VISCOSITY OF SATURATED

HYDROCARBON MIXTURES

By

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PREFACE

The behavior of liquid mixture viscosity is only partially understood. Data and correlations are needed to more completely understand the change in viscosity under varying conditions of temperature, pressure and composition. This study presents experimental data on saturated liquid viscosity for methane-n-decane, ethane-n-decane, methane-n-hexane, and methane-n-butane-n-decane mixtures at pressures up to 1200 psia. A temperature range of 1 degree F to 174 degrees F was covered.

I wish to thank Professor R. N. Maddox who provided invaluable advice and assistance while serving as my adviser during the research for this project. Professor J. H. Erbar aided in applying the NGPA computer program whenever needed during this work. Mr. Eugene McCroskey, laboratory technician, deserves a special thanks for his many helpful contributions to this project. Several graduate students aided greatly and I would like to acknowledge them: Stuart E. Bennett, for designing and constructing the experimental apparatus; Harry G. Rackett, for his assistance in applying his saturated liquid density correlation; Carl W. Orrick, for his aid in writing computer programs; and Matt Sooter, for his help in the coordination of the final printing efforts.

My parents were a source of constant encouragement during my graduate study and deserve a very special thanks for all that they have done.

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CHAPTER I

INTRODUCTION

Viscosity is an important parameter in many scientific and engineering areas, such as momentum, heat, and mass transfer. Only a small amount of experimental data is available in the literature for saturated hydrocarbon systems and a general reliable, correlation does not exist at present.

This study was undertaken to measure experimentally kinematic viscosity for binary and ternary mixtures of light with heavier hydrocarbons.

A capillary viscometer was used to obtain experimental measurements of liquid kinematic viscosity for the methane-n-decane, ethane-n-decane, methane-n-hexane binary systems, and for the methane-n-butane-n-decane ternary system.

Absolute viscosity was calculated from kinematic viscosity and liquid density. Variations of viscosity with temperature, pressure, and composition are graphically illustrated.

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CHAPTER II

LITERATURE REVIEW

Previous Experimental Measurements

In 1943 Bicher and Katz (3) reported one of the first investigations of hydrocarbon mixture viscosity to cover a wide pressure and temperature range. They used a rolling ball inclined tube viscometer to measure the viscosity of methane, propane and four of their binary mixtures (20, 40, 60, and 80 mole percent methane). Their pressure range was from 400 to 5000 psia and temperatures from 77 to 437 degrees F were used.

Experimental viscosity data for liquid, gaseous and dense fluid propane were published in 1960 by workers (20) at the Institute of Gas Technology (IGT). The data were obtained with a capillary viscometer and an accuracy of 0.5% was claimed. Their pressure range was from 100 to 8000 psia for nine temperatures from 77 to 280 degrees F. Dolan and co-workers (7) continued the work at IGT, publishing data for n-butane in 1963 and later data for methane-n-butane mixtures (8). The mixture pressure range was from 100 to 10,000 psia with temperatures from 100 to 460 degrees F.

Reamer, et. al. (18) reported information in 1959 on

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the construction of a new type viscometer employing a rotating cylinder. They used the new instrument in the measurement of viscosities of n-pentane. Later this viscometer was used by Carmichael and associates (5) to study the viscosity behavior of methane-n-butane mixtures. Comparison with the data of Dolan et. al. (8) showed an average deviation of 1.1% for a mixture of 0.394 mole fraction methane.

Lee et. al. (12) measured the viscosity of liquid methane-n-decane mixtures using the IGT capillary viscometer. Their three mixtures contained 0.3, 0.5, and 0.7 mole fraction methane. A temperature range of 100 to 340 degrees F was used and pressures from 1500 to 7000 psia were employed. Their measurements were generally not made on saturated mixtures.

Fourteen binary hydrocarbon mixtures were studied by Heric and Brewer (9) while Katte and Chaudri (11) presented data for binary systems of benzyl acetate, aniline, dioxane, and m-cresol. These two studies were conducted at atmospheris pressure and at temperatures from 20 to 40 degrees C.

Recently Bennett (2) studied the viscosity behavior of the methane-n-nonane system using a Zeitfuchs capillary viscometer. Kinematic viscosity data were obtained for saturated mixtures in a temperature range of -30 to +78 degrees F and for a pressure range of 150 to 1200 psia. The variance of absolute viscosity with changes in temperature, pressure, composition, and density were

investigated. The viscosity data were also correlated with
surface tension.

The viscosity behavior of the n-butane-n-decane system
was reported by White (22) in 1969. Using the equipment
built by Bennett (2), kinematic viscosity data were ob-
tained for saturated mixtures. A liquid composition range
of 0.25 to 0.85 mole fraction butane was investigated using
a temperature range of 50 to 130 degrees F and a pressure
range of 15.0 to 31.5 psia. The experimental viscosity
data were used to test several liquid viscosity correla-
tions.

Capillary Viscometer

Bird et. al. (4) present the following result of the
derivation of Poiseuille's Law for fluid flow inside tubes

$$Q = \frac{\pi (\Delta P) r^4}{8 \mu L} \tag{1}$$

Van Waser et. al. (17) showed this relationship could
be applied to capillary viscometer measurements if the fol-
lowing substitutions were made.

$$\Delta P = \rho g h \qquad \text{and} \qquad Q = V/t$$

In addition, the introduction of a kinetic energy term, ϵ,
and rearrangement of Equation 1 results in the following:

$$\mu = \frac{\pi r^4 \rho g h t}{8 L V} - \frac{\epsilon \rho V}{8 \pi L t} \tag{2}$$

Noting that kinematic viscosity, ν, is equal to (μ/ρ), the

following expression may be obtained:

$$\nu = \frac{\pi r^4 g h t}{8 L V} - \frac{\in V}{8 \pi L t}$$ (3)

This relationship can be written as

$$\nu = K_1 t - K_2 / t$$ (4)

in which K_1 is characteristic of a given viscometer and K_2 is reported by Van Waser (21) to be a function of the Reynolds' number.

The difficulty in evaluation of K_2 reported by Johnson et. al.(10) suggests that the best solution to this problem is to use a viscometer designed to make K_2 as small as possible. The Zeitfuchs style viscometer was found to have a constant K_2 small enough to give a correction for kinetic energy of about 0.03% (10). Ignoring this small term, Equation 4 may be written in the following form:

$$\nu = K_1 t \qquad or \qquad \nu = K t$$ (5)

Equation 5 served as the basis for the viscosity measurements made during this study. K was determined by measuring the efflux time, t, of a specified volume of a liquid having a known kinematic viscosity, ν. Once K was determined, the kinematic viscosity of a test liquid was then determined by measuring the efflux time.

Johnson et. al.(10) evaluated the Zeitfuchs capillary viscometer and reported that the crossarm design of the instrument virtually eliminated error that could be intro-

duced by the difference in surface tension between the calibration and test liquids. The crossarm design eliminates error resulting from the liquid clinging to the walls of the vessel from which the liquid is drawn during the flow process of viscosity measurement.

In all of the investigations cited, viscosity was reported in absolute units, that is, in units of poise or the equivalent. Kinematic viscosity in units of stokes was reported, in addition to absolute viscosity, by Dolan et. al. (7,8), Heric and Brewer (9), Bennett (2) and White (22). In most, if not all, investigations the absolute viscosity was determined indirectly by first measuring the kinematic viscosity and then multiplying by the liquid density in consistent units to obtain the absolute viscosity.

CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURE

Experimental Apparatus

The apparatus employed was basically the same as constructed by Bennett (2) and the reader is referred to his thesis for a more detailed description of the experimental equipment.

The experimental equipment consisted primarily of the capillary viscometer, the pressure cell, the constant temperature bath, and the flow system used to introduce the test gas into the cell. Other equipment included a refrigeration system, temperature controller, and vacuum pump.

Viscometer

A model C-50 Zeitfuchs crossarm viscometer (Figure 1) was used to make all viscosity measurements. Manufactured by the California Laboratory Equipment Company, the viscometer had a one piece glass body with a metal support attached. The viscometer consisted of a reservoir, crossarm, capillary tube, measuring bulb, and supports.

The liquid sample was held in the reservoir and
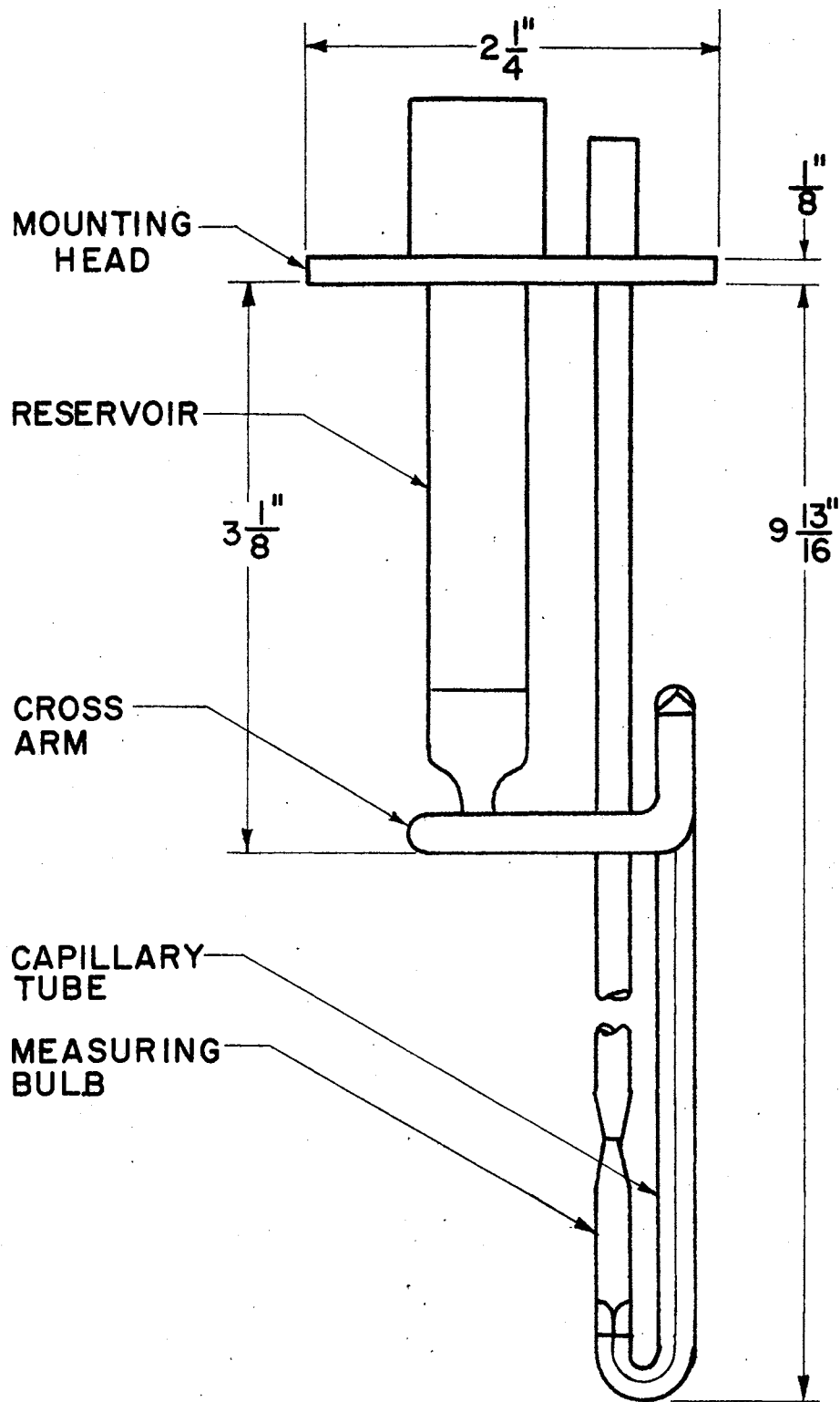
Figure I.   Zeitfuchs Style Viscometer

carried to the capillary tube by the crossarm. The capillary tube had a measuring bulb with scribed lines above and below the bulb body. These lines served as timing marks for the viscosity measurements. The capillary support served to hold the viscometer in place within the pressure cell.

The viscometer was connected to the test gas feed line by a 1½ inch length of "Tygon" tubing fitted over the end of the capillary tube. A "Teflon" sleeve fitted inside the reservoir in the original equipment was found to produce fine shreds of "Teflon" which did plug the capillary tube of the viscometer and were very difficult to remove. This prompted the removal of the sleeve. The apparatus was found to operate well without the troublesome part.

The viscometer was held in place with a 1/8 inch screw attached to the pressure cell top.

Pressure Cell

The pressure cell (Figure 2) contained the viscometer during operation and allowed observation of the viscometer reservoir and measuring bulb. The pressure cell served to hold the desired pressure on the sample during viscosity measurements.

Observation of the viscometer inside the pressure cell was accomplished through 4 view ports (Figure 3) installed in the sides of the pressure cell body. The windows for

Figure 2. Pressure Cell
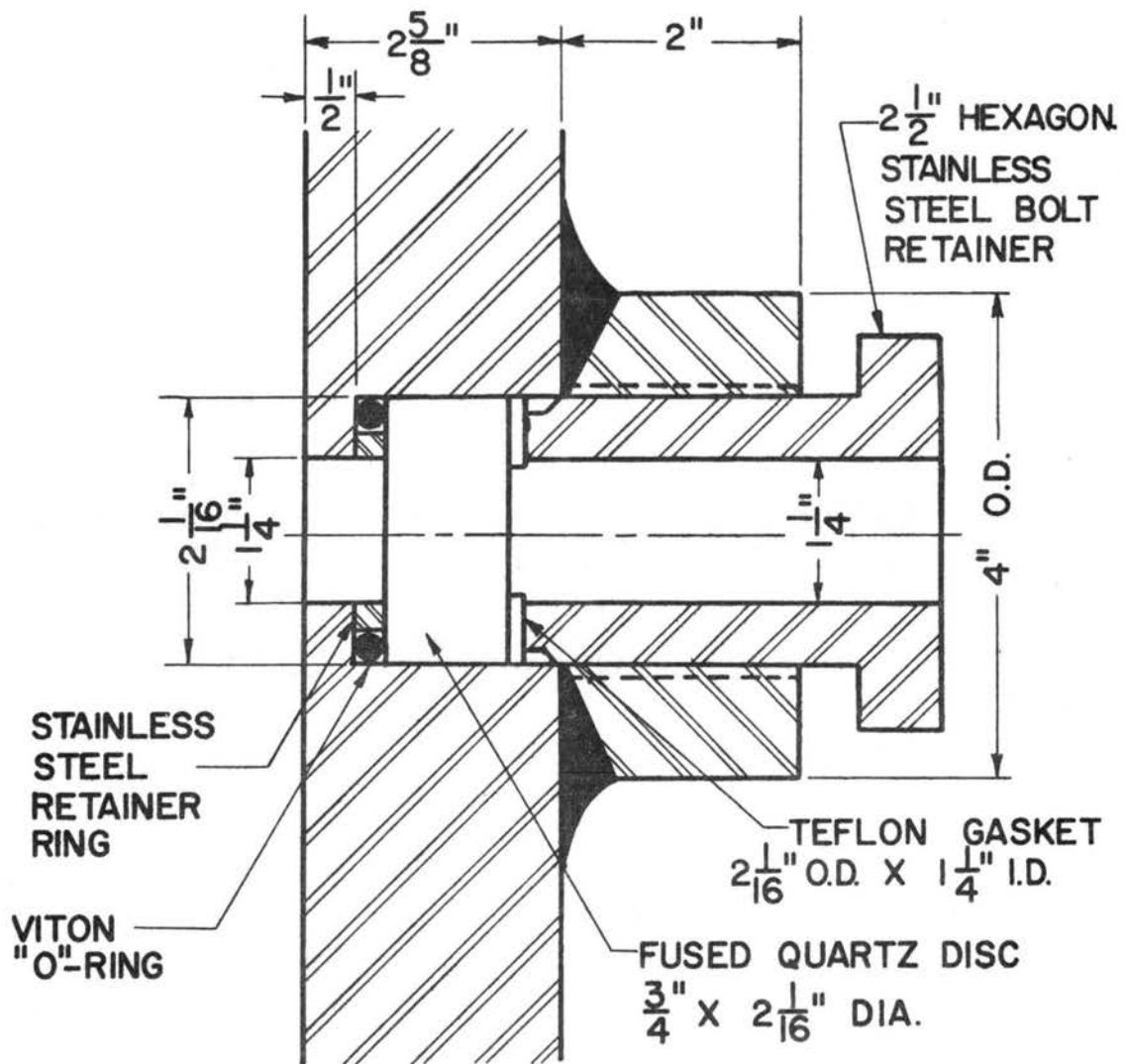
Figure 3.   View Port Details

the view ports were made of fused quartz. All obser-
vations were made indirectly by mirror reflection due to
the possibility of view port failure at high pressure.

The heavy cell body and top were constructed of 304
stainless steel. A tight seal was accomplished by the
use of "Viton" O-rings in all view port assemblies and
the top to cell body seal. The cell body and top assembly
is shown in Figure 4. Eight 5/8 inch diameter bolts
secured the cell top to the cell body.

The liquid injection system of the original equip-
ment was found to operate unsatisfactorily and was
removed. The exterior opening left by the removal of
the liquid injection system was sealed with a threaded
brass plug. Experimentation showed that the liquid
sample could be placed directly into the viscometer
reservoir and then evacuated to a pressure of 25 mm. of
mercury. After evacuation, the system was swept three
times with test gas (method described in Experimental
Procedure). The loss of the liquid sample amounted to
less than 0.1% by weight.

Temperature Control

Surrounding the pressure cell was a constant temp-
erature bath. A refrigeration unit circulating methanol
as the coolant was attached to the bath. For measure-
ments below ambient temperature, the refrigeration system
provided an easy method of cooling for long periods of

SOLID
BRASS PLUG

TO
PRESSURE
SYSTEM

TO
PRESSURE
SYSTEM

STANDARD
AUTOCLAVE
HI-PRESSURE
FITTING

PRESSURE
CELL
FLANGE

O-RING
SEAL

PLASTIC
TUBING
CONNECTOR

ANNULAR
REGION-
PERMITS
GAS FLOW

TO CAPILLARY
OF VISCOMETER

TO CROSS ARM
OF VISCOMETER
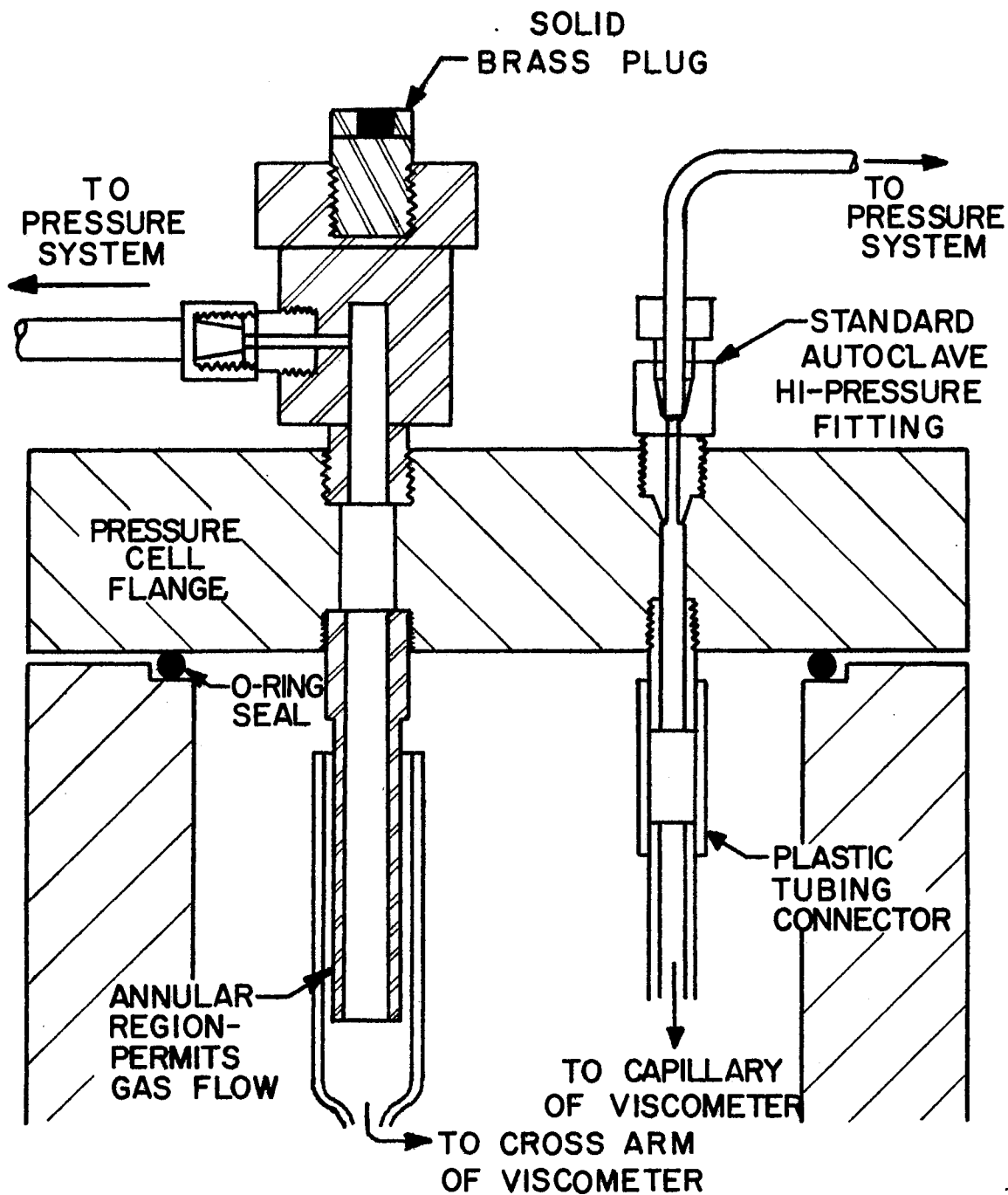
Figure 4. Details of Viscometer Connections

time. Fine temperature control was achieved with an immersion heater and Hallikainen Thermotrol. An electric stirrer was used to improve bath mixing.

At temperatures above ambient, the refrigeration lines were sealed in the bath and water was substituted as the bath medium.

Pressure Distribution System

The pressure distribution system (Figure 5) served to introduce the test gas into the pressure cell, control the liquid level in the viscometer, and to achieve fine adjustment of the system pressure.

Two pressure gauges were used to measure the system pressure. A Heise Bourdon tube gauge graduated in 5 psi increments from 0 psig to 3000 psig was used for high pressure measurements. For low pressure and partial vacuum measurements, an Ascroft-American Duragauge graduated in $\frac{1}{2}$ psi increments from 0 psig to 30 psig and in $\frac{1}{2}$ inch of mercury increments from 0 to 30 inches of mercury vacuum was used. (See Appendix C for calibrations.)

Coarse control of the system pressure was maintained by adjustment of the regulator on the test gas cylinder. Fine control was achieved by use of the inline pressure controller. The inline pressure controller consisted of a cylinder and a piston attached to a screw drive. Adjusting the piston position in the cylinder by means of the screw drive changed the system volume and pressure.

HEISE BOURDON- TUBE
PRESSURE GAUGE

INLINE
PRESSURE
CONTROLLER

LOW
PRESSURE
& VACUUM
GAUGE

VENT
VALVE

A

B

C

FROM
TEST GAS
SOURCE VIA
MATHESON
REGULATOR

F

E

OBSERVATION
PORTS

D

G

TO
VACUUM
PUMP

PRESSURE CELL
AND
TEMPERATURE BATH
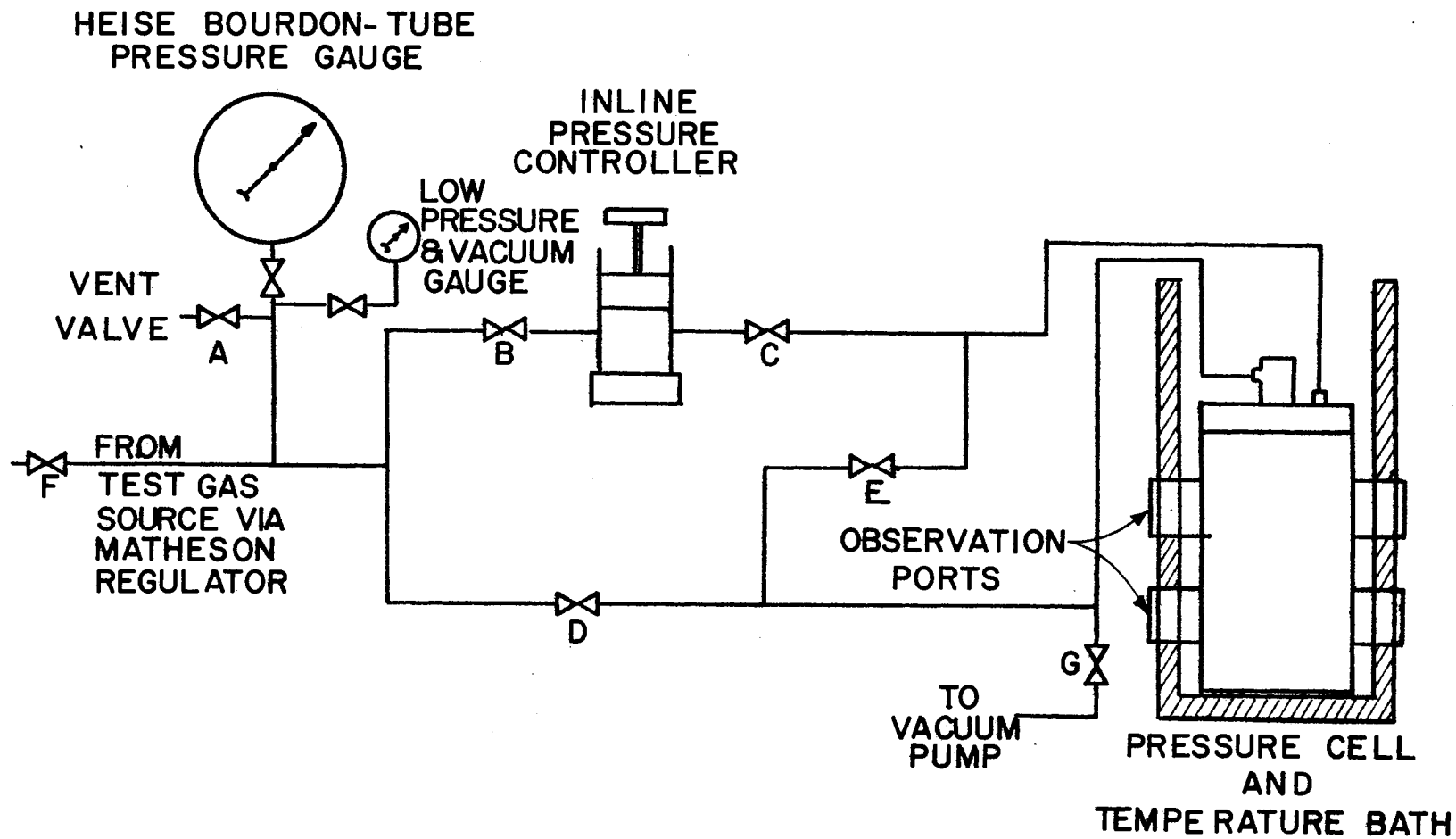
Figure 5.   Schematic Diagram of the Experimental Apparatus

The removal of air from the system before pressurizing with test gas was accomplished with a Duo-Seal vacuum pump.

Materials Tested

The materials tested and their respective purities are listed below in Table I. All materials listed were obtained from Phillips Petroleum Company, Special Products Division, Bartlesville, Oklahoma.

TABLE I

TEST MATERIAL SPECIFICATIONS

MATERIAL	GRADE	GUARANTEED MIN. MOLE % PURITY
Methane	Instrument	99.5
Ethane	Pure	99.0
n-Butane	Instrument	99.5
n-Hexane	Pure	99.0
n-Nonane	Pure	99.0
n-Decane	Pure	99.0

EXPERIMENTAL PROCEDURE

Calibration of Viscometer

A model C-50 Zeitfuchs crossarm viscometer bearing the identification number U-3821 was used for all the experimental viscosity measurements. The viscometer constant was determined by calibration with distilled water in the following manner. First, the viscometer was cleaned thoroughly by three washings with absolute ethanol and then dried by flowing dry, filtered air through the viscometer. Two milliliters of distilled water were pipetted into the viscometer reservoir and the viscometer was then secured to the pressure cell top. After the pressure cell top had been bolted onto the pressure cell body and the external connections made, the constant temperature bath was filled with tap water. A thermometer was placed in the bath to measure the temperature. A slight suction was applied to the capillary exit tube to start the test sample flowing down the capillary tube. After flow had been initiated, the flow would continue due to siphon action. A stopwatch having divisions of 0.2 seconds was used to measure the time necessary to fill the measuring bulb from the lower to the upper scribed lines of the viscometer. After a measurement had been made, a slight pressure was applied

to the capillary exit tube and the flow reversed. When the sample was all back in the reservoir, the process of measurement could be repeated. The first measurement was conducted with a dry capillary tube and was not recorded. Subsequent measurements were made with the capillary tube wetted from the preceding measurements. Bennett (2) made an extensive study of viscosity measurements using a wetted Zeitfuchs capillary viscometer and found the measurements were reproducible. The reader is referred to his work for an elaboration on the subject. In this study the viscometer calibration and all experimental measurements were made with a wetted capillary viscometer. The reproducibility of experimental measurements obtained in this manner is evidenced throughout Appendix E where maximum percent deviations for all systems studied are +0.38 and -0.41, with an overall average absolute value of 0.08 percent. Proof of the basic accuracy of measurements is given in Table II where the average experimental values have a maximum error of -0.57 percent.

Due to the large volume of water in the bath and the ability to hold ambient temperature for a time sufficient to conduct the necessary measurements, a temperature control system was not necessary for the calibration.

The viscometer measuring bulb was illuminated by a 150 watt projection lamp. Observation of the bulb was made through a 14 power cathetometer. The cathetometer allowed a viscometer having a smaller capillary tube diameter to be

TABLE II

RELIABILITY OF EXPERIMENTAL DATA

Substance	T, $^{\circ}$C	Experimental Viscosity, centipoise	API Project 44 Viscosity (1), centipoise	Error %
n-Hexane	23.1	0.2973	0.2983	-0.30
n-Nonane	22.3	0.6870	0.6878	-0.12
n-Decane	22.3	0.8797	0.8847	-0.57

used than would be possible otherwise. The unaided eye cannot observe the clear liquid flowing in the fine capillary tube. The viscometer having a smaller capillary tube affords the advantage of a longer flow time. For a constant time error, a longer flow time gives a smaller relative error. The cathetometer aided the vision to the extent that the average time deviation decreased. A comparison of data from Bennett's (2) viscometer calibration with the viscometer calibration data of this work is presented in Table III. Bennett's data show an average difference of 1.24 second from the average flow time value or 1.52% deviation. Similar data for this work give a 0.45 second average difference and 0.168% deviation. Thus the cathetometer and smaller viscometer capillary tube afford almost an order of magnitude improvement of reproducibility.

All calibration observations were made indirectly by mirror reflection in order to simulate experimental measurement technique.

One series of calibration measurements was made in the pressure cell and three series of measurements were made on a laboratory table using a 2 liter glass vessel as a constant temperature bath. The calibration measurements are shown in Table IV. Distilled water viscosity data are from Perry (15). The three external series of measurements gave an average viscometer constant of 0.003432 while the one internal series of measurements gave a value of 0.003428

TABLE III

EVALUATION OF REPRODUCIBILITY IMPROVEMENT

Calibration fluid: Distilled water at atmospheric pressure

Calibration data from Bennett (2)		Viscometer No. U-2839		Calibration data this work		Viscometer No. U-3821	
T,°F	Run No.	Flow Time, seconds	Deviation, seconds	T,°F	Run No.	Flow Time, seconds	Deviation, seconds
77	1	84.4	+3.0	75	1	267.6	-0.5
	2	81.6	+0.2		2	267.8	-0.3
	3	83.0	+1.6		3	268.2	+0.1
	4	81.0	-0.4		4	268.8	+0.7
	5	80.4	-1.0		5	268.0	-0.1
	6	80.4	-1.0		6	268.6	+0.5
	7	80.3	-1.1		7	267.2	-0.9
	8	79.8	-1.6		8	267.4	-0.7
	9	82.0	+0.6		9	267.3	+0.2
	10	79.7	-1.7		10	268.9	+0.8
	11	80.8	-1.4		11	268.2	+0.1
	Avg.	81.4	1.24		Avg.	268.1	0.45
			or 1.54%				or 0.168%

TABLE IV

CALIBRATION OF VISCOMETER U-3821 WITH DISTILLED WATER

Set 1 (T = 75°F)		Set 2A (T = 77°F)		Set 2B (T = 75°F)		Set 2C (T = 75°F)	
Run No.	Flow Time, seconds	Run No.	Flow Time, seconds	Run No.	Flow Time, seconds	Run No.	Flow Time, seconds
1	267.6	1	260.7	1	267.8	1	268.8
2	267.8	2	260.6	2	267.6	2	268.6
3	268.2	3	262.6	3	267.2	3	268.0
4	268.8	4	261.6	4	266.8	4	267.2
5	268.0	5	261.4	5	266.8	5	267.2
6	268.6	6	260.5	6	266.3	6	268.0
7	267.2	7	263.9	7	266.7	Avg.	268.0
8	267.4	8	262.0	8	266.6		
9	268.3	Avg.	261.6	9	266.8		
10	268.9			Avg.	267.0		
11	268.2						
Avg.	268.1						
ν = 0.9188 centistoke $K = 0.003428$		ν = 0.8963 centistoke $K = 0.003426$		ν = 0.9188 centistoke $K = 0.003441$		ν = 0.9188 centistoke $K = 0.003428$	

A value of 0.00343 was chosen to be used in all calculations.

Operation of Experimental Apparatus

While the equipment was dismantled, the viscometer was cleaned in the manner previously described. A 2 milliliter sample of test liquid was pipetted into the viscometer reservoir. The weight of the liquid was found by accurately weighing several 1 milliliter pipette liquid samples on a Type B-6 Mettler balance. The balance had an error of less than 0.1 milligram in the range 0.5 to 2.0 gram as determined by standardized weights supplied by the Chemical Engineering Department of Oklahoma State University. The liquid samples weighed did not vary more than 1 milligram or approximately 0.14% by weight. After the test liquid sample had been added to the viscometer reservoir, the viscometer was connected to the pressure cell head as shown in Figure 4. The head was then placed on the pressure cell and bolted securely in place. The two exterior pipes shown in Figure 4 were then connected to the gas flow system.

The test gas source was then connected to the system and all valves were opened except the source shut-off valve, the vent valve A, and the valve to the Heise gauge (see Figure 5). The vacuum pump was started and the system evacuated to a pressure of 25 millimeters of mercury. The system was then swept with test gas by closing the valve to the vacuum pump, raising the system pressure to 30 psia with test gas, venting and then evacuating again. This

sweeping procedure was conducted three times, resulting in the removal of air to the same extent that an evacuation to an absolute pressure of 0.11 micron of mercury would attain (see Appendix D). The valve to the vacuum pump was then closed and the system pressure brought up to about 30 psia. The valve to the low pressure gauge was then closed and the Heise gauge was coupled into the system. The bath medium was then added to the constant temperature bath and the system pressure brought up to the desired level by flowing test gas into the viscometer tube and bubbling it through the test liquid in the viscometer reservoir. After the temperature was set at the desired value, the system was allowed to stand for several hours and achieve equilibrium, i. e. saturation.

For temperatures of ambient or higher, tap water was used as the bath medium. Methanol was used for all temperatures below ambient.

To measure the viscosity, all system valves were closed except C and D. The handle of the inline pressure controller was turned to the right, causing the test liquid to begin flowing through the viscometer capillary. After flow had been initiated, valve C was closed and valve E was opened. A stopwatch was used to measure the flow time necessary to fill the viscometer measuring bulb from the lower hairline to the upper hairline. Valve E was then closed and valve C was opened. The inline pressure controller handle was turned to the left and the test liquid

was forced back up into the viscometer reservoir. This process was repeated to verify the measurement. As discussed previously, the first measurement was made with a dry capillary tube and was therefore not recorded. When the flow times remained constant for several measurements over a period of about 2 hours, equilibrium was assumed. The pressure could then be raised to a new level and more measurements made.

After completing a series of measurements at one temperature, the bath medium was removed and the cell depressurized by opening valves C, D, and A. The apparatus could then be dismantled, cleaned and recharged with test liquid for a new series of measurements at a new temperature.

The ternary procedure closely resembled that of the binary. A 2 milliliter sample of liquid n-decane was added to the viscometer using a 1 milliliter pipette (see Appendix C for calibration of pipette). After the cell was evacuated and swept in the manner previously described, n-butane gas was added to the system via the flow system until the cell pressure reached atmospheric pressure (742 millimeters of mercury). This corresponded to a composition parameter value of 0.846. The composition parameter is defined as the ratio of the moles of n-butane in the system to the sum of the moles of n-decane and n-butane. After the addition of n-butane was completed, valve F (Figure 5) was closed, thus sealing the system. The n-butane source was

removed and the methane source was then coupled into the system. The system pressure was then raised by adding methane gas to the system.

The composition parameter treatment of ternary systems was not as useful for this study as it has been in other applications (19). This was a result of the relatively small amount of liquid in relation to the larger amount of gas present in the cell, especially at higher pressures. The composition parameter used in this study was for convenience of data set identification rather than the more conventional fixing of the ratio of n-butane to the sum of n-decane and n-butane in the liquid phase.

The number of moles of n-decane in the system was calculated from the weight of liquid added, while the number of moles of n-butane was calculated from a knowledge of the cell volume, temperature, pressure and compressibility (14). The amount of methane was calculated from the increase in pressure and compressibility calculations of a trial and error nature. The n-decane acted as a non-distributed component, aiding in the calculations.

CHAPTER IV

RESULTS AND DISCUSSION OF RESULTS

Attainment of Equilibrium

The attainment of equilibrium by the two phase system is illustrated in Table V by the data obtained on the methane-n-butane-n-decane system at 72 degrees F and 200 psia. The final five flow time readings were within ± 0.2 seconds of the average value for 4.5 hours and therefore equilibrium was assumed.

The data of Table V are plotted in Figure 6 and illustrate the approach to equilibrium by the system. For an elapsed time greater than 40 hours, the flow time is constant. In general, the binary systems achieved equilibrium more quickly than did the ternary system.

Methane-n-Decane System

Table VI gives the experimental and calculated data for the methane-n-decane system. The liquid densities and compositions were interpolated from the experimental data of Reamer et. al. (18) for temperatures of 100 degrees F or greater. For 1, 32, and 72 degrees F the liquid compositions were calculated via the NGPA K & H Value Computer Program (13) and the liquid densities were calculated by the Rackett method (16).

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TABLE V

TYPICAL RUN FOR THE METHANE-N-BUTANE-N-DECANE SYSTEM

Elapsed Time, hours	Temperature, $^\circ F$	Pressure, psia	Flow Time, seconds
0.0	72	200	351.5
14.00			282.4
14.25			275.2
15.50			266.8
15.75			266.7
16.50			264.8
16.60			264.6
17.70			261.5
18.30			261.0
19.40			258.0
35.90			255.0
36.20			254.8
42.75			254.0
43.25			254.2
47.00		Equilibrium	254.0
47.10			254.3
47.25			254.1
		Average	254.1
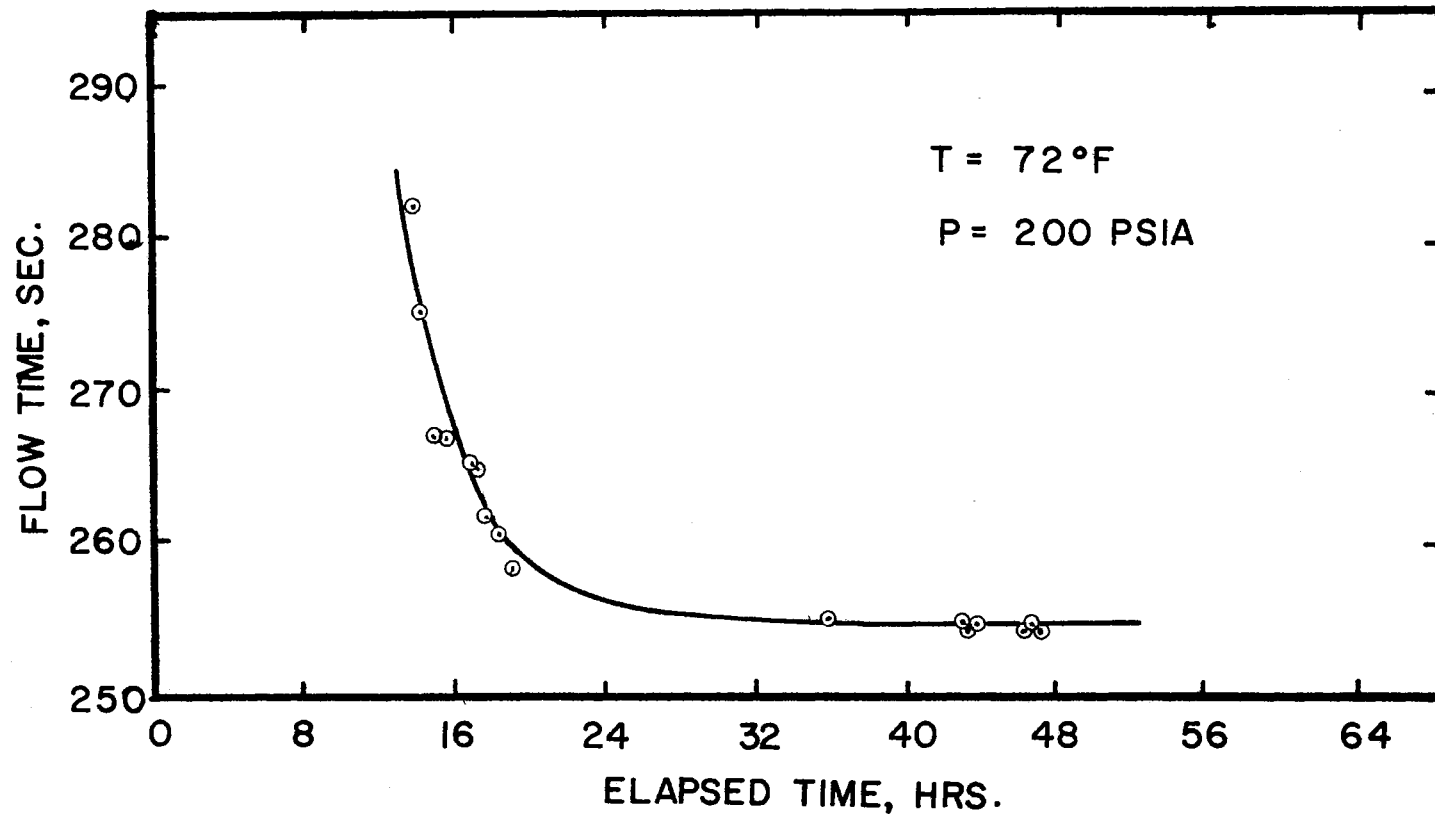
Figure 6. Flow Time of Methane-n-Butane-n-Decane System

TABLE VI

EXPERIMENTAL AND CALCULATED DATA FOR THE METHANE-N-DECANE SYSTEM

Temp., °F	Press., psia	Mole Fraction Methane	Kinematic Viscosity, centistoke	Density, gm/cm^3	Absolute Viscosity, centipoise
1	100	0.0468	2.201	0.7516	1.654
	300	0.1324	1.874	0.7371	1.382
	700	0.2745	1.457	0.7112	1.036
	1200	0.4042	1.191	0.6844	0.8148
32	100	0.0406	1.6248	0.7404	1.2030
	300	0.1157	1.4300	0.7278	1.0408
	700	0.2434	1.1834	0.7050	0.8343
	1200	0.3662	0.9944	0.6804	0.6766
72	100	0.0351	1.1549	0.7251	0.8374
	200	0.0688	1.1158	0.7195	0.8028
	400	0.1316	1.0448	0.7089	0.7407
	600	0.1888	0.9786	0.6989	0.6839
	800	0.2410	0.9158	0.6893	0.6313
	1000	0.2884	0.8654	0.6802	0.5886
	1200	0.3315	0.8239	0.6715	0.5532

TABLE VI (Continued)

Temp., °F	Press., psia	Mole Fraction Methane	Kinematic Viscosity, centistoke	Density, gm/cm^3	Absolute Viscosity, centipoise
100	100	0.0345	0.9503	0.7167	0.6811
	200	0.0659	0.9248	0.7132	0.6596
	400	0.1251	0.8761	0.7063	0.6188
	600	0.1773	0.8284	0.6992	0.5793
	800	0.2243	0.7844	0.6923	0.5430
	1000	0.2679	0.7494	0.6854	0.5136
	1200	0.3099	0.7192	0.6785	0.4880
130	100	0.0327	0.7889	0.6869	0.5419
	200	0.0630	0.7707	0.6838	0.5270
	400	0.1195	0.7384	0.6779	0.5006
	600	0.1701	0.7048	0.6717	0.4734
	800	0.2161	0.6760	0.6655	0.4499
	1000	0.2588	0.6519	0.6592	0.4297
	1200	0.2885	0.6262	0.6528	0.4088

Figure 7 is a plot of the kinematic viscosity as a function of pressure for various isotherms of the methane-n-decane system. Figure 8 is a cross-plot of Figure 7 giving kinematic viscosity as a function of temperature for various isobars. Kinematic viscosity as a function of methane mole fraction in the liquid phase is given in Figure 9 for various isotherms. The methane-n-decane system absolute viscosity as a function of methane mole fraction in the liquid phase is given in Figure 10 for various isotherms. The four figures illustrating the viscosity behavior of the methane-n-decane system show that the system viscosity, absolute and kinematic, decreases with increasing temperature, pressure and methane concentration in the liquid phase. Absolute viscosity decreases with decreasing density. The pure n-decane data are from API Project 44 (1).

Ethane-n-Decane System

Table VII gives the experimental and calculated data for the ethane-n-decane system. The compositions were interpolated from the experimental equilibrium data of Reamer and Sage (17) while the liquid density was calculated by the Rackett method (16).

Figure 11 shows the kinematic viscosity behavior of the ethane-n-decane system as a function of pressure for various isotherms. Kinematic viscosity is seen to decrease with increasing temperature and pressure.

Figure 12 shows ethane-n-decane kinematic viscosity behavior as a function of temperature for various isobars.

Figure 7. Kinematic Viscosity of Methane–n–
Decane
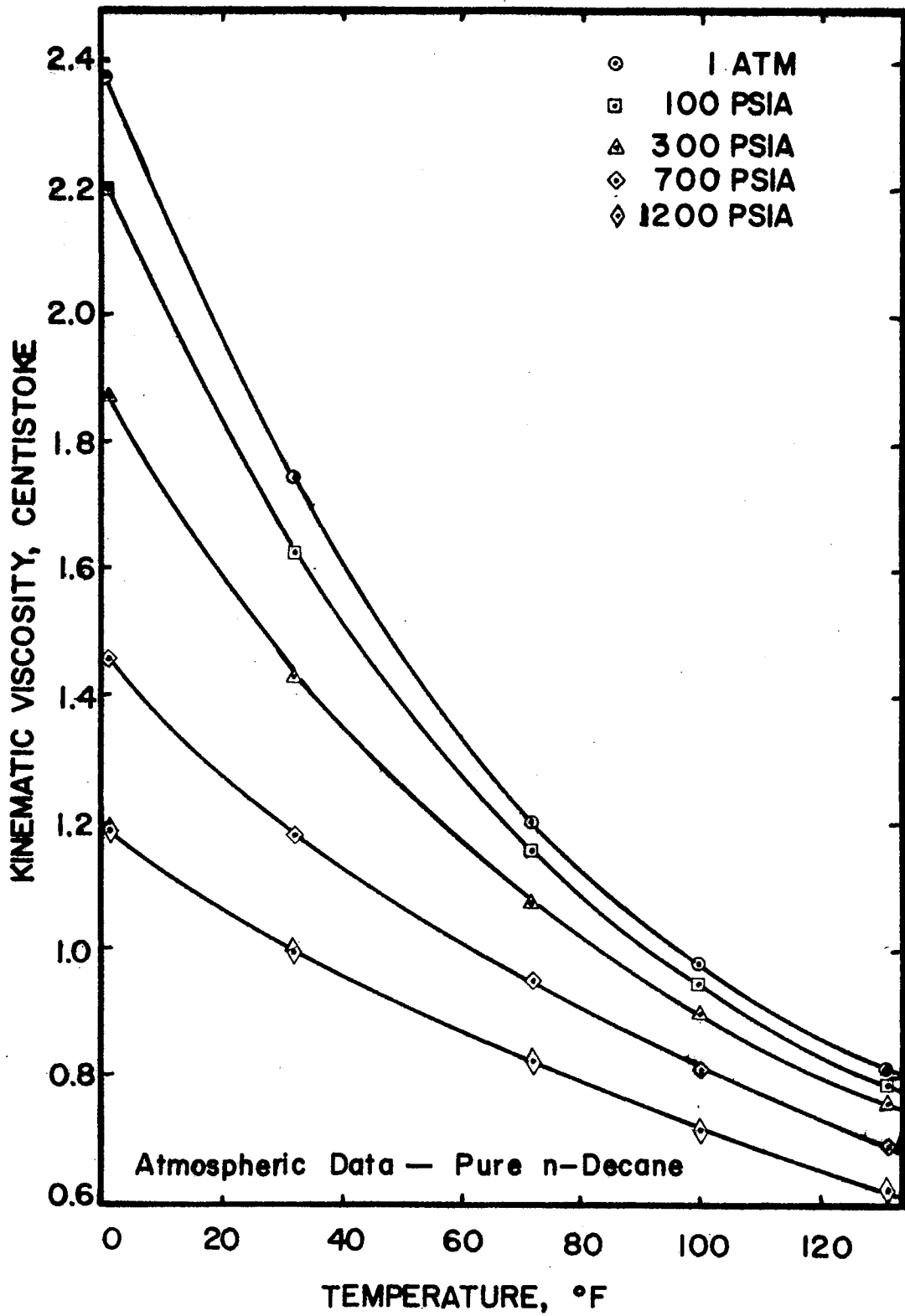
Figure 8. Kinematic Viscosity of Methane-n-Decane

Figure 9. Kinematic Viscosity of Methane-n-Decane

Figure 10.   Absolute   Viscosity   of   Methane—n—
Decane

TABLE VII

EXPERIMENTAL AND CALCULATED DATA FOR
THE ETHANE-N-DECANE SYSTEM

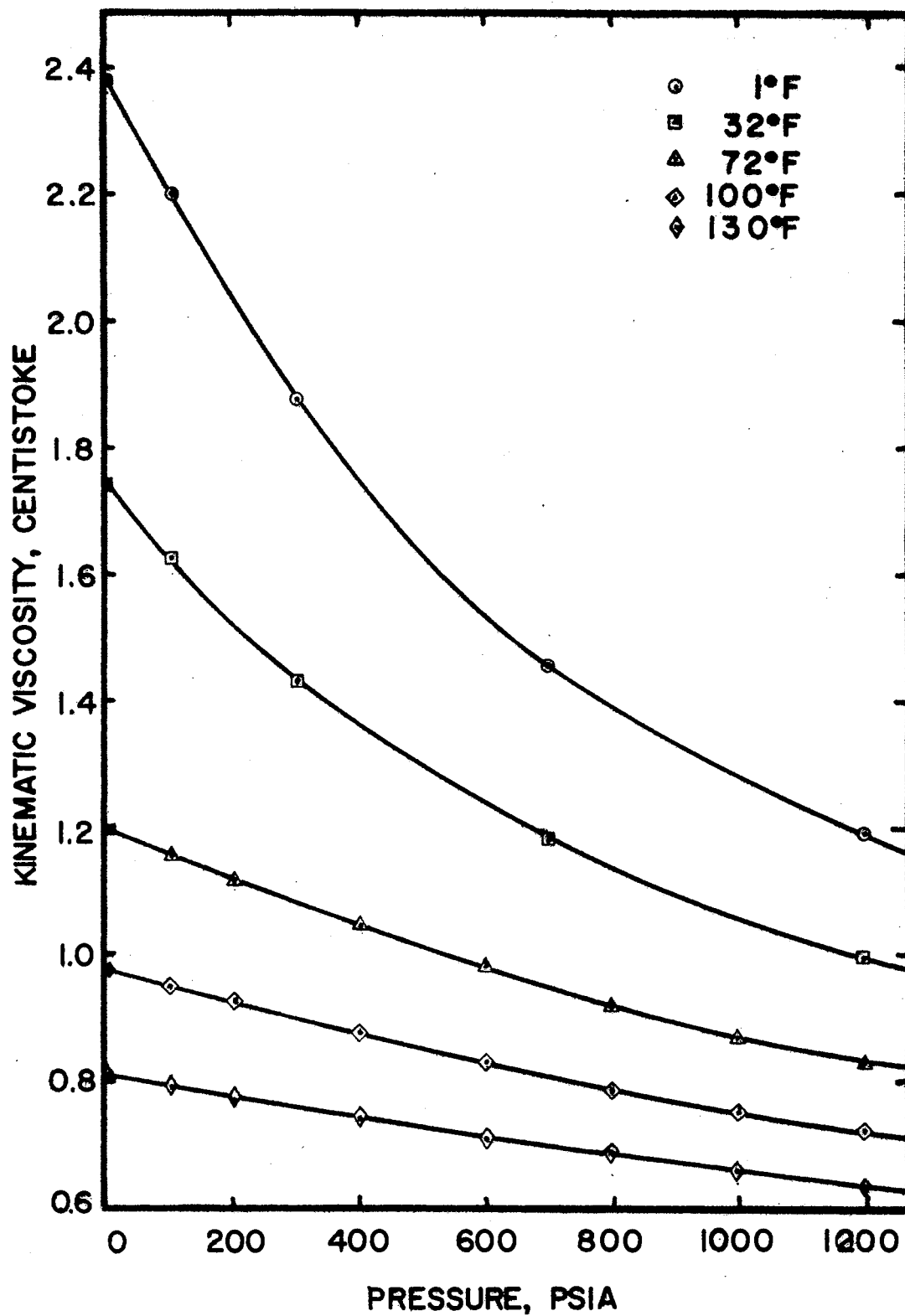| Temp., °F	Press., psia	Mole Fraction Ethane	Kinematic Viscosity, centistoke	Density, gm/cm³	Absolute Viscosity, centipoise
31	50	0.142	1.2509	0.7270	0.9095
	100	0.283	0.9683	0.7067	0.6843
80	50	0.090	0.9659	0.7157	0.6913
	100	0.180	0.8575	0.7031	0.6029
	150	0.269	0.7457	0.6898	0.5144
	200	0.359	0.6675	0.6750	0.4506
110	50	0.073	0.8314	0.7055	0.5866
	100	0.146	0.7700	0.6953	0.5354
	200	0.292	0.6421	0.6731	0.4322
	300	0.430	0.5344	0.6486	0.3466
140	50	0.061	0.7179	0.6941	0.4983
	100	0.122	0.6761	0.6857	0.4636
	200	0.240	0.5927	0.6682	0.3960
	300	0.349	0.5196	0.6490	0.3472
174	50	0.051	0.6133	0.6806	0.4174
	100	0.101	0.5817	0.6734	0.3917
	200	0.201	0.5289	0.6586	0.3483
	300	0.296	0.4987	0.6441	0.3212
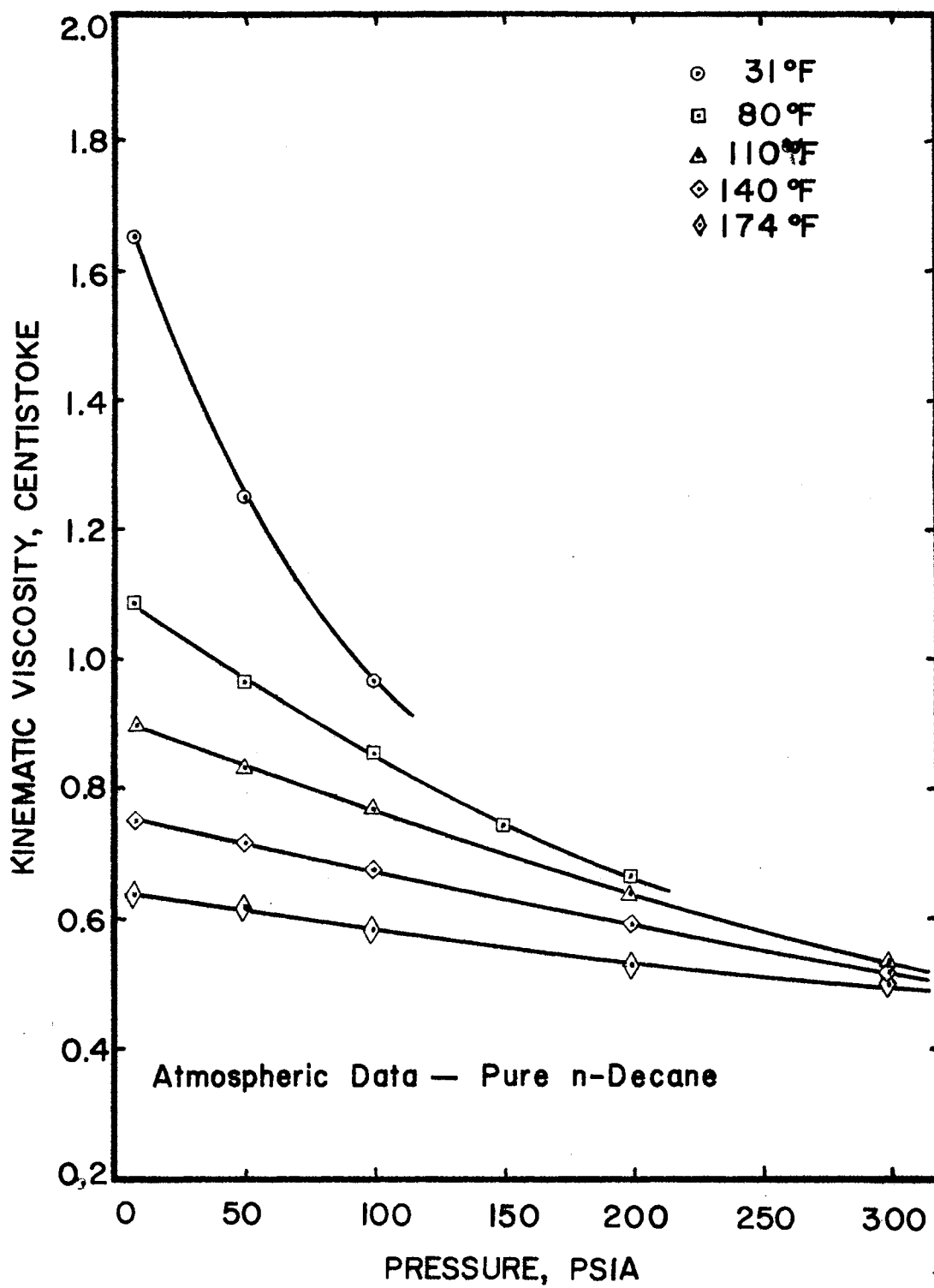
Figure II.   Kinematic Viscosity of Ethane-n-Decane
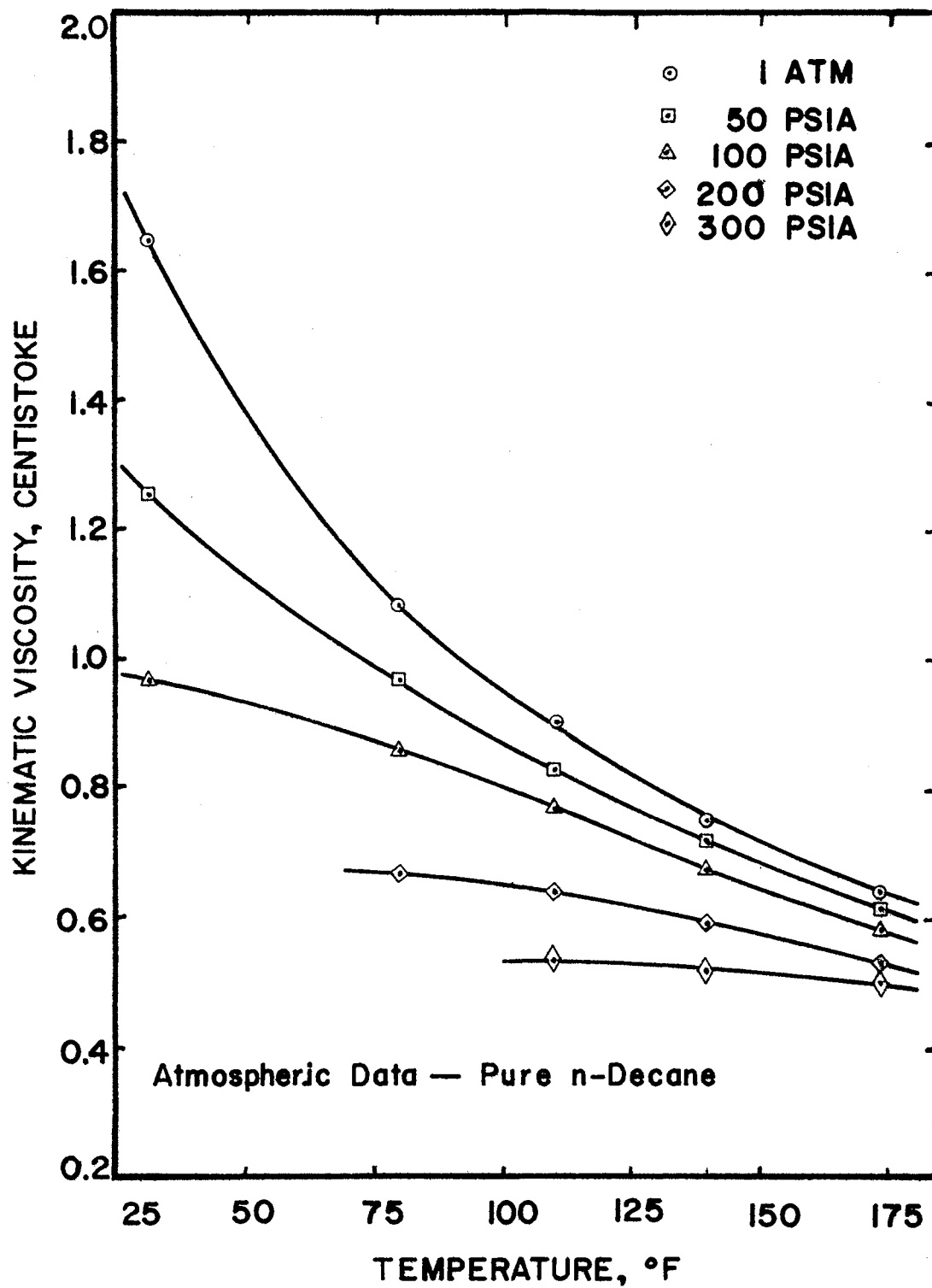
Figure 12. Kinematic Viscosity of Ethane-n-Decane

The kinematic viscosity decreases with increasing pressure throughout the region tested but the variance with temperature is more complex. For pressures less than or equal to 100 psia, the kinematic viscosity decreases with increasing temperature. Above 100 psia and 100 degrees F, the kinematic viscosity decreases with increasing temperature. At temperatures less than 100 degrees F and pressures greater than 100 psia, the ethane becomes very soluble in the liquid phase. This region could not be fully explored because the increasing ethane concentration would cause the viscometer reservoir to overfill.

Figure 13 shows the behavior of the kinematic viscosity of the ethane-n-decane system as a function of ethane mole fraction in the liquid phase. Figure 14 illustrates the variance of absolute viscosity with ethane mole fraction in the liquid phase for the ethane-n-decane system. Figures 13 and 14 show that absolute and kinematic viscosity decrease with increasing temperature and increasing ethane concentration. Absolute viscosity decreases with decreasing density. Pure n-decane data from API Project 44 (1) are included for comparison with experimental saturated liquid data.

Methane-n-Hexane System

Table VIII shows the calculated and experimental data for the methane-n-hexane system. Liquid compositions were calculated by using the NGPA K & H Computer Program (13) and densities for the liquid were calculated by the Rackett procedure (16). No experimental compositions or
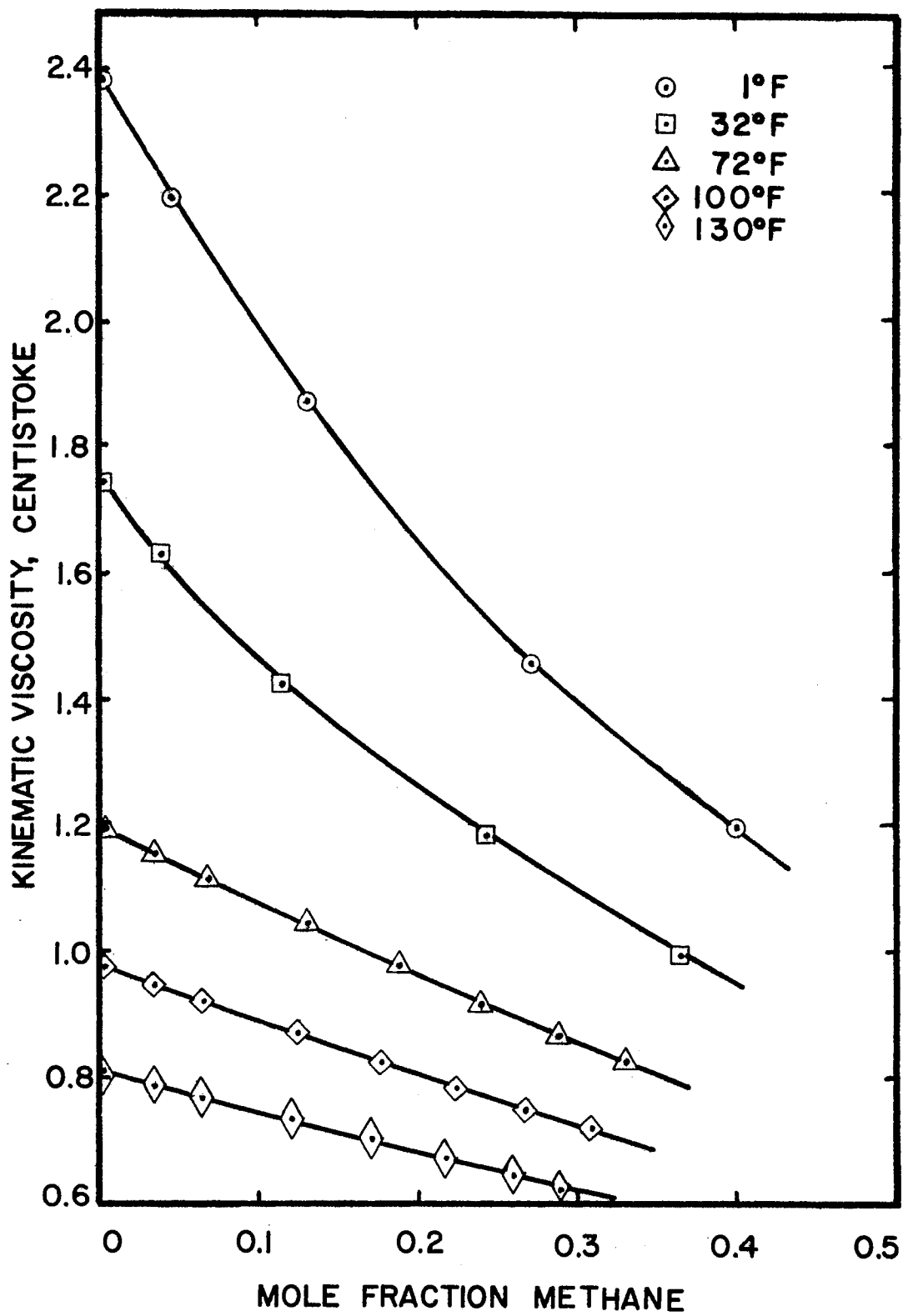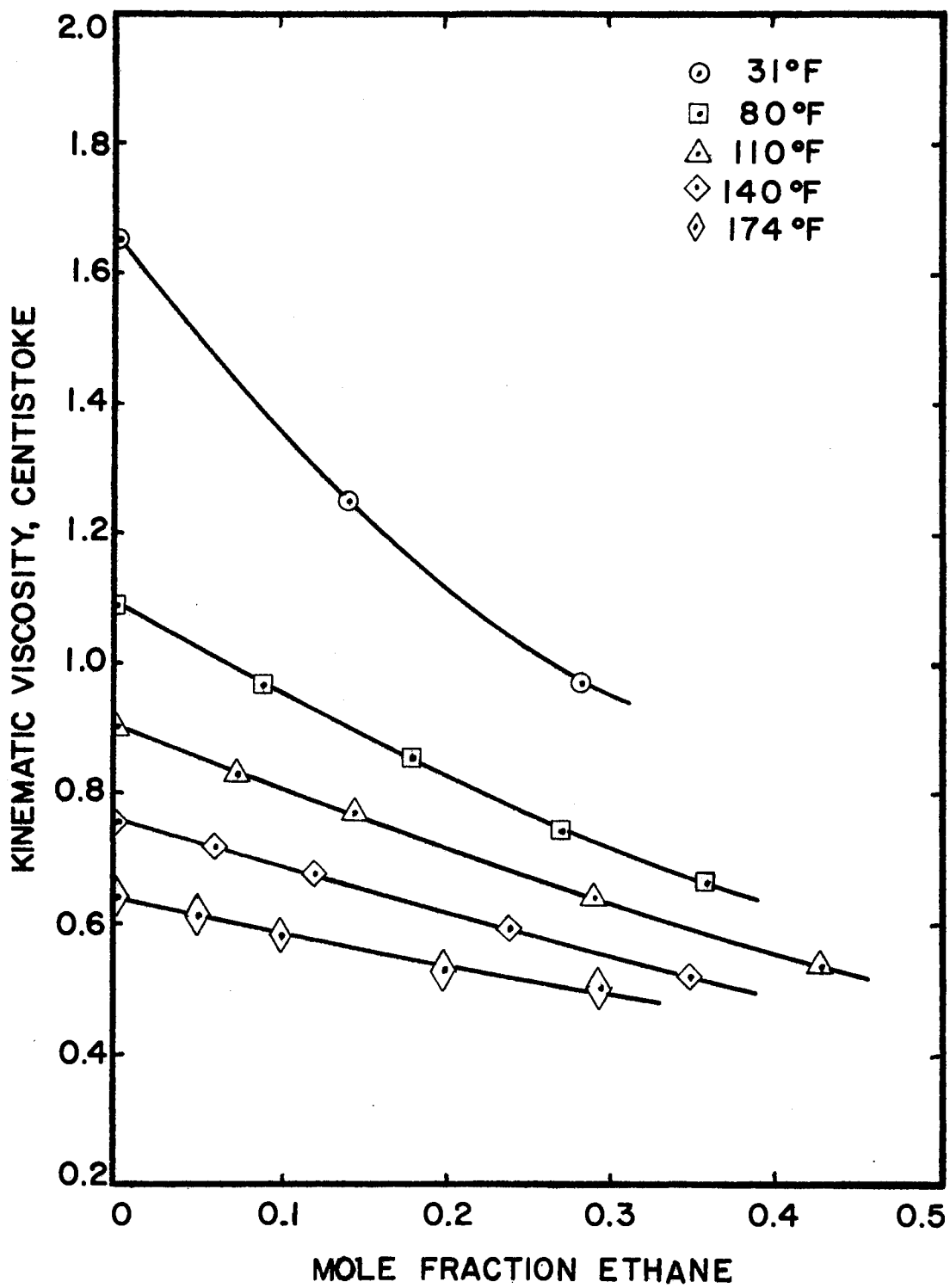
Figure 13.   Kinematic Viscosity of Ethane-n—
Decane
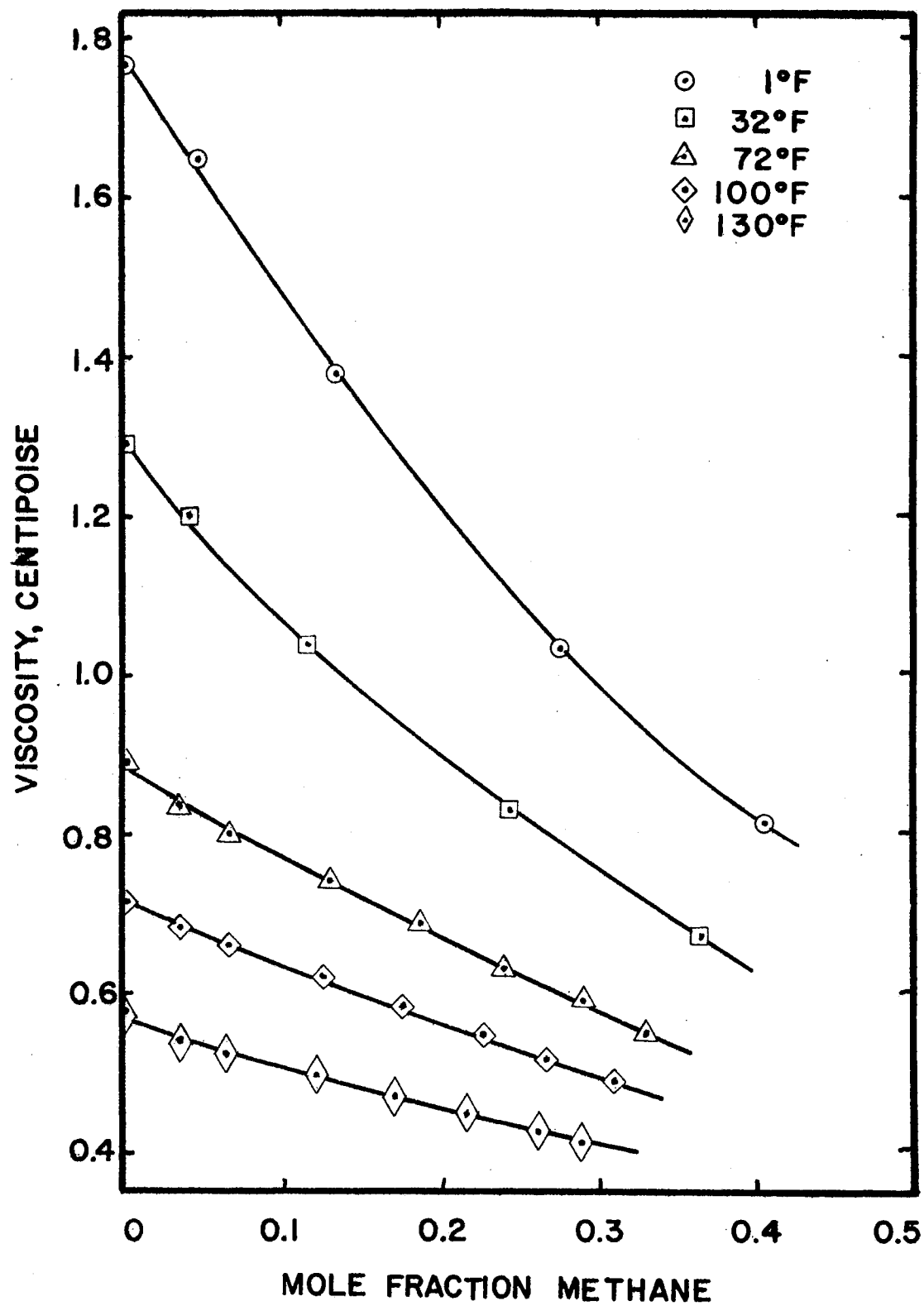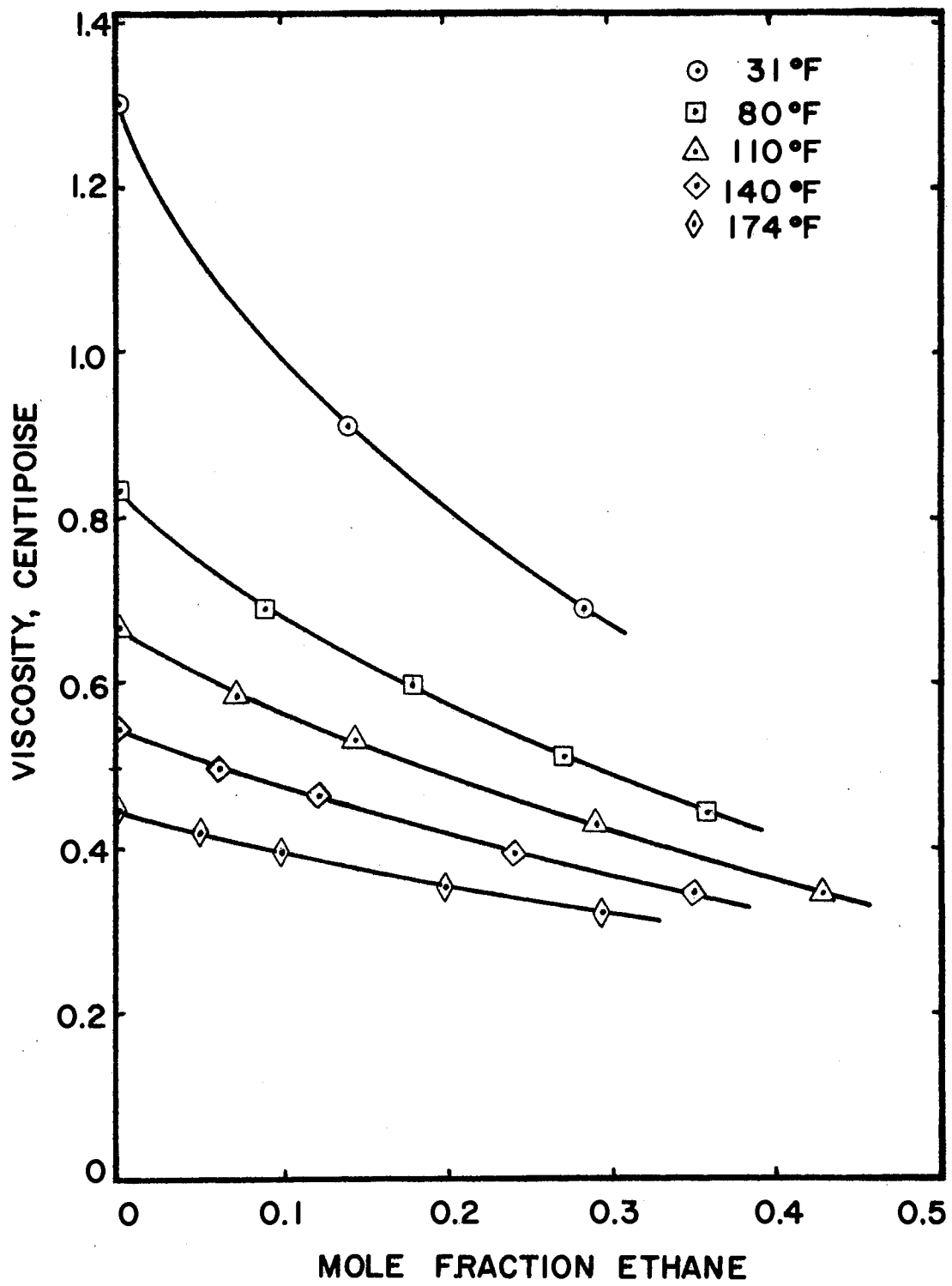
Figure 14.   Absolute Viscosity of Ethane-n—
Decane

TABLE VIII

EXPERIMENTAL AND CALCULATED DATA FOR
THE METHANE-N-HEXANE SYSTEM

Temp., $^\circ F$	Press., psia	Mole Fraction Methane	Kinematic Viscosity, centistoke	Density, gm/cm^3	Absolute Viscosity, centipoise
1	100	0.0552	0.6339	0.6874	0.4357
	300	0.1566	0.5798	0.6695	0.3882
	700	0.3246	0.4860	0.6348	0.3085
	1200	0.4753	0.4092	0.5954	0.2436

density data were found in the literature for the methane-
n-hexane system.

Figure 15 shows the variance of kinematic viscosity
with pressure for the methane-n-hexane system at a tem-
perature of 1 degree F. Figures 16 and 17 show the vari-
ance of kinematic viscosity and absolute viscosity,
respectively, with the mole fraction methane in the liquid
phase. Figures 15, 16, and 17 all show that the methane-
n-hexane viscosity decreases with increasing pressure and
mole fraction methane. Absolute viscosity decreases with
decreasing density.

Methane-n-Butane-n-Decane System

Table IX shows the calculated and experimental data
for the methane-n-butane-n-decane system. Liquid com-
positions were calculated from the NGPA K & H Computer
Program (13) and liquid densities were calculated by the
Rackett procedure (16).
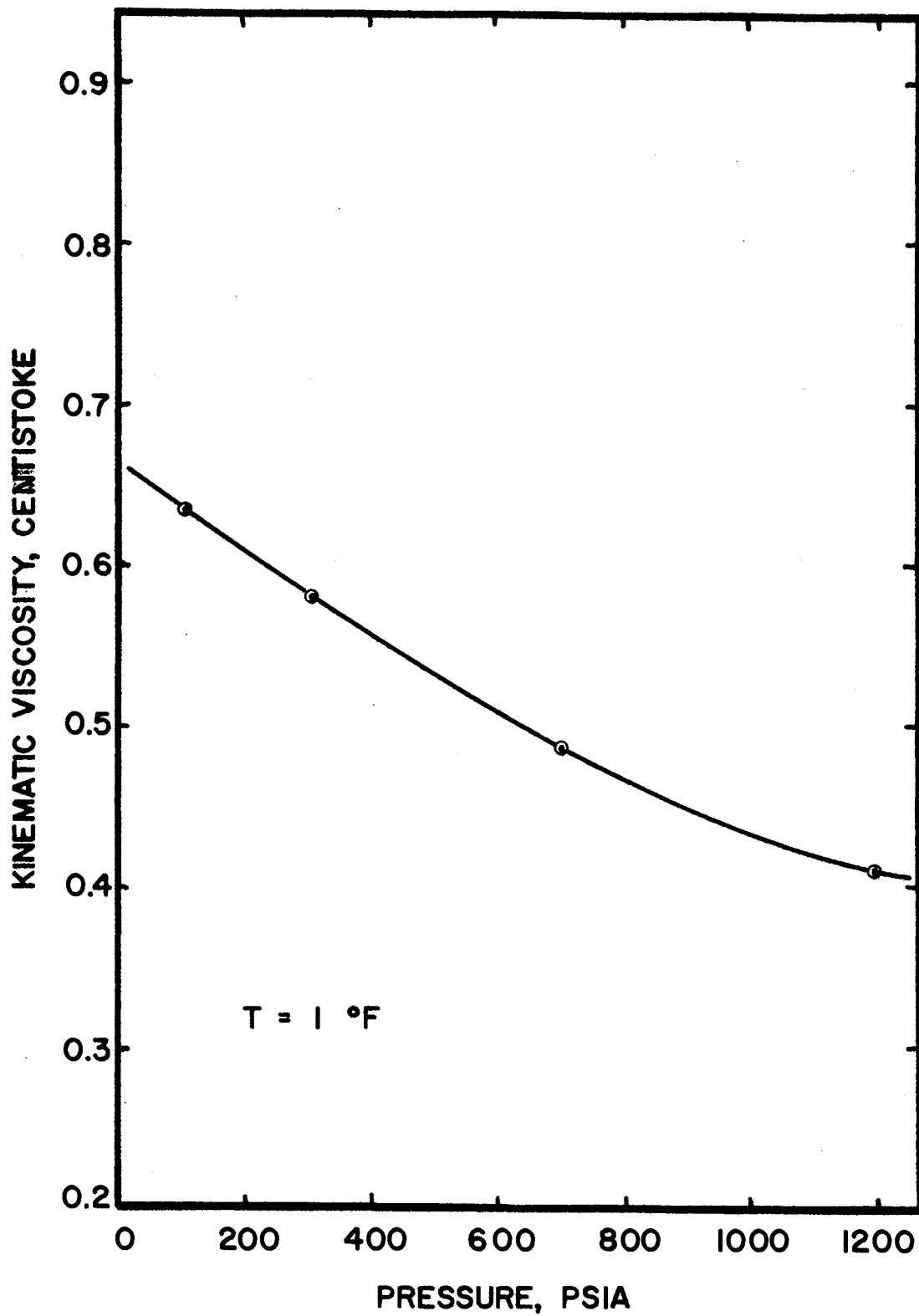
Figure 15. Kinematic Viscosity of Methane—n—Hexane
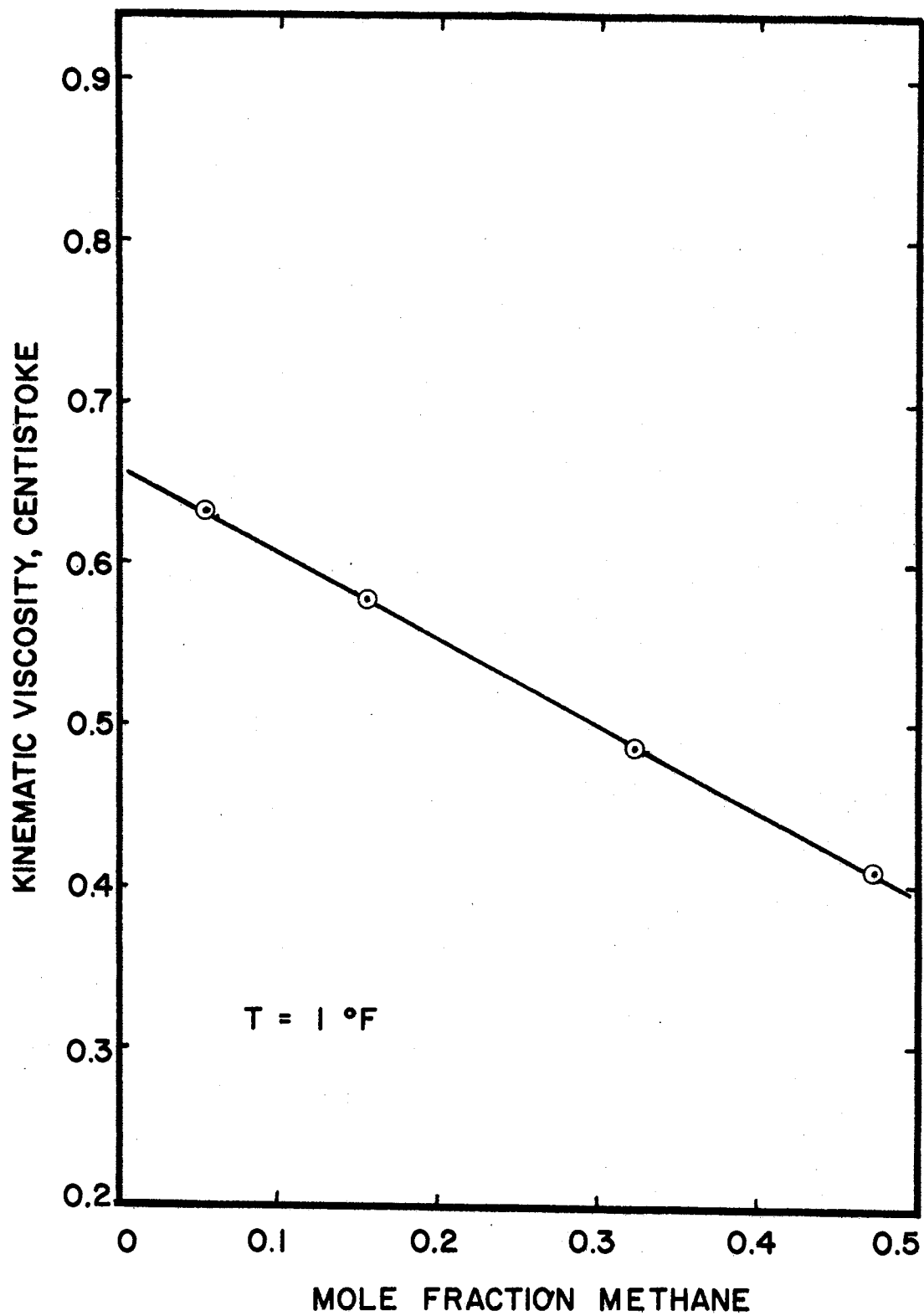
Figure 16. Kinematic Viscosity of Methane-n-Hexane

T = 1 °F
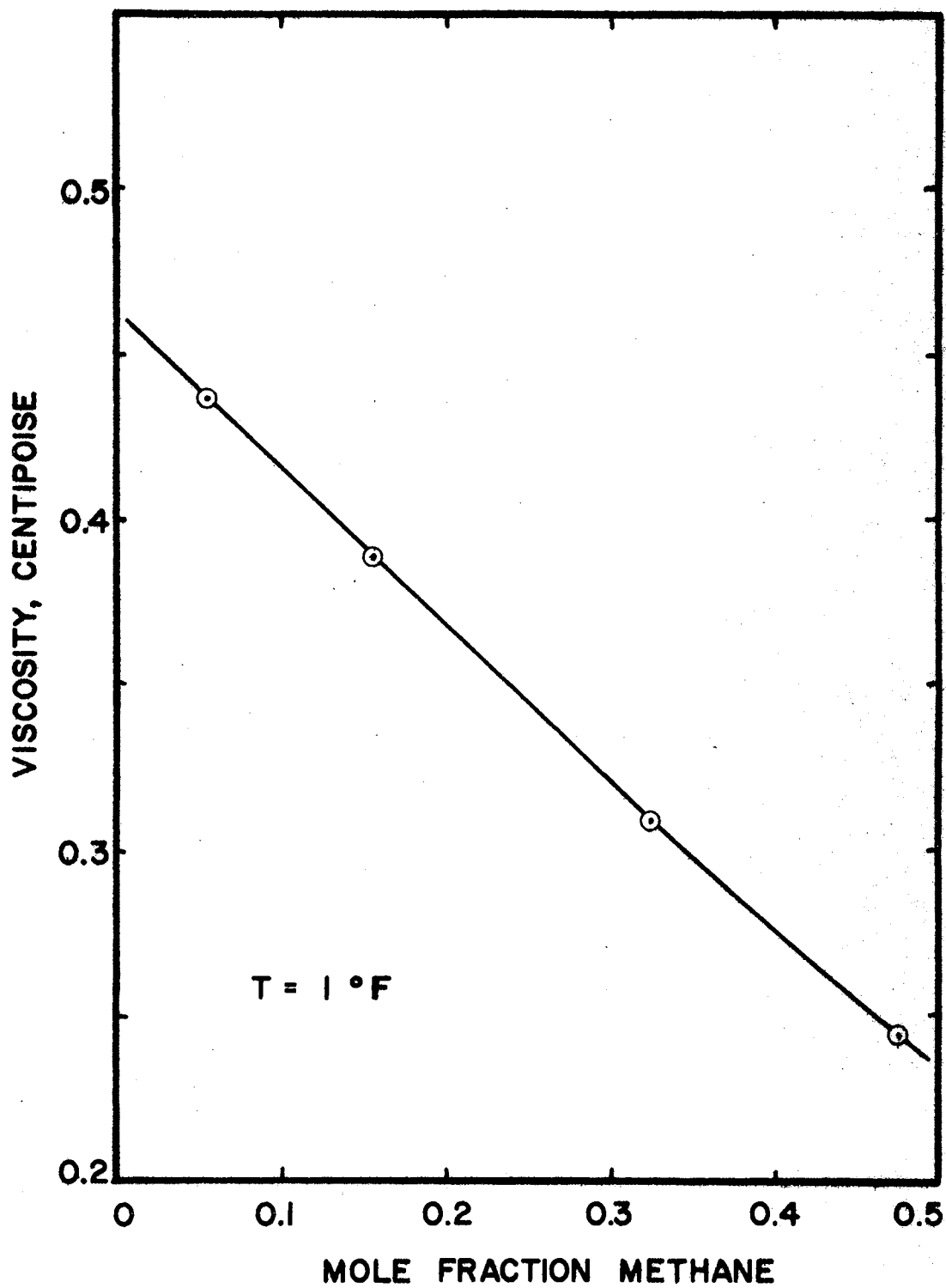
Figure 17. Absolute Viscosity of Methane-n-
Hexane

TABLE IX

EXPERIMENTAL AND CALCULATED DATA FOR THE
METHANE-N-BUTANE-N-DECANE SYSTEM

Temperature = 72 degrees F

Press., psia	Liquid Mole Fraction			ν centi-stoke	ρ gm/cm^3	μ centi-poise
	Methane	n-Butane	n-Decane			
100	0.0330	0.3442	0.6229	0.8461	0.6885	0.5825
200	0.0688	0.3033	0.6279	0.8717	0.6864	0.5983
400	0.1345	0.2343	0.6311	0.8650	0.6819	0.5898
600	0.1932	0.1790	0.6277	0.8390	0.6770	0.5680
800	0.2459	0.1376	0.6165	0.8064	0.6715	0.5415
1000	0.2934	0.1069	0.5999	0.7769	0.6655	0.5170
1200	0.3362	0.0828	0.5811	0.7484	0.6593	0.4934

Figure 18 shows the variance of kinematic viscosity with changing pressure for the methane-n-butane-n-decane system at a temperature of 72 degrees F. Figure 19 shows the system absolute viscosity as a function of pressure for a temperature of 72 degrees F. Liquid volume observations in the pressure cell indicate that butane will dissolve to a high concentration (see Table IX) and then be replaced or revaporized by increasing methane pressure. Some of this behavior is reflected by the increasing-decreasing nature of the viscosity curves of Figures 18 and 19.
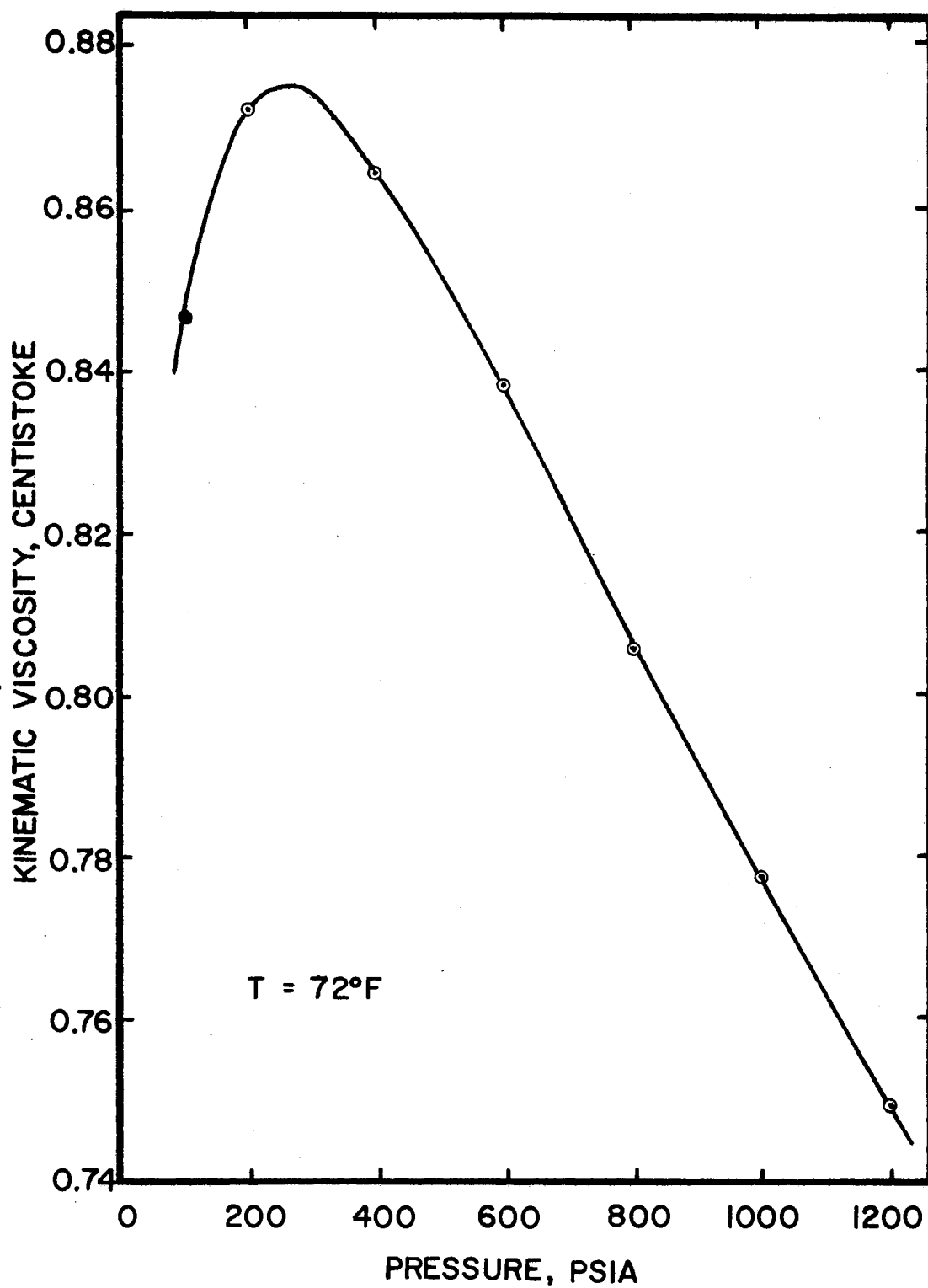
Figure 18. Kinematic Viscosity of Methane -n-
Butane-n-Decane
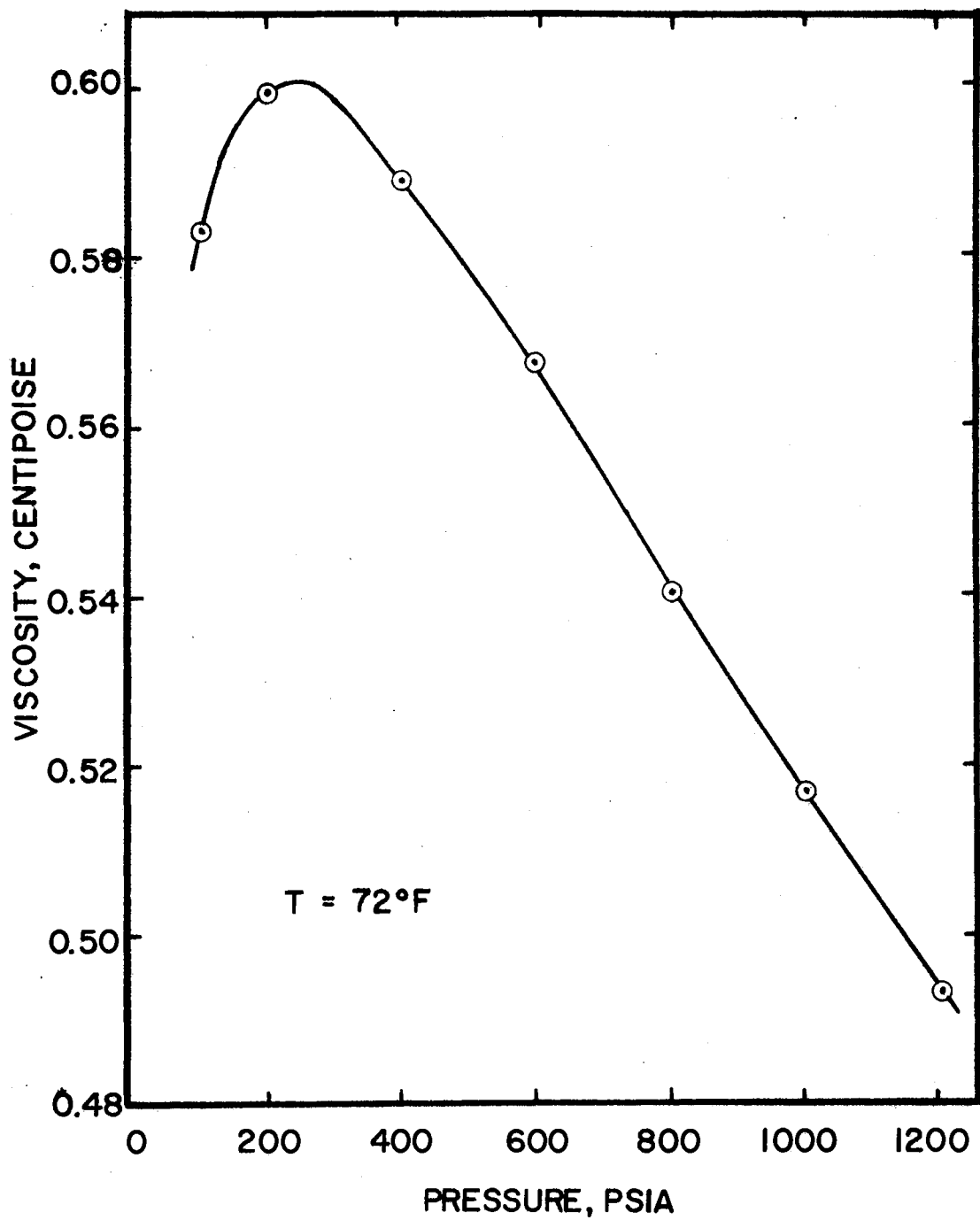
Figure 19.   Absolute Viscosity of Methane-n-
Butane-n-Decane

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The equipment functioned very well and a high degree of reproducibility was exhibited on all systems studied. The use of the 14 power cathetometer and smaller capillary tube viscometer resulted in almost an order of magnitude increase in reproducibility, reducing the percent deviation from 1.52% to 0.168%. The cathetometer and small tube viscometer should be utilized in all future experimental viscosity studies using a capillary tube viscometer and pressure cell.

For all binary systems studied, viscosity, kinematic and absolute, decreased with increasing pressure. The methane-n-decane system exhibited a decreasing viscosity for an increasing temperature. The ethane-n-decane system showed a similar behavior except in the region above 100 psia and below 100 degrees F. Trends in the data indicate that viscosity may increase with increasing temperature in this area but the region could not be fully explored because the increasing ethane concentration in the liquid phase would cause the viscometer reservoir to overfill. The behavior of the ternary methane-n-butane-n-decane system is complex and is due further study.

For all systems studied, absolute viscosity was

obtained by multiplying kinematic viscosity with density.
Therefore, a change in density produced a proportional
change in absolute viscosity.

Persons continuing this investigation are encouraged
to make the following changes:

1. Modify the equipment as shown in Figure 20. The modi-
fications would allow samples to be taken from the liquid
and vapor in the pressure cell. This would allow systems
to be studied for which equilibrium distribution coeffi-
cients are either not available or questionable.

2. An insertable collar should be placed inside the pres-
sure cell to take up as much of the cell volume as possible
when investigating a ternary system. Most of the remaining
open space in the cell could then be filled with test
liquid. These two changes, decreasing the vapor space in-
side the pressure cell, would allow the use of the fixed
composition parameter treatment found to be of great value
during investigation of ternary systems by Reamer, Sage and
Lacey (18).

LIQUID
SAMPLING VALVE

VAPOR
SAMPLING VALVE

INLINE
PRESSURE
CONTROLLER

VISCOMETER
RESERVOIR

MODIFICATIONS SHOWN IN BOLD LINES

PRESSURE CELL
AND
TEMPERATURE BATH
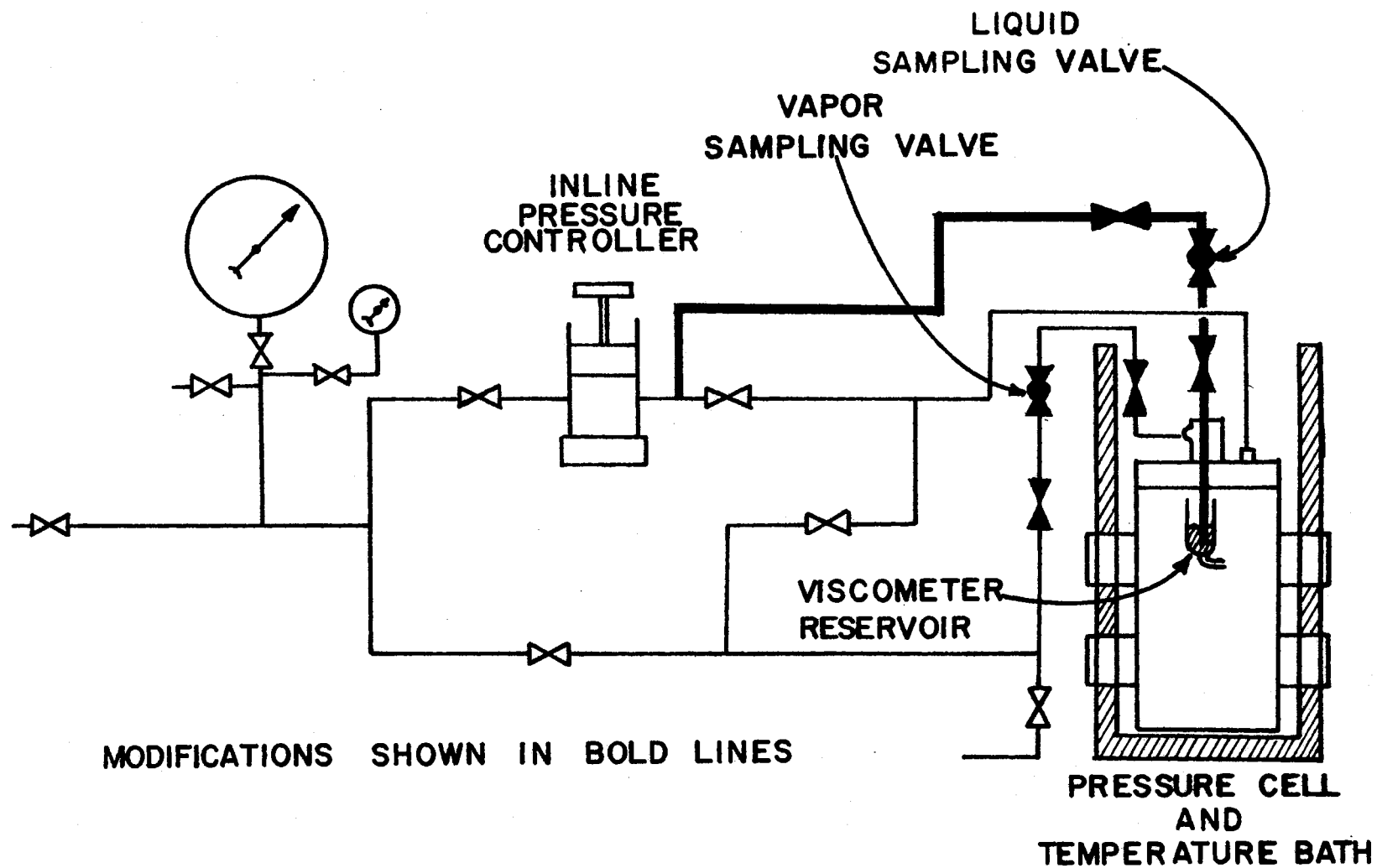
Figure 20. Proposed Modifications of the Experimental Apparatus

NOMENCLATURE

English Letters

g = acceleration of gravity, cm/sec/sec

h = height of liquid, cm

K = viscometer constant, centistoke/sec

ΔP = pressure drop, dyne/cm^2/cm

Q = volumetric flow rate, cm^3/sec

r = radius of capillary, cm

t = flow time, sec

Tc = critical temperature, $^\circ$K

Tr = weighted reduced temperature

V = volume of fluid, cm^3

Vc = critical volume, cm^3/gmole

Vs = saturated liquid volume, cm^3/gmole

x_i = component mole fraction

Zc = critical compressibility

Greek Symbols

π = constant 3.1416 . . .

ν = kinematic viscosity, centistoke

$\Delta\nu$ = total error in ν

ρ = density, gm/cm^3

μ = absolute viscosity, centipoise

$\Delta\mu_k$ = error in μ due to uncertainty in K

53

NOMENCLATURE (Continued)

$\Delta \mu_t$ = error in μ due to uncertainty in t

$\Delta \mu_\rho$ = error in μ due to uncertainty in ρ

$\Delta \mu$ = total error in μ

δ_K = uncertainty in K

δ_t = uncertainty in t

δ_ρ = uncertainty in ρ

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APPENDIX A

ERROR ANALYSIS

ANALYSIS OF ERROR

METHOD AND EVALUATION

J. R. Deam (6) presented the method of calculating the most probable value of error as a result of experimental measurements. The errors attributable to each term of the basic viscosity equation,

$$\mu = K t \rho \tag{6}$$

are combined to determine the experimental error.

The errors due to each quantity can be defined as follows:

$$\Delta \mu_K = \frac{\partial \mu}{\partial K} \delta_K = t \rho \, \delta_K \tag{7a}$$

$$\Delta \mu_t = \frac{\partial \mu}{\partial t} \delta_t = K \rho \, \delta_t \tag{7b}$$

$$\Delta \mu_\rho = \frac{\partial \mu}{\partial \rho} \delta_\rho = K t \, \delta_\rho \tag{7c}$$

where δ_K, δ_t and δ_ρ are uncertainties in each of the quantities, K, t, and ρ.

The total error is defined as follows:

$$\Delta \mu = \sqrt{(\Delta \mu_K)^2 + (\Delta \mu_t)^2 + (\Delta \mu_\rho)^2} \tag{8}$$

Equation 6 may be differentiated and substituted into equation 8 to obtain

$$\Delta \mu = \mu \sqrt{\left(\frac{\delta_K}{K}\right)^2 + \left(\frac{\delta_t}{t}\right)^2 + \left(\frac{\delta_\rho}{\rho}\right)^2} \tag{9}$$

Only K and t were evaluated experimentally. The error associated with K was estimated from the 3 viscometer calibrations made while the viscometer was on the laboratory shelf. Their values of 0.003426, 0.003441, and 0.003428 give an average deviation of 0.088%.

As pointed out previously, equilibrium conditions

were considered achieved when a consistent set of flow times was achieved for a set of operating conditions. Therefore deviations associated with one set of operating conditions serve only to express the consistency of flow times and not the accuracy of the measurements. To get a representative value of the deviations in flow times, three measurements were made on the methane-n-decane system at 100 psia and 72 degrees F using three separate test samples. The measured flow times of 337.8 seconds, 336.7 seconds and 334.9 seconds give an average deviation of 0.3%.

The density data of Reamer et. al. (17) had an estimated error of ±1% while the mixture density calculated by the Rackett (16) procedure had an estimated error of ±1.5%. Calculations from the NGPA K and H Computer Program (13) could result in an error of ±6% in composition. From plots of density as a function of composition for the methane-n-decane and the ethane-n-decane systems, an error of 6% in composition would produce an error of 0.4% in the calculated density. Adding this value of 0.4% to the estimated error of 1.5% gives an error of 1.9% in the Rackett calculated density where the NGPA computer program was used.

The methane-n-decane system had density data available at 100 degrees F and 130 degrees F. Therefore the following uncertainty values apply:

$$\delta_t = 0.003$$

$$\delta_\rho = 0.01$$

$$\delta_K = 0.00088$$

Dividing the total error , $\Delta\mu$ of equation 8, by the measured viscosity, μ, gives the following result for relative error.

$$\frac{\Delta\mu}{\mu} = \sqrt{\left(\frac{0.00088\ K}{K}\right)^2 + \left(\frac{0.003\ t}{t}\right)^2 + \left(\frac{0.01\ \rho}{\rho}\right)^2}$$

Therefore,

$$\frac{\Delta\mu}{\mu} = 0.0101$$

or an average percent error of 1.01%.

The 1, 32 and 72 degree F isotherms for the methane-n-decane system, the methane-n-hexane system and the methane-n-butane-n-decane system lacked literature density values. Their compositions were calculated via the NGPA computer program (13) and the Rackett (16) procedure was used to calculate the liquid density. The following uncertainty values apply:

$$\delta_t = 0.003$$

$$\delta_\rho = 0.019$$

$$\delta_K = 0.00088$$

A similar procedure to that previously used for the relative error gives:

$$\frac{\Delta\mu}{\mu} = 0.0191$$

or an average percent error of 1.91%.

The ethane-n-decane system had literature composition values available. The lack of density data again necessitated the use of the Rackett procedure. The following uncertainties apply:

$$\delta_t = 0.003$$

$$\delta\rho = 0.015$$

$$\delta_K = 0.00088$$

The relative error calculation gives

$$\frac{\Delta\mu}{\mu} = 0.0151$$

or an average percent error of 1.51%

The kinematic viscosity equation

$$\nu = K\,t$$

does not depend on density and therefore the error associated with kinematic viscosity is

$$\frac{\Delta\nu}{\nu} = \sqrt{\left(\frac{0.00088\ K}{K}\right)^2 + \left(\frac{0.003\ t}{t}\right)^2}$$

$$\frac{\Delta\nu}{\nu} = 0.00313$$

or an average percent error of 0.313%.

As can be seen from this analysis, the uncertainty in the liquid density is, by far, the controlling factor in the error associated with the absolute viscosity, μ.

APPENDIX B

DATA USED WITH RACKETT CORRELATION

RACKETT EQUATION

The Rackett (16) equation for saturated liquid volumes is

$$Vs = Vc \left[Zc^{(1-Tr)^{2/7}} \right]$$

The saturated liquid density is calculated as $1/Vs$.

Critical Constants and Molecular Weights

	Tc, $^{\circ}K$	Zc	Vc, $cm^3/mole$	Mol. Wt.
Methane	191.1	0.289	99.0	16.04
Ethane	308.0	0.279	146.3	30.07
n-Butane	425.2	0.273	254.0	58.12
n-Hexane	507.9	0.264	368.0	86.17
n-Decane	619.0	0.251	614.9	142.28

Rackett Weighting Factors for Mixture Critical Temperature

Methane-n-Decane System

Methane	1.00
n-Decane	4.52

Ethane-n-Decane System

Ethane	1.00
n-Decane	2.72

Methane-n-Hexane System

Methane	1.00
n-Hexane	2.83

Methane-n-Butane-n-Decane System

A system of three or more components requires the use of a matrix type combination of binary weighting factors to

calculate the component weighting factors. The reduced matrix used in this work for the methane-n-butane-n-decane system is given as:

Methane $\quad$ $(1/1.98)^{X_2}$ $\quad$ X $\quad$ $(1/4.52)^{X_3}$

n-Butane $\quad$ $(1.98)^{X_1}$ $\quad$ X $\quad$ $(1/1.70)^{X_3}$

n-Decane $\quad$ $(4.52)^{X_1}$ $\quad$ X $\quad$ $(1.70)^{X_2}$

APPENDIX C

EQUIPMENT CALIBRATIONS

CALIBRATION OF PRESSURE GAUGES

The calibration of the 3000 psig Heise gauge given in Table X was conducted on August 11, 1969. A 1500 psig Heise gauge having an accuracy of 2 psi for the range of 100 psig to 1200 psig (as determined by a model number 2400 HL Ruska Pressure System, having an accuracy of 1 part in 10,000) was used to measure the calibration pressure. A second check was made on January 15, 1970, and no change was noted.

The calibration of the 30 psig Ascroft-American Duragauge is given in Table XI. A calibration from 28 inches of mercury vacuum to 14.5 psig was made on August 11, 1969, using a 30 inch mercury manometer. A second check made on September 9, 1969, showed the same results, no error greater than ¼ inch mercury for the vacuum range and no error greater than ¼ psi for pressures greater than atmospheric. The full range calibration presented in Table XI was made on May 19, 1970, and again no errors greater than those stated above were noted up to a pressure of 29 psig.

TABLE X

HEISE GAUGE CALIBRATION

Pressure, psig	Deviation* from Standard Gauge
0	set
100	-
200	-
300	-
400	-
500	-
600	-
700	-
800	-
900	-
1000	-
1100	-
1200	-

*Corrections are indicated where error was 3 psi or more. None were required.

TABLE XI

ASCROFT-AMERICAN DURAGAUGE CALIBRATION

Vacuum, inches of mercury	Deviation* from 60 inch manometer
28	-
26	-
24	-
22	-
20	-
18	-
16	-
14	-
12	-
10	-
8	-
6	-
4	-
2	-
0	-
Pressure, psig	
1	-
2	-
5	-

TABLE XI (Continued)

Pressure, psig	Deviation* from 60 inch manometer
10	-
15	-
20	-
25	-
29	-

Atmospheric pressure   742 mm mercury

*Corrections are indicated where error was more than ½ inch of mercury on the vacuum scale or ½ psi on the pressure scale. None were required.

TABLE XII

CALIBRATION OF ONE MILLILITER PIPETTE

Run No.	Sample Weight, gram	Sample Weight Minus Avg. Weight Absolute Value, gram
1	0.7254	0.0004
2	0.7248	0.0002
3	0.7255	0.0005
4	0.7256	0.0006
5	0.7243	0.0007
6	0.7259	0.0009
7	0.7253	0.0003
8	0.7241	0.0009
9	0.7244	0.0006
10	0.7246	0.0004
Avg.	0.7250	0.00055

Test liquid   n-decane

Ambient Temperature $72^\circ F$

APPENDIX D

EVALUATION OF THE TEST GAS

SWEEPING PROCEDURE

Following the initial evacuation to an absolute
pressure of 25 mm mercury, the cell pressure was raised to
30 psia (1550 mm mercury) with test gas, vented and
evacuated to 25 mm mercury three times. This results in
an equivalent one time evacuation calculated as:

25 mm mercury $\quad X \left(\dfrac{25}{1550}\right) \quad X \left(\dfrac{25}{1550}\right) \quad X \left(\dfrac{25}{1550}\right)$

$= 0.105 \; X \; 10^{-3}$ mm mercury

$= 0.105$ micron of mercury pressure absolute

APPENDIX E

EXPERIMENTAL DATA

TABLE XIII

EXPERIMENTAL FLOW TIMES

Methane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
1	100	1	641.0	-0.03
		2	641.4	+0.03
		3	641.2	0.00
		Avg.	641.2	
1	300	1	545.1	-0.16
		2	546.8	+0.15
		3	546.0	0.00
		Avg.	546.0	
1	700	1	428.0	nonequilibrium
		2	424.0	-0.05
		3	424.3	+0.02
		4	424.2	0.00
		Avg.	424.2	
1	1200	1	346.7	-0.03
		2	346.8	0.00
		3	346.8	0.00
		Avg.	346.8	
32	100	1	474.0	+0.06
		2	473.9	+0.04
		3	473.4	-0.06
		4	473.4	-0.06
		Avg.	473.7	
32	300	1	418.3	nonequilibrium
		2	417.0	+0.02
		3	416.6	-0.07
		4	417.0	+0.02
		Avg.	416.9	
32	700	1	344.7	-0.09
		2	345.0	0.00
		3	345.2	+0.06
		Avg.	345.0	
32	1200	1	289.8	-0.03
		2	289.8	-0.03
		3	290.0	+0.03
		Avg.	289.9	
72	100	1	338.5	nonequilibrium
		2	337.8	0.00

TABLE XIII (Continued)

Methane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
72	100	3	337.6	-0.06
		4	337.7	-0.03
		5	337.9	+0.03
		6	338.0	+0.06
		Avg.	337.8	
72	100	1	335.2	+0.09
		2	334.8	-0.03
		3	335.0	+0.03
		4	334.6	-0.06
		5	334.9	0.00
		6	334.8	-0.03
		Avg.	334.9	
72	100	1	336.6	-0.03
		2	336.7	0.00
		3	336.9	+0.06
		4	336.9	+0.06
		5	336.5	-0.06
		Avg.	336.7	
72	200	1	325.0	-0.09
		2	325.6	+0.09
		3	325.6	+0.09
		4	325.0	-0.09
		5	325.4	+0.03
		Avg.	325.3	
72	400	1	305.2	+0.20
		2	304.7	+0.03
		3	304.8	+0.06
		4	304.2	-0.13
		5	304.2	-0.13
		Avg.	304.6	
72	600	1	285.4	+0.04
		2	285.5	+0.07
		3	285.0	-0.11
		4	285.3	0.00
		5	285.3	0.00
		Avg.	285.3	
72	800	1	269.4	nonequilibrium
		2	266.7	-0.07
		3	267.3	+0.15

TABLE XIII (Continued)

Methane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
72	800	4	266.9	0.00
		5	266.7	-0.07
		Avg.	266.9	
72	1000	1	253.0	+0.27
		2	251.9	-0.16
		3	251.9	-0.16
		Avg.	252.3	
72	1200	1	240.3	+0.04
		2	241.1	+0.37
		3	239.2	-0.41
		Avg.	240.2	
100	100	1	276.4	-0.14
		2	276.6	-0.07
		3	277.0	+0.07
		4	277.0	+0.07
		5	277.1	-0.11
		6	276.8	0.00
		Avg.	276.8	
100	200	1	269.1	-0.11
		2	269.5	+0.04
		3	269.4	0.00
		4	269.5	+0.04
		Avg.	269.4	
100	400	1	254.6	-0.24
		2	255.4	+0.08
		3	255.3	+0.04
		4	255.3	+0.04
		Avg.	255.2	
100	600	1	241.6	+0.12
		2	241.3	0.00
		3	241.0	-0.12
		4	241.4	+0.04
		Avg.	241.3	
100	800	1	229.0	+0.22
		2	228.6	+0.04
		3	228.4	-0.04
		4	228.2	-0.13
		Avg.	228.5	

TABLE XIII (Continued)

Methane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
100	1000	1	218.3	0.00
		2	218.3	0.00
		3	218.2	-0.05
		Avg.	218.3	
100	1200	1	209.3	-0.10
		2	209.8	+0.14
		3	209.3	-0.10
		Avg.	209.5	
130	100	1	229.8	0.00
		2	229.8	0.00
		3	230.0	+0.09
		4	229.6	-0.09
		Avg.	229.8	
130	200	1	224.8	+0.13
		2	224.4	-0.04
		3	224.6	+0.04
		4	224.3	-0.09
		Avg.	224.5	
130	400	1	215.0	-0.05
		2	214.9	-0.09
		3	215.4	+0.14
		Avg.	215.1	
130	600	1	205.5	+0.24
		2	204.5	-0.24
		3	204.9	-0.05
		Avg.	205.0	
130	800	1	196.9	0.00
		2	196.9	0.00
		3	196.8	-0.05
		Avg.	196.9	
130	1000	1	190.0	+0.11
		2	189.6	-0.11
		3	189.8	0.00
		Avg.	189.8	
130	1200	1	182.1	-0.16
		2	182.0	-0.22
		3	183.0	+0.33
		Avg.	182.4	

TABLE XIII (Continued)

Ethane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
31	50	1	364.4	-0.08
		2	364.7	0.00
		3	364.9	+0.06
		Avg.	364.7	
31	100	1	282.4	+0.04
		2	283.2	+0.32
		3	281.4	-0.32
		Avg.	282.3	
80	50	1	281.7	+0.04
		2	281.5	-0.04
		3	281.6	0.00
		Avg.	281.6	
80	100	1	250.1	+0.04
		2	250.0	0.00
		3	249.8	-0.08
		Avg.	250.0	
80	150	1	217.7	+0.14
		2	217.4	0.00
		3	217.2	-0.09
		Avg.	217.4	
80	200	1	194.7	+0.05
		2	194.6	0.00
		3	194.5	-0.05
		Avg.	194.6	
110	50	1	242.3	-0.04
		2	242.6	+0.08
		3	242.0	-0.17
		4	242.6	+0.08
		Avg.	242.4	
110	100	1	224.4	-0.04
		2	224.5	0.00
		3	224.6	+0.04
		Avg.	224.5	
110	200	1	187.4	+0.11
		2	186.9	-0.16

TABLE XIII (Continued)

Ethane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
110	200	3	187.4	+0.11
		Avg.	187.2	
110	300	1	156.1	+0.19
		2	155.5	-0.19
		3	155.7	-0.06
		Avg.	155.8	
140	50	1	209.3	0.00
		2	209.6	+0.14
		3	209.1	-0.10
		Avg.	209.3	
140	100	1	197.0	-0.05
		2	197.3	+0.10
		3	197.1	0.00
		Avg.	197.1	
140	200	1	173.4	+0.35
		2	172.8	0.00
		3	172.7	-0.06
		4	172.5	-0.17
		Avg.	172.8	
140	300	1	151.4	-0.07
		2	151.5	0.00
		3	151.6	+0.07
		Avg.	151.5	
174	50	1	179.2	+0.22
		2	179.0	+0.11
		3	178.6	-0.11
		4	178.6	-0.11
		Avg.	178.8	
174	100	1	169.5	-0.06
		2	169.6	0.00
		3	169.6	0.00
		Avg.	169.6	
174	200	1	154.1	-0.06
		2	154.3	+0.06
		3	154.3	+0.06
		Avg.	154.2	

TABLE XIII (Continued)

Ethane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
174	300	1	145.0	-0.28
		2	145.7	+0.21
		3	145.5	+0.07
		Avg.	145.4	

Methane-n-Hexane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
1	100	1	184.6	-0.11
		2	185.0	+0.11
		3	184.8	0.00
		4	184.7	-0.05
		Avg.	184.8	
1	300	1	169.1	+0.12
		2	168.8	-0.06
		3	168.8	-0.06
		4	169.0	+0.06
		Avg.	168.9	
1	700	1	141.4	-0.21
		2	142.0	+0.21
		3	141.7	0.00
		4	141.7	0.00
		Avg.	141.7	
1	1200	1	119.4	-0.37
		2	120.0	+0.18
		3	119.6	-0.18
		4	120.0	+0.18
		Avg.	119.8	

TABLE XIII (Continued)

Methane-n-Butane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
72	100	1	253.4	nonequilibrium
		2	250.0	"
		3	248.8	"
		4	247.2	+0.20
		5	246.6	-0.04
		6	246.7	0.00
		7	246.4	-0.12
		8	246.9	+0.08
		9	246.4	-0.12
		10	247.0	+0.12
		Avg.	246.7	
72	100	1	268.4	nonequilibrium
		2	255.1	"
		3	252.1	"
		4	250.2	"
		5	246.9	-0.12
		6	247.7	+0.20
		7	246.4	-0.32
		8	247.2	0.00
		9	247.6	+0.16
		10	247.4	+0.08
		Avg.	247.2	
72	200	1	257.5	nonequilibrium
		2	256.0	+0.12
		3	256.0	+0.12
		4	255.8	+0.04
		5	255.9	+0.08
		6	256.0	+0.12
		7	255.7	0.00
		8	255.7	0.00
		9	255.6	-0.04
		10	255.1	-0.23
		Avg.	255.7	
72	200	1	351.5	nonequilibrium
		2	282.4	"
		3	275.2	"
		4	266.8	"
		5	266.7	"
		6	264.8	"
		7	264.6	"
		8	261.5	"

TABLE XIII (Continued)

Methane-n-Butane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
72	200	9	261.0	nonequilibrium
		10	258.0	"
		11	255.0	"
		12	254.8	"
		13	254.0	-0.04
		14	254.2	+0.04
		15	254.0	-0.04
		16	254.3	+0.08
		17	254.1	0.00
		Avg.	254.1	
72	400	1	254.0	nonequilibrium
		2	253.3	"
		3	253.2	"
		4	252.8	"
		5	252.4	+0.08
		6	252.6	+0.16
		7	252.2	0.00
		8	251.8	-0.16
		9	252.0	-0.08
		10	252.4	+0.08
		Avg.	252.2	
72	600	1	245.8	nonequilibrium
		2	244.4	"
		3	245.5	"
		4	244.3	-0.12
		5	244.0	-0.24
		6	244.3	-0.12
		7	245.4	+0.33
		8	245.0	+0.16
		9	244.6	0.00
		10	244.4	-0.08
		Avg.	244.6	
72	800	1	233.9	nonequilibrium
		2	233.8	"
		3	233.1	"
		4	234.6	-0.21
		5	234.3	-0.34
		6	235.4	+0.13
		7	234.8	-0.13
		8	236.0	+0.38
		9	235.7	+0.25
		Avg.	235.1	

TABLE XIII (Continued)

Methane-n-Butane-n-Decane System

Temp., °F	Press., psia	Run No.	Flow Time, sec.	Percent Deviation
72	1000	1	228.4	nonequilibrium
		2	227.7	"
		3	226.8	+0.13
		4	226.2	-0.13
		5	227.0	+0.22
		6	226.4	-0.04
		7	226.2	-0.13
		Avg.	226.5	
72	1200	1	227.8	nonequilibrium
		2	218.6	+0.19
		3	217.6	-0.29
		4	217.6	-0.29
		5	218.9	+0.34
		6	217.7	-0.24
		7	218.7	+0.24
		Avg.	218.2	

VITA

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