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SAVANNAH RIVER LABORATORY

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M E M O R A N D U M

TO: F. H. BROWN

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PRESSURIZED VESSEL SLURRY PUMPING

Introduction

In the reference Defense Waste Processing Facility (DWPF) an abrasive slurry of frit and sludge is fed to the melter through a small tube (3/8-inch to 1/2-inch dia.) connected to a pressurized recirculating pipe loop.[1] Flow rate to the melter is controlled by regulating pipe loop pressure developed by a centrifugal pump. Severe abrasion of the pump impeller, casing, and seal during initial testing resulted in early pump failure.[2] A peristaltic pump unsuited for long term exposure to radioactive materials was used temporarily to feed the melter pending resolution of the abrasion problem.

This memorandum summarizes testing of an alternate "pressurized vessel slurry pumping" apparatus, (Figure 1). The principle is similar to rural domestic water systems and "acid eggs" used in chemical laboratories in that material is extruded by displacement with compressed air. Also included are a future equipment development program and appropriate design recommendations for adapting this principle to DWPF canyon operation.

Summary and Conclusions

Extrusion of slurry from a sealed agitated tank pressurized with compressed air is a viable method for continuous metering of frit-sludge slurry to a melter. The severe erosion problem and sensitivity to slurry rheology expected with centrifugal pumps are effectively avoided. Wear is minimized by low fluid velocities, and pumping characteristics are insensitive to wear.

A wide range of slurries were tested as follows:

- o Consistencies from 8 to 49 centipoises
- o Yield stresses from 58 to 511 dynes/cm^2
- o Solids from 40 to 48 wt %
- o Fine and coarse frits, -200 to +100 mesh
- o Formic acid treated, and untreated.

These were transported through 1/4-inch, 3/8-inch, and 1/2-inch diameter tubes (Figures 4 thru 11). Flow rates were controlled by varying air pressure. Line pluggage in the small lines due to settling solids did not occur even at fluid velocities <0.25 ft/sec. All except one instance of line pluggage was attributable to lumpy material and debris in the slurry. The exception occurred in a "dead leg" (stagnant) section of 1-inch pipe.(Figure 14)

Description of Equipment and Process

The concept of the pressurized tank is the application of a constant overpressure of air which will force slurry continuously from the tank through the feed tube and nozzle into the melter. The initial equipment (Figure 1) designed to test this concept consisted of a 17 gallon tank which was proof tested to 150 psig. (Air system supply pressure was 90 psig, and safety considerations were satisfied by proof testing at least 1-1/2 x 90 = 135 psig). A 1/2 hp, 1750 rpm agitator with three 4" diameter marine type impellers was used to maintain suspension of solids in the slurry. The agitator shaft was equipped with a packing gland seal to prevent excessive air leakage from the tank. Air supply was controlled by a pressure regulator. A back pressure regulator maintained constant air pressure in the tank by bleeding air as the slurry level rose during filling. The tank was placed on weight scales so that the slurry level could be monitored. Initially, a small rate drum was used to determine feed rate. In later experiments a magnetic flowmeter was also installed.

Three sizes of feed tubing 1/4-inch, 3/8-inch, and 1/2-inch-diameter were tested to determine the effect of cross sectional area on pressure drop and line pluggage. Each tube was 77 feet long, and included four long radius 180° bends, two long radius 90° bends and four couplings. Any slurry transport system can be used to fill the tank. During this test a diaphragm pump with a 1-inch discharge pipe was utilized. Calibrated pressure gages and duplicate thermometers were used. Slurry takeoff was near the bottom of the pressurized tank to prevent accumulation of solids on the tank bottom.

For flushing the system, ball valves were installed so that water could be flushed in either direction through the piping to the pressurized tank or feed nozzle. Similarly, the 1-inch supply line to the pressurized tank could be flushed with water.

Water Tests

Initial system checkout was performed using water (Figure 2). Characterization of the system with a Newtonian fluid simplified determination of equivalent tubing length and provided a familiar basis for comparison when later pumping slurry. Flow began at slightly less than 1 psig in all cases because at low velocities the 2 foot elevation head (Figure 1) constituted the major portion of the total head at the beginning of flow. The system behaved as anticipated verifying that flow could be controlled by varying air pressure. At a pressure of 25 psi, flow rates were 0.34, 1.22, and 3.39 gpm, respectively, for 1/4-inch, 3/8-inch, and 1/2-inch-diameter tubing. Corresponding fluid velocities were 4.28, 5.34, and 7.49 fps, respectively.

To determine equivalent tubing length the Darcy equation can be used. The Darcy equation can be stated as:

$$H_L = f \frac{L_e}{D} \frac{V^2}{2g}$$

H_L = head loss, (ft of fluid)

f = friction factor (from Moody diagram)

D = tubing diameter, ft

V = fluid velocity, ft/sec

g = gc = 32.2 ft/sec.^{2}

L_e = equivalent tubing length, ft

Thus,

$$Le = \frac{2g\ D\ H_L}{f\ V^2}$$

A pipe roughness of 0.00007 inch was assumed.[3] The Reynolds numbers (Re) were computed, and the friction factors (f) were obtained from the Moody diagram. Thus, equivalent tubing lengths (Le) of about 90 to 100 feet were determined by iterative substitution in the Darcy equation (Tables 1, 2, and 3).

Slurry Tests - TDS Sludge, Frits 131 and 140

Slurries were a 28 wt % solids (on oxide basis) simulated waste sludge[4,5] combined with either Frit 131[5] or Frit 140[6] (Appendix A). Both formated and unformated were run. The formated feeds were made by E. J. Weber in the large scale slurry mix evaporator.[7] Many of the slurry properties were varied to determine the effect on pumping characteristics. Frit sizes ranged from -200 to +100 mesh and yield stresses from 58 to 511 dynes/cm^2 (as determined with the "Haake Rotoviscometer").

Waste slurry properties resemble those of a Bingham plastic in that higher shear stresses, and greater pressure drops in pipe are required to initiate flow than with Newtonian fluids such as water (Figure 3). For example, pressures in the range of 7 to 31 psi as compared with 1 psi with water were required to initiate flow with six slurries tested in three tube sizes (more about this later under Rheology, page 9)

- **Formated vs. Nonformated Slurry**

  Two batches of sludge-frit slurry containing Frit 131, -80 mesh were tested. One batch was treated with formic acid, and one was untreated. Each batch was run through the three tube sizes (Figures 4, 5, and 6). Flow began at about 13, 16 and 21 psi with the treated material, and at about 10, 16, and 25 psi with untreated material in 1/2-inch, 3/8-inch, and 1/4-inch tubing, respectively (Slurry batches 1 and 2, Table 4). Thus, about the same pressures were required to initiate flow with both batches. The general conclusion is that treatment of slurry with formic acid affects the actual yield stress very little although the Haake determinations indicated 100 vs. 190 dynes/cm^2 for treated and untreated, respectively. Significant pressure differences exist at higher flow rates. In all tube sizes (Figures 4, 5, and 6), the pressure drop for formate treated material was less at low flow rates, and greater at high flow rates than with untreated material, i.e.; the curves cross. This is not understood.

At the reference flow rate of 1/2 gpm, (DWPF melter feed will be 1/2 gpm through each of two feed nozzles) pressure drops were lowest with the treated material. They were 16 and 33 psi through 1/2 and 3/8 tubes, respectively, with the treated material and 19 and 36 psi, respectively, with untreated material. Corresponding fluid velocities were 1.1 and 2.2 ft/sec for 1/2 and 3/8 tubes respectively. At pressures of 70 to 80 psi, only about 1/4 gpm flowed through 1/4-inch tubing. Thus, 1/4-inch diameter tubing is impractical for feeding the melter at 1/2 gpm because of the high pressure required.

- <u>Unformated Slurry with Coarse Frit</u>

  Two batches of sludge-frit slurry containing Frit 131, 50% -100 mesh, and 50% -50 +100 mesh were tested with 1/2-inch, 3/8-inch, and 1/4-inch diameter tubing (Figures 7, 8, and 9). A 41 wt % slurry was divided into two batches (batches 3 and 4, Table 4). The thicker, more dense batch No. 4 was prepared by decanting water to final 48 wt % solids.

  The pressure required to initiate flow was about the same with both batches. As anticipated, pressures required for the reference flow rate of 1/2 gpm are lower for the 41 wt % than the 48 wt % material. They were 22 vs. 24 psi with 1/2-inch tubing, and 35 vs. 48 with 3/8-inch tubing (Figures 7 and 8). The reference flow rate was not attained with 1/4-inch tubing. At 85 psi flows were only about 1/3 gpm with 41 wt % slurry, and 1/8 gpm with 48 wt %.

- **Unformated Slurry with Fine Frit**

  Two batches of sludge-frit slurry containing Frit 140, -200 mesh were tested with 1/2 and 3/8-inch tubing. One batch contained 47 and the other 39 wt % solids. The thicker more dense slurry had a yield stress of 511 dynes/cm^2 and consistency of 49 centipoises, while the other had a yield stress of 58 dynes/cm^2 and consistency of 8 centipoises. Rheologies were determined with the Haake Rotoviscometer (See Rheology later in report). Pressures required to initiate flow in the 1/2-inch tube were about 10 psi for the more dense material and about 7 psi for the other (Table 4 batches 5 and 6). Flow began at 10 psi in 3/8-inch tubing with the less dense slurry. The thicker more dense material was not run in the 3/8-inch tube, and neither material was run in 1/4-inch tubing.

  Pressures required for the reference flow rate of 1/2 gpm in 1/2-inch tubing was 45 psi for the more dense material and 10 psi for the other (Figure 10). A flow of 1/2 gpm of the less dense material in 3/8-inch tubing required a pressure of 31 psi (Figure 11).

Other Areas of Investigation

o **Rheology**

Slurry rheological properties were determined using a Haake Rotoviscometer. This apparatus employs a rotating cylinder in a close fitting sample cup. The torque requirement is measured as the speed of the rotor is varied. Torque versus RPM is translated into a rheogram that is shear stress versus shear rate. The rheogram shows yield stress (τy, dynes/cm^2) and consistency, (η, centipoise).

Several Haake runs were made for each slurry batch tested in the pressurized tank facility. The Haake produced erratic rheograms and showed considerable variation in yield stress and consistency, even for samples from the same batch. This is probably the result of settling and/or grinding of the frit in the instrument's small clearances. For example, Table 5 shows the results of multiple Haake runs of two different slurries, one formic acid treated and one untreated. Standard deviations (σ) for yield stresses were 17.4 and 74.4, respectively. Standard deviations for consistencies were 5.8 and 6.1, respectively. Variance in solids concentrations and density, also shown in Table 5, is low.

A more reliable determination of rheological properties is needed. Alternatives to the Haake Rotoviscometer include:

- A suitable instrumented/calibrated pressurized tank system. Georgia Iron Works Hydraulic Laboratory employs a similar "extrusion" rheometer which accurately predicts performance.[8]
- A smaller capillary viscometer, such as the one developed at SRL.[9]

If Haake-generated rheological properties (yield stress and consistency) are used to predict pressure drop, the results vary considerably from data obtained in the pressurized tank facility. For example, Figure 12 compares data from an actual run to the values that would be predicted from the Haake data. The actual pressure drop is considerbly lower than the predicted values.

One reason for this disagreement is error in determination of rheological properties with the Haake. Also, the correlations used to predict Bingham Plastic behavior are mathematical conveniences, but do not always accurately represent our slurries, especially at very low flow rates. A typical Bingham Plastic will have an actual yield stress about 25% lower than the theoretical. Waste slurry simulations tested at Georgia Iron Works showed no actual yield stress, even when the nominal yield stress was high.[8] The nominal value can often be used to predict pressure drop through most of the laminar region, but not at the very low flows. These concepts are illustrated in Figure 13.

- **<u>Line Plugging and Location of Valves</u>**

  One instance of line pluggage occurred in a 10-foot-long "dead leg" section of 1-inch piping between a pipe tee and block valve

(Figure 14). Application of 120 psi water pressure failed to dislodge it. The pluggage was removed by rodding, and it consisted of a small percentage of sludge mixed with coarse frit particles (mostly +100, -50 mesh) firmly packed. No further plugging occurred after the valve was relocated 6-inches from the tee. This indicates that 2-way valves are satisfactory for slurry service but should be located close to junctions. Also, plugging did not occur in the 10-foot-long "dead leg" when handling slurry containing the finer -80 and -200 mesh frits. Apparently, most of the finer particles remained suspended in the fluid stream as it passed through the tee, but some of the coarse particles settled into the "dead leg" and formed the plug.

All other instances of plugging were attributable to dried lumps of slurry or debris, such as fragments of rubber and plastics. The dried lumps formed in the open rate drum and the partially covered mix tank (Figure 1). Straining slurry through 14 mesh screen eliminated the problem. A separate program is underway to develop a slurry filter or strainer system which will be applicable to DWPF canyon operation.

On several occasions the tank and piping remained filled with slurry with the agitator stopped during weekend shutdowns (64 to 90 hrs). Flow restarted without difficulty in every instance. On one occasion the system remained filled (with unformated slurry, batch No. 2, Table 4) during a 7-day shutdown. Flow restarted slowly after about 10 seconds at 50 psi tank pressure.

Initially, the material was very thick and contained soft lumps. Full flow was restored within 1/2 minute. However, 72 feet of the tubing ran horizontally, and only 5 feet ran vertically. Vertical tubing might be more susceptible to plugging as a result of settling of solids during shutdowns. In any event, water flushing the system may not be required prior to short shutdown periods when handling slow settling slurries.

- **Slurry Deposits on Tank Walls and Lid**

  Thick "mud like" deposits of slurry were observed on the underside of the flanged tank cover. Similar deposits existed above the liquid level in the large slurry storage tanks in Building 675-G. The deposits apparently resulted when water drains from slurry splashed against the tank walls. While wet and soft the material recombined easily with the slurry. If allowed to dry, it can form lumps and cause line plugging.[7]

- **Agitation**

  The 12-inch pressurized tank was equipped with an agitator located off center. This was done to avoid using tank baffles because slurry tends to "cake up" on them. The agitator was stopped for short periods without apparent adverse effect indicating that continuous operation may not be necessary with slow settling slurries. Adequate agitation might be provided by frequent addition of slurry near the tank bottom, thus, incorporating and mixing the slurry heels with the newly introduced material.

Advantages would be extended useful life of agitator motor, impellers, and shaft seal.

- **Abrasion and Erosion of Impellers**

  A 1/2 hp, 1750 rpm agitator was mounted off center in the 12-inch tank. The off center location limited impeller diameters to 4 inches maximum. Thus, three 4-inch diameter marine type impellers of Type 316 stainless steel were mounted 10 inches apart on the 3/4-inch diameter shaft. After 500 hours of operation at tip speeds of 1600 to 1800 ft/min., the impellers were worn sharp at the edges and reduced to 3-1/2-inch diameter with a 15% weight loss (130 to 110 grams).

  The high impeller tip speeds (A. W. Etchells of ESD recommended a maximum of 600 ft/min) were required to maintain agitation in the off-center location. A larger tank would permit larger diameter impellers and lower tip speeds.

FUTURE SYSTEM AND PROGRAM

A similar but larger 2-foot-diameter x 3-foot-high (70 gallons capacity) pressurized-tank, slurry-feed system (Figure 15) has been fabricated for further testing of this concept. Areas of investigation follows:

- **Flow Control and Tank Filling**

  In previous tests the tank sat on weight scales and was periodically refilled by manually starting a pump. Flow to the melter was monitored by a magnetic flow meter and controlled by manual adjustment of tank air pressure. The flow rate varied (reduced) slightly between tank fillings (Figure 16). This happened because the lowering fluid level in the tank resulted in a corresponding reduction in available pressure head. No adverse conditions resulted from these small variations. It could be corrected by simultaneous increase of air pressure as the slurry level in the tank decreased.

The new (24-inch-diameter) system incorporates a Hewlett-Packard micro computer and appropriate accessory apparatus specified by F. M. Heckendorn and programed by D. M. Sabatino. This equipment will be used to control slurry flow rates and tank filling automatically. Outputs from load cells will be utilized in the computer program to effect control. Similarly, output to the computer from a magnetic flowmeter will be evaluated for flow control. Also, a separate liquid level probe will be evaluated.

- <u>Agitation</u>

  With the new equipment the slurry can be added to the tank at the sides near the top or bottom, and at points between top and bottom. As previously mentioned, the objective is to determine if an inrushing slurry stream will adequately mix with the slurry heel and maintain solids suspension without mechanical agitation. The new equipment also permits variable speed mechanical agitators to be mounted on the tank centerline or off-center. Tank baffles are removable.

- **Line Plugging and Settling of Solids**

  Plans are to determine if solids settle in long vertical tubes during extended shutdowns and cause line plugging.

- **Slurry Strainer**

  The problem of eliminating or removing debris from slurry streams in a radioactive canyon environment will be addressed.

- **Slurry Deposits on Tank Walls and Lid**

  The new 24-inch-diameter tank design incorporates a slinger on the center mounted agitator shaft. Provision is made for periodically directing a stream of water and/or slurry onto the rotating slinger so that it will be centrifugally spread to the tank wall. Expectations are that this will wash thick slurry deposits from the tank cover and walls.

References

1. Technical Data Summary, DPSTD-80-38-2.

2. CMOG Report No. 5.

3. Crane technical paper No. 410, and Du Pont Std. D6 2.38, Table 1.

4. DPST-81-484, Table 2.

5. DPST-82-624, Table 2.

6. DPST-80-402, Table 6.

7. DPST-82-733.

8. DPST-82-954, DPST-82-955.

9. Unpublished work by T. Motyka.

Acknowledgements

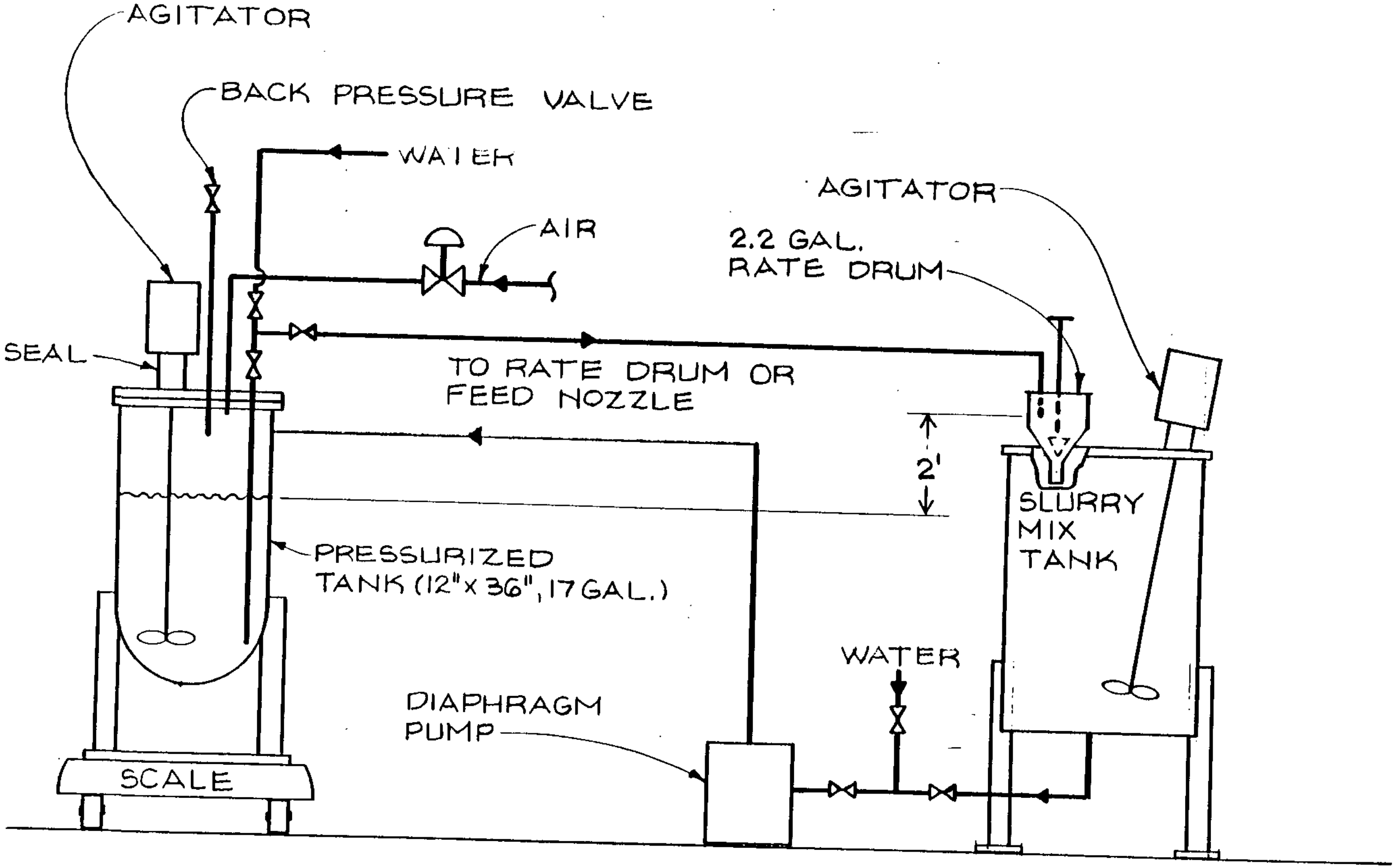
Appreciation is expressed to:
W. L. Isom and D. J. Trapp for design assistance.

D. P. Lewis for assistance in evaluating test data.

D. M. Sabatino for assisting in equipment operation and preparing operating procedures.

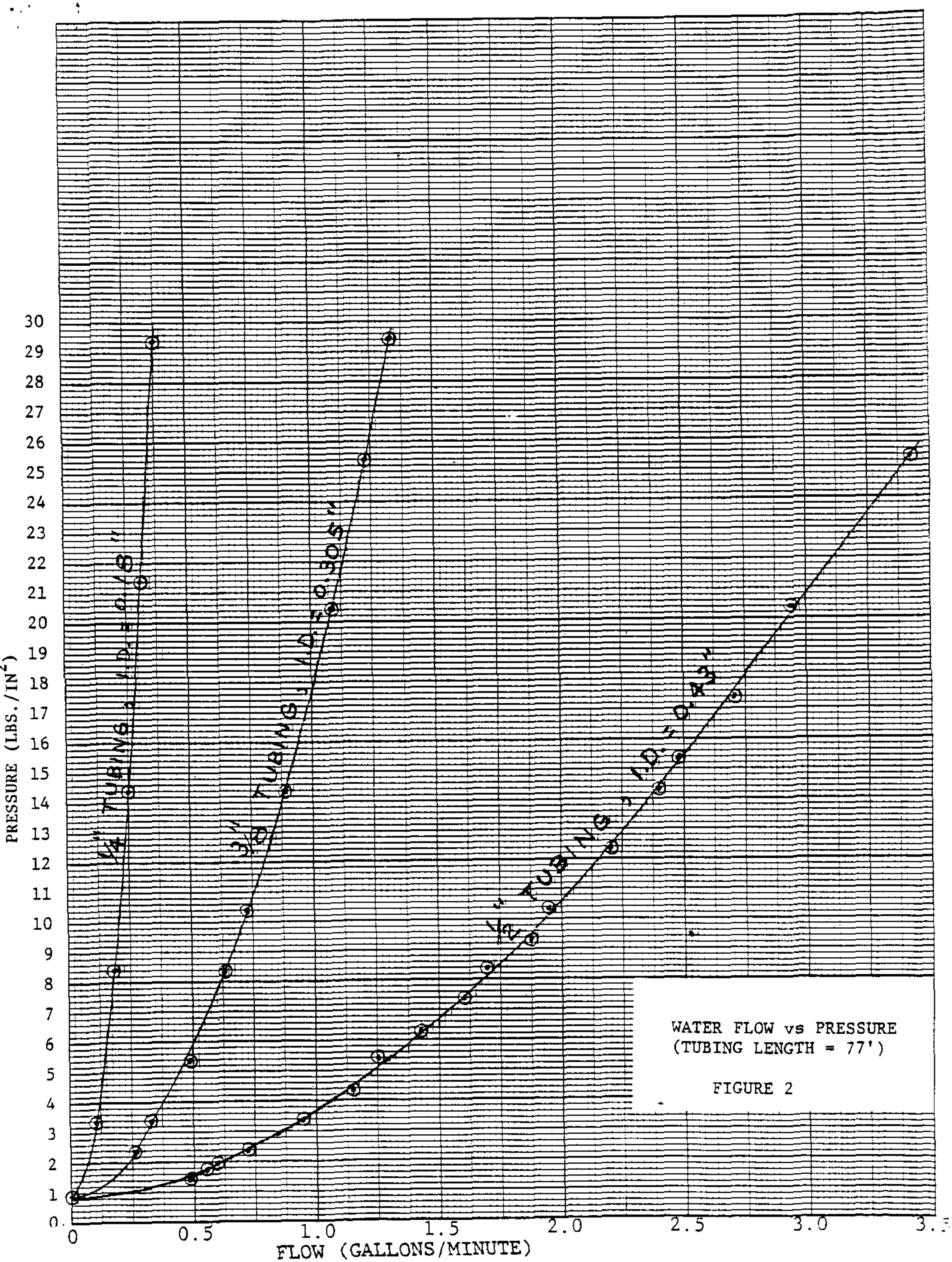
Quality Assurance

All data in this report may be used for design purposes. Measurements were taken with calibrated and/or dual sensors. Data and pertinent informatin are recorded in research notebooks DPSTN-1500, 4046, and QA files. Equipment design details are shown on Drawings SX5-00196, 00522, and 00523.



PRESSURIZED TANK
(INITIAL TEST SET-UP)

FIG. 1



WATER FLOW vs PRESSURE
(TUBING LENGTH = 77')

FIGURE 2

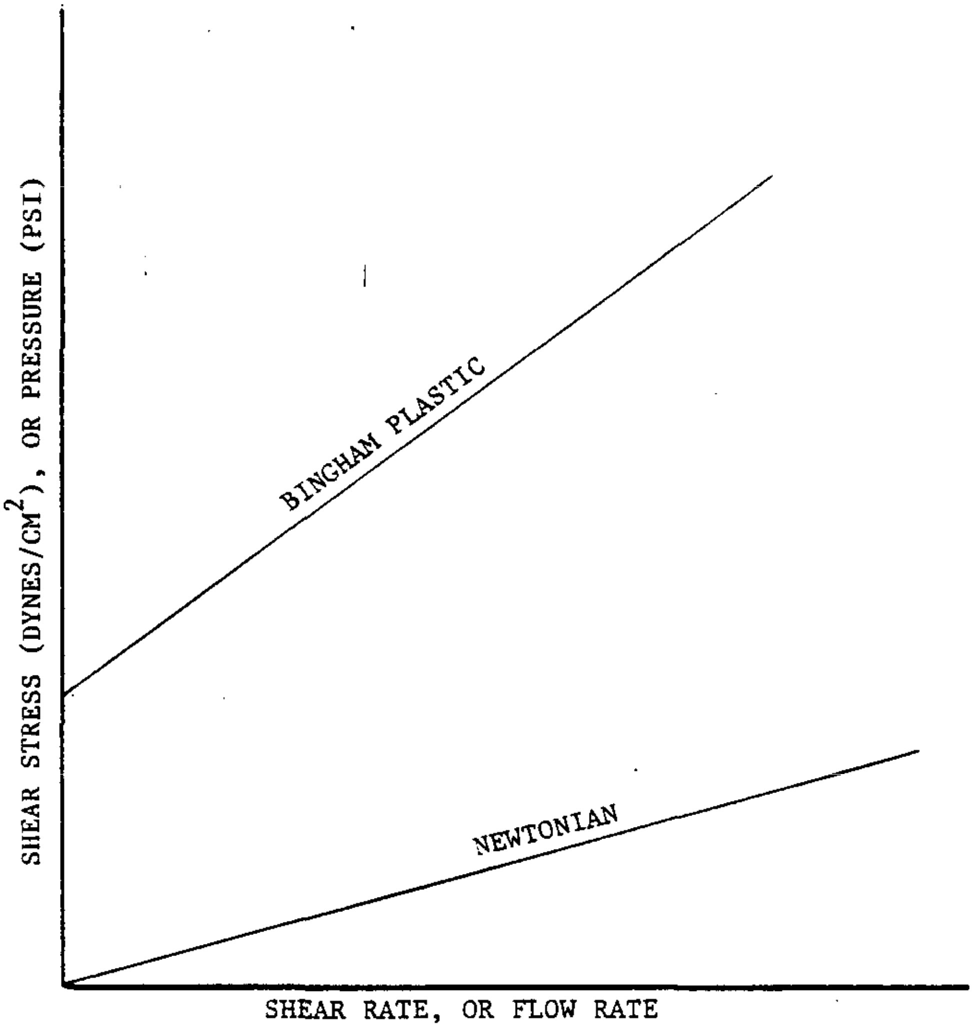

SHEAR STRESS (DYNES/CM2), OR PRESSURE (PSI)
BINGHAM PLASTIC
NEWTONIAN
SHEAR RATE, OR FLOW RATE

FIGURE 3

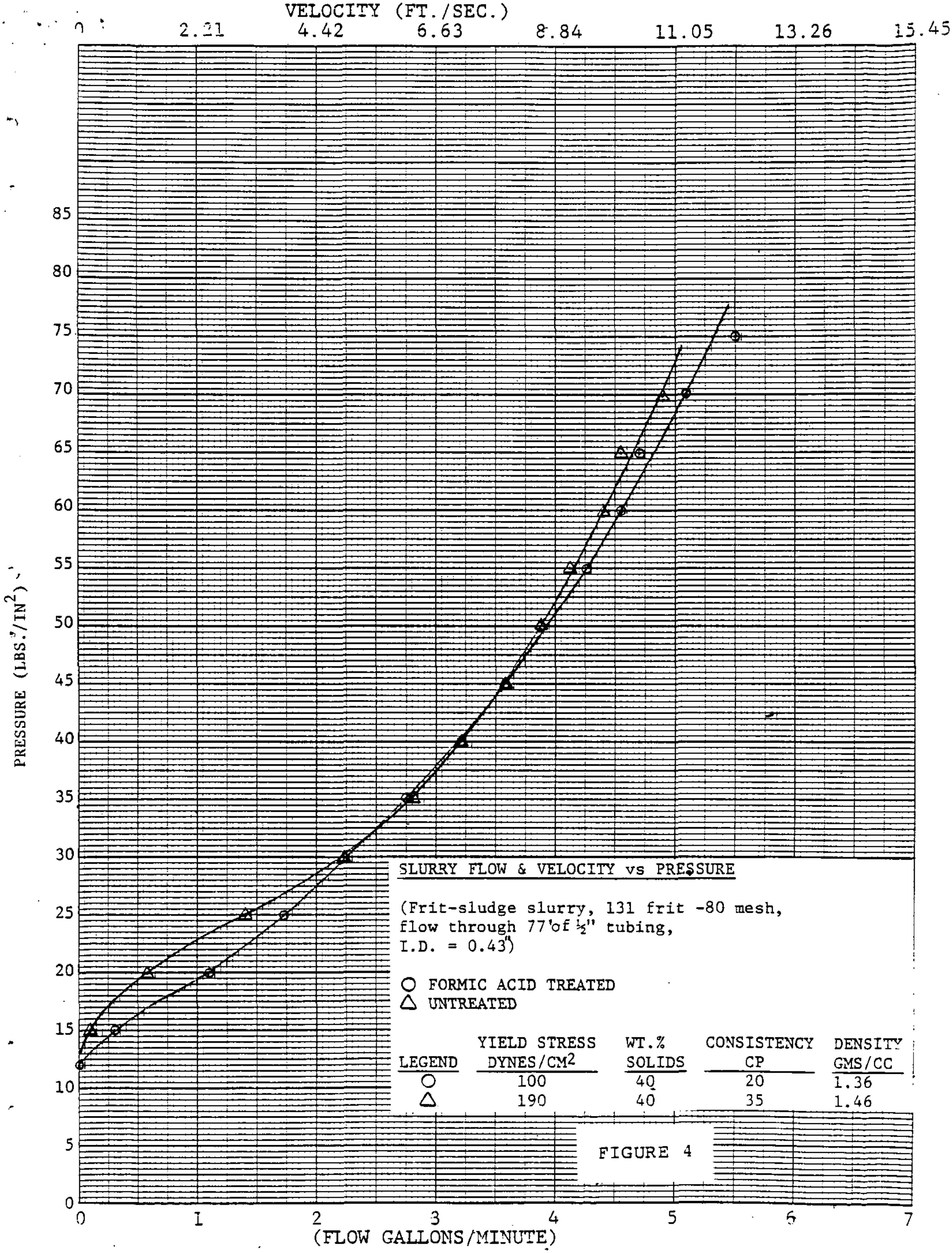

VELOCITY (FT./SEC.)
0
2.21
4.42
6.63
8.84
11.05
13.26
15.45
PRESSURE (LBS./IN²)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
(FLOW GALLONS/MINUTE)
0
1
2
3
4
5
6
7
SLURRY FLOW & VELOCITY vs PRESSURE
(Frit-sludge slurry, 131 frit -80 mesh,
flow through 77' of ½" tubing,
I.D. = 0.43")
○ FORMIC ACID TREATED
△ UNTREATED
LEGEND
YIELD STRESS DYNES/CM2
WT.% SOLIDS
CONSISTENCY CP
DENSITY GMS/CC
○ 100 40 20 1.36
△ 190 40 35 1.46

FIGURE 4

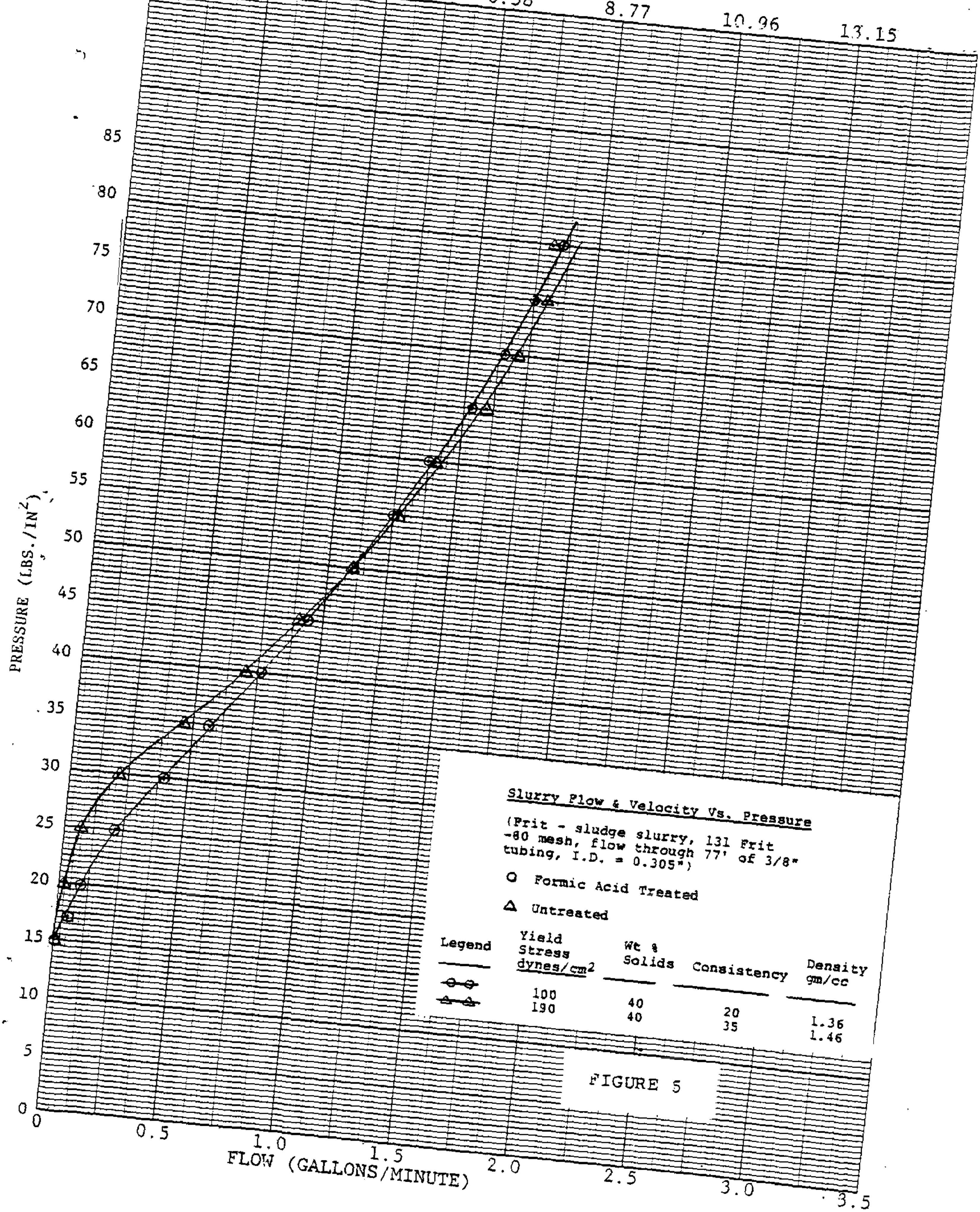

6.58
8.77
10.96
13.15
PRESSURE (LBS./IN^2)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
FLOW (GALLONS/MINUTE)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Slurry Flow & Velocity Vs. Pressure
(Frit - sludge slurry, 131 Frit -80 mesh, flow through 77' of 3/8" tubing, I.D. = 0.305")
O Formic Acid Treated
Δ Untreated
Legend
Yield Stress dynes/cm^2
Wt % Solids
Consistency
Density gm/cc
100
190
40
40
20
35
1.36
1.46

FIGURE 5

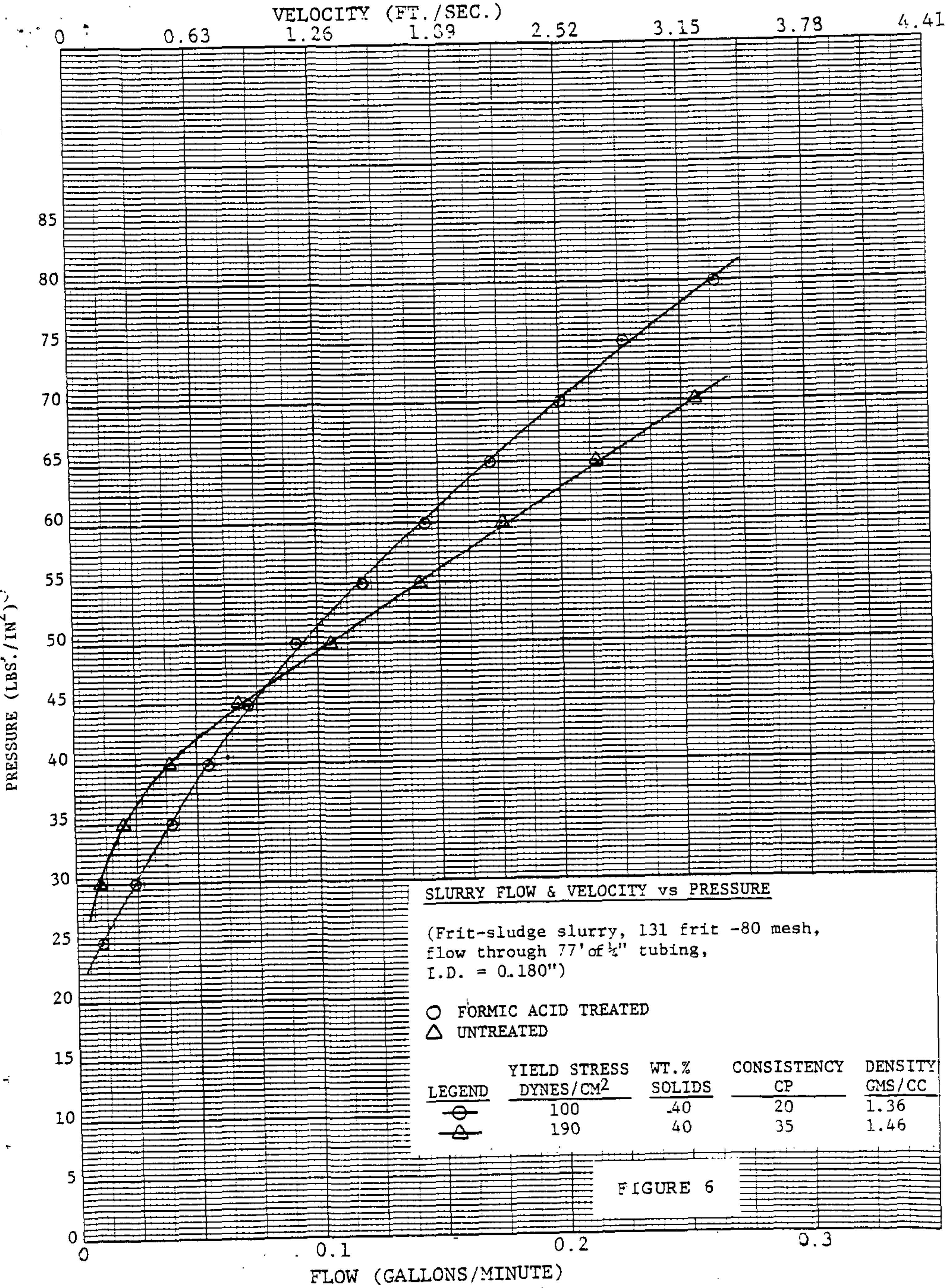

VELOCITY (FT./SEC.)
0
0.63
1.26
1.89
2.52
3.15
3.78
4.41
PRESSURE (LBS./IN^2)
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
FLOW (GALLONS/MINUTE)
0
0.1
0.2
0.3
SLURRY FLOW & VELOCITY vs PRESSURE
(Frit-sludge slurry, 131 frit -80 mesh,
flow through 77' of ½" tubing,
I.D. = 0.180")
○ FORMIC ACID TREATED
△ UNTREATED
LEGEND
YIELD STRESS DYNES/CM^2
WT.% SOLIDS
CONSISTENCY CP
DENSITY GMS/CC
100
40
20
1.36
190
40
35
1.46

FIGURE 6

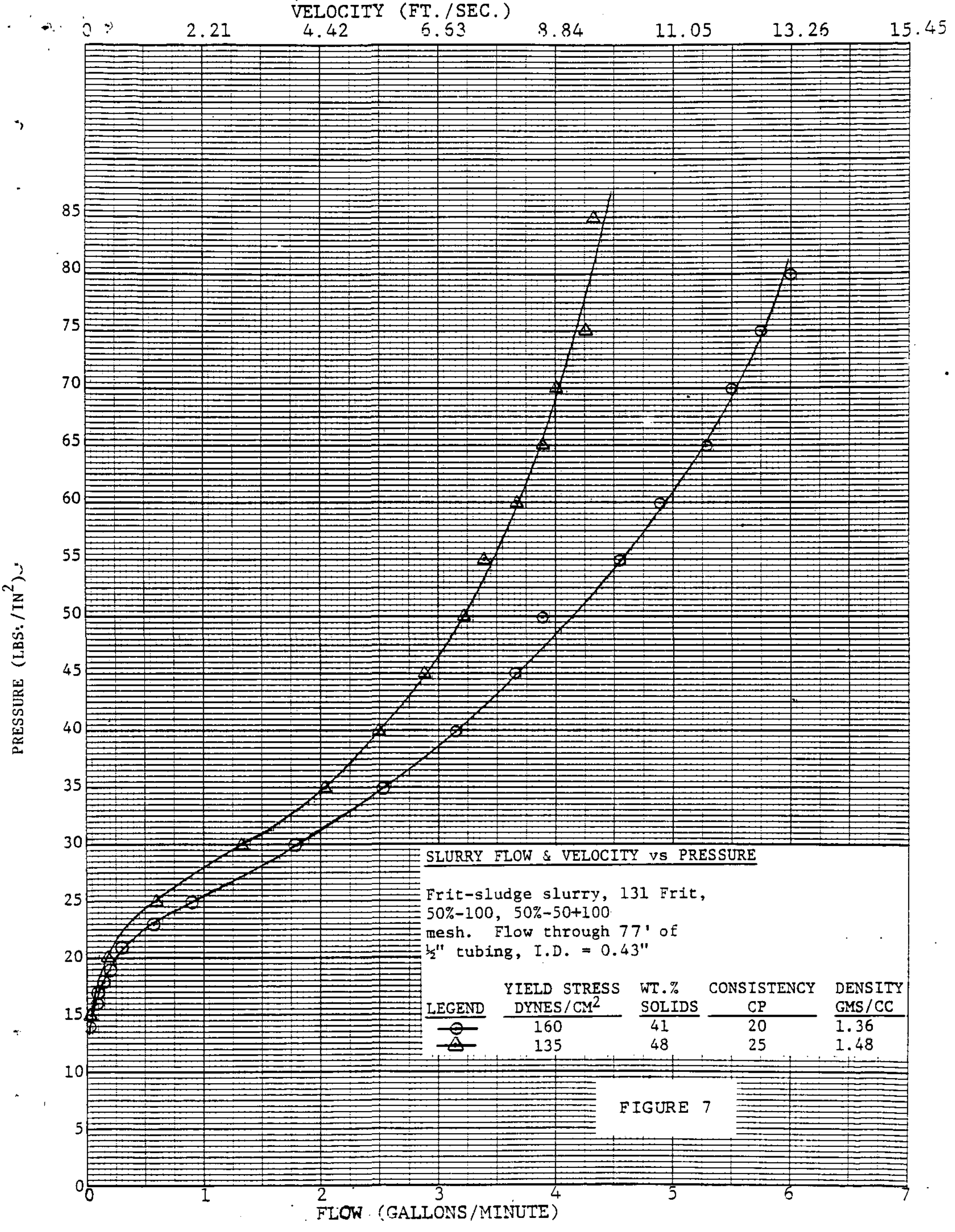

VELOCITY (FT./SEC.)
0 2.21 4.42 6.63 8.84 11.05 13.26 15.45
PRESSURE (LBS./IN²)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
FLOW (GALLONS/MINUTE)
0 1 2 3 4 5 6 7
SLURRY FLOW & VELOCITY vs PRESSURE
Frit-sludge slurry, 131 Frit,
50%-100, 50%-50+100
mesh. Flow through 77' of
½" tubing, I.D. = 0.43"
LEGEND
YIELD STRESS DYNES/CM²
WT.% SOLIDS
CONSISTENCY CP
DENSITY GMS/CC
160 41 20 1.36
135 48 25 1.48

FIGURE 7

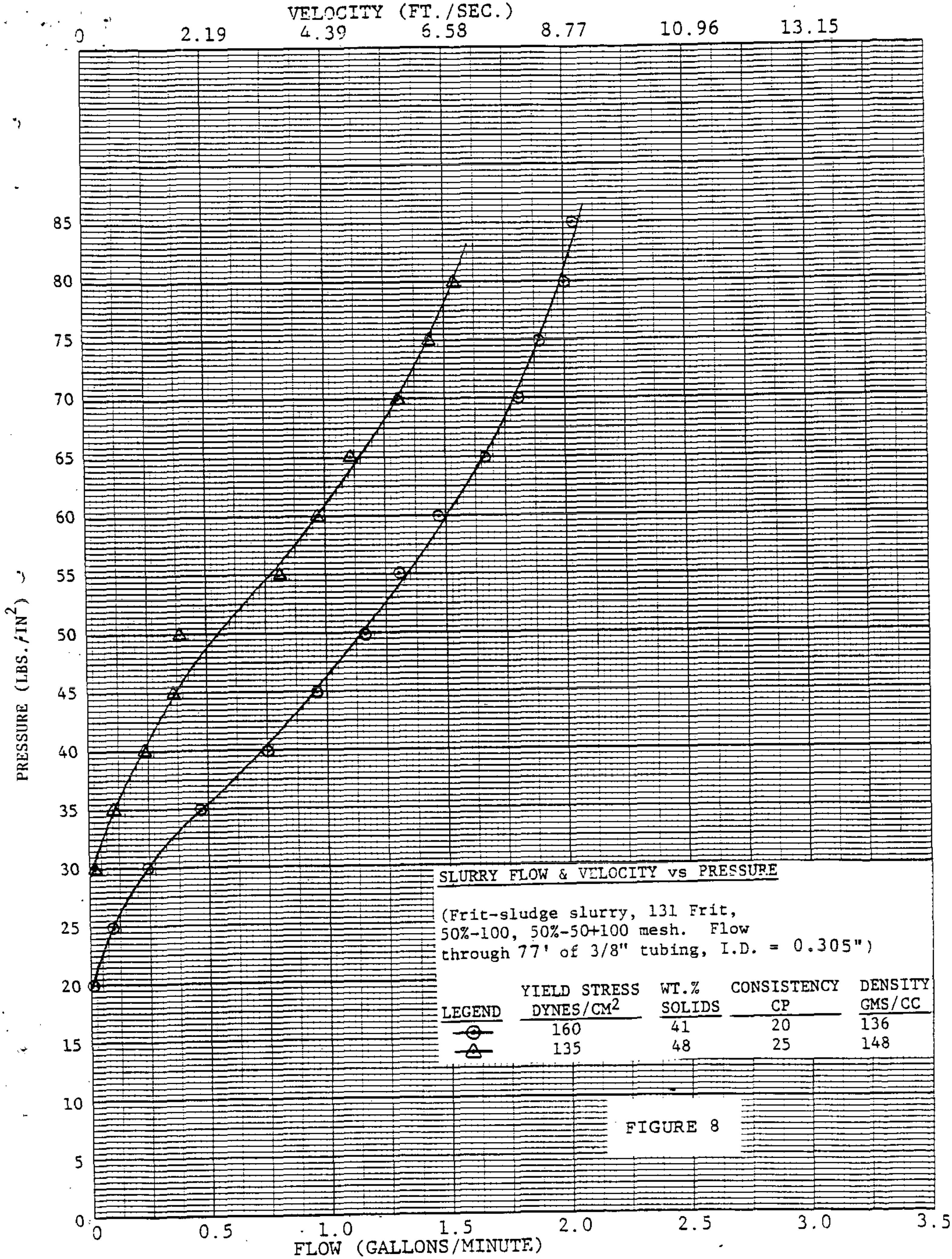
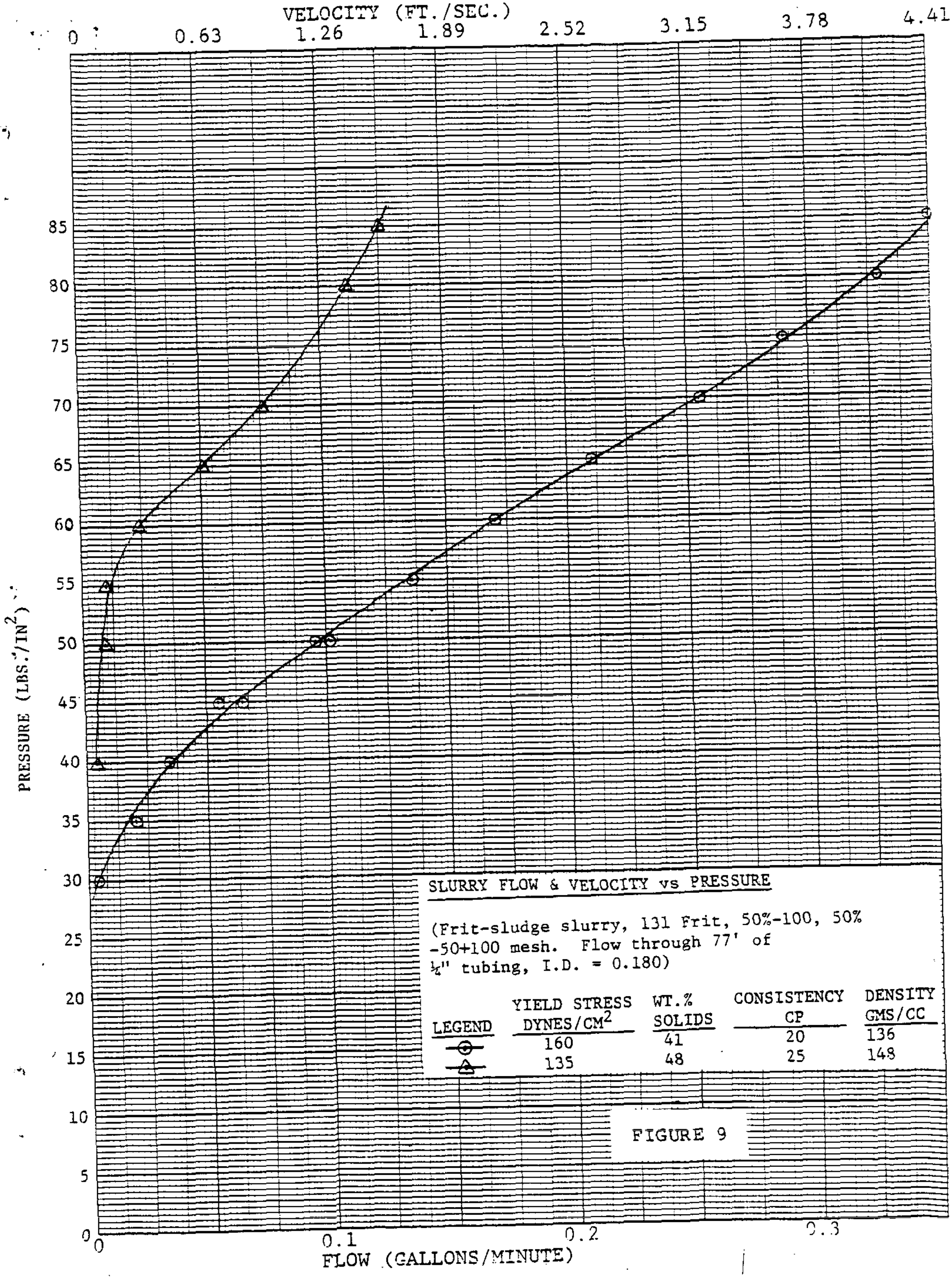

VELOCITY (FT./SEC.)
0
2.19
4.39
6.58
8.77
10.96
13.15
PRESSURE (LBS./IN2)
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
FLOW (GALLONS/MINUTE)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
SLURRY FLOW & VELOCITY vs PRESSURE
(Frit-sludge slurry, 131 Frit, 50%-100, 50%-50+100 mesh. Flow through 77' of 3/8" tubing, I.D. = 0.305")
LEGEND
YIELD STRESS DYNES/CM2
WT.% SOLIDS
CONSISTENCY CP
DENSITY GMS/CC
160
41
20
136
135
48
25
148

FIGURE 8



VELOCITY (FT./SEC.)
0
0.63
1.26
1.89
2.52
3.15
3.78
4.41
PRESSURE (LBS./IN^2)
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0
0.1
0.2
0.3
FLOW (GALLONS/MINUTE)
SLURRY FLOW & VELOCITY vs PRESSURE
(Frit-sludge slurry, 131 Frit, 50%-100, 50% -50+100 mesh. Flow through 77' of ¼" tubing, I.D. = 0.180)
LEGEND
YIELD STRESS DYNES/CM^2
WT.% SOLIDS
CONSISTENCY CP
DENSITY GMS/CC
160
41
20
136
135
48
25
148

FIGURE 9

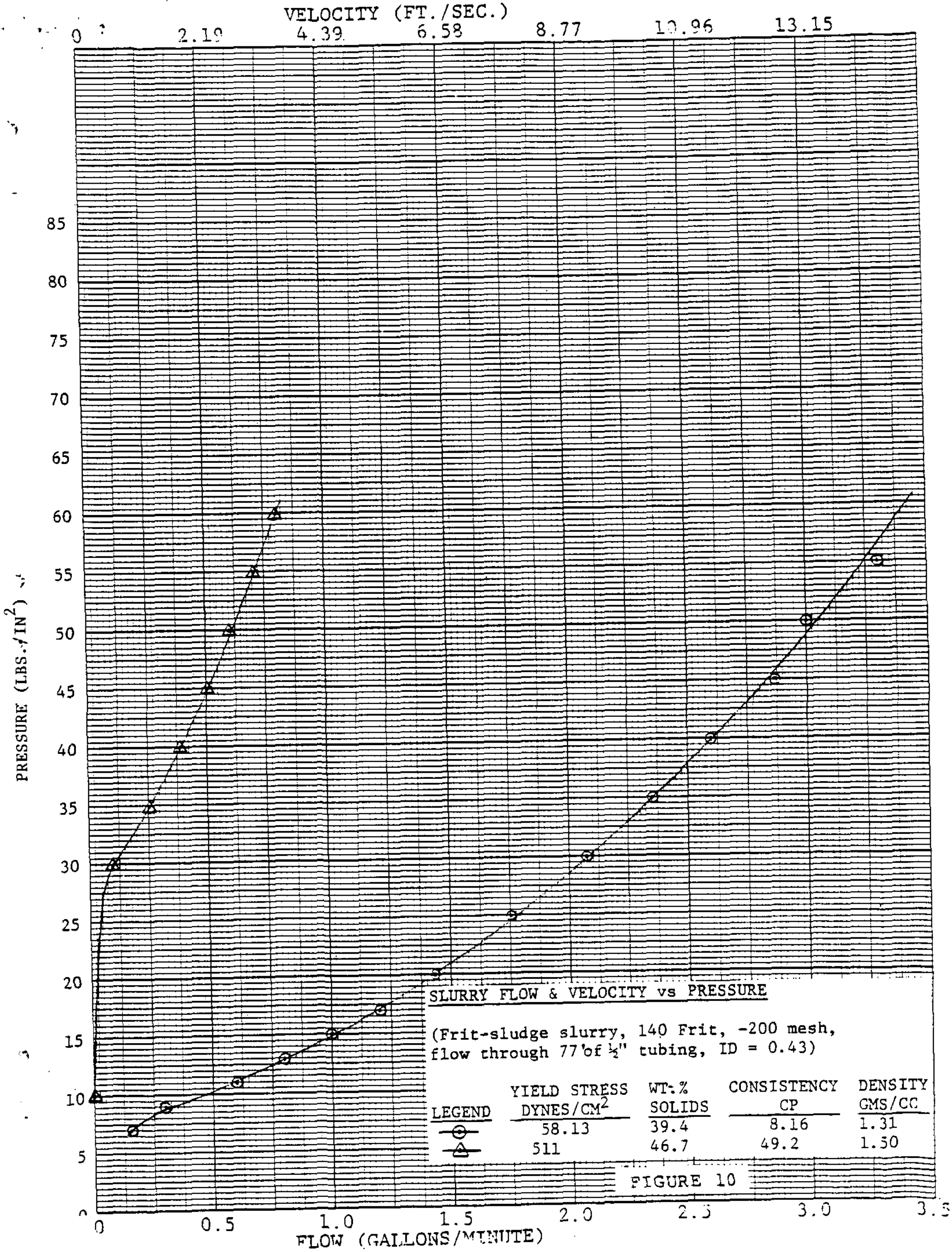

VELOCITY (FT./SEC.)
0
2.19
4.39
6.58
8.77
10.96
13.15
PRESSURE (LBS./IN²)
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
FLOW (GALLONS/MINUTE)
SLURRY FLOW & VELOCITY vs PRESSURE
(Frit-sludge slurry, 140 Frit, -200 mesh, flow through 77' of ½" tubing, ID = 0.43)
LEGEND
YIELD STRESS DYNES/CM²
WT.% SOLIDS
CONSISTENCY CP
DENSITY GMS/CC
58.13
39.4
8.16
1.31
511
46.7
49.2
1.50

FIGURE 10

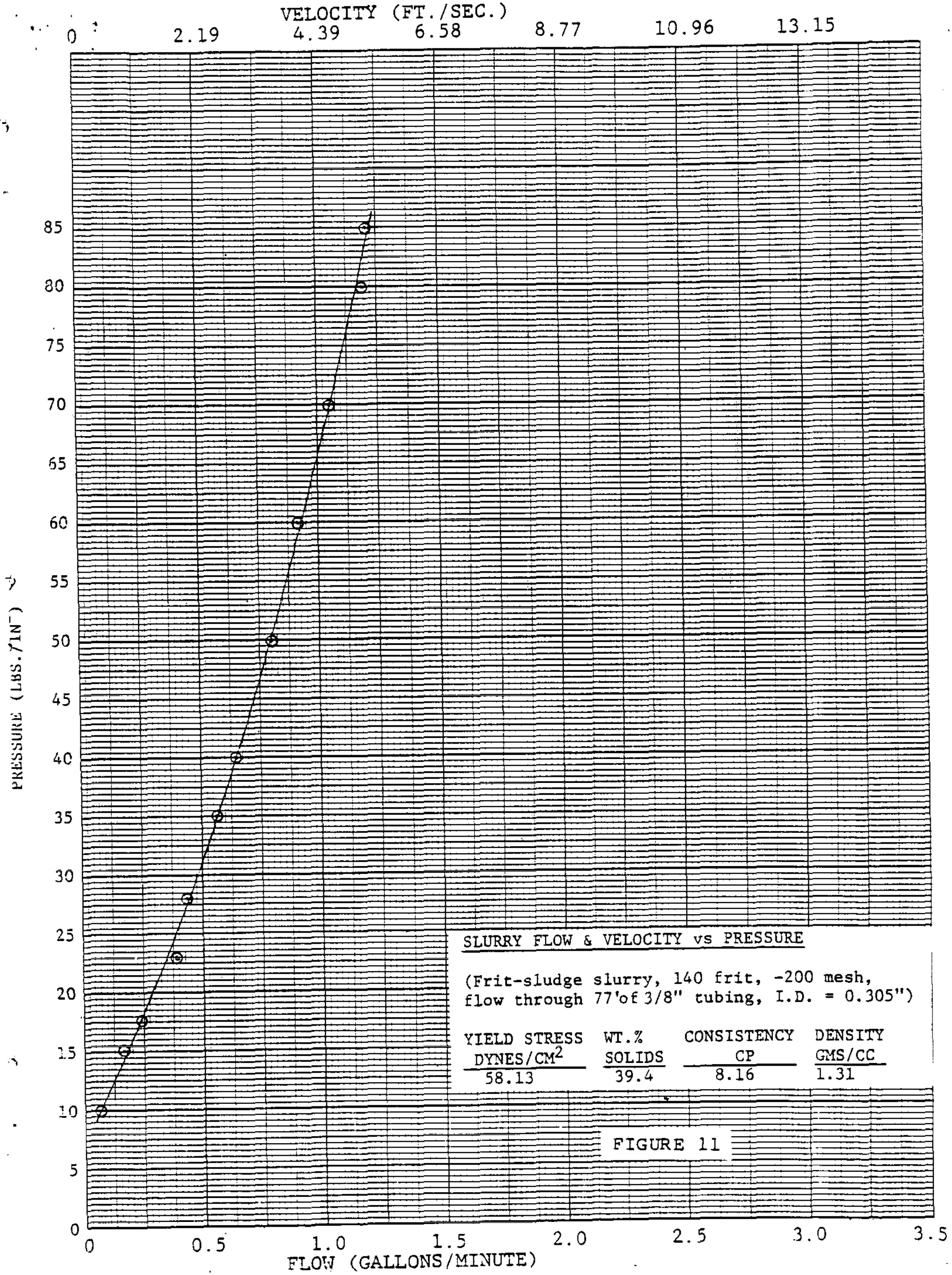
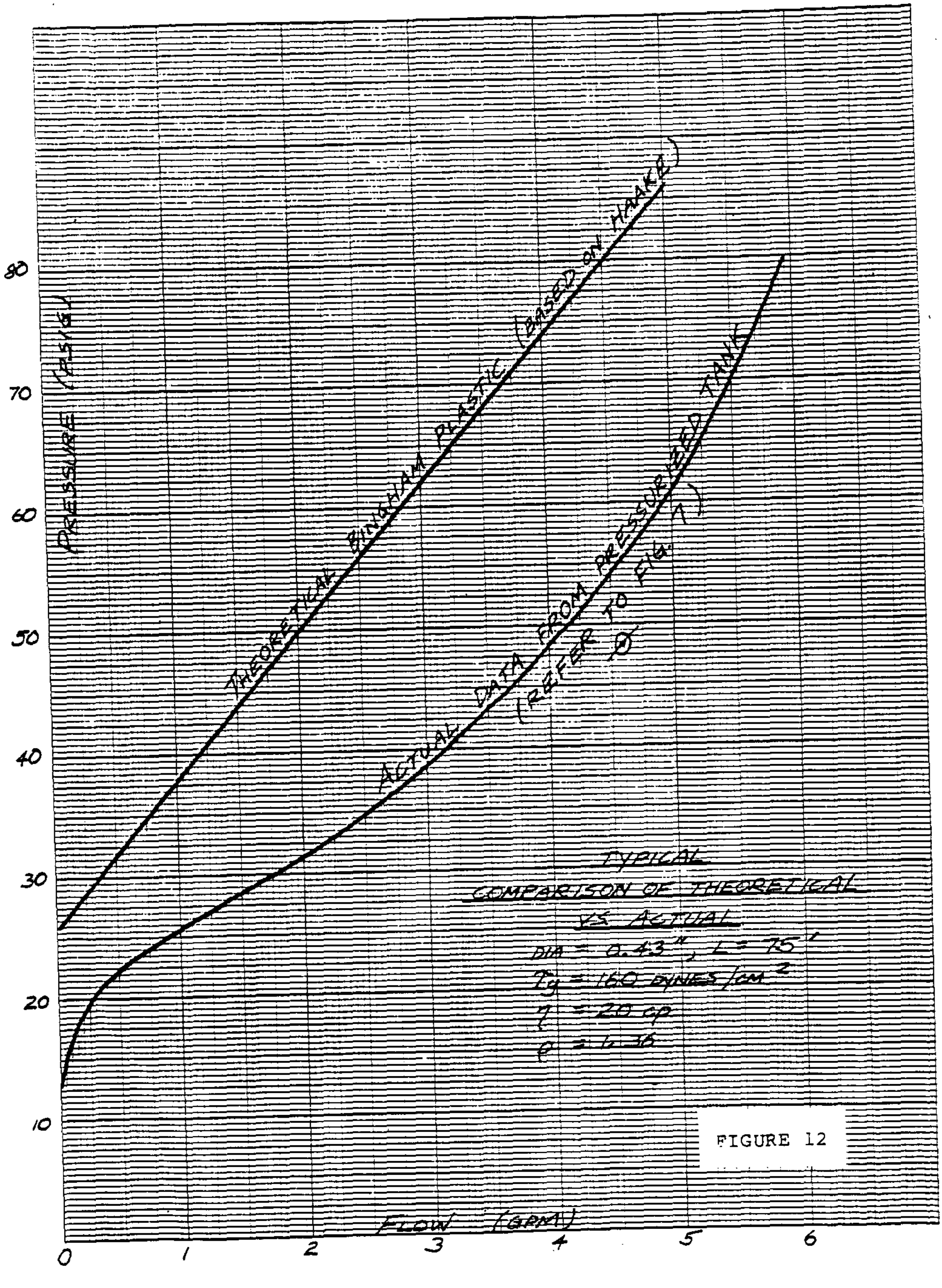
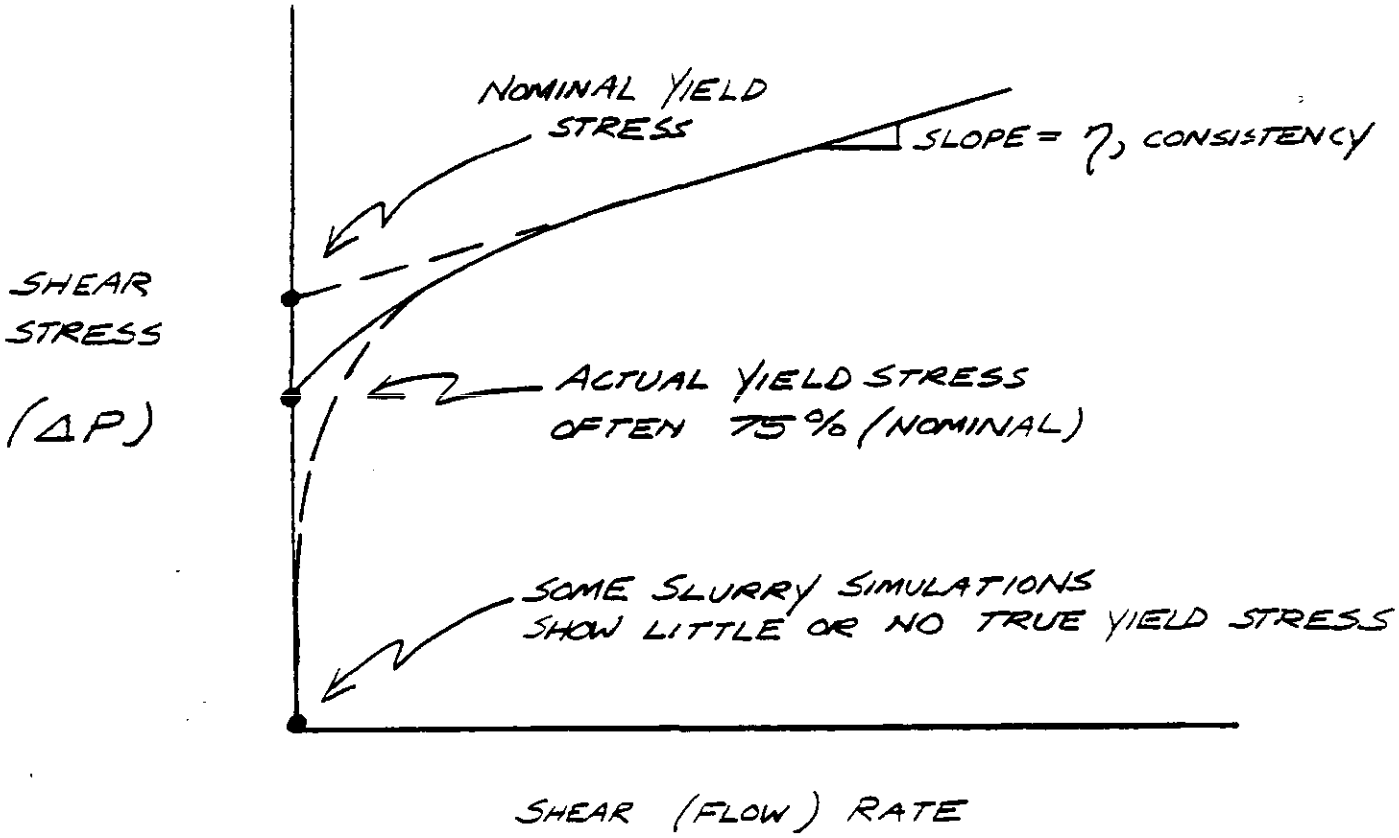

VELOCITY (FT./SEC.)
0 2.19 4.39 6.58 8.77 10.96 13.15
PRESSURE (LBS./IN²)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
FLOW (GALLONS/MINUTE)
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
SLURRY FLOW & VELOCITY vs PRESSURE
(Frit-sludge slurry, 140 frit, -200 mesh, flow through 77'of 3/8" tubing, I.D. = 0.305")
YIELD STRESS DYNES/CM² 58.13
WT.% SOLIDS 39.4
CONSISTENCY CP 8.16
DENSITY GMS/CC 1.31

FIGURE 11



PRESSURE (PSIG)
80
70
60
50
40
30
20
10
THEORETICAL BINGHAM PLASTIC (BASED ON HAAKE)
ACTUAL DATA FROM PRESSURIZED TANK
(REFER TO FIG. 7)
TYPICAL
COMPARISON OF THEORETICAL
VS ACTUAL
DIA = 0.43", L = 75'
τ_y = 160 DYNES/CM^2
η = 20 cp
ϕ = 4.36
FLOW (GPM)
0
1
2
3
4
5
6

FIGURE 12



GENERALIZED FLOW DIAGRAM

FIGURE 13

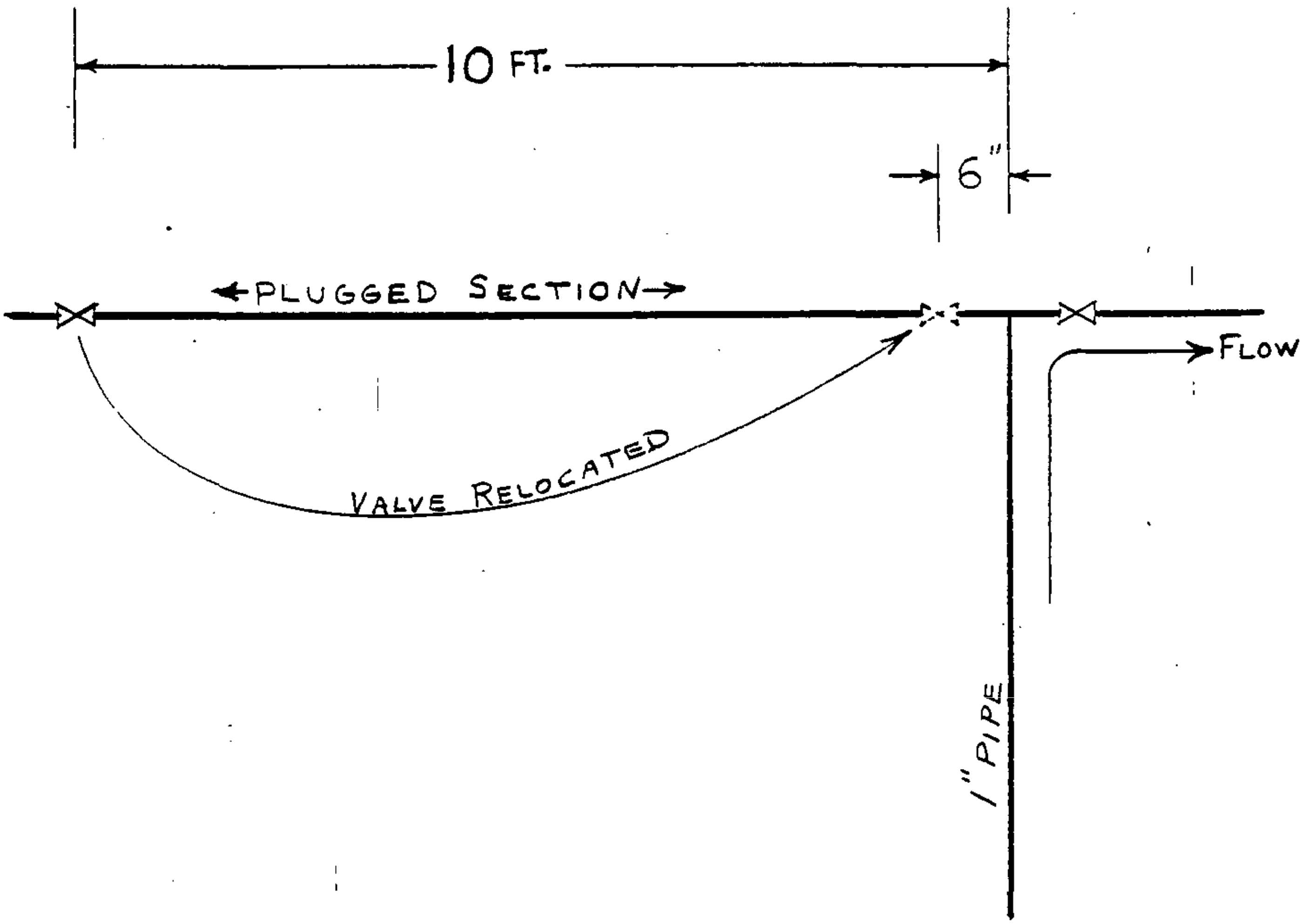
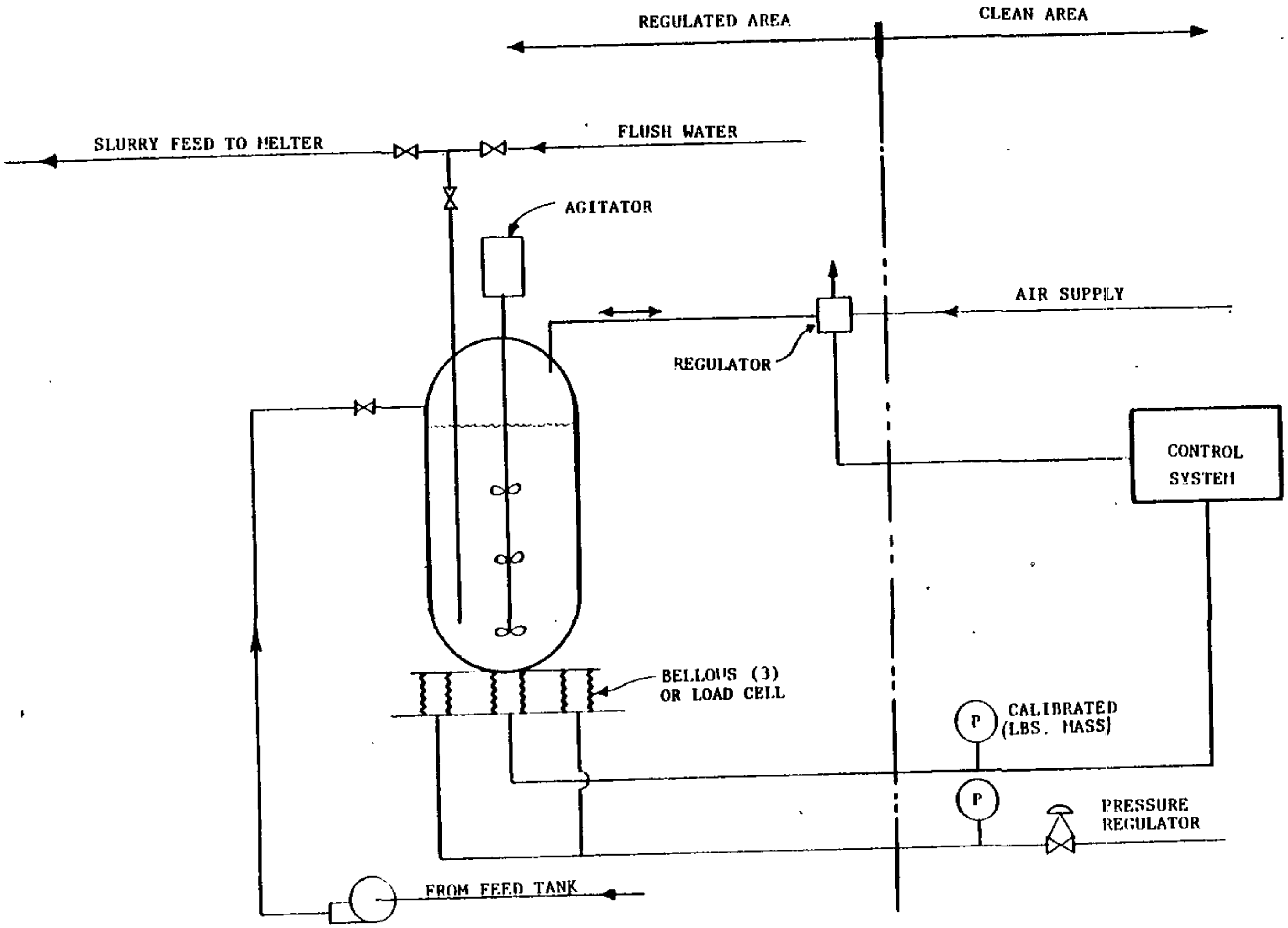


FIGURE 14



PRESSURIZED TANK (FUTURE)

FIGURE 15

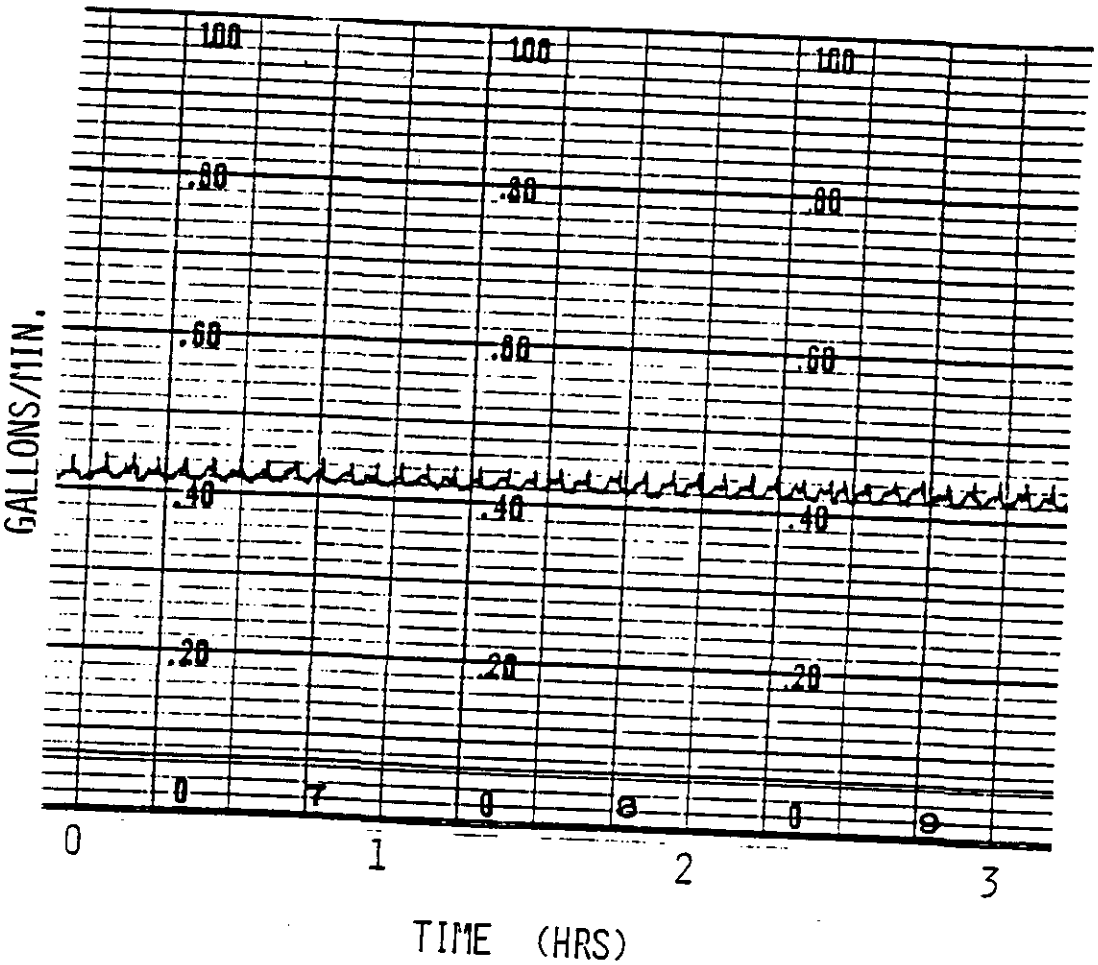


FIGURE 16

TABLE 1

(For Water Flow in 1/2-inch O.D., 0.430-inch I.D. Tubing)

Pressure (lbs/in^2) *	Velocity (ft/sec)	Reynolds # (Re)	E/D (in/in) **	f ***	H_L (ft) ****	Le (ft)
1.4	1.075	3966	0.000163	0.0397	1.27	63.9
1.8	1.233	4598	0.000163	0.038	2.16	84.8
2.0	1.3	4792	0.000163	0.0375	2.63	97.1
2.4	1.59	5865	0.000163	0.035	3.55	93.5
3.4	2.085	7692	0.000163	0.0325	5.86	96.5
4.4	2.55	9388	0.000163	0.031	8.17	94.5
5.4	2.79	10292	0.000163	0.030	10.49	104.1
6.4	3.15	11617	0.000163	0.029	12.8	103.1
7.4	3.534	13037	0.000163	0.285	15.11	98.3
8.4	3.742	13804	0.000163	0.28	17.42	102.9
9.4	4.131	15239	0.000163	0.275	19.74	97.4
10.4	4.298	15855	0.000163	0.27	22.05	102.3
12.4	4.894	18054	0.000163	0.265	26.68	97.2
15.4	5.484	20230	0.000163	0.26	33.62	99.4
20.4	6.492	23949	0.000163	0.245	45.18	101.2
25.4	7.574	27940	0.000163	0.24	56.75	95.3
29.4	8.371	30880	0.000163	0.235	66.00	92.6

* Pressure from Figure 2.

** E = 0.00007 inch (CRANE Technical Paper 410 and Du Pont Std DG 2.3 B, Table 1), E/D = relative roughness, D = tubing I.D. (inch).

*** f - friction factor from MOODY diagram.

**** (2.313 x Pressure) - 2, see 2' dimension Figure 1.

TABLE 2

(For Water Flow in 3/8-inch O.D., 0.305-inch I.D. Tubing)

Pressure (lbs/in^2) *	Velocity (ft/sec)	Reynolds # (Re)	E/D (in/in) **	f ***	H_L (ft) ****	Le (ft)
2.4	1.16	2455	0.00023	0.048	3.55	90.7
3.4	1.434	3034	0.00023	0.044	5.86	106.7
5.4	2.122	4490	0.00023	0.038	10.49	100.6
8.4	2.785	5893	0.00023	0.035	17.42	105.2
10.4	3.193	6756	0.00023	0.034	22.05	103.2
14.4	3.903	8258	0.00023	0.032	31.3	105.2
20.4	4.754	10059	0.00023	0.03	45.18	109.2
25.4	5.358	11338	0.00023	0.0296	56.75	109.4
29.4	5.827	12330	0.00023	0.029	66.0	109.8

* Pressure from Figure 2.

** E = 0.00007 inch (CRANE Technical Paper 410 and Du Pont Std DG 2.3 B, Table 1), E/D = relative roughness, D = tubing I.D. (inch).

*** f - friction factor from MOODY diagram.

**** (2.313 x Pressure) - 2, see 2' dimension Figure 1

TABLE 3

(For Water Flow in 1/4-inch O.D., 0.180-inch I.D. Tubing)

Pressure (lbs/in^2) *	Velocity (ft/sec)	Reynolds # (Re)	E/D (in/in) **	f ***	H_L (ft) ****	Le (ft)
3.4	1.462	2257	0.00054	0.048	5.9	55.5
8.4	2.304	3557	0.00054	0.041	17.46	77.49
14.4	3.191	4927	0.00054	0.037	31.34	80.35
21.4	4.008	6188	0.00054	0.0345	47.53	82.84
29.4	4.765	7357	0.00054	0.033	66.04	85.13

* Pressure from Figure 2.

** E = 0.00007 inch (CRANE Technical Paper 410 and Du Pont Std DG 2.3 B Table 1), E/D = relative roughness, D = tubing I.D. (inch).

*** f - friction factor from MOODY diagram.

**** (2.313 x Pressure) - 2, see 2' dimension Figure 1.

TABLE 4

Slurry Batch	Frit, type and size	Rheology*: Yield Stress, τ, dynes/cm^2	Rheology*: Consistency (η, centipoise)	Wt. % Solids	Flow Tube Size, inch	Pressure Drop, psi at 0.5 gpm	Pressure to Initiate Flow, ±2 psi
No. Formic Acid Treated	131 Frit, -80 Mesh	100	20	40	1/2	16	13
					3/8	33	16
					1/4	-	21
No. 2 Untreated	131 Frit, -80 Mesh	190	35	40	1/2	19	10
					3/8	36	16
					1/4	-	25
No. 3 Untreated	131 Frit, 50% -100, 50% -50 +100 Mesh	170	20	41	1/2	22	15
					3/8	35	20
					1/4	-	30
No. 4 Untreated	131 Frit, 50% -100, 50% -50 +100, Mesh	135	25	48	1/2	24	13
					3/8	49	19
					1/4	-	33
No. 5 Untreated	140 Frit, -200 Mesh	58	8	39	1/2	10	7
					3/8	31	10
					1/4	-	-
No. 6 Untreated	140 Frit, -200 Mesh	511	49	47	1/2	45	10
					3/8	-	-
					1/4	-	-

* Values shown are averages of several determinations rounded to nearest whole numbers.

TABLE 5

Slurry Rheology Data

	FORMIC ACID TREATED SLURRY				UNTREATED SLURRY			
	Yield Stress, τ_y dynes/cm^2	Consistency, η, centipoise	Density, , gms/cc	Wt. % Solids	Yield Stress, τ_y dynes/cm^2	Consistency, η, centipoise	Density, , gms/cc	Wt. % Solids
Number of Samples	6	6	6	6	7	4	6	7
Mean, $\overline{X}$	104.16	22.14	1.36	39.7	191.57	34.87	1.49	40.64
Std. Deviation,	17.4	5.8	0.046	0.26	74.4	6.1	0.079	0.27
Variance, ^{2}	303.4	33.88	0.002	0.068	5541	36.5	0.0062	0.073
	Laboratory Sample Identification 82-176, 177, 181, 183, 186, 187				Laboratory Sample Identification 82-168, 169, 174, 175, 201, 205, 206			

Appendix A

Typical Feed Compositions

Frit

Type 131

Component	Wt%
SiO_2	57.9
B_2O_3	14.7
Na_2O	17.7
Li_2O	5.7
MgO	2.0
TiO_2	1.0
La_2O_3	.5
ZrO_2	.5

Type 140

Component	Wt%
SiO_2	60.20
B_2O_3	16.20
Na_2O	13.90
Li_2O	4.70
MgO	1.63
Al_2O_2	0.63
CaO	1.10
TiO_2	0.06
H_2O	0.14
ZnO	0.34
BaO	0.40

Sludge

Unformated Component	Wt%
Fe_2O_3	45.5
Al_2O_3	16.8
MnO	12.5
CaO	5.4
Zeolite	7.4
NiO	3.8
CsOH	.06
SiO_2	7.2
Na_2CO_3	.9
Na_2SO_4	.4

Formated Component	Wt%
$Fe(OH)_3$	41.2
$Al(OH)_3$	17.3
$Mn(COOH)_2$	14.3
$Ca(COOH)_2$	8.5
Zeolite	5.1
$Ni(COOH)_2$	4.3
CsOH	0.06
SiO_2	7.9
Na_2CO_3	1.0
Na_2SO_4	0.4