National Defence Défense nationale

UNCLASSIFIED

DRES

SUFFIELD REPORT

NO. 390

#59511

THE CHARACTERIZATION OF THE SIMULANT SYSTEM, K125/METHYL SALICYLATE (U)

by

S.J. Armour

and

J.M.G. Ogston

PCN 051 SP

February 1989

DEFENCE RESEARCH ESTABLISHMENT SUFFIELD : RALSTON : ALBERTA

Canada

UNCLASSIFIED

DEFENCE RESEARCH ESTABLISHMENT SUFFIELD
RALSTON, ALBERTA

SUFFIELD REPORT NO. 390

THE CHARACTERIZATION OF THE SIMULANT SYSTEM, K125/METHYL SALICYLATE

by

S.J. Armour and J.M.G. Ogston

PCN 051SP

UNCLASSIFIED

DEFENCE RESEARCH ESTABLISHMENT SUFFIELD
RALSTON, ALBERTA

SUFFIELD REPORT NO. 390

THE CHARACTERIZATION OF THE SIMULANT SYSTEM, K125/METHYL SALICYLATE

by

S.J. Armour and J.M.G. Ogston

ABSTRACT

50|| The thickened simulant system, K125/methyl salicylate (MS), which is used to replace thickened chemical agents for Trialing and Training purposes, has been characterized. The parameters measured, namely density, viscosity and first normal stress difference in steady shear and storage and loss moduli in dynamic mode, can be used to describe and identify the solution system and to predict and correlate its properties. ||

TABLE OF CONTENTS

Page No.

ABSTRACT
TABLE OF CONTENTS
LIST OF FIGURES
LIST OF TABLES

TABLES

FIGURES

LIST OF FIGURES

LIST OF TABLES

DEFENCE RESEARCH ESTABLISHMENT SUFFIELD
RALSTON, ALBERTA

SUFFIELD REPORT NO. 390

THE CHARACTERIZATION OF THE SIMULANT SYSTEM, K125/METHYL SALICYLATE

by

S.J. Armour and J.M.G. Ogston

INTRODUCTION

1. The display of munitions containing thickened chemical agents at Shikhany confirmed earlier intelligence reports that thickened chemical agents constitute an appreciable percentage of the Soviet chemical arsenal. Consequently, an understanding of the properties and characteristics of thickened materials in general and thickened agents in particular, is required to be able to develop adequate defensive equipment and postures for the Canadian Forces. The dissemination characteristics of thickened agents under a variety of release conditions are particularly relevant since this information is required for development of a comprehensive assessment of the hazards that the Canadian Forces might face in a CW environment. Since it is not possible to conduct dissemination trials using actual thickened chemical agents, thickened simulants have been developed which mimic the properties of the agents. These simulants are also used for other trialing applications, such as the development and testing of decontamination equipment and procedures, and for training purposes.

2. The simulant methyl salicylate (MS) thickened with the acryloid polymer K125-EA is used at the Defence Research Establishment Suffield (DRES)(1,2) and at US and UK laboratories (3) for a variety of trialing and training purposes. DRES has used K125/MS solutions in explosive dissemination trials (1) and in high velocity release (aerodynamic break up) studies (2). These solutions are also used in decontamination training and in chemical agent monitor trials as simulants for thickened mustard.

3. Thickened agents and thickened simulants, such as K125/MS, are polymeric solutions and belong to the general class of non-Newtonian solutions. The principal characteristic of a non-Newtonian solution is the dependence of viscosity on shear rate as well as temperature. Non-Newtonian solutions may also exhibit elasticity (first normal stress difference in steady shear). Thus, to be able to identify and describe a solution, its density, viscosity and first normal stress difference in steady shear and storage and loss moduli in dynamic mode must be determined. These parameters, as well as identifying the solution, are used to predict and correlate its behavior (e.g., to predict drop size). Therefore, a knowledge of these parameters is a necessary requirement for any experiments using the solution. Since very little information existed on K125/MS solutions (4), the present study was initiated in 1987 to characterize the system.

MATERIALS AND PREPARATION

4. The solvent, methyl salicylate (MS), was obtained as analytical reagent (lot number 99046/1879) from BDH Chemicals Ltd. It was used directly as obtained from the manufacturer. The physical properties of MS are given in Table I.

5. The current TTCP accepted formulation of K125 (K125-EA lot 3-6326), supplied by Rohm and Haas, was used. It consists of 82 mole percent methyl methacrylate, 12 mole percent ethyl acrylate and 6 mole percent butyl acrylate and has a weight average molecular weight of 2.05×10^6 (determined by gel permeation chromatography) and a polydispersity of 3.41 (5).

6. The solutions were prepared by placing the solvent in a linear polyethylene bottle, adding the polymer, shaking vigorously to disperse the polymer and then rolling on a roller mixer for at least 24 hours at room temperature. Solution preparation took place entirely at room temperature; heat was not applied to hasten dissolution of the polymer. In all cases the resultant solutions were clear, homogenous and colorless.

EXPERIMENTAL

7. The densities of the K125/MS solutions were measured at 25.0°C using an Anton Paar Model DMA 45 Digital Density Meter (6).

8. Since viscosity and first normal stress difference (FNSD) and storage and loss moduli are functions of both temperature and shear rate or frequency, these parameters must be measured over as wide a temperature range as required for the particular application, and as wide a shear rate or frequency as practical. Several different test instruments are normally used to make a full set of measurements (7,8, 9). For standard field trial applications, the temperature range 15 to 45°C was considered adequate.

9. A series of Brookfield SyncroLectric Viscometers (BSLV), (LVT, RVT, HAT and HBT) (7) were used in the concentric cylinder

configuration, to measure the viscosity of K125/MS solutions as a function of temperature from 15.0 to 45.0°C.

10. Since the traditional method of characterizing solutions used in field trials is Ostwald viscosity, glass capillary viscometers of the Cannon Fenske type (7) were used for this measurement.

11. A Rheometrics Fluids Rheometer (RFR) (8), a constant shear rate rotary rheometer, was used to measure viscosity and first normal stress difference in steady shear and storage and loss moduli in dynamic mode for the K125/MS solutions. The instrument was used in cone and plate configuration with a 2.29 degree cone and 5 cm diameter plates. All measurements were made at 25.0 ± 0.1°C.

12. For each solution, steady shear measurements were made in the clockwise and counterclockwise directions on at least 3 separate samples and the results averaged. Dynamic measurements were also made on these samples and the results averaged.

13. A Carri-Med Constant Stress Rheometer (CMCSR)(9), a constant shear stress rotary rheometer, was used to measure viscosity in steady shear and storage and loss modului in dynamic mode. It was used in cone and plate configuration with either a 2 degree cone and 5 cm diameter plate or a 1 degree cone and 6 cm diameter plate. Measurements were made at 25.0 ± 0.1°C. The CMCSR was used to extend the range of measurements to lower shear rates and frequencies than were possible with the RFR.

RESULTS AND DISCUSSION

14. The densities of 6 solutions of K125/MS are given in Table II.

In all cases the densities were within one percent of the solvent densities.

15. The Ostwald viscosities, η_{C-F}, of the K125/MS solutions as determined by glass capillary viscometers at 25.0°C are also given in Table II. For concentrations greater than 60.0 g/L the viscosity increased very rapidly with concentration. Over the concentration range $25 < \eta_{C-F} < 100$ g/L, the viscosity obeyed the relationship

$$\eta_{C-F} = 21.6 - 2.32C + 9.50\times10^{-2}C^2 - 1.76\times10^{-3}C^3 + 1.57\times10^{-5}C^4 - 3.97\times10^{-8}C^5 \quad [1]$$

Steady Shear Data

Viscosity-Shear Rate-Temperature Relationship

16. Viscosity-shear rate curves were measured at 15.0°C, 20.0°C, 25.0°C, 35.0°C and 45.0°C using Brookfield SyncroLectric Viscometers. This data is listed in Tables III-VIII for the 24.9 g/L, 40.0 g/L, 49.9 g/L, 60.0 g/L, 74.4 g/L, and 99.5 g/L K125/MS solutions respectively. Figure 1 illustrates a set of viscosity-shear rate curves for the 49.9 g/L solution. These curves were of similar shape which implied that temperature variations influenced viscosity only by altering the zero shear viscosity η_0, and the shear rate, $\dot{\gamma}_0$ at which the viscosity began to decrease (10). Consequently, the data could be reduced to a single master curve. The method of superposition employed was that described by Mendelson (11). The shear stress (τ_{12})-shear rate ($\dot{\gamma}$) curves were plotted at each temperature with the 25°C curve chosen as the reference curve. The values of the horizontal shift factors, a_T, at each temperature were obtained by choosing two shear rates, $\dot{\gamma}_A$ and $\dot{\gamma}_B$, on the reference temperature curve and shifting the corresponding

points (constant shear stress) to the other curves to coincide with these shear rates. The values of a_T were calculated from:

$$a_T = \dot{\gamma}(ref)/\dot{\gamma}(T) \qquad [2]$$

where τ_{12} = constant

The a_T values obtained at the two shear rates ($\dot{\gamma}_A$ and $\dot{\gamma}_B$) were averaged to minimize errors. Figure 2 illustrates the resultant master curve for the 49.9 g/L K125/MS solution.

17. The values of the a_T factors are listed in Table IX. The temperature dependence of the a_T factors could be expressed by an Arrhenius type equation of the form

$$a_T = \beta \exp (Ea/RT) \qquad [3]$$

where T = temperature (°K) and Ea = shift factor activation energy (Kcal/mole) (see Figure 3). Values of β and Ea are listed in Table IX.

18. Consequently, a general technique exists for predicting viscosity flow curve data at various temperatures. Equation 2 can be considered in terms of shear rate at any temperature, T, so that

$$\dot{\gamma} (T) = \dot{\gamma}(ref)/a_T \qquad [4]$$

where corresponding shear stress is the same at the two shear rates. Thus, given a set of shear stress-shear rate data at the reference temperature and a knowledge of a_T as a function of temperature, sets of τ_{12}-$\dot{\gamma}$-η data can be obtained at any desired temperature. This is particularly useful for field trial work, where experiments are carried out at a variety of temperatures.

19. The viscosity and first normal stress difference in steady shear have been measured at 25.0°C for the 24.9 g/L, 40.0 g/L, 49.9 g/L, 60.0 g/L, 74.4 g/L and 99.5 g/L solutions of K125/MS using the Rheometrics Fluids Rheometer (RFR). This data is listed in Tables X - XV. Viscosity-shear rate data measured at 25.0°C using the Carri-Med Constant Stress Rheometer (CMCSR) is listed in Tables XVI - XXI.

20. Figures 4-9 illustrate plots of viscosity and first normal stress difference as a function of shear rate.

Equations Used to Describe the Dependency of Viscosity on Shear Rate

21. Several different equations have been suggested to describe the functional dependence of viscosity on shear rate (10). These equations describe either a portion of or the complete viscosity shear rate curve. The most commonly used equations are the power law equation, the Carreau equation (10) and the Allen-Uhlherr equation (12).

22. The power law equation, which has the form

$$\eta = m\dot{\gamma}^{n-1} \qquad [5]$$

where η = viscosity (poise)

$\dot{\gamma}$ = shear rate (1/sec)

m and n = constants characteristic of the particular solution

describes the tilted straight line portion of the curve. The values of the power law parameters, m and n, obtained from a least squares fit of the data, are given in Table XXII.

23. This equation, coupled with a knowledge of the zero shear rate viscosity, η_0, and the shear rate $\dot{\gamma}_0$, at which the viscosity begins to decrease from η_0, can be used to adequately describe most non-Newtonian viscosity curves. Inspection of Figures 4-9 indicates that, in some cases, measurements could not be made at low enough shear rates for the viscosity to reach a constant value, thus giving a definitive value of the zero shear rate viscosity, η_0. In these cases, values of η_0 were obtained by using the extrapolation method of Vinogradov and Malkin (13) in which log $1/\eta$ vs shear stress (τ_{12}) was extrapolated to $\tau_{12} = 0$. The shear rate, $\dot{\gamma}_0$, was arbitrarily chosen as the rate at which the viscosity dropped to 90% of its value at η_0. The values obtained for η_0 and $\dot{\gamma}_0$ are given in Table XXII.

24. Several equations have been proposed to fit the complete viscosity-shear rate curve (10). The four-parameter Carreau equation, which has the form

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = [1 + (\lambda\dot{\gamma})^2]^{(n-1)/2} \qquad [6]$$

where η_0 = zero shear rate viscosity (poise)
η_∞ = infinite shear rate viscosity (poise)
λ = time constant (sec)
n = dimensionless power law index

is the most widely used of these. Since data is not normally available in the infinite shear rate viscosity region, η_∞ is usually set equal to the solvent viscosity giving a 3-parameter equation. The data were fitted to the 3-parameter Carreau equation using a non-linear least squares regression routine. The values of three parameters are given in Table XXIII.

25. A second 4-parameter equation, which fits the complete viscosity-shear rate curve, was recently proposed by Allen and Uhlherr (12). They claimed that this equation, which has the form

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = (1 + \lambda \dot{\gamma})^{n-1} \qquad [7]$$

where η_0 = zero shear rate viscosity (poise)
η_∞ = infinite shear rate viscosity (poise)
λ = time constant (sec)
n = dimensionless power law parameter

gave a better fit to viscosity-shear rate data, especially in the region of onset of shear thinning behaviour ($\lambda\dot{\gamma}=1$), than the Carreau equation. The Allen-Uhlherr equation is reduced to a 3-parameter equation by setting η_∞ equal to the solvent viscosity. The data is then fitted to the 3-parameter equation using a non-linear least squares regression routine. The values of the 3 parameters are given in Table XXIV.

26. To assess the adequacy of fit of the Carreau and Allen-Uhlherr equations to the viscosity-shear rate data, a point by point comparison was made between the measured data and the data calculated using each equation. The sum of the squares of the differences of the calculated and measured viscosity, the average percentage error and the maximum percentage error were determined (see Tables XXV and XXVI). The greatest differences between the measured and calculated values occurred at the highest shear rates with the Carreau equation predicting values higher than the measured values and the Allen-Uhlherr equation predicting values lower. Since the Allen-Uhlherr equation

gave smaller values for all 3 assessment parameters, it was considered to give the better fit to the data. The fit by the Carreau equation was, however, still considered to be satisfactory. Fits of both equations to the data from a 60.0 g/L solution of K125/MS are illustrated in figures 10 and 11.

27. When the zero shear viscosity, η_0, and the Ostwald viscosity, η_{C-F}, as measured by glass capillary viscometers, were compared the following relationship was observed to hold:

$$\eta_{C-F} = 8.43 \times 10^{-1} \eta_o^{0.998} \qquad [8]$$

28. A power law relationship was also observed between N_1 and the shear stress, τ_{12}:

$$N_1 = \alpha \tau_{12}^{\beta} \qquad [9]$$

Values of the power law parameters α and β are listed in Table XXVII.

Dynamic Data

29. Measurements of the storage and loss moduli as a function of angular frequency, ω, were made at 25.0°C for the 24.9 g/L, 40.0 g/L, 49.9 g/L, 60.0 g/L, 74.4 g/L, 99.5 g/L K125/MS solutions using the Rheometrics Fluids Rheometer (RFR) and the Carri-Med Constant Stress Rheometer (CMCSR). The RFR data is listed in Tables XXVIII-XXXIII and the CMCSR data in Tables XXXIV-XXXIX respectively.

30. The loss modulus is converted to the dynamic viscosity by equation 10:

$$\eta' = G''/\omega \qquad [10]$$

Figures 12-17 illustrate plots of dynamic viscosity and storage modulus as a function of frequency.

31. As in the case of the viscosity-shear rate data obtained in steady state experiments, the dynamic viscosity-frequency data can be described in terms of η_0, a characteristic frequency ω_0, at which η has decreased to 90% of its values at η_0, and a power law slope observed at high frequencies. The values of ω_0 and the power law parameters for the equation

$$\eta'(\omega) = a\omega^{b-1} \qquad [11]$$

are listed in Table XL.

32. A comparison between $\eta(\dot{\gamma})$ and $\eta'(\omega)$ indicate that both reach a limiting value of η_0 as $\dot{\gamma}$ and ω approach zero and that both begin to decline at comparable values of $\dot{\gamma}$ and ω. However, η' falls off more rapidly with ω, than η with $\dot{\gamma}$, as is shown by the lower value of the power law slope, b. This decrease in $\eta'(\omega)$ is more pronounced for higher concentrations.

33. The Cox-Merz rule (14) was developed to obtain an improved relationship at high frequencies and shear rates. This rule predicts that the complex viscosity, η^*, should be comparable with viscosity, η, at equal values of ω and $\dot{\gamma}$. The complex viscosity is calculated from equation 12:

$$\eta^*(\omega) = [(\eta'(\omega))^2+(G'(\omega)/\omega)^2]^{1/2} \qquad [12]$$

Figure 18 shows a plot of $|\eta^*/\eta_0|$, η'/η_0, and η/η_0 as functions of reduced frequency, β', and shear rate, β, for the representative solution of 60.0 g/L K125/MS.

$$\beta' = (\eta_0 - \eta_s)M\omega/cRT \qquad [13]$$

$$\beta = (\eta_0 - \eta_s)M\dot{\gamma}/cRT \qquad [14]$$

where η_o = zero shear rate viscosity (poise)
η_s = solvent viscosity (poise)
M_s = molecular weight in g/mole of the polymer ($M = 2.06 \times 10^6$ g/mole for K125)
R = universal gas constant 8.314×10^7 erg/deg mole
c = concentration of the polymer solution in g/cm^3
T = absolute temperature (degrees K)

As expected $\eta^*(\omega)$, follows $\eta(\dot{\gamma})$ more closely than $\eta'(\omega)$ but still falls off more rapidly with ω than η does with $\dot{\gamma}$.

34. The data given in Tables XXII and XL and presented in Figures 4-9 and 12-17 clearly show that dynamic data can be used to obtain a value of η_0 and a reasonable approximation to $\dot{\gamma}_0$. The decrease of η (ω) or η^* (ω) with ω is more pronounced than that of $\eta(\dot{\gamma})$ with $\dot{\gamma}$. This is consistent with previous observations of polymethyl methacrylate (PMMA) solutions (15).

35. When $N_1/\dot{\gamma}^2$ and $2G'/\omega2$ are plotted as functions of $\dot{\gamma}$ and ω, the $2G'/\omega^2$ curve falls off more rapidly with ω than the $N_1/\dot{\gamma}^2$ curve with $\dot{\gamma}$. Figure 19 shows these curves for a representative solution of 60.0 g/L K125/MS. This is again consistent with previous observations of PMMA solutions (15).

CONCLUSIONS

36. A detailed characterization has been made of the thickened simulant K125/methyl salicylate. The parameters obtained can be used to identify and describe the solutions and to predict and correlate their behaviour.

37. Measurements were made of viscosity as a function of shear rate, temperature and concentration for 6 different K125/MS solutions. The first normal stress difference was measured as a function of shear rate and concentration at 25°C for these solutions. Storage and loss moduli were also measured as a function of frequency and concentration at 25°C for these solutions.

38. Three equations, the power law, the Carreau and the Allen-Uhlherr were used to describe viscosity-shear rate data. The Allen-Uhlherr equation was found to give the best fit to the data over the complete shear rate range.

39. Comparison between viscosity as a function of shear rate and complex viscosity as a function of frequency showed that while both measurements go to η_0 as $\dot{\gamma}$ and ω approach zero and give similar values for $\dot{\gamma}_0$ and ω_0, the complex viscosity decreases more rapidly as a function of frequency than the viscosity as a function of shear rate. This implies that complex viscosity data cannot be used in place of shear rate data for the K125/MS system.

REFERENCES

1. S.B. Mellsen, DRES Memorandum 3613-1 (CHEM) 1986.

2. S.J. Armour, "Aerodynamic Breakup of K125/MS Solutions", Suffield Report (in draft).

3. International Task Force - 8, "Simulants and Training Agents", Report of Second Meeting, February 1988. UNCLASSIFIED.

4. S.J. Armour and M.D. Gauthier-Mayer, "Survey of Possible Simulant Systems (U)", Suffield Report No. 387, (1986). UNCLASSIFIED.

5. B.V. Gerber, TTCP-E3 correspondence DRD ARCLB-P 22 February 1980.

6. O. Kratky, H. Leopold and H. Stabinger, "DMA 45 Calculating Digital Density Meter-Instruction Manual", Anton Paar K.G., Graz, Austria.

7. S.J. Armour, M.D. Gauthier-Mayer and P. Wu, "DRES Physical Chemistry Laboratory Manual, Volume I, Viscosity Measurement", in preparation. UNCLASSIFIED.

8. M.D. Gauthier-Mayer, "DRES Physical Chemistry Laboratory Procedures Manual, Volume II, Rheometrics Fluids Rheometer", Suffield Special Publication No. 105 (1987). UNCLASSIFIED.

9. S.J. Armour and J.M.G. Ogston, "Evaluation of the Carri-Med Constant Stress Rheometer", in preparation. UNCLASSIFIED.

TABLE III

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 24.9 G/L SOLUTION OF K125/MS

T = 45°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
5.55	4.79	.863
7.85	6.67	.850
11.09	9.41	.848
15.70	13.14	.837
27.73	22.64	.816
39.25	31.16	.794
65.41	49.09	.750
92.44	67.17	.727
130.82	93.19	.712

TABLE IV

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 40.0 G/L SOLUTION OF K125/MS

T = 15°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.79	4.68	5.93
1.40	8.34	5.97
1.97	11.70	5.93
2.79	16.50	5.91
3.95	23.01	5.83
5.58	32.07	5.74
9.30	48.81	5.25
13.15	68.23	5.19
18.61	95.10	5.11
26.30	127.30	4.84
46.52	204.57	4.40
65.76	264.80	4.03
93.05	349.40	3.75
131.51	428.51	3.26

T = 20°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.79	4.29	5.44
1.40	7.31	5.24
1.97	10.41	5.28
3.94	20.16	5.11
5.58	27.71	4.96
13.15	60.32	4.59
18.61	83.47	4.48
26.30	113.16	4.30
46.53	182.45	3.92
65.75	239.01	3.64
93.06	312.68	3.36
131.49	389.82	2.96

TABLE IV

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 40.0 G/L SOLUTION OF K125/MS

T = 25°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.79	4.03	5.11
1.40	6.68	4.79
1.97	9.22	4.67
2.79	12.80	4.59
3.95	17.85	4.52
5.58	24.85	4.45
7.89	34.47	4.37
13.15	54.08	4.11
18.61	74.53	4.01
26.31	101.39	3.85
46.52	164.85	3.54
65.76	215.63	3.28
93.04	285.13	3.06
131.53	367.24	2.79

T = 35°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
1.39	5.26	3.78
1.97	7.21	3.66
2.79	10.13	3.64
3.94	14.31	3.63
5.57	19.80	3.55
7.88	27.68	3.54
11.14	38.48	3.45
13.14	44.10	3.36
18.57	59.30	3.19
26.27	82.79	3.15
46.43	135.47	2.92
65.68	179.93	2.74
92.85	238.56	2.57
131.37	312.64	2.38

TABLE IV

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 40.0 G/L SOLUTION OF K125/MS

T = 45°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
1.39	4.58	3.29
2.78	8.77	3.15
11.14	32.71	2.94
18.56	49.72	2.68
46.40	116.77	2.52
92.80	209.36	2.26
46.40	118.59	2.56
92.80	208.91	2.25

TABLE V

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 49.9 G/L SOLUTION OF K125/MS

T = 15°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
1.41	17.27	12.25
1.99	24.30	12.19
2.82	33.69	11.95
4.70	52.46	11.16
6.64	70.72	10.64
9.40	101.72	10.82
13.29	134.38	10.11
18.80	181.08	9.63
26.58	232.97	8.77
46.99	364.68	7.76
66.45	447.23	6.73
93.99	578.37	6.15
132.90	708.08	5.33

T = 20°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.56	6.20	11.06
.79	8.77	11.06
1.40	15.22	10.86
1.98	20.86	10.52
2.80	29.72	10.60
6.61	63.65	9.63
9.34	88.03	9.42
13.22	121.06	9.16
18.69	159.65	8.54
26.43	211.13	7.99
46.72	326.13	6.98
66.08	407.71	6.17
93.44	526.83	5.64
132.17	643.18	4.87

TABLE V

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 49.9 G/L SOLUTION OF K125/MS

T = 25°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.40	4.17	10.42
1.41	14.07	10.00
1.99	18.77	9.45
2.81	26.64	9.47
3.97	36.19	9.10
6.62	56.58	8.54
9.38	78.91	8.41
13.25	105.88	7.99
18.76	144.75	7.72
26.50	189.08	7.14
46.90	299.82	6.39
66.25	373.73	5.64
93.80	483.23	5.15
132.50	592.42	4.47

T = 35°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.56	4.32	7.73
1.40	10.48	7.50
1.98	14.66	7.40
2.79	20.65	7.39
3.96	28.66	7.23
5.59	39.89	7.14
6.60	45.76	6.93
9.32	62.15	6.67
13.21	85.74	6.49
18.63	117.82	6.32
26.42	155.33	5.88
46.58	248.36	5.33
66.04	318.05	4.82
93.15	415.87	4.46
132.08	520.03	3.94

TABLE V

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 49.9 G/L SOLUTION OF K125/M8

T = 45°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
1.40	9.71	6.93
1.98	14.16	7.15
2.80	18.13	6.47
3.96	24.41	6.17
5.61	34.63	6.18
13.20	72.39	5.49
18.68	101.49	5.43
26.39	136.04	5.15
46.71	218.49	4.68
65.99	282.07	4.27
93.42	368.33	3.94
131.97	473.44	3.59

TABLE VI

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 60.0 G/L SOLUTION OF K125/MS

T = 15°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	7.27	25.75
.56	14.24	25.22
1.41	34.51	24.45
2.35	53.37	22.69
4.70	101.72	21.62
6.73	130.22	19.34
9.41	181.08	19.25
13.47	229.02	17.00
18.82	310.63	16.51
26.94	380.53	14.13
47.04	580.66	12.34
67.34	696.43	10.34
94.08	899.03	9.56
134.68	1048.39	7.78

T = 20°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	6.27	22.27
.40	8.38	21.11
.56	11.90	21.14
.79	16.50	20.78
1.41	28.75	20.42
3.31	62.40	18.87
4.69	85.30	18.18
6.61	115.86	17.52
9.39	156.22	16.65
13.23	206.14	15.58
18.77	272.04	14.49
26.46	347.65	13.14
46.93	517.25	11.02
66.14	642.76	9.72
93.85	805.07	8.58
132.28	965.18	7.30

TABLE V1

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 60.0 G/L SOLUTION OF K125/MS

T = 25°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	5.75	20.43
.40	7.80	19.65
.56	10.55	18.75
.79	14.59	18.38
1.41	25.48	18.12
1.98	35.10	17.69
3.31	55.50	16.78
4.69	76.17	16.25
6.61	103.01	15.57
9.38	141.04	15.04
13.23	184.51	13.95
18.75	248.73	13.26
26.46	314.31	11.88
46.88	473.46	10.10
66.15	588.26	8.89
93.77	748.88	7.99
132.29	897.95	6.79

T = 35°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.40	6.04	15.28
.56	8.04	14.31
.79	11.47	14.49
1.40	19.88	14.16
1.98	27.81	14.06
2.81	38.91	13.86
3.30	42.85	13.00
4.68	60.21	12.86
6.59	84.04	12.75
9.36	114.72	12.26
13.19	152.68	11.58
18.72	204.12	10.90
26.37	265.22	10.06
46.80	411.74	8.80
65.93	510.88	7.75
93.60	661.39	7.07
131.86	796.27	6.04

TABLE VI

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 60.0 G/L SOLUTION OF K125/MS

T = 45°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.40	5.11	12.91
.56	7.18	12.79
1.40	17.44	12.43
2.81	33.41	11.90
4.68	52.00	11.11
9.36	99.89	10.67
13.19	134.17	10.18
18.72	179.72	9.60
26.37	232.14	8.80
46.79	365.13	7.80
65.93	448.89	6.81
93.59	579.29	6.19
131.86	702.25	5.33

TABLE V11

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 74.4 G/L SOLUTION OF K125/MS

T = 15°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	16.55	58.22
.40	23.13	57.63
.57	31.38	55.21
.95	50.63	53.44
1.34	66.98	50.08
2.37	117.68	49.68
3.34	156.01	46.66
4.74	208.68	44.05
6.69	270.21	40.41
9.47	355.10	37.48
13.37	440.99	32.97
18.95	571.99	30.19
26.75	697.68	26.08
47.37	1003.49	21.18
66.87	1188.17	17.77
94.74	1481.51	15.64
133.75	1727.34	12.91

T = 20°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	14.67	51.65
.40	19.90	49.73
.57	27.92	49.16
.80	38.33	47.91
1.33	61.99	46.48
2.37	104.68	44.24
3.33	135.96	40.78
4.73	185.78	39.26
6.67	239.92	35.98
9.47	319.25	33.73
13.34	400.16	30.01
18.93	516.80	27.30
26.67	636.52	23.87
47.33	912.26	19.28
66.63	1098.31	16.47
94.65	1365.66	14.43
133.36	1614.18	12.10

TABLE VII

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 74.4 G/L SOLUTION OF K125/MS

T = 25°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	12.89	45.47
.40	17.74	44.42
.57	24.50	43.22
.80	34.05	42.61
1.33	53.58	40.24
2.36	91.23	38.63
3.33	121.94	36.63
4.72	165.89	35.12
6.66	217.58	32.68
9.45	289.42	30.63
13.32	364.55	27.38
18.89	474.83	25.13
26.63	584.52	21.95
47.24	861.72	18.24
66.58	1021.76	15.35
94.47	1277.17	13.52
133.16	1507.68	11.32

T = 35°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.57	22.96	40.23
.80	29.64	36.97
1.34	47.01	35.19
2.38	74.35	31.26
3.34	100.89	30.21
4.76	136.61	28.72
6.68	179.52	26.87
9.51	240.84	25.32
13.36	308.28	23.08
19.03	407.17	21.40
26.72	505.06	18.90
47.57	741.67	15.59
66.80	905.27	13.55
95.13	1112.96	11.70
133.60	1354.58	10.14

TABLE VII

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 74.4 G/L SOLUTION OF K125/MS

T = 45°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.28	8.33	29.75
.40	11.70	29.40
.56	16.33	28.99
.80	22.50	28.27
1.41	38.82	27.56
2.35	60.67	25.84
3.32	85.91	25.91
4.70	115.86	24.67
6.63	153.51	23.15
9.39	207.77	22.12
13.26	268.13	20.21
18.78	354.57	18.89
26.53	451.39	17.02
46.96	662.30	14.10
66.32	818.74	12.35
93.91	1007.14	10.72
132.64	1218.12	9.18

TABLE VIII

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 99.5 G/L SOLUTION OF K125/MS

T = 15°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
4.99	551.01	110.43
9.98	875.77	87.76
19.96	1324.61	66.36
49.90	2145.64	43.00

T = 20°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.49	78.91	162.20
.68	107.96	158.79
.97	144.82	148.84
1.36	196.16	144.26
2.43	306.52	126.01
3.40	393.42	115.71
4.87	503.11	103.41
6.80	642.76	94.54
9.73	800.51	82.27
13.60	981.82	72.21
19.46	1204.19	61.88
27.19	1454.43	53.48
48.65	1952.24	40.13
67.99	2319.76	34.12
97.30	2627.32	27.00
135.97	3178.44	23.38

TABLE V111

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 99.5 G/L SOLUTION OF K125/MS

T = 25°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.48	68.42	141.32
.68	97.14	143.14
.97	127.72	131.90
1.36	175.77	129.50
2.42	278.01	114.84
3.39	354.04	104.34
4.84	457.04	94.40
6.79	578.69	85.27
9.68	738.93	76.31
13.57	898.62	66.21
19.37	1120.26	57.85
27.15	1354.58	49.90
48.42	1842.77	38.06
67.86	2179.98	32.12
96.83	2543.39	26.27
135.73	3005.37	22.14

T = 35°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.29	34.33	119.43
.48	54.05	112.81
.68	74.88	110.86
.96	103.77	108.28
1.35	139.99	103.55
2.40	227.95	95.15
3.38	298.29	88.32
4.79	389.08	81.20
6.75	490.29	72.58
9.58	634.25	66.18
13.51	783.17	57.97
19.17	987.07	51.50
27.02	1184.84	43.85
47.92	1667.62	34.80
67.55	1950.33	28.87
95.83	2371.98	24.75
135.10	2720.81	20.14

TABLE VIII

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 99.5 G/L SOLUTION OF K125/MS

T = 45°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
.48	46.98	98.08
.67	63.65	94.50
.96	90.31	94.27
1.35	117.17	86.48
2.40	201.84	84.27
3.37	257.73	76.53
4.79	350.08	73.08
6.74	433.08	64.30
9.58	576.09	60.13
13.47	703.50	52.22
19.18	909.61	47.42
26.94	1085.00	40.27
47.90	1550.85	32.38
67.36	1807.22	26.83
95.80	2218.62	23.16
134.71	2542.75	18.88

Table IX

Shift Factors for K125/MS Solutions

Conc.			T(°C)			B	Ea
(g/L)	15	20	25	35	45		(Kcal/mole)
24.9	1.33	1.13	1.00	0.800	0.662	8.93x10^{-4}	4.17
40.0	1.28	1.12	1.00	0.802	0.697	1.77x10^{-3}	3.76
49.9	1.29	1.13	1.00	0.809	0.692	1.77x10^{-3}	3.76
60.0	1.30	1.13	1.00	0.816	0.687	1.52X10^{-3}	3.86
74.4	1.29	1.12	1.00	0.805	0.689	1.61x10^{-3}	3.82
99.5	1.28	1.13	1.00	0.822	0.713	2.54x10^{-3}	3.55

TABLE X

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 24.9 G/L SOLUTION OF K125/MS RHEOMETRICS FLUIDS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
5.00	1.352
6.30	1.342
7.93	1.325
9.98	1.325
12.56	1.328
15.81	1.318
19.91	1.303
25.06	1.287
31.55	1.273
39.72	1.250
50.01	1.223
62.96	1.193
79.26	1.158
99.78	1.118
125.60	1.080
158.20	1.035
199.10	.984

TABLE XI

VISCOSITY AND FIRST NORMAL STRESS DIFFERENCE AS A FUNCTION OF SHEAR RATE FOR A 40.0 G/L SOLUTION OF K125/MS RHEOMETRICS FLUIDS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)	FIRST NORMAL STRESS DIFFERENCE (DYNE/CM2)
5.00	4.88	
6.30	4.82	
7.93	4.76	
9.98	4.68	
12.56	4.57	
15.81	4.46	
19.91	4.34	
25.06	4.20	
31.55	4.04	102.7
39.72	3.89	138.9
50.01	3.71	202.6
62.96	3.51	242.4
79.26	3.32	324.6
99.78	3.13	435.4
125.60	2.93	562.7
158.20	2.73	722.6
199.10	2.53	913.6

TABLE XII

VISCOSITY AND FIRST NORMAL STRESS DIFFERENCE AS A FUNCTION OF SHEAR RATE FOR A 49.9 G/L SOLUTION OF K125/MS RHEOMETRICS FLUIDS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)	FIRST NORMAL STRESS DIFFERENCE (DYNE/CM2)
5.00	9.72	
6.30	9.54	
7.93	9.32	
9.98	9.05	
12.56	8.76	
15.81	8.45	109.5
19.91	8.10	149.5
25.06	7.73	200.0
31.55	7.34	260.5
39.72	6.94	342.7
50.01	6.51	445.1
62.96	6.09	574.5
79.26	5.66	740.3
99.75	5.24	948.2
125.60	4.83	1199.6
158.20	4.43	1512.8
199.10	4.04	1995.6

TABLE III

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 24.9 G/L SOLUTION OF K125/MS

T = 25°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
3.92	4.96	1.26
5.55	7.05	1.27
7.85	9.79	1.25
11.10	13.91	1.25
15.70	19.26	1.23
27.74	33.42	1.20
46.24	52.09	1.13
65.42	71.69	1.10
92.48	99.30	1.07
130.83	132.34	1.01

T = 35°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
3.92	4.13	1.054
5.55	5.81	1.048
7.85	7.96	1.014
11.10	11.33	1.021
15.69	15.64	.996
27.75	27.24	.981
39.24	37.55	.957
65.39	58.66	.897
92.51	80.28	.868
130.78	108.58	.830

TABLE III

SHEAR STRESS AND VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 24.9 G/L SOLUTION OF K125/MS

T = 15°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
2.77	4.70	1.70
3.93	6.75	1.72
5.55	9.28	1.67
7.86	13.10	1.67
11.10	18.24	1.64
15.73	25.35	1.61
46.24	68.19	1.47
65.54	93.81	1.43
92.48	126.80	1.37
131.07	165.99	1.27

T = 20°C

SHEAR RATE (1/SEC)	SHEAR STRESS (DYNE/CM2)	VISCOSITY (POISE)
3.93	5.73	1.46
5.55	7.91	1.42
7.86	11.11	1.41
11.10	15.82	1.42
15.71	21.81	1.39
27.76	37.84	1.36
46.27	59.30	1.28
65.47	81.75	1.25
92.54	110.16	1.19
130.95	145.40	1.11

TABLE II

DENSITY AND OSTWALD VISCOSITY FOR K125/MS SOLUTIONS

concentration (g/L)	density (g/cm^3)	viscosity (η_{C-F}) (poise)
25.0	1.1793	1.16
40.0	1.1797	4.30
49.9	1.1801	8.84
60.0	1.1803	17.0
74.4	1.1805	40.7
99.5	1.1807	149.1

TABLE 1

PHYSICAL PROPERTIES OF METHYL SALICYLATE

Formula	$C_8H_8O_3$
Molecular Weight	152.14
Melting Point (°C)	-8.6*
Boiling Point (°C)	220-224*
Density (g/cm³) @ 25.0°C	1.179
Viscosity (cp) @ 25.0°C	3.03
Surface Tension (dyne/cm) @ 25.0°C	38.84
Vapour Pressure (mmHg) @ 25.0°C	0.140**
Solubility Parameter (hildebrand)	10.66***

---

* Merck Index, 10th Edition, Merck and Co., Inc., 1983.

** Handbook of Chemistry and Physics, 62nd Ed., CRC Press, 1981.

*** Polymer Handbook, ed. Brandrup and Immergut, Wiley-Interscience, 1975.

10. R.B. Bird, R.C. Armstrong and O. Hassager, "Dynamics of Polymer Liquids", John Wiley, (1977).

11. R.A. Mendelson, "Prediction of Melt Viscosity Flow Curves at Various Temperatures for Some Olefin Polymers and Copolymers", Polymer Eng. Sci., 8: 235-240 (1968).

12. E. Allen and P.H.T. Uhlherr, "Elastic Parameters for Polymer Solutions from Simple Steady Shear", IUPAC Polymer '85 Sym. Melbourne (1985), 358-362.

13. G.V. Vinogradov and A.Y. Malkin, "Temperature Independent Viscosity Characteristics of Polymer Systems", J. Polymer Sci., A2: 2357-2372 (1964).

14. W.P. Cox and E.H. Merz, "Correlation of Dynamic and Steady Flow Viscosities", J. Polymer Sci., 38: 619-622 (1958).

15. K. Osaki, M. Tamura, T. Kotaka and M. Karata, "Normal Stress and Dynamic Moduli in Polymer Solutions", J. Phys. Chem., 69: 3642-3645 (1965).

TABLE XIII

VISCOSITY AND FIRST NORMAL STRESS DIFFERENCE AS A FUNCTION OF SHEAR RATE FOR A 60.0 G/L SOLUTION OF K125/MS
RHEOMETRICS FLUIDS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)	FIRST NORMAL STRESS DIFFERENCE (DYNE/CM2)
5.00	17.72	
6.30	17.18	
7.93	16.56	
9.98	15.90	132.8
12.56	15.18	179.1
15.81	14.43	235.8
19.91	13.64	311.3
25.06	12.80	412.8
31.55	11.97	528.9
39.72	11.16	683.4
50.01	10.32	872.0
62.96	9.50	1105.5
79.26	8.71	1394.2
99.78	7.95	1745.5
125.60	7.21	2168.8
158.20	6.53	2686.7
199.10	5.88	3319.3

TABLE XIV

VISCOSITY AND FIRST NORMAL STRESS DIFFERENCE AS A FUNCTION OF SHEAR RATE FOR A 74.4 G/L SOLUTION OF K125/MS RHEOMETRICS FLUIDS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)	FIRST NORMAL STRESS DIFFERENCE (DYNE/CM2)
1.00	46.76	
1.26	46.20	
1.59	45.24	
2.00	44.13	
2.51	42.88	
3.16	41.44	
3.98	39.81	
5.01	38.17	124.9
6.31	36.33	177.1
7.94	34.47	242.1
10.00	32.49	324.9
12.59	30.45	430.5
15.85	28.37	561.5
19.96	26.30	727.4
25.12	24.25	929.3
31.63	22.25	1178.6
39.82	20.28	1479.6
50.13	18.42	1851.0
63.11	16.64	2295.0
79.45	14.97	2837.4
100.00	13.41	3475.0
125.90	11.97	4236.4

TABLE XV

VISCOSITY AND FIRST NORMAL STRESS DIFFERENCE AS A FUNCTION OF SHEAR RATE FOR A 99.5 G/L SOLUTION OF K125/MS
RHEOMETRICS FLUIDS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)	FIRST NORMAL STRESS DIFFERENCE (DYNE/CM2)
.13	171.80	
.16	171.12	
.20	169.92	
.25	168.33	
.32	169.33	
.40	165.15	
.50	161.58	
.63	158.17	
.79	154.07	
1.00	149.18	
1.26	144.15	
1.59	138.37	135.1
2.00	132.28	187.1
2.51	125.62	256.0
3.16	118.55	338.4
3.98	111.25	447.0
5.01	104.12	585.2
6.31	96.60	751.2
7.94	89.16	956.4
10.00	81.83	1212.0
12.59	74.66	1517.4
15.85	67.69	1890.2
19.96	61.07	2338.0
25.12	54.81	2883.6
31.63	48.98	3522.8
39.82	43.50	4275.2
50.13	38.45	5166.0
63.11	33.83	6186.4
79.43	29.67	7407.2
100.00	25.92	8853.4

TABLE XVI

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 24.9 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
1.81	1.468
2.56	1.379
3.23	1.369
3.94	1.347
4.67	1.326
5.35	1.321
6.38	1.316
7.47	1.301
8.62	1.282
9.74	1.270
11.19	1.264
13.71	1.226
16.25	1.197
18.75	1.179
22.02	1.185
27.62	1.152
32.85	1.130
37.53	1.119
45.10	1.098
55.03	1.076
65.41	1.060
75.68	1.034
85.10	1.018
95.10	.999
112.25	.975
137.58	.942
162.56	.914
187.59	.889
202.47	.873

TABLE XVII

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 40.0 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
1.50	5.20
1.59	5.14
3.06	4.87
3.47	4.69
4.55	4.58
5.48	4.52
6.45	4.44
7.48	4.10
8.60	4.33
9.52	4.30
11.24	4.07
13.75	3.95
13.85	4.31
14.66	4.07
16.25	3.88
18.70	3.82
22.43	3.74
27.52	3.62
34.92	3.49
44.92	3.33
54.76	3.21
55.25	3.20
64.83	3.09
75.37	2.93
85.84	2.89
95.14	2.82
119.43	2.70
139.42	2.53

TABLE XVIII

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 49.9 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
.86	11.61
1.13	11.32
1.39	10.88
1.62	10.77
1.85	10.59
2.18	10.41
2.72	9.97
4.50	9.58
5.55	9.32
6.54	9.13
6.75	8.85
7.59	8.80
8.56	8.66
9.50	8.54
11.16	8.40
13.56	8.22
16.11	7.99
18.79	7.78
22.61	7.50
27.40	7.24
34.88	6.96
44.97	6.58
49.03	6.17
55.01	6.08
64.88	5.83
74.90	5.33
80.41	5.30
95.31	4.95
112.26	4.68
137.03	4.35

TABLE XIX

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 60.0 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
1.29	18.51
1.65	18.10
2.19	17.51
3.58	16.70
4.50	16.59
5.40	16.04
6.51	15.60
7.48	15.15
8.41	14.90
9.60	14.62
11.43	14.11
13.82	13.60
16.18	13.10
18.64	12.65
22.51	12.08
27.39	11.48
32.31	10.90
37.35	10.47
44.58	9.92
54.23	9.25
64.79	8.75
74.40	8.32
84.44	7.95
94.48	7.61
112.04	7.12
137.92	6.55
161.70	6.11
186.73	5.74
224.83	5.31

TABLE XX

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 74.4 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
.69	43.12
1.12	43.55
1.43	41.68
1.91	39.05
2.23	38.61
2.71	37.86
3.28	36.80
3.79	36.08
4.17	35.75
4.54	34.66
5.51	33.45
6.52	32.32
7.54	31.65
8.58	30.15
10.06	29.64
11.16	28.04
13.74	26.51
16.26	25.21
18.67	24.14
22.39	22.79
27.50	21.25
32.45	20.02
37.43	18.96
45.01	17.64
54.82	16.41
56.23	15.92
65.02	15.25
75.21	14.29
85.00	13.52
90.98	13.12

TABLE XXI

VISCOSITY AS A FUNCTION OF SHEAR RATE FOR A 99.5 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

SHEAR RATE (1/SEC)	VISCOSITY (POISE)
.11	172.90
.14	169.05
.19	162.85
.19	158.50
.22	158.98
.28	154.43
.36	152.88
.39	152.00
.43	148.76
.52	147.23
.63	143.32
.74	140.88
.86	139.40
.86	137.40
.96	136.54
1.10	132.98
1.35	128.31
1.62	124.30
1.84	120.61
2.26	116.49
2.68	111.38
2.74	111.82
3.20	107.30
3.76	103.17
4.48	98.28
5.49	92.56
6.57	86.77
7.52	83.89
8.52	80.97
9.46	77.34
12.03	72.71
13.77	67.68
16.32	62.42
18.88	58.79
22.46	54.39
27.53	49.65
32.55	45.87
37.51	42.79
44.50	39.11
54.72	35.21
64.78	32.17
74.97	29.68
84.93	27.72
94.80	26.07
111.70	23.71
135.80	21.18
150.17	19.87
151.68	19.67

TABLE XXII

Parameter for the Power Law Equation $\eta = m\dot{\gamma}^{n-1}$ *

concentration (g/L)	$\eta_\circ$ (poise)	m	n	$\dot{\gamma}_\circ(0.90)$ (1/sec)
24.9	1.36	2.86	0.799	54.0
40.0	5.11	12.2	0.704	12.0
49.9	10.6	26.8	0.644	7.00
60.0	20.4	51.4	0.592	3.50
74.4	50.4	106.1	0.555	1.40
99.5	173.7	293.1	0.478	0.640

*RFR data

TABLE XXIII

Parameters for the Carreau Viscosity Equation *

concentration (g/L)	η_0 (poise)	$\lambda \times 10^{-2}$ (sec)	n
24.9	1.34	2.67	0.824
40.0	4.87	5.60	0.740
49.9	9.78	7.35	0.685
60.0	18.1	9.62	0.634
74.4	46.4	25.6	0.637
99.5	166.1	68.3	0.607

*RFR data

TABLE XXIV

Parameters for the Allen-Ulherr Viscosity Equation *

concentration (g/L)	η_0 (poise)	$\lambda \times 10^{-2}$ (sec)	n
24.9	1.36	0.602	0.585
40.0	5.11	2.71	0.623
49.9	10.5	4.31	0.580
60.0	20.2	6.76	0.543
74.4	49.9	15.0	0.532
99.5	176.0	36.4	0.491

*RFR data

TABLE XXV

Comparison of Measured Data and Data Calculated Using the Carreau Equation

concentration (g/L)	$\sum(\eta_{obs}-\eta_{cal})^2$	average % error	maximum % error	$\dot{\gamma}$(max % error)
24.9	7.48×10^{-4}	0.441	-1.22	5.00
40.0	2.40×10^{-2}	0.897	2.65	199.1
49.9	0.120	1.13	3.78	199.1
60.0	0.418	1.24	4.72	199.1
74.4	9.94	2.38	9.83	199.1
99.5	323.0	4.30	21.9	100.0

TABLE XXVI

Comparison of Measured Data and Data Calculated Using the Allen-Uhlherr Equation

concentration (g/L)	$\sum(\eta_{obs}-\eta_{cal})^2$	average % error	maximum % error	$\dot{\gamma}$(max % error)
24.9	3.16×10^{-4}	0.245	0.935	7.93
40.0	6.93×10^{-4}	0.149	0.381	199.1
49.9	4.76×10^{-3}	0.235	0.849	199.1
60.0	2.72×10^{-2}	0.344	1.29	199.1
74.4	0.684	0.634	2.90	125.9
99.5	31.5	1.30	7.46	100.0

TABLE XXVII

Parameter for the Power Law Equation $N_1 = \alpha \tau_{12}{}^{\beta}$

concentration (g/L)	$\alpha \times 10^{-2}$	β
40.0	4.78	1.59
49.9	4.78	1.58
60.0	3.85	1.61
74.4	1.85	1.69
99.5	1.65	1.72

TABLE XXVIII

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 24.9 G/L SOLUTION OF K125/MS

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
7.93	1.35	1.14
9.98	1.33	1.60
12.56	1.31	2.25
15.81	1.28	3.15
19.91	1.25	4.41
25.06	1.22	6.16
31.55	1.18	8.52
39.72	1.14	11.70
50.01	1.09	15.99
62.96	1.04	21.84
79.26	.99	29.76
99.78	.94	40.77

TABLE XXIX

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 40.0 G/L SOLUTION OF K125/MS

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
5.00	4.63	3.32
6.30	4.51	4.66
7.93	4.40	6.36
9.98	4.29	8.74
12.56	4.13	11.82
15.81	3.97	15.88
19.91	3.80	21.14
25.06	3.61	27.88
31.55	3.41	36.39
39.72	3.20	46.97
50.01	2.99	60.02
62.96	2.78	76.18
79.26	2.58	96.04
99.78	2.39	120.95
125.60	2.20	151.17
158.20	2.03	190.33
199.10	1.89	243.22

TABLE XXX

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 49.9 G/L SOLUTION OF K125/MS

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
5.00	9.18	8.59
6.30	8.86	12.40
7.93	8.51	16.38
9.98	8.16	21.95
12.56	7.74	28.87
15.81	7.32	37.71
19.91	6.88	48.77
25.06	6.42	62.38
31.55	5.96	79.01
39.72	5.50	98.89
50.01	5.06	122.62
62.96	4.62	150.90
79.26	4.21	184.27
99.78	3.84	224.10
125.60	3.48	270.32
158.20	3.17	327.45
199.10	2.92	401.32

TABLE XXXI

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 60.0 G/L SOLUTION OF K125/MS

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
5.00	15.97	20.49
6.30	15.19	26.99
7.93	14.43	35.44
9.98	13.64	46.23
12.56	12.75	59.28
15.81	11.87	75.44
19.91	10.98	95.17
25.06	10.10	118.72
31.55	9.23	146.65
39.72	8.39	179.22
50.01	7.59	217.10
62.96	6.84	260.73
79.26	6.14	310.93
99.78	5.52	369.33
125.60	4.93	434.80
158.20	4.46	513.48
199.10	4.06	612.75

TABLE XXXII

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 74.4 G/L SOLUTION OF K125/MS

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
1.00	44.53	7.38
1.26	43.46	9.99
1.59	41.86	13.86
2.00	40.20	18.79
2.51	38.80	25.08
3.16	36.88	32.93
3.98	35.00	43.51
5.01	32.88	56.65
6.31	30.85	72.62
7.94	28.61	92.38
10.00	26.41	116.45
12.59	24.21	145.05
15.85	22.08	179.22
19.96	19.54	219.13
25.12	18.00	265.28
31.63	16.11	318.33
39.82	14.36	378.87
50.13	12.73	446.83
63.11	11.26	523.15
79.45	9.93	608.05
100.00	8.75	702.38
125.90	7.72	807.20

TABLE XXXIII

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 99.5 G/L SOLUTION OF K125/MS

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
.10	173.60	2.35
.13	165.85	3.05
.16	171.63	4.24
.20	169.80	5.43
.25	168.44	7.14
.32	162.59	9.40
.40	159.70	12.53
.50	155.98	16.60
.63	150.62	21.98
.79	145.25	29.12
1.00	138.22	38.41
1.26	130.77	50.15
1.59	123.25	65.39
2.00	115.57	84.23
2.51	108.18	107.12
3.16	100.09	135.25
3.98	92.06	169.55
5.01	84.06	210.95
6.31	76.41	259.23
7.94	68.78	315.73
10.00	61.59	381.32
12.59	54.77	456.07
15.85	48.46	541.68
19.96	42.59	637.30
25.12	37.25	743.70
31.63	32.40	861.30
39.82	28.08	990.45
50.13	24.26	1131.17
63.11	20.91	1283.17
79.45	17.98	1446.17
100.00	15.47	1621.33

TABLE XXXIV

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 24.9 G/L SOLUTION OF K125/MS CARRI-MED CONSTANT STRESS RHEOMETER DATA

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
2.91	1.19	
5.19	1.21	
7.47	1.23	1.10
9.76	1.24	1.53
12.04	1.25	1.81
14.32	1.24	2.34
16.60	1.23	2.87
18.88	1.24	3.68
21.16	1.24	3.86
23.45	1.22	4.55
25.73	1.20	5.55
28.01	1.19	5.70
30.29	1.20	6.70
32.57	1.20	7.82
34.85	1.18	9.10
37.41	1.12	10.14
39.42	1.10	10.26
41.70	1.09	11.89

TABLE XXXV

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 40.0 G/L SOLUTION OF K125/MS
CARRI-MED CONSTANT STRESS RHEOMETER DATA

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
.63	4.88	.00
1.26	4.66	.00
1.89	4.56	.00
2.51	4.51	.00
2.91	4.52	1.30
3.14	4.43	1.25
3.77	4.40	1.61
4.40	4.31	2.17
5.03	4.24	2.74
5.19	4.31	3.20
5.66	4.22	3.30
6.28	4.15	3.81
7.47	4.14	5.34
9.76	3.96	7.86
12.04	3.84	10.38
14.32	3.72	13.11
16.60	3.61	16.19
18.88	3.52	19.14
21.16	3.47	22.25
23.45	3.40	25.28
25.73	3.33	28.31
28.01	3.29	31.36
30.29	3.26	34.83
32.57	3.20	38.49
34.85	3.16	41.59
37.14	3.13	44.39
39.42	3.10	48.58
41.70	3.08	50.85
43.98	3.00	52.46

TABLE XXXVI

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 49.9 G/L SOLUTION OF K125/MS CARRI-MED CONSTANT STRESS RHEOMETER DATA

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
1.89	9.93	1.88
2.51	9.83	2.90
2.91	9.42	3.36
3.14	9.26	3.90
3.77	9.00	5.59
4.40	8.77	6.57
5.03	8.60	7.70
5.19	8.57	8.65
5.66	8.37	9.17
6.28	8.44	10.90
7.47	8.05	13.01
9.76	7.65	18.14
12.04	7.28	24.36
14.32	6.99	29.99
16.60	6.72	37.08
18.88	6.56	45.08
21.16	6.32	51.89
23.45	6.26	56.74
25.73	6.12	66.19
28.01	6.00	70.29
30.29	5.88	80.35
34.85	5.64	81.30
37.14	5.57	116.44
39.42	5.45	117.02

TABLE XXXVII

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 60.0 G/L SOLUTION OF K125/MS CARRI-MED CONSTANT STRESS RHEOMETER DATA

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
.63	19.93	1.50
1.26	19.68	2.83
1.89	18.54	5.27
2.51	17.63	7.86
2.91	17.14	9.29
3.14	17.18	10.30
3.77	16.98	12.89
4.40	16.30	15.73
5.03	15.76	18.91
5.19	15.51	19.90
5.66	15.44	21.87
6.28	15.13	25.47
7.47	14.56	29.57
9.76	13.45	41.11
12.04	12.77	49.80
14.32	12.06	58.42
16.60	11.62	70.25
18.88	11.12	80.57
21.16	10.82	88.50
23.45	10.57	93.49
25.73	10.10	106.81
30.29	9.77	117.50
34.85	9.33	147.30
43.98	8.66	175.10

TABLE XXXVIII

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 74.4 G/L SOLUTION OF K125/MS CARRI-MED CONSTANT STRESS RHEOMETER DATA

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
.63	44.06	3.25
2.91	34.77	28.27
5.19	30.13	56.98
7.47	26.94	82.93
9.76	24.63	111.07
12.04	22.84	134.80
14.32	21.30	158.50
16.60	20.10	182.33
18.88	18.97	204.63
21.16	18.09	225.87
23.45	17.34	251.90
25.73	16.73	268.67
28.01	16.12	292.33
30.29	15.68	310.53
32.57	15.24	332.83
34.85	14.89	354.03
37.14	14.48	365.87
39.42	14.38	381.27
41.70	14.00	412.90
43.98	13.90	425.00

TABLE XXXIX

DYNAMIC VISCOSITY AND STORAGE MODULUS AS A FUNCTION OF FREQUENCY FOR A 99.5 G/L SOLUTION OF K125/MS CARRI-MED CONSTANT STRESS RHEOMETER DATA

FREQUENCY (1/SEC)	DYNAMIC VISCOSITY (POISE)	STORAGE MODULUS (DYNE/CM2)
.63	132.65	16.62
1.26	120.73	46.37
1.89	110.00	76.83
2.51	99.61	109.06
2.91	95.42	118.37
3.14	93.72	131.87
3.77	89.17	164.07
4.40	83.29	186.03
5.03	78.72	210.80
5.19	76.59	208.70
5.66	75.68	237.67
6.25	72.39	263.40
7.47	64.91	293.90
9.76	58.06	370.40
12.04	52.25	446.70
14.32	47.84	509.40
16.60	44.04	566.43
18.88	41.19	623.80
21.16	38.78	681.40
23.45	36.44	734.13
25.73	34.73	787.13
28.01	32.36	830.63
30.29	31.64	879.13
32.57	30.28	927.90
34.85	29.19	967.93
37.14	28.03	1022.57
39.42	27.45	1066.67
41.70	26.51	1112.67
43.98	25.87	1153.33

TABLE XL

Parameters for the Power Law Equation $\eta = a\ \omega^{b-1}$ *

concentration (g/L)	a	b	$\omega_o(0.90)$ (1/sec)
24.9	2.56	0.783	27.0
40.0	10.6	0.675	5.00
49.9	22.8	0.613	3.50
60.0	40.6	0.567	1.80
74.4	92.7	0.489	0.850
99.5	255.7	0.396	0.500

*RFR data

Figure 1: Viscosity as a Function of Shear Rate and Temperature for a 49.9 g/L Solution of K125/MS

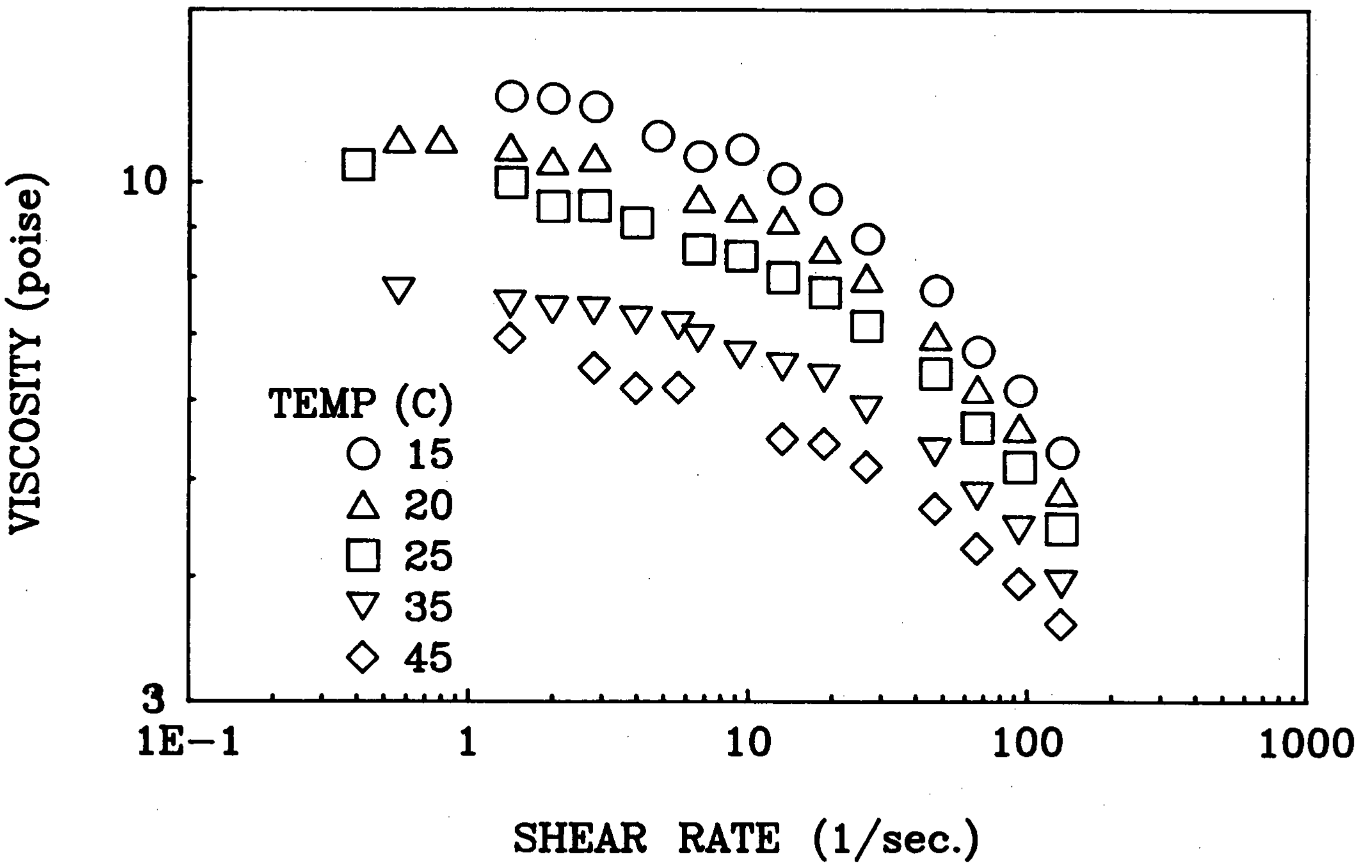


Figure 2: Viscosity as a Function of Shear Rate for a 49.9 g/L Solution of K125/MS. All Data Reduced to 25.0 °C.

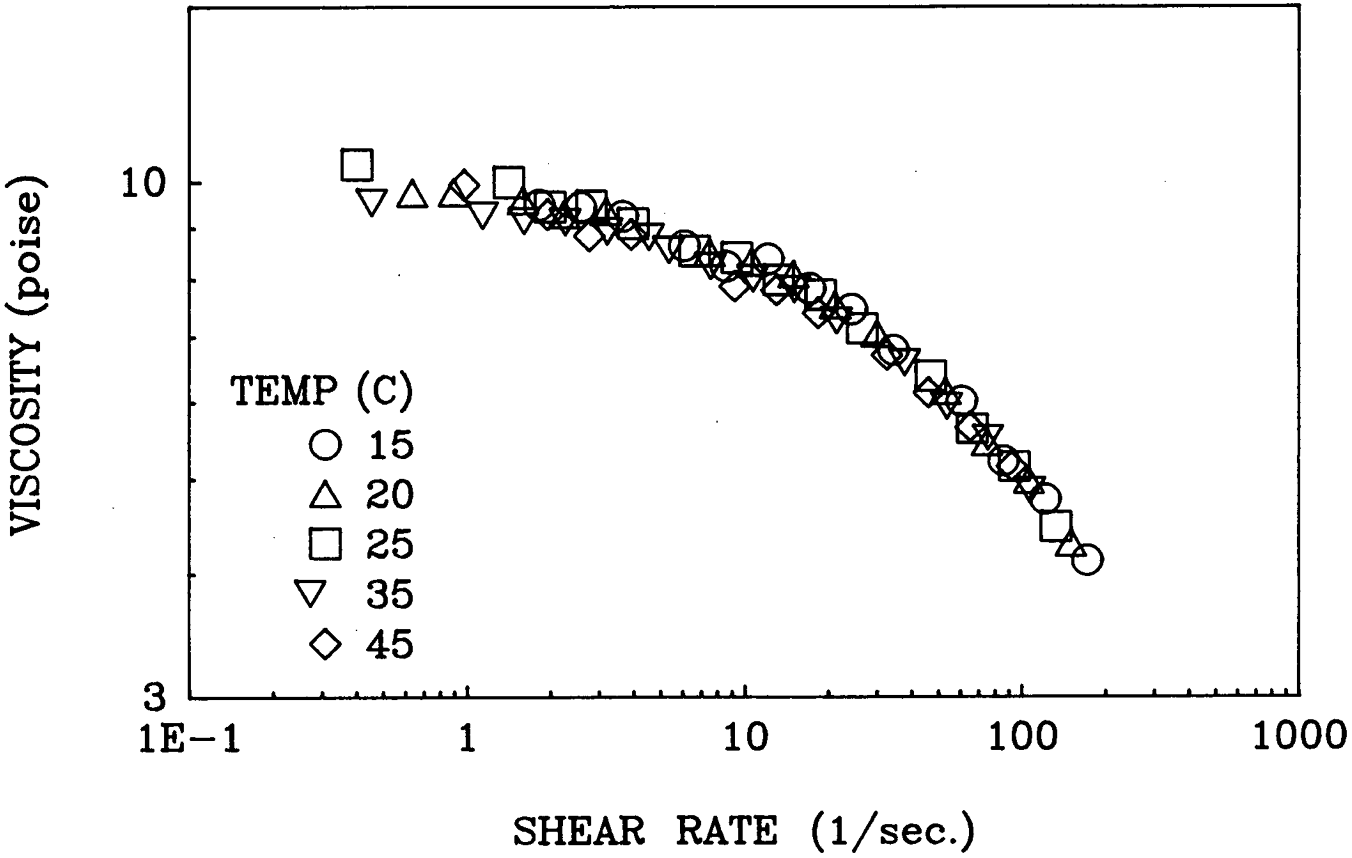


Figure 3: A_T as a Function of 1/T for a 49.9 g/L Solution of K125/MS

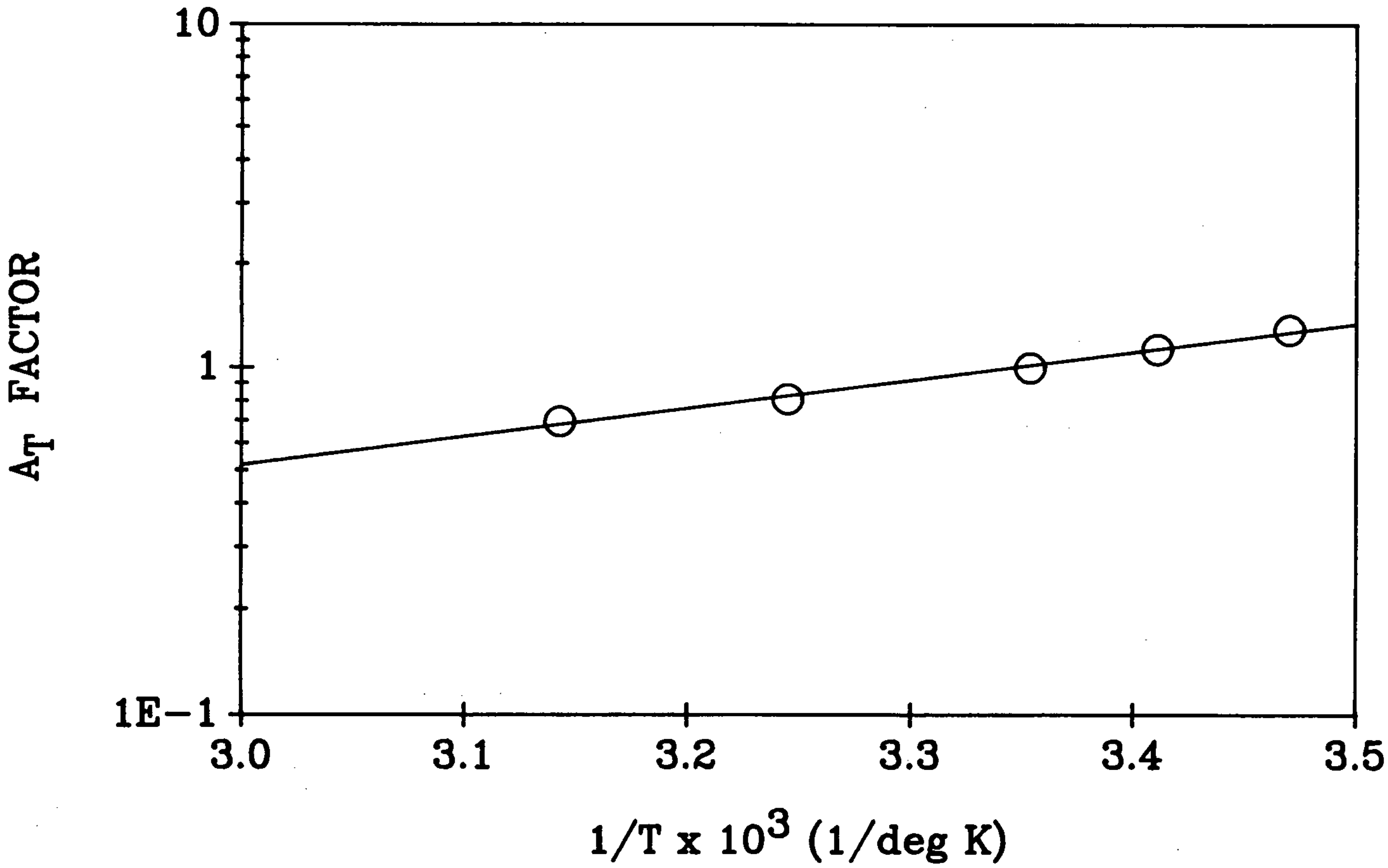


Figure 4: Viscosity as a Function of Shear Rate for a 24.9 g/L Solution of K125/MS

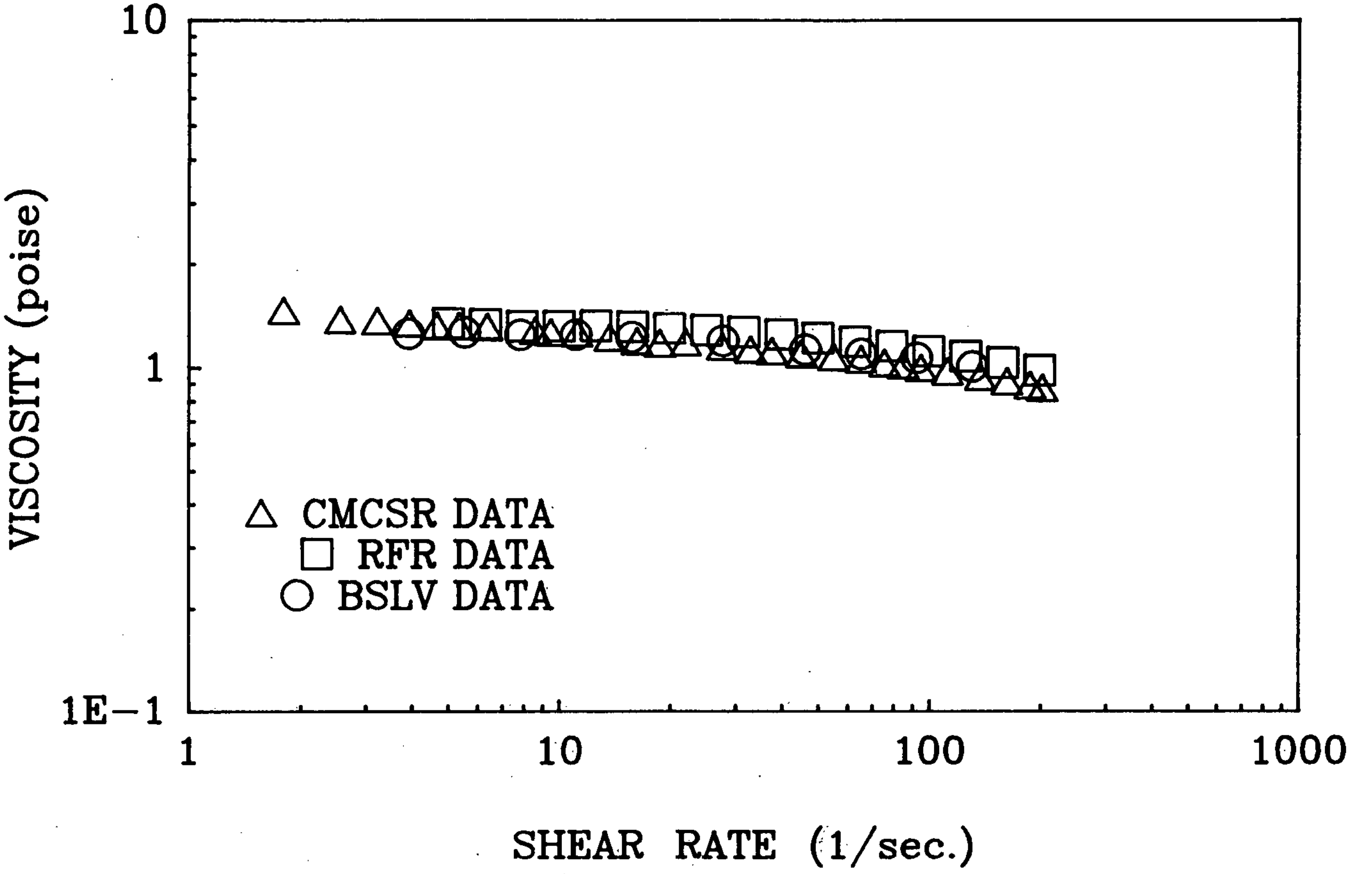


Figure 5: Viscosity and First Normal Stress Difference as a Function of Shear Rate for a 40.0 g/L Solution of K125/MS

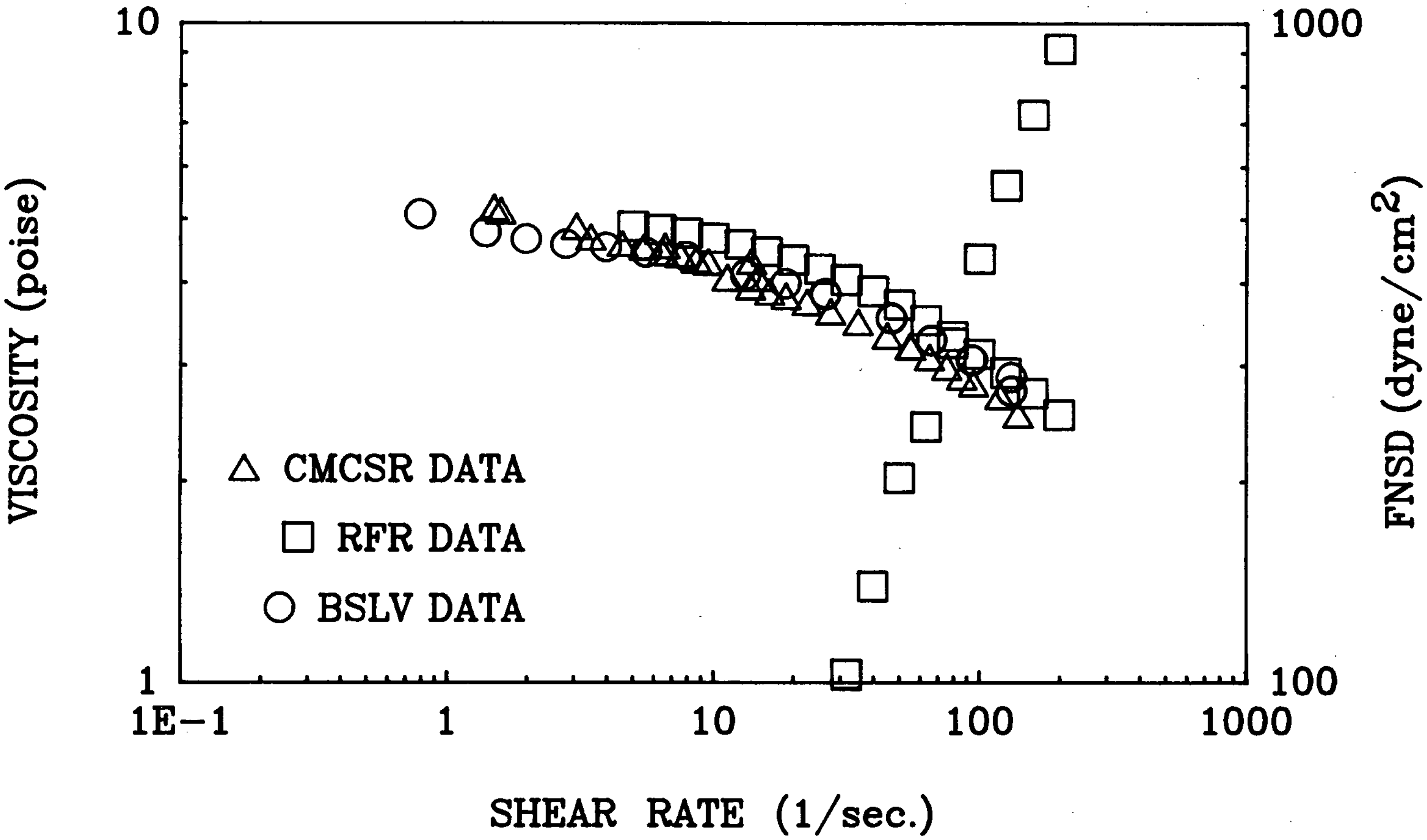


Figure 6: Viscosity and First Normal Stress Difference as a Function of Shear Rate for a 49.9 g/L Solution of K125/MS

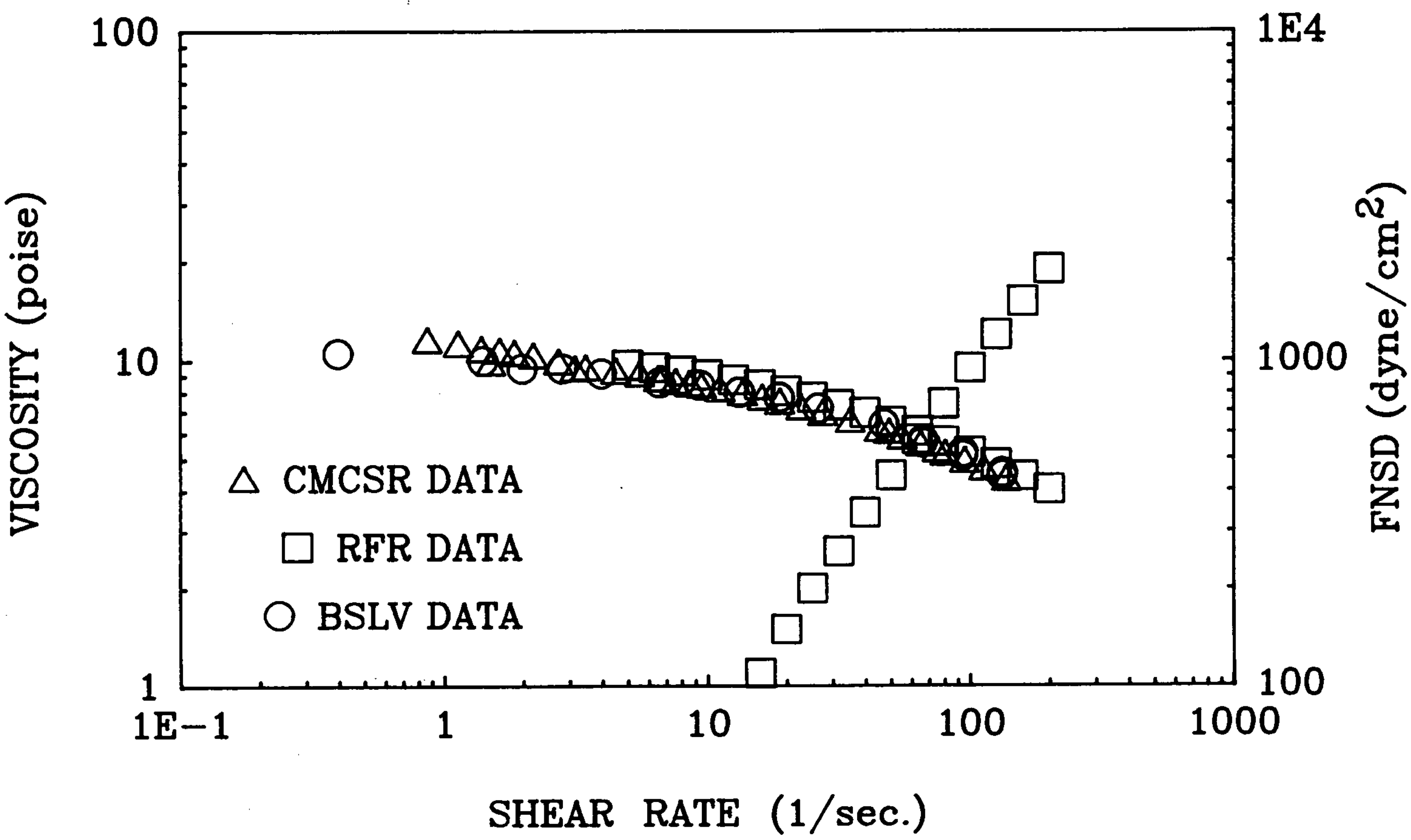


Figure 7: Viscosity and First Normal Stress Difference as a Function of Shear Rate for a 60.0 g/L Solution of K125/MS

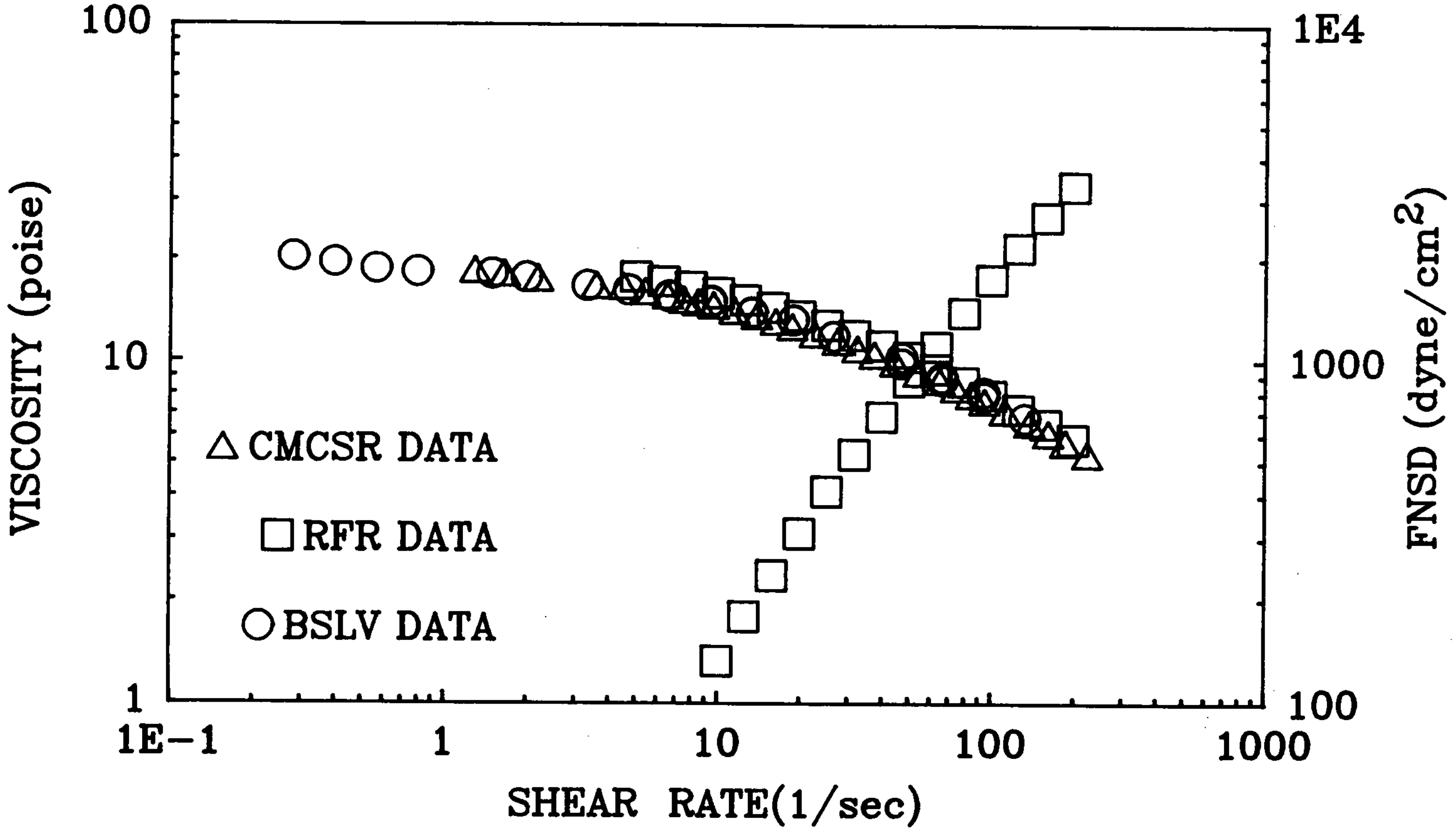


Figure 8: Viscosity and First Normal Stress Difference as a Function of Shear Rate for a 74.4 g/L Solution of K125/MS

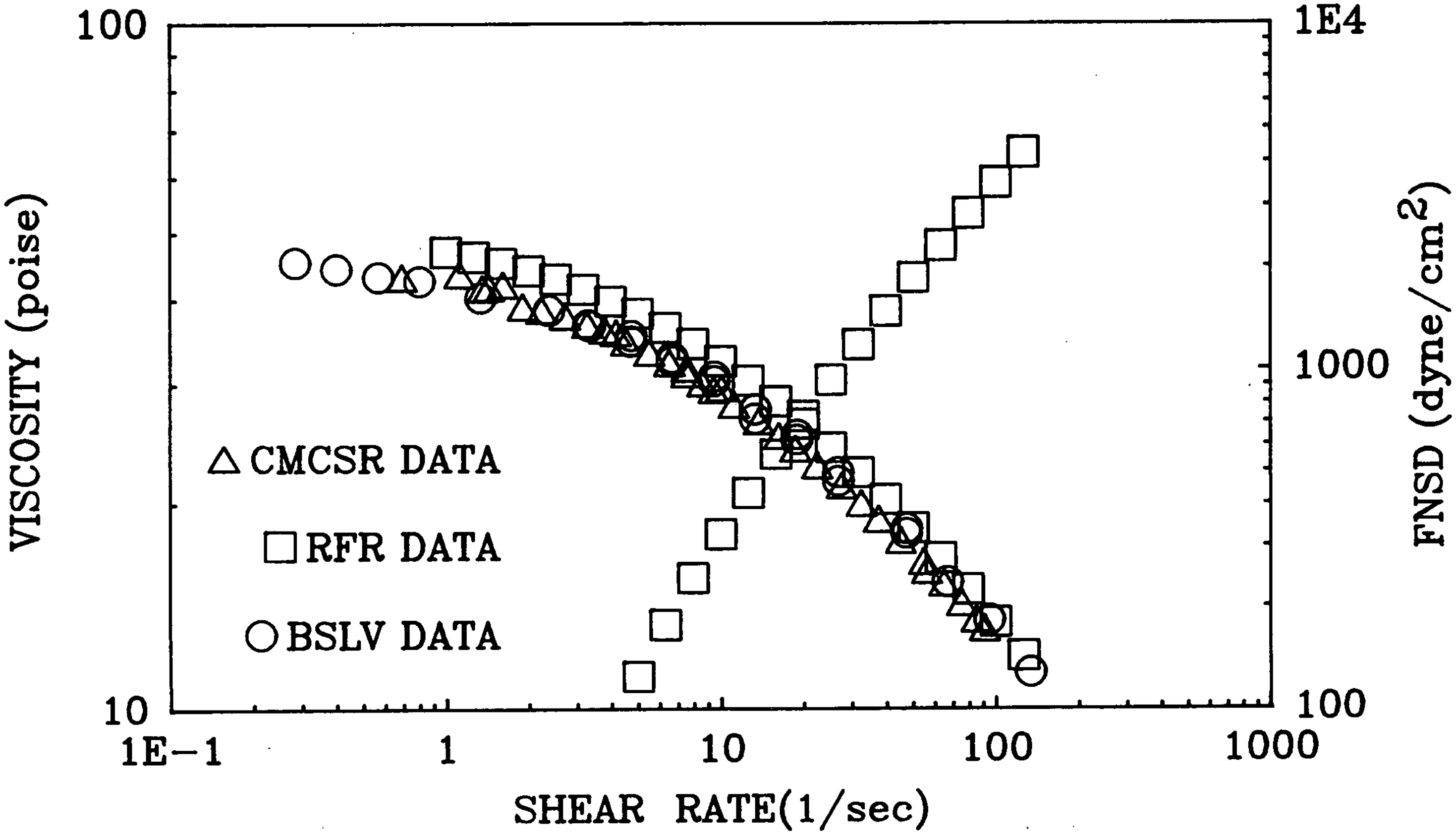


Figure 9: Viscosity and First Normal Stress Difference as a Function of Shear Rate for a 99.5 g/L Solution of K125/MS

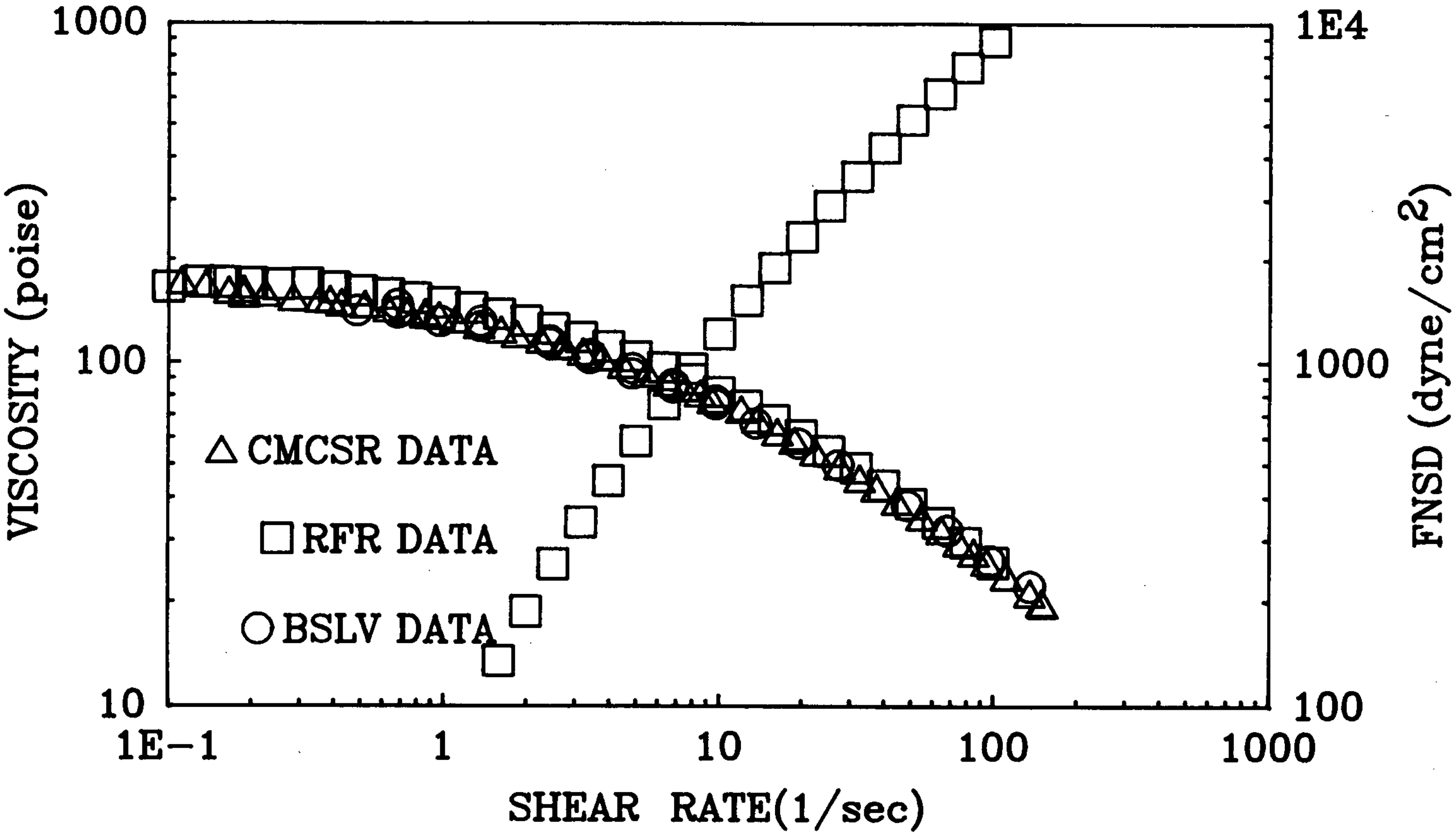


Figure 10: Carreau Equation Fitted to Viscosity – Shear Rate Data for a 60.0g/L Solution of K125/MS

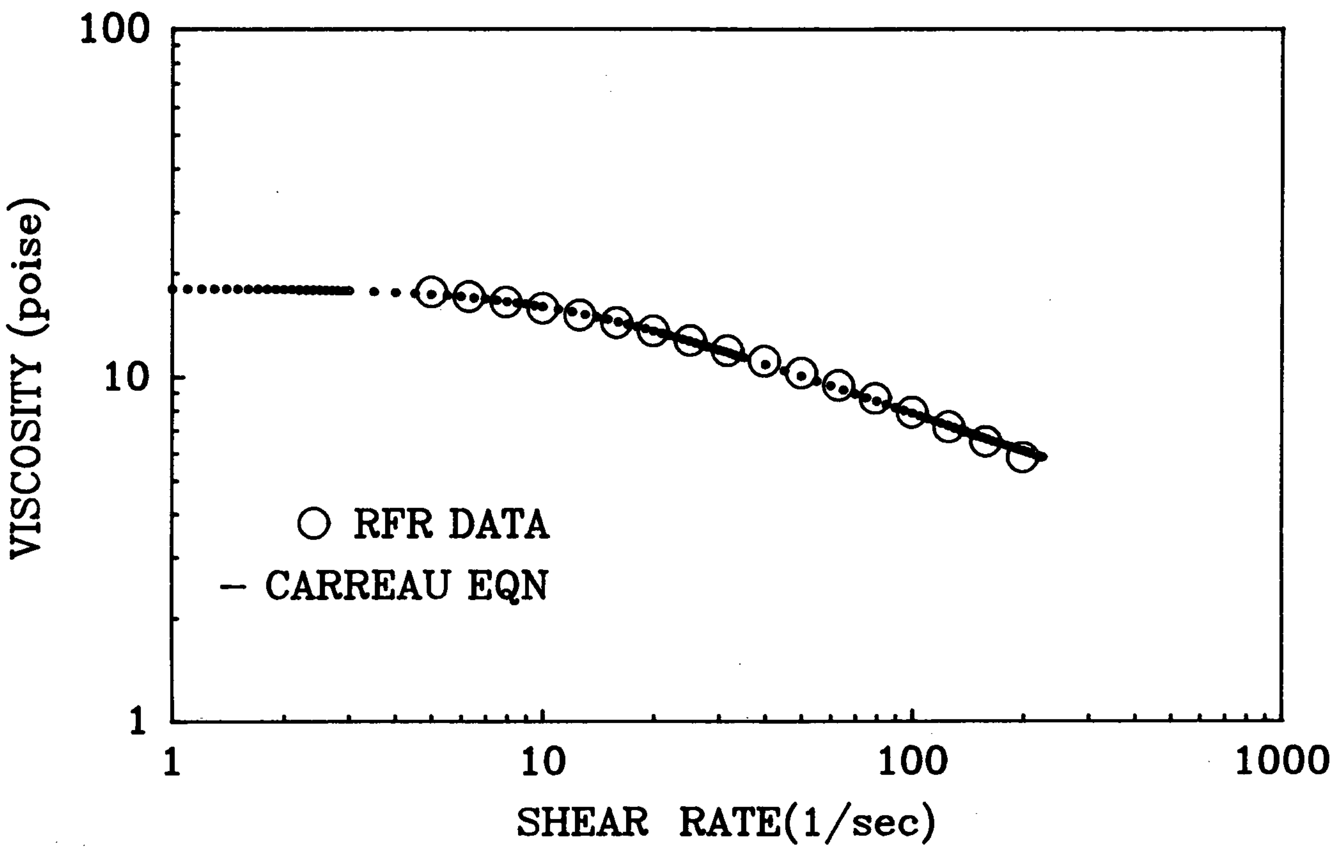


Figure 11: Allen–Uhlherr Equation Fitted to Viscosity – Shear Rate Data for a 60.0g/L Solution of K125/MS

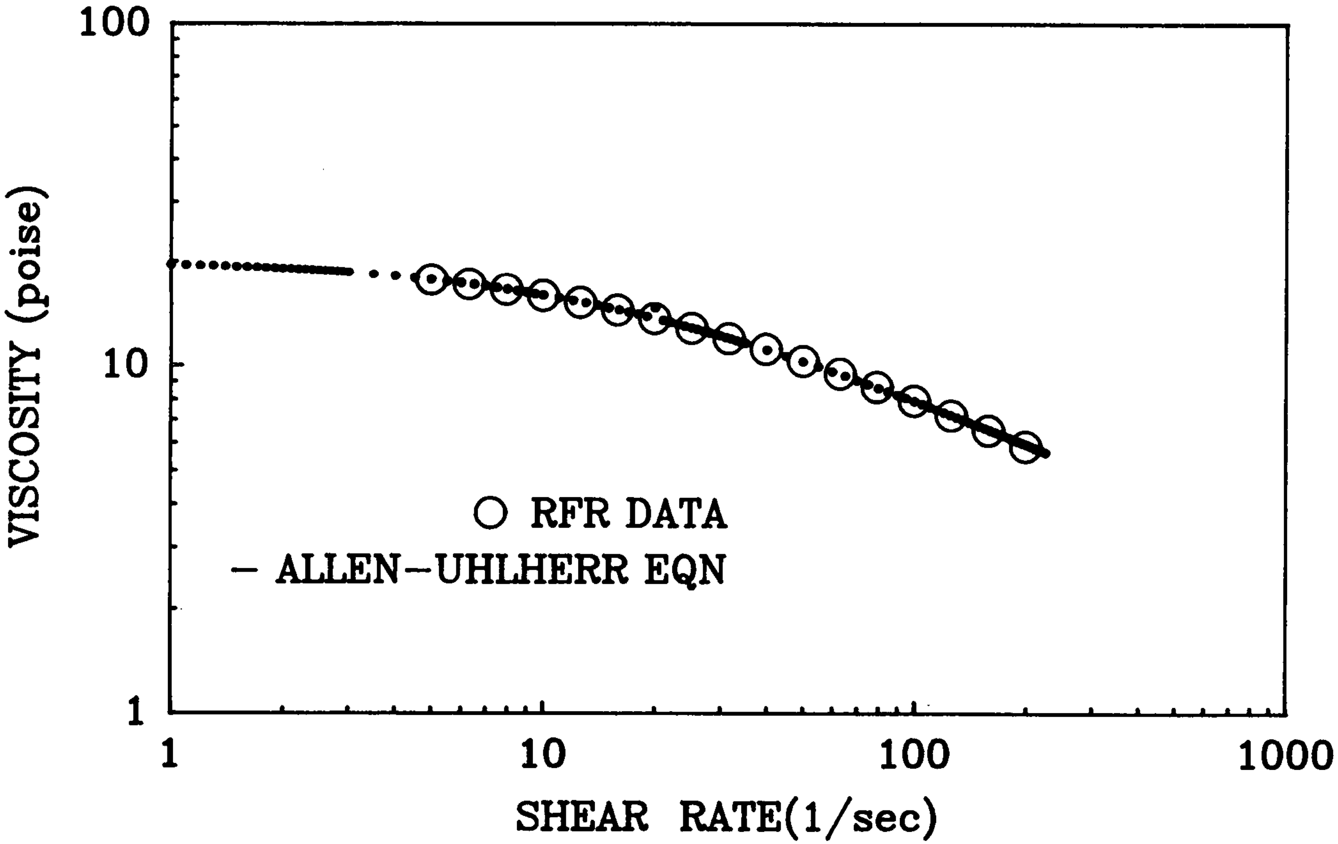


Figure 12: Dynamic Viscosity and Storage Modulus as a Function of Frequency for a 24.9g/L Solution of K125/MS

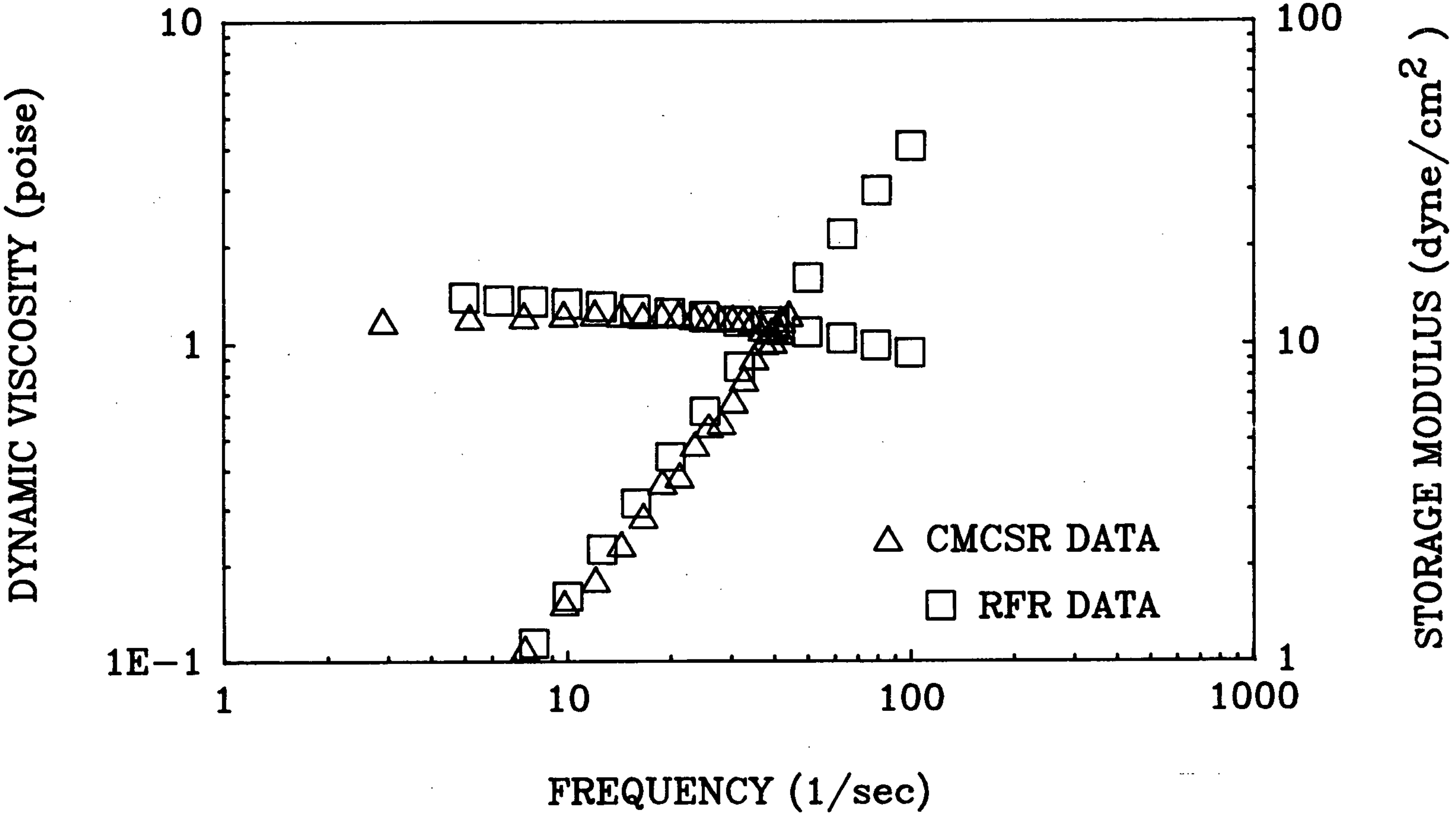
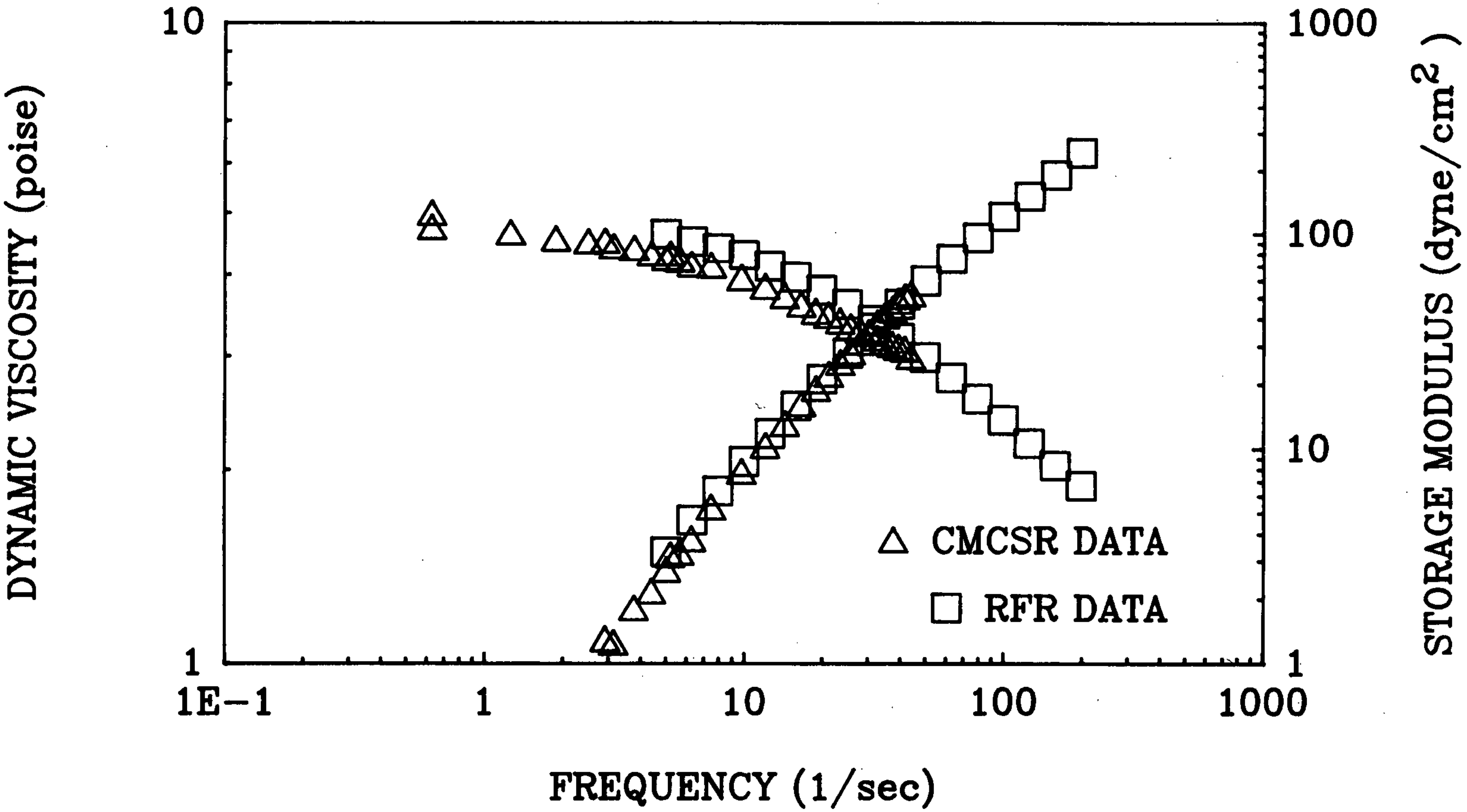
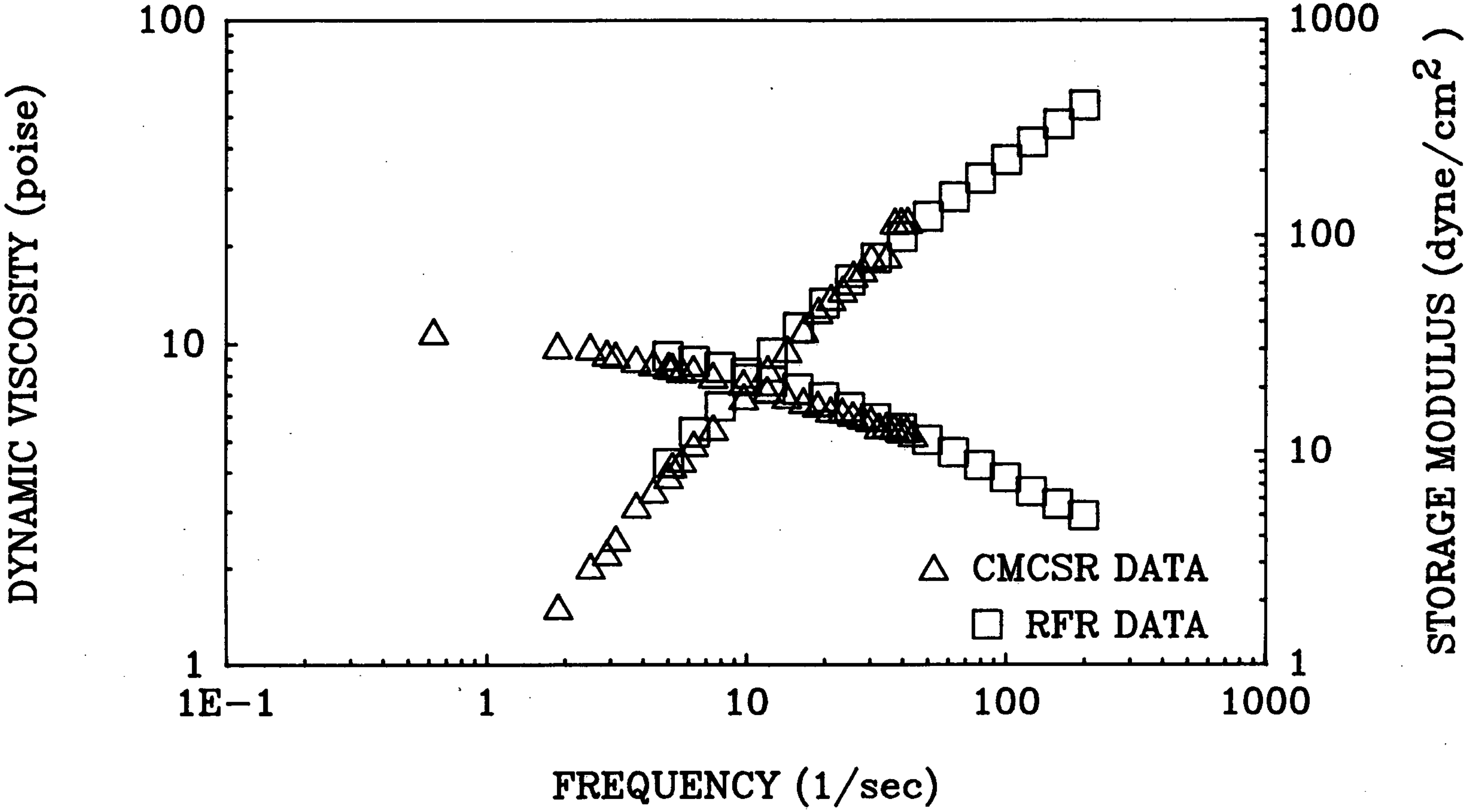


Figure 13: Dynamic Viscosity and Storage Modulus as a Function of Frequency for a 40.0g/L Solution of K125/MS



UNCLASSIFIED

Figure 14: Dynamic Viscosity and Storage Modulus as a Function of Frequency for a 49.9 g/L Solution of K125/MS



UNCLASSIFIED

Figure 15: Dynamic Viscosity and Storage Modulus as a Function of Frequency for a 60.0g/L Solution of K125/MS

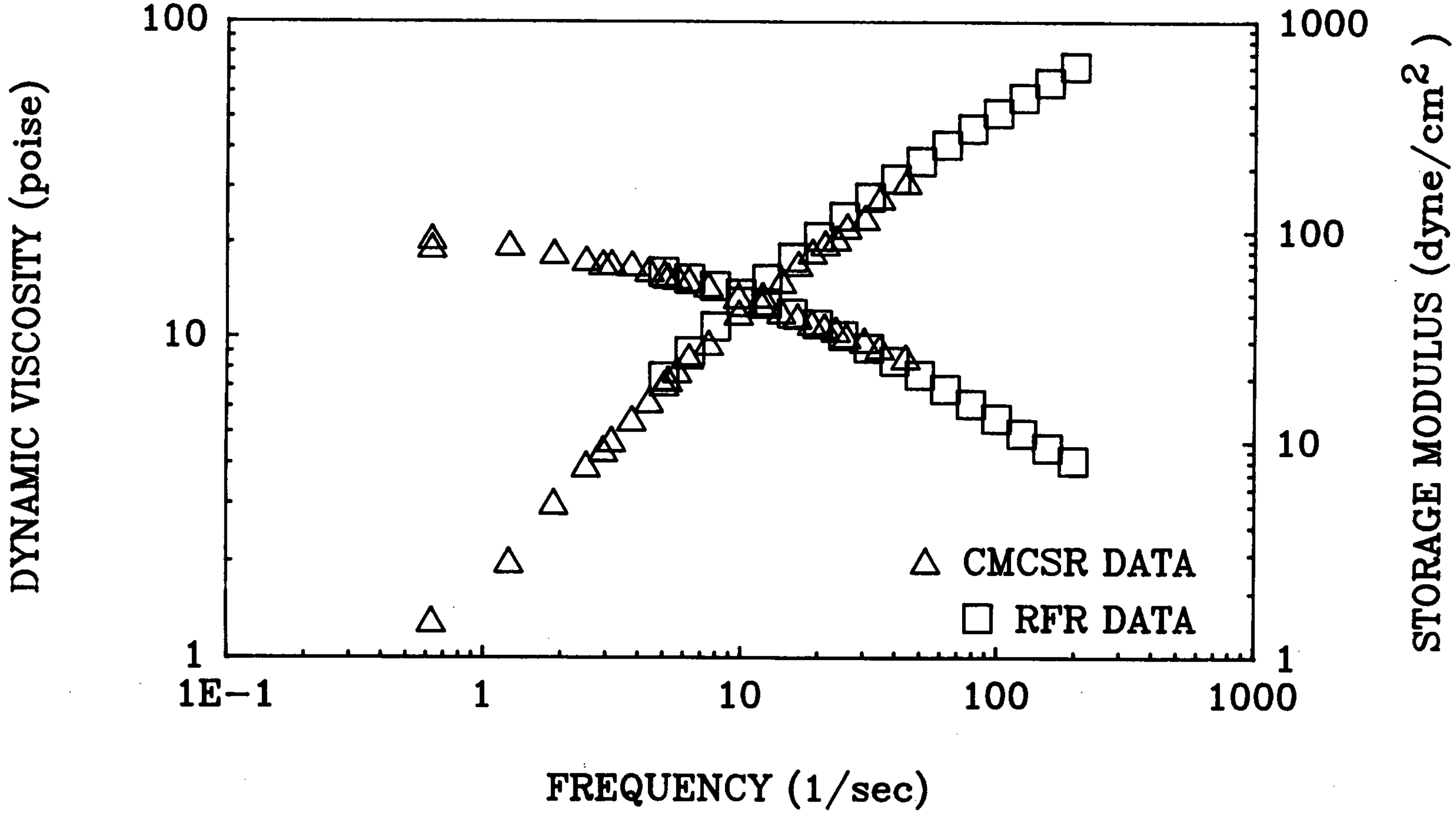
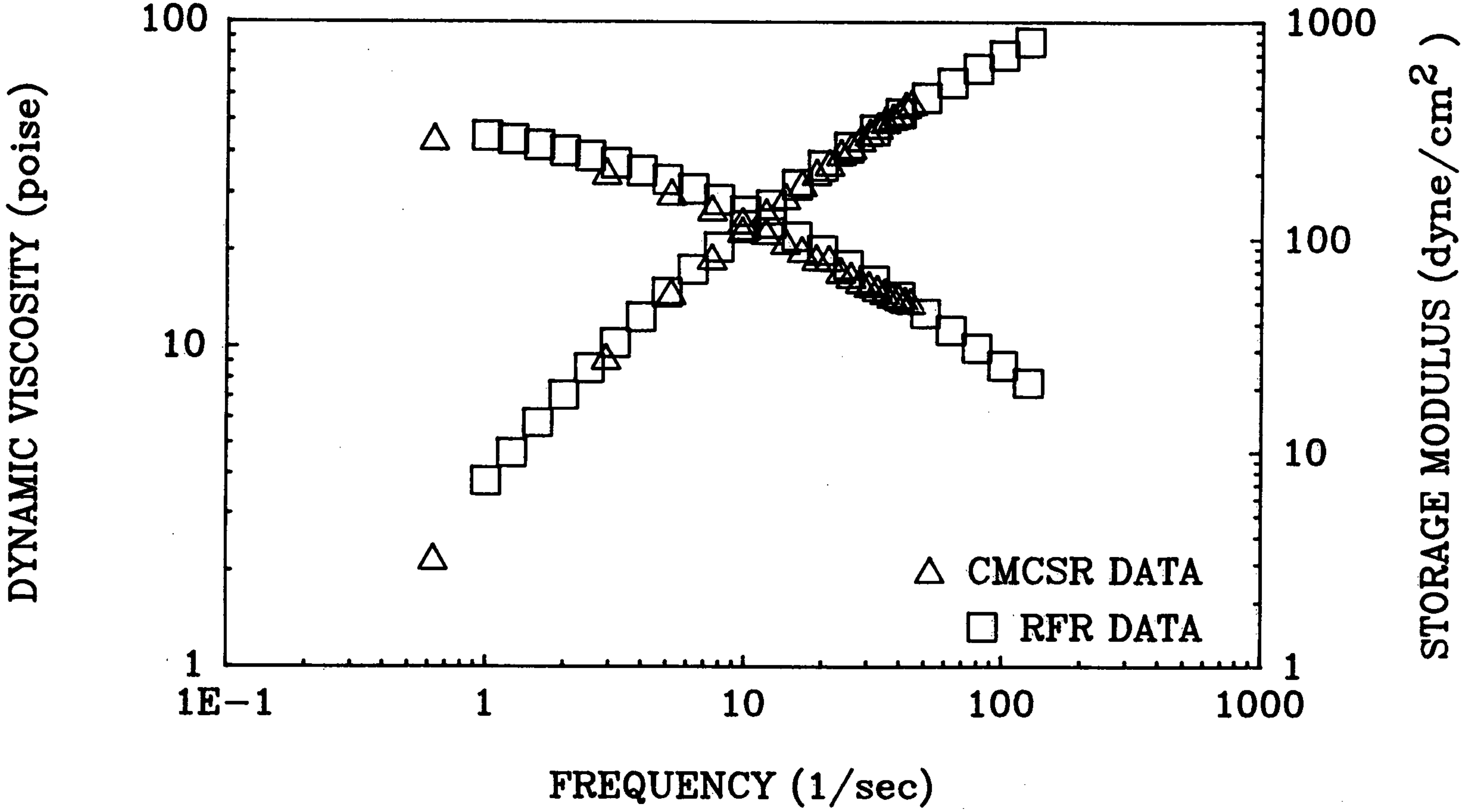
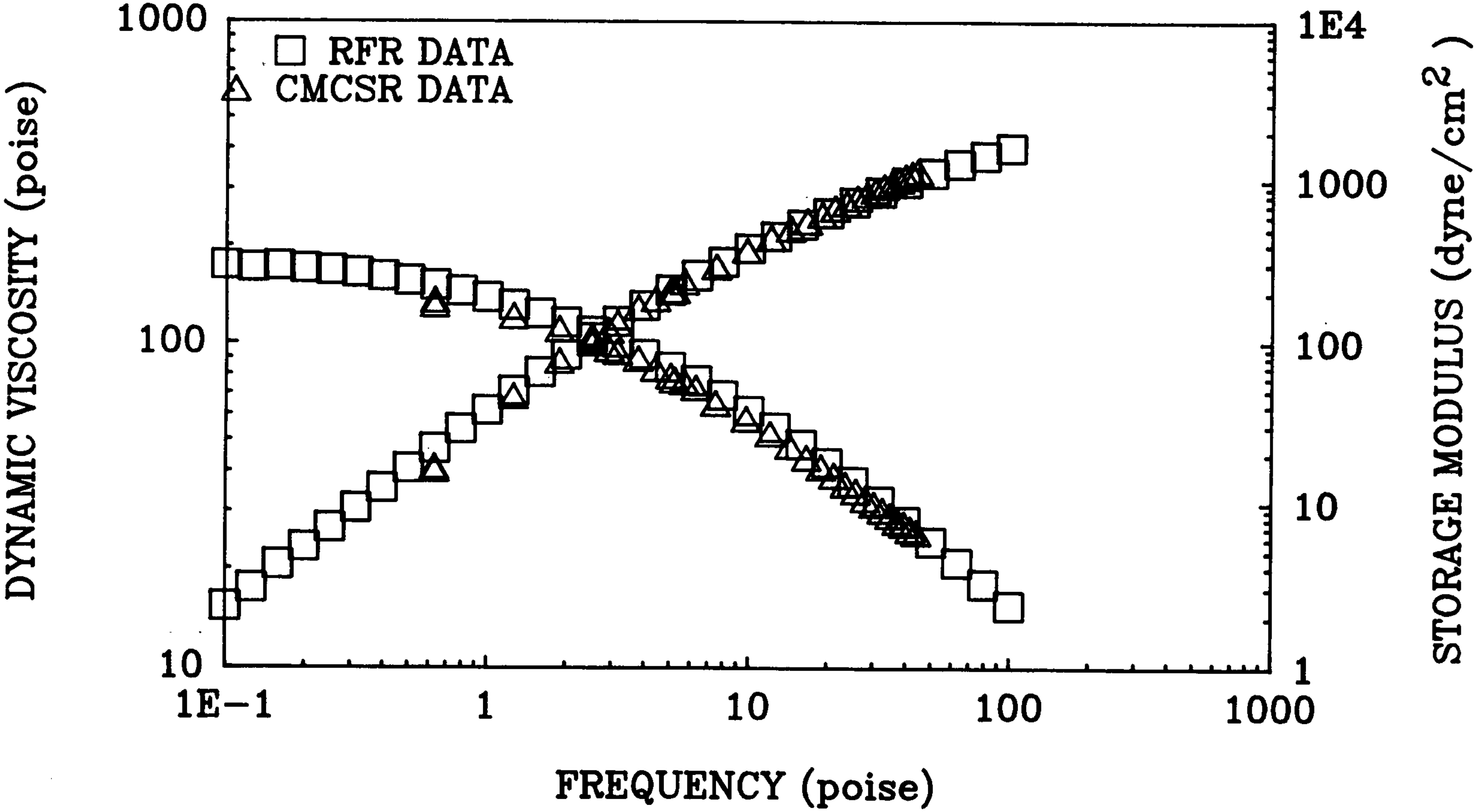


Figure 16: Dynamic Viscosity and Storage Modulus as a Function of Frequency for a 74.4g/L Solution of K125/MS



UNCLASSIFIED

Figure 17: Dynamic Viscosity and Storage Modulas as a Function of Frequency for a 99.5g/L Solution of K125/MS



UNCLASSIFIED

Figure 18: Reduced Viscosity, Dynamic Viscosity and Complex Viscosity as a Function of Reduced Shear Rate or Frequency

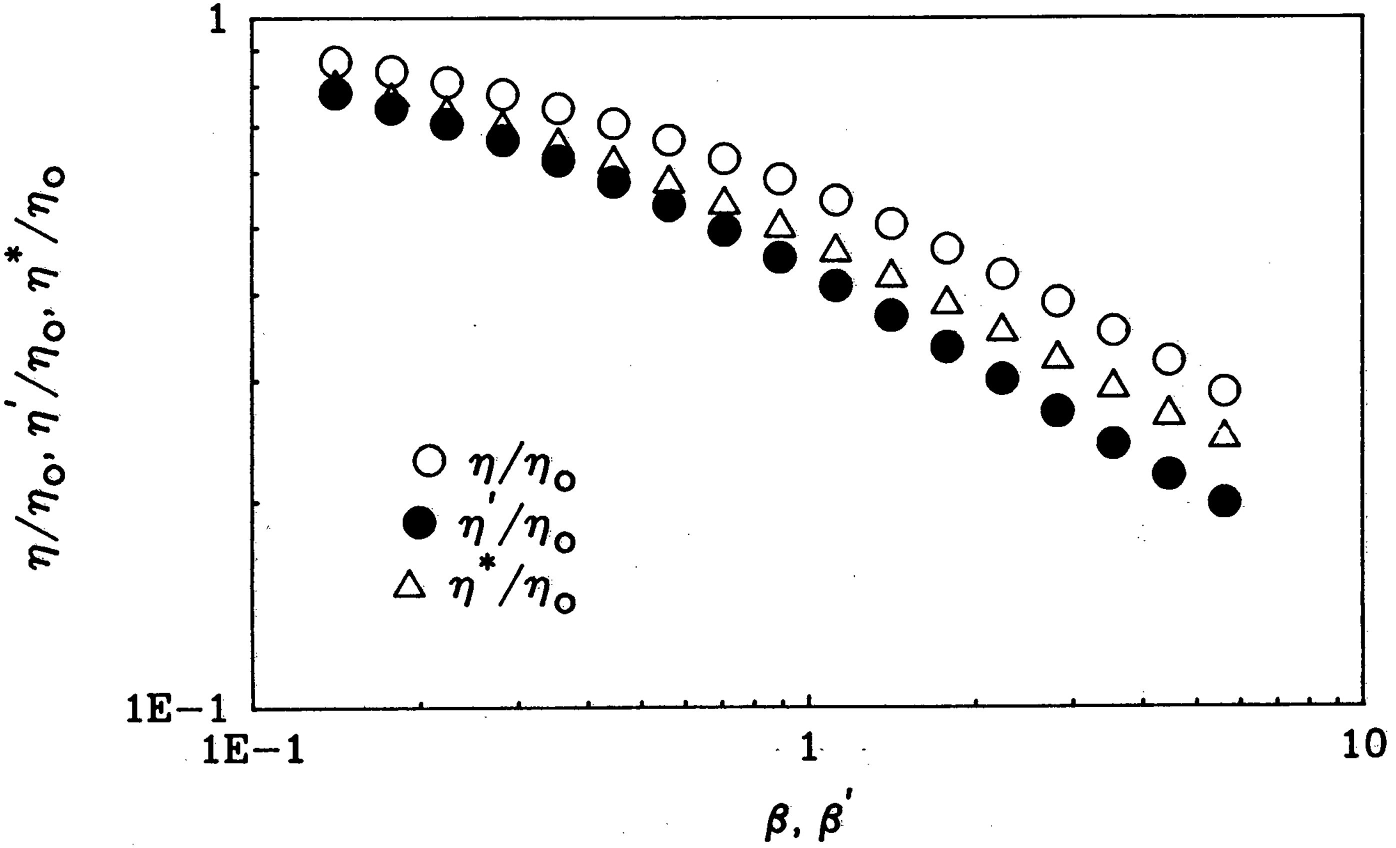


Figure 19: ($N_1/\dot{\gamma}^2$) and ($2G'/\omega^2$) as a Function of Shear Rate of Frequency for a 60.0 g/L Solution of K125/MS