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TECHNICAL REPORT AFATL-TR-75-17✓

**EVALUATION OF RHEOLOGICAL PROPERTIES
OF
FLAME FUELS**

USING A CAPILLARY EXTRUSION RHEOMETER

**FAE AND FLAME BRANCH
MUNITIONS DIVISION**

JANUARY 1975

FINAL REPORT: JANUARY 1973 TO JULY 1974

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PREFACE

This technical report is based on a study conducted at the Air Force Armament Laboratory, Armament Development and Test Center, in support of Project 10820302 during the period from January 1973 to July 1974.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



WILLIAM F. BROCKMAN, Colonel, USAF
Chief, Munitions Division

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SECTION I

INTRODUCTION

Requirements for firebombs include a capability for high speed delivery over a wide temperature range. High speed delivery conditions expose the firebomb fuel to high wind shear forces as well as the explosive forces used in dissemination of the fuel. In addition, temperature dependence of the flow behavior of a thermoplastic material such as the polystyrene in Napalm B results in large variations in its properties.

The rheological properties of concentrated polymer solutions are of major importance in the development of improved flame agents for these high speed delivery conditions over a wide temperature range. An understanding of the rheological behavior of standard agents (such as Napalm B) and candidate systems will enable researchers to predict the behavior of candidate fuels based on laboratory studies, as well as providing guidance as to the type of materials which should be investigated.

The rheological properties which are most important to fuel behavior are the viscosity and elasticity (termed recoverable shear or percent memory) as a function of shear rate. Gaskins¹ has correlated shear rate with the velocity of a gelled hydrocarbon extruded at high speeds from a nozzle. Based on these calculations, it has been estimated that exposure of a fuel to an air stream at 900 feet per second is equivalent to a shear rate in the range of 10^6 sec^{-1} .

Numerous researchers have studied the viscosity of flame agents with rotational viscometers such as the Brookfield or MacMichael instruments; however, these instruments are limited to low shear rate ranges and require exposure of the sample to the atmosphere during the measurement. Gaskins² has designed a capillary extrusion rheometer to study both viscosity and recoverable shear as a function of shear rate. However, the instrument utilized is limited in shear rate to about 10^5 sec^{-1} and requires numerous runs to overcome data scatter. The technique utilized for studying recoverable shear involves a large number of laboratory experiments and a long data reduction process.

Reference

1. Gaskins, Frederick. A Study of Jet-Tension Instrument and Mechanical Flame Thrower. Franklin Institute Report F-A 1978.
2. Gaskins, Frederick. Rheological Properties and Performance of Napalm B in Comparison to Standard Flame and Incendiary Agents (U). EATR 4155, February 1968.

The objective of this study was to develop simple instrumentation and reproducible techniques necessary to study the rheological properties of polymer solutions. A parallel, contractual effort 3, 4 was utilized in part to develop the required instrumentation.

To establish the procedures and provide a data baseline for comparison with experimental formulations, an extensive investigation of Napalm B has been included in this study.

Reference

3. Long, R. L. Flame Agents for High Velocity/Low Temperature Use (U). Air Force Armament Laboratory Report AFATL-TR-71-55. Monsanto Research Corporation, May 1971.
4. Long, R. L. Improved Flame Agents (U). Air Force Armament Laboratory Report AFATL-TR-72-177. Monsanto Research Corporation, September 1972.

SECTION II

THEORETICAL

Rheology is the science of the deformation and flow of matter. Comprehensive theoretical discussions of rheology are adequately discussed in the literature.⁵ A limited explanation of the parameters studied and the equations used to calculate these parameters will be included.

The deformation of a body can be arbitrarily divided into two general types: (1) spontaneously reversible deformation called elasticity, and (2) irreversible deformation called flow or viscous behavior. In an idealized case, if deformation is carried out infinitely slow, there will be no viscous contribution and only elastic effects will show up. On the other hand, in continuous, steady-state flow at a uniform rate there will be no elastic contribution and the entire effect will be viscous.

The polymer solutions studied in this program exhibit both reversible deformation or elasticity and irreversible deformation or flow and are called viscoelastic materials.

SHEAR STRESS

To produce flow or an elastic strain, a stress, defined as a force per unit area, must be applied. In a capillary extrusion rheometer, it is assumed that steady flow is obtained in the capillary and that all the forces applied to the solution cause flow. In this case, the viscous forces tending to retard the flow will be exactly balanced by the force resulting from the pressure differential between the two ends of the capillary. The shear stress in a fluid flowing through a capillary is directly proportional to the distance from the center of the capillary, varying from zero shear stress at the center to a maximum at the wall. The most convenient location for measurement of the shear stress is at the wall of the capillary. The shear stress applied at the wall in the capillary extrusion rheometer used in this study is calculated from the following equation:

$$\tau = \frac{Fr}{2 R^2 L}$$

Reference

5. Van Wazer, J. R., et. al. Viscosity and Flow Measurement. Interscience Publishers, 1963.

where: T = Shear stress, dynes/cm²

F = Force applied (ram load, dynes)

r = Orifice radius, cm

R = Barrel radius, cm

L = Orifice length, cm

SHEAR RATE

The rate of deformation for flow is a function of shear. Simple shear can be considered as a process in which infinitely thin, parallel plates slide over each other.

Viscous deformation is expressed in terms of rate of shear, which is the change in velocity of flow with a distance measured at right angles to the direction of flow. In the capillary rheometer, the rate of shear also varies with the radius of the capillary and must be calculated at the same point as the shear stress for the construction of flow curves. The shear rate at the wall is a more difficult quantity to determine from experimental data than shear stress. For the calculation of shear rate at the wall in a capillary extrusion rheometer, the Rabinowitsch⁶ correction factor is applied to the rate of shear which has been calculated from the volumetric flow rate of the fluid, according to the following equation:

$$\dot{\gamma}_{\omega} = \left(\frac{4Q}{\pi r^3} \right) \left(\frac{3+b}{4} \right)$$

where: $\dot{\gamma}_{\omega}$ = Corrected shear rate, sec⁻¹

Q = Extrusion rate in cm³/sec⁻¹ = volume extruded/
extrusion time

r = Orifice radius, cm

$\left(\frac{3+b}{4} \right)$ = Rabinowitsch correction factor, where b is the slope
of the flow curve (log shear rate versus shear stress)

Reference

6. Rabinowitsch, B., Z. Physik, Chem., A 145, 1 (1929).

VISCOSITY

The ratio of applied shearing stress to rate of shear for ideal viscous bodies is called the coefficient of viscosity or, more commonly, viscosity. This viscosity is a measure of the resistance to flow and can be expressed as:

$$\text{Viscosity} = \frac{\text{Shear stress}}{\text{Shear rate}}$$

or

$$N = \frac{T}{\dot{\gamma}}$$

ω

The ideal viscous body is the Newtonian fluid for which the coefficient of viscosity is a constant. If the viscosity changes with shear rate or shear stress, it is called non-Newtonian or apparent viscosity. Most solutions of polymers, such as polystyrene, exhibit an apparent viscosity that is constant at low shear rates and then decreases in magnitude as the shear rate is increased. This decrease in viscosity as the shear rate is increased is called shear thinning or pseudoplastic flow.

ELASTICITY

The calculation of shear stress, shear rate, and viscosity from the equations shown assumes that the energy input to the solution, or the pressure drop across the capillary, is primarily utilized to overcome viscous resistance to flow, and that all other effects are small and can be neglected. Since the capillary has rigid walls, the elastic deformation of the fluid is minimized. However, when the fluid emerges from the capillary, it is no longer restrained by the walls, and energy which was reversibly stored is recovered by expansion of the fluid. Thus, highly viscoelastic materials may have elastic components that reversibly absorb a portion of the energy input. Philippoff and Gaskins⁷ have discussed this elastic energy correction and have developed a graphical procedure for the calculation of recoverable shear stress, based on the capillary length.

a. Recoverable Shear

In order to determine the elasticity or recoverable shear by the capillary length technique, the polymer solutions are extruded through capillary tubes of the same diameter but of different lengths. Flow curves (log shear rate versus log shear stress) are then prepared for each capillary. From these plots, the pressure differential (ΔP) required

Reference

7. Philippoff, W. and Gaskins, F. H., "The Capillary Experiment in Rheology," Transactions of the Society of Rheology, II (1958), p. 263-284.

for each capillary with a different length and radius (L/r) ratio is determined at various levels of shear rate. Figure 1 is an example of this type plot for Napalm B at 23.9°C (75°F). This procedure is required to obtain the data for each capillary over a variation of shear rates. Plots are then made of ΔP versus the L/r ratio for each selected shear rate, as in Figure 2. For each of the shear rates plotted, there is an initial pressure drop (ΔP) at L/D = 0 which is a combination of the entrance losses and the pressure input that is reversibly stored and can be recovered outside the capillary. Flow curves of data collected with various capillaries give a curve independent of capillary dimensions, indicating that the end effects are negligible; thus, the initial pressure drop is primarily the pressure input that is reversibly stored and can be recovered outside the capillary. Philippoff and Gaskins⁷ have shown that the most direct way of determining the elastic energy function is by measuring the x-intercept (as in Figure 2) and calculating the recoverable shear as:

$$S_r = -2 \text{ (x-intercept)}$$

The recoverable shear is then plotted against shear rate as in Figure 3.

b. Memory

Monsanto Research Corporation⁵ has shown that the elasticity of a polymer solution can also be studied by measuring the expansion of the solution as it is extruded from the capillary. The basic technique for determining the die swell or memory of polymer melts is the measuring of the diameter of the extruded polymer strand. For the solutions studied in this program, the liquid strand is photographed as it emerges from the capillary and the measurements are made from the photograph. The diameter of the extruded strand, D_1 , and the capillary orifice diameter, D_0 , are used to calculate the percent memory by the following equation:

$$\text{Percent memory} = \frac{D_1 - D_0}{D_0} \times 100$$

From the equation it can be seen that if the extruded strand is the same diameter as the orifice, the solution has no recoverable shear and the percent memory will be zero. The percent memory is plotted as a function of the shear rate as shown in Figure 4 for Napalm B at 23.9°C (75°F).

c. Comparison of Recoverable Shear and Memory

The elastic nature of a polymer solution can be studied by either the capillary length or memory technique. In the capillary length technique, the energy which is recoverably stored in the solution is measured. While the theoretical basis of the technique is sound, a considerable number of

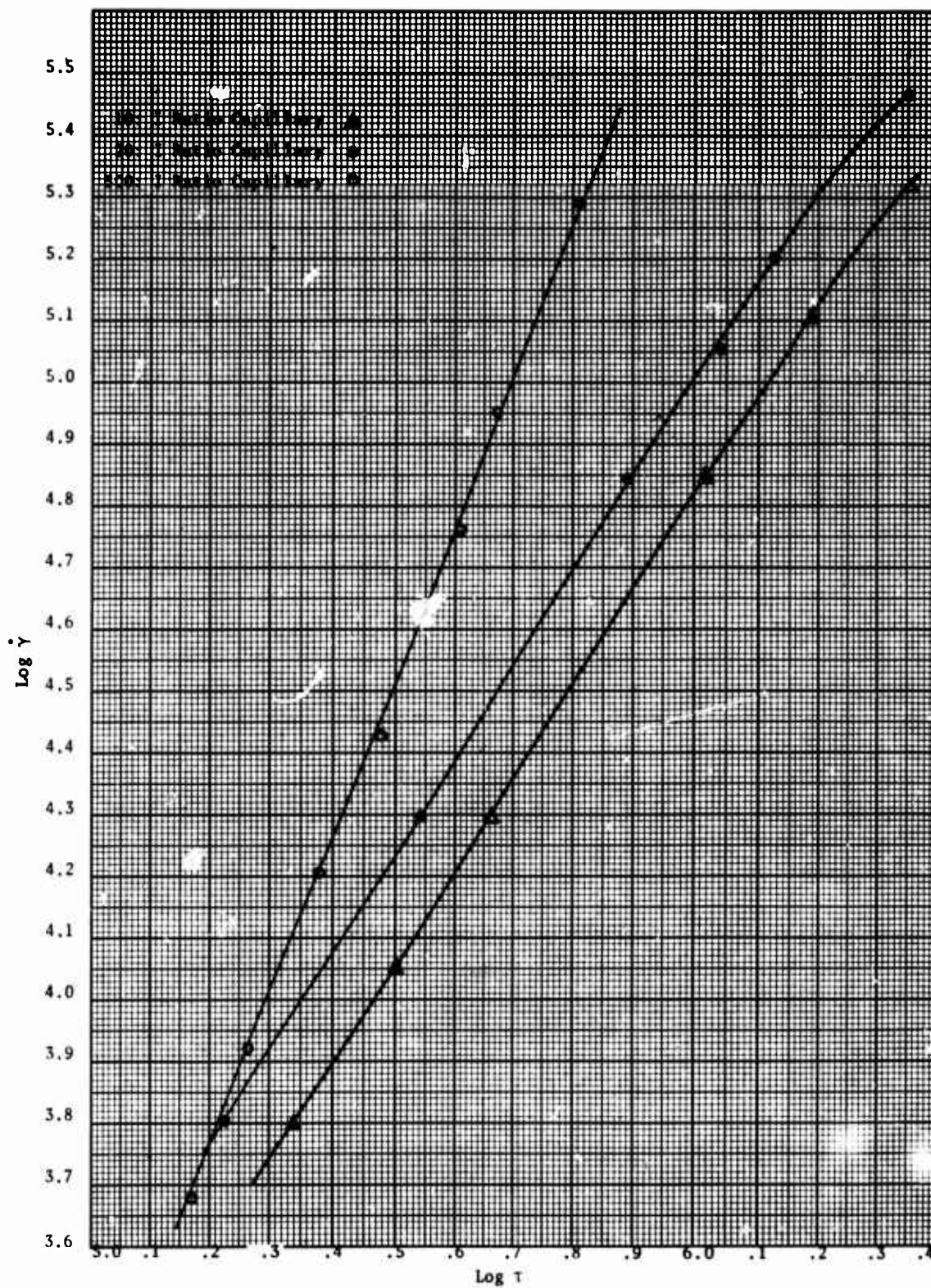


Figure 1. Log Shear Rate versus Log Shear Stress of Various Capillaries at 23.9°C

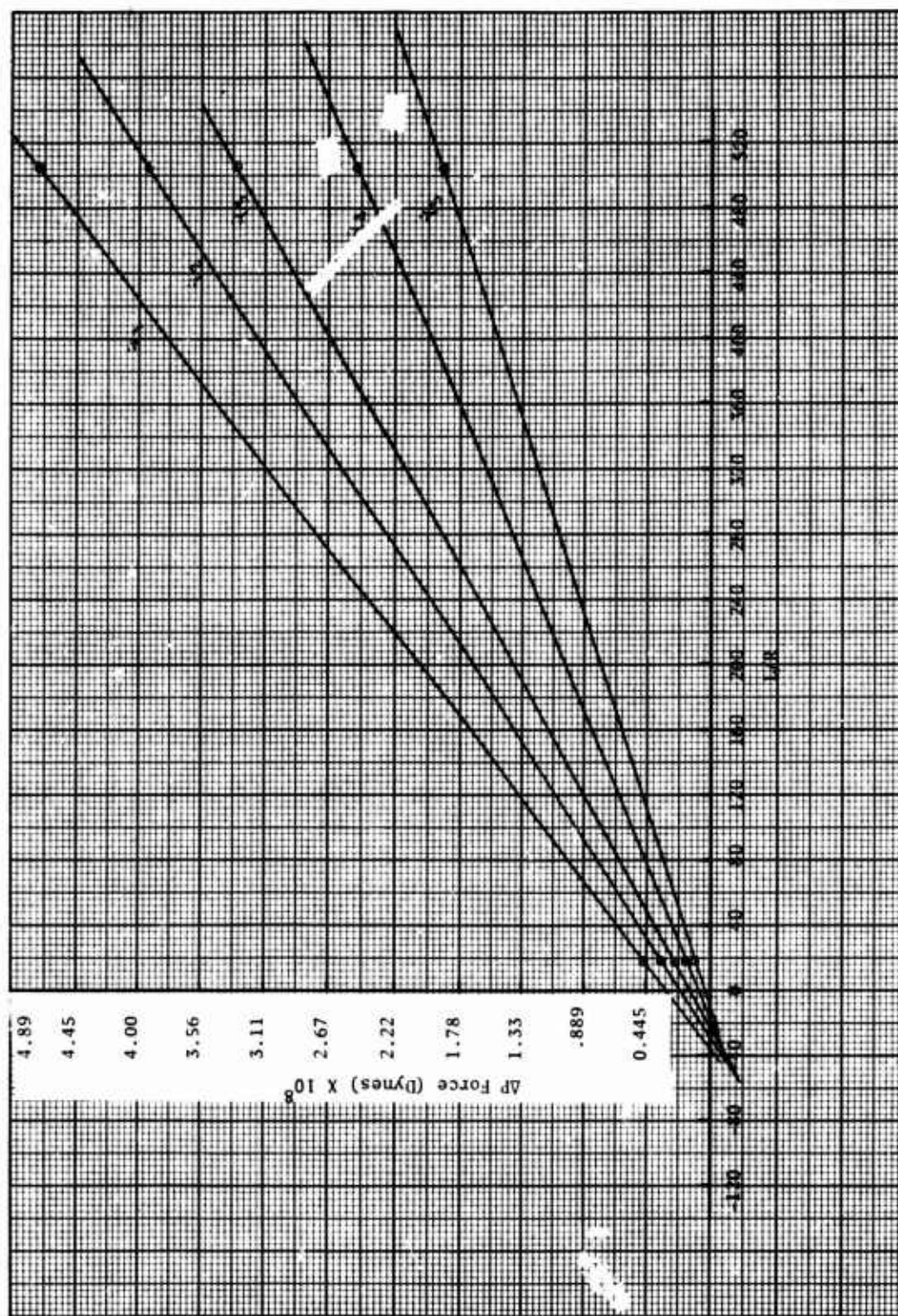


Figure 2. Pressure (Dynes) versus L/D of Two Different Size Capillaries at Four Different Shear Rates at 23.9°C

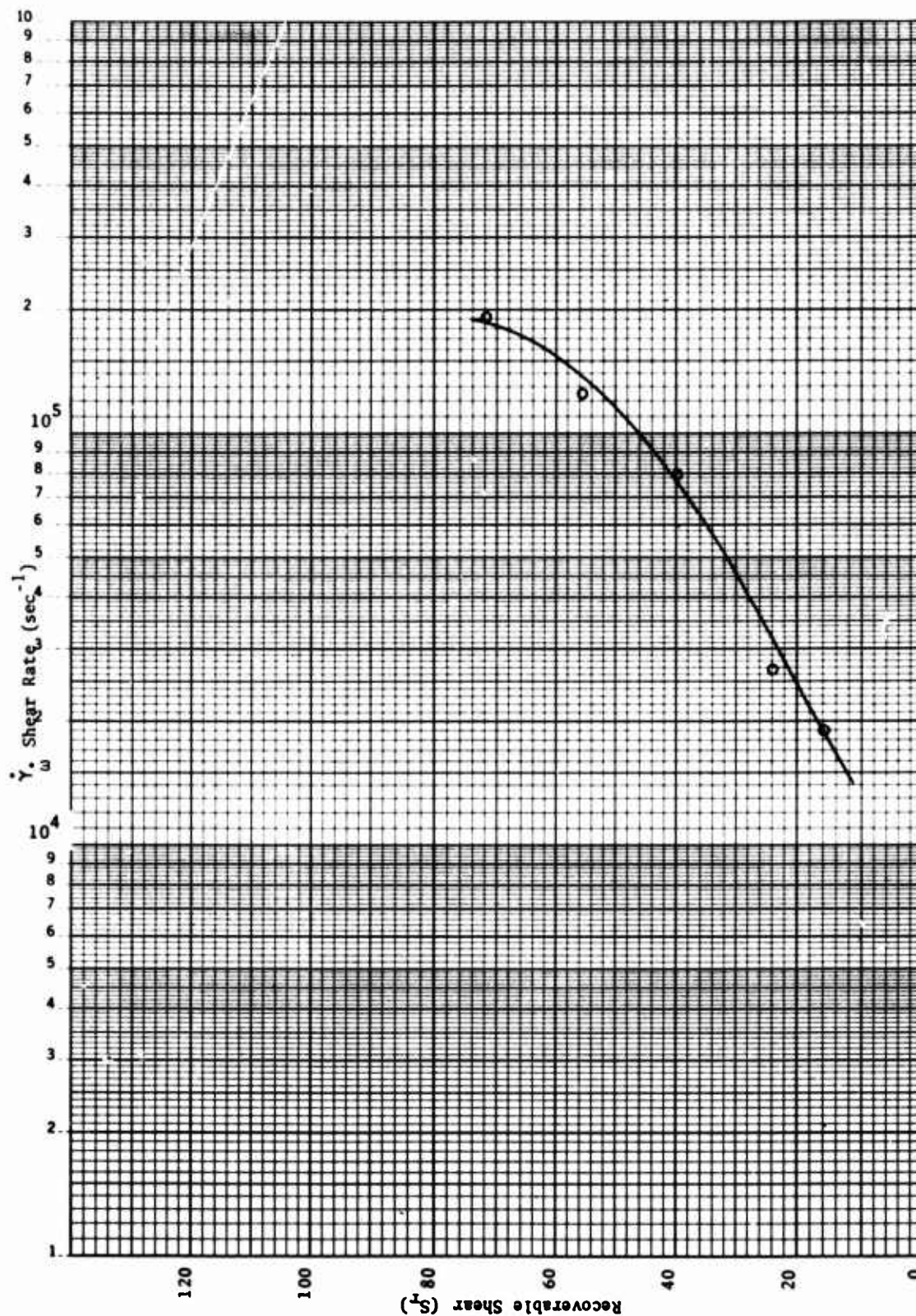


Figure 3. Recoverable Shear versus Shear Rate for Napalm B

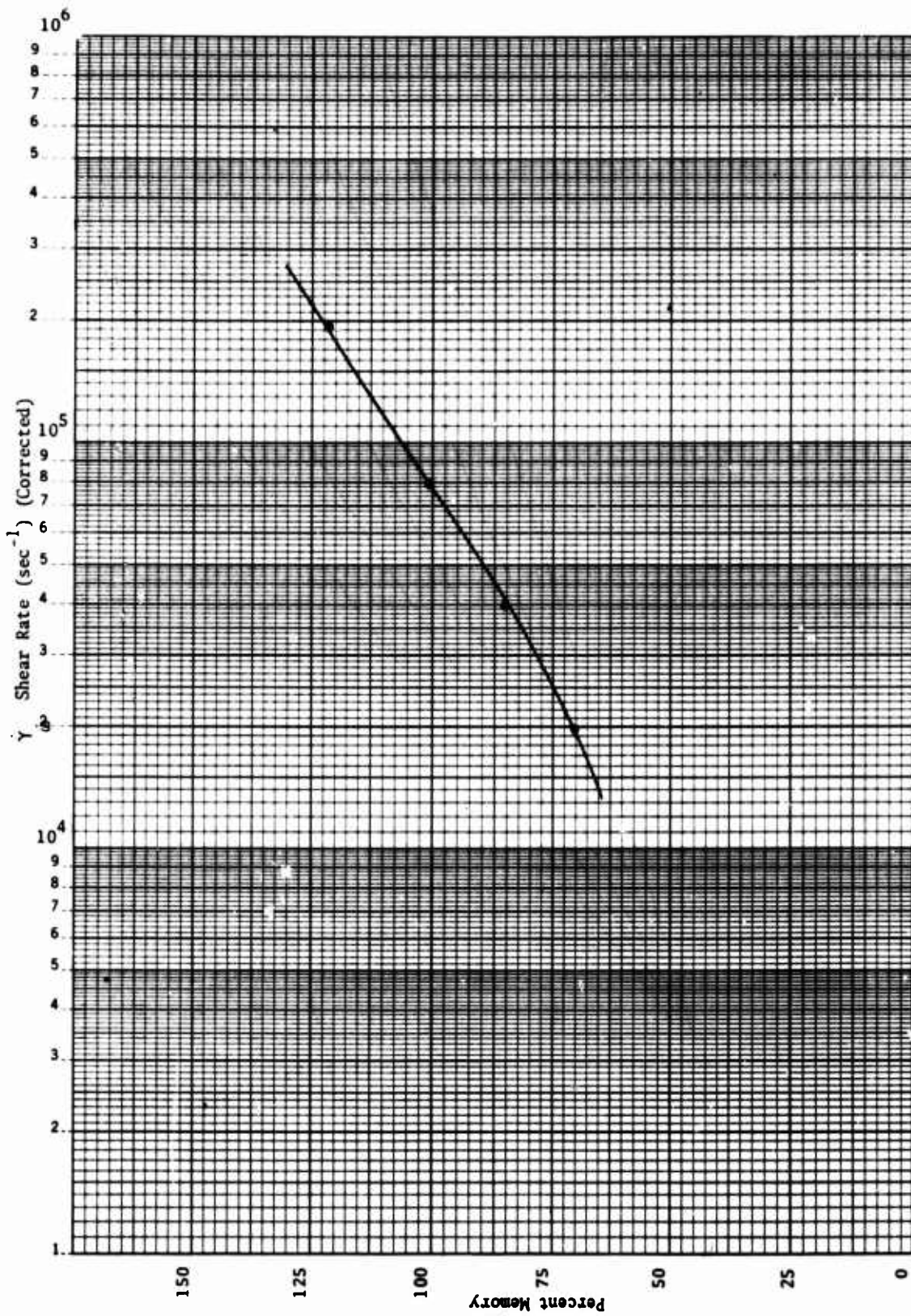


Figure 4. Percent Memory versus Shear Rate for Napalm B

measurements are required, with an involved analysis procedure to determine the recoverable shear number. In the memory technique, the physical response to the stored energy or the swelling of the material emerging from the capillary is measured. While the technique is more empirical than theoretical, the procedure required for measuring the phenomenon is considerably easier than that for determining the recoverable shear. Either of the methods can be applied to the problem of predicting the behavior of candidate flame fuel formulations on a relative basis. The relationship between recoverable shear and memory is discussed by Bagley and Duffy⁸. It is a complex relationship deeply involved with rheological theory and is beyond the scope of this report.

Reference

8. Bagley, E. B. and Duffy, H. I., "Recoverable Shear, Strain, and the Barnes Effect in Polymer Extrusions," Transactions of the Society of Rheology, 14:4 (1970), p. 545.

SECTION III

EXPERIMENTAL

APPARATUS

The flow data obtained during this study was acquired using a modified Monsanto Research Corporation Model 3501 Capillary Extrusion Rheometer shown in Figure 5. The instrument is designed for measuring the melt flow of thermoplastics. In addition to a capability for determination of the ASTM melt index, provisions are made in the design to vary the temperature from -17.8°C (0°F) to 204.4°C (400°F) and the pressure or stress applied from 0 to 160 psi. The L/r (length to radius) ratio of the capillaries used may be varied over a wide range. Thus, varying the capillaries used and the applied pressure, shear rates to 10^4 sec^{-1} can be obtained with the basic instrument. Additional modifications to the instrument by the Air Force Armament Laboratory have extended the shear rate range to 10^6 sec^{-1} .

For operation at temperatures of 40°C and below, temperature control is obtained by circulating a cooling fluid through the barrel from an external cooler. The temperature controllers and heaters built into the instrument are used to maintain the desired temperature. Measurements below -6.7°C (20°F) were not attempted because of water condensation inside the barrel.

Pressure is applied to the solution with a ram driven by oil pumped nitrogen in the range of 0 to 160 psi gauge reading. Dual gages are used to improve the precision of the measurements in the lower pressure ranges. The ram designed for the instrument is fabricated of stainless steel with a loose fit to the barrel wall. At higher pressures this loose fit allows some flow-by of material past the ram. To eliminate this flow-by, the ram has been modified by the addition of a Teflon® sleeve on the lower 12 to 15 mm of the ram. (Figure 6 shows the rams used in this study.) This sleeve is slightly tapered with the larger portion at the bottom, thus allowing the Teflon® to flow when under pressure. To compensate for the friction between the Teflon® and the wall, the instrument is calibrated with a Moorhouse Ring Dynamometer with the ram in place to determine the actual force on the solution at each pressure setting at various temperatures.

The capillary is located at the bottom of the barrel and is held in place by a retaining nut shown in Figure 7. The small rod on the nut is used as a reference for measurement of the strand diameter in the determination of elasticity as memory. The capillary length and diameter is selected according to the viscosity of the solution and the shear rates desired. The smaller diameter capillaries made in the Air Force Armament Laboratory machine shop were fabricated from constant bore, type 316 stainless capillary tubing. The capillary tubing was set into the machined capillary



Figure 5. Capillary Extrusion Rheometer

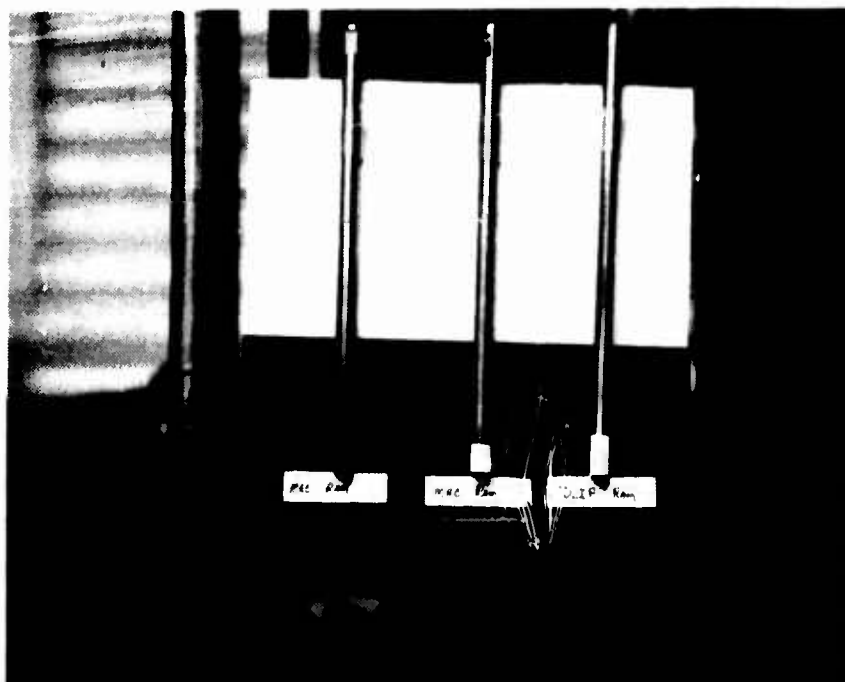


Figure 6. Extrusion Rams used in the Study

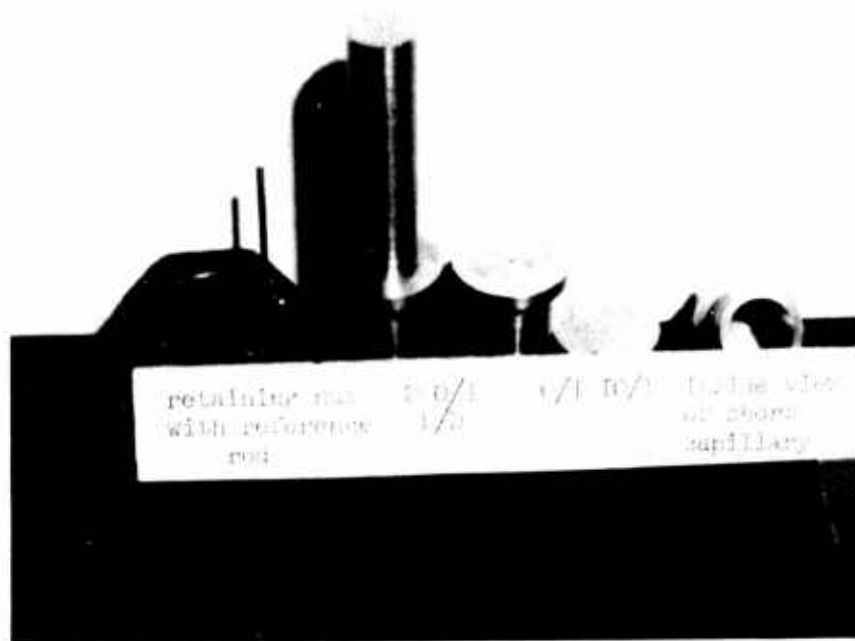


Figure 7. Capillaries used for the Recoverable Shear (S_r) Study

block by freezing the capillary tube and inserting it into the pre-drilled block, which is heated to enlarge the hole for tube insertion. Figure 7 also shows several of the capillaries fabricated by the Air Force Armament Laboratory machine shop. Table I gives a summary of the capillaries used in the study. The dimensions of each capillary used in the study were measured by physical means, using a micrometer to determine the length and an optical comparator to determine the diameter. The viscosities of Brookfield standard solutions were then determined with each capillary to verify these measurements.

The basic rheometer is equipped with four timers which are used to measure the time required to extrude a predetermined volume of material to the nearest 0.01 minute. Using a series of microswitches riding on a cam traveling with the ram, the rheometer in the automatic mode first compresses the fluid, then extrudes four set volumes of material in series from a single filling of the barrel. The time required for each extrusion of 1.245 cm^3 (0.0762 in^3) is recorded. To obtain higher shear rates or study less viscous materials where the times are very short, a Hewlett-Packard Model 5325B electrical counter (Figure 8), capable of measuring to 0.0001 second, has been wired into the first and last microswitches

TABLE I. CAPILLARY REFERENCE DATA

SOURCE	RATIO	LENGTH	DIAMETER
	L/R	(cm)	(cm)
AFATL	10/1	0.125	0.0250
AFATL	20/1	0.2525	0.0250
AFATL	49.8/1	1.2450	0.0500
MRC	65.7/1	2.5450	0.0775
AFATL	66.9/1	2.5088	0.0750
AFATL	74.9/1	1.8725	0.0500
AFATL	99/1	1.2375	0.0250
AFATL	99.8/1	2.4950	0.0500
AFATL	150/1	1.8750	0.0250
MRC	176/1	1.8608	0.0213
AFATL	200/1	2.5088	0.0250
AFATL	499.8/1	6.2475	0.0250

AFATL - Made by the Air Force Armament Laboratory

MRC - Made by the Monsanto Research Corporation

on the cam. By setting the rheometer to the manual mode of operation, the entire volume of the barrel, 6.751 cm^3 (0.4119 in^3), may be extruded at one time with an accurate measure of the time required; also, the pressure is recorded during the extrusion for each data point.

For the determination of elasticity by the memory technique, the strand of polymer being extruded is photographed with a Singer Super Graphic Camera equipped with a 4 by 5-inch Polaroid® back and modified with a 45.5-cm tube to extend the focal length. This modification gives approximately a 4x magnification on the photograph. The photograph of the strand is then measured with a magnifying comparator, and memory is calculated by the previously mentioned equation.

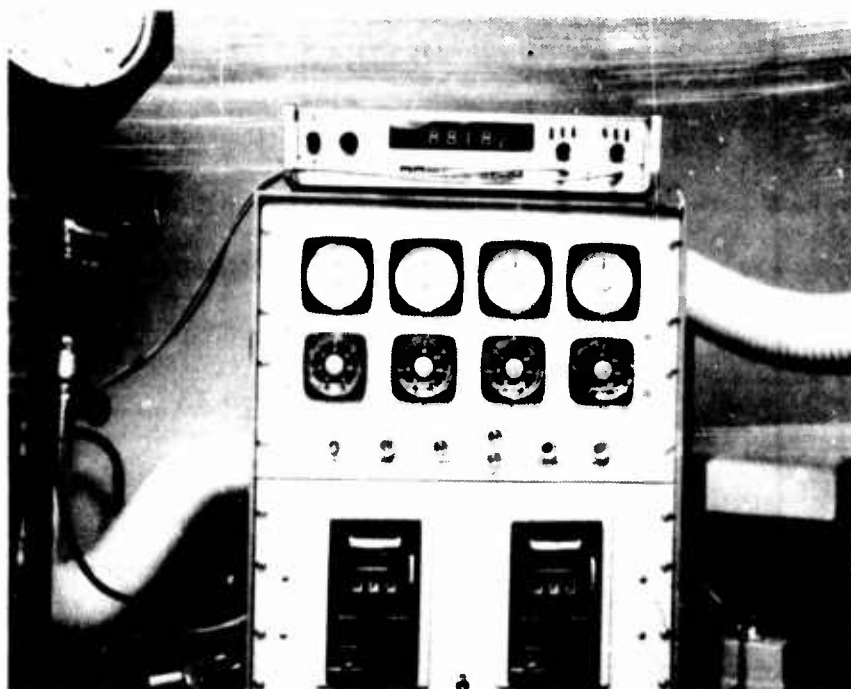


Figure 8 H/P 5325B Electrical Counter

TECHNIQUES

The high volatility and viscous nature of the polymer solutions studied caused problems in loading the rheometer barrel. The procedure used for filling of the barrel must minimize solvent losses and the solution must contain no voids or air bubbles. The technique developed for barrel loading utilized a modified 30 cc disposable syringe fitted with a nominal 0.48 cm x 15.25 cm I. D. piece of Teflon® tubing, as

shown in Figure 9. The sample jar is fitted with a modified lid containing a Swagelok® fitting for tube insertion. The jar is inverted and the syringe filled through this fitting, thus minimizing the solvent loss. The Teflon® tubing is then slipped onto the end of the syringe and the tubing inserted to the bottom of the barrel. The tube is slowly removed as the barrel is filled. When filled, the barrel is sealed with either a rubber stopper or the Teflon® tipped ram. For solutions of low viscosity, the capillary tip is plugged with a round wooden toothpick to prevent solvent losses. The solution is allowed to equilibrate for 5 minutes prior to a run at 23.9°C (75°F) and for 10 minutes prior to a run at 10°C (50°F) or lower.

The orifice is removed and cleaned between each run with a wire reamer and solvents. The barrel is cleaned with a 20-gauge gun barrel cleaner and a soft cloth. After cleaning, the barrel is closed to prevent water condensation at lower temperatures.

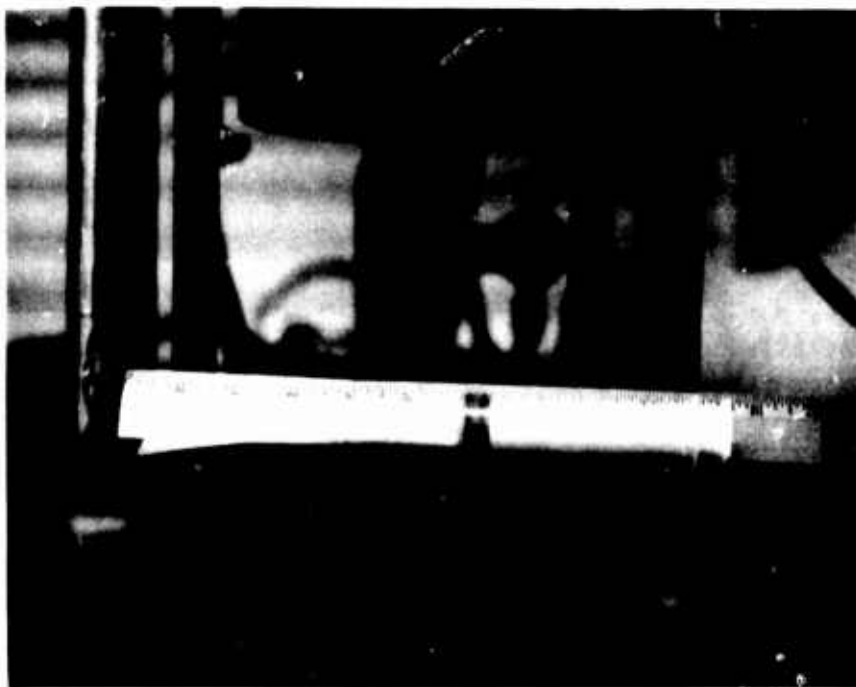


Figure 9. Modified Syringe with Tubing

MATERIALS

The Napalm B used in the study was prepared in the laboratory in accordance with the Air Force Armament Laboratory Purchase Description Assignment No. 5, Napalm B, dated 27 April 1966, or procured from Atlas Fabricators, Inc., Torrence, California, as a part of a large purchase of

production material for use in filling experimental weapons. Napalm B is composed of polystyrene (46% $\pm$ 1.0%), gasoline (33% $\pm$ 1.0%) and benzene (21% $\pm$ 1.0%). Regular-grade gasolines were used; most of them contained lead and were obtained from the Eglin Air Force Base motor pool or from local service stations. The polystyrene used was DOW 666, obtained from Dow Chemical Company.

The styrene-butadiene copolymers (SBR) were obtained from the B. F. Goodrich Chemical Company. The two SBRs used in this study were Ameripol® 1513, designated SBR 40 (contains 40 percent styrene) and Ameripol® 1013, designated SBR 43 (contains 43 percent styrene). Solutions of the SBRs were prepared containing a total of 20 percent of one of the copolymers, 43.7 percent gasoline, and 27.3 percent benzene.

The styrene-methylmethacrylate (NAS) used was obtained from the Richardson Company. Solutions were prepared containing 40 percent NAS, 36.9 percent gasoline, and 23.1 percent benzene.

In order to minimize variations in the solutions and eliminate any possible shear degradation of the polymers by mixing, all solutions were prepared by adding the required components to a glass jar, sealing the lid with tape to minimize solvent losses, and slowly rotating the jars on an approximately 66-cm diameter wheel. From two to three days were required to obtain clear solutions with no indications of undissolved material. As an additional check for solvent loss, the prepared samples were weighed before and after mixing.

DATA REDUCTION

The pressure applied for extrusion, the time required for the extrusion, strand diameter measured from the photograph, and the temperature are required for each data point. The data, along with the capillary dimensions and the fixed volume extruded, are used to calculate the shear stress, shear rate, apparent viscosity, and percent memory using a CDC 6600 computer. The computer program is included as Appendix A.

The data generated is presented in graphical form as log-log plots of shear stress versus shear rate and apparent viscosity versus shear rate and semi-log plots of percent memory versus shear rate.

Final curves for the plots of apparent viscosity versus shear rate are determined from a least square analysis of the data points as a part of the computer program.

RESULTS AND DISCUSSION

CALIBRATION OF EQUIPMENT

In order to verify the uniformity of results from the various capillaries used in the study, a series of runs were carried out using each of the capillaries to measure the viscosity of the same solution. The results of these runs at 23.9°C (75°F) on a sample of Napalm B formulated with regular grade gasoline are shown in Figure 10. All of the data points are well within normal experimental error. This data verifies both the reproducibility of the capillaries and the techniques used to handle the solution and load the rheometer barrel.

Another problem which must be considered is the reproducibility of solution preparation. In order to verify the reproducibility of mixing techniques, three separate solutions of Napalm B formulated with regular grade gasoline were prepared. Figure 11 shows the data obtained from these solutions.

COMPARISON OF RECOVERABLE SHEAR AND MEMORY

The type data obtained from recoverable shear and percent memory determinations can best be illustrated by comparing the results of the two methods on the same solution. Figure 12 shows a comparison of the results of the two methods, using Napalm B at 23.9°C as an example. While the numerical values obtained from the two methods are quite different, both values increase as the shear rate is increased. As can be seen from the lines in this figure, the change in memory with increasing shear rate is near linear, while the change in recoverable shear is more drastic and appears to be a logarithmic-type function.

RHEOLOGICAL BEHAVIOR OF NAPALM B

Flow curves (viscosity as a function of shear rate) were prepared for Napalm B at six different temperatures from -6.7°C (20°F) to 60°C (140°F). The results of these experiments, using a production lot of Napalm B, are shown in Figure 13. As has previously been discussed, polystyrene (and thus Napalm B) is a thermoplastic material; that is, its rheological behavior varies as a function of temperature. For the solution studied, the viscosity increases by a factor of about five as the temperature is decreased from 60°C to -6.7°C. The curves obtained are similar to those obtained by Gaskins² at Edgewood Arsenal and Long^{3,4} at Monsanto Research Corporation. Small differences in this data and previous data can easily be attributed to actual differences in the solutions, since Long has observed considerable variations from different samples of

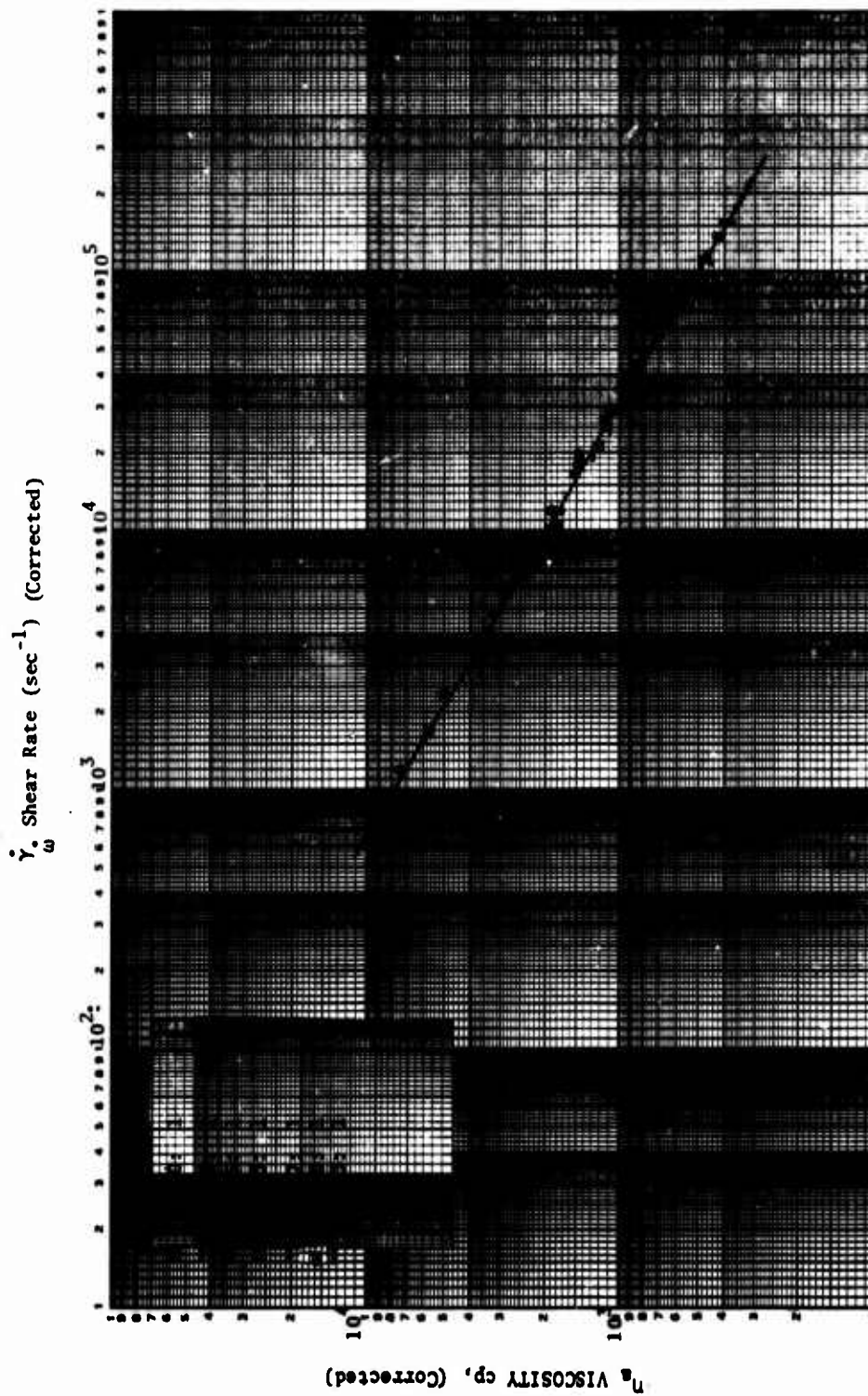


Figure 10. Flow Curves of Various Capillaries for Napalm B

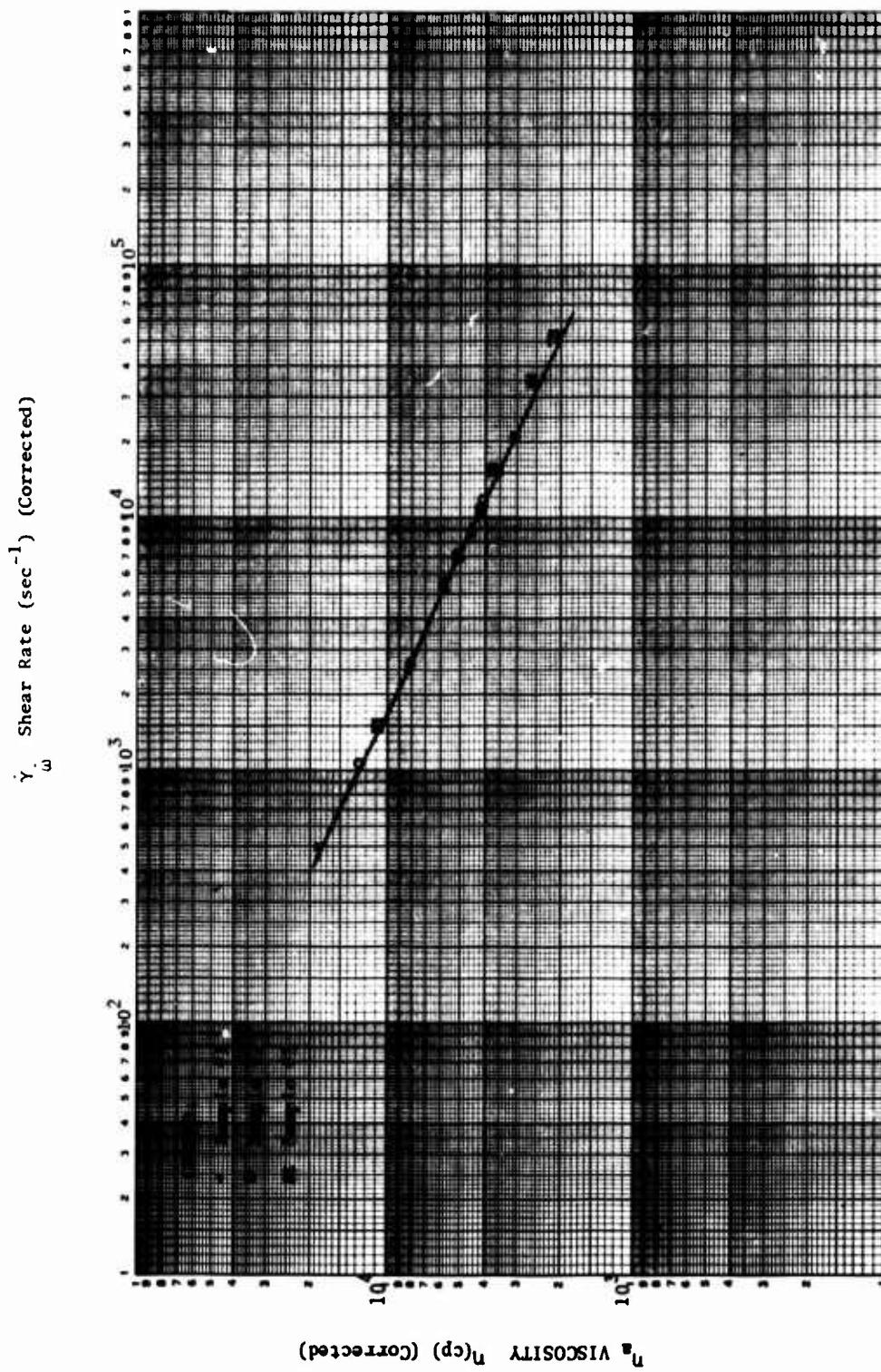


Figure 11. Flow Curve for Napalm B with Chevron Gasoline at OC (32°F)

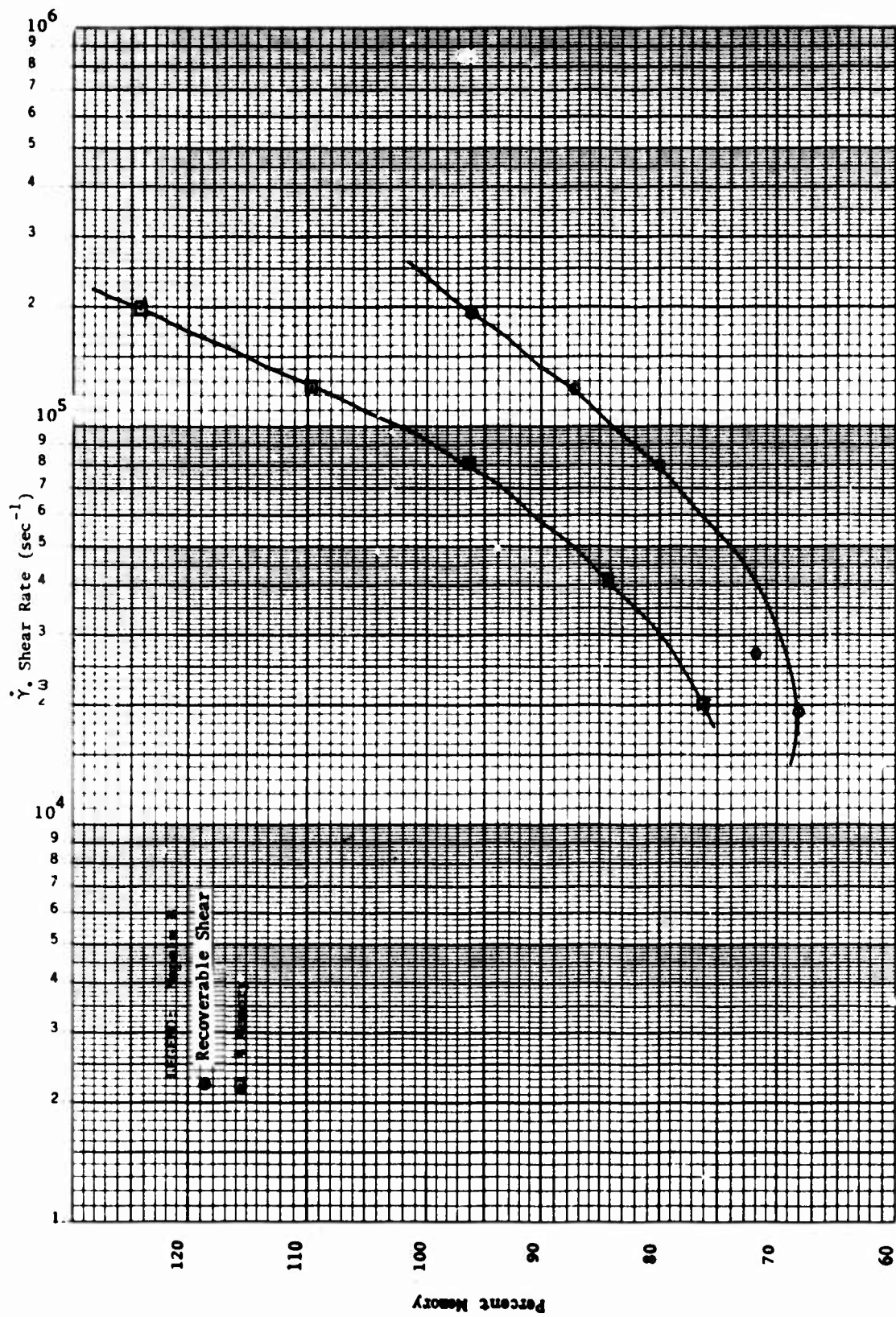


Figure 12. Comparison of Percent Memory and S_r for Napalm B

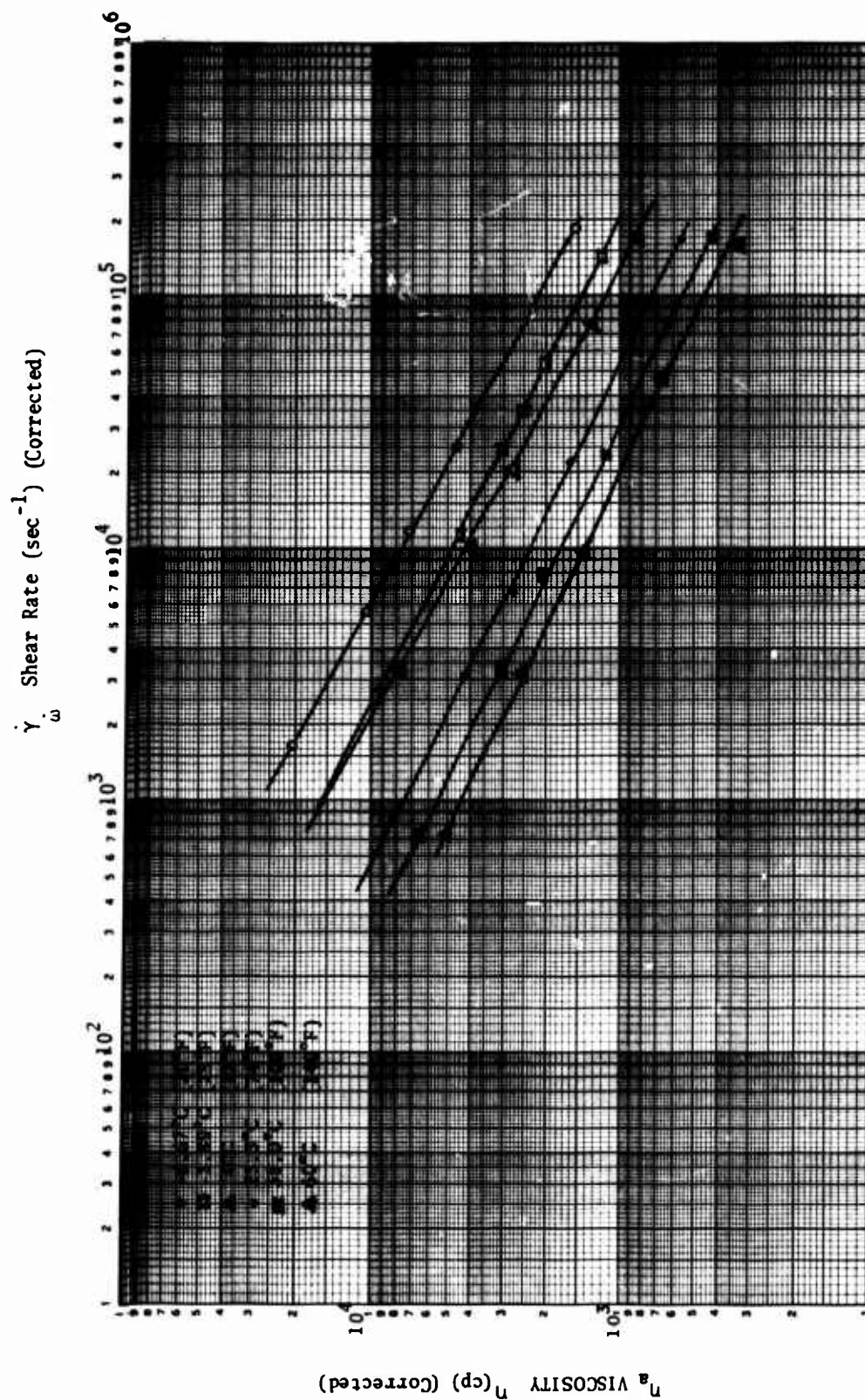


Figure 13. Flow Curve for a 46 Percent Styrene-Methylmethacrylate at 23.9°C

the production lot of Napalm B. These results show that the change in viscosity over the shear rate range of 10^3 sec^{-1} to 10^5 sec^{-1} is linear, as compared to the same curvature in the lines reported in previous efforts^{2, 3}. Since the primary interest is in the high shear forces during fuel dissemination where a bomb case opens, the lower shear rate range is not of interest to our application and no attempt was made to collect data below 10^2 sec^{-1} .

Figure 14 shows the percent memory of Napalm B as a function of shear rate at -3.89°C and 23.9°C . As was the case for the viscosity, the thermoplastic behavior is evident from the considerable difference in the memory at the two temperatures.

The solvent system used to prepare the polystyrene solution has a definite effect on the rheological properties of the solution. To illustrate this, several Napalm B formulations were prepared using different brands of gasoline. The percentages of polystyrene, benzene, and gasoline were constant so the only variable was the brand of the gasoline. Figures 15 and 16 show the effects of various gasolines on the viscosity and memory. Some of the gasolines used did not appear to form a true solution and were not included in the reported studies. As can be seen in the figures, the type of behavior (in the shape and slope of the curves) is the same for the different formulations. However, the absolute values of viscosity and memory are somewhat different for the various gasolines. This behavior emphasizes the importance of controlling experimental variables in a precise laboratory study and illustrates one of the major problems when data from various laboratories is compared.

RHEOLOGICAL BEHAVIOR OF EXPERIMENTAL FORMULATIONS

In previous efforts^{3, 4} several experimental formulations have been evaluated as candidate flame fuels. Three of these formulations are included in this report to illustrate the investigation of different polymer solutions with different properties by this technique.

Figures 17 and 18 show the properties of a 40 percent styrene-methylmethacrylate (NAS) solution. The elastic properties of this solution are very similar to those of Napalm B, as shown in Figure 18. The viscosity is slightly less dependent on shear rate than that of Napalm B; i.e., the viscosity versus shear rate curve is more horizontal. In addition, the temperature dependence is even more pronounced than for Napalm B. Based on this information, it would be predicted that NAS would be equal to or slightly better than Napalm B at 75°F ; however, the increased viscosity at 25°F indicates that the performance would be inferior at low temperatures.

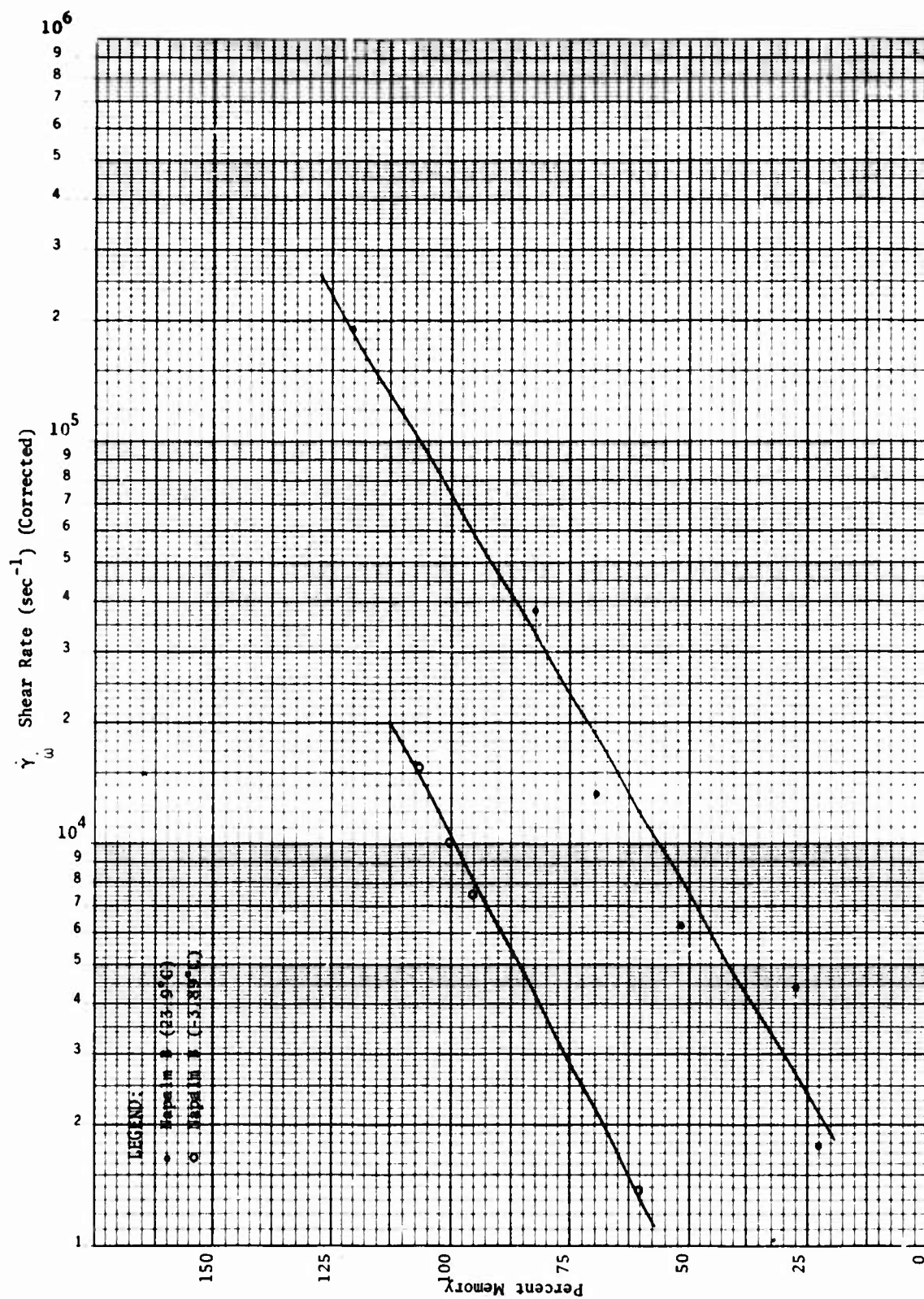


Figure 14. Percent Memory of Napalm B (Dow Mixed)

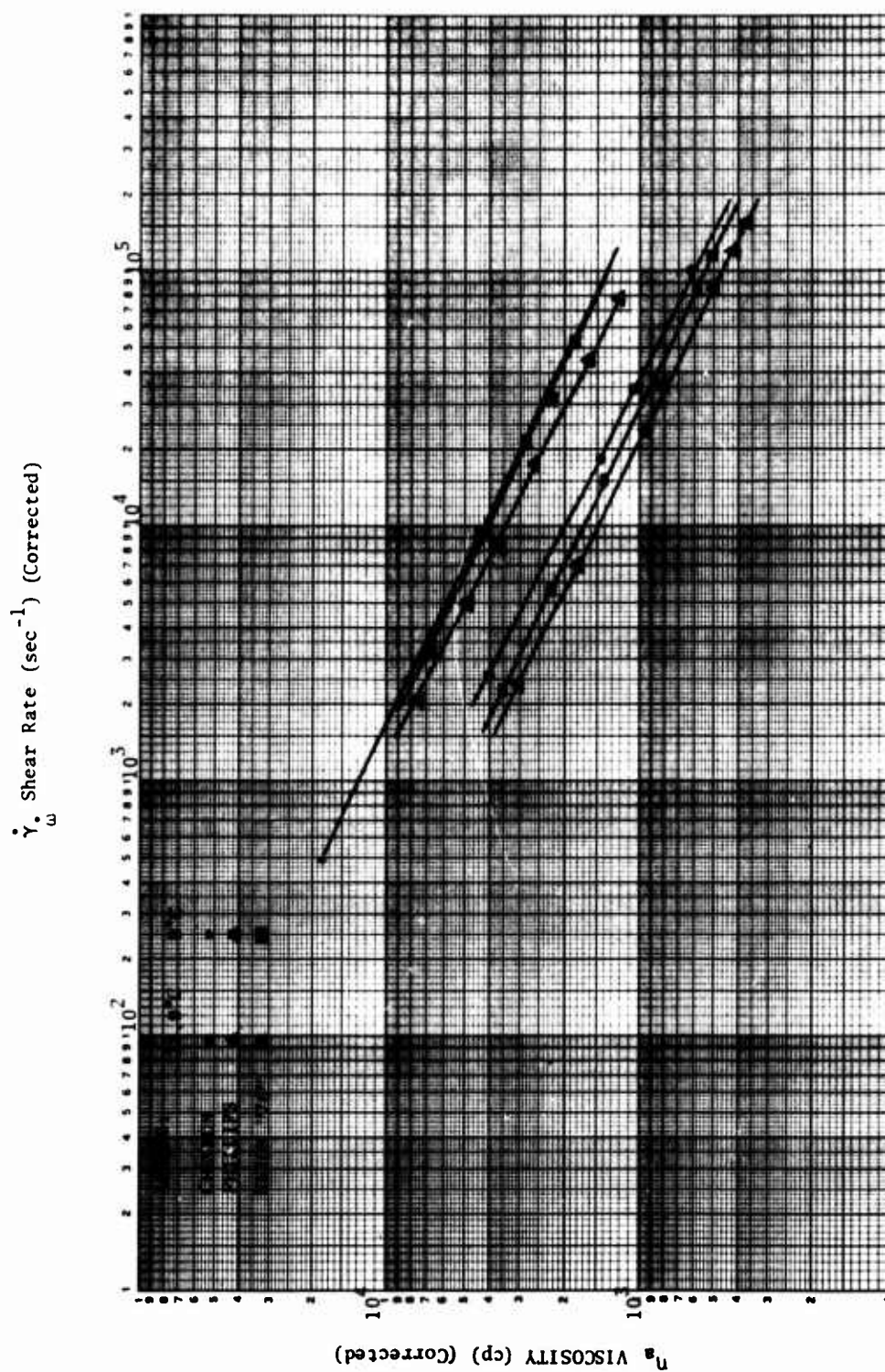


Figure 15. Flow Curve of Napalm B Formulated with Various Gasolines

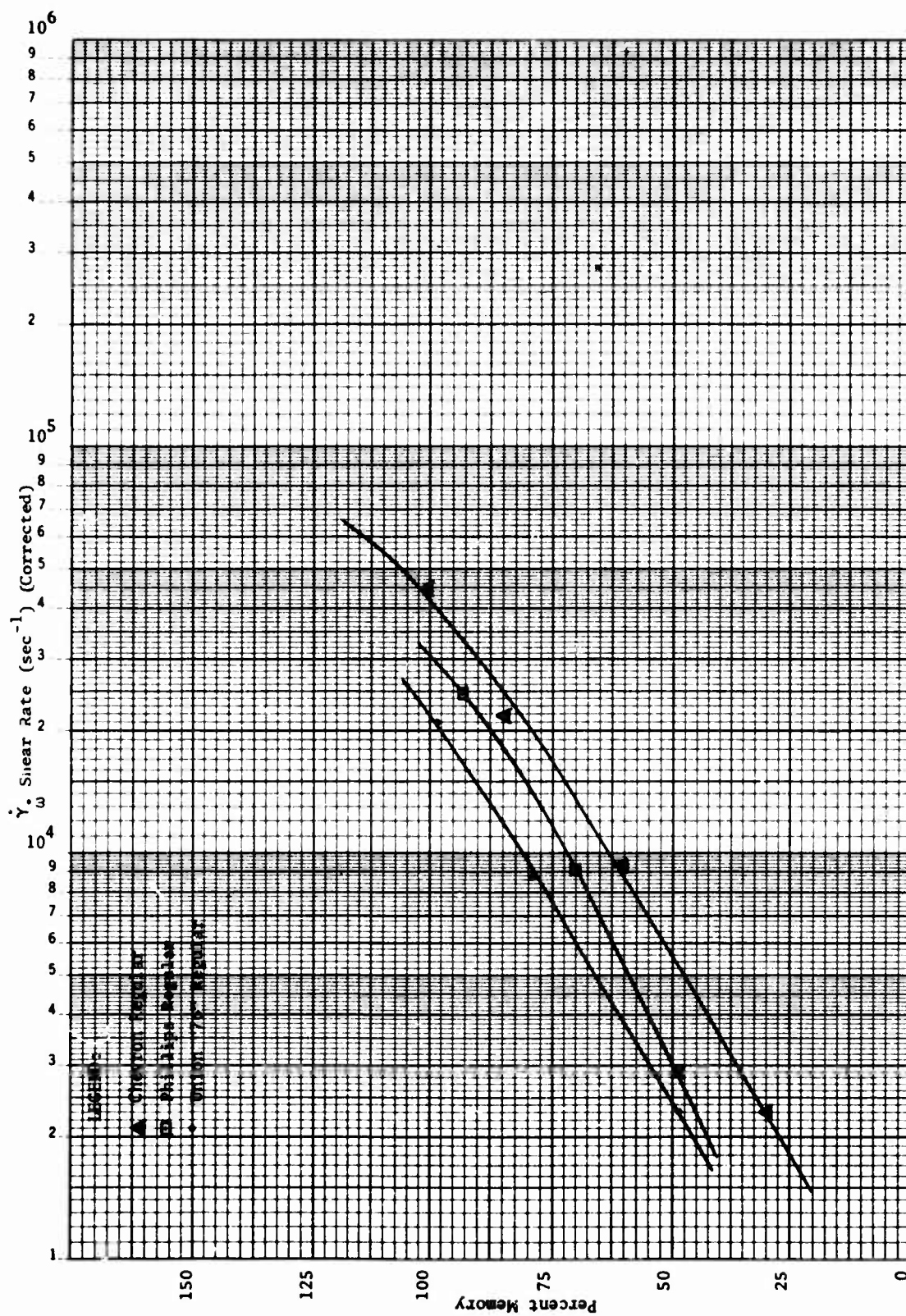


Figure 16. Percent Memory of Various Gasolines and Polystyrene Formulations

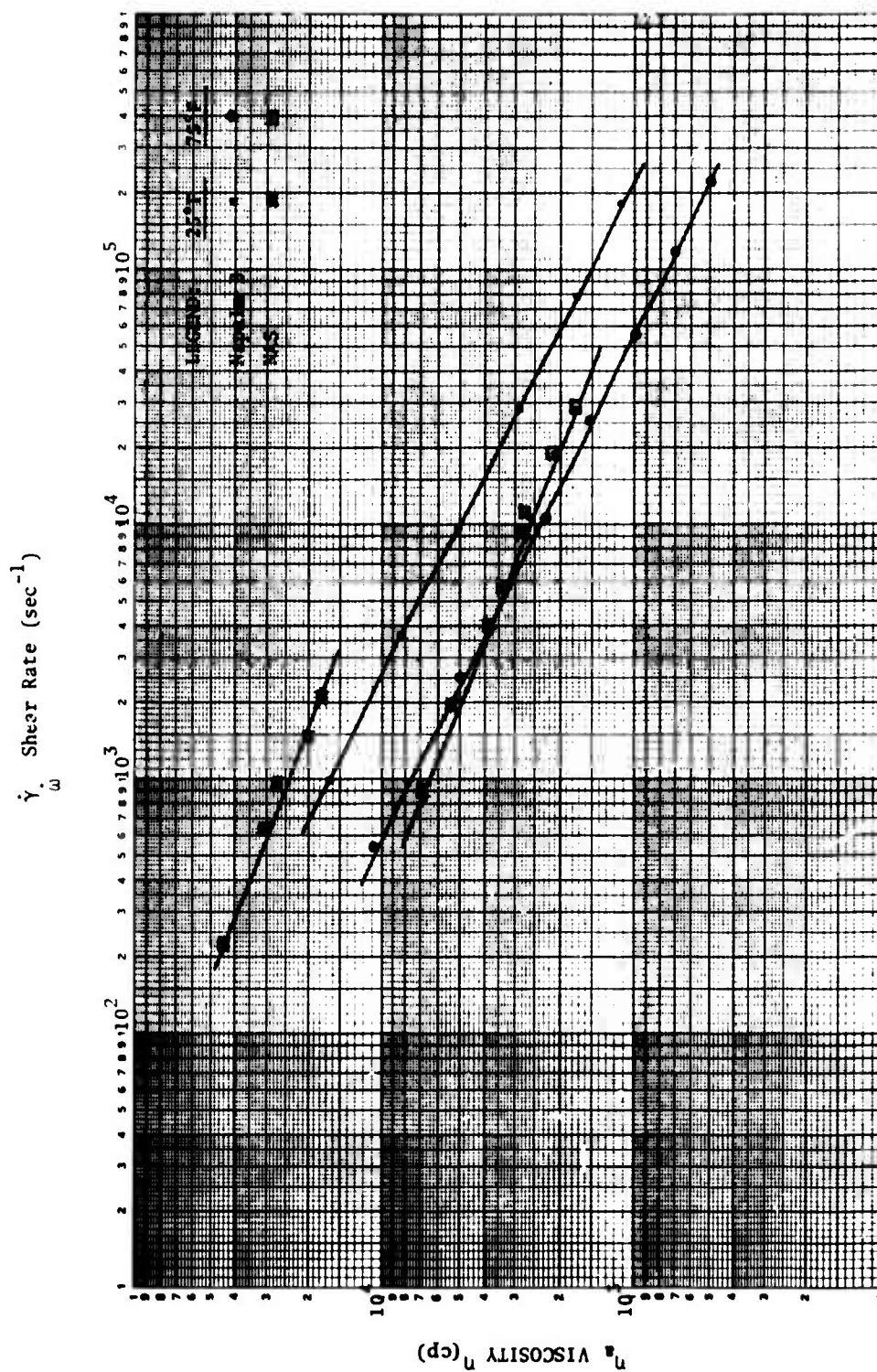
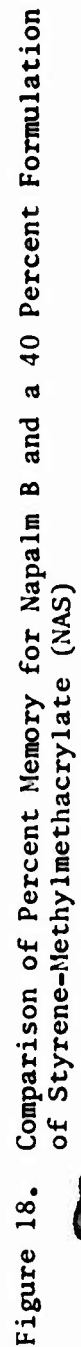


Figure 17. Flow Curve of Napalm B and Styrene-Methylmethacrylate at 25°F and 75°F



The most promising candidate materials investigated to date have been the styrene-butadiene (SBR) copolymers. The viscoelastic properties of these rubber-like materials are considerably less temperature dependent than the properties of a thermoplastic material like polystyrene. In addition, the viscosity and elasticity can be varied by changing the percentage of styrene in the copolymer and by altering the molecular weight distribution.

The properties of a 29 percent solution of SBR 40 (containing 40 percent styrene) are shown in Figures 19 and 20. Although the viscosity is lower than that of Napalm B, it is significantly less temperature dependent. The elastic properties are almost independent of the shear rate, contrasting sharply to the steep shear rate dependence of Napalm B.

Figures 21 and 22 show the properties of a 29 percent solution of SBR 43 (containing 43 percent styrene). The rheological properties are very similar to those observed for SBR 40, except the absolute value of percent memory is higher; that is, the solution has a greater elastic strength.

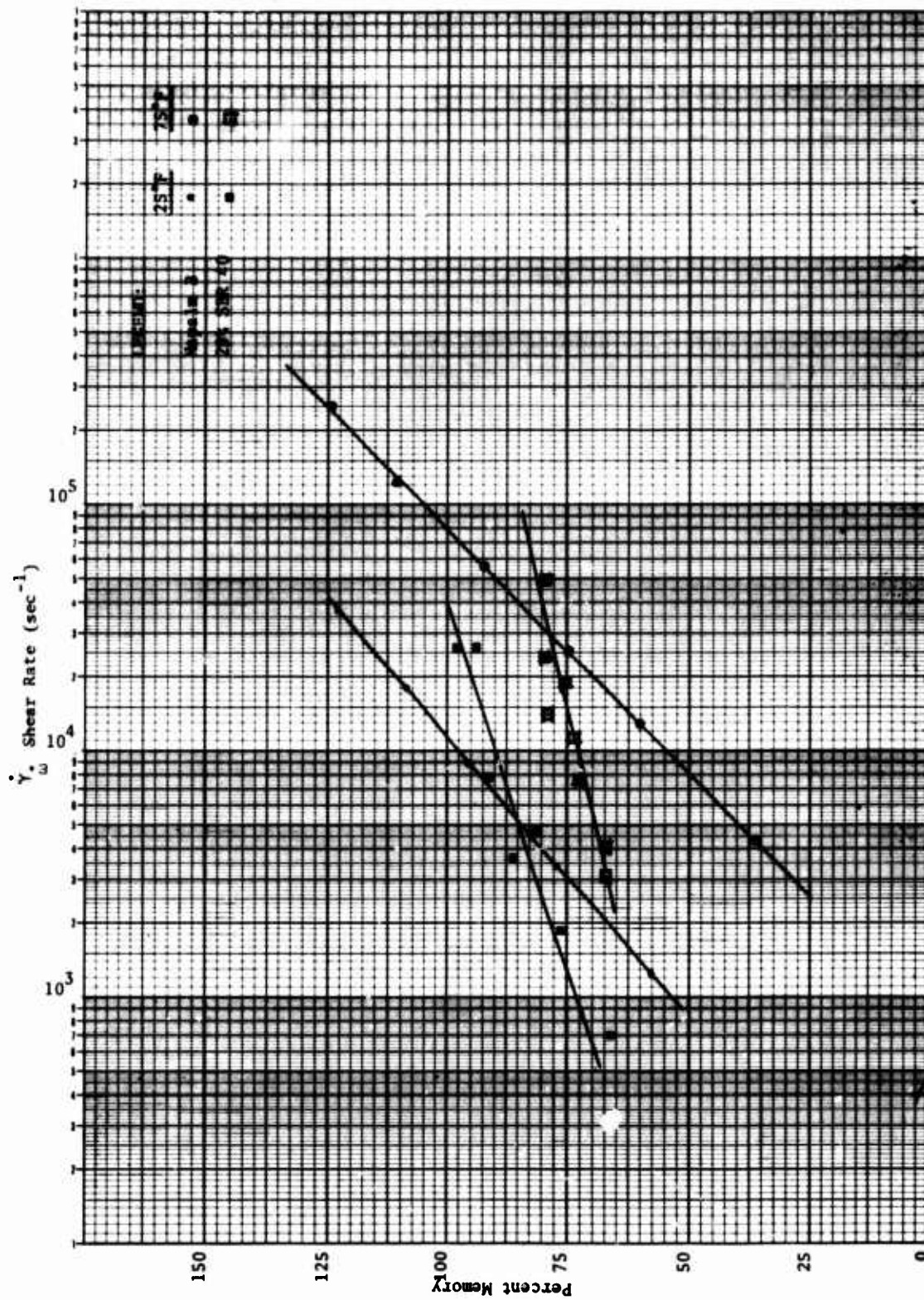


Figure 19. Comparison of Percent Memory for Napalm B and 29 Percent SBR 40 Solution

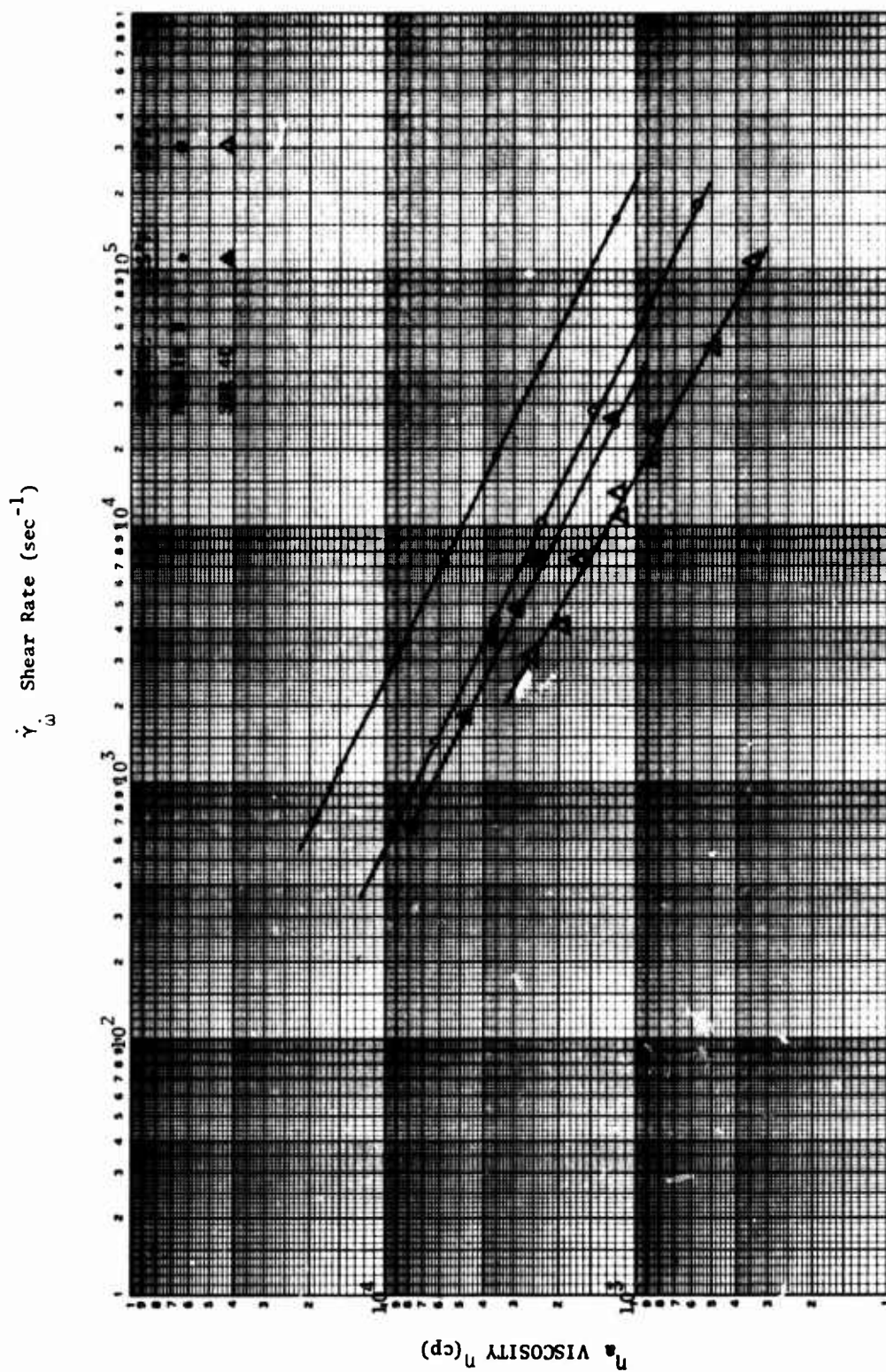


Figure 20. Comparison of Viscosity versus Shear Rate of 29 Percent SBR 40

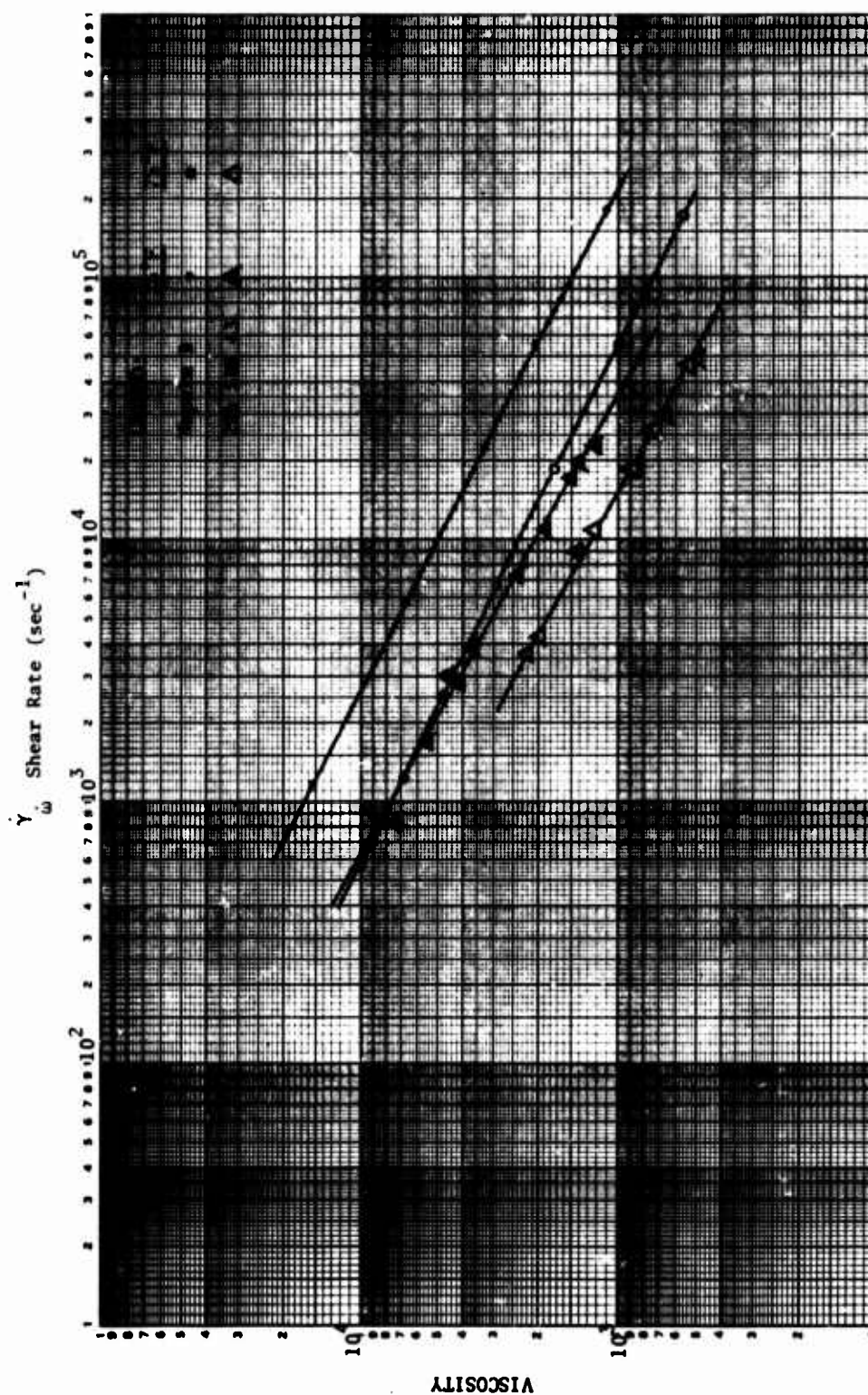


Figure 21. Comparison of Viscosity for Napalm B and a 29 Percent SBR 43 Formulation

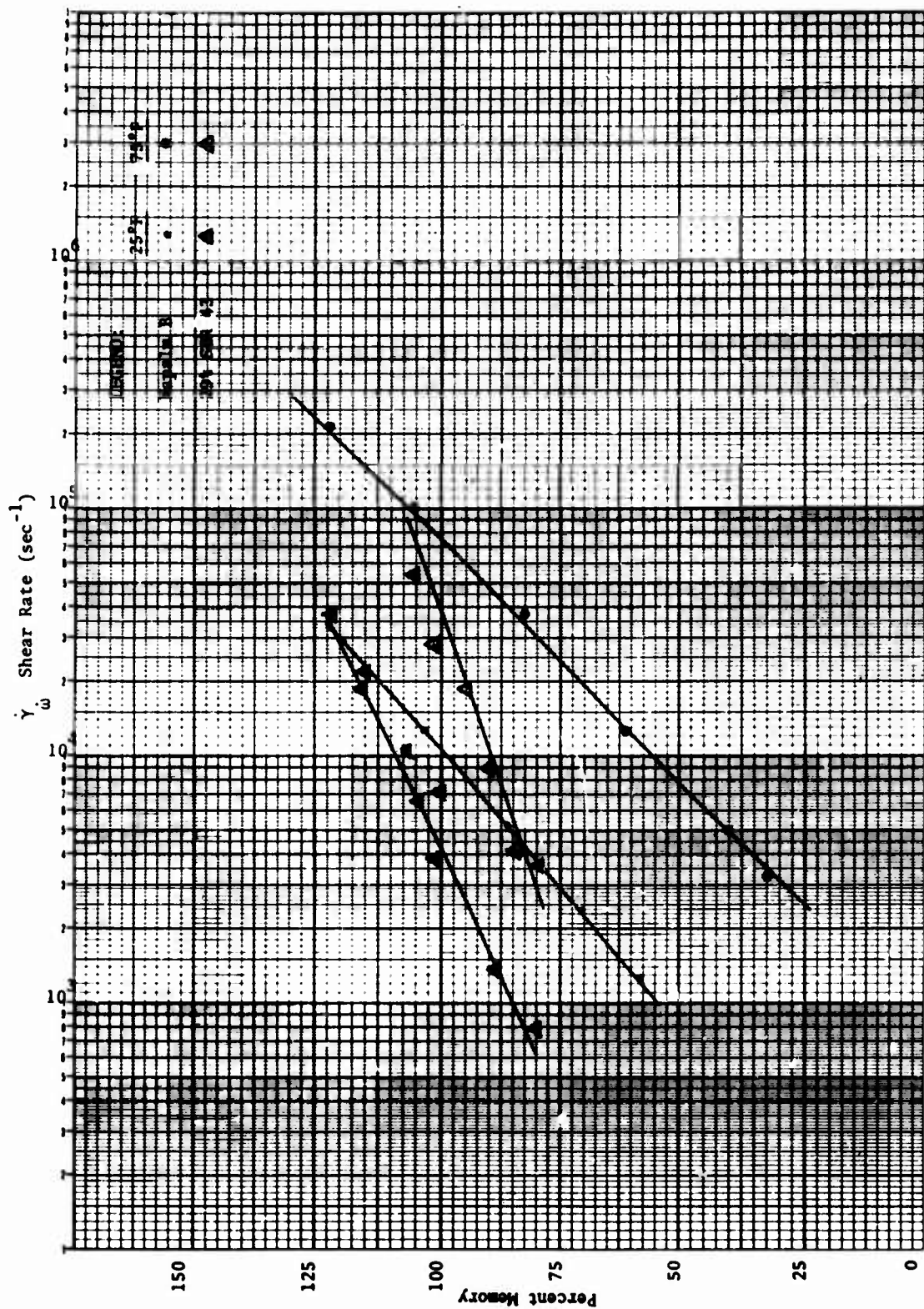


Figure 22. Comparison of Percent Memory for Napalm B and 29 Percent SBR 43 Formulation

SECTION V

SUMMARY AND CONCLUSIONS

The instrumentation and techniques developed during this study represent a significant advancement in the Air Force capability for development of improved flame agents for use in firebombs. The study has shown that a capillary extrusive rheometer can be utilized to measure the rheological properties of polymer solutions with viscosities in the range of 10^2 to 10^5 centipoise at shear rates from 10^2 to 10^6 sec^{-1} , as a function of temperature from 25°F to 100°F.

The rheological behavior of a given polymer solution can be utilized to predict the dynamic behavior of the material during dissemination from a firebomb. Thus, this laboratory-scale technique can be used to screen candidate firebomb fuels.

While either the die swell or recoverable shear methods may be used to study the elastic properties of a solution, the die swell method has been shown to be a much faster and simpler method of obtaining the desired information.

The solvent system used in preparation of a solution has been shown to have an effect on the values of viscosity and elasticity of a solution but not on the shapes of the curves. A series of curves obtained for solutions prepared with different brands of gasoline are parallel but offset in the value of viscosity or elasticity. These results emphasize the importance of using a standardized gasoline or gasoline simulant when data from different techniques or different laboratories are compared.

The rheological properties of solutions of the styrene-butadiene copolymers (SBR) have been shown to be less dependent on temperature or shear rate than thermoplastics, such as polystyrene.

More data are required to determine the extent of shear degradation with a given viscoelastic property. However, the test used did not attempt to measure all the controlling parameters encountered in dynamic air gun and sled track tests. It should be recognized that the test used in this study was designed for laboratory purposes and does not necessarily predict the field behavior of the agent when exposed to various means of dissemination.

APPENDIX A

CAPILLARY EXTRUSION RHEOLOGY DATA REDUCTION PROGRAM 1939

```

5      PROGRAM P1939(INPUT,OUTPUT,FILMPL,TAPE1,TAPE0)
        DIMENSION SAMPLE(6),FORCE(20),TIME(20),CAPD(30),T(20),O(20),
1      DIA(20),TLOG(20),DLOG(20),SRC(20),
        DIMENSION BVOL1(20),
        COMMON /FIT1/ B
        DIMENSION PERM(20)
        COMMON NOF,XMAX,XMIN,YMAX,YMIN
        EXTERNAL TAB1V
        DATA (CAPD(I),I=1,19)/ 5.22,39.00,14.000,3110.0,16600000.,
1      377000.,377000.,377000.,1274000.,1274000.,1274000.,10192000.,
2      10192000.,10192000.,1274000.,10190000.,1274000.,10190000.,
3      10190000./
        DATA (CAPT(I),I=1,19)/ 309300.,15530.,10350.,4002.,1774.,4643.,
1      6208.,9316.,6237.,4147.,3112.,3137.,2071.,1548.,60890.,31060.,
2      1239.,621.2,15380./
        C THE ORDER OF STORAGE OF CONSTANTS FOR CAPILLARIES-
        C (1)4-1 (2)10-1 (3)15-1 (4)33-1 (5)88-1 (6)33.45-1
        C (7)25-1 (8)16.6E-1 (9)24.9-1 (10)37.4-1 (11)49.9-1 (12)49.5-1
        C (13)75-1 (14)100-1 (15)2.55-1 (16)5-1 (17)127.49 (18)249.9-1
        C (19)10.1-1
        WRITE(0,5)
        REMIND 1
        ASSIGN 150 TO IE0F
11     LINE = 0
        PRINT 5
        5 FORMAT(1M1)
19     READ 1,ITEMP,CAP,CLEN,CDIA,IC,IM,IY,SAMPLE
        IF(E0F(1).NE.0.0) GO TO 999
        1 FORMAT(13,A7,2F5.4,A2,A3,A2,5A10,A3)
30     READ 2,BVOL,ODIA,ICAP,IREC
        IF(E0F(2).NE.0.0) GO TO 150
        2 FORMAT(2F10.5,2I5)
        I = 1
35     READ 3,F0RCE(I),TIME(I),DIA(I),BVOL1(I)
        IF(E0F(3).NE.0.0) GO TO 150
        IF(F0RCE(I).EQ.0.) GO TO 25
        I = I+1
        GO TO 20
25     NOF = I-1
        3 FORMAT(4F10.0)
40     CALCULATE Q - VOLUMETRIC FLOW
        DO 30 I=1,NOF
            IF(BVOL.GT.0.) Q(I) = BVOL/TIME(I)
            IF(BVOL.LE.0.) Q(I) = BVOL1(I)/TIME(I)

```

```

45      C CALCULATE SHEAR STRESS
      T(I) = FORCE(I)*CAPT(ICAP)
46      C CALCULATE APPARENT RATE OF SHEAR AT WALL
      D(I) = Q(I)*CAPD(ICAP)
47      C0 CONTINUE
48      C CONVERT SHEAR STRESS(T) AND SHEAR RATE (D) TO LOG NUMBERS FOR PLOTS
49      C T - X AXIS      D - Y AXIS
50      DO 35 I=1,NOF
51      TLOG(I) = ALOG10(T(I))
52      DTLOG(I) = ALOG10(D(I))
53      C
54      C PRINT OUT OF POINTS THAT ARE PLOTTED.
55      WRITE(8,8) CAP, (TLOG(I), I=1,NOF)
      WRITE(8,9) (DLG(I), I=1,NOF)
      8 FORMAT(1H0,9X,*CAPILLARY *,47/10X,*X = *,3X,(10F8.4))
      9 FORMAT(10X,*Y = *,3X,(10F8.4))
60      C
      CALL MAXMIN(TLOG,DLOG)
      IF(IREC.EQ.1) WRITE(1) NOF, (TLOG(I), I=1,NOF), XMIN, XMAX, CAP, CLEM
61      C
62      C PLOT OF LOG SHEAR STRESS VS LOG SHEAR RATE
63
64      CALL SETMIV(107,54,54,107)
65      LL = 1
      LLL = 1
      IF((XMAX-XMIN).GT.2.) LL = 2
      IF((YMAX-YMIN).GT.2.) LLL = 2
      XMAX = XMAX+.10000
      YMAX = YMAX+.20000
      CALL SMXYV(9,0)
      CALL GRIDIV(3,XMIN,XMAX,YMIN,YMAX,.1,.1,1,1,LLL,3,3)
66      C
67      CALL CHSIZV(2,2)
68      CALL RITSTV(13,19,TAB1V)
69      C HORIZONTAL
70      CALL RITE2V(400,70,1024,90,1.20,-1,20HLOG T - SHEAR STRESS,NL)
71      C VERTICAL
72      CALL RITE2V(10,689,1024,90,1.1,-1,1H,NL)
73      CALL RITE2V(10,670,1024,90,1.1,-1,1H0,NL)
74      CALL RITE2V(10,651,1024,90,1.1,-1,1H0,NL)
75      CALL RITE2V(10,613,1024,90,1.1,-1,1H0,NL)
76      CALL RITE2V(10,575,1024,90,1.1,-1,1H,NL)
77      CALL RITE2V(10,537,1024,90,1.1,-1,1H0,NL)
78      CALL RITE2V(10,518,1024,90,1.1,-1,1H0,NL)
79      CALL RITE2V(10,499,1024,90,1.1,-1,1H0,NL)
80      C
81      C
82      C
83      C
84      C
85      C
86      C
87      C
88      C
89      C

```

90	CALL RITE2V(10,400,1024,90,1,1,-1,1HA,NL)	P1939	90
	CALL RITE2V(10,461,1024,90,1,1,-1,1MR,NL)	P1939	91
	CALL RITE2V(10,423,1024,90,1,1,-1,1MR,NL)	P1939	92
	CALL RITE2V(10,404,1024,90,1,1,-1,1HA,NL)	P1939	93
	CALL RITE2V(10,385,1024,90,1,1,-1,1HT,NL)	P1939	94
95	CALL RITE2V(10,366,1024,90,1,1,-1,1HE,NL)	P1939	95
	C	P1939	96
	CALL APL0TV(NOF,TLOG,DLOG,1,1,1,1H*,IERR)	P1939	97
	CALL APL0TV(NOF,TLOG,DLOG,1,1,1,1H*,IERR)	P1939	98
100	C	P1939	99
	CALL TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IV,SAMPLE)	P1939	100
	C	P1939	101
	C	P1939	102
	C	P1939	103
	C	P1939	104
105	CALL FIT(TLOG,CLCG)	P1939	105
	COMPUTE CORRECTION FACTOR	P1939	106
	CORF = (B*3.)/4.	P1939	107
	SSMIN = 999999.	P1939	108
	C	P1939	109
	COMPUTE CORRECTED RATE OF SHEAR AT WALL	P1939	110
110	DO 45 I = 1,NOF	P1939	111
	SRC(I) = CORF*C(I)	P1939	112
	SSMIN = AMIN1(SRC(I),SSMIN)	P1939	113
	45 CONTINUE	P1939	114
	IF(IREC.EQ.1) WRITF(1) (SRC(I),I=1,NOF)	P1939	115
115	C	P1939	116
	COMPUTE APPARENT CORRECTED VISCOSITY AT WALL (VISM)-CENTIPOISE UNITS	P1939	117
	DO 50 I=1,NOF	P1939	118
	50 VISM(I) = T(I)/SRC(I)*100.	P1939	119
	C	P1939	120
120	PLOT - VISM VS SRC ON LOG-LOG PAPER	P1939	121
	C	P1939	122
	C	P1939	123
	C	P1939	124
	Y-AXIS- VISM X-AXIS - SRC	P1939	125
	CALL SETMIV(100,54,54,100)	P1939	126
	CALL SMXVV(1,1)	P1939	127
	XLIM = 1000.	P1939	128
125	IF(SSMIN.LT.1000.) XLIM = 100.	P1939	129
	CALL GRIDIV(3,XLIM,1000000.,100.,100000.,1.0,1.0,N,M,IXX,IYY,-2,	P1939	130
	1 -2)	P1939	131
	C	P1939	132
	CALL APL0TV(NOF,SRC,VISM,1,1,1,1H*,IERR)	P1939	133
	CALL APL0TV(NOF,SRC,VISM,1,1,1,1H*,IERR)	P1939	134
130	CALL TITLE(ITEMP,CAP,CLEN,CDIA,ID,IM,IV,SAMPLE)	P1939	
	C	P1939	
	VERTICAL AND HORIZONTAL LABELS	P1939	
	CALL RITE2V(10,744,1024,90,1,1,-1,1HM,NL)	P1939	
	CALL RITE2V(10,736,1024,90,1,1,-1,1H*,NL)	P1939	
	CALL RITE2V(10,668,1024,90,1,1,-1,1HA,NL)	P1939	

135	CALL RITE2V(10,649,1024,90,1,1,-1,1MP,NL)	P1939	135
	CALL RITE2V(10,630,1024,90,1,1,-1,1MP,NL)	P1939	136
	CALL RITE2V(10,611,1024,90,1,1,-1,1HA,NL)	P1939	137
	CALL RITE2V(10,592,1024,90,1,1,-1,1MR,NL)	P1939	138
	CALL RITE2V(10,573,1024,90,1,1,-1,1HE,NL)	P1939	139
140	CALL RITE2V(10,554,1024,90,1,1,-1,1MN,NL)	P1939	140
	CALL RITE2V(10,535,1024,90,1,1,-1,1MT,NL)	P1939	141
	CALL RITE2V(10,497,1024,90,1,1,-1,1MV,NL)	P1939	142
	CALL RITE2V(10,478,1024,90,1,1,-1,1MI,NL)	P1939	143
	CALL RITE2V(10,459,1024,90,1,1,-1,1MS,NL)	P1939	144
145	CALL RITE2V(10,440,1024,90,1,1,-1,1MC,NL)	P1939	145
	CALL RITE2V(10,421,1024,90,1,1,-1,1MC,NL)	P1939	146
	CALL RITE2V(10,402,1024,90,1,1,-1,1MS,NL)	P1939	147
	CALL RITE2V(10,393,1024,90,1,1,-1,1MI,NL)	P1939	148
	CALL RITE2V(10,364,1024,90,1,1,-1,1MT,NL)	P1939	149
150	CALL RITE2V(10,345,1024,90,1,1,-1,1MY,NL)	P1939	150
	CALL RITE2V(10,317,1024,90,1,1,-1,1H,NL)	P1939	151
	CALL RITE2V(10,279,1024,90,1,1,-1,1MC,NL)	P1939	152
	CALL RITE2V(10,260,1024,90,1,1,-1,1MP,NL)	P1939	153
155	CALL RITE2V(326,20,1024,90,1,38,-1,38HGAMMA DOT - CORRECTED SHEAR 1RATE . SEC,NL)	P1939	154
	CALL RITE2V(320,30,1024,90,1,2,-1,2H-1,NL)	P1939	155
	CALL LCGFIT(SRC,VISN)	P1939	156
		P1939	157
160	COMPUTE PERCENT MEMORY	P1939	158
	DO 60 I=1,NOF	P1939	159
	60 PERM(I) = (DIA(I)-ODIA)/ODIA*100.	P1939	160
	C CHECK ON PERCENT MEMORY PLOTS	P1939	161
165	IFPC = 0	P1939	162
	DO 65 I=1,NOF	P1939	163
	IF(PERM(I).LE.C.) GO TO 55	P1939	164
	IFPC = 1	P1939	165
	65 CONTINUE	P1939	166
170	IF(IFPC.EQ.0) GO TO 66	P1939	167
	C PLOT - PERCENT MEMORY AGAINST LOG SHEAR RATE	P1939	168
		P1939	169
175	X-AXIS CORRECTED SHEAR RATE - SRC Y-AXIS PERCENT MEMORY - PERM	P1939	170
	CALL SETMIV(100,54,54,100)	P1939	171
	CALL SMXVV(1,0)	P1939	172
	CALL GRIDIV(3,1000,1000000,0,202,1,0,20,0,MN,1,II,1,-2,6)	P1939	173
	CALL APLQTV(NOF,SRC,PERM,1,1,1,1M*,IERR)	P1939	174
180	CALL APLQTV(NOF,SRC,PERM,1,1,1,1M*,IERR)	P1939	175
	CALL TITLE(ITEPP,CAP,CLEN,COIA,10,IM,IV,SAMPLE)	P1939	176
	C VERTICAL AND HORIZONTAL LABELS	P1939	177
	CALL RITE2V(326,20,1024,90,1,35,-1,38HGAMMA DOT - CORRECTED SHEAR 1RATE . SEC,NL)	P1939	178
		P1939	179
		P1939	180
		P1939	181
		P1939	182
		P1939	183
		P1939	184

195	CALL RITE2V(32C,38,1024,90,1,2,-1,2M-1,NL)	P1939	185
	CALL RITE2V(10,622,1024,90,1,1,-1,1MP,NL)	P1939	186
	CALL RITE2V(10,603,1024,90,1,1,-1,1ME,NL)	P1939	187
	CALL RITE2V(10,584,1024,90,1,1,-1,1MR,NL)	P1939	188
199	CALL RITE2V(10,565,1024,90,1,1,-1,1MC,NL)	P1939	189
	CALL RITE2V(10,546,1024,90,1,1,-1,1ME,NL)	P1939	190
	CALL RITE2V(10,527,1024,90,1,1,-1,1MN,NL)	P1939	191
	CALL RITE2V(10,508,1024,90,1,1,-1,1MT,NL)	P1939	192
195	CALL RITE2V(10,478,1024,90,1,1,-1,1MM,NL)	P1939	193
	CALL RITE2V(10,451,1024,90,1,1,-1,1ME,NL)	P1939	194
	CALL RITE2V(10,432,1024,90,1,1,-1,1MM,NL)	P1939	195
	CALL RITE2V(10,413,1024,90,1,1,-1,1MO,NL)	P1939	196
	CALL RITE2V(10,394,1024,90,1,1,-1,1MR,NL)	P1939	197
	CALL RITE2V(10,375,1024,90,1,1,-1,1MY,NL)	P1939	198
200		P1939	199
		P1939	200
		P1939	201
205	OUTPUT	P1939	202
	66 IF(LINE.GE.41) PRINT 5	P1939	203
	IF(LINE.GE.41) LINE = 9	P1939	204
	PRINT 4,SAMPLE,CAP,CLEN,COIA,ITEMP,IO,IM,IY	P1939	205
	LINE = LINE+9	P1939	206
	4 FORMAT(1M0/	P1939	207
210	1 1M0,1X,*SAMPLE*,2X,5410,43/2X,*CAPILLARY*,2X,A7,2X,*L = *	P1939	208
	1F5.4,2X,*D = *,F6.4,2X,*TEMP = *,I3,*F*,4X,A2,1X,A3,1X,A2/	P1939	209
	2 1M0,91X,*RABINOMITSCH*,4X,*CORRECTED*,7X,*CORRECTED*/13X,*OMIFICE	P1939	210
	3*,4X,*STRAND PERCENT*,11X,*VOLUMETRIC*,7X,*SHEAR*,11X,*SHEAR*,7X,	P1939	211
	4*CORRECTION*,8X,*SHEAR*,7X,*VISCOSITY*/5X,*FORCE*2X,*DIAMETER*,	P1939	212
	52X,*DIAMETER*,2X,*MEMORY*,2X,*VOLUME*,9X,*FLOW*8X,*RATE*,10X,	P1939	213
	6 *STRESS*,11X,*FACTOR*,9X,*RATE*,6X,*CENTIPOISE*/	P1939	214
215	00 7* I=1,NOF	P1939	215
	IF(RVOL.LE.0.) PRINT 7,I,FORCE(I),ODIA,OIA(I),PERM(I),9VOL1(I),Q(I	P1939	216
	1),D(I),T(I),CORF,SRC(I),VISN(I)	P1939	217
	IF(RVOL.GT.0.) PRINT 7,I,FORCE(I),ODIA,OIA(I),PERM(I),8VOL	P1939	218
22*	1),D(I),T(I),CORF	P1939	219
	1,SRC(I),VISN(I)	P1939	220
	7 FORMAT(2X,I2,F6.0,3X,F6.3,3X,F6.4,0,2X,F6.4,1X,E13.7,2(2X,	P1939	221
	1 E13.7),2X,E13.7,2(2X,E13.7))	P1939	222
	LINE = LINE+1	P1939	223
	IF(LINE.LT.50) GO TO 70	P1939	224
225	PRINT 5	P1939	225
	PRINT 4,SAMPLE,CAP,CLEN,COIA,ITEMP,IO,IM,IY	P1939	226
	LINE = 9	P1939	227
	70 CONTINUE	P1939	228
	GO TO 19	P1939	229
230	999 GO TO IEOF,(150,1000)	P193900	4
	150 IF(IREC.EQ.1) CALL RECOVER	P1539	230
	IF(IREC.EQ.1) CLEN = -1.	P1939	231
	IF(IREC.EQ.1) CALL TITLE(ITEMP,CAP,CLEN,COIA,IO,IM,IY,SAMPLE)	P1939	232
	REIND 1	P1939	233
235	ASSIGN 1000 TO IEOF	P1939	234
	GO TO 19	P1939	235
	1000 CALL EXIT	P1939	236
	END	P1939	237

```

C
C SUBROUTINE LOGFIT(X,Y)
C
5  DIMENSION X(20),Y(20)
COMMON NOF
SUMX = 0.0
SUMY = 0.0
SUMX2 = 0.0
SUMXY = 0.0
DO 5 K=1,NOF
IF(X(K).EQ.0.0)XX= 0.0001
IF(Y(K).EQ.0.0) Y(K) = 0.0001
ALY = ALOG10(Y(K))
XX = ALOG10(X(K))
SUMX = SUMX+XX
SUMX2 = SUMX2+XX*XX
SUMY = SUMY+ALY
SUMXY = SUMXY+XX *ALY
5  CONTINUE
FN = NOF
OL = (FN*SUMX2)-(SUMX*SUMX)
IF(OL.EQ.0.0) GO TO 10
AL = ((SUMY*SUMX2)-(SUMXY*SUMX))/OL
BL = ((FN*SUMXY)-(SUMX*SUMY))/OL
A = 10.0**AL
B = BL
YST = A*X(1)**B
YLT = A*X(NOF)**B
CALL LINEV(NXV(X(1)),MYV(YST),NXV(X(NOF)),MYV(YLT))
CALL LINEV(NXV(X(1)),MYV(YST),NXV(X(NOF)),MYV(YLT))
RETURN
10 PRINT 101
101 FORMAT(1H0,'COEFFICIENT DET. IS 0. NO SOLUTION')
RETURN
END

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SUBROUTINE FIT(X,Y)
C
C SUBROUTINE FOR LEAST SQUARES FIT FOR LINEAR PLOTS
C
5      COMMON NOF
      COMMON /FIT1/ E
      DIMENSION X(20),Y(20)
      SUMXY = 0.
      SUMY = 0.
      SUMX = 0.
      SUMX2 = 0.
      DO 10 I=1,NOF
      SUMX = SUMX+X(I)
      SUMX2 = SUMX2+X(I)*X(I)
      SUMY = SUMY+Y(I)
      SUMXY = SUMXY+X(I)*Y(I)
10      O = NOF*SUMX2-(SUMX*SUMX)
      B = ((NOF*SUMXY)-(SUMX*SUMY))/O
      A = ((SUMX2*SUMY)-(SUMX*SUMXY))/O
      YST = A+B*X(1)
      YEND = A+B*X(NCF)
      CALL LINEV(NXV(X(1)),NYV(YST),NXV(X(NOF)),NYV(YEND))
      CALL LINEV(NXV(X(1)),NYV(YST),NXV(X(NOF)),NYV(YEND))
      RETURN
      END
25

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C
C
C THIS ROUTINE IS USED ONLY FOR CAPILLARY 10-1 AND 250-1 FOR
C RECOVERABLE SHRESS NUMBER CALCULATIONS.
C
C
C DIMENSION TLOG(20),SRC(20),TLOG1(20),SRC1(20),DUM(20)
COMMON NNOF,XMAX,XMIN,YMAX,YMIN
EXTERNAL TABL1V
DO 5 I=1,20
5 DUM(I) = 0.
REWIND 1
C X-AXIS TLOG Y-AXIS SRC
C FIRST CAPILLARY
READ(1) NNOF1,(TLOG(I),I=1,NNOF1),XMIN1,XMAX1,CAP1,CLEN1
READ(1)(SRC(I),I=1,NNOF1)
C SECOND CAPILLARY
READ(1) NNOF2,(TLOG1(I),I=1,NNOF2),XMIN2,XMAX2,CAP2,CLEN2
READ(1) (SRC1(I),I=1,NNOF2)
IF(EOF(1).NE.0.0) CALL EXIT
C MAX AND MIN X FOR PLOTS
XMIN5 = AMIN1(XMIN1,XMIN2)
XMAX5 = AMAX1(XMAX1,XMAX2)
C CONVERT SRC AND SRC1 TO LOG NUMBERS
DO 10 I=1,NNOF1
10 SRC(I) = ALOG10(SRC(I))
DO 15 I=1,NNOF2
15 SRC1(I) = ALOG10(SRC1(I))
NNOF = NNOF1
CALL MAXMIN(SRC,DUM)
XMIN = XMIN
XMAX = XMAX
NNOF = NNOF2
CALL MAXMIN(DUM,SRC1)
YMIN = AMIN1(XMIN,YMIN)
YMAX = AMAX1(XMAX,YMAX)
XMIN = XMIN5
XMAX = XMAX5
LL = 1
LL = 1
IF((XMAX-XMIN).GT.2.) LL = 2
IF((YMAX-YMIN).GT.2.) LLL = 2
XMAX = XMAX+.1000

```

```

45      YMAX = YMAX+.20000
C
C   PRINT OUT OF POINTS THAT ARE PLOTTED.
C   WRITE(8,1) CAP1,(TLOG(I),I=1,NOF1)
C   WRITE(8,2) (SRC(I),I=1,NOF1)
C   WRITE(8,3) CAP2,(TLOG1(I),I=1,NOF2)
C   WRITE(8,2) (SRC1(I),I=1,NOF2)
C   1 FORMAT(1H0,9X,*RECOVERABLE SHEAR NUMBERS*/10X,*CAPILLARY *A7/
C     1 1PX,*X = *.3X,(10F8.4))
C     2 FORMAT(10X,*Y = *.3X,(10F8.4))
C     3 FORMAT(10X,*CAPILLARY *A7/10X,*X = *.3X,(10F8.4))
C     CALL SETMIV(100,54,54,100)
C     CALL SMXVV(8,0)
C     CALL GRID1V(3,XMIN,XMAX,YMIN,YMAX,.1,1,1,1,LL,LLL,3,3)
C     CALL CHSIZV(2,2)
C     CALL RITSTV(13,19,TABL1V)
C
C   HORIZONTAL
C   CALL RITE2V(400,30,1024,90,1,2C,-1,20HLOG T - SHEAR STRESS,ML)
C
C   VERTICAL
C   CALL RITE2V(10,850,1024,90,1,1,-1,1MG,ML)
C   CALL RITE2V(10,831,1024,90,1,1,-1,1MA,ML)
C   CALL RITE2V(10,812,1024,90,1,1,-1,1MP,NL)
C   CALL RITE2V(10,793,1024,90,1,1,-1,1HM,NL)
C   CALL RITE2V(10,774,1024,90,1,1,-1,1HA,NL)
C   CALL RITE2V(10,736,1024,90,1,1,-1,1HD,NL)
C   CALL RITE2V(10,717,1024,90,1,1,-1,1HC,NL)
C   CALL RITE2V(10,698,1024,90,1,1,-1,1HT,NL)
C   CALL RITE2V(10,660,1024,90,1,1,-1,1H.,NL)
C   CALL RITE2V(10,622,1024,90,1,1,-1,1HC,NL)
C   CALL RITE2V(10,603,1024,90,1,1,-1,1MC,NL)
C   CALL RITE2V(10,594,1024,90,1,1,-1,1MR,NL)
C   CALL RITE2V(10,565,1024,90,1,1,-1,1MR,NL)
C   CALL RITE2V(10,546,1024,90,1,1,-1,1ME,NL)
C   CALL RITE2V(10,527,1024,90,1,1,-1,1MC,NL)
C   CALL RITE2V(10,508,1024,90,1,1,-1,1MT,NL)
C   CALL RITE2V(10,489,1024,90,1,1,-1,1ME,NL)
C   CALL RITE2V(10,470,1024,90,1,1,-1,1HD,NL)
C   CALL RITE2V(10,432,1024,90,1,1,-1,1MS,NL)
C   CALL RITE2V(10,413,1024,90,1,1,-1,1MH,NL)
C   CALL RITE2V(10,394,1024,90,1,1,-1,1ME,NL)
C   CALL RITE2V(10,375,1024,90,1,1,-1,1MA,NL)
C   CALL RITE2V(10,356,1024,90,1,1,-1,1MR,NL)
C   CALL RITE2V(10,318,1024,90,1,1,-1,1MR,NL)
C   CALL RITE2V(10,299,1024,90,1,1,-1,1MA,NL)
C   CALL RITE2V(10,281,1024,90,1,1,-1,1HT,NL)
C   CALL RITE2V(10,262,1024,90,1,1,-1,1ME,NL)
C   CALL RITE2V(54,968,1024,90,1,22,-.22HCAPILLARY DIAMETER = ,ML)
C   CALL RITE2V(444,960,1024,90,1,11,-1,1MLENGTHS = ,ML)
C   ENCODE(6,4,CLENN1)CLEM1
C   ENCODE(6,4,CLENN1)CLEM2

```


12/02/75 09.29.15.

FTM 4.2+ REL

CPT=1

74/74

SUBROUTINE TITLE

SUBROUTINE TITLE(IITEMP,CAP,CLEN,COIA,IO,IM,IY,SAMPLE)

DIMENSION SAMPLE(6)

C TWO LINES OF HEADERS ON PLOTS

CALL RITE2V(54,1000,1024,90,1,6,-1,6HSAMPLE,NL)

CALL RITE2V(15,1000,1024,90,1,53,1,1,SAMPLE,NL)

IF(CLEN.LI.0.) GO TO 25

CALL RITE2V(54,980,1024,90,1,9,-1,9MCAPILLARY,NL)

CALL RITE2V(194,390,1024,90,1,7,1,CAP,NL)

CALL RITE2V(304,980,1024,90,1,3,-1,3ML=,NL)

ENCODE(6,21,CLENN)CLEN

21 FORMAT(F6.4)

CALL RITE2V(356,980,1024,90,1,6,1,CLENN,NL)

CALL RITE2V(460,980,1024,90,1,3,-1,3MD=,NL)

ENCODE(6,21,COIAA)COIA

CALL RITE2V(512,980,1024,90,1,6,1,COIAA,NL)

30 CALL RITE2V(616,980,1024,90,1,6,-1,6HTFMP=,NL)

ENCODE(3,22,IITEMP)IITEMP

22 FORMAT(I3)

CALL RITE2V(737,980,1024,90,1,3,1,IITEMP1,NL)

CALL RITE2V(755,980,1024,90,1,1,-1,1MF,NL)

CALL RITE2V(798,980,1024,90,1,2,1,1D,NL)

CALL RITE2V(837,980,1024,90,1,3,1,1IM,NL)

CALL RITE2V(889,980,1024,90,1,2,1,1IY,NL)

RETURN

25 CALL RITE2V(54,980,1024,90,1,25,-1,25HRECOVERABLE SHEAR NUMBERS,

1 NL)

ENCODE(6,21,COIAA)COIA

CALL RITE2V(345,960,1024,90,1,6,1,COIAA,NL)

GO TO 30

END

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SUBROUTINE MAXMIN 74/74 CPT=1

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5      SUBROUTINE MAXMIN(X,Y)
        DIMENSION X(20),Y(20)
        COMMON NOF,XMAX,XMIN,YMAX,YMIN
        C MAX AND MIN VALUES FOR PLCTS
          XMAX = -9999.
          XMIN = 9999.
          YMAX = -9999.
          YMIN = 9999.
          DO 10 I=1,NOF
            IF(X(I).GT.XMAX) XMAX = X(I)
            IF(X(I).LT.XMIN) XMIN = X(I)
            IF(Y(I).GT.YMAX) YMAX = Y(I)
            IF(Y(I).LT.YMIN) YMIN = Y(I)
          10 CONTINUE
        C RESET MAX AND MIN LIMITS FOR PLOTS
          MAX = XMAX*.9
          XMAX = MAX
          MAX = YMAX*.3
          YMAX = MAX
          MIN = XMIN*.5
          XMIN = MIN
          MIN = YMIN*.5
          YMIN = MIN
          RETURN
        END
25

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PROGRAM P1939 74/74 CPT#1 FTM 4.2+ REL 12/02/75 09.28.59.

CARD NR. SEVERITY DETAILS 24 CD 29 FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM

29 I 24 CD 29 FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM
SPECIFIED FOR THAT DESCRIPTOR.

SYMBOLS

L/D	length to diameter of capillary
ASTM	American Society for Testing and Materials
sec ⁻¹	reciprocal second
F	force in pounds or dynes
Na	absolute viscosity, poise
R	barrel radius, cm
r	capillary radius, cm
L	capillary length, cm
Q	extrusion rate, cm ³ /sec
$\dot{\gamma}$ $\dot{\omega}$	shear rate, sec ⁻¹ (corrected)
cp	centipoise
b	slope of flow curve
P	pressure difference (dynes/cm ²)
T	shear stress (dynes/cm ²)
S _r	recoverable shear number
D	diameter strand or capillary diameter

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