

A NOMOGRAPHIC METHOD OF PREDICTION  
OF RESERVOIR OIL VISCOSITY

By

ABUL MOZAFFER MALICK

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science.

Signed: Abul Mozaffer Malick  
Abul Mozaffer Malick  
Dacca, Pakistan

Approved: Clark F. Barb  
Clark F. Barb  
Head, Department of  
Petroleum Engineering

Approved: David A. Rowland  
David A. Rowland  
Thesis Advisor

Golden, Colorado

Date: May 12, 1958

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ABSTRACT

This investigation presents a method of predicting reservoir oil viscosity with the knowledge of only the gas-free crude oil viscosity, the bubble-point pressure, and the solubility of gas at the pressures at which the viscosities are desired. Two different empirical equations have been derived for this purpose, and nomographs have been constructed for these equations. The equations can be used directly for the crude oil viscosity prediction, or the nomographs can be used for speed and convenience.

The investigation is based on 363 viscosity observations from 28 samples of crude oil taken from 10 oil fields out of which nine are in the Rocky Mountain region of the United States and one in California.

A sample of crude oil from the Rocky Mountain region (not used previously for this investigation) has been used to illustrate the procedure of practical use of the above-mentioned nomographs and also to show the comparison between the measured crude oil viscosity data and the predicted values.

In conclusion, it has been observed that it might be possible to extend the use of this method of reservoir oil viscosity prediction if further research is carried on with more extensive data representing various types of crude oils.

## INTRODUCTION

### Importance of Reservoir Oil Viscosity Prediction

The viscosity of the oil in the reservoir is one of the properties of oil that have a profound influence on its movement through the sand to producing wells. A knowledge of the oil viscosity, therefore, is pertinent and important to problems associated with well behavior and with the estimation of recoveries. It also affords an indirect means of partial evaluation of various methods of controlling reservoir behavior.

Direct measurements on sub-surface samples of oils are still the only accurate method for determining the viscosity of any particular oil under reservoir conditions. These methods of direct measurement, the Rolling-ball Viscosimeter method for example, are rather difficult to perform and time-consuming and, as a result, rather expensive. With the Rolling-ball Viscosimeter every determination of viscosity takes three to four hours with luck and skill; otherwise the process might take longer (Hocott and Buckley, 1941).

The isolated effects of different factors on oil viscosity have been studied (Beecher and Parkhurst, 1926; Sage, Mendenhall, and Lacey, 1935; Katz, 1934), but there is a scarcity of published literature on the definite prediction of viscosity of crude oil on the whole, taking all the different influencing factors into consideration.

Because of a rather large number of physical factors which have to be taken into consideration for prediction of oil viscosity, and the difficulty in determining the effects of the chemical composition of various crudes, accurate predictions may not be expected (Beal, 1946), but any empirical relation that would permit the estimate of the viscosity of crude oil within a degree of accuracy sufficient for oil field estimates would be of high value to the petroleum industry.

#### Purpose and Scope of this Investigation

The purpose of this investigation is to establish some empirical relationship between the viscosity of crude oil at reservoir conditions and other properties of the crude oil which can conveniently be measured, such that by the use of the latter properties and the empirical relationship, the oil viscosity at reservoir conditions could be predicted with reasonable accuracy.

The variation of oil viscosity with a change in the chemical composition is not defined to an exact extent (Calhoun, 1957, p. 35); an investigation of this variation would require a separate study.

### Analysis of the Problem

The viscosity of crude oils depends on the following variables: pressure, temperature, amount and chemical composition of the gas in solution, oil and gas gravity, bubble-point pressure, and the base (chemical composition) of the crude (Beal, 1946, p. 104).

A typical plot of reservoir-oil viscosity versus reservoir pressure is shown in Figure A. If the reservoir were under-saturated at the original pressure, there would be at first a slight decrease in the oil viscosity due to release of pressure. At the saturation or bubble-point pressure the viscosity would be a minimum. At lower pressures the evolution of gas from solution would increase the density and consequently the viscosity of the reservoir oil. This change would continue so long as gas evolved from solution giving a maximum viscosity at atmospheric pressure (Calhoun, 1957, p. 37).

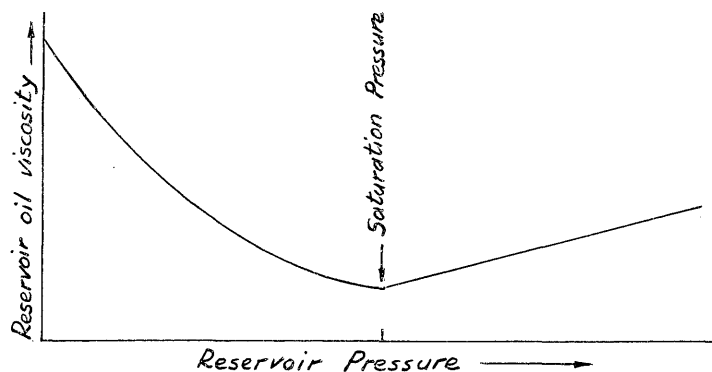


Figure A. Typical variation of reservoir-oil viscosity with pressure (After Calhoun, 1957, Fundamentals of Reservoir Engineering, p. 36)

Johnston and Sherborne have presented an empirical method for estimating viscosity of crude oil at reservoir temperature and pressure by applying a "Viscosity Reduction Factor" to the gas-free (atmospheric) crude oil viscosity at 100°F (Johnston, 1941, p. 184-185; Johnston and Sherborne, 1943, p. 68-69). The "Viscosity Reduction Factor" was based on the study of only two different crudes of 33.9° and 17.0° API gravities. Since the viscosity data of the former crude were used for crude oil gravities above 20°API and those of the latter crude for crude oil gravities below 20°API, considerable error is likely to be encountered at gravities removed from either 33.9° or 17.0° API.

A correlation for the viscosity of oils at reservoir pressures (Beal, 1946) is based on the observed fact that the change in oil viscosity is due primarily to the change in the amount of solution gas. The correlation consists of two parts: one to estimate viscosity below the saturation pressure and another to estimate viscosity above the saturation pressure. With the use of viscosity observations from different samples of crude oil taken from different oil fields, a series of correlation charts have been prepared for predicting the viscosity of crude oil under reservoir conditions. By the use of these charts, the average deviation of the predicted values of viscosity was found to be 19.8 per cent.

In the present work a method of viscosity prediction is sought which would simplify the problem and also improve upon the accuracy

of the predicted values of viscosities. Because of the definite change in the viscosity behavior of crude oils at the bubble-point, as shown in Figure A, the problem is dealt with in two parts as done by Beal: one viscosity prediction below the bubble-point and another above the bubble-point. For the former case, a subtractive "Viscosity Reduction Factor" is found such that this factor subtracted from the atmospheric viscosity of the crude gives the viscosity at any pressure between atmospheric and bubble-point. For values above the bubble-point, an additive "Viscosity Increment Factor" is found such that this factor added to the crude viscosity at bubble-point gives the viscosity at any pressure above the bubble-point.

The procedure followed for this investigation comprises of graphically analyzing the data for different crude oil samples and then deriving empirical equations involving a minimum number of variables needed to predict the reservoir oil viscosity.

## APPROACH TO THE PROBLEM

It has been observed in the "Analysis of the Problem" (page 3) that the crude oil viscosity is a function of various factors. Theoretical considerations demand that all of these different variables be taken into account to make the study of prediction of crude oil viscosity complete; but practical considerations require that the number of variables needed for such prediction be the minimum such that the knowledge of only a limited number of influencing factors would be necessary for the viscosity prediction. Hence, before the actual investigation for the method of crude oil viscosity prediction is embarked upon, it would be pertinent to select the minimum essential variables for such prediction; and that would necessitate a survey of the nature and relative importance of all the different variables.

### Theoretical Considerations

The viscosity of reservoir oil is a function of various physical factors. The effects of these factors, taken individually and keeping

the others constant, on the oil viscosity have not been defined in definite terms, but they are known in general terms as summarized below:

Pressure: In general the viscosity of crude oil increases with an increase in pressure, provided the only result of the pressure is to compress the oil (Calhoun, 1957, p. 35).

Temperature: The viscosity of crude oil decreases with increase in temperature (Calhoun, 1957, p. 35).

Solubility of gas: The higher the amount of gas in solution, the lower the viscosity of crude oil (Calhoun, 1957, p. 37).

Gas-free crude oil (atmospheric) viscosity: The higher the atmospheric crude oil viscosity, the higher the oil viscosity at reservoir conditions (Beal, 1946, p. 103).

Oil density: The higher the oil density, the higher the viscosity (Beal, 1946, p. 103).

Gas density: The higher the density of hydrocarbon gas, the higher the solubility of gas and as a result the lower the crude oil viscosity at the same temperature and pressure (Sage, Mendenhall, and Lacey, 1935, p. 47-49).

Saturation or Bubble-point pressure: The importance of this point is that the viscosity of any crude oil is minimum at this point. This point, in effect, determines the change in the behavior of the viscosity of the crude oil (Calhoun, 1957, p. 37).

Besides the above-mentioned physical factors, the chemical

composition of the crude oil and the gas in solution influence the viscosity behavior of the reservoir oil. So it can be shown that all these physical and chemical properties have to be studied and taken into consideration in making the study and prediction of crude oil viscosity comprehensive and complete. But, whereas this kind of an investigation would be comprehensive from the theoretical point of view, it would have a rather limited practical value. If all the above-mentioned variables have to be known so that they can be used to predict the viscosity of crude oil, the time and trouble taken to determine these variables can be spared and used instead to measure the viscosity of the oil directly. In order for the method of prediction of oil viscosity to have practical value, the variables required for the prediction have to be minimized so that only limited numbers of variables determined rather easily and conveniently would be needed for the prediction.

#### Practical Considerations

Most of the variables mentioned in the preceding section are interdependent; so a critical survey and study of these would indicate which ones are important in the prediction of viscosity. It has been observed (Beal, 1946, p. 104 and p. 108) that:

1. Most crude oils follow a general pattern of decline in oil viscosity as a function of dissolved gas relative to the viscosity of a gas-free (atmospheric) crude oil at reservoir temperature.

2. The amount of gas dissolved (solubility) in crude oil for a particular oil gravity has a more important bearing on gas-saturated crude oil viscosity than has pressure.

3. In the under-saturated zone (above the bubble-point pressure), a greater viscosity increase occurs as the absolute bubble-point viscosity increases. The viscosity increases in proportion to the increase in pressure above the bubble-point.

These observations indicate that in the saturated zone (below the bubble-point pressure) the decline in oil viscosity relative to the viscosity of gas-free crude oil at reservoir temperature is essentially a function of the amount of gas in solution and the gas-free crude oil viscosity itself. In the under-saturated zone (above the bubble-point pressure), the increase in viscosity relative to the bubble-point viscosity is a function of the increase in pressure above the bubble-point and the absolute bubble-point viscosity itself.

The amount of dissolved gas itself depends upon the character of the gas, the character of the oil, temperature and reservoir pressure (Beecher and Parkhurst, 1926). The viscosity of the gas-free crude at reservoir temperatures, likewise, depends upon the oil gravity, the chemical character of the crude and the reservoir temperature.

So, in the saturated zone the consideration of the amount of gas in solution and the gas-free crude viscosity for the prediction of viscosity at reservoir conditions automatically almost eliminates

the necessity of the consideration of variables like the reservoir pressure, temperature, the oil and gas gravities and also the chemical characters of the oil and gas up to an extent. In the under-saturated zone, likewise, the consideration of the bubble-point viscosity almost eliminates the need to consider the foregoing variables since the bubble-point viscosity itself depends upon the gas-free crude oil viscosity and the amount of gas in solution at the bubble-point. From there on, since the amount of gas in solution is constant, the increase in viscosity is considered in terms of the increase in pressure. Thus, it is seen that the variables mentioned in the preceding section can be minimized so that consideration of only the amount of gas in solution and gas-free crude oil viscosity is adequate for a method of reservoir oil viscosity prediction in the saturated zone. Similarly, the consideration of the bubble-point viscosity and increase in pressure with respect to the saturation pressure is adequate for a method of reservoir oil viscosity prediction in the under-saturated zone. Such methods would be of practical use and value.

#### Accumulation of Data

There is a scarcity of published data on the viscosity behavior of different crude oils under reservoir conditions. The data for this investigation were gathered from some of the Reports of Investigations of the United States Bureau of Mines (Cupps, Lipstate, and Fry, 1951; Cupps Espach, and Fry, 1954; Cook and Shea, 1947) and

also from the Shell Oil Company, the Texas Company and the California Company. The total data gathered for this investigation represent 363 viscosity observations from 28 samples of crude oil taken from 10 oil fields, out of which nine are in the Rocky Mountain region of the United States and one in California. It is assumed that these data, although drawn from different sources, are consistent and accurate enough for this investigation.

In compliance with the requests made by the above-mentioned oil companies to keep the source of the data confidential, none of the crude oil samples used in this analysis is identified as to its origin.

PROCEDURE FOR GRAPHICAL ANALYSIS AND  
PREDICTION

It has been noted in the "Analysis of the Problem" (page 5) that the proposed method of crude oil viscosity prediction is comprised of two parts: one viscosity prediction for the saturated crude oil below the bubble-point and another for the under-saturated crude oil above the bubble-point. This method of approach is necessitated because of the definite change in the viscosity behavior of crude oils at the bubble-point. The viscosity data are analyzed separately for the saturated and the under-saturated crude oils, and eventually two different equations are derived for the prediction of crude oil viscosity over the full range of pressure -- atmospheric to anywhere above the bubble-point.

Saturated Crude Oil Below the Bubble-point Pressure

It has been observed in the "Analysis of the Problem" (page 5) that it would be possible to predict the reservoir oil viscosity between the atmospheric and bubble-point pressures if a subtractive "Viscosity Reduction Factor" is applied to the gas-free crude oil

viscosity. It has also been noted in the "Approach to the Problem" (page 10) that the variables needed to be taken into account for such a prediction would be the amount of gas in solution (solubility) and the gas-free crude oil (atmospheric) viscosity. Hence, if

$$\mu_a - \mu = \Delta\mu \dots \dots \dots (1)$$

where  $\mu$  is the absolute viscosity of crude oil at reservoir conditions below the bubble-point pressure in centipoises,

$\mu_a$  is the absolute gas-free crude oil viscosity at reservoir temperature in centipoises,

and  $\Delta\mu$  is the subtractive "Viscosity Reduction Factor," a function of gas solubility  $S$  and  $\mu_a$ , in centipoises,

it would be possible to predict the correction factor  $\Delta\mu$  and hence  $\mu$  from an empirically established relationship between  $\Delta\mu$  and variables  $S$  and  $\mu_a$ . This relationship would necessitate the knowledge of the values of  $S$  and  $\mu_a$  only.

Gas solubility,  $S$ , is a conveniently and commonly known variable in most of the analyses of crude oils. In case the measured values of  $S$  are not available, the graphical correlation between reservoir pressure and gas solubility based on the works of Gosline, Dodson, Katz and Beal (Beal, 1946, p. 105 - 108) can be used to obtain the values of gas solubility at any given reservoir pressure. The average deviation in this correlation is reported to be 22.0 per cent (Beal, 1946, p. 108).

The gas-free crude oil viscosity,  $\mu_a$ , can be measured easily and conveniently at reservoir temperature with the use of a simple

viscosimeter like the Saybolt Universal viscosimeter. The Saybolt Universal reading can be converted to centipoises by the use of a viscosity conversion chart.

It is possible to predict  $\mu_a$  by the knowledge of the crude oil gravity and the reservoir temperature (Beal, 1946, p. 103), but it is noticed that this prediction is not very accurate and is usually the source of the maximum error amongst all the predicted values of reservoir oil viscosities at different reservoir pressures (Beal, 1946, p. 112 - 113). Since all the other predicted values of viscosities are related to  $\mu_a$  and since their accuracies depend upon the accuracy of  $\mu_a$ , an accurate value of  $\mu_a$  would result in rather accurate predicted values of viscosities and vice versa. Hence, in view of the facts that  $\mu_a$  can be measured directly with relative ease and that its accuracy is of prime importance in the prediction of oil viscosities at reservoir conditions, the measured values of  $\mu_a$  would be used in this method of reservoir oil viscosity prediction.

The correction factor  $\Delta\mu$  was calculated for the different crude oil samples (Tables I - XXVIII) at the reservoir conditions. These data were used as a basis for constructing Figure 1. It should be noted that with the knowledge of the amount of gas in solution and the atmospheric viscosity of the crude oil, the correction factor  $\Delta\mu$  can be read off Figure 1 and then Equation (1) would give the desired  $\mu$ . The reliability of the predicted values of

viscosity from Figure 1, however, is questionable since the curves were obtained by the process of interpolation and extrapolation. These curves do indicate a parabolic relationship between the solubility,  $S$ , and the correction factor  $\Delta\mu$ , and the following procedure was followed to further investigate and find an empirical relationship between  $\Delta\mu$  and the variables  $S$  and  $\mu_a$ .

For all the different samples of crude oil  $\Delta\mu$  was plotted against  $S$  on log paper and the results -- a series of straight line graphs -- are shown in Figures 2 - 10. For the sake of accuracy and clarity the different graphs are plotted on various scales, but the slopes and intercepts of these curves are all tabulated in Table XXIX. It is noted that all the different straight lines have almost the same slope whereas the intercepts on the ordinate ( $\Delta\mu$  equal to 1.0) vary inversely as the  $\mu_a$ .

The general equation for these straight lines is:

$$S = b (\Delta\mu)^m \dots \dots \dots (2)$$

where  $b$  is the intercept of the straight line on the ordinate when  $\Delta\mu$  equals 1.0,

and  $m$  is the slope of the straight line.

The root mean square value of the slopes of the straight lines (Table XXIX) is calculated to be 1.77, so the equation for the  $S - \Delta\mu$  plots would be

$$S = b (\Delta\mu)^{1.77} \dots \dots \dots (3)$$

To investigate the relationship between the ordinate intercepts

b and  $\mu_a$  of the different samples, b was plotted versus  $\mu_a$  on rectangular co-ordinate paper (Figure 11). The resulting graph indicated a hyperbolic relationship. Consequently, b was plotted versus  $\mu_a$  on log paper (Figure 12) and the result appeared to be a straight line. The equation for this straight line, then, would be

$$b = b_1 (\mu_a)^{-m_1} \dots \dots \dots (4)$$

where  $b_1$  is the ordinate intercept of the straight line when  $\mu_a$  equals 1.0,

and  $m_1$  is the slope of the straight line.

In this case it can be seen from Figure 12, that

$$b_1 = 1250$$

$$m_1 = 2.0$$

Substituting the values in Equation (4),

$$b = \frac{1250}{(\mu_a)^{2.0}} \dots \dots \dots (5)$$

Substituting the value of b in Equation (3),

$$S = \frac{1250 (\Delta\mu)^{1.77}}{(\mu_a)^{2.0}}$$

or

$$(\Delta\mu)^{1.77} = \frac{S (\mu_a)^{2.0}}{(1250)}$$

or

$$\Delta\mu = \frac{(S \mu_a^{2.0})^{0.565}}{56.20} \dots \dots \dots (6)$$

An alignment chart (Figure 13) has been prepared for the foregoing equation such that with the knowledge of the gas solubility, S, and the gas-free crude oil viscosity,  $\mu_a$ , the value of the

"Viscosity Reduction Factor" or "Correction Factor,"  $\Delta\mu$ , can be read off directly and then by the use of Equation (1) the viscosity of reservoir oil can be predicted.

Under-saturated Crude Oil above the Bubble-point Pressure

It has been observed in the "Analysis of the Problem" (page 5) that an additive "Viscosity Increment Factor" has to be found for prediction of the crude oil viscosity above the bubble-point pressure. The predicted value of the viscosity at any pressure in the under-saturated zone would be obtained by adding this "Viscosity Increment Factor" to the bubble-point viscosity of the crude, which in turn is either calculated from Equation (6) or directly read off the alignment chart (Figure 13). It has also been noted in the "Approach to the Problem" (page 10) that the variables needed to be taken into account for such a prediction would be the absolute bubble-point viscosity and the increase in pressure with respect to the saturation pressure. Hence, if

$$\mu' - \mu_b = \Delta\mu' \dots \dots \dots (7)$$

where  $\mu'$  is the absolute viscosity of crude oil at reservoir conditions above the bubble-point pressure, in centipoises,

$\mu_b$  is the absolute crude oil viscosity at bubble-point pressure and reservoir temperature, in centipoises,

and  $\Delta\mu'$  is the additive "Viscosity Increment Factor," a function of  $\mu_b$  and the increase in pressure with respect to the saturation pressure,  $(P' - P_b)$ , in centipoises,

it would be possible to predict the correction factor  $\Delta\mu'$  and

hence,  $\mu^i$  from an empirically established relationship between  $\Delta\mu^i$  and the variables  $\mu_b$  and  $(P^i - P_b)$  where  $P^i$  is the pressure at which  $\mu^i$  is desired and  $P_b$  is the bubble-point pressure.

From a typical reservoir pressure -- crude oil viscosity curve (Figure A, page 3) it is seen that the part of the curve above the bubble-point pressure can be represented by the general form of the equation for a straight line

$$\mu = m^i P + b \dots \dots \dots (8)$$

where  $m^i$  is the slope of the straight line,

and  $b$  is the ordinate intercept.

By translating the origin of the graph to  $(\mu_b, P_b)$  Equation (8) can be written as

$$(\mu^i - \mu_b) = m^i (P^i - P_b)$$

or

$$\Delta\mu^i = m^i \Delta P \dots \dots \dots (9)$$

where  $\Delta P = (P^i - P_b)$

Equation (9) is the equation for a straight line passing through the origin,  $\Delta\mu^i$  as the ordinate, and  $\Delta P$  as the abscissa and  $m^i$  as the slope.

The values of  $\Delta\mu^i$  and  $\Delta P$  were calculated for all the crude oil samples (Tables I - XXVIII) and plotted on rectangular co-ordinate paper (Figures 14 - 22). For the sake of accuracy and clarity the different curves are drawn on various scales, but the values of their slopes  $m^i$  for the corresponding values of  $\mu_b$  are tabulated in

Table XXX. The slopes of these curves -- the measures of the rate of increase of  $\Delta\mu^i$  with P -- are noticed to vary as a function of  $\mu_b$ .

The values of  $m^i$  were plotted against the corresponding values of  $\mu_b$  on rectangular co-ordinate paper (Figure 23) to determine the relationship between them; the resulting smooth parabolic curve indicates a definite relationship between  $\mu_b$  and  $m^i$ . Consequently, the data were plotted on log paper as shown by curve (a) of Figure 24. This plot shows that the resulting graph is slightly but definitely curved suggesting the possibility of rectification of the curve to a straight line by the use of a rectification constant (Hoelscher, Arnold, and Pierce, 1952, p. 48).

The rectification constant  $c$  was found from the equation

$$c = \frac{(Y_1)(Y_2) - (Y_3)^2}{Y_1 + Y_2 - 2Y_3} \dots \dots \dots (10)$$

where  $Y_1$ ,  $Y_2$ , and  $Y_3$  represent the ordinate values corresponding to the abscissa values of  $X_1$ ,  $X_2$ , and  $X_3$  on rectangular co-ordinate paper (Hoelscher, Arnold, and Pierce, 1952, p. 48). From the original graph (Figure 23) two points were selected near the extremities of the curve such that

$$X_1 = 0.50, \quad Y_1 = 0.03 \times 10^{-3}$$

and 
$$X_2 = 25.0, \quad Y_2 = 4.50 \times 10^{-3}$$

From these values, and the equation  $X_3 = \sqrt{(X_1)(X_2)}$ ,

$$X_3 = \sqrt{(0.50)(25.0)} = 3.53$$

The corresponding value of  $Y_3$  is  $0.30 \times 10^{-3}$ . Hence from Equation (10)

$$\begin{aligned} c &= \frac{[(0.03)(4.50) - (0.30)^2] \times 10^{-6}}{[0.03 + 4.50 - 2(0.30)] \times 10^{-3}} \\ &= \frac{[0.135 - 0.09]}{[4.53 - 0.60]} \times 10^{-3} \\ &= \frac{0.045}{3.93} \times 10^{-3} = 0.0115 \times 10^{-3} \end{aligned}$$

Using this value of  $c$ , the second curve (b) of Figure 24 was plotted with  $(m - c)$ , the rectified values of the slopes (Table XXX), on the vertical axis and then the graph appears to be a straight line.

Hence, the equation for this straight line would be

$$(m^i - c) = A(\mu_b)^M,$$

or

$$m^i = A(\mu_b)^M + c$$

where  $A$  is the intercept of the straight line on the ordinate when  $\mu_b$  equals 1.0,

$M$  is the slope of the straight line,

and  $c$  is the rectification constant.

The value of  $A$  is  $0.06 \times 10^{-3}$  and the value of  $M$  is 1.34 for this straight line and hence the equation is

$$\begin{aligned} m^i &= [0.06 (\mu_b)^{1.34} + 0.115] \times 10^{-3} \\ &= 6.0 \times 10^{-5} [(\mu_b)^{1.34} + 0.192] \dots \dots \dots (11) \end{aligned}$$

Substituting this value of  $m^i$  in Equation (9),

$$\Delta \mu^i = 6.0 \times 10^{-5} (\Delta P)(\mu_b^{1.34} + 0.192) \dots \dots (12)$$

An alignment chart (Figure 25) was prepared for the foregoing equation such that with the knowledge of the absolute viscosity of the crude oil at bubble-point pressure,  $\mu_b$ , and the pressure

differential between the under-saturated pressure at which the crude oil viscosity is desired and the bubble-point pressure,  $\Delta P$ , the value of the "Viscosity Increment Factor" or "Correction Factor"  $\Delta\mu^0$  can be read off directly. Then by use of Equation (7) the viscosity of the reservoir oil at any pressure above the bubble-point pressure can be predicted.

APPLICATION OF THE METHOD OF  
RESERVOIR OIL VISCOSITY PREDICTION

It has been pointed out briefly in the "Procedure for Graphical Analysis and Prediction" (pages 16-17 and 20-21) how the proposed method of reservoir oil viscosity prediction could be put to practical use. It has been mentioned that the alignment charts -- one for pressures below bubble-point (Figure 13) and another for pressures above bubble-point (Figure 25) -- can be used conveniently for such predictions. An explanation of the ways the proposed prediction method can be used for practical purposes and an example of the procedure of prediction would, at this stage, be of value in the understanding of the problem. A survey of some of the obtained results of this method of prediction, especially of the two different types of crude oils which indicated different characteristics in the analysis of the data previously, would be of value in evaluating the accuracy of the results of prediction.

### Outline of the Method of Prediction

The data needed for the use of the proposed method of prediction of reservoir oil viscosity over the full range of pressure -- original reservoir pressure to the atmospheric pressure -- are:

- (1) the gas-free crude oil viscosity,  $\mu_a$ , in centipoises,
  - (2) the solubility of gas at bubble-point pressure and at other pressures where the viscosities are desired,  $S$ , in SCF/bbl,
- and (3) the bubble-point pressure,  $P_b$ , psig.

For the viscosities desired at any pressure below the bubble-point pressure (saturated zone) the values of  $S$  at that particular pressure and  $\mu_a$  of the crude oil in question can be substituted in the equation

$$\Delta\mu = \frac{(S \mu_a^2)^{0.565}}{56.20} \dots \dots \dots (6)$$

from which the value of the Viscosity Reduction Factor  $\Delta\mu$  would be obtained. Then the desired viscosity  $\mu$  would be given by the equation

$$\mu_a - \mu = \Delta\mu \dots \dots \dots (1)$$

Another possible way to obtain  $\Delta\mu$  would be to plot a series of curves,  $S$  versus  $\Delta\mu$ , each curve being valid for one particular value of  $\mu_a$ . The curves would be based on the values of  $\Delta\mu$  calculated from Equation (6) for different values of  $S$  and  $\mu_a$ . Once the curves are drawn,  $\Delta\mu$  can be read directly from them and then the use of Equation (1) would give the desired  $\mu$ .

A third way -- the one followed in this study -- to make use of Equation (6) is by constructing an alignment chart or nomograph for the equation (Figure 13).

Of the three possible ways of obtaining  $\Delta\mu$  from Equation (6), the nomographic method would be the most convenient to use. Probability of repeated solution of Equation (6) makes the method of direct substitution of values undesirable. In the second method the process of drawing a whole set of curves for different values of  $\mu_a$  would be rather tedious and time-consuming. With alignment charts less time is required, and there is less likelihood of error than in the use of the slide rule or other methods. Less mental effort is required, and the solution of problems can often be delegated to someone with comparatively little training (Hoelscher, Arnold, and Pierce, 1952, p. 62).

For the viscosities desired at any pressure above the bubble-point pressure (under-saturated zone), the crude oil viscosity at bubble-point pressure,  $\mu_b$ , has to be found from the alignment chart mentioned above (Figure 13). Then the values of  $\mu_b$  and the pressure differential between the pressures at which the viscosity is desired and that at the bubble-point,  $\Delta P$ , can be substituted in the equation

$$\Delta\mu^i = 6.0 \times 10^{-5} (\Delta P) [(\mu_b)^{1.34} + 0.192] \dots (12)$$

from which the value of the Viscosity Increment Factor  $\Delta\mu^i$  would be obtained. Then the desired viscosity  $\mu^i$  would be given by the

equation

$$\mu^i - \mu_b = \Delta\mu^i \dots \dots \dots (7)$$

Another possible way to obtain  $\Delta\mu^i$  would be -- similar to the one mentioned previously for the saturated zone -- to plot a series of curves,  $\Delta P$  versus  $\Delta\mu^i$ , each curve being valid for one particular value of  $\mu_b$ . But for the same reasons as mentioned previously, use of an alignment chart (Figure 25) is considered preferable.

#### Sample of the Method of Prediction

A sample of crude oil (not used previously in this investigation) from the Rocky Mountain region was obtained for a practical illustration of the proposed method and also for comparison of the results obtained by this method with the actual measured values of crude oil viscosities at various pressures. The data for this sample along with the predicted values of viscosities -- both by the proposed nomographic method and by Beal's method (Beal, 1946, p. 103 - 110) -- are tabulated in Table XXXI. The comparison of the crude oil viscosity predictions with measured data is shown graphically by pressure-viscosity curves in Figure 26.

The gas-free viscosity,  $\mu_a$ , of this crude oil is 1.93 centipoises, so one end of a straight edge was placed on the figure 1.93 on the  $\mu_a$ -scale of the nomograph (Figure 13) and the other end of the straight edge on the figure showing the solubility of gas S corresponding to the pressure at which the viscosity is desired; then

the value of the viscosity reduction factor was read from the figure lying along the straight edge on the  $\Delta\mu$ -scale. Thus, at the pressure of 200 psig, the solubility of gas is 62 SCF/bbl. From the nomograph, when the straight edge is placed on 1.93 of the  $\mu_a$ -scale and 62 of the S-scale, a value of 0.38 is read off the  $\Delta\mu$ -scale. The difference between 1.93 and 0.38 gives the value for viscosity at 200 psig as 1.55 centipoises. This process is repeated for the various pressures placing the straight edge along the corresponding values of S every time and the value of 1.93 for  $\mu_a$  until the bubble-point pressure is reached. In this particular case, at bubble-point pressure of 1662 psig, the solubility of gas is 303 SCF/bbl. The viscosity reduction factor, then, is observed to be 0.93, and hence, the bubble-point viscosity,  $\mu_b$ , is 1.00, this being the difference of 1.93 and 0.93 centipoises.

Making use of  $\mu_b$ , obtained as outlined above, the nomograph in Figure 25 is used for viscosity predictions above the bubble-point pressure. By placing a straight edge along the value of bubble-point viscosity on the  $\mu_b$ -scale and the value of the pressure differential between the pressure at which the viscosity is desired and the bubble-point pressure on the  $\Delta P$ -scale, the value of the viscosity increment factor is read as the figure lying along the straight edge on the  $\Delta\mu^i$ -scale.

Thus, at the pressure of 1820 psig, when  $\Delta P$  equals 158 psi, the straight edge is placed along 1.00 on  $\mu_b$ -scale and along 158 on

$\Delta P$ -scale; and then the value of viscosity increment factor is read as 0.011 on the  $\Delta\mu$ -scale. Hence, the absolute viscosity of the crude oil at 1820 psig is 1.011 centipoises (which can be rounded off to 1.01), this being the sum of 1.00 and 0.011 centipoises. This procedure is repeated similarly for all the values of pressure above the bubble-point.

#### Survey of the Predicted Results

It has been observed in the "Procedure for Graphical Analysis and Prediction" (page 15) that the different straight line graphs of Viscosity Reduction Factor,  $\Delta\mu$ , versus solubility of gas,  $S$ , have almost the same slope. The derivation of Equation (6) for the prediction of crude oil viscosity in the saturated zone is based on the root mean square value of the above-mentioned slopes.

To check the accuracy of the proposed method of prediction as applied to the two different crude oil samples which give the maximum divergence in the values of slopes of the  $S - \Delta\mu$  curves, crude oil samples 1 and 23 with the minimum and the maximum values of slopes, respectively, of all the samples investigated, were selected for study. The comparison of the measured crude oil viscosity data with the predicted values for these two samples is shown graphically as pressure versus viscosity curves in Figures 27 and 28.

Some of the possible reasons for this variation in values of slopes of the  $S - \Delta\mu$  curves -- like the source of the crude oils,

the source of the available data, and the  $N_2$  content of the gases in solution -- were investigated, but no correlation could be established between the variation in the slopes and any of the above-mentioned possible reasons. If any such correlation can be established by further research based on more extensive crude oil data, it might be possible to incorporate a correction factor to rectify the divergence of the slopes from the mean and thus improve the accuracy of the proposed method of crude oil viscosity prediction.

It is deemed possible that a slight error might be introduced in the predicted values of the crude oil viscosity by the assumption that the measured atmospheric viscosities used in this analysis are representative of, or are valid for, the range of temperatures encountered in the reservoir. This error would possibly be more pronounced for higher API gravity crude oils. The fact, however, that the graphs representative of the high API gravity crude oils used in this investigation do not show any pronounced divergence from the graphs representing the other crude oils, indicates this error to be insignificant for the range of the crude oil densities studied.

CONCLUSIONS

By the use of the method presented in this investigation, it would be possible to predict the viscosity of crude oil at reservoir conditions, with the knowledge of only the gas-free crude oil viscosity, the bubble-point pressure, and the solubility of gas at the pressures at which the viscosities are desired. The equations derived for the predictions can be used directly or else the nomographs constructed for these equations can be used for speed and convenience.

The crude oil data which have been available for this investigation were mainly from the oil fields of the Rocky Mountain region and hence the accuracy of this method of prediction, as applied to the crude oils of other parts of the world, cannot be asserted unless this method is put to test. It would be possible, however, to extend the use of this method of prediction if further research is carried on with more extensive data representing various types of crude oils. It is also possible to refine the co-efficients and constants in the equations derived for the crude oil viscosity prediction in this investigation for the Rocky Mountain region crude oils by statistically analyzing more sets of data representative of this region; thus it might be possible to improve upon the accuracy of the proposed method.

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APPENDIX

NOMENCLATURE

SYMBOLS	EXPLANATIONS	UNITS	ABBREVIATIONS OF UNITS
$\mu$	Absolute viscosity of crude oil at reservoir temperature and any pressure between atmospheric and bubble-point	Centipoises	cps.
$\mu_a$	Absolute viscosity of gas-free crude oil (atmospheric pressure) at reservoir temperature	Centipoises	cps.
$\Delta\mu$	Viscosity Reduction Factor (VRF), or viscosity correction factor at any pressure between atmospheric and bubble-point; equals $(\mu_a - \mu)$	Centipoises	cps.
$\mu^i$	Absolute viscosity of crude oil at reservoir temperature and any pressure above bubble-point	Centipoises	cps.
$\mu_b$	Absolute viscosity of crude oil at reservoir temperature and bubble-point pressure	Centipoises	cps.
$\Delta\mu^i$	Viscosity Increment Factor (VIF), or viscosity correction factor at any pressure above bubble-point; equals $(\mu^i - \mu_b)$	Centipoises	cps.
S	Amount of gas in solution, or the solubility of gas in crude oil	Standard cubic feet per barrel	SCF/bbl.
$\Delta P$	Pressure differential: Pressure above bubble-point less the pressure at bubble-point	Pounds per square inch	psi.
$P_b$	Pressure at bubble-point	Pounds per square inch gauge	psig.

TABLE I

Data for Crude Oil Sample 1

API Gravity: 48.7°

Reservoir Temperature: 172°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
3,500		0.44		0.04	2,422
1,880		0.42		0.02	802
1,490		0.41		0.01	412
1,078*	536	0.40	0.51	0	0
1,010	526	0.40	0.51		
745	488	0.43	0.48		
709	472	0.44	0.47		
510	434	0.46	0.45		
469	418	0.47	0.44		
410	408	0.49	0.42		
310	369	0.51	0.40		
250	355	0.54	0.37		
20	144	0.75	0.16		
0	0	0.91	0		

\* Bubble-point pressure

TABLE II

## Data for Crude Oil Sample 2

API Gravity: 47.4<sup>o</sup>Reservoir Temperature: 154<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
1,500		0.51		0.03	860
1,250		0.50		0.02	610
1,030		0.495		0.015	390
810		0.49		0.01	170
640*	440	0.48	0.55	0	0
600	438	0.48	0.55		
565	428	0.49	0.54		
410	375	0.55	0.48		
270	325	0.58	0.45		
105	220	0.69	0.34		
43	135	0.78	0.25		
0	0	1.03	0		

\* Bubble-point pressure

TABLE III

Data for Crude Oil Sample 3

API Gravity: 40.2°

Reservoir Temperature: 133°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
2,030		0.645		0.03	655
1,595		0.625		0.01	220
1,375*	413	0.615	0.625	0	0
1,245	395	0.640	0.600		
1,030	320	0.700	0.540		
740	237	0.780	0.460		
495	175	0.850	0.390		
285	110	0.950	0.290		
120	62	1.020	0.220		
0	0	1.240	0		

\* Bubble-point pressure

TABLE IV

Data for Crude Oil Sample 4

API Gravity: 39.0°

Reservoir Temperature: 178° F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
2,500		0.680		0.060	1,226
2,100		0.660		0.040	826
1,700		0.640		0.020	426
1,400		0.625		0.005	126
1,274*	424	0.620	0.82	0	0
1,000	360	0.690	0.75		
800	309	0.720	0.72		
600	257	0.780	0.66		
400	203	0.850	0.59		
200	142	0.960	0.48		
108	105	1.040	0.40		
0	0	1.44	0		

\* Bubble-point pressure

TABLE V

## Data for Crude Oil Sample 5

API Gravity: 34.9°

Reservoir Temperature: 165°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
3,005		1.528		0.204	2,220
2,505		1.472		0.148	1,720
2,005		1.427		0.103	1,220
1,505		1.384		0.060	720
1,005		1.342		0.018	220
785*	206	1.324	0.707	0	0
705	196	1.342	0.689		
505	170	1.378	0.653		
305	135	1.470	0.561		
105	88	1.618	0.413		
0	0	2.031	0		

\* Bubble-point pressure

TABLE VI

Data for Crude Oil Sample 6

API Gravity: 31.3°

Reservoir Temperature: 166° F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
2,948		1.53		0.10	898
2,804		1.52		0.09	754
2,644		1.49		0.06	594
2,391		1.47		0.04	342
2,145		1.44		0.01	95
2,049*	250	1.43	1.17	0	0
1,945	243	1.44	1.18		
1,687	225	1.45	1.15		
1,582	216	1.47	1.13		
1,187	183	1.54	1.06		
641	132	1.71	0.89		
237	77	1.91	0.69		
99	50	2.08	0.52		
0	0	2.60	0		

\* Bubble-point pressure

TABLE VII

Data for Crude Oil Sample 7

API Gravity: 36.1<sup>o</sup>Reservoir Temperature: 86<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential $\Delta P$ psi
2,000		2.655		0.175	916
1,633		2.580		0.100	549
1,300		2.518		0.038	216
1,100		2.488		0.008	16
1,084*	228	2.480	2.843	0	0
940	202	2.560	2.763		
810	176	2.750	2.573		
687	152	2.850	2.473		
547	124	3.200	2.123		
410	97	3.510	1.813		
295	74	3.760	1.563		
200	55	4.020	1.303		
113	36	4.360	0.963		
0	0	5.323	0		

\* Bubble-point pressure

TABLE VIII

Data for Crude Oil Sample 8

API Gravity: 23.1°

Reservoir Temperature: 133°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
2,570		5.70		0.50	1,030
2,300		5.57		0.37	760
2,000		5.43		0.23	460
1,540*	200	5.20	6.60	0	0
1,400	187	5.45	6.35		
1,210	160	5.90	5.90		
930	125	6.75	5.05		
600	80	7.82	3.98		
400	50	9.06	2.74		
195	26	10.02	1.78		
0	0	11.80	0		

\* Bubble-point pressure

TABLE IX

## Data for Crude Oil Sample 9

API Gravity: 47.2°

Reservoir Temperature: 158°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
2,147		0.58		0.06	1,660
1,766		0.56		0.04	1,279
1,530		0.55		0.03	1,043
1,180		0.54		0.02	693
487*	490	0.52	0.65	0	0
412	460	0.54	0.63		
318	428	0.56	0.61		
217	375	0.58	0.59		
115	295	0.66	0.51		
45	206	0.78	0.39		
0	0	1.17	0		

\* Bubble-point pressure

TABLE X

Data for Crude Oil Sample 10

API Gravity: 37.2°

Reservoir Temperature: 184°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
5,000		1.36		0.32	4,170
4,000		1.27		0.23	3,170
3,000		1.19		0.15	2,170
2,000		1.12		0.08	1,170
1,000		1.06		0.02	170
830*	245	1.04	0.71	0	0
615	205	1.07	0.68		
420	167	1.11	0.64		
305	143	1.14	0.61		
150	108	1.22	0.53		
70	84	1.27	0.48		
0	0	1.75	0		

\* Bubble-point pressure

TABLE XI

Data for Crude Oil Sample 11

API Gravity: 33.8°

Reservoir Temperature: 160°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
3,000		1.60		0.16	1,250
2,700		1.56		0.12	950
2,400		1.52		0.08	650
2,100		1.48		0.04	350
1,800		1.45		0.01	50
1,750*	217	1.44	1.03	0	0
1,700	210	1.45	1.02		
1,555	200	1.47	1.00		
1,300	182	1.50	0.97		
965	153	1.58	0.89		
684	128	1.67	0.80		
443	100	1.76	0.71		
244	73	1.87	0.60		
105	48	2.00	0.47		
0	0	2.47	0		

\*Bubble-point pressure

TABLE XII

Data for Crude Oil Sample 12

API Gravity: 33.7°

Reservoir Temperature: 160°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
3,000		1.78		0.15	1,071
2,800		1.74		0.11	871
2,600		1.72		0.09	671
2,400		1.70		0.07	471
2,200		1.67		0.04	271
1,929*	215	1.63	1.15	0	0
1,600	191	1.67	1.11		
1,000	143	1.77	1.01		
700	112	1.88	0.90		
400	78	2.04	0.74		
100	27	2.33	0.45		
0	0	2.78	0		

\* Bubble-point pressure

TABLE XIII

Data for Crude Oil Sample 13.

API Gravity: 21.2°

Reservoir Temperature: 133°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
2,220		8.95		0.65	820
1,900		8.70		0.40	500
1,650		8.50		0.20	250
1,400*	168.0	8.30	8.60	0	0
1,275	157.7	8.60	8.30		
1,110	136.0	9.40	7.50		
820	100.0	10.50	6.40		
515	62.0	12.20	4.70		
295	37.0	13.40	3.50		
105	12.0	15.30	1.60		
30	3.0	16.20	0.70		
0	0	16.9	0		

\* Bubble-point pressure

TABLE XIV

Data for Crude Oil Sample 14

API Gravity: 44.5°

Reservoir Temperature: 156°

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
1,950		0.58		0.05	1,332
1,610		0.57		0.04	992
1,323		0.56		0.03	705
1,040		0.55		0.02	422
728		0.54		0.01	110
618*	453	0.53	0.60	0	0
490	405	0.56	0.57		
350	350	0.60	0.53		
245	300	0.64	0.49		
150	240	0.71	0.42		
73	180	0.80	0.33		
0	0	1.13	0		

\*Bubble-point pressure

TABLE XV

Data for Crude Oil Sample 15

API Gravity: 39.0<sup>o</sup>Reservoir Temperature: 173<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
2,555		0.980		0.090	1,434
2,075		0.950		0.060	954
1,750		0.925		0.035	629
1,470		0.910		0.020	349
1,121*	408	0.890	1.00	0	0
907	356	0.920	0.97		
762	319	0.960	0.93		
517	257	1.030	0.86		
369	218	1.100	0.79		
115	131	1.300	0.59		
0	0	1.890	0		

\* Bubble-point pressure

TABLE XVI

Data for Crude Oil Sample 16

API Gravity: 34.2<sup>o</sup>Reservoir Temperature: 133<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
2,050		1.12		0.05	675
1,840		1.11		0.04	465
1,620		1.09		0.02	245
1,375*	387	1.07	1.33	0	0
1,175	336	1.16	1.24		
915	280	1.27	1.13		
615	212	1.42	0.98		
375	150	1.59	0.81		
275	125	1.69	0.71		
90	65	1.92	0.48		
0	0	2.40	0		

\* Bubble-point pressure

TABLE XVII

Data for Crude Oil Sample 17

API Gravity: 33.4<sup>o</sup>Reservoir Temperature: 166<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
3,108		1.53		0.12	1,063
2,907		1.51		0.10	862
2,706		1.49		0.08	661
2,507		1.47		0.06	463
2,307		1.44		0.03	262
2,108		1.42		0.01	63
2,045*	256	1.41	1.17	0	0
1,800	232	1.42	1.16		
1,540	214	1.47	1.11		
1,323	196	1.50	1.08		
1,010	167	1.57	1.01		
732	141	1.66	0.92		
427	105	1.78	0.80		
218	76	1.90	0.68		
100	50	2.02	0.56		
52	36	2.11	0.47		
0	0	2.58	0		

\*Bubble-point pressure

TABLE XVIII

Data for Crude Oil Sample 18

API Gravity: 48.1°

Reservoir Temperature: 154°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
1,500		0.49		0.03	945
1,300		0.49		0.03	745
1,100		0.48		0.02	545
900		0.47		0.01	345
700		0.46		0	145
610		0.46		0	55
555*	454	0.46	0.50	0	0
470	426	0.50	0.46		
365	383	0.53	0.43		
235	325	0.61	0.35		
115	258	0.65	0.31		
40	140	0.76	0.20		
0	0	0.96	0		

\* Bubble-point pressure

TABLE XIX

Data for Crude Oil Sample 19

API Gravity: 34.2°

Reservoir Temperature: 159°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
2,500		1.53		0.09	840
2,300		1.51		0.07	640
2,100		1.49		0.05	440
1,900		1.47		0.03	240
1,700		1.45		0.01	40
1,600*	229	1.44	1.11	0	0
1,570	223	1.44	1.11		
1,455	213	1.46	1.09		
1,250	196	1.50	1.05		
955	170	1.55	1.00		
670	142	1.64	0.91		
405	106	1.74	0.81		
255	84	1.82	0.73		
85	50	2.00	0.55		
0	0	2.55	0		

\*Bubble-point pressure

TABLE XX

Data for Crude Oil Sample 20

API Gravity: 48.5°

Reservoir Temperature: 156°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
1,500		0.48		0.03	900
1,300		0.48		0.03	700
1,100		0.47		0.02	500
900		0.46		0.01	300
700		0.45		0	100
630		0.45		0	30
600*	514	0.45	0.61	0	0
495	475	0.48	0.58		
385	424	0.50	0.56		
260	365	0.53	0.53		
135	265	0.63	0.43		
50	186	0.72	0.34		
0	0	1.06	0		

\*Bubble-point pressure

TABLE XXI

## Data for Crude Oil Sample 21

API Gravity: 34.2<sup>o</sup>Reservoir Temperature: 162<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
3,108		1.17		0.06	726
2,907		1.15		0.04	525
2,706		1.13		0.02	324
2,382*	371	1.11	1.32	0	0
2,148	345	1.12	1.31		
1,888	319	1.17	1.26		
1,590	290	1.21	1.22		
1,335	260	1.25	1.18		
1,020	222	1.32	1.11		
730	182	1.42	1.01		
465	144	1.52	0.91		
250	104	1.64	0.79		
112	72	1.78	0.65		
25	36	1.93	0.50		
0	0	2.43	0		

\* Bubble-point pressure

TABLE XXII

## Data for Crude Oil Sample 22

API Gravity: 45.6°

Reservoir Temperature: 153°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
1,500		0.570		0.030	810
1,300		0.560		0.020	610
1,100		0.555		0.015	410
910		0.550		0.010	220
725		0.540		0	35
690*	350	0.540	0.50	0	0
640	340	0.560	0.48		
510	295	0.600	0.44		
355	250	0.640	0.40		
240	205	0.690	0.35		
120	155	0.760	0.28		
48	92	0.890	0.20		
0	0	1.040	0		

\* Bubble-point pressure

TABLE XXIII

Data for Crude Oil Sample 23

API Gravity: 35.0°

Reservoir Temperature: 158°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
3,007		1.52		0.16	1,404
2,726		1.48		0.12	1,123
2,440		1.46		0.10	837
2,143		1.42		0.06	540
1,823		1.39		0.02	220
1,603*	230	1.36	1.19	0	0
1,506	220	1.38	1.17		
1,260	200	1.43	1.12		
982	185	1.48	1.07		
610	134	1.58	0.97		
378	102	1.68	0.87		
190	75	1.81	0.74		
76	50	1.91	0.64		
33	36	2.00	0.55		
0	0	2.55	0		

\* Bubble-point pressure

TABLE XXIV

Data for Crude Oil Sample 24

API Gravity: 45.6°

Reservoir Temperature: 153°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
1,500		0.57		0.03	810
1,300		0.56		0.02	610
1,100		0.555		0.015	410
910		0.55		0.01	220
725		0.54		0	35
690*	350	0.54	0.50		
640	340	0.56	0.48		
510	295	0.60	0.44		
355	250	0.64	0.40		
240	205	0.69	0.35		
120	155	0.76	0.28		
48	92	0.89	0.20		
0	0	1.04	0		

\* Bubble-point pressure

TABLE XXV

Data for Crude Oil Sample 25

API Gravity: 35.2°

Reservoir Temperature: 156°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
3,200		1.13		0.07	730
3,000		1.11		0.05	530
2,800		1.09		0.03	330
2,600		1.07		0.01	130
2,470*	414	1.06	1.39	0	0
2,300	395	1.09	1.36		
2,095	376	1.11	1.34		
1,790	340	1.17	1.28		
1,405	290	1.24	1.21		
1,115	255	1.30	1.15		
825	211	1.39	1.06		
535	167	1.51	0.94		
295	122	1.65	0.80		
180	94	1.73	0.72		
70	62	1.90	0.55		
0	0	2.45	0		

\* Bubble-point pressure

TABLE XXVI

Data for Crude Oil Sample 26

API Gravity: 44.5<sup>o</sup>Reservoir Temperature: 158<sup>o</sup>F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu$ Centipoises	Pressure Differential, $\Delta P$ psi
2,050		0.58		0.06	1,395
1,770		0.56		0.04	1,115
1,420		0.55		0.03	765
1,125		0.54		0.02	470
787		0.52		0	132
655*	489	0.52	0.57	0	0
590	477	0.53	0.56		
480	435	0.56	0.53		
345	350	0.60	0.49		
230	305	0.64	0.45		
123	230	0.72	0.37		
45	117	0.87	0.22		
0	0	1.09	0		

\* Bubble-point pressure

TABLE XXVII

Data for Crude Oil Sample 27

API Gravity: 35.0°

Reservoir Temperature: 157°F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
3,007		1.17		0.06	677
2,806		1.15		0.04	476
2,606		1.13		0.02	276
2,407		1.11		0	77
2,330*	375	1.11	1.25	0	0
2,275	370	1.12	1.24		
2,162	360	1.12	1.24		
1,910	333	1.16	1.20		
1,650	304	1.19	1.17		
1,286	270	1.26	1.10		
886	222	1.36	1.00		
539	157	1.50	0.86		
298	118	1.64	0.72		
125	78	1.78	0.58		
42	45	1.90	0.46		
0	0	2.36	0		

\* Bubble-point pressure

TABLE XXVIII

Data for Crude Oil Sample 28

API Gravity: 17.2°

Reservoir Temperature: 133° F

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Viscosity, $\mu$ Centipoises	Viscosity Reduction Factor, $\Delta\mu$ Centipoises	Viscosity Increment Factor, $\Delta\mu'$ Centipoises	Pressure Differential, $\Delta P$ psi
2,220		31.8		4.6	815
1,960		30.3		3.1	555
1,710		29.0		1.8	305
1,405*	152	27.2	33.6	0	0
1,195	130	27.5	33.3		
970	106	31.0	29.8		
700	78	36.0	24.8		
500	54	41.1	19.7		
288	28.7	48.5	12.3		
113	7.6	55.2	5.6		
0	0	60.8	0		

\* Bubble-point pressure

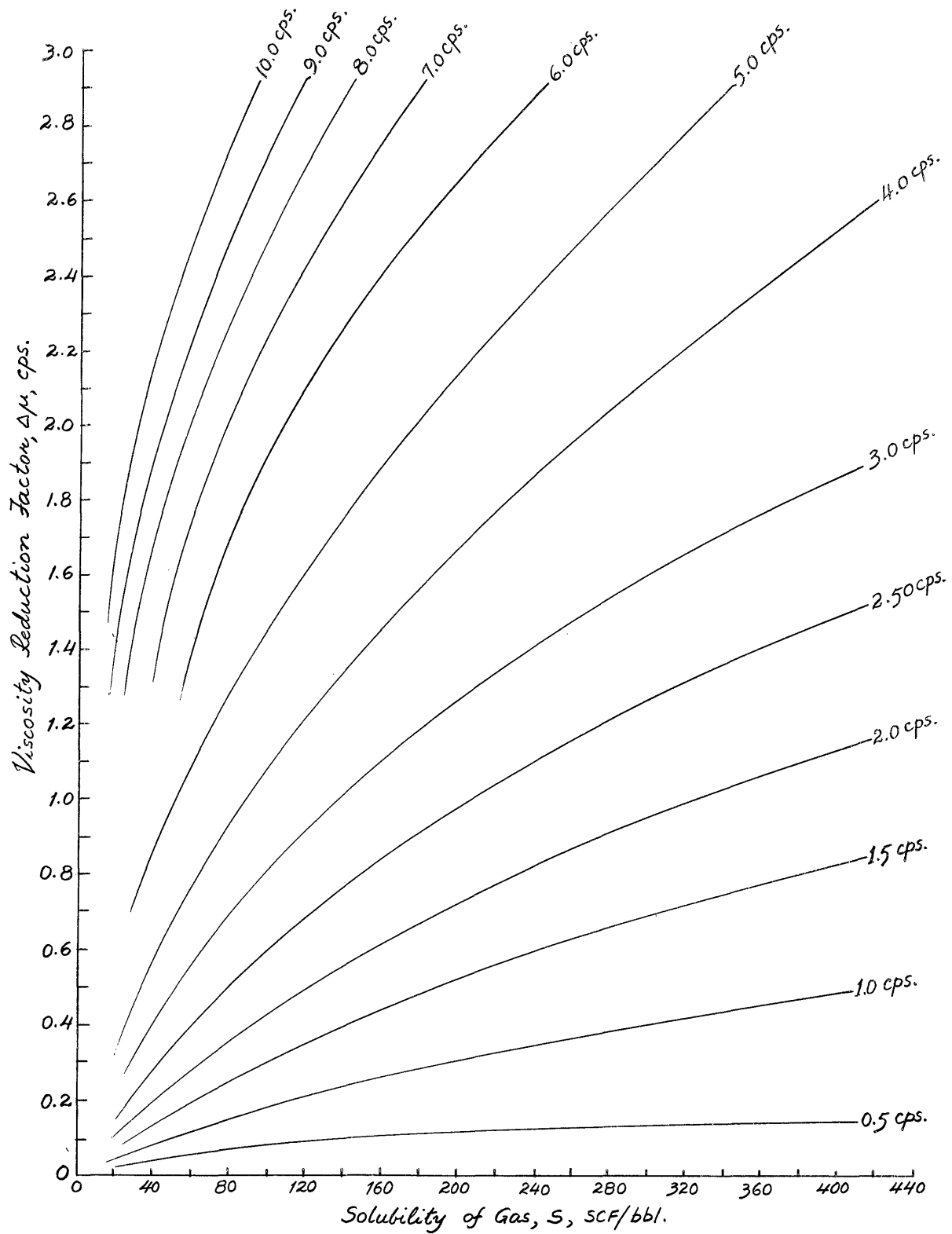


Figure 1. Viscosity Reduction Factor as related to Solubility of gas and gas-free crude oil viscosity.

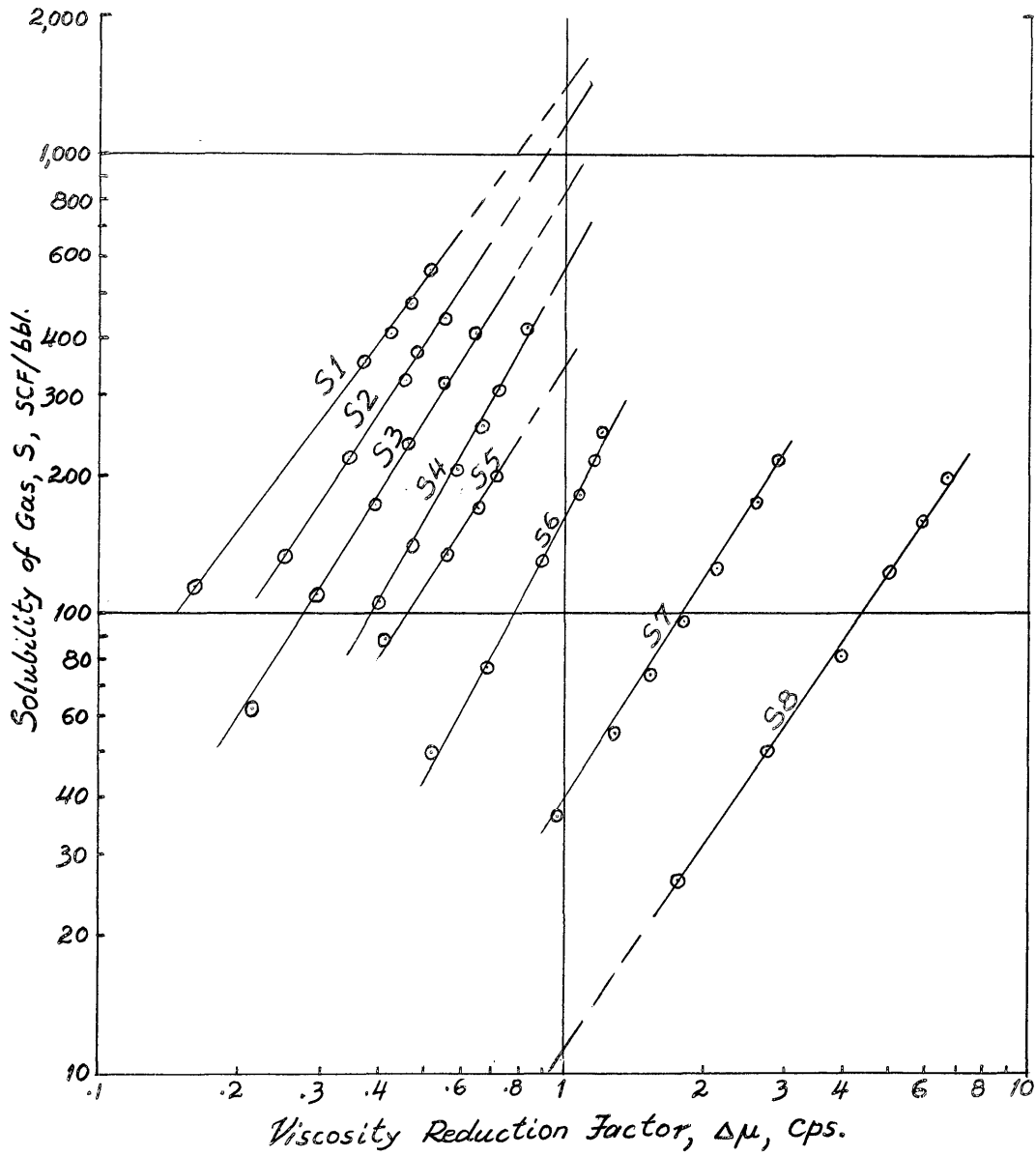


Figure 2. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 1 - 8.

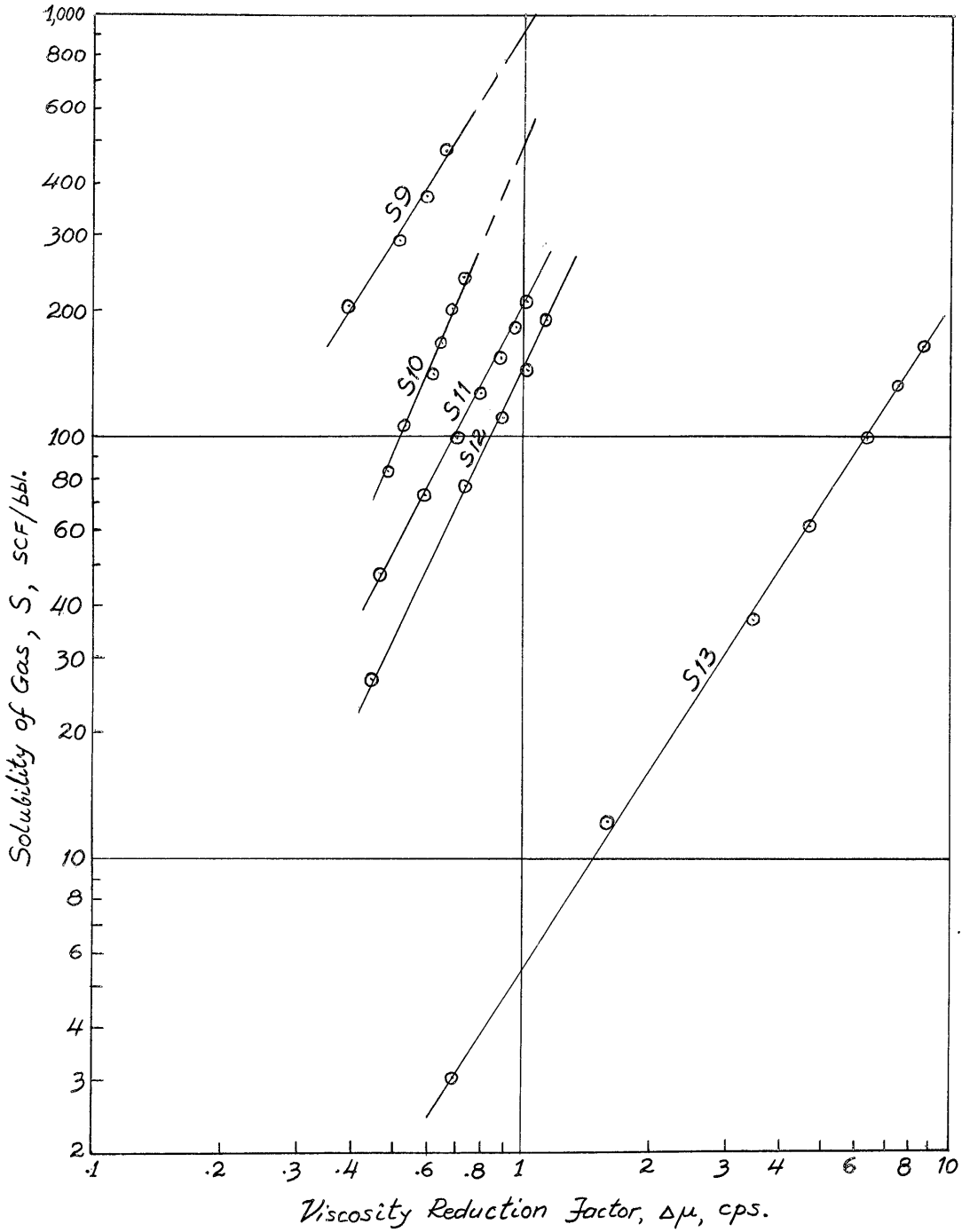


Figure 3. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 9 - 13.

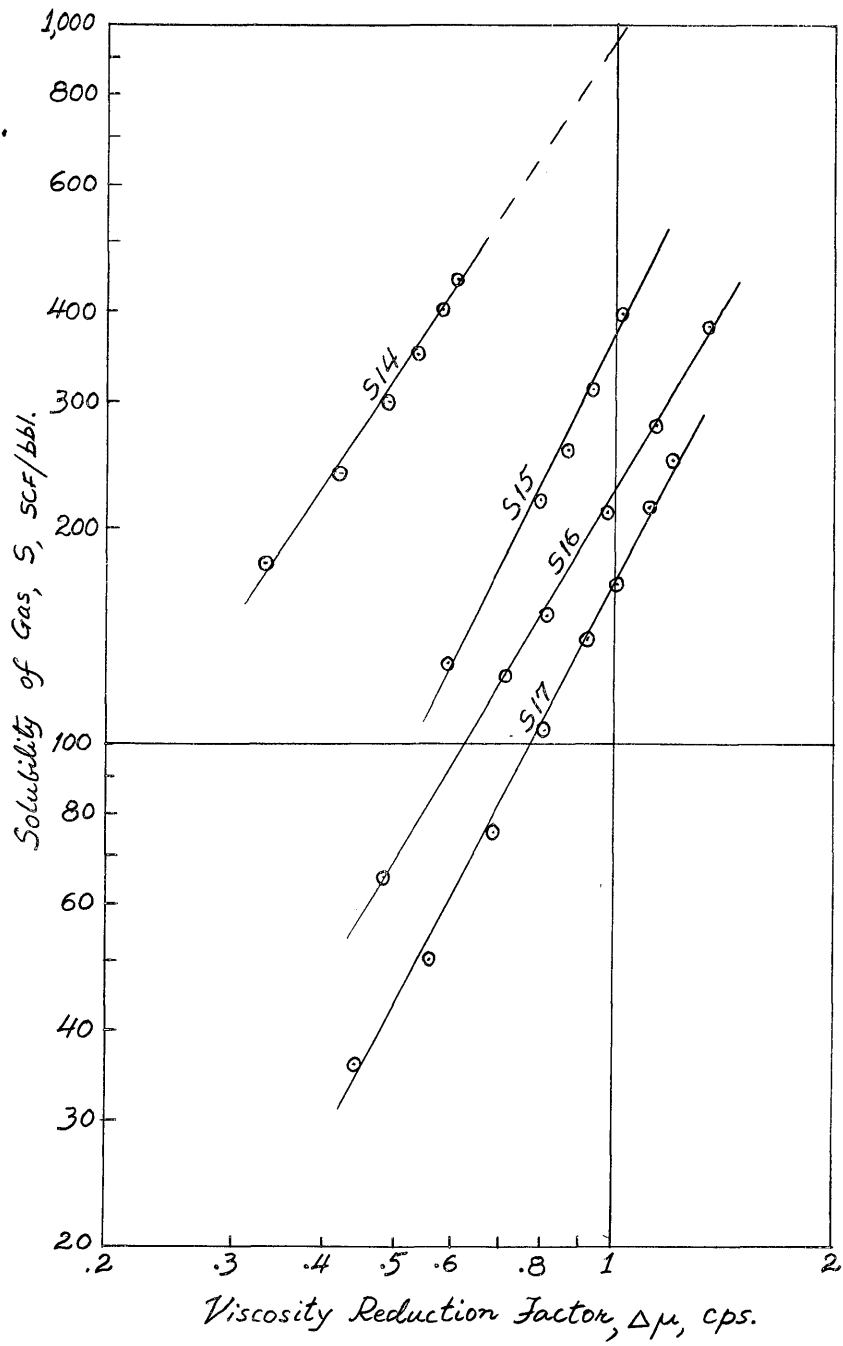


Figure 4. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 14 - 17.

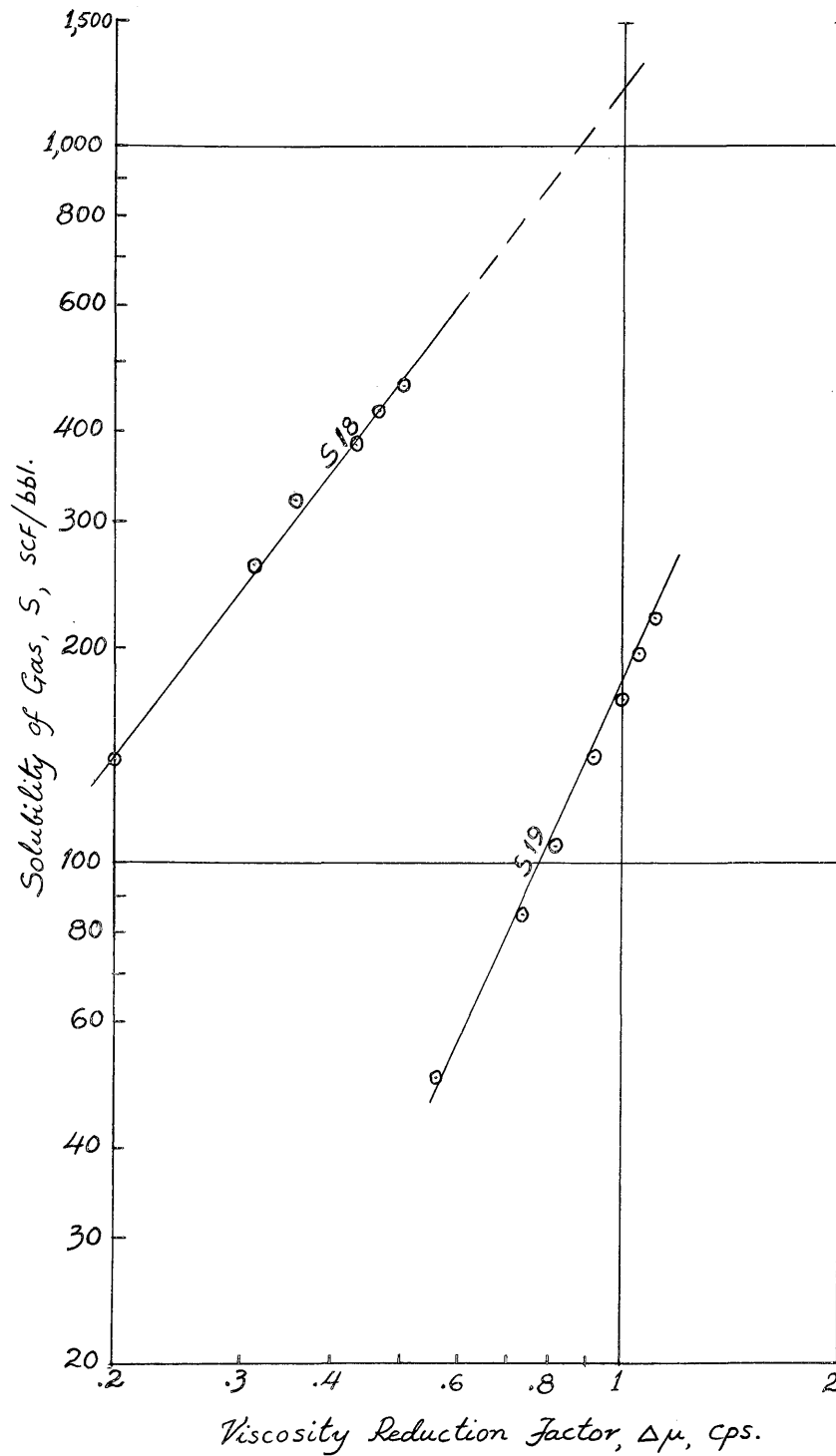


Figure 5. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 18 - 19.

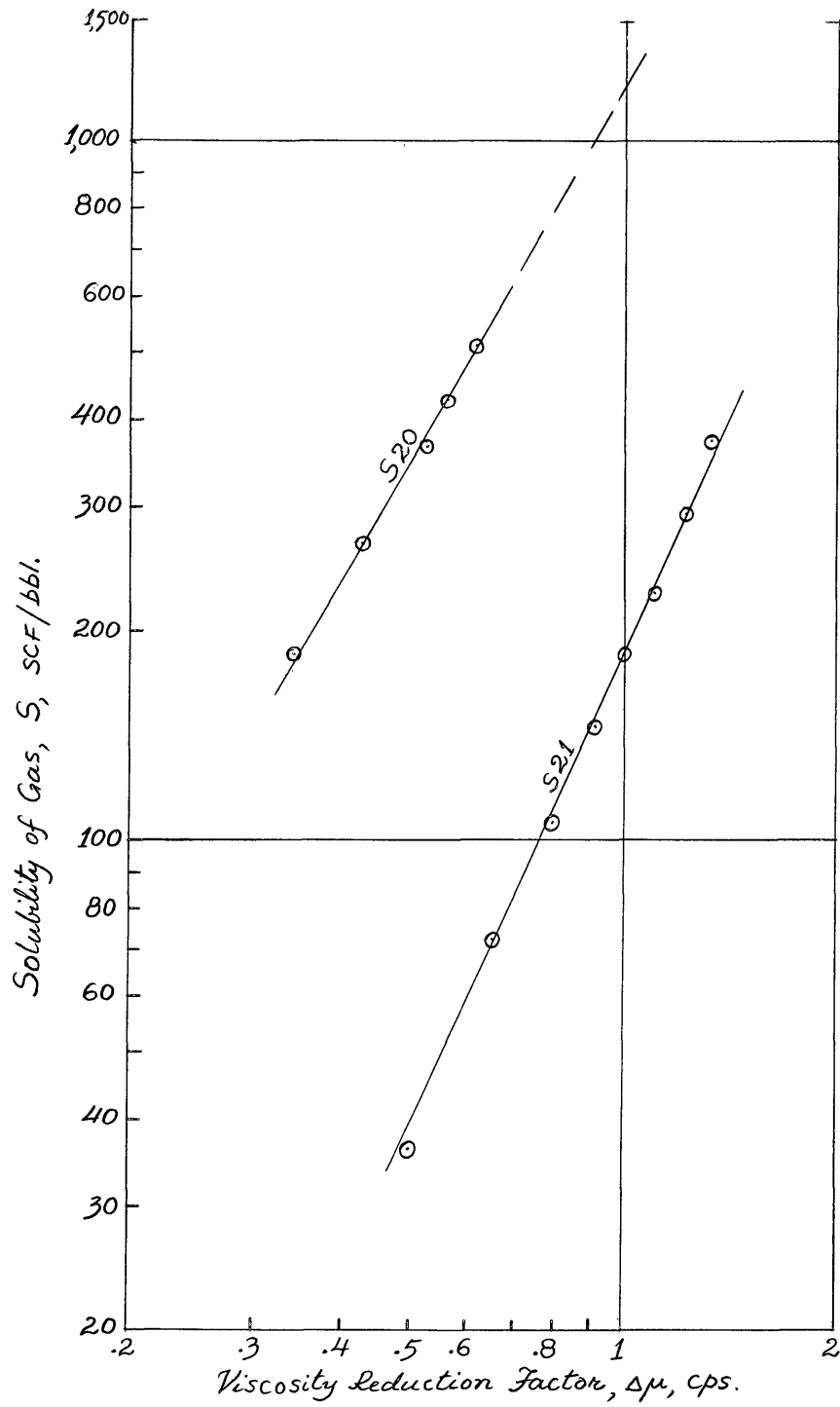


Figure 6. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 20 and 21.

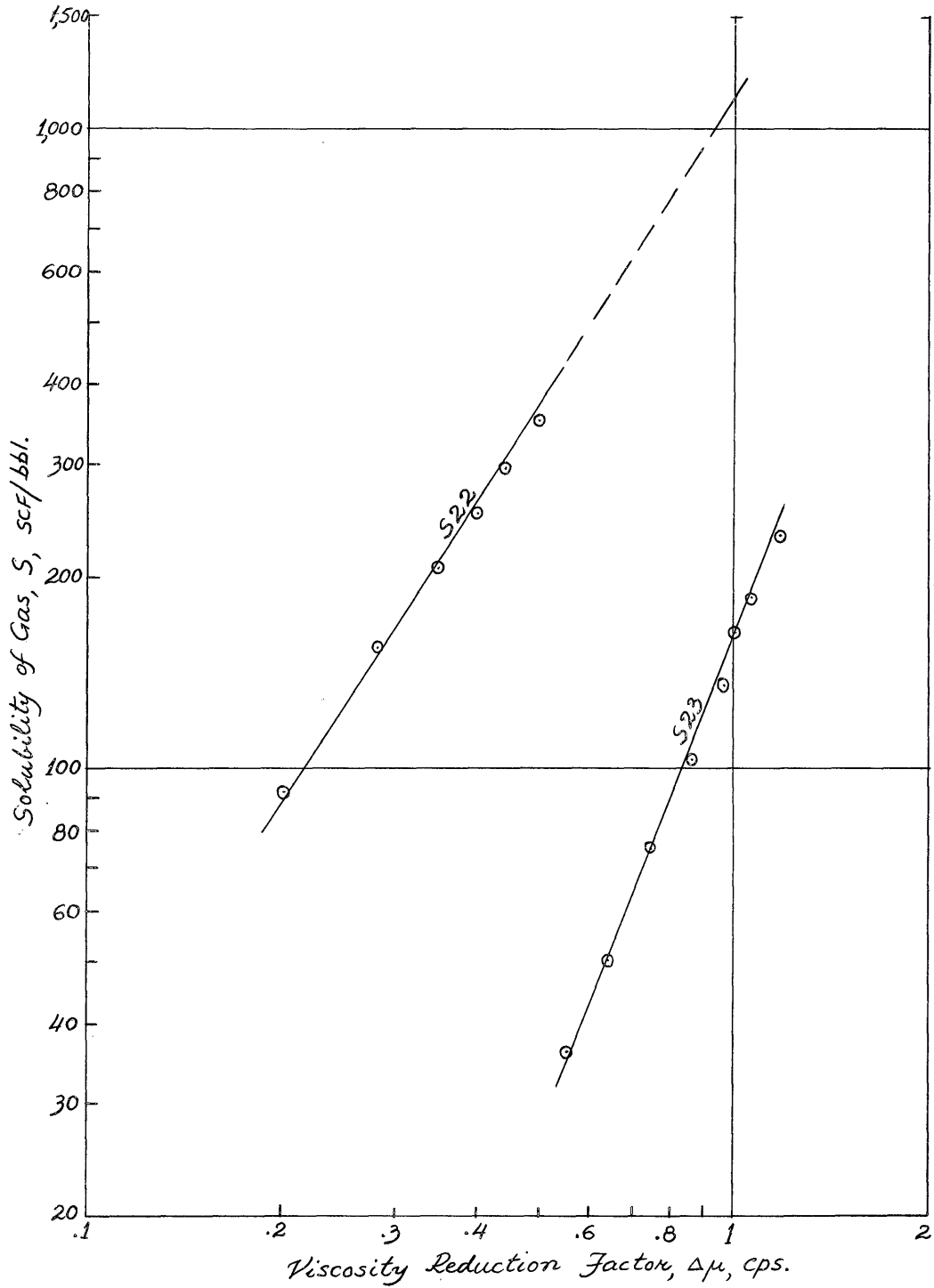


Figure 7. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 22 and 23.

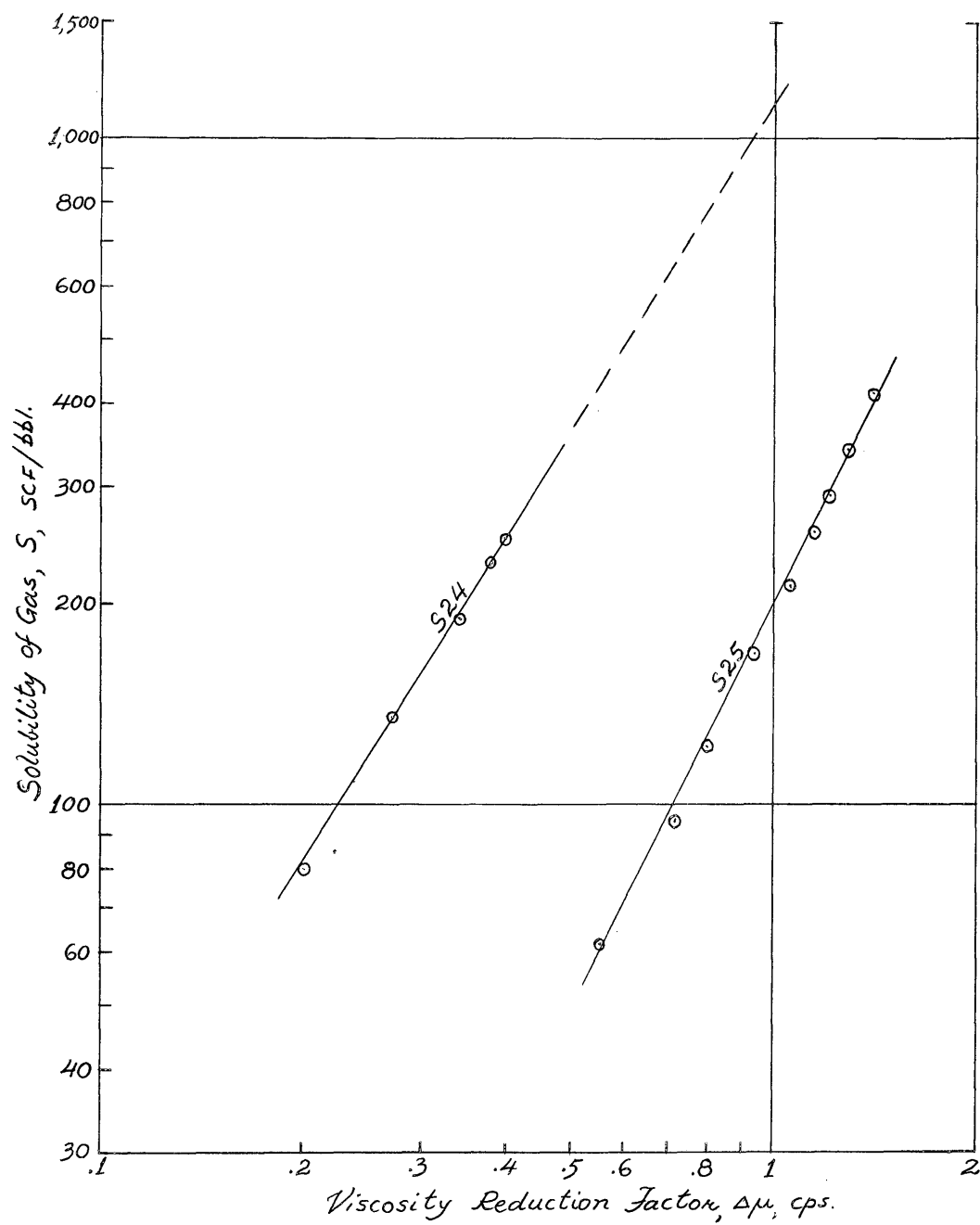


Figure 8. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 24 and 25.

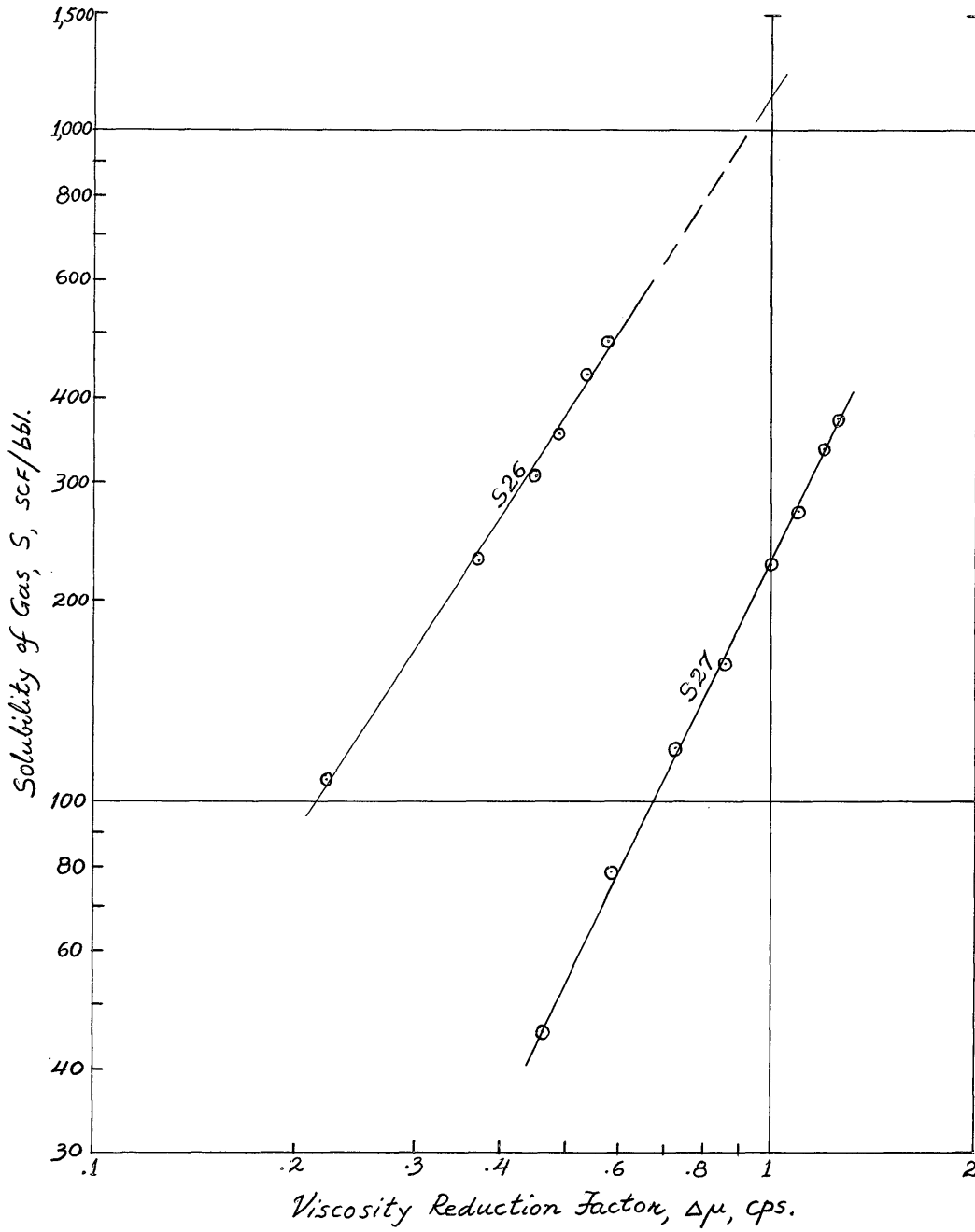


Figure 9. Viscosity Reduction Factor as related to solubility of gas for crude oil Samples 26 and 27.

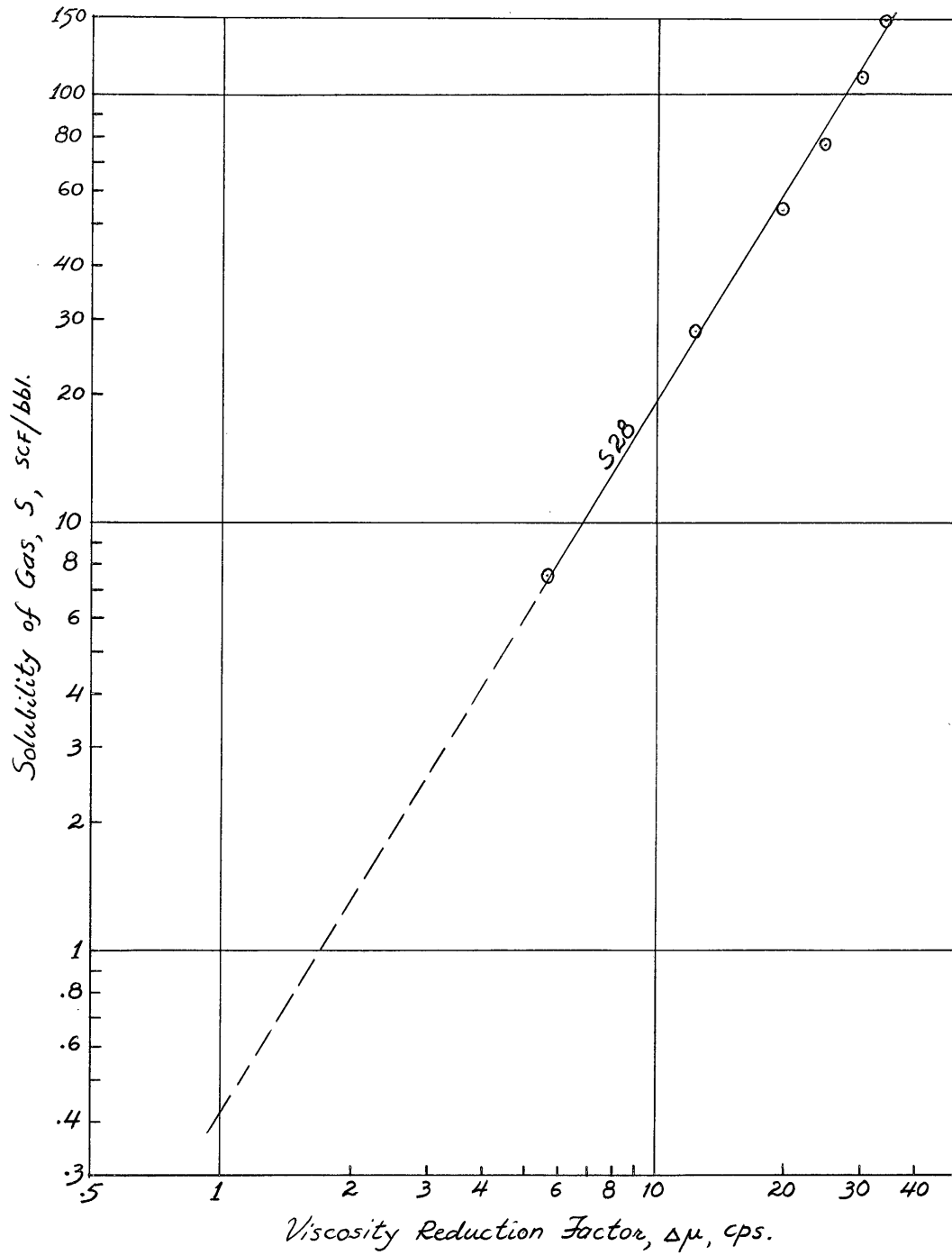


Figure 10. Viscosity Reduction Factor as related to solubility of gas for crude oil Sample 28.

TABLE XXIX

Slopes and Intercepts of Curves of Viscosity Reduction Factor,  
 $\Delta\mu$ , versus Solubility of Gas,  $S_g$ , (Figures 2 - 10)

Crude Oil Sample	Gas-free Crude Oil Viscosity, $\mu_a$ Centipoises	Intercept, b	Slope, m	$m^2$
1	0.91	1,400	1.36	1.85
2	1.03	1,170	1.49	2.22
3	1.24	820	1.58	2.50
4	1.44	595	1.92	3.72
5	2.03	350	1.65	2.72
6	2.60	163	1.91	3.65
7	5.32	40	1.84	3.40
8	11.80	11.30	1.50	2.25
9	1.17	900	1.58	2.50
10	1.75	475	2.00	4.00
11	2.47	205	1.88	3.53
12	2.78	150	2.00	4.00
13	16.90	5.30	1.60	2.56
14	1.13	960	1.58	2.50
15	1.89	375	2.00	4.00
16	2.40	230	1.74	3.03
17	2.58	167	1.91	3.65
18	0.96	1,200	1.37	1.89

TABLE XXIX (Continued)

Crude Oil Sample	Gas-free Crude Oil Viscosity, $\mu_a$ Centipoises	Intercept, b	Slope, m	$m^2$
19	2.55	180	1.91	3.65
20	1.06	1,170	1.59	2.53
21	2.43	190	2.15	4.62
22	1.04	1,100	1.55	2.40
23	2.55	165	2.30	5.29
24	1.04	1,100	1.55	2.40
25	2.45	200	2.00	4.00
26	1.09	1,120	1.49	2.22
27	2.36	230	2.00	4.00
28	60.80	0.42	1.67	2.81

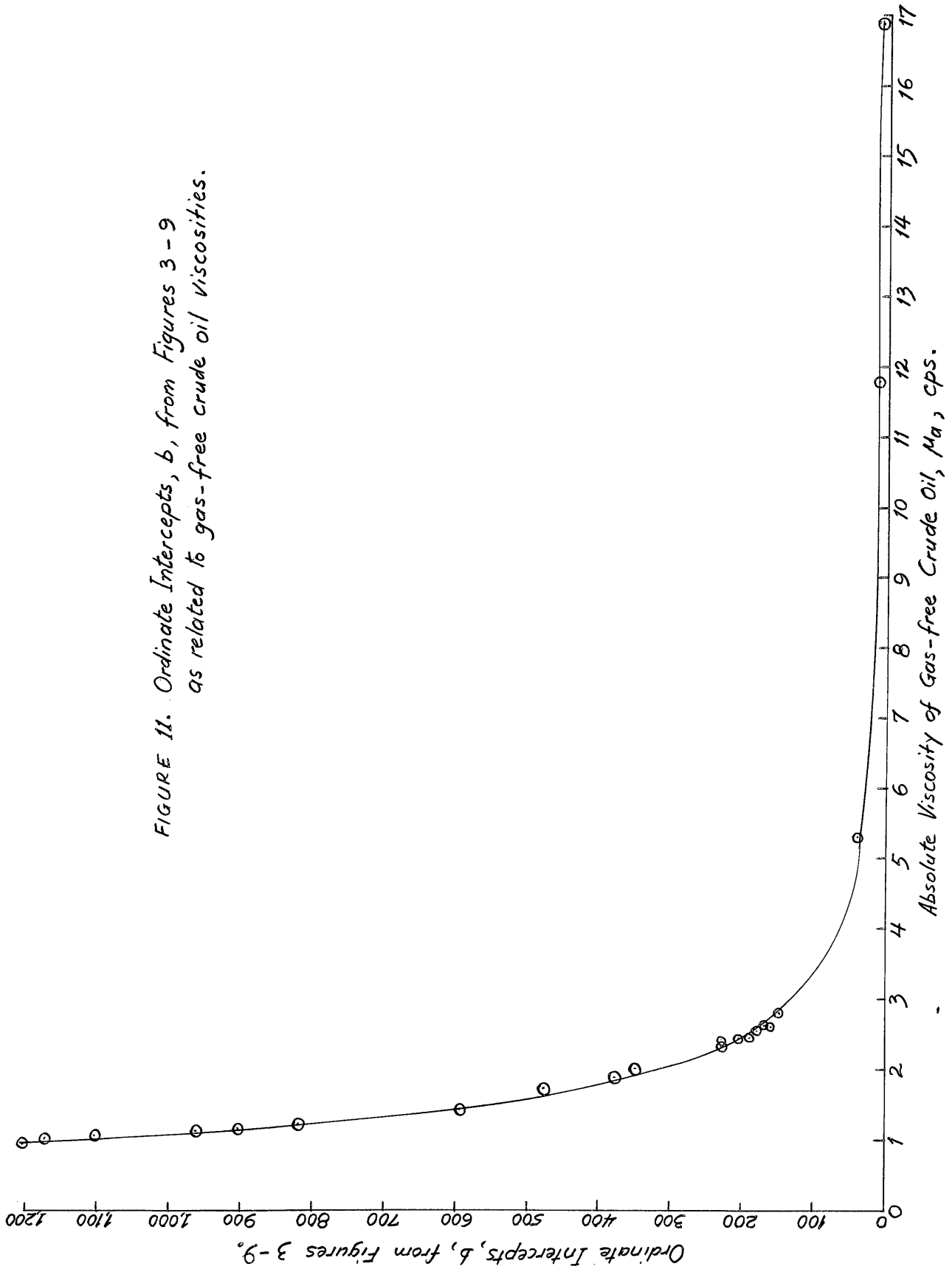
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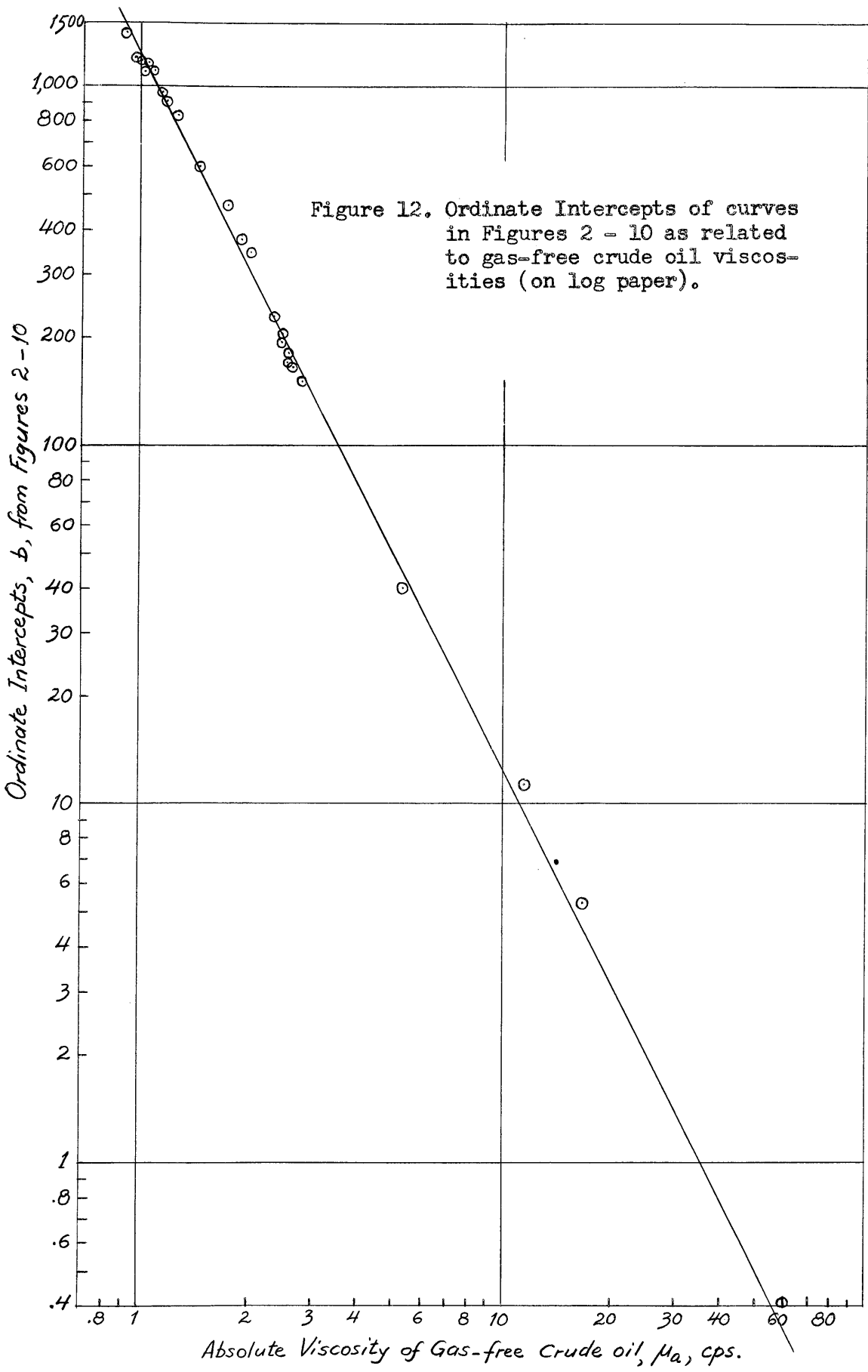

$$\sum m^2 = 87.89$$

$$m^2 = \frac{87.89}{28}$$

$$m = 1.77$$

FIGURE 11. Ordinate Intercepts,  $b$ , from Figures 3-9 as related to gas-free crude oil viscosities.





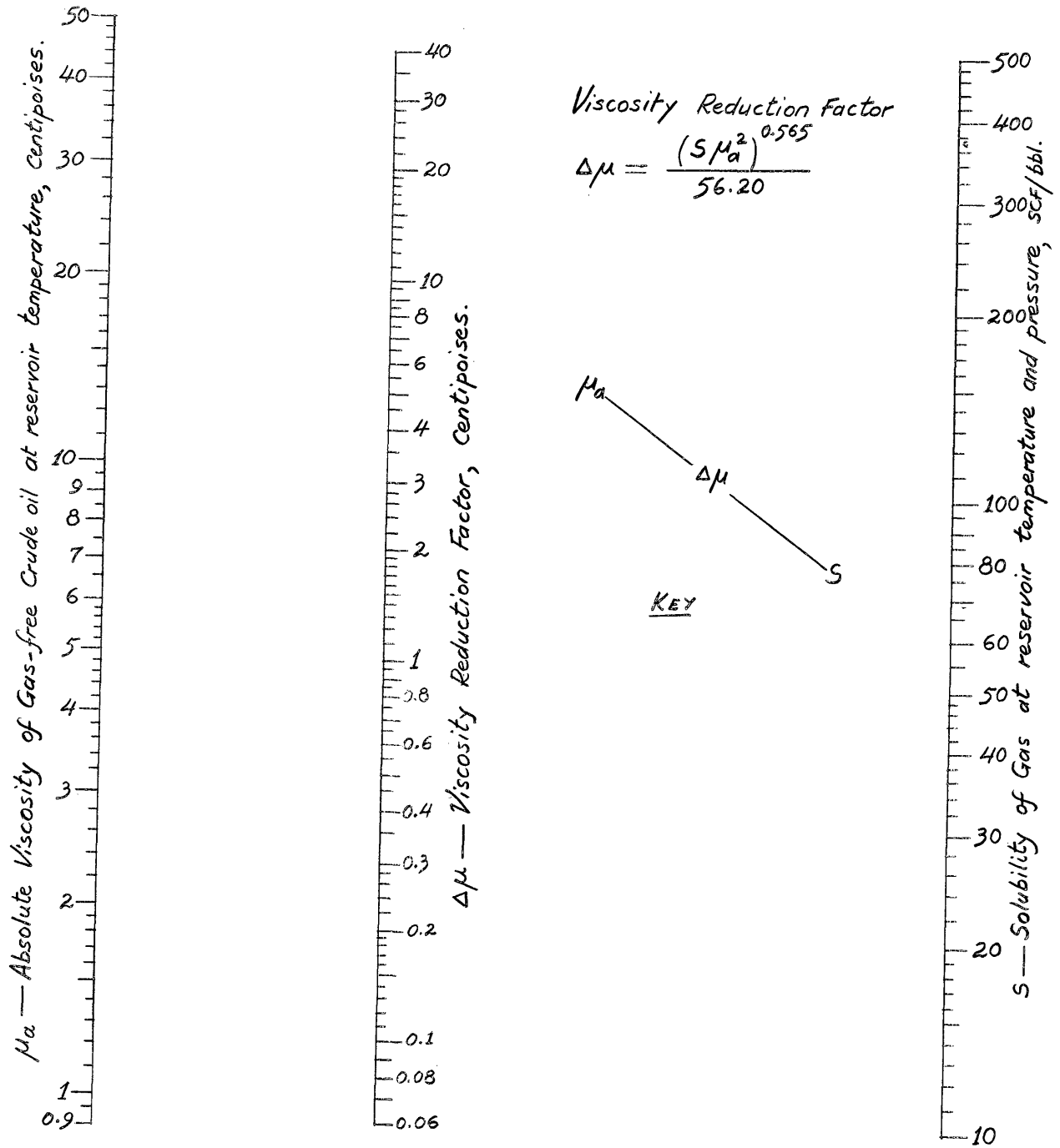


Figure 13. Alignment chart for the Viscosity Reduction Factor Equation.

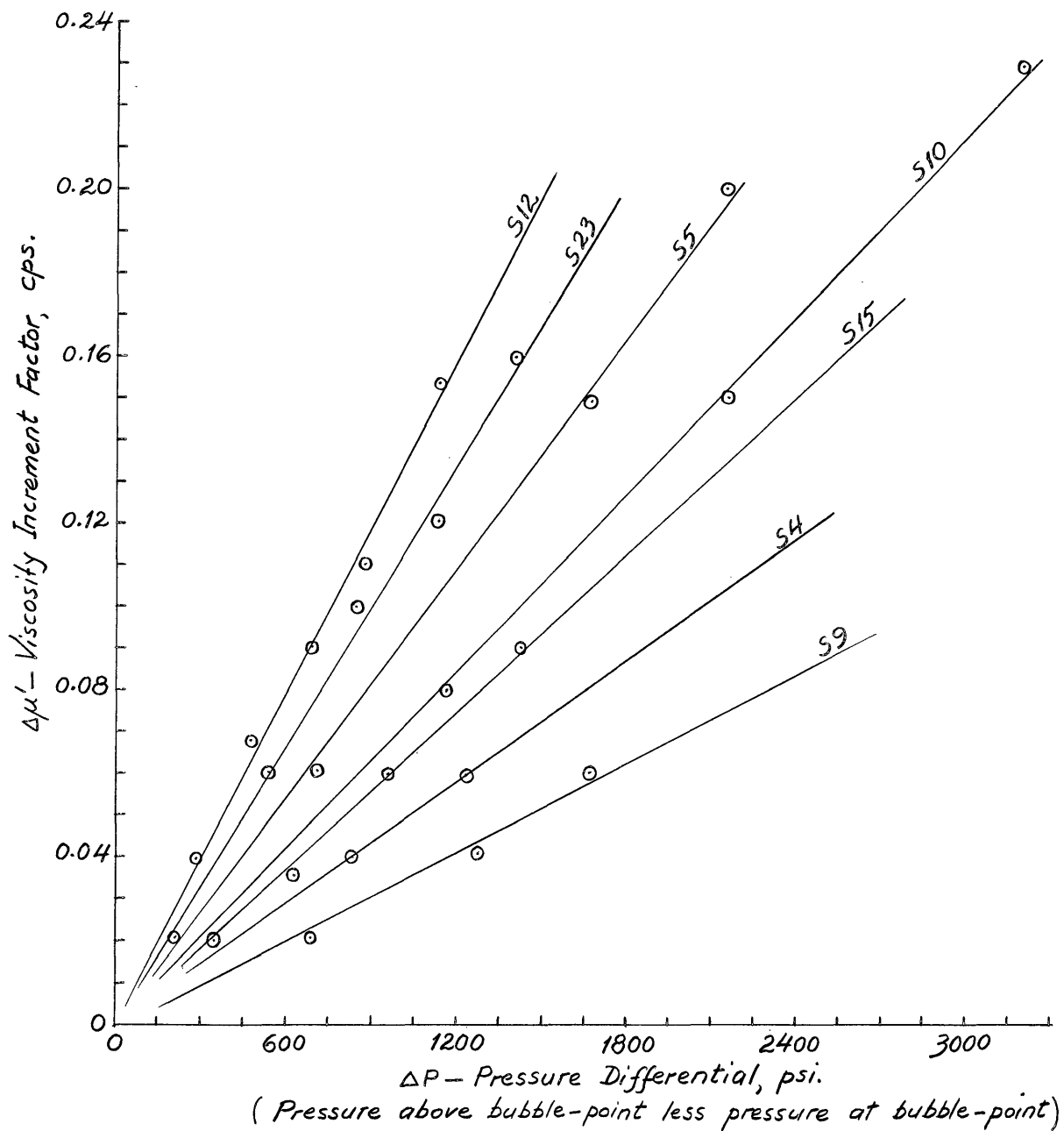


Figure 14. Viscosity Increment Factor as related to Pressure Differential for crude oil samples 4, 5, 9, 10, 12, 15, and 23.

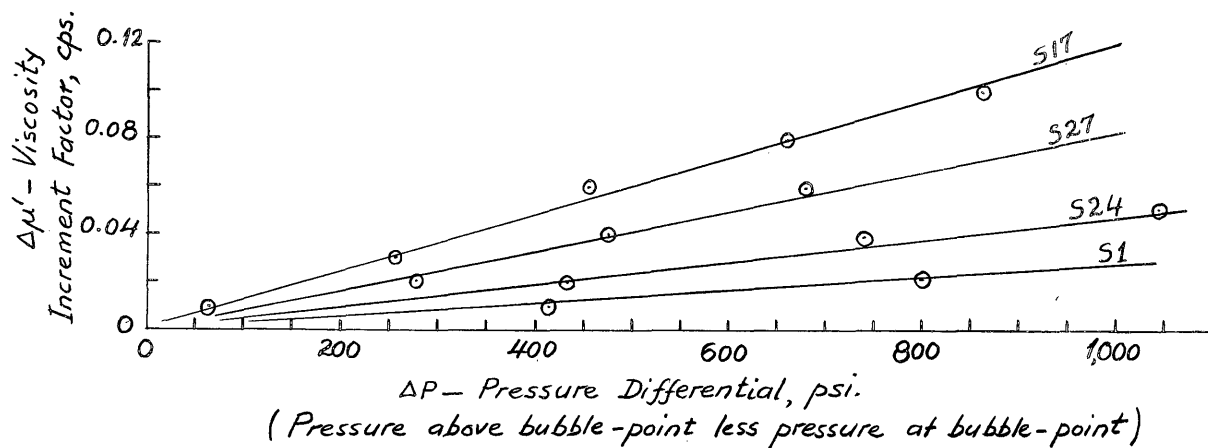


Figure 15. Viscosity Increment Factor as related to Pressure Differential for crude oil samples 1, 17, 24, and 27.

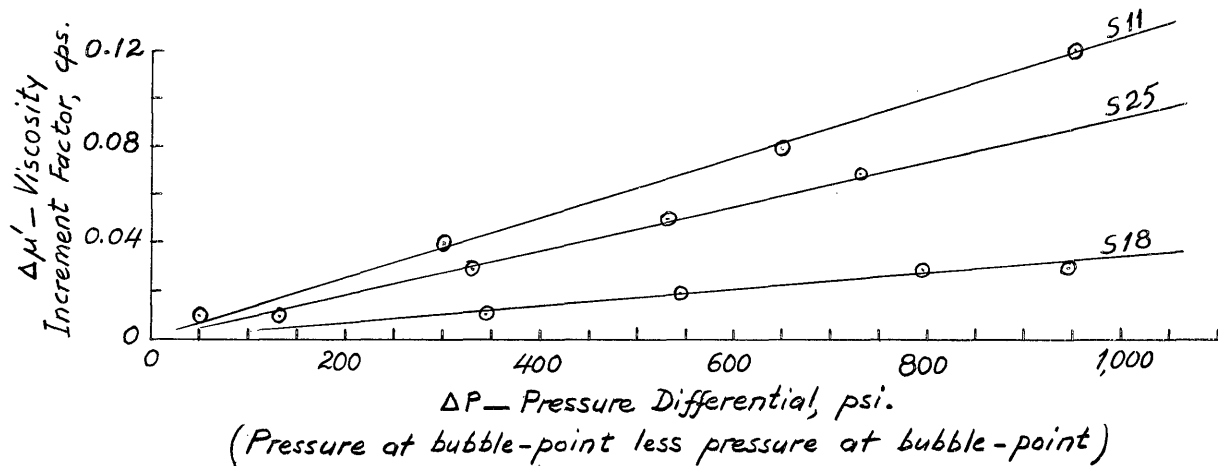


Figure 16. Viscosity Increment Factor as related to Pressure Differential for crude oil samples 11, 18, and 25.

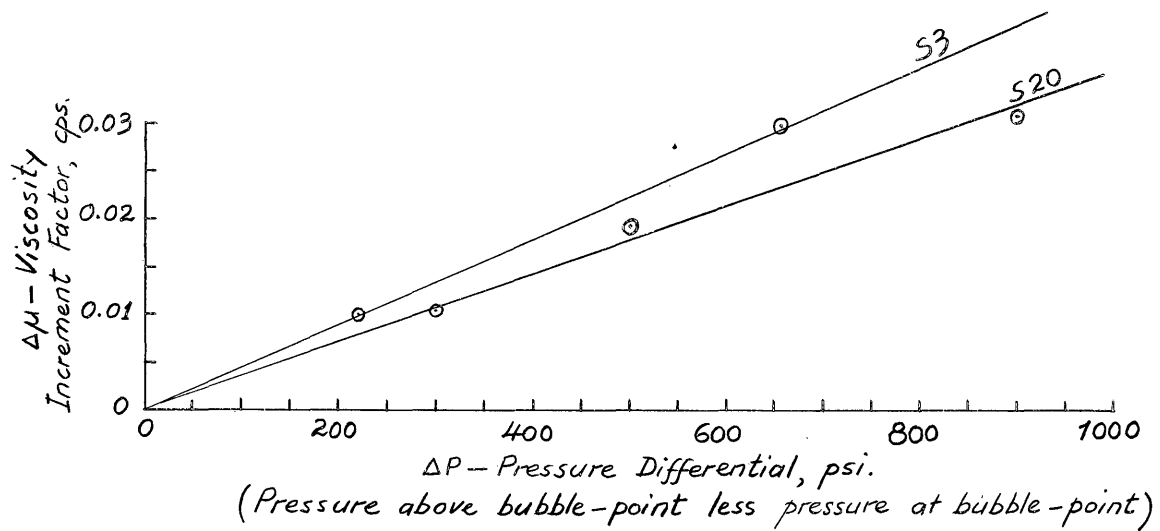


Figure 17. Viscosity Increment Factor as related to Pressure Differential for crude oil samples 3 and 20.

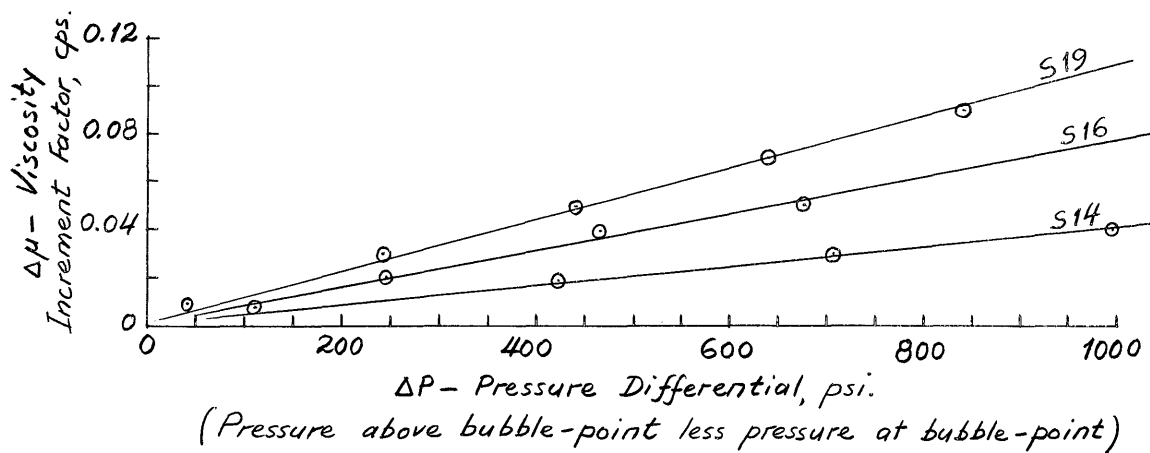


Figure 18. Viscosity Increment Factor as related to Pressure Differential for crude oil samples 14, 16, and 19.

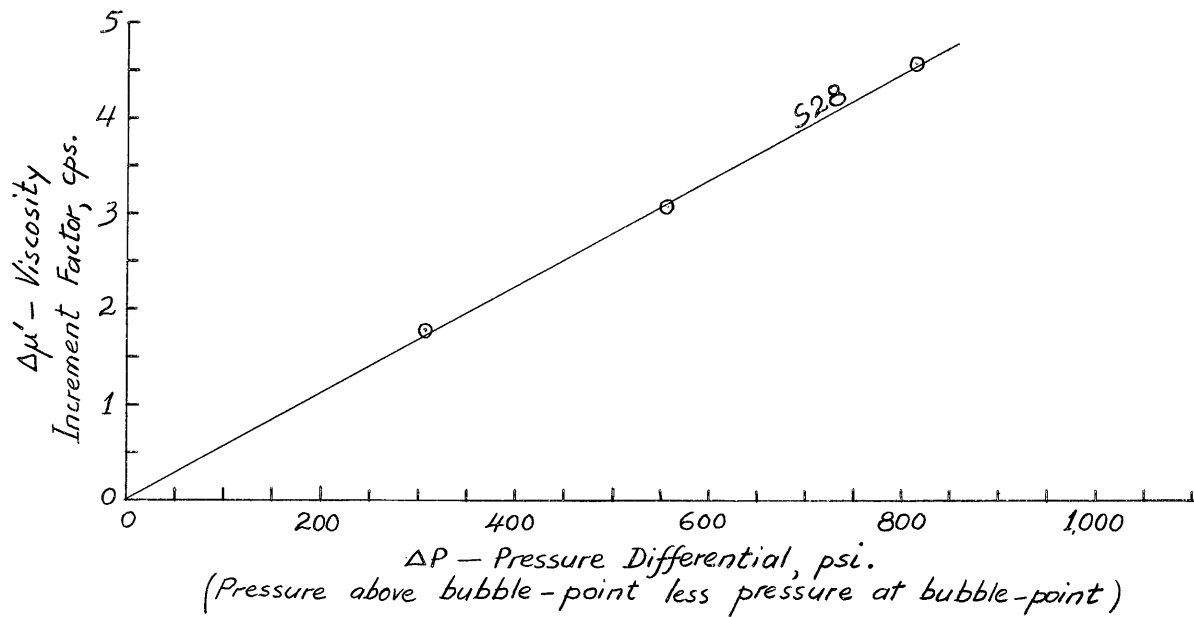


Figure 19. Viscosity Increment Factor as related to Pressure Differential for crude oil sample 28.

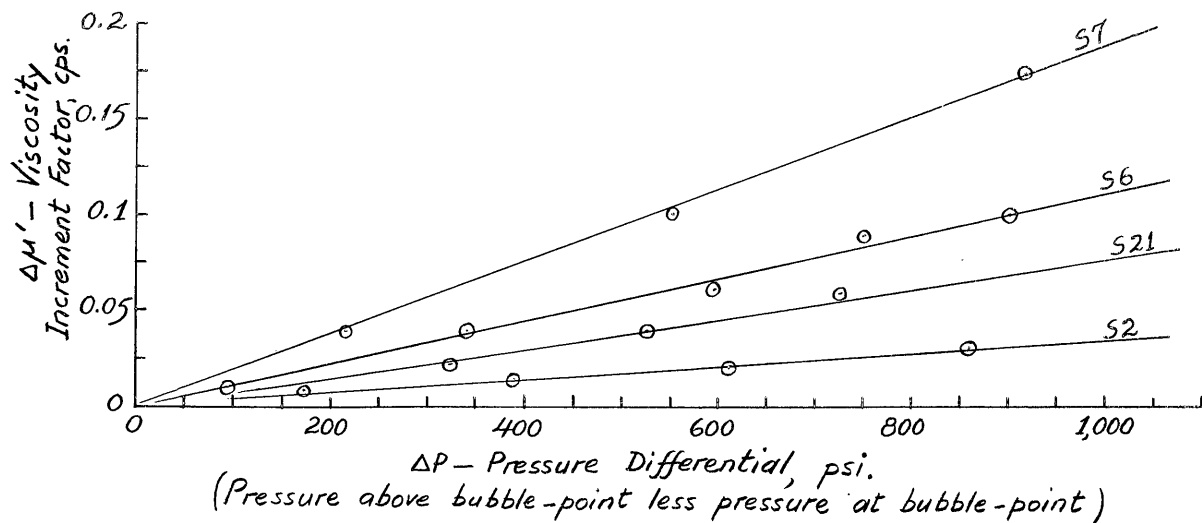


Figure 20. Viscosity Increment Factor as related to Pressure Differential for crude oil samples 2, 6, 7, and 21.

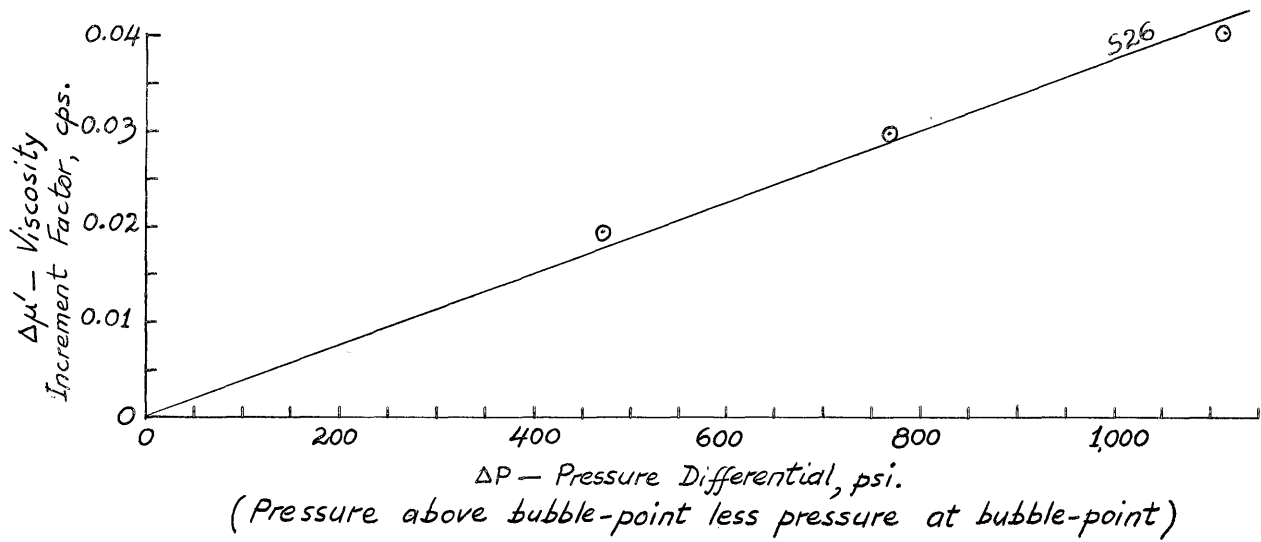


Figure 21. Viscosity Increment Factor as related to Pressure Differential for crude oil sample 26.

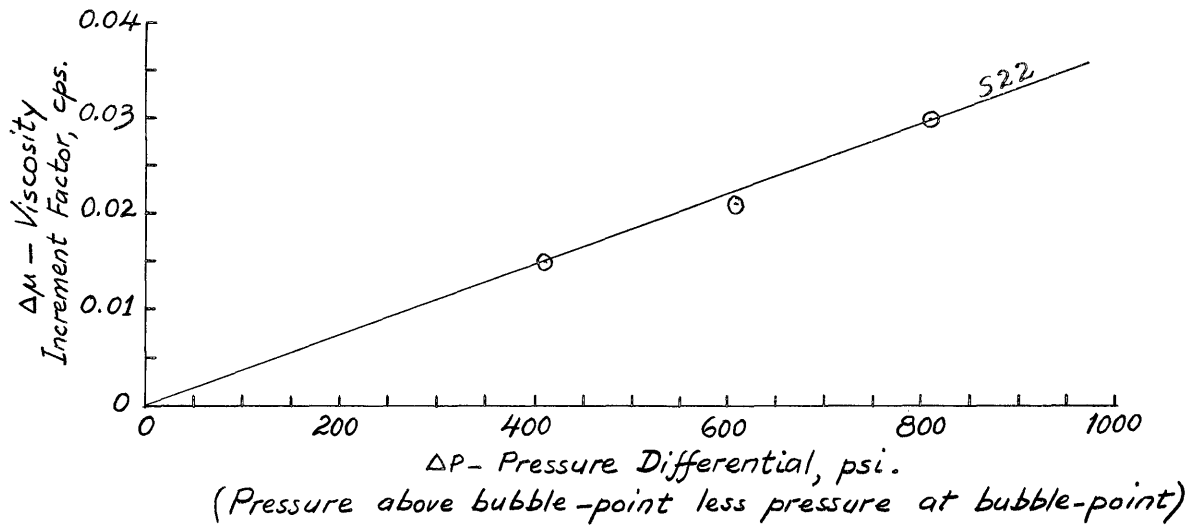


Figure 22. Viscosity Increment Factor as related to Pressure Differential for crude oil sample 22.

TABLE XXX

Slopes of Curves in Figures 14 - 22  
Before and After Rectification

(Rectification Constant  $c = 0.0115 \times 10^{-3}$ )

Crude Oil Sample	Bubble-point Viscosity, $\mu_b$ Centipoises	Slope, $m^1 \times 10^3$	Rectified Slope, $(m^1 - c) \times 10^3$
1	0.40	0.030	0.0185
2	0.48	0.035	0.0235
3	0.615	0.045	0.0335
4	0.62	0.047	0.0355
5	1.324	0.090	0.0785
6	1.43	0.110	0.0985
7	2.48	0.185	0.1735
8	5.20	0.550	0.5385
9	0.52	0.035	0.0235
10	1.04	0.070	0.0585
11	1.44	0.125	0.1135
12	1.63	0.130	0.1185
13	8.30	0.800	0.7885
14	0.53	0.040	0.0285
15	0.88	0.060	0.0485
16	1.07	0.075	0.0635

TABLE XXX (Continued)

Crude Oil Sample	Bubble-point Viscosity, $\mu_b$ Centipoises	Slope, <sup>3</sup> $m^1 \times 10^3$	Rectified Slope, $(m^1 - c) \times 10^3$
17	1.41	0.120	0.1085
18	0.46	0.034	0.0225
19	1.44	0.110	0.0985
20	0.45	0.035	0.0235
21	1.11	0.080	0.0685
22	0.54	0.037	0.0255
23	1.36	0.110	0.0985
24	0.62	0.450	0.0335
25	1.06	0.085	0.0735
26	0.52	0.037	0.0255
27	1.11	0.080	0.0685
28	27.20	5.650	5.6385

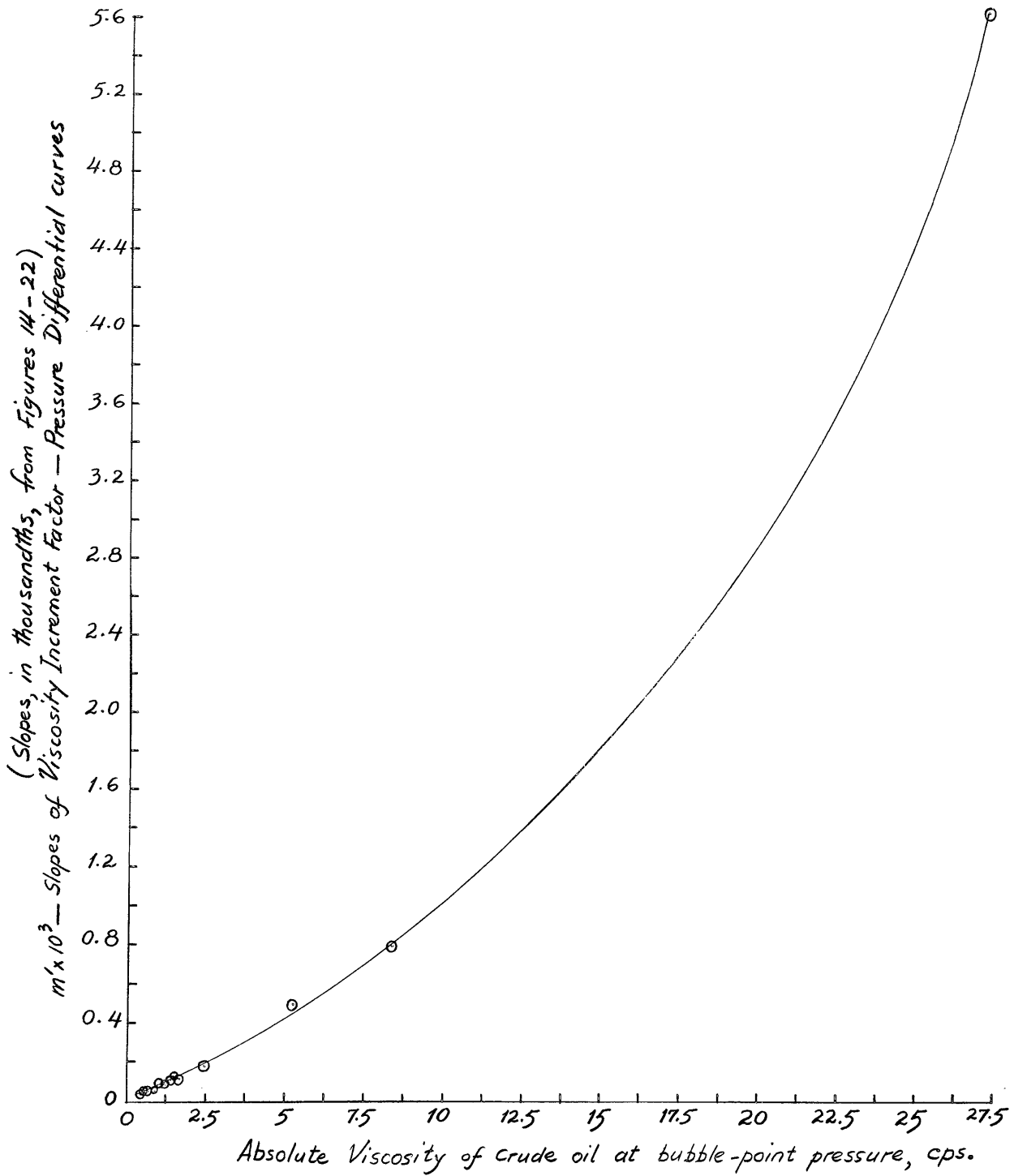


Figure 23. Slopes of curves in Figures 14 - 22 as related to crude oil viscosities at bubble-point pressure (on rectangular co-ordinate paper).



Figure 24. Slopes of curves in Figures 14 - 22 (before and after rectification) as related to crude oil viscosities at bubble-point pressure (on log paper).

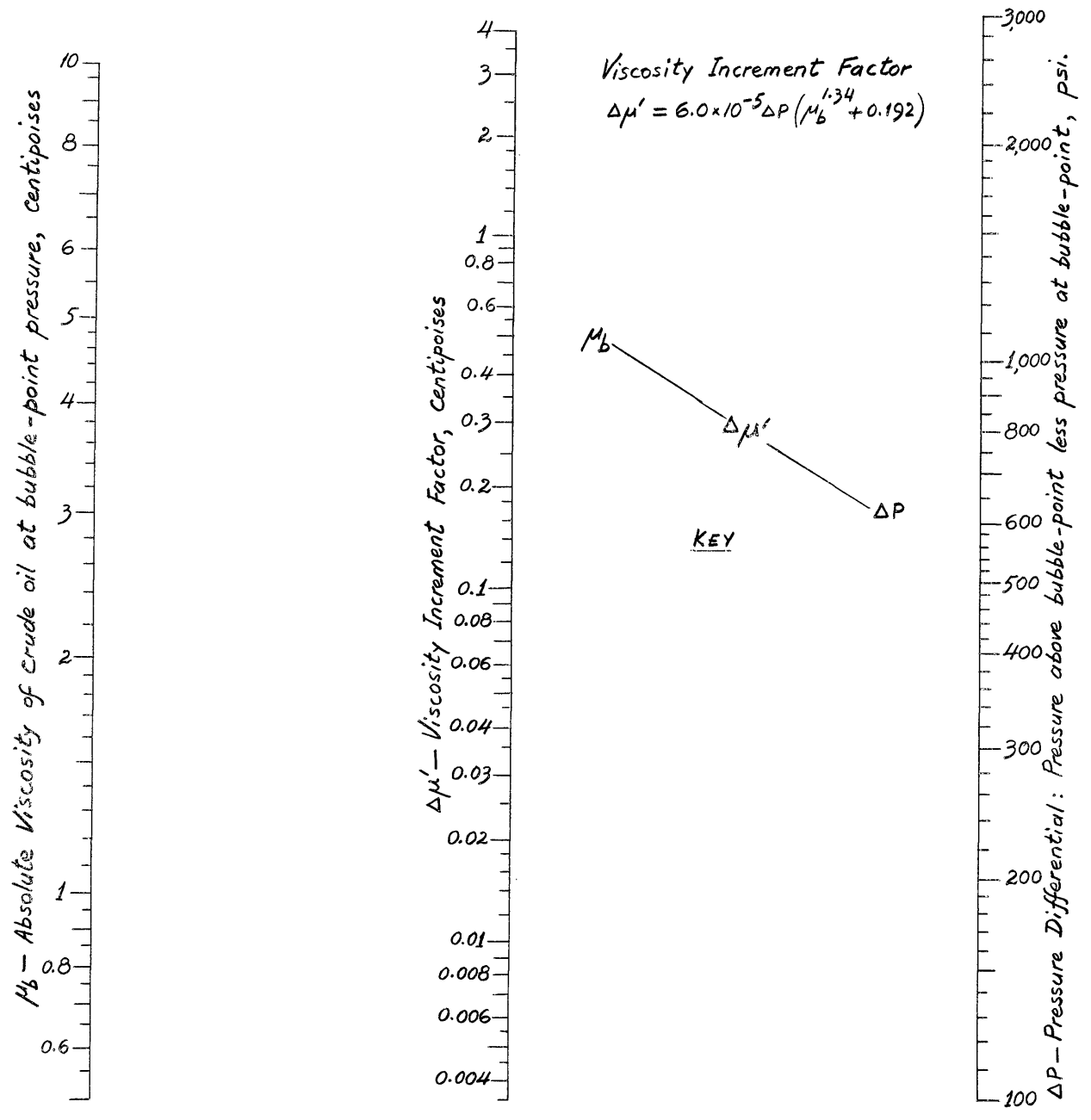


Figure 25. Alignment chart for the Viscosity Increment Factor Equation.

TABLE XXXI

Comparison of Measured Crude Oil Viscosity Data with Predicted Values for a Rocky Mountain Region Crude Oil Sample<sup>1/</sup>

Pressure, P psig	Solubility of Gas, S SCF/bbl.	Pressure Differential, psi	<u>Absolute Viscosity, Centipoises</u>		
			Nomographic method	Measured values	Beal's method
2,500		838	1.060	1.10	1.04
2,230		568	1.040	1.08	1.02
1,820		158	1.011	1.01	0.99
1,662*	303	0	1.000	1.00	0.98
1,400	267		1.060	1.04	1.04
1,000	208		1.180	1.15	1.18
800	174		1.230	1.21	1.30
600	140		1.330	1.28	1.42
400	104		1.410	1.36	1.60
200	62		1.550	1.49	1.80
0	0		1.930	1.93	2.50

<sup>1/</sup> API Gravity of the crude oil: 34.0°  
Reservoir Temperature: 155°F

\* Bubble-point pressure

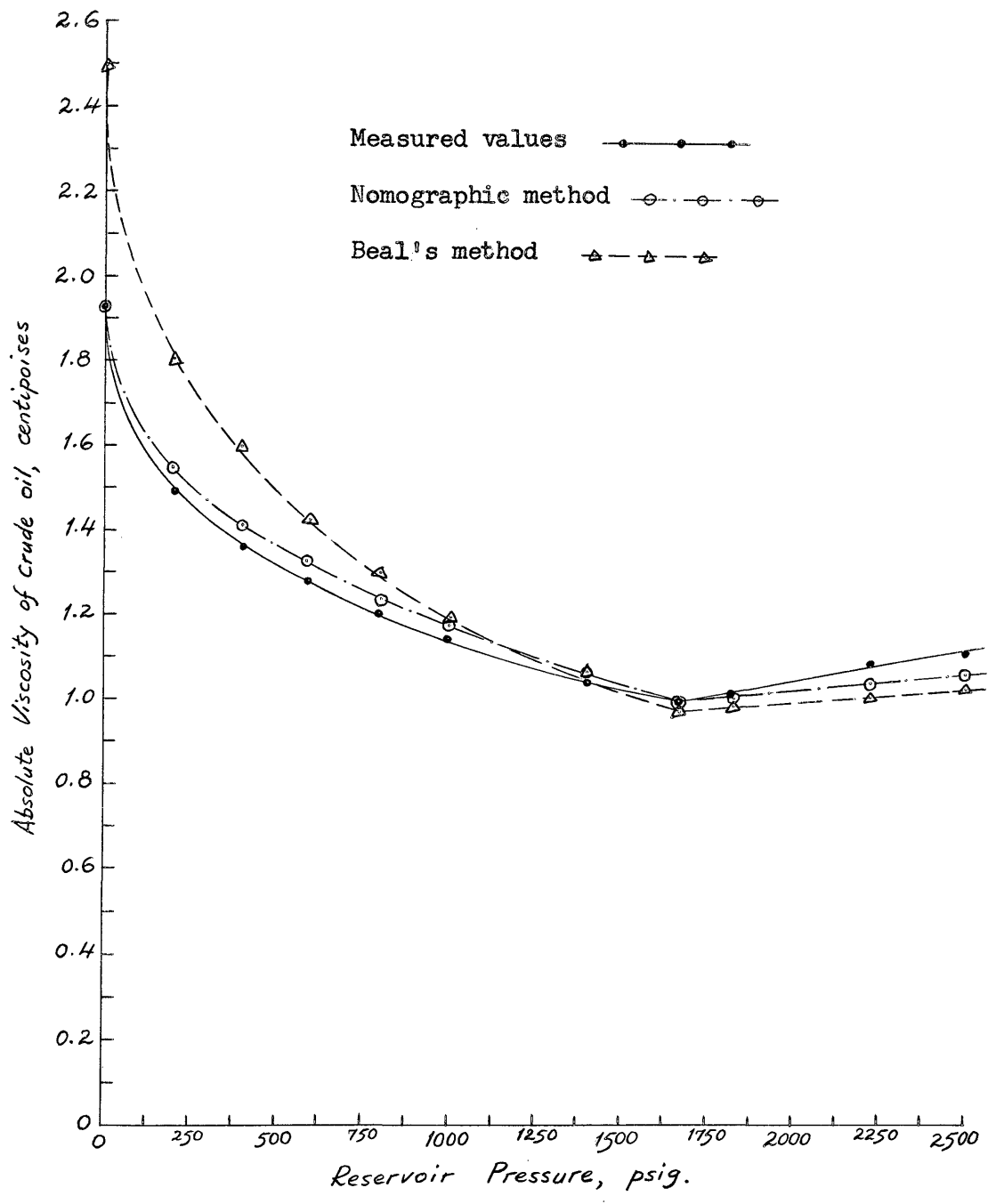


Figure 26. Comparison of measured crude oil viscosity data with predicted values for a Rocky Mountain region oil sample.

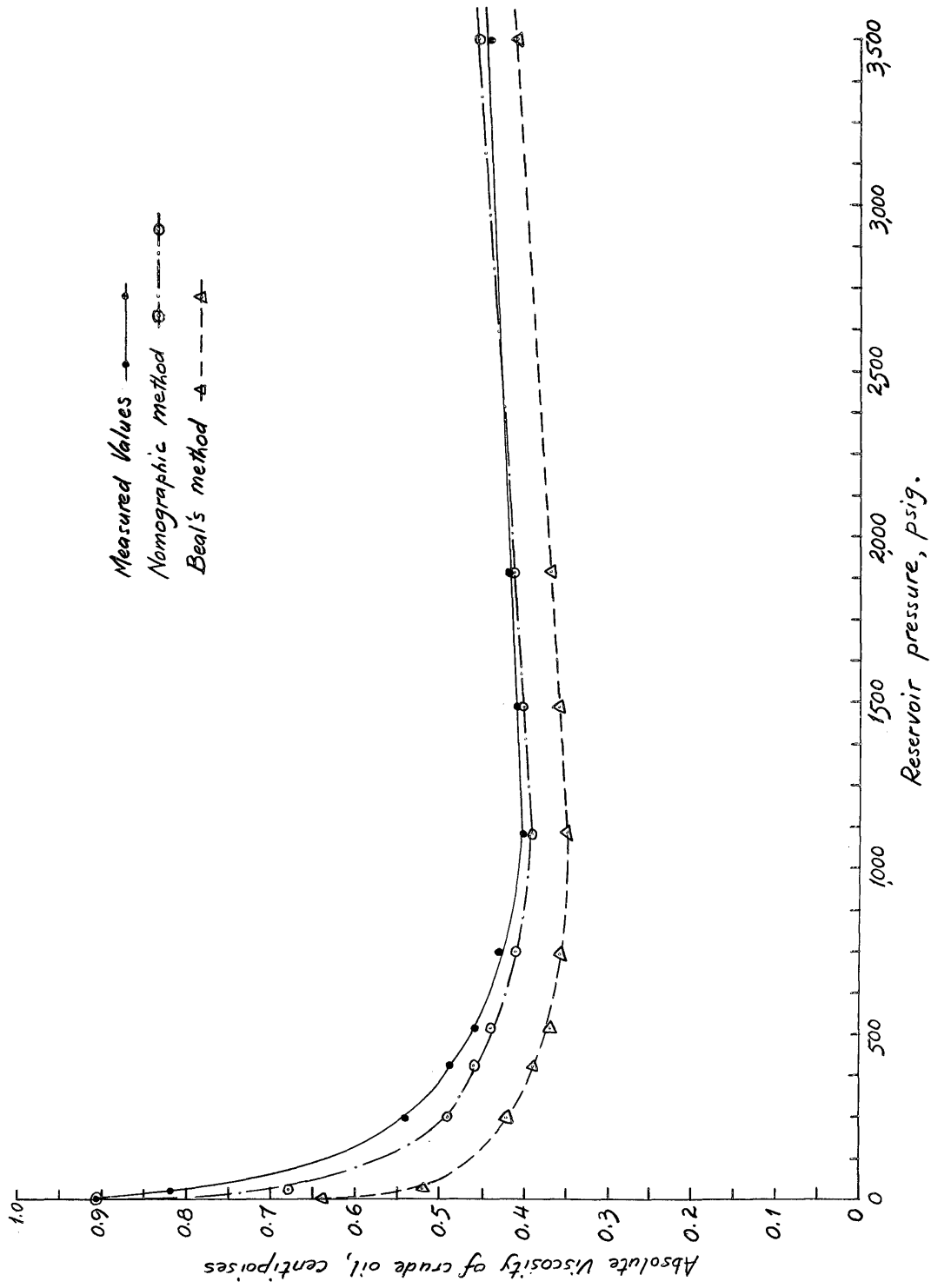


Figure 27. Comparison of measured crude oil viscosity data with predicted values for Oil Sample 1.

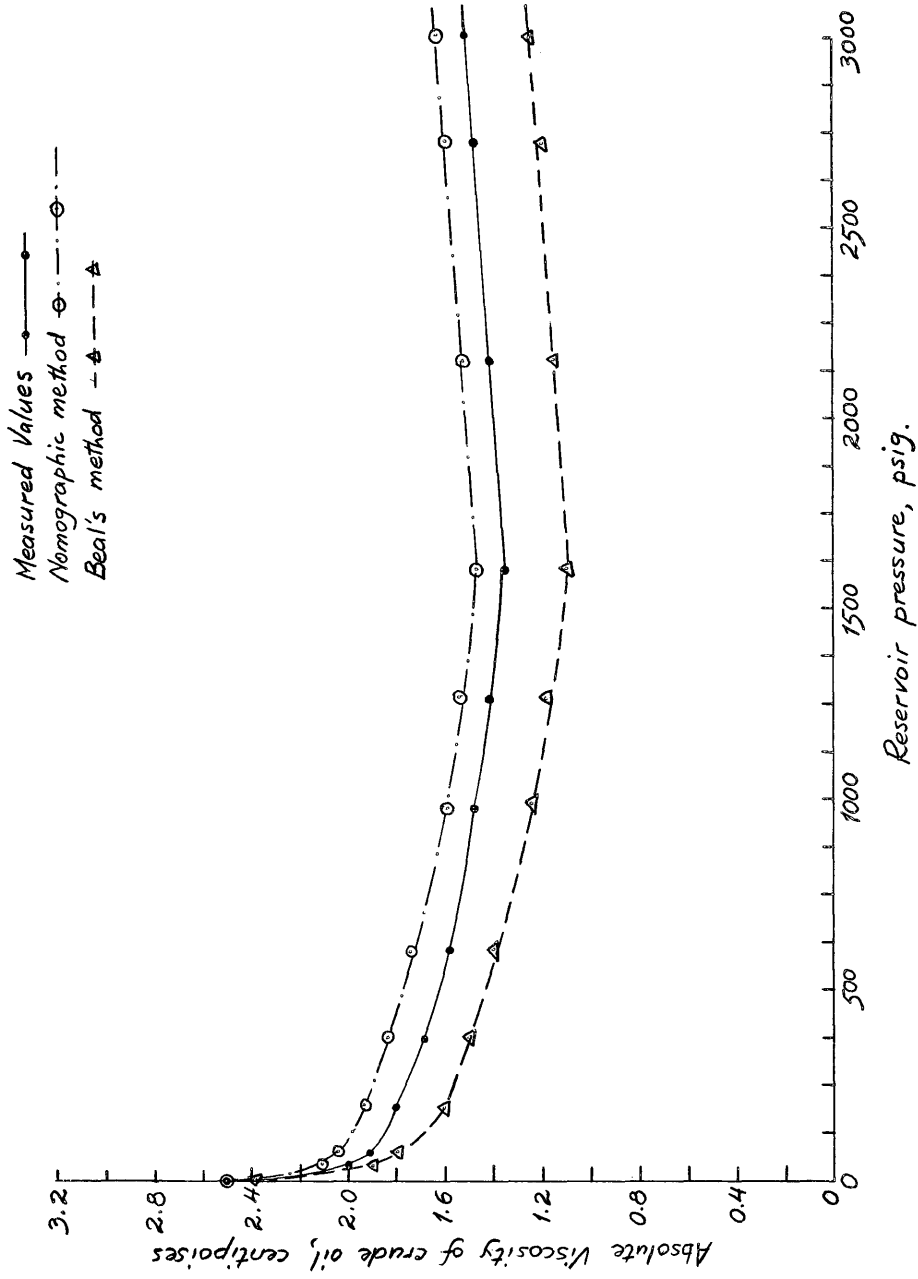


Figure 28. Comparison of measured crude oil viscosity data with predicted values for Oil Sample 23.