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FINAL REPORT

EFFECT OF WALL SHEAR STRESS
ON
DRAG REDUCTION OF VISCOELASTIC FLUIDS

by

Norman F. Whitsitt
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This research was carried out under the Naval Ship Systems Command General Hydromechanics Research Program SR 009 01 01, administered by the Naval Ship Research and Development Center. Prepared under the Office of Naval Research Contract Nonr 4306(00).

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Report No. DTMB-3

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FOREWORD

The studies described in this report were designed to aid in understanding the effects of boundary layer thickness and velocity on drag-reduction characteristics of aqueous polymer solutions as related to their naval applications.

The study was performed in The Western Company's Research Division laboratories in Richardson, Texas, under the Naval Ship Systems Command, Fundamental Hydromechanics Research Program administered by Naval Ship Research and Development Center under Contract Nonr-4306(00).

The authors wish to express their appreciation to Duane Standlee, Roland Forester and Jerry Boysen for their assistance. The authors also wish to express their appreciation for the six-inch flow section data made available for correlations obtained under Federal Water Pollution Administration Contract 14-12-34.

ABSTRACT

Drag-reducing flow tests were carried out over a wide range of polymer concentrations in flow sections ranging from 0.18 inch to 6.0 inches in diameter. The water-soluble polymers used in this study were Separan AP-30 (Dow Chemical Company), a highly efficient drag reducer, and J2-FP (The Western Company,, a guar-type, lower molecular weight, moderately efficient drag reducer.

It was found that the critical shear stress, at the inception of drag reduction, was independent of flow-section diameter (or boundary layer thickness). This critical shear stress was strongly dependent on polymer concentration for the highly efficient additive (AP-30). For the moderately efficient J2-FP, only a very slight dependence of critical shear stress on additive concentration was found.

For a given concentration of a specific polymer, the drag reduction was found to be a unique function of wall shear stress.

The high molecular weight polymer solutions were found to exhibit a decreased percentage of drag reduction at the higher shear rates which the lower molecular weight polymer solutions did not. This lower percentage was attributed to the mechanical scission of the high molecular weight polymer by shearing action of the fluid.

CONTENTS

LIST OF SYMBOLS

A	$\frac{2.303}{k} = 5.75$, Constant related to the universal mixing coefficient.
a	Constant.
B	Defined by equation (A5) and equal to a constant (5.5) for Newtonian flow.
D	Pipe diameter.
f	$\frac{\tau_0}{1/2\ \frac{\rho V^2}{2\ g_c}}$ = Friction factor.
g_c	32.2 $\mathrm{lbm\text{-}ft/lb_f - sec^2}$ = gravitational constant.
k	0.4 = Universal mixing coefficient.
k_1	Constant of proportionality.
k_2	Constant of proportionality.
k_3	Constant of proportionality.
m	Constant defined by equation (2).
Re	$\rho VD/\mu_a$ = Reynolds number.
U_m	Centerline or maximum velocity in turbulent pipe flow.
$u^{\#}$	$\sqrt{\frac{\tau_0\ g_c}{\rho}}$ = Friction velocity.
wppm	Weight parts per million.
$\left(\frac{8V}{D}\right)$	Shear rate.
δ	Laminar sublayer thickness.
θ_s	Relaxation time of an aqueous polymer solution.
ν	μ_a/ρ = Apparent kinematic viscosity.

μ_a	Apparent absolute viscosity as determined from rheograms for aqueous polymer solutions.
ρ	Fluid density.
τ	Shear stress.
λ	Friction factor defined by $\lambda = 4f$.
ψ	$\left(\dfrac{f_t - f_a}{f_t - f_l}\right)_{Re}$ = Friction reduction factor.
$(\ )_a$	Apparent.
$(\ )_c$	Critical conditions at inception of friction reduction.
$(\ )_l$	Evaluated at laminar flow conditions.
$(\ )_o$	Evaluated at wall conditions.
$(\ )_t$	Evaluated at Newtonian turbulent flow conditions.
$(\ )_{Re}$	Evaluated at constant Reynolds number.

SUMMARY

OBJECTIVE

This work was to study the effect of boundary layer thickness and velocity on the drag-reduction characteristics of dilute polymer solutions.

CONCLUSIONS

1. The drag reduction for a given concentration of a specific aqueous polymer solution is a unique function of wall shear stress (or friction velocity). This relationship was found to be independent of boundary layer thickness (or flow-section diameter) and included all the turbulent friction-loss data (above a Reynolds number of 5000) obtained in this study. This unique relationship was found to hold over flow-section diameters ranging from 0.18 inch to 6 inches. This relationship also proved valid for polymer solutions exhibiting widely varying drag-reducing efficiencies. The only exception to this relationship seems to be for Reynolds numbers below about 5000 for solutions which have a critical wall shear stress lower than the laminar wall shear stress would be at the transition region.

2. The critical shear stress (or friction velocity) at which drag reduction begins is clearly a function of concentration for the high molecular weight polymer (AP-30). The critical shear stress decreased by a factor of about 100 as the concentration of Separan AP-30 was increased from 10 to 250 wppm.

3. The critical shear stress also appears to be a function of concentration for the lower molecular weight polymers (e.g., guar gum and carboxymethyl cellulose) although this dependence is much less pronounced.

EFFECT OF WALL SHEAR STRESS ON DRAG REDUCTION OF VISCOELASTIC FLUIDS

I. INTRODUCTION

This study -- a part of an overall study of the Naval implications of drag reducing polymers introduced to the Navy by The Western Company in 1960 -- is concerned primarily with the flow velocity and diameter (or boundary layer thickness) effects on drag reduction of dilute polymer solutions in turbulent flow.

Several attempts have been made to correlate the friction-reducing abilities of these fluids and to account for the diameter effects. One of the more successful approaches was made by Meyer[1] who looked at the effects from the standpoint of the laminar sublayer thickness increase and its resulting effect on the friction factor derived from the turbulent universal velocity profile. Further refinement of this type of analysis is given by Granville.[2] The limitations of this analysis, for various polymers, concentrations, and pipe diameters are pointed out.

Most correlations of the diameter effects have had to rely on flow data in only a very limited range of pipe sizes. In addition, several experiments subjected the dilute polymer solutions to the high-shear environment of a pump upstream of the calibrated flow section. It has been found very difficult to compare data from various sources, because of polymer age and batch differences (resulting in differing drag-reduction characteristics) and the varying amounts of shear degradation that the dilute solutions have experienced before entering the flow section.

With these differences in polymers and test conditions, it is very difficult to compare data from various sources. As a result, this study undertook the experimental evaluation of the drag-reduction characteristics of two polymers, Separan AP-30 (a high molecular-weight copolymer produced by Dow Chemical Company) which exhibits very good friction-reducing properties at low concentrations and Western's J2-FP (a guar gum) which exhibits good friction reduction properties at concentrations about one order of magnitude greater than that required for Separan AP-30.

The tests with Separan AP-30 were conducted at concentrations of 10, 50, 100 and 250 wppm in flow sections of 0.18, 0.416 and 1.624 inches in diameter. For the 100 and 250 wppm solutions, data were also obtained in a test section with an inside diameter of six inches. This facility is the largest accurately instrumented flow test section designed for large-scale evaluation of friction-reducing aqueous solutions known to be in existence. This six-inch facility was built with the support of the Federal Water Pollution Control Administration.

The tests with J2-FP were conducted for solution concentrations of 10, 50, 250 and 1250 wppm in test sections of 0.18, 0.416 and 1.624 inch diameters. In addition, data were also made available for a 1000 wppm J2-FP solution evaluated in the six-inch test section.

II. APPARATUS AND TEST PROCEDURE

Special care was taken to assure that all of the dilute polymer solutions were exposed to minimum shear prior to entrance into the test section. Both the 0.18-inch and the 0.416-inch test sections were air driven (Figures 1 and 2). The dilute polymer solutions were never exposed to the degrading shear environment of a pump. All solution passed through the test section was discarded. The 1.624-inch system was gravity driven from two 200-gallon reservoirs which developed a maximum of about five feet of head pressure. This system is shown schematically in Figure 3. All flow rates for these systems were measured by timing the flow of a given weight of solution. This flow measurement system, along with the technique used for preparing the polymer solutions, is discussed in Reference 3.

In the six-inch fluid flow test facility, the dilute solutions were prepared "on the fly" from a concentrated solution reservoir (a schematic of this system is shown in Figure 4). The water was pumped at varying flow rates through a magnetic flow meter (Foxboro 1806-KABS-RA) into a surcharge reservoir. The concentrated solution was metered through a calibrated, positive displacement pump and injected (in the desired proportions) into the primary water flow down stream of the primary water pump and magnetic flow meter. The fluid was allowed to flow from the injection ports to the surcharge reservoir. After mixing it passed into the six-inch flow test section.

The pressure difference in the test section was measured with a Foxboro 613 DM d/p transmitter differential pressure gage whose output was monitored on a strip chart recorder. This system provided readings plus or minus one percent of the full-scale transducer capability. The transducer full-scale capability was 20 inches of water pressure differential.

III. RHEOLOGICAL PROPERTIES

Each of the polymer solutions tested was rheologically characterized using a Burrell-Severs capillary extrusion rheometer. The procedures and methods used to reduce these data are discussed in Reference 3. The rheogram for the 10, 50, 100 and 250 wppm aqueous solutions of Separan AP-30 is given in Figure 5. The rheological data for 10, 50, 250 and 1250 wppm solutions of J2-FP are given in Figure 6.

These rheograms illustrate that the effects of these polymers on the viscous nature of the solvent are approximately equivalent; however, as evidenced by the friction-reduction data, the Separan AP-30 is a much more effective friction reducer than J2-FP at the lower concentrations.

IV. DISCUSSION OF TEST RESULTS

The reduced flow data for 10, 50, 100 and 250 wppm of aqueous solutions of AP-30 are shown in the conventional <u>friction factor</u> versus <u>apparent Reynolds number</u> form (Figures 7 through 10) for all diameters tested. The equivalent flow data for aqueous solutions of J2-FP for concentrations of 10, 50, 250 and 1250 wppm are shown in Figures 11 through 14. Also, Figure 14 illustrates the 6-inch flow data for the 1000 wppm solution of J2-FP.

On cursory analysis, the data seem to indicate two different types of drag-reduction characteristics:

> The friction loss characteristics of the polymer solutions coincide with those of a Newtonian fluid through the transition region and begin to exhibit drag reduction at some high flow rate (see 6-inch and 1.624-inch data, Figure 9).
>
> The polymer solutions coincide in the laminar region, and do not exhibit the Newtonian transition to turbulence, but do exhibit drag reduction at all Reynolds numbers greater than 3000 (see 0.18-inch and 0.416-inch data, Figure 9).

In reality these manifestations both derive from the fact that, for a given polymer solution, a critical shear stress exists below which no drag reduction occurs. In the case of the small diameters cited above, this critical shear stress is exceeded in laminar flow, and drag reduction occurs in all of the turbulent region. For the larger diameters this critical shear stress is not obtained until after transition to turbulence.

Even through the representation of the data on a friction factor versus Reynolds number plot (Figures 7 through 14) is by far one of the most useful representations of flow data, it has a somewhat questionable theoretical foundation for the turbulent flow phenomena of even Newtonian fluids. On the other hand, a general theoretical representation of the friction loss characteristics of Newtonian and purely viscous non-Newtonian fluids can be developed from the universal velocity profile representation of turbulent pipe flow. As a result, the data for both the AP-30 and J2-FP aqueous solutions are presented in the general universal velocity profile friction factor form,

$$\frac{1}{\sqrt{f}} = A \log(Re\sqrt{f}) + B, \qquad (1)$$

in Figures 15 through 22.

Using this representation, the data appeared to illustrate a general order for both AP-30 and J2-FP. For example, in Figure 17 for the 100 wppm solution of AP-30, the friction-reducing data for all pipe diameters appear to deviate from the ordinary turbulent line in an orderly manner. Also, at the moderately high Reynolds numbers all the data (for various diameters at a given polymer concentration) seem to fall into a family of lines with similar slopes.

The $1/\sqrt{f}$ versus $Re\sqrt{f}$ plots (Figures 15 through 22) indicate that, for a given concentration, the slope of the lines is independent of diameter, but increases as the concentration increases. This slope approaches a maximum value, however, as the drag reduction reaches the observed maximum of about 80 to 85 percent.

It should also be noted that, at high values of Reynolds number (more correctly shear stress) or $Re\sqrt{f}$, the slope decreases (Figure 16). Two reasons for this occurrence have been postulated. One indicates that this decreased drag reduction is reversible and due to so much increased flow turbulence that the additive is unable to overcome this increased turbulence. Savins found this to be true for sodium soaps in water. The other explanation is that the increased shear in the flow environment causes irreversible mechanical clearage of the polymer molecules, making its drag-reducing ability less effective.

In analyzing these data, more support for the latter explanation was found. For example, the data for AP-30, a highly efficient but shear-sensitive polymer, the shearing-out effects are clearly seen in Figures 16 and 17. On the other hand, J2-FP is a less efficient but more shear-stable polymer which, as seen in Figures 21 and 22, does not exhibit this shearing-out phenomenon.

Following the method suggested by Meyer, the deviation of the value of the B term from the constant of 5.5 (which holds for Newtonian fluids) was computed as a function of wall shear stress. This computation is essentially the same as Meyer's correlation with the friction velocity (u^{*}). This deviation is given in the Appendix to clarify the definition and implications of the B term as related to the postulated increase in thickness of the laminar sublayer and its effect on the frictional loss characteristics of fluid flow.

These data are shown in Figures 23 through 26 for 10, 50, 100 and 250 wppm of AP-30 solutions and in Figures 27 through 30 for 10, 50, 250 and 1250 wppm of J2-FP solutions. Only the 10 wppm of AP-30 and the 50 wppm and 250 wppm J2-FP data tend to match the assumption that the relationship of B and τ_0 is independent of diameter for a given concentration. Further, these data also indicate that the critical shear stress, above which the friction-reduction phenomenon begins to become evident, is not a unique value independent of both diameter and polymer concentration, at least for the AP-30 solution. This fact can be ascertained by comparing Figures 23 through 26 (showing B versus τ_0). The critical shear stress, although independent of diameter appears to decrease significantly with increasing concentration within the range of applicability of these relations.

Considering that J2-FP is generally a less viscoelastic, less effective reducer than AP-30 at equivalent concentrations, some interesting suggestions regarding the nature of friction-reducing flow can be made. For example, from Meyer's observations as well as these data, it seems reasonable to assume that in very dilute solutions (or possibly more correctly at low to moderate friction-reducing levels) the action of the polymer is to damp the turbulence in the transition region and thus effectively increase the thickness of the laminar sublayer. As the additive concentration is increased (along with the drag reduction increasing to the maximum level), it appears that an increase in the laminar sublayer thickness alone does not fully explain the friction-reducing phenomena. The data suggest that one of two things may occur.

1. The laminar sublayer may increase in thickness to such an extent that the universal velocity profile may be applicable over only a very small area of the flow section. As a result any theoretical analysis developed around the fact that the universal velocity profile is the predominant factor would probably provide uncorrelatable results.

2. The flow character at or near the maximum friction-reduction level may be a great deal different from that postulated for the moderate friction-reduction levels of dilute polymer solutions. As a result, the higher or more effective additive concentrations may tend to not only thicken the laminar sublayer, but also have some affect on the universal mixing coefficient.

In addition, the B term is not independent of diameter when the drag reduction approaches 80 percent. This fact can be noted by investigating the following related ($1/\sqrt{f}$ versus $Re\sqrt{f}$ and B versus τ_0) curves:

Figures 17 and 25 for 100 wppm AP-30.
Figures 18 and 26 for 250 wppm AP-30.
Figures 22 and 30 for 1250 wppm AP-30.

If B and τ_0 are related by a single function, independent of diameter, then a corresponding family of lines (one for each pipe diameter) can be represented on the corresponding $1/\sqrt{f}$ versus $Re\sqrt{f}$ plot. This family of lines will have the same slope, but the value of $Re\sqrt{f}$ at their intercept with the Newtonian line will decrease as the pipe diameter decreases; therefore, if the polymer solution flow in the 0.416-inch test section exhibits 80 to 85 percent drag reduction and B versus τ_0 is related by a single valued function, this would infer that more than 80 to 85 percent drag reduction would be obtained in the 0.18-inch test section. This is not the case observed in the above related figures. As the maximum drag reduction level of 80 to 85 percent is reached, B versus τ_0 does not appear to be independent of diameter (Figures 25, 26 and 30). Second, Figures 17, 18 and 22 (plots of $1/\sqrt{f}$ versus $Re\sqrt{f}$) show that the maximum obtainable drag reduction is from 80 to 85 percent and independent of flow-section diameter (or turbulent boundary layer thickness) at Reynolds numbers greater than about 5000.

At the maximum drag reduction level, the flow seems more laminar than turbulent. A few of the actual velocity profile measurements[4] on the highly drag-reducing flows illustrate a velocity profile in which the turbulent eddy losses are suppressed in all except a small center region of the pipe flow. In this core region, it appears that the eddy losses are about the same to somewhat greater than the purely viscous losses.

Generally speaking, Reference 1 indicates that, for a given polymer, there is a critical wall shear stress, independent of concentration, above which any concentration of the polymer will exhibit the friction-reducing phenomena. Accordingly, below this critical shear stress no friction reduction should occur. In the present study, this assumption was evaluated for both the AP-30 and J2-FP solutions. For the AP-30, we found that the critical shear stress was a function of concentration. This is readily seen in Figure 40 where the critical friction velocity (or the square root of shear stress) decreases by a factor of 10 as the concentration is increased by a factor of 25.

As shown in Figure 41, our data for J2-FP indicate a very slight change (with concentration) of the critical shear stress. Indeed, it is possible that the critical shear stress for the low molecular weight polymers, such as guar and CMC, is essentially independent of concentration.

Overall it appears that the correlation techniques presently available are insufficiently general to explain the flow behavior of the friction-reducing polymer solutions over the wide variation in concentrations and pipe diameters studied in this program. As a result, a slightly more empirical approach was selected for data interpretation. This correlation of the complete range of data obtained in this study is discussed in the following section of this report.

V. DATA CORRELATION

In the correlation of the wide range of concentration and pipe diameter data obtained in this study, the factor which was considered of most importance was the development of data correlations or trends which would apply to as wide a range of data as possible. The most successful and apparently general correlation approach found for these data was developed from the observation that the friction-reducing ability of these solutions was related to:

- Polymer type.
- Polymer concentration.
- Shear stress level.

It is known that most polymers exhibit different friction-reducing ability at various concentrations in the water solvent. Generally speaking, the higher the molecular weight of the polymer, the lower the concentration required in a water solvent to produce maximum friction reduction (80 to 85 percent). In addition, it was shown by Pruitt and Crawford[3] that the segmental constitution of the polymer has a major influence on its friction-reducing ability. That is, for a given molecular weight, the larger the length to diameter ratio of the polymer molecule the greater is its friction-reducing ability. These authors also indicated that the critical shear stress was concentration dependent for some polymers.

In investigating the vast amount of friction-reducing data obtained in this work, it is apparent that, for a given polymer concentration, the friction reduction is greater for the smaller tubing diameters than for the larger diameters at a given Reynolds number (see, for example, Figures 9, 13 and 14). At the higher concentrations and small pipe diameters such as is shown in Figure 10, however, the 0.18-inch and 0.416-inch pipe diameter data almost overlay on a maximum friction reduction line of between 80 and 85 percent.

Now, for a given Reynolds number, the shear stress in a small pipe will be larger than that in a large pipe. This suggests that the shear stress to which the fluid is being subjected may influence the friction-reducing ability of a given polymer solution. As a result, the friction-reduction factor dependence on wall shear stress or, more conveniently, the friction velocity, was investigated.

The measured drag reduction, ψ , at all pipe diameters for a given polymer concentration in a water solution is shown versus friction velocity (effectively, wall shear stress) in Figures 32 through 39. Figures 32 through 35 are for 10, 50, 100 and 250 wppm solutions of AP-30 and Figures 36 through 39 are for 10, 50, 250 and 1250 wppm solutions of J2-FP.

Investigation of each individual curve indicates that a single unique relation can be defined as representative of these data. In addition, within an experimental accuracy of ± 15 percent, this relationship is independent of diameter. That is, for a given polymer and concentration, such as a 250 wppm AP-30 solution, the friction reduction which will be obtained is a unique function of the wall shear stress. (For example, it can be determined by graphic relationship, Figure 35.) This should also be true for an exterior flow, such as that around a torpedo with a polymer solution injected into its boundary layer.

In comparing Figures 32 through 35 for AP-30 and Figures 36 through 39 for J2-FP, several interesting observations can be made. For example, there appears to be a well-defined shear stress (for a given polymer and concentration) at which inception of the friction-reduction occurs. After the critical shear stress is exceeded, the friction reduction increases at a decreasing rate until a maximum friction-reduction level is reached. These critical shear stresses, as related to the polymer concentration, are shown in Figure 40 for AP-30 and Figure 41 for J2-FP.

The critical friction velocity (or wall shear stress) for the inception of friction reduction appears to decrease markedly as polymer concentration increases for the AP-30 solutions; however, this does not seem to be the case for J2-FP solutions where the critical shear stress exhibits only a very slight decrease with increasing concentration.

The correlation data for the various concentrations of AP-30 shown in Figures 32 through 35 are summarized in Figure 42. Similarly, the correlation data for J2-FP shown in Figures 36 through 39 are summarized in Figure 43.

For a given polymer, the friction reduction increases with concentration until it reaches the 80 to 85 percent level. After reaching this level, an increase in concentration will not increase the drag reduction above this level; howeve increasing the polymer concentration will cause the inception of drag reduction to occur at lower shear stress levels, at least for the more effective friction-reducing solutions such as AP-30. Consequently, higher friction reduction can be produced at lower shear stress levels.

As the shear stress increases the friction reduction increases to the maximum level and then begins to decrease for the AP-30 solutions, but apparently remains constant for the J2-FP solutions. This decrease is attributed to a "shearing out" of the polymer. Shearing out is believed to be an actual degradation or breaking up of the polymer molecules caused by the shearing action within the fluid. It is interesting to note in Figures 32, 33 and 34 (where the 80-percent friction reduction level has just been reached) that the degradation begins to occur at a friction velocity of about one foot per second. Figure 35 represents a 250 wppm AP-30 solution which is actually of greater additive concentration than is required to produce maximum friction reduction at this shear stress level. This higher polymer concentration appears to delay the loss in percentage drag reduction until a higher shear stress (Figures 34 and 35).

One other interesting point to note is that none of the J2-FP data was taken at a shear rate sufficiently high to produce a degradation of friction-reducing ability of the polymer. This fact can be seen in Figures 37, 38 and 39. It is to be expected, since exhaustive tests[9] have shown J2-FP to be virtually insensitive to shear degradation while AP-30 is known to be moderately sensitive.

Only 5- to 10-percent friction reduction was measured for the 10 wppm J2-FP solution; however, the data points were presented in Figure 36 for completeness.

In obtaining the graphical correlations presented in Figures 41 and 42 for AP-30 and J2-FP, only one minor portion of the data did not fit the correlation. The troublesome data were those which deviated smoothly from the laminar friction factor line for Reynolds numbers less than about 5000. For these data, it is seen (from inspection of Figures 9, 10 and 14) that the viscoelastic characteristic of the fluid has delayed transition to a Reynolds number greater than 3000. As a result, if the data between Reynolds numbers of 3000 and 5000 are included, the friction reduction changes from 100 percent (i.e., flow is still laminar) to the 80- to 85-percent level at a Reynolds number above about 5000. Rationalizing that this transition region was only a small part of the turbulent flow region, the data below a Reynolds number of about 5000 were excluded.

The correlating curves for the J2-FP solutions look quite similar to those for the AP-30 solutions; however, at a given concentration, the degree of friction reduction is less and the critical shear stress (or friction velocity) at which friction reduction starts to occur is much higher than for the equivalent concentration of the AP-30 solution.

A unique functionality was found between the friction-reducing ability of a given polymer concentration of a specific polymer and the friction velocity or wall shear stress. This particular functionality, at least in the presented form, does not appear to offer the presumed advantages of nondimensionality; however, there is a unique rheological relationship between wall shear stress and wall shear rate, and the data in Figures 32 through 39 could just as easily be presented as a unique function of the wall shear rate.

It has been suggested (References 10 and 11) that the correlation of turbulent friction reduction can be made in terms of the Deborah number. The Deborah number is defined as a ratio of the relaxation time of the solution to a representative time of the process. If it is assumed that the time of the process can be represented by the inverse of the shear rate, it then appears that the data may be correlated and normalized (with respect to the inception of friction reduction) if presented in terms of Deborah number instead of the friction velocity. The difficulity arises, however, in predicting or measuring the relaxation times of the solutions.

Investigation of the critical value of the friction velocity may give some useful information regarding the relaxation times of the solutions. If, following the suggestion of Reference 11, it is assumed that the inception of friction reduction occurs at a unique value of Deborah number, then the following relationship is valid:

$$\theta_s = \frac{k_1}{\left(\frac{8V}{D}\right)_c} \quad . \qquad (2)$$

Also, since, for a given concentration of a specific polymer, there is a unique relationship between shear rate (8V/D) and shear stress, the following relation would hold:

$$\theta_s = \frac{k_2}{(\tau_0)_c} = \frac{k_3}{u_c^{\#}} \quad . \qquad (3)$$

From equation (3) and Figure 40 it can be seen that, for a high molecular-weight, highly effective friction-reducing polymer, the relaxation time of the solution increases with polymer concentration. In addition, from Figure 41, it would appear that for a relatively low molecular weight, less effective polymer, the relaxation time of the solution remains constant or decreases very slightly with increasing polymer concentration in the solution.

It can be seen that, as presented, the Deborah number offers no means of normalizing the magnitude of friction reduction obtained. It appears that another parameter is needed to correlate the level of friction-reduction obtained as function of polymer type and concentration. This parameter is probably the Weissenberg number. Thus, as suggested by Metzner, White and Denn[12] as well as other investigators, turbulent friction-reducing flow may be related to the three functional groups, Reynolds number, Deborah number and Weissenberg number. It then may be found that the magnitude of the observed friction reduction can be correlated with the Weissenberg number which essentially is the ratio of the elastic to the viscous forces.

APPENDIX

FRICTIONAL LOSS CONSIDERATIONS FOLLOWING MEYER'S[1] DEVELOPMENT

APPENDIX

FRICTIONAL LOSS CONSIDERATIONS FOLLOWING MEYER'S[1] DEVELOPMENT

Studies of friction loss and turbulent velocity profiles of friction-reducing fluids have been carried out by a number of investigators, some of whom are given in References 1 through 7. From the experimental velocity profile data,[4,6] it has been postulated by Meyer that friction reduction is affected by an increase in the thickness of the laminar sublayer. It is also suggested that the universal mixing constant is unaffected by the elastic nature of these fluids. (The universal mixing constant is defined as the ratio of the mixing length to the distance from the wall.) These two assumptions have some basis from experimental measurements made in dilute solutions of moderately effective friction-reducing additives[4,6]. These assumptions were invoked in the theoretical arguments of Meyer[1] which are outlined below.

The universal velocity profile has been developed for Newtonian fluids from the theoretical arguments of Prandtl regarding the nature of turbulent flow[8]. It can be expressed as

$$\frac{u}{u^{\#}} = A \log \frac{(yu^{\#})}{\nu} + B, \qquad \text{(A1)}$$

where $A = \dfrac{2.303}{k} = 5.75$

$B =$ 5.5 for a Newtonian fluid and is treated as a variable related to the thickness of the laminar sublayer by Meyer.

$k =$ 0.4, the experimentally determined universal mixing constant which is assumed to hold for all fluids both Newtonian and viscoelastic (non-Newtonian).

In the above equation (A1) the term B is determined experimentally. In the analytical development of the above equation, however, B is functionally related to a distance from the pipe wall. This distance is of the order of and related to the thickness of the laminar sublayer.

$$B = \frac{(\delta u_0^{\#})}{\nu} - A \log \frac{(\delta u_0^{\#})}{\nu} . \tag{A2}$$

Based on the two previously mentioned assumptions regarding the nature of viscoelastic, friction-reducing flow, the following relation between the term B and the easily measured flow characteristic can be developed by using the universal velocity profile along with the relations:

$$\frac{\tau_0}{\rho} = \left(u_0^{\#}\right)^2 = \frac{\lambda}{8} \rho V^2 , \tag{A3}$$

where $f = \frac{\lambda}{4}$,

$u_0^{\#}$ = the friction velocity evaluated at the wall shear stress,

V = the bulk velocity (area averaged),

λ = the coefficient of friction defined by

$$\frac{\Delta P}{L} = \frac{\lambda}{D} \frac{\rho V^2}{2 g_c} , \text{ and} \tag{A4}$$

$V = U_m - 3.75 u^{\#}$

where U_m = the maximum velocity, it can be shown that

$$\frac{1}{\sqrt{\lambda}} = 2.03 \log Re \sqrt{\lambda} + 0.353B - 2.74 \tag{A5}$$

From equation (A5), we see that the frictional loss characteristics are related to the B term or the thickness of the laminar sublayer.

REFERENCES

1. Meyer, V A., "A Correlation of the Frictional Characteristics for Turbulent Flow of Dilute Viscoelastic Non-Newtonian Fluids in Pipes," AIChEJ Volume 12, No. 3, pp 522-525, (May 1966).

2. "The Frictional Resistance and Velocity Similarity Laws of Drag-Reducting Dilute Polymer Solutions," Report 2502, Hydromechanics Laboratory, Naval Ship Research and Development Center, (September 1967).

3. Pruitt, G. T. and Crawford, H. R., "Effect of Molecular Weight and Segmental Constitution on the Drag Reduction of Water Soluble Polymers," Report No. DTMB-1, The Western Company, Richardson, Texas, conducted under Contract Nonr-4306(00) for the Naval Hydromechanical Laboratory, Washington, D.C., (April 1965).

4. Pruitt, G. T. and Crawford, H. R., "Investigation for the Use of Additives for the Reduction of Pressure Losses," Final Report, Contract No. DA-23-072-AMC-309(T) for Army Tank Automotive Center, (January 1965).

5. Fabula, A. G., Hoyt, J. W. and Greene, J. H., "Drag Reduction Through the Use of Additive Fluids," CONFIDENTIAL NAVWEPS Report 8434, NOTS TP 3385, U. S. Naval Ordnance Test Station, China Lake, California, (March 1964).

6. Wells, C. S., "On the Turbulent Shear Flow of an Elastico-Viscous Fluid," Presented at Aerospace Sciences Mtg., AIAA, (January 1964).

7. Ernst, W. D., "Investigation of the Turbulent Shear Flow of Dilute Aqueous CMC Solutions," AIChEJ, Volume 12, No. 3 (1966).

8. Schlichting, H., Boundary Layer Theory, McGraw-Hill, (1960).

9. Whitsitt, N. F. and Crawford, H. R., "Friction Drag Loss Characteristics of Enclosed Rotating Disks Operating in a Viscoelastic Fluid Media," Technical Report prepared for U. S. Naval Ordinance Test Station, Pasadena, California, Contract No. N60530-12741, by The Western Company, Research Division, (April 1967).

10. Rodriquez, J. M., Zakin, J. L. and Patterson, G. K., "Correlation of Drag Reduction with Modified Deborah Number for Dilute Polymer Solutions," SPE 1678, Presented at the Symposium on Mechanics of Rheologically Complex Fluids, Houston, Texas, (December 15-16, 1966).

11. Ram, A., Finkelstein, E. and Elata, G., "Reduction of Friction in Oil Pipelines by Polymer Additives," I&EC, Process Design and Development, Volume 6, No. 3 (July 1967).

12. Metzner, A. B., White, J. L. and Denn, M. M., "Constitutive Equations for Viscoelastic Fluids for Short Deformation Periods and for Rapidly Changing Flows: Significance of the Deborah Number," AIChEJ, Volume 12, No. 5, (1966).

FIGURES

1

THROUGH

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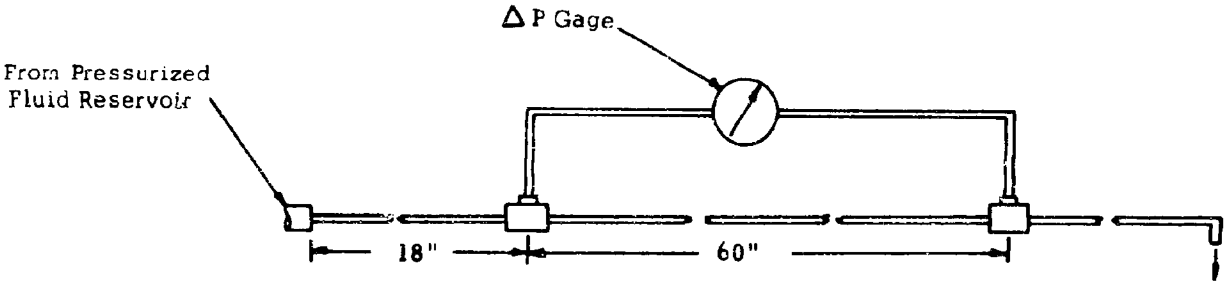


Figure 1
Schematic of 0.18 inch, Air Driven Test Section

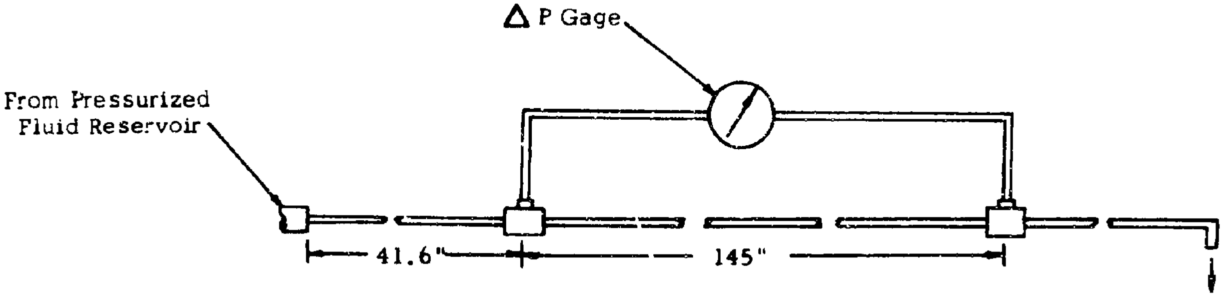


Figure 2
Schematic of 0.416 inch, Air Driven Test Section

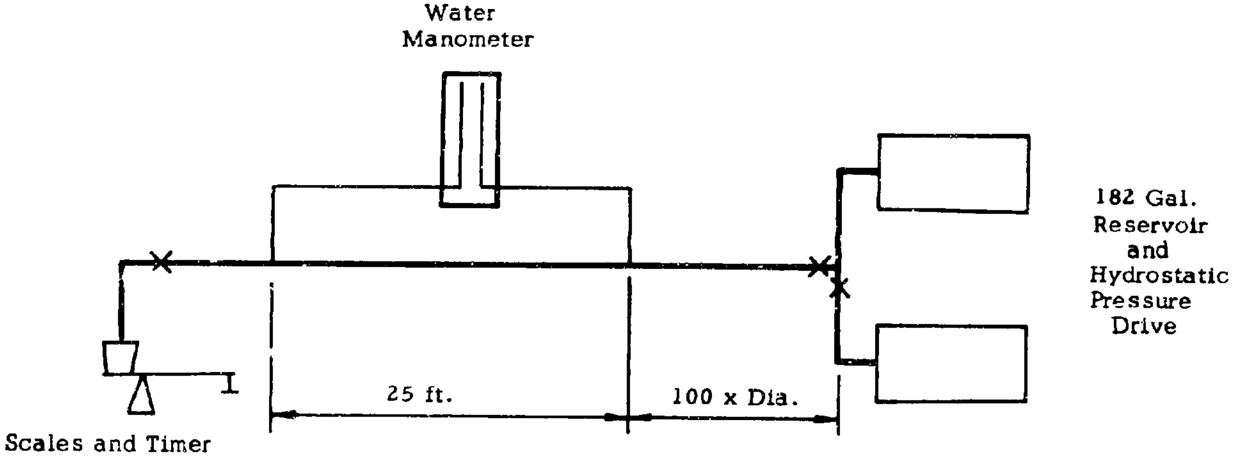


Figure 3.

Schematic of 1.624-inch Hydrostatic Head Driven Test Section

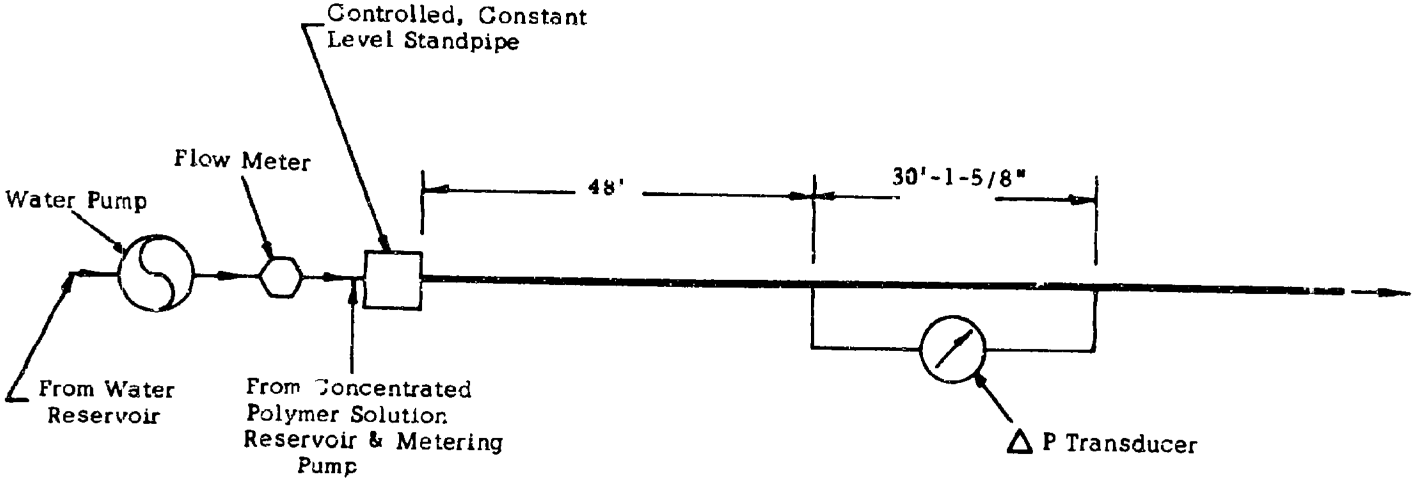


Figure 4
Schematic of the 6-inch Flow System

Figure 5
Rheogram of AP-30 Solutions at the Indicated Concentrations

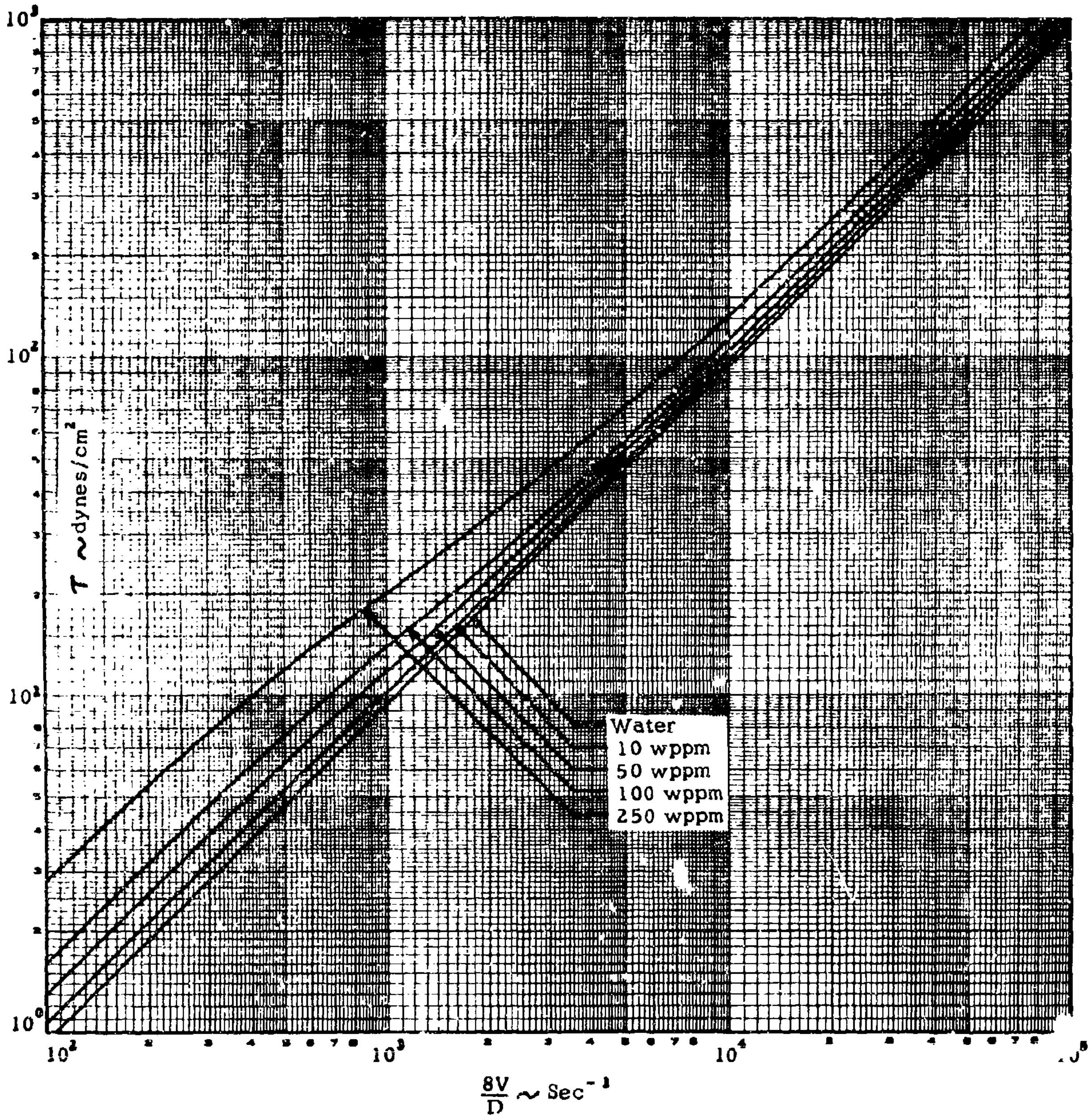


Figure 6
Rheogram of J2-FP Solutions at the Indicated Concentrations

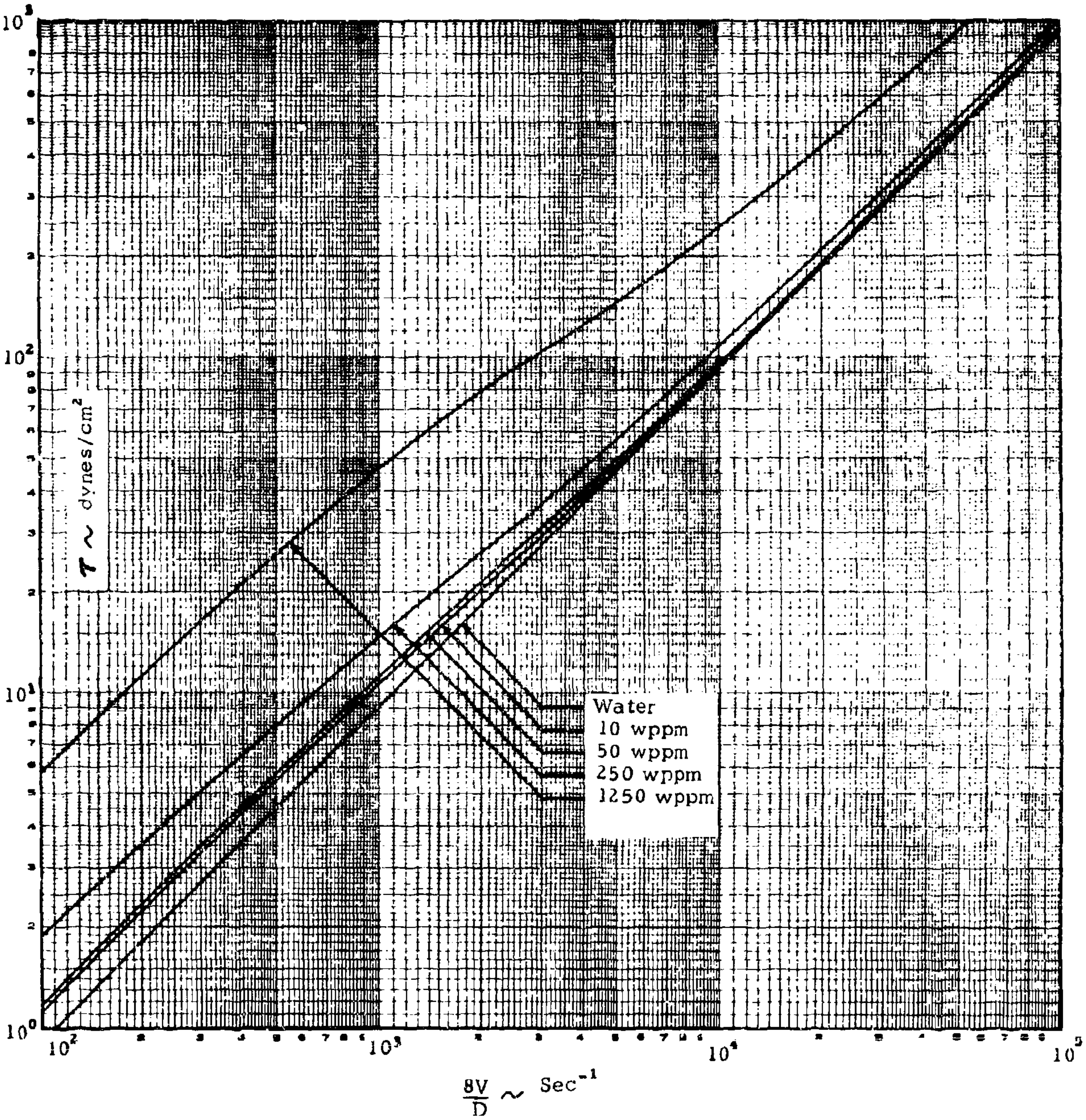


Figure 7
Friction Factor versus Reynolds Number for
10 wppm AP-30 Solution in Specified Tubing Sizes

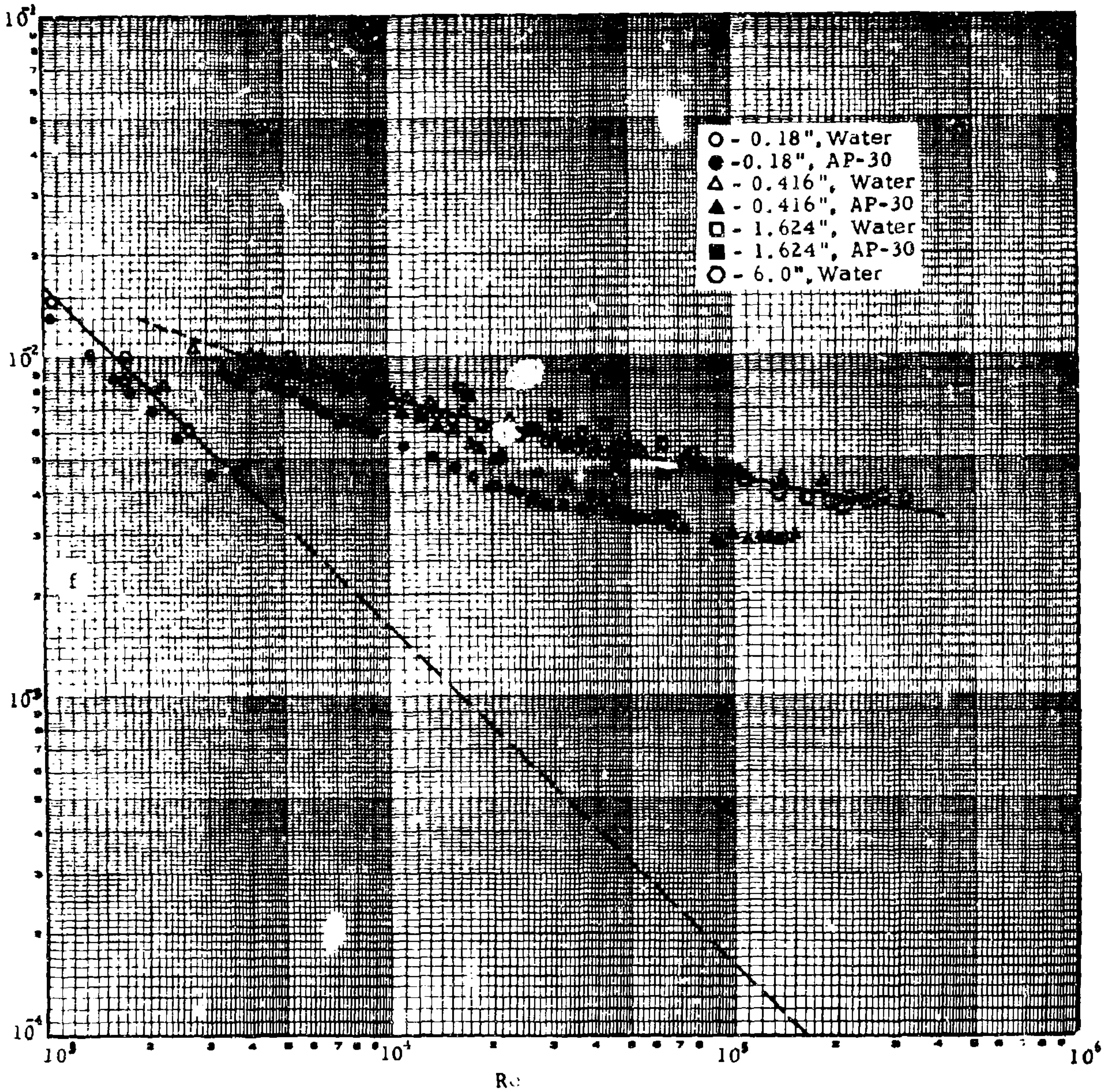


Figure 8
Friction Factor versus Reynolds Number for
50 wppm AP-30 Solution in Specified Tubing Sizes

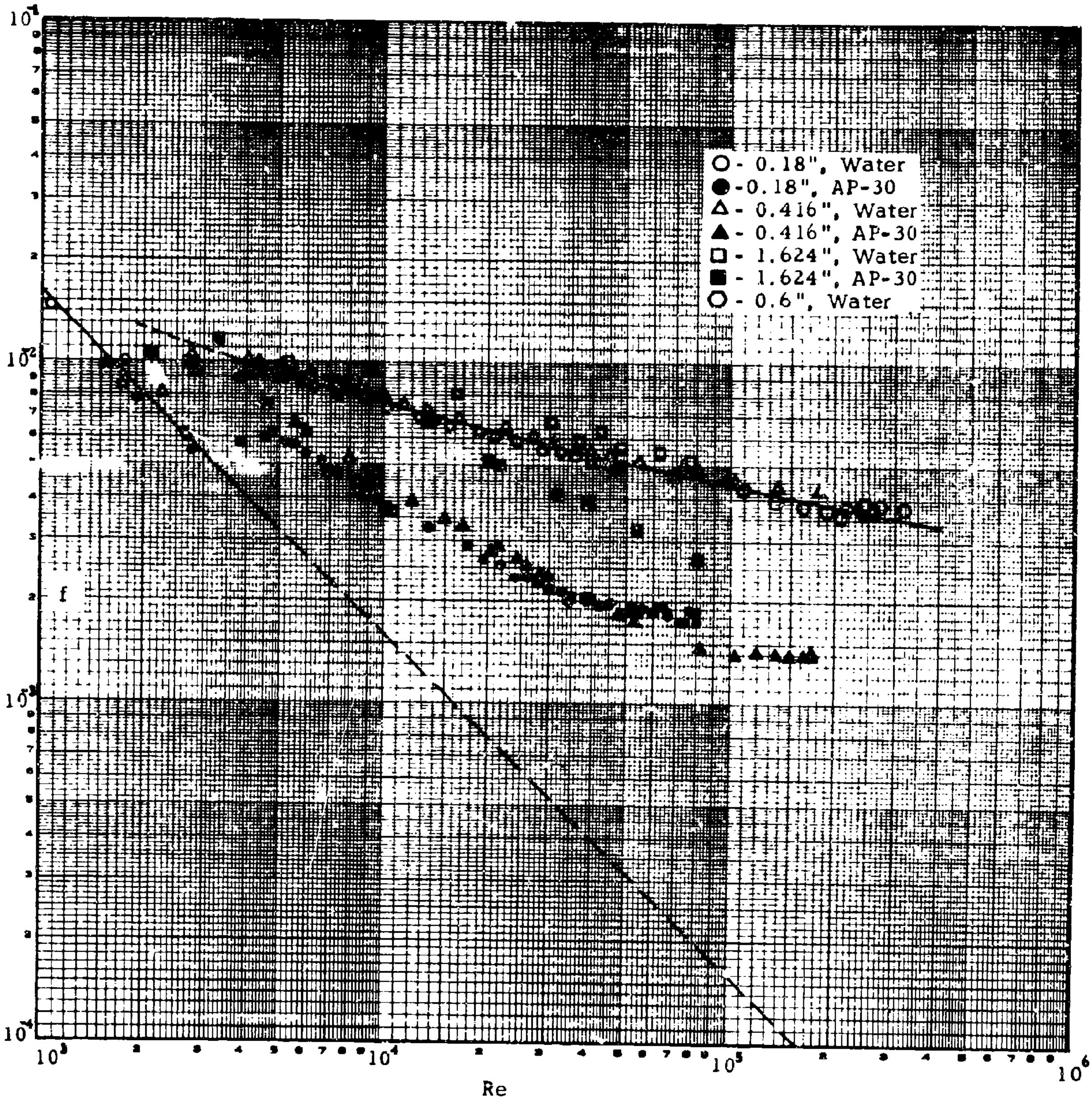


Figure 9
Friction Factor versus Reynolds Number for
100 wppm AP-30 Solution in Specified Tubing Sizes

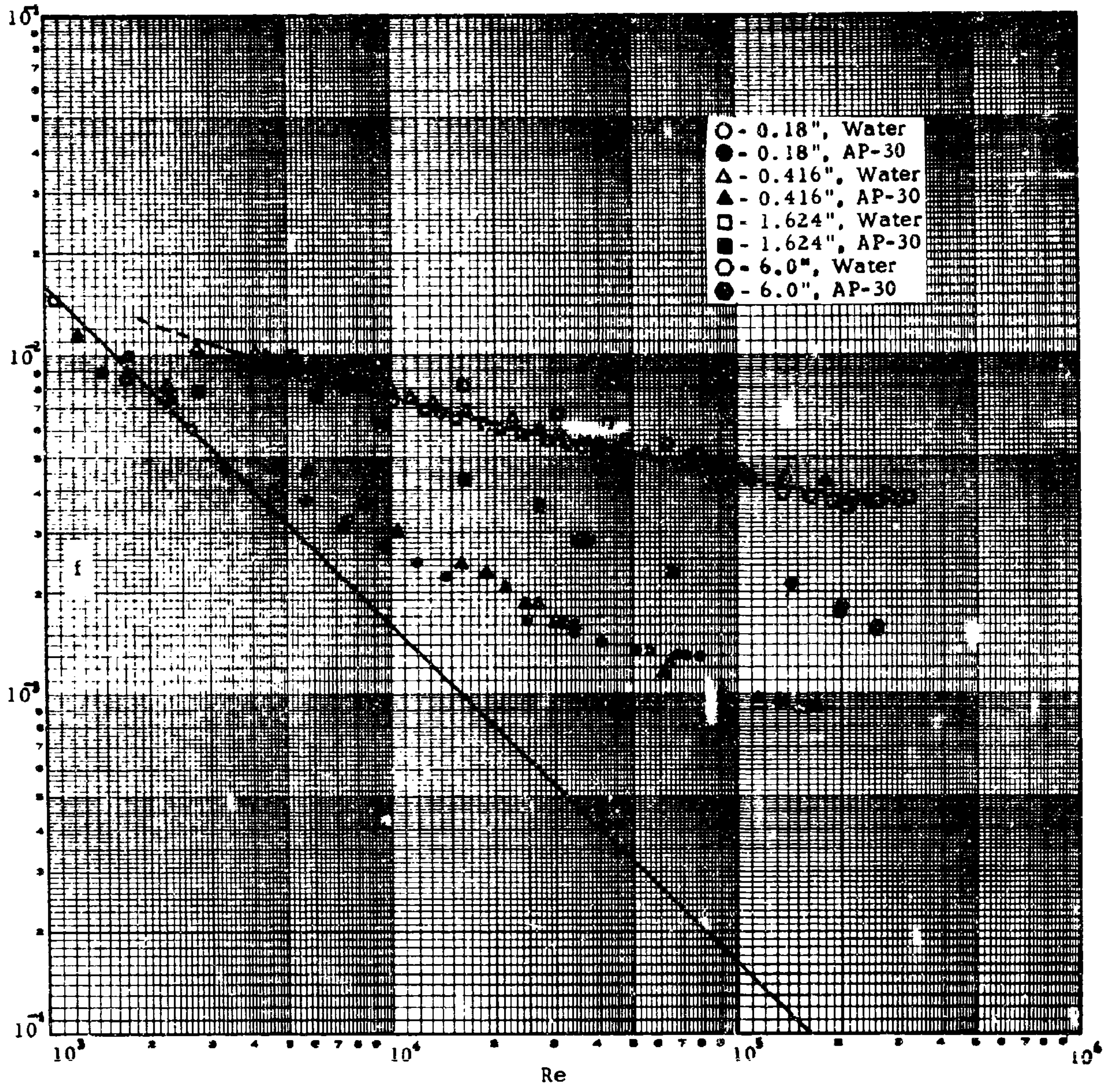


Figure 10
Friction Factor versus Reynolds Number for
250 wppm AP-30 Solution in Specified Tubing Sizes

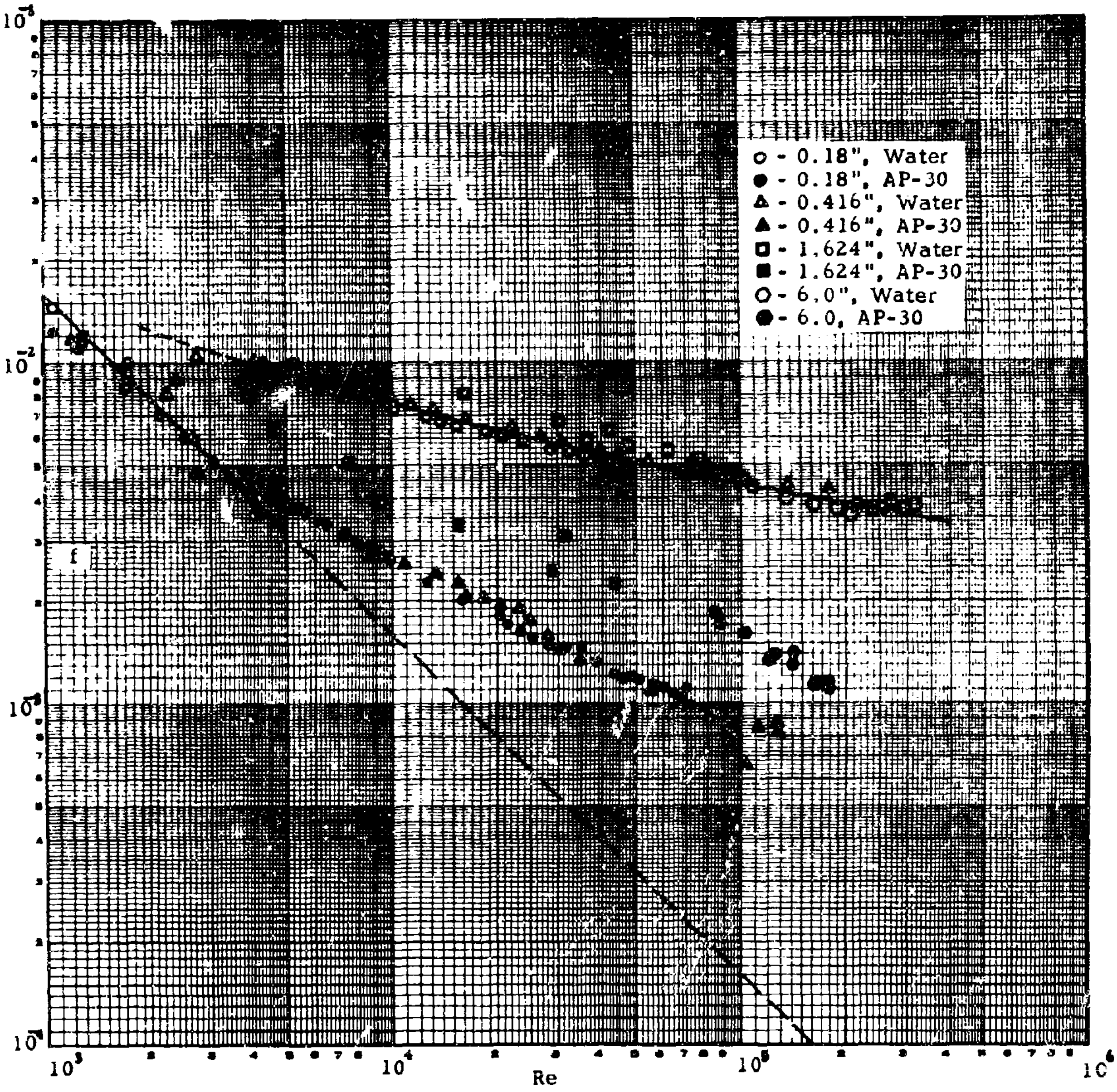


Figure 11
Friction Factor versus Reynolds Number for
10 wppm J2-FP Solution in Specified Tubing Sizes

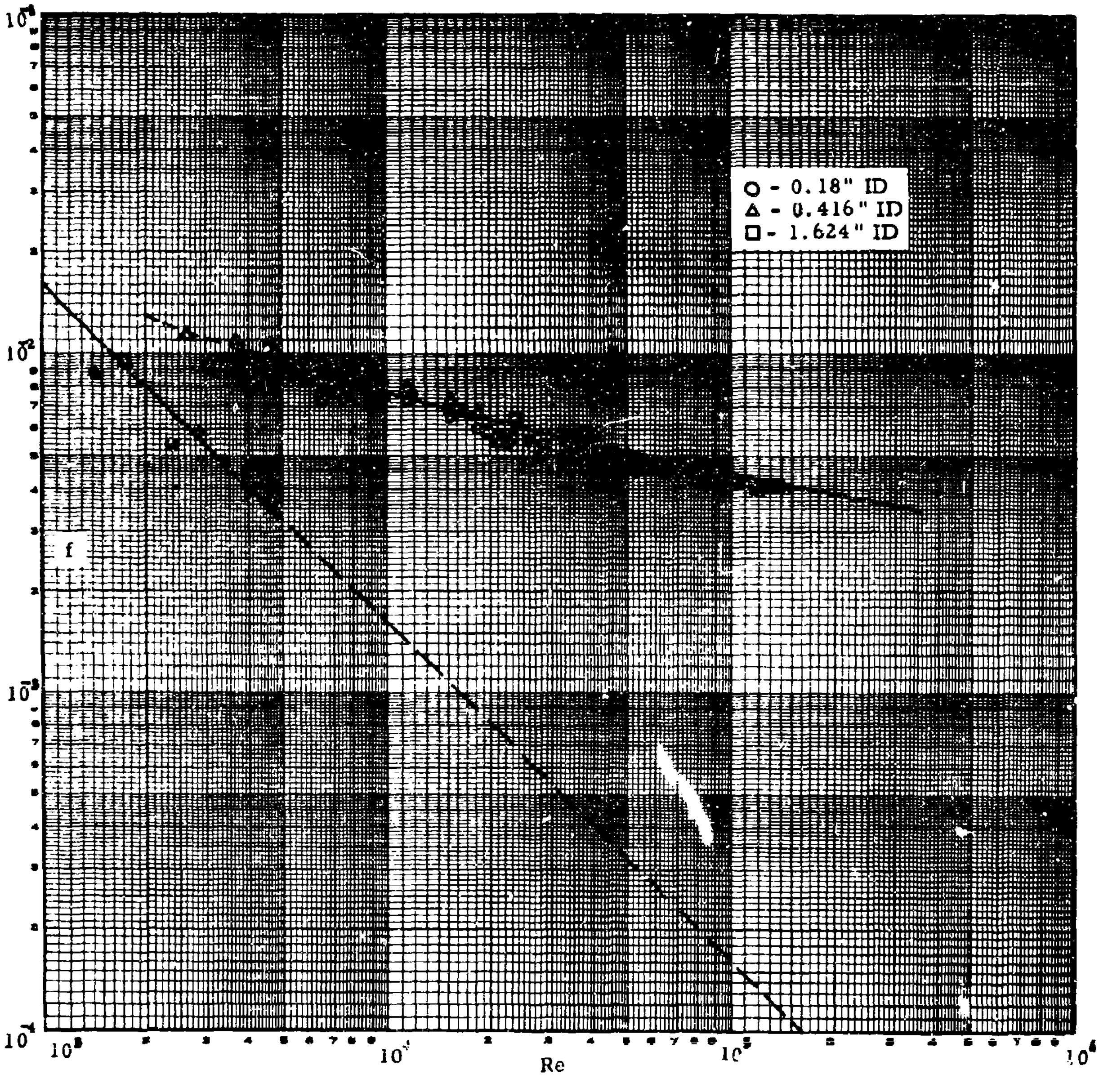


Figure 12
Friction Factor versus Reynolds Number for
50 wppm J2-FP Solution in Specified Tubing Sizes

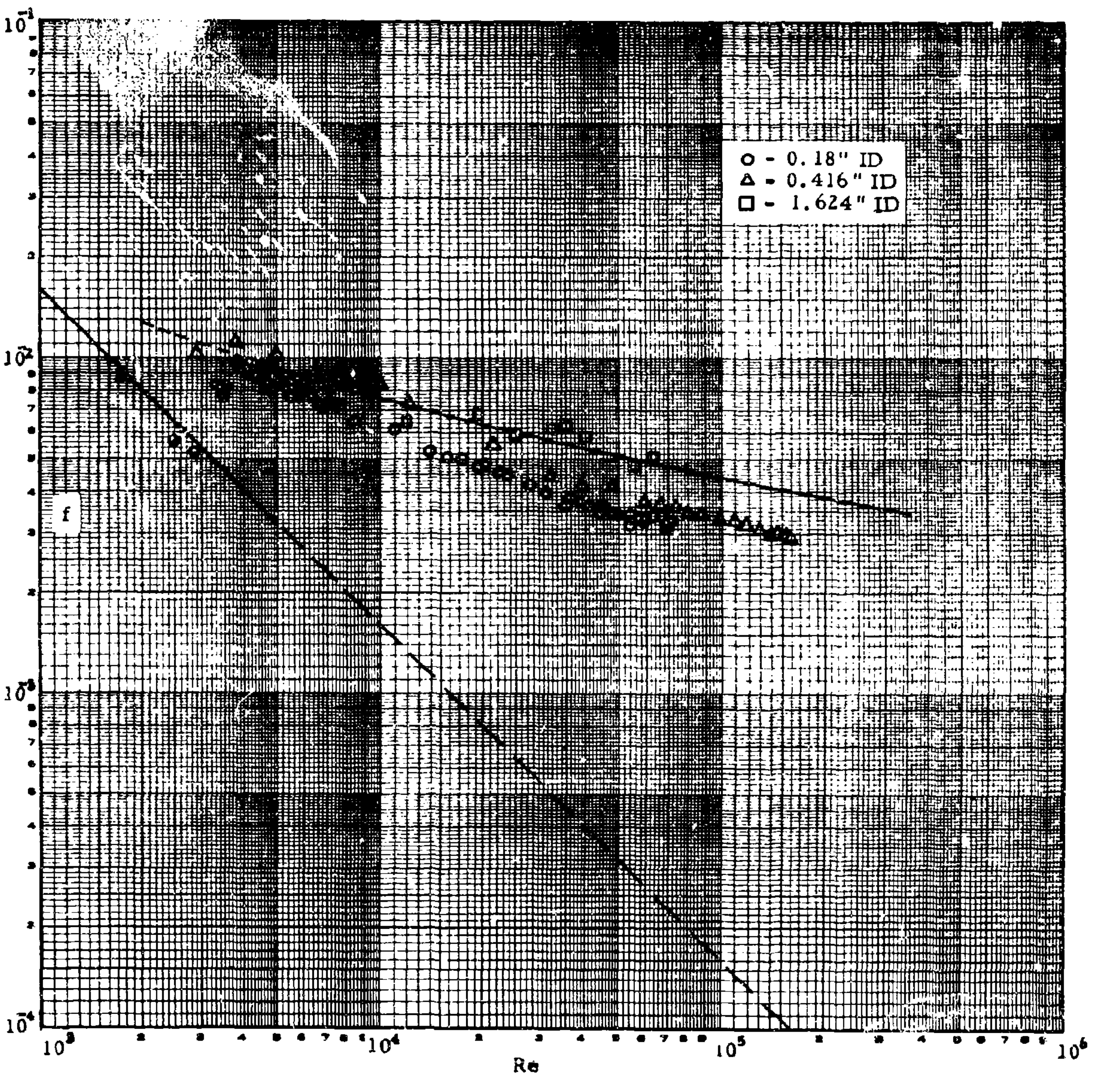


Figure 13
Friction Factor versus Reynolds Number for
250 wppm J2-FP Solution in Specified Tubing Sizes

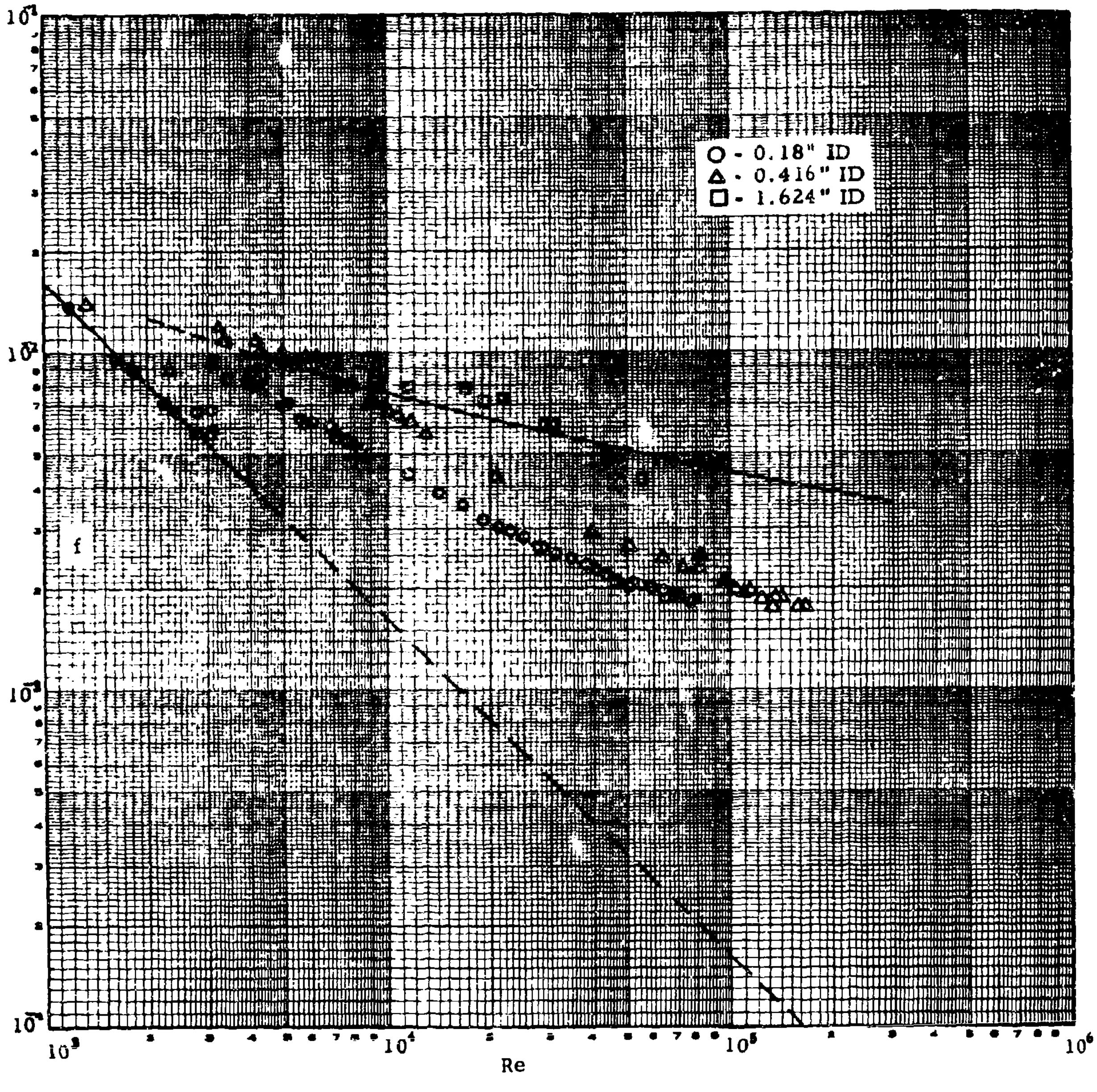
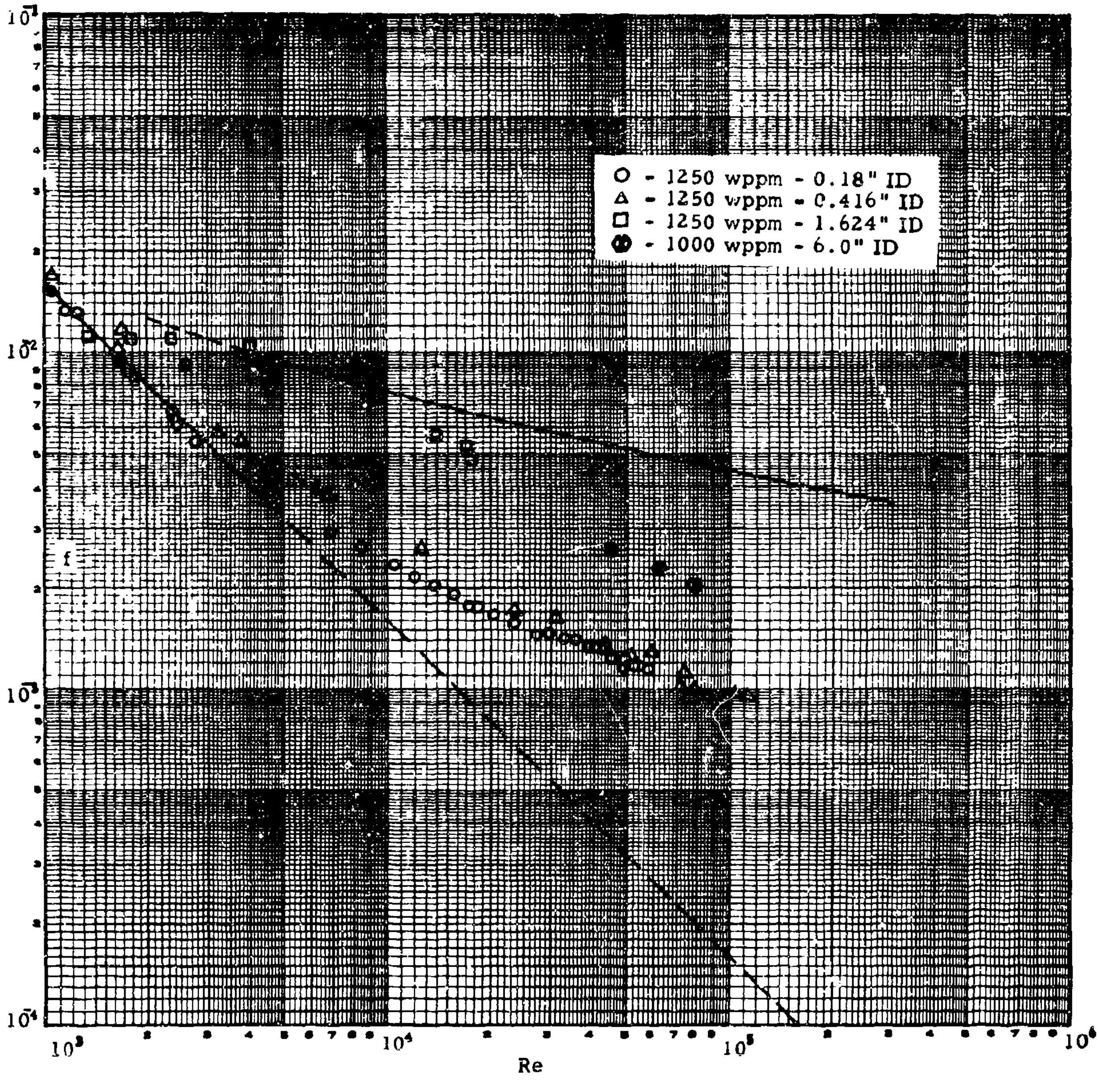


Figure 14
Friction Factor versus Reynolds Number for 1000 and 1250 wppm J2-FP Solution in Specified Tubing Sizes



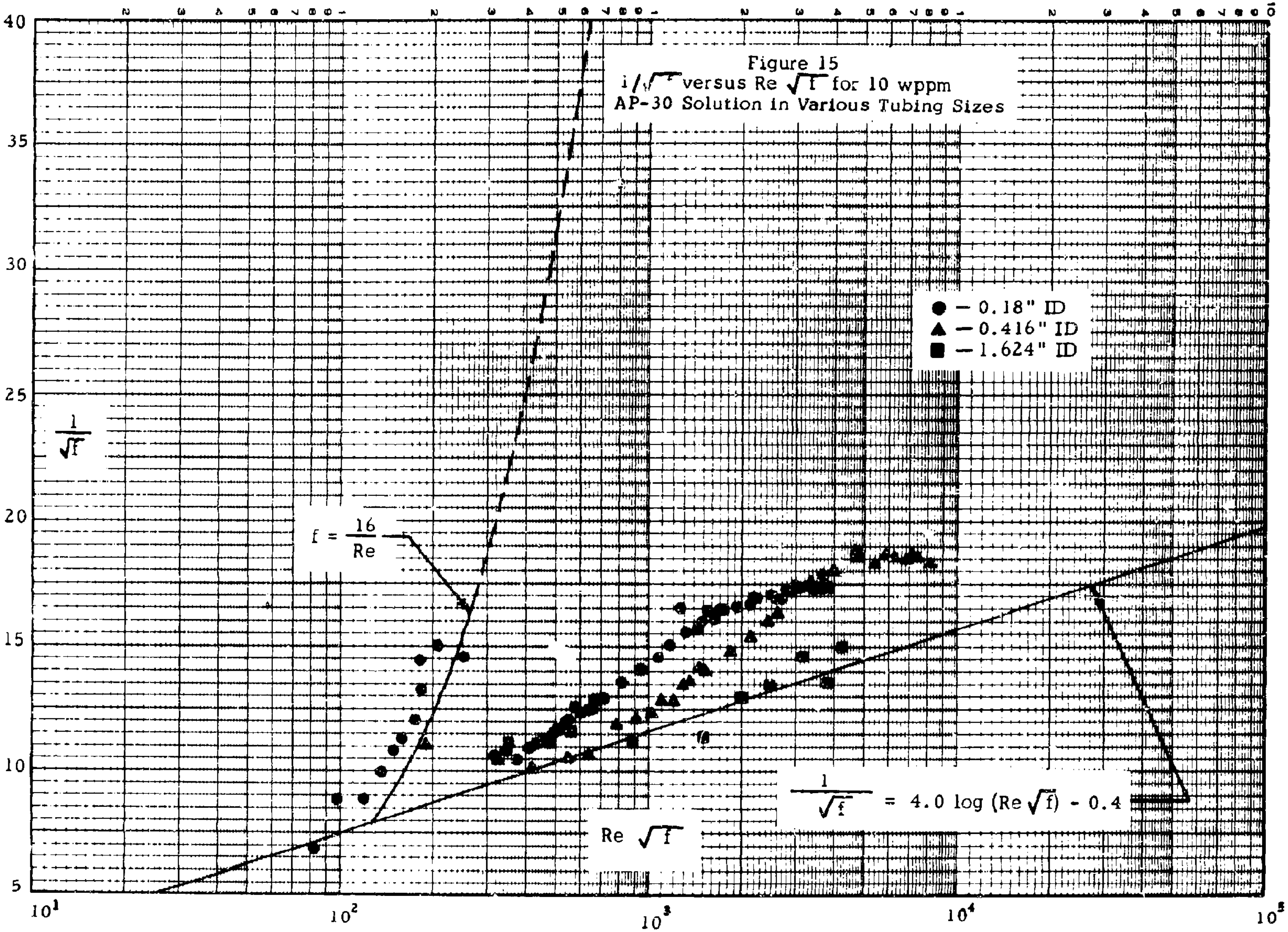
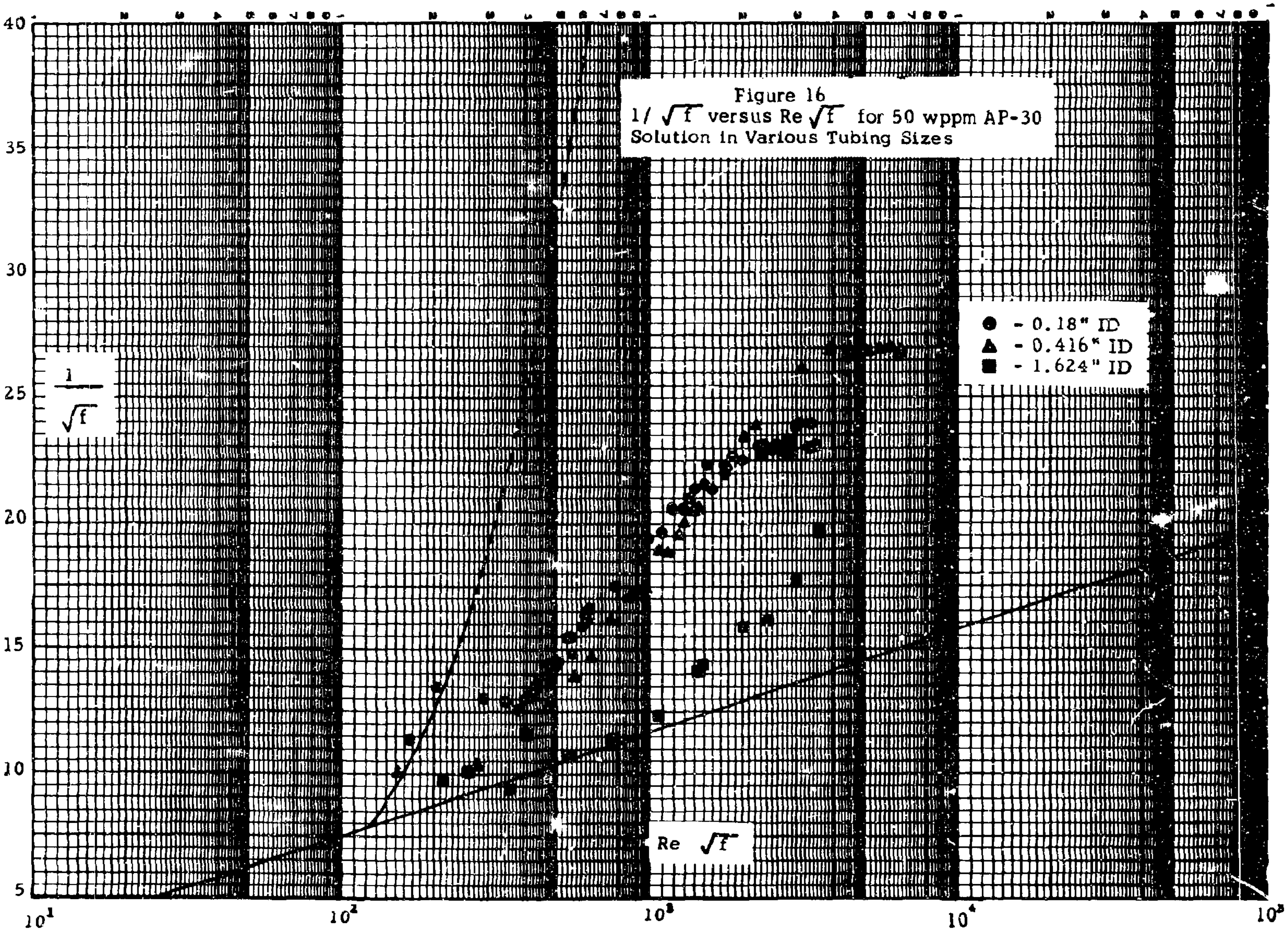


Figure 15
$1/\sqrt{f}$ versus Re $\sqrt{f}$ for 10 wppm
AP-30 Solution in Various Tubing Sizes



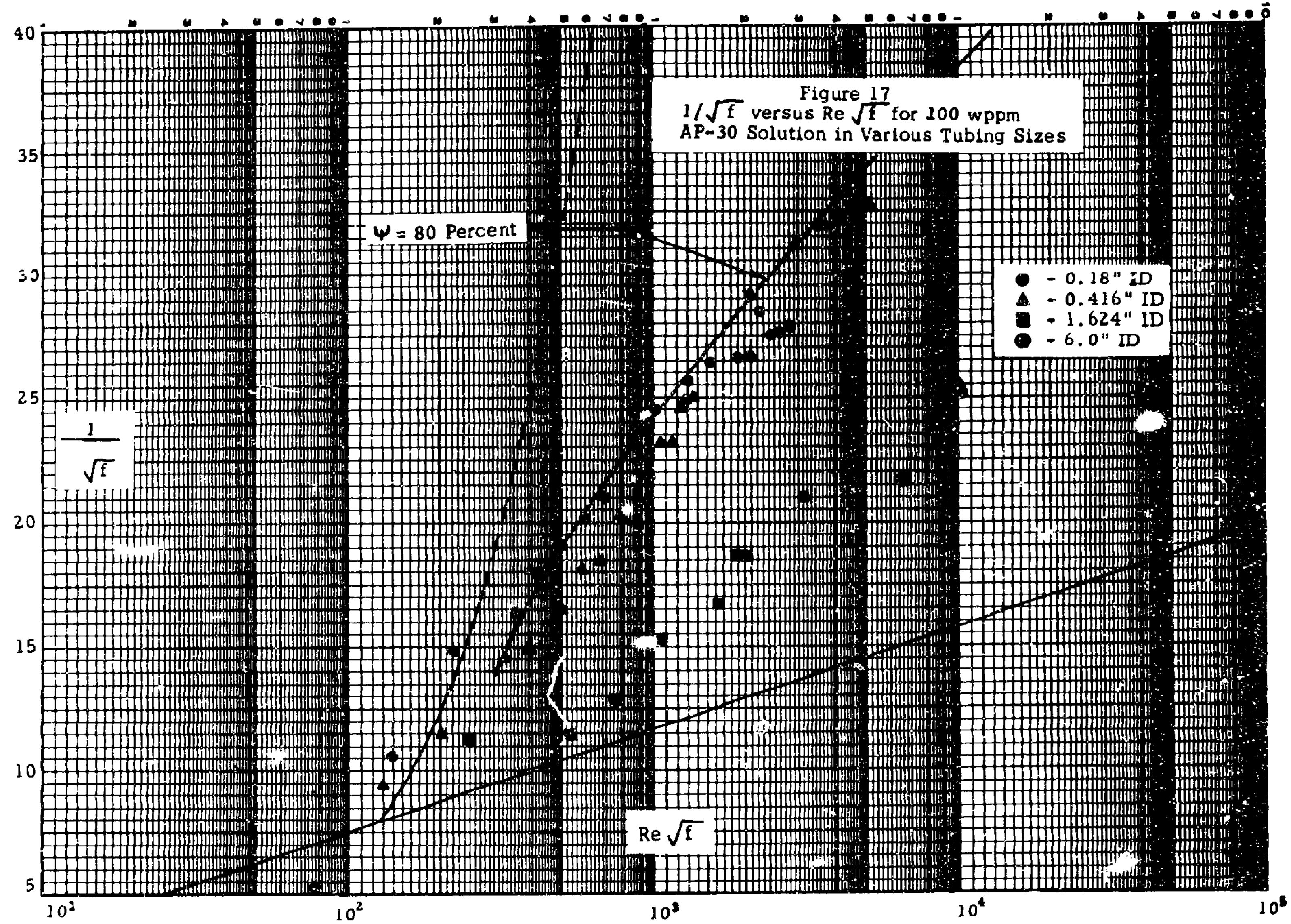


Figure 17
$1/\sqrt{f}$ versus Re $\sqrt{f}$ for 100 wppm
AP-30 Solution in Various Tubing Sizes

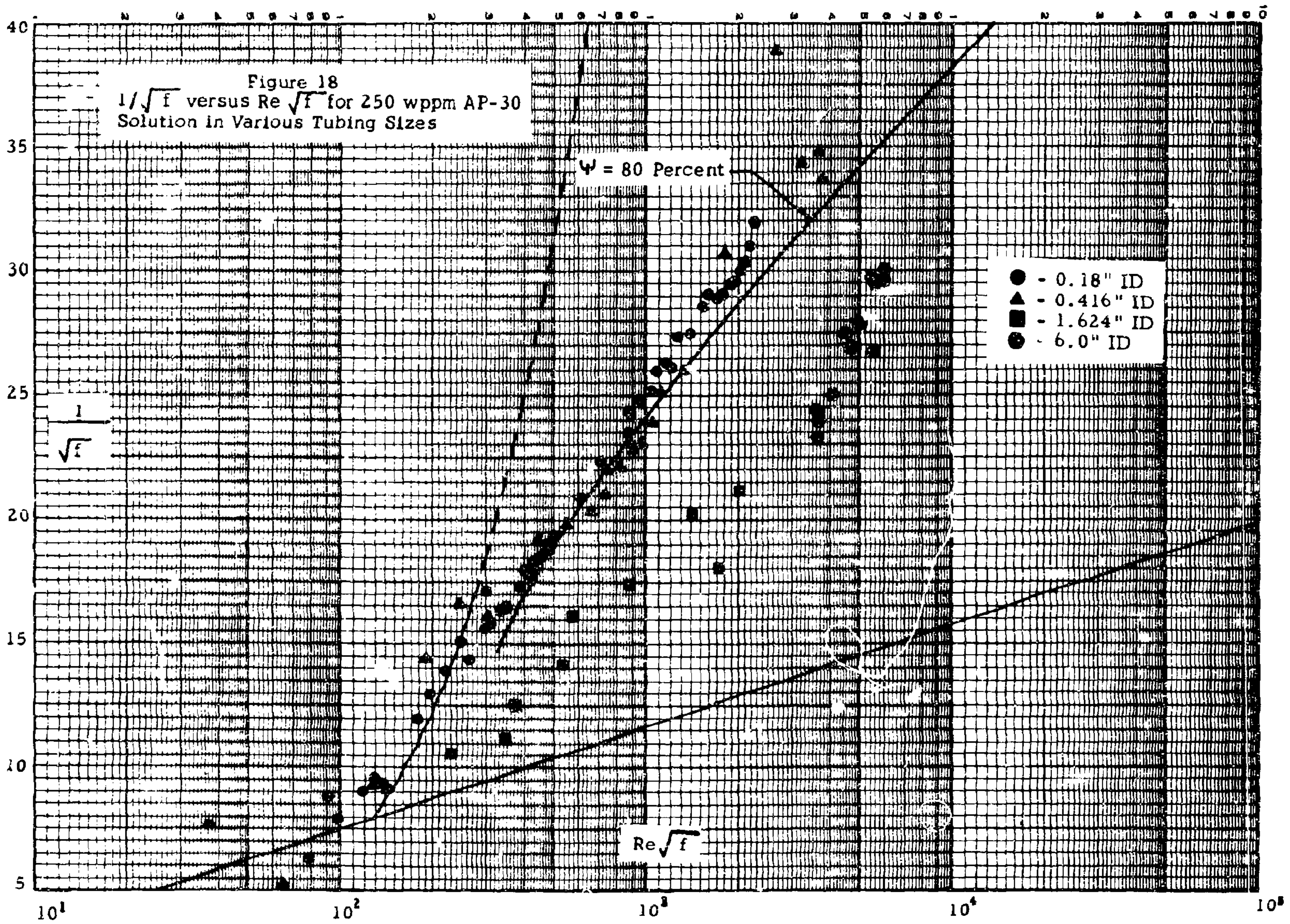


Figure 18
$1/\sqrt{f}$ versus Re $\sqrt{f}$ for 250 wppm AP-30 Solution in Various Tubing Sizes

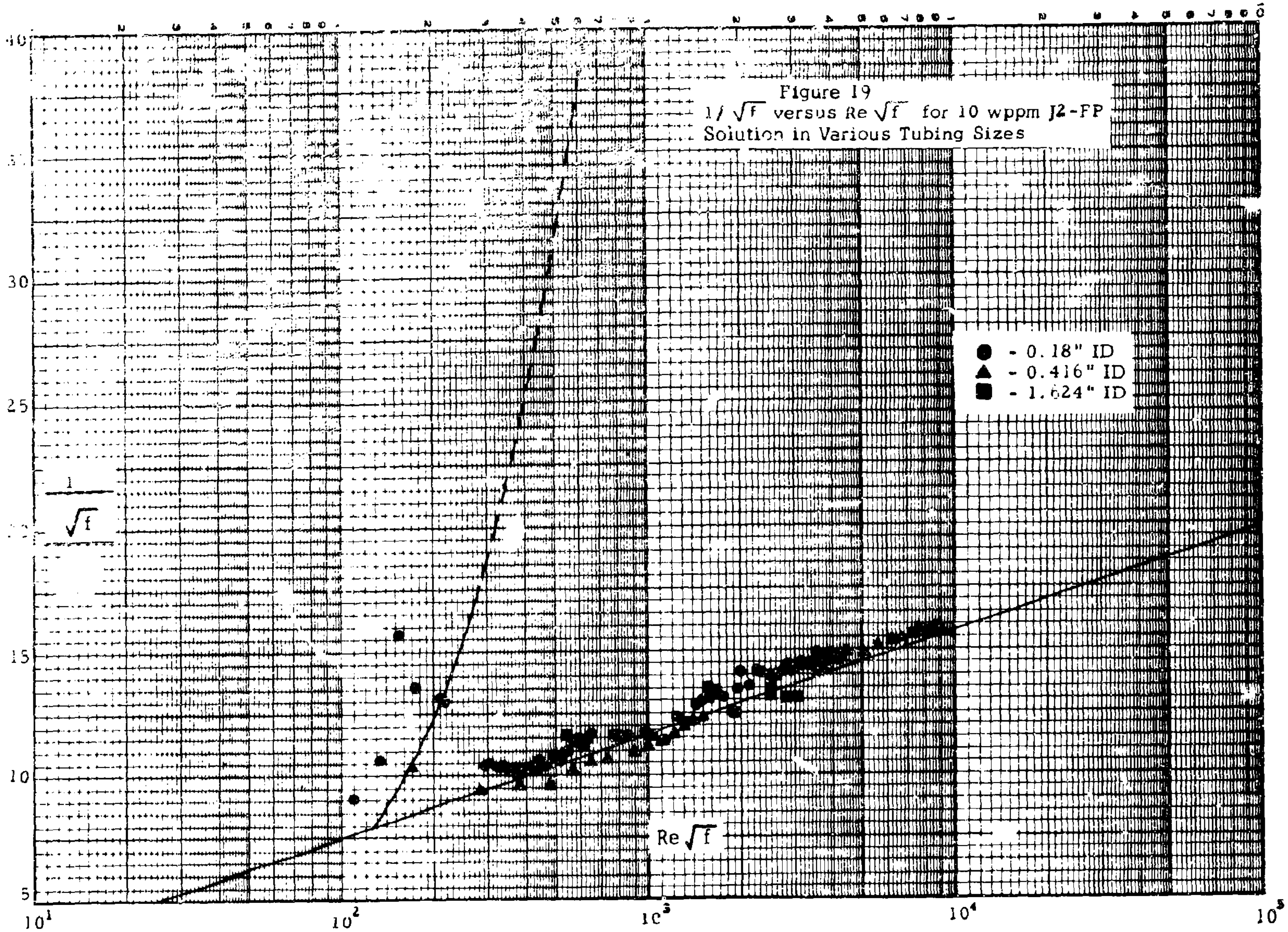


Figure 19
$1/\sqrt{f}$ versus $\mathrm{Re}\sqrt{f}$ for 10 wppm J2-FP Solution in Various Tubing Sizes

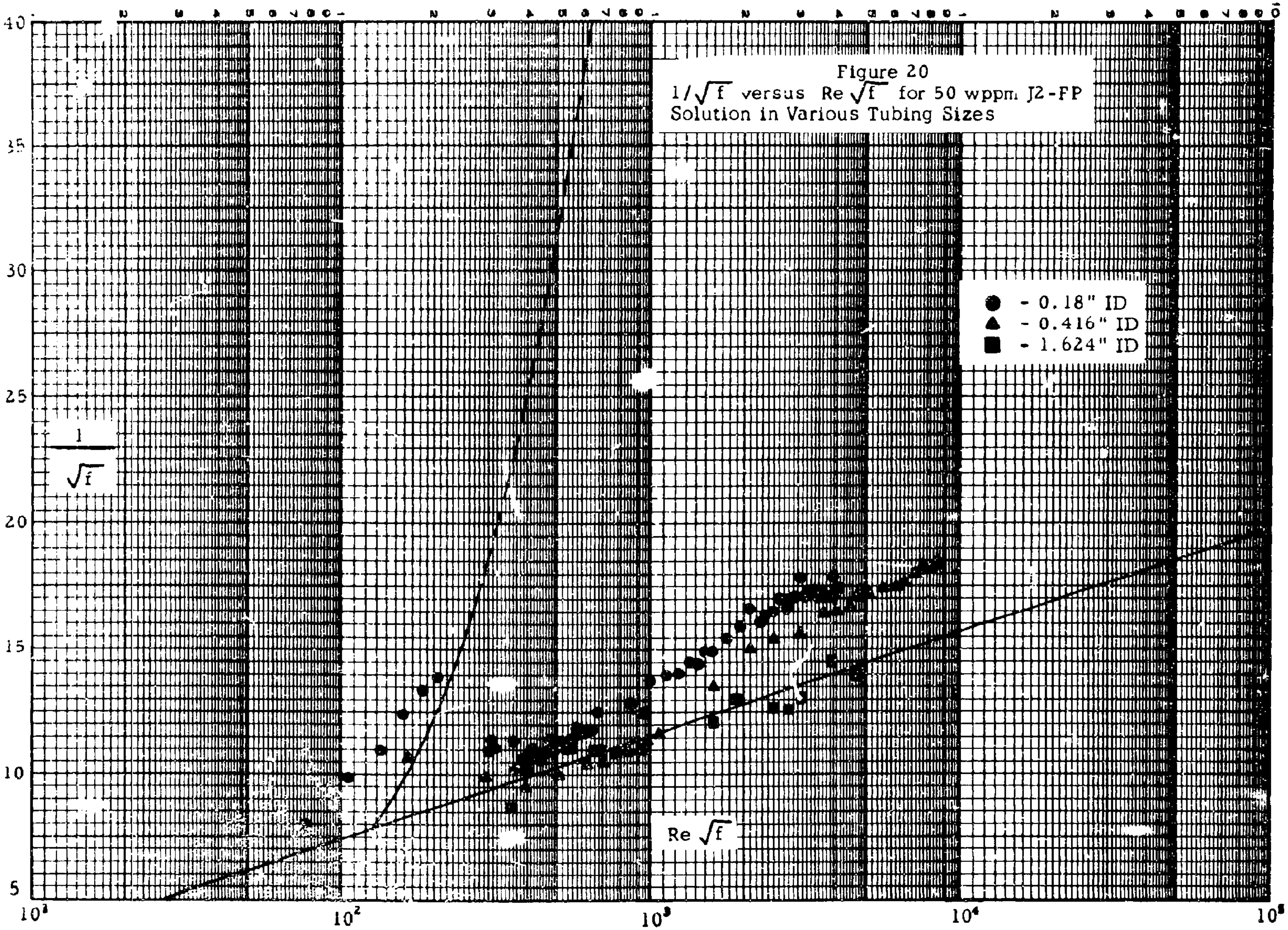


Figure 20

$1/\sqrt{f}$ versus $Re\sqrt{f}$ for 50 wppm J2-FP Solution in Various Tubing Sizes

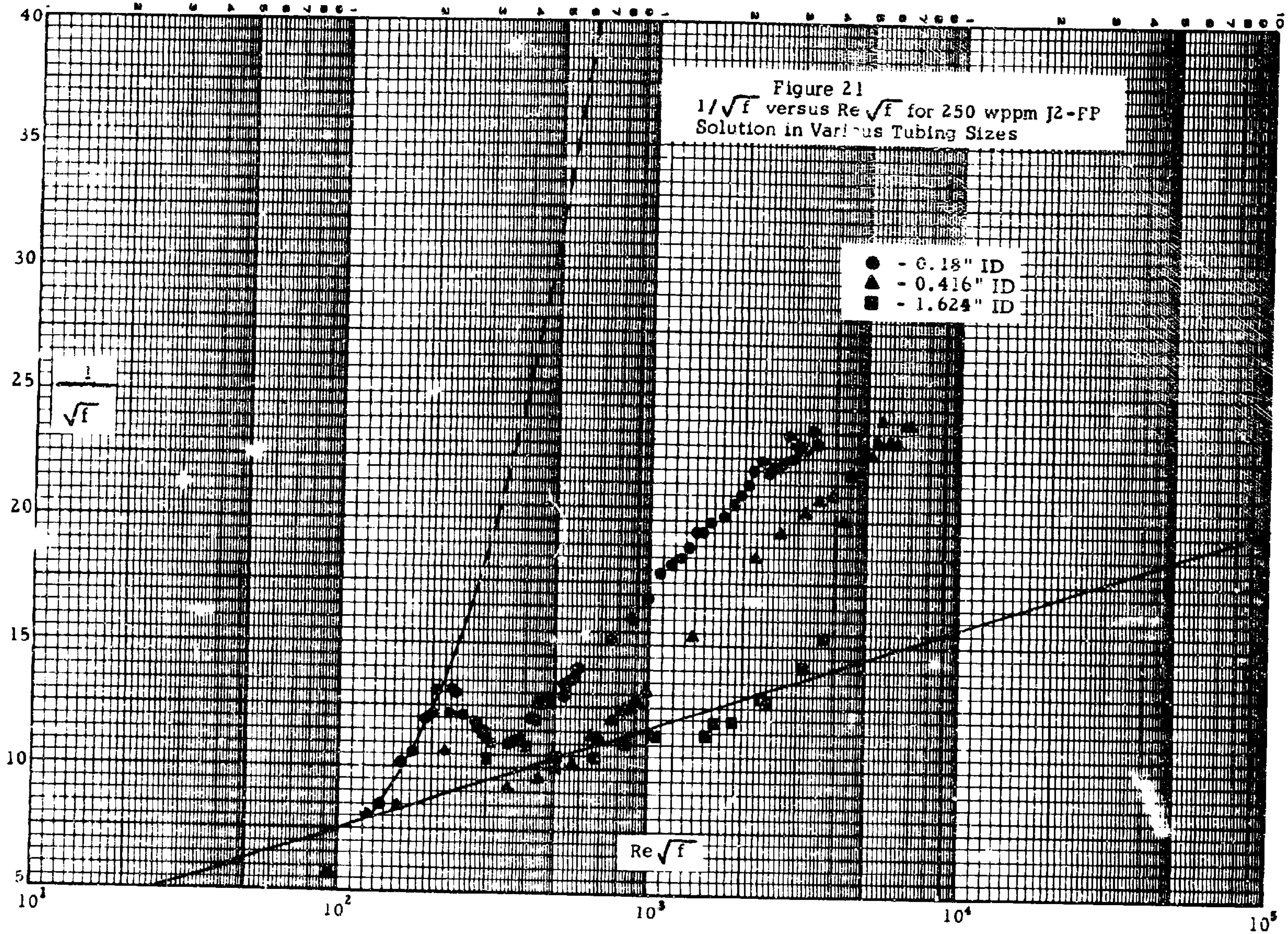


Figure 21
$1/\sqrt{f}$ versus $Re\sqrt{f}$ for 250 wppm J2-FP Solution in Various Tubing Sizes

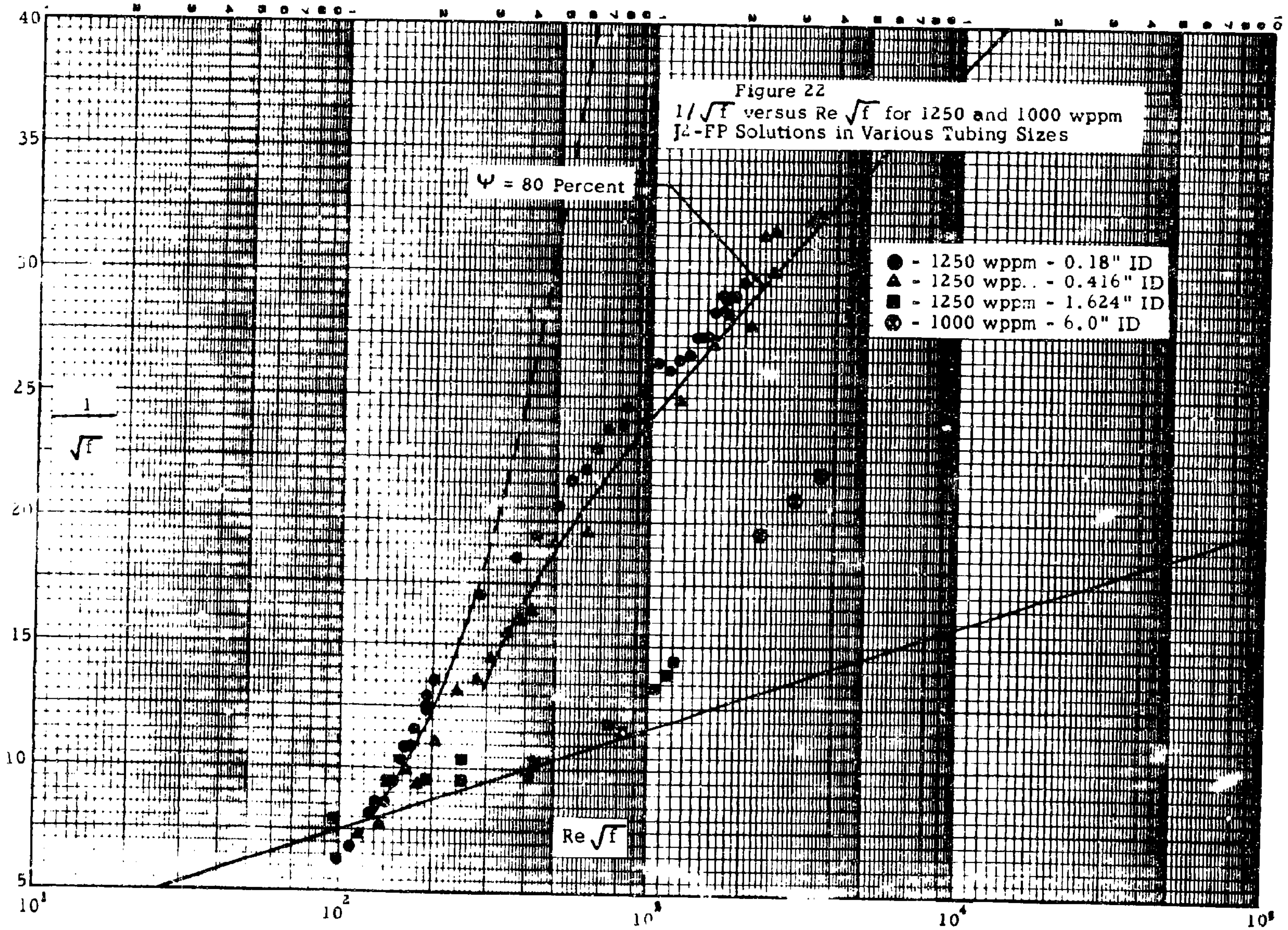


Figure 22
$1/\sqrt{f}$ versus Re $\sqrt{f}$ for 1250 and 1000 wppm J4-FP Solutions in Various Tubing Sizes

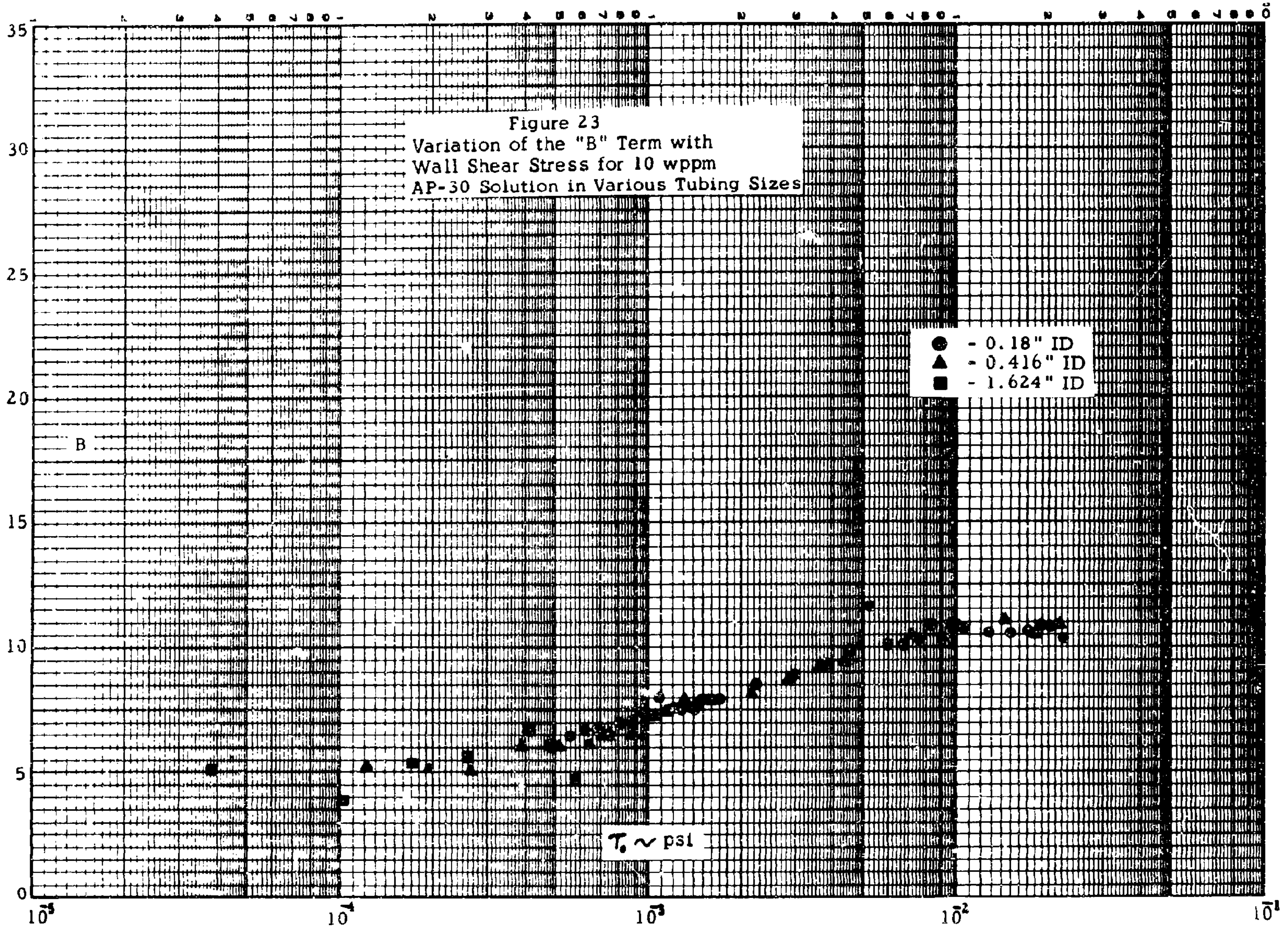


Figure 23
Variation of the "B" Term with
Wall Shear Stress for 10 wppm
AP-30 Solution in Various Tubing Sizes

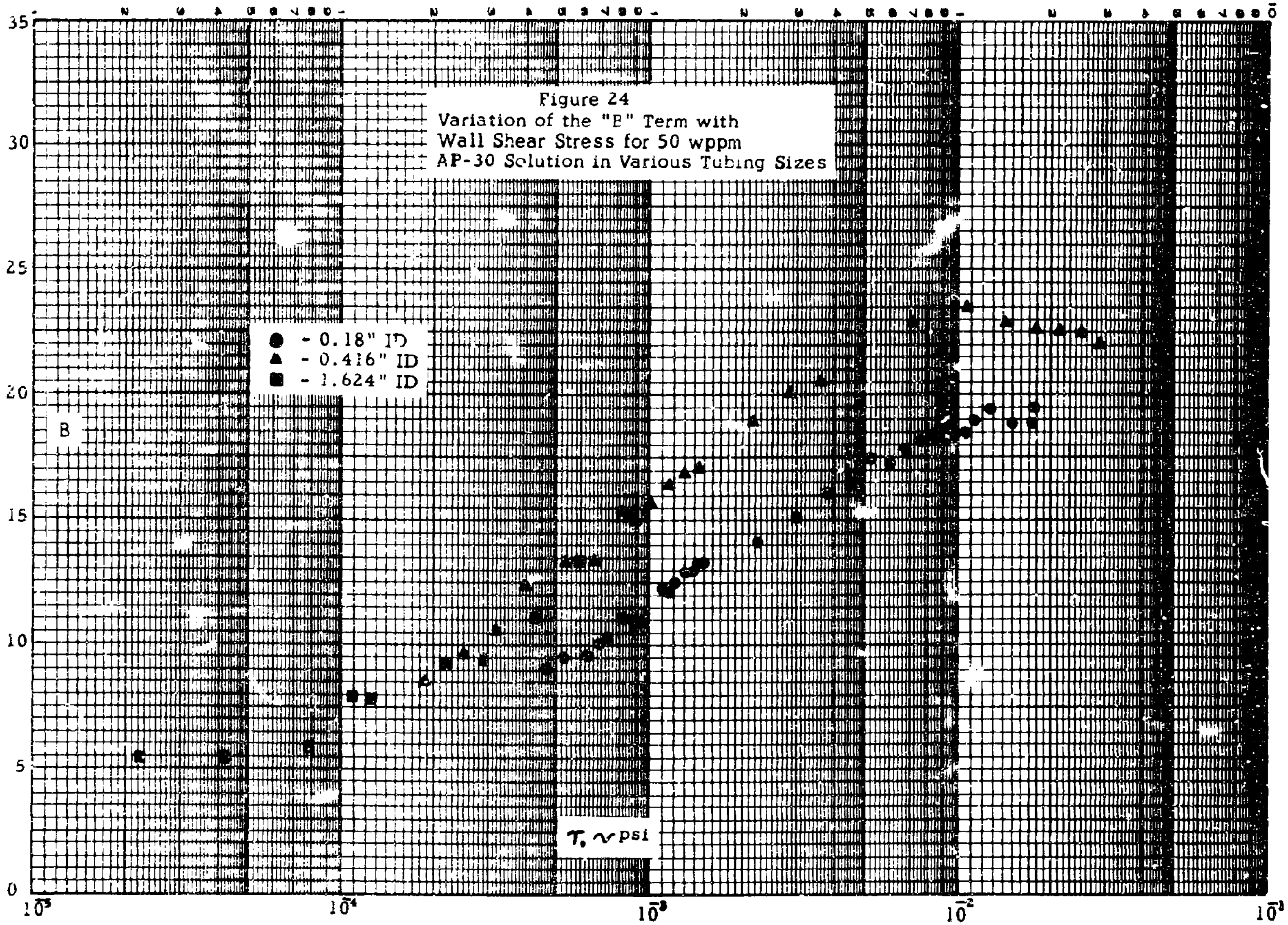


Figure 24
Variation of the "B" Term with
Wall Shear Stress for 50 wppm
AP-30 Solution in Various Tubing Sizes

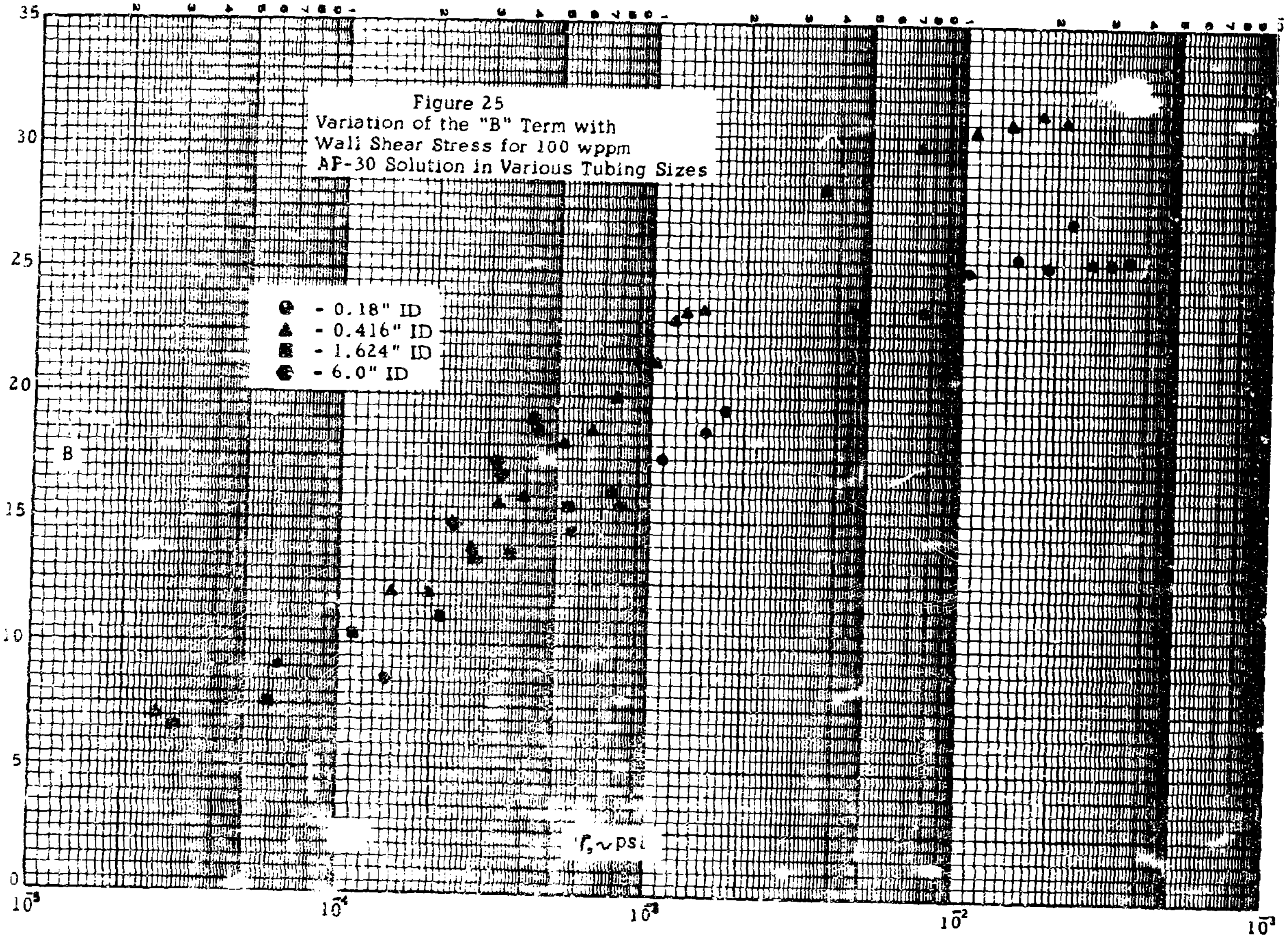


Figure 25
Variation of the "B" Term with Wall Shear Stress for 100 wppm AP-30 Solution in Various Tubing Sizes

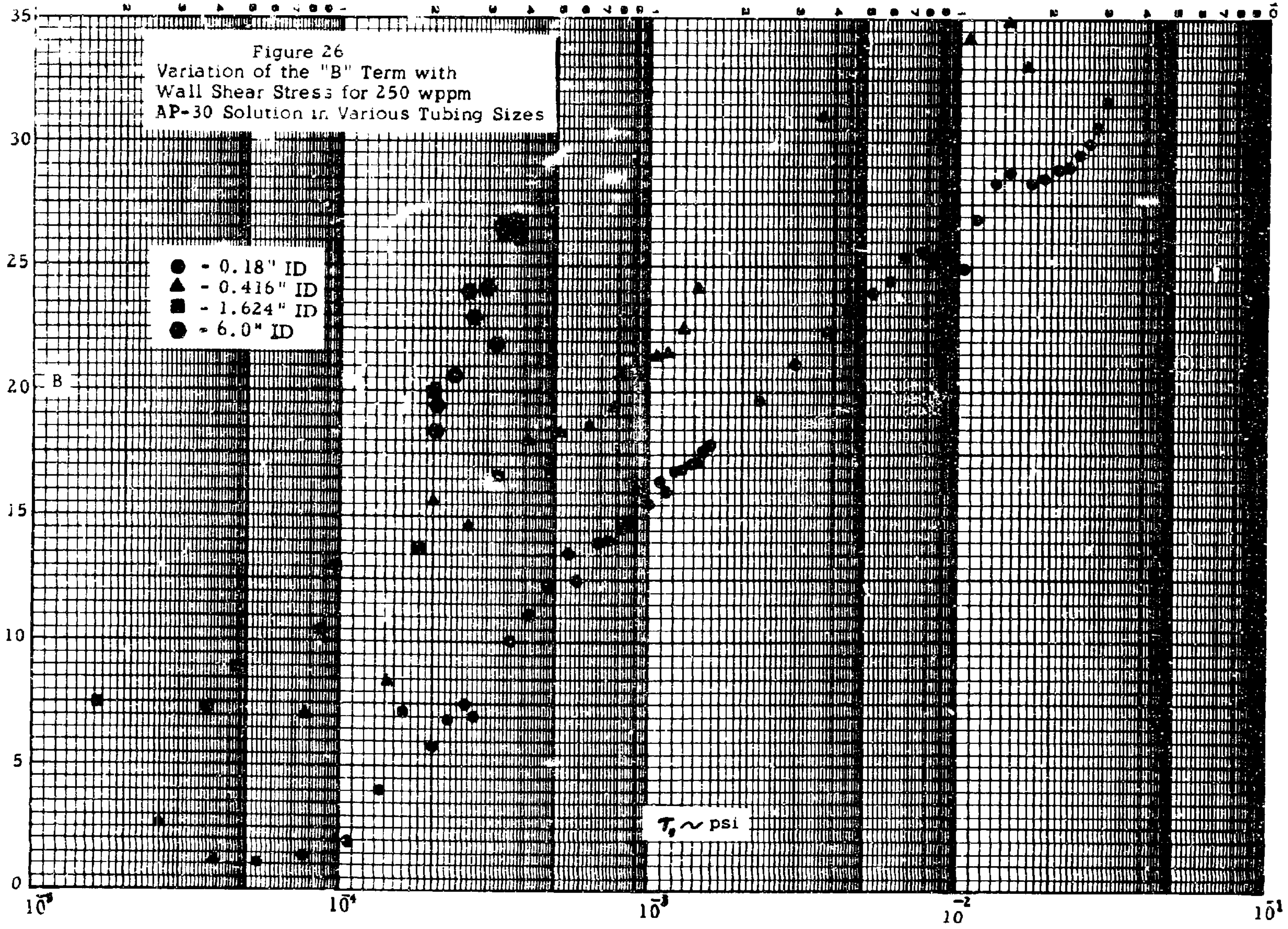


Figure 26
Variation of the "B" Term with
Wall Shear Stress for 250 wppm
AP-30 Solution in Various Tubing Sizes

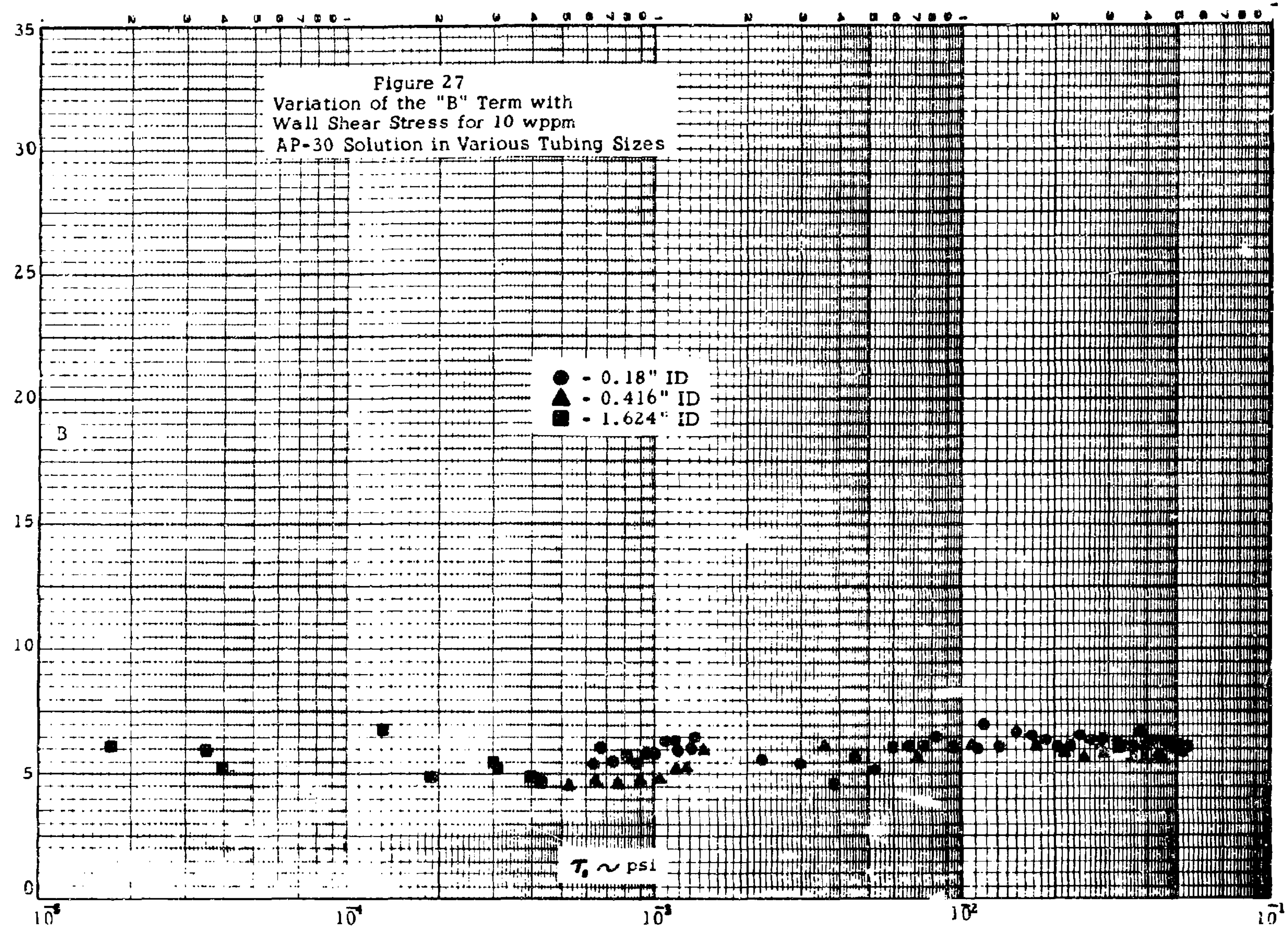


Figure 27
Variation of the "B" Term with Wall Shear Stress for 10 wppm AP-30 Solution in Various Tubing Sizes

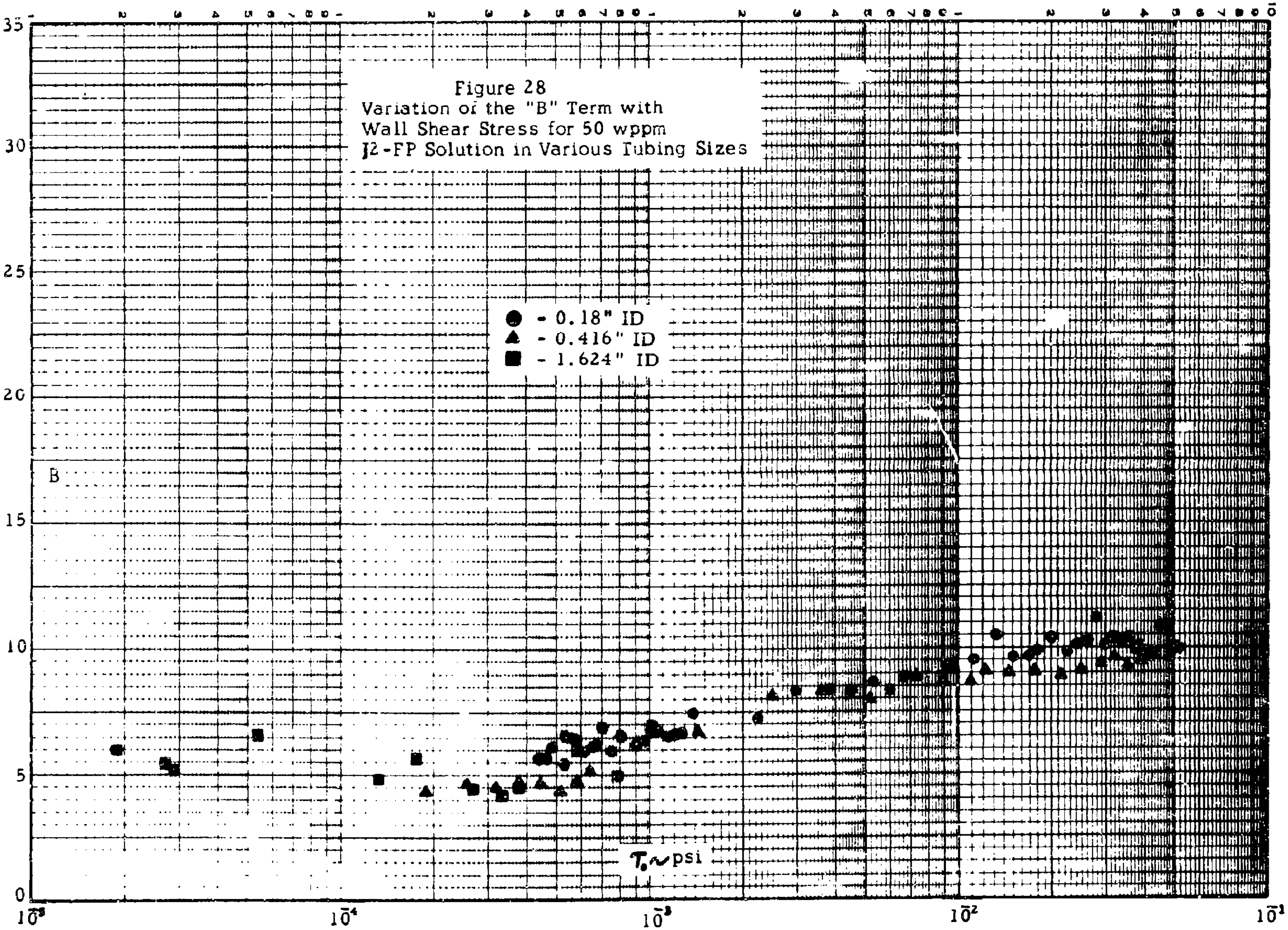


Figure 28
Variation of the "B" Term with Wall Shear Stress for 50 wppm J2-FP Solution in Various Tubing Sizes

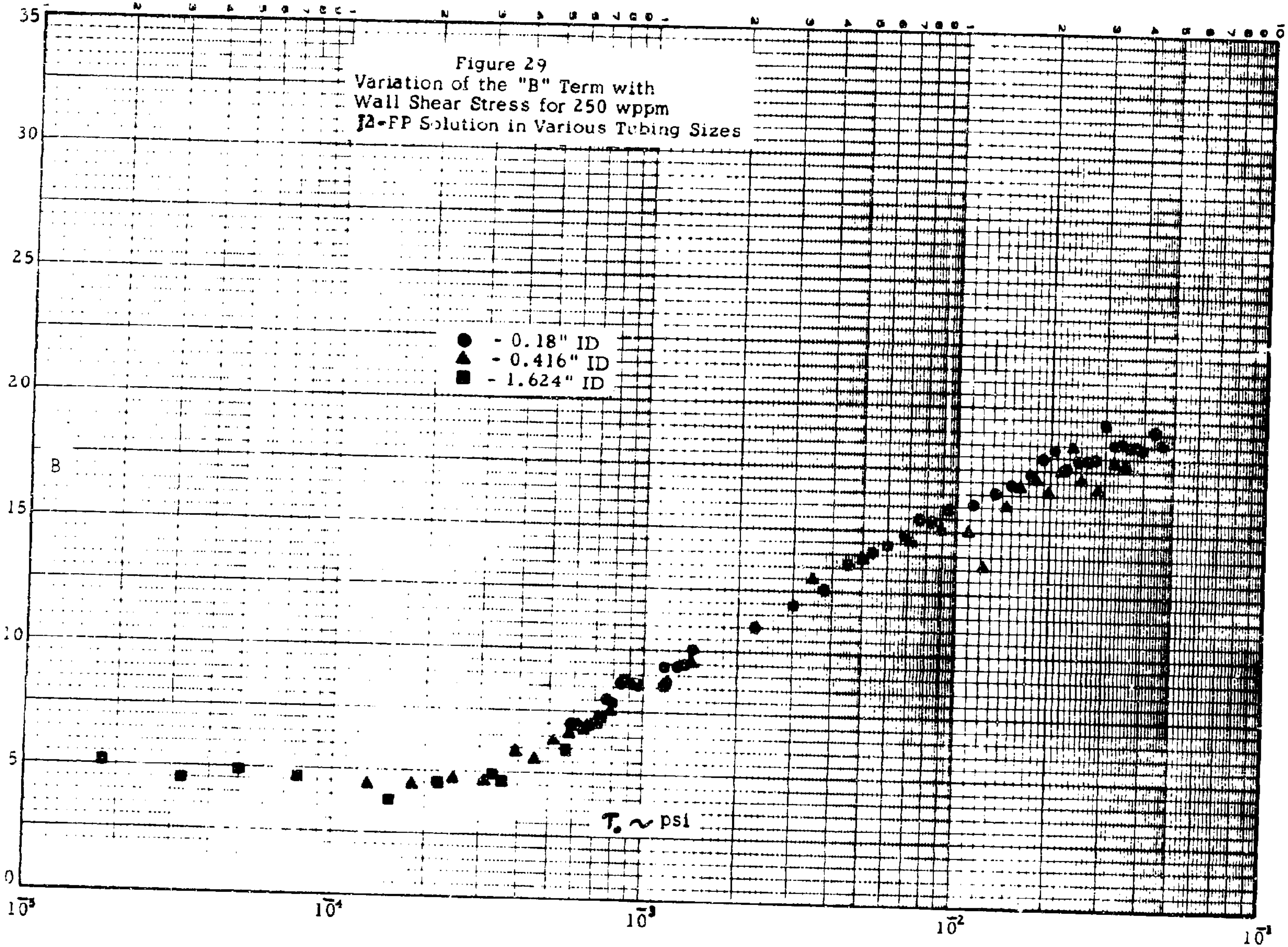


Figure 29
Variation of the "B" Term with
Wall Shear Stress for 250 wppm
J2-FP Solution in Various Tubing Sizes

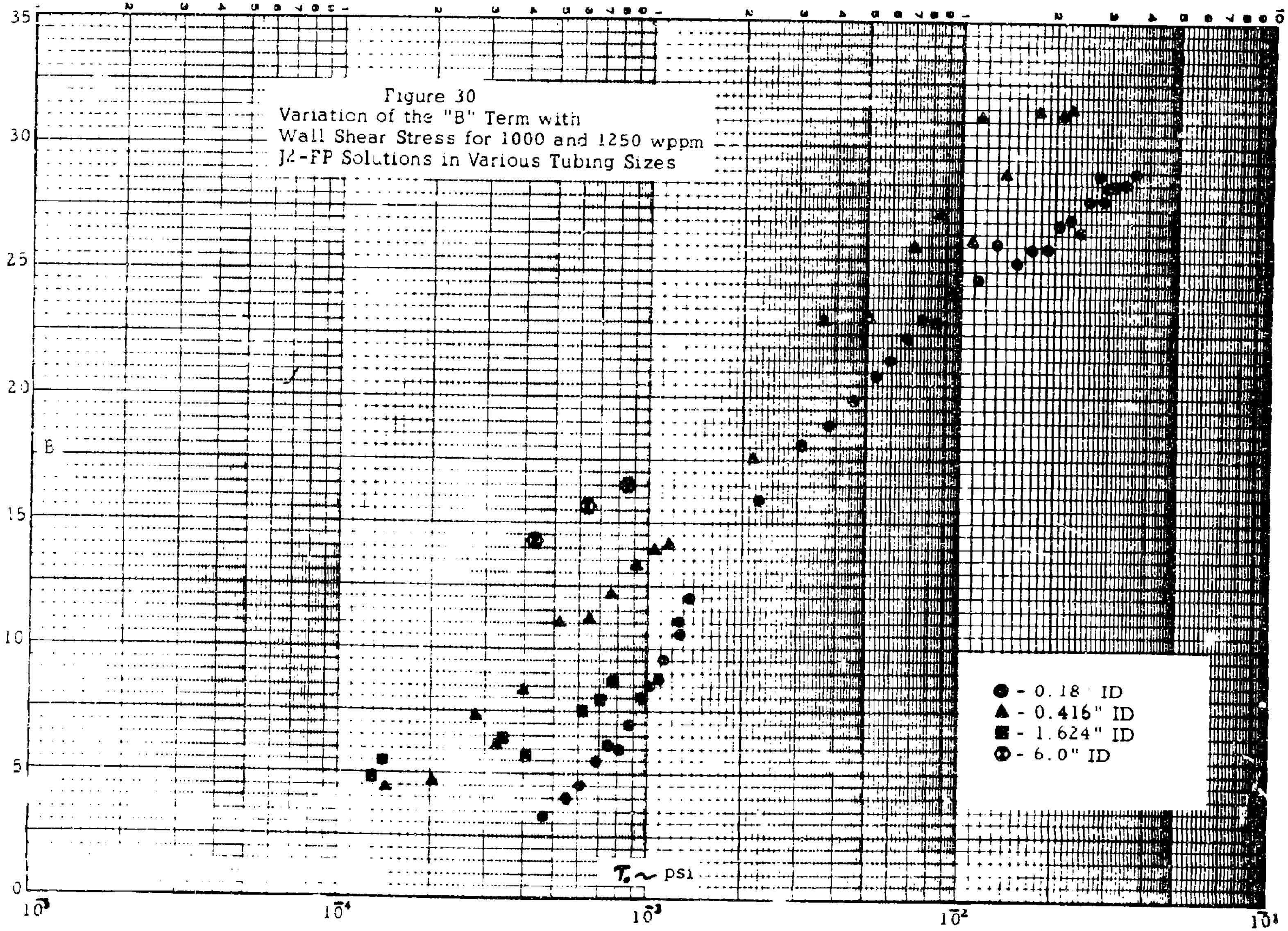


Figure 30
Variation of the "B" Term with
Wall Shear Stress for 1000 and 1250 wppm
J2-FP Solutions in Various Tubing Sizes

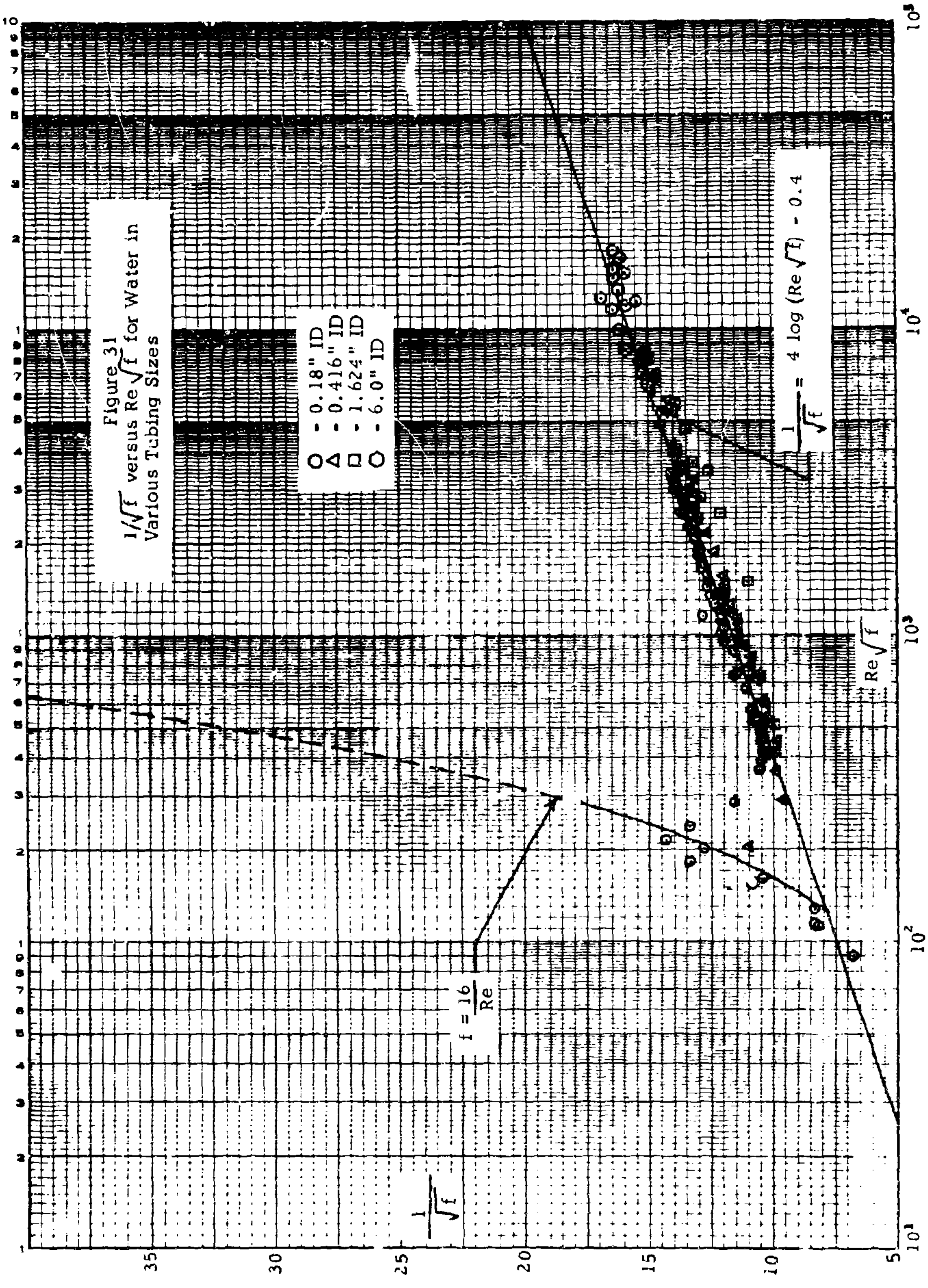


Figure 31
$1/\sqrt{f}$ versus $Re\sqrt{f}$ for Water in Various Tubing Sizes

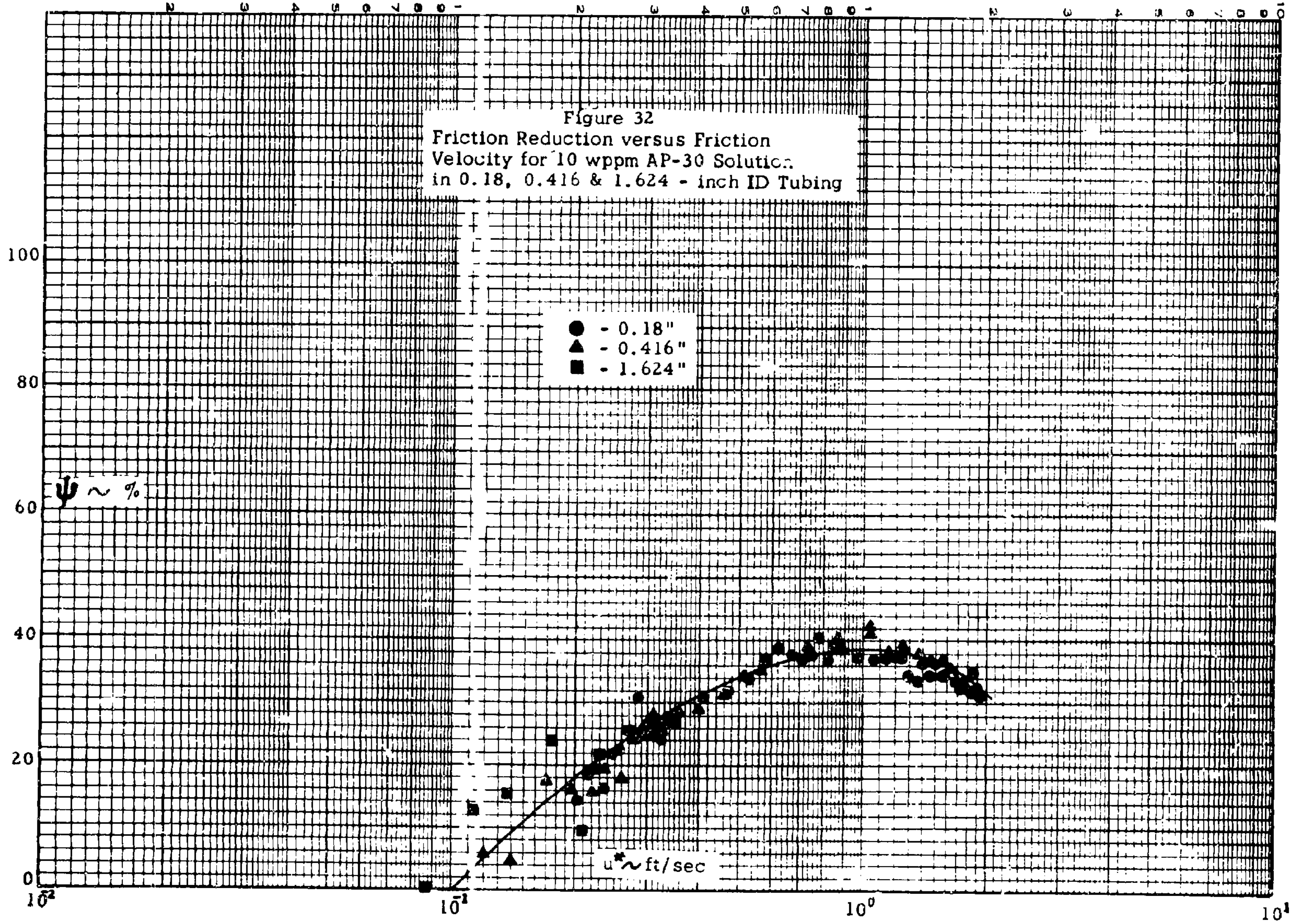


Figure 32
Friction Reduction versus Friction Velocity for 10 wppm AP-30 Solution in 0.18, 0.416 & 1.624 - inch ID Tubing

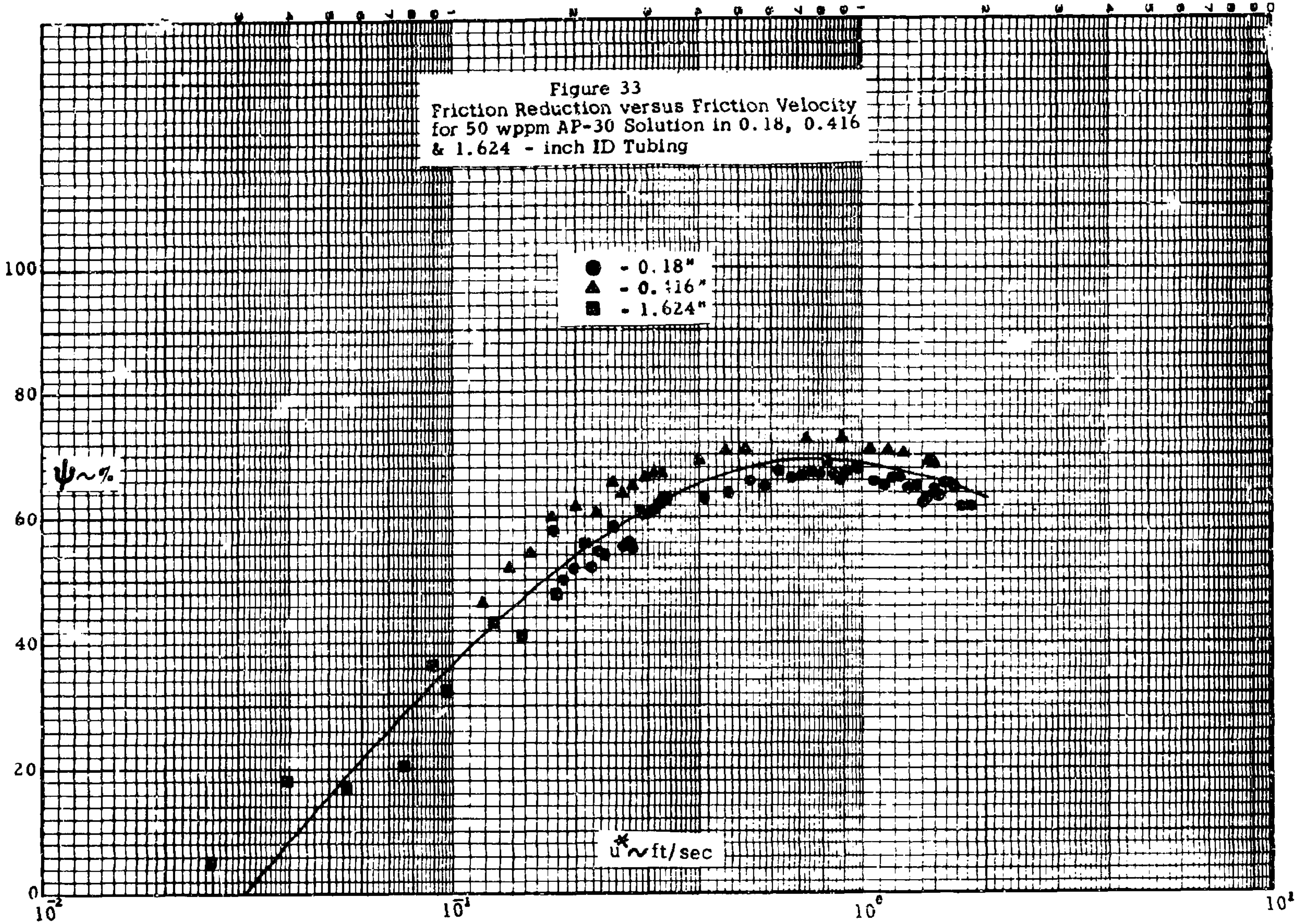


Figure 33
Friction Reduction versus Friction Velocity for 50 wppm AP-30 Solution in 0.18, 0.416 & 1.624 - inch ID Tubing

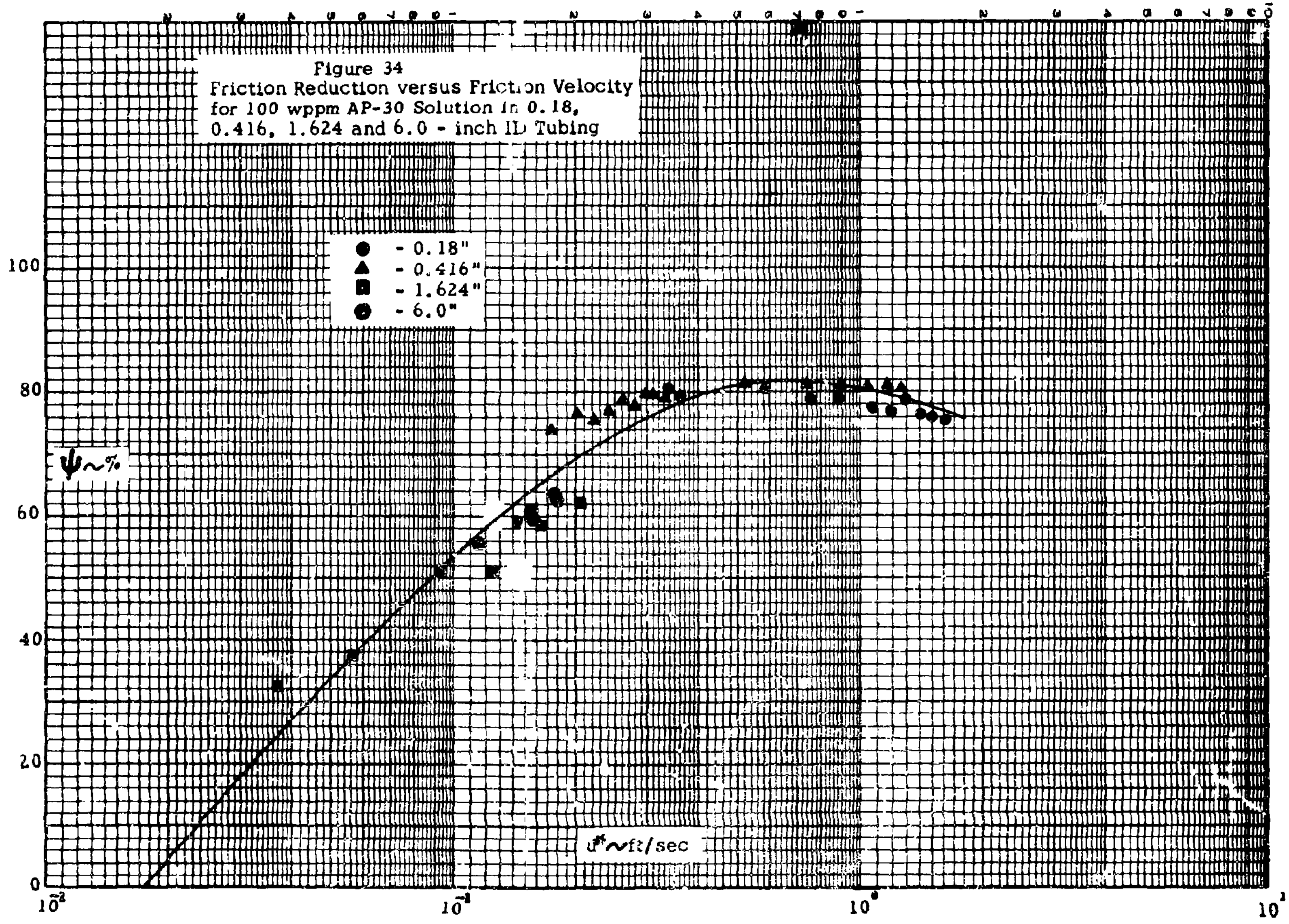


Figure 34
Friction Reduction versus Friction Velocity for 100 wppm AP-30 Solution in 0.18, 0.416, 1.624 and 6.0 - inch ID Tubing

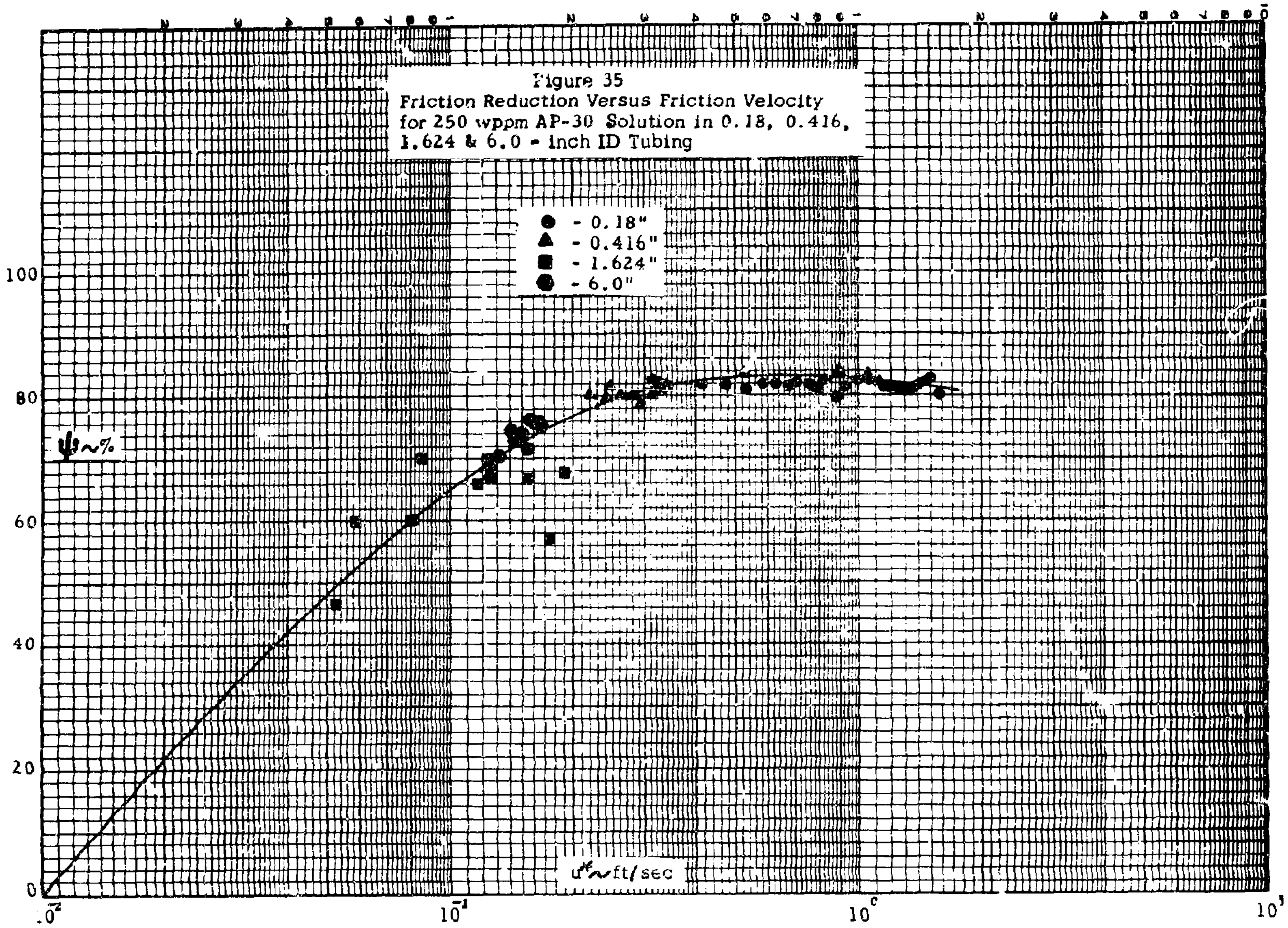


Figure 35
Friction Reduction Versus Friction Velocity for 250 wppm AP-30 Solution in 0.18, 0.416, 1.624 & 6.0 - inch ID Tubing

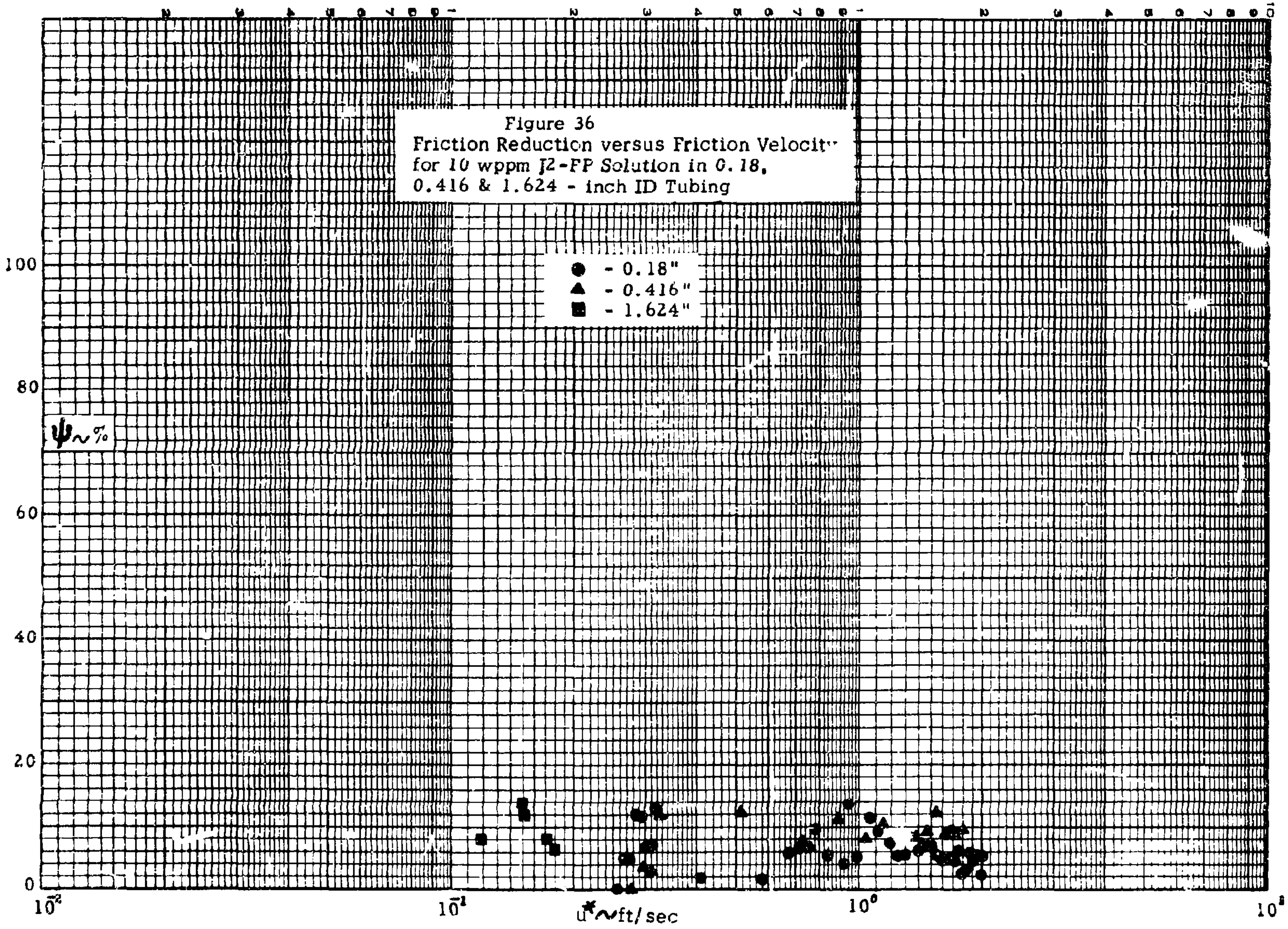


Figure 36
Friction Reduction versus Friction Velocit
for 10 wppm J2-FP Solution in 0.18, 0.416 & 1.624 - inch ID Tubing

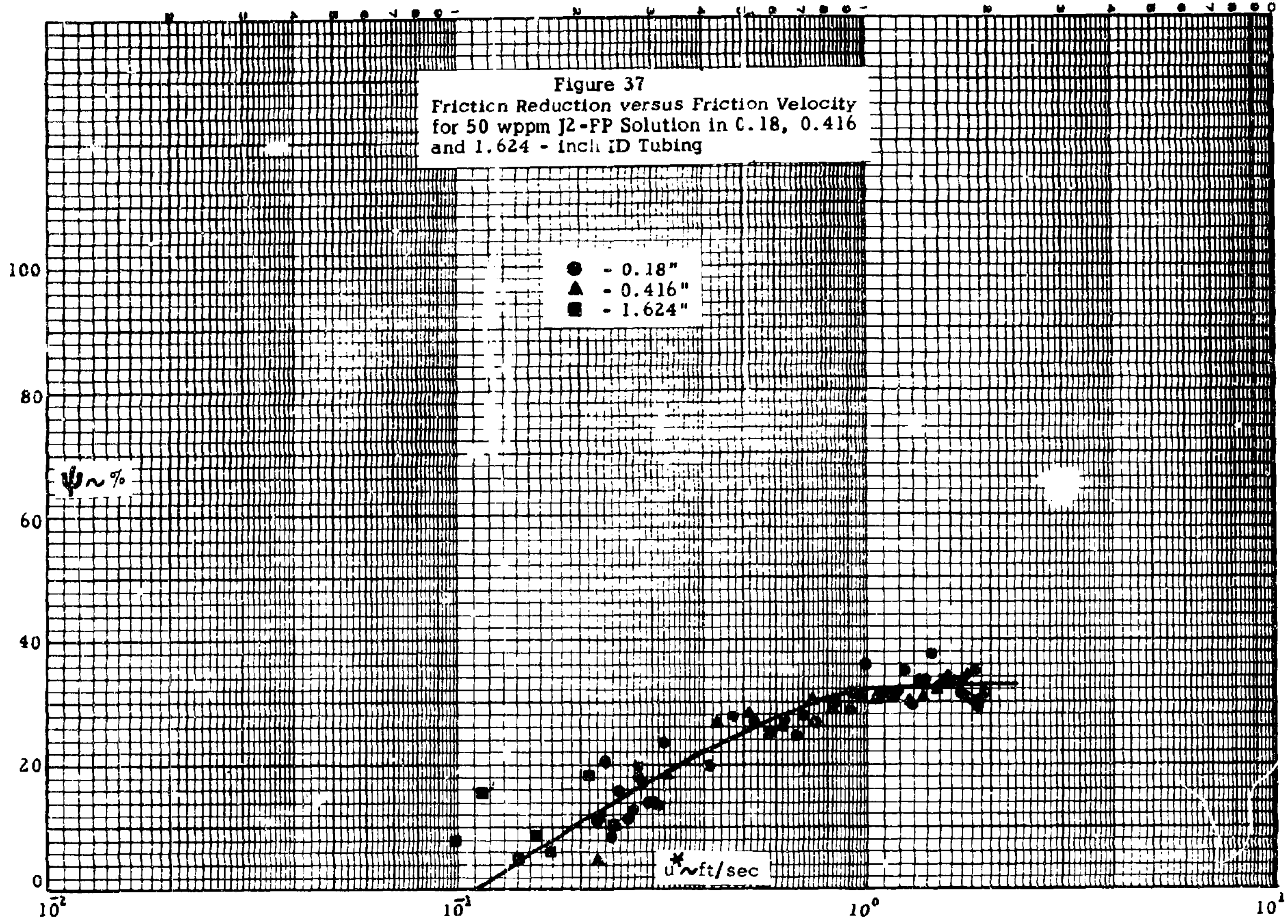


Figure 37
Friction Reduction versus Friction Velocity for 50 wppm J2-FP Solution in 0.18, 0.416 and 1.624 - Inch ID Tubing

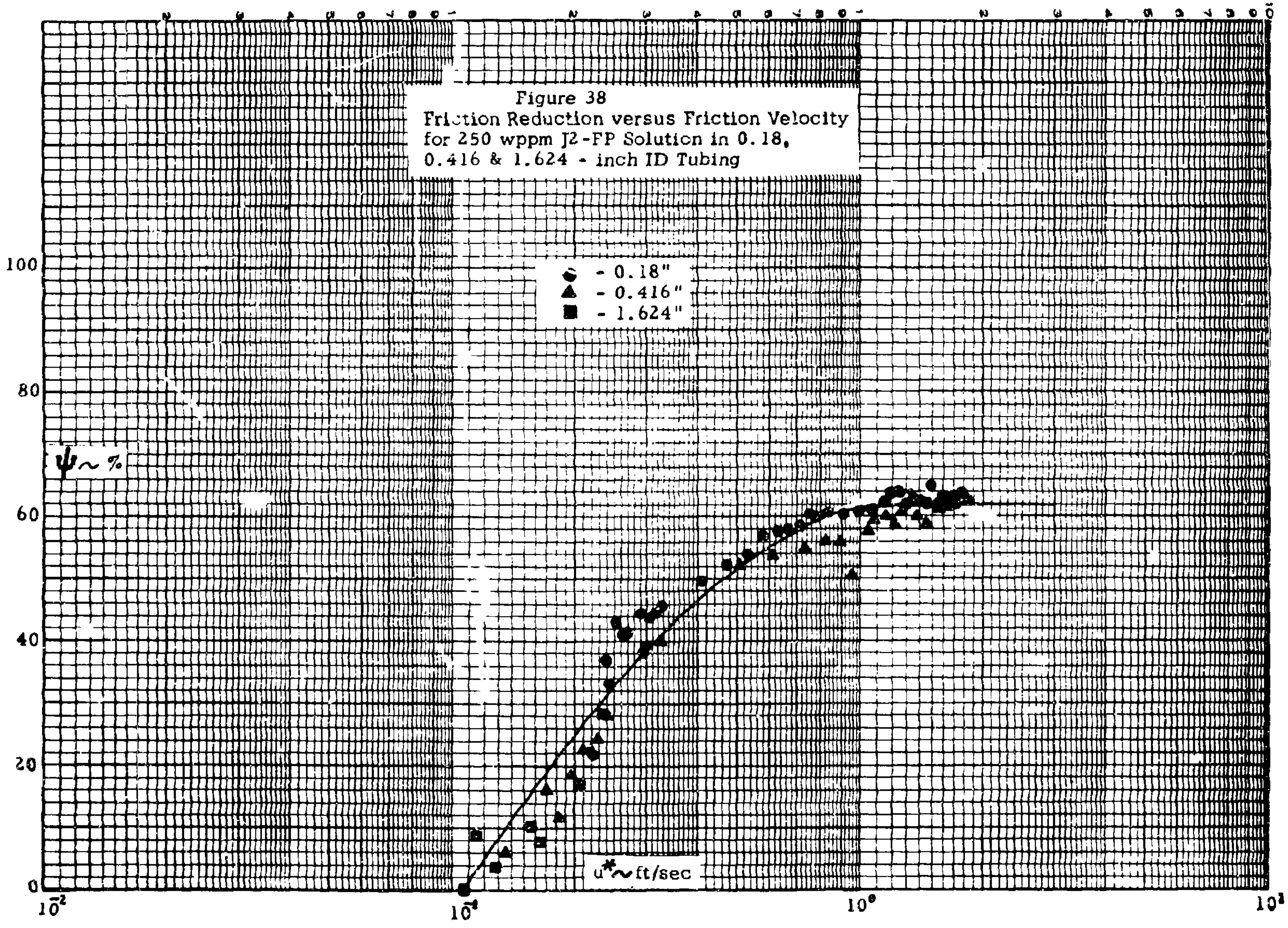


Figure 38
Friction Reduction versus Friction Velocity for 250 wppm J2-FP Solution in 0.18, 0.416 & 1.624 - inch ID Tubing

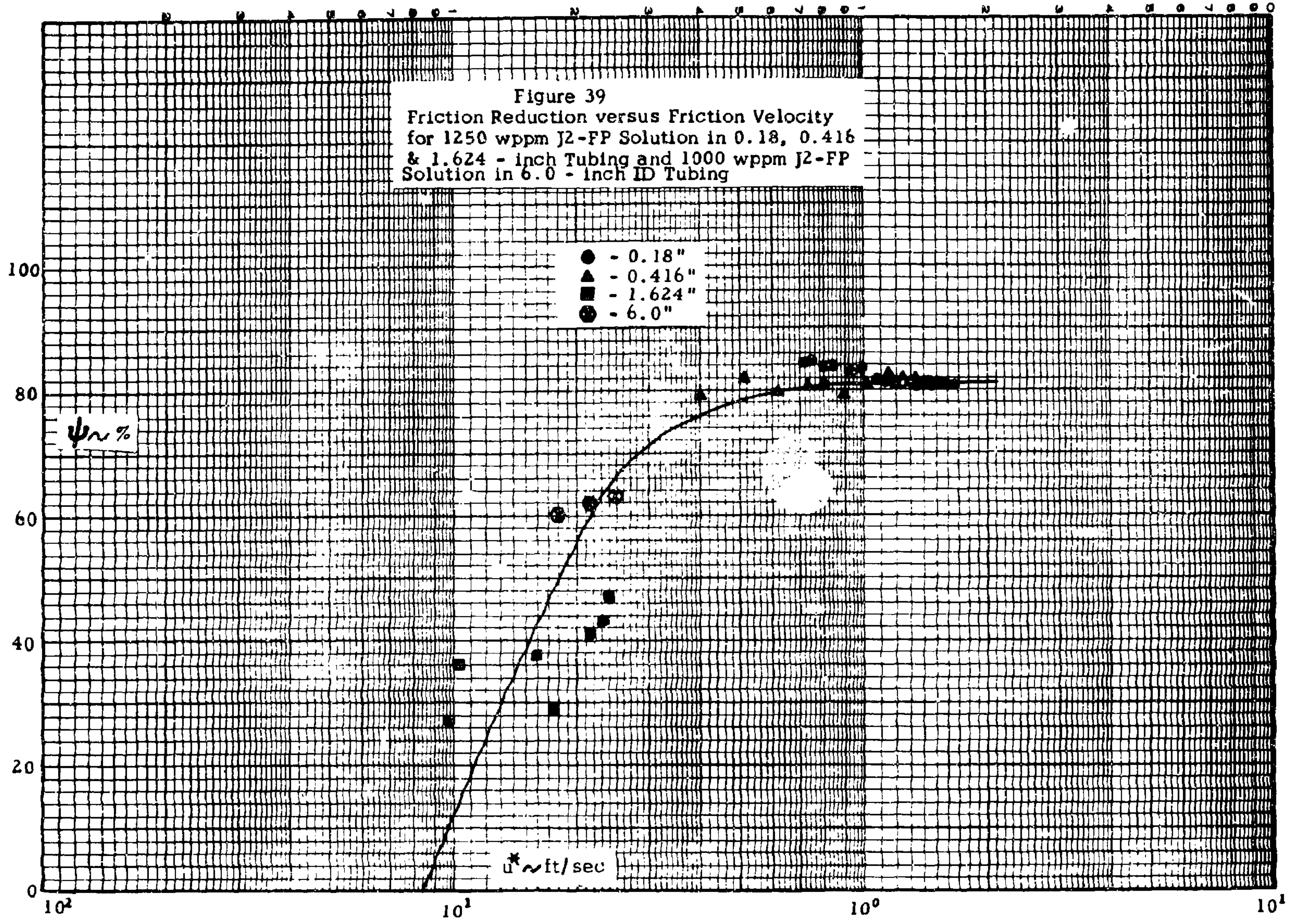


Figure 39
Friction Reduction versus Friction Velocity for 1250 wppm J2-FP Solution in 0.18, 0.416 & 1.624 - inch Tubing and 1000 wppm J2-FP Solution in 6.0 - inch ID Tubing

Figure 40
Effect of AP-30 Concentration on the Friction Velocity at which the Inception of Friction Reduction Occurs

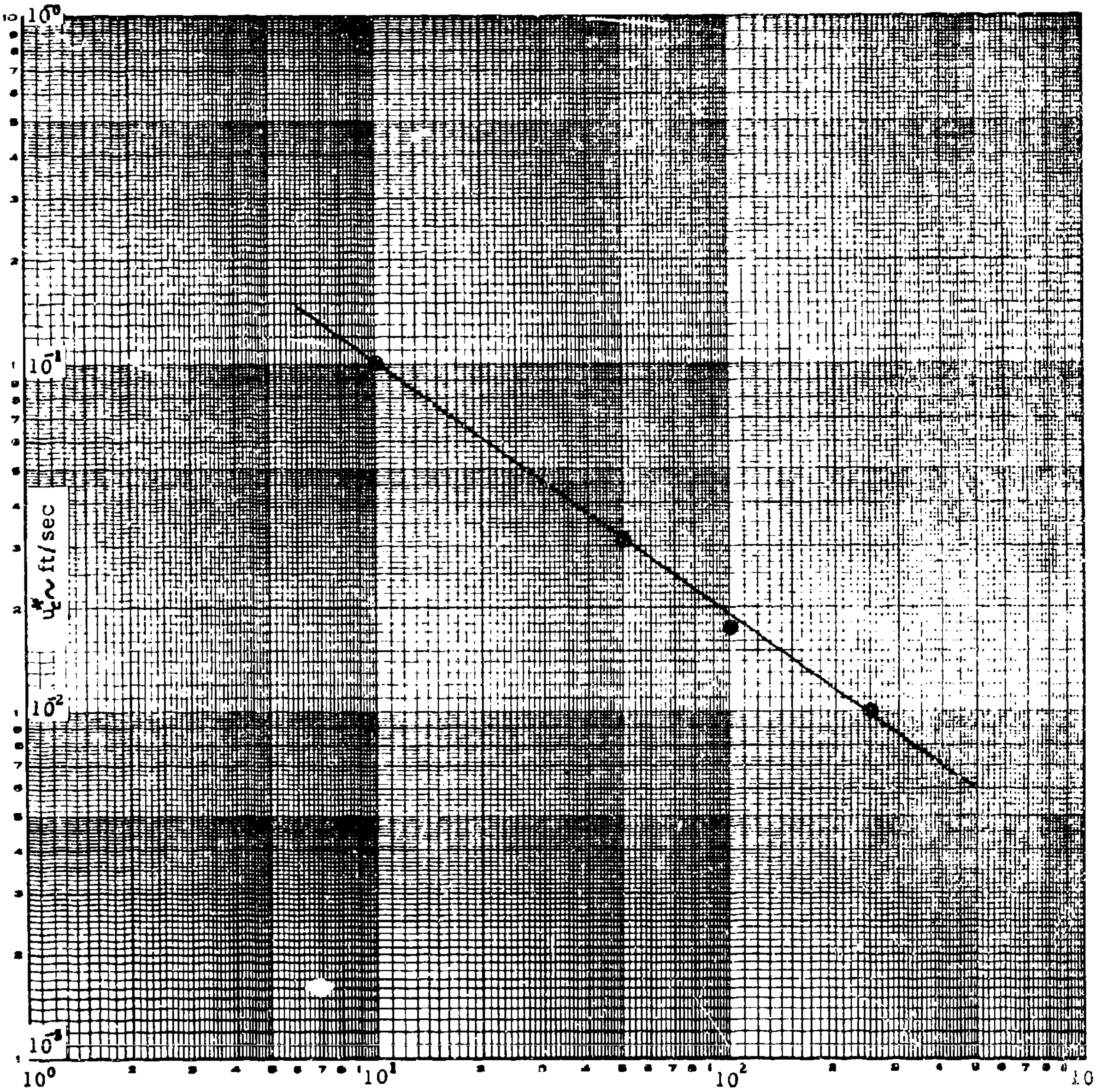
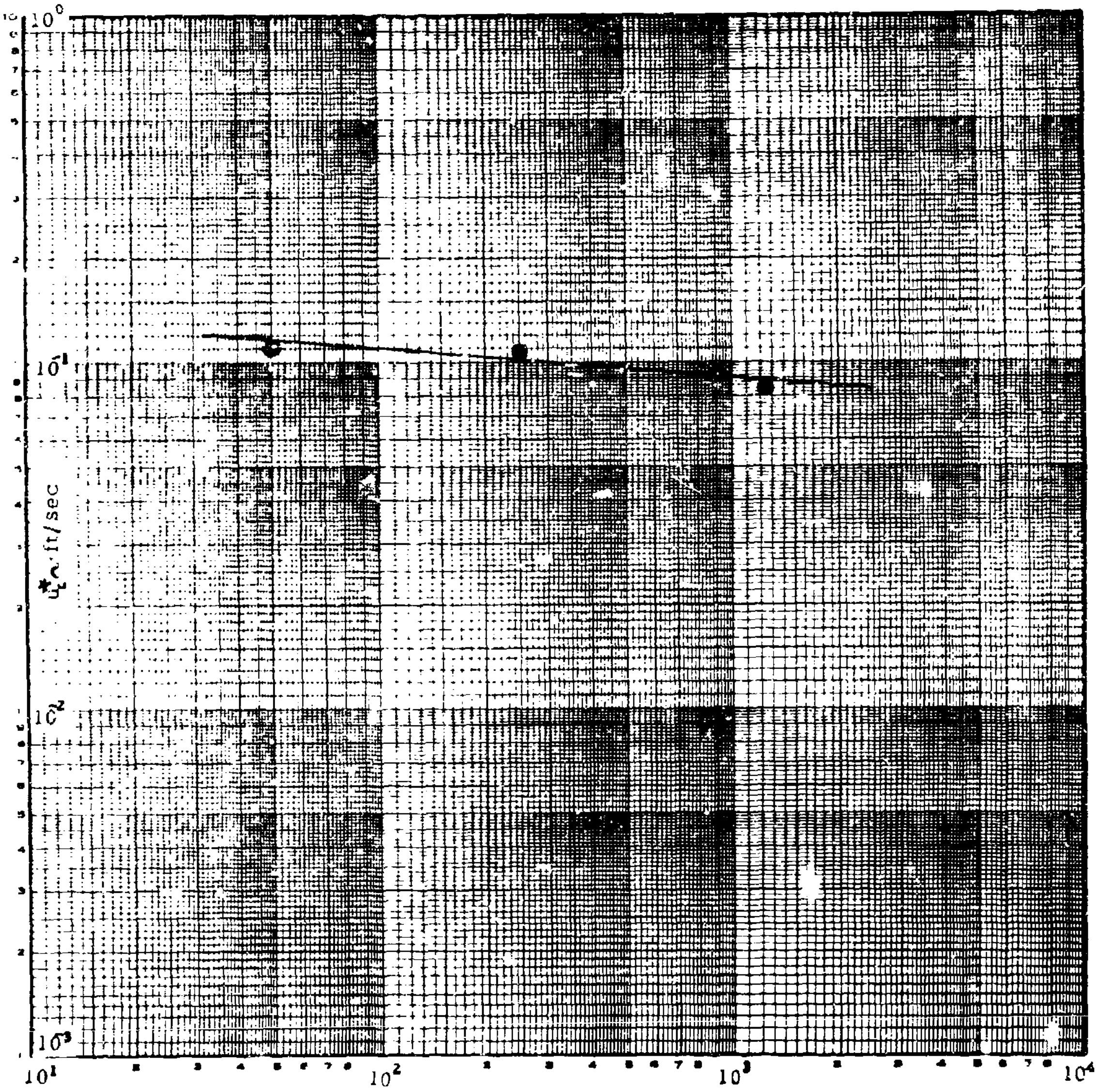


Figure 41
Effect of J2-FP Concentration on the Friction Velocity at which the Inception of Friction Reduction Occurs



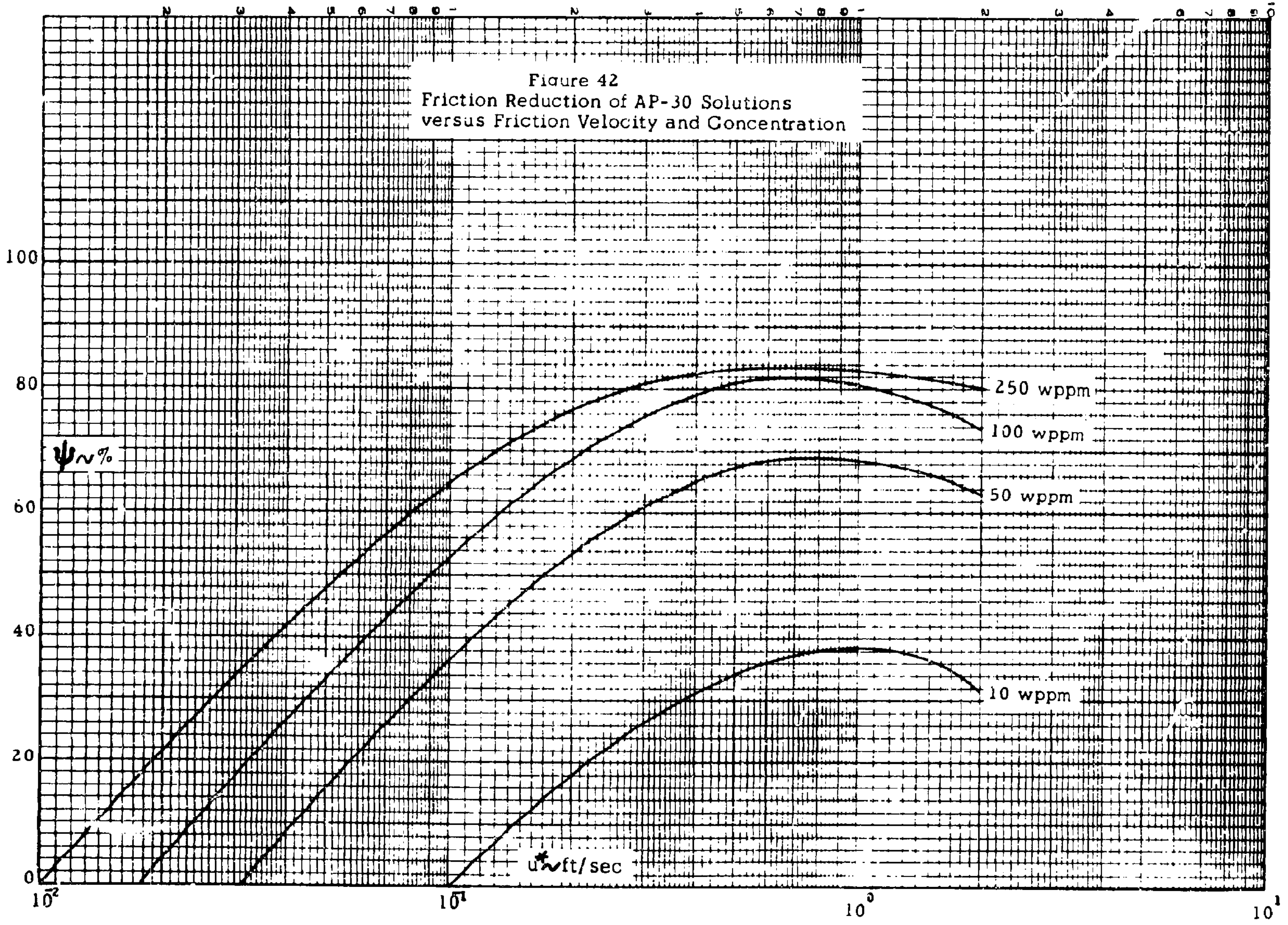


Figure 42
Friction Reduction of AP-30 Solutions
versus Friction Velocity and Concentration

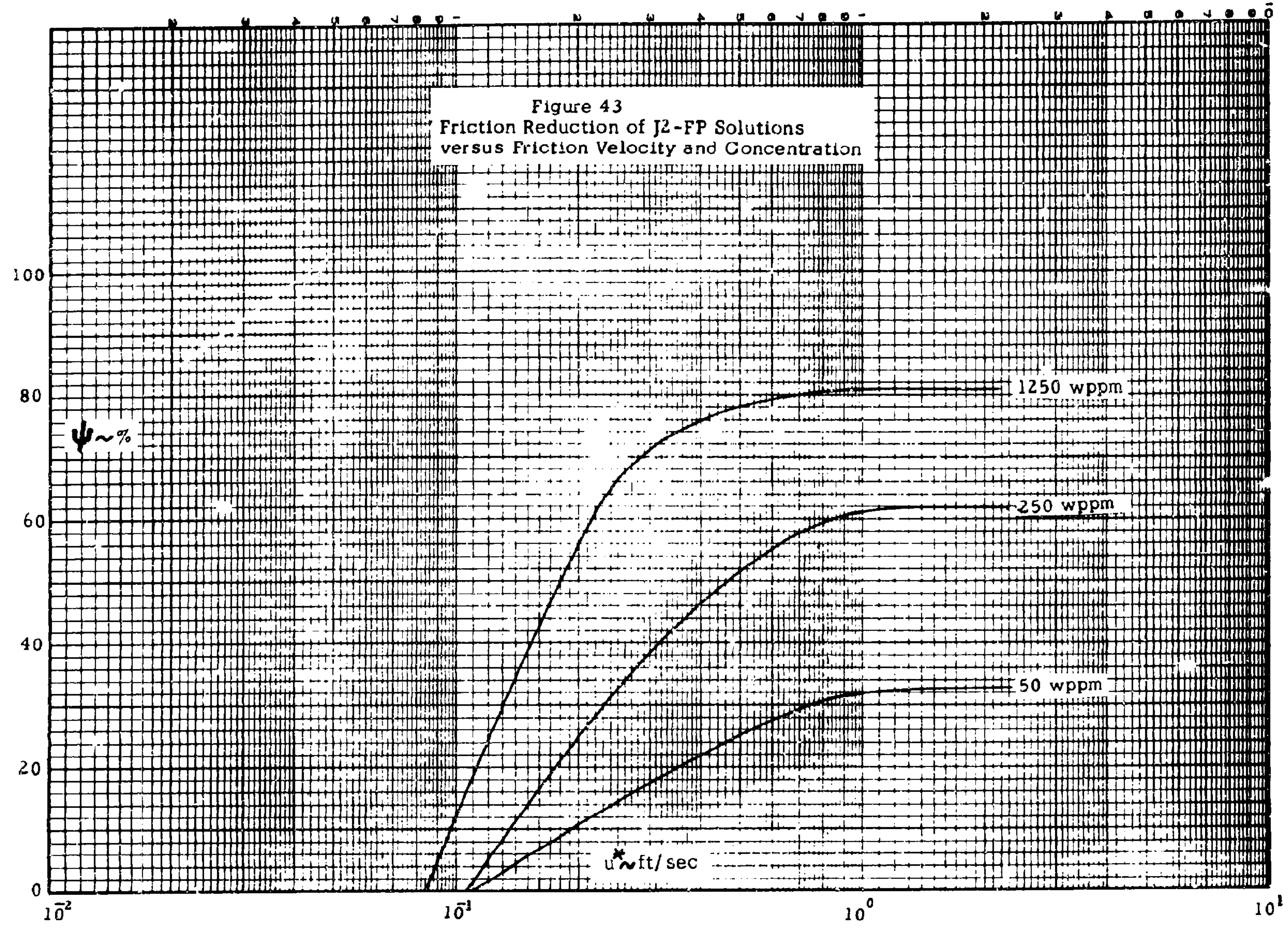


Figure 43
Friction Reduction of J2-FP Solutions
versus Friction Velocity and Concentration

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4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

5. AUTHOR(S) *(Last name, first name, initial)*

Whitsitt, Norman F., Harrington, Lawrence J. and Crawford, Horace R.

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13. ABSTRACT

Drag-reducing flow tests were carried out over a wide range of polymer concentrations in flow sections ranging from 0.18 inch to 6.0 inches in diameter. The water-soluble polymers used in this study were Separan AP-30 (Dow Chemical Company), a highly efficient drag reducer, and J2-FP (The Western Company), a guar-type, lower molecular weight, moderately efficient drag reducer.

It was found that the critical shear stress at the inception of drag reduction, was independent of flow-section diameter (or boundary layer thickness). This critical shear stress was strongly dependent on polymer concentration for the highly efficient additive (AP-30). For the moderately efficient J2-FP, only a very slight dependence of critical shear stress on additive concentration was found.

For a given concentration of a specific polymer, the drag reduction was found to be a unique function of wall shear stress.

The high molecular-weight polymer solutions were found to exhibit a decreased percentage of drag reduction at the higher shear rates which the lower molecular weight polymer solutions did not. This lower percentage was attributed to the mechanical scission of the high molecular weight polymer by shearing action of the fluid.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Polymer Solutions						
Drag Reduction						
Pipe Flow						
Viscoelastic Fluids						

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