SLUDGE HANDLING CHARACTERISTICS IN PIPED SYSTEMS

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ABSTRACT

Depending on the percentage, size and condition of solids; pipe size; and many other factors, sludge flow may exhibit near-Newtonian fluid characteristics, non Newtonian homogeneous, or hetero-homogeneous characteristics. A survey of data for sludge flow characteristics in piping shows the diversity of results expected from the immense possibility of variables. Hazen-Williams or the Fanning equations may be used for friction loss calculations in piping, using factors derived from previously published data, as long as the user recognizes the margin of error possible due to the many variations in sludge content. Vacuum filter cake can be best described in non-Newtonian terminology as "False-Body" and a useful tool appears to be the Power Law relationship of;

$$\Delta P \propto \frac{L\ Q^{n}}{d^{3n+1}}$$

where:

P is friction pressure drop

L is length of pipe

Q is flow rate

d = diameter of pipe

n = power law factor

INTRODUCTION

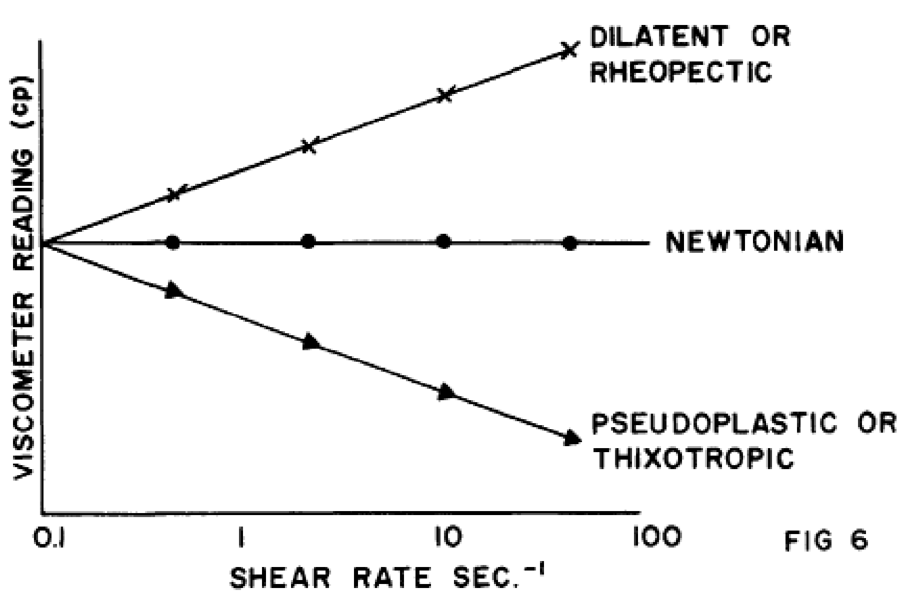
Although flow behavior of most liquids has been mathematically described and empirically verified, similar knowledge about solid-liquid mixtures is not available. Because of the complex nature of solid-liquid mixtures, postulations about their flow dynamics are presently beyond the reach of the most sophisticated computer programs. It has thus become necessary to gain this knowledge through empiricisms. Even though a substantial amount of data is beginning to accumulate, there exist wide variations among the results of different investigators — more as a consequence of the complexity of the phenomena rather than errors in investigation.

The following is a discussion of the various fluid classifications, what complicates the flow calculations, how this applies to sewage sludge, and what can be done to predict its behavior in a pipe.

First, in the terminology of rheologists, is a description of the various types of flow behavior that can take place in a pipe.

The initial classification is into single phase and multi-phase fluids. A layman's definition of a single phase fluid would describe it as a single liquid or a liquid-solids mixture so finely dispersed that it moves as a single liquid regardless of the velocity; i.e., a homogenous mixture. Although this reference is a liquid-solids mixture, it obviously could also be a liquid-gas, or a liquid-liquid mixture.

FIGURE 1

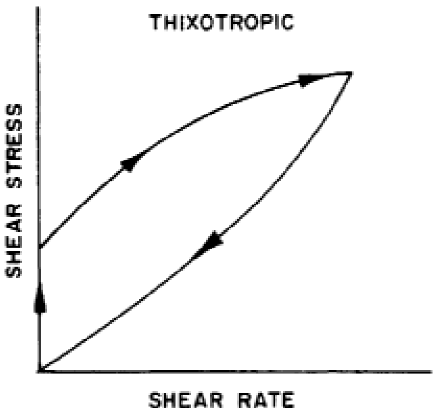


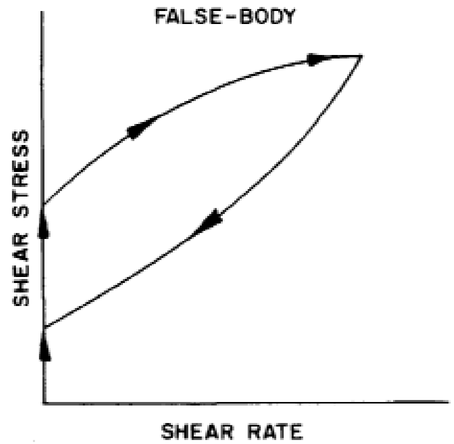
A discussion of the types of single phase fluids and their behaviors would have to start with Newtonian fluids such as water, oil, etc. Here, the rate of shear of the fluid is directly proportional to the shearing stress. The proportionality constant which we call viscosity, doesn't change with velocity or shearing rate. Sludge under low concentrations will often approach this condition.

From there we move into the more commonly encountered phenomena of non-Newtonian fluids . . . those which display pseudoplastic, dilatant, thixotropic, or rheopectic properties. Pseudoplastic and dilatant fluids are time independent. Pseudoplastics drop in apparent viscosity as shear rate or pipe velocity increases, while dilatants increase in viscosity. Dilatant phenomena in slurries to be handled by pipe lines are very uncommon. Certain very high solids contents fluids and filter cakes of calcium carbonate have shown dilatant properties; but, a sewage sludge would seldom, if ever, display those characteristics.

Rheopectic is the time-dependent equivalent of dilatant. Not only does the apparent viscosity increase with an increase in

FIGURE 2





shear rate or pipe velocity; but, apparent viscosity also increases with time, The faster you shear it and the longer you shear it, the most viscous it apparently becomes, as witnessed by the amount of force required.

Were sewage sludge truly homogenous, thixotropic behavior could probably best describe its properties. Thixotropic fluids become less viscous as the rate of shear (or agitation) is increased, and also with the length of time they are agitated or sheared. In those instances where sludge exhibits these tendencies, you would find that even though the velocity in the pipe was the same at two different points, the viscosity of the sludge at one point would be higher at that moment than at the point a mile further down the line, because it has been subjected to the shearing stresses of flow for a lesser time interval. This time-dependency of sludge viscosity is obviously troublesome when it comes to predicting pipe line specifications, or for that matter, laboratory testing. It rules out valid data obtained through recirculation of the sludge. Even laboratory tests performed with uncirculated sludge are of questionable validity; for, if the identical sludge has been transported it is no longer in the same conditions of shear rate and time that it would be subjected to in the system.

The author of a recent technical paper on the subject described that to the best of his knowledge he was keeping all conditions constant and his repeatability was ± 40%. Such research is not only discouraging, but deleterious to the acquisition of further knowledge.

In addition to the above mentioned phenomena of apparent viscosity varying with shear and time, many fluids exhibit a yield stress below which no movement occurs. They exhibit rigidity as force is applied up to a certain degree and then break down exhibiting usually pseudoplastic or thixotropic tendencies. They may be called yield pseudoplastics, Bingham plastics, false bodies, or any other name an author may care to coin. Vacuum filter cake, centrifuge discharge, and other high concentrations of sludge exhibit this characteristic, Although it continues to drop in apparent viscosity with an increase in agitation or shear stress, when at rest a filter cake still exhibits a rigid shape that requires a certain minimum force (though diminished from the original) to make it flow again. In his attempt to categorize different types of thixotropic behavior, Pryce-Jones labeled this phenomenon "false-body" (note Figure 2.)

Probably one of the most convenient formulas for the prediction of non-Newtonian flow is the power law originally proposed by Ostwald. Whereas Newton's law for true fluids stated that the shear stress varied directly as the shear rate, the power law says that for true fluids, pseudoplastic, or dilatant fluids the shear stress varies as the shear rate to the "n"th power. The power factor "n" is equal to 1 for Newtonian or true fluids; is greater than one for dilatant fluids; and, is less than one for pseudoplastic or thixotropic fluids.

Newton's Law of
Fluid Mechanics

$$\tau = \mu \gamma$$

τ = shear stress
γ = shear rate
μ = coefficient of viscosity

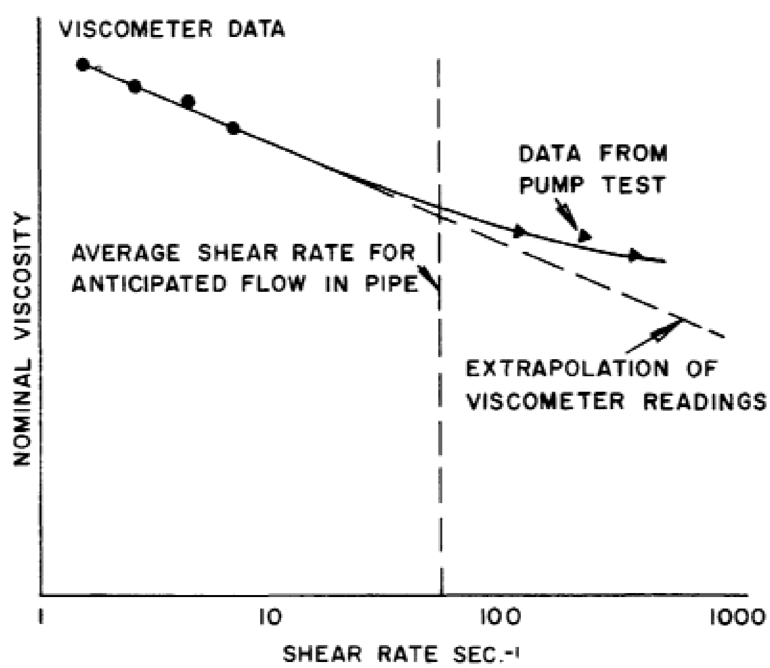
Power Law

$$\tau = K \gamma^n$$

K = consistency constant (K = viscosity when $n = 1$)
n = power law exponent
$n = 1$ Newtonian
$n > 1$ dilatent or rheopectic
$n < 1$ pseudoplastic or thixotropic

The fluid analysis techniques at Moyno over the years have been based primarily on this precept. (Figure 3) Any function raised to a power will produce

FIGURE 3



a straight line on a log-log graph. By plotting viscometer readings (either rotational or capillary or both) on such a curve, one can extrapolate to the nominal shear rate in the pipe and pick off an apparent viscosity that is used in the Fanning equation to estimate pipe friction losses. If sufficient material is available for a pump test, the curve may be verified or altered by adding additional data points. These points are gathered by running what is termed a “cavitation curve”. (Figure 4) Using Newtonian fluids of varying viscosities such as glucose or silicone oils, it is simple to develop characteristic curves of the point of deviation from the straight line capacity vs speed curve and shape of the curve for each true viscosity at a given N.P.S.H. Obviously the higher the viscosity the lower the speed of cavitation. When a non-Newtonian fluid is run under the same conditions, it is usually found that it matches none of the Newtonian curves, but behaves like one viscosity at speed A, another viscosity at speed B, and a third viscosity at speed C. Knowing the average shear rate in the pump at those speeds, we then have additional points to affirm or contradict the slurry’s adherence to the power law; and, additional confidence that the pipe friction calculations will effect a practical degree of accuracy. (Note Figure 4)

Worth showing at this time, is the velocity profile within a pipe for various values of the factor “n”. (figure 5) For a true fluid where n=1, the flow pattern for streamline flow is parabolic with the maximum velocity at the center of the pipe double that of the average velocity. For a dilatant fluid (where “n” is greater than 1) the larger the number, the closer the velocity approaches that of the purely theoretical perfect dilatant where n=∞. That shape is conical rather than parabolic and the maximum velocity at the center of the pipe is three times the average. As mentioned previously this dilatant or rheophetic phenomena (“n” greater than 1) does not exist in any known sewage sludge flow conditions. On the other hand, the perfect pseudoplast, where n=0, would flow as a solid plug, with no difference in velocity from the pipe walls to the center. Even though a perfect pseudoplast could not possibly exist, note that for a pseudoplastic or thixotropic slurry with a power factor “n” equal to 1/3, there is no appreciable difference in velocity over the inner third of the pipe, so the center portion flows as a plug.

Moving back into sewage sludge, how would the various concentrations fit into any of these categories? Vaughn Behn published one set of curves ran with a capillary viscometer that, although it is obviously going to differ with results from other types of sludges, shows at a glance some discouraging facts. (figure 6) Remember, that if the shear stress is proportional to the shear rate to the “n” power when we plot one against the other on log-log curve, we would have a straight line. If n = 1 or the shear varies directly as the rate of shear, the fluid is Newtonian and would have a slope of 1 on the curve or a 45 degree angle. For a perfect pseudoplast, (n = 0), the line would be horizontal, and for a perfect dilatant (n =∞), the line would be vertical. Behn’s curve shows water to have its expected 45 degree slope; and, sludge of 2.8% solids is parallel to it, thereby showing Newtonian tendencies or a constant (although higher) viscosity over a wide shear rate. On this particular sludge a constant multiplier to water curves regardless of pipe sizes and flow rates, is valid for streamline flow up to 3%. However, what happens as the percentage of solids goes over 5%. The line is no longer parallel to water, indicating that the flow is no longer Newtonian and that a constant multiplier to water curves would no longer be accurate. In fact, not only is the line not parallel; but, it is no longer straight. Calculating the “n” factor at various points for 10.5% solids shows a range of almost three to one over the range of velocities or shear rate. So, even the convenient power law calculations do not fit unless used over a relatively narrow range of pipe velocities.

This really wouldn’t surprise anyone with any knowledge of slurry flow; because, as previously mentioned, the relationships really exist for only homogeneous or single phase flows, i.e., slurries that flow at a continuous mass velocity without tendencies to separate or flow at different rates from that of the carrier fluid. This usually exists only when the size of the particles is in the extremely small low micron range. Obviously, sewage sludge doesn’t fit this description. Although there is a portion of the sludge that is fine enough to flow as a homogeneous slurry, there are obviously enough large particles to throw it into the wild, wild world of two phase or heterogenous flow. When you ponder the wide variation in solids density, shape, and size that would normally exist in a sewage sludge, you don’t wonder whether its flow is following the power law, but whether

FIGURE 4

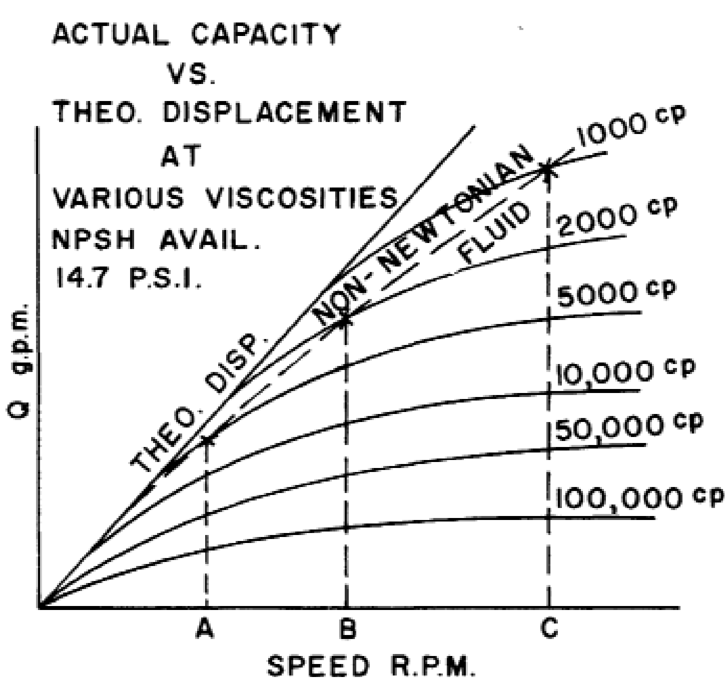
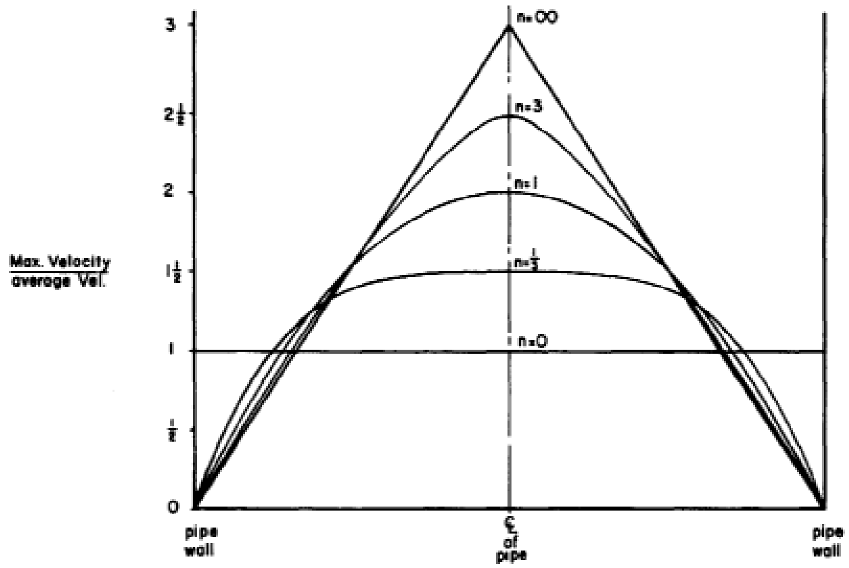


FIGURE 5

Velocity profiles for non-Newtonian fluids.



some of it is flowing at all! The largest particle reported to the author as having flowed through a 6 inch pipe line was a 12 foot extension ladder. The maintenance superintendent who reported it stated that it had to have been pumped through the line since that was the only way it could have gone into his new digestor. The contractor swore he didn't leave it; so, there was no other way to explain it's presence.

The only mention here of the theory of heterogeneous flow is to say, it's obvious that the total energy gradient or head loss for a two phase water slurry would be equal to the head loss for the water alone, plus energy loss as a result of suspended solids. How to calculate this energy loss is where the theorists differ. The number of variables involved are so many that the task of purely theoretical analysis is hopelessly impossible at the present time. Scientists are still working with graded spherical particles, etc, trying not to find out why the solid particles are behaving in a particular manner; but, what is their particular manner of behavior. They're a long way from predicting sludge behavior with high accuracy; but, some of the things that they do find are interesting and applicable. Particles of reasonable density, under 300 microns, tend to flow in suspension while larger particles tend to move downstream faster than the fluid (such as heavy particles flowing down in a vertical pipe). They also migrate and concentrate around the walls of the pipe. When the particles tend to move downstream slower than the carrier, they migrate to the center of the pipe. Buoyant particles with the same density as the carrier flow in a ring surrounding the axis, about half way between the center and the wall of the pipe. A change in the amount of fine particles in suspension changes the fall-out velocity of a coarse particle. A small percentage of fine particles in water actually reduces the friction head loss. Turbid water flows at a greater volume under the same head than clear water. Apparently, in a solution with a very small percentage of flowing solids the particles act as guide vanes and reduce the water turbulence. When you stop to consider that particles are lagging, or leading the fluid, migrating into more concentrated areas, etc., you realize that even the percentage of solids is not constant at every point in your pipe line. In addition, consider the necessity of calculating the energy required to move at certain velocities those particles not flowing with the liquid, but tumbling along either a stationary or sliding bed of concentrated solids settled at the bottom of a horizontal pipe; and, even the most talented rheologist scratches his head.

The state of the art, at present, is that calculations and predictions can be made in two-phase flow with doubtful accuracy, if you can be sure that all of your particles are spheres of the same size and density. A lot of work by very talented scientists continues to go on; and progress is being made. But look at all of the variables in sewage sludge. The particles aren't spheres - - or cubes or discs, but each with a different shape, a different drag coefficient, a different surface to volume ratio, etc. The particle densities vary from lighter than water through hard heavies. The particle sizes vary from fine micron silts to 12 ft. extension ladders. And just when you've had them all completely classified for your particular sludge and begin your calculations, you find that what was a particle yesterday, is a gas bubble today, or has conglomerated into a different shape and density completely.

You can easily see that location of the plant, type of grit removal, type of sludge, mechanical action from preceeding op-

FIGURE 6

SEWAGE SLUDGE VARIABLE SOLID CONTENT

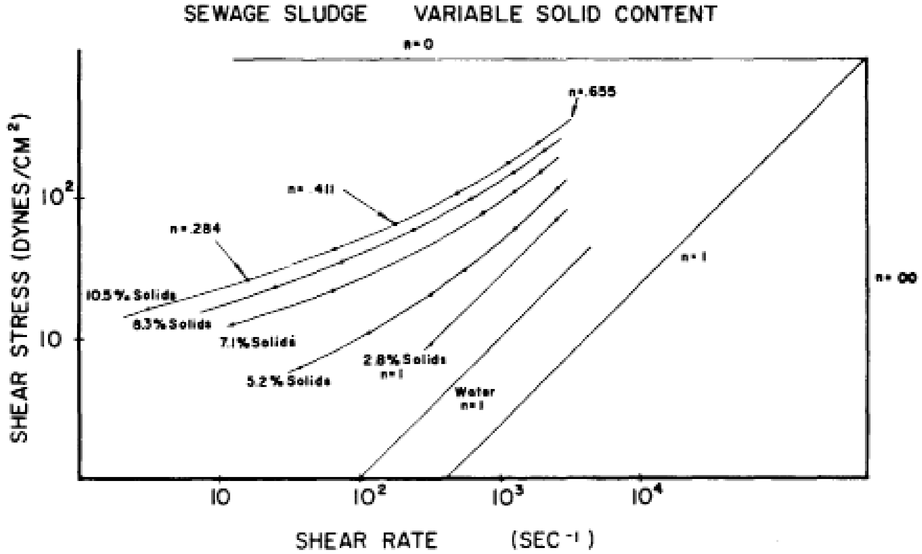
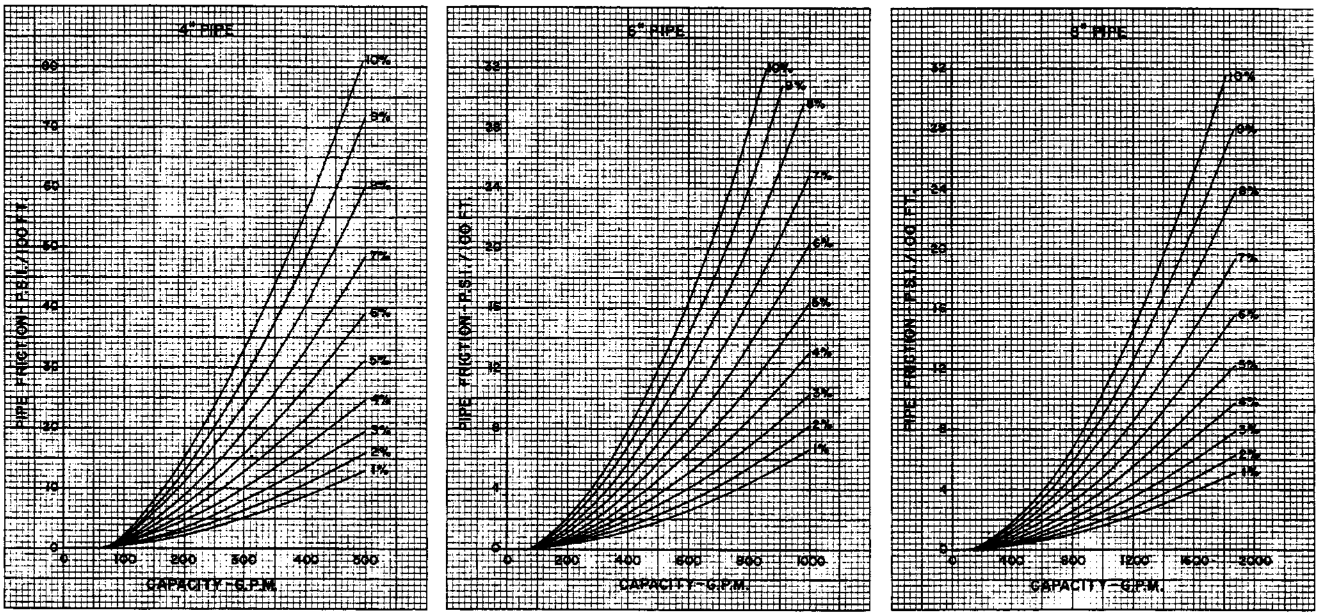


FIGURE 7



eration, chemical treatment and many other variables will change the complete flow characteristics of the sludge. Anyone who says he can accurately predict the action of any sludge in a pipe line is misleading you and himself. What can be done then? Obviously some estimate has to be made. Even laboratory tests tend toward irrelevance. More than one engineer has haphazardly opened a bulged plastic bottle of sludge shipped in from Texas, or where-ever, and discovered that the properties have changed from the time when it was poured into the bottle to the time when he wiped it from his face, clothing, lab walls, ... Obviously whatever method is used to calculate sludge pipe friction losses, it must be empirical and based on past experience with similar sludges at similar flow conditions. This must be with the full realization that the flow characteristics of no two sludges will he exactly the same; and, a sizeable margin of error exists.

Speaking in generalities, sludges below 3% are usually (as mentioned previously) near Newtonian; and, multipliers to water curves for friction loss are valid regardless of the shear rate or velocity. An increase of approximately 25% of the value for water should suffice. When the percent of solids is higher than that, the thixotropic or pseudoplastic properties begin to take over; and, a constant multiplier to water curves is no longer valid. One test indicated 9% sludge to have friction losses of almost 10 times that of water of 1 ft/sec pipe velocity, while the same sludge had only 3 times the friction loss of water at 3 ft/sec velocity. Using our computer and data reported in as many papers on sludge handling as could be found, one of our engineers, Harry Conrad, worked up a series of sludge friction loss tables or curves for 4", 6", and 8" pipe (figure 7), plotted by percent of solids for sludge bands varying from raw through complete digestion.

CONCLUSION

The wide range of possible solid-liquid mixture makes it very unlikely that information about the friction loss of a particular mixture will be listed in some book or table. But consolidation of available data complemented by good judgement and a reasonable safety factor should enable any competent engineer to obtain reliable estimates.