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THICKENING OF SLUDGES**

The excent to which sludges are thickened has a significant influence on the overall cost of sludge treatment and disposal. Yet, rational approaches to the design and operation of thickeners to accomplish an optimal degree of thickening have not traditionally been implemented. The purposes of this paper are to review basic thickening concepts and to illustrate that appreciable cost savings may be realized by avoiding the use of conventional, arbitrary, design loadings for thickeners. Instead, thickeners should be designed to achieve a degree of sludge concentration which, in concert with other sludge treatment processes, minimizes overall sludge treatment and disposal costs.

1. INTRODUCTION

Thickening inevitably is involved in all schemes for treatment and disposal of sludges. Often, separate thickeners are used to reduce the volume of sludge contributed by wastewater treatment processes prior to subsequent sludge treatment and disposal. However, even if a separate thickener is not provided, thickening is still involved in sludge treatment and disposal schemes. This is because facilities which separate solids from the wastewater treatment process and divert them to sludge handling and disposal facilities normally involve use of sedimentation basins. Such basins serve to clarify wastewater prior to discharge and, indeed, frequently bear the name "clarifier". In addition to accomplishing clarification, these sedimentation basins also are expected to concentrate or "thicken" the solids separated from the wastewater. The concepts of thickening discussed in this paper relate as much to the thickening function of sedimentation basins as to thickening occurring in separate sludge thickeners. In either case, clarification also is going on and must be considered in the design.

In spite of the frequent use of separate thickeners in sludge treatment and disposal schemes, as well as the more common occurrences of thickening within sedimantation basins, the design and operation of such facilities has not usually been accomplished on a rational basis. Thickeners

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** The author has continued work on integration of thickeners with other processes for sludge management. Recent results are summarized in Dick et al., 1982.

ordinarily have been designed using arbitrary design standards with a little consideration being given to the perfomance which should be anticipated or to the possible benefits of constructing a thickener of different size. In design, the interaction of thickeners with other treatment and disposal processes has not been rationally evaluated either. Yet, because the performance of thickeners influences the performance of other processes, some optimal degree of thickening must be appropriate for each particular sludge and sludge treatment and disposal scheme. Similarly, those charged with the operation of thickeners usually have not explored, on a rational basis, the manner in which their facilities should be operated to make optimal use of the installed thickener capacity.

The technology for making rational assessments in the design and operation of thickeners would seem to be available. The purpose of this paper is to review those concepts and to show their utility in design and operation of wastewater treatment facilities. To do this, thickening theory will be briefly reviewed, the interactions of thickening with other sludge treatment and disposal processes will be discussed, and the economic implication of these interactions will be illustrated.

2. THE RATIONAL ANALYSIS OF THICKENER PERFORMANCE

Rational bases for design of thickeners and for analyzing the performance of existing thickeners have been presented and reviewed elsewhere [4] and the concepts will only be capsulized here. The following discussion is oriented to gravity thickeners, but to applicable to flotation thickeners by substituting the rise rate for the settling velocity and reversing the direction of the movement of tank contents due to sludge removal.

The basic concept in thickener design is to provide sufficient area so that the solids loading per unit area per unit time (the applied flux, ordinarily expressed as $kg/m^2 \cdot d$) does not exceed the rate at which solids can reach the bottom of the gravity thickener (or top of the flotation thickener). The rate at which solids can reach the bottom of a thickener depends on the rate at which they settle under the influence of gravity and the rate at which they are transported through the thickener due to removal of thickened sludge. That is

$$G_i = c_i v_i + c_i u \tag{1}$$

where G_i is the possible flux of solids through a layer of concentration c_i, $c_i v_i$ is the gravity settling velocity of the sludge solids at concentration c_i, and u is the bulk downward velocity in the thickener produced by the removal of sludge from the bottom of the tank. Equation 1 is an expression of the possible rate of solids transport per unit area for any concentration in a continuous thickener (one from which thickened sludge is continuously withdrawn). Batch thickeners are a special case in which the $c_i u$ term in eq. 1 is zero.

It should be noted that the $c_i v_i$ term in eq. 1 depends only on the physical properties of the sludge and is not susceptible to control by the designer or operator of the thickener unless physical, biological, or chemical alteration of sludge solids (as by use of a polyelectrolyte is practiced. In contrast, the magnitude of the $c_i u$ term in the equation depends on the rate at which thickened sludge is removed from the bottom of the tank, and is therefore susceptible to control by the thickener designer and operator.

TOTAL FLUX = TRANSPORT DUE TO SEDIMENTATION + TRANSPORT DUE TO SLUDGE REMOVAL

$$G_i = c_i v_i + c_i \frac{Q_u}{A}$$

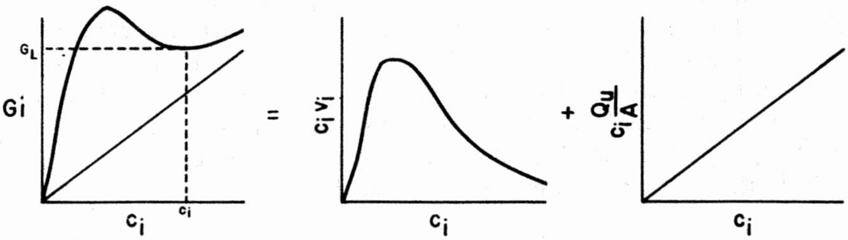

Fig. 1. Determination of allowable loading on a thickener

For optimal performance of a thickener, sludge removal equipment must be designed to uniformly collect thickened sludge from the bottom of the tank so that

$$u = Q_u/A \tag{2}$$

where Q_u is the volumetric rate of removal of thickned sludge from a continuous thickener of area A. Thus, it is seen that the capacity of a thickener for receiving sludge solids can be increased by increasing the rate of removal of thickened sludge. While this may be a desirable course of action for an overloaded thickener, it conflicts with the basic goal of thickening – the production of a concentrated thickening underflow. This is because

$$Q_u = c_f Q_f / c_u \tag{3}$$

and it is desired to maximize the underflow concentration c_u. Equation 3 was obtained from a mass balance on a thickener receiving feed sludge at a volumetric flow rate Q_f with a suspended solids concentration c_f assuming that the clarified effluent from the thickener was essentially free of suspended solids.

If the relationship between settling velocity v_i and concentration c_i is known (see [2] for procedures and difficulties in determining the settleability of sludges), and if a value of u is selected, then the value of the batch flux and underflow in eq. 1 can be determined for each possible concentration of sludge which might exist in a thickener.

Figure 1 illustrates the variation of the two terms in eq. 1 with suspensed solids concentration and shows the resulting total flux G_i possible for each concentration of sludge which might exist in a thickener. It is seen that, in the higher range of concentrations which typically exist in thickeners the value of G_i passes through a minimum. It is this limiting capacity for transmitting solids to the bottom of a thickener, G_L, which limits the capacity of thickeners. Thus, one must ascertain that solids are not applied at a rate greater than G_L, or

$$A = c_f Q_f / G_L . \tag{4}$$

It should be noted that, because u, the underflow velocity, is controlled by the designer or operator of a thickener, the value of G_L is controllable. Thus, for a thickener receiving a given solids load $c_f Q_f$ the value of G_L in eq. 4 can be varied to give any desired thickener area. However, from eq. 1, it can be seen that if a high value of G_L is selected, a high value of u, the underflow velocity, must also be used. From eqs. 2 and 3, it is seen that the use if a high underflow velocity would result in the removal of dilute sludge from the thickener. When a new thickener is being designed, area, and thus underflow velocity, are unknown. Thus, the solution outlined above becomes a laborious trial and error situation. This difficulty can be circumvented by use of a graphical solution [2]. This simplified procedure is highly recommended for design and routine analysis of the performance of existing thickeners.

3. INTERACTION OF THICKENING WITH OTHER SLUDGE TREATMENT AND DISPOSAL PROCESSES

To illustrate the influence of gravity thickening on the economics of sludge treatment and disposal, the cost of thickening a typical municipal sludge to various concentrations was compared with the savings resulting from the improved thickening in the cost of various sludge treatment techniques. To illustrate the effect of the size of the waste treatment facility on the economics of thickening, calculations were conducted for cities of 10,000, 100,000, and 1,000,000 people.

Sludge quantities

The following equation was developed to estimate the quantities of sludge to be treated by the various sized cities:

production of sludge = suspended solids removed in primary clarifier + nonbiodegradable volatile solids in raw waste which become incorporated in activated sludge + nonvolatile suspended solids carried into activated sludge process + synthesis of activated sludge solids + any inorganic precipitates formed during biological treatment – autooxidation of biological solids – suspended solids lost in effluent.

This equation may be written as:

$$S = \left[p_{SS} c_{SS} + fh(1 - p_{SS}) c_{SS} + (1-h)(1-p_{SS}) c_{SS} + a(1-p_{BOD}) c_{BOD} \cdot m_{BOD} + c_p - b \frac{(1-p_{BOD}) c_{BOD}\, m_{BOD}}{L} - c_{Se} \right] Q . \tag{5}$$

The meaning of symbols in eq. 5 is indicated below along with dimensions:

a – amount of biological synthesis per unit of BOD removed, M suspended solids/M BOD (0.5),

b – fraction of mixed liquor volatile suspended solids which are autooxidized daily, dimensionless (0.12),

c_{BOD} – concentration of BOD in raw waste, M/L^3 (178 mg/dm^3),

c_p – concentration of inorganic precipitates formed during biological treatment, M/L^3 (0 mg/dm^3),

c_{Se} – concentration of suspended solids in effluent from treatment plant, M/L^3 (15 mg/dm^3),

c_{SS} – concentration of suspended solids in raw waste, M/L^3 (205 mg/dm^3),

f – fraction of volatile suspended solids entering aeration tank which are not biologically oxidized, dimensionless (0.35),

h – fraction of suspended solids entering aeration tank which are volatile, dimensionless (0.75),

L – oraganic loading intensity in activated sludge process, M BOD removed/M volatile suspended solids in aeration tank (0.4),

m_{BOD} – fraction of BOD entering the secondary process which is removed (based on filtered effluent sample), dimensionless (0.90),

p_{BOD} – fraction of BOD removed in primary settling tank, dimensionless (0.33),

p_{SS} – fraction of suspended solids removed in primary settling tank, dimensionless (0.6),

Q – wastewater flow rate, L^3/T (486 dm^3/d/capita),

S – daily production of waste sludge solids, M/T.

Equation 5 is a modification of Eckenfelder's equation (11.3) [6] with the addition of terms to account for primary sludge, any organic solids precipitated in the biological reactor [9], incorporation of nonvolatile solids contained in the raw waste into activated sludge and loss of solids over the final sedimantation tank weir. Values of the various constants, as assumed for purposes of this illustration are indicated in parantheses in the preceding list. All of these values are subject to variation from waste to waste and none are necessarily applicable to any particular plant. In the absence of information on the amount of inorganic precipitates formed during biological treatment, this contribution toward sludge production was ignored. A waste flow rate of 486 dm^3/d/capita, a per capita suspended solids loading of 0.1 kg/d, and a per capita BOD contribution of 0.09 kg/d were assumed based on data presented by LOEHR [7]. No allowance was made for the probable variation in quality and quantity of waste as a function of the size of the municipality.

Based on the assumed values, sludge production per 1 m^3 of wastewater flow would be 171 g of which 122 g would be primary sludge, and 49 g would be waste secondary solids. The magnitude of secondary sludge production is perhaps on the low side of reported experience.

4. COST OF GRAVITY THICKENING OF SLUDGES

To obtain an indication of current probable costs of thickening and to achieve a basis for illustrating the interaction of thickeners with other processes of sludge handling and disposal, estimates were developed for the cost of thickening sludge to various degrees in municipalities of various sizes. This was done by assuming sludge settling properties (settling velocity as a function of concentration), determining the allowable loading on a thickener to concentrate the sludge to varying degrees, sizing the thickener, and estimating the cost of construction and operation of the thickener of the necessary size.

4.1. REQUIRED THICKENER SIZE

As described in an earlier section, the required size of a thickener is a function of the extent to which it is desired to concentrate sludge and of the settling characteristic of the sludge being thickened. In this illustration, the settling properties of a combined primary–secondary sludge were assumed and expressed in the form of an equation used by DICK and YOUNG [5]:

$$v_i = ac_i^{-n} \tag{6}$$

where v_i is the settling velocity of sludge at concentration c_i, and a and n are constants characterizing the properties of the particular sludge being considered. For purposes of this illustration, a was taken as 0.014 m/min, and n as 2.57, when c_i is expressed in percent.

The allowable solids loading (the limiting flux) for achieving various degrees of concentration of the sludge were calculated and are shown in fig. 2 along with the resulting required total thickener area for a city of 100,000. Because no differences in sludge production between cities of various sizes were considered, the required thickener areas for achieving various degrees of sludge concentration for cities of 1,000,000 and 10,000 are of order of magnitude greater or smaller than the values shown in fig. 2.

4.2. THICKENER COSTS

In addition to requiring an understanding of factors affecting process performance, optimal integration of sludge treatment processes requires information on the cost of treatment by various techniques as a function of the level of process performance. Unfortunately, rational selection, design, and operation of sludge treatment processes is hampered by a dearth of such cost information. In the case of gravity thickening, such data are in particularly short supply. This is, perhaps, because thickening normally is the cheapest step in sludge treatment and disposal and, thus, thickening costs often tend to be lumped into the cost of other sludge processing techniques. Additionally, sludges vary widely in their thickening characteristics, and unit costs for thickening would be expected to vary accordingly. As with all current cost estimations, inflation also imposes complications. In BURD's review [1] of the state of the art in sludge handling and disposal, it was generalized that separate sludge thickening costs from two to five dollars per ton of dry solids. SMITH [13] presented equations for the cost of construction of gravity thickeners asa a function of area. In neither case was the thickening cost related to the degree of sludge concentration achieved. That was accomplished here by estimating the cost of the thickeners sized (fig. 2) to give various degrees of sludge concentration.

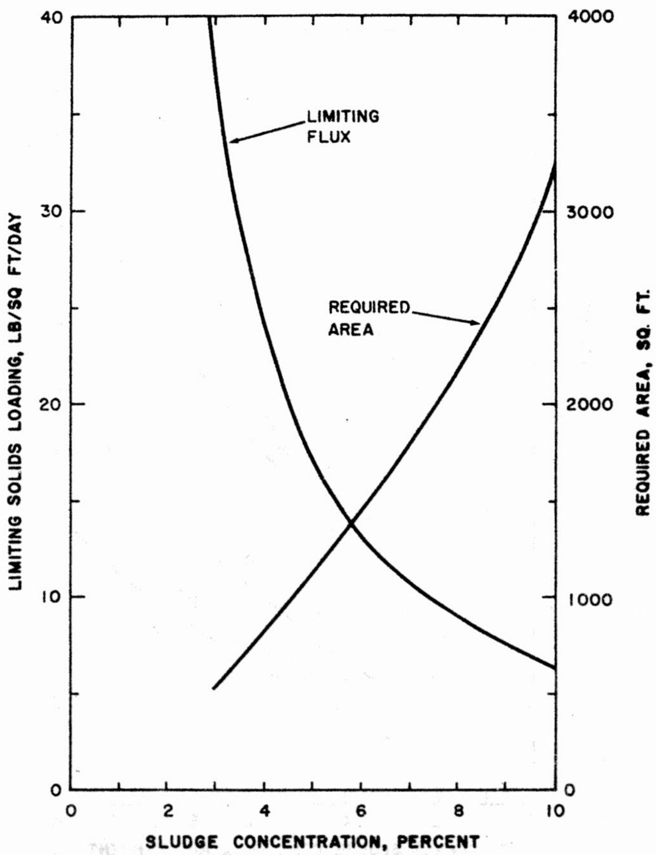

Fig. 2. Required size of thickeners for concentrating hypothetical sludge to varying degrees in city of 100,000 people

Capital costs for thickeners of various sizes were obtained by adjusting cost data presented by SMITH [13] to April, 1974 on the basis of the Engineering News Record Construction Cost Index (the April, 1974 value being 1940) and then increasing the cost by 25 percent to account for contractor's profit, contingencies, and engineering. The resulting capital cost equation was

$$C_S = \left[54.3 + 26.3e^{-A/13400}\right] A. \tag{7}$$

Extensive data on the operation and maintenance of gravity thickeners as a function of their area were not available. In the absence of such information, costs reported by SMITH [13] on operation and maintenance costs for primary clarifiers as a function of their area were used. It was reasoned that the equipment and operational requirements were similar to separate thickeners. Arbitrarily, Smith's operational and maintenance costs were adjusted by use of the

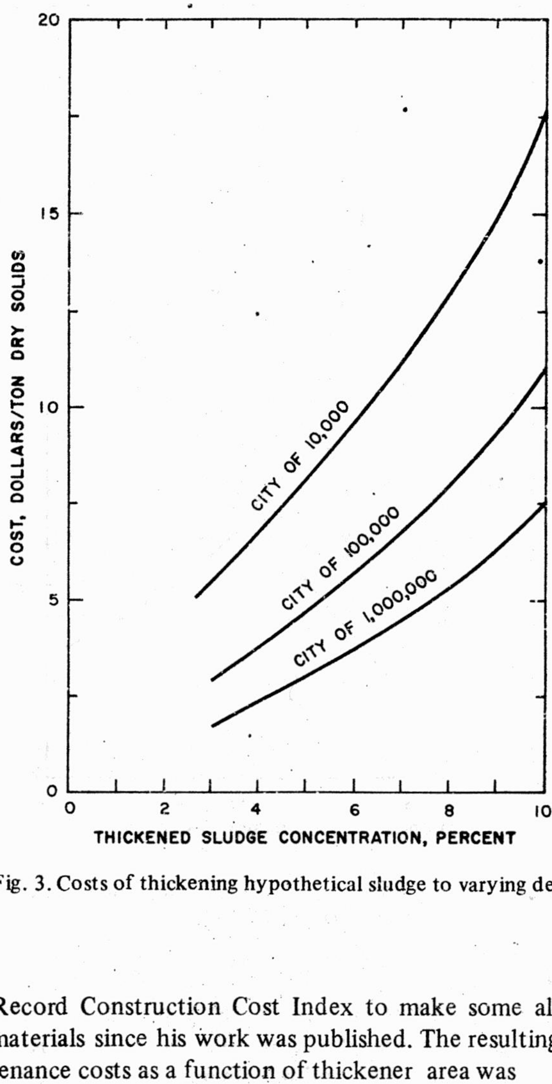

Fig. 3. Costs of thickening hypothetical sludge to varying degrees

Engineering News Record Construction Cost Index to make some allowance for changes in costs of labor and materials since his work was published. The resulting equation for an annual operating and maintenance costs as a function of thickener area was

$$OM_{\$} = 2.39A + 189A^{0.5}. \tag{8}$$

To obtain an overall cost of thickening to various degrees, annual costs (operation and maintenance plus amortization of capital costs) were calculated. Then, as shown in fig. 3, costs of thickening to various degrees for various sizes of municipalities could be expressed on the basis of total cost per unit of sludge production. For this purpose, the approximate current interest rate on Grade A municipal bonds (6.5 percent) was used with a 20-yr amortization period.

5. THICKENING AND DEWATERING OF RAW SLUDGE

The yield of sludge dewatering devices is increased when water is removed from sludge (as by gravity thickening) prior to being fed to the dewatering device. This is because less water must then be passed through the somewhat impermeable sludge cake in the course of dewatering than would be necessary if the excess water was not removed previously by thickening. Additionally, the degree to which sludge can be mechanically dewatered increases when concentrated sludge is fed to the dewatering equipment [8].

To illustiate the optimal integration of thickening and dewatering processes, the cost of sludge dewatering by vacuum filtration was considered. Then, the total cost of the combination of the thickening and dewatering processes could be evaluated to determine the proper design for each of the two processes.

The effect of feed sludge concentration of filter yield was taken from data presented by SCHEPMAN and CORNELL [12] which indicated that

$$Y = 0.88 c_u - 1.0 \tag{9}$$

where Y is the filter yield in 4.9 kg dry solids/h/m^2 and c_u is the concentration of sludge in the thickener underflow. Extrapolation of the Schepman and Cornell data was necessary to include the range of interests here, but the extrapolated data agreed closely with information on relationship between feed solids concentration and filter yield presented by QUIRK [10].

Capital costs for vacuum filters were taken from information presented by SMITH [13]. As with the capital costs for thickeners, Smith's estimates were adjusted to the April, 1974 Engineering News Record Construction Cost Index of 1940 and then 25% was added for contractor's profit, contingencies, and engineering. Capital costs were amortized at 6.5 percent for 20 yr. Costs for labor, power, and maintenance were taken from estimates prepared by QUIRK [10] and, arbitrarily, were adjusted to current costs by use of the Engineering News Record Construction Cost Index. Chemical costs for sludge conditioning were taken as $12/909 kg of dry solids and were not considered to vary with the size of the city or the excent to which the sludge was thickened.

Resulting total costs for thickening and dewatering are shown in fig. 4. The contribution of thickening and vacuum filtration (including conditioning) to the total cost is illustrated for the city of 1,000,000. Total costs curves are shown for all three cities. The relative contribution for thickening and dewatering to the total cost for cities of 10,000 and 100,000 people can be obtained by comparing figs. 3 and 4.

It is seen from fig. 4 that the optimal degree to which the sludge considered here should be thickened for this city of 10,000 people is of about 8 percent. For the two larger cities, a total cost became relatively insensitive to the degree of thickening at a concentration of around 8 percent, but a true optimum was not reached within the range of concentrations considered. While the thickening costs involved in reaching these high concentrations are in excess of the costs normally considered for thickening, results would suggest that, with this sludge and these estimates of capital and operating costs, more money should be spent for thickening than is normal practice. However, because sludge properties vary from plant to plant, the more important point is that great savings in the combined cost of thickening and dewatering is possible by use of a rational approach to design of sludge treatment systems.

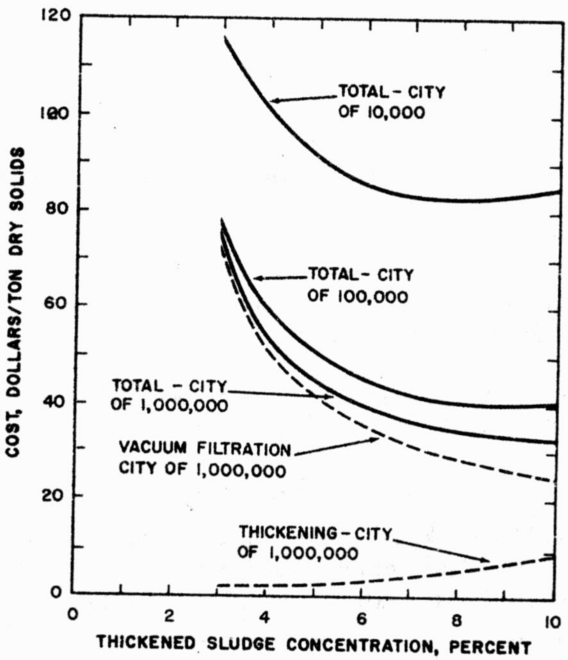

Fig. 4. Optimal integration of thickening and dewatering

6. OVERALL COSTS OF THICKENING AND TRANSPORTING SLUDGE BY TRUCK

To illustrate the effect of thickening on another phase of sludge handling, overall costs of thickening and subsequent trucking were evaluated for thickeners designed to achieve varying degrees of sludge concentration. For this purpose, trucking costs were taken from estimates prepared by RIDDELL and CORMACK [11] for trucking sludge a distance of 40 km. Riddell and Cormack's data (which were developed for sludge at 3.5 percent concentration) were adjusted to evaluate the cost of transporting different volumes of sludge containing the same total amount of dry solids. Figures then were adjusted for inflated labor and materials costs by use of the Engineering News Record Construction Cost Index.

Total overall costs for thickening and transporting sludge 40 km by truck for various sized cities are illustrated in fig. 5. Again, the breakdown of costs is shown only for the city of 1,000,000 people, but the relative contributions of trucking and thickening for the cities of 100,000 and 10,000 people can be obtained by comparing figs. 3 and 5. As before, a true optimum was not achieved within the range of sludge concentrations considered. That is, even though sludge thickening became for more expensive than usual, the incremental cost was justified by the reduction in the cost of transporting the sludge.

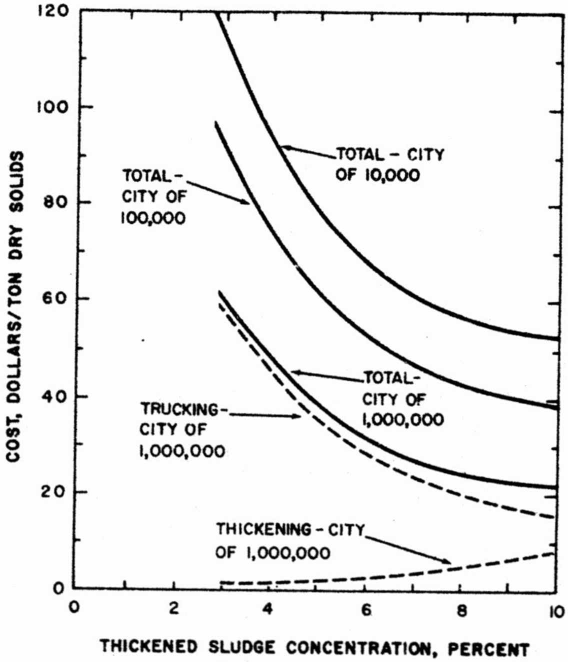

Fig. 5. Optimal integration of thickening and trucking

7. SUMMARY AND CONCLUSIONS

Thickening is involved in all schemes of sludge treatment and disposal. If a separate gravity or flotation thickener is not used, then thickening still is involved because it occurs in the sedimentation tanks which produce the sludge. Thickening has a great influence on the cost of sludge treatment and disposal because the cost effectiveness of sludge treatment and disposal techniques depends on the concentration of solids in the sludge.

Traditionally, thickeners have been sized in an arbitrary fashion without regard to the thickening properties of the sludge being treated or to the degree of thickening desired. Yet the size of a thickener does effect the amount of thickening achieved and this effect can be estimated if the settling characteristics of the sludge are known. This allows thickeners to be designed and operated to achieve any desired degree of sludge concentration. The degree to which sludge should be concentrated in a thickener depends on factors such as the nature of the sludge, the size of the community, and the types of other sludge treatment and disposal processes involved in the system.

The effect of designing thickeners to accomplish varying degrees of solids concentration on sludge treatment and disposal costs are illustrated herein. Integration of the design of thickeners with the design of other processes offers significant potential for reducing costs. While this approach to the design of sludge treatment and disposal facilities requires appreciably more information about sludge treatability than normally is available, the results suggest that the potential cost savings warrant the cost of conducting the special studies required.

ACKNOWLEDGMENTS

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ZAGĘSZCZANIE OSADÓW ŚCIEKOWYCH

Stopień zagęszczenia osadów ściekowych ma duży wpływ na całkowity koszt ich oczyszczania i usuwania. Dotychczas istniejące koncentratory nie gwarantują optymalnego stopnia zagęszczania osadów. Celem przedstawionej pracy jest przegląd podstawowych koncepcji zagęszczania i wskazanie na fakt, że można uzys-

kać znaczne obniżenie kosztów dzięki rezygnacji ze stosowania konwencjonalnych obciążeń koncentratorów. Koncentratory powinny być zaprojektowane w ten sposób, aby zapewniać taki stopień zatężenia osadu, który minimalizowałby całkowite koszty oczyszczania i usuwania osadu.

КОНЦЕНТРАЦИЯ ВОДОСТОЧНЫХ ОСАЖДЕНИЙ

Степень концентрации водосточных осаждений имеет большое влияние на полные затраты, на их очистку и удаление. Существующие до сих пор концентраторы не обеспечивают оптимальной степени концентрации осаждений. Целью настоящей работы является обзор основных концентрации и указание на факт, что можно получить значительное понижение затрат, благодаря отказу от применения конвенциональных нагрузок концентраторов. Концентраторы должны быть запроектированы так, чтобы обеспечивать такую степень концентрирования осаждений, которая минимизировала бы полные затраты на очистку и удаление осаждений.