NOTICE

**CERTAIN DATA
CONTAINED IN THIS
DOCUMENT MAY BE
DIFFICULT TO READ
IN MICROFICHE
PRODUCTS.**

E. I. DU PONT DE NEMOURS & COMPANY

INCORPORATED

ATOMIC ENERGY DIVISION

SAVANNAH RIVER LABORATORY

AIKEN, SOUTH CAROLINA 29801

(TWX: 810-771-2870, TEL: 803-726-8211, WVA: AUGUSTA, GA.)

DPST-82-954

PROJECT S-1780 No. LP-10001

CC: R. Maber, 703-A
J. B. Mellen, SF (5)*
B. G. Kitchen, 773-29A
W. R. Stevens, III, 773-A
M. D. Boersma, 676-G
D. P. Lewis, 676-4G

DEC 03 1990

April 15, 1983

J. T. GRANAGHAN, PLANT MANAGER
SAVANNAH RIVER PLANT

ATTENTION: D. C. NICHOLS, 773-29A (5)*

SLUDGE SLURRY HYDRAULIC DATA

Attached to designated (*) copies of this letter is a copy of DPST-82-954 by D. P. Lewis, "Hydraulic Testing of Simulated DWPF Waste Slurries at the Georgia Iron Works Hydraulic Laboratory: Summary Report".

This report summarizes tests that expand our data base for sludge slurries to include formatted sludges and sludge-frit slurries. Previous conclusions and recommendations are confirmed, viz:

- a) All DWPF sludge and (sludge + frit) slurries can be modeled as Bingham plastics for design purposes. Deviation toward psuedo plastic behavior occurs at velocities (shear rates) below normal design conditions.
- b) Resistances of fittings, expressed as equivalent lengths of straight pipe, are the same as or less than those for water. Again, deviation is greater at velocities lower than normal design.
- c) Although the sludge-frit slurries in these tests showed no settling tendencies, a minimum velocity of 3 fps is still recommended as in DPST-83-274. This will protect against settling or plugging from sand and other large particles in actual waste or introduced in the process.

J. F. ORTALDO, RESEARCH MANAGER
WASTE SOLIDIFICATION TECHNOLOGY DIVISION

MDB:tkb

*Att DPST-82-954

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

DPST-82-954

ACC. NO. 155462

CC: W. R. Stevens, III, 773-A 235
J. F. Ortaldo, 773-A 212
R. B. Ferguson, 773-A
M. J. Plodinec, 733-A B-120
M. D. Boersma, 676-G
H. D. Martin, 704-G
D. C. Witt, 676-1G
C. R. Pound, 676-4G
P. L. Graf, 704-G
E. J. Weber, 676-1G
T. Motyka
SRL Records (2)

December 31, 1982

TO: F. H. BROWN

FROM: D. P. LEWIS *DL*

HYDRAULIC TESTING OF SIMULATED DWPF WASTE SLURRIES
AT THE GEORGIA IRON WORKS HYDRAULIC LABORATORY:
SUMMARY REPORT

Abstract

Pipeline tests of current simulations of DWPF waste slurries were performed during August, 1982 at the Georgia Iron Works Hydraulic Laboratory (GIW). Measurements of pressure gradient versus flow in 3-inch pipes and fittings were made for various concentrations of unformatted sludge and formatted sludge with frit. All slurries were shown to behave generally as Bingham Plastic fluids. Formated sludge/frit slurries behaved generally like unformatted sludge slurries of comparable yield stress. No frit settling problems were observed.

Introduction

Essential to proper specification of slurry pumps is an understanding of the slurry's pipeline behavior. A high percentage of slurry pump problems are caused by a lack of understanding of transport system requirements, and misapplication of the pump.

Testing in November, 1979 by C. T. Randall at the Georgia Iron Works Hydraulic Laboratory (GIW) showed that the behavior of non-settling simulated waste sludge is predictable with Bingham plastic correlations.¹

It was originally assumed that the addition of frit had no effect on the hydraulic characteristics of the slurry, for the same nominal rheology (yield stress and consistency). However, as slurry batch sizes increased and formulations changed, "thinner" slurries were produced. There was increased concern over the effect of frit addition.

The August, 1982 tests were performed to quantify the behavior of current slurry simulations with special attention on the effect of frit. (Reference: DPST-82-694, Georgia Iron Works Slurry Testing Program Update, July, 12, 1983.)

This memorandum summarizes the results of this test program. In addition, a detailed 186-page report has been submitted by GIW.² This memorandum summarizes that report and relates the results to information contained in the DWPF Technical Data Summary.⁶

Description of Slurries

Slurries were intended to simulate sludge, similar to DWPF feed, and sludge with frit, similar to DWPF glass melter feed. It is emphasized that these slurries were simulations only, and may not behave exactly as the real slurries.

The test slurries were specified and prepared by D. M. Sabatino and E. J. Weber as part of the normal LSFM feed preparation (SRAT Batch No. 7 and SME Batch No. 6).

Unformatted sludge was concentrated to about 31 wt% solids and 10 drums were filled. Table 1 shows the estimated chemical composition of the sludge solids. The remainder of the batch was processed as usual with formic acid treatment and Frit 131 addition. This formatted sludge with frit was concentrated to about 57 wt% total solids and 10 drums were filled. Table 2 shows the estimated composition of formatted sludge and frit solids. Table 3 reports initial frit size distribution.

The slurries were allowed to settle in the drums for about 30 days, then transported to GIW by flatbed truck. Approximately 20-25% of the total volume was water above the settled slurry. This contrasts samples taken at the same time as the drumming, but retained at TNX/ETF, which showed only 10-15 vol % decantable water. Much of the extra settling can probably be attributed to the vibrating action of the truck ride to GIW.³

The sludge was decanted to about 37 wt% solids and loaded into the system. This slurry and 4 dilutions were tested. Similarly, the sludge/frit slurry was decanted to about 60 wt% solids and loaded into the system. Due to difficulty in maintaining uniform flow with this very thick slurry, it was diluted to about 55 wt% solids for the first sludge/frit test. After that, 3 more dilutions were tested. Table 4 reports the solids concentration data for each of the nine slurries tested. Note that the last 2 sludges and the last 3 sludge/frit slurries are rheologically in the TDS range.

Slurries will be referred to by GIW test number or nominal (pipeline measured) specific gravity in this memorandum. This will facilitate any further investigation of data presented in the full GIW report.²

Experimental Equipment and Procedure

The test piping is sketched in Figure 1. The primary test section was a 3-inch, Schedule 40, 304 stainless steel loop built by SRL for the 1979 GIW slurry test.⁴ The test section contains:

- o A 38 ft. straight pipe section with 28 ft. (109 diameters) of straight pipe immediately upstream.
- o Two 45° elbows with 15-in radius
- o A 90° miter bend (simulating a "Hanford connector" elbow)
- o A 90° elbow with 4.5 in. radius (standard long radius elbow)
- o A 90° elbow with 15-in. radius

The test section was flanged to GIW's 4-inch pipe loop powered by a GIW 4 x 6 LSA 25 pump (6-in suction, 4-in discharge, 25-in impeller, 750 rpm). The GIW piping includes a U-tube meter for continuous measurement of specific gravity⁵ and a 4-in. view section.

Flow was measured by a 3-in magnetic flowmeter and an elbow flowmeter. Pressure gradients across each of the fittings listed above were measured. Power consumption, torque, and total dynamic head of the pump were measured. Slurry temperature was measured. Details of all the instruments employed are contained in the GIW report.²

Each slurry "test" consisted of recording all of the measurements above at 10-15 steady state velocities. After each slurry dilution was made, slurry was circulated around the loop in turbulent flow for 10-30 minutes to ensure proper mixing. Steady state flow was established at the desired velocity and data recorded. This was repeated at decreasing flow rates. After each test, several measurements through-out the range of flows were checked to ensure reproducibility.

Several slurry samples were taken during each test, both early and late in the run. Some samples were analyzed for solids content and rheological properties. Others will be analyzed for particle size distribution and relative abrasivity. (Results will be reported in a future DPST.)

Water Calibration Tests

Water tests, procedurally similar to the slurry tests described above, were performed to verify the magnetic flowmeter and estimate the relative roughness of the pipe. Pressure gradient (straight test section) versus velocity data were compared against the theoretical values by the Darcy-Weisbach and Colebrook equations, as outlined in Appendix A. The data closely approximated the theoretical curve when a pipe relative roughness of 10^{-4} was used. This is reasonable by comparison with the value for new steel pipe, $5.9 (10^{-4})$,² and indicated that the instrument was operating satisfactorily.

Water calibration of friction losses in pipe fittings will be discussed with the slurry test results.

Water tests were performed before and after the nine slurry tests.

Slurry Test Results

A. Straight Pipe

Figures 2 and 3 summarize the behavior of the sludge and sludge/frit slurries, respectively, in terms of shear stress, τ_o , versus $8V/D$, where:

τ_o = shear stress at the pipe wall

$$\tau_o = \frac{D}{4} \frac{\Delta p}{L}$$

and V = velocity
 D = pipe inner diameter
 L = length of pipe
 Δp = pressure drop

Data expressed this way can be used to directly predict pressure drop of the slurries in other pipe sizes. Both laminar and turbulent flow regimes are shown. Do not confuse $8V/D$ (sec^{-1}), or apparent shear rate, with the actual shear rate (also sec^{-1}) one would find on a rheogram. (Rheograms, discussed later are superfluous except for comparisons of rheological characteristics determined by other viscometers.)

All of the slurries showed behavior generally like a Bingham plastic. However, at very low velocities, shear stress dropped off rapidly. The slurries appeared more like pseudoplastic fluids in this low flow region. (Figure 4 illustrates the generalized behavior of Bingham and pseudoplastic fluids.) Although it was difficult to maintain steady state at near zero flows, little or no true yield stress was observed. When the pump was shut down,

pressure gradient in the test loop dropped immediately to zero. However, the flat pressure gradient curves throughout most of the laminar region indicate that Bingham plastic correlations can be used (with a nominal yield stress) to quantify slurry behavior for most of the region.

A good example of the lack of yield stress is the sludge slurry of specific gravity 1.34 (M-75-82) shown in Figure 2. Up to an apparent shear rate ($8V/D$) of 2000 sec^{-1} , it behaved as a viscous pseudoplastic. With no true yield stress, slurry flow was easily started. Above 200 sec^{-1} the shear stress leveled off, with the nominal yield stress greater than 900 dynes/cm^2 .

The sludge with frit slurries (Figure 3) showed no apparent frit settling problems even at very low velocities. There had been concern that frit would cause a minimum in the pressure gradient curve, typical of the settling slurry behavior illustrated in Figure 5. Only a slight dip appeared with the thickest sludge/frit slurry (M-79-82, sp.gr. = 1.54) between $300\text{--}400 \text{ sec}^{-1}$. Even the thinnest sludge/frit slurries showed no minimum. Settling, if any, would've been expected with these dilute slurries where the hindered settling effect is minimized. (Note, however, that final frit particle size distribution is yet to be determined.)

Visual inspection at the 4" pipe section was somewhat limited by the muddy nature of the slurry. The 40 wt% sludge/frit slurry (sp.gr. = 1.33) showed some evidence of a "moving bed" below 3 ft/sec. ("Moving bed" refers to a high solids region with "settled" appearance but no stationary solids.) At 2 ft/sec this high solids region covered the bottom 1/4 of the pipe. At 1/2 to 1 ft/sec, about 1/3 of the pipe appeared "settled". However, there was no indication of stationary beds.

The most dilute sludge/frit slurry (33 wt%, sp.gr. = 1.25) showed less "bedding". Apparently the reduced hindered-settling effect was balanced by the increased turbulence with the thin slurry. (Transition to turbulence was at 4 ft/sec.)

Transition from laminar to turbulent flow occurred at just slightly higher velocities than would've been predicted from the method presented in the Technical Data Summary (TDS).⁶ (This method assumes transition when the Reynolds Number, based on apparent viscosity, is about 2100. The concept of apparent viscosity is included in Figure 4.) Table 5 compares the actual transition velocities versus the predicted velocities.

Turbulent region pressure gradient was plotted versus velocity. Using the Darcy-Weisbach and Colebrook equations described in Appendix A, curves were fit to the points by varying the slurry viscosity until a reasonable fit was obtained. An example of this approach is shown in Figure 6. Table 5 compares the values obtained in this manner versus the slurry consistency. This

comparison is made because the TDS⁶ recommends using the slurry consistency to determine the turbulent region pressure drop. The values are close for the sludge with frit slurries. The viscosity values obtained for the sludge slurries are close to that of water. All of the differences are small enough that the TDS should still be considered valid.

Rheological properties determined in the pipeline were cross-checked with a Haake Rotoviscometer. Two problems were encountered during the process. As expected, sludge with frit slurries produced erratic results. The Haake rheograms generally agreed with the pipeline results, but some were of limited quantitative value, as illustrated in Figure 7. Some samples contained large particles which had to be screened before running the rheogram. These solids, approximately 20 mesh, were apparently left in the test piping from previous testing or sand-slurry cleaning. Better results were then possible, as illustrated in Figure 8.

T. Motyka, SRL, performed a quantitative comparison of pipeline, rotoviscometer, and capillary measured properties for two sludge slurries. The results, shown in Table 6, are in reasonable agreement. Table 6 also includes the results of a similar comparison for slurries tested at GIW in 1979.¹

Appendix B explains the derivation of rheograms from pipeline data.

B. Fittings

Pressure gradient was measured across each fitting (previously described) during both clear water and slurry runs. This data is expressed here as equivalent length of straight pipe.

The results of the water runs do not compare well against the literature values ^{7,8,9}, as shown in Figure 9 for the 90° elbows.

The poor agreement of experimental results and literature values indicates a limitation of the test loop layout. The typical spacing between fittings and pressure taps is about 30 pipe diameters of straight pipe. M. R. Carstens, consultant to GIW, recommends much greater lengths of straight pipe between fittings and taps. He suggests at least 50, and preferably 100, pipe diameters up and down-stream of the fitting to eliminate non-uniform flow.

Non-uniform flow, induced by a fitting, may be moved a long distance before becoming uniform again. The non-uniformity (such as rotational or vortex motion) can adversely affect a pressure gradient measurement. This is especially true if the absolute value of the measurement is very small, as is the case for most

of the fittings tested. The sharp 90° miter bend (simulated Hanford connector elbow) gave the best results, probably because the absolute values of the measurements are the largest.

Although the absolute values for pressure drop through fittings are questionable, the comparison between clear water and slurry results are useful.

Figures 10 and 11 show the equivalent length of the 90° miter elbow (simulated Hanford connector elbow) for sludge and sludge/frit slurries. At low velocities, the equivalent length for slurries is considerably lower than for water. As velocity increases, and flow enters the turbulent regime, the slurry equivalent length approaches that of water.

Note also the slight maximum/minimum behavior of the thin sludge and all sludge/frit slurries. This maximum appears just after transition into turbulent flow. This behavior could be the result of improper system layout, already discussed. If real, the slight minimum would not create a problem minimum in a system pressure drop curve. This is because the total system pressure drop is increasing rapidly with velocity in the turbulent regime.

Figure 12 and 13 report the equivalent length of the standard long radius ($R/D = 1.5$) 90° elbow for sludge and sludge/frit slurries. With slurries in laminar flow, the elbow showed low resistance to flow. As flow turned turbulent, the equivalent length agreed with the clear water tests.

The results from the low-resistance fittings (the extra-long radius 90° and the 45° bends) are more erratic, presumable because the pressure gradient measurements were so small. The maximum equivalent length exhibited by these fittings was approximately 6 pipe diameters, that is, only 1.5 feet of 3-inch pipe. These results are not shown here, due to the very low and erratic values.

The TDS⁶ recommends assuming the equivalent length of fittings to be equal to that of water in turbulent flow. These experimental results indicate that the TDS recommendation is valid for a "conservative"¹⁰ pressure drop estimate, but that fittings will present less resistance to flow at low velocities and with thicker slurries. A designer must consider the sensitivity of total system pressure drop, and hence, pump specification, to equivalent length assumptions.

Pump Performance

Slurry effects on pump performance were determined by comparing pump head and efficiency for both slurries and clear water. The effects are expressed as dimensionless parameters:

$$\frac{H_m - H_w}{H_w} \quad \text{and}$$

$$\frac{\eta_m - \eta_w}{\eta_w}$$

H = pump head
η = pump efficiency
m, signifies slurry
w, signifies water

These are plotted versus flow (expressed as a percentage of flow at best efficiency) for sludge with frit in Figures 14 and 15.

Pump head was generally 2-5% lower with slurries versus clear water performance and relatively independent of specific gravity. Pump efficiency was very dependent on solids concentration. Slurries in the range of DWPF design reduced pump efficiency 1-10 %, versus clear water. This is consistent with information presented in the TDS.⁶

It is recognized that performance corrections are not readily scalable to other pump sizes. However, the solids effects are minor and are not expected to vary much with pump size.

Pump Starting and Line Flushing

Slurries were generally easy to handle. In most cases, the pump was easily started. (Some problems were encountered with very thick slurries well outside the DWPF rheology range - effective yield stresses greater than 1000 dynes/cm²). Restarting after extended shutdowns was easy. The dilute sludge slurry (20 wt%, sp.gr. = 1.16) and the 49 wt% sludge/frit slurry (sp.gr. = 1.44) were left idle in the test loop for about 60 hours then easily restarted.

Flushing was easily performed also. Approximately 120 ft of 3-inch pipe was flushed clean within 5 minutes, at a velocity of about 6 ft/sec. This test is summarized in Figure 16.

Note that pump starting and line flushing may have been easy due to the lack of true yield stress.

In terms of pump hydraulics, the large capacity GIW would not be expected to have any starting advantage over the smaller-sized DWPF centrifugal pumps. However, the GIW piping configuration (with positive suction static head) probably has some advantage over the suction lift configuration (with negative suction static head) of DWPF pumps. (See DPST cited in Reference 10 for additional discussion.)

Conclusion

Current simulations of waste slurries, with and without frit, behaved generally like Bingham Plastics as stated in the TDS.⁶ The addition of frit had little effect of slurry behavior.

Quality Assurance

Sound engineering principles were employed in designing and conducting these experiments.

GIW is a well established contract laboratory with its own quality control program. Excellent test and instrument calibration records are maintained. (More details are contained in Appendix A of DPST-QA-82-2-45, Quality Assurance Review for the DWPF Slurry Pump Development Program, October 28, 1982).

DPL:dhw

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Notes:

1. Carstens, M. R., "Slurry Tests in 3-in. Diameter Pipe", Georgia Iron Works Hydraulic Laboratory, November, 1979.
2. Carstens, M. R., "Flow Characteristics of Simulated Slurries", Georgia Iron Works Hydraulic Laboratory, September, 1982. A cover letter, DPST-82-955, accompanies this report.
3. GIW engineers described other test slurries, claimed by customers to be totally nonsettling, which were easily settled during transportation to GIW.
4. This piping, designed by C. T. Randall in 1979, is shown in Drawing ST5-20625 (AMO 4632-15).
5. The "counter-flow" or "U-tube" specific gravity meter is explained in detail in: Lewis, D. P., "DWPF Slurry Rheology", memorandum to F. H. Brown and M. D. Boersma, April 12, 1982.
6. Technical Data Summary for the Defense Waste Processing Facility Sludge Plant, DPSTD-80-38-2, September, 1982, Part 10, Item 200.
7. Perry, R. H. editor, "Chemical Engineer's Handbook", 5th edition, Section 5.
8. "Flow of Fluids Through Valves, Fittings, and Pipe", Crane Technical Paper No. 410, 1976.
9. "Pipe Friction Manual", 3rd Edition, 1961, The Hydraulic Institute.
10. Slurry pump manufacturers caution slurry system designers about "conservative" pressure drop estimates. Some times over estimation of pressure drop can lead to improper pump selection. This concept is discussed in DPST-82-650, "DWPF Slurry Pumping Technical Considerations", D. P. Lewis, 6/17/82.

GIW TESTS

DPL

SRL/ETF
9 82

TABLE 1
SLUDGE CHEMICAL COMPOSITION

<u>COMPONENT</u>	<u>WT %</u>
Fe (OH) ₃	39.27
Mn O ₂	9.03
CaCO ₃	4.66
Ni (OH) ₂	2.62
Al (OH) ₃	16.10
Si O ₂	12.56
Zeolite	4.67
Ca ₃ (PO ₄) ₂	0.47
KOH	0.49
Na ₂ SO ₄	0.66
Si CO ₃	0.32
Cs NO ₃	0.01
Na NO ₃	4.21
NaOH	4.93

REFERENCE : E. J. WEBER, 7/19/82, SRAT RUN 7

GIW TESTS

DPL

SRL/ETF
9 82TABLE 2
SLUDGE/FRIT CHEMICAL COMPOSITIONFORMATED SLUDGE SOLIDS : 38% OF TOTALComponent Wt % of Sludge

$\text{Fe}(\text{OH})_3$	34.83
$\text{Mn}(\text{COOH})_2$	13.35
$\text{Ca}(\text{COOH})_2$	5.37
$\text{Ni}(\text{COOH})_2$	3.72
$\text{Al}(\text{OH})_3$	14.26
SiO_2	11.13
Zeolite	4.13
$\text{Ca}_3(\text{PO}_4)_2$	0.42
$\text{K}(\text{COOH})$	0.94
Na_2SO_4	0.59
$\text{Sr}(\text{COOH})_2$	0.35
CsNO_3	0.01
NaNO_3	3.74
NaCOOH	7.16

GLASS FRIT 131 SOLIDS : 62% OF TOTALComponent Wt % of Glass

SiO_2	57.4
B_2O_3	14.5
Na_2O	18.2
Li_2O	5.1
La_2O_3	0.3
MgO	1.5
TiO_2	1.2
ZrO_2	0.5

REFERENCE : E J WEBER, 7/19/82, SME RUN 6

GIW TESTS
FRIT

DPL

SRL
11-4 82

TABLE 3
INITIAL FRIT SIZE DISTRIBUTION
(TYPE 131)

<u>ANALYSIS</u>	<u>SIZE DISTRIBUTION : - THROUGH</u> + RETAINED ON			
• SRL / ETF 1 SAMPLE	<u>MESH</u> :	+80	+200	+325 -325
	<u>WT%</u> :	0.04	70.8	16.1 13.6
• RAM TEC (VENDOR) 6 SAMPLES	<u>MESH</u> :	+80	+100	+200 -200
	<u>MEAN WT%</u> :	0	21.0	66.2 12.8
	<u>STAND. DEV.</u> :	0	7.1	3.5 8.7

REFERENCES :

- NOMINAL -80+200 MESH PART OF AX 576703 G
ANALYSIS 7/14/82 BY RAM TEC , TYPE 131
- SRL /ETF ANALYSIS PER EJ WEBER , 7/19/82

GIW Slurry Tests

DPL

SRL/ETF
3-11 83

TABLE 4
TEST SLURRY PROPERTIES

SLURRY	GIW NO.	SOLIDS CONCENTRATION				PIPELINE		
		WT%	WT% SOLUBLE	VOL %	SP. GR.	γ_g	η	SP. GR.
UNFORMATED SLUDGE ↓	74-82	37.4	3.9	60	1.22 *	†	†	1.37
	75-82	35.5	3.7	54	1.24	†	†	1.34
	76-82	33.0	3.4	48	1.24	560	19	1.31
	77-82	28.7	2.8	43	1.24	225	9	1.25
	78-82	20.5	1.8	28	1.24	40	6	1.16
FORMATED SLUDGE/ FRIT ↓	79-82	55.2	11.5	75	1.57	540	8	1.54
	80-82	48.7	8.9	66	1.44	225	6	1.44
	81-82	40.4	6.5	51	1.35	100	3	1.33
	82-82	33.4	4.8	41	1.25	40	1	1.25

for GIW TEST RPT.

for SRL/ETF LAB

* NOTE FOR LAB / PIPELINE AGREEMENT ON SLUDGE SP. GR.
† NOT TO BE USED FOR MINIMUM FLUIDS

GIW TESTS

DPL

SRL

10

82

TABLE 5

TURBULENT FLOW BEHAVIOR

SLURRY / SP. GR.	TRANSITION VELOCITY		CONSISTENCY η_m (CP)	EFFECTIVE VISCOSITY μ_m
	PREDICTED	EXPERIMENTAL (FT/SEC)		
SLUDGE ↓	13.0	18.0	19.	NOT ENOUGH DATA
	8.5	10.5	9.	1.4
	3.8	4.7	6.	1.4
SLUDGE / FRIT ↓	11.8	13.3	8.	9.6
	8.0	9.4	6.	4.3
	5.4	5.9	3.	2.9
	3.5	4.0	1.	1.4

NOTES : • SEE TEXT P. 5

• η_m AS INTERPRETED BY GIW, REFERENCE 2

• FOR COMPARISON, μ_w , WATER VISCOSITY AT TYPICAL TEST TEMP. WAS 0.70 CP (40°C)

GIW TESTS

TM, DPL

SRL/ETF
3-15 83

TABLE 6
COMPARISON OF RHEOLOGY MEASUREMENTS
UNFORMED SLUDGE
(T. MOTYKA)

TEST NO.	YIELD STRESS (DYNES/CM ²)		CONSISTENCY (CENTIPOISE)		
	HAAKE	CAPILLARY	LINEAR APPROX	FULL FIT	
77-82	173	-	172	204	20
78-82	27.5	25	31	28.7	5.6
111-79	274 ³	-	181	219	62
113-79	62	-	28	30	8
					23.4
					11.6
					20.3
					30.5
					16.1
					16.6
					12
					29

PIPELINE

PIPELINE

NOTES: 1. COMPARISON IS BETWEEN: HAAKE ROTOVISCOMETER, A CAPILLARY VISCOMETER, LINEAR APPROXIMATION OF GIW DATA, AND FULL BUCKINGHAM EQ'N. FIT OF GIW DATA.

2. 111, 113-79 FROM 1979 GIW TESTS BY C.T. RANDALL ;
REFERENCE 1

3. QUESTIONABLE ANALYSIS DUE TO LARGE ROTOR GAP

4. REFERENCE: 10/29/82 TRANSMITTAL FROM T. MOTYKA

FIGURE 1 : GIW TEST PIPING

GIW TESTS

LPL

SRL
2

83

FIGURE 4

GENERALIZED SHEAR DIAGRAMS

FIGURE 5
SETTLING SLURRY BEHAVIOR

FIGURE 6

TURBULENT REGION PRESSURE DROP
(SEE TEXT)

FIGURE 12
EQUIVALENT LENGTH
OF 3" 90° ELBOW, R/D = 1.5
WITH SLUDGE

FIGURE 13
EQUIVALENT LENGTH
OF 3" 90° ELBOW, R/D = 1.0
SLUDGE WITH FRIT

FIGURE 14
PUMP PERFORMANCE (HEAD)

(BY M.R. CARSTENS, GIW, DPST-82-955, p 137)

FIGURE 15
PUMP PERFORMANCE (EFFICIENCY)

(BY M.R. CARSTENS, GIW, DPST-82-955, p. 138)

GIW TESTS
FLUSHING

DPL

SRL/ETF
11 82

FIGURE 16
GIW FLUSHING EXPERIMENT

TURBULENT FLOW DATA TREATMENTColebrook Equation:

$$\frac{1}{\sqrt{f}} = 1.14 - 2 \log \left(\frac{\epsilon}{D} + \frac{9.35}{Re \sqrt{f}} \right)$$

Darcy - Weisbach Equation:

$$i = \frac{f \rho V^2}{2 D g_c}$$

 Re = Reynolds No. f = Darcy-Weisbach fric. factor $\frac{\epsilon}{D}$ = relative roughness i = pressure gradient

METHOD: (1) ϵ/D is determined through the water calibration step

(2) turbulent region pressure gradient is determined with above eqns by using a Re calculated by assuming viscosity =

- viscosity of water
- Bingham consistency

(3) these are compared with slurry data in the turbulent region, as on next page

DPL

SRL-TNX
7-1 82

TREATMENT OF LAMINAR FLOW DATA
DERIVATION OF RHEOGRAMS

(REFERENCE : M.R. CARSTENS, GIW, NOTE 1)

LAMINAR REGION

$$\tau_o = \eta \dot{s}_o + \tau_y$$

 τ = INTERNAL SHEAR STRESS $\dot{s}$ = RATE OF STRAIN τ_y = YIELD STRESS η = COEFFICIENT OF RIGIDITY

PER RABINOWITSCH - MOONEY :

$$\dot{s}_o = \left(\frac{1+3n}{4n} \right) \frac{8V}{D} \quad \text{_____ 1)}$$

$$n = \frac{d \ln \tau_o}{d \ln \left(\frac{8V}{D} \right)} \quad \text{_____ 2)}$$

$$\tau_o = \frac{D \left(\frac{\Delta P}{L} \right)}{4} \quad \text{_____ 3)}$$

 $\left. \begin{matrix} s_o \\ \tau_o \end{matrix} \right\}$ SIGNIFIES @ PIPE WALL

- METHOD :
- (1) measure $\Delta P/L$ in pipe
 - (2) compute τ_o , eqn. 3)
 - (3) compute $8V/D$
 - (4) plot τ_o vs. $8V/D$ on log-log paper
 - (5) per eqn. 2), get n from above plot
 - (6) calculate $\dot{s}_o$, eqn. 1)
 - (7) plot τ_o vs $s_o \rightarrow$ RHEOGRAM

END

DATE FILMED

01 / 10 / 91