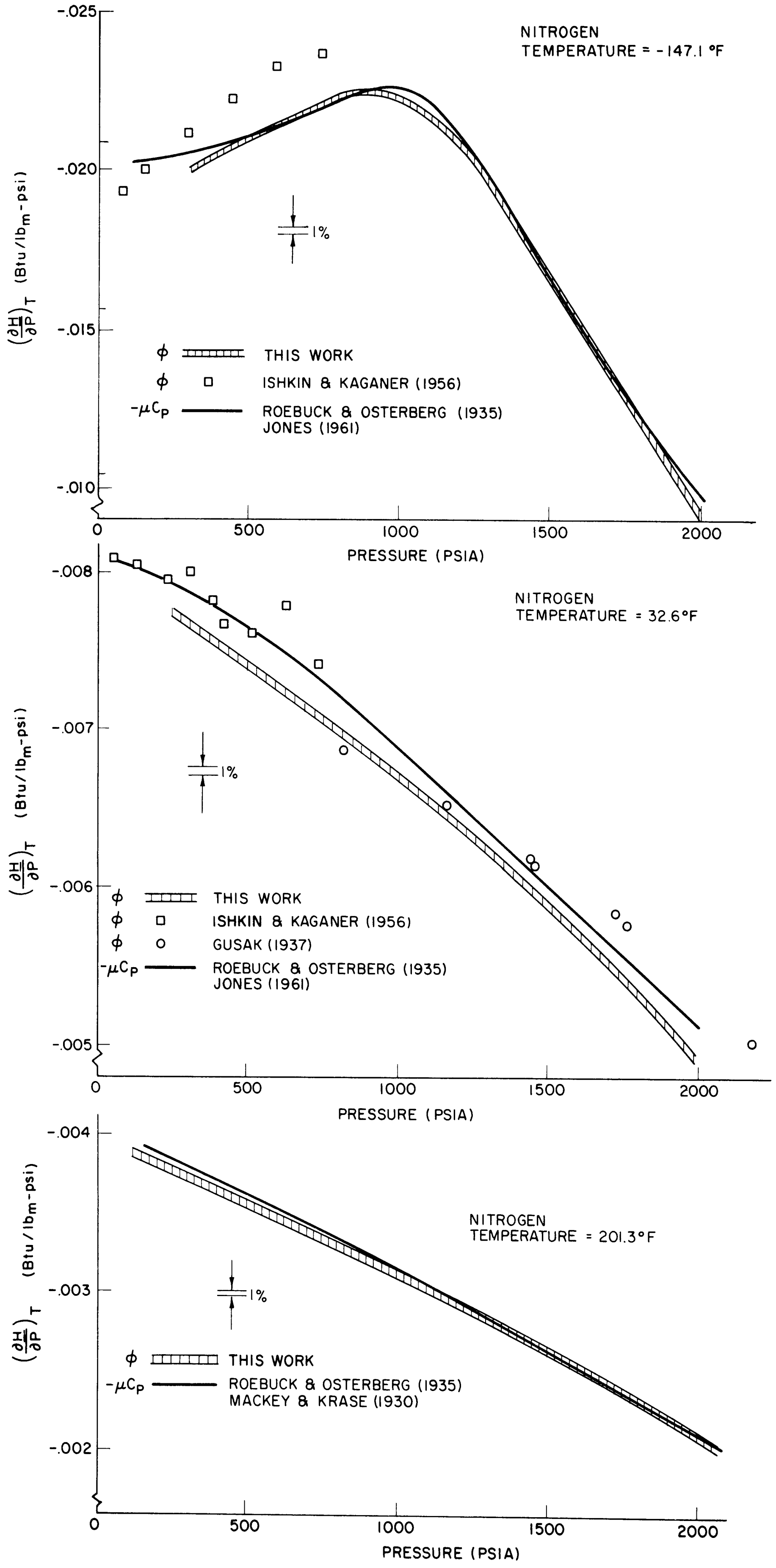


Figure 26. Comparison of Isothermal Data With Other Experimental Data

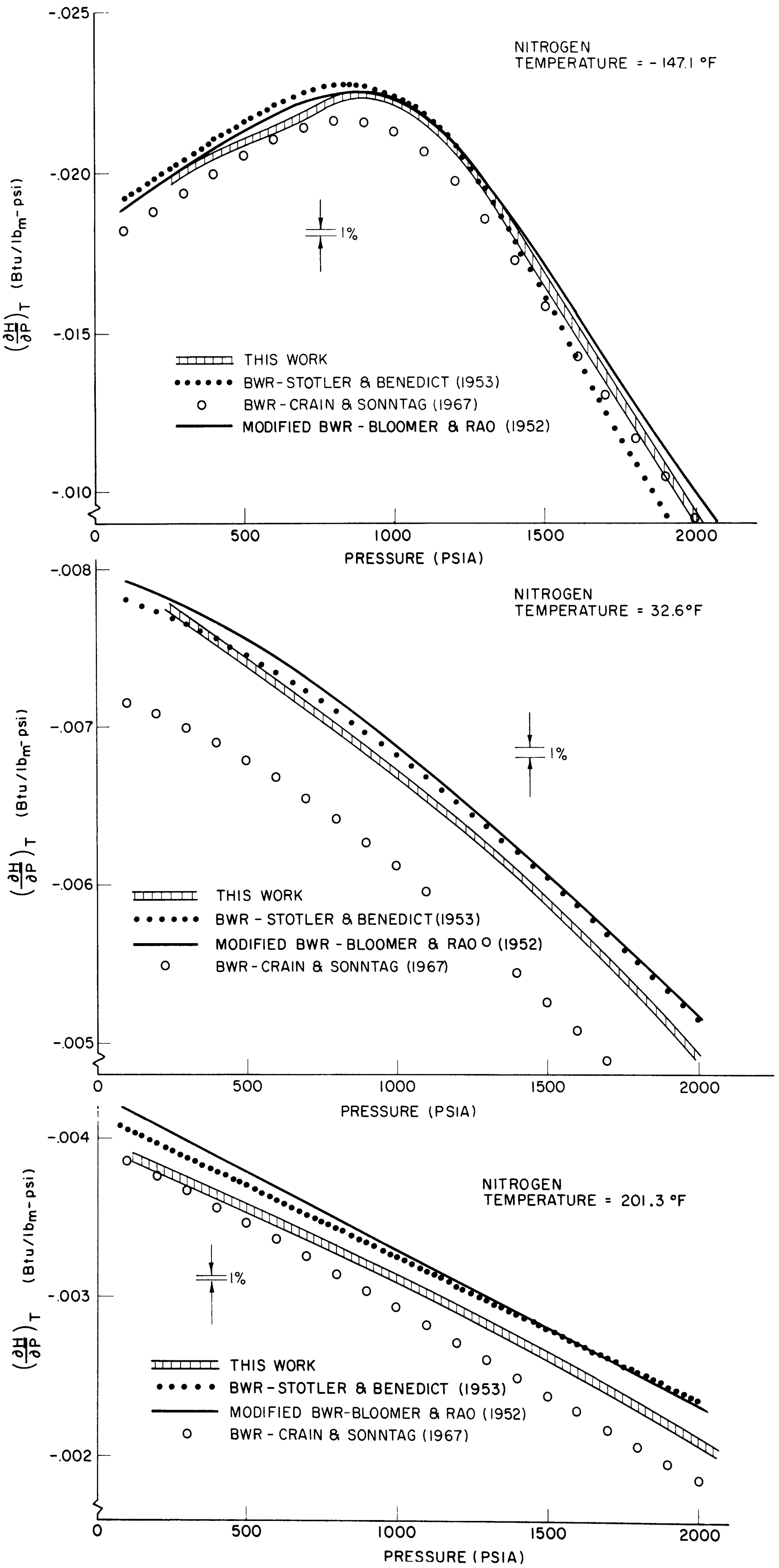


Figure 27. Comparison of Isothermal Data With Equations of State

Enthalpies were obtained from Din[43], Lunbeck, Michels, & Wolkers[113], Hilsenrath et al[79], Strobridge[182] and Pfenning, Canfield, & Kobayashi[146]. The values of ϕ derived from these compilations are compared with the experimental data in Figures 28 through 30 and are seen to be in agreement within about 4 percent.

It is apparent that the tests made with nitrogen to establish the accuracy of the calorimeter are inconclusive since the published data are not in agreement among themselves within the precision of the present experiments.

Enthalpy departures were calculated from the experimental data by integration with respect to pressure. The results for the three isotherms of this work are compared with other compilations in Table XXIII. The present data are at least as accurate as the most recent values in the literature.

The zero-pressure values of ϕ are directly related to the coefficients of the virial equation of state by Equation (15). The experimental values of ϕ were extrapolated to zero pressure for comparison with values of ϕ^o from the literature. The results are shown in Figure 31 where the present data are in good agreement with values calculated from zero pressure Joule-Thomson data together with values of the ideal gas heat capacity, Cp^o, other isothermal throttling data, and the virial equation of state.

The consistency of the low temperature nitrogen data was tested by loop checks with the isobaric data of Jones[94]. Deviations were less than one percent and the results are given in Appendix C.

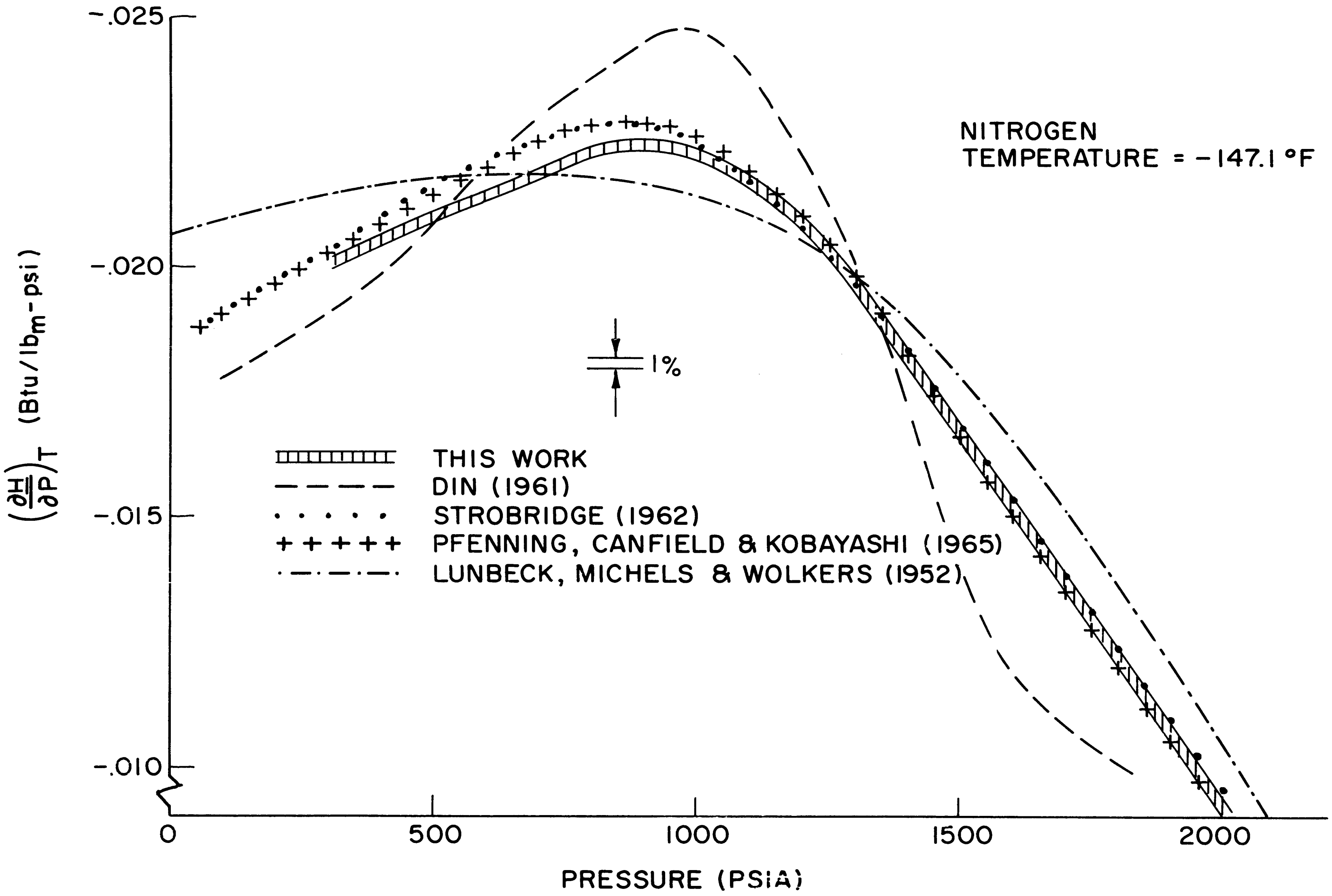


Figure 28. Comparison of Isothermal Data at -147.1^{o} F with Values from Compilations

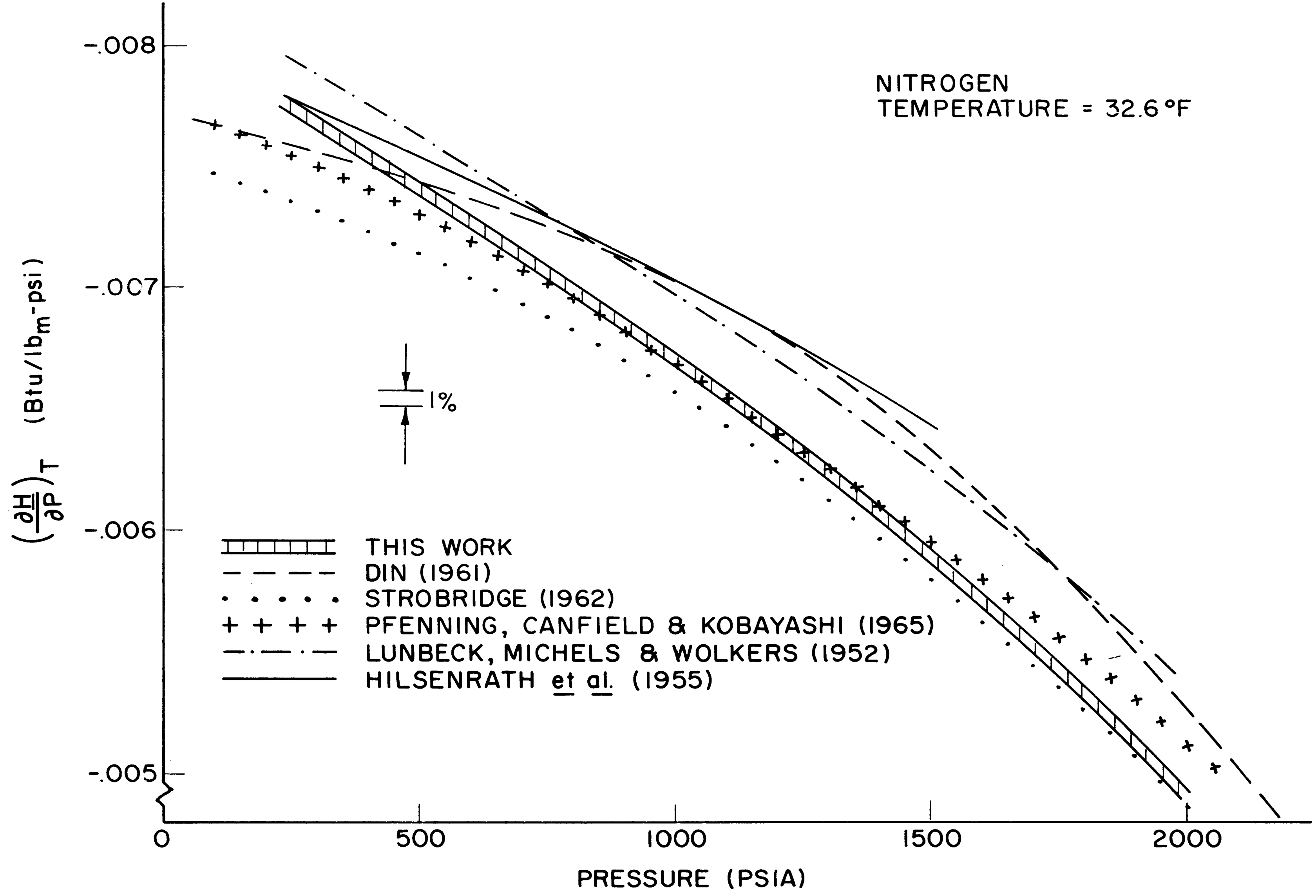


Figure 29. Comparison of Isothermal Data at 32.6° F with Values from Compilations

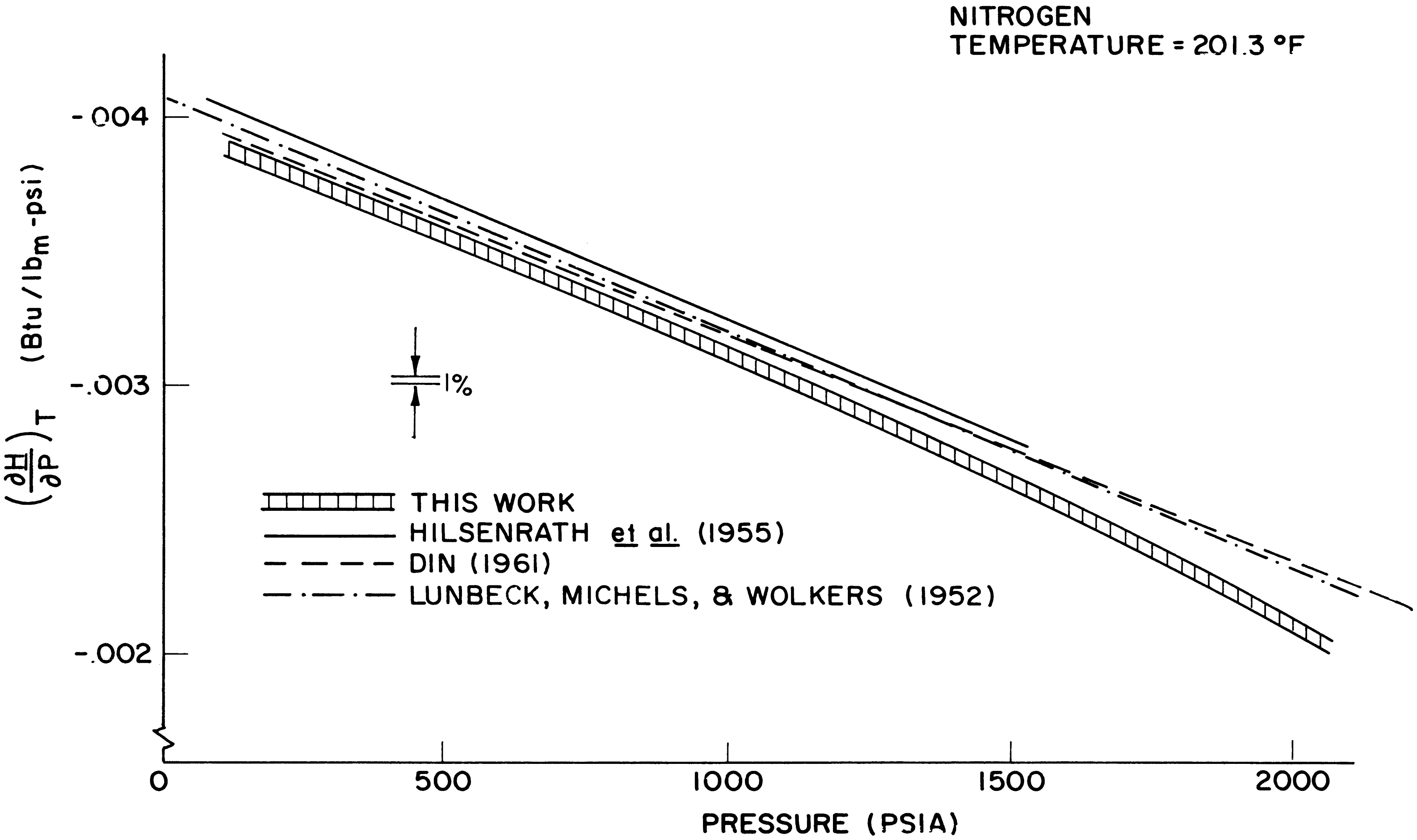


Figure 30. Comparison of Isothermal Data at 201.3° F with Values from Compilations

TABLE XXIII

COMPARISON OF EXPERIMENTAL ENTHALPY DEPARTURES FOR NITROGEN WITH VALUES FROM OTHER SOURCES

Temperature (^oF)	Pressure (psia)	$(H^o - H^P)_T$ (Btu/lb) This work	M^a	BWR^b	BWR^c	IGT^d	Din^e	LMW^f	H^g	S^h	PCK^i
201.3	500	1.89	---	2.0	1.9	2.0	1.9	1.8	2.1	----	----
	1000	3.55	---	3.7	3.5	3.8	3.6	3.5	3.7	----	----
	1500	4.99	---	5.2	4.8	5.3	5.1	4.9	5.2	----	----
	2000	6.18	---	6.5	5.9	6.6	6.4	6.0	----	----	----
32.6	500	3.89	4.0	3.8	3.5	3.9	3.9	4.0	4.2	3.5	3.8
	1000	7.33	7.6	7.4	6.7	7.5	7.5	7.7	7.6	6.9	7.3
	1500	10.47	10.9	10.7	9.6	10.7	10.9	10.9	10.9	10.0	10.5
	2000	13.17	13.7	13.5	12.0	13.6	13.7	13.1	----	12.7	13.2
-147.1	500	9.87	9.5	10.1	9.5	9.9	9.3	10.9	----	10.1	10.0
	1000	20.83	21.0	21.3	20.2	21.0	20.9	22.2	----	21.3	20.9
	1500	30.77	31.8	31.1	29.7	31.1	30.9	31.6	----	31.3	31.1
	2000	37.20	37.6	37.0	35.9	37.7	35.6	37.6	----	37.8	37.5

a Mage *et al.*[119]
b Benedict, Webb, and Rubin Equation--constants of Stotler & Benedict[179]
c Benedict, Webb, and Rubin Equation--constants of Crain & Sonntag[36]
d Bloomer & Rao[15]
e Din[43]
f Lunbeck, Michels, & Wolkers[113]
g Hilsenrath *et al*[79]
h Strobridge[182]
i Pfenning, Canfield, & Kobayashi[146]

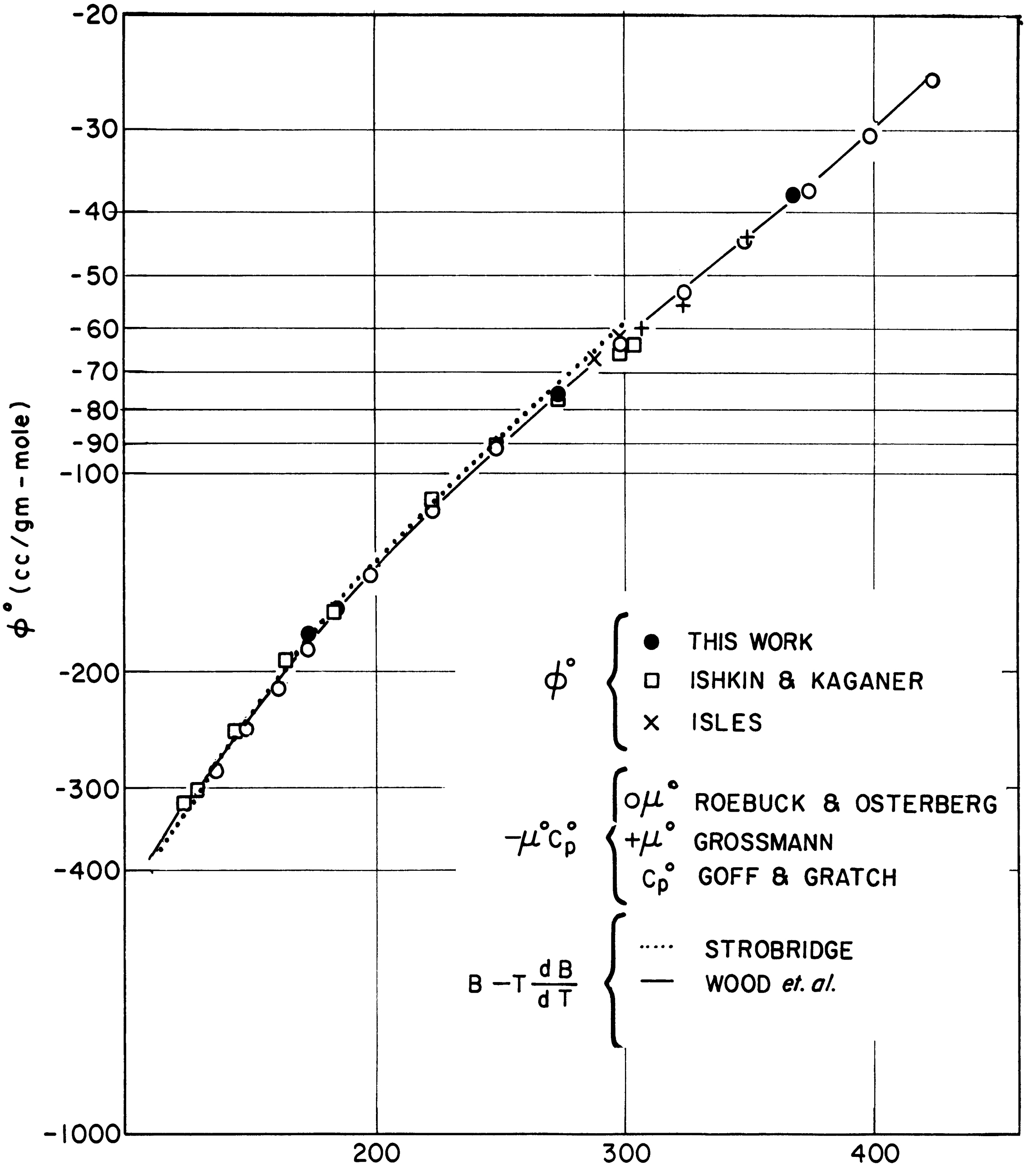


Figure 31. Comparison of Zero-Pressure Isothermal Throttling Coefficients for Nitrogen

Experimental Results for a Nominal 5 Percent Propane in Methane Mixture

The nominal 5 percent propane in methane mixture was studied in the isothermal mode only. Data were obtained with both the 17 BWG and 16 BWG coils at 200° F to test the effect of possible flow rate dependence. The 16 BWG coil was used to obtain data at 91.6° and -27°F in the gaseous region. In the compressed liquid region, at -147.4°F, data were obtained with a 19 BWG coil. The location of the experimental runs is shown in Figure 2 in the isobaric data section. The isothermal data for this mixture are given in Table L of Appendix D.

Analysis of Results (Nominal 5 Percent Mixture)

The isothermal data for the nominal 5 percent mixture were plotted as a function of pressure and equal-area curves passed through the data bars to obtain point values of ϕ. Values obtained from these plots are given in Table XXIV for the four isotherms. The two runs made at 200° F. in different coils are shown in Figure 32. The agreement between the two runs is good at high and low pressures with a difference of about two percent at mid-range. This difference is consistent with the probable error given in Table XXI. A band representing the data of Figure 32 is plotted in Figure 33 for comparison with other data.

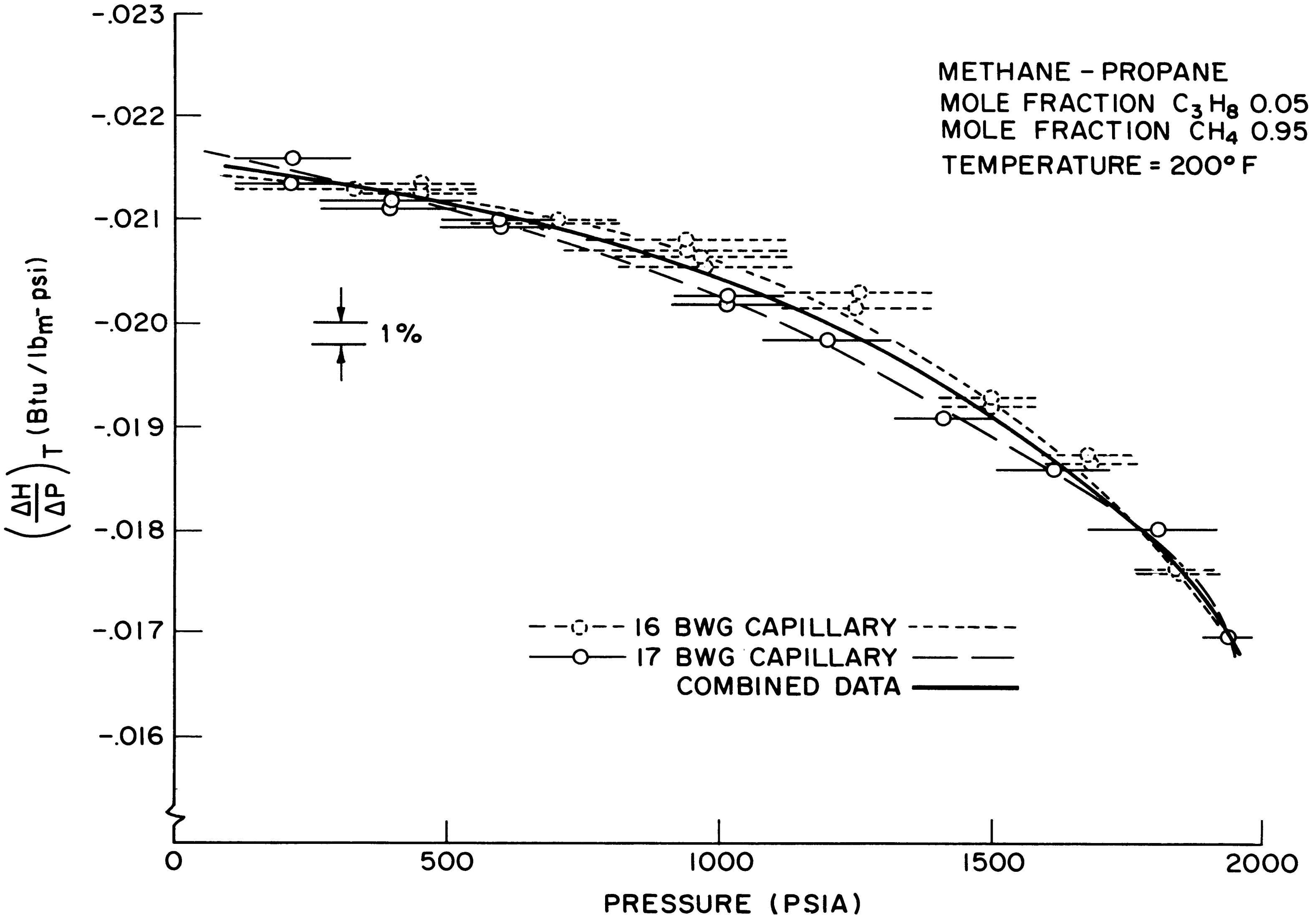


Figure 32. Comparison of Isothermal Data Obtained with Different Capillaries

TABLE XXIV

ISOTHERMAL THROTTLING COEFFICIENTS FOR THE NOMINAL 5 PERCENT MIXTURE

ϕ (Btu/lb-psi)

Pressure (Psia)	Temperature (°F) -147.4	-27.0	91.6	200.0
0		-.044	-.0294	-.0215
100		-.047	-.0297	-.0214
200		-.050	-.0301	-.0214
300		-.053	-.0304	-.0213
400		-.056	-.0308	-.0212
500	-.0023	-.060	-.0311	-.0211
600	-.0018	-.063	-.0313	-.0210
700	-.0014	-.067	-.0315	-.0209
800	-.0009	-.070	-.0316	-.0207
900	-.0005	-.075	-.0317	-.0206
1000	-.0002	-.078	-.0317	-.0204
1100	.0002	-.080	-.0316	-.0201
1200	.0004	-.078	-.0315	-.0199
1300	.0006	-.074	-.0312	-.0196
1400	.0008	-.066	-.0307	-.0193
1500	.0011	-.057	-.0302	-.0190
1600	.0013	-.049	-.0296	-.0187
1700	.0015	-.041	-.0288	-.0183
1800	.0017	-.034	-.0279	-.0178
1900	.0019	-.028	-.0268	-.0172
2000	.0022	-.022	-.0255	-.0166

Dillard[41] determined values of the enthalpy departure from the ideal gas state to pressures of 500, 1000, 1500, and 2000 psia for a nominal 5 percent mixture. These results are not precise, but at most conditions a number of runs were made and the average value may be meaningful. Some of the data of Dillard are plotted in Figure 33. The values from 0 to 500 psia represent the experimental data while the values from 1000 to 1500 psia and from 1500 to 2000 psia represent differences between the experimental enthalpy departures. No values are plotted between 500 and 1000 psia because a number of values can be obtained depending upon which departure at 500 psia is chosen to calculate the difference. The data of Dillard are not precise. Within the limits of their precision, however, they agree with the present work.

Values of ϕ calculated from Equation (9) using the Joule-Thomson data of Budenholzer _et al._[23] together with the heat capacity data of this work (See Section II) are shown in Figure 33. The results agree with the experimental band within a few percent. At low pressures the Joule-Thomson data of Sage and co-workers are believed to be inaccurate [See Manning & Canjar[124]], and this may account for the shape of the curve as the pressure approaches zero.

Figure 33 also shows values of ϕ calculated using the Benedict-Webb-Rubin equation of state with constants for methane and propane from the original article[10] and mixing rules recommended by the same authors[11]. The agreement with the experimental band is generally within a few percent.

Enthalpy departures were calculated from the experimental ϕ data by integration with respect to pressure. The values obtained are compared with other data and with correlations in Table XXV. The direct determinations of Dillard[41] have already been mentioned. The B-W-R equation was used as an example of an equation of state. Edmister & Yarborough[52] used the P-V-T data of Reamer, Sage, and Lacy[152] to derive values of the enthalpy depar-

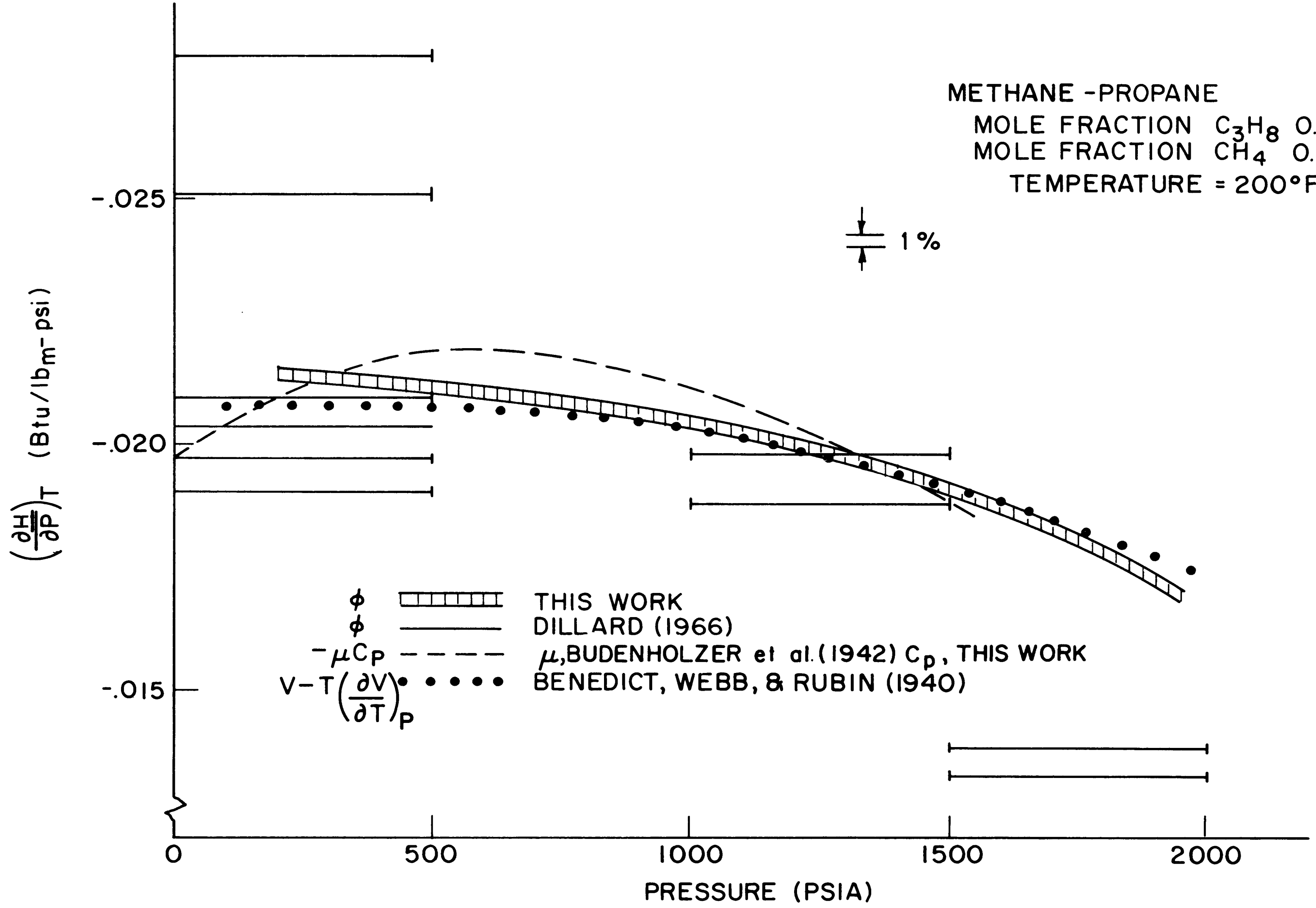


Figure 33. Comparison of Isothermal Data at 200° F with Other Experimental Data

ture. The correlations of Lydersen, Greenkorn, and Hougen[114], Curl & Pitzer[38], and the recent revision of the L-G-H method by Yen[201] were used to calculate enthalpy departures. The average values of Dillard are generally within a few percent except at 200° F. and 2000 psia. The B-W-R equation of state is in closer agreement with the experimental values than the generalized correlations or values derived from P-V-T data.

TABLE XXV

COMPARISON OF EXPERIMENTAL ENTHALPY DEPARTURES WITH VALUES FROM OTHER SOURCES

Temp. (^{o}F)	Pressure (psia)	$(H^{o}-H^{P})_T$ (Btu/lb)						
		This work	D[a]	BWR[b]	EY[c]	LGH[d]	Yen[e]	CP[f]
-27	500	25.87	--	26.2	--	21.4	25.7	24.1
	1000	60.27	--	61.1	--	55.2	58.4	56.9
	1500	96.89	--	98.0	--	83.7	89.3	90.7
	2000	116.01	--	117.5	--	100.9	108.6	111.2
91.6	500	15.13	14.9	15.0	14.0	11.2	15.2	14.6
	1000	30.89	30.2	30.8	29.8	26.8	29.4	29.7
	1500	46.49	45.6	46.5	46.2	39.8	45.1	46.4
	2000	60.58	60.2	60.8	62.9	51.1	58.8	60.5
200	500	10.66	10.0	10.4	10.6	7.2	10.4	11.1
	1000	21.05	19.8	20.7	21.3	17.1	20.8	21.5
	1500	30.91	29.1	30.6	31.4	25.5	31.1	31.3
	2000	39.88	35.8	39.7	40.6	32.5	39.6	39.6

a Dillard[41]
b Benedict, Webb and Rubin[10,11]
c Edmister and Yarborough[52]
d Lydersen, Greenkorn and Hougen[114]
e Yen[201]
f Curl and Pitzer[38]

The experimental values of ϕ were extrapolated to zero pressure in order to compare with values calculated from published virial coefficients. Data for the second virial coefficient of methane [Huff & Reed[85], Douslin *et al.*[45]], propane [Dawson & McKetta[40], Huff & Reed[85]] and mixtures of methane and propane [Huff & Reed] were graphically differentiated to obtain dB/dT. The results are given in Table XXVI together with values of ϕ^o calculated from Equation (15) and values obtained by linear extrapolation of the experimental data to zero pressure. The agreement between the calculated and experimental results is fair.

TABLE XXVI

Calculation of Zero-Pressure Isothermal Throttling Coefficients from Virial Coefficient Data

T (^oF)		B (cc/mole)	dB/dT (cc/mole-^oK)	ϕ^o(Eqn. 15) (Btu/lb - psi) x 10^{-2}	ϕ^o(Experimental) (Btu/lb - psi) x 10^{-2}
200	CH_4	- 20.4	0.30		
	C_3H_8	-247	1.22	-2.45	-2.15
	CH_4-C_3H_8	- 85.4	0.49		
91.6	CH_4	- 39.7	0.35		
	C_3H_8	-375	2.97	-2.90	-2.94
	CH_4-C_3H_8	-125.8	0.84		

SECTION IV-ENTHALPY TABLES AND DIAGRAMS

The experimental data on the effect of temperature and pressure on enthalpy of Sections II and III has been used to prepare skeleton enthalpy tables and diagrams. New tables and diagrams are presented for the nominal 5, 12, and 28 percent propane in methane mixtures, and the nominal 43 percent nitrogen in methane mixture. Comparisons are made with vapor-liquid equilibrium data, calculations of the latent heat of vaporization and enthalpy data from the literature.

Nominal 5 Percent Propane in Methane Mixture

A skeleton enthalpy table and a pressure-enthalpy-temperature diagram for this mixture have been prepared which are based almost entirely on experimental calorimetric data obtained in the Thermal Properties Laboratory of the University of Michigan. The following procedure was used in preparing the diagram and table:

1) Reference states of 0 Btu/lb were taken to be the pure components as saturated liquids under their own vapor pressure at -280°F. This choice is consistent with that previously used for methane[95] and the previous diagram for this mixture[122].

2) The enthalpy of pure methane as a gas at zero pressure and 200° F. was calculated using the data on the heat of vaporization at 5 psia of Frank and Clusius[64], the B-W-R equation of state to correct from 5 psia to zero pressure, and values of the ideal gas enthalpies from Rossini[161]. The following results were obtained:

	Enthalpy, Btu/lb
Latent heat of vaporization at -280° F.	228.27
Effect of pressure on enthalpy (0 to 5 psia)	1.43
Ideal gas enthalpy (-280° F to 200° F.)	248.09
	477.79

Colwell, Gill, and Morrison[32] have recently measured the latent heat of vaporization at 100° K which agrees with Frank and Clusius to within 0.25 percent.

3) The enthalpy of pure propane as a gas at zero pressure and 200° F. was calculated using liquid phase heat capacity data and the latent heat of vaporization at one atmosphere from Kemp and Egan[98], the B-W-R equation of state to correct from one atmosphere to zero pressure and values of the ideal gas enthalpies from Rossini[161]. The following results were obtained:

	Enthalpy, Btu/lb
Liquid heat capacity (-280° F to -43.7°F)	115.30
Latent heat of vaporization at -43.7° F	183.17
Effect of pressure on enthalpy (0 to 94.7 psia)	2.70
Ideal gas enthalpy (-43.7 to 200° F)	97.51
	398.68

4) The enthalpy of the methane-propane mixture at zero pressure and 200° F was calculated assuming zero heat of mixing under these conditions.

$$\underline{H}mix = 0.131\ (398.68) + 0.869\ (477.79)$$

$$= 467.43 \text{ Btu/lb.}$$

5) The isothermal effect of pressure on enthalpy at -27° F, 91.6° F and 200° F. was obtained from the integrated ϕ data of Section III at pressures from 0 to 2000 psia. In the previous diagram for this mixture prepared by Manker[123], the effect of pressure on enthalpy at 70° F was estimated from approximate Joule-Thomson measurements made with the isobaric calorimeter combined with experimental heat capacity data. The enthalpy departure at 2000 psia obtained in this way agreed within 3 percent with the integration of the Joule-Thomson data of Budenholzer <u>et al.</u>[23] combined with the experimental heat capacities. The Joule-Thomson

data of Budenholzer _et al._ extend only to 1500 psia and an extrapolation to 2000 psia was necessary to make this comparison.

The enthalpy departures for this mixture are presented as a function of temperature in Figure 34. A comparison is shown between the measured isothermal data of this work, the isothermal data of Dillard[41] and the Joule-Thomson data of Budenholzer _et al._[23] combined with experimental heat capacities of this work. It appears that the values calculated from the Joule-Thomson data are in error at 1500 psia and the extrapolation to 2000 psia only compounds the error. The B-W-R equation is seen to predict departures in excellent agreement with the measured isothermal data of this work.

6) The isobaric enthalpy data of this work and that of Manker[123] were used to determine the isobaric effect of temperature on enthalpy in both the gaseous and liquid regions as well as within the two-phase envelope. The limits of the two-phase region were determined using results of the traverses of the two phase region made by Manker, supplemented by the data of Price and Kobayashi[151].

Since enthalpy is a property, changes in enthalpy are independent of the path chosen and the consistency of the experimental data can be tested by making loop checks. A grid consisting of 11 loops was constructed and the enthalpy change around each loop evaluated. In all but one case the closure, defined as the difference in the enthalpy change by the two paths, was less than one percent. The grid is shown as Figure 52 of Appendix C together with the values of the enthalpy change along each path. In most cases, a loop with a positive closure was adjacent to one with a negative closure. The enthalpy difference common to both loops was adjusted to close each loop. This adjustment was made until all eleven loops closed exactly.

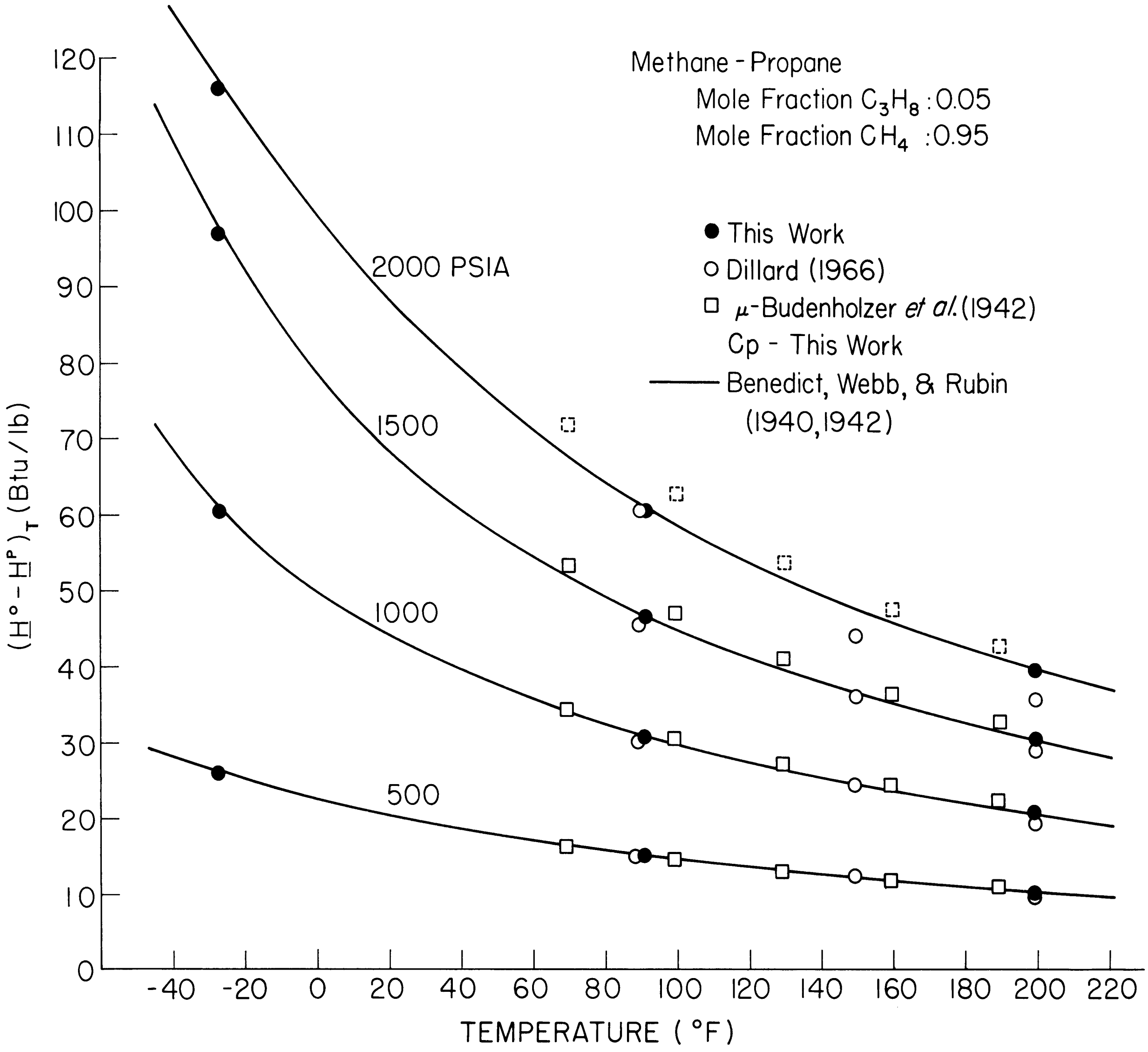


Figure 34. Enthalpy Departures for the Nominal 5 Percent Mixture

7) A smooth plot of the results was prepared and is shown in Figure 35. The shape of the isotherms in the liquid region is chosen so as to allow the -280° F isotherm to be drawn to the value of 0.3 Btu/lb for the heat of mixing of methane and propane at -280° F calculated from the data of Cutler and Morrison[39].

8) The values of enthalpy are given in Table XXVII.

The chief differences between this diagram and the one presented by Manker[123] or the later revision[130] are:

i) The effect of pressure on enthalpy is based on experimentally determined values of ϕ.

ii) The diagram has been extended to 300° F by additional experimental data to 250° F and calculations from the B-W-R equation of state.

Nominal 12 Percent Propane in Methane Mixture

A skeleton enthalpy table and a pressure-enthalpy-temperature diagram for this mixture have been prepared.

In a previous report of this work[130] the effect of pressure was determined from the integration of the Joule-Thomson coefficients of Budenholzer et al.[23] together with the experimentally determined heat capacities. The experimental results on the nominal 5 percent mixture indicated that the effect of pressure on enthalpy estimated in this way is likely to be in error at pressures above about 1000 psia and that the extrapolation to 2000 psia is not desirable (See Figure 34). Enthalpy departures calculated by the B-W-R equation, experimental values of Dillard et al.[42], and values obtained by combining μ from Budenholzer et al.[23] with the experimental C_p are compared in Figure 36. Again the dotted squares represent departures calculated from μ data which were

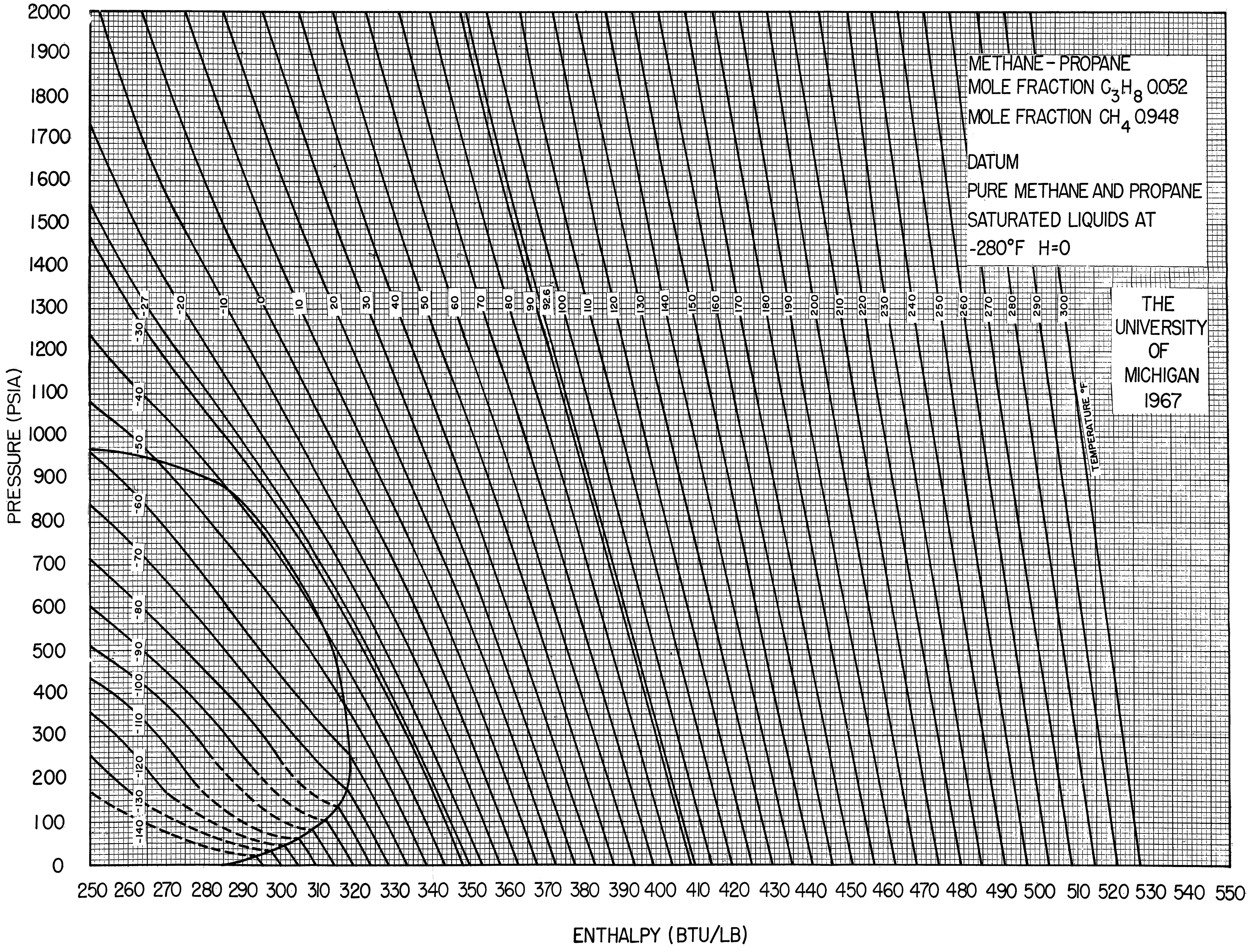


Figure 35. Pressure-Temperature-Enthalpy Diagram for the Nominal 5 Percent Mixture (High Temperature)

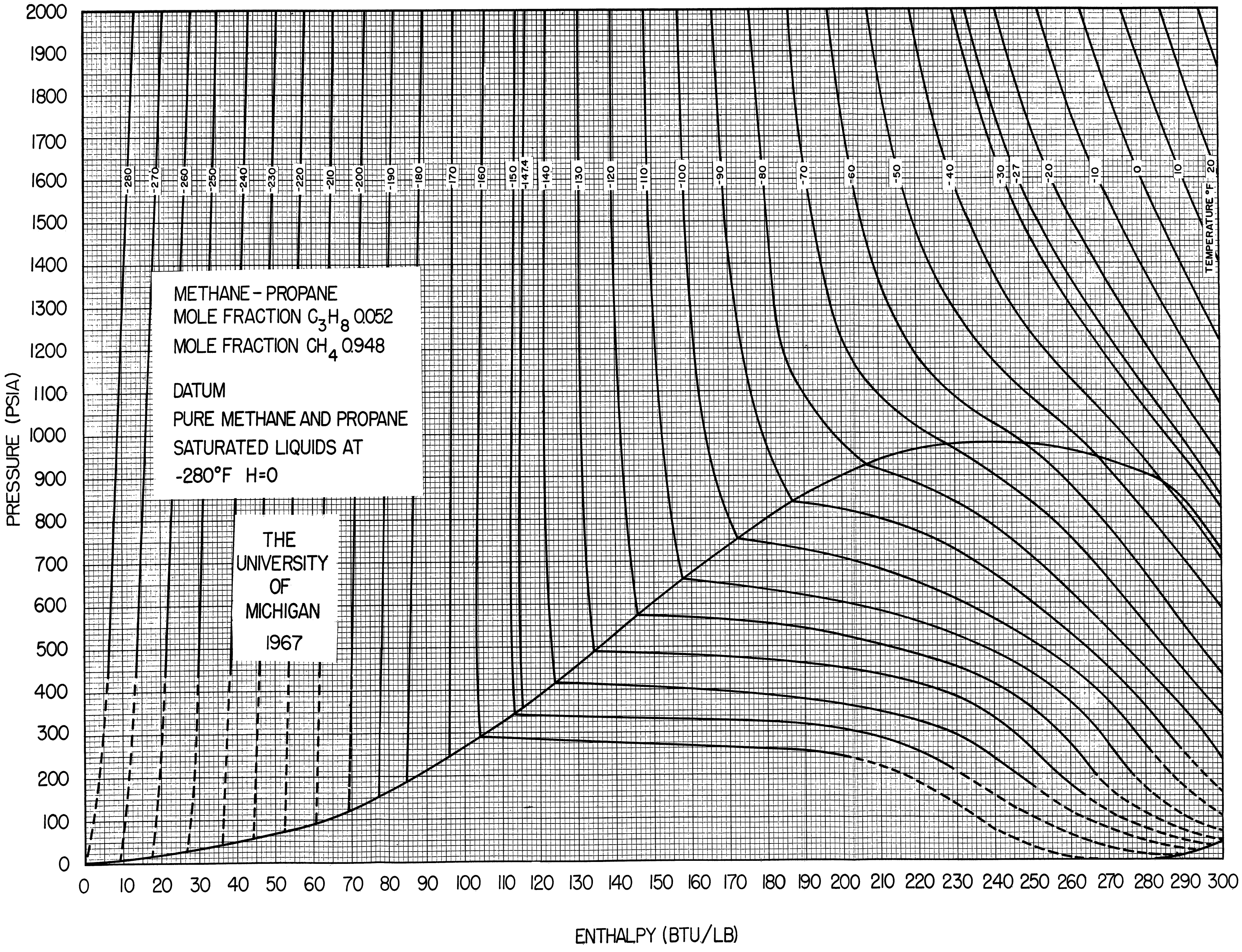


Figure 35. Pressure-Temperature-Enthalpy Diagram for the Nominal 5 Percent Mixture (Low Temperature)

TABLE XXVII

TABULATED VALUES OF ENTHALPY FOR THE NOMINAL 5 PERCENT MIXTURE

Pressure (psia)	Temperature, °F Bubble Point	Temperature, °F Dew Point	Saturated Liquid Enthalpy (Btu/lb)	Saturated Vapor Enthalpy (Btu/lb)	Latent Heat of Vaporization (Btu/lb)
100	-208	-92	63.1	311.4	248.3
200	-178	-66	88.5	318.1	229.6
300	-159	-56	106.6	317.9	211.3
400	-142	-49	122.0	316.0	194.0
500	-129	-42	135.9	313.5	177.6
600	-117	-39	149.4	308.9	159.5
700	-107	-38	164.0	302.1	138.1
800	-95	-38	180.1	294.1	114.0
900	-84	-42	200.2	281.8	81.6

H (Btu/lb)

Temperature (°F)	Pressure, psia 0	250	500	750	1000	1250	1500	1750	2000
-280	230.5	*5.0*	*7.0*	*8.1*	*9.0*	*10.1*	*11.1*	*12.2*	*13.2*
-270	235.1	*12.6*	*14.5*	*15.6*	*16.6*	*17.9*	*18.9*	*20.0*	*21.0*
-260	239.7	*20.6*	*22.0*	*23.1*	*24.3*	*25.5*	*26.5*	*27.6*	*28.6*
-250	244.3	*29.9*	*31.1*	*31.9*	*32.5*	*33.4*	*34.1*	*35.0*	*35.8*
-240	248.9	*38.0*	39.1	*39.8*	*40.6*	*41.5*	42.4	*43.1*	*44.0*
-230	253.5	*45.7*	46.6	*47.5*	48.3	*49.2*	50.1	*50.6*	*51.5*
-220	258.2	*53.7*	54.4	*55.1*	55.9	*56.5*	57.3	*58.0*	*58.6*
-210	262.8	*61.7*	62.4	*63.1*	63.9	*63.5*	65.2	*65.9*	*66.4*
-200	267.5	*69.9*	70.6	*71.3*	72.0	*72.6*	73.2	*73.9*	*74.4*
-190	272.1	*78.0*	78.5	*79.2*	79.8	*80.4*	80.9	*81.5*	82.2
-180	276.7	85.7	86.3	*86.9*	87.5	*88.3*	88.8	*89.4*	90.0
-170	281.4	96.3	96.4	*96.7*	97.0	*97.3*	97.5	*97.8*	98.0
-160	286.1	196.5	103.7	*103.6*	104.0	*104.4*	105.0	*105.5*	105.9
-150	290.8	211.0	113.1	*113.0*	112.8	*112.8*	113.2	*113.8*	114.0
-147.4	292.0		115.6		115.1	115.1	115.3	115.5	116.1
-140	295.5	237.9	123.2	*122.2*	121.9	*121.8*	121.8	*122.0*	122.3
-130	300.2	251.0	134.3	*132.5*	131.4	*131.0*	130.6	*130.6*	130.9
-120	304.9	262.2	212.9	*143.8*	141.5	*140.1*	139.4	*139.5*	139.5
-110	309.6	272.3	237.5	*156.1*	152.3	*150.2*	149.0	*148.5*	148.3
-100	314.3	281.8	251.9	*175.0*	164.5	*160.7*	158.9	*157.9*	157.3
-90	319.1	290.4	263.7	*224.6*	179.1	*172.5*	169.5	*167.9*	166.5
-80	323.8	299.1	274.4	*245.0*	198.3	*183.8*	180.7	*178.4*	176.3
-70	328.6	308.5	284.8	*260.9*	222.7	*199.3*	192.8	*188.6*	186.3
-60	333.4	318.5	294.5	*273.2*	244.5	*215.6*	205.9	*200.2*	196.7
-50	338.2	324.8	305.0	*285.9*	261.3	*233.0*	219.9	*212.1*	207.4
-40	343.0	330.2	315.2	*296.8*	274.5	*249.0*	234.2	*224.5*	218.5
-30	348.7	335.7	321.5	*305.5*	285.9	*264.4*	248.3	*237.1*	229.8
-27	349.3	337.3	323.4	307.3	289.0	269.0	252.4	240.7	233.3
-20	352.7	341.1	327.8	*312.4*	295.9	*277.8*	261.5	*249.2*	241.1
-10	357.5	346.5	333.9	*319.4*	304.9	*288.7*	273.7	*261.2*	252.4
0	362.5	351.9	340.0	*327.3*	313.3	*298.2*	284.9	*273.1*	269.5
10	367.4	357.2	346.0	*334.1*	321.2	*307.8*	295.1	*284.1*	274.4
20	372.3	362.6	351.9	*340.8*	328.8	*316.4*	304.7	*294.0*	284.7
30	377.3	367.9	357.8	*347.3*	336.1	*325.0*	313.7	*304.0*	294.7
40	382.3	373.3	363.6	*353.6*	343.2	*332.6*	322.3	*312.8*	304.2
50	387.4	378.7	369.5	*360.1*	350.1	*340.2*	330.6	*321.8*	313.4
60	392.5	384.1	375.2	*366.2*	356.9	*347.6*	338.5	*330.0*	322.2
70	397.6	389.5	381.0	*372.7*	363.6	*354.9*	346.2	*338.3*	330.7
80	402.7	394.9	386.8	*378.8*	370.2	*361.8*	353.7	*346.0*	338.8
90	407.9	400.4	392.6	*384.7*	376.7	*368.9*	361.1	*353.8*	346.9
91.6	408.7	401.3	393.5	385.6	377.8	370.2	362.2	355.2	348.2
100	413.1	*405.9*	398.4	*390.6*	383.3	*375.5*	368.3	*361.0*	354.8
110	418.3	*411.9*	404.1	*396.8*	389.7	*382.4*	375.4	*368.8*	362.5
120	423.6	*417.1*	409.9	*402.6*	396.1	*388.9*	382.5	*376.9*	370.2
130	428.9	*422.7*	415.7	*408.9*	402.4	*395.8*	389.5	*383.5*	377.7
140	434.3	*428.2*	421.6	*415.4*	408.8	*402.3*	396.3	*390.9*	385.1
150	439.7	*433.5*	427.4	*421.8*	415.1	*409.4*	403.2	*397.5*	392.3
160	445.1	*439.3*	433.3	*427.4*	421.4	*415.5*	410.0	*404.5*	399.6
170	450.6	*444.6*	439.2	*433.6*	427.7	*421.5*	416.7	*411.5*	406.7
180	456.2	*450.5*	445.1	*439.7*	434.0	*428.6*	423.5	*418.5*	413.8
190	461.8	*456.4*	451.1	*445.3*	440.3	*434.8*	430.2	*425.4*	420.9
200	467.4	462.2	457.0	451.8	446.6	441.6	436.9	432.5	427.9
210	473.1	*468.0*	*463.0*	*458.1*	*453.0*	*448.1*	*443.5*	*439.0*	434.9
220	478.8	*474.0*	*469.1*	*464.1*	*459.3*	*454.4*	*450.2*	*446.2*	441.9
230	484.6	*479.7*	*475.1*	*470.3*	*465.7*	*460.8*	*456.9*	*453.1*	448.9
240	490.4	*486.1*	*481.3*	*476.6*	*472.1*	*467.6*	*463.5*	*459.9*	455.9
250	496.3	*492.1*	*487.4*	*482.7*	*478.5*	*474.4*	*470.2*	*466.6*	462.9
260	502.2	*498.0*	*493.6*	*489.3*	*484.9*	*481.1*	*476.9*	*473.4*	469.9
270	508.1	*504.5*	*499.8*	*495.1*	*491.4*	*487.2*	*483.6*	*480.1*	*476.8*
280	514.1	*510.3*	*506.0*	*501.8*	*497.9*	*494.2*	*490.4*	*487.1*	*483.8*
290	520.2	*516.3*	*512.3*	*508.3*	*504.4*	*500.6*	*497.1*	*493.9*	*490.7*
300	526.3	*522.4*	*518.6*	*514.7*	*510.9*	*507.3*	*503.9*	*500.6*	*497.7*

extrapolated to 2000 psia. On the basis of the results for the 5 percent mixture and the comparison of Figure 36, the isothermal effect of pressure on enthalpy for this mixture was estimated using the B-W-R equation of state.

The data were extended down to -280°F from the lower experimental limit of -240°F by extrapolating plots of C_p versus T prepared from the experimental data. The change in C_p is relatively small over this range of temperature. The data were extended up to 300°F from the upper experimental limit of +140°F by blending experimental C_p data with values calculated using the B-W-R equation at higher temperatures. Enthalpies are tabulated in Table XXVIII and the diagram is presented as Figure 37.

Nominal 28 Percent Propane in Methane Mixture

A skeleton enthalpy table and a pressure-enthalpy-temperature diagram for the nominal 28 mole percent propane in methane mixture have been prepared and are presented as Table XXIX and Figure 38.

The procedure followed in preparing this table was identical to that used for the nominal 5 percent mixture except that the isothermal effect of pressure on enthalpy was estimated using the B-W-R equation at 130° F. In a previous report of the work on the nominal 28 percent mixture[131], the effect of pressure on enthalpy was determined from the integration of the Joule-Thomson coefficients of Budenholzer *et al.*[23] together with the experimentally determined heat capacities at 130° F. As shown in the construction of the enthalpy diagrams for the nominal 5 and 12 percent mixtures, the Joule-Thomson data are believed to be in error and it was decided to use the B-W-R equation of state which predicts heat capacities at this temperature at pressures up to 2000 psia within two percent.

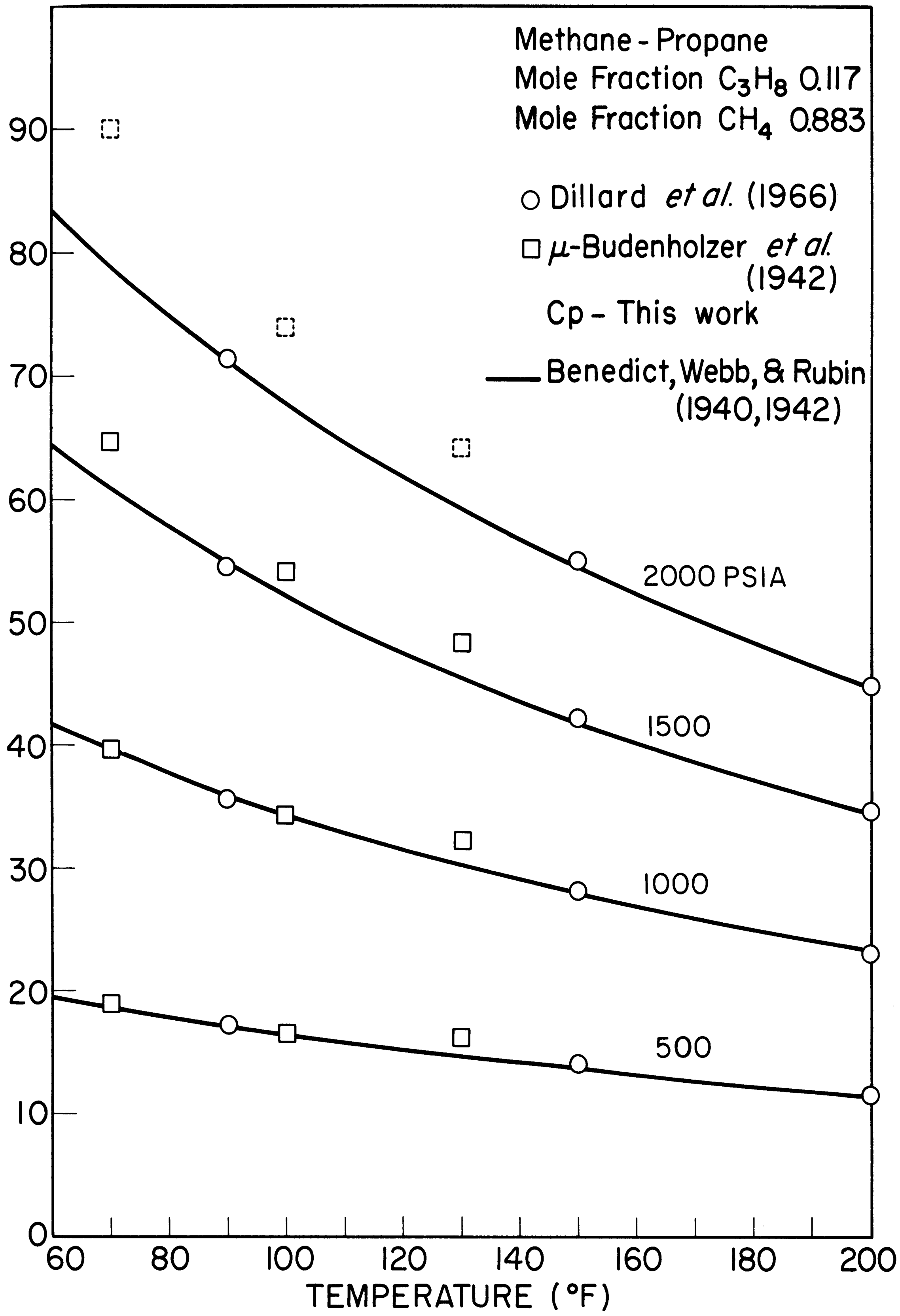


Figure 36. Enthalpy Departures for the Nominal 12 Percent Mixture

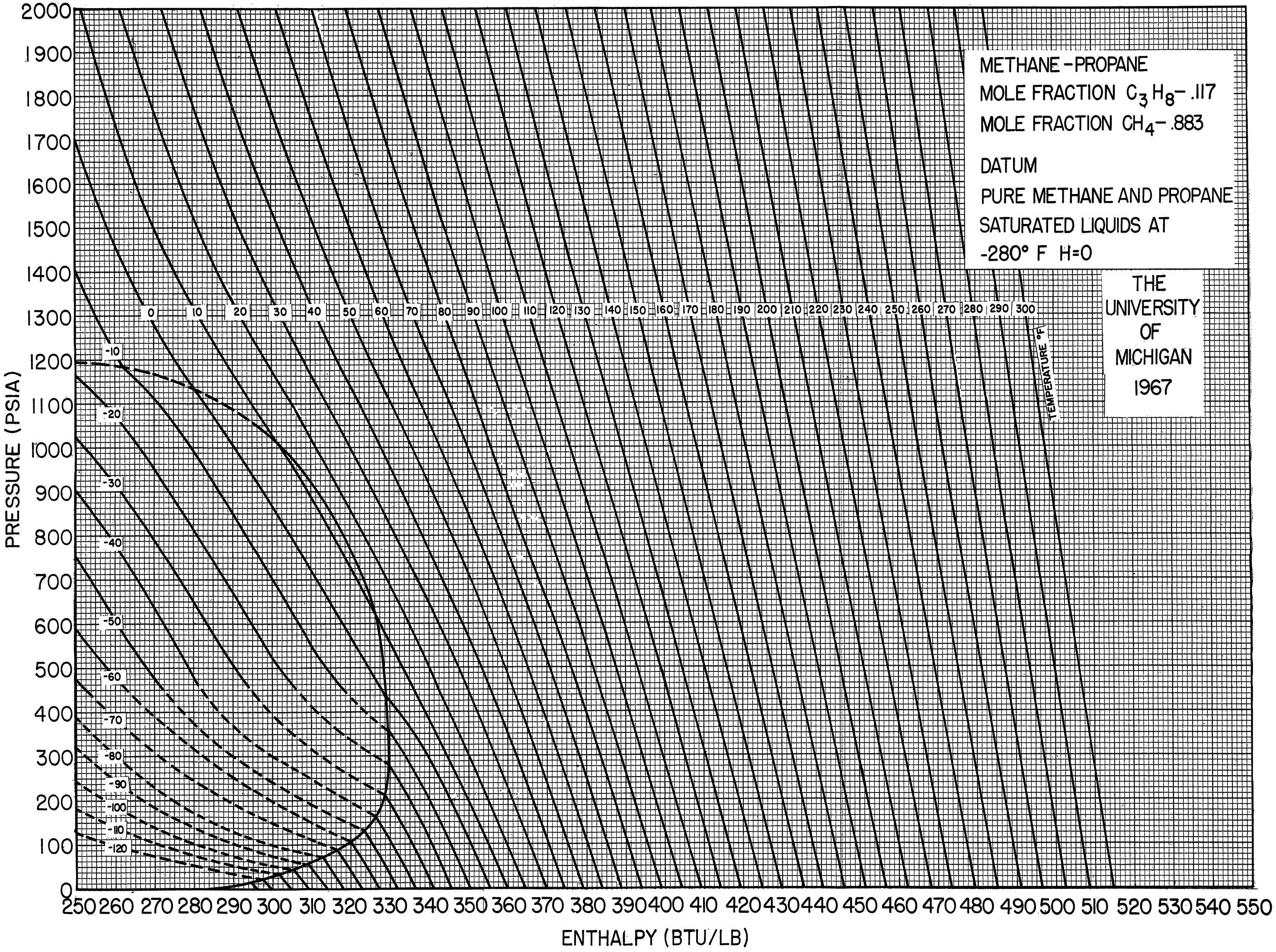


Figure 37. Pressure-Temperature-Enthalpy Diagram for the Nominal 12 Percent Mixture (High Temperature)

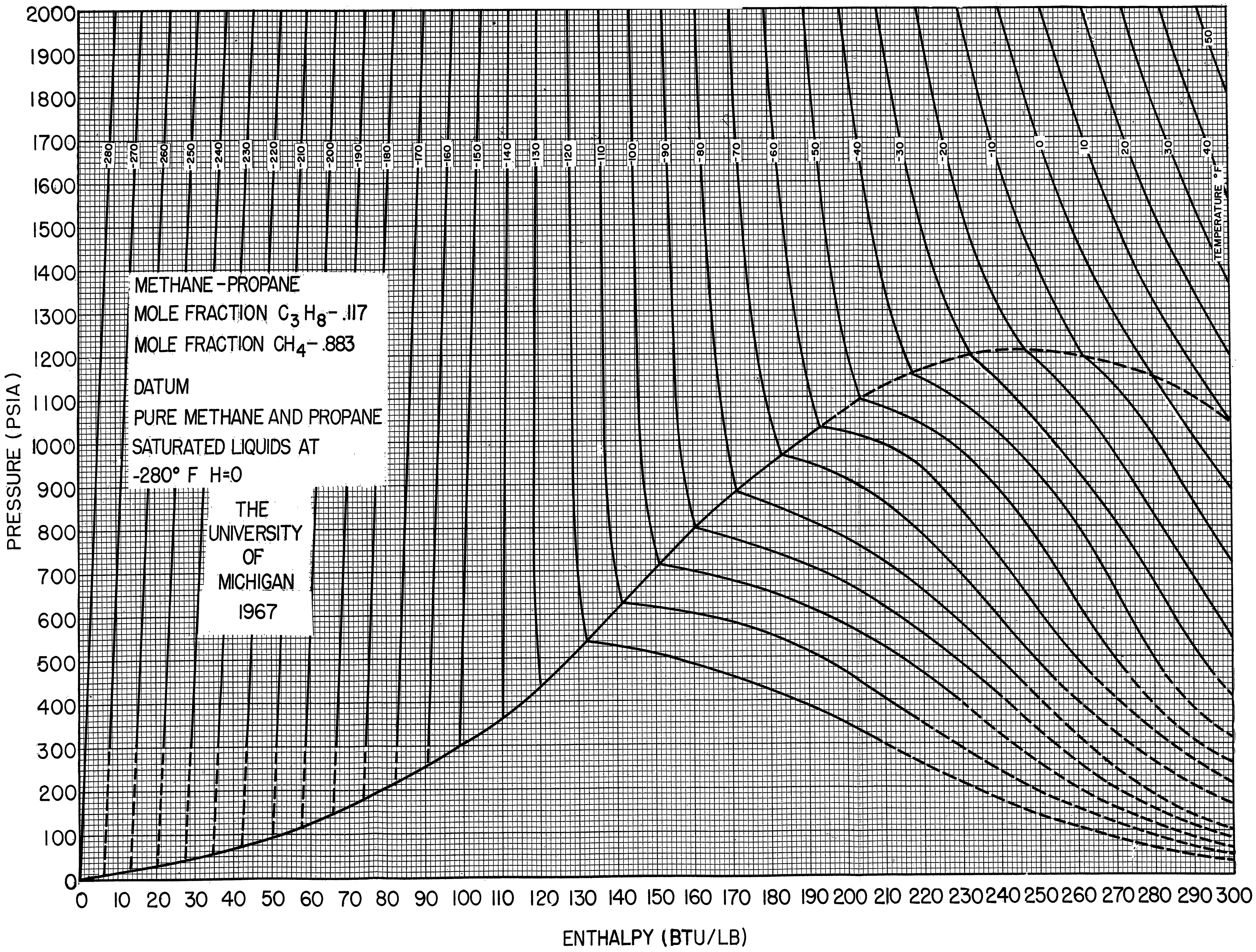


Figure 37. Pressure-Temperature-Enthalpy Diagram for the Nominal 12 Percent Mixture (Low Temperature)

TABLE XXVIII

TABULATED VALUES OF ENTHALPY FOR THE NOMINAL 12 PERCENT MIXTURE

Pressure (psia)	Temperature, °F Bubble Point	Temperature, °F Dew Point	Saturated Liquid Enthalpy (Btu/lb)	Saturated Vapor Enthalpy (Btu/lb)	Latent Heat of Vaporization (Btu/lb)
100	-209	-63	51.0	319.3	268.3
200	-172	-34	79.5	327.9	248.4
300	-150	-18	99.2	329.4	230.2
400	-136	-5	115.0	329.0	214.0
500	-124	4	127.8	327.9	200.1
600	-112	8	138.9	325.4	186.5
700	-101	10	149.6	322.1	172.5
800	-89	11	160.7	317.9	157.2
900	-77	12	174.4	311.5	137.1
1000	-65	10	188.7	303.0	114.3
1100	-49	4	205.5	287.5	82.0

H (Btu/lb)

Temperature (°F)	Pressure, psia 0	250	500	750	1000	1250	1500	1750	2000
-280	231.3	1.5	2.7	4.0	5.3	6.5	7.7	9.0	10.1
-270	235.5	7.7	9.0	10.5	11.8	13.2	14.5	15.9	17.1
-260	239.8	14.5	16.1	17.5	18.9	20.4	21.8	23.2	24.5
-250	244.1	21.5	23.1	24.5	26.0	27.4	28.8	30.1	31.5
-240	248.3	28.8	30.2	31.8	33.2	34.6	36.1	37.5	38.9
-230	252.6	36.2	37.4	39.0	40.4	41.8	43.2	44.5	45.8
-220	256.9	43.2	44.8	46.0	47.6	49.0	50.5	51.8	53.0
-210	261.2	51.0	52.2	53.7	55.0	56.4	57.6	58.9	60.1
-200	265.5	58.4	59.8	61.0	62.4	63.6	65.0	66.2	67.5
-190	269.9	66.2	67.5	68.7	70.0	71.4	72.5	73.8	75.0
-180	274.1	74.0	75.3	76.5	77.8	79.0	80.2	81.4	82.5
-170	278.3	82.2	83.3	84.5	85.6	86.8	87.9	89.0	90.1
-160	282.9	90.5	91.6	92.6	93.6	94.5	95.5	96.5	97.4
-150	287.3		99.9	100.9	101.8	102.6	103.5	104.4	105.1
-140	291.7		109.8	109.6	110.0	110.6	111.3	111.8	112.4
-130	296.1		119.5	118.4	118.4	118.8	119.3	119.5	120.1
-120	300.5	218.9	152.8	129.0	127.6	127.5	127.5	127.7	127.9
-110	305.0	237.7	193.1	138.9	136.5	136.0	135.8	135.9	135.9
-100	309.5	249.4	213.1	149.1	145.7	144.9	144.5	144.3	144.1
-90	313.9	259.7	226.8	176.5	156.3	154.2	153.5	153.0	152.4
-80	318.4	267.5	238.1	203.5	168.1	164.7	162.8	161.7	161.0
-70	322.9	280.0	248.3	222.3	181.6	176.0	172.7	171.1	169.9
-60	327.5	290.8	258.1	236.7	205.0	187.1	183.2	181.0	179.0
-50	332.1	299.5	268.3	250.5	225.2	199.0	194.4	191.4	188.5
-40	336.6	309.7	279.1	262.3	240.6	213.1	206.4	202.2	198.2
-30	341.2	321.7	290.3	273.5	252.5	229.2	219.3	213.0	208.3
-20	345.8	331.9	302.1	284.9	266.5	243.4	232.3	224.4	218.7
-10	350.5	337.1	313.6	297.0	280.1	257.8	245.3	236.1	229.3
0	355.2	342.3	324.6	308.0	291.9	271.4	257.7	248.0	240.0
10	359.9	347.2	332.6	319.0	302.3	284.0	269.7	259.4	250.7
20	364.6	353.0	340.0	327.2	311.7	295.2	281.1	270.5	261.3
30	369.4	359.0	346.9	334.5	320.3	305.2	291.7	281.3	271.7
40	374.2	364.4	353.3	341.0	328.3	314.2	301.7	291.1	281.7
50	379.1	369.3	359.4	348.3	335.9	322.5	311.0	300.8	291.5
60	383.9	374.5	365.2	354.6	343.1	331.0	319.9	310.2	301.0
70	388.9	379.8	370.9	360.6	350.0	338.5	328.3	318.9	310.2
80	393.8	385.2	376.4	366.2	356.7	346.1	336.4	327.6	319.1
90	398.8	390.4	381.9	372.8	363.3	353.4	344.2	335.5	327.7
100	403.9	395.8	387.3	378.7	369.7	360.6	351.8	343.9	336.1
110	408.9	401.1	393.1	384.6	376.2	367.5	359.3	351.6	344.2
120	414.0	406.5	398.8	390.8	382.7	374.5	366.6	359.4	352.2
130	419.2	411.8	404.5	396.9	389.1	381.2	373.8	367.0	360.0
140	424.4	417.5	410.2	402.9	395.5	388.1	380.9	374.2	367.7
150	429.7	422.8	416.0	409.1	401.8	394.8	387.9	381.5	375.3
160	435.0	428.6	421.7	415.0	408.1	401.5	394.9	388.8	382.7
170	440.3	434.0	427.5	421.1	414.5	408.0	401.7	396.0	390.1
180	445.7	439.5	433.3	427.0	420.7	414.8	408.5	402.7	397.3
190	451.1	445.2	439.1	433.1	427.1	421.1	415.3	410.0	404.5
200	456.6	450.8	445.0	439.2	433.3	427.6	422.1	416.9	411.7
210	462.1	456.5	450.9	445.3	439.7	434.1	428.8	423.6	418.8
220	467.7	462.4	456.8	451.4	446.0	440.6	435.5	430.6	425.9
230	473.4	468.0	462.8	457.5	452.3	447.0	442.2	437.5	432.9
240	479.0	474.0	468.8	463.7	458.6	453.9	448.9	444.0	439.9
250	484.8	479.7	474.8	469.8	465.0	460.2	455.6	451.2	446.9
260	490.6	485.8	480.9	476.0	471.3	466.7	462.3	458.0	453.9
270	496.4	491.6	487.0	482.4	477.7	473.2	468.9	464.9	460.9
280	502.3	497.7	493.1	488.8	484.2	479.8	475.7	471.2	467.8
290	508.2	503.8	499.3	495.0	490.6	486.5	482.4	478.4	474.8
300	514.2	509.9	505.5	501.3	497.1	493.1	489.1	485.4	481.7

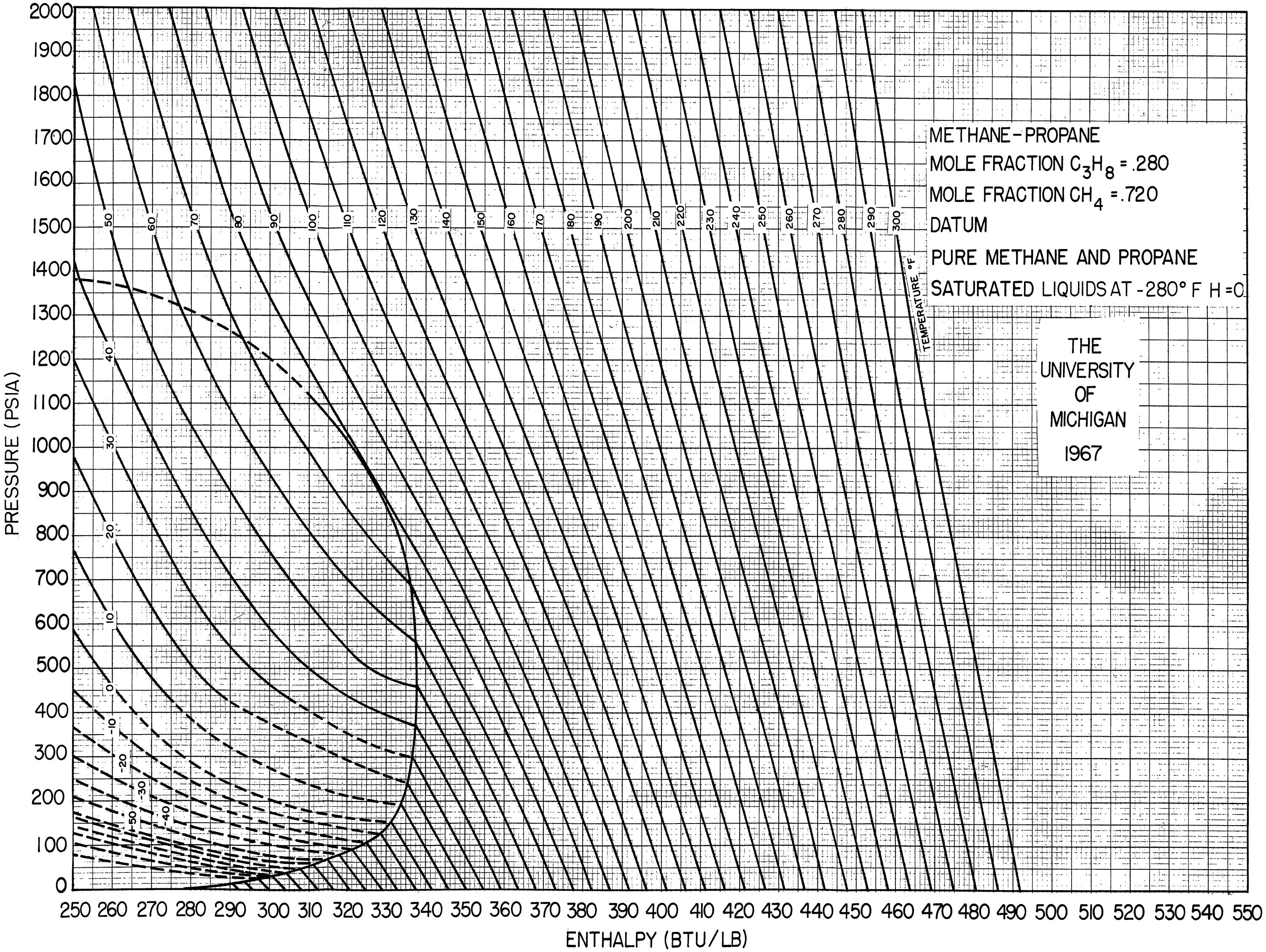


Figure 38. Pressure-Temperature-Enthalpy Diagram for the Nominal 28 Percent Mixture (High Temperature)

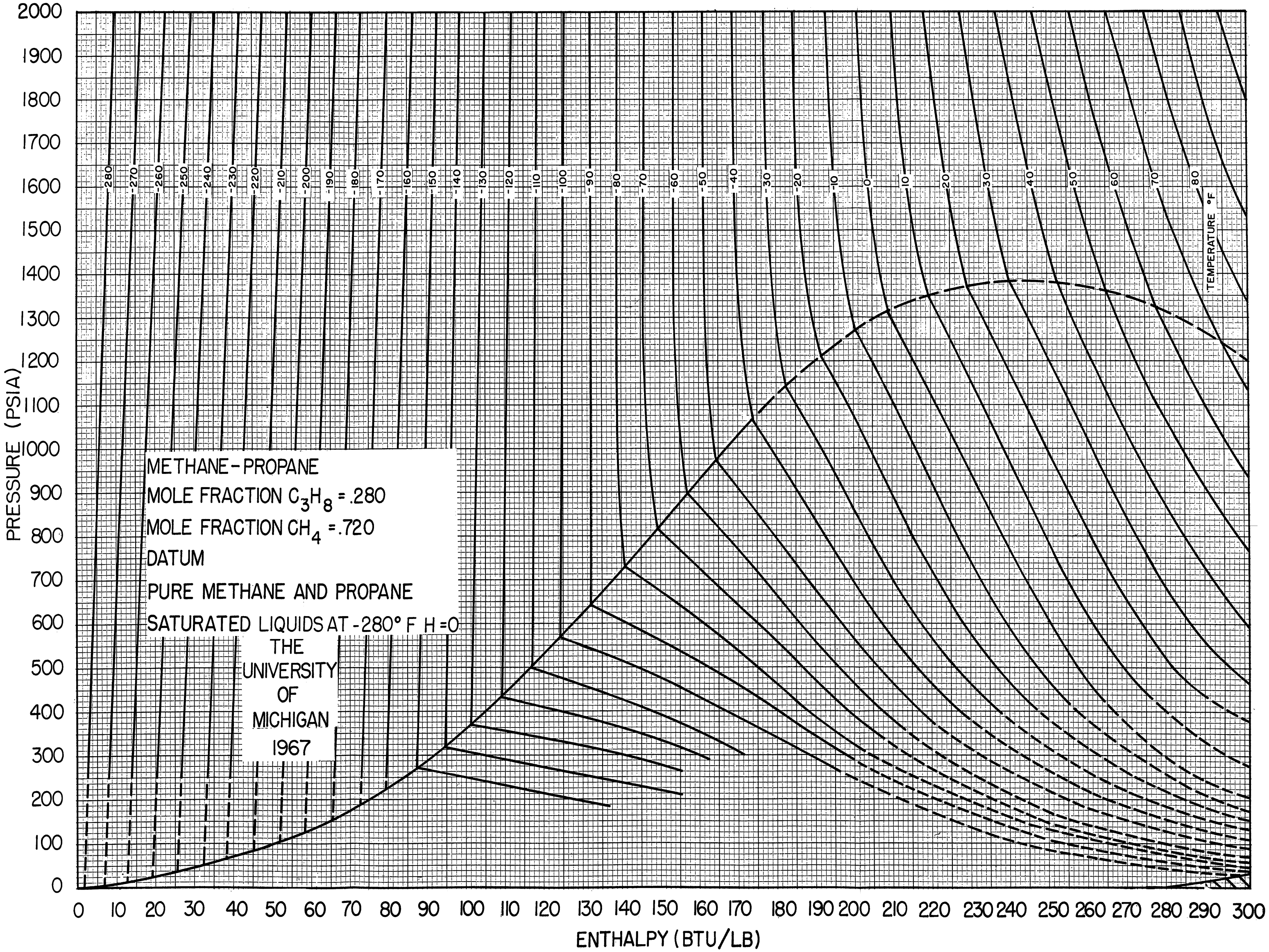


Figure 38. Pressure-Temperature-Enthalpy Diagram for the Nominal 28 Percent Mixture (Low Temperature)

TABLE XXIX

TABULATED VALUES OF ENTHALPY
FOR THE NOMINAL 28 PERCENT MIXTURE

Pressure (psia)	Temperature, °F Bubble Point	Dew Point	Saturated Liquid Enthalpy (Btu/lb)	Saturated Vapor Enthalpy (Btu/lb)	Latent Heat of Vaporization (Btu/lb)
100	-202	-25	50.0	323.5	273.5
200	-167	11	74.5	334.1	259.6
300	-145	30	91.1	336.6	245.5
400	-126	43	104.3	337.7	233.4
500	-110	55	116.0	337.9	221.9
600	-96	64	126.9	337.1	210.2
700	-84	71	137.0	335.9	198.9
800	-72	78	147.0	331.1	184.1
900	-59	80	156.9	328.4	171.5
1000	-47	79	166.5	321.5	155.0
1100	-36	77	177.0	312.5	135.5
1200	-21	74	189.3	300.5	111.2
1300	-4	64	205.0	283.0	78.0

H (Btu/lb)

Temperature (°F)	Pressure, psia 0	250	500	750	1000	1250	1500	1750	2000
-280	232.8	2.5	3.3	4.0	4.9	5.8	6.5	7.8	9.0
-270	236.4	7.4	8.6	9.8	10.9	12.1	13.4	14.5	15.8
-260	240.0	13.6	14.8	16.0	17.1	18.4	19.5	20.6	21.9
-250	243.6	20.0	21.0	22.4	23.5	24.6	26.0	27.3	28.5
-240	247.2	26.4	27.5	28.6	29.8	31.0	32.1	33.3	34.4
-230	250.9	33.2	34.3	35.3	36.4	37.4	38.5	39.5	40.5
-220	254.6	38.9	40.2	41.4	42.5	43.6	44.8	45.9	47.0
-210	258.3	45.6	46.8	47.9	49.0	50.1	51.2	52.4	53.4
-200	262.0	52.0	53.0	54.1	55.2	56.3	57.3	58.5	59.4
-190	265.7	58.4	59.4	60.6	61.6	62.8	63.8	64.9	66.0
-180	269.5	66.0	66.7	67.6	68.5	69.3	70.1	71.0	71.8
-170	273.3	72.3	73.1	73.9	74.7	75.6	76.4	77.1	78.0
-160	277.1	79.1	79.8	80.6	81.5	82.2	83.0	83.8	84.5
-150	280.9	101.4	87.5	88.1	88.6	89.4	90.0	90.6	91.3
-140	284.8	135.6	94.2	94.7	95.3	95.8	96.3	97.0	97.5
-130	288.7		101.0	101.5	101.9	102.5	103.0	103.5	103.9
-120	292.6		108.4	108.7	108.9	109.5	109.9	110.4	110.7
-110	296.5		116.0	116.3	116.5	116.8	117.0	117.3	117.5
-100	300.5	198.7	143.7	123.4	123.5	123.7	124.0	124.1	124.3
-90	304.5	207.3	161.3	131.2	131.0	131.0	131.0	131.0	131.0
-80	308.5	214.2	174.3	139.5	138.2	138.0	138.0	138.0	138.0
-70	312.5	222.6	186.0	156.2	146.5	145.4	145.5	145.4	145.4
-60	316.6	230.1	195.2	171.0	154.9	153.0	152.7	152.7	152.8
-50	320.7	241.4	205.5	182.8	163.0	161.2	160.5	160.3	160.2
-40	324.9	251.4	215.3	195.0	177.7	170.5	168.5	168.0	167.8
-30	329.1	261.3	225.1	206.0	191.0	179.5	177.0	176.1	175.5
-20	333.3	271.0	235.7	217.3	203.2	189.5	185.6	183.7	183.4
-10	337.5	280.0	246.4	228.9	215.4	200.8	194.7	192.8	191.5
0	341.8	287.5	256.9	240.5	226.2	211.9	204.4	201.5	199.9
10	346.1	306.5	268.1	251.1	237.6	223.9	214.5	211.0	208.5
20	350.5	333.9	280.7	263.0	248.9	235.3	225.2	220.9	217.3
30	354.9	340.3	295.7	275.0	260.2	247.1	236.3	.231.0	226.3
40	359.3	345.5	310.2	287.3	271.9	258.1	247.6	241.1	235.5
50	363.8	350.6	326.7	301.2	283.7	269.0	259.0	251.9	244.9
60	368.3	355.8	341.2	315.5	296.1	280.6	270.2	261.6	254.5
70	372.9	360.9	347.3	330.7	309.4	293.1	281.1	272.5	264.1
80	377.5	366.1	353.2	338.2	321.7	305.5	291.6	282.1	273.7
90	382.2	371.2	359.1	345.4	330.4	315.0	301.6	291.5	283.2
100	386.9	376.4	364.8	351.7	338.2	323.5	311.1	301.4	292.6
110	391.7	381.5	370.5	358.6	345.6	332.2	320.1	310.1	301.7
120	396.5	386.7	376.2	364.9	352.7	340.2	328.8	319.1	310.7
130	401.4	391.9	381.8	371.1	359.7	348.3	337.2	327.5	319.4
140	406.3	397.2	387.5	377.4	366.5	355.6	345.3	336.5	328.2
150	411.2	402.5	393.2	383.4	373.3	363.5	354.1	345.2	336.7
160	416.2	407.8	398.9	389.4	379.9	370.5	361.8	353.5	345.2
170	421.3	413.1	404.6	395.6	386.5	377.6	369.3	361.5	353.4
180	426.4	418.5	410.3	401.6	393.0	384.6	376.7	369.0	361.5
190	431.6	423.9	416.1	407.9	399.5	391.6	384.0	376.8	369.5
200	436.8	429.4	421.8	413.7	405.9	398.1	391.2	384.2	377.3
210	442.1	434.9	427.6	420.0	412.3	405.0	398.3	391.5	385.0
220	447.4	440.4	433.4	425.9	418.7	411.8	405.3	398.9	392.6
230	452.8	446.0	439.3	432.0	425.1	418.4	412.3	406.2	400.1
240	458.2	451.7	445.1	438.3	431.5	425.0	419.2	413.4	407.6
250	463.7	457.3	451.0	444.4	437.9	431.7	426.1	420.4	414.9
260	469.3	463.1	456.9	450.5	444.2	438.4	432.9	427.5	422.3
270	474.9	468.8	462.9	456.6	450.6	445.2	439.7	434.7	429.5
280	480.5	474.6	468.9	462.9	457.0	451.5	446.6	441.5	436.7
290	486.2	480.5	474.9	469.2	463.4	458.4	453.4	448.7	443.9
300	491.9	486.4	481.0	475.0	469.9	464.8	460.2	455.8	451.1

In the previous report[131] difficulty in reconciling the enthalpy traverses across the two-phase region at 500 and 700 psia with the rest of the enthalpy data was encountered. The enthalpy difference across the two-phase region at these pressures was 5 to 6 percent high. In reworking the data, arithmetic errors were found in the tabulations of enthalpy differences for these two pressures and the corrected data were found to be consistent with the other enthalpy data.

As in the case of the nominal 12 percent mixture, the data were extended down to -280° F by extrapolation and up to +300° F by blending the experimental heat capacities with those calculated from the B-W-R equation of state.

Nominal 43 Percent Nitrogen in Methane Mixture

A skeleton enthalpy table and a pressure-enthalpy-temperature diagram for this mixture have been prepared. The following procedure was used in preparing the table and diagram:

1) Reference states of 0 Btu/lb were taken to be the pure components as saturated liquids under their own vapor pressure at -280°F.

2) The enthalpy of pure methane as a gas at zero pressure and 100°F was calculated using the data on the heat of vaporization at 5 psia of Frank and Clusius[64], the B-W-R equation of state to correct from 5 psia to zero pressure and values of the ideal gas heat capacities from Rossini[161]. The enthalpy of methane at 100°F and zero pressure was found to be 421.97 Btu/lb.

3) The enthalpy of pure nitrogen as a gas at zero pressure and 100°F was calculated using a value of the latent heat at 111 psia (-280°F) from Bloomer and Rao[15], data from their report for the enthalpy difference between 111 psia and zero pressure and values of the ideal gas heat

capacities from Rossini[161]. The following results were obtained:

	Enthalpy, Btu/lb
Latent heat of vaporization at -280° F	69.45
Effect of pressure on enthalpy (0 to 111 psia)	7.08
Ideal gas enthalpy (-280° F to 100° F)	94.36 .
	170.89

(The B-W-R equation gave 7.46 Btu/lb for the effect of pressure on enthalpy)

4) The enthalpy of the methane-nitrogen mixture at zero pressure and 100 F was calculated assuming zero heat of mixing.

$\underline{H}$mix = 0.5725 (170.89) + 0.4275 (421.97)

= 278.23 Btu/lb

5) The isothermal effect of pressure on enthalpy at 100°F was estimated using the B-W-R equation of state with constants for nitrogen given by Stotler and Benedict[179] and the mixing rules originally proposed by Benedict, Webb, and Rubin[11].

6) The isobaric effect of temperature on enthalpy was determined in the gaseous, two-phase, and liquid regions using the data of this work. The phase boundaries were determined using results of traverses made during this research, together with data from Bloomer and Parent[14] and Cines *et al.*[29]

7) A smooth plot of the results was prepared and is shown in Figure 39.

The values of enthalpy are given in Table XXX. These values are compared with results of calculations using the B-W-R equation of state combined with enthalpy data of Rossini[161] at zero pressure in Table XXXI. The agreement between the calculated and experimental en-

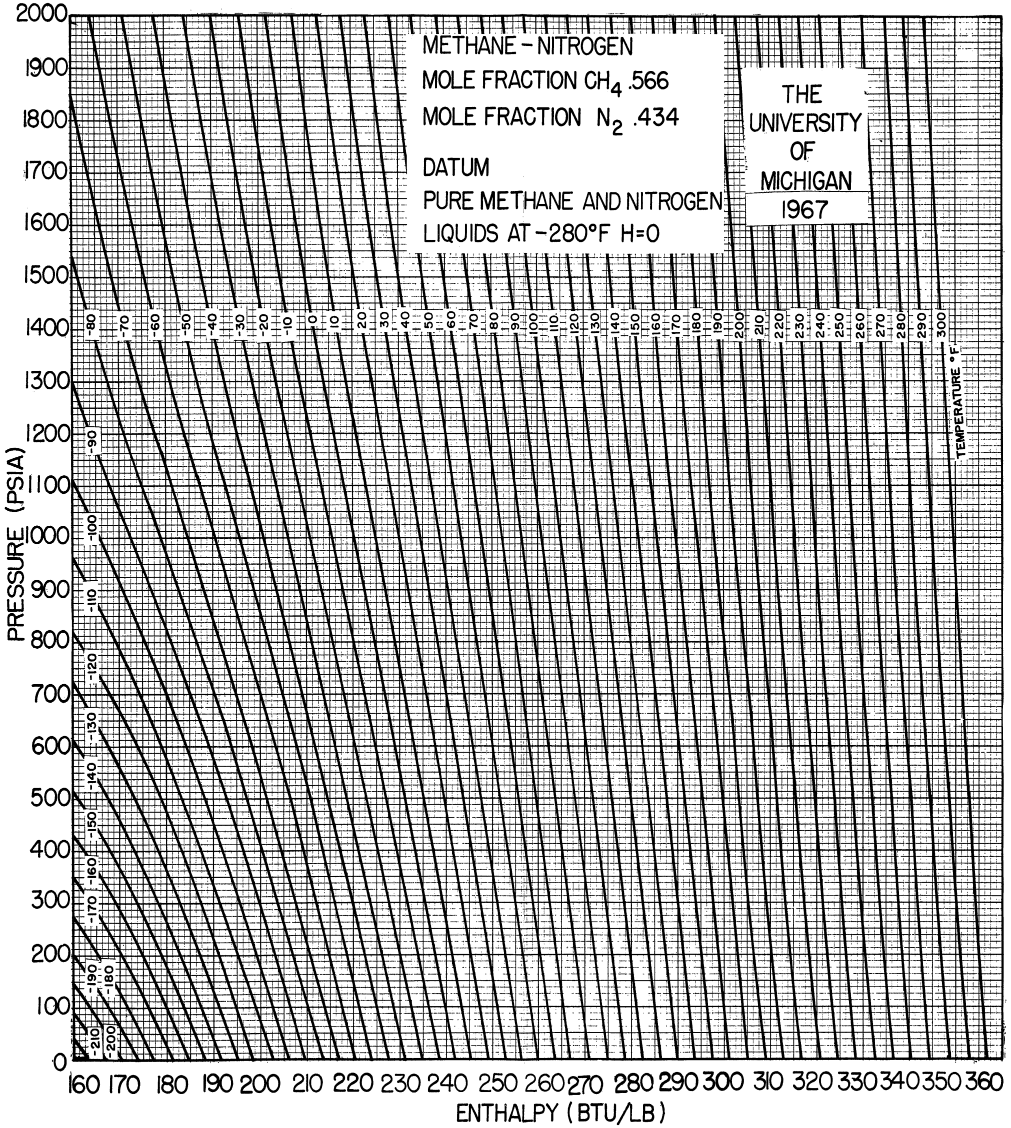


Figure 39. Pressure-Temperature-Enthalpy Diagram for the Nominal 43 Percent Mixture (High Temperature)

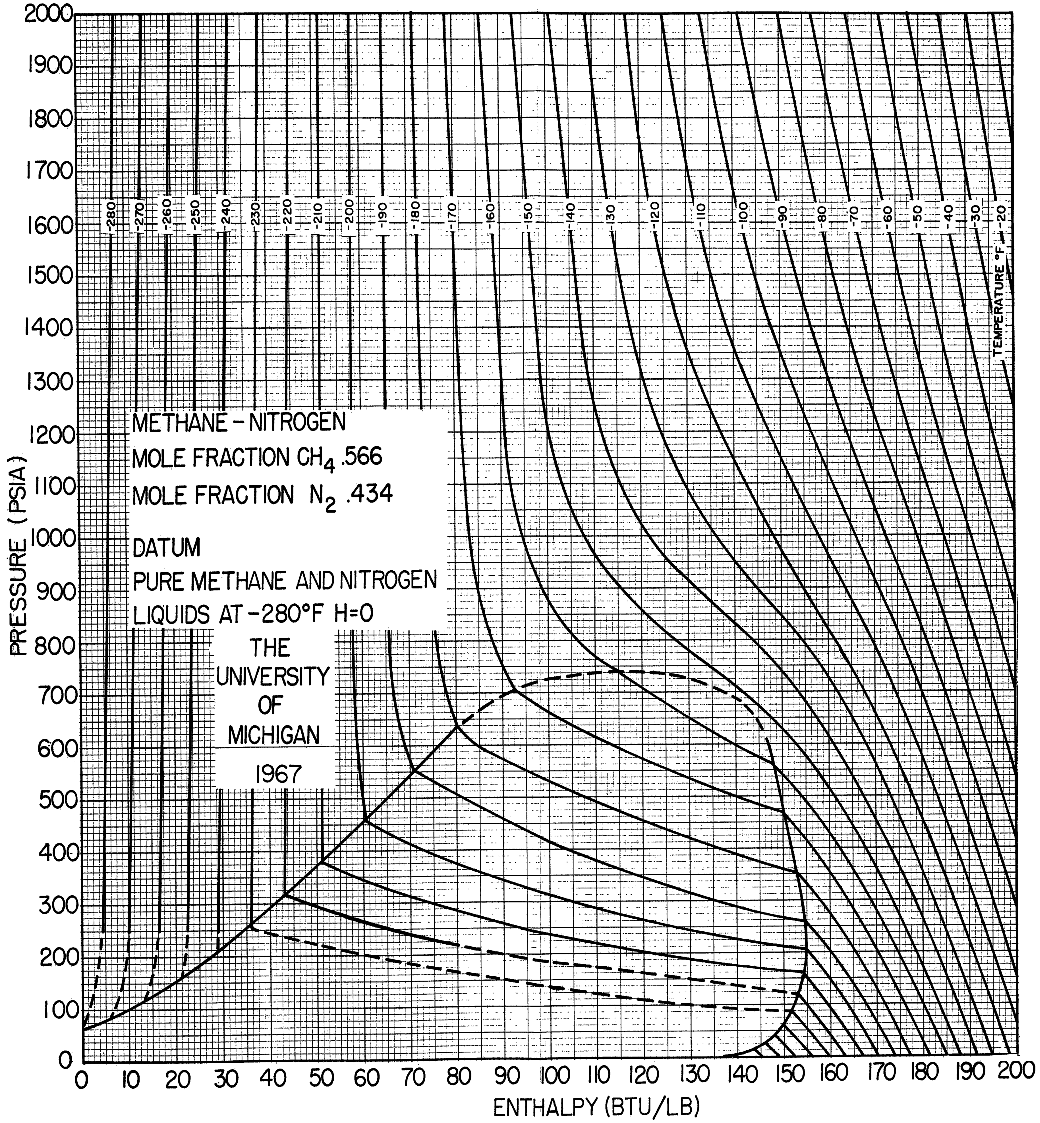


Figure 39. Pressure-Temperature-Enthalpy Diagram for the Nominal 43 Percent Mixture (Low Temperature)

TABLE XXX

TABULATED VALUES OF ENTHALPY FOR THE NOMINAL 43 PERCENT MIXTURE

Pressure (psia)	Temperature, °F Bubble Point	Dew Point	Saturated Liquid Enthalpy (Btu/lb)	Saturated Vapor Enthalpy (Btu/lb)	Latent Heat of Vaporization (Btu/lb)
100	-268	-225	8.8	152.5	143.7
200	-243	-202	27.5	154.9	127.4
300	-224	-186	41.0	154.1	113.1
400	-208	-175	53.4	152.0	98.6
500	-197	-166	65.0	149.7	84.7
600	-184	-157	76.0	147.0	71.0
700	-171	-152	92.0	138.5	46.5

H (Btu/lb)

Temperature (°F)	Pressure, psia 0	250	500	750	1000	1250	1500	1750	2000
-280	142.0	*4.2*	*4.6*	*5.3*	*5.9*	*6.7*	*7.1*	*7.7*	*8.3*
-270	145.5	*10.5*	*10.9*	*11.5*	*12.0*	*12.5*	*13.1*	*13.5*	*14.3*
-260	149.1	*16.8*	*17.3*	*17.7*	*18.3*	*18.8*	*19.2*	*19.8*	*20.3*
-250	152.6	*23.0*	*23.3*	*23.8*	*24.3*	*24.8*	*25.4*	*25.9*	*26.3*
-240	156.1	*29.2*	*29.7*	*30.1*	30.5	*31.0*	31.7	*32.1*	32.5
-230	159.7	*38.2*	*37.0*	*37.3*	37.4	*38.0*	38.1	*38.5*	38.8
-220	163.2	*66.9*	*43.9*	*44.0*	44.3	*44.5*	44.7	*44.9*	45.1
-210	166.8	*93.9*	*51.3*	*51.2*	51.2	*51.3*	51.4	*51.4*	51.5
-200	170.3	*126.4*	*60.0*	*58.3*	58.3	*58.2*	58.2	*58.2*	58.1
-190	173.9	*155.6*	*82.2*	*66.1*	65.7	*65.5*	65.2	*65.0*	64.8
-180	177.4	*162.0*	*108.6*	*76.8*	73.8	*73.0*	72.5	*72.0*	71.6
-170	180.9	*167.4*	*140.6*	*90.2*	83.0	*81.0*	80.2	*79.1*	78.5
-160	184.5	172.0	*154.1*	*113.1*	94.2	*90.3*	88.2	*87.0*	85.7
-150	188.0	176.4	*161.1*	*135.0*	108.0	*99.4*	96.9	*94.7*	93.1
-140	191.6	180.7	*167.6*	*149.4*	122.1	*110.4*	106.2	*103.3*	100.8
-130	195.1	184.9	*173.1*	*158.4*	136.1	*122.7*	115.9	*111.4*	108.7
-120	198.7	189.1	*178.8*	*165.0*	148.3	*134.7*	125.6	*120.2*	116.8
-110	202.2	193.1	*183.2*	*172.0*	157.9	*145.1*	135.3	*129.3*	124.9
-100	205.8	197.2	*188.2*	*178.1*	165.9	*154.0*	144.6	*138.0*	133.1
-90	209.3	201.2	192.8	*183.2*	172.8	*162.2*	153.3	*146.7*	141.1
-80	212.9	205.2	197.4	*188.5*	179.1	*169.5*	161.3	*155.3*	148.9
-70	216.5	209.1	201.8	*193.4*	185.0	*176.2*	168.6	*162.4*	156.5
-60	220.0	213.1	206.2	*198.6*	190.6	*182.6*	175.4	*169.5*	163.7
-50	223.6	217.0	210.5	*203.5*	195.9	*188.3*	181.9	*176.4*	170.7
-40	227.2	220.9	214.7	*207.8*	201.1	*194.1*	187.9	*182.8*	177.4
-30	230.8	224.8	218.8	*212.4*	206.1	*199.8*	193.7	*188.9*	183.8
-20	234.3	228.6	223.0	*217.1*	211.0	*204.8*	199.3	*194.5*	189.9
-10	238.0	232.5	227.1	*221.5*	215.8	*209.9*	204.8	*200.0*	195.9
0	241.6	236.3	231.1	*225.9*	220.5	*215.0*	210.1	*205.6*	201.6
10	245.2	240.1	235.2	*230.2*	225.1	*219.8*	215.3	*211.2*	207.1
20	248.8	244.0	239.3	*234.5*	229.7	*225.2*	220.4	*216.5*	212.5
30	252.5	247.8	243.3	*238.7*	234.2	*229.5*	225.4	*221.5*	217.8
40	256.1	251.6	247.3	*242.8*	238.6	*234.0*	230.3	*226.2*	223.0
50	259.7	255.5	251.4	*247.1*	243.0	*238.9*	235.1	*231.5*	228.1
60	263.4	259.3	255.4	*251.2*	247.4	*243.4*	239.9	*236.1*	233.1
70	267.1	263.1	259.4	*255.4*	251.7	*247.9*	244.5	*241.4*	238.0
80	270.8	267.0	263.3	*259.6*	256.0	*252.4*	249.1	*246.0*	242.9
90	274.5	270.9	267.3	*263.7*	260.3	*256.9*	253.7	*250.8*	247.7
100	278.2	274.7	271.3	*268.0*	264.5	*261.4*	258.2	*255.4*	252.5
110	282.0	278.6	275.3	*272.1*	*268.8*	*265.6*	262.7	*260.2*	257.2
120	285.7	*282.5*	279.2	*276.2*	*273.0*	*270.0*	*267.1*	*264.8*	*261.9*
130	289.5	*286.4*	*283.2*	*280.1*	*277.2*	*274.2*	*271.6*	*269.3*	*266.5*
140	293.3	*290.3*	*287.2*	*284.4*	*281.4*	*278.8*	*276.0*	*273.6*	*271.1*
150	297.1	*294.2*	*291.2*	*288.1*	*285.6*	*283.0*	*280.4*	*278.2*	*275.7*
160	300.9	*298.0*	*295.2*	*292.4*	*289.8*	*287.3*	*284.8*	*282.5*	*280.3*
170	304.7	*301.9*	*299.2*	*296.8*	*294.0*	*291.7*	*289.2*	*287.0*	*284.9*
180	308.6	*305.9*	*303.3*	*300.7*	*298.2*	*296.0*	*293.6*	*291.4*	*289.4*
190	312.4	*309.8*	*307.3*	*304.8*	*302.5*	*300.2*	*298.0*	*295.8*	*293.9*
200	316.3	*313.8*	*311.3*	*309.1*	*306.7*	*304.6*	*302.3*	*300.4*	*298.5*
210	320.3	*317.8*	*315.4*	*313.1*	*310.9*	*308.8*	*306.7*	*304.7*	*303.0*
220	324.2	*321.8*	*319.5*	*317.4*	*315.1*	*313.1*	*311.1*	*309.3*	*307.5*
230	328.1	*325.8*	*323.6*	*321.5*	*319.3*	*317.5*	*315.5*	*313.9*	*312.0*
240	332.1	*329.9*	*327.7*	*325.6*	*323.6*	*321.7*	*319.8*	*318.0*	*316.5*
250	336.1	*333.9*	*331.8*	*329.7*	*327.8*	*326.1*	*324.2*	*322.6*	*320.9*
260	340.1	*338.0*	*335.9*	*334.0*	*332.1*	*330.4*	*328.6*	*327.0*	*325.4*
270	344.1	*342.1*	*340.1*	*338.3*	*336.4*	*334.6*	*333.0*	*331.5*	*329.9*
280	348.2	*346.2*	*344.3*	*342.5*	*340.7*	*339.0*	*337.4*	*335.8*	*334.4*
290	352.2	*350.3*	*348.4*	*346.5*	*344.9*	*343.3*	*341.8*	*340.5*	*338.9*
300	356.3	*354.5*	*352.6*	*351.0*	*349.3*	*347.7*	*346.2*	*344.9*	*343.4*

thalpies is within one percent at temperatures as low as -100°F. Below this temperature significant deviations are noted, especially at elevated pressures.

TABLE XXXI
COMPARISON OF ENTHALPIES PREDICTED BY BWR EQUATION OF STATE WITH EXPERIMENTAL RESULTS

DATUM: $\underline{H}$ = 0 for saturated liquid methane and saturated liquid nitrogen at -280°F

T (°F)	P (psia)	$\underline{H}$ (Btu/lb) BWR	Experimental
100	250	274.7	274.7*
50	250	255.6	255.5
0	250	236.4	236.3
- 50	250	217.7	217.0
-100	250	197.3	197.2
-150	250	176.0	176.4
-200	250	150.6	126.4
-250	250	4.6	23.0
100	500	271.3	271.3*
50	500	251.3	251.4
0	500	231.2	231.1
- 50	500	210.3	210.5
-100	500	187.7	188.2
100	1000	264.5	264.5*
50	1000	243.0	243.0
0	1000	220.5	220.5
- 50	1000	195.7	195.9
-100	1000	164.7	165.9
-150	1000	104.5	108.0
-200	1000	55.2	58.3
-250	1000	6.4	24.3
100	1500	258.2	258.2*
50	1500	235.1	235.1
0	1500	210.1	210.1
- 50	1500	181.3	181.9
-100	1500	142.8	144.6
-150	1500	95.9	96.9
-200	1500	55.9	58.2
-250	1500	8.1	25.4
100	2000	252.5	252.5*
50	2000	227.9	228.1
0	2000	201.1	201.6
- 50	2000	169.8	170.7
-100	2000	132.1	133.1
-150	2000	93.9	93.1
-200	2000	56.7	58.1
-250	2000	9.6	26.3

---

* Isotherm at 100°F is the reference line.

Comparison of Methane-Nitrogen Mixture Enthalpy Data

In the methane-propane system the two-phase region covers a large portion of the experimentally accessible P-T surface and comparisons of enthalpies as function of composition are difficult because one component is a liquid and the other is a gas under most conditions. With the methane-nitrogen system, however, most of the data are obtained in the gaseous region and comparisons where all mixtures and the pure components are gaseous are possible.

The heat of mixing or excess enthalpy for the nominal 43 percent mixture was calculated at high pressures from the data of Table XXX together with the methane data of Jones[94] and the nitrogen data of Mage[120]. The heats of mixing are presented in Figure 40 as a function of temperature. It can be seen that in the region above the critical point large deviations from ideal mixing exist. Also shown in this Figure are the heat of mixing data of Van Eijnsbergen[188], directly determined using a flow calorimeter. The agreement is very good except at the highest temperature. Here the values calculated from mixture and pure component data may be in error because of the small differences between large numbers which are involved.

A comparison can be made with other enthalpy data on the methane-nitrogen system. Isothermal enthalpy changes at low and high temperatures and isobaric enthalpy changes at low and high pressure were selected as representative checks of the data of this work with other published data. The isothermal comparisons at -100°F and 100°F are shown in Figures 41 and 42. The isobaric comparisons at 500 psia and 1500 psia are shown in Figures 43 and 44. Straight lines joining the pure component values on this type of graph define ideal mixing [the excess

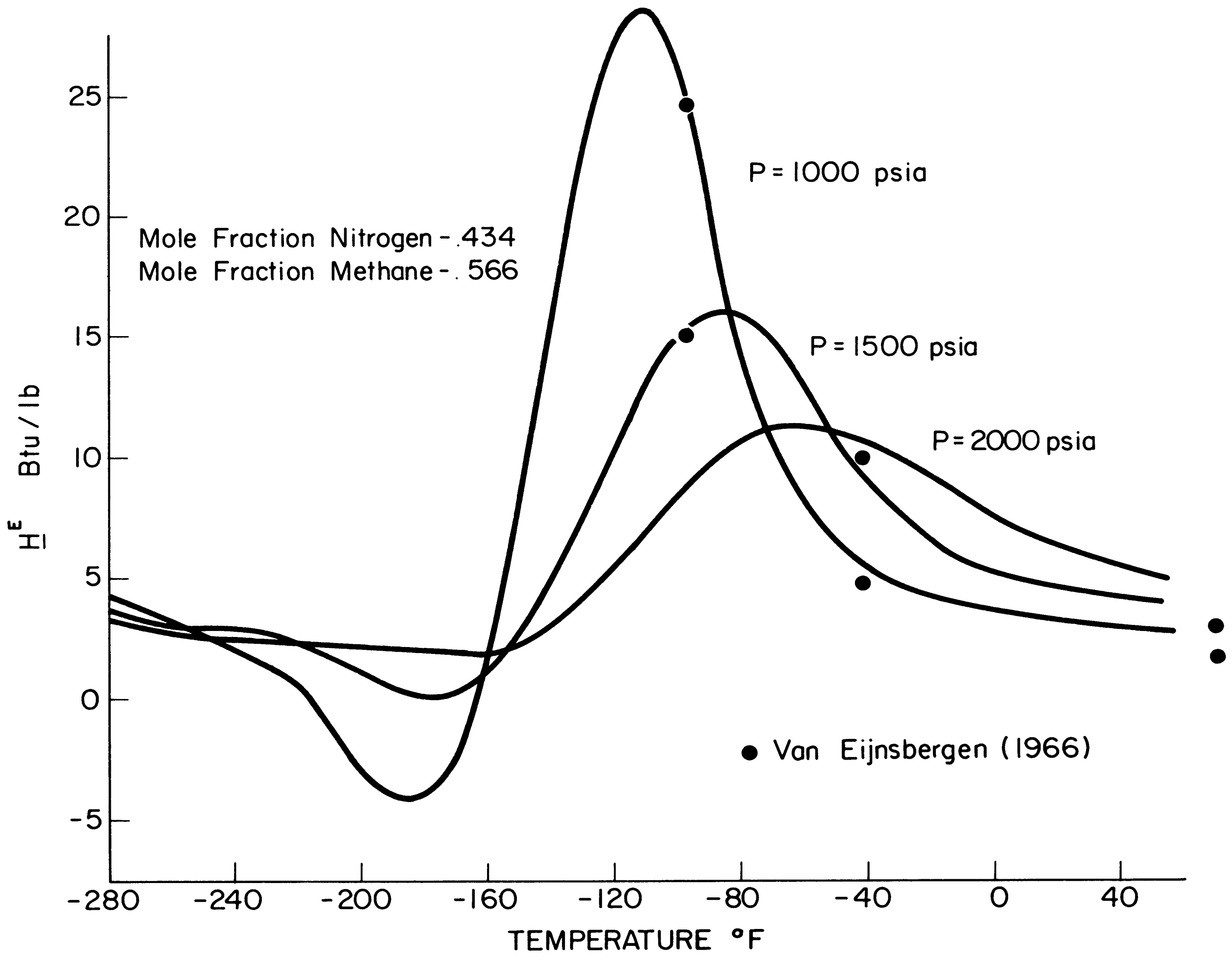


Figure 40. Heats of Mixing at High Pressure

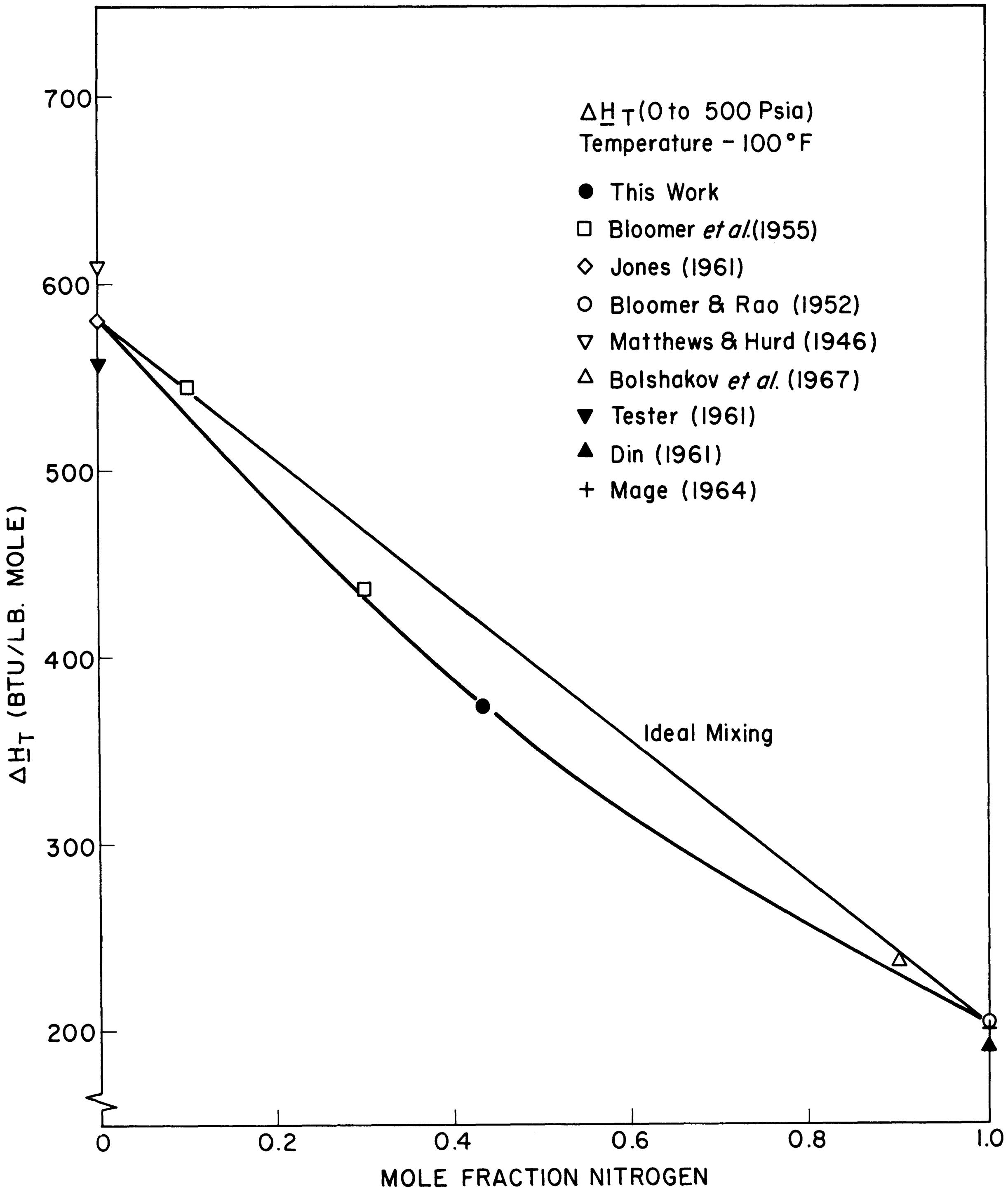


Figure 41. Isothermal Enthalpy Comparison at Low Temperature

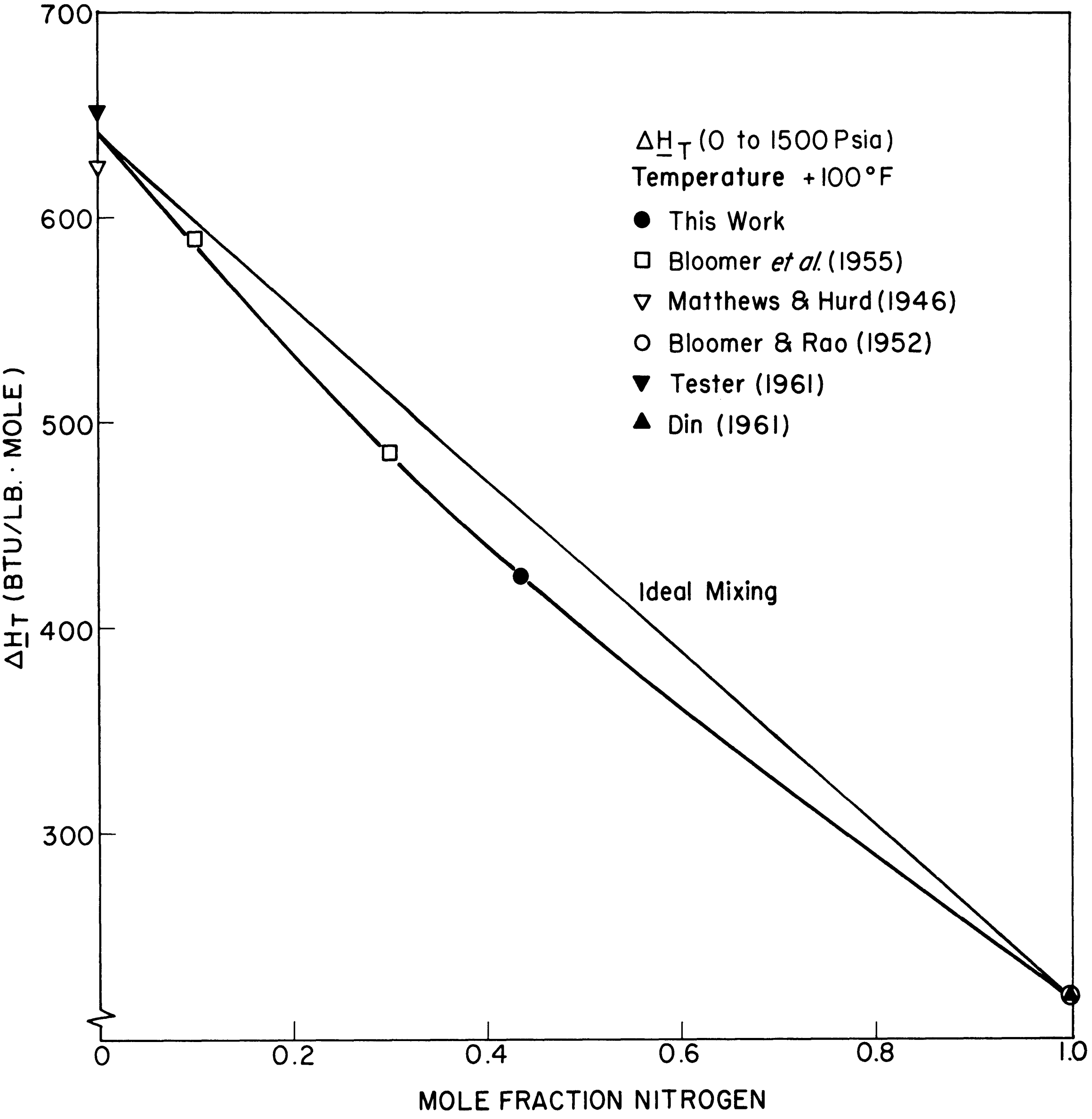


Figure 42. Isothermal Enthalpy Comparison at High Temperature

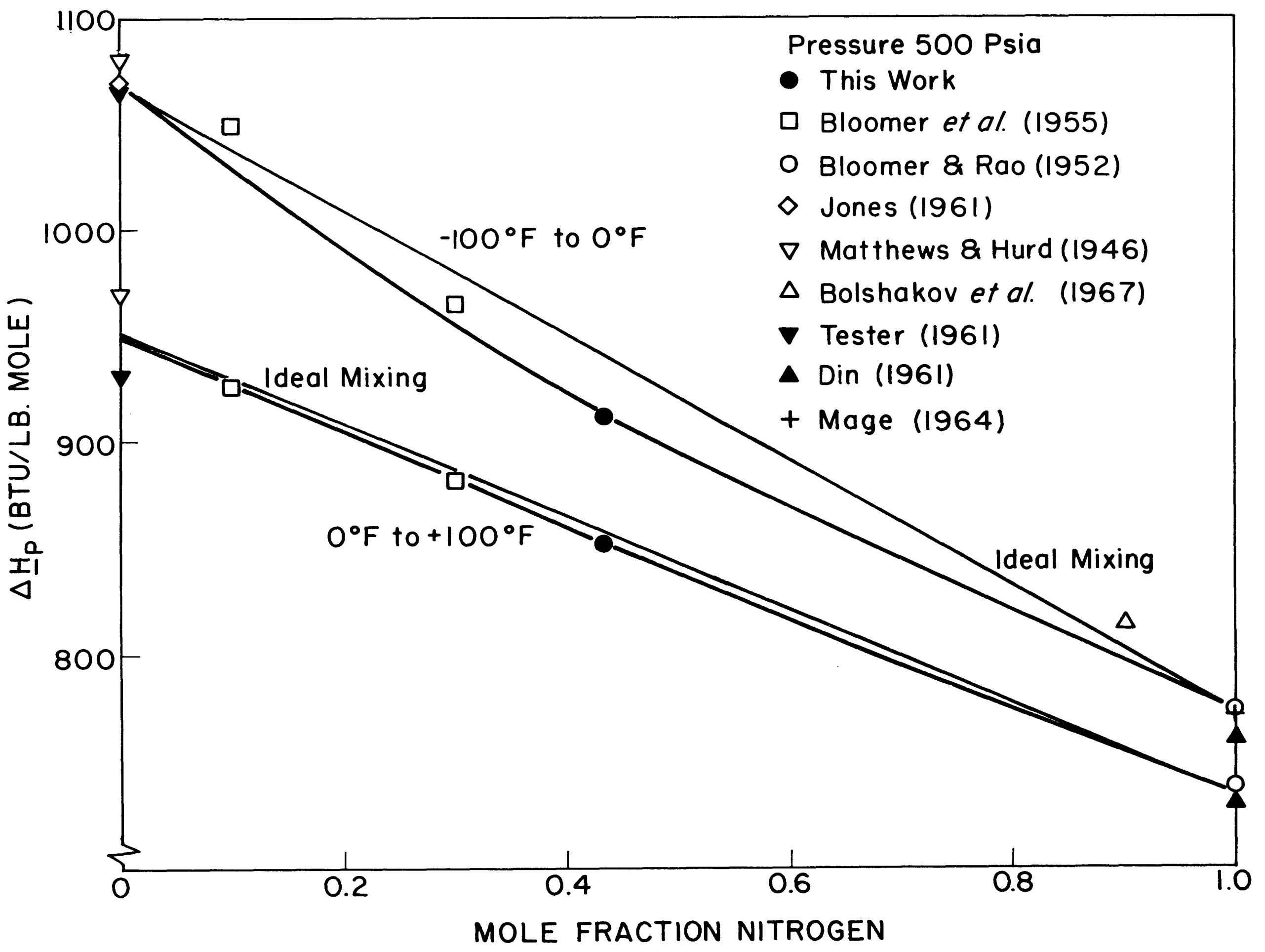


Figure 43. Isobaric Enthalpy Comparisons at 500 psia

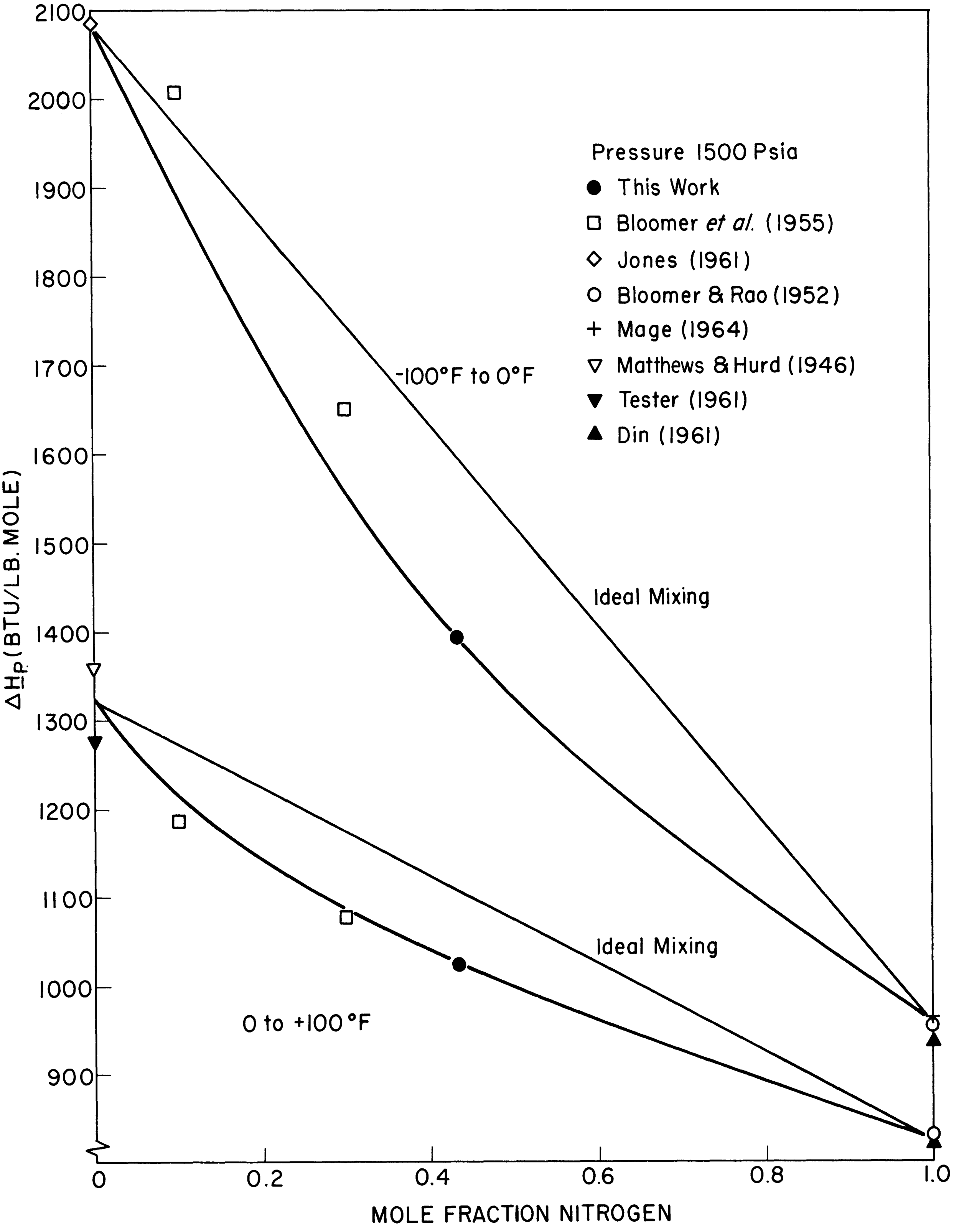


Figure 44. Isobaric Enthalpy Comparisons at 1500 psia

enthalpy, Equation (19), is zero]. The lines showing actual mixing are biased to include the nominal 43 percent nitrogen mixture and the points for methane of Jones[94] and nitrogen of Mage[120] if these were available. It can be seen that the data of Bolshakov *et al.*[18] are not in agreement with the present work and the tabulation of Bloomer *et al.*[16] is in fair agreement. The values for methane from the three tabulations are in poor agreement with discrepancies as high as 7 to 10 percent. It appears that more work on methane to resolve these discrepancies would be desirable.

Vapor-Liquid Equilibria

In the course of measurements across the two-phase region, it is possible to obtain estimates of the bubble and dew points from abrupt changes in the curvature of a plot of energy added versus temperature like Figure 8. Table XXXII compares the results for the three methane-propane mixtures and the methane-nitrogen mixture with data from the literature.

TABLE XXXII

COMPARISON OF PHASE EQUILIBRIA OBTAINED FROM ENTHALPY TRAVERSES WITH VAPOR-LIQUID EQUILIBRIUM DATA

Methane-Propane

a) Nominal 5% Propane Mixture

	Bubble Point (°F)		Dew Point (°F)	
Pressure (psia)	Manker[123]	Price and Kobayashi[151]	Manker[123]	Price and Kobayashi[15]
250	-166	-167	-58	-61
400	-142	-143	-50	-50
500	-128	-130	-42	-44
600	-117	-118	-39	-41
650	-112	-113	-39	-40
800	- 96	- 97	-38	-40

b) Nominal 12% Propane Mixture

Pressure (Psia)	Bubble Point (°F) This work	Bubble Point (°F) Price & Kobayashi[151]	Dew Point (°F) This work	Dew Point (°F) Price & Kobayashi[151]
500	-123	-124	3	- 2
800	- 89	- 88	10	10
1000	- 66	- 64	11	7.5

c) Nominal 28% Propane Mixture

Pressure (Psia)	Bubble Point (°F) This work	Bubble Point (°F) Price & Kobayashi[151]	Dew Point (°F) This work	Dew Point (°F) Price & Kobayashi[151]
500	-111	-116	59	54
700	- 83	- 87	72	69
1000	- 46	- 47.5	79	83

Methane-Nitrogen

a) Nominal 43% Nitrogen Mixture

Pressure (psia)	Bubble Point (°F) This work	Bubble Point (°F) Bloomer & Parent[14]	Dew Point (°F) This work	Dew Point (°F) Bloomer & Parent[14]
250	-231	-232	-191	-196
400	-208	-208	-176	-177
600	-183	-183	-157	-163

It can be seen that, in general, the direct vapor-liquid equilibrium measurements and the values derived from the enthalpy traverses agree within a few degrees. Mage[120] also found this to be the case with the dew points of the helium-nitrogen system.

Heats of Vaporization

In many instances the latent heat of vaporization comprises the major portion of a particular heat duty. It is important then, to be able to estimate values of the integral isobaric heat of vaporization accurately. Manker[123] compared the latent heats determined on the nominal 5 percent mixture and concluded that the method of Peters[145] gave the best estimates of the latent heat. A number of the methods for estimating enthalpies in Table II and specifically those intended for latent heats were used to compare with the experimental results for the methane-propane and methane-nitrogen mixtures. The results are compared in Table XXXII and it is seen that the method of Peters appears to predict the trend of latent heat with pressure reliably. Values calculated by the method of Stevens and Thodos[176] for the nominal 12 percent mixture appear to be badly in error. The method of Edmister[49], although specifically derived for hydrocarbons, gives reasonable results for the methane-nitrogen mixture.

No method of predicting the isobaric latent heat compared here is completely satisfactory and further work in this area of prediction is necessary.

TABLE XXXIII

CALCULATED AND EXPERIMENTAL ISOBARIC HEATS OF VAPORIZATION

Pressure (psia)	This Work	Stevens & Thodos[176]	Scheibel & Jenny[167]	Edmister[49]	Maxwell[133]	Canjar & Peterka[24]	Peters[145]
a) Nominal 12 Percent Propane in Methane							
500	200	173	245	229	196	222	203
800	173	73	205	188	162	161	165
1000	111	46	170	174	142	163	122
b) Nominal 28 Percent Propane in Methane							
500	227	214	245	244	208	237	214
700	196	187	222	207	200	218	200
1000	153	142	180	172	182	181	166

c) Nominal 43 Percent Nitrogen in Methane

	This work	Edmister[49]	Curl & Pitzer[38]	Yen[201]
250	120	126	118	115
400	99	102	95	108
600	71	89	61	36

Summary and Conclusions

1. The recycle system originally designed by Faulkner was modified to allow measurements under conditions different from those for which the equipment was designed.

2. Isobaric data on the effect of temperature on enthalpy were obtained for nominal mixtures of 12 percent propane in methane, 28 percent propane in methane, and 43 percent nitrogen in methane. These data cover the liquid, two-phase, and gaseous regions at temperatures from $-240^{\circ}F$ to $+140^{\circ}F$ at pressures from 250 to 2000 psia.

3. Skeleton enthalpy tables and enthalpy-pressure-temperature diagrams for those three mixtures were prepared using supplemental data from the literature.

4. An isothermal throttling calorimeter for the direct determination of the effect of pressure on enthalpy was designed, fabricated, and tested.

5. Measurements of the effect of pressure on enthalpy were made on nitrogen at -147 F, $33^{\circ}F$, and $201^{\circ}F$ at pressures from 2000 to 100 psia. The data are in fair agreement with literature values, considering that the disagreement among the literature values is up to 4 percent.

6. Measurements of the effect of pressure on enthalpy were made on a nominal mixture of 5 percent propane in methane at $-147^{\circ}F$, $-27^{\circ}F$, $93^{\circ}F$, and $200^{\circ}F$. Isobaric experiments were also made on this mixture to extend the data of Manker from 70 F. to $250^{\circ}F$.

7. A skeleton enthalpy table and an enthalpy-pressure-temperature diagram for the nominal 5 percent mixture covering the range $-280^{\circ}F$ to $+300^{\circ}F$ at pressures up to 2000 psia was prepared which is based almost entirely on direct experimental determinations.

Recommendations for Future Work

1. The Roebuck pressure balance should be replaced with transducers to allow more accurate readings of the pressures and pressure drops and eliminate the problem of fluid of variable density and composition in the lead lines.

2. The substitution of electrical measurements for mechanical devices in the flow rate and pressure drop determinations to eliminate water and mercury from the system and improve the precision of the measurements is recommended.

3. Use of an automatic controller on the electrical energy input to the guard heater of the isobaric calorimeter and the energy input to the isothermal throttling calorimeter would facilitate precise control in these variables and minimize corrections to the data.

4. A Joule-Thomson device should be constructed to provide an independent check on the data of this laboratory.

5. Numerical techniques for the smoothing and interpolation of the data should be developed to minimize the time spent in working up of data into tables and charts. When data for the complete composition range of the methane-propane system become available, tables and diagrams smoothed with respect to composition, temperature, and pressure should be compiled. At this time, the basis for enthalpy should be changed to the pure components as perfect crystals at $0^{o}K$.

6. A thorough study of the prediction methods for thermodynamic properties should be made with the goal of devising a new method with improved accuracy. Data of the type presented here will be useful in developing and testing such a new correlation method.

APPENDIX A

CALORIMETER DRAWINGS

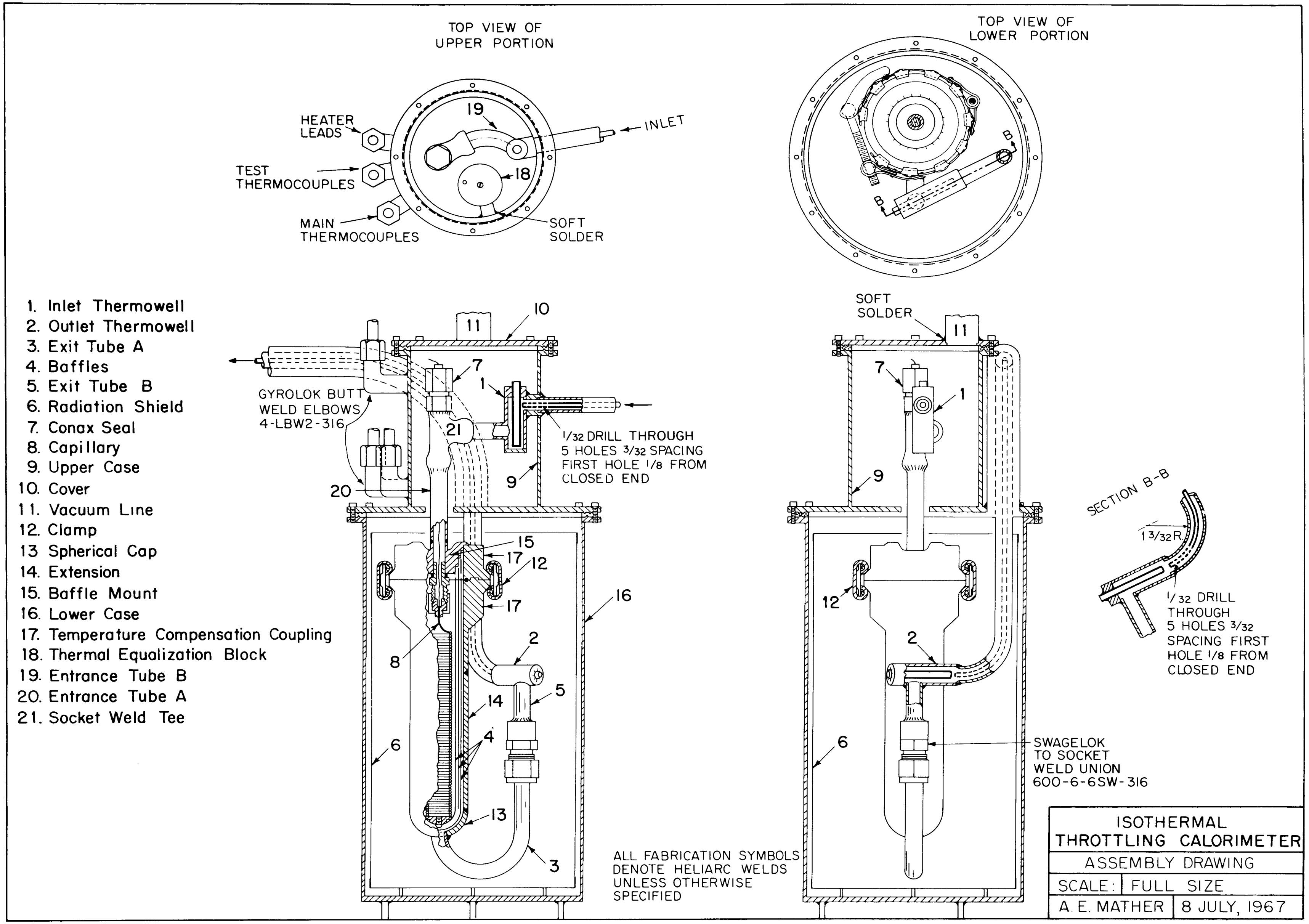


Figure 45. Assembly Drawing for Isothermal Throttling Calorimeter

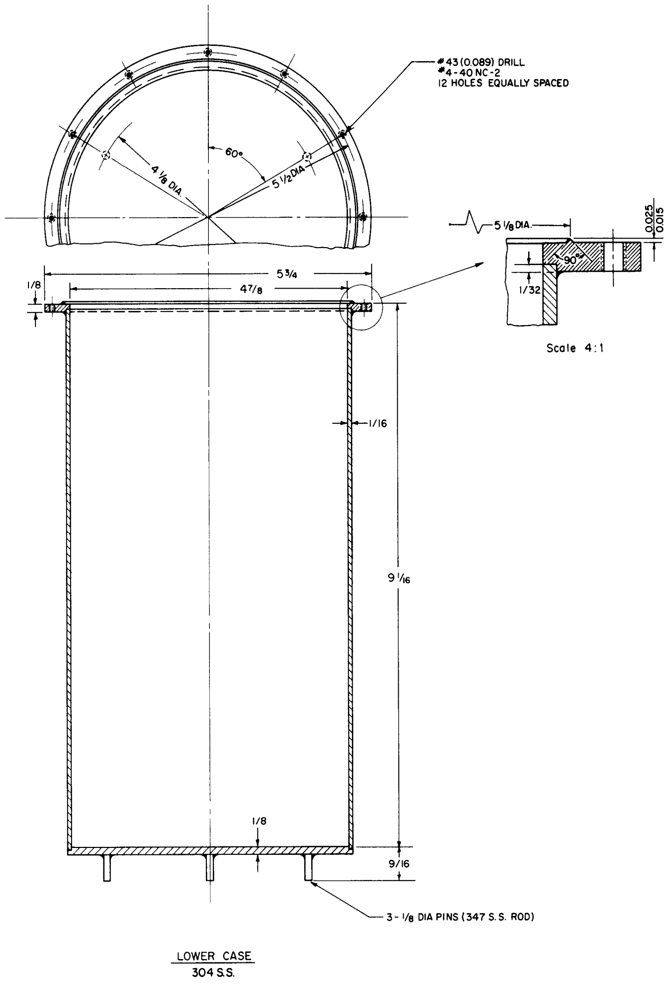
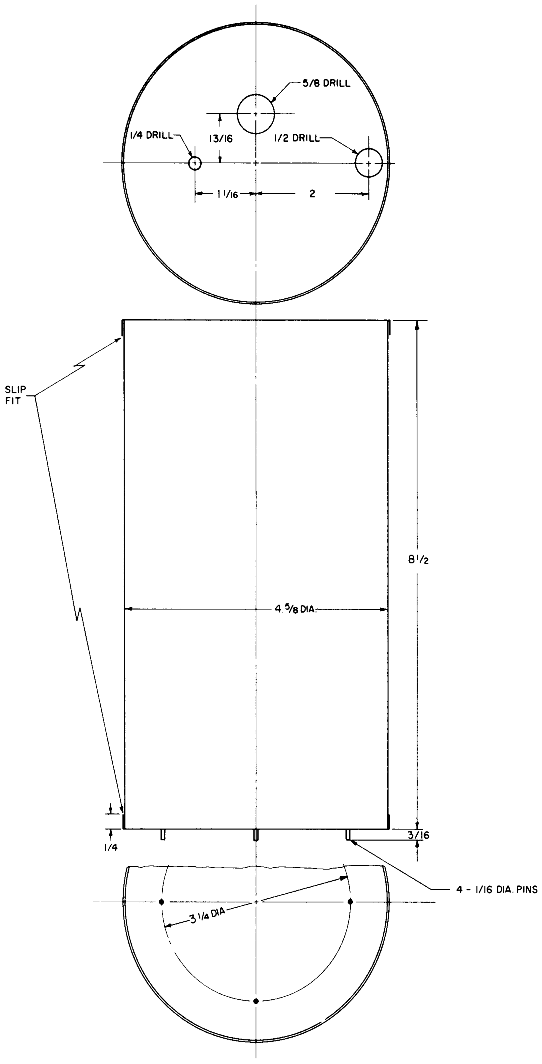


Figure 46. Detail Drawings for Isothermal Throttling Calorimeter



RADIATION SHIELD
.02 COPPER SHEET
CHROME PLATED

Figure 46. Detail Drawings (Continued)

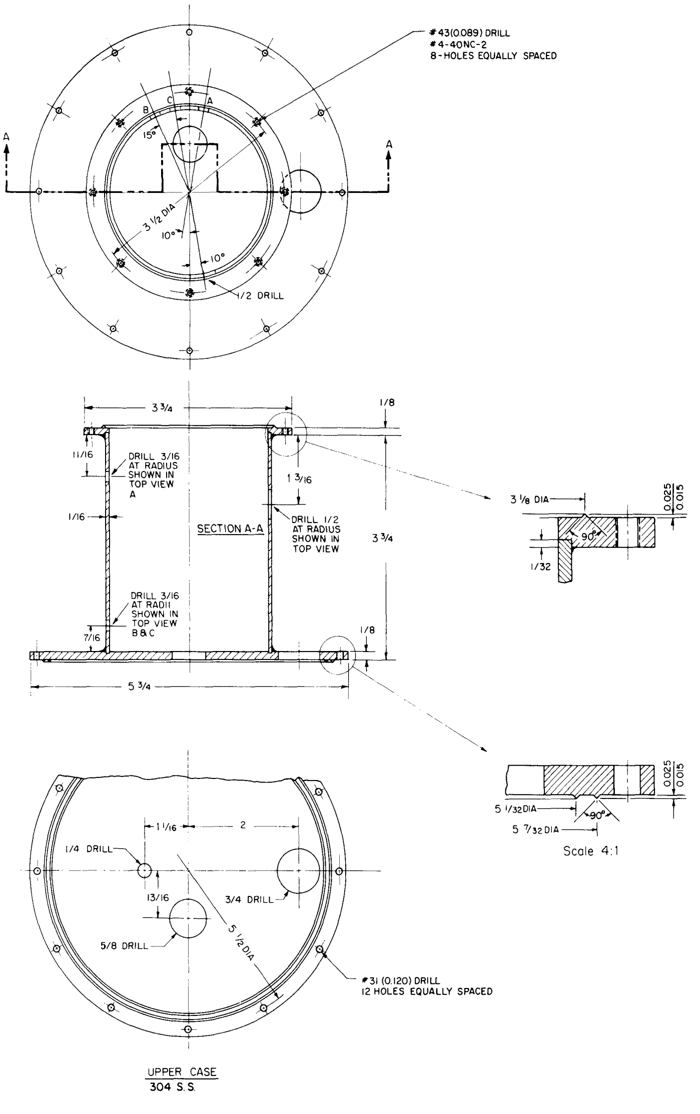
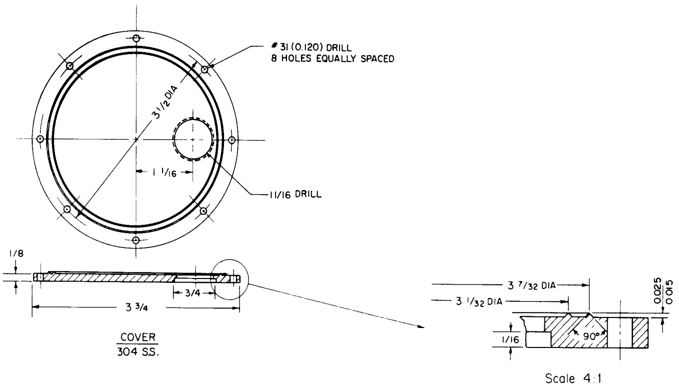
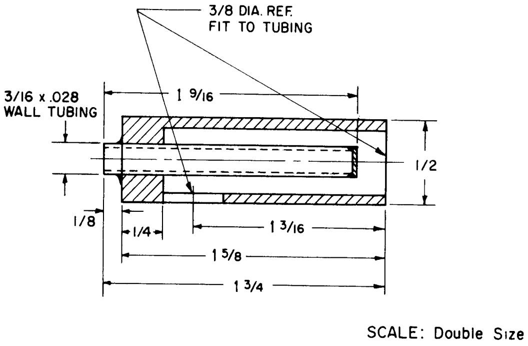


Figure 46. Detail Drawings (Continued)



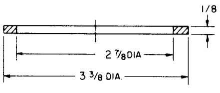
COVER
304 SS.

Scale 4:1

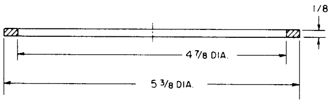


SCALE: Double Size

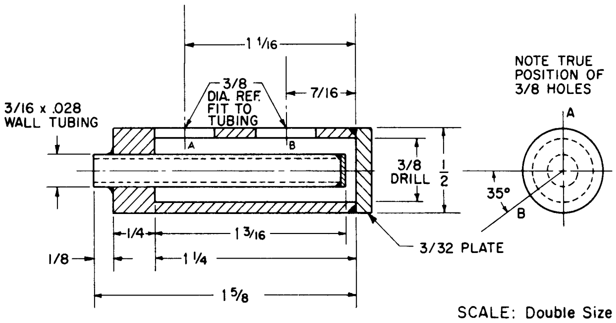
OUTLET THERMOWELL
304 S.S. 1 REQ'D



GASKET
TEFLON 12 REQ'D



GASKET
TEFLON 12 REQ'D

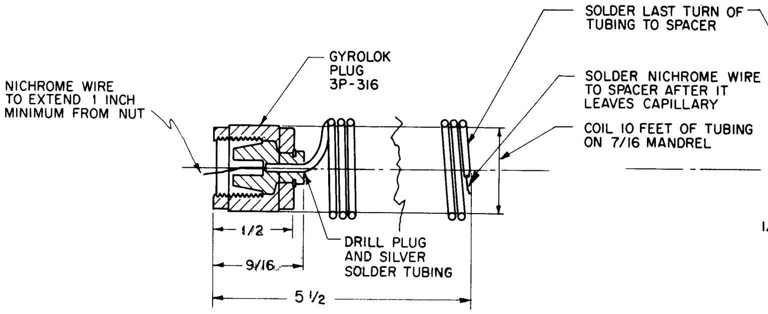


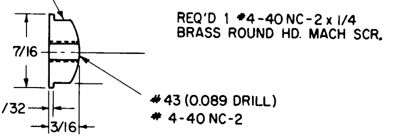
SCALE: Double Size

REQ'D 20 #4-40NC-2 x 5/8 SOCKET HD. CAP SCR. (S. STEEL)

INLET THERMOWELL
304 S.S. 1 REQ'D

Figure 46. Detail Drawings (Continued)





SCALE: Double Size

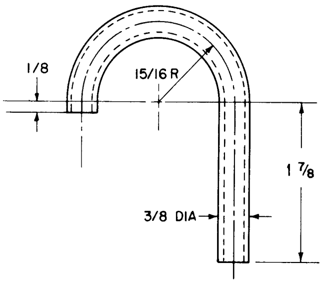
SPACER
BRASS 1 REQ'D

CAPILLARY

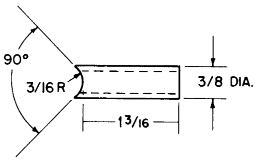
TUBING - 304 S.S.
NUT - 316 S.S. 3 REQ'D

NOTE: NICHROME WIRE TO BE INSERTED IN TUBING AFTER SILVER SOLDERING BUT BEFORE FORMING COIL

NO.	TUBING GAUGE	WIRE GAUGE
1	17 BWG	36 B&S
2	16 BWG	36 B&S
3	19 BWG	36 B&S



EXIT TUBE A
304 S.S. 1 REQ'D

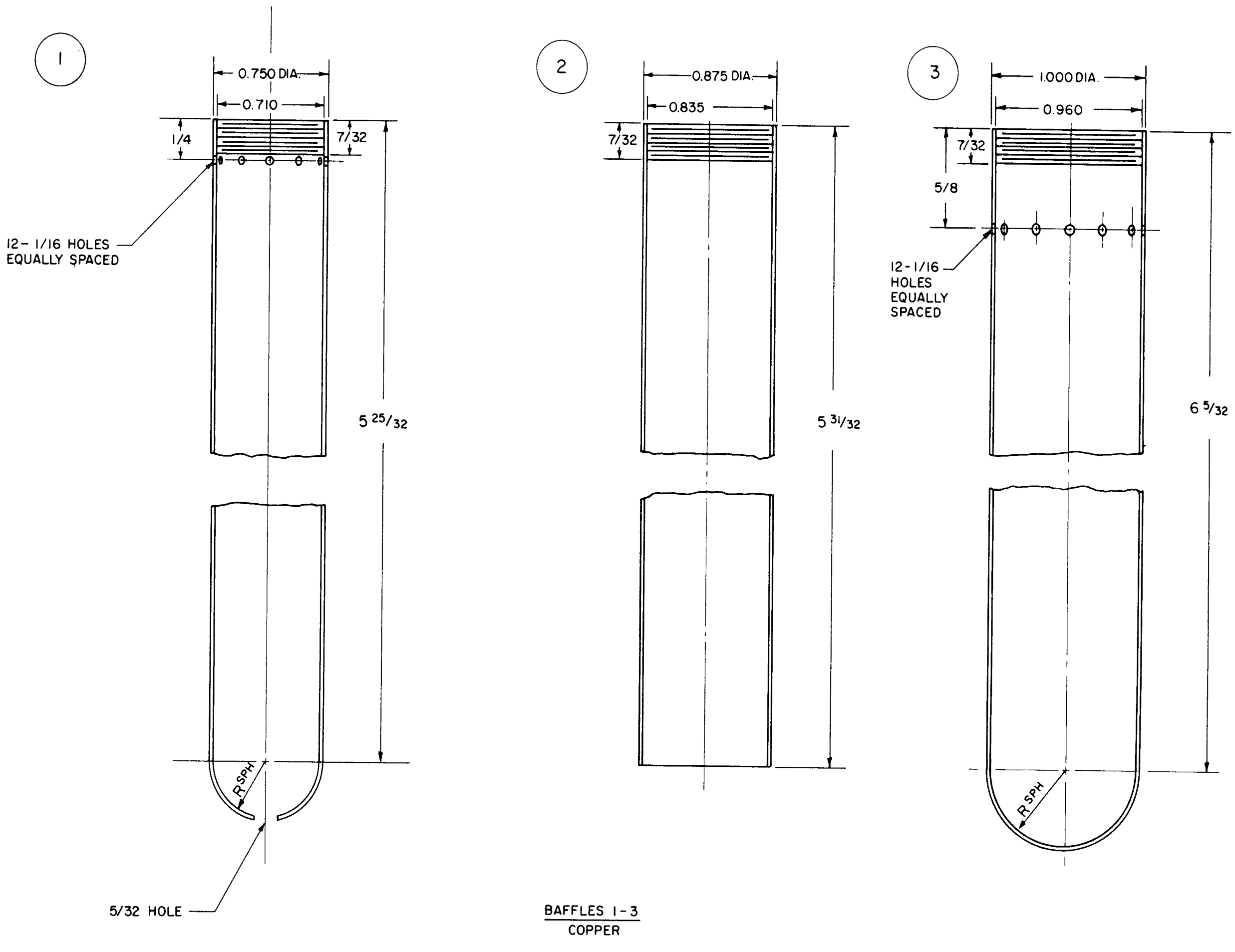


304 S.S. TUBING 1 REQ'D

EXIT TUBE B

Figure 46. Detail Drawings (Continued)

NOTE: INTERNAL THREADS OF BAFFLES
ARE NF (SHALLOW) WITH 40
THREADS/INCH TO FIT MALE
SECTION OF BAFFLE MOUNT



Scale: Double Size

Figure 46. Detail Drawings (Continued)

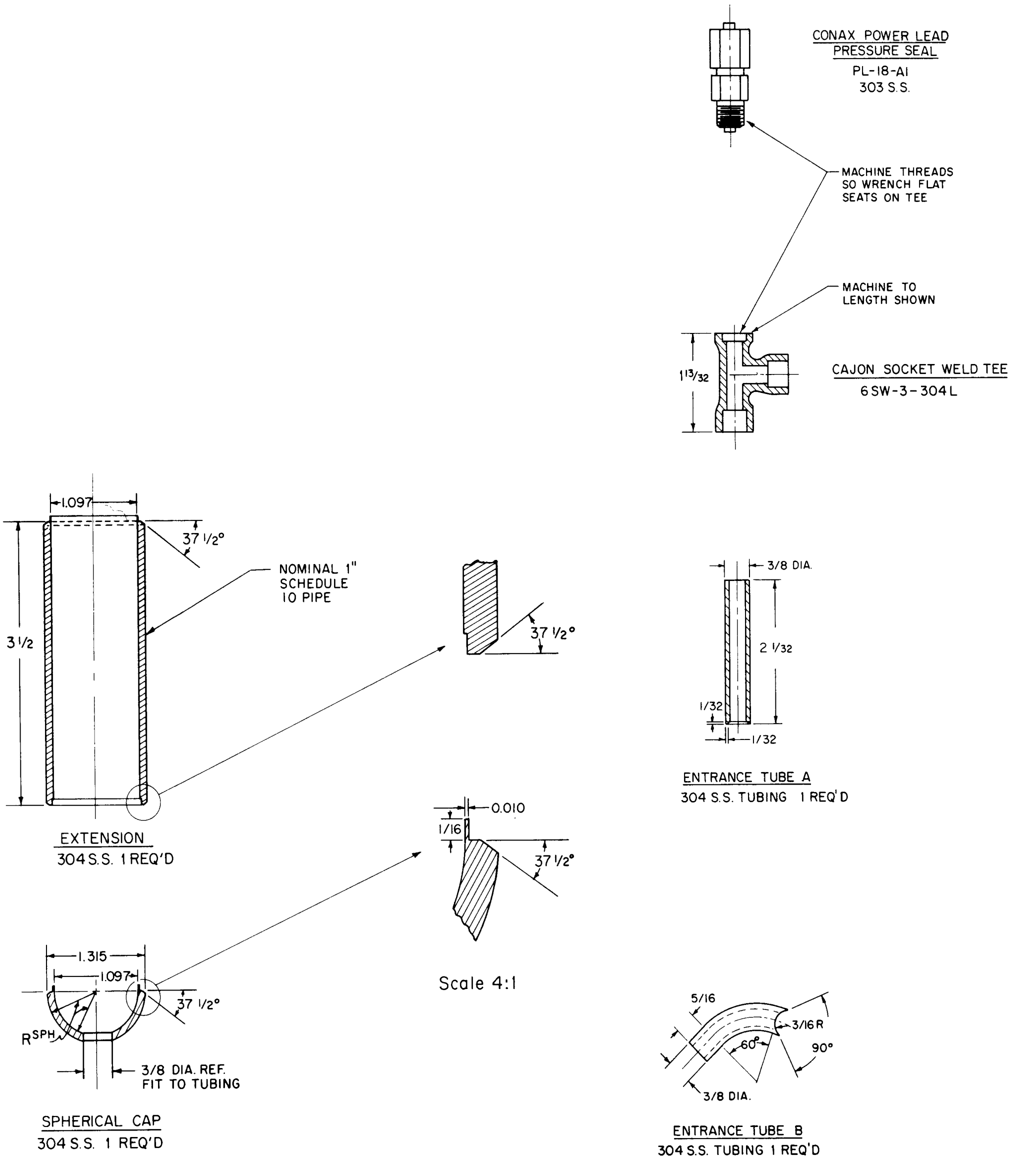


Figure 46. Detail Drawings (Continued)

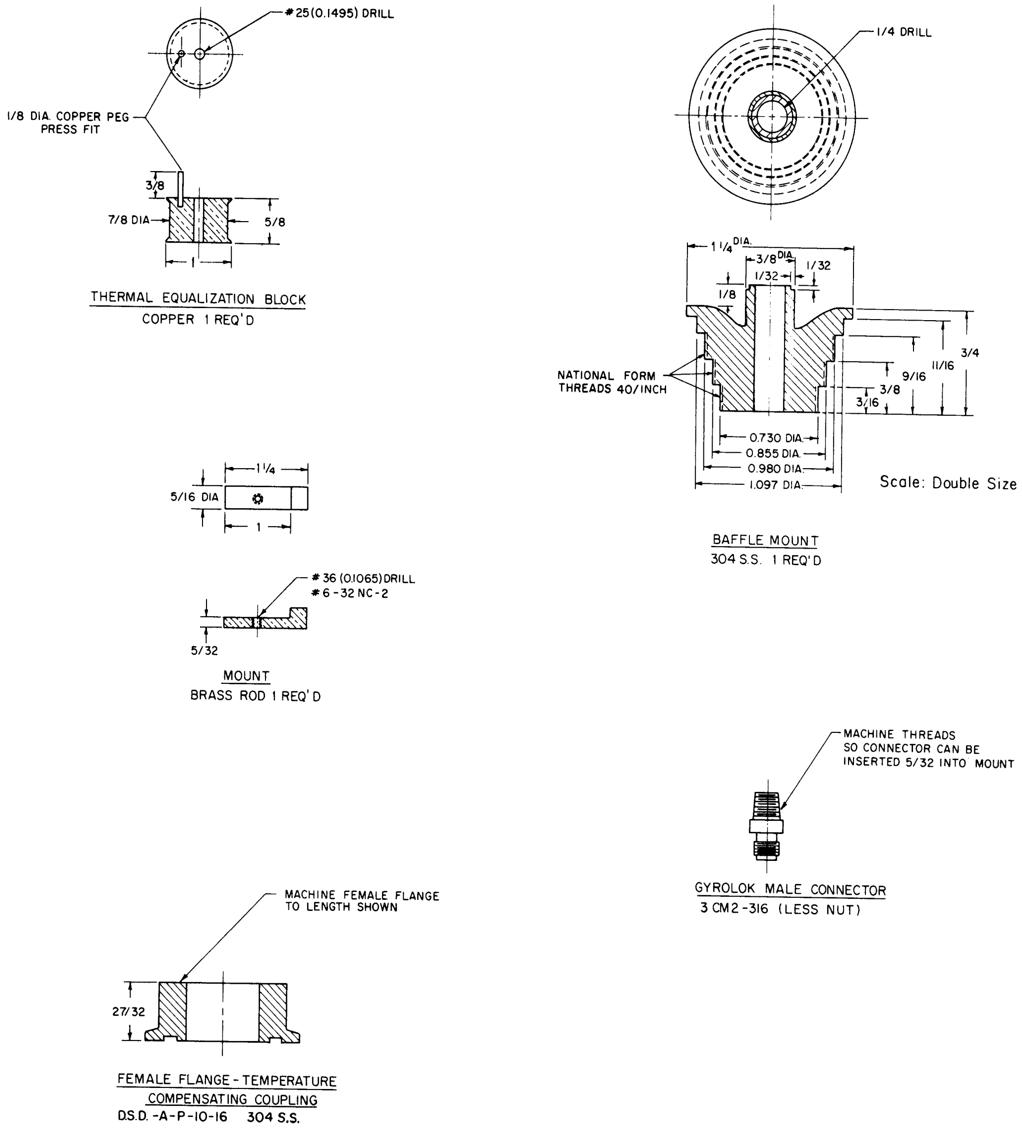


Figure 46. Detail Drawings (Continued)

APPENDIX B

CALIBRATIONS

TABLE XXXIV

MAIN THERMOPILE CALIBRATIONS

T (°C)	EMF (microvolts)		
	Isobaric Calorimeter	Isothermal Calorimeter	
	G-32321	G-36972 A	G-36972 C
-196	-33342	----	----
-195	----	-33239	-33275
-183	-32018	-31988	-32018
-120	-23626	-23616	-23616
-100	-20347	-20340	-20336
- 80	-16786	-16782	-16772
- 60	-12962	-12958	-12946
- 40	- 8880	- 8878	- 8868
- 20	- 4557	- 4556	- 4550
0	0	0	0
+ 20	4772	4776	4771
40	9760	9764	9752
60	14947	14949	14933
80	20326	20328	20302
100	25882	25880	25855
120	31612	31606	31578
140	37501	37498	37464
150	40508	40504	40468

TABLE XXXV

CALIBRATION OF HIGH PRESSURE GAUGE

H-41060

Actual Pressure	Heise Gauge	
(psi)	Up	Down
0	0	0
100	97	98
200	198	199
300	298	298
400	398	398
500	497	498
600	598	599
700	698	698
800	799	799
900	899	899
1000	999	999.5
1100	1099	1100
1200	1198.5	1199
1300	1299.5	1300
1400	1400	1400
1500	1500	1500
1600	1600	1601
1700	1701	1702
1800	1801	1801
1900	1902	1902.5
2000	2002	2002

TABLE XXXVI

CALIBRATION OF DEAD WEIGHT GAUGE

Type Mansfield and Green, Model 26 Q

Serial No. 1707

Nominal Pressure (psi)	True Pressure (psi)	Percent Deviation
200	200.03	+.016
400	400.07	.017
600	600.10	.016
800	800.13	.017
1000	1000.14	.014
1200	1200.16	.014
1400	1400.19	.013
1600	1600.21	.013
1800	1800.22	.012
2000	2000.23	.011
2200	2200.24	.011
2400	2400.24	.010
2600	2600.25	.009

TABLE XXXVII

FLOW METER CALIBRATION DATA FOR THE NOMINAL 5 PERCENT MIXTURE

COEFFICIENTS OF POWER SERIES

B = .10429332E+00 A = .18286465E+02 C = -.25382477E+04 D = -.72631994E+06

F/μ	$\frac{\rho\Delta P}{F\mu}$ (Experimental)	$\frac{\rho\Delta P}{F\mu}$ (Calculated)
.12158071E-02	.12389500E+00	.12407946E+00
.10071255E-02	.12067428E+00	.12087749E+00
.10073230E-02	.12071711E+00	.12088053E+00
.14488375E-02	.12757478E+00	.12766827E+00
.16074577E-02	.12994626E+00	.13014620E+00
.16094896E-02	.12988808E+00	.13017822E+00
.17286645E-02	.13194371E+00	.13207145E+00
.12152859E-02	.12371387E+00	.12407147E+00
.40525619E-03	.11157140E+00	.11133550E+00
.40631917E-03	.11145261E+00	.11135313E+00
.80505908E-03	.11787704E+00	.11774889E+00
.80344690E-03	.11793558E+00	.11772372E+00
.12824088E-02	.12525354E+00	.12510153E+00
.15847820E-02	.13008884E+00	.12978940E+00
.19155983E-02	.13528357E+00	.13511423E+00
.19117513E-02	.13505512E+00	.13505056E+00
.21383972E-02	.13868045E+00	.13889249E+00
.21423645E-02	.13888026E+00	.13896153E+00
.40525620E-03	.11144223E+00	.11133550E+00
.40631953E-03	.11069222E+00	.11135313E+00
.80505911E-03	.11755274E+00	.11774889E+00
.80344694E-03	.11763945E+00	.11772372E+00
.12824089E-02	.12499732E+00	.12510153E+00
.15847821E-02	.12981169E+00	.12978940E+00
.62634065E-03	.11514401E+00	.11492958E+00
.62555376E-03	.11503828E+00	.11491702E+00
.95063943E-03	.12020746E+00	.12000728E+00
.94997649E-03	.12021732E+00	.11999706E+00
.14426247E-02	.12774611E+00	.12757197E+00
.14425444E-02	.12770911E+00	.12757072E+00
.18097748E-02	.13349186E+00	.13337950E+00
.18073287E-02	.13348569E+00	.13333979E+00
.20287652E-02	.13705591E+00	.13701001E+00
.20208159E-02	.13703207E+00	.13687534E+00

AVERAGE DEVIATION = .17 PERCENT

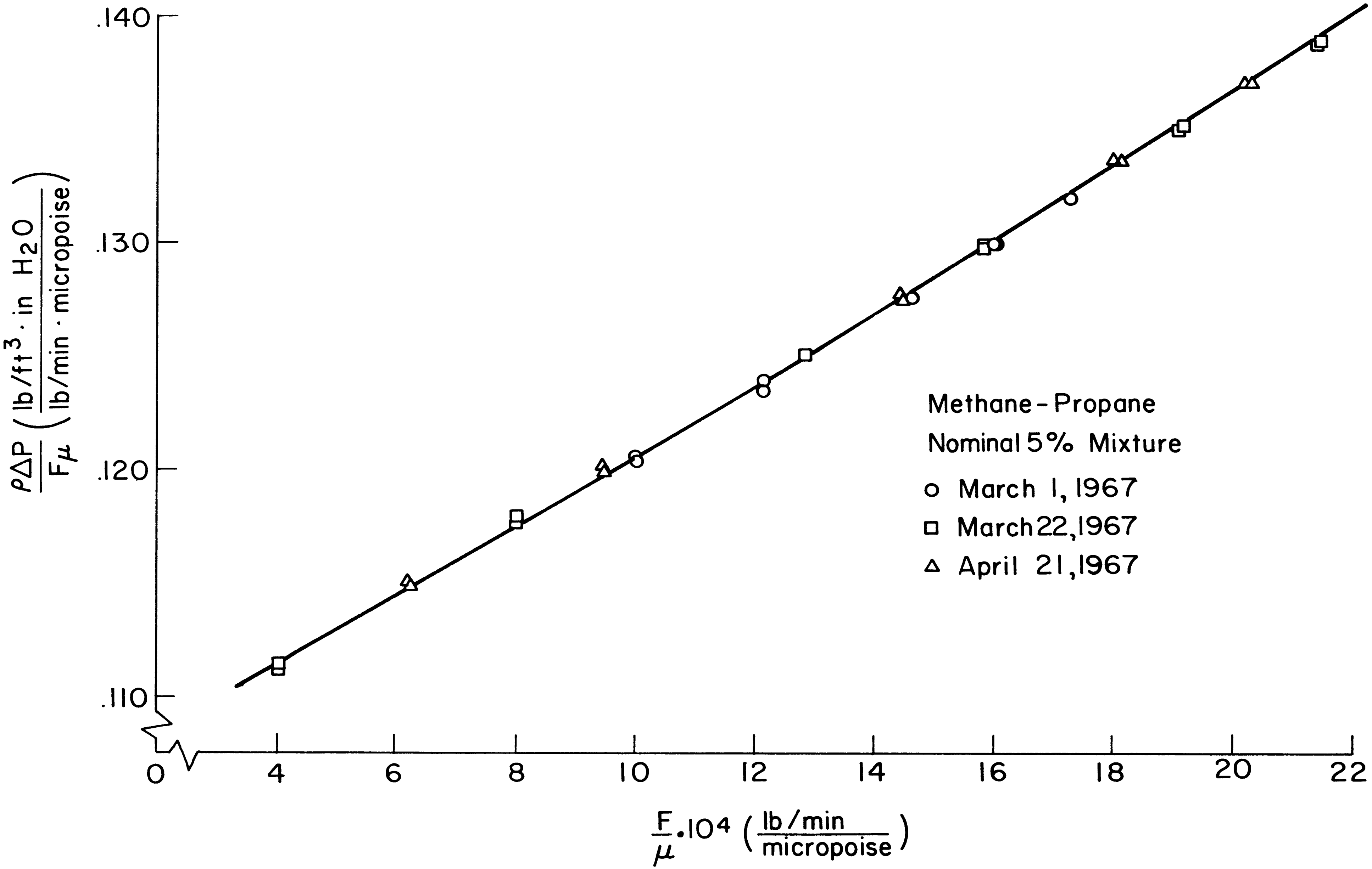


Figure 47. Flow Meter Calibration for Nominal 5 Percent Mixture

TABLE XXXVIII

FLOW METER CALIBRATION DATA FOR THE NOMINAL 12 PERCENT MIXTURE

COEFFICIENTS OF POWER SERIES

B = .10386161E+00 A = .16766623E+02 C = -.13278800E+04 D = .38507479E+06

F/μ	$\frac{\rho\Delta P}{F\mu}$ (Experimental)	$\frac{\rho\Delta P}{F\mu}$ (Calculated)
.18039820E-02	.13193017E+00	.13204760E+00
.18054526E-02	.13192652E+00	.13207074E+00
.15907346E-02	.12858312E+00	.12872276E+00
.13808359E-02	.12529727E+00	.12549553E+00
.13804297E-02	.12534351E+00	.12548931E+00
.68974047E-03	.11506218E+00	.11492086E+00
.68961348E-03	.11501919E+00	.11491889E+00
.92717181E-03	.11862950E+00	.11857256E+00
.92650254E-03	.11864523E+00	.11856232E+00
.51184905E-03	.11213967E+00	.11214734E+00
.93095375E-03	.11815414E+00	.11863041E+00
.93204147E-03	.11871489E+00	.11864705E+00
.13906675E-02	.12567009E+00	.12564600E+00
.13896230E-02	.12568149E+00	.12563001E+00
.16447889E-02	.13016168E+00	.12956028E+00
.60830638E-03	.11338979E+00	.11365617E+00
.60905811E-03	.11350080E+00	.11366788E+00
.11214573E-02	.12137351E+00	.12153775E+00
.11217180E-02	.12145351E+00	.12154172E+00
.15131303E-02	.12767217E+00	.12752548E+00
.15178077E-02	.12744414E+00	.12759749E+00
.16944095E-02	.13024351E+00	.13033203E+00
.18939855E-02	.13340699E+00	.13347023E+00
.18942446E-02	.13346861E+00	.13347434E+00
.58222119E-03	.11324685E+00	.11324937E+00
.58203948E-03	.11332691E+00	.11324653E+00
.79914694E-03	.11685977E+00	.11660910E+00
.79874659E-03	.11688086E+00	.11660294E+00
.12566991E-02	.12373478E+00	.12359935E+00
.12558574E-02	.12360021E+00	.12358651E+00
.16687066E-02	.12996661E+00	.12993190E+00
.16675259E-02	.12997585E+00	.12991354E+00
.18277858E-02	.13253059E+00	.13242259E+00
.18274578E-02	.13241039E+00	.13241742E+00

AVERAGE DEVIATION = .148 PERCENT

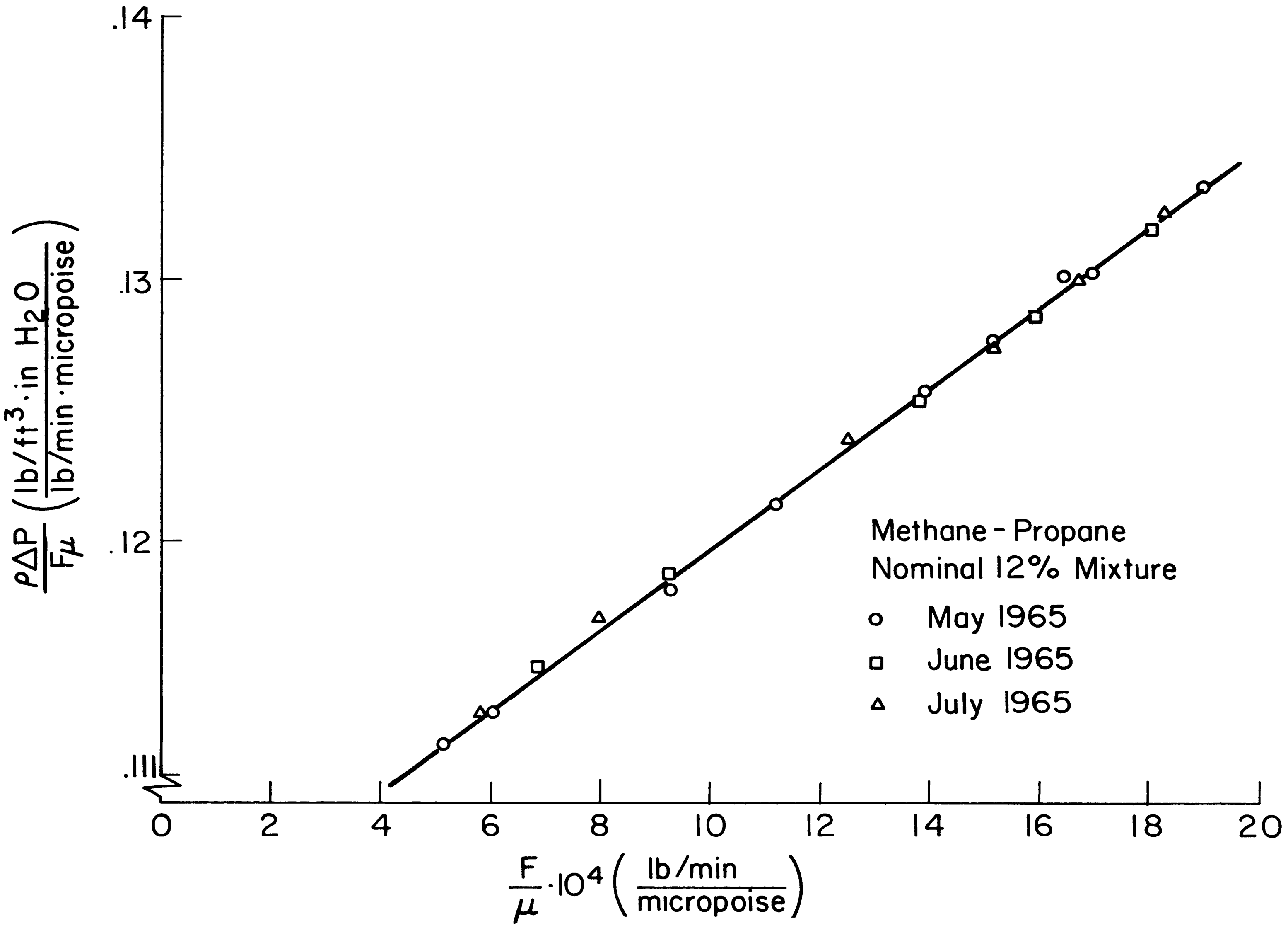


Figure 48. Flow Meter Calibration for Nominal 12 Percent Mixture

TABLE XXXIX

FLOW METER CALIBRATION DATA FOR THE NOMINAL 43 PERCENT MIXTURE

COEFFICIENTS OF POWER SERIES

B = .10067089E+00 A = .85250609E+01 C = .11651994E+05 D = -.58634480E+07

F/μ	$\frac{\rho\Delta P}{F\mu}$ (Experimental)	$\frac{\rho\Delta P}{F\mu}$ (Calculated)
.42690457E-03	.10606186E+00	.10597763E+00
.42592783E-03	.10603690E+00	.10596273E+00
.27921277E-03	.10402569E+00	.10383195E+00
.27955479E-03	.10376308E+00	.10383662E+00
.66486751E-03	.10993819E+00	.10976639E+00
.66475715E-03	.10994463E+00	.10976459E+00
.90656413E-03	.11358703E+00	.11360703E+00
.90524073E-03	.11367214E+00	.11358691E+00
.11389194E-02	.11696768E+00	.11683221E+00
.11369421E-02	.11697271E+00	.11680795E+00
.30413977E-03	.10399112E+00	.10417656E+00
.30241248E-03	.10402783E+00	.10415242E+00
.53689645E-03	.10746613E+00	.10769929E+00
.53668284E-03	.10741450E+00	.10769588E+00
.76631544E-03	.11130106E+00	.11140767E+00
.76595315E-03	.11128002E+00	.11140186E+00
.10209598E-02	.11509553E+00	.11528027E+00
.10198925E-02	.11527714E+00	.11526534E+00
.11625529E-02	.11698900E+00	.11711694E+00
.11631606E-02	.11684887E+00	.11712414E+00
.27697935E-03	.10382947E+00	.10380147E+00
.27594865E-03	.10390651E+00	.10378743E+00
.55502090E-03	.10811915E+00	.10798936E+00
.55540400E-03	.10801977E+00	.10799551E+00
.78626323E-03	.11184506E+00	.11172713E+00
.78446160E-03	.11178402E+00	.11169834E+00
.10054930E-02	.11500985E+00	.11506253E+00
.10015507E-02	.11495840E+00	.11500656E+00
.11790895E-02	.11738896E+00	.11731036E+00
.11753148E-02	.11741785E+00	.11726664E+00

AVERAGE DEVIATION = .127 PERCENT

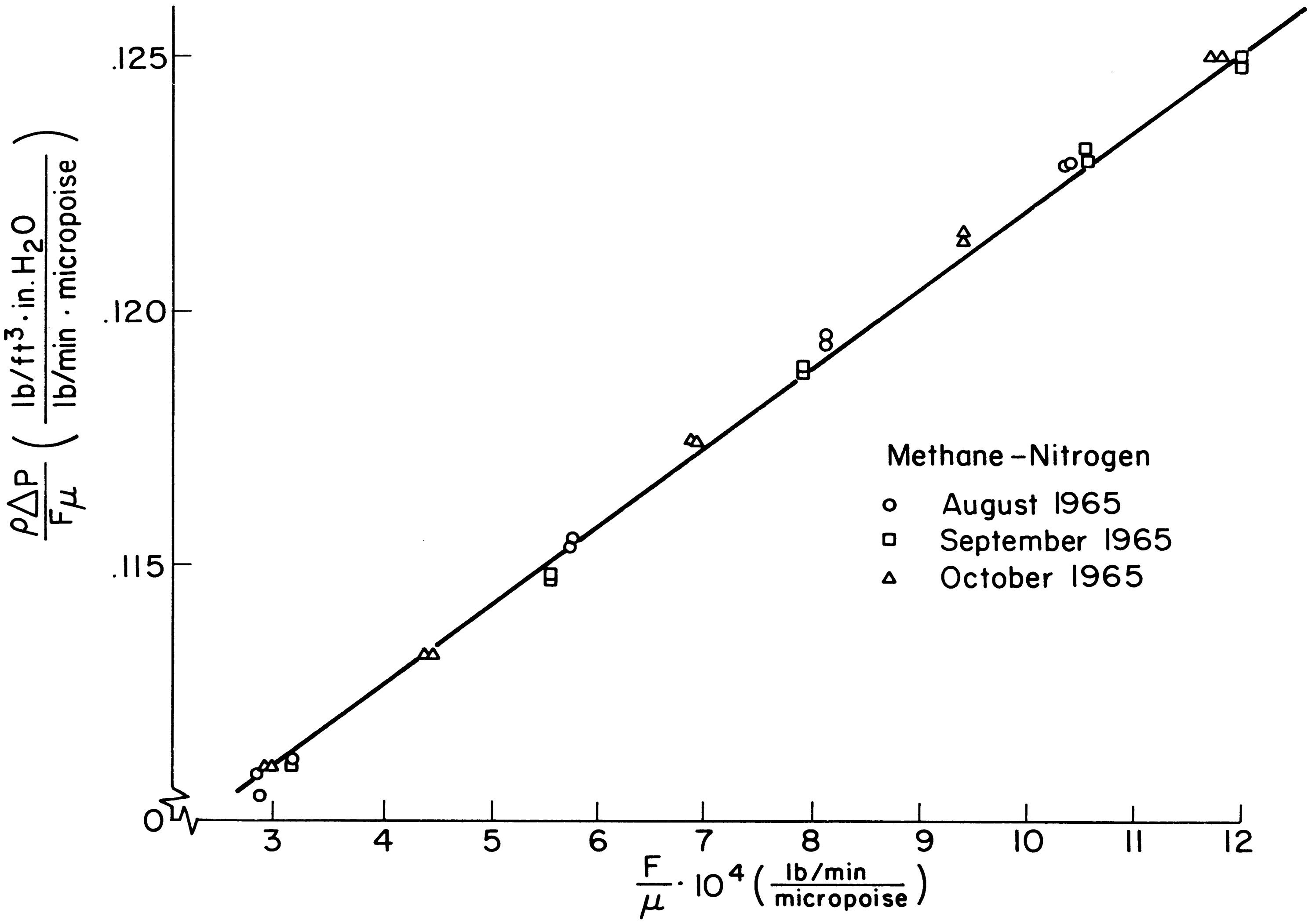


Figure 49. Flow Meter Calibration for Nominal 43 Percent Mixture

TABLE XL

FLOW METER CALIBRATION DATA FOR NITROGEN

COEFFICIENTS OF POWER SERIES

B = .10567430E+00   A = .11254779E+02   C = .59290619E+04   D = -.19771369E+07

F/μ	$\frac{\rho\Delta P}{F\mu}$ (Experimental)	$\frac{\rho\Delta P}{F\mu}$ (Calculated)
.25906299E-03	.10900363E+00	.10895355E+00
.25939652E-03	.10888096E+00	.10895819E+00
.49707107E-03	.11234170E+00	.11249086E+00
.49771342E-03	.11223095E+00	.11250093E+00
.70573235E-03	.11593362E+00	.11587523E+00
.92211015E-03	.11941012E+00	.11954366E+00
.92434654E-03	.11937018E+00	.11958201E+00
.10322788E-02	.12111519E+00	.12143554E+00
.10357567E-02	.12110370E+00	.12149527E+00
.37020735E-03	.11034186E+00	.11055319E+00
.37303991E-03	.11030025E+00	.11059523E+00
.50597636E-03	.11260405E+00	.11263076E+00
.50547236E-03	.11247773E+00	.11262283E+00
.60311609E-03	.11389254E+00	.11418518E+00
.71704447E-03	.11605096E+00	.11606401E+00
.71834207E-03	.11605006E+00	.11608570E+00
.82806718E-03	.11787468E+00	.11793693E+00
.82729270E-03	.11783567E+00	.11792375E+00
.38096998E-03	.11117831E+00	.11071325E+00
.38081578E-03	.11107639E+00	.11071095E+00
.60736357E-03	.11473771E+00	.11425424E+00
.82002912E-03	.11838538E+00	.11780029E+00
.10150260E-02	.12137512E+00	.12113917E+00
.10181365E-02	.12143421E+00	.12119261E+00
.11114738E-02	.12293422E+00	.12279353E+00
.11128751E-02	.12291541E+00	.12281750E+00

AVERAGE DEVIATION = .224 PERCENT

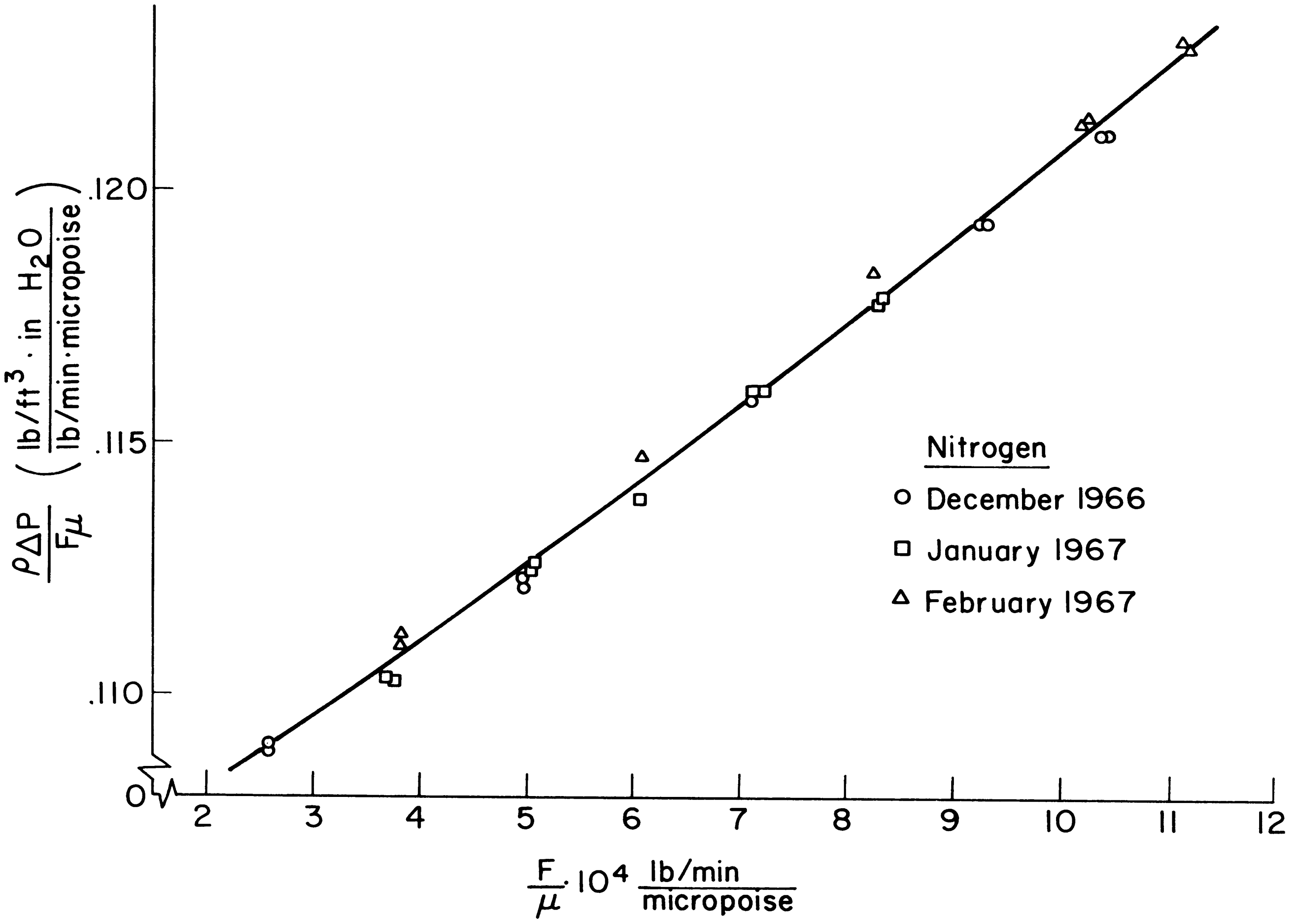


Figure 50. Flow Meter Calibration for Nitrogen

APPENDIX C

ENTHALPY FORMULAE

and

LOOP CHECKS

I FORMULAE USED IN CALCULATION OF PROPERTIES FROM EQUATIONS OF STATE

1. Benedict-Webb-Rubin Equation

(a) Enthalpy Departure

$$\underline{H} - \underline{H}^o = (B_oRT - 2A_o - \frac{4C_o}{T^2})\rho + (bRT - \frac{3a}{2})\rho^2 + \frac{6a\alpha\rho^5}{5} + \frac{c\rho^2}{T^2}\left[\frac{3(1 - e^{-\gamma\rho^2})}{\gamma\rho^2} - \frac{e^{-\gamma\rho^2}}{2} + \gamma\rho^2 e^{-\gamma\rho^2}\right]$$

(b) Isothermal Throttling Coefficient

$$\phi = \frac{(B_oRT - 2A_o - \frac{4C_o}{T^2}) + (2bRT - 3a)\rho + 6a\alpha\rho^4 + \frac{ce^{-\gamma\rho^2}}{T^2}\left[5\rho + 5\gamma\rho^3 - 2\gamma^2\rho^5\right]}{RT + 2\rho(B_oRT - A_o - \frac{C_o}{T^2}) + 3\rho^2(bRT - a) + 6a\alpha\rho^5 + \frac{ce^{-\gamma\rho^2}}{T^2}\left[3\rho^2(1 + \gamma\rho^2) - 2\gamma^2\rho^6\right]}$$

(c) Heat Capacity

$$C_p = C_p^{\,o} - R + \frac{6C_o\rho}{T^3} - \frac{6c}{\gamma T^3} + (\frac{6c}{\gamma T^3} + \frac{3c\rho^2}{T^3})\, e^{-\gamma\rho^2}$$

$$+ \frac{\left[R + B_oR\rho + bR\rho^2 + \frac{2C_o\rho}{T^3} - (\frac{2c\rho^2}{T^3})(1 + \gamma\rho^2)\, e^{-\gamma\rho^2}\right]^2}{R + \rho(2B_oR - \frac{2A_o}{T} - \frac{2C_o}{T^3}) + \rho^2(3bR - \frac{3a}{T}) + \frac{6a\alpha\rho^5}{T} + (\frac{3c\rho^2 + 3c\gamma\rho^4 - 2c\gamma^2\rho^6}{T^3})\, e^{-\gamma\rho^2}} .$$

2. IGT Modified B-W-R Equation

(a) Enthalpy Departure

$$\underline{H} - \underline{H}^{o} = \left(B_{o}RT - 2A_{o} - \frac{4C_{o}}{T^{2}} - \frac{6D_{o}}{T^{4}}\right)\rho + \left(bRT - \frac{3a}{2}\right)\rho^{2} + \frac{6a\alpha\rho^{5}}{5} + \frac{c\rho^{2}}{T^{2}}\left[\frac{3(1 - e^{-\gamma\rho^{2}})}{\gamma\rho^{2}} - \frac{e^{-\gamma\rho^{2}}}{2} + \gamma\rho^{2}e^{-\gamma\rho^{2}}\right]$$

$$+ \frac{\delta\rho^{2}}{T^{4}}\left[\frac{5(1 - e^{-\gamma\rho^{2}})}{\gamma\rho^{2}} - \frac{3e^{-\gamma\rho^{2}}}{2} + \gamma\rho^{2}e^{-\gamma\rho^{2}}\right]$$

(b) Isothermal Throttling Coefficient

$$\phi = \frac{\left(B_{o}RT - 2A_{o} - \frac{4C_{o}}{T^{2}} - \frac{6D_{o}}{T^{4}}\right) + (2bRT - 3a)\rho + 6a\alpha\rho^{4} + \frac{ce^{-\gamma\rho^{2}}}{T^{2}}\left[5\rho + 5\gamma\rho^{3} - 2\gamma^{2}\rho^{5}\right] + \frac{\delta e^{-\gamma\rho^{2}}}{T^{4}}\left[7\rho + 7\gamma\rho^{3} - 2\gamma^{2}\rho^{5}\right]}{RT + 2\rho\left(B_{o}RT - A_{o} - \frac{C_{o}}{T^{2}} - \frac{D_{o}}{T^{4}}\right) + 3\rho^{2}(bRT - a) + 6a\alpha\rho^{5} + e^{-\gamma\rho^{2}}\left[3\rho^{2}(1 + \gamma\rho^{2}) - 2\gamma^{2}\rho^{6}\right]\left[\frac{c}{T^{2}} + \frac{\delta}{T^{4}}\right]}$$

II. Thermodynamic Consistency Checks

1. Nitrogen

The isothermal data of this work were used in conjunction with the isobaric data of Jones[94] to test the consistency of the experimental data at low temperatures. Two loops are shown in Figure 51, and the experimental enthalpy changes along different paths are given in Table XLI.

TABLE XLI

CONSISTENCY CHECKS ON NITROGEN

	Path	ΔH (Btu/lb)	Percent Deviation
A.	1-2-5	64.53	0.78
	1-4-5	65.04	
B.	2-3-6	63.24	0.22
	2-5-6	63.38	

2. Nominal 5 Percent Mixture

The isothermal data of this work and the isobaric data of Manker[123] were used to make consistency checks of the experimental data. The location of the loops is shown in Figure 52 and the enthalpy changes along different paths are given in Table XLII.

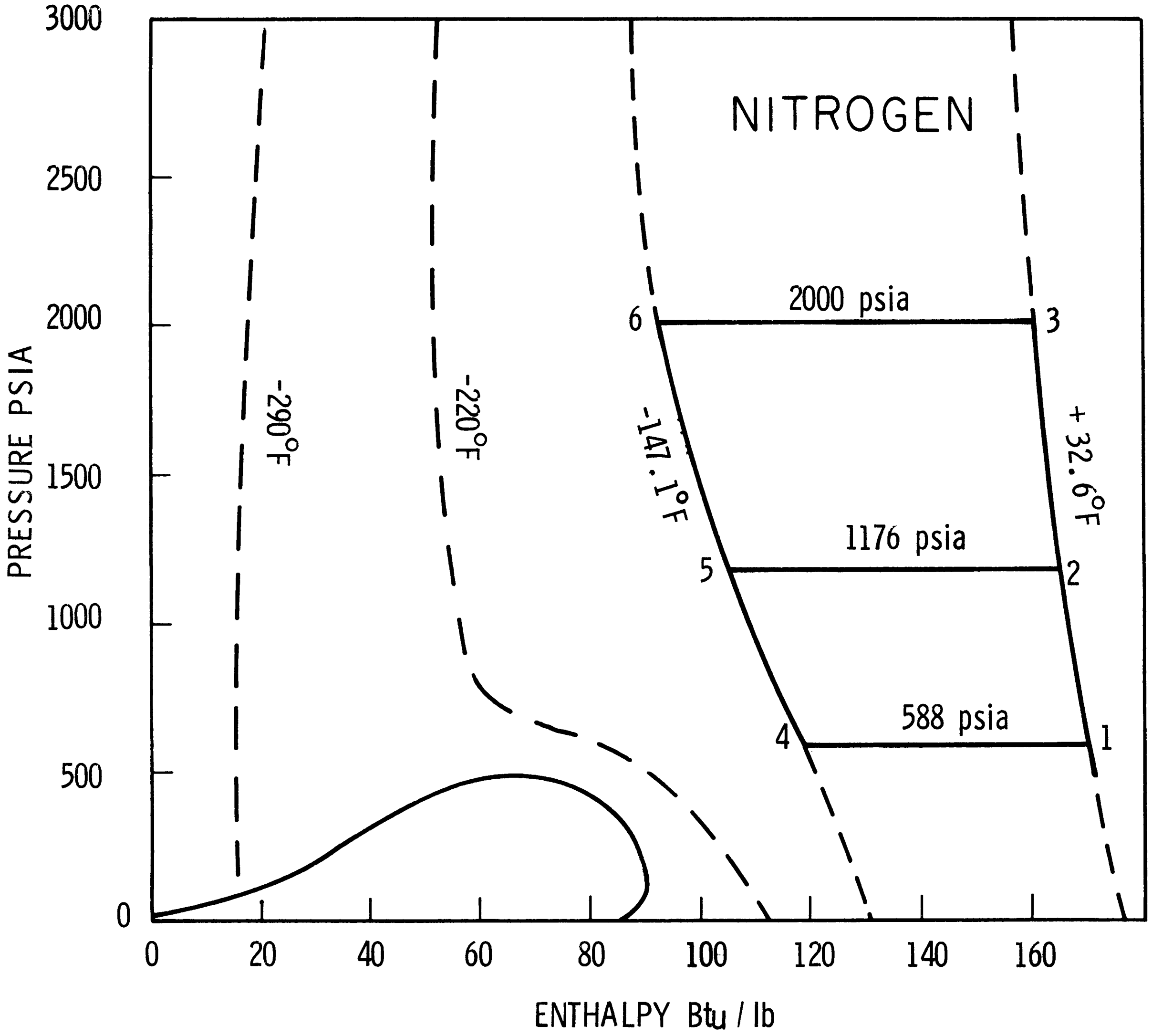


Figure 51. Location of Experimental Loops for Nitrogen

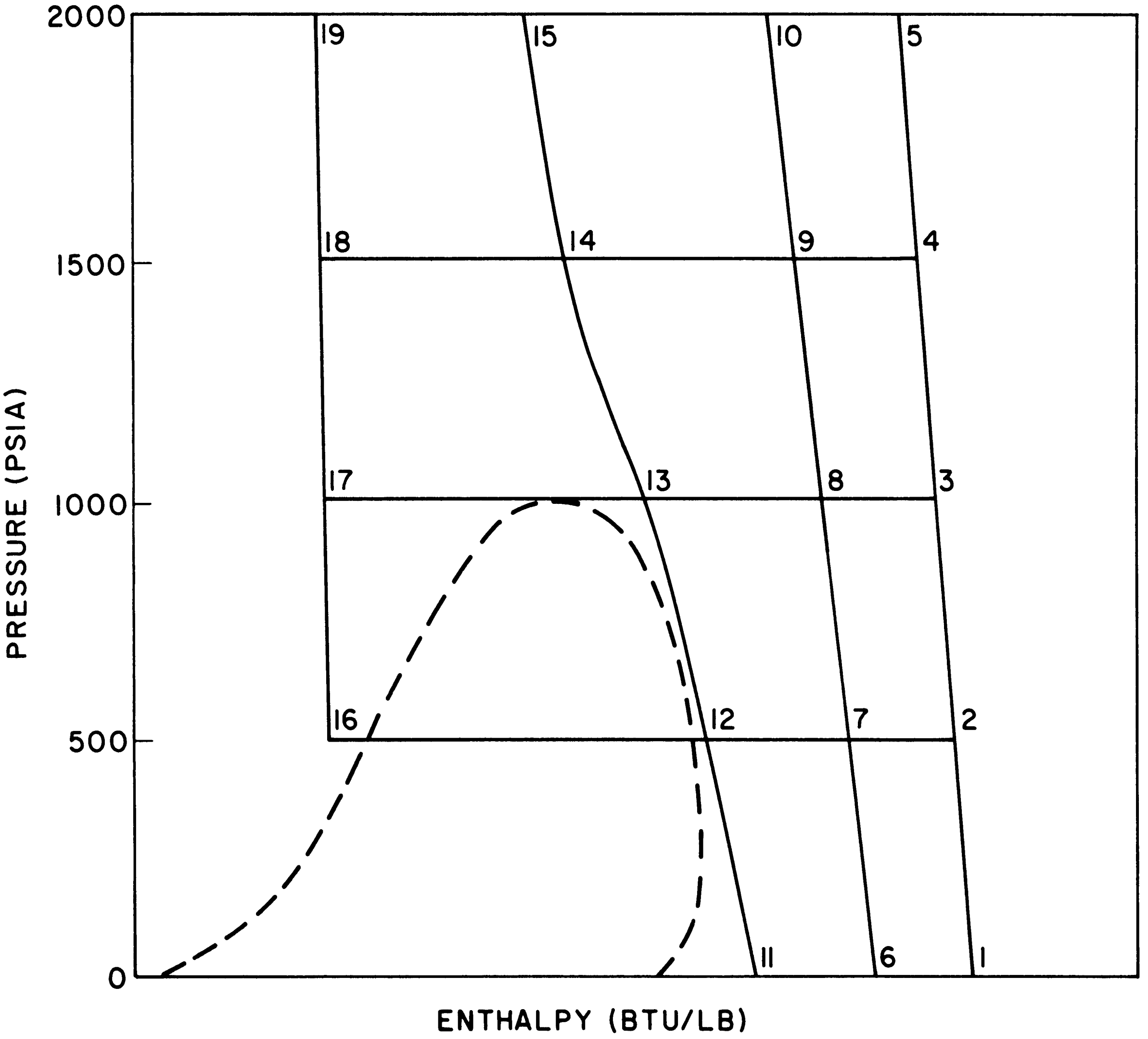


Figure 52. Location of Experimental Loops for Nominal 5 Percent Mixture

TABLE XLII

CONSISTENCY CHECKS ON THE NOMINAL 5 PERCENT MIXTURE

	Path	$\Delta \underline{H}$ (Btu/lb)	Percent Deviation
A.	1- 2- 7	74.16	0.46
	1- 6- 7	73.82	
B.	2- 3- 8	79.24	0.01
	2- 7- 8	79.25	
C.	3- 4- 9	84.50	0.05
	3- 8- 9	84.46	
D.	4- 5-10	88.82	0.10
	4- 9-10	88.73	
E.	6- 7-12	85.21	0.12
	6-11-12	85.31	
F.	7- 8-13	104.92	0.42
	7-12-13	104.48	
G.	8- 9-14	125.47	0.25
	8-13-14	125.79	
H.	14-15-19	129.07	0.07
	14-18-19	128.98	
I.	12-13-17	209.60	1.45
	12-16-17	206.58	
J.	13-14-18	173.37	0.91
	13-17-18	174.96	
K.	14-15-19	136.52	0.43
	14-18-19	135.94	

APPENDIX D

EXPERIMENTAL

DATA

TABLE XLIII

TABULATED EXPERIMENTAL ISOBARIC DATA FOR THE NOMINAL 5 PERCENT MIXTURE

Run	Mole Fraction C_3H_8	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} \left(\frac{\partial H}{\partial P}\right)_T dP$ (Btu/lb)	ΔH_P (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
3.020	.052	1499.2	191.55	204.54	12.99	1.187	.1365	.006	8.688	.6690
3.030	.052	1499.7	191.57	198.36	6.79	.613	.1355	.006	4.517	.6653
4.010	.052	501.2	191.59	198.10	6.52	.607	.1551	.028	3.888	.5967
4.021	.052	500.0	191.62	204.70	13.07	1.218	.1548	.027	7.840	.5997
4.020	.052	500.0	191.64	204.73	13.09	1.218	.1550	.028	7.829	.5982
5.010	.052	1000.2	191.61	198.16	6.55	.646	.1549	.013	4.159	.6349
5.020	.052	1000.7	191.61	204.73	13.12	1.335	.1601	.013	8.326	.6344
6.010	.052	1499.8	87.52	94.89	7.37	.875	.1618	.009	5.398	.7323
6.020	.052	1502.2	87.54	102.03	14.49	1.720	.1619	.008	10.612	.7322
6.030	.052	1500.9	87.54	123.49	35.95	4.163	.1617	.009	25.739	.7159
6.041	.052	1500.8	87.54	150.62	63.08	7.193	.1615	.009	44.521	.7058
6.040	.052	1501.1	87.48	150.59	63.10	7.194	.1616	.009	44.506	.7053
7.010	.052	501.0	87.51	94.88	7.37	.695	.1614	.034	4.269	.5794
7.020	.052	500.5	87.41	101.84	14.43	1.349	.1609	.034	8.351	.5787
7.030	.052	501.5	87.52	123.46	35.94	3.365	.1610	.031	20.870	.5806
7.041	.052	500.3	86.83	150.03	63.20	5.900	.1606	.030	36.700	.5807
7.040	.052	500.5	87.58	150.82	63.24	5.901	.1605	.031	36.744	.5810
8.010	.052	2001.0	87.45	94.92	7.48	.988	.1655	.005	5.965	.7976
8.020	.052	2002.7	87.47	101.93	14.45	1.899	.1656	.005	11.463	.7932
8.030	.052	2001.5	87.47	123.16	35.69	4.602	.1658	.005	27.749	.7775
8.041	.052	2002.9	87.45	163.64	76.19	9.416	.1637	.005	57.500	.7547
8.040	.052	2002.1	87.47	163.79	76.32	9.416	.1634	.005	57.611	.7549
9.010	.052	2002.2	200.47	257.17	56.71	1.802	.0450	.000	40.014	.7056
9.020	.052	1999.3	200.50	257.22	56.73	6.529	.1641	.005	39.792	.7015
9.031	.052	2000.6	200.52	257.28	56.76	8.880	.2230	.009	39.808	.7013
9.030	.052	2002.0	200.51	257.31	56.80	8.880	.2229	.009	39.829	.7012
9.019	.052	2002.2	200.47	257.17	56.71	1.802	.0450	.000	40.033	.7060
9.029	.052	1999.3	200.50	257.22	56.73	6.529	.1640	.005	39.805	.7017

TABLE XLIV

TABULATED EXPERIMENTAL ISOBARIC DATA FOR THE NOMINAL 12 PERCENT MIXTURE

Run	Mole Fraction C_3H_8	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T dP$ (Btu/lb)	ΔHp (Btu/lb)	$(\Delta H/\Delta T)_p$ (Btu/lb-°F)
22.010	.117	1000.3	51.23	63.55	12.32	1.327	.1510	.002	8.787	.7130
22.011	.117	1000.3	51.25	63.58	12.33	1.327	.1511	.003	8.783	.7123
22.020	.117	1002.3	51.23	63.56	12.32	1.044	.1189	.011	8.774	.7121
22.021	.117	1000.3	51.23	63.55	12.32	1.044	.1190	.015	8.762	.7111
22.030	.117	1000.3	51.24	63.54	12.30	.803	.0918	.019	8.725	.7094
22.031	.117	1000.3	51.23	63.52	12.29	.803	.0918	.022	8.721	.7093
22.040	.117	1000.3	51.21	63.58	12.37	.604	.0685	.033	8.779	.7099
22.041	.117	1000.3	51.22	63.59	12.37	.604	.0684	.033	8.784	.7100
22.042	.117	1000.3	51.21	63.55	12.34	.603	.0685	.003	8.804	.7134
23.010	.117	512.3	50.24	55.16	4.92	.425	.1478	.000	2.875	.5844
23.011	.117	512.3	50.21	55.13	4.92	.425	.1478	.000	2.873	.5835
23.020	.117	512.3	50.21	61.43	11.23	.962	.1479	.006	6.499	.5788
23.021	.117	512.3	50.22	61.44	11.22	.962	.1480	.007	6.490	.5783
23.030	.117	512.3	50.27	77.49	27.22	2.316	.1478	.007	15.658	.5753
23.031	.117	512.3	50.22	77.45	27.24	2.317	.1478	.007	15.666	.5752
24.010	.117	503.8	-148.70	-146.15	2.55	.196	.0903	-.000	2.176	.8530
24.020	.117	496.2	-148.70	-136.13	12.56	.976	.0891	.000	10.953	.8718
24.030	.117	500.8	-148.71	-128.97	19.74	1.578	.0899	.002	17.547	.8888
24.040	.117	498.6	-148.71	-123.05	25.65	2.550	.0892	.003	28.584	1.1142
24.050	.117	497.6	-149.15	-123.96	25.19	2.025	.0891	.005	22.724	.9020
25.020	.119	1502.2	-220.52	-208.69	11.83	.973	.1128	-.002	8.631	.7293
25.030	.119	1502.2	-220.52	-194.44	26.08	2.167	.1131	-.003	19.155	.7345
25.040	.119	1505.0	-221.09	-159.96	61.12	4.840	.1071	-.004	45.211	.7397
25.050	.119	1504.2	-220.53	-137.12	83.41	6.727	.1070	-.003	62.889	.7540
26.010	.118	2017.2	-213.42	-204.08	9.35	.858	.1269	-.000	6.765	.7239
26.020	.118	2015.1	-213.43	-192.26	21.17	1.965	.1267	-.001	15.511	.7329
26.030	.118	2014.1	-213.41	-168.00	45.41	4.254	.1270	-.002	33.508	.7379
26.040	.118	2016.1	-213.42	-145.94	67.48	6.388	.1268	-.002	50.369	.7465
26.050	.118	2018.1	-213.43	-126.94	86.49	8.243	.1271	-.003	64.864	.7500
26.060	.118	2014.1	-213.39	-102.18	111.21	10.743	.1267	-.001	84.785	.7624
27.010	.116	498.3	-129.61	-124.00	5.60	.441	.0506	.000	8.714	1.5554
27.020	.116	496.3	-128.92	-122.57	6.35	.867	.0505	-.001	17.189	2.7087
27.030	.116	498.3	-128.90	-119.34	9.56	1.964	.0508	-.000	38.697	4.0464
27.040	.116	501.3	-128.92	-105.80	23.12	4.296	.0510	.003	84.227	3.6432
27.050	.116	494.3	-128.92	-50.33	78.59	7.529	.0503	-.005	149.798	1.9061
27.060	.116	494.3	-129.11	-9.84	119.27	9.898	.0506	.045	195.386	1.6382
27.070	.116	494.3	-128.71	20.77	149.48	11.185	.0505	.029	221.372	1.4810
27.080	.116	500.3	-129.42	3.27	132.69	10.628	.0506	.059	209.968	1.5823
28.010	.118	2006.1	-99.76	-92.49	7.27	.893	.1470	.000	6.071	.8352
28.020	.118	2008.1	-99.75	-83.52	16.24	2.012	.1462	.000	13.762	.8476
28.030	.118	2005.1	-99.79	-75.59	24.20	3.034	.1471	.000	20.620	.8520
28.040	.118	2003.1	-99.81	-65.92	33.89	4.317	.1473	.002	29.316	.8650
28.050	.118	2003.1	-99.79	-52.24	47.55	6.167	.1470	.007	41.944	.8821
28.060	.118	2007.1	-99.84	-31.08	68.76	9.179	.1458	.013	62.956	.9155
29.010	.118	2006.2	-46.20	-41.82	4.38	.674	.1584	.000	4.255	.9725
29.011	.118	2004.2	-46.15	-41.77	4.38	.674	.1581	-.000	4.262	.9733
29.020	.118	2006.2	-46.16	-33.16	13.00	2.038	.1588	.004	12.827	.9863
29.030	.118	2004.2	-46.19	-18.67	27.52	4.385	.1579	.015	27.760	1.0089
29.040	.118	2004.2	-46.18	.61	46.79	7.628	.1579	.026	48.285	1.0320
29.050	.118	2004.2	-46.18	20.10	66.28	10.908	.1578	.032	69.077	1.0422
29.051	.118	2004.2	-46.18	20.14	66.32	10.907	.1577	.032	69.134	1.0424
30.010	.117	1706.2	-49.09	-43.11	5.97	.931	.1459	.000	6.379	1.0678
30.020	.117	1702.2	-49.06	-36.20	12.87	2.041	.1461	.002	13.974	1.0861
30.030	.117	1706.2	-49.07	-26.95	22.12	3.573	.1455	.009	24.544	1.1095
30.040	.117	1704.3	-49.01	-15.29	33.72	5.561	.1455	.013	38.206	1.1330
30.041	.117	1702.3	-49.05	-15.33	33.73	5.560	.1451	.011	38.297	1.1355
30.050	.117	1702.3	-49.06	6.07	55.13	9.260	.1451	.028	63.772	1.1568
30.060	.117	1704.3	-49.11	34.29	83.40	13.756	.1453	.043	94.603	1.1344
31.010	.118	1503.2	-69.20	-62.01	7.19	1.079	.1446	.000	7.465	1.0378
31.020	.118	1498.2	-69.09	-54.26	14.83	2.287	.1445	.000	15.828	1.0676
31.030	.118	1500.2	-69.07	-44.48	24.59	3.911	.1439	.003	27.170	1.1048
31.041	.118	1500.2	-69.06	-31.12	37.94	6.313	.1442	.000	43.793	1.1543
31.040	.118	1500.2	-69.15	-31.24	37.91	6.313	.1442	.000	43.770	1.1547
31.050	.118	1500.2	-69.06	-10.83	58.23	10.168	.1443	.000	70.442	1.2097
31.060	.118	1500.2	-69.11	4.07	73.17	12.883	.1445	.005	89.158	1.2184
32.010	.116	2002.1	1.34	6.79	5.44	.984	.1674	.000	5.876	1.0792
32.022	.116	2002.1	1.34	13.38	12.04	2.176	.1675	.004	12.986	1.0784
32.021	.116	2006.1	1.40	13.44	12.05	2.178	.1678	.024	12.957	1.0756
32.020	.116	2004.1	1.40	13.48	12.09	2.178	.1674	.025	12.984	1.0742
32.030	.116	2003.1	1.40	27.07	25.68	4.579	.1669	.045	27.390	1.0667
32.040	.116	2004.1	1.35	51.61	50.26	8.670	.1664	.046	52.044	1.0355
33.010	.117	1502.2	1.40	6.43	5.03	1.012	.1662	.000	6.089	1.2110
33.020	.117	1502.2	1.42	12.55	11.12	2.196	.1665	.000	13.193	1.1859
33.031	.117	1498.2	1.44	25.42	23.98	4.520	.1660	.000	27.226	1.1355
33.030	.117	1498.2	1.43	25.43	24.00	4.519	.1659	.000	27.248	1.1353
33.041	.117	1498.2	1.43	51.35	49.92	8.659	.1657	.000	52.239	1.0464
33.040	.117	1501.2	1.47	51.20	49.74	8.654	.1663	.004	52.033	1.0462

TABLE XLIV

(Continued)

Run	Mole Fraction C_3H_8	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} \left(\frac{\partial H}{\partial P}\right)_T dP$ (Btu/lb)	ΔH_P (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
34.011	.117	2004.2	51.25	57.44	6.18	.995	.1694	.000	5.873	.9497
34.010	.117	2003.2	51.24	57.41	6.17	.995	.1695	.000	5.869	.9507
34.020	.117	2002.2	51.25	64.94	13.69	2.171	.1691	.006	12.832	.9376
34.030	.117	2002.2	51.27	80.24	28.97	4.479	.1692	.007	26.461	.9134
34.041	.117	2002.2	51.30	109.49	58.19	8.597	.1691	.012	50.818	.8733
34.040	.117	2002.2	51.32	109.36	58.04	8.594	.1695	.012	50.705	.8735
35.010	.116	1502.2	51.32	58.80	7.48	.995	.1512	.000	6.577	.8792
35.020	.116	1502.2	51.34	67.85	16.51	2.148	.1511	.000	14.216	.8609
35.030	.116	1502.3	51.39	86.88	35.48	4.457	.1515	.007	29.412	.8289
35.031	.116	1503.3	51.39	86.85	35.45	4.457	.1517	.007	29.366	.8283
35.040	.116	1502.3	51.33	103.20	51.87	6.336	.1514	.007	41.844	.8067
35.050	.116	1500.2	51.39	123.45	72.07	8.556	.1512	.006	56.592	.7853
36.010	.117	250.3	51.25	62.19	10.95	.986	.1699	.000	5.807	.5305
36.020	.117	249.3	51.28	70.69	19.41	1.736	.1692	.000	10.263	.5288
36.030	.117	249.3	51.29	81.98	30.69	2.744	.1690	.000	16.239	.5291
36.041	.117	248.3	51.32	101.30	49.98	4.464	.1684	.000	26.515	.5305
36.040	.117	248.3	51.30	101.34	50.04	4.464	.1681	.000	26.554	.5306
36.051	.117	250.3	51.30	124.77	73.47	6.630	.1693	.000	39.149	.5328
36.050	.117	249.3	51.26	124.76	73.50	6.630	.1692	.000	39.181	.5331
37.020	.117	998.3	51.24	58.66	7.42	.790	.1487	.000	5.313	.7160
37.030	.117	1000.3	51.29	65.23	13.94	1.473	.1488	.007	9.892	.7094
37.040	.117	998.3	51.26	85.67	34.41	3.539	.1486	.007	23.811	.6920
38.010	.117	1000.2	-73.98	-71.50	2.48	.255	.0690	.000	3.699	1.4909
38.020	.117	999.1	-74.02	-68.50	5.52	.596	.0713	.015	8.346	1.5117
38.030	.117	1000.2	-73.99	-66.64	7.36	.826	.0707	.015	11.670	1.5858
38.040	.117	998.2	-73.98	-65.49	8.50	1.086	.0698	.016	15.538	1.8281
38.050	.117	998.2	-74.02	-66.03	7.99	.966	.0684	.016	14.094	1.7649
38.060	.117	998.1	-74.02	-61.33	12.69	1.913	.0723	.025	26.441	2.0833
38.070	.117	1002.1	-73.95	-23.48	50.46	6.196	.0732	.028	84.600	1.6764
38.080	.117	1002.1	-73.97	12.14	86.11	9.167	.0720	.025	127.299	1.4782
38.090	.117	1002.1	-73.95	25.36	99.30	9.982	.0715	.015	139.569	1.4055
38.100	.117	1000.1	-73.98	.81	74.79	8.134	.0702	.020	115.919	1.5499
39.010	.117	1498.1	-139.03	-132.25	6.78	.699	.1281	-.000	5.461	.8060
39.020	.117	1498.1	-139.01	-120.80	18.20	1.905	.1284	-.000	14.843	.8153
39.030	.117	1498.1	-138.98	-100.79	38.19	4.125	.1294	.000	31.871	.8344
39.040	.117	1502.1	-139.00	-88.98	50.03	5.544	.1300	.002	42.637	.8523
39.041	.117	1502.1	-139.02	-88.81	50.21	5.544	.1293	.002	42.865	.8537
39.050	.117	1502.1	-139.02	-68.49	70.54	8.051	.1285	.006	62.634	.8880
40.010	.116	802.2	-97.60	-90.94	6.66	.473	.0598	.000	7.916	1.1894
40.020	.116	801.2	-97.55	-87.95	9.60	.904	.0601	-.003	15.038	1.5668
40.030	.116	800.2	-97.57	-88.51	9.06	.757	.0602	-.006	12.585	1.3894
40.040	.116	798.2	-97.56	-83.00	14.56	2.211	.0603	-.004	36.685	2.5198
40.050	.116	798.2	-97.58	-63.72	33.86	4.618	.0598	-.004	77.171	2.2794
40.060	.116	798.2	-97.55	-7.42	90.13	8.700	.0599	-.021	145.251	1.6116
40.070	.116	798.2	-97.56	16.92	114.49	10.311	.0601	-.011	171.627	1.4991
40.080	.116	799.2	-97.55	31.18	128.73	10.767	.0593	.017	181.612	1.4108
40.090	.116	801.2	-97.59	5.36	102.94	9.565	.0596	.042	160.550	1.5596
41.010	.117	1000.2	-177.86	-168.22	9.64	.921	.1241	-.000	7.424	.7699
41.020	.117	999.2	-177.86	-156.91	20.94	2.026	.1238	-.000	16.366	.7814
41.030	.117	998.2	-177.84	-136.32	41.52	4.094	.1235	.000	33.159	.7986
41.040	.117	1000.2	-177.85	-117.28	60.58	6.157	.1239	.000	49.693	.8203
41.050	.117	1000.2	-177.86	-98.20	79.66	8.397	.1239	.001	67.755	.8506
41.051	.117	1000.2	-177.86	-98.40	79.45	8.398	.1242	.002	67.607	.8509
41.060	.117	999.2	-177.87	-86.14	91.73	9.968	.1237	.010	80.551	.8781
42.010	.117	1003.3	-235.98	-229.77	6.21	.476	.1067	-.000	4.463	.7187
42.011	.117	1002.3	-235.99	-229.79	6.19	.476	.1069	-.000	4.456	.7194
42.020	.117	1000.3	-235.97	-216.75	19.22	1.492	.1066	-.000	13.993	.7281
42.030	.117	999.3	-235.95	-193.79	42.16	3.308	.1066	-.003	31.042	.7363
42.040	.117	1001.2	-235.98	-170.59	65.38	5.225	.1071	-.000	48.804	.7464
43.010	.117	500.3	-235.98	-226.42	9.56	.657	.0944	-.000	6.955	.7275
43.020	.117	502.3	-235.93	-215.21	20.72	1.442	.0935	-.000	15.420	.7441
43.030	.117	497.2	-235.98	-192.45	43.52	3.047	.0943	-.000	32.303	.7422
44.010	.116	356.2	-178.05	-166.82	11.23	.742	.0818	.000	9.066	.8072
44.020	.116	352.2	-178.04	-163.01	15.03	.990	.0815	.004	12.144	.8079
44.030	.116	355.2	-178.01	-156.49	21.52	1.436	.0818	.010	17.542	.8151
44.040	.116	351.2	-178.06	-148.88	29.18	1.955	.0810	.020	24.108	.8261
45.010	.117	1210.3	-64.53	-57.83	6.71	.709	.0790	.000	8.973	1.3379
45.020	.117	1201.3	-64.53	-47.84 ✓	16.69	1.899	.0792	.000	23.965	1.4357
45.030	.117	1200.3	-64.51	-38.22	26.28	3.146	.0792	.000	39.715	1.5110
45.040	.117	1200.3	-64.53	-28.45	36.08	4.419	.0793	.004	55.724	1.5443
45.050	.117	1201.3	-64.54	-15.89	48.65	5.889	.0794	.013	74.156	1.5242
45.060	.117	1198.3	-64.54	-2.47	62.08	7.258	.0789	.043	91.897	1.4804
45.070	.117	1198.3	-64.52	26.27	90.79	9.605	.0788	.059	121.819	1.3417

TABLE XLV

TABULATED EXPERIMENTAL ISOBARIC DATA FOR THE NOMINAL 28 PERCENT MIXTURE

Run	Mole Fraction C_3H_8	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T dP$ (Btu/lb)	ΔH_P (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
20.010	.280	999.3	86.36	96.20	9.84	1.609	.2074	.015	7.744	.7870
20.020	.280	998.3	86.30	106.44	20.15	3.239	.2095	.015	15.443	.7666
20.030	.279	1000.3	86.31	121.01	34.70	5.428	.2092	.014	25.934	.7475
20.041	.279	1001.3	86.29	143.03	56.73	8.602	.2090	.012	41.138	.7251
20.040	.279	1000.3	86.31	143.14	56.83	8.604	.2090	.012	41.154	.7241
21.010	.280	1998.2	86.31	96.29	9.98	1.988	.2110	.004	9.417	.9435
21.020	.280	2000.2	86.29	105.31	19.02	3.750	.2111	.003	17.762	.9338
21.030	.280	1998.2	86.28	121.13	34.85	6.793	.2121	.003	32.024	.9189
21.040	.280	2002.2	86.30	140.16	53.86	10.262	.2138	.002	48.007	.8913
23.010	.281	1502.3	86.25	95.98	9.73	2.010	.2610	.006	7.695	.7907
23.020	.281	1502.3	86.55	110.89	24.34	4.911	.2658	.006	18.473	.7588
23.030	.281	1501.3	86.48	130.29	43.81	8.337	.2618	.006	31.843	.7269
23.040	.281	1500.3	86.43	144.84	58.40	10.815	.2609	.005	41.445	.7096
24.010	.281	2002.0	86.46	97.31	10.84	2.184	.2650	.003	8.239	.7599
24.020	.281	1999.0	86.45	104.25	17.80	3.506	.2581	.003	13.579	.7627
24.030	.281	2000.1	85.93	121.36	35.43	6.793	.2554	.001	26.599	.7508
24.042	.281	1998.1	86.43	144.50	58.07	10.738	.2504	.001	42.879	.7384
24.041	.281	1997.1	86.43	144.75	58.32	10.737	.2491	.001	43.103	.7390
24.040	.281	2003.1	86.42	144.50	58.08	10.737	.2508	.001	42.802	.7370
25.010	.278	1001.1	86.35	97.70	11.35	1.856	.2087	.016	8.877	.7822
25.020	.278	998.2	86.42	104.89	18.47	2.884	.2035	.015	14.157	.7664
25.030	.278	998.2	86.44	121.16	34.72	5.216	.2015	.014	25.869	.7450
25.040	.278	1002.2	86.45	143.81	57.36	8.367	.2021	.012	41.398	.7218
26.010	.278	501.2	86.44	99.08	12.64	1.529	.2102	.034	7.240	.5728
26.020	.278	502.2	86.35	112.11	25.76	3.102	.2100	.032	14.740	.5722
26.030	.278	502.2	86.35	129.79	43.44	5.210	.2101	.031	24.766	.5701
26.040	.278	501.2	86.37	143.69	57.32	6.837	.2093	.030	32.629	.5692
27.012	.281	252.2	86.39	100.70	14.30	1.663	.2253	.079	7.303	.5106
27.011	.281	252.2	86.39	100.63	14.23	1.663	.2264	.079	7.266	.5104
27.010	.281	254.2	86.40	100.58	14.18	1.663	.2272	.079	7.240	.5106
27.021	.281	251.2	86.42	113.10	26.68	3.089	.2246	.074	13.682	.5128
27.020	.281	251.2	86.40	113.04	26.54	3.089	.2248	.074	13.667	.5131
27.031	.281	253.2	86.38	125.93	39.55	4.614	.2258	.076	20.357	.5147
27.030	.281	253.2	86.41	125.86	39.45	4.615	.2265	.077	20.293	.5144
27.041	.281	254.2	86.40	144.47	58.07	6.849	.2277	.076	30.003	.5167
27.040	.281	253.2	86.37	144.92	58.55	6.844	.2254	.075	30.283	.5172
28.010	.280	2000.1	1.53	16.05	14.52	2.643	.2103	.001	12.568	.8653
28.020	.280	2000.1	1.52	24.94	23.42	4.319	.2107	.001	20.499	.8753
28.030	.280	1999.1	1.41	45.19	43.79	8.306	.2107	.002	39.426	.9004
28.040	.280	1999.1	1.40	61.58	60.19	11.704	.2123	.001	55.125	.9159
29.010	.280	1497.1	1.36	13.95	12.60	2.652	.2103	.002	12.609	1.0009
29.021	.280	1502.1	1.56	27.51	25.95	5.850	.2112	.004	27.697	1.0673
29.020	.280	1498.1	1.38	27.39	26.01	5.850	.2104	.004	27.800	1.0688
30.010	.282	1498.2	1.41	14.10	12.69	2.275	.1738	.004	13.087	1.0313
30.011	.282	1500.2	1.39	14.02	12.63	2.274	.1748	.004	13.011	1.0304
30.020	.282	1498.2	1.50	25.02	23.52	4.702	.1886	.006	24.929	1.0599
30.021	.282	1498.2	1.50	27.10	25.59	4.702	.1725	.007	27.254	1.0649
30.030	.282	1498.2	1.41	42.37	40.96	8.394	.1880	.009	44.637	1.0899
30.040	.282	1498.2	1.41	60.89	59.47	12.268	.1871	.009	65.548	1.1021
30.041	.282	1498.2	1.44	60.96	59.52	12.268	.1871	.009	65.559	1.1014
31.010	.280	1499.2	-150.21	-135.87	14.35	1.932	.2020	.018	9.545	.6652
31.020	.280	1498.2	-150.21	-122.90	27.31	3.681	.2011	.019	18.281	.6695
31.021	.280	1497.2	-150.86	-123.37	27.49	3.681	.2006	.019	18.333	.6669
31.040	.280	1500.2	-150.21	-61.77	88.44	12.383	.1993	-.000	62.117	.7024
31.041	.280	1498.2	-150.16	-61.78	88.39	12.382	.1994	-.000	62.111	.7027
31.030	.280	1498.2	-150.22	-101.47	48.74	6.668	.2002	-.000	33.305	.6833
32.011	.280	2002.1	-148.83	-134.11	14.72	1.930	.1994	-.001	9.680	.6575
32.010	.280	2000.1	-148.79	-134.03	14.76	1.930	.1984	-.001	9.726	.6592
32.020	.280	1998.1	-148.77	-121.08	27.70	3.669	.1997	-.001	18.369	.6632
32.031	.280	2001.1	-148.76	-101.35	47.41	6.314	.1990	-.001	31.725	.6692
32.030	.280	2000.1	-148.79	-101.48	47.31	6.316	.1993	-.001	31.688	.6698
32.041	.280	2000.1	-149.20	-71.11	78.10	10.595	.1999	-.001	53.003	.6787
32.040	.280	2000.1	-148.75	-70.92	77.83	10.595	.1995	-.001	53.096	.6822
33.010	.280	999.2	-149.11	-135.07	14.04	1.954	.2051	-.001	9.531	.6790
33.020	.280	1000.1	-149.11	-122.72	26.39	3.691	.2041	-.001	18.084	.6853
33.031	.280	1001.1	-149.12	-98.58	50.54	7.044	.1994	-.001	35.322	.6989
33.030	.280	999.1	-149.11	-98.52	50.59	7.048	.1991	-.001	35.402	.6998
33.040	.280	1002.1	-149.13	-74.44	74.68	10.665	.1990	-.000	53.587	.7175
34.010	.279	1001.2	-54.19	-49.44	4.75	.511	.1236	.001	4.134	.8704
34.020	.279	1001.2	-54.19	-46.49	7.70	.837	.1237	.001	6.765	.8786
34.030	.279	1001.2	-54.21	-43.72	10.49	1.405	.1235	.002	11.374	1.0847
34.040	.279	999.1	-54.21	-33.63	20.57	3.193	.1189	.001	26.854	1.3053
34.050	.279	998.1	-54.15	-41.85	12.30	1.746	.1190	.001	14.676	1.1936
34.060	.279	1000.1	-54.16	-6.14	48.02	7.018	.1163	.006	60.354	1.2570
34.070	.279	998.1	-54.21	14.55	68.76	9.794	.1171	.010	83.646	1.2166
34.081	.279	998.1	-54.25	42.01	96.27	13.344	.1160	.005	114.992	1.1945
34.080	.279	1000.1	-54.19	40.03	94.21	13.340	.1184	.022	112.623	1.1954

TABLE XLV

(Continued)

Run	Mole Fraction C_3H_8	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T \, dP$ (Btu/lb)	ΔHp (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
34.090	.279	998.1	-54.21	62.94	117.15	16.644	.1181	.010	140.907	1.2028
34.100	.279	999.1	-54.19	73.51	127.69	18.245	.1179	.007	154.769	1.2121
34.111	.279	998.1	-54.19	77.02	131.21	18.800	.1178	.007	159.635	1.2166
34.110	.279	997.1	-54.17	77.14	131.31	18.796	.1179	.007	159.378	1.2138
34.121	.279	998.1	-54.00	88.09	142.09	19.942	.1176	.007	169.553	1.1933
34.120	.279	998.1	-54.18	88.24	142.41	19.946	.1175	.007	169.695	1.1916
34.130	.279	998.1	-54.20	95.52	149.72	20.604	.1175	.006	175.420	1.1716
34.140	.279	998.1	-54.18	82.83	137.01	19.387	.1173	.008	165.212	1.2058
35.011	.279	1998.2	-74.41	-61.45	12.96	1.928	.2056	-.000	9.377	.7236
35.010	.279	2002.2	-74.42	-61.47	12.95	1.928	.2058	.001	9.368	.7235
35.020	.279	1999.2	-74.40	-50.15	24.25	3.700	.2065	-.000	17.918	.7388
35.030	.279	2000.2	-74.35	-28.82	45.53	7.085	.2087	.000	33.952	.7457
35.040	.279	1998.2	-74.22	-9.67	64.55	10.205	.2072	.001	49.242	.7629
36.011	.279	1500.2	-74.30	-61.62	12.69	1.975	.2040	-.000	9.681	.7631
36.010	.279	1499.2	-74.29	-61.57	12.71	1.975	.2034	-.000	9.711	.7638
36.021	.279	1498.2	-74.27	-47.25	27.02	4.244	.2041	-.000	20.796	.7696
36.020	.279	1498.2	-74.26	-47.28	26.98	4.244	.2044	-.000	20.763	.7695
36.030	.279	1499.3	-74.22	-30.28	43.94	7.090	.2040	.001	34.761	.7911
36.041	.279	1499.3	-74.28	-10.37	63.91	10.736	.2041	.002	52.589	.8229
36.040	.279	1498.3	-74.24	-10.33	63.91	10.737	.2042	.002	52.579	.8227
37.010	.281	699.3	-99.34	-93.50	5.84	.537	.1213	-.000	4.430	.7579
37.021	.281	698.3	-99.79	-89.34	10.45	.971	.1216	-.000	7.987	.7644
37.020	.281	702.3	-99.79	-89.33	10.46	.971	.1223	-.000	7.941	.7594
37.030	.281	699.3	-99.73	-85.96	13.78	1.282	.1215	-.000	10.556	.7662
37.040	.280	698.3	-99.67	-83.42	16.26	1.610	.1210	-.000	13.305	.8185
37.050	.280	700.3	-99.70	-82.18	17.52	1.956	.1217	-.000	16.074	.9172
37.061	.280	701.3	-99.71	-79.96	19.75	2.575	.1217	-.000	21.164	1.0714
37.060	.280	701.3	-99.70	-79.99	19.71	2.575	.1218	-.000	21.144	1.0725
37.070	.280	700.3	-99.67	-70.53	29.14	4.821	.1219	-.000	39.541	1.3568
37.081	.280	699.3	-99.72	-49.01	50.71	8.216	.1196	.001	68.718	1.3550
37.080	.280	698.3	-99.71	-48.85	50.87	8.216	.1195	.001	68.776	1.3521
37.090	.280	702.3	-99.68	-19.53	80.15	12.082	.1210	.031	99.799	1.2452
37.100	.280	700.3	-99.67	8.84	108.51	15.741	.1209	.027	130.173	1.1996
37.110	.280	698.3	-99.66	33.00	132.66	18.871	.1196	.010	157.737	1.1890
37.120	.280	698.3	-99.70	48.34	148.04	21.254	.1191	.025	178.414	1.2051
37.130	.279	698.3	-99.81	59.20	159.01	23.097	.1185	.018	194.862	1.2255
37.140	.279	698.3	-99.78	69.45	169.24	25.018	.1185	.013	211.053	1.2471
37.150	.279	699.3	-99.82	65.92	165.74	24.412	.1188	.018	205.542	1.2401
37.160	.279	699.3	-99.82	76.59	176.41	25.761	.1186	.014	217.113	1.2307
38.010	.280	499.3	-123.92	-117.63	6.29	.537	.1180	-.000	4.546	.7230
38.020	.280	499.3	-123.87	-113.03	10.84	.915	.1160	-.000	7.888	.7280
38.021	.280	499.3	-123.83	-112.94	10.89	.915	.1163	-.000	7.864	.7221
38.030	.280	499.3	-124.01	-110.05	13.96	1.436	.1165	-.000	12.327	.8830
38.040	.280	498.3	-123.99	-108.85	15.14	1.952	.1162	-.000	16.801	1.1100
38.050	.279	500.3	-123.93	-101.22	22.71	4.230	.1157	-.000	36.550	1.6097
38.061	.279	497.3	-123.90	-87.88	36.02	6.705	.1120	-.000	59.876	1.6621
38.060	.279	498.3	-123.87	-87.78	36.09	6.705	.1121	-.000	59.800	1.6569
38.071	.280	498.3	-123.97	-70.18	53.79	8.953	.1102	.000	81.238	1.5103
38.070	.280	498.3	-123.96	-69.60	54.36	8.954	.1099	.000	81.456	1.4984
38.080	.280	499.3	-123.90	-47.52	76.38	11.522	.1118	.001	103.086	1.3497
38.090	.280	501.3	-123.90	-24.16	99.74	14.370	.1134	.007	126.712	1.2704
38.100	.279	498.3	-123.90	.87	124.77	17.318	.1127	.060	153.604	1.2311
38.110	.279	499.3	-123.91	25.51	149.42	20.739	.1128	.028	183.879	1.2306
38.120	.279	499.3	-123.91	35.91	159.82	22.425	.1125	.022	199.317	1.2471
38.130	.279	499.3	-123.83	46.88	170.70	24.348	.1123	.021	216.796	1.2700
38.140	.280	499.3	-123.83	53.87	177.69	25.600	.1123	.023	227.875	1.2824
38.150	.280	499.3	-123.83	59.10	182.92	26.424	.1119	.025	236.087	1.2906
38.160	.280	499.3	-123.95	66.23	190.18	27.076	.1125	.024	240.700	1.2656
39.040	.280	1503.2	-123.99	-69.05	54.94	8.550	.2186	-.000	39.109	.7119
39.041	.280	1498.2	-124.05	-69.12	54.93	8.550	.2186	-.000	39.110	.7120
39.030	.280	1498.2	-124.00	-68.88	55.12	6.802	.1736	-.001	39.186	.7109
39.020	.280	1498.2	-123.98	-69.04	54.94	4.962	.1267	-.000	39.168	.7129
39.010	.280	1498.2	-124.06	-69.05	55.01	2.563	.0658	-.000	38.966	.7083
40.040	.280	1998.2	-227.88	-128.94	98.94	14.674	.2002	-.001	73.294	.7408
40.030	.280	2001.2	-227.88	-160.32	67.56	9.996	.2016	-.001	49.595	.7340
40.020	.280	1998.2	-227.98	-198.22	29.76	4.338	.2011	-.001	21.570	.7247
40.010	.280	1998.2	-227.88	-213.27	14.61	2.024	.2020	-.001	10.020	.6858
41.040	.280	1499.2	-228.17	-132.13	96.04	11.837	.1899	-.001	62.348	.6492
41.041	.280	1500.2	-228.15	-132.22	95.93	11.837	.1902	-.001	62.249	.6489
41.030	.280	1500.2	-228.09	-164.64	63.45	7.739	.1902	-.001	40.690	.6413
41.020	.280	1498.2	-228.12	-192.03	36.08	4.385	.1913	-.001	22.929	.6355
41.010	.280	1498.2	-227.91	-210.96	16.95	2.048	.1908	-.001	10.732	.6331
42.040	.280	1000.3	-228.27	-131.41	96.86	11.923	.1877	-.001	63.536	.6560
42.030	.280	998.3	-228.61	-170.43	58.18	7.092	.1890	-.001	37.532	.6451
42.031	.280	998.3	-228.64	-170.80	57.83	7.093	.1902	-.001	37.284	.6447
42.020	.280	1000.3	-228.05	-196.46	31.59	3.905	.1935	-.001	20.178	.6387
42.021	.280	999.3	-227.99	-196.39	31.61	3.905	.1933	-.001	20.206	.6393
42.010	.280	1000.3	-228.13	-214.11	14.03	1.739	.1949	-.001	8.925	.6363
43.040	.280	500.3	-228.35	-125.84	102.51	14.770	.2166	-.001	68.201	.6653
43.030	.280	498.3	-228.37	-154.72	73.65	10.257	.2128	-.001	48.210	.6545
43.020	.280	498.3	-228.33	-177.96	50.37	7.030	.2155	-.001	32.620	.6476
43.010	.280	501.3	-228.16	-199.97	28.19	3.927	.2169	-.001	18.105	.6422

TABLE XLV

(Continued)

Run	Mole Fraction C_3H_8	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T dP$ (Btu/lb)	ΔH_P (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
44.040	.277	248.3	-228.44	-152.36	76.08	12.926	.2068	-.000	62.503	.8215
44.030	.277	249.3	-228.18	-169.07	59.11	8.579	.2216	-.001	38.723	.6550
44.020	.277	249.3	-228.66	-193.03	35.63	5.145	.2228	-.001	23.090	.6480
44.010	.277	249.3	-228.23	-210.75	17.48	2.544	.2257	-.001	11.270	.6447
45.010	.279	251.3	-159.01	-155.07	3.94	.640	.2367	-.002	2.707	.6879
45.020	.279	252.3	-159.03	-153.53	5.50	1.277	.2361	-.001	5.409	.9843
45.030	.279	252.3	-159.03	-153.98	5.05	.885	.2342	-.001	3.777	.7482
45.040	.279	250.3	-159.03	-153.30	5.73	1.982	.2332	-.001	8.501	1.4831
45.050	.279	250.3	-159.03	-151.05	7.98	4.507	.2353	-.001	19.155	2.4017
45.060	.279	249.3	-159.02	-147.25	11.77	8.618	.2383	-.001	36.170	3.0733
45.070	.278	248.3	-159.01	-134.66	24.35	13.966	.2061	.019	67.762	2.7826
46.010	.281	250.3	41.21	54.89	13.68	1.618	.2265	.168	6.976	.5100
46.020	.281	248.3	41.20	66.66	25.46	2.991	.2277	.335	12.799	.5028
46.030	.281	248.3	41.20	81.91	40.71	4.762	.2273	.159	20.786	.5105
46.041	.281	257.3	41.19	98.18	56.99	6.659	.2275	.155	29.120	.5110
46.040	.281	259.3	41.19	97.78	56.59	6.658	.2290	.156	28.913	.5110
46.050	.281	260.3	41.20	109.80	68.60	8.103	.2297	.153	35.119	.5120
47.012	.280	999.2	86.35	100.29	13.94	2.115	.1937	.024	10.894	.7817
47.011	.280	998.2	86.34	100.31	13.97	2.115	.1932	.024	10.922	.7818
47.010	.280	1001.2	86.34	100.20	13.86	2.115	.1936	.024	10.903	.7868
47.024	.280	998.2	86.34	111.18	24.84	3.681	.1935	.025	18.995	.7645
47.023	.280	998.2	86.39	111.30	24.90	3.681	.1934	.027	19.013	.7635
47.022	.280	998.2	86.38	111.25	24.87	3.682	.1932	.025	19.032	.7653
47.021	.280	998.2	86.37	111.20	24.83	3.682	.1935	.027	18.996	.7651
47.020	.280	1002.2	86.32	111.01	24.69	3.682	.1944	.027	18.908	.7658
47.031	.280	1001.2	86.31	125.23	38.91	5.625	.1935	.024	29.040	.7463
47.030	.280	1002.2	86.31	125.15	38.84	5.624	.1937	.024	29.007	.7468
47.042	.280	1000.2	86.34	146.94	60.60	8.473	.1932	.024	43.839	.7234
47.041	.280	998.2	86.35	147.12	60.77	8.472	.1928	.023	43.914	.7226
47.040	.280	998.2	86.37	147.21	60.84	8.471	.1928	.023	43.917	.7218
48.010	.281	1300.2	-14.05	-7.78	6.27	.865	.1359	-.000	6.365	1.0155
48.020	.281	1300.2	-14.06	-3.99	10.07	1.429	.1360	.000	10.506	1.0435
48.030	.281	1298.2	-14.01	.49	14.50	2.125	.1358	.000	15.644	1.0790
48.040	.281	1298.2	-14.01	3.99	17.99	2.739	.1358	.000	20.170	1.1209
48.050	.281	1298.2	-14.00	8.08	22.09	3.443	.1358	.000	25.359	1.1482
48.060	.281	1302.2	-14.02	23.70	37.72	6.009	.1368	.000	43.917	1.1642
48.070	.281	1299.2	-14.02	34.65	48.66	7.759	.1363	.000	56.926	1.1698
48.080	.281	1298.2	-14.07	44.30	58.36	9.301	.1362	.000	68.270	1.1697
48.091	.281	1298.2	-13.92	60.45	74.36	11.925	.1364	.001	87.439	1.1758
48.090	.281	1301.6	-14.05	60.25	74.30	13.248	.1369	.000	96.752	1.3021
49.010	.281	1998.0	41.94	50.46	8.52	1.757	.2180	.004	8.052	.9448
49.021	.281	2000.0	41.93	56.34	14.40	2.995	.2188	.005	13.681	.9498
49.020	.281	1998.0	41.93	56.41	14.48	2.995	.2178	.005	13.748	.9495
49.030	.281	1999.0	41.87	64.81	22.94	4.770	.2178	.005	21.897	.9546
49.041	.281	1998.0	41.93	72.60	30.67	6.354	.2167	.006	29.320	.9558
49.040	.281	1998.0	41.93	72.61	30.69	6.344	.2165	.006	29.291	.9545
49.051	.281	1998.0	41.96	79.44	37.47	7.732	.2157	.005	35.835	.9563
49.050	.281	1999.0	41.87	79.33	37.46	7.733	.2159	.005	35.814	.9561
49.060	.281	1999.0	41.89	87.04	45.15	9.307	.2156	.006	43.162	.9560
49.070	.281	1998.0	41.93	93.88	51.95	10.635	.2144	.006	49.610	.9549
49.081	.281	1999.0	41.95	100.30	58.35	11.935	.2148	.005	55.545	.9520
49.080	.281	1998.0	41.97	100.46	58.49	11.935	.2143	.006	55.675	.9519
49.091	.281	1996.0	41.00	107.75	66.75	13.532	.2141	.005	63.207	.9470
49.090	.281	2000.0	41.93	108.54	66.61	13.532	.2144	.004	63.115	.9476
49.100	.281	1999.0	41.83	118.92	77.10	15.579	.2143	.004	72.683	.9428
50.010	.279	1498.2	-10.10	10.81	20.91	4.447	.2147	.005	20.704	.9900
50.020	.279	1501.2	-8.67	30.84	39.51	8.908	.2157	.008	41.302	1.0455
50.030	.279	1498.2	-8.64	41.70	50.34	11.471	.2140	.010	53.582	1.0643
50.040	.279	1501.2	-8.63	52.32	60.95	13.834	.2110	.011	65.549	1.0755
50.051	.279	1497.2	-8.67	62.58	71.25	15.636	.2027	.010	77.129	1.0826
50.050	.279	1499.2	-8.67	62.61	71.28	15.636	.2029	.010	77.053	1.0810
50.060	.279	1498.2	-8.62	71.82	80.44	17.621	.2022	.010	87.138	1.0833
50.070	.279	1498.2	-8.66	92.20	100.86	22.015	.2042	.010	107.822	1.0690
50.082	.279	1498.2	-8.68	111.49	120.17	25.873	.2059	.009	125.664	1.0457
50.081	.279	1499.2	-8.75	111.42	120.17	25.889	.2062	.010	125.555	1.0448
50.080	.279	1498.2	-8.75	111.38	120.13	25.872	.2063	.010	125.396	1.0438
51.010	.279	1060.3	-14.07	-3.93	10.14	1.487	.1391	.003	10.682	1.0531
51.020	.279	1259.3	-14.07	6.12	20.19	3.215	.1386	.002	23.191	1.1486
51.030	.279	1259.2	-14.05	16.46	30.51	5.047	.1414	.006	35.679	1.1692
51.040	.279	1258.2	-14.05	26.14	40.19	6.636	.1409	.004	47.090	1.1716
51.050	.279	1261.2	-14.02	35.68	49.70	8.160	.1407	.007	57.979	1.1667
51.061	.279	1259.2	-14.08	45.58	59.66	9.709	.1389	.003	69.882	1.1713
51.060	.279	1258.2	-14.10	45.43	59.53	9.710	.1395	.006	69.607	1.1692
51.071	.279	1259.2	-14.06	54.43	68.49	11.166	.1390	.002	80.303	1.1725
51.070	.279	1258.2	-14.08	54.41	68.48	11.169	.1391	.005	80.274	1.1722
51.081	.279	1259.2	-14.06	63.17	77.22	12.636	.1390	.002	90.881	1.1769
51.080	.279	1258.2	-14.06	63.25	77.31	12.637	.1390	.003	90.923	1.1761

TABLE XLVI

TABULATED EXPERIMENTAL ISOBARIC DATA FOR

THE NOMINAL 43 PERCENT MIXTURE

Run	Mole Fraction N_2	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T dP$ (Btu/lb)	ΔHp (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
1.010	.434	1001.3	51.68	59.96	8.27	.490	.1362	.002	3.594	.4344
1.020	.434	1002.2	51.61	71.77	20.16	1.192	.1362	.002	8.746	.4339
1.030	.434	1001.2	50.88	96.96	46.08	2.699	.1361	.002	19.829	.4304
1.031	.434	1001.2	51.05	96.96	45.90	2.701	.1364	.002	19.808	.4315
2.010	.434	2000.1	53.15	60.46	7.31	.489	.1338	.001	3.652	.4999
2.020	.434	1999.1	53.23	71.17	17.94	1.188	.1335	.001	8.898	.4959
2.030	.434	1999.1	53.20	81.84	28.64	1.874	.1329	.001	14.103	.4925
2.040	.434	1998.1	53.22	101.20	47.97	3.109	.1327	.001	23.422	.4882
2.050	.434	1998.1	53.25	116.93	63.69	4.088	.1327	.001	30.807	.4837
3.010	.434	1501.1	53.49	61.70	8.21	.484	.1255	.001	3.858	.4701
3.020	.434	1501.1	53.73	73.78	20.05	1.181	.1266	.001	9.331	.4654
3.030	.434	1501.1	54.02	85.66	31.64	1.865	.1269	.001	14.694	.4644
3.040	.434	1501.1	54.06	115.38	61.31	3.538	.1259	.001	28.099	.4583
4.010	.434	499.2	51.79	62.30	10.51	.484	.1151	.004	4.204	.3999
4.020	.434	498.2	51.71	77.83	26.12	1.205	.1147	.003	10.498	.4019
4.030	.434	499.2	51.70	93.19	41.49	1.915	.1148	.003	16.677	.4019
4.031	.434	499.2	51.70	93.21	41.51	1.914	.1146	.003	16.689	.4020
4.040	.434	498.2	51.56	124.16	72.60	3.330	.1145	.003	29.074	.4005
5.010	.434	249.3	51.16	59.05	7.90	.485	.1562	.012	3.092	.3914
5.020	.434	249.3	51.30	70.72	19.41	1.185	.1560	.014	7.580	.3905
5.030	.434	250.2	51.37	82.07	30.70	1.876	.1567	.012	11.958	.3895
5.040	.434	251.2	51.63	105.75	54.12	3.320	.1572	.011	21.105	.3899
5.041	.434	251.2	51.66	105.81	54.15	3.320	.1573	.011	21.091	.3895
6.010	.434	501.2	-99.06	-91.92	7.14	.476	.1429	.008	3.323	.4653
6.020	.434	502.2	-99.14	-76.40	22.73	1.481	.1420	.007	10.424	.4585
6.030	.434	501.2	-99.13	-57.99	41.14	2.618	.1414	.007	18.508	.4499
6.040	.434	501.2	-99.11	-14.72	84.39	5.189	.1416	.005	36.640	.4342
7.010	.433	999.2	-98.79	-91.40	7.39	.766	.1499	.006	5.104	.6906
7.020	.433	998.2	-98.79	-82.32	16.48	1.637	.1500	.006	10.907	.6620
7.030	.433	1003.2	-98.81	-63.98	34.83	3.274	.1504	.005	21.761	.6248
7.040	.433	1002.2	-98.80	-23.05	75.76	6.444	.1502	.004	42.887	.5661
8.010	.433	1499.1	-98.82	-92.86	5.96	.792	.1517	.005	5.219	.8757
8.020	.433	1499.1	-98.83	-83.10	15.73	2.006	.1517	.005	13.217	.8405
8.030	.433	1498.1	-98.79	-62.54	36.24	4.265	.1514	.004	28.172	.7773
8.040	.433	1498.1	-98.81	-18.99	79.82	8.240	.1511	.002	54.528	.6832
9.010	.433	1998.0	-98.78	-90.56	8.22	.995	.1501	.003	6.624	.8055
9.020	.433	1998.1	-98.77	-80.55	18.22	2.178	.1501	.003	14.505	.7959
9.030	.433	1998.1	-98.76	-62.05	36.71	4.253	.1501	.002	28.333	.7719
9.040	.433	1998.0	-98.77	-21.50	77.26	8.275	.1504	.001	55.027	.7122
10.010	.434	247.2	-98.75	-85.63	13.12	.752	.1431	.013	5.239	.3992
10.020	.434	247.2	-98.76	-70.54	28.22	1.604	.1427	.012	11.230	.3979
10.030	.434	248.2	-98.76	-46.13	52.63	2.987	.1436	.012	20.793	.3950
10.040	.434	247.2	-98.76	-18.65	80.12	4.509	.1434	.011	31.431	.3923
10.041	.434	247.2	-98.76	-18.49	80.27	4.513	.1432	.011	31.511	.3925
11.010	.433	999.2	-18.90	-10.82	8.08	.568	.1473	.003	3.850	.4764
11.020	.433	999.2	-18.33	-1.21	17.13	1.202	.1475	.003	8.148	.4757
11.030	.433	999.2	-18.88	11.32	30.20	2.083	.1475	.002	14.123	.4677
11.041	.433	999.1	-18.81	37.43	56.24	3.819	.1474	.002	25.900	.4605
11.040	.433	999.1	-18.86	37.44	56.30	3.820	.1474	.002	25.915	.4603
12.010	.433	1499.1	-18.87	-11.13	7.74	.586	.1427	.002	4.109	.5306
12.020	.433	1499.1	-18.88	-3.40	15.48	1.191	.1423	.002	8.365	.5403
12.030	.433	1500.1	-18.88	16.69	35.57	2.663	.1423	.002	18.711	.5261
12.040	.433	1501.1	-18.83	45.02	63.85	4.660	.1425	.001	32.697	.5121
13.010	.434	1998.9	-18.85	-10.86	7.99	.679	.1434	.002	4.729	.5917
13.011	.434	1998.9	-18.83	-10.82	8.01	.679	.1435	.002	4.726	.5898
13.020	.434	2000.9	-18.80	-.90	17.90	1.495	.1439	.002	10.388	.5803
13.031	.434	2000.0	-18.87	19.14	38.01	3.080	.1434	.001	21.474	.5650
13.030	.434	2001.0	-18.84	19.17	38.01	3.080	.1434	.001	21.470	.5649
13.040	.434	2002.0	-18.83	47.52	66.35	5.205	.1436	.001	36.244	.5462
14.010	.435	501.3	-18.83	-9.04	9.79	.557	.1426	.000	3.907	.3991
14.021	.435	501.3	-18.79	1.70	20.49	1.164	.1426	.000	8.165	.3984
14.020	.435	501.3	-18.80	1.15	19.94	1.164	.1426	.005	8.161	.4092
14.030	.435	500.3	-18.98	23.15	42.13	2.439	.1422	.005	17.142	.4068
14.040	.435	500.3	-18.81	42.37	61.18	3.532	.1423	.005	24.824	.4058
15.010	.435	247.3	-18.80	-10.53	8.27	.462	.1452	.011	3.171	.3833
15.020	.433	247.8	-18.77	-.35	18.43	1.028	.1451	.011	7.075	.3839
15.030	.433	247.3	-18.73	20.94	39.68	2.204	.1449	.010	15.203	.3832
15.040	.433	247.8	-18.80	40.12	58.92	3.274	.1449	.010	22.587	.3834
16.010	.433	1501.1	-168.94	-163.59	5.35	.677	.1581	.001	4.282	.8008
16.020	.433	1501.1	-169.00	-148.98	20.02	2.660	.1581	.002	16.821	.8402
16.030	.433	1502.1	-169.02	-125.81	43.20	6.159	.1582	.004	38.934	.9012
16.040	.433	1500.1	-169.01	-88.74	80.27	11.640	.1581	.003	73.645	.9174
17.010	.434	2000.1	-168.87	-159.48	9.39	1.062	.1569	.000	6.771	.7208
17.020	.434	1999.0	-168.87	-142.48	26.39	3.064	.1567	.001	19.553	.7408
17.030	.434	1999.0	-168.89	-122.65	46.24	5.489	.1557	.001	35.261	.7626
17.040	.434	1999.1	-168.87	-90.30	78.57	9.561	.1554	.002	61.541	.7832

TABLE XLVI

(Continued)

Run	Mole Fraction N_2	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	$\overline{\Delta T}$ (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T dP$ (Btu/lb)	ΔH_P (Btu/lb)	$(\Delta H/\Delta T)_P$ (Btu/lb-°F)
18.010	.433	999.2	-169.09	-162.12	6.97	1.189	.1548	.012	7.668	1.0996
18.020	.433	1000.2	-169.04	-149.47	19.56	3.850	.1548	.011	24.863	1.2710
18.030	.433	999.2	-168.86	-120.02	48.84	9.970	.1550	.009	64.308	1.3167
18.041	.433	1003.2	-168.84	-66.31	102.53	15.878	.1556	.003	102.061	.9955
18.040	.433	1003.2	-168.82	-66.43	102.39	15.881	.1558	.003	101.938	.9956
18.050	.433	1001.2	-168.83	-98.91	69.91	12.686	.1555	.004	81.592	1.1671
19.010	.437	252.3	-169.03	-153.96	15.07	1.046	.1535	.020	6.791	.4506
19.020	.437	250.3	-166.74	-136.39	30.35	2.034	.1526	.017	13.314	.4387
19.030	.437	249.2	-169.37	-118.80	50.56	3.307	.1516	.017	21.795	.4310
19.040	.437	250.2	-169.36	-88.08	81.28	5.199	.1517	.015	34.255	.4214
20.010	.434	1499.2	-247.28	-239.60	7.69	.769	.1583	-.001	4.856	.6317
20.020	.434	1499.2	-247.22	-215.18	32.05	3.294	.1589	-.001	20.735	.6470
20.030	.434	1501.2	-247.14	-191.82	55.32	5.814	.1585	-.000	36.684	.6631
20.040	.434	1499.2	-246.96	-154.83	92.12	10.400	.1587	.001	65.516	.7112
21.010	.434	396.3	-229.02	-225.40	3.63	.229	.0893	-.001	2.566	.7075
21.020	.434	397.3	-228.08	-219.58	8.49	.546	.0896	-.001	6.096	.7176
21.030	.434	398.2	-228.65	-212.83	15.82	1.020	.0852	-.000	11.969	.7566
21.040	.434	398.2	-228.89	-206.88	22.01	1.621	.0848	.025	19.094	.8674
21.050	.434	401.2	-228.81	-204.22	24.59	2.246	.0857	.013	26.182	1.0649
21.060	.434	401.2	-228.88	-194.03	34.85	4.643	.0859	.020	54.053	1.5512
21.070	.434	399.2	-228.85	-185.11	43.75	6.860	.0844	-.004	81.308	1.8586
21.080	.434	400.2	-228.92	-177.61	51.31	9.216	.0848	.008	108.661	2.1177
21.090	.434	400.2	-228.88	-161.57	67.31	10.459	.0842	.000	124.271	1.8463
21.100	.434	399.2	-228.90	-170.19	58.71	9.994	.0841	.003	118.866	2.0246
21.110	.434	399.2	-228.99	-174.21	54.78	9.756	.0839	.002	116.275	2.1224
22.010	.434	999.1	-242.50	-233.08	9.42	.806	.1304	-.001	6.182	.6562
22.020	.434	1001.1	-242.51	-207.49	35.03	3.133	.1307	-.001	23.964	.6842
22.030	.434	1001.1	-242.36	-188.67	53.69	5.010	.1310	-.000	38.257	.7126
22.040	.434	999.1	-242.35	-154.34	88.01	9.683	.1306	.014	74.149	.8425
23.010	.434	599.2	-197.94	-188.22	9.72	.597	.0638	.002	9.357	.9628
23.020	.434	602.2	-197.93	-182.14	15.79	1.083	.0639	.001	16.932	1.0720
23.030	.434	602.2	-197.90	-178.73	19.17	1.700	.0639	.069	26.526	1.3835
23.040	.434	600.2	-197.97	-172.08	25.89	2.941	.0636	.027	46.215	1.7852
23.050	.434	600.2	-197.69	-158.26	39.43	5.322	.0637	.004	83.551	2.1190
23.061	.434	602.2	-197.89	-126.37	71.53	6.935	.0640	.000	108.364	1.5150
23.060	.434	603.2	-197.91	-126.42	71.49	6.935	.0641	.000	108.182	1.5132
23.070	.434	601.2	-197.89	-139.79	58.10	6.347	.0638	.001	99.505	1.7126
23.080	.434	600.2	-197.88	-153.00	44.89	5.683	.0637	-.000	89.172	1.9866
24.010	.434	800.3	-198.57	-190.47	8.10	.578	.0857	.002	6.745	.8327
24.020	.434	798.3	-198.52	-171.13	27.39	2.293	.0855	.004	26.799	.9784
24.030	.434	800.3	-198.51	-154.81	43.70	5.018	.0856	.024	58.604	1.3411
24.040	.434	799.3	-198.42	-93.69	104.73	10.187	.0856	.001	118.959	1.1358
24.050	.434	799.3	-198.52	-137.26	61.26	7.437	.0853	.002	87.152	1.4227
24.060	.434	798.3	-198.52	-115.35	83.17	9.006	.0852	.001	105.676	1.2706
25.010	.434	1997.2	-243.49	-231.32	12.17	.830	.1202	-.002	6.905	.5676
25.020	.434	2001.2	-244.01	-210.84	33.17	2.518	.1201	-.002	20.965	.6320
25.030	.434	1999.2	-243.82	-185.88	57.93	4.488	.1199	-.000	37.434	.6461
25.040	.434	2000.2	-243.82	-151.86	91.96	7.410	.1201	.001	61.702	.6710
26.010	.433	248.9	51.61	62.02	10.42	.626	.1561	.010	3.999	.3838
26.020	.433	248.9	51.61	70.75	19.14	1.150	.1561	.010	7.357	.3844
26.030	.433	248.9	51.55	84.31	32.75	1.969	.1560	.010	12.611	.3850
26.041	.433	249.0	51.55	108.56	57.00	3.436	.1561	.010	21.996	.3859
26.040	.433	249.0	51.59	108.68	57.09	3.437	.1560	.010	22.014	.3856
27.011	.434	999.2	50.52	74.05	23.53	.474	.0462	.000	10.257	.4359
27.010	.434	999.2	50.51	74.11	23.60	.474	.0462	.000	10.257	.4347
27.020	.434	998.2	50.52	73.96	23.44	.870	.0856	.003	10.160	.4335
27.030	.434	998.2	50.76	74.27	23.51	1.265	.1243	.001	10.181	.4331
27.040	.434	998.2	50.76	74.48	23.71	1.626	.1580	.002	10.288	.4338
28.010	.434	249.2	-237.39	-232.45	4.93	.501	.1405	.104	3.457	.7007
28.020	.436	249.2	-238.24	-230.30	7.94	1.072	.1408	.043	7.571	.9532
28.030	.436	250.2	-238.23	-227.52	10.71	2.292	.1412	.018	16.211	1.5139
28.040	.436	249.2	-237.47	-220.86	16.61	4.749	.1413	.039	33.571	2.0216
28.050	.436	248.8	-238.28	-211.19	27.09	8.546	.1409	.012	60.631	2.2378
28.060	.436	247.2	-238.55	-203.69	34.87	11.919	.1403	.027	84.915	2.4353
28.070	.436	249.2	-238.57	-191.34	47.23	17.862	.1414	.014	126.298	2.6740
28.081	.436	248.2	-238.45	-182.98	55.47	18.364	.1404	.012	130.770	2.3577
28.080	.436	247.2	-238.79	-182.77	56.03	18.374	.1402	.012	131.012	2.3384
29.010	.436	1498.2	-198.14	-189.72	8.42	.971	.1629	-.000	5.961	.7079
29.020	.433	1498.2	-198.16	-167.61	30.55	3.690	.1624	.001	22.723	.7437
29.030	.433	1498.2	-198.22	-145.89	52.33	6.705	.1622	.002	41.340	.7900
29.040	.433	1498.2	-198.23	-117.81	80.42	11.140	.1622	.004	68.659	.8537
30.010	.433	501.2	50.72	56.97	6.25	.371	.1478	.005	2.503	.4006
30.021	.433	501.2	50.70	72.53	21.83	1.292	.1479	.004	8.733	.4000
30.020	.433	500.8	50.70	72.58	21.88	1.292	.1475	.004	8.755	.4001
30.030	.433	501.2	50.70	84.57	33.87	2.006	.1481	.004	13.537	.3996

TABLE XLVII

TABULATED EXPERIMENTAL ISOBARIC DATA FOR NITROGEN

Run	Inlet Pressure (psia)	Inlet Temperature (°F)	Outlet Temperature (°F)	ΔT (°F)	Power (Btu/min)	Flow (lb/min)	$\int_{P_1}^{P_2} (\frac{\partial H}{\partial P})_T dP$ (Btu/lb)	$\Delta \underline{H}_P$ (Btu/lb)	$(\Delta \underline{H}/\Delta T)_P$ (Btu/lb-°F)
2.010	1001.9	-196.07	-172.23	23.83	.845	.0492	.000	17.170	.7204
2.020	1001.4	-196.07	-172.40	23.67	1.526	.0899	.001	16.981	.7173
2.030	1000.4	-196.08	-172.12	23.96	2.268	.1324	.003	17.125	.7146
2.040	1000.4	-196.06	-172.36	23.70	2.805	.1646	.003	17.042	.7191
2.050	999.4	-196.06	-172.22	23.83	3.292	.1919	.006	17.148	.7195
2.060	1000.4	-196.05	-150.44	45.60	2.505	.0893	.001	28.041	.6149
2.070	1000.4	-196.05	-150.53	45.53	3.551	.1277	.002	27.805	.6108
2.080	1001.4	-196.01	-111.31	84.70	3.703	.0861	.001	43.004	.5077
2.090	1000.4	-196.08	-111.05	85.03	5.562	.1281	.003	43.402	.5104
2.101	1001.4	-196.07	-37.94	158.13	5.977	.0878	.001	68.079	.4305
2.100	1001.4	-196.04	-37.68	158.36	5.926	.0881	.001	67.226	.4245
2.110	999.4	-196.03	-37.53	158.50	8.704	.1297	.002	67.122	.4235
2.120	1000.4	-196.04	33.38	229.42	11.403	.1297	.002	87.922	.3832
2.130	1001.4	-196.03	33.31	229.34	7.830	.0887	.001	88.272	.3849

TABLE XLVIII

TABULATED EXPERIMENTAL ISENTHALPIC DATA FOR NITROGEN

Run	Inlet Temperature (°F)	Inlet Pressure (psia)	Pressure Drop (psi)	ΔT_A (°F)	ΔT_C (°F)	Flow (lb/min)	$\int_{T_1}^{T_2} C_p dT$	$(\Delta T_A/\Delta P)$ (°F/psi)	$(\Delta T_C/\Delta P)$ (°F/psi)
2.010	-147.1	1996.3	37.6	-.654	-.626	.1023	-.329	.01739	.01666
2.020	-147.1	1996.4	115.8	-2.181	-2.185	.1919	-1.118	.01884	.01887
3.010	-147.1	1886.3	116.0	-2.465	-2.480	.1914	-1.259	.02125	.02138
3.040	-147.1	1793.3	120.2	-2.882	-2.881	.1909	-1.458	.02398	.02397
3.050	-147.1	1677.3	127.6	-3.460	-3.477	.1902	-1.738	.02712	.02726
3.070	-147.1	1570.3	143.4	-4.450	-4.473	.1958	-2.208	.03103	.03119
3.100	-147.1	1436.3	147.6	-5.310	-5.354	.1897	-2.591	.03598	.03628
3.110	-147.1	1303.8	176.6	-7.388	-7.469	.1967	-3.462	.04184	.04230
3.140	-147.1	1152.2	201.4	-9.826	-9.931	.1950	-4.179	.04879	.04931
3.150	-147.1	962.2	189.0	-10.570	-10.690	.1673	-3.997	.05593	.05657
4.010	-147.1	837.2	151.8	-8.942	-9.035	.1365	-3.173	.05891	.05952
4.040	-147.1	690.2	189.2	-12.133	-12.299	.1329	-3.860	.06413	.06501
4.050	-147.1	504.2	220.8	-15.411	-15.608	.1130	-4.343	.06980	.07070
5.010	32.6	1995.3	185.6	-2.956	-3.015	.1689	-.911	.01593	.01625
5.040	32.6	1832.3	212.8	-3.683	-3.736	.1738	-1.113	.01731	.01756
5.050	32.6	1628.2	205.6	-3.884	-3.943	.1607	-1.151	.01889	.01918
5.080	32.6	1446.2	243.0	-4.983	-5.062	.1638	-1.441	.02051	.02083
5.090	32.6	1239.2	206.0	-4.673	-4.747	.1403	-1.328	.02269	.02305
5.120	32.7	1225.2	392.8	-9.063	-9.198	.1865	-2.511	.02308	.02342
5.130	32.6	848.2	282.8	-7.315	-7.425	.1294	-1.968	.02587	.02626
5.160	32.6	749.6	515.4	-14.281	-14.475	.1467	-3.666	.02771	.02809
6.010	201.4	1999.3	236.0	-1.788	-1.842	.1583	-.494	.00758	.00780
6.040	201.3	1878.3	292.4	-2.363	-2.469	.1730	-.650	.00808	.00845
6.050	201.4	1585.9	417.6	-3.999	-4.153	.1871	-1.068	.00958	.00995
6.080	201.3	1202.4	380.2	-4.104	-4.269	.1525	-1.084	.01080	.01123
6.090	201.4	878.4	390.4	-4.691	-4.878	.1261	-1.215	.01202	.01250
6.120	201.4	581.4	475.8	-6.246	-6.510	.0970	-1.588	.01313	.01368

TABLE XLIX

TABULATED EXPERIMENTAL ISOTHERMAL DATA FOR NITROGEN

Run	Inlet Temperature (°F)	Inlet Pressure (psia)	Pressure Drop (psi)	Power (Btu/min)	Flow (lb/min)	$\int_{T_1}^{T_2} C_p dT$ (Btu/lb)	$\Delta \underline{H}_T$ (Btu/lb)	$(\Delta \underline{H}/\Delta P)_T$ (Btu/lb-psi)
2.030	-147.1	1996.4	117.4	.229	.1920	.007	1.184	-.010087
3.020	-147.1	1888.3	117.8	.260	.1915	-.003	1.358	-.011532
3.030	-147.1	1794.3	121.6	.300	.1911	-.004	1.577	-.012969
3.060	-147.1	1679.3	130.6	.363	.1903	-.000	1.909	-.014620
3.080	-147.1	1572.3	147.6	.481	.1956	.003	2.455	-.016636
3.090	-147.1	1437.3	152.6	.541	.1890	.005	2.855	-.018710
3.120	-147.1	1306.8	184.6	.743	.1957	.001	3.795	-.020557
3.130	-147.1	1155.3	212.6	.893	.1932	-.016	4.635	-.021804
3.160	-147.1	965.2	198.4	.734	.1659	.002	4.421	-.022288
4.020	-147.1	839.2	159.0	.470	.1354	-.002	3.471	-.021830
4.030	-147.1	692.2	197.2	.555	.1312	-.003	4.232	-.021462
4.060	-147.1	507.2	229.4	.521	.1108	.002	4.696	-.020475
5.020	32.6	1989.3	184.4	.161	.1683	.011	.944	-.005120
5.030	32.7	1833.3	213.6	.203	.1737	-.000	1.169	-.005473
5.060	32.6	1629.2	207.4	.194	.1606	-.003	1.210	-.005837
5.070	32.6	1446.2	245.4	.250	.1635	.008	1.519	-.006189
5.100	32.6	1227.2	210.0	.189	.1387	.002	1.363	-.006492
5.110	32.6	1226.2	398.0	.495	.1855	-.001	2.669	-.006707
5.141	32.6	851.2	289.8	.265	.1292	-.002	2.055	-.007090
5.140	32.6	852.2	289.8	.265	.1294	-.009	2.059	-.007106
5.150	32.5	750.6	520.2	.558	.1448	.007	3.850	-.007402
6.020	201.3	2037.3	236.6	.084	.1618	-.004	.523	-.002209
6.030	201.3	1883.3	292.4	.123	.1734	-.002	.713	-.002440
6.060	201.3	1590.4	420.8	.218	.1873	-.001	1.166	-.002772
6.070	201.3	1206.9	383.8	.182	.1528	-.005	1.195	-.003114
6.100	201.4	879.4	391.4	.167	.1258	.002	1.325	-.003385
6.110	201.4	581.4	475.6	.169	.0962	.003	1.754	-.003688

TABLE L

TABULATED EXPERIMENTAL ISOTHERMAL DATA FOR

THE NOMINAL 5 PERCENT MIXTURE

Run	Mole Fraction C_3H_8	Inlet Temperature (°F)	Inlet Pressure (psia)	Pressure Drop (psi)	Power (Btu/min)	Flow (lb/min)	$\int_{T_1}^{T_2} C_p dT$ (Btu/lb)	$\Delta \underline{H}_T$ (Btu/lb)	$(\Delta \underline{H}/\Delta P)_T$ (Btu/lb-psi)
7.010	.052	199.9	1915.8	165.0	.323	.1102	.017	2.912	-.017648
7.011	.052	199.9	1925.8	165.0	.322	.1102	.016	2.906	-.017612
7.020	.052	199.9	1760.2	169.0	.343	.1077	.031	3.155	-.018672
7.021	.052	199.9	1763.4	169.0	.343	.1072	.034	3.165	-.018731
7.030	.052	199.9	1580.7	181.4	.368	.1044	.020	3.500	-.019294
7.031	.052	199.9	1577.5	181.6	.368	.1042	.039	3.489	-.019212
7.040	.052	199.9	1393.9	283.4	.698	.1213	.001	5.753	-.020303
7.041	.052	199.9	1388.3	284.0	.693	.1210	.008	5.721	-.020146
7.050	.052	199.9	1129.2	325.4	.759	.1132	.013	6.694	-.020573
7.051	.052	199.9	1125.8	324.2	.757	.1128	.010	6.696	-.020657
7.060	.052	199.9	824.9	286.6	.526	.0873	.010	6.016	-.020994
7.061	.052	199.9	818.5	284.2	.518	.0866	.017	5.961	-.020978
7.070	.052	199.9	554.9	217.0	.277	.0597	.012	4.630	-.021339
7.071	.052	199.9	551.7	216.6	.274	.0593	.021	4.604	-.021260
7.080	.052	199.9	554.7	451.2	.719	.0747	.011	9.612	-.021305
7.081	.052	199.9	553.7	450.4	.715	.0744	.006	9.599	-.021315
7.090	.052	199.9	1120.5	370.4	.914	.1191	.004	7.670	-.020710
7.091	.052	199.9	1119.5	369.6	.914	.1187	.003	7.696	-.020823
8.010	.051	200.9	1978.0	99.2	.232	.1381	-.007	1.686	-.016996
8.019	.051	200.9	1978.0	99.2	.232	.1381	-.007	1.687	-.017005
8.020	.051	200.9	1910.6	241.0	.940	.2158	.012	4.345	-.018033
8.030	.051	200.9	1715.8	218.0	.782	.1926	-.002	4.056	-.018608
8.039	.051	200.9	1715.8	218.0	.782	.1930	-.002	4.052	-.018588
8.040	.051	200.9	1504.0	191.4	.612	.1676	-.008	3.659	-.019121
8.050	.051	200.9	1315.0	244.4	.846	.1747	-.003	4.849	-.019843
8.060	.051	200.9	1115.5	209.4	.621	.1469	-.002	4.227	-.020188
8.061	.051	200.9	1114.4	208.8	.621	.1467	-.000	4.231	-.020265
8.070	.051	200.9	909.7	206.8	.553	.1291	.001	4.281	-.020701
8.071	.051	200.9	909.9	206.8	.553	.1291	.004	4.277	-.020684
8.080	.051	200.9	704.5	227.3	.549	.1147	.009	4.773	-.021000
8.081	.051	200.9	707.0	228.7	.553	.1152	.013	4.788	-.020937
8.090	.051	200.9	514.8	254.9	.521	.0967	.001	5.379	-.021105
8.091	.051	200.9	512.9	254.2	.520	.0964	.013	5.384	-.021181
8.100	.051	200.9	319.2	218.2	.301	.0636	.018	4.710	-.021586
8.101	.051	200.9	317.5	218.2	.294	.0633	-.013	4.657	-.021345
9.010	.051	91.6	1999.5	91.0	.379	.1592	.010	2.373	-.026082
9.011	.051	91.6	2000.3	91.4	.379	.1592	.010	2.374	-.025975
9.020	.051	91.7	1932.3	148.4	.820	.2024	.017	4.034	-.027183
9.021	.051	91.7	1932.1	148.6	.820	.2024	.005	4.046	-.027233
9.030	.051	91.6	1802.3	179.0	1.095	.2143	.004	5.105	-.028521
9.031	.051	91.6	1802.6	178.6	1.095	.2144	.000	5.108	-.028604
9.040	.051	91.6	1620.0	217.2	1.451	.2217	.003	6.543	-.030125
9.041	.051	91.6	1621.4	217.2	1.445	.2217	-.001	6.517	-.030009
9.050	.051	91.6	1440.0	240.8	1.623	.2171	-.002	7.478	-.031057
9.051	.051	91.7	1440.8	239.8	1.617	.2168	.011	7.446	-.031056
9.060	.051	91.6	1234.5	266.6	1.737	.2067	.001	8.406	-.031534
9.061	.051	91.6	1235.4	265.8	1.730	.2067	-.011	8.381	-.031535
9.070	.051	91.6	970.2	215.6	1.090	.1600	.011	6.804	-.031561
9.071	.051	91.6	969.4	215.4	1.090	.1599	.013	6.807	-.031603
9.080	.051	91.6	786.0	209.6	.908	.1377	.012	6.583	-.031409
9.081	.051	91.6	786.0	209.4	.908	.1377	.002	6.592	-.031485
9.090	.051	91.6	580.7	239.8	.882	.1187	-.001	7.434	-.031002
9.091	.051	91.6	580.4	239.4	.882	.1186	-.001	7.437	-.031070
9.100	.051	91.6	346.3	241.4	.581	.0801	-.005	7.265	-.030096
9.101	.051	91.6	345.6	241.4	.586	.0800	.014	7.306	-.030268
10.010	.051	-27.0	1941.5	86.4	.514	.2123	-.020	2.440	-.028244
10.011	.051	-27.0	1943.9	86.8	.518	.2129	-.019	2.452	-.028246
10.020	.051	-27.0	1886.1	100.2	.722	.2267	.001	3.184	-.031775

TABLE L

(Continued)

Run	Mole Fraction C_3H_8	Inlet Temperature (°F)	Inlet Pressure (psia)	Pressure Drop (psi)	Power (Btu/min)	Flow (lb/min)	$\int_{T_1}^{T_2} C_p dT$ (Btu/lb)	ΔH_T (Btu/lb)	$(\Delta H/\Delta P)_T$ (Btu/lb-psi)
10.021	.051	-27.0	1887.7	100.0	.722	.2261	.031	3.161	-.031613
10.030	.052	-27.0	1800.2	100.4	.830	.2230	.012	3.710	-.036951
10.031	.051	-27.0	1799.6	100.2	.830	.2228	.001	3.724	-.037171
10.040	.051	-27.0	1704.8	107.0	1.067	.2242	.013	4.744	-.044339
10.041	.051	-27.0	1704.2	106.8	1.061	.2238	.025	4.716	-.044164
10.050	.051	-27.0	1597.8	121.0	1.512	.2306	.019	6.540	-.054055
10.051	.051	-27.0	1596.2	121.2	1.512	.2305	-.008	6.569	-.054208
10.060	.051	-27.0	1479.8	127.0	1.858	.2250	.016	8.241	-.064899
10.061	.051	-27.0	1479.0	127.2	1.858	.2249	.007	8.255	-.064900
10.070	.051	-27.0	1362.4	139.4	2.281	.2216	-.005	10.302	-.073908
10.071	.051	-27.0	1361.8	139.4	2.280	.2214	.007	10.295	-.073860
10.080	.051	-27.0	1254.8	159.8	2.781	.2212	.028	12.546	-.078517
10.081	.051	-27.0	1251.4	159.4	2.763	.2205	.032	12.502	-.078436
10.090	.051	-27.0	1129.0	174.0	2.884	.2111	.001	13.660	-.078511
10.091	.051	-27.0	1127.2	174.2	2.874	.2106	.013	13.634	-.078274
11.010	.051	-27.1	1013.1	146.4	1.979	.1781	.018	11.092	-.075771
11.011	.051	-27.1	1012.9	146.4	1.979	.1781	.022	11.088	-.075742
11.020	.051	-27.1	837.6	145.0	1.530	.1527	.019	9.998	-.068958
11.021	.051	-27.1	837.3	145.2	1.530	.1526	.018	10.006	-.068917
11.030	.051	-27.1	702.7	177.0	1.628	.1460	-.005	11.151	-.063004
11.031	.051	-27.1	702.3	177.0	1.628	.1460	-.001	11.148	-.062989
11.040	.051	-27.1	535.9	223.2	1.645	.1311	-.011	12.561	-.056282
11.041	.051	-27.1	535.3	222.8	1.645	.1308	.008	12.561	-.056381
11.050	.051	-27.1	305.1	199.6	.806	.0806	.010	9.989	-.050048
11.051	.051	-27.1	304.6	199.4	.806	.0805	.013	9.993	-.050122
11.060	.051	-27.1	1109.3	186.2	3.117	.2145	.021	14.509	-.077927
11.061	.051	-27.1	1108.3	186.0	3.106	.2142	.017	14.483	-.077872
12.010	.051	-147.3	1791.2	604.9	.000	.1129	.637	-.637	.001054
12.011	.051	-147.4	1787.4	605.3	.000	.1127	.630	-.630	.001041
12.020	.051	-147.4	1747.1	223.8	.000	.0669	.304	-.304	.001359
12.021	.051	-147.4	1744.9	224.0	.000	.0668	.301	-.301	.001345
12.030	.051	-147.4	1290.3	284.2	.000	.0750	.083	-.083	.000293
12.031	.051	-147.4	1292.1	285.6	.000	.0753	.075	-.075	.000263
12.040	.051	-147.4	1307.5	510.0	.000	.1023	-.014	.014	-.000028
12.041	.051	-147.5	1305.1	509.4	.000	.1021	-.018	.018	-.000035
12.050	.051	-147.4	1315.1	758.8	.047	.1260	.002	.370	-.000488
12.051	.051	-147.4	1312.6	757.0	.047	.1259	-.001	.373	-.000493

TABLE LI

CONSTANTS FOR BENEDICT-WEBB-RUBIN EQUATIONS OF STATE

Units: atmospheres, litres, gram-moles, °K

R = 0.08206
T(°K) = 273.15 + T(°C)

	Methane[10]	Propane[10]	Nitrogen		
			Stotler & Benedict[179]	Crain & Sonntag[36]	Bloomer & Rao[15]
A_o	1.855	6.87225	1.1925	0.872086	1.27389
B_o	0.0426	0.097313	0.0458	0.0281066	0.0484824
C_o	22570.	508256.	5889.07	7813.75	4273.
a	0.0494	0.9477	0.0149	0.0312319	0.0178444
b	.00338004	0.0225	0.00198154	0.0032351	0.00232373
c	2545.	129000.	548.064	547.364	475.
α	0.000124359	0.000607175	0.000291545	0.0000709232	0.000153
γ	0.006	0.022	0.0075	0.0045	0.0065
D_o					7617810.
δ					832000.

TABLE LII

COMBINING RULES FOR CONSTANTS IN THE B-W-R EQUATION OF STATE

$$A_{o\ mix} = (\sum_i x_i A_{o_i}^{1/2})^2$$

$$B_{o\ mix} = \frac{1}{8} \sum_i \sum_j x_i x_j (B_{o_i}^{1/3} + B_{o_j}^{1/3})^3$$

$$C_{o\ mix} = (\sum_i x_i C_{o_i}^{1/2})^2$$

$$a_{mix} = (\sum_i x_i a_i^{1/3})^3$$

$$b_{mix} = (\sum_i x_i b_i^{1/3})^3$$

$$c_{mix} = (\sum_i x_i c_i^{1/3})^3$$

$$\alpha_{mix} = (\sum_i x_i \alpha_i^{1/3})^3$$

$$\gamma_{mix} = (\sum_i x_i \gamma_i^{1/2})^2$$

SAMPLE CALCULATION

The conditions chosen are 1500 psia and 50°F for the nominal 43 mole percent nitrogen in methane mixture. The following procedure was used to obtained the enthalpy tabulated in Table XXX:

1. The enthalpy of the ideal gas mixture of 100°F and zero pressure was calculated from the values of Rossini adjusted to the enthalpy datum of the present work. This calculation is given on Page 127 and results in a value of 278.23 BTU/lb.
2. The effect of pressure on enthalpy from zero pressure to 1500 psia was estimated using the Benedict-Webb-Rubin equation for the enthalpy departure given on Page 167 with the constants for nitrogen of Stotler and Benedict and those for methane of Benedict, Webb, and Rubin given in Table LI. The constants for the mixture were determined using the combining rules given in Table LII. This calculation resulted in an enthalpy departure of 20.05 BTU/lb. making the enthalpy at 1500 psia and 100°F equal to 258.18/lb.
3. The experimental data of $(\Delta \underline{H}/\Delta T)P$ for Run 3 given on Page 180 were plotted as shown in Figure 14 and a smooth curve drawn through the data bars in the region of 50 to 115°F.
4. Integration of the smooth curve with respect to temperature between 50°F and 100°F gave a value of the enthalpy difference of 23.04 BTU/lb.
5. The enthalpy at 1500 psia and 50°F was calculated by subtracting 23.04 BTU/lb from the value at 1500 psia and 100°F of 258.18 to give 235.14 BTU/lb.
6. This value, rounded off, is listed in Table XXX for this mixture at 1500 psia and 50°F.

REFERENCES

1. Ahlert, R. C., Ph.D. Thesis, Lehigh University (1964).

2. Akers, W. W., Burns, J. F., and Fairchild, W. R., Ind. Eng. Chem., 46, 2531 (1954).

3. Andersen, J. R., Trans. Am. Soc. Mech. Eng., 72, 759 (1950).

4. Ayber, R., VDI-Forschungsh. 511 (1965).

5. Barieau, R. E., U. S. Bur. Mines Information Circular 8245 (1965).

6. Barnard, A. J., Luthra, S. P., Newitt, D. M., and Pai, M. U., Proc. Roy. Soc. (London), A209, 143 (1951).

7. Barner, H. E. and Schreiner, W. C., Hydrocarbon Processing, 45, (6), 161 (1966).

8. Beenakker, J. J. M. and Coremans, J. M. J., Prog. Intern. Res. Thermodyn. Transport Properties, Papers Symp. Thermophys. Properties, 2nd, Princeton, N. J., 1962, 3.

9. Beenakker, J. J. M., Van Eijnsbergen, B., Knoester, M., Taconis, K. W., and Zandbergen, P., Symp. Thermophys. Properties, Papers, 3rd Lafayette, Ind., 1965, 114.

10. Benedict, M., Webb, G. B., and Rubin, L. C., J. Chem. Phys., 8, 334 (1940).

11. Idem, ibid., 10, 747 (1942).

12. Bicher, L. B. and Katz, D. L., Ind. Eng. Chem., 35, 754 (1943).

13. Blagoi, Y. P., Ukrain. Fiz. Zhur., 4, 577 (1959).

14. Bloomer, O. T. and Parent, J. D., Physical-Chemical Properties of Methane-Nitrogen Mixtures, IGT Research Bulletin No. 17, April 1952.

15. Bloomer, O. T. and Rao, K. N., Thermodynamic Properties of Nitrogen, IGT Research Bulletin No. 18, October 1952.

16. Bloomer, O. T., Eakin, B. E., Ellington, R. T., and Gami, D. C., Thermodynamic Properties of Methane-Nitrogen Mixtures, IGT Research Bulletin No. 21, February 1955.

17. Bolshakov, P. E., Gelperin, I. I., and Ostronov, M. G., Zhur. Fiz. Khim., 40, 1914 (1966).

18. Bolshakov, P. E., Gelperin, I. I., Ostronov, M. G., and Orlova, A. A. Zhur. Fiz. Khim., 41, 689 (1967).

19. Brewer, J. and Geist, J. M., J. Chem. Eng. Data, 6, 405 (1961).

20. Buckingham, E., Phil. Mag., 6, 518 (1903).

21. Budenholzer, R. A., Sage, B. H., and Lacey, W. N., Ind. Eng. Chem., 31, 1288 (1939).

22. Idem, ibid., 32, 384 (1940).

23. Budenholzer, R. A., Botkin, D. F., Sage, B. H., and Lacey, W. N., ibid., 34, 878 (1942).

24. Canjar, L. N. and Peterka, V. J., A.I.Ch.E. J., 2, 343 (1956).

25. Canjar, L. N. and Edmister, W. C., Chem. Eng. Prog. Symp. Ser., 49, No. 7, 73 (1953).

26. Charnley, A., Isles, G. L., and Townley, J. R., Proc. Roy. Soc. (London), A218, 133 (1953).

27. Charnley, A., Rowlinson, J. S., Sutton, J. R., and Townley, J. R., Proc. Roy. Soc. (London), A230, 354 (1955).

28. Cheung, H. and Wang, D. I.-J., I&EC Fundamentals, 3, 355 (1964)

29. Cines, M. R., Roach, J. T., Hogan, R. J. and Roland, C. H., Chem. Eng. Prog. Symp. Series, 49, No. 6, 1(1953).

30. Collins, S. C. and Keyes, F. G., Proc. Am. Acad. Arts Sci., 72, 283 (1938).

31. Collins, S. C. and Keyes, F. G., J. Phys. Chem., 43, 5 (1939).

32. Colwell, J. H., Gill, E. K., and Morrison, J. A., J. Chem. Phys., 39, 635 (1963).

33. Cope, J. Q., Lewis, W. K., and Weber, H. C., Ind. Eng. Chem., 23, 887 (1931).

34. Costa, E. C. and Smith, J. M., J. Chem. Eng. Data, 8, 289 (1963).

35. Couch, H. T., Kozicki, W., and Sage, B. H., J. Chem. Eng. Data, 8, 346 (1963).

36. Crain, R. W., Jr. and Sonntag, R. E., J. Chem. Eng. Data, 12, 73 (1967).

37. Cuffel, R. F., Kozicki, W., and Sage, B. H., Can. J. Chem. Eng., 41, 19 (1963).

38. Curl, R. F., Jr., and Pitzer, K. S., Ind. Eng. Chem., 50, 265 (1958).

39. Cutler, A. J. B. and Morrison, J. A., Trans. Farad. Soc., 61, 429 (1965).

40. Dawson, P. P., Jr. and McKetta, J. J., Petroleum Refiner, 39, (4), 151 (1960).

41. Dillard, D. D., M. S. Thesis, Oklahoma State University (1966).

42. Dillard, D. D., Edmister, W. C., Erbar, J. H., and Robinson, R. L., Jr., Unpublished Manuscript (1966).

43. Din, F. in Thermodynamic Functions of Gases, ed. F. Din, Vol. 3, 72 (1961).

44. Dolan, J. P., Ph.D. Thesis, Illinois Institute of Technology (1967).

45. Douslin, D. R., Harrison, R. H., Moore, R. T., and McCullough, J. P., J. Chem. Eng. Data, 9, 358 (1964).

46. Eckert, C. A., Renon, H., and Prausnitz, J. M., I&EC Fundamentals, 6, 58 (1967).

47. Edmister, W. C., Ind. Eng. Chem., 30, 352 (1938).

48. Edmister, W. C. and Canjar, L. N., Chem. Eng. Prog. Symp. Ser., 49, No. 7, 85 (1953).

49. Edmister, W. C., A.I.Ch.E. J., 1, 38 (1955).

50. Edmister, W. C., Persyn, C. L., and Erbar, J. H., Proc. Ann. Conv., Nat. Gas. Process. Assoc., Tech. Papers, 42, 50 (1963).

51. Edmister, W. C., Thompson, R. E., and Yarborough, L., A.I.Ch.E. J., 9, 116 (1963).

52. Edmister, W. C., and Yarborough, L., A.I.Ch.E. J., 9, 240 (1963).

53. Erbar, J. H., Persyn, C. L., and Edmister, W. C., Proc. Ann. Conv., Nat. Gas Process. Assoc., Tech. Papers, 43, 26 (1964).

54. Eubank, P. T. and Smith, J. M., J. Chem. Eng. Data, 7, 75 (1962).

55. Eucken, A., Clusius, K., and Berger, W., Z. tech. Physik, 13, 267 (1932).

56. Eucken, A. and Berger, W., Z. tech. Physik, 15, 369 (1934).

57. Eucken, A. and Berger, W., Z. ges. Kälte-Ind., 41, 145 (1934).

58. Fastovsky, V. G. and Krestinsky, Yu. A., Zhur. Fiz. Khim., 15, 525 (1941).

59. Fastovsky, V. G. and Petrovsky, Yu. V., Zhur. Fiz. Khim., 31, 2317 (1957).

60. Faulkner, R. C., Jr., Ph.D. Thesis, University of Michigan (1959).

61. Fedorova, M., Acta physicochim. U.R.S.S., 10, 539 (1939).

62. Findlay, R. A., Mora, M. and Jacoby, R. H., Paper presented at the 32nd Midyear Meeting of the American Petroleum Institute's Division of Refining, Los Angeles, California, May 16, 1967.

63. Francis, P. G., McGlashan, M. L., and Wormald, C. J., Symposium on Thermodynamics and Thermochemistry, Lund, Sweden (1963).

64. Frank, A. and Clusius, K., Z. physik. Chem., B36, 291 (1937).

65. Frolich, P. K., Tauch, E. J., Hogan, J. J., and Peer, A. A., Ind. Eng. Chem., 23, 548 (1931).

66. Fuks, S. and Bellemans, A., Bull. Soc. Chim. Belges, 76, 290 (1967).

67. Gelperin, I. I., Bolshakov, P. E., and Ostronov, M. G., Zhur. Fiz. Khim., 41, 369 (1967).

68. Giddings, J. G., Kao, J. T. F., and Kobayashi, R., J. Chem. Phys., 45, 578 (1966).

69. Gilliland, E. R., and Lukes, R. V., Ind. Eng. Chem., 32, 957 (1940).

70. Gilliland, E. R. and Parekh, M. D., Ind. Eng. Chem., 34, 360 (1942).

71. Gladun, A., Cryogenics, 6, 31 (1966).

72. Goff, J. A. and Gratch, S., Trans. Am. Soc. Mech. Eng., 72, 741 (1950)

73. Grossmann, E. D., Ph.D. Thesis, University of Pennsylvania (1965).

74. Gusak, I. M., Phys. Z. Sowjet., 11, 60 (1937).

75. Head, J. F., Ph.D. Thesis, University of London (1960).

76. Helgeson, N. L. and Sage, B. H., J. Chem. Eng. Data, 12, 47 (1967).

77. Hermsen, R. W. and Prausnitz, J. M., Chem. Eng. Sci., 21, 803 (1966).

78. Hestermans, P. and White, D., J. Phys. Chem., 65, 362 (1961).

79. Hilsenrath, J. et al., Tables of Thermal Properties of Gases, NBS Circular 564 (1955).

80. Hobson, M. and Weber, J. H., Petroleum Processing, 12, (9), 153 (1957).

81. Idem, Chem. Eng., 64, (12), 272 (1957).

82. Holcomb, D. E. and Brown, G. G., Ind. Eng. Chem., 34, 590 (1942).

83. Houseman, J. and Sage, B. H., J. Chem. Eng. Data, 10, 250 (1965).

84. Huang, E. T. S., Swift, G. W., and Kurata, F., A.I.Ch.E. J., 13, 846 (1967).

85. Huff, J. A. and Reed, T. M., III, J. Chem. Eng. Data, 8, 306 (1963).

86. Huisman, J. and Sage, B. H., J. Chem. Eng. Data, 9, 223 (1964).

87. Idem, ibid., 9, 536 (1964).

88. Hujsak, K. L., Froning, H. R., and Goddin, C. S., Chem. Eng. Prog. Symp. Ser., 59, No. 44, 88 (1963).

89. Ishkin, I. P. and Kaganer, M. G., Zhur. Tekh. Fiz., 26, 2329 (1956).

90. Ishkin, I. P. and Rogovaya, I. A., Zhur. Fiz. Khim., 31, 410 (1957).

91. Isles, G. L., Ph.D. Thesis, University of Leeds (1951).

92. Jenkins, A. C. and Berwaldt, O. E., I&EC Process Design Develop., 2, 193 (1963).

93. Johnston, H. L., and White, D., Trans. Am. Soc. Mech. Eng., 70, 651 (1948).

94. Jones, M. L., Jr., Ph.D. Thesis, University of Michigan (1961).

95. Jones, M. L., Jr., Mage, D. T., Faulkner, R. C., Jr., and Katz, D. L., Chem. Eng. Prog. Symp. Ser., 59, No. 44, 52 (1963).

96. Kay, W. B., Ind. Eng. Chem., 28, 1014 (1936).

97. Kelley, R. E. and Lipscomb, T. G., M. S. Thesis, Rice University (1951).

98. Kemp, J. D., and Egan, C. J., J. Am. Chem. Soc., 60, 1521 (1938).

99. Keyes, F. G. and Burks, H. G., J. Am. Chem. Soc., 50, 1100 (1928).

100. Keyes, F. G. and Collins, S. C., Proc. Natl. Acad. Sci. (U.S.), 18, 328 (1932).

101. Knapp, H., Ind. Eng. Chem., 51, 783 (1959).

102. Knoester, M., Taconis, K. W., and Beenakker, J. J. M., Physica, 33, 389 (1967).

103. Koeppe, W., Kältetechnik, 11, 363 (1959).

104. Kohne, R. F., Anderson, R. P., and Miller, F. D., Unpublished data, U.S. Industrial Chemicals Co. (1966).

105. Koppel, L. B. and Smith, J. M., J. Chem. Eng. Data, 5, 437 (1960).

106. Kozicki, W., and Sage, B. H., J. Chem. Eng. Data, 5, 331 (1960).

107. Idem, Chem. Eng. Sci., 15, 270 (1961).

108. Kozicki, W., Cuffel, R. F., and Sage, B. H., J. Chem. Eng. Data, 7, 173 (1962).

109. Kritschewsky, I. R. and Levchenko, G. T., Acta physicochim. U.R.S.S., 14, 271 (1941).

110. Kuloor, N. R., Newitt, D. M., and Bateman, J. S., in Thermodynamic Functions of Gases, ed. F. Din, Vol. 2, 115 (1956).

111. Laverman, R. J. and Selcukoglu, Y. A., Paper presented at 11th International Institute of Refrigeration Congress, Madrid (1967).

112. Lenoir, J. M., Hydrocarbon Processing, 46, (5), 161 (1967).

113. Lunbeck, R. J., Michels, A., and Wolkers, G. J., Appl. Sci. Res., A3, 197 (1952).

114. Lydersen, A. L., Greenkorn, R. A., and Hougen, O. A., Univ. Wisc. Eng. Exp. Sta. Rept. 4 (1955).

115. McCracken, P. G. and Smith, J. M., A.I.Ch.E. J., 2, 498 (1956).

116. McKay, R. A. and Sage, B. H., J. Chem. Eng. Data, 5, 21 (1960).

117. McTaggart, H. A. and Edwards, E., Trans. Roy. Soc. Canada, 13, Section III, 57 (1919).

118. Mackey, B. H. and Krase, N. W., Ind. Eng. Chem., 22, 1060 (1930).

119. Mage, D. T., Jones, M. L., Jr., Katz, D. L., and Roebuck, J. R., Chem. Eng. Prog. Symp. Ser., 59, No. 44, 61 (1963).

120. Mage, D. T., Ph.D. Thesis, University of Michigan (1964).

121. Mage, D. T., and Katz, D. L., A.I.Ch.E. J., 12, 137 (1966).

122. Manker, E. A., Mage, D. T., Mather, A. E., Powers, J. E., and Katz, D. L., Proc. Ann. Conv., Nat. Gas Process. Assoc., Tech. Papers, 43, 3 (1964).

123. Manker, E. A., Ph.D. Thesis, University of Michigan (1964).

124. Manning, F. S. and Canjar, L. N., J. Chem. Eng. Data, 6, 364 (1961).

125. Martin, J. J. and Hou, Y. C., A.I.Ch.E. J., 1, 142 (1955).

126. Martin, J. J., J. Chem. Eng. Data, 8, 311 (1963).

127. Martin, J. J., Forthcoming paper, to appear in Ind. Eng. Chem.

128. Masi, J. F., Trans. Am. Soc. Mech. Eng., 76, 1067 (1954).

129. Mather, A. E., Powers, J. E., and Katz, D. L., Proc. Ann. Conv., Nat. Gas Process. Assoc., Tech. Papers, 44, 3 (1965).

130. Mather, A. E., Yesavage, V. F., Powers, J. E., and Katz, D. L., Proc. Ann. Conv., Nat. Gas Process. Assoc., Tech Papers, 45, 12 (1966).

131. Mather, A. E., Yesavage, V. F., Powers, J. E., and Katz, D. L., Proc. Ann. Conv., Nat. Gas Process. Assoc., Tech. Papers, 46, 3 (1967).

132. Matthews, C. S. and Hurd, C. O., Trans. A.I.Ch.E., 42, 55 (1946).

133. Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand, Princeton, N. J. (1950).

134. Medvedev, V. A., Dedikov, Yu. A., and Astrov, D. N., Zhur. Fiz. Khim., 41, 1480 (1967).

135. Montgomery, J. B. and DeVries, T., J. Am. Chem. Soc., 64, 2372 (1942).

136. Nathan, D. I., Ph.D. Thesis, University of Leeds (1965).

137. Nathan, D. I., Brit. Chem. Eng., 12, 223 (1967).

138. Natural Gas Processors Supplymens Association Data Book, Eighth ed., 203, Tulsa, Okla. (1966).

139. Orentlicher, M. and Prausnitz, J. M., Can. J. Chem. Eng., 45, 78 (1967).

140. Osborne, A., A.I.Ch.E. J., 12, 377 (1966).

141. Papadopoulos, A., Pigford, R. L., and Friend, L., Chem. Eng. Prog. Symp. Ser., 49, No. 7, 119 (1953).

142. Parekh, M.D., Sc.D. Thesis, M.I.T. (1940).

143. Pattee, E. C. and Brown, G. G., Ind. Eng. Chem., 26, 511 (1934).

144. Perry, J. H. and Herrmann, C. V., J. Phys. Chem., 39, 1189 (1935).

145. Peters, H. F., Petroleum Refiner, 28, (5), 109 (1949).

146. Pfenning, D. B., Canfield, F. B., and Kobayashi, R., J. Chem. Eng. Data, 10, 9 (1965).

147. Pitzer, K. S. and Hultgren, G. O., J. Am. Chem. Soc., 80, 4793 (1958).

148. Potter, J. H., Prog. Intern. Res. Thermodyn. Transport Properties, Paper Symp. Thermophys. Properties, 2nd, Princeton, N. J., 1962, 83.

149. Potter, J. H. and Levy, M. J., *ibid.*, 147.

150. Prausnitz, J. M. and Gunn, R. D., *A.I.Ch.E. J.*, 4, 430 (1958).

151. Price, A. R. and Kobayashi, R., *J. Chem. Eng. Data*, 4, 40 (1959).

152. Reamer, H. H., Sage, B. H., and Lacey, W. N., *Ind. Eng. Chem.*, 42, 534 (1950). See Corrections, *Ind. Eng. Chem.*, 42, 1258 (1950).

153. Redlich, O. and Kwong, J. N. S., *Chem. Rev.*, 44, 233 (1949).

154. Reid, R. C. and Sherwood, T. K., *The Properties of Gases and Liquids*, 2nd ed., p. 326, McGraw-Hill (1966).

155. Roebuck, J. R., *Phys. Rev.*, 2, 299 (1913).

156. Roebuck, J. R. and Osterberg, H., *Phys. Rev.*, 43, 60 (1933).

157. *Idem*, *ibid.*, 48, 450 (1935).

158. *Idem*, *J. Am. Chem. Soc.*, 60, 341 (1938).

159. *Idem*, *J. Chem. Phys.*, 8, 627 (1940).

160. Roof, J. G. and Baron, J. D., *J. Chem. Eng. Data*, 12, 292 (1967).

161. Rossini, F. D., *et al.*, *Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds*, Carnegie Press, Pittsburgh, Pennsylvania (1953).

162. Rutherford, W. M., *Soc. of Pet. Engrs. J.*, 2, 340 (1962).

163. Sage, B. H., Lacey, W. N., and Schaafsma, J. G., *Ind. Eng. Chem.*, 26, 214 (1934).

164. Sage, B. H., Botkin, D. F., and Lacey, W. N., *Trans. Am. Inst. Min. Met. Eng.*, 151, 206 (1943).

165. Sahgal, P. N., Ph.D. Thesis, University of London (1959).

166. Sahgal, P. N., Geist, J. M., Jambhekar, A., and Wilson, G. M., *Intern. Advan. Cryogen. Eng.*, 10, 224 (1965).

167. Scheibel, E. G. and Jenny, F. J., *Ind. Eng. Chem.*, 37, 990 (1945).

168. Sehgal, I. J. S., Yesavage, V. F., Katz, D. L. and Powers, J. E., Forthcoming publication, *Hydrocarbon Processing* (1968).

169. Shannon, P. T., Gustafson, D. B., and O'Neill, P. S., *A.I.Ch.E. J.*, 9, 64 (1963).

170. Shannon, P. T. and O'Neill, P. S., *A.I.Ch.E. J.*, 9, 229 (1963).

171. Sirota, A. M. and Grishkov, A. Ya., *Teploenergetika*, 8, 61 (1966).

172. Smith, W. J. S., Durbin, L. D., and Kobayashi, R., *J. Chem. Eng. Data*, 5, 316 (1960).

173. Sprow, F. B. and Prausnitz, J. M., *A.I.Ch.E. J.*, 12, 780 (1966).

174. Steckel, F. A. and Zinn, N. M., *Zhur. khim. Prom.*, 16, (8), 24 (1939).

175. Stepanov, G. V. and Mursalov, B. A., *Dokl. Akad. Nauk SSSR*, 163, 1189 (1965).

176. Stevens, W. F. and Thodos, G., *A.I.Ch.E. J.*, 9, 293 (1963).

177. Stockett, A. L. and Wenzel, L. A., *A.I.Ch.E. J.*, 10, 557 (1964).

178. Storvick, T. S. and Smith, J. M., *J. Chem. Eng. Data*, 5, 133 (1960).

179. Stotler, H. H. and Benedict, M., *Chem. Eng. Prog. Symp. Ser.*, 49, No. 6, 25 (1953).

180. Stribolt, K. Ö. and Lydersen, A., *Chem.-Ing.-Tech.*, 39, 96 (1967).

181. Strickland-Constable, R. F., *Proc. Roy. Soc. (London)*, A209, 14 (1951).

182. Strobridge, T. R., U.S. Nat. Bur. Stds., Technical Note 129 (1962).

183. Tester, H. E. in *Thermodynamic Functions of Gases*, ed. F. Din, Vol. 3, 1.

184. Tooke, J. F. and Hays, G. E., *Proc. Ann. Conv., Nat. Gas Process. Assoc., Tech. Papers*, 42, 45 (1963).

185. Torocheshnikov, N. S. and Levius, L. A., *Zhur. khim. Prom.*, 16, (1), 19 (1939).

186. Trautz, M. and Sorg, K. G., *Ann. Physik*, 10, 81 (1931).

187. Tully, P. C. and Edmister, W. C., *A.I.Ch.E. J.*, 13, 155 (1967).

188. Van Eijnsbergen, B., Ph.D. Thesis, University of Leiden (1966).

189. Van Eijnsbergen, B. and Beenakker, J. J. M., Forthcoming publication, *Physica* (1967).

190. Vellinger, E. and Pons, E., *Compt. Rend.*, 217, 689 (1943).

191. Vukalovich, M. P., Altunin, V. V., and Gureev, A. N., *Teploenergetika*, 11 (9), 68 (1964).

192. Weinaug, C. F. and Katz, D. L., *Ind. Eng. Chem.*, 35, 239 (1943).

193. Wiener, L. D., Paper presented at 58th National A.I.Ch.E. Meeting, Dallas (1966).

194. Wiener, L. D., Hydrocarbon Processing, 46, (4), 131 (1967).

195. Wilson, G. M., Intern. Advances in Cryogenic Eng., 11, 392 (1966).

196. Wilson, G. M. and Barton, S. T., Proc. Ann. Conv., Nat. Gas. Process. Assoc., Tech. Papers, 46, 18 (1967).

197. Wood, R. E., Boone, W. J., Jr., Marshall, J. D., and Baer, F. W., U.S. Bur. Mines, Rept. Inv. 6896 (1967).

198. Yarborough, L., Ph.D. Thesis, Oklahoma State University (1964).

199. Yarborough, L. and Edmister, W. C., A.I.Ch.E. J., 11, 492 (1965).

200. Yen, L. C. and Alexander, R. E., A.I.Ch.E. J., 11, 334 (1965).

201. Yen, L. C., Personal Communication, April 24 (1967).