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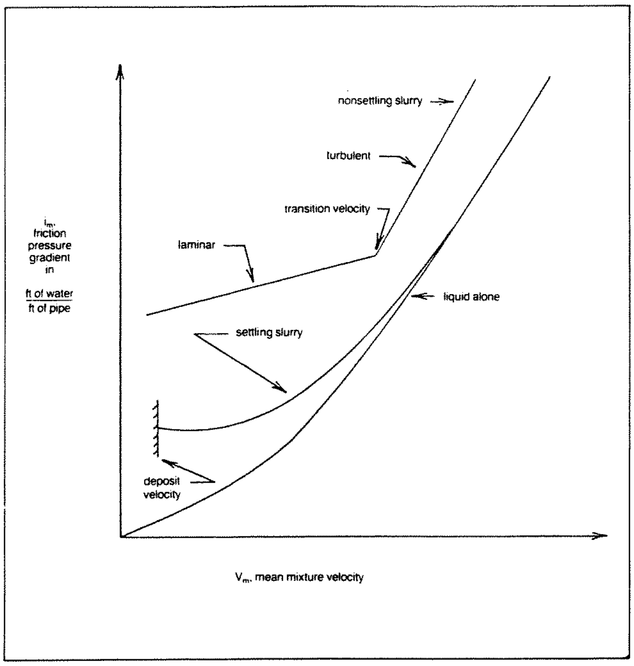
SLURRY PIPELINE DESIGN MANUAL

The flow of a solid-liquid mixture through a pipe is a complex phenomenon with the flow characteristics and subsequent pipe friction being dependent upon size, distribution, shape, density, and concentration of the solids, plus pipe diameter, mean velocity, slope of the pipeline, etc. When accurate values of head loss and other data are required, pipe-flow tests using the solid particles to be transported should be performed under controlled conditions such as the GIW* Hydraulic Lab. For feasibility and preliminary-design studies empirical methods may be adequate. The following is intended as a guide for engineers who need to make estimates of slurry pipeline friction and associated centrifugal slurry pump selection.

Slurries may be categorized as *nonsettling* or *settling slurries.* The accepted criteria is based on a 62μ m diameter quartz sand grain, which has a settling velocity of 1.5mm/sec (0.059 in/sec) in 20 degrees C (68 degrees F) water. Higher settling velocities denote settling slurries, whereas lower settling velocities denote nonsettling slurries.

The importance of differentiating between settling and nonsettling slurries is that the flow characteristics are quite different. Figure 1 shows the difference in friction pressure gradient, i_m. The nonsettling-slurry curve is that of non-Newtonian laminar flow of a pseudofluid to the left of the transition velocity and of turbulent flow of a pseudofluid at higher velocities. The settling-slurry curve is turbulent flow which approaches asymptotically to the curve for liquid flow as the velocity is increased. Deviation from the liquid curve is caused by the increased resistance of solid particles sliding, rolling, and bouncing along the lower portion of the pipe. As the velocity is decreased, a greater portion of solid particles are carried as bed load rather than as suspended load. As the velocity is decreased further, the velocity is reached at which a stationary bed begins to form in the bottom of the pipe.

Figure 1. Friction pressure gradient as a function of velocity.



The most efficient slurry transport is achieved when the *specific-energy consumption,* SEC, is a minimum. In dimensionless form

$$\text{SEC} = \frac{i_m}{S_s C_{vd}} \qquad (1)$$

in which i_m = friction pressure gradient in ft of water per ft of pipe,
S_s = specific gravity of the solids, and
C_{vd} = delivered volume concentration. (Decimal)

The dimensionless value of SEC is the ft-lb of energy required to move one pound of solids a horizontal distance of one foot with units as shown. The more commonly used unit is the HP-HR/Ton Mile of dry solids transported. Chart 9 is included to allow easy calculation of this value. Even though operation at SEC (min.) is most efficient from the energy standpoint, cost of the pipeline, deposit velocity, or centrifugal-pump characteristics will probably result in the selected velocity, V_m (operating) being greater than V_m minimum (SEC). In any event, curves of $i_m = \phi(V_m)$ and $\text{SEC} = \phi(V_m)$ should be scrutinized by a designer before selecting pipeline size and operating conditions.

NONSETTLING SLURRIES flowing in a pipe have a uniform distribution of particles across the flow section and an axisymmetric velocity distribution. Flow of a nonsettling slurry can be treated as that of a pseudofluid having the density, ρ_m, of the mixture, that is, $\rho_m = \rho_f$. As indicated in Figure 1, the flow may be *turbulent* but can be *laminar* since the apparent viscosity of the pseudofluid can be many times that of the carrier liquid.

In *laminar flow* the internal shear stress, τ, is a function of the rate of strain. Plots of shear stress as a function of rate of strain are called rheograms. Slurry pseudofluids are classified by the nature of the rheograms as indicated in Figure 2. The simplest rheogram is that of a Newtonian fluid shown in the lower part of Figure 2. The slope of the straight-line rheogram of a Newtonian fluid is the viscosity, μ. Water is a Newtonian fluid. Some clay slurries such as dispersed kaolin are Newtonian pseudofluids, but many are pseudoplastics or yield pseudoplastics.

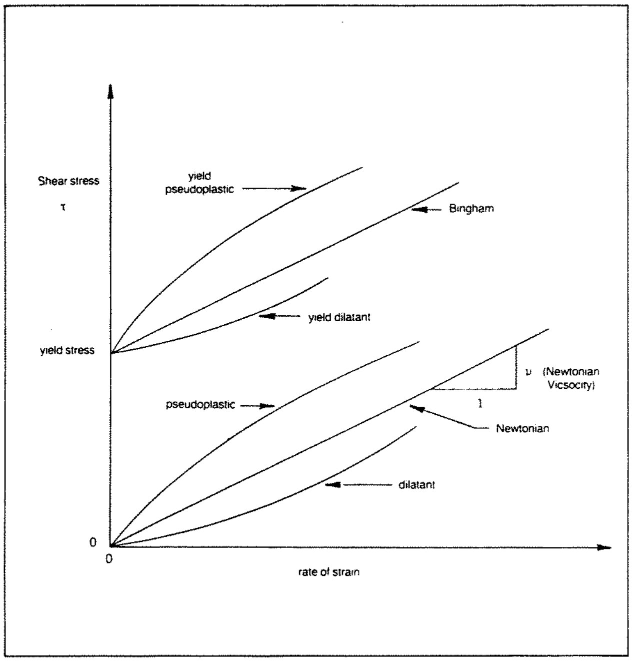
As a result of the theoretical proofs of Rabinowitsch and Mooney, rheologic properties of a fluid can be determined by means of experimental measurements of steady, uniform, laminar flow in a circular conduit. For all laminar flows in a pipe Rabinowitsch and Mooney have shown that

$$\tau_o = p_x \frac{8V_m}{D} \qquad (2)$$

where p is a slurry consistency property.

Equation 2 is the scaling relation whereby tube-type viscometer measurements can be applied to engineering design. In addition to developing a scaling law, Rabinowitsch and Mooney derived the relationship between rate of strain at the pipe wall and $8V_m/D$ by means of which the rheogram can be determined from experimental measurements.

Figure 2. Rheograms of time-independent fluids.



The laminar scaling relation, equation 2, does not apply to turbulent flow. Here, a different evaluation procedure is necessary. The Darcy-Weisbach and Colebrook equations provide a satisfactory means where the friction pressure gradient is shown by

$$\rho_o g_o i_m = \frac{f_m}{D}\,\frac{\rho_m V_m^2}{2} \qquad (3)$$

in which $\rho_o g_o$ = specific weight of water 62.4 lb/ft^3 or 9800 N/m^3,

i_m = friction pressure gradient in ft of water per ft of pipe,

f_m = dimensionless boundary-drag coefficient,

D = inside diameter of pipe,

ρ_m = density of the mixture (pseudofluid), and

V_m = mean velocity.

The Colebrook equation for the boundary-drag coefficient for a single-phase fluid is assumed to apply to the pseudofluid, that is, the nonsettling slurry.

$$\frac{1}{\sqrt{f_m}} = 1.14 - 2\log\left(\frac{k}{D} + \frac{9.35}{Re\sqrt{f_m}}\right) \qquad (4)$$

in which

k = equivalent sand-grain roughness height, and

$$Re = \frac{\rho_m V_m D}{\mu_m}$$

For many nonsettling slurries flowing turbulently the viscosity, μ_m, is that of the fluid, μ_l, and density is that of the mixture, ρ_m, but for other nonsettling slurries the viscosity, μ_m, is different.

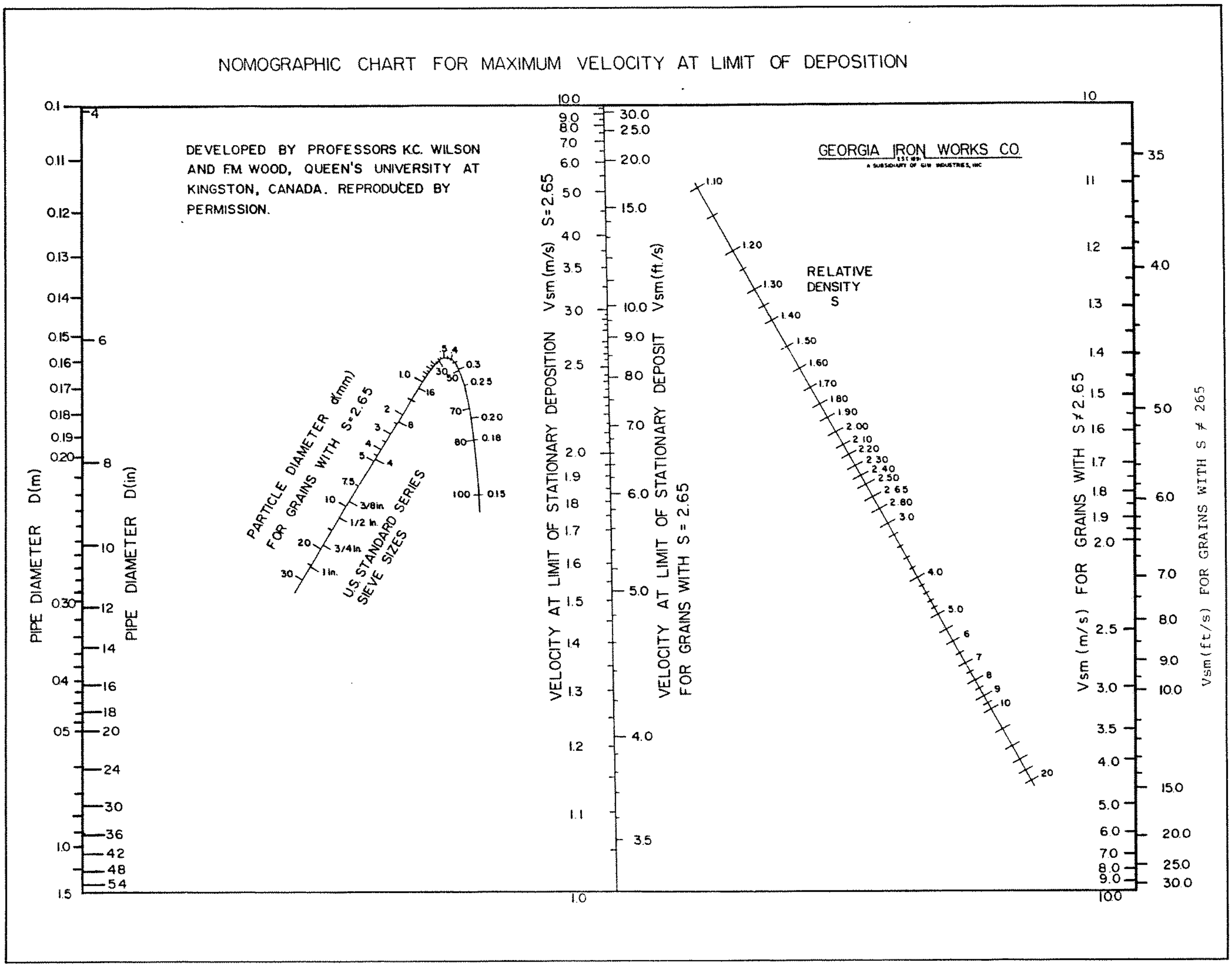
In general, no reliable method exists at present for estimating the flow properties of nonsettling slurries by calculation from the properties of the solids and carrier liquid. Brookfield and other types of cone viscometers are generally unsatisfactory for slurry so that pipe-flow tests are necessary to determine the rheologic characteristics of nonsettling slurry flow. These tests should be performed at velocities which are high enough to obtain some data with turbulent flow to be able to identify the transition from laminar to turbulent flow.

In practice, slurry transport of nonsettling slurries as laminar flow is avoided primarily because some larger particles may settle to the bottom of the pipe forming a stationary bed. In most cases, systems are designed to run at velocities slightly in excess of those of the transition point. In these cases, a reasonable first estimate may be obtained for the pipe friction using equation 3 or using Chart 2 (or the GIW Slide Rule) and taking the resultant pipe friction as being in feet of slurry.

A SETTLING SLURRY flowing in a pipe normally flows as a *heterogeneous mixture* in which a portion of the solid particles are carried as suspended load and the remainder are moved as bed load. The bed-load or stratification ratio, R, which is the ratio of the bed-load transport to total transport, is a useful parameter to characterize the flow conditions. Since the mechanism of suspension, turbulence, is a function of mean velocity in the pipe, the value of R is also a function of V_m. At a sufficiently high mixture velocity, all of the solid particles will be conveyed as suspended load or as a *pseudohomogeneous suspension* for which $R = 0$. At lesser velocities the solid particles tend to settle toward the bottom of the pipe with the result that some of the transport is bed-load transport in which particles bounce, roll, and slide along the lower portion of the pipe. There is large resistance to solid/solid bed-load transport and little additional resistance resulting from suspended-load transport; therefore, the friction pressure gradient diverges more and more from the water curve, Figure 1, as R increases due to reducing V_m.

The lower limit of the heterogeneous-suspension regime occurs when the velocity is reduced to the deposit velocity and the solids start to form a stationary bed. A small stationary bed is harmless, but there is no reason to waste a part of the flow cross section with a stationary bed. In order to preclude a stationary bed, pipelines are designed so that $V_m >$ deposit velocity. The deposit velocity can be estimated from a nomograph developed by Wilson and Wood 4/ which is reproduced as Figure 3. The values on the left of the nomograph are for slurries in which $S_s = 2.65$, whereas the right half pertains to slurries in which $S_s \neq 2.65$.

Figure 3. Nomograph for determining deposit velocity.



The role of and even the meaning of deposit velocity is obscure. Because naturally degraded rock and ground ores consist of a spectrum of particle sizes, observations of the beginning of a stationary bed simply may be the deposit velocity of the most easily deposited sizes. Referring to Figure 3, particles in the 400 to 500 μm size range have the largest deposit velocity which is indicative that particles in this size range would be the first to remain stationary as V_m was decreased. To compound the confusion, some experimenters unfortunately have referred to the minimum of the $i_m = fn(V_m)$ curve as the critical limit deposit velocity. However, for settling slurries with centrifugal pumps as prime movers, the conveying velocity is normally well above the deposit velocity in order to maintain operating stability. In spite of the vagaries about the value of the deposit velocity, the flow condition at which a stationary bed is incipient is the lower limit of the regime described as a heterogeneous suspension and is the lower limit of V_m for design of pipelines.

Closely associated with a stationary bed is the concept of the velocity, U_u, at the threshold of turbulent suspension. According to Wilson and Watt 5/,

which $$U_u = 0.6\,V_t \sqrt{\frac{8}{f_f}}\; e^{45(d/D)} \qquad (5)$$

V_t = terminal settling velocity,
f_f = friction factor of fluid flowing at velocity V_m,
d = particle diameter, and
D = internal pipe diameter.

The predominant variable on the right side of equation 5 is V_t. The less significant variables $\sqrt{8/f_f}$ and the exponent 45d/D, are measures of turbulence intensity and scale, respectively. Subjectively, equation 5 is rational.

Physical interpretations of deposit and suspension-threshold velocities are easier from graphs such as shown in Figure 4.

Figure 4. Deposit and suspension velocities

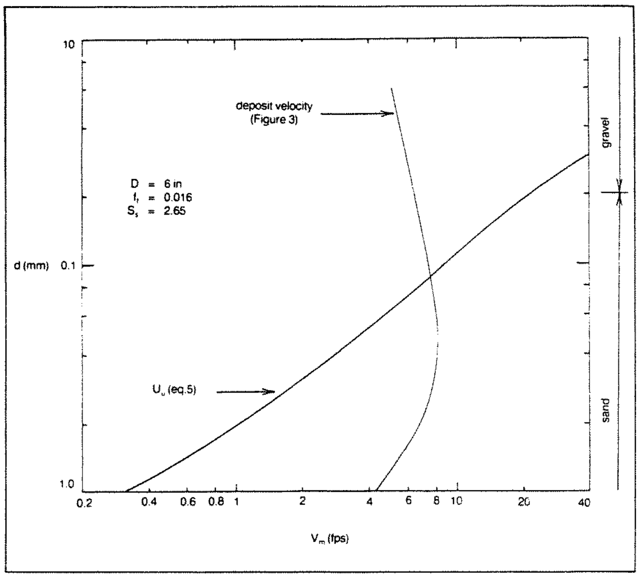


Figure 4 shows (1) the smallest gravel will not move as suspended load, (2) that 1 to 2 mm sand can be moved as bed load, (3) for material finer than 0.9 mm a stationary bed will form if $V_m <$ deposit velocity, (4) with sands smaller than 0.9 mm and $U_u < V_m <$ deposit velocity some of the sand will reside in the stationary bed and some carried as suspended load, and (5) if $V_m < U_u$ and deposit velocity, a full bed will exist.

Wilson and Clift used the concept of a stratification ratio R and the threshold of turbulent suspension to show the total excess friction pressure gradient $(i_m - i_f)$ is

$$\frac{i_m - i_f}{S_{md} - 1} = BR + A' \, i_f (1 - R) \qquad (6)$$

where the stratification ratio $R = \left(\frac{U_u}{V_m}\right)^n$ (7)

and A' and B are properties of the slurry
S_{md} = specific gravity of the delivered mixture
i_f = pipe friction due to carrier liquid only.

By considering flow only in the heterogeneous region and replacing the values of B and U_u with a value U_u' derived from a large number of laboratory test results, the above can be simplified to

$$i_m = i_f + (S_{md} - 1) \left(\frac{U_u'}{V_m}\right)^{1.7} \qquad (8)$$

where values of U_u' for different mean sizes of clean solids is shown in Chart 4. The form of equation 8 is the inverted parabola shown in Figure 1. The minimum friction point is the lowest velocity, V_{min}, for stable operation. The first derivative of equation 8 provides a means of directly determining $V_{min\ stable}$.

Chart 5 has been derived from the first derivative of equation 8 and provides a means of estimating the lower limit of V_m for stable operation in terms of a given mean size of typical slurry solids, concentration, and smooth pipe ID.

With a pipeline design velocity, V, derived from Chart 5 plus some suitable safety margin, the pipe friction due to the carrier liquid may be found using Chart 6 (for the GIW Slide Rule), and the pipe friction due solids may be found using Chart 7.

The total pipe friction converted into feet of slurry per 100 ft of pipe may then be found using Chart 8.

The specific energy consumption (SEC) for the resultant pipe friction and design concentration can be determined by using Chart 9 and Chart 2. If the pipe diameter and/or concentration of the system can be altered, then the previous exercise should be repeated with different pipe sizes and concentrations to determine the minimum SEC. Capital cost considerations may need to be included into this evaluation.

Finally, calculate total system friction by multiplying by the system length in 100 ft and adding elevation change with all units in feet of slurry.

Values found using the above should provide good estimates of minimum pumping velocity and pipe friction.

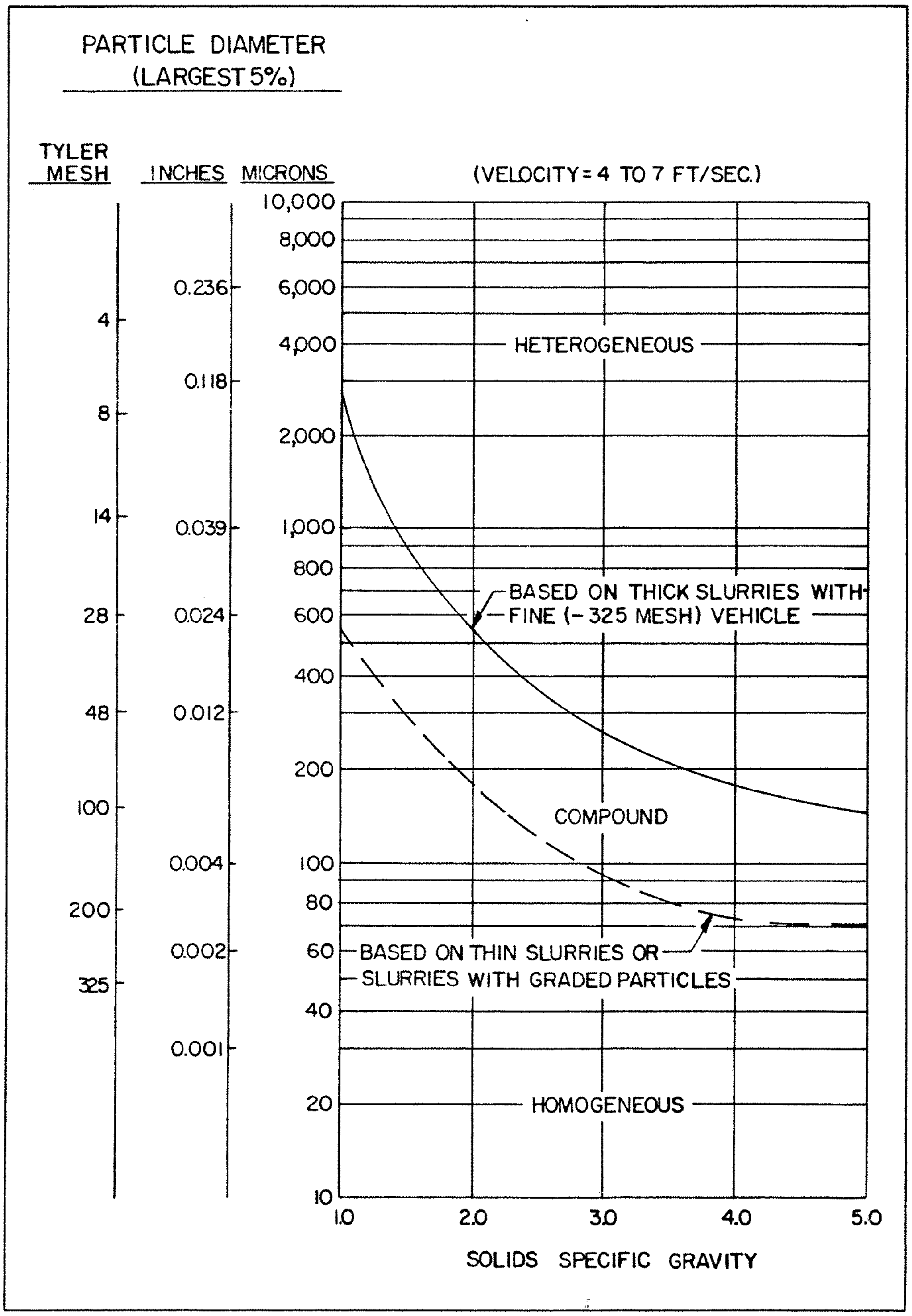
The values of U_u shown in Chart 1 are based on clean, uniformly sized slurries in range 150 to 1000 micron mean size. The presence of material sizes different from those tested will modify the results given by the above. In particular, where overall sizing is above 1000 micron, care should be taken to allow for the significance of the $e^{45(d/D)}$ term in equation 5 and where size distribution includes small proportions of clays or fines, a decrease in pipe friction should be expected.

Centrifugal pump selection is made by assuming that the head in feet of slurry produced is the same as that produced on water, less a solids effect for the particular size slurry and concentration.

For smooth operation the net pump head must equal the total system head. To achieve this, it may be necessary to adjust the net pump head by varying the pump speed or impeller diameter.

G.R. Addie
September, 1982

CHART 1



SLURRY FLOW REGIME (HETEROGENEOUS, HOMOGENEOUS) IS A FUNCTION OF SOLIDS SIZE AND SPECIFIC GRAVITY.

CHART 2

BASIC EQUATIONS FOR MIXTURES OF WATER AND SOLIDS

$$Sm = 1 + \frac{Cv}{100}(S-1) = \frac{1}{1 - \frac{Cw}{100}\left(\frac{S-1}{S}\right)} = \frac{100-Cv}{100-Cw} = \left(S\frac{Cv}{Cw} = Sm\right) *$$

$$Cw = \frac{100S}{\frac{100}{Cv} + (S-1)}$$

* THIS EQUATION HOLDS FOR MIXTURES OF SOLIDS AND ANY LIQUID

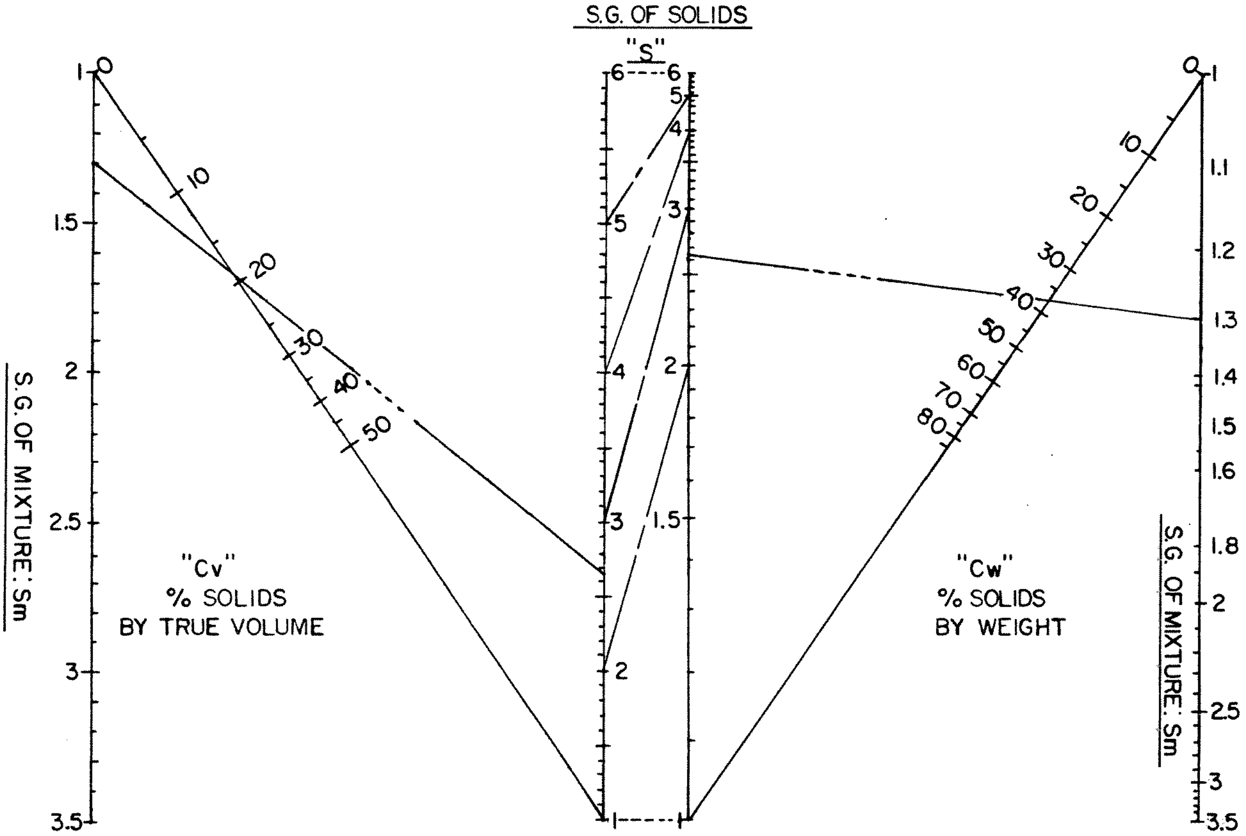
WHERE :

S = S.G. OF SOLIDS

Sm = S.G. OF WATER – SOLIDS MIXTURE

Cw = % SOLIDS IN MIXTURE BY WEIGHT

Cv = % SOLIDS IN MIXTURE BY TRUE VOLUME



DENSITY CONCENTRATION NOMOGRAMS FOR SOLIDS-WATER MIXTURES

CHART 3

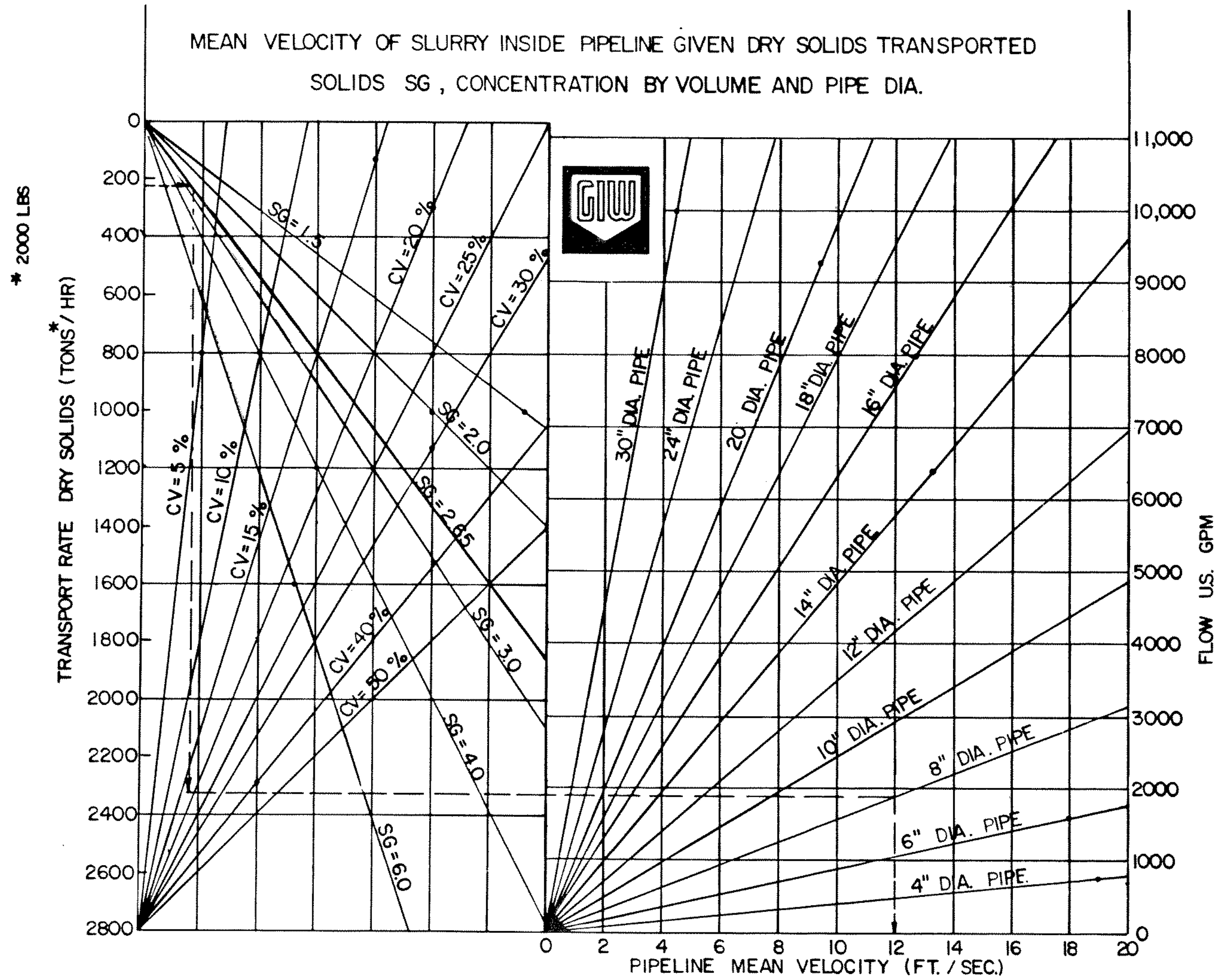
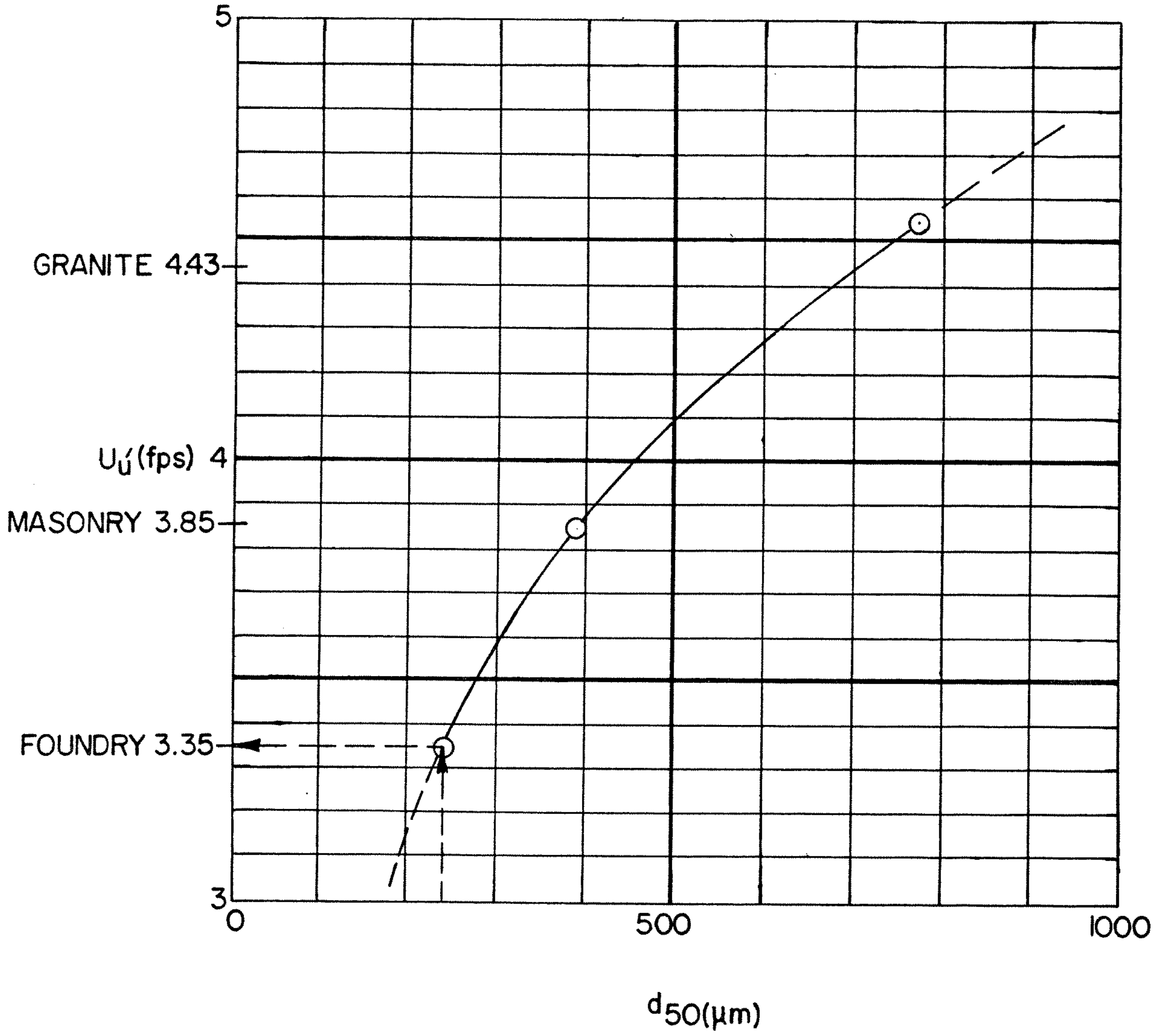
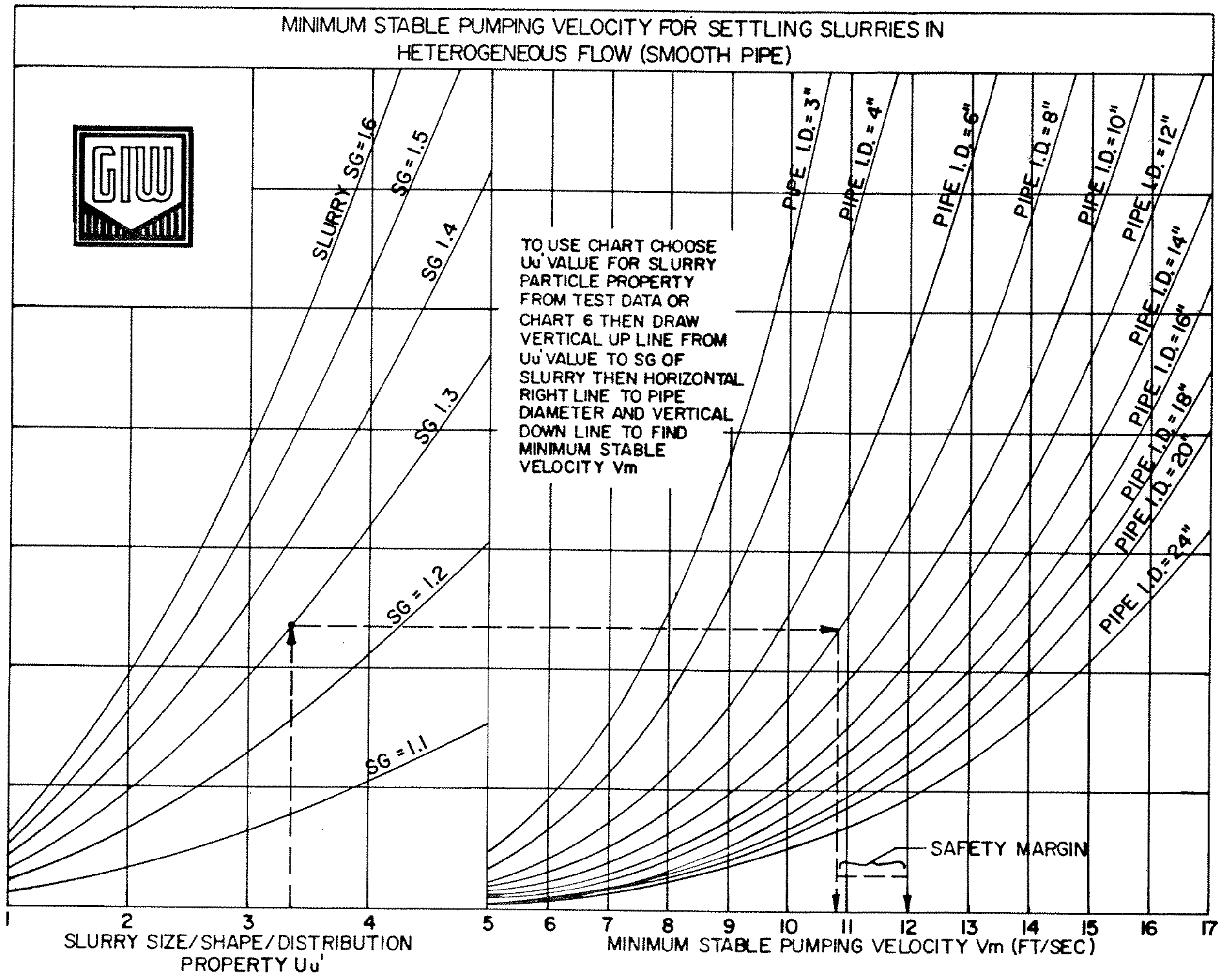

MEAN VELOCITY OF SLURRY INSIDE PIPELINE GIVEN DRY SOLIDS TRANSPORTED
SOLIDS SG , CONCENTRATION BY VOLUME AND PIPE DIA.
* 2000 LBS
TRANSPORT RATE DRY SOLIDS (TONS* / HR)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
SG=1.5
SG=2.0
SG=2.65
SG=3.0
SG=4.0
SG=6.0
CV=5 %
CV=10 %
CV=15 %
CV=20 %
CV=25 %
CV=30 %
CV=40 %
CV=50 %
GIW
30" DIA. PIPE
24" DIA. PIPE
20 DIA. PIPE
18" DIA. PIPE
16" DIA. PIPE
14" DIA. PIPE
12" DIA. PIPE
10" DIA. PIPE
8" DIA. PIPE
6" DIA. PIPE
4" DIA. PIPE
11,000
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
FLOW US. GPM
0
2
4
6
8
10
12
14
16
18
20
PIPELINE MEAN VELOCITY (FT. / SEC.)

CHART 4



VALUES OF U_u' OF SAND WITHOUT
ANY SILT OR CLAY COMPONENT

CHART 5



MINIMUM STABLE PUMPING VELOCITY FOR SETTLING SLURRIES IN HETEROGENEOUS FLOW (SMOOTH PIPE)

TO USE CHART CHOOSE Uu' VALUE FOR SLURRY PARTICLE PROPERTY FROM TEST DATA OR CHART 6 THEN DRAW VERTICAL UP LINE FROM Uu' VALUE TO SG OF SLURRY THEN HORIZONTAL RIGHT LINE TO PIPE DIAMETER AND VERTICAL DOWN LINE TO FIND MINIMUM STABLE VELOCITY Vm

CHART 6

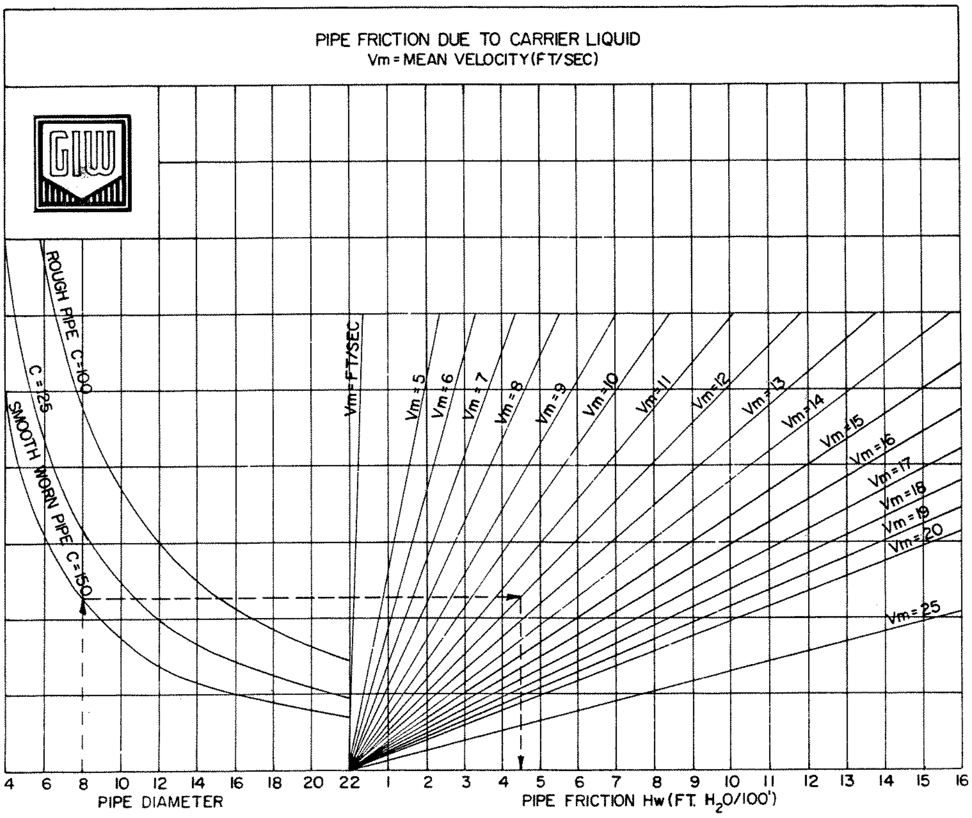


CHART 7

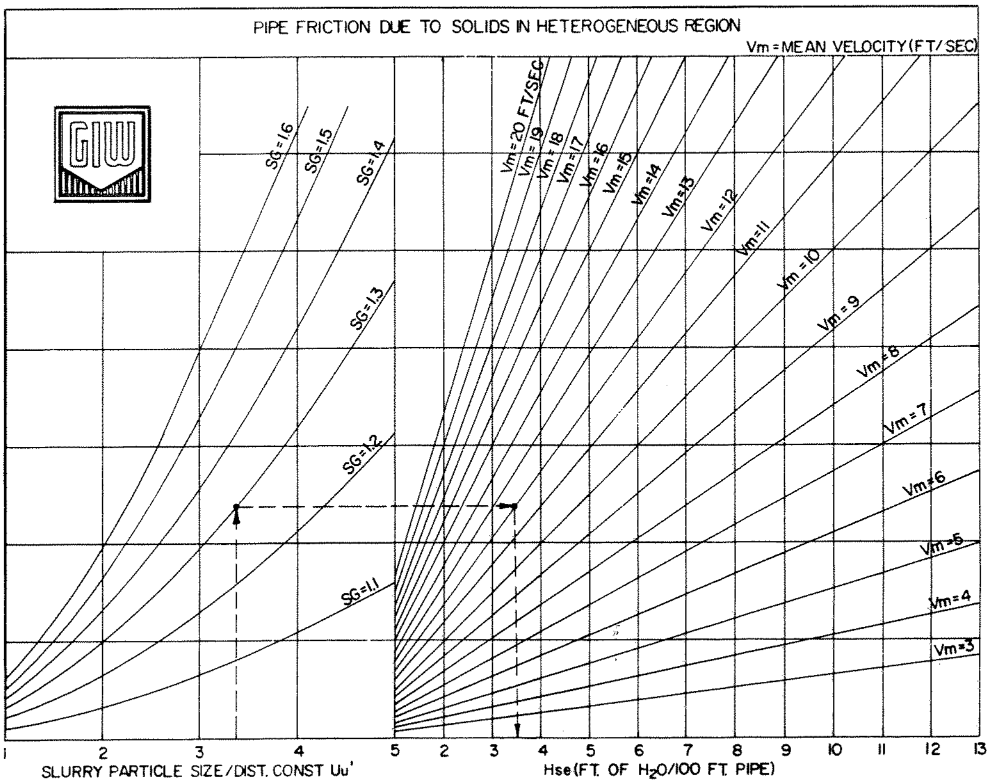
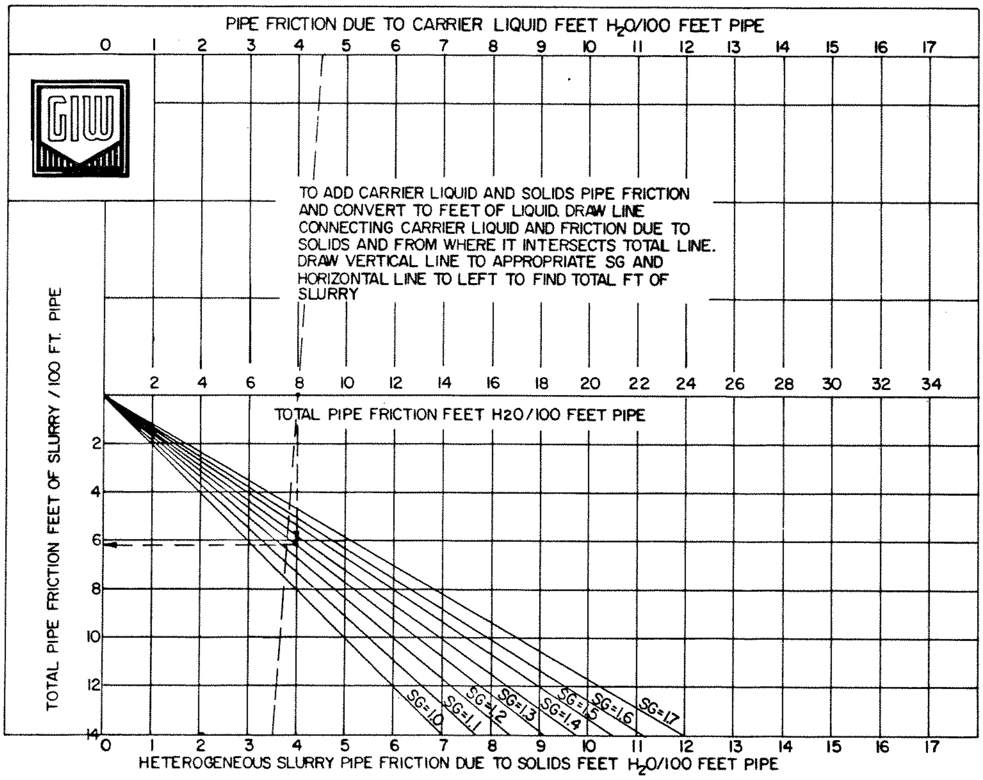


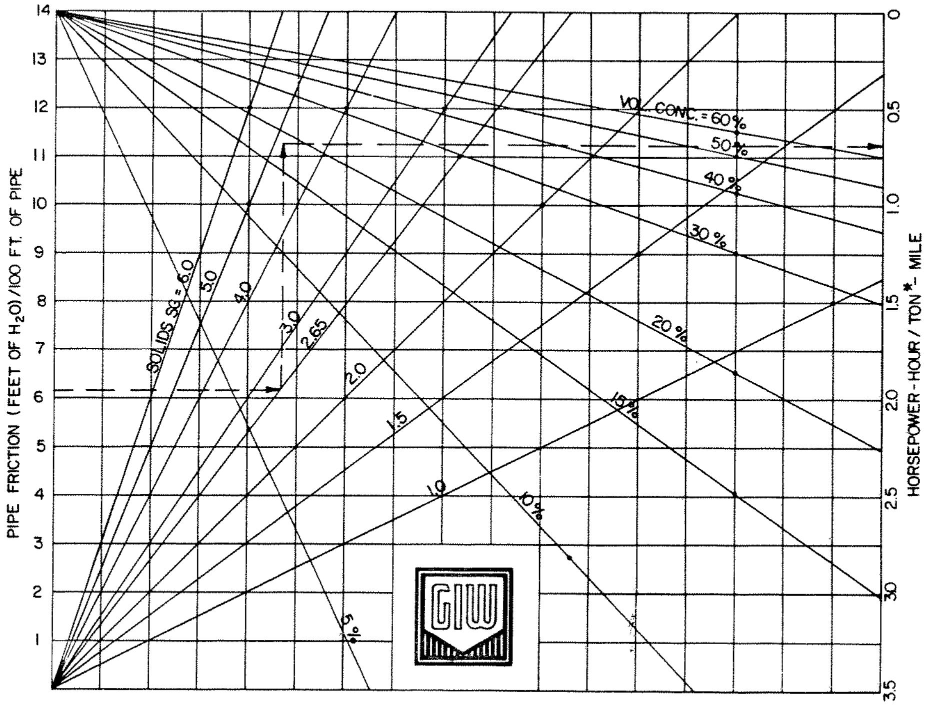
CHART 8



TO ADD CARRIER LIQUID AND SOLIDS PIPE FRICTION AND CONVERT TO FEET OF LIQUID. DRAW LINE CONNECTING CARRIER LIQUID AND FRICTION DUE TO SOLIDS AND FROM WHERE IT INTERSECTS TOTAL LINE. DRAW VERTICAL LINE TO APPROPRIATE SG AND HORIZONTAL LINE TO LEFT TO FIND TOTAL FT OF SLURRY

CHART 9

SPECIFIC ENERGY CONSUMPTION (SEC)



REFERENCES

A. Specific

1. R. Clift, K.C. Wilson, G.R. Addie, and M.R. Carstens, "A Mechanistically-Based Method for Scaling Pipeline Tests for Settling Slurries," *Hydrotransport 8,* pp B1-91-101, BHRA Fluid Engineering (1982).
2. G.R. Addie, "Slurry Pipeline Friction Using Nomographs," CIMM District No. 2 Meeting-1982, paper #51.
3. M.R. Carstens and G.R. Addie, "Sand-Water Slurry Experiment," Journal of Hydraulics Division, *Proceedings* of ASCE, Vol. 107, No. HY4, 1981, pp 501-507.
4. K.C. Wilson, "Deposition-Limit Nomograms for Particles of Various Densities in Flow," *Hydrotransport 6,* pp A1-1-12, BHRA Fluid Engineering (1979).
5. K.C. Wilson and Watt, W.E., "Influence of Particle Diameter on the Turbulent Support of Solids in Pipeline Flow," *Hydrotransport 3,* pp D1-1-19, BHRA Fluid Engineering (1975).
6. D.M. Newitt, J.F. Richardson, M. Abbott, and R.B. Turtle, "Hydraulic Conveying of Solids in Horizontal Pipes," *Transactions,* Institution of Chemical Engineers, Vol. 33, 1955, pp 93-113.

B. General

1. R. Clift, J.R. Grace, and M.E. Weber, *Bubbles, Drops, and Particles,* 1st ed., Academic Press, 1978, pp 380.
2. G.W. Govier and K. Aziz, *The Flow of Complex Mixtures in Pipes,* 1st ed., 2nd printing, Robert E. Kreiger Publishing Company, Huntington, New York, 1977, pp 745.
3. V.A. Vanoni (editor), *Sedimentation Engineering,* American Society of Civil Engineers, New York, 1977, 745 pp.

EXAMPLE

To transport 225 TPH of foundry sand slurry of 240 micron D50 size along a horizontal pipeline of 8" I.D.

Chart 1 verifies that the slurry can be treated as a settling slurry.

From Chart 2 slurry sg is 1.3, and concentration by volume is 18%.

From Chart 3 we can also establish that the mean velocity in the pipeline is 12 ft/sec.

Chart 4—U_u value for the slurry is 3.35

Chart 5—minimum stable pumping velocity is 10.8 ft/sec. The 12 ft/sec is a satisfactory pumping velocity since it gives a suitable safety margin.

Chart 6—12 ft/sec in a smooth 8" I.D. pipe, the pipe friction due to the carrier liquid is 4.4 ft H_2O/100' of pipe.

Chart 7—friction due to the solids = 3.6 ft H_2O/100' pipe.

Chart 8—values from Charts 6 and 7 combined and converted into friction loss of 6.15 ft slurry/100' pipe.

Chart 9—specific energy consumption is 0.687 HP-HR/TON mile.

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