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## Absolute viscosity of the n-paraffin liquids

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### ABSTRACT

The absolute viscosity of the normal paraffins  $C_5H_{12}$  to  $C_{20}H_{42}$  was studied to determine a relationship more useful in predicting liquid viscosities than existing correlations such as the methods of Andrade, Souders, Thomas, and Doolittle.

It was found that a function of corresponding liquid states could be designed which related viscosity to the number of carbon atoms. This function, here called liquidity, is defined as the extent to which a substance exists as a liquid with respect to temperature. This function can be expressed mathematically as:

$$L_c = \frac{t - t_m}{t_c - t_m} \quad \text{or} \quad L_b = \frac{t - t_m}{t_b - t_m} \quad ;$$

where:  $L_c$  = liquidity based on the critical temperature

$L_b$  = liquidity based on the normal boiling temperature

$t$  = any temperature,  $^{\circ}C$

$t_b$  = normal boiling temperature,  $^{\circ}C$

$t_c$  = critical temperature,  $^{\circ}C$

$t_m$  = normal melting temperature,  $^{\circ}C$

Once the basis for liquidity is determined, the denominator in the above expressions remain constant, and the % liquidity becomes a straight line function of the temperature.

It was further found that a plot of  $L_c$  vs. number of carbon atoms for the n - paraffins resulted in curves of iso - viscosity which, when fitted to straight lines, could be used for calculation, extrapolation, or interpolation of viscosity data. Thus, a method was developed for the viscosity prediction of the n - paraffins above  $C_4H_{10}$  to apply at any temperature within the normal liquid range. Deviations from the experimental values of viscosity to those resulting from the designed liquidity function are within  $\pm 10$  per cent for the majority, and less than  $\pm 20$  per cent for the extreme cases. This approach to viscosity prediction is valid with or without the availability of experimental data.

ABSOLUTE VISCOSITY OF THE n - PARAFFIN LIQUIDS

BY

GERALD PERMUTT

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PRESENTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENT FOR THE DEGREE

OF

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AT

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## INTRODUCTION

The term viscosity may be considered as the measure of internal fluid friction which tends to oppose any dynamic change in the fluid motion. Another definition is that viscosity is the ratio of shearing stress to the rate of shear. However one may choose to define viscosity, it remains as one of the important properties of the fluid state.

The importance of viscosity is readily apparent in the design calculations involving heat transfer and fluid flow. These two areas of engineering interest depend in part on definite values of viscosity. It therefore follows that the more accurately one can determine the viscosity of a fluid under a given set of conditions, the more accurately can the problems of heat transfer and fluid flow be calculated or predicted.

Since the studies of fluids must take viscosity into consideration, voluminous work has been recorded on this subject. The theory of gas viscosity, based on the theory of corresponding states, seems relatively well established and mathematical relationships agree with the experimental results much more so than for the case of liquid viscosity.

The existing and more commonly accepted methods for predicting liquid viscosity, i.e., Andrade (2), Souders (2), Thomas (2), and Doolittle (5,6), fall short of ideal due to one or more of the following:

1. Accurate experimental data is required.
2. The accuracy of prediction does not hold over an extended temperature range.
3. The prediction is unduly complicated.
4. The accuracy of prediction does not hold over the entire range of molecular weights within a homologous series.

In this study, the experimental values of absolute viscosity (1) for the n - paraffins were used as the basis for investigation. The purpose of this paper was to improve the state of viscosity prediction by developing a correlation which would minimize or eliminate the above-mentioned shortcomings which presently exist in the accepted methods. As a result, a method for viscosity prediction is presented for the n - paraffins above  $C_4H_{10}$  at any temperature within the liquid range. This method appears applicable whether or not experimental data is available.

## METHODS OF VISCOSITY PREDICTION

The methods of viscosity prediction which are accepted and found to be most generally useful are those of Andrade (2), Souders (2), Thomas (2), and Doolittle (5,6).

The Andrade equation is an explicit temperature-viscosity relation taking the form of an exponential:

$$\ln u = \frac{B}{T} + A \quad \text{or} \quad u = De^{B/T};$$

where;  $u$  = viscosity, centipoise

$T$  = temperatur, °K

$A, B, D,$  = constants

At least two experimental points are required to solve for the constants which appear in the equation. This method is recommended for the correlation of data on liquids under low pressure, and at temperatures below the normal boiling point. Errors may range up to several per cent.

Souders' method is an empirical relation of a log log viscosity function:

$$\log (\log 10 u) = m p_L - 2.9 ;$$

where:  $u$  = viscosity at low pressure, centipoise

$p_L$  = density, g/cm<sup>3</sup>

$m$  = constant =  $1/M$

$1$  = viscosity-constitutional constant  
calculated from atomic and  
structural constants

$M$  = molecular weight

Accurate knowledge of the density at a questioned temperature level is required along with a constant which is calculated from atomic and structural constants. These constants must be known very precisely since it appears as an exponential multiplier. Hydrocarbons, except for the low-molecule-weight n - paraffins, unsaturates, and branched compounds, may be expected to yield values in error  $\pm 20$  per cent.

Thomas' method is an empirical relationship of the log viscosity as a function of a constant, density, and reduced temperature.

$$\log \frac{8.569 u}{(\rho_L)^{1/2}} = \theta \left( \frac{1}{T_r} - 1 \right);$$

where: u = viscosity at low pressure, centipoise

$\rho_L$  = density, g/cm<sup>3</sup>

$\theta$  = viscosity-constitutional constant  
calculated from atomic values

$T_r$  = reduced temperature

This method is restricted to temperatures below the normal boiling point and does not apply to alcohols, acids, or multihalogenated compounds.

Doolittle has developed a method for viscosity prediction of the n - paraffins which is satisfactorily valid but complicated. It involves a logarithmic integral, and constants of integration which vary with molecular weights above 240. This method was further developed to include the consideration of 'Free Space' but was limited to molecular weights between 100 and 240, and is expressed :

$$\ln u = - A e^{500/T} ( -E_i ( -500/T ) ) - 4.66 + c e^{500/T} ;$$

where:  $-E_i ( -500/T )$  is the logarithmic integral

$c$  = molecular weight constant of integration

'Free Space' in a liquid is considered to be that space seemingly arising from the total thermal expansion of the liquid without a change of phase. Deviations from measured  $u$  of values calculated to these integrated forms are within the accuracy of measurements in a majority of cases.



### DEVELOPMENT OF THE CORRELATION

This study was restricted to available data for the n - paraffins within the normal liquid range, i.e., at the temperatures between boiling and freezing under atmospheric pressure. The compounds under consideration were CH<sub>4</sub> through C<sub>20</sub>H<sub>42</sub>.

It was believed, that since a plot of temperature vs. absolute viscosity, Figure I, for each individual compound resulted in fairly parallel curves, that a straight line relationship might exist. A function of corresponding liquid states, here called liquidity, was developed and defined in terms of the temperature.

$$L_b = \frac{t - t_m}{t_b - t_m} ; \quad \text{where:}$$

$L_b$  = liquidity based on the normal boiling temperature

$t$  = any temperature, °C

$t_b$  = normal boiling temperature, °C

$t_m$  = normal melting temperature, °C

This parameter, when substituted for temperature in the above viscosity vs. temperature plot, resulted in Figure II.

Because of the intersecting character of the curves in Figure II, a correlation in this form appeared doubtful and, therefore, a different form of liquidity,  $L_c$ , was introduced to replace  $L_b$  and is shown in Figure III.

$$L_c = \frac{t - t_m}{t_c - t_m} ; \quad \text{where:}$$

$L_c$  = liquidity based on the critical temperature

$t_c$  = critical temperature, °C

In essence,  $L_C$  may be defined as the extent to which the chemical compound exists as a liquid. A compound, therefore, would possess 0 per cent liquidity at the freezing point and 100 per cent liquidity at the boiling or critical temperature depending on whether  $L_b$  or  $L_c$  is in question.

Since the denominator in the equation for liquidity remains constant, a straight line function relating  $L_C$  to temperature results, and is shown in Figure IV.

As is visible in Figure III, the  $L_C$  function based on the critical temperature again resulted in parallel curves. When  $L_C$  was plotted against the number of carbon atoms,  $N_C$ , for curves of constant viscosity, here called iso-viscosity, a series of curves resulted which somewhat resembled a damped harmonic motion, Figure V. It appeared that the amount of dispersion from an imaginary neutral axis was almost constant for each curve when related to  $N_C$ . Furthermore, the oscillation decreased with the increase in the number of carbon atoms. It is possible that this oscillation may involve a shape and/or weight factor, but this was not investigated at this time.

The method of Least Squares (3) was employed to fit this oscillating curve to a straight line, Figure VI. In order to minimize the effect of the oscillations, the values for  $CH_4$  to  $C_4H_{10}$  were excluded. Thus, the fitted straight lines gave liquidity, which is a function of temperature, as a function of the number of carbon atoms.

$$L_C = m N_C + b ; \quad \text{where: } \begin{array}{l} m = \text{slope} \\ N_C = \text{number of carbon atoms} \\ b = \text{intercept value of the iso-viscous} \\ \quad \text{lines on the } L_C \text{ axis} \end{array}$$

It was desirable to attempt to relate the constants, m and b, with a known parameter. While no useful relationship for the slope was developed, the intercept, b, was found to be an exponential curve function of viscosity. Since a plot of intercept vs. parametric viscosity lines resulted in a smooth curve which asymptotically approached both axes, Figure VII, it was found that this curve could be fitted according to statistical methods.

This curve, which takes the name of Gompertz (3) describes a series in which the decay (or growth) of the logarithms of the parameters are declining by a constant percentage. The Gompertz curve was found to fit well the variation of intercept with respect to the parametric iso-viscosity of Figure VI. If an empirical equation is desired, the following is offered:

$$u^* = \frac{\log \left( \frac{\log b - 9.1572}{-9.5356} \right)}{-0.004625}$$

where:  $u^*$  = a coded viscosity  
resulted from the  
Gompertz curve

The decoding of  $u^*$  is done directly from the following:

$\frac{u^*/ 0 / 1 / 2 / 3 / 4 / 5 / \dots / 20, \text{ increasing by units of one}}{u / 2.30 / 2.20 / 2.10 / 2.00 / 1.90 / 1.80 / \dots / 0.30, \text{ decreasing by units of 0.10}}$

In lieu of explaining the method of application for the developed correlation, the following typical problem is presented as an illustration.

Determine the absolute viscosity of hexadecane at 60 °C.

At 60 °C, hexadecane, C<sub>16</sub>H<sub>34</sub>, has a liquidity of 9.64 per cent. This value can be approximated directly from Figure IV, or can be calculated from the expression for liquidity:

$$L_c = \frac{t-t_m}{t_c-t_m} = \frac{60 - 18.2}{452 - 18.2} = \frac{41.8}{433.8} \times 100 = 9.64\%$$

Interpolation of Figure VI between the constant viscosity lines of 2.00 and 1.50 for the point L<sub>c</sub> = 9.64 and N<sub>c</sub> = 16 results in a viscosity prediction of 1.60. This predicted value differs from the experimental value of 1.57 by 0.03 centipoise, or +1.9 per cent.

Should direct interpolation for the viscosity be undesirable, then Figure VIII or the empirical equation of u\* may be used. The only factor needed for these alternative methods is the intercept along the the liquidity axis of Figure VI corresponding to the given point L<sub>c</sub> = 9.64 and N<sub>c</sub> = 16. This intercept is approximated to be 2.0, and u\* is solved as follows:

$$u^* = \frac{\log \left\{ \frac{\log 2.0 - 9.1572}{- 9.5356} \right\}}{- 0.004625} = \frac{\log \left\{ \frac{0.30 - 9.1572}{- 9.5356} \right\}}{- 0.004625}$$

$$= \frac{\log \left( \frac{- 8.8562}{- 9.5356} \right)}{- 0.004625} = \frac{\log 0.93}{- 0.004625} = \frac{- 0.032}{- 0.004625} = 6.92$$

Using Figure VII, u\* is found to be 6.8 for an intercept of 2.0. These coded viscosities are decoded according to the values given in Table IV, and are 1.608 and 1.62 respectively, and differ from the experimental value by 2.4 and 3.2 per cent.

All three methods for viscosity prediction are expected to prove valid for the n - paraffins from  $C_4H_{10}$  through  $C_{20}H_{42}$  and above. When the critical temperature for a compound is unknown, a line on Figure IV can be drawn parallel to  $C_{20}H_{42}$  with the origin at the melting temperature, 0 per cent liquidity.

### CURVE FITTING (3)

In order to fit the curves in Figure V to a straight line, the method of Least Squares was employed. For the iso-viscous line  $u = 1.0$ , only the following points were considered:

$N_c$	$L_c$
5	12.0
6	8.8
7	13.6
8	10.4
9	13.8
10	12.0
11	14.0
12	13.8
13	15.4
14	15.5
15	16.5
16	16.8
17	18.0
18	18.4
19	19.2
20	19.6

The straight line is of the form  $y = m x + b$  or, in this particular case,  $L_c = m N_c + b$ . The slope and intercept,  $m$  and  $b$ , are found according to the general formula:

$$b n_T + m \sum N_c = \sum L_c$$

$$b \sum N_c + m \sum (N_c^2) = \sum (N_c L_c)$$

or

$$16 b + 200 m = 237.8$$

$$200 b + 2840 m = 3182.5$$

solving these simultaneous equations resulted in  $m = 0.618$  and  $b = 7.14$ .

Table III gives the values of  $m$  and  $b$  for all the iso-viscous lines in Figure VI.

The values for the constants in the empirical equation for  $u^*$ , Gompertz curve, were developed in Table IV and then solved as follows:

$$g^n = \frac{\Sigma_3 \log b - \Sigma_2 \log b}{\Sigma_2 \log b - \Sigma_1 \log b} = \frac{8.3601 - 4.0445}{4.0445 + 0.6052}$$

$$\frac{g^7}{g} = \frac{4.3156}{4.6497} = \underline{0.9281}$$

$$\log g^7 = 9.96764 - 10 = -0.03236$$

$$\log g = -0.0046229 = 9.9954 - 10$$

$$\underline{g = 0.98941}$$

$$\log a = (\Sigma_2 \log b - \Sigma_1 \log b) \frac{g - 1}{(g^7 - 1)^2}$$

$$= 4.0445 + 0.6052 \left\{ \frac{0.98941 - 1}{(0.9281 - 1)^2} \right\} = 4.6497 \left\{ \frac{-0.01059}{-(0.07186)^2} \right\}$$

$$\underline{\log a = 4.6497 (-2.0508) = -9.5356}$$

$$\begin{aligned} \log k &= \frac{1}{7} \left\{ \Sigma_1 \log b - \left( \frac{g^7 - 1}{g - 1} \right) \log a \right\} \\ &= \frac{1}{7} \left( \Sigma_1 \log b - \frac{\Sigma_2 \log b - \Sigma_1 \log b}{g^7 - 1} \right) \end{aligned}$$

$$= \frac{1}{7} \left\{ \frac{(\Sigma_1 \log b)(\Sigma_3 \log b) - (\Sigma_2 \log b)^2}{\Sigma_1 \log b + \Sigma_3 \log b - 2 \Sigma_2 \log b} \right\}$$

$$= \frac{1}{7} ( -0.60523 - ( 6.7856 ) ( -9.5356 ) )$$

$$= \frac{1}{7} ( -0.60523 - ( -64.7053 ) ) = \frac{1}{7} ( 64.1001 )$$

$$\underline{\log k = \frac{1}{7} ( 64.1001 ) = 9.1572}$$

$$\log b = \log k + (\log a) g^{u^*}$$

$$= 9.1572 + (-9.5356)(0.98941)^{u^*}$$

$$u^* \log 0.98941 = \log \left( \frac{\log b - 9.1572}{-9.5356} \right)$$

$$u^* = \frac{\log \left( \frac{\log b - 9.1572}{-9.5356} \right)}{\log 0.98941}$$
$$= 0.004625$$



## RESULTS AND CONCLUSIONS

A function of corresponding liquid states expressing the degree of liquid which a substance exhibits was termed liquidity. This term was mathematically defined as:  $L_C = \frac{t - t_m}{t_c - t_m}$ . Since the denominator is constant, for any one substance, liquidity becomes a straight line function of the temperature and is shown in Figure IV.

Liquidity was designed as a straight line function of the number of carbon atoms for lines of iso-viscosity. This function was empirically stated as:  $L_C = m N_C + b$  and is shown in Figure VI for viscosity values ranging from 0.21 to 2.50 centipoise.

Plotting the intercept of the iso-viscous lines in Figure IV as a function of viscosity resulted in a smooth Gompertz curve, Figure VII, which has the following empirical equation:

$$u^* = \frac{\log \left( \frac{\log b - 9.1572}{- 9.5356} \right)}{- 0.004625} .$$

The initial plotting of liquidity vs.  $N_C$  resulted in an oscillating curve resembling damped harmonic motion. The amplitude along any given iso-viscous line decreased as the number of carbon atoms increased. It was also found that the amplitude for a given  $N_C$ , at all values of viscosity, was of the same phase and magnitude.

By means of the liquidity function, it is possible to predict the viscosity of all n - paraffins above  $C_4H_{10}$  at any temperature within the normal liquid range. Deviations from the experimental values to those resulting from the methods presented in this paper are within  $\pm 10$  per cent for the majority, and less than  $\pm 20$  per cent for the extreme cases. Representative comparisons are shown in Table V.

The method developed in this study, of which there are three modes of application, may be employed to predict the viscosity values of the n - paraffin liquids when no experimental data is available by means of extrapolating in Figure VI, and in Figure IV if the critical temperature is unknown.

## RECOMMENDATIONS

The elimination of the oscillatory tendency of Figure V would improve the accuracy of the method developed by this study. This tendency might be due to a weight and/or shape factor and should be investigated.

In line with the results of this paper, it is felt that similar studies of other homologous series be initiated to determine to what extent the liquidity function applies throughout the chemical families. If future efforts prove favorable, a generalized viscosity function might then be designed to cover all liquids.

It is recommended that experimental values of viscosity for the n - paraffins above  $C_{20}H_{42}$  be determined for the normal liquid range. These values would establish the accuracy of predicting viscosity from Figure VI by means of extrapolation.

It is further felt that some relationship exists between the slopes of the iso-viscous lines of Figure VI and another parameter exists. If this relationship was found and its empirical expression relatively simple, then the need for interpolating in order to solve for the intercept would be eliminated.

APPENDIX

TABLE I

(3)

ABSOLUTE VISCOSITY OF THE n - PARAFFIN LIQUIDS

<u>TEMP.</u>	<u>n - PARAFFINS</u>						
	<u>CH<sub>4</sub></u>	<u>C<sub>2</sub>H<sub>6</sub></u>	<u>C<sub>3</sub>H<sub>8</sub></u>	<u>C<sub>4</sub>H<sub>10</sub></u>	<u>C<sub>5</sub>H<sub>12</sub></u>	<u>C<sub>6</sub>H<sub>14</sub></u>	<u>C<sub>7</sub>H<sub>16</sub></u>
-190			13.8				
-185	.226*		8.78				
-180	.188		5.96				
-175	.161	.985	4.26				
-170	.142	.805	3.18				
-165	.127	.673	2.46				
-160	.115	.574	1.96				
-155		.500	1.60				
-150		.442	1.34				
-145		.396	1.14				
-140		.359	.984				
-135		.328	.861				
-130		.301	.762		3.63		
-125		.278	.681		2.89		
-120		.257	.614		2.35		
-115		.238	.558		1.96		
-110		.222	.510		1.66		
-105		.207	.469		1.43		
-100		.195	.433		1.24		
-95		.183	.402		1.09	2.14	

\*All values for absolute viscosity given in centipoise.

<u>°C</u>	<u>C<sub>2</sub>H<sub>6</sub></u>	<u>C<sub>3</sub>H<sub>8</sub></u>	<u>C<sub>4</sub>H<sub>10</sub></u>	<u>C<sub>5</sub>H<sub>12</sub></u>	<u>C<sub>6</sub>H<sub>14</sub></u>	<u>C<sub>7</sub>H<sub>16</sub></u>	<u>C<sub>8</sub>H<sub>18</sub></u>
-90	.172	.374	.630	.973	1.83	3.77	
-85	.162	.350	.580	.874	1.58	3.11	
-80		.327	.536	.791	1.38	2.61	
-75		.307	.497	.720	1.22	2.22	
-70		.288	.462	.659	1.09	1.92	
-65		.272	.431	.607	.978	1.68	
-60		.256	.403	.562	.888	1.48	
-55		.242	.378	.522	.809	1.31	2.12
-50		.228	.355	.487	.741	1.18	1.86
-45		.216	.335	.455	.683	1.06	1.64
-40		.205	.315	.428	.632	.965	1.46
-35			.298	.403	.587	.882	1.31
-30			.282	.380	.547	.810	1.18
-25			.267	.359	.511	.747	1.07
-20			.253	.341	.480	.692	.981
-15			.241	.323	.451	.643	.900
-10			.229	.307	.426	.600	.829
-5			.219	.293	.402	.561	.767
0			.210	.279	.381	.526	.713
5				.267	.362	.495	.664
10				.255	.344	.467	.620
15				.245	.328	.441	.582

<u>°C</u>	<u>C<sub>9</sub>H<sub>20</sub></u>	<u>C<sub>10</sub>H<sub>22</sub></u>	<u>C<sub>11</sub>H<sub>24</sub></u>	<u>C<sub>12</sub>H<sub>26</sub></u>	<u>C<sub>13</sub>H<sub>28</sub></u>	<u>C<sub>14</sub>H<sub>30</sub></u>	<u>C<sub>15</sub>H<sub>32</sub></u>
-90							
-85							
-80							
-75							
-70							
-65							
-60							
-55	3.52						
-50	2.99						
-45	2.58						
-40	2.24						
-35	1.97						
-30	1.75	2.56					
-25	1.56	2.25	3.19				
-20	1.40	1.99	2.78				
-15	1.27	1.77	2.44				
-10	1.15	1.59	2.16	2.91			
- 5	1.06	1.44	1.93	2.57	3.36		
0	.969	1.30	1.73	2.28	2.95		
5	.893	1.19	1.57	2.04	2.61	3.33	
10	.827	1.09	1.42	1.83	2.33	2.94	3.66
15	.768	1.00	1.30	1.66	2.09	2.62	3.23

<u>°C</u>	<u>C<sub>5</sub>H<sub>12</sub></u>	<u>C<sub>6</sub>H<sub>14</sub></u>	<u>C<sub>7</sub>H<sub>16</sub></u>	<u>C<sub>8</sub>H<sub>18</sub></u>	<u>C<sub>9</sub>H<sub>20</sub></u>	<u>C<sub>10</sub>H<sub>22</sub></u>
20	.235	.313	.418	.547	.716	.928
25	.225	.299	.397	.515	.670	.861
30	.216	.285	.377	.487	.628	.802
35	.207	.273	.359	.461	.590	.749
40		.262	.343	.437	.556	.701
45		.251	.327	.415	.525	.658
50		.241	.313	.395	.497	.619
55		.231	.299	.376	.471	.584
60		.222	.287	.359	.447	.552
65		.213	.275	.343	.425	.522
70		.205	.264	.327	.405	.495
75			.253	.313	.386	.470
80			.243	.300	.369	.448
85			.234	.288	.353	.426
90			.225	.277	.338	.407
95			.217	.266	.323	.389
100			.209	.256	.310	.372
105				.246	.298	.356
110				.237	.286	.341
115				.228	.275	.327
120				.220	.264	.314
125				.212	.254	.301



<u>°C</u>	<u>C<sub>11</sub>H<sub>24</sub></u>	<u>C<sub>12</sub>H<sub>26</sub></u>	<u>C<sub>13</sub>H<sub>28</sub></u>	<u>C<sub>14</sub>H<sub>30</sub></u>	<u>C<sub>15</sub>H<sub>32</sub></u>	<u>C<sub>16</sub>H<sub>34</sub></u>	<u>C<sub>17</sub>H<sub>36</sub></u>
20	1.19	1.51	1.89	2.34	2.87	3.48	4.21
25	1.10	1.38	1.71	2.11	2.57	3.10	3.71
30	1.01	1.27	1.56	1.91	2.31	2.77	3.30
35	.939	1.17	1.43	1.74	2.09	2.49	2.95
40	.873	1.08	1.31	1.59	1.90	2.25	2.65
45	.815	1.00	1.21	1.46	1.74	2.04	2.40
50	.763	.932	1.12	1.35	1.59	1.87	2.18
55	.716	.870	1.04	1.24	1.47	1.71	1.99
60	.673	.815	.973	1.15	1.35	1.57	1.82
65	.634	.764	.909	1.07	1.25	1.45	1.67
70	.599	.719	.851	1.00	1.17	1.35	1.55
75	.567	.678	.800	.938	1.09	1.25	1.43
80	.537	.640	.753	.880	1.02	1.17	1.33
85	.510	.606	.710	.827	.953	1.09	1.24
90	.485	.574	.671	.780	.895	1.02	1.16
95	.462	.545	.635	.736	.843	.959	1.08
100	.440	.518	.602	.696	.795	.902	1.02
105	.420	.494	.572	.659	.751	.850	.958
110	.402	.471	.544	.625	.711	.803	.903
115	.384	.449	.518	.594	.674	.760	.852
120	.368	.429	.494	.565	.640	.720	.806
125	.353	.411	.472	.539	.609	.684	.764

<u>°C</u>	<u>C<sub>18</sub>H<sub>38</sub></u>	<u>C<sub>19</sub>H<sub>40</sub></u>	<u>C<sub>20</sub>H<sub>42</sub></u>
20			
25			
30	3.891	4.565	
35	3.458	4.033	4.699
40	3.093	3.588	4.156
45	2.782	3.212	3.701
50	2.516	2.891	3.316
55	2.286	2.616	2.988
60	2.087	2.379	2.706
65	1.912	2.172	2.461
70	1.760	1.992	2.249
75	1.625	1.833	2.063
80	1.505	1.693	1.900
85	1.398	1.568	1.755
90	1.303	1.458	1.627
95	1.217	1.359	1.513
100	1.140	1.269	1.410
105	1.070	1.189	1.318
110	1.006	1.116	1.235
115	0.948	1.058	1.159
120	0.896	0.989	1.091
125	0.847	0.934	1.028

<u>°C</u>	<u>C<sub>11</sub>H<sub>24</sub></u>	<u>C<sub>12</sub>H<sub>26</sub></u>	<u>C<sub>13</sub>H<sub>28</sub></u>	<u>C<sub>14</sub>H<sub>30</sub></u>	<u>C<sub>15</sub>H<sub>32</sub></u>	<u>C<sub>16</sub>H<sub>34</sub></u>
130	.339	.393	.451	.514	.580	.650
135	.325	.377	.431	.491	.553	.619
140	.312	.362	.413	.470	.528	.590
145	.301	.347	.396	.450	.505	.563
150	.289	.334	.386	.431	.483	.538
155	.278	.321	.365	.413	.463	.515
160	.268	.309	.351	.397	.444	.493
165	.259	.297	.338	.381	.426	.473
170	.249	.287	.325	.366	.409	.454
175	.240	.276	.313	.353	.393	.436
180	.232	.266	.302	.340	.378	.419
185	.224	.257	.291	.327	.364	.403
190	.216	.248	.281	.315	.351	.388
195	.209	.239	.271	.304	.338	.373
200		.231	.262	.294	.326	.360
205		.223	.252	.283	.315	.347
210		.215	.244	.273	.303	.335
215		.208	.235	.264	.293	.323
220			.227	.255	.283	.312
225			.219	.246	.273	.301
230			.211	.238	.264	.291
235			.204	.230	.255	.281

<u>°C</u>	<u>C<sub>17</sub>H<sub>36</sub></u>	<u>C<sub>18</sub>H<sub>38</sub></u>	<u>C<sub>19</sub>H<sub>40</sub></u>	<u>C<sub>20</sub>H<sub>42</sub></u>
130	.725	.803	.884	.971
135	.689	.762	.838	.919
140	.656	.724	.795	.871
145	.625	.689	.756	.827
150	.597	.657	.719	.786
155	.570	.627	.686	.748
160	.545	.599	.654	.713
165	.522	.573	.625	.680
170	.501	.548	.598	.650
175	.480	.526	.573	.622
180	.461	.504	.549	.596
185	.443	.484	.526	.571
190	.426	.465	.506	.548
195	.410	.448	.486	.526
200	.395	.431	.468	.506
205	.381	.415	.450	.486
210	.367	.400	.433	.468
215	.354	.385	.417	.451
220	.342	.372	.402	.435
225	.330	.359	.388	.419
230	.319	.347	.375	.404
235	.308	.335	.362	.390

<u>°C</u>	<u>C<sub>14</sub>H<sub>30</sub></u>	<u>C<sub>15</sub>H<sub>32</sub></u>	<u>C<sub>16</sub>H<sub>34</sub></u>	<u>C<sub>17</sub>H<sub>36</sub></u>	<u>C<sub>18</sub>H<sub>38</sub></u>	<u>C<sub>19</sub>H<sub>40</sub></u>	<u>C<sub>20</sub>H<sub>42</sub></u>
240	.222	.246	.272	.308	.324	.350	.377
245	.215	.238	.263	.298	.313	.338	.365
250	.207	.231	.254	.288	.303	.327	.353
255	.201	.223	.246	.279	.29	.32	.34
260		.216	.238	.261	.28	.31	.33
265		.209	.231	.253	.27	.30	.32
270		.202	.223	.245	.27	.29	.31
275			.216	.237	.26	.28	.30
280			.210	.230	.25	.26	.29
285			.203	.223	.24	.26	.28
290				.216	.23	.25	.27
295				.209	.23	.25	.26
300				.202	.22	.24	.26
305					.21	.23	.25
310					.21	.22	.24
315					.20	.22	.23
320						.21	.23
325						.20	.22
330						.20	.21
335							.21
340							.20

TABLE II

ISO - VISCOUS VALUES OF LIQUIDITY ( $L_c$ )

VS.

NUMBER OF CARBON ATOMS ( $N_c$ ).

$N_c$	$u = 0.21$ $L_c$	$u = 0.25$ $L_c$	$u = 0.30$ $L_c$	$u = 0.35$ $L_c$	$u = 0.40$ $L_c$
5	50.4	43.2	37.6	33.6	29.6
6	50.0	42.0	36.6	32.0	28
7	53.2	45.4	40.8	36.0	32.2
8	51.8	44.8	38.8	33.6	30
9	54.4	48.4	41.8	37.0	33.6
10	54.6	48.6	42.0	36.8	32.1
11	56.2	49.8	43.4	38.4	34.6
12	56.8	50.4	44.2	39.2	35.4
13	58.4	51.2	45.1	40.2	36.6
14	60.0	52.8	46.4	40.8	37.2
15	60.8	53.4	47.2	42.0	38.0
16	61.6	53.6	47.5	42.4	38.4
17	63.2	56	49.6	44.8	40.4
18	64	56	50.2	45.0	40.8
19	64.5	57.6	51.1	45.8	42.8
20	64	57.6	52.0	46.8	44.8

$N_c$	$u = 0.50$ $L_c$	$u = 0.60$ $L_c$	$u = 0.80$ $L_c$	$u = 1.00$ $L_c$	$u = 1.50$ $L_c$	$u = 2.00$ $L_c$	$u = 2.50$ $L_c$
5	24	20	15.2	12	5.6	4.4	2.4
6	22	17.6	12.5	8.8	4		
7	26.7	22.4	17.0	13.6	8.4	5.3	3.2
8	23.6	20	14.2	10.4	4.6	1.3	
9	27.5	23.5	17.6	13.8	8	4.8	2.4
10	26	22.0	15.8	12	6	2.6	
11	28.4	24.2	18.0	14	8.4	4.6	2.1
12	29.1	24.4	18	13.8	7.6	4.0	1.3
13	30	25.6	19.5	15.4	9.2	5.6	2.9
14	30.8	26	20	15.5	9.2	5.3	2.8
15	31.6	27.2	21.2	16.5	10	6.4	3.5
16	32	27.8	21.2	16.8	10.4	6.6	3.9
17	33.6	29.2	22.8	18	11.6	7.6	4.8
18	34	29.6	22.8	18.4	11.6	7.7	4.1
19	34.8	30.2	23.6	19.2	12.2	8.3	5.6
20	35.5	30.6	24	19.6	12.8	8.8	6

TABLE III

SLOPE AND INTERCEPT  
FOR LINES OF ISO-VISCOSITY

<u>VISCOSITY,</u> <u>u</u>	<u>SLOPE,</u> <u>m</u>	<u>INTERCEPT,</u> <u>b</u>
0.21	1.097	44.04
0.25	0.921	39.18
0.30	1.000	32.14
0.35	0.955	27.72
0.40	1.000	23.40
0.50	0.847	18.76
0.60	0.805	14.96
0.80	0.703	10.18
1.00	0.618	7.14
1.50	0.520	2.23
2.00	0.374	0.72
2.50	0.230	0.35



TABLE IV

TABULATED PROCEDURE FOR GOMPERTZ CURVE-FITTING

<u>u</u>	<u>u*</u>	<u>b</u>	<u>log b</u>	<u>g<sup>u*</sup></u>	<u>(log a)g<sup>u*</sup></u>	<u>log b = log k</u> <u>+ (log a)g<sup>u*</sup></u>	<u>b<sub>c</sub></u>
2.30	0	0.492	-.3080	1.0000	-9.5356	-.3785	.418
2.20	1	0.563	-.2495	.9894	-9.4346	-.2775	.528
2.10	2	0.637	-.1959	.9789	-9.3347	-.1775	.664
2.00	3	0.717	-.1445	.9686	-9.2359	-.0787	.834
1.90	4	0.987	-.0057	.9583	-9.1381	+.0191	1.045
1.80	5	1.27	.1038	.9482	-9.0413	.1159	1.306
1.70	6	1.565	.1945	.9382	-8.9455	.2116	1.628
$\Sigma_1 \log b = -.6053$							
1.60	7	1.88	.2742	.9282	-8.8508	.3064	2.03
1.50	8	2.23	.3483	.9184	-8.7570	.4001	2.51
1.40	9	3.07	.4871	.9086	-8.6643	.4928	3.11
1.30	10	4.00	.6021	.8990	-8.5726	.5846	3.84
1.20	11	4.99	.6981	.8895	-8.4818	.6753	4.74
1.10	12	6.04	.7810	.8800	-8.3920	.7652	5.82
1.00	13	7.14	.8538	.8708	-8.3031	.8540	7.15
$\Sigma_2 \log b = 4.0445$							
.90	14	8.60	.9345	.8615	-8.2152	.9420	8.75
.80	15	10.18	1.0078	.8524	-8.1282	1.0290	10.69
.70	16	12.40	1.0934	.8434	-8.0421	1.1150	13.03
.60	17	14.96	1.17493	.8344	-7.9570	1.2002	15.86
.50	18	18.76	1.27323	.8256	-7.8727	1.2845	19.25
.40	19	23.40	1.3692	.8169	-7.7893	1.3679	23.33
.30	20	32.14	1.5071	.8082	-7.7068	1.4504	28.21
$\Sigma_3 \log b = 8.36010$							

TABLE V

COMPARISON OF CALCULATED AND EXPERIMENTAL

LIQUID VISCOSITIES <sup>(2)</sup>

<u>COMPOUND</u>	<u>t, °C</u>	<u>Exp. <math>\mu</math></u>	<u>THOMAS</u>		<u>SOUDERS</u>		<u>PERMUTT</u>	
			<u><math>\mu</math></u>	<u>% ERROR</u>	<u><math>\mu</math></u>	<u>% ERROR</u>	<u><math>\mu</math></u>	<u>% ERROR</u>
ETHANE	-175	0.985	1.521	+54	0.288	-72	1.365	+38.6
	-120	0.257	0.330	+27	0.173	-33	.350	+36
PROPANE	-140	0.984	1.15	+17	0.398	-60	0.670	-32
	- 80	0.327	0.332	+1.5	0.222	-32	0.285	-12.8
	-40	0.205	0.199	-2.9	0.169	-18	0.190	- 7.3
BUTANE	-90	0.63	0.68	+8.0	0.45	-29	0.69	+9.5
	-60	0.403	0.414	+2.7	0.316	-21	0.415	+3.0
	-30	0.282	0.280	-0.7	0.239	-15	0.24	-15.0
	0	0.210	0.205	-2.4	0.191	-9.0	0.22	+ 4.8
PENTANE	-120	2.35	2.55	+8.6	1.40	-40	1.84	-21
	-80	0.791	0.921	+16	0.673	-15	0.752	- 4.9
	-40	0.428	0.471	+10	0.402	-6.1	0.415	- 3.0
	0	0.279	0.289	+3.6	0.271	-2.8	0.275	- 1.4
	30	0.216	0.216	0.0	0.212	-1.8	0.220	+ 1.8

COMPOUND	t, °C	Exp. u	THOMAS		SOUDERS		PERMUTT	
			u	% ERROR	u	% ERROR	u	% ERROR
HEXANE	-60	0.888	0.963	+8.5	0.845	-4.8	1.05	+19
	0	0.381	0.393	+3.2	0.379	-0.5	0.405	+6.3
	40	0.262	0.260	-0.8	0.262	0.0	0.269	+2.7
HEPTANE	-40	0.965	0.966	+0.1	0.948	-1.8	0.870	-10
	20	0.418	0.413	-1.2	0.425	+1.7	0.385	-8.0
	60	0.287	0.274	-4.5	0.284	-1.0	0.275	-4.2
OCTANE	-30	1.18					1.40	+18
	40	0.437					0.475	+8.7
	100	0.256					0.260	+1.5
DODECANE	25	1.38					1.45	+5.1
	100	0.518					0.52	+0.4
	200	0.23					0.23	-8.7
HEXADECANE	60	1.57					1.62	+3.5
	150	0.538					0.53	-0.9
	250	0.254					0.25	-1.6
EICOSANE	75	2.06					2.00	-3.0
	185	0.571					0.580	+1.6
	300	0.26					0.263	+1.2

TABLE VI

TEMPERATURE CONSTANTS

<u>COMPOUND</u>	<u>MELTING TEMPERATURE</u> $t_m, ^\circ\text{C}$	<u>CRITICAL TEMPERATURE</u> $t_c, ^\circ\text{C}$	<u>BOILING TEMPERATURE</u> $t_b, ^\circ\text{C}$
CH <sub>4</sub>	-182.5	-82.5	-161.5
C <sub>2</sub> H <sub>6</sub>	-183.3	32.3	- 88.6
C <sub>3</sub> H <sub>8</sub>	-187.7	96.8	- 42.1
C <sub>4</sub> H <sub>10</sub>	-138.4	152.01	- 0.5
C <sub>5</sub> H <sub>12</sub>	-129.7	196.6	36.1
C <sub>6</sub> H <sub>14</sub>	- 95.3	234.7	68.7
C <sub>7</sub> H <sub>16</sub>	- 90.6	267.0	98.4
C <sub>8</sub> H <sub>18</sub>	- 56.8	296.2	125.7
C <sub>9</sub> H <sub>20</sub>	- 53.5	322.0	150.8
C <sub>10</sub> H <sub>22</sub>	- 29.7	346.0	174.1
C <sub>11</sub> H <sub>24</sub>	- 25.6	367.0	195.9
C <sub>12</sub> H <sub>26</sub>	- 9.6	386.0	216.3
C <sub>13</sub> H <sub>28</sub>	- 5.4	404.0	235.4
C <sub>14</sub> H <sub>30</sub>	5.9	422.0	253.6
C <sub>15</sub> H <sub>32</sub>	9.9	437.0	270.6
C <sub>16</sub> H <sub>34</sub>	18.2	452.0	286.8
C <sub>17</sub> H <sub>36</sub>	22.0	462.0	301.8
C <sub>18</sub> H <sub>38</sub>	28.2	477.0	316.1
C <sub>19</sub> H <sub>40</sub>	32.1	487.0	329.7
C <sub>20</sub> H <sub>42</sub>	36.8	502.0	342.7

FIGURE 1

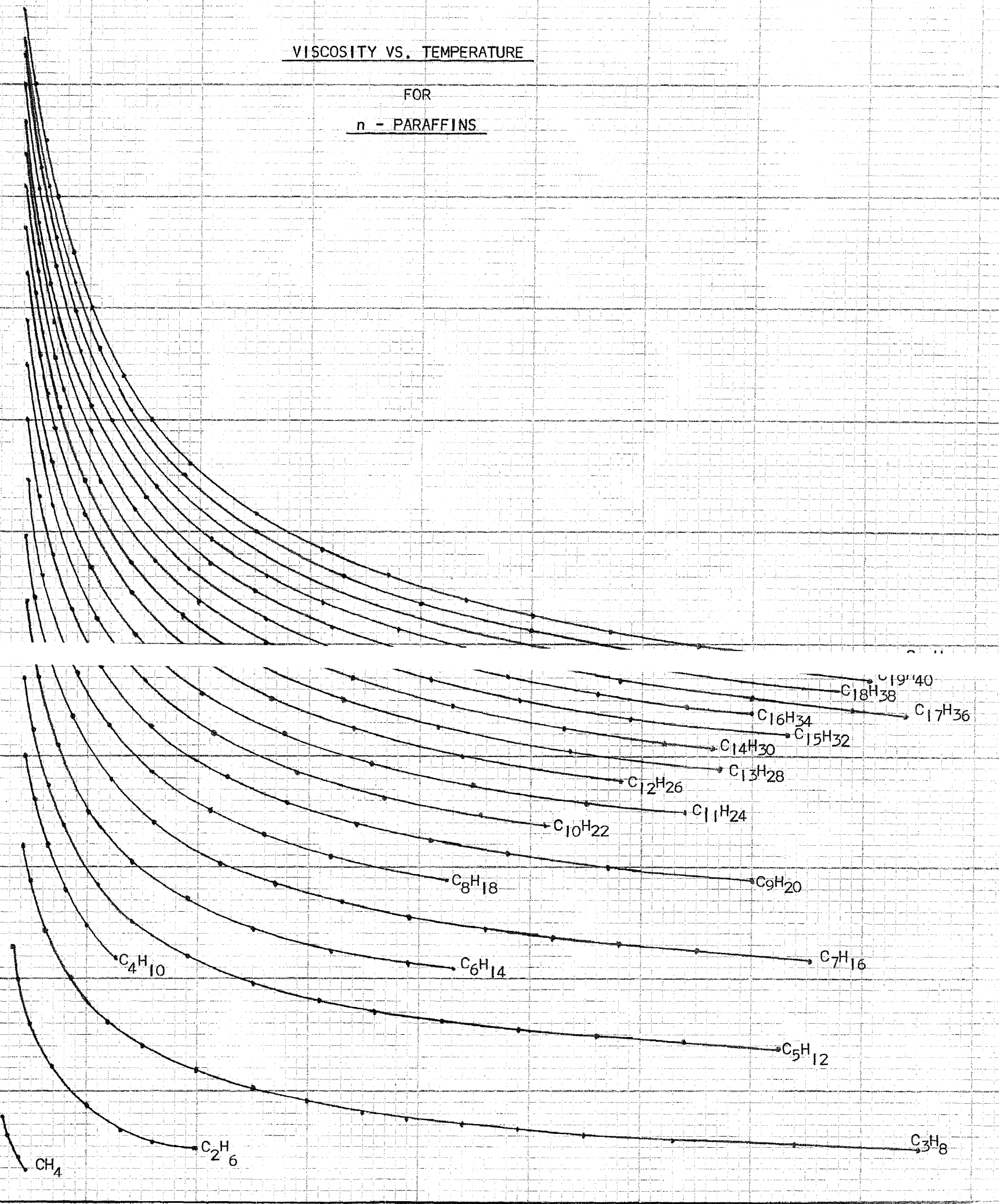
VISCOSITY VS. TEMPERATURE

FOR  
n - PARAFFINS

TEMPERATURE, °C

46

400  
300  
200  
100  
0  
-100  
-200



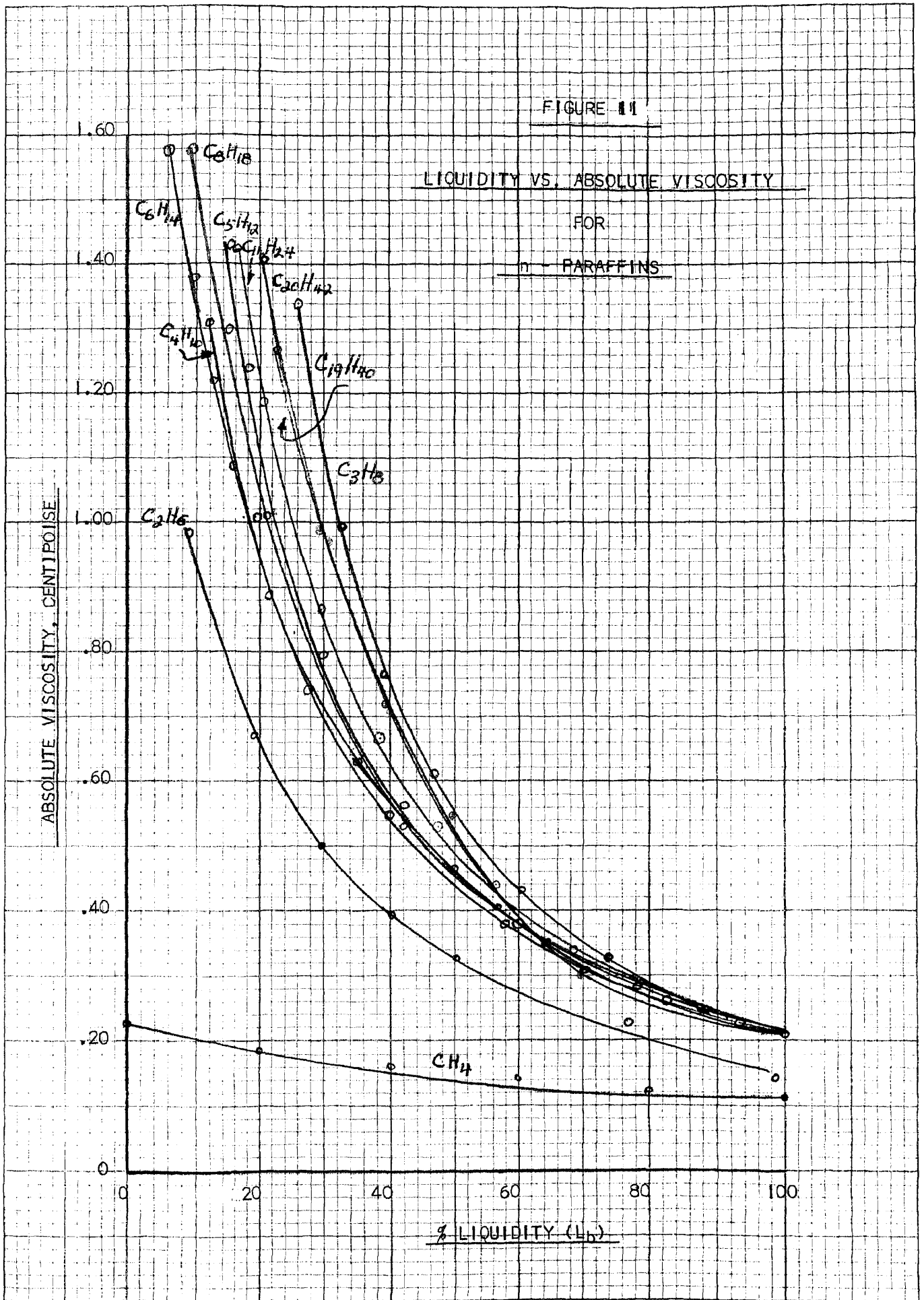
ABSOLUTE VISCOSITY, centipoise

FIGURE 11

LIQUIDITY VS. ABSOLUTE VISCOSITY

FOR

n - PARAFFINS



- FIGURE III -

LIQUIDITY VS. ABSOLUTE VISCOSITY

FOR

n - PARAFFINS

ABSOLUTE VISCOSITY, CENTIPOISE

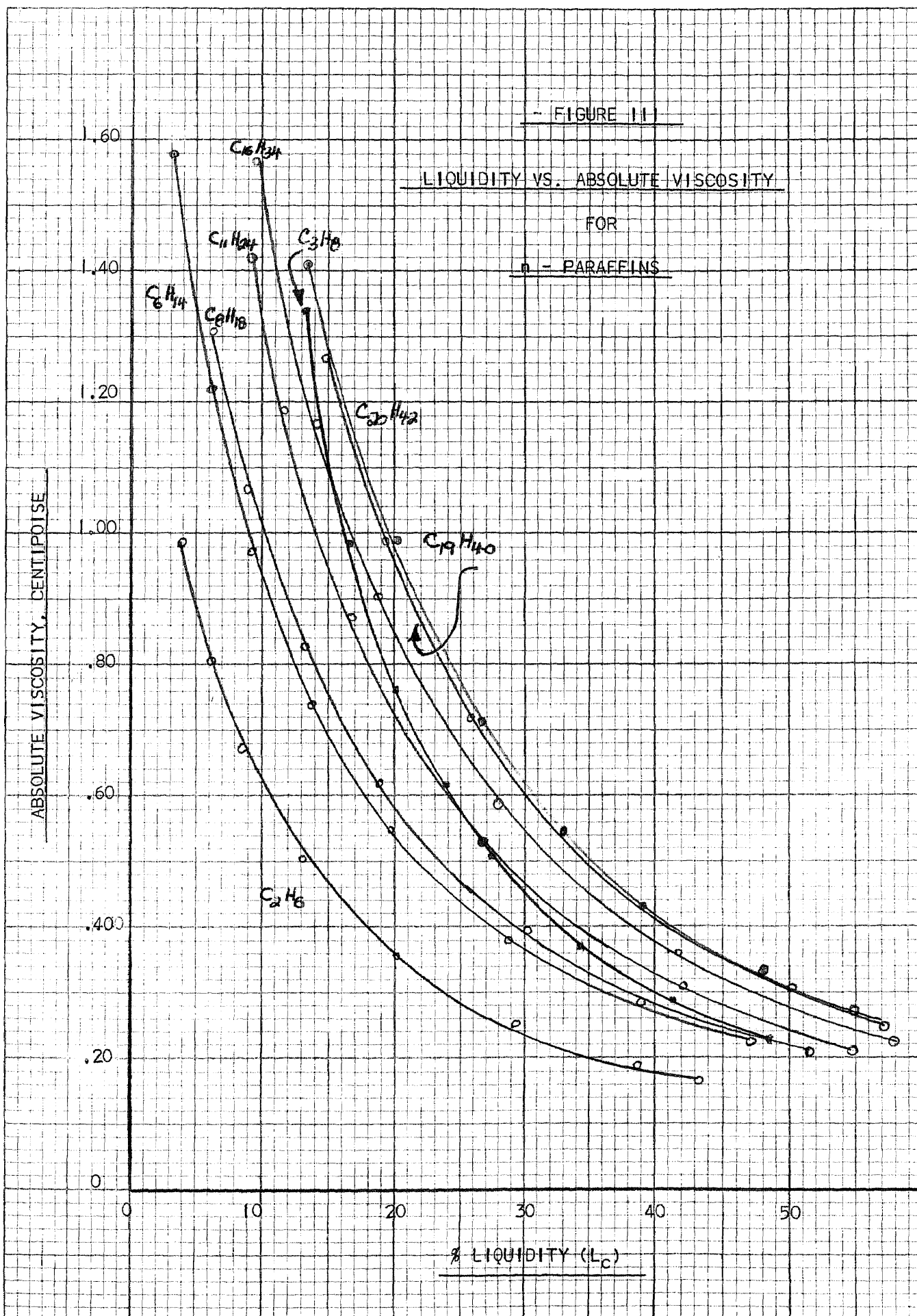
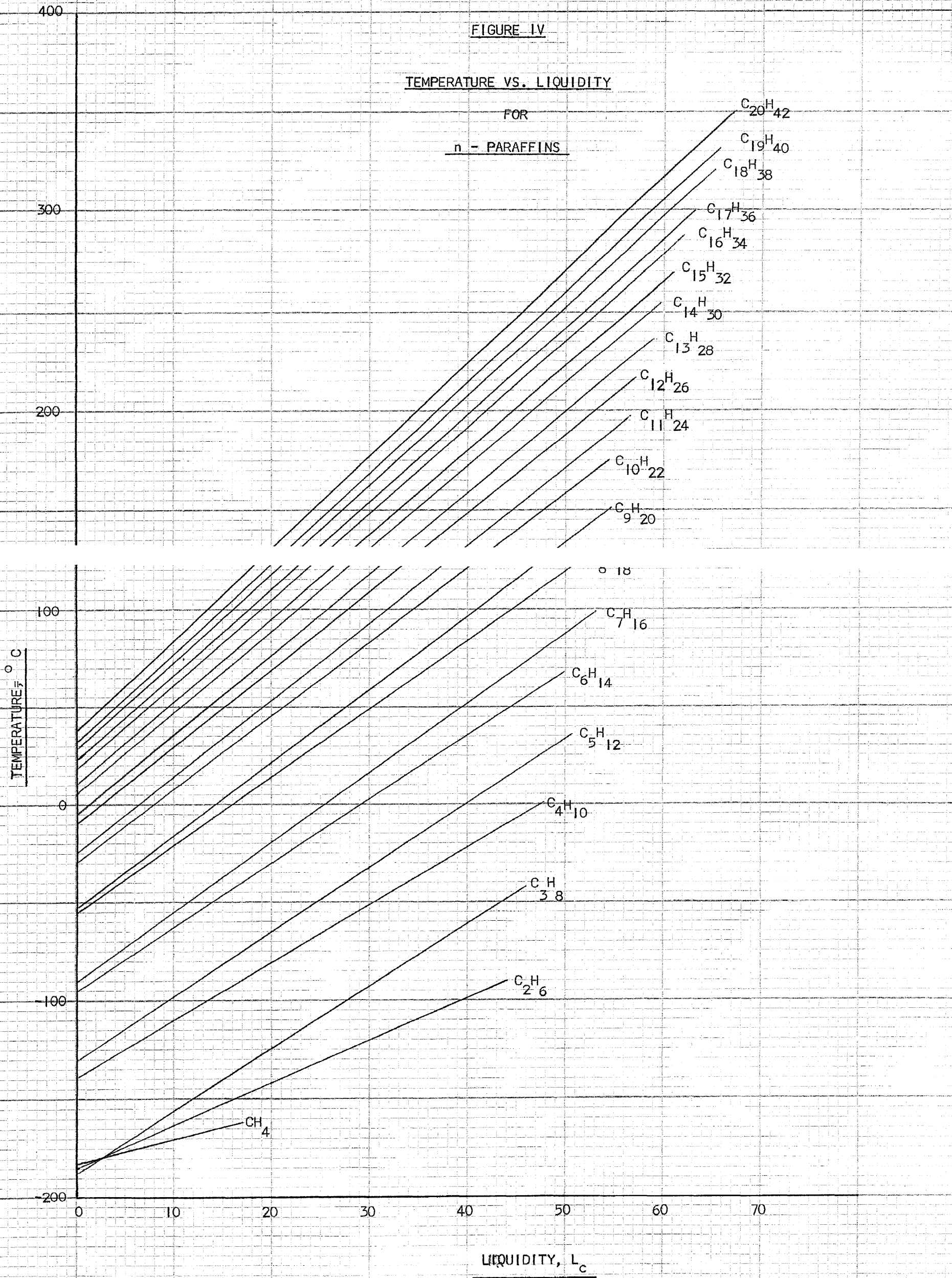


FIGURE IV

TEMPERATURE VS. LIQUIDITY

FOR  
n - PARAFFINS

-87-





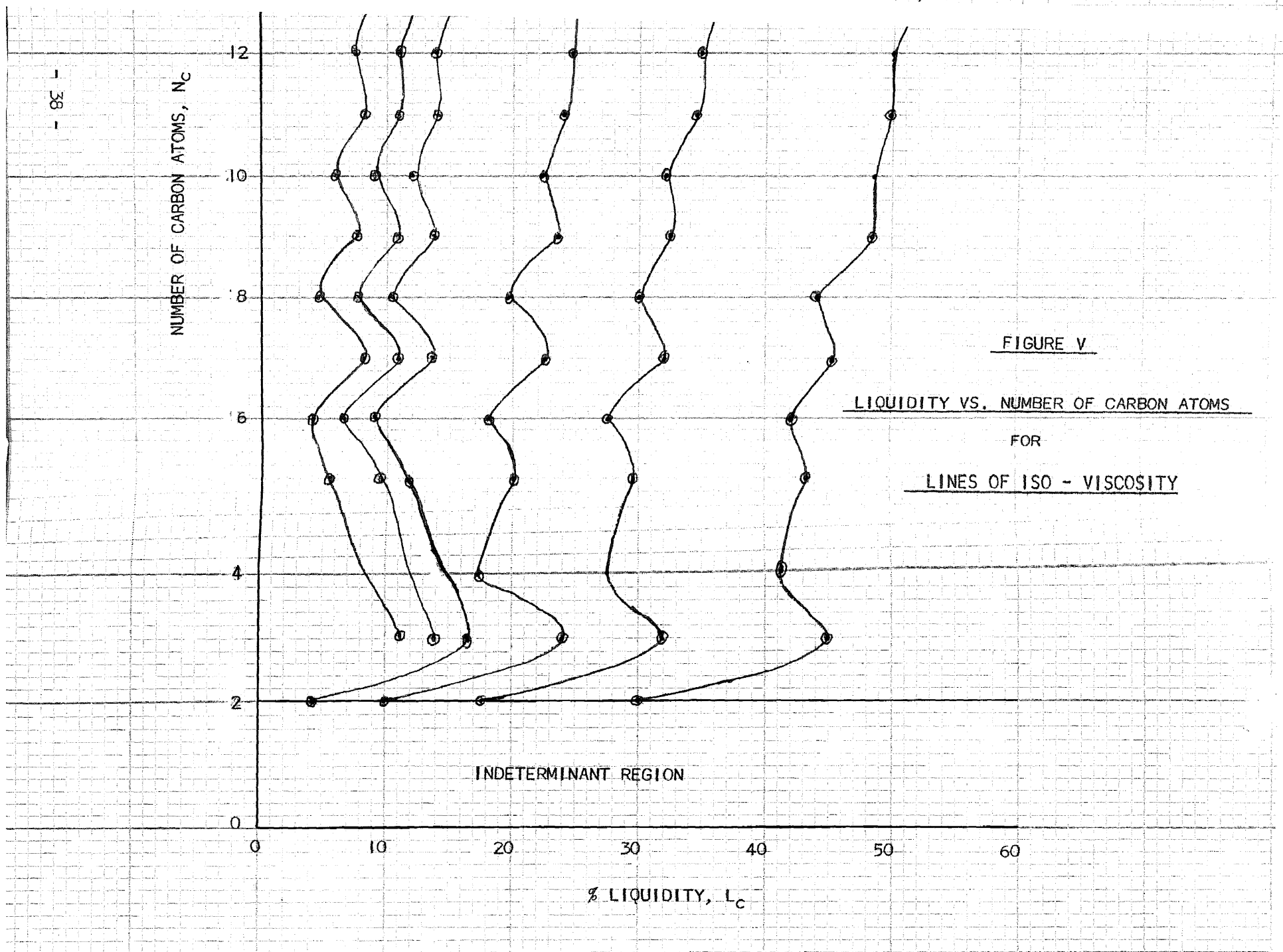
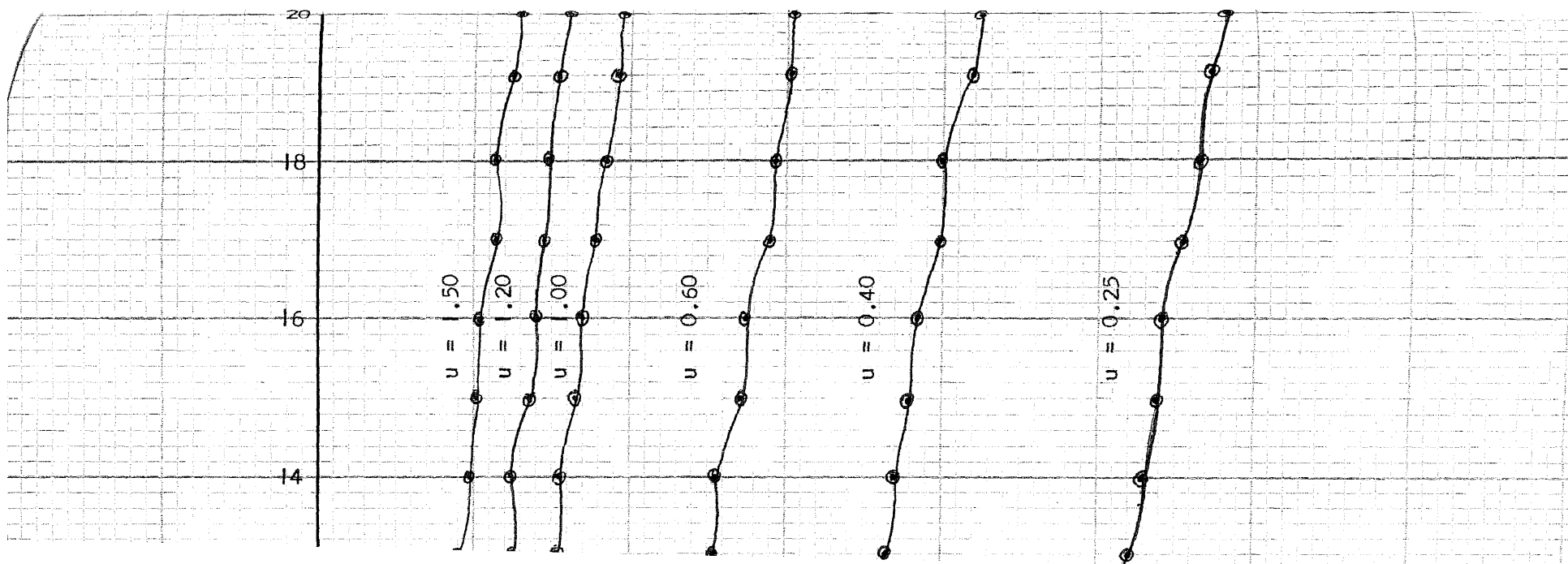


FIGURE V

LIQUIDITY VS. NUMBER OF CARBON ATOMS

FOR

LINES OF ISO - VISCOSITY

FIGURE VI

LIQUIDITY VS. NUMBER OF CARBON ATOMS

CURVE - FITTED FOR

STRAIGHT LINES OF ISO - VISCOSITY

EXTRAPOLATED REGION

EXPERIMENTAL REGION

REJECTED REGION

NUMBER OF CARBON ATOMS,  $N_c$

% LIQUIDITY,  $L_c$

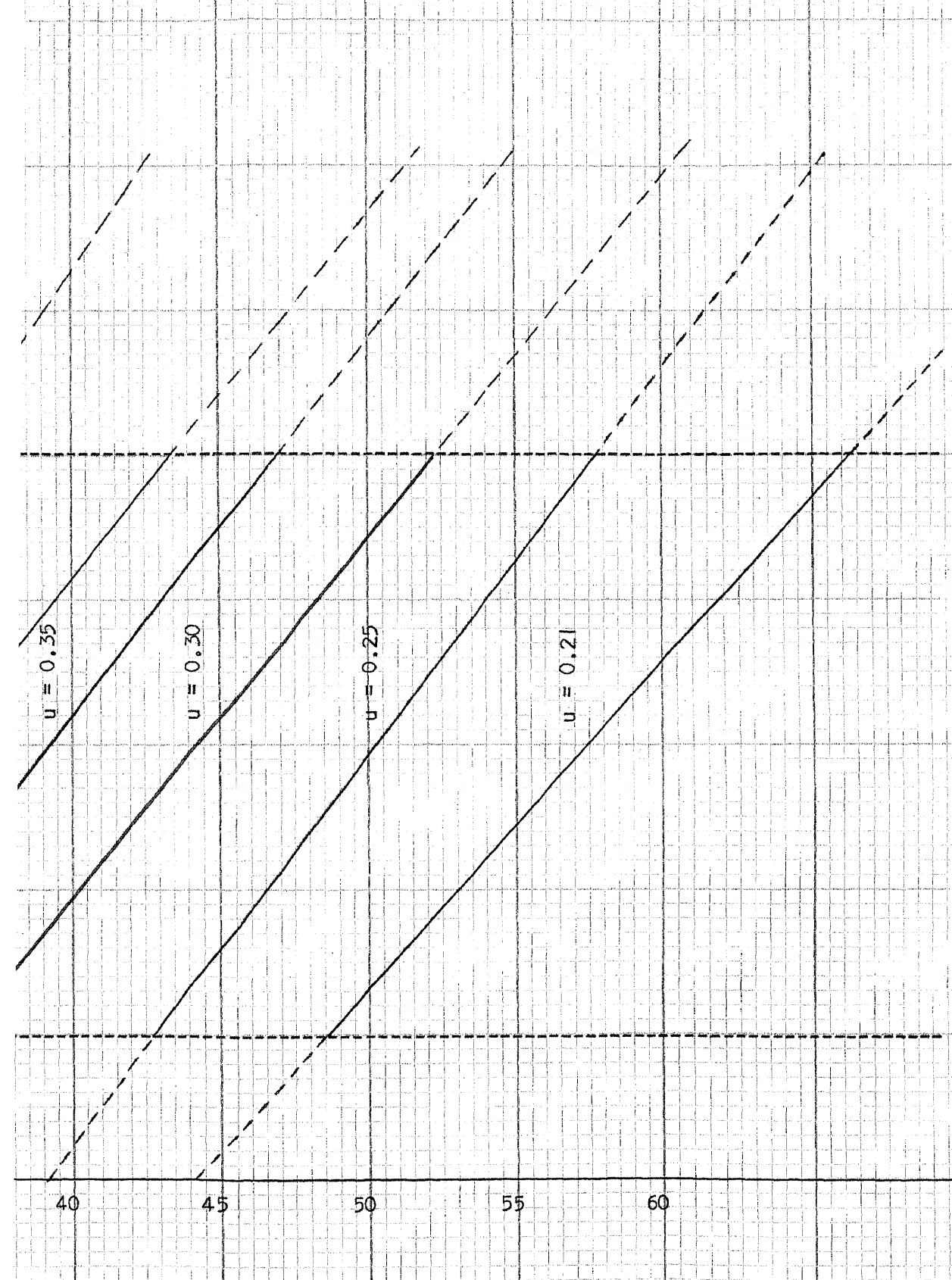
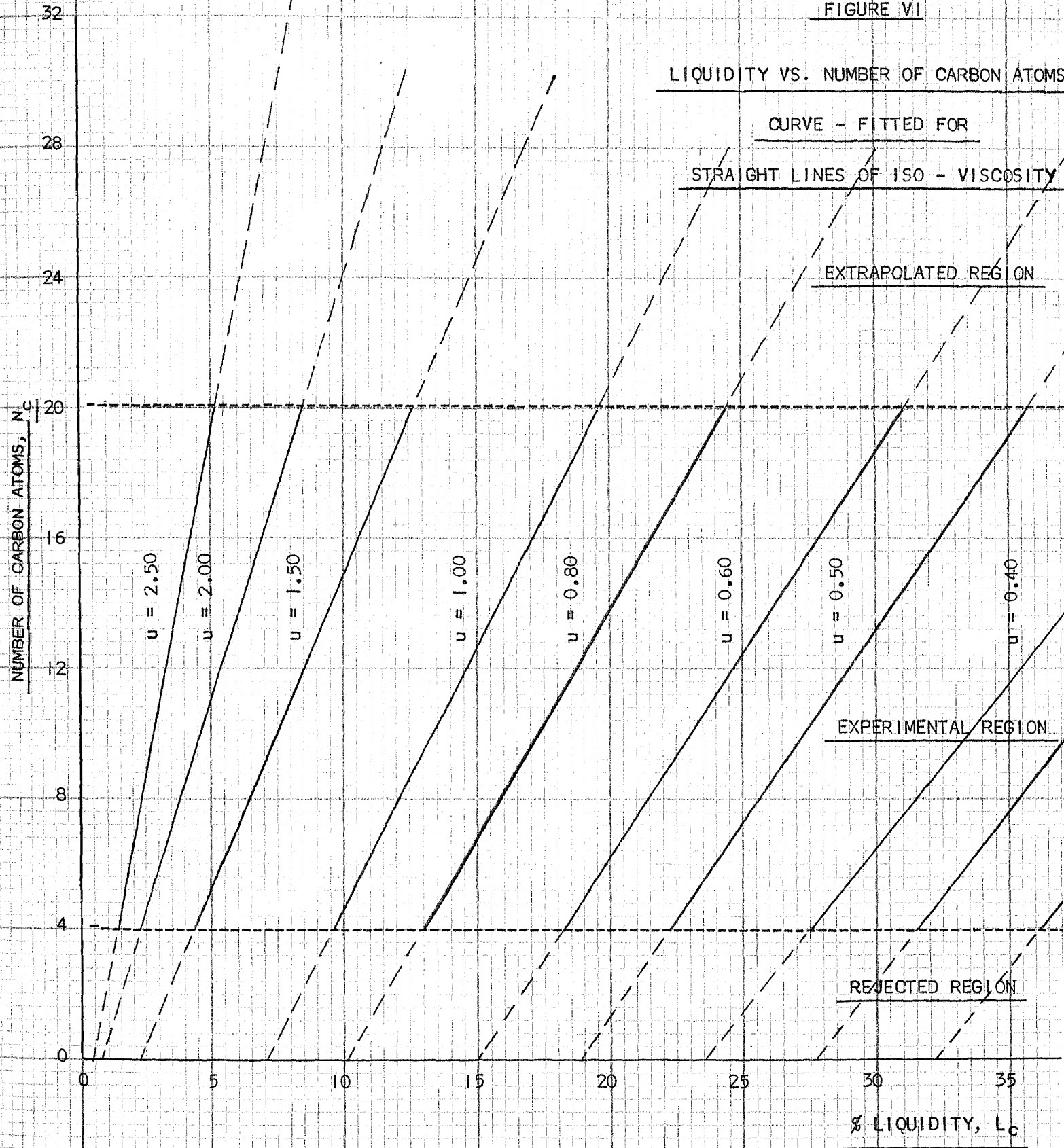
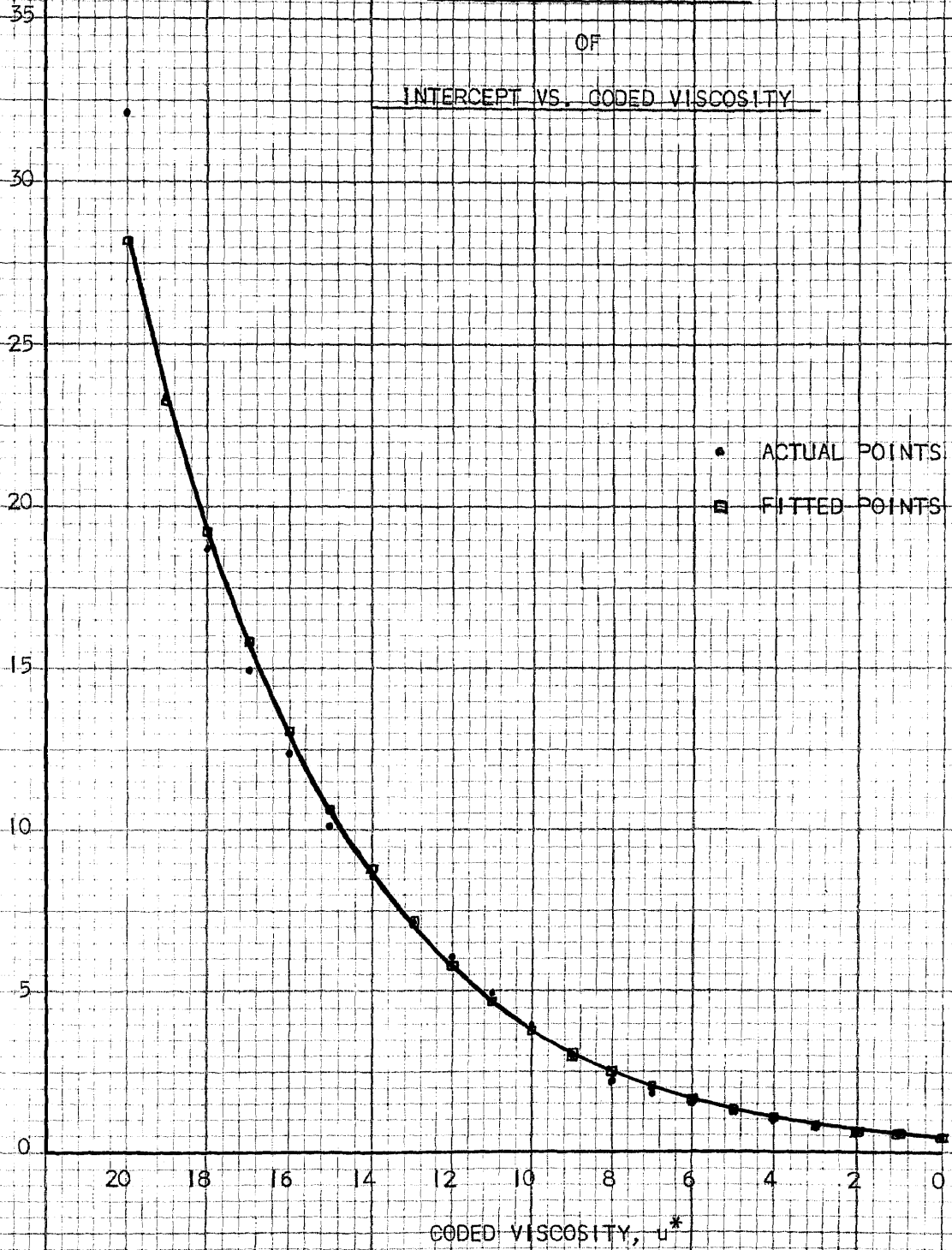


FIGURE VII

FITTED GOMPERTZ CURVE  
OF  
INTERCEPT VS. CODED VISCOSITY

INTERCEPT



## NOMENCLATURE

a - constant

b- intercept

g - constant

k - constant

$L_b$  - liquidity based on normal boiling temperature

$L_c$  - liquidity based on critical temperature

m - slope; change in  $L_c$  / change in  $N_c$

$N_c$  - number of carbon atoms

$n_t$  - total number of points fitted to a straight line

t - temperature, °C

$t_b$  - normal boiling temperature, °C

$t_c$  - critical temperature, °C

$t_m$  - normal melting temperature, °C

u\* - coded viscosity to be converted to absolute viscosity

u - absolute viscosity, centipoise

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