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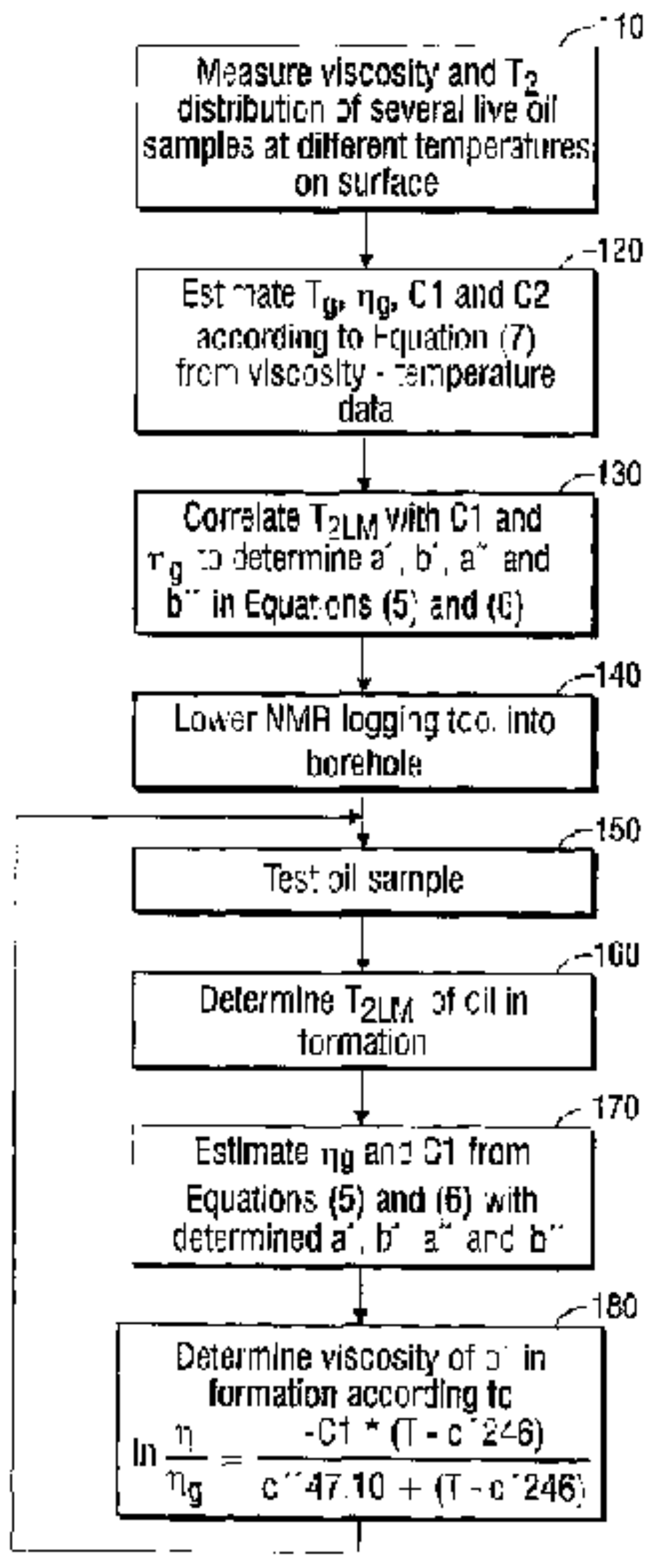
(54) **Titre : METHODE DE DETERMINATION IN SITU DE LA VISCOSITE D'ECHANTILLONS DE PETROLE LOURD AU MOYEN DE MESURES DU TEMPS DE RELAXATION EN RESONANCE MAGNETIQUE NUCLEAIRE**

(54) **Title: METHODS FOR DETERMINING IN SITU THE VISCOSITY OF HEAVY OIL USING NUCLEAR MAGNETIC RESONANCE RELAXATION TIME MEASUREMENTS**



(57) **Abrégé/Abstract:**

The viscosity η (in centipoise) of a heavy oil sample is determined according to an equation of the form $\ln\frac{\eta}{\eta_g} = \frac{-C1*(T-c'246)}{c''47.10+(T-c'246)}$ where T is the temperature of the heavy oil, T_{2LM} is the logarithmic mean of the T_2 distribution of the sample obtainable from nuclear magnetic resonance (NMR) measurements, $c' = 1.0 \pm .05$, $c'' = 1.0 \pm .04$, η_g is the glass transition temperature viscosity of the heavy oil and a function of T_{2LM}, and C1 is a variable which is a constant for the heavy oil and is a function of T_{2LM}. Both C1 and η_g are considered functions of certain NMR values associated with the heavy oil sample, with ηg and C1 preferably estimated by empirically fitting data to the equations $\ln T_{2LM} = a' + b' \ln \eta_g$ and $\ln T_{2LM} = a'' + b''C1$, where a', b', a'' and b'' are constants.

ABSTRACT OF THE DISCLOSURE

The viscosity η (in centipoise) of a heavy oil sample is determined according to an equation of the form $\ln\frac{\eta}{\eta_g}=\frac{-C1*(T-c'246)}{c''47.10+(T-c'246)}$, where T is the temperature of the heavy oil, T_{2LM} is the logarithmic mean of the T_2 distribution of the sample obtainable from nuclear magnetic resonance (NMR) measurements, c' = 1.0 ± .05, c" = 1.0± .04, η_g is the glass transition temperature viscosity of the heavy oil and a function of T_{2LM}, and C1 is a variable which is a constant for the heavy oil and is a function of T_{2LM}. Both C1 and η_g are considered functions of certain NMR values associated with the heavy oil sample, with η_g and C1 preferably estimated by empirically fitting data to the equations $\ln T_{2LM} = a' + b' \ln \eta_g$ and $\ln T_{2LM} = a'' + b''C1$, where a', b', a" and b" are constants.

METHODS FOR DETERMINING IN SITU THE VISCOSITY OF HEAVY OIL USING NUCLEAR MAGNETIC RESONANCE RELAXATION TIME MEASUREMENTS

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The invention relates broadly to the investigation of geological formations. More particularly, this invention relates to in situ methods of determining the viscosity of heavy oils using nuclear magnetic resonance (NMR) techniques.

Description of Related Art

[0002] Most of the world's oil reservoirs contain heavy and viscous hydrocarbons which are difficult and costly to produce. Heavy oil viscosity is one of the few criteria available to assess production economics by helping predict if cold production will yield economic production rates, or if thermal processes will be required to reduce the oil viscosity to achieve the required production rates. If cold production is selected, viscosity is again used to help determine whether vertical or horizontal wells should be used. Viscosity data are also used to adjust cold production exploitation strategies if the production rates are significantly lower than expected.

[0003] The use of NMR techniques has been known to provide a good correlation between viscosity and NMR relaxation time for relatively light oils. However, such techniques fail for highly viscous oils (heavy oils).

[0004] More particularly, NMR relaxation time of bulk fluids is sensitive to the viscosity and temperature due to the dependence of rotational and translational correlation times of fluids. Presently in the petroleum industry, there are three widely used correlations between oil viscosity and the NMR logarithmic mean of the spin-spin relaxation time distribution:

$$T_{2LM} = \frac{1200}{\eta^{0.9}} \quad \text{(Straley-Kleinberg-Vinegar correlation)} \qquad (1)$$

$$T_{2LM} = 7.13\frac{T}{\eta} \quad \text{(Zega-Zhange correlation)} \qquad (2)$$

$$T_{2LM} = 9.56\frac{T}{\eta} \quad \text{(Lo correlation)} \qquad (3)$$

where η is the viscosity of the oil in centipoise (cp), T is the temperature in degrees Kelvin, and T_{2LM} is the logarithmic mean of the T_2 distribution in milliseconds (msec). Unfortunately, as can be seen from Fig. 1 which plots the viscosity values measured in a lab (using a capillary viscometer) for heavy oil (HO) samples collected from different locations against the viscosities predicted by the correlations set forth above (using a 2 MHz Maran Ultra NMR instrument available from Oxford Instruments plc of Abingdon, Oxon, United Kingdom), none of the above expressions provided a good correlation.

BRIEF SUMMARY OF THE INVENTION

[0005] According to the invention, the viscosity η (in centipoise) of a heavy oil sample (i.e., an oil having an API gravity of 22.3 degrees or less) is determined according to an equation of the form

$$\ln\frac{\eta}{\eta_g}=\frac{-C1*(T-c'246)}{c''47.10+(T-c'246)} \quad (4)$$

where T is the temperature in degrees Kelvin of the heavy oil sample, C1 is a constant associated with the oil sample, c' is a constant between 0.95 and 1.05 (preferably 1.0), c'' is a constant between 0.96 and 1.04 (preferably 1.0), and η_g is the viscosity of the heavy oil at its glass transition temperature.

[0006] According to one aspect of the invention, both C1 and η_g are considered functions of certain NMR values associated with the heavy oil sample. More particularly, both C1 and η_g are considered functions of the logarithmic mean of the measurable T_2 distribution of the heavy oil sample. The glass transition temperature viscosity η_g can be estimated by empirically fitting data to the equation

$$\ln T_{2LM}=a'+b'\ln\eta_g \quad (5)$$

while C1 can be estimated by empirically fitting data to the equation

$$\ln T_{2LM}=a''+b''\ln C1 \quad (6)$$

[0007] In a preferred embodiment, a' = 6.16 and b' = -0.18, while a" = 6.34 and b" = -0.16. Depending upon the particular NMR experiment conducted and the equipment utilized, a', b', a", and b" may change somewhat, thereby affecting the determinations of C1 and η_g. However, the resulting change in the determination of the value of the viscosity η will be small.

[0008] According to another aspect of the invention, the viscosity of a heavy oil sample is determined in situ in a formation by placing an NMR tool into a borehole in the formation, conducting an NMR experiment on the formation's heavy oil sufficient to generate a T_2 distribution, and using the T_2 distribution obtained from the experiment, determining the viscosity of the heavy oil sample according to an equation of the form of Equation (4) above.

[0009] Objects and advantages of the invention will become apparent to those skilled in the art upon reference to the detailed description taken in conjunction with the provided figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Fig. 1 is a double logarithmic plot showing predicted viscosities of heavy oil samples using prior art correlations versus the measured viscosities.

[0011] Fig. 2 is a graph showing the relationship between the viscosity and temperature of fourteen different heavy oil samples.

[0012] Fig. 3 is a logarithmic plot showing the viscosity of a heavy oil sample as a function of the inverse of its temperature and two different curves fit to the data.

[0013] Fig. 4 is a plot showing the correlation of the natural log of T_{2LM} at 80 °C and the natural log of the viscosity of thirteen heavy oil samples at their glass transition temperatures.

[0014] Fig. 5 is a plot showing the correlation of the natural log of T_{2LM} at 80 ^{o}C and the constant C1 for thirteen heavy oil samples.

[0015] Fig. 6 is a double logarithmic plot comparing measured viscosities of heavy oil samples at different temperatures and the predicted viscosities according to the invention.

[0016] Fig. 7 is a flow diagram of the method of one aspect of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Before discussing the methods of the invention, a theoretical understanding is useful of how a relationship between viscosity of heavy oil samples and NMR test results can be generated.

[0018] A starting point for the theoretical understanding does not relate to heavy oils at all, but rather deals with the relationship of viscosity and temperature of simple liquids. The temperature dependence of the viscosity of a liquid is readily observable as the viscosity of the liquid tends to fall (i.e., its fluidity increases) as the temperature of the liquid increases. In the 1890's, Arrhenius showed that there is a logarithmic relationship between viscosity and inverse temperature in many fluids. While this logarithmic relationship well describes certain liquids, it was found that the Arrhenius equations did not describe polymers, such as plastics, which underwent a "glass transition", a pseudo-second order transition in which melt plastics become rigid on cooling. A model based on free volume theory has been used for polymers. In the free volume model, the molecules are thought to be confined in a space surrounded by their immediate neighbors and perform considerable displacement within it due to an occasional fluctuation in density. The translation of the molecules across the void is a result of activation rather than a result of redistribution of the free volume within the liquid. The free volume of a given molecule is the volume within its surroundings less the volume of the molecule and it should exceed a critical volume just large enough to permit another molecule to jump in after the displacement.

[0019] In 1950, Flory and Fox postulated that glass expands at constant free volume, i.e., that glassy expansion, which is much weaker than melt/rubber thermal expansion, involves expansion of the occupied volume of the sample at constant free volume. By inducing the dependence of the free volume υ_f on temperature T, the molecular motion results in a viscosity η for the polymer which can be described by the William–Landel-Ferry (WLF) equation (Williams, M. et al., *Journal of the American Chemical Society* 77, 3701 (1955):

$$\ln\frac{\eta}{\eta_g}=\frac{-C1*(T-T_g)}{C2+(T-T_g)} \tag{7}$$

where T is the temperature in degrees Kelvin of the polymer, T_g is the glass transition temperature of the polymer, C1 and C2 are constants for the polymer, and η_g is the viscosity of the polymer at its glass transition temperature. According to Doolittle (Doolittle, A. K., *Journal of Applied Physics*, 22, 1471 (1951), $C1=\upsilon^*/\upsilon_g$ where υ^* is the required free volume to perform a jump and υ_g is the free volume at the glass transition temperature T_g. In addition, $C2 = (\upsilon_g/\upsilon_m)\Delta\alpha$, where υ_m is the fictive volume of the molecule at absolute zero without free volume, and $\Delta\alpha$ is the difference of the thermal expansion coefficients in the glassy and the liquid phases, respectively.

[0020] Although Equation (7) was obtained empirically to describe the temperature dependence of viscosity of polymer materials, to the best of Applicants' knowledge, it has never been used in conjunction with heavy oils in geological formations. As will be discussed in more detail hereinafter, the Applicants determined that for heavy oils, the values of C2 and T_g do not vary widely and may be assumed to be constant values, whereas the values of C1 and η_g do vary and mast be determined. In addition, from the above-discussed physical meanings, it is believed that C1 and η_g are related to the flow properties of the substance being tested. From Equation (7), it appears that the larger C1 and η_g are, the more viscous the liquid is; i.e., the value for Equation (7) gets larger with a larger C1 and a larger η_g.

[0021] As set forth above, relationships between the NMR T_2 spin-spin relaxation time and the viscosity of lighter oils have been posited for some time. In general, the NMR T_2 time increases with increasing η_g and with decreasing C1. Thus, it is posited that η_g and C1 may be estimated from NMR measurements according to linear equations such as Equations (5) and (6) set forth above; i.e., $\ln T_{2LM} = a' + b' \ln \eta_g$ and $\ln T_{2LM} = a'' + b'' \ln C1$, where T_{2LM} is the logarithmic mean of the T_2 distribution and is given by

$$T_{2LM} = \left(\prod_{i=1}^{n} T_{2i}^{n_i} \right)^{1 / \sum_i n_i}, \text{ or } \quad \ln(T_{2LM}) = \frac{\sum_i n_i \ln(T_{2i})}{\sum_i n_i} \qquad (8)$$

where n_i is the mole of proton corresponding to the i-th component with T_2 relaxation time in the T_2 distribution. Thus, generally, using NMR measurements, in situ determinations of η_g and C1 may be estimated using Equations (5) and (6). From those estimations and from Equation (7), an in situ estimation (determination) of the viscosity of the heavy oil sample can be made at any temperature.

[0022] Given the above understanding of how the viscosity of heavy oil can be determined from NMR test results, fourteen heavy oil samples were collected from different regions of the world. Their viscosities at different temperatures were measured with a capillary viscometer. Table 1 presents the viscosity data (all numbers in centipoise) of the fourteen heavy oils at eight different temperatures:

TABLE 1

Samples	10°C	20°C	25°C	50°C	80°C	120°C	160°C	200°C
HO#1	x	73,000	37,400	2908	372	64.5	21.4	10.0
HO#2	249,408	x	30,956	2111	259	45.8	14.8	6.8
HO#4	140,151	x	17,805	1473	198	37.6	12.1	5.9
HO#5	316,417	x	35,978	2722	356	57.0	16.8	7.9
HO#6	x	x	14,816	1322	193	38.6	13.1	6.4
HO#7	z	x	572,472	19,272	1370	145.0	32.6	13.0
HO#8	x	x	5415	530	82	17.2	6.2	3.0
HO#9	x	x	1290	194	42	11.0	4.7	2.7
HO#10	x	x	11,514	844	109	20.7	7.0	3.6
HO#11	x	x	41,051	2259	222	34.2	10.4	4.8
HO#12	z	x	289,067	11,886	903	107.0	26.5	10.9
HO#13	x	x	45,946	2827	325	53.0	15.7	7.3
HO#14	z	x	550,107	19,202	1358	134.0	29.5	10.9
HO#15	21,435	x	3810	507	94.9	22.4	8.36	4.40

x = not determined. z = not measurable.

[0023] Fig. 2 is a graph showing the relationship between the viscosity and temperature of the fourteen different heavy oil samples. Fig. 2 graphs the natural log of the viscosity (taken from the data set of Table 1) of the heavy oil samples against the inverse of the Kelvin temperature at which the viscosity data was obtained.

[0024] The viscosity data at different temperatures set forth in Table 1 were fitted to Equation (7) in order to find the glass transition temperature $T_{g,}$ viscosity at the glass transition temperature $\eta_{g,}$ and C1 and C2 by a least squares fitting technique. As a result, as seen in Table 2, the following parameters were obtained for the samples:

TABLE 2

HO Sample	T_g (°K)	$\ln(\eta_g)$	C1	C2
1	244	25.85	28.30	45.85
2	252	22.71	25.39	48.59
4	246	23.70	26.54	47.38
5	241	26.46	29.56	48.73
6	246	23.00	25.59	47.51
7	249	30.63	34.05	47.26
8	245	21.90	25.12	47.30
9	242	19.30	21.95	45.53
10	254	21.06	24.05	46.65
11	253	24.27	27.49	45.97
12	247	30.49	33.82	45.52
13	251	23.89	26.75	48.76
14	244	32.65	36.66	48.06
15	235	23.35	26.15	46.23

Average	246	24.95	27.96	47.10

[0025] From Table 2 it will be appreciated that the values of C2 and T_g do not vary widely across the various heavy oil samples. More particularly, it is seen that for the fourteen samples, C2 varies from a low value of 45.52 to a high value of 48.76, with the average being 47.10, and thus the variation (high or low) from the average is typically 4% or less. Thus, it is reasonable to take C2 as a constant. The constant C2 is preferably set equal to 47.10 ± 4%, and more preferably set equal to 47.10. Similarly, it is seen that for the fourteen samples, the glass transition temperature T_g (°K) varies from a low value of 235 to a high value of 254, with the average being 246, and thus the variation (high or low) from the average it typically 5% or less. Thus, it is reasonable to take T_g as a constant. The constant T_g is preferably set equal to 246 ± 5%, and more preferably set equal to 246.

[0026] With T_g and C2 set as constants, it will be appreciated that Equation (7) can be rewritten as

$$\ln\frac{\eta}{\eta_g}=\frac{-C1*(T-c'246)}{c''47.10+(T-c'246)} \qquad (9)$$

where c' is a constant between 0.95 and 1.05 (i.e., 1.0 ± 5%) and preferably 1.0, and c" is a constant between 0.96 and 1.04 (i.e., 1.0 ± 4%) and preferably equal to 1.0. Equation (9), with c' = 1.0 and c" = 1.0 was employed to predict the viscosities of heavy oil sample #1 at different temperatures. The predicted viscosities are compared to the measured viscosities in Fig. 3 (which also shows the straight line prediction of the Arrhenius equation) and provides an excellent fit.

[0027] While C2 and T_g may be taken as constants, it will be appreciated from Table 2 that the variations in $\ln(\eta_g)$ and C1 (which each range from about 20% to 30%) are much greater, and that neither should be considered a constant for heavy oil. In order to be able to find in situ values for the variables $\ln(\eta_g)$ and C1, relationships were developed between the variables and NMR values that can be determined downhole. To establish the relationships, each of the fourteen heavy oil samples was pressed into temperature controlled ceramic tubes for nuclear magnetic resonance testing. NMR experiments were conducted at a Larmor frequency of 2MHz on a Maran Ultra NMR instrument. Proton spin-lattice relaxation time (T_1) was measured at 10, 15, 25, 50, 80 and 110 °C by the saturation recovery technique. Proton spin-spin relaxation times (T_2) were determined at the above-stated temperatures, and a modified Carr-Purcell-Gill-Meiboom (CPGM) sequence ($\pi/2$-τ-π-τ-echoes-5T_1-$\pi/2$-τ-π-τ-echoes-5T_1) was used with $\tau = 100$ μs and a cycle time greater than 5 times T_1. The T_2 distribution was recovered by the inverse Laplace transform of time domain CPGM echo signals. The logarithmic mean of the T_2 distribution (T_{2LM}) was determined according to Equation (8) above.

[0028] With the T_{2LM} determinations as well as the values for $\ln(\eta_g)$ and C1 established for the heavy oil samples, thirteen of the samples (excluding heavy oil sample #1) were evaluated to obtain the empirical determinations for the constants in Equations (5) and (6): $\ln T_{2LM} = a' + b'\ln\eta_g$; and $\ln T_{2LM} = a'' + b''C1$. A best fit yielded values of $a' = 6.16$, $b' = -0.18$, $a'' = 6.34$ and $b'' = -0.16$. The correlation between T_{2LM} and $\ln(\eta_g)$ is seen in Fig. 4 ($R^2 = 0.84$), while the correlation between T_{2LM} and C1 is seen in Fig. 5 ($R^2 = 0.81$). It will be appreciated that depending upon the particular NMR experiment conducted and the equipment utilized, a', b', a", and b" may change somewhat, thereby affecting the determinations of C1 and η_g. However, the resulting change in the determination of the value of the viscosity η will be small. The viscosity of heavy oil sample #1 was then predicted from Equations (5), (6), and (9) ("leave-one-out" method).

[0029] The results in Fig. 6 were obtained using the above-referenced "leave-one-out" method whereby each sample was removed from the database of fourteen heavy oil samples and its viscosity was predicted from the remaining thirteen heavy oil samples in the database according to Equations (5), (6), and (9). The predicted viscosities of fourteen of the heavy oil samples at various temperatures were plotted in a logarithmic-logarithmic plot against the measured viscosity of the heavy oil samples. As seen in Fig. 6, the predicted viscosities matched well with the measured viscosities.

[0030] Turning now to Fig. 7, a flow diagram of a method in accordance with an aspect of the invention is shown. As shown in Fig. 7, at step 110 the viscosity T_2 distribution of several live oil samples are measured at different temperatures at the surface. Next, at step 120, the glass transition temperature T_g, viscosity at the glass transition temperature η_g, and constants C1 and C2 are estimated according to Equation (7). At step 130 the logarithmic mean of the T_2 distribution, T_{2LM}, is correlated with η_g and C1 to determine constants a', b', a" and b" in Equations (5) and (6). At step 140 NMR logging tool is lowered in a borehole traversing an earth formation. The logging tool may be any tool capable of making T_2 measurements of oil in the formation such as the CMR-Plus tool available from Schlumberger Technology Corporation of Sugar Land, Texas, USA. At step 150, an oil sample at a location in the formation is subjected to testing by the NMR logging tool. At step 160, using the results of the testing, a determination of a T_{2LM} value is made for that sample. Then, at step 170, using the T_{2LM} value and Equations (5) and (6), estimated values for the glass transition temperature viscosity η_g and C1 are obtained. Preferably, at step 170, values of a' = 6.16, b' = -0.18, a" = 6.34 and b" = -0.16 are utilized. However, it will be appreciated that other values could be used. Regardless, at step 180, a determination (estimation) of the viscosity of the in situ oil sample is made using the estimated values for the glass transition temperature viscosity η_g and C1, the temperature of the oil sample, and an equation of the form of Equation (9). Steps 150, 160, 170, and 180 may be repeated for any number of oil samples in the formation. The method of Fig. 7 is particularly useful for determining in situ the viscosity of heavy oils in a formation.

[0031] Several embodiments of a method of determining in situ the viscosity of heavy oils have been described and illustrated herein. While particular embodiments of the invention have been described, it is not intended that the claims be limited thereto, as it is intended that the invention be as broad in scope as the art will allow and that is consistent with the description. Thus, while it was disclosed that a particular number (fourteen) of oil samples were used to generate values for certain constants used in finding parameters η_g and C1, it will be appreciated that other numbers of samples could be utilized. Also, while a particular NMR tool was described for carrying out the methods, it will be understood that other tools could be used, provided the tool is capable of generating a determination of the T_2 distribution. Similarly, while a particular NMR sequence (modified CPGM) was described as being utilized in conjunction with correlating the glass temperature viscosity and the constant C1 to NMR measurements in order to find particular values for a', b', a", and b", it will be appreciated that other sequences could be utilized which would result in other values being utilized. It will therefore be appreciated by those skilled in the art that yet other modifications could be made to the particular embodiments described without deviating from its scope as claimed.

CLAIMS:

1. A method for determining the viscosity of a heavy oil located in a formation traversed by a borehole, comprising:

a) placing a nuclear magnetic resonance (NMR) logging tool in the borehole;

b) making T_2 measurements of the heavy oil in situ in the borehole with the NMR logging tool; and

c) determining the viscosity η of the heavy oil according to

$$\ln\frac{\eta}{\eta_g} = \frac{-C1*(T-c'246)}{c''47.10+(T-c'246)}$$

, where T is the temperature of the heavy oil, T_{2LM} is the logarithmic mean of the T_2 distribution of the heavy oil obtainable from said T_2 measurements, c’ is a constant between 0.95 and 1.05, c” is a constant between 0.96 and 1.04, η_g is the glass transition temperature viscosity of the heavy oil and a function of T_{2LM}, and C1 is a variable which is a constant for the heavy oil and is a function of T_{2LM}.

2. A method according to claim 1, wherein c' has a value of 1.0 and c” has a value of 1.0.

3. A method according to claim 2, further comprising determining η_g according to $\ln T_{2LM}$ = a’ + b” $\ln\eta_g$, where a’ and b’ are constants.

4. A method according to claim 3, further comprising determining C1 according to $\ln T_{2LM}$ = a” + b” lnC1, where a” and b” are constants.

5. A method according to claim 4, further comprising finding a', b', a" and b" empirically by testing a plurality of heavy oil samples.

6. A method according to claim 4, wherein a' = 6.16, b' = -0.18, a" = 6.34 and b" = -0.16.

7. A method according to claim 1, further comprising:

prior to locating said NMR logging tool in the borehole, obtaining a plurality of samples of heavy oil from at least one formation;

testing said plurality of samples of heavy oil to obtain glass transition temperatures of said heavy oil samples; and

averaging said glass transition temperatures to obtain an average, wherein c'246 equals said average.

8. A method according to claim 7, further comprising:

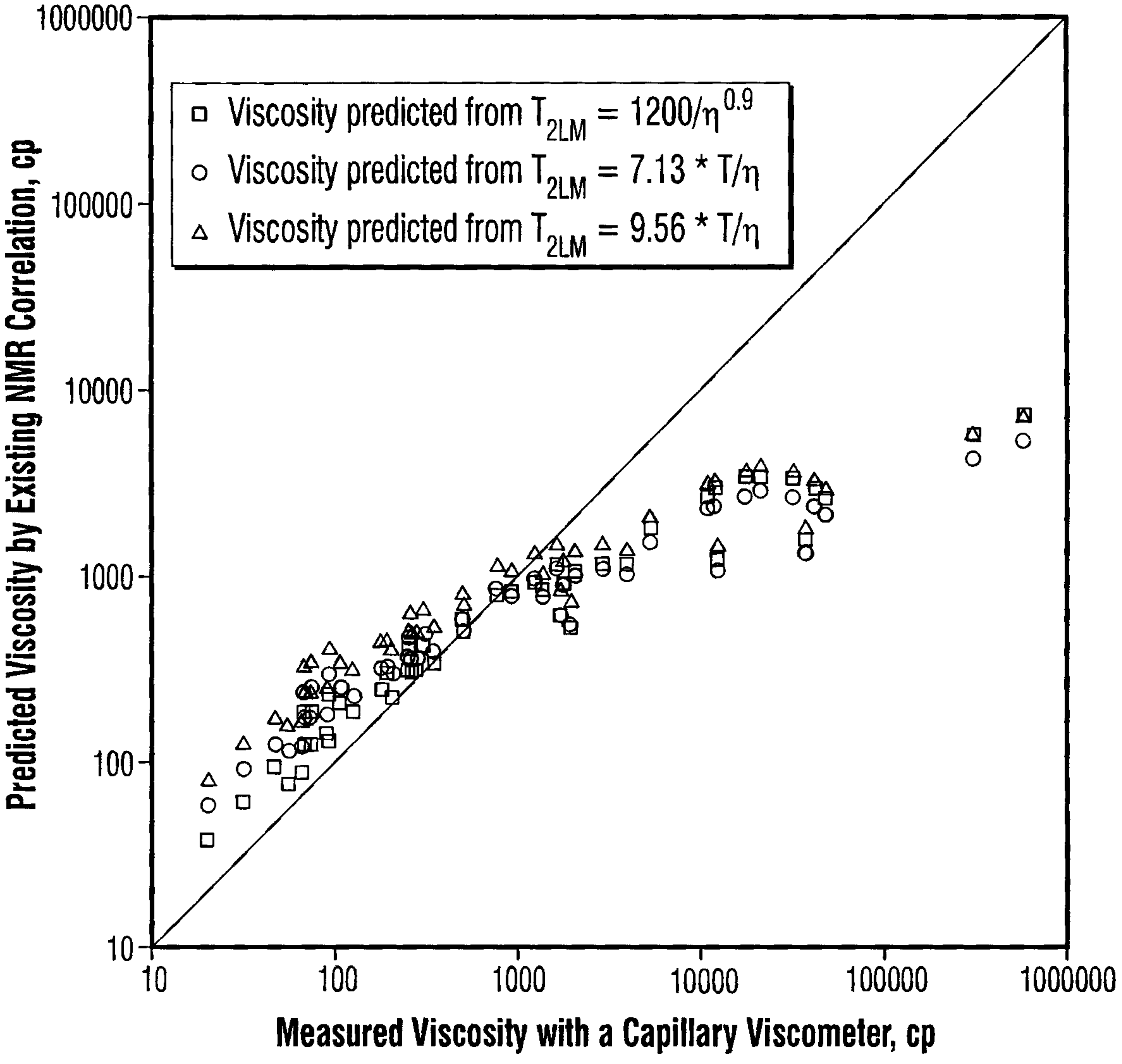
testing said plurality of samples of heavy oil to obtain a glass transition viscosity value for each heavy oil sample at its glass transition temperature;

measuring viscosity values for each sample of heavy oil at a plurality of different temperatures; and

using said viscosity values at different temperatures and said glass transition viscosity values, and said glass transition temperatures, finding values for a variable C2;

averaging said C2 values to find a C2 average, wherein c”47.10 equals said C2 average.

9. A method according to claim 1, further comprising moving said NMR logging tool in the borehole, wherein making T_2 measurements of the heavy oil in situ comprises making T_2 measurements of multiple samples of heavy oil, and determining the viscosity η of the heavy oil comprises determining the viscosities of the multiple samples of heavy oil.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Viscosity predicted from $T_{2LM} = 7.13 * T/\eta$
Viscosity predicted from $T_{2LM} = 9.56 * T/\eta$
Predicted Viscosity by Existing NMR Correlation, cp
Measured Viscosity with a Capillary Viscometer, cp
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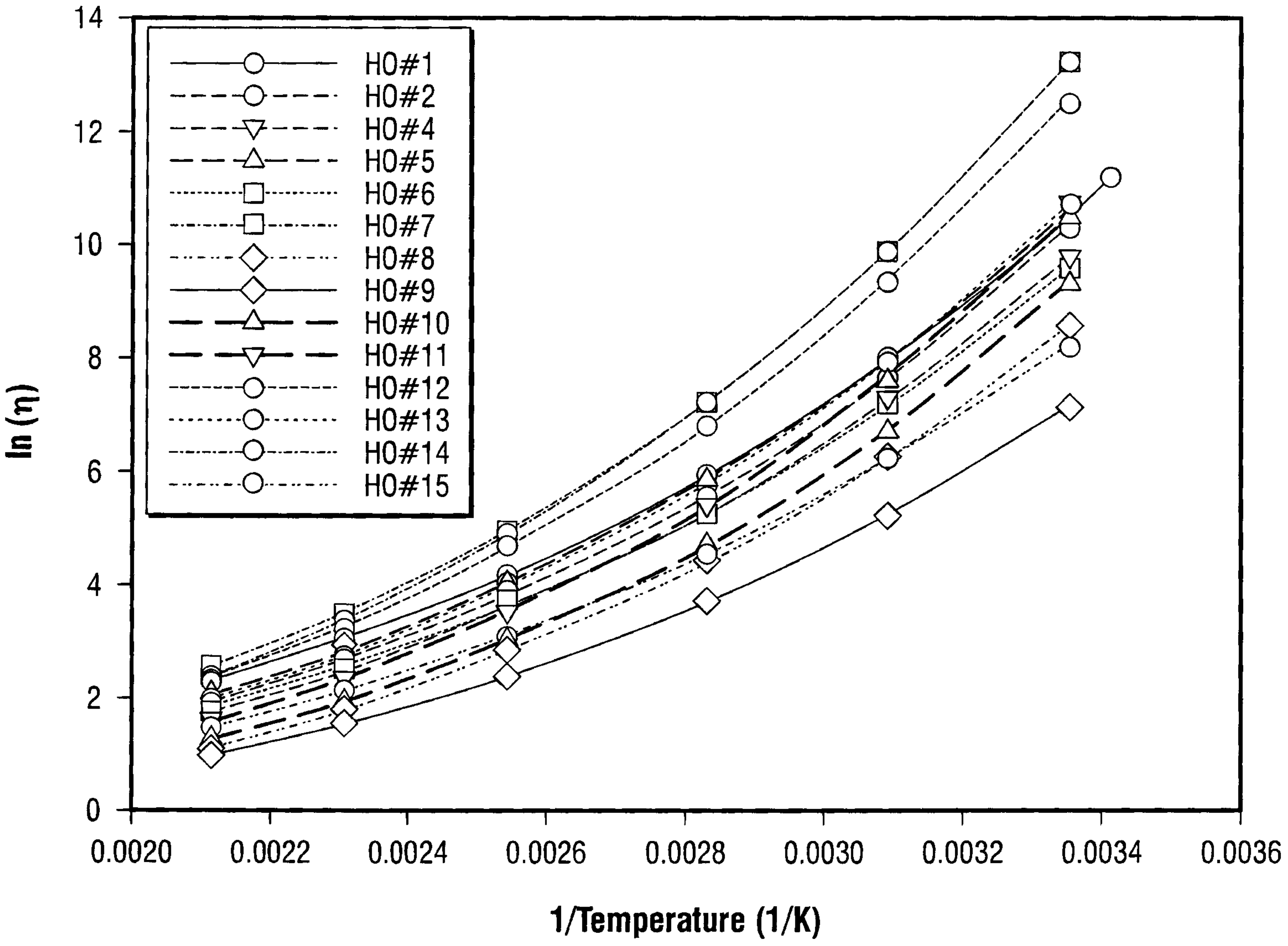
100000
10000
1000
100
10
10
100
1000
10000
100000
1000000

FIG. 1


ln (η)
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12
10
8
6
4
2
0
0.0020
0.0022
0.0024
0.0026
0.0028
0.0030
0.0032
0.0034
0.0036
1/Temperature (1/K)
H0#1
H0#2
H0#4
H0#5
H0#6
H0#7
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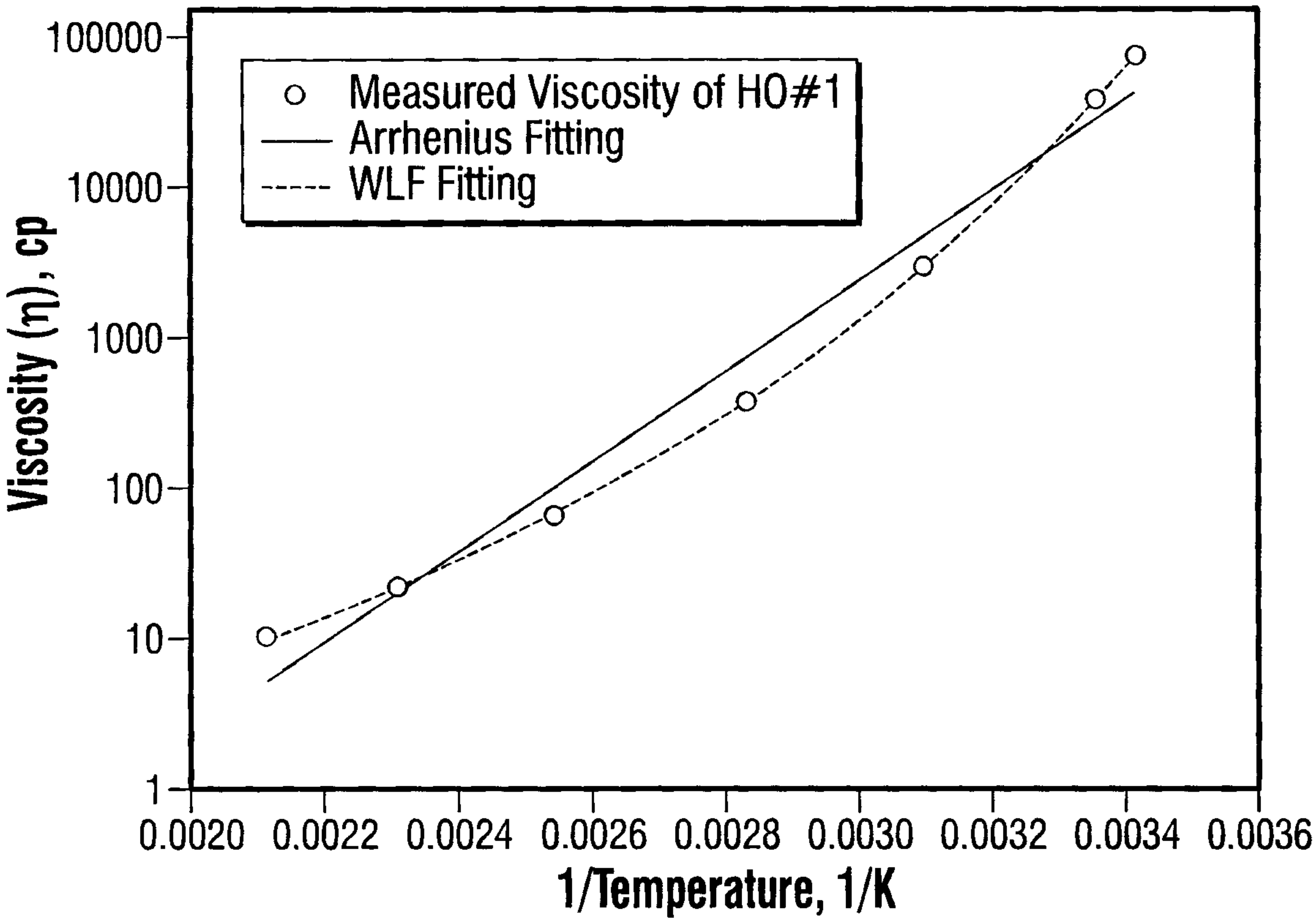
FIG. 2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1000
100
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WLF Fitting
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0.0026
0.0028
0.0030
0.0032
0.0034
0.0036
1/Temperature, 1/K

FIG. 3

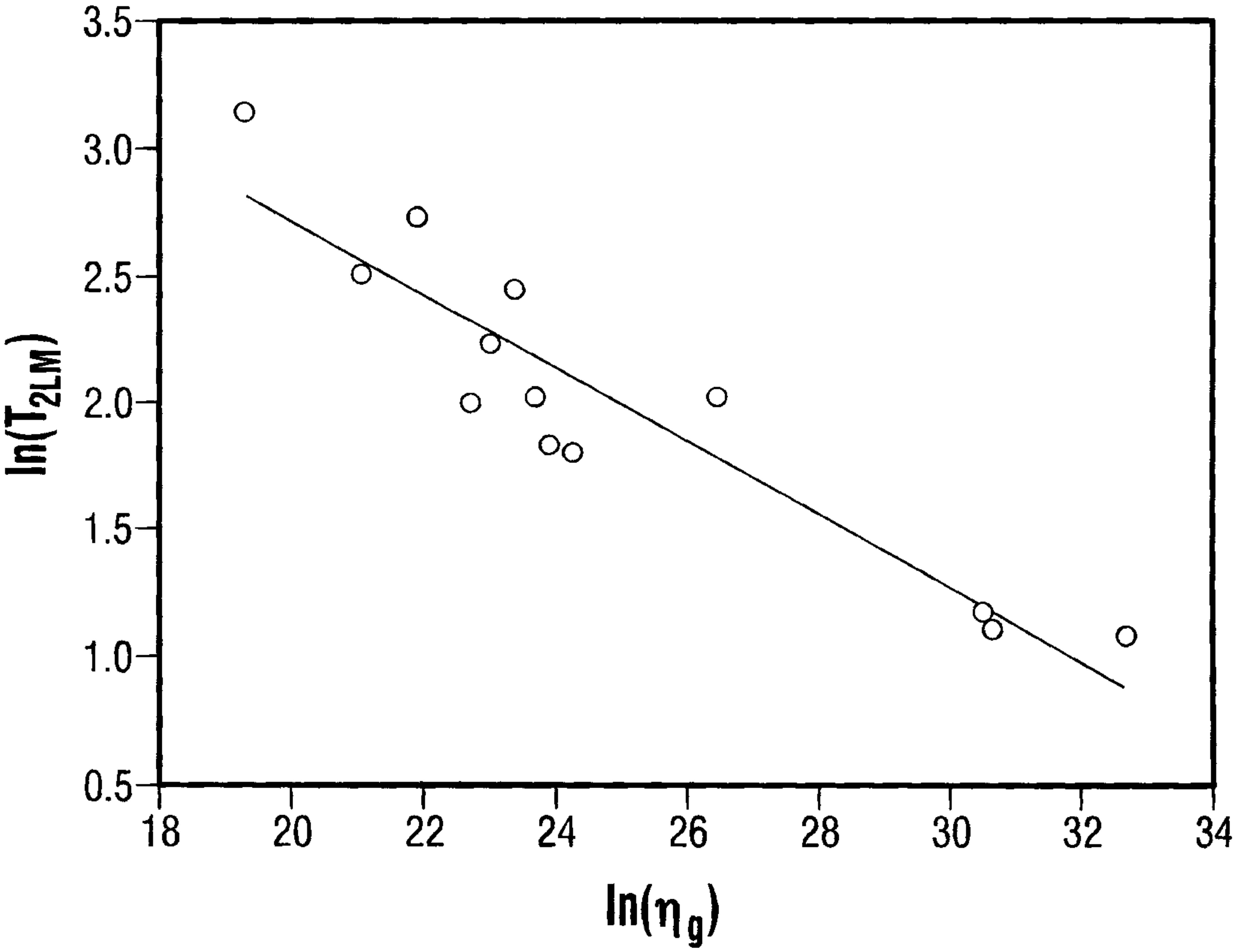

3.5
3.0
2.5
2.0
1.5
1.0
0.5
ln(T2LM)
18
20
22
24
26
28
30
32
34
ln(ηg)

FIG. 4

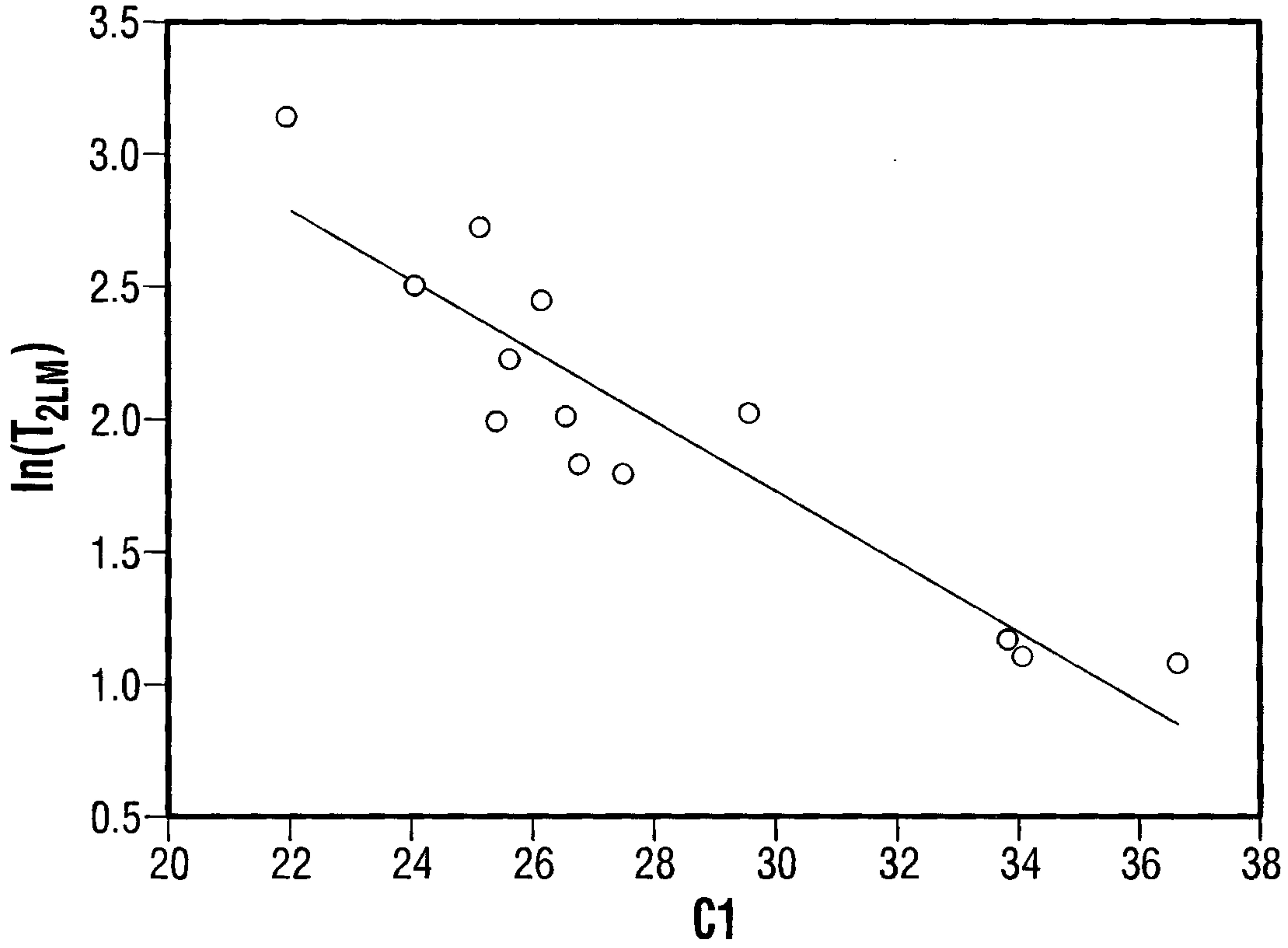

3.5
3.0
2.5
2.0
1.5
1.0
0.5
ln(T_2LM)
20
22
24
26
28
30
32
34
36
38
C1

FIG. 5

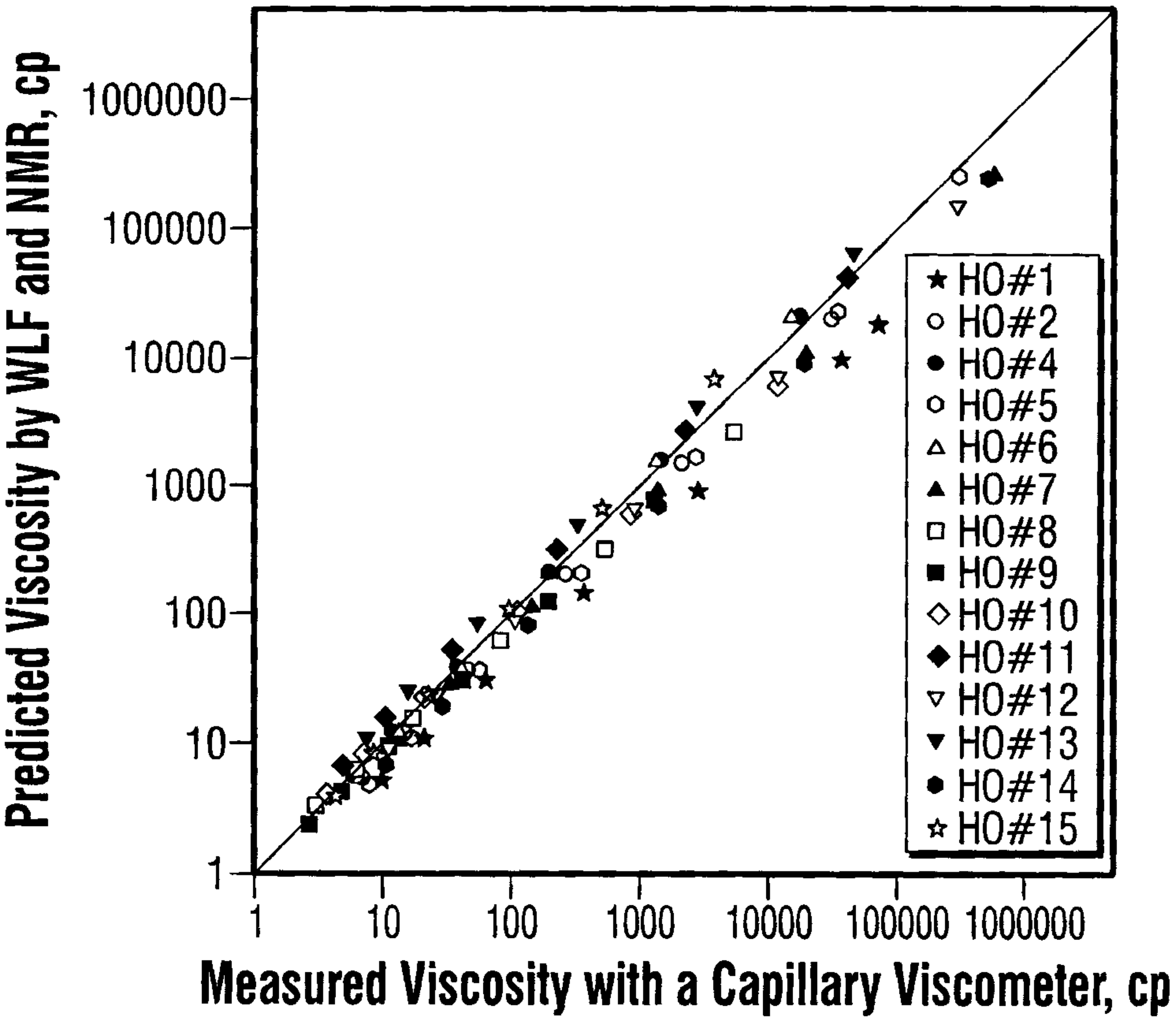

1000000
100000
10000
1000
100
10
1
Predicted Viscosity by WLF and NMR, cp
1
10
100
1000
10000
100000
1000000
Measured Viscosity with a Capillary Viscometer, cp
★ HO#1
○ HO#2
● HO#4
○ HO#5
△ HO#6
▲ HO#7
□ HO#8
■ HO#9
◇ HO#10
◆ HO#11
▽ HO#12
▼ HO#13
⬢ HO#14
☆ HO#15

FIG. 6

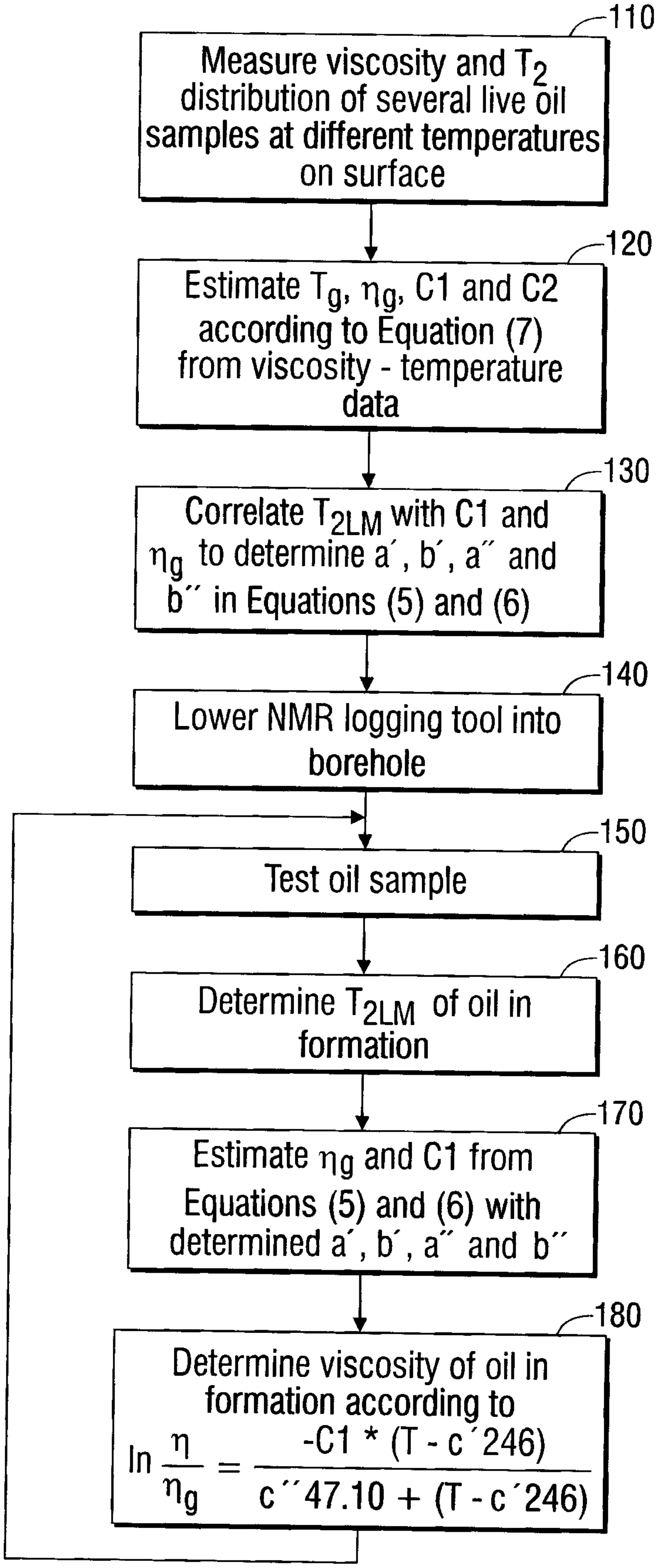
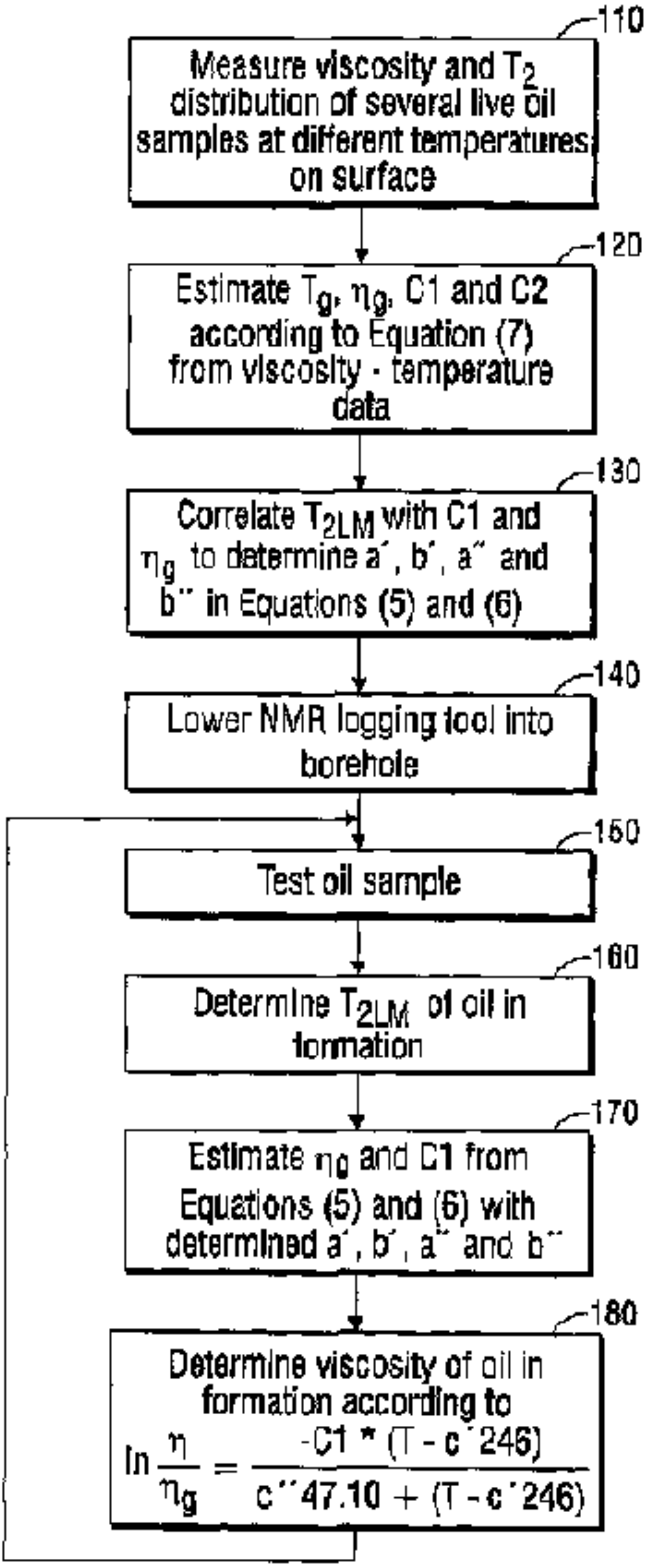

110
Measure viscosity and T_2 distribution of several live oil samples at different temperatures on surface
120
Estimate T_g, η_g, C1 and C2 according to Equation (7) from viscosity - temperature data
130
Correlate T_{2LM} with C1 and η_g to determine a′, b′, a″ and b″ in Equations (5) and (6)
140
Lower NMR logging tool into borehole
150
Test oil sample
160
Determine T_{2LM} of oil in formation
170
Estimate η_g and C1 from Equations (5) and (6) with determined a′, b′, a″ and b″
180
Determine viscosity of oil in formation according to
$\ln \frac{\eta}{\eta_g} = \frac{-C1 * (T - c'246)}{c''47.10 + (T - c'246)}$

FIG. 7


110
Measure viscosity and T_2 distribution of several live oil samples at different temperatures on surface
120
Estimate T_g, η_g, C1 and C2 according to Equation (7) from viscosity - temperature data
130
Correlate T_{2LM} with C1 and η_g to determine a′, b′, a″ and b″ in Equations (5) and (6)
140
Lower NMR logging tool into borehole
150
Test oil sample
160
Determine T_{2LM} of oil in formation
170
Estimate η_g and C1 from Equations (5) and (6) with determined a′, b′, a″ and b″
180
Determine viscosity of oil in formation according to
$\ln\frac{\eta}{\eta_g} = \frac{-C1 * (T - c'246)}{c''47.10 + (T - c'246)}$