ECONOMIC TRANSPORT OF DIGESTED SLUDGE SLURRIES

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The handling and disposal of digested sludge is frequently described in the literature as one of the more onerous tasks for the operator of the conventional wastewater treatment plant. It is also expensive, particularly in plants using vacuum filtration and incineration and operations associated with these steps. An idea of the costs per dry ton for filtration and incineration may be obtained from the literature (1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11). These costs, including capital costs, operating and maintenance expense, and administrative overheads, are given in Table I.

A less expensive conventional method of sludge disposal is the sludge drying bed. This practice, although still widely used, has fallen into disfavor for several reasons: (*a*) the cost of land directly adjoining and available for treatment plants is commonly considered excessive; (*b*) the fertilizer values of the sludge solids are ordinarily insufficient in comparison to commercial nitrogen-phosphate fertilizers for economical drying and truck haulage over even short distances; and (*c*) public relations problems may arise. Another method, sludge lagoon disposal, suffers from land cost and especially from public relations factors, although it too is lower in cost than filtration plus incineration.

This paper concerns a different approach to sludge disposal and one which is expected, where applicable, both to reduce costs of wastewater treatment and also to make beneficial use of sludge slurries. The concept is a combination of established technologies or practices and includes the transport of digested sludge slurries by pipeline and their use on strip mines and other land areas difficult to revegetate. The established arts and techniques of producing digested sludge, of using digested sludges to promote growth of organic plants, and the potential cost savings of transport of many kinds of solids in pipes are all previously described; it is the combination of ultimate cost reduction to the wastewater treatment operation and the beneficial use in land reclamation at the pipeline terminus that is novel.

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History of the Project

In 1964, the U. S. Public Health Service was approached with the suggestion that economic transport of digested sludge slurries by pipeline to strip mines and other areas difficult to reclaim should be studied seriously for its potential economic benefit to water pollution control and abatement effects. The proposal emphasized primarily an effort to reduce the overall costs of disposing of digested sludges and thereby the costs of wastewater treatment, but included specifically the equally important resulting provisions of an economical and effective means of land restoration.

Reclaiming and restoring stripped land areas to vegetative cover also constitute water pollution control because erosion and often acid water production cease when these areas are reclaimed. There are, according to the Department

TABLE I.—Disposal by Filtration and Incineration

Population Served	Cost* ($/dry ton)
100,000	60–90
500,000	50–75
1,000,000	30–50
2,000,000	25–40

*Activated sludge plants.
Note: $/ton ÷ 0.9 = $/metric ton.

of the Interior, over 2 mil acres (800,000 ha) of stripped areas requiring some remedial reclamation (12) with an additional 150,000 acres (60,000 ha) being stripped annually in expanding commercial activity. Some of these areas do not easily support organic plant growth and restoration aid must be provided.

The study included demonstration of the effectiveness of digested sludge slurry in reclaiming strip mine areas, but more importantly was pointed to the economics of pipeline transport of the material over considerable distances. Population centers, where the great quantities of digested sludge slurry are produced, are often many miles from stripped areas.

Design Considerations

Large cities—those with populations greater than about 1.5 million—produce relatively large quantities of sludge slurry daily, and so the design of pipelines for economic, continuously operated transport is reasonably conventional. Smaller cities generally produce so little slurry that economic design for transport in small pipes, perhaps under 4 in. (10.2 cm), is somewhat more of a challenge. The design is influenced also by the flow characteristics of digested sludge slurry.

The most prominent literature concerned with the flow of digested sludge slurries in pipes is either empirical and intended for in-plant, very short-length slurry movement, or related to large [about 6-in. (15.2-cm) diam] pipe sizes. There are relatively few references emphasizing either small-diam pipes or long-distance transport, or transport at optimum overall economic cost. Digested sludges are described (13) (14) (15) (16) (17) (18) (19) (20) (21) (22) (23) (24) as exhibiting both plastic or Bingham fluid characteristics as well as non-Bingham, or Newtonian, flow characteristics; below about 5 percent solids the flow behavior is Newtonian. As solids concentrations increase beyond 5 or 6 percent, the plastic nature increases; at 30 percent solids, as in filter cakes, sludge can be handled with a common pitchfork, as treatment plant operators well know.

The change in fluid characteristics with change in solids concentration is of fundamental importance to economic pipeline design. Below 5 percent solids concentration, the economics of sludge slurry transport will resemble water transport costs with respect to fluid friction and power requirements. Costs of transport will increase in roughly inverse proportion to the solids concentration from 0 to 5 percent solids. It should be noted that there is no operational difficulty in handling reduced solids concentration. A reduction in solids concentration will only increase the area of disposal or reclamation land flooded at any given time period; subsequent applications would then be necessary to put down the quantity of sludge solids required per acre of land for reclamation purposes. The only economic penalty to be paid is the cost of transporting excess water.

It is considered that optimum-cost design calls for operation at a solids concentration just within the upper limits for Newtonian flow.

Other design considerations include operation at velocities permitting turbulent flow. Turbulent flow is desired to keep the variety of settleable solids in digested sludges in suspension. It is worth reiterating that proposed pipeline operations must be able to accommodate variable materials. Not only

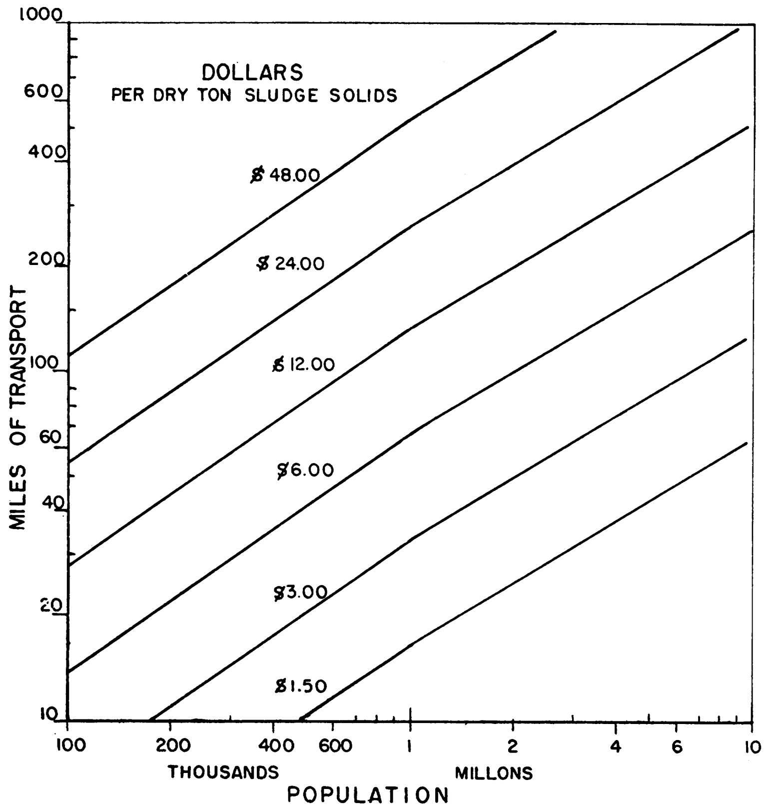

FIGURE 1.—Transportation costs per dry ton sludge solids. ($/ton ÷ 0.9 = $/metric ton; miles × 1.6 = km.)

may wide variations in solids concentration exist above and below a desired 5 percent concentration, but also a variety of tramp materials may have to be accepted. In this sense, design for optimum economics has interesting limitations.

The distances involved in transport of sludge slurry for reclamation or disposal may be as short as 1 mile (1.6 km) or less, or as long as 100 to 200 miles (160 to 320 km). Criteria include the availability of land areas to undergo reclamation and the quantity of sludge available. Shorter distances may be involved if the slurry is simply to be disposed of and used on existing farm land or other verdant land, but in the main it is expected that these slurries will be used in restoration work. Transport costs have been estimated for distances over which slurries might be economically transported (25), attempting to take into account major population centers, the major stripped and disturbed land areas, and the transport of slurry in the 5 percent solids concentration Newtonian flow region. In the absence of data evolved for sludge slurry transport, capital costs published by the oil pipeline industry (26) were used. Figure 1 gives these cost, distance, and population estimates. It seemed wise in preparing this paper to assume higher capital and other costs for the near term until operating experiences were obtained with a number of these pipelines, and a 50 percent cost increase is shown in Figure 1 over the estimates of earlier reports (27).

Experiment Results

To demonstrate that small-diameter pipes may be used to transport digested

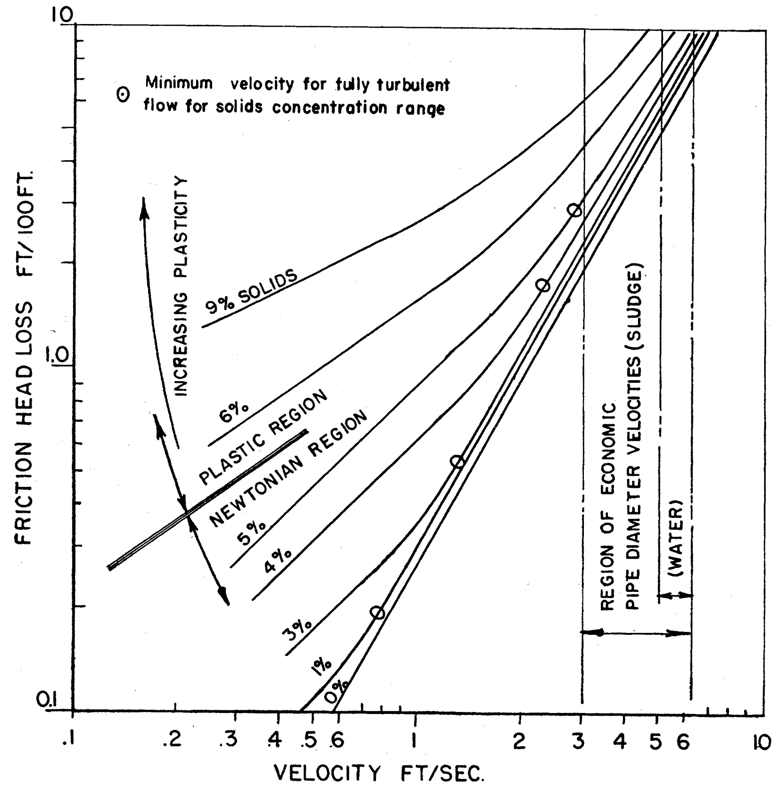

FIGURE 2.—Stylized diagram of influence of solids concentration of sludge slurries on minimum velocities at which fully turbulent flow is achieved. (Fps × 0.305 = m/sec.)

sludge slurries and to provide data from which to predict the economics of such pipeline transport, a series of experiments was conducted. Using a number of digested sludge slurries from different wastewater treatment plants in and around Cleveland, Ohio, a fluid friction loss over a range of solids concentrations and velocities in 1.5- and 2-in. (3.8- and 5.1-cm) diam pipes was determined. Figure 2 (25) is a presentation of friction head losses and velocities for varying sludge concentrations, compared to water. The figure illustrates that digested sludge slurries exhibit plastic flow at concentrations above 5 percent and Newtonian flow below this concentration. Chou (16) predicted 4 percent for this solids level. Chou's prediction and the findings of those conducting these experiments may be demonstrated conveniently with a simple hydrometer; concentrated sludge is diluted until zero yield properties are exhibited as the float is gently raised and lowered. At the solids concentration at which plastic properties are lost, reproducible specific gravity readings are obtained; above that concentration the range between readings indicates the plasticity levels. The figure also indicates the economic transport velocity range for water, taken from the literature (11).

As the solids content in digested sludge slurry increases from 0 to about 5 percent, the velocity or flow rate at which the transition from laminar to turbulent flow occurs also increases. Up to about 4 percent, the transition is relatively abrupt. Above 5 percent, the transition is gradual. The data ndicate that for sludges having solids concentrations of about 5 percent and in small-diameter pipes, turbulence occurs approximately at velocities at which water is economically pumped.

For solids concentrations above 5 percent, the friction head losses to be suffered in operating in the turbulent range are such that despite the reduced volume of material to be transported, dilution provides economic advantage. This seems to be a valid conclusion for pipe diameters below 10 in. (25.4 cm). In large-diameter pipes, even plastic sludges will become turbulent in the region of accepted economic velocities, and head losses will be comparable to those found in pipelining conventional watery slurries. In wastewater treatment practice, this will mean pipelines will be built to serve only the very largest cities, or pipeline networks will be built to serve a number of contributing districts.

Large-Scale Use

Table II shows the various pipe sizes that can carry the digested sludge slurries from various population levels and related quantities of dry materials conveyed. The table assumes a 5 percent solids sludge slurry being transported at 4 fps (1.2 m/sec), but does not represent specific recommendations.

The predicted pipeline transport costs shown in Figure 1 may be compared to costs incurred today in wastewater treatment plants.

Example 1

A municipality of just over 2 mil persons, treating its wastewater by conventional secondary means and producing about 590,000 gal (2.2 mil) of about 5 percent digested sludge slurry daily can, it is estimated, pump its slurry a distance of 100 miles (160 km) and simply dispose of it at a cost of about $6/ton ($6.70/metric ton) of dry solids. This cost does not include beneficial application of sludge as a restoration aid. The total estimated cost of transportation and constructive application of the sludge in land restoration purposes is estimated to total about $7.25/dry ton ($8.10/metric ton). This cost estimate includes interest and depreciation on capital investment, operating and maintenance costs, utilities, labor, and supervision. This total cost compares to an expense in the order of $35/dry ton ($39/metric ton) to vacuum filter and incinerate the sludge solids.

TABLE II.—Design Data

Population Served	Nominal Pipe Size (in.)	Approximate Annual Dry Sludge Solids (tons)
100,000	1–1.5 ⎫ design	1,600
500,000	2.5–3.5 challenge	8,000
1,000,000	4 marginal	16,000
2,000,000	5	32,000
3,000,000	6	48,000
4,000,000	8	64,000

Note: In.×2.54 = cm; tons×0.9 = metric tons.

The pipeline would be 8 in. (20.3 cm) in diam. The velocity would be in the order of 2.6 fps (0.78 m/sec) for 5 percent (or less) solids concentration to minimize solids settling and also to reduce power costs. A number of booster stations are indicated, and the total working head might be of the order of 15,000 psi (1,050 kg/sq cm), depending in part on the terrain traversed.

Example 2

A municipality of about 200,000 people, treating its wastewater by conventional means and producing some 33,000 gal (125,000 l) of about 8 percent/day digested sludge slurry could, it is estimated, pump its slurry a distance of 40 miles (65 km) and dispose of it at a cost of about $11/dry ton ($12/metric ton) of solids. To transport and use the slurry as a restoration aid would total, it is estimated, about $15/dry ton ($17/metric ton). Alternatively, the municipality would incur an expense of approximately $60/ton ($67/metric ton) to vacuum filter and incinerate the sludge solids.

Taking overall capital costs into consideration, the pipeline would be most economical if it were 2.5 in. (6.3 cm) in diam. The velocity of the slurry through the pipe, diluted to 4 percent solids concentration, would be chosen to be about 3.0 fps (0.9 m/sec) both to minimize solids settling and also to reduce power costs. The total working head would be of the order of 2,500 psi (105 kg/sq cm). Booster stations would probably be used.

Cost Allocation

Throughout this work, and in cost estimates prepared in reports to the sponsors (25), we have placed the total cost of transport and subsequent application of the digested sludge slurry for land reclamation on the wastewater treatment plant operation. Ultimately, some sharing of the costs may be made. A further "savings" results as a side benefit as barren lands are restored to useful productivity and as the pollutional effects they sometimes create are eliminated from the environment. Although these cost reductions are all real, those conducting these experiments have not attempted to evaluate them, pending broad acceptance of the concept of pipelining digested sludge slurry for use in reclamation.

Pilot Operation

At present we have under construction a 2-in. (5.1-cm) diam experimental steel pipeline to carry digested sludge slurry produced in a new conventional primary treatment plant serving Morgantown, W. Va., to a strip mine area 4.5 miles (7.2 km) away. In this pilot operation it is expected to learn more about a number of interesting aspects of the flow of digested sludge slurries in small-diameter pipes, although the main purpose of this project is development and innovation, rather than research. The line will be instrumented with pressure and temperature sensors and continuous flow and solids-concentration recording. The facility will store sludge slurry produced at about 14 percent solids concentration and will be provided with dilution tankage so that a broad range of solids concentrations may be studied. Practical problems that may be expected in the field, but that do not show up in a laboratory friction head loss determination pumping apparatus, will have to be dealt with should they develop. Of particular interest is the pumping system itself; overall pressure losses in this 2-in. (5.1-cm) line as high as 1,000 psig (70 kg/sq cm) are expected at some velocities. There seems to be no previous experience of this nature for digested sludge slurry pumping for pipeline transport, and it will be interesting to observe pump behavior in this pilot installation. Procedures to assure uninterrupted long-time service flow must be developed, if and as required. Special attention will be given to developing the least expensive techniques required to maintain low friction-head losses.

Land Reclamation

A few comments concerning land reclamation using digested sludge slurry are in order. Digested sludge slurries have been applied to spaces of about 14 different acidities—the overburden in strip mining as well as land exposed in roadbuilding and similar operations. These applications have confirmed long-accepted knowledge that digested sludges will assist plant growth by extending this knowledge to deliberate use on highly acidic soils. As the slurry dewaters by percolation and evaporation, the resulting higher solids cake characteristically cracks. These crevices provide excellent conditions for the germination of seeds of grasses, legumes, and trees. Dried sludge is in effect a low-grade topsoil providing moisture and nutrients. After getting a start in the sludge, plant roots penetrate into even the most acidic soil thus far restored to pH 2.3. Restoration has been demonstrated by self-germinated plant growth after 2 yr. It was confirmed also, the literature (28) (29) (30) (31) reports, that digested sludge may be used with no hazard to public health or convenience as long as sensible precautions are taken to place it and retain it where it is wanted, and as long as groundwater or surface water are not directly influenced. In this instance, the physical properties of high solids-concentration sludge are a plus factor; drying and even dry sludge resists erosion and unpredictable movement.

Conclusions

The major purpose of this continuing investigation of the pipelining of digested sludge slurries is the reduction of the cost and operating difficulties involved in handling these slurries within conventional wastewater treatment plants. Pipeline transport to disposal areas located even at considerable distances from the generating treatment plant may offer the wastewater plant operator substantial economic benefits. The distance over which the digested slurry may be transported at a cost savings is related to the quantity being generated and also to the solids concentration at which the slurry is pumped, among other variables.

This work has confirmed that digested sludge slurries vary in flow behavior as a function of solids concentration. At solids concentrations above 5 percent they behave as Bingham plastics, while below 5 percent their flow behavior is Newtonian. Pipelining in the Newtonian region, although dilution of the slurry to such concentrations may be necessary, should be the most economical procedure despite the increased volume of material to be transported. Even where dilution is practiced, the quantity of digested sludge available from many wastewater treatment plants dictates the use of pipelines perhaps as small as 2 in. (5.1 cm) in diam.

A further purpose of this work is to encourage the use of digested sludge slurry in the reclamation of land areas in need of revegetative assistance, and in particular, those strip mine areas or similar land areas that constitute water pollution problems in themselves.

Each of these aspects of this work is well known—the production of digested sludge slurries, their use to grow crops or other organic plant life, and the pipeline transport of solids as slurries. The particular combination of these practices and techniques described here will be of special interest to the water pollution control industry. At least one large American city is planning to transport digested sludge slurry 50 miles (80 km) and utilize it on farming land, using some of the data developed and costs predicted in the course of the project described in this paper.

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