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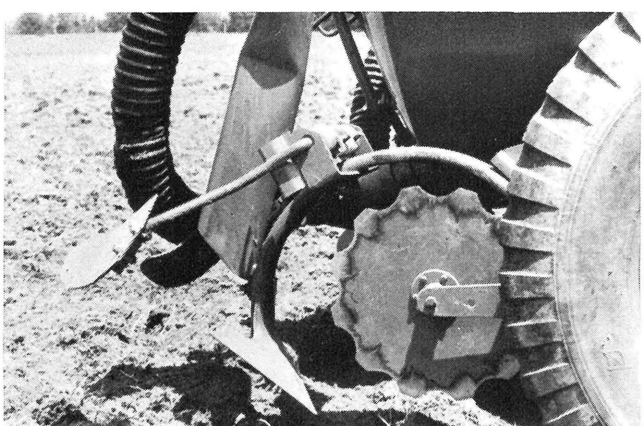

OHIO AGRICULTURAL RESEARCH AND DEVELOPMENT CENTER

WOOSTER, OHIO

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ON THE COVER: Tank truck with gravity discharge and deflector plate spreads sludge . . . The coulter placed ahead of the injector shank is a desirable feature when injecting in sods.

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Systems and Equipment for Disposal of Organic Wastes on Soil

R. K. WHITE, M. Y. HAMDY, and T. H. SHORT[1]

SUMMARY

One of the principal organic wastes produced by man's activities is sewage sludge. The handling and disposal of sludge is a major item in municipal sewage treatment costs. Sludge disposal on the soil is cost effective when compared to other disposal systems and recycles some of the sludge components. This report reviews processes and equipment which can be used in a soil disposal system for sludge and other organic wastes.

The components of sludge disposal systems are discussed in terms of the quantity of sludge produced and its physical and chemical characteristics. The effects of climate, topography, vegetative cover, soil type, and land availability are considered. Transport and disposal equipment are considered for sludges in both the slurried and solid form. Surface application and soil incorporation techniques are also presented. Equipment characteristics and power requirements are discussed for different methods of field application. Photographs of different equipment in operation are included.

In the analysis of sludge disposal systems, components of the treatment, transportation, and soil application are considered. Cost considerations are discussed based on the nature of the raw waste, annual quantity, seasonal waste distribution, geographic location, and total solids content. A mathematical model is developed which puts the concepts discussed in this report into a quantitative form which lends itself to known optimization techniques.

INTRODUCTION

Raw wastewater contains both dissolved and suspended solid pollutants. After conventional biological wastewater treatment, approximately 0.2 lb. of solids (defined as sludge) per 100 gallons of wastewater treated are separated from the effluent before discharge. This sludge has to be disposed of safely and economically. One method for disposing of this sludge is by land spreading. The purpose of this study is to discuss systems and equipment which can be applied for disposing of the sludge on soil.

Solids are separated from water in a sewage treatment plant in two major operations. One is in the primary sedimentation tank where much of the suspended solids in the raw sewage are settled out, constituting what is called primary sludge. The second is the final clarifier which separates biological solids after the sewage has been treated in an activated sludge tank, trickling filter, or by some other biological process. These sludges may be stabilized by anaerobic digestion, aerobic treatment, or lime addition.

All of this activity does not reduce to a significant degree the volume of solids to be handled. From 50 to 60% of the solids in the raw sewage will still have to be disposed somehow, even after treatment in the sewage treatment plant. The cost of solids handling and disposal comprises up to 50% of the total treatment costs of a large sewage plant. While the water component of the sewage is disposed by discharging it back into a river, solids cannot be discharged into the river, even after they have been stabilized and most of the pollution potential removed. Besides exerting an oxygen demand on the river, the presence of sludge in the waters would mechanically interfere with light penetration and would adversely affect bottom dwelling organisms.

Disposal of the solids then becomes a critical problem. The problem is not limited to large plants. Some small communities find sludge disposal a problem, but others find homeowners and farmers anxious to use liquid sludge or sludgecake as a fertilizer and soil conditioner. Liquid sludge is often delivered and spread by the treatment plant staff. In other communities, it takes a concerted effort to convince local farmers or homeowners to accept sludge from sewage treatment plants. Dewatered sludge is bulky, low in nutrients, and expensive to handle; and farmers are better equipped with machinery for the application of commercially produced fertilizers than they are for application of dried sludge. In major cities, the large volume of sludge produced requires extensive land areas for its disposal by land spreading.

Large sewage treatment plants may also digest and then incinerate sludge or dehydrate it for use as fertilizer. The ash from incineration can be disposed in landfills or large lagoons. Alternatively, dried sludge is sometimes mixed with other ingredients and marketed in garden stores and other outlets.

In small sewage treatment plants, the usual method of dewatering digested sludge is through the use of drying beds. The dried dewatered sludge is either landfilled, used on surrounding agricultural land, or picked up by local homeowners.

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The amount of sludge produced per year varies, of course, with the locality. However, for municipal sewage which does not include excessive amounts of industrial wastewater, sludge solids are produced at the rate of about 30 lb. per capita per year. A city of 100,000 people will need to dispose of 1,500 tons of dry solids. Just to store this waste temporarily will require nearly 1 million cubic feet of space per year if the sludge is stored at 5% solids.

On the other hand, sludge contains both fertilizing elements and organic matter. The latter can easily be decomposed into humus and act as an excellent soil conditioner. Except for sewage treatment plants which receive wastewater from electroplating industries or other plants which discharge heavy metals in their wastewater, sludge will not contain elements in amounts which would be severely detrimental to the quality of the soil environment in which agricultural crops are grown. An analysis by the city of Chicago of the cost of processing sludge beyond the anaerobic digester stage has shown that land disposal of sludge would cost about one-third as much as it would cost to incinerate or chemically dehydrate digested sludge (8).

Experiments with the use of sludge as a feed for animals have met with moderate success. Animals fed hydrolyzed protein from activated sewage sludge at low levels in the diet are able to use the amino acids without any major difficulties. The cost of processing activated sludge for animal feed prohibits its use in this manner at the present time.

Dr. R. B. Dean (9), writing on the subject of alternate methods of ultimate disposal of wastewater solids, concluded that: ". . . The use of land surface as low cost dewatering and oxidizing systems has some promise. In many areas, farmers compete for available wet sludge to spread on their fields, indicating the possibility of developing some market value. In a typical operation, sludge is sprayed from a tank truck. If the soil is too wet to bear the weight of a truck, a high pressure hose and sprinkler may be used to bring sludge from the roadside. Soils can oxidize and destroy large quantities of sludge each year, provided they are kept well aerated."

Dr. James Law, research soil scientist, FWPCA, wrote in the preface of an annotated bibliography on Agricultural Utilization of Sewage Effluent and Sludge (18): "Interestingly, the bulk of literature covering agricultural use of reclaimed wastewaters comes not from agricultural scientists, but from those working in the sewage disposal field."

However, not all the technology necessary for the safe utilization of soils for waste renovation has been developed to the point that the public would accept land disposal without reservations. Improved engineering systems for surface and subsurface application of wastes to soil and mechanisms for soil injection of slurries are needed to demonstrate both the desirability and technical feasibility of using organic wastes on agricultural soils.

One of the most frequent objections to the utilization of sludge on productive land is the problem of odor. Well-processed sludge does not have an offensive odor. This has been demonstrated at the Arcola Disposal Site in Illinois, where well-digested and long-aged sludge was disposed of on agricultural soil.

However, the public associates odors with all sludges and organic slurries. Recently, the Metropolitan Denver Sewage Disposal District, which had requested bids on a land disposal project for its sludges, received bids much higher than the engineering estimates. The reason for this appeared to be the apprehension of the contractors about the lawsuits and local objection to the use of nearby land for sludge disposal.

The unwarranted fears about offensive odors from well-digested sludge could be reduced by education. In addition, more research needs to be done on odor amelioration so that disposal of sewage sludges, animal manures, or any other materials which are to be biologically degraded can be made on land near residences or areas where people work with confidence that odors will not result.

The fact that odor is an important limiting factor in the disposal of sludges on land does not mean that work on the technological feasibility of disposal of sludges on land must cease.

The aims of this study were to determine the availability, the performance characteristics, and the cost of equipment and machinery which could be used to dispose of sewage treatment plant sludge and other wastes of similar characteristics on agricultural soils. Agricultural engineers have been involved with the design of mechanized systems for the use of soil to grow crops. As the capacity of air and water resources to receive and assimilate waste is being depleted, the soil is being looked upon as the depository for the vast discard of an affluent society. In the future, agricultural soils will not only be used to support crop and forest production, it may also be used to assimilate organic wastes.

There has not been a major industry effort to design and develop mechanized systems for the transport of a secondary product like sludge. On the other hand, the highly developed technology for the handling and transporting of materials in the manufacturing industry should be a great help in designing such systems.

Agricultural engineers are familiar with soil properties and the use of soil for the production of food and fiber. Work on transport and application of organic slurries on agricultural soils would simply extend that expertise to a new area of application of their knowledge, while at the same time keeping organic wastes from becoming pollutants.

The procedure used in completing the study was to make site visits to areas where either experiments or demonstration projects on land disposal of sludge and other organic wastes were being practiced. Manufacturers of machines and equipment for the transport of slurries and for the incorporation of such slurries in soils were contacted and performance characteristics of their equipment were obtained. Several universities were visited and conferences were held with engineers and scientists who have been incorporating slurries into the land. Furthermore, an attempt was made to delineate the unit processes and the total system which would be involved in the handling of sludge after it had been digested and before sludge nutrients had been harvested as crops. It is hoped that the system analysis of the study will stimulate agricultural, sanitary, and transport engineers to cooperate in refining the model delineated in this study and to fill in the existing gaps of knowledge so that the system can be routinely engineered in the future for any location in the United States.

COMPONENTS OF SLUDGE DISPOSAL SYSTEMS

Different systems have been developed to dispose of sludge and waste slurries on agricultural lands. These systems, in many cases, have been developed on the basis of experience and available equipment in order to dispose of an accumulation of waste. Based on site observations and literature search, a compilation of the components usable in sludge disposal is presented here. The factors which relate a particular component to a complete disposal system will be discussed so that each individual or group interested in developing a system can evaluate the suitability of components for their situation.

Under certain circumstances, e.g., disposal of toxic refuse, industrial sludge, or tailings, soils have been polluted to the degree that no vegetation will grow or that it is unsuitable for cropping. In the development of a disposal system, consideration must be given to the prevention of soil pollution. Consideration also must be given to avoiding pollution of surface or ground waters and nuisance conditions, such as malodors, attraction of rodents or flies, or unsightliness.

SELECTION FACTORS

In selecting sludge disposal systems for a particular community, several factors must be considered such as the size of the community or the quantity of sludge produced, land availability, and sludge characteristics, such as the presence of potential pollutants, toxic elements, or metals.

Quantity of Sludge:

Sludge disposal on farmland from Celina, Ohio, a town of 9,000 inhabitants, was observed in this project. They produced 140 tons of dry solids per year or on a wet basis with 4% solids, 3,500 tons per year (840,000 gallons). On the other extreme, Chicago produces 360,000 tons of dry solids per year or 9 million tons of wet sludge per year (2.15 billion gallons). From these two extreme examples of the quantities of sludge produced, it is evident that different sludge disposal systems will be required.

Sludge Characteristics:

The characteristics of the sludge will be important in determining how much can be applied per acre per year. It will also determine the type of equipment which can be used in transporting the sludge and applying it to the soil.

- **Physical.** The solids content of sludge will be a principal factor in its handling characteristics. If the sludge has a low solids content (4 to 8%), it may be easily pumped, but as the solids content increases it will be more difficult to pump. From field work where sludge with approximately 8% solids was pumped, the f factor in the Weisback-Darcy equation was estimated to be 10 times that of water; i.e., $f = 0.15$ for sludge.

When sludge is dewatered to a solids content of 15% or higher, it must be handled as a solid waste. The type of equipment which can handle sludge in the solid form will be discussed under Available Processes and Equipment.

- **Chemical:** The presence of elements which might be toxic to plants or create adverse soil conditions must be considered, particularly as related to application rate and time of application. It has been shown in the research report, Agricultural Benefits and Environmental Changes Resulting from the Use of Digested Sludge on Field Crops, by Hinesley, *et al* (14), that application of fresh digested sludge inhibited seed germination. Lagooned sludge did not show an inhibitory effect. The inhibitory effect of the digested sludge was isolated to the supernatant and is believed to be caused partially by free ammonia. Therefore, time of sludge application to fields as related to planting of crops is important.

In communities where waste from iron, plating, or chemical industries is discharged into the municipal sewers, metals and other elements can be expected to accumulate in the sludge and disposal on land will cause an accumulation in the soil. In the report by Hinesley, *et al* (14), data were presented on the uptake of metals by plants, leaves, and grain for corn and soybeans. Sludge had been applied in 1969, 10 cm. maximum, and in 1970 about 25 cm. maximum. Tests conducted on the 1970 experiments showed an accumulation of Zn, Fe, Al, and Cu in the corn leaves; Zn, Fe, and perhaps Al in the corn grain; Zn, Mn, Mg, P, Na, and Al in the soybean leaves; and Zn, Fe, Ca, Al, and Cu in the soybean grain. None of the analyses indicated that the crops might be detrimental to human or animal life. Yet it is important to note that these tests were conducted during the second year of sludge application. The effects of many years of application or higher application rates are not known.

Nitrogen is considered by many to be the factor which will limit the application rate. This is because of the concern that nitrate nitrogen (NO_3-N) will pollute ground and surface waters. The source of nitrates is principally from the nitrification of ammonia nitrogen (NH_3-N). Nitrate is soluble in water and is the form of nitrogen which plant roots take up. When NO_3 in solution is in excess of plant needs at that time, it will move with the ground or surface water. Hinesley, *et al* (14) reported that the leachate from sludge-treated plots, in all cases, exceeded the 10 mg./l. NO_3-N drinking water standard. Leachates collected in the fall contained the highest NO_3 concentration and the lowest concentrations generally occurred in the late spring.

The ratio of NH_3-N to organic-N in fresh digested sludge is about 50:50. When digested sludge is lagooned, the ratio changes to 30:70. Digested sludge has a carbon to nitrogen ratio (C:N) of 7:1 or 8:1. The type of soil and the C:N ratio affect the mineralization of organic-N, i.e., the conversion of organic-N to NO_3-N by the soil bacteria. Approximately 5% of the organic-N in sludge applied to the soil will be mineralized in a year's time. The application rate should consider the amount of NH_3-N and organic-N in the sludge as well as the organic-N already in the soil. Research is presently being conducted by several universities to determine application rates, as related to allowable nitrogen applications.

Particularly in regions with low rainfall, consideration must be given to the amount of mono-valent cations in the sludge, in particular sodium and potassium. These cations can cause dispersal of soil aggregates and reduce the hydraulic conductivity of the soil. In regions where evapotranspiration exceeds the rainfall, these and other salts will accumulate in the surface layer of the soil, creating saline conditions which inhibit plant growth. In such regions, additional high quality irrigation water is needed to flush excess salts from the soil. It is recommended that an agricultural engineer or agronomist from the U. S. Dept. of Agriculture, the State Department of Agriculture, or the State Agricultural Experiment Station be consulted before applying sludge on soils in dry regions.

- **Nuisance.** When raw sludge, septage (septic-tank sludge), or animal wastes are applied to the soil, an odor nuisance condition can be created. The waste also may attract rodents or provide a breeding place for flies. Therefore, it is usually desirable to incorporate into the soil any wastes which might produce a nuisance condition. Equipment designed especially for the soil incorporation of wastes will be discussed later.

Climate:

Seasonal temperature and rainfall conditions will affect the physical characteristics of sludge, the choice of equipment for disposing of sludge, and the application rate. In warm regions with light rainfall, the use of sludge drying beds and evaporation lagoons may be feasible to dry or dewater sludge. However, in regions with long, cold winters and/or high humidity, sludge drying beds are not as suitable. A liquid sludge handling system may be more functional.

Where winter freezing of the soil occurs, the use of a soil incorporation method of applying sludge will be prevented while soil is frozen. On the other hand, frozen ground may be traveled by trucks and tractors more easily and with less soil compaction than unfrozen, moist ground. However, the spreading of sludge on snow-covered or frozen ground is not recommended because snow melt or rainfall may cause a significant portion of the waste to run off into streams unless contour furrows have been prepared to prevent runoff. In most situations where cold winters occur, some form of sludge storage will be required.

As noted previously, in arid and semi-arid regions, the accumulation of inorganic salts in the surface layer of the soil, causing saline conditions, can be detrimental to the soil. In dry regions, the application rate will most likely be controlled by the concentration of salts in the sludge, particularly sodium and potassium. Salts can be leached beyond the root zone by applying water in excess of plant needs.

Land Considerations:

Several factors will affect the choice of land for disposing of sludge. The topography will be a principal factor in selection of application equipment as well as affecting application rate. Vegetative cover and soil types will be factors. The feasibility of a site for sludge disposal will be affected by land costs and proximity to treatment facility. Sludge is produced throughout the year, so a system should be flexible enough to permit disposal at all times or provide for storage when land application is restricted.

- **Topography:** Level or gently sloping land will permit the use of trucks, tank wagons, or irrigation (both spray and ridge and furrow). Rough terrain and steep slopes will eliminate the use of vehicles and ridge and furrow irrigation, unless extensive land leveling precedes application. This leaves only spray and overland flow irrigation as possible modes of disposal. Yet in many cases the land most available will be rough and steep, such as stripmined areas, which can be reclaimed quickly with the application of sludge as demonstrated by research at the Pennsylvania State University (22).

- **Vegetative cover:** Vegetative cover and cropping practices for farmland will affect the type of disposal system which can be used. Land in row crops, such as corn, soybeans, wheat, etc., is not suitable in humid areas for use of vehicles in the spring because the vehicle will cut deep ruts in the soft ground. During the growing season, vehicular traffic will be restricted on the fields which are cropped, and in some cases frequent spray irrigations are not feasible because the plant leaves will become coated with sludge (e.g., soybeans, because they have leaves with hairlike surfaces). Fields in forage crops and pasture will generally support vehicular traffic except when the ground is wet, especially in the spring.

- **Soil type:** The texture of soils has slight effect upon the rate at which sludge can be applied. Infiltration of water is more rapid into coarse-textured soils (sands) than it is into soils with fine-texture (clay). However, when liquid sludge is applied, this difference is minimized by the rapid sealing which takes place regardless of the texture of the soil. Infiltration of liquid sludge becomes very slow after the soil becomes sealed with suspended sludge solids.

Some other properties which are important in choosing soils for assimilation of liquid sludge are drainage, pH, cation exchange capacity, and depth. Soils remaining wet or having a water table near the surface during much of the year are suitable for limited use as sludge assimilators, but the time that sludge can be applied without causing anaerobic conditions to develop is limited to periods of relatively dry soil. Metals in sludge are phytotoxic at lower concentrations in acid soils than in alkaline or neutral soils. Cation exchange capacity is an indicator of the capacity of a soil to adsorb and hold metals and other pollutants of the ground water. A minimum depth of about 6 feet of aerobic soil is needed to assimilate and treat wastes.

- **Availability:** Land requirements are related to the amount of sludge a community produces. A small community will have much less difficulty obtaining a few hundred acres near the treatment plant than a large city which will need several thousand acres. The large city may need to transport the sludge a great distance, even several hundred miles, in order to locate a suitable disposal site. Distance will put a constraint upon the sludge transportation mode and method of ultimate disposal on the land.

Land costs also will be a factor in selecting land for disposal for several reasons. Land near urban areas is generally more costly, and may require special equipment for disposal in order to avoid nuisance conditions. Land which can be farmed, i.e., permit truck and tractor travel, will be more expensive than rough and steep land.

Farmed land will not be available for sludge disposal at certain times of the year. Leasing farmland for 1 year and removing it from cropping has been suggested as a method of making more land available for sludge disposal. Because sludge is an organic fertilizer, farmers may make their fields available if compensation is received for the loss of that year's crop. Application of sludge to the soil during the summer months is more suitable and less expensive than during the non-cropping season. Arrangements could be made ahead of time for leasing, so that the city would be assured of having land available for disposal.

AVAILABLE PROCESSES AND EQUIPMENT

In considering the disposal of slurried wastes and sludges on agricultural land, the system can be conveniently separated into three phases: treatment facility processes as related to solids content and conditioning of the sludge, transportation modes, and field application modes. The processes or components which are available for use in each area are described and their characteristics and limitations are discussed. In addition, storage might be considered as another phase because storage is usually needed at the treatment facility prior to transporting, or at the disposal site prior to field application.

It is recognized that these phases are interrelated. The transportation mode will be related to the extent of sludge treatment, i.e., stabilization, dewatering, or drying. The method of field application will also depend on the solids content of the sludge, possibly controlled by the transportation distance.

Treatment Facility:

Depending on the type of waste and the desired solids contents for transportation and/or disposal, different processes at the treatment facility may be used. The processes indicated in Figure 1 are those usually associated with a sewage treatment facility, but are applicable to other type of wastes, e.g., agriculturevegetable processing wastes, livestock manures, or industrial-paper pulping wastes. There are several alternate routes and different processes which can be applied to sludge before application to the soil. The choice of processes to be used in a particular situation will depend on the selection consideration discussed in the previous section and on the cost factors which will be discussed later.

The unit operations and characteristics for each sludge process noted in Figure 1 are listed in Table 1. The waste characteristics and the disposal system criteria will determine whether the waste produced can be taken directly to the disposal site or whether it will need some degree of treatment. Where complete treatment and stabilization of the organic material are needed, the primary and secondary steps plus digestion are normally used.

Most organic wastes are subjected to some form of solids digestion. This treatment is designed to stabilize the organic material to facilitate further

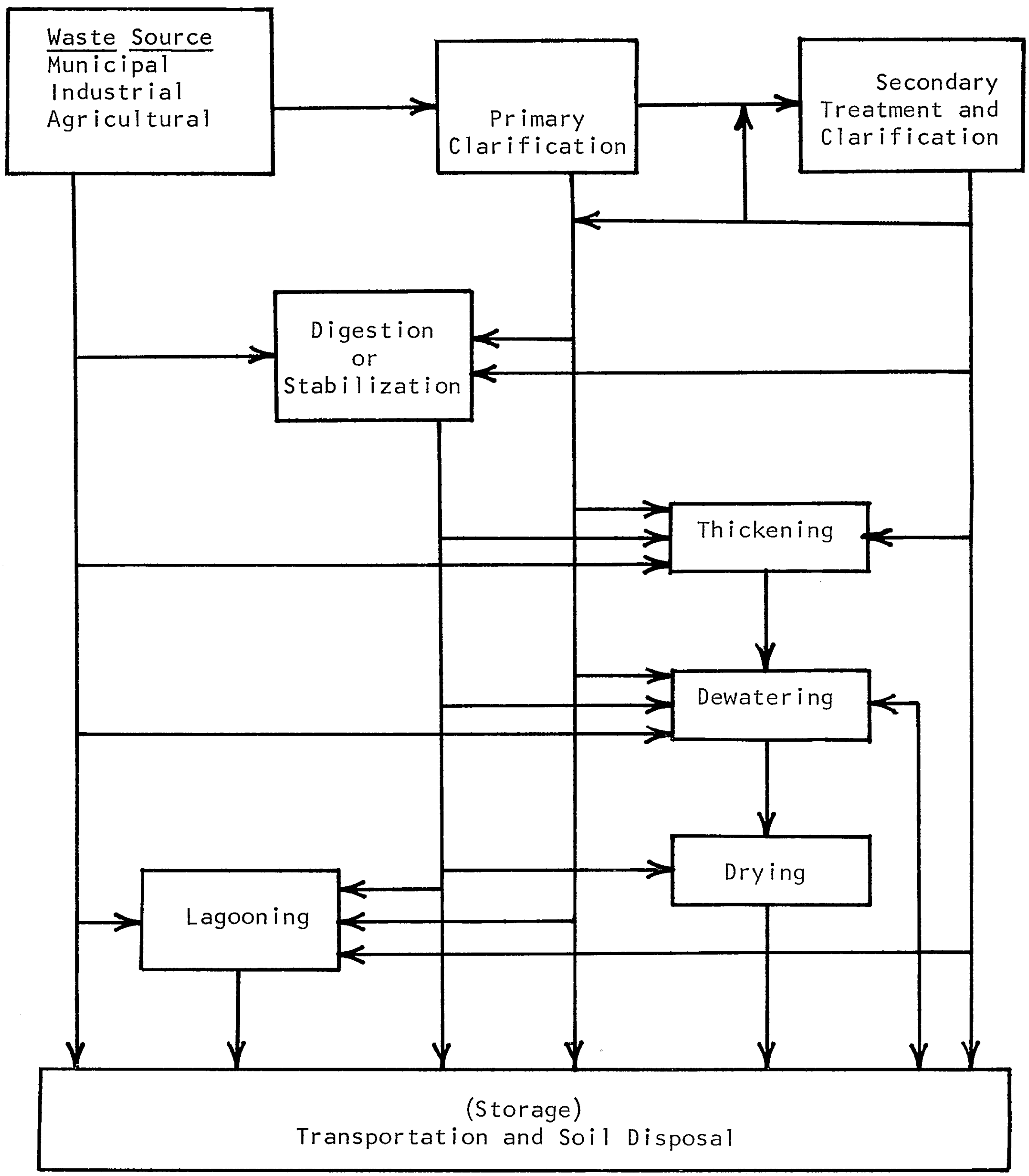

FIG.1.—Flow diagram of principal sludge processes.

handling and/or to avoid nuisance conditions. The type of digestion process is usually related to the amount of wastes to be treated, i.e., the size of city. Small towns most frequently use an aerobic digester. Larger cities principally use the anaerobic digester, and recently the wet oxidation method is being tried. The solids content of the digested sludge varies for each process and in part is controlled by management decisions.

The use of chemicals to condition sludges for dewatering is becoming more common. The decision whether to use chemical conditioning will in part depend on the type of sludge, e.g., digested sludge, activated sludge, or sludges from industrial processes. Air flotation is used in some sewage treatment facilities to thicken sludges.

Depending upon the disposal method and equipment to be used for handling, the solids content of sludges can be increased by a dewatering process or by dehydration. A method of handling in solid form is used after these processes. In the event of drying, the solids may be marketed commercially.

Lagooning is a process which may be used for several purposes: thickening sludge, additional biological treatment, and storage. For thickening, provision will need to be made for removal of water by evaporation or discharge of supernatant. If treatment is proposed for the lagoon process, the sludge loading rate will need to be adjusted to acceptable design criteria. Equipment will be needed to agitate and mix the sludge if it is to be removed from the lagoon as a pumpable slurry.

Transport Modes:

The selection of the transportation mode will depend upon several factors, e.g., sludge production rate, distance to disposal site, solids content of sludge, proximity of disposal site to waterway or railway, method of disposal (whether disposal is seasonal or year-round), length of contract for land usage, etc. The relation of these factors to the selection of a transportation mode will be considered later. The transportation modes for slurried sludge are presented in Table 2 and for sludge in the solid, nonslurried form in Table 3.

Both rail and barge haul are similar in that loading and disposal sites are required to be near a railroad or waterway, respectively. In both cases, the solids will settle, requiring either some form of agitation or flushing action to remove the settled solids. Railcars, specially adapted with discharge valves and quick connect couplings, have been used by the Soil Enrichment Materials Corporation of Chicago for hauling sludge from the Chicago Metropolitan Sanitary District to Arcola, Ill. (Figure 2).

The use of a pipeline for transporting sludge has advantages, particularly when the daily production of sludge is large. The problem of solids settling is eliminated when the velocity of flow is maintained at 1 f.p.s. or greater. Unit costs decrease more rapidly than with other transportation methods as larger amounts are transported. The buried pipeline is suitable for year-round use. For small treatment facilities, the large capital investment will likely make another transportation mode more suitable.

The use of tank trucks provides flexibility in disposal site selection and hauling schedule. Sludge can be applied directly from the truck when soil conditions permit. However, capacity of the system can only be increased by using additional trucks or using larger trucks. The use of large trucks, particularly trailer rigs, will necessitate transfer to another vehicle for the actual field application. If flotation tires are

TABLE 1.—Sludge Treatment Processes.

Process	Unit Operation	Characteristic
Clarification	Primary treatment	Removal of settleable solids and floating material from incoming wastes
Clarification	Secondary settling	In secondary aerobic treatment, the activated sludge is settled and recycled or wasted to subsequent treatment process
Digestion (stabilization)	Aerobic digester, anaerobic digester, wet oxidation, Imhoff tank	2 to 8% total solids
Thickening	Chemical coagulation, gravity thickening, air flotation	Used to prepare sludges for dewatering, e.g. digested, activated sludge, or industrial wastes
Dewatering	Vacuum filtration, filter press, centrifuge	15 to 40% total solids, depending primarily on types of sludge and thickening
Dehydration	Sludge drying beds, dehydrators (heated)	25 to 80% total solids, depending upon type of sludge, time, and climatic conditions.
Lagooning	Lagoon	Solids settle and may increase to 30 to 40% over several years. Sludge is further stabilized. NH_3-N concentration is reduced.

TABLE 2.—Transport Modes for Slurried Sludge.

Mode	Characteristics	Comments
Rail Tank Car	Capacity 100 wet tons (24,000 gal.). Need loading and disposal sites near RR.	Solids will settle while in transit; some form of agitation desirable.
Barge	Capacity related to size barge waterway permits. Chicago used 1,200 wet ton (290,000 gal.) barges. Need loading and disposal sites near waterway.	Frozen waterways will prohibit use in winter.
Pipeline: Fixed (buried)	Suitable for year-round use.	As diameter of pipe increases, pressure loss due to friction decreases (inversely proportional to pipe diameter to the fifth power). Need minimum velocity of 1 f.p.s. to keep solids in suspension.
Portable (surface)	Will freeze if used intermittently, not suitable for winter use unless provision made for draining.	Use at disposal site to provide flexibility in selecting field for disposal.
Vehicles: Tank Truck	Capacity, 500 gal. up to maximum allowed on road. Can have gravity discharge or forced (pressure or pump) discharge.	Can use for highway transport and field application. Can use large tractor trailer rig for highway transport but must transfer for field application. If flotation tires used for field travel, not recommended for long distance highway travel.
Farm Tractor and Tank Wagon	Capacity, 800 to 3,000 gal.	Low speed; principal use would be field application, not distance hauling.

TABLE 3.—Transport Modes for Solid Sludge.

Mode	Characteristics	Comments
Rail Hopper Car	Need special unloading site and equipment for field disposal.	Possible use when final disposal is of landfill type. Sludge can be flushed from cars to a lagoon for disposal as a slurry.
Trucks, dump or other type	Suitable for wastes or sludges in solid, nonslurried form.	Trucks can be fitted with equipment to spread waste on ground surface. If dump truck used, will need to level sludge piles. With large application rates, soil incorporation desirable.
Farm Wagons or Manure Spreaders	Suitable for wastes or sludges in solid, nonslurried form.	Principal use would be field application, not distance hauling. With large application rates, soil incorporation desirable.

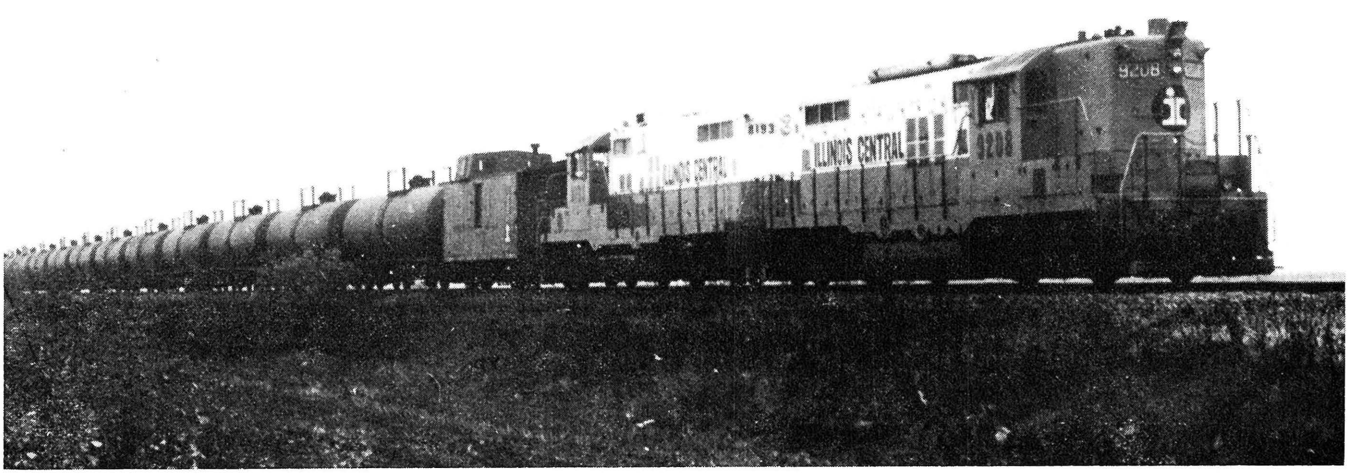

FIG. 2.—Rail tank cars used for hauling sludge from Chicago to Arcola, Ill.

used to improve field trafficability, highway travel should be limited. Commercial tank trucks are available from companies handling equipment for sewage and sludge treatment and handling. Several small cities have adapted tank trucks for discharge of sludge on fields.

Gravity discharge from the tank truck is most common (Figure 3). The rate of discharge can be increased by using a pressurized tank or pumped discharge. The area of application also can be enlarged by using a forced discharge. One truck observed in this project had the tank mounted so that the front end can be elevated, like a dump truck, which helps to give a more uniform discharge rate and to remove settled solids (Figure 4). Settling of solids has been a problem in the transport of sludge. The number of storage events should be a minimum. It would be advisable to provide some form of agitation, either during transit or prior to discharge from railcars and large tank trucks on long hauls.

Many commercial tank wagons are designed for disposal of animal manures in the liquid form. Different models are shown in Figures 9, 11 and 14. These units are ideally suited for field application, usually having flotation tires. Because of the low tractor speeds, however, they are not suitable for distance hauling. The use of tractors and tank wagons will be discussed in more detail under Application Modes.

The transporting of solid, nonslurried sludge may be required under certain circumstances, e.g., where dewatering of sludge is desirable due to disposal restrictions. The number of feasible transportation modes is less than for slurried sludge. The principal concerns in transporting solid sludge are

FIG. 3.—Gravity discharge of sludge.

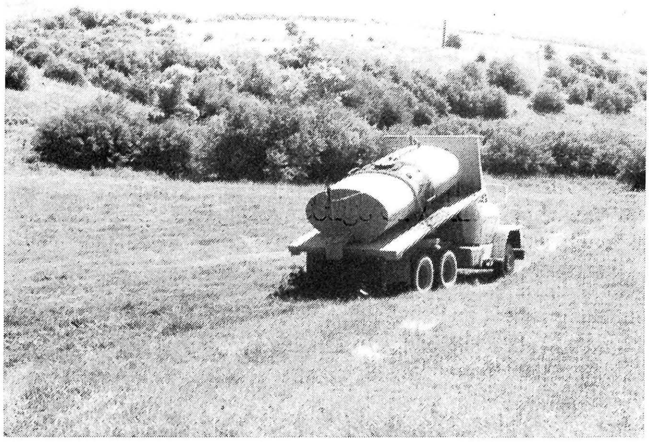

FIG. 4.—Elevating tank to give more uniform discharge and remove solids (Pullman, Wash., 1972).

FIG. 5.—Conventional farm manure spreader.

FIG. 6.—Large, commercial spreader. Courtesy of BJ Manufacturing Co., Dodge City, Kan.

TABLE 4.—Field Application Modes for Slurried Sludges.

Mode	Characteristics	Topographical and Seasonal Suitability	Comments
		SURFACE APPLICATION (Not suitable where odor nuisance is a factor)	
Irrigation			
Spray (sprinkler)	Large orifices required for nozzle Large power requirement Low labor requirement Wide selection of commercial equipment	Can be used on rough or steep land Can be used year-round with provision for draining in winter Not suitable for application to some crops during growing season Sludges must be flushed from pipes when irrigation stops	Application rate not recommended to be over 1/4 in./hr.; less if runoff begins to occur Permanent irrigation set can be used on pasture and woodlands
Ridge and Furrow	Less power requirement than spray irrigation Land preparation needed	Between 1/2 and 1 1/2 % of slope, depending on percent solids Can be used in furrows between row crops during growing season Can be used year-round with provision for draining pipes in winter	
Overland Flow	Used on sloping ground, vegetation controls runoff	Can be applied from ridge roads	Suitable for emergency operations. Hard to get uniform applications. Helpful on very poor soil
Tank Truck	Capacity, 500 to 2,000 gallons Larger volume trucks require flotation tires	Smooth and level or slightly sloping land Not usable with row crops or soft ground	Can be used for transport and disposal With pressure or pump, discharge can be sprayed from roadway along field
Farm Tractor and Tank Wagon	Capacity 800 to 3,000 gallons	Smooth and level or slightly sloping land Not usable with row crops or on soft ground	Can be used with overland flow
		SUB-SURFACE APPLICATION (Suitable to control odors)	
Tank Truck with Plow Furrow Cover	Capacity, 500 gallons Single furrow plow mounted on rear of truck	Smooth and level or slightly sloping land Not usable on wet or frozen soil	Not suitable for long transport
Farm Tractor and Tank Wagon Plow Furrow Cover	Sludge discharge into furrow ahead of single plow; 170 to 225 wet tons/acre /application (40,000 to 55,000 gal.) Sludge spread in narrow swath and immediately covered with plows; 50 to 125 wet tons/acre/application (12,000 to 30,000 gal.)	Smooth and level or slightly sloping land Not usable on wet or frozen soil	Additional tractor power needed to pull plow These application rates may cause pollution, depending on the amount and the form of nitrogen; i.e., NH_3 or organic
Subsurface	Sludge placed in channel opened by tillage tool; 25 to 50 wet tons/acre/application (6,000 to 12,000 gal.)	Smooth and level or slightly sloping land Not usable in wet, hard, or frozen soil	Additional tractor power needed to pull tillage tool Vehicles should not traverse injected area for a week or more

TABLE 5.—Field Application Modes for Solid Sludges.

Mode	Characteristics	Comments
Spreading, either truck mounted or farm spreaders	Waste spread evenly over ground. Normally followed by soil incorporation, disking or plowing. Use plow or disc large enough to give complete coverage.	Very light applications (less than 2 dry tons/acre) need not be incorporated unless surface runoff is likely to occur.
Piles or Windrows	Spreading (bulldozer) may be needed for large piles. Leveling (scraper or grader) may be needed to give uniform application. Incorporation, large moldboard and disc plows can incorporate 4 to 6-inch layer adequately.	Two limitations should be considered for large application, amount of nitrogen, particularly NH_3-N, and amount of salts, particularly sodium and potassium cations.
Reslurry and handle as in Table 4		Suitable for long hauls where rail transport is available.

spreading it evenly upon the ground surface and incorporating into the soil. It has been the experience of the Metropolitan Denver Sewage District that the conventional farm manure spreader (Figure 5) is not large enough. A commercial truck spreader (Figure 6) has a capacity of up to 20 tons (590 cu. ft.).

Field Application Modes:

The characteristics of the wastes or sludges will affect application methods. Wastes or sludges which are slurries can be handled and applied to fields with certain types of equipment (Table 4). The application of sludges in the solid form will necessitate using different equipment and techniques (Table 5).

When slurried sludges are not likely to cause an odor problem, surface application is feasible. However, when the sludge is likely to cause odor problems, e.g., raw sludge, septage (septic tank solids), activated sludge, and other wastes not completely stabilized, it is advisable to incorporate the sludge into the soil immediately upon application. Soil incorporation not only reduces odor nuisance but will prevent waste from attracting flies or rodents and prevent surface runoff carrying the sludge to streams.

- **Surface application.** Two basic types of equipment can be used for surface application: irrigation and tank truck or wagon. The irrigation equipment can be divided into the spray or sprinkler type and into the ridge and furrow type. A wide variety of commercial irrigation equipment is available (Figures 22 and 24). A listing of irrigation equipment manufacturers is given annually in the Product File issue of Implement and Tractor Magazine (16). Many irrigation equipment manufacturers will provide consulting services. But it is advisable to get at least three proposals for evaluation or use a professional engineer to obtain the set-up best suited for a particular situation.

The decision whether to establish fixed irrigation sets or portable sets will depend upon the land use, expected life of the particular disposal site, and management available. It is recommended for sludge that large nozzles, 1 to 2-inch diameter or larger, be used to reduce the danger of clogging. A minimum of 50 p.s.i. will be required at the nozzle to provide small droplets. A pressure of 80 to 100 p.s.i. is recommended with the larger nozzles. Utilizing a flexible hose and a trailer-mounted nozzle which can be winched across the field, 8 to 10 acres can be irrigated with one setting. Specific irrigation designs and power requirements can be obtained from irrigation equipment manufacturers.

Research at the Pennsylvania State University on irrigating treated sewage effluent has demonstrated the feasibility of year-round applications, even during sub-zero weather (20). More recently, mixed sludge and effluent was irrigated. In the Penn State study, both the reclamation of land and recharge of ground water were accomplished in conjunction with the disposal of effluent and sludge.

Spray irrigation can be used on both smooth and rough land, provided runoff is controlled. Ridge and furrow irrigation requires that the land have a slope between ½ and 1-½%. The smaller slope would be for sludge with less solids, i.e., more liquid. Ridge and furrow irrigation is suitable for row crops such as corn or soybeans. Spray irrigation may damage some growing crops due to sludge drying on leaves. During the growing season, pasture or woodland can be used for spreading. The ridge and furrow system requires much less power for pumping the sludge as the liquid flows out of equally spaced holes (1 inch or larger) along the pipe.

Tank trucks and farm tank wagons are in common use. Commercial tank wagons are listed annually in the Farm and Industrial Equipment issue (Red Book) of the Implement and Tractor Magazine (16). Both require relatively smooth and level or gently sloping land. These tank vehicles are not usable on soft ground, i.e., wet or plowed ground. The tank truck is suitable for use by treatment facilities where the haul distance is but a few miles. Attachments required for field spreading are very simple: a quick opening or closing valve and a deflector plate to fan the slurry over a large area. In most cases, a gravity discharge is used but some commercial tanks can be pressurized or have a pump. The vehicles with large tanks, 2,000 gallons and larger, usually require flotation tires to improve field travel.

The use of gravity discharge tanks requires that the vehicle traverses the ground where application is made, which may be prohibitive because of wet or soft ground. The use of a pressurized tank or truck-

FIG. 7.—Commercial tank truck with pump discharge. Courtesy of Gorman-Rupp Co., Mansfield, Ohio.

FIG. 8.—Covering of slurried waste with a single, moldboard plow. Courtesy of Prof. C. H. Reed, Biological and Agricultural Engineering, Rutgers Univ.

FIG. 9.—Discharging slurried waste in narrow swath from a tank wagon.

FIG. 10.—Immediately covering discharged waste with a four-moldboard plow.

mounted pump enables the discharge to be directed to the side of the vehicle (Figure 7). The truck can drive on a road or improved lane during soft ground conditions and spray the waste over into the field. It is recommended that local and state regulations be checked before discharging from public roads. The use of a pressurized tank or pumped discharge should be considered if only one unit is to be used and continuous field application is required.

- **Soil incorporation:** Equipment for incorporating slurried sludges in soil is available for attachment to either tank trucks or farm tank wagons. Two principal methods used to incorporate sludge in the soil are plow furrow cover and subsurface injection.

A single moldboard plow attachment has been used where the sludge is placed in the furrow ahead of the plow and immediately covered (Figure 8). This method was developed by Reed (21) at Rutgers University. Where large quantities of slurried sludge or waste need to be applied to the soil, the waste may be discharged onto the ground surface (Figure 9), and then immediately covered with a tractor pulling a gang of moldboard or disc plows (Figure 10). This method has been successfully used to control odors from slurried animal manures (23).

Subsurface injection utilizes a chisel, sweep, or other tillage tool to open a channel in the soil and the liquid waste flows either by gravity or under pressure into the opening. Depending on the tillage tool used and the ground cover, the channel may close by itself or it may be necessary to apply pressure. The application rate will depend on the size of the opening and whether gravity or pressure feed is used. It has been the experience where this type of equipment has been used that a vehicle cannot be driven over the track within a week without causing the waste to ooze to the surface.

With the single plow furrow cover, application rates have been calculated to be between 170 to 225 wet tons (40,000 to 55,000 gal.) per acre per application. When the sludge is spread in a narrow band on the ground surface and then plowed under, the application rate is between 50 to 125 wet tons (12,000 to 30,000 gal.) per acre per application. When the sludge is injected into the soil, the application rate is between 25 and 50 wet tons (6,000 to 12,000 gal.) per acre per application.

Soil incorporation is limited to smooth and level or gently sloping land and to soils which are free from large rocks or heavy root systems. Incorporation cannot be done with wet soil conditions or when the ground is frozen. No cropping can be done at the time of incorporation.

If the soil is particularly hard, such as a clay pan, or if rocks are present, tillage tools with a vibratory input can be used. The power requirements will be about the same for tillage tools with vibratory input as regular tillage tools, because the power required for the vibratory input will be about the same as the draft power reduction.

Incorporation of sludges below the normal plow depth, 6 to 10 inches, has been found to retard the biological breakdown. This slowdown is likely due to lack of soil mixing and reduced soil aeration. Therefore, depth of soil injection and incorporation should not be below the normal plow depth for the particular area if beneficial effects of sludge additions to the soil are desired.

- **Application of solid sludge:** When the solid sludge is spread evenly on the ground surface, using either a manure spreader or some spreading device on a truck, incorporation can be accomplished using plows or discs. The size of the plow or disc selected should be such as to give complete coverage. When the sludge is hauled in a dump truck and put in piles or windrows, leveling and spreading the material should precede incorporation. Where several inches of sludge will need to be incorporated, large moldboard or disc plows can be used. Available plows are listed in the Farm and Industrial Equipment issue (Red Book) of the Implement and Tractor Magazine (16).

Surface application of large quantities of beef cattle feedlot manure has been researched by Johnson (17). Application rates used were 0 (control), 150, 300, and 450 tons of dry matter per acre. The moisture content of manure was about 50%. This work evaluated the degree of soil incorporation when 30-inch and 18-inch moldboard plows and a 27-inch trencher were used. Leveling of piles dumped from a truck was done before incorporation. The 27-inch moldboard plow (30 to 36 inch depth) satisfactorily incorporated the 300 tons/acre application. The 18-inch plow (21-inch depth) worked well up to 150 tons/acre. The trencher incorporated the highest loading, but its cost per ton was higher. It is recognized that these application rates are large and could cause pollution.

CHARACTERISTICS OF FIELD EQUIPMENT FOR SLUDGE APPLICATION

Most equipment used for applying sludge to soil is a modification or direct use of either irrigation or animal and septic waste handling equipment. Until the early 1960's, animal wastes were primarily handled in dry form. Now, liquid handling is a popular technique and is complemented with a large number of tank-type spreaders. With some of these liquid spreaders, soil injection is available for immediately incorporating the waste with the soil to control odors. Irrigation equipment can be used when sludge is handled in liquid form. Irrigation is especially desirable when the disposal area remains fixed and well defined. Equipment selections range from solid-set sprinkler systems to open flow flooding.

EQUIPMENT FOR DIFFERENT APPLICATION METHODS

Tank Wagon and Tank Truck Spreaders for Liquid Type Wastes:

Tank wagons pulled by tractors offer a great amount of in-field mobility and flexibility for spreading sludge. The relatively low road speeds of tractors, however, limit hauling to short distances. According to the Implement and Tractor 1972 Red Book (16), the load capacities for currently available spreaders range from 800 to 3,000 gallons. Some tank wagons surface spread, some have knives to inject the material into the soil, and some wagons (Figure 11) are capable of both. In almost all cases, the tanks are constructed of steel with flexible rubber hoses used in the pipelines. Corrosion would probably not be a major problem when handling treated sludge.

The loading opening height varies appreciably among wagons. Some have a top hatch 80 to 90 inches above ground and others use a pump to load. This pump may either handle the material directly or an air pump is sometimes used to create a vacuum in the tank. Some manufacturers provide both top hatch and pump. The top hatch is desirable for many sludge-handling operations, since it allows rapid filling.

All large tanks subjected to high speed operations should have some sort of baffling. The inertia of liquid wastes in a large tank can make starting,

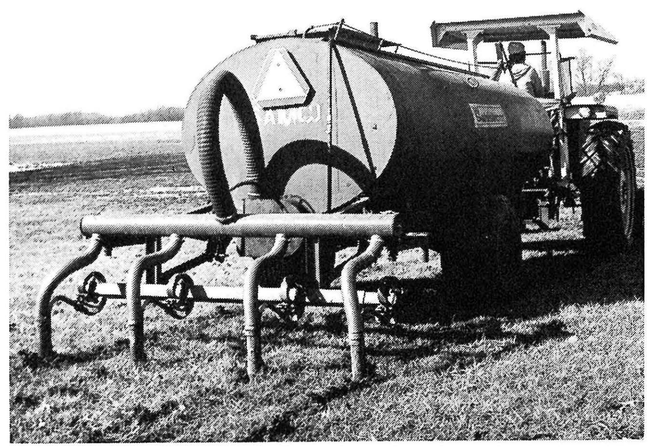

FIG. 11.—Tank wagon injecting liquid waste into soil.

stopping, and cornering very hazardous. Likewise, this liquid in motion may subject the equipment frames and hitching points to high enough yield stresses that the size of the power unit may be dictated by the maximum vertical load imposed upon the tractor drawbar. The American Society of Agricultural Engineers (2) recommends that ". . . the loads imposed by the implement tongue on the tractor drawbar positioned for power take-off operation shall meet the following specifications: Under field conditions, the vertical dynamic load on the drawbar shall not exceed 70 lb. (32 kg.) per maximum drawbar horsepower; and with the implement and tractor at rest on level ground, the vertical static load on the drawbar shall not exceed 30 lb. (14 kg.) per maximum drawbar horsepower."

A few spreaders designed to handle semi-liquids have open tops. Such an arrangement allows rapid loading and the possibility of using a bucket-type loader. These spreaders, however, are limited to low-speed operation to avoid spillage. Odors are not confined.

Many of the tank characteristics for trucks are the same as those for tank wagons. Most manufacturers will fabricate a given size tank and spreader for either trailer mount or truck mount. The tank truck shown in Figure 12 has a gravity discharge with a deflector plate for spreading. Figure 13 shows the same truck spreading sludge on a cold day. Injection shanks are not available for trucks due to the additional power and traction requirements.

The major disadvantage of trucks is the decrease in field mobility compared to tractors. There are, however, an increasing number of off-road, high-flotation vehicles available which can handle injection equipment and are capable of longer haul distances than conventional tractors.

- **Surface spreading from mobile tanks:** The unloading rate is variable and not well known for some wagons, but many can surface spread at a rate of 350 gallons per minute over a 25 to 40-foot width. The unloading and spreading is usually accomplished with either a pump, a flail, a spinner, or a deflector plate with gravity flow. A pump system often attains the most uniform spreading throughout the entire load. Most systems which rely on gravity have a decreasing flow rate as the tank empties. Although the pump adds to the initial cost and maintenance of the spreader, it can also be used for filling the spreader tank.

Some pumps handle the slurry directly, and some create a vacuum within the tank for filling and pressurize the tank for unloading. The slurry pump has the advantage of providing agitation via a bypass valve to keep all solids in suspension. Other systems sometimes use auger devices for agitation. For any sludge spreader, it is important that tank agitation is available to avoid settling of solids. Otherwise, the period from filling to unloading will have to be minimized.

- **Soil injecting from mobile tanks:** Most manufacturers of liquid manure tank wagons now have soil injectors available for some or all models. The common arrangement is to have two injectors spaced 50 to 60 inches apart. Injection depth or shank penetration can be variable and depends on the soil characteristics and ruggedness of the injector shank. Typically, penetration is from 6 to 14 inches.

There is some variation in injector design. The spreader in Figure 11 uses a 2 to 3-inch wide chisel shovel followed by a 3 to 4-inch discharge pipe. The result is a channel in the soil filled with liquid waste. The machine in Figure 14 uses a deep-tillage sweep-

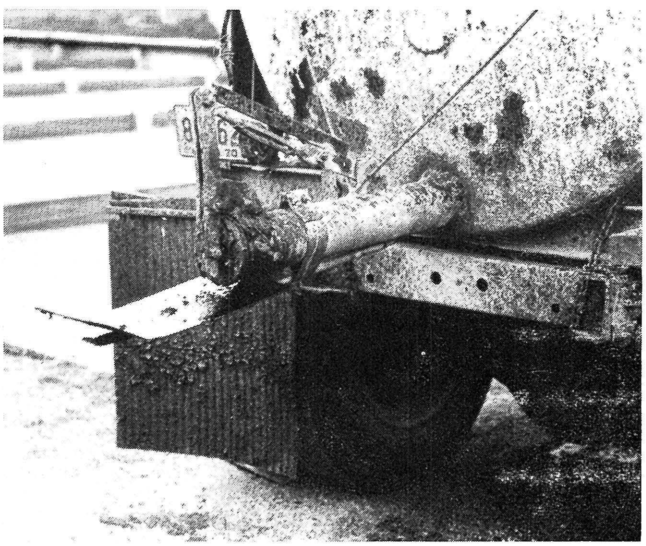

FIG. 12.—Deflector plate on tank truck.

FIG. 13.—Spreading digested sludge on a cold day.

shovel which produces a wider cavity than the chisel. In either case, the spring loaded covering *spoons* shown in Figure 15 are desirable to avoid exposure of malodorous wastes to the air. The coulter ahead of the injector shank in Figure 15 is a desirable feature when injecting in sods. The coulter will cleanly cut plant roots and surface trash which might otherwise collect on the injector shank.

Some interesting techniques for soil injecting have been tried by Professor Charles Reed, Department of Agricultural Engineering, Rutgers University. One technique was called plow-furrow-cover and consisted of a liquid manure tank with a discharge chute just ahead of a moldboard plow. Another more unique method was called sub-sod injection. To accomplish this, Professor Reed fastened together the landsides of one left-hand and one right-hand moldboard plow. The soil inverting moldboards were then reshaped to only lift the soil about 2 inches. The left side of the injection plow is shown in Figure 16. Liquid was transferred through the shank to fill the 2-inch cavity made by the plow. The plow was mounted on a three-point hitch tractor pulling a tank wagon. Demonstrations indicated that a 2 by 24-inch band of liquid waste could be injected 6 to 8 inches below the surface with very little disturbance to a sod.

A second type of sub-sod injection plow developed by Professor Reed is shown in Figures 17 and 18. Wastes flow from the tank through a 6-inch diameter flexible hose into the sub-sod injector. Figure 19 shows an injection strip 100 feet long, containing 500 gallons of manure slurry with 10% solids.

Such a system has a potential for applying sludges in parks or along public roadways. For large operations, the task could actually be accomplished with a series of injectors all placed on the same tool bar.

Box Spreaders for Dried Wastes:

There is a long list of pull and truck mounted box-type manure spreaders which could be used for dried sludge. Load capacities range from under 100 bushels to 524 bushels (125 to 650 cu. ft.). All of the large pull and truck types are power-take-off driven, while some small pull types are ground driven. The box may be constructed of either wood, steel, or a combination of each. Often the box has a wood floor with steel sides.

Many box spreaders have an optional gate system for holding and spreading liquid wastes. This feature provides much versatility, but the open top and lack of baffling can promote spillage during transport. The large top surface area also can allow rapid release of malodors.

FIG. 14.—Tank wagon with sweep-shovel injectors.

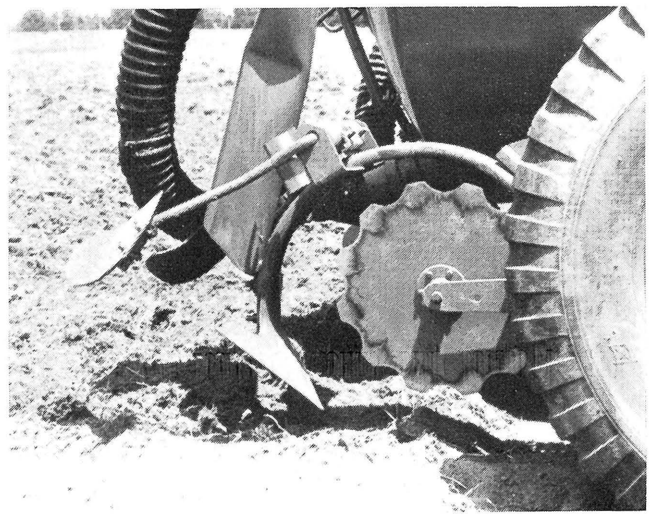

FIG. 15.—Sweep-shovel injectors with covering spoons.

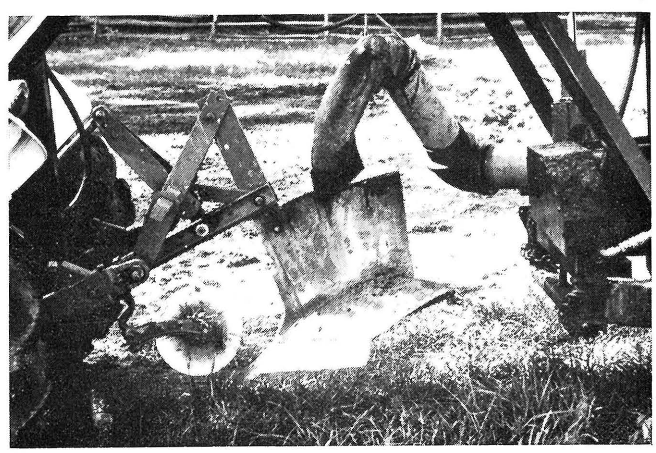

FIG. 16—Sub-sod injection plow made from mold boards.

Overland Flow (Flood) Irrigation:

Overland flow irrigation is sometimes used on long grass slopes by allowing open flow from a pipe. The major difficulty is controlling the uniformity of application when soil slopes and infiltration rates are quite variable. If the slopes are not steep enough and the solids content is high, solids will settle out near the discharge pipe. It has potential for use on wooded slopes as well as grass-covered slopes.

Ridge and Furrow Irrigation of Liquid Wastes:

Ridge and furrow irrigation is used primarily with row cropping. High crops such as corn are planted on a ridge and irrigation is done in the furrow. The corn shown in Figure 20 was irrigated with sludge from the Hanover, Ill., treatment plant. Gated pipe (Figure 21) is used at the top end of each

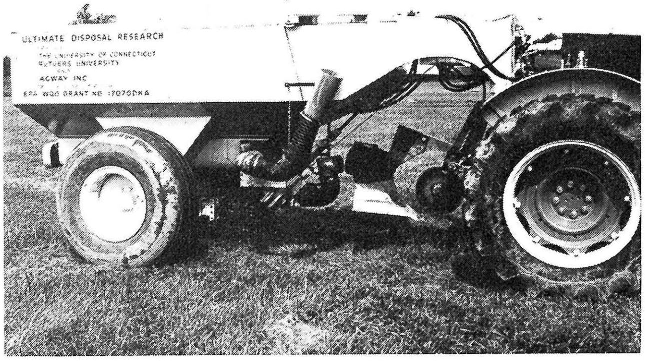

FIG. 17.—Second type of injection plow with 1,000-gal. tank trailer with gooseneck tongue. Injector mounted on three-point hitch of tractor. Courtesy of Prof. C. H. Reed, Rutgers University.

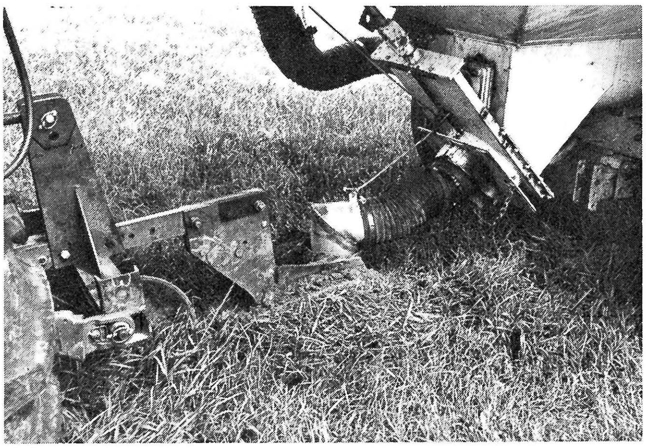

FIG. 18.—Sub-sod injection plow in the ground. Courtesy of Prof. C. H. Reed, Rutgers University.

FIG. 19.—Sub-sod injection strip. Courtesy of Prof. C. H. Reed, Rutgers University.

FIG. 20.—Sludge applied to cornfield via ridge and furrow irrigation.

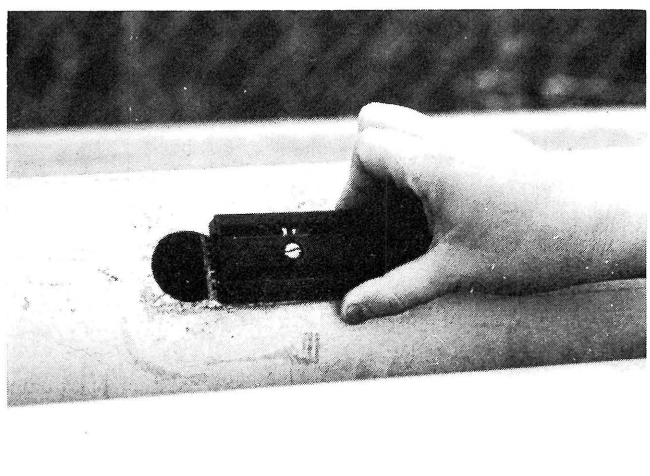

FIG. 21.—Opening on pipe for ridge and furrow irrigation.

furrow for discharge. The gated pipe is preferred over an open channel header to prevent early settling of solids. The furrows should have a $\frac{1}{2}$ to $1\frac{1}{2}\%$ slope away from the header, depending on the solids content of the sludge. Greater slopes for higher solids will prevent early settling. The major disadvantage of this system is that it may initially require extensive land forming with continuous maintenance and preparation for each crop.

Pipe and Sprinkler Irrigation of Liquid Wastes:

Pipe and sprinkler irrigation may be either a solid-set or portable pipe system. A solid-set system has the piping network permanently located under ground. A portable-pipe system has all the pipe above ground and can be disassembled and moved to different locations. Pipe and sprinkler systems are usually used on a well-defined disposal area which is in continuous grass. It cannot be used continuously with some crops because the solids collect on the plants and retard growth. Sludge must be flushed or drained from pipes whenever the system is shut down to prevent solids accumulation.

Center Pivot Irrigation of Liquid Wastes:

Center pivot irrigation is a highly mechanized portable sprinkler system. It is designed to cover areas up to 160 acres by sprinkling along a radius of 1,320 feet. These systems are capable of traversing highly variable terrain and the pivoting speed can be adjusted to control application rates. Figure 22 shows the pivot point and mobile towers of a center pivot system. Experience of SEMCO at Arcola, Ill., indicated that sludge at 10% solids could settle in various parts of the moving pipe. Slurries of less than 5% solids could probably be handled by these systems, but their pricinpal potential is for the handling of effluents. This equipment can distribute water effectively in tall crops, but the sludge build-up on leaves might be detrimental if sludge is applied frequently.

Big Gun Nozzle Irrigation of Liquid Wastes:

Big gun nozzles similar to the one shown in Figure 23 seem to be preferred for large application rates of high percent solids. Nozzle orifice diameters are typically 1 to 2 inches. To obtain the 80 to 100 p.s.i. pressure recommended at the nozzle, an auxiliary pump is usually an integral part of the sprinkler. Some systems have both the pump and nozzle, and others have just the nozzle mounted on a wagon which is winched across the field at a desired application rate (Figure 24). Water or sludge is brought to the nozzle through a flexible hose. The winch and a flexible feeder line allow up to 10 acres to be covered with one setting.

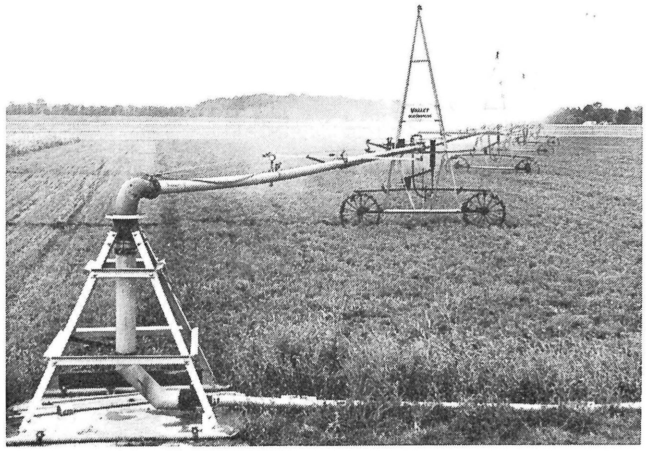

FIG. 22.—Center pivot irrigation system.

FIG. 23.—Big gun nozzle for traveling irrigation system.

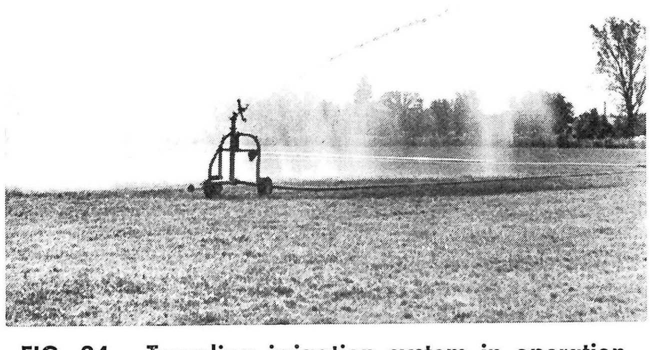

FIG. 24.—Traveling irrigation system in operation.

POWER REQUIREMENTS AND POWER UNITS

Power Requirements for Field Spreading and Soil Injection:

The total power required for field spreading consists of that needed for motive power, plus power-take-off power for pump distribution equipment, and/or the power required to pull injector blades through the soil. Motive power requirements are a function of the soil and its load-bearing capacity, cross-sectional and outside diameter of the tires, tire inflation pressure, and the total load placed on the tires. The load-bearing capacity of soils increases with a decrease in soil moisture and is also increased by vegetation, preferably grass. Because of the great variability of soil conditions, motive power requirements will vary widely and may be estimated from Figure 25.

As tire size is increased, less sinkage occurs and motive power requirements will be decreased. In comparing two tires of similar ground contact area, a tire with a small cross section and a large outside diameter will have a lower motive power requirement than a tire with a large cross section and small outside diameter. Similarly, four tires of equal size will have lower motive power requirements if used in a tandem rather than a dual configuration.

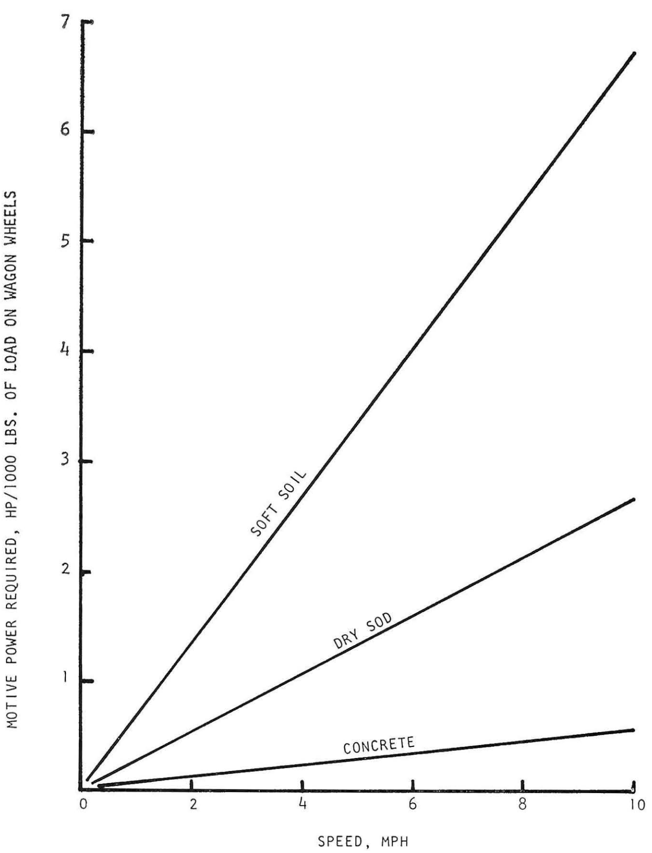

FIG. 25.—Possible range of motive power required to pull a tank wagon on different surfaces.

Power-take-off power may vary from zero on certain units to a maximum of about 15 horsepower on any of the commercial units now available. Almost all of the larger units are power-take-off driven and the manufacturer should be asked for those specifications.

Power requirements for injectors operating at a 10-inch depth will range from about 2 to 4 horsepower per mile per hour of forward travel, depending upon soil conditions. It is generally assumed that one to two injectors will require 10 additional horsepower under most conditions.

Total power requirements will require a tractor in the range of 50 to 60 horsepower for a 1,000-gallon tank wagon, 80 to 90 horsepower for a 2,000-gallon tank wagon, and 110 to 120 horsepower for a 3,000-gallon tank wagon.

Tractors are available from all of the major farm equipment companies. The units will vary in size from less than 25 to more than 170 horsepower. Models may have a choice of gasoline, LP gas, or diesel engines. However, in the larger sizes of tractors, diesels predominate. The most economical choice for a particular location can be recommended by the tractor dealer. Performance and specification data for all tractors are published by the University of Nebraska (19).

Power Requirements for Pipeline Transport and Irrigation:

Pumping power requirements are a function of the gallons per minute pumped, the specific weight of the sludge, the efficiency of the pump, and the total head in feet (pressure) against which the material must be pumped.

$$HP = \frac{Qwh}{33{,}000\ E_p}$$

where:

- HP = horsepower input to pump,
- Q = pump discharge in gal/min,
- w = specific weight in lbs/gal,
- h = total head in feet,
- E_p = pump efficiency as a decimal fraction.

The head consists of the suction lift in feet, the friction head loss in the pipe, and the pressure head at the irrigation nozzle. The suction head and the pressure head at the nozzle are readily determined. The friction head loss, however, cannot be computed for sewage sludge by the use of common hydraulic formulas. Chou (7) proposed a method for calculating friction head loss, and such calculations should be performed in the design of a system. However, the power requirements can be roughly approximated since it is unlikely that friction head losses will exceed 10% of the total head to operate a large irrigation nozzle requiring 180 to 280 feet of head for operation.

Stationary power units may either be electric motors or internal combustion engines fueled by LP gas, gasoline, or diesel fuel. When internal combustion engines are used, they should be equipped with monitors to protect the engine from overloading, overheating, or loss of oil pressure. The characteristics of available internal combustion engines may be found in the Implement and Tractor Red Book (16).

If electric power is available, electric motors have many advantages such as low initial cost, ease of control, low maintenance cost, and low operational cost.

ANALYSIS OF SLUDGE DISPOSAL SYSTEMS

Waste treatment and disposal on agricultural land is generally divided into three phases: treatment at the plant, transportation between the plant and the disposal site (or sites), and application to the soil. Similarly the cost of the overall operation is generally divided into three components associated with the three phases: treatment cost, transportation cost, and disposal cost.

The cost distinctions are especially apparent for large plants serving large municipalities. They might not be as apparent for smaller plants where sludge need not be hauled for long distances, and therefore may be transported and applied to the land with the same equipment. These distinctions may also be a carryover from the time (not too long ago) when waste recycling was not seriously considered and what happened to the sludge beyond the treatment plant was of very little interest to the public. As a result, the plant absorbed just about the entire cost of the operation and very little was spent on disposing of the plant output. When public opinion changed and considerably more transportation and disposal costs became necessary, they were distinguished from the traditional treatment cost.

The cost distinctions are quite convenient from an economic point of view and could indeed be used to perform a sound cost analysis of the overall operation. The risk one might run by using them is to emphasize one phase of the operation and attempt to minimize its cost without due regard to the effect on the other phases. It should be clear that the three phases are matched together and interact with each other. For example, there is no advantage in reducing treatment cost by producing less concentrated sludge (lower total solids content) unless the savings exceed the additional transportation and disposal costs due to the additional amounts of water which must be hauled and disposed of (the amount of dry matter does not change). Similarly, reducing the transportation cost by using a small pipeline all year-round may not be justified when sludge cannot be disposed of during the winter unless the savings exceed the additional handling and storage costs at the disposal site.

The three phases, therefore, form a dynamic system which could be analyzed according to the well-established techniques of systems analysis. The system consists of all possible processes which raw waste must undergo until it is applied to the soil. The individual process which the sludge actually undergoes is a pathway, or pathways, of this system. The system will be referred to in this study simply as the *disposal system.* The name is quite general but will be used to designate disposal by soil application only, and not by other methods (landfill, incineration, etc.).

The objective here is to formulate the mathematical model which describes the disposal system and to discuss the method of obtaining its optimal solution. This would require a detailed description of the system, some discussion of its cost function and constraints, and some reference to available solution techniques.

DISPOSAL SYSTEM DESCRIPTION

A block diagram of a *typical* sludge disposal system is shown in Figure 26. The blocks represent *some* of the possible processes raw waste might undergo until it is applied to the soil. The diagram is a compromise between an oversimplified block diagram which can describe sludge disposal only qualitatively (such as three blocks for treatment, transportation, and disposal) and a detailed diagram describing each possible pathway quantitatively. The diagram is intended just to communicate the concept of the disposal system quantitatively, rather than to describe every possible pathway in sludge disposal. The mathematical model presented later is sufficiently general to accommodate additional disposal alternatives.

The one-way lines connecting the various blocks denote the one-way transfer of sludge between the consecutive processes represented by these blocks. No processing is represented by these lines and no cost is incurred along them. The composition of sludge flowing along the lines is determined by the treatment facility and may vary from pathway to pathway. Lines originating (or terminating) at the same block represent the transfer of various quantities of sludge which was (or may be) mixed into the same product.

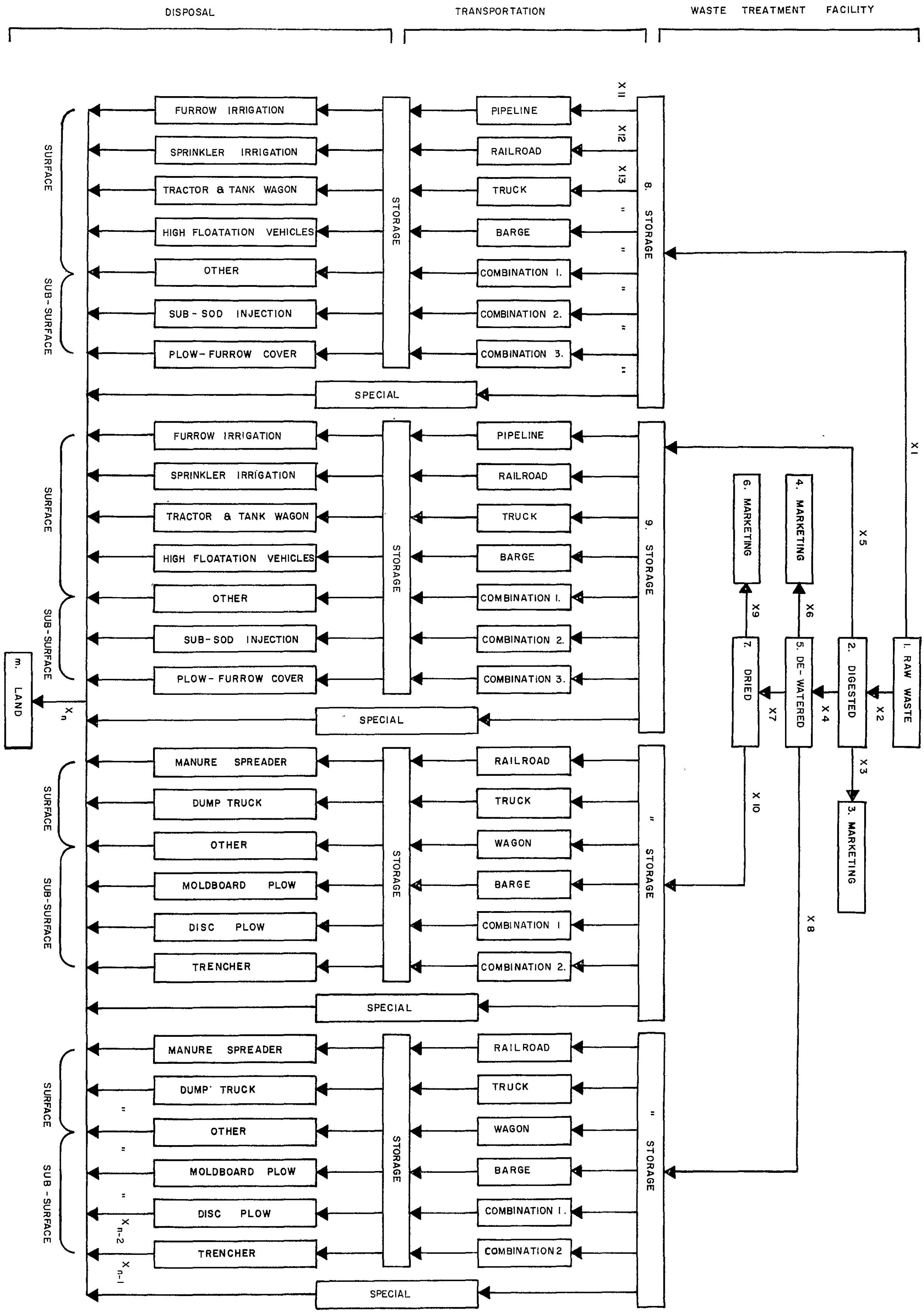

FIG. 26.—Block diagram of a typical sludge disposal system.

The block diagram describes some possible pathways from one treatment facility to one disposal site. Processes not used in a given situation can be eliminated from the diagram or retained at a zero cost so that they would not affect the choice of the optimal pathway. If more than one treatment facility or disposal site is considered, a block diagram must be used for each facility-site combination. The obtained composite block diagram would still be analyzed in the same manner as Figure 26.

Figure 26 shows the three general phases of the disposal system: treatment, transportation, and disposal. They will be discussed in some detail.

Treatment Facility:

The treatment facility generally produces digested sludge with total solids content of 2.5 to 5%, but typically in the 3 to 4% range. If the sludge is going to be hauled over long distances, the transportation cost may, in general, be reduced by further concentrating the sludge through a thickening process, thereby reducing the amount of sludge to be hauled. Thickened sludge would have a TS of 6 to 10% (wb), although 8 to 9% would be more typical. More water could still be removed through an additional vacuum filtration process producing dewatered sludge with a solids content of about 20%. Finally, the sludge could be dried in drying beds to a solids content of 60 to 80%.

Treated sludge might be suitable for sale as a fertilizer if offered at a sufficiently attractive price to potential buyers. A marketing block is included after each treatment process to represent this pathway. It is intended to denote all the special handling, packaging (if any), storage, etc., which would be associated with marketing. The utilization of sludge sold by this method will not be considered in this study beyond the marketing stage.

Treatment plants will have to have facilities to store their output so the transportation would not be hindered by the fluctuations of the output due to the intermittent nature of their processes. The storage also allows the plant to continue operation should the transportation stop for a period of time due to a breakdown or unfavorable conditions at the disposal site. Sludge can be stored in digesters or clarifiers for a few days at the most. Some form of digestion or stabilization should precede storage in open lagoons to control odors.

Storage may be considered a process of the treatment phase used to regulate the fluctuating plant output. It may also be considered a transportation phase process when used as a standby dump in case of transportation breakdown, or even a disposal process when necessitated by conditions at the disposal site. Its cost may therefore be assigned to any particular phase or shared by more than one. The important points are to recognize it as a process of the total system, select it based on the needs of the total system, and include its cost in the cost of the total system.

Sludge Transportation:

Sludge is produced in a slurried or a solid form. Slurried sludge is mostly liquid and can be pumped, whereas solid sludge cannot. The sludge form is determined by its moisture content; i.e., its total solids content. In general, sludge with less than 10% TS (wb) is slurried and that with more than 15% TS (wb) is solid. It may be noted that, according to this distinction, digested and thickened sludge are both slurried, and dewatered and dried sludge are both solid.

The distinction between slurried and solid sludge affects the choice of transportation modes which may be used to haul it. Slurried sludge can be transported by pipeline, railroad tank cars, tanker trucks, barges, various combinations of these modes, or specialized vehicles. Examples of the last mode are trucks and tractor-wagons equipped with spray nozzles, moldboard plows, sub-sod injection implements, etc., which are also used to apply sludge to the soil. They are particularly suited for smaller treatment plants with short hauling distances. On the other hand, solid sludge can be hauled by railroad hopper cars, trucks, tractor wagons, barges, appropriate combinations of these modes, or specialized vehicles such as manure spreaders with an oversized bed for storage. Such specialized equipment also would be more suited for smaller treatment plants.

Storage may generally be needed at the disposal site to provide flexibility in the time and rate of sludge application. Storage would be needed if either the transportation or the disposal is intermittent, such as transportation by truck or railroad and disposal by tractor and tank wagon. If the system is unreliable, more storage capacity is needed. For example, a standby dump could provide storage for the unhauled sludge if the disposal equipment should break down. Stored sludge could be used to keep the disposal equipment running if the sludge inflow to the disposal site should be interrupted. This storage may be considered a transportation phase process, a disposal phase process, or even a treatment phase process, depending on which phase is most intermittent and least reliable. Its cost may therefore be assigned to any one phase or shared by more than one. Again, as in the treatment plant storage, the important points are to recognize it as a process of the total system, to select it based on the needs of the total system, and include its cost in the cost of the total system.

Sludge Application to Soil:

Sludge may be applied to agricultural land either above or below the soil surface. The application method is affected by the sludge form: slurried or solid. Slurried sludge may be applied to the soil surface by furrow irrigation, sprinkler irrigation, tractor and tank wagon, or high flotation vehicle. Subsurface application is performed with sub-sod injection and with the plow-furrow cover methods. Special multi-purpose equipment has also been used to haul the sludge to the disposal site and apply it to the soil. Two and four-wheel drive tank trucks, equipped with high flotation tires and spray nozzles or moldboard plows, have been used. Tank wagons, equipped with augers inside the tank and sub-sod injection implements, have also been used. Other multi-purpose equipment might be already in existence and being used.

Solid sludge and animal manure have been applied to the soil surface successfully by manure spreaders. Dump trucks, bulldozers, and levelers have also been used but were less successful in obtaining uniform spreading.

Sub-surface application has been performed with moldboard plows, disc plows, and trenchers. Johnson (17) described manure incorporation into the soil produced by trenchers as "remarkable." Special multi-purpose equipment to apply solid manure are not known but seem quite feasible. Manure spreaders with extra large storage capacities, or trucks with manure-spreading type mechanisms are conceivable.

COST CONSIDERATIONS

The total cost of the treatment, transportation, and disposal of sludge is the sum of the costs of all processes of the disposal system (Figure 26). The cost of an individual process should be based on the total cost of the process; i.e., both fixed and variable costs. Variable costs are those which increase with the use of the equipment performing the process, whereas fixed costs are independent of use. The equipment use is proportional to quantity of sludge processed.

It may not be readily apparent which cost items are fixed and which change with the quantity of sludge processed. Interest on the investment, taxes (where applicable), housing, and insurance are functions of time and essentially independent of the quantity of sludge processed. On the other hand, the costs of electric power, fuel, daily maintenance, repairs, and labor are essentially functions of the quantity of sludge processed. Finally, the depreciation cost seems to be a function of both the quantity of sludge processed and time. Detailed discussion of the various cost items is beyond the scope of this bulletin and is available in management textbooks such as Hunt (15). The purpose of citing these costs is only to make sure that *all* cost items of the process are taken into account.

Knowing the quantity of sludge processed by a given process over a given period of time and knowing the total cost of the process during the same period, the cost per ton is far less dependent upon the quantity of sludge processed than the total process cost. It is almost independent of the sludge quantity when the equipment is working near its rated capacity. As such, the cost per ton is considerably more convenient to use.

The cost per ton could be based upon the sludge quantity before or after processing. The two quantities are the same unless the process produces a change in the sludge concentration. The cost per ton of processed sludge would therefore depend upon concentration changes, if any, as well as the total process cost. It seemed desirable to make the processing cost per ton directly proportional to the total process cost and independent of the extent of concentration changes by basing it on the sludge quantity before processing. In other words, the cost per ton of processed sludge would therefore depend upon concentration changes, if any, as well as the total process cost. It seemed desirable to make the processing cost per ton directly proportional to the total process cost and independent of the extent of concentration changes by basing it on the sludge quantity before processing. In other words, the cost per ton will be associated with sludge quantities flowing along lines terminating at the block and not originating there (Figure 26).

Defining n as the number of lines in Figure 26, m as the number of blocks, and X_j as the weight of sludge which flows along the *jth* line per unit time (day, week, month, or year), the input to the *ith* block, q_i, can be expressed as follows:

$$q_i = \sum_{j=1}^{n} a_{ij}X_j \text{ for } i = 1, 2, \ldots m \qquad (1)$$

where a_{ij} is equal to 1 if j is associated with a line *terminating* at the *ith* block, and is equal to zero if the line does not terminate there. The equation is simply the summation of all sludge quantities entering the *ith* block. Defining the processing cost per ton C_i for the *ith* block, the total cost Z of the entire disposal system would be given by

$$Z = \sum_{i=1}^{m} C_i q_i$$

$$= \sum_{i=1}^{m} C_i \sum_{j=1}^{n} a_{ij} X_j$$

$$= \sum_{j=1}^{n} \left(\sum_{i=1}^{m} a_{ij} C_i \right) X_j$$

$$= \sum_{j=1}^{n} c_j X_j \qquad (2)$$

where:

$$c_j = \sum_{i=1}^{m} a_{ij} C_i \qquad (3)$$

Designating the block at which the *jth* line terminates by the subscript k and knowing that a line terminates at one and only one block, it follows from the definition of a_{ij} that

$$a_{ij} = 0 \quad \text{for } i \neq k,$$

$$a_{kj} = 1,$$

hence:

$$c_j = C_k \qquad (4)$$

Equations 2 and 4 suggest that the total system cost could be calculated by directly assigning the processing cost per ton of each block to all lines terminating at it and summing the cost of the sludge quantities flowing along these lines. This is merely a convenient way of arriving at the total system cost because, strictly speaking, no processing is represented by these lines and no cost is incurred along them.

The treatment, transportation, and disposal costs per ton of sludge are not constant but are functions of many factors. Some of these factors are external to the disposal system and, as such, are imposed on whatever disposal system used. They are constraints which the system has to cope with and at the same time they affect the processing cost per ton for one or more blocks (Figure 26). Examples of these factors are the nature of the raw waste to be treated, its annual quantity and seasonal distribution, the geographic location of the treatment facility, any governmental regulations which must be satisfied, etc. Other factors are internal to the system, such as the total solids content of the treated sludge. It would not only affect the amount of sludge to be transported and disposed of, but also the treatment cost per ton, which makes the system nonlinear. The pertinent factors affecting the cost coefficients c_j's are discussed in more detail.

Nature of Raw Wastes:

The nature of the raw waste such as its chemical composition, concentration, heavy metal content, odor, etc., affects the treatment cost. It essentially determines the type and extent of the treatment required (if any) to stabilize the incoming raw waste; hence, it affects the total cost of the treatment facility (interest on investment, depreciation, power, housing, etc.). It also affects the quality of the produced sludge which in turn affects its commercial value. The transportation and disposal methods are directly related to the sludge commercial value. Can it be applied beneficially to agricultural land and warrant transportation and disposal in a certain form, or should it be incinerated or buried in a landfill? In fact, even if the sludge is beneficial to the soil, its transportation and disposal would be affected by its nature. For example, sludge with obnoxious odors requires more expensive handling equipment and disposal methods (plow-furrow cover or sub-sod injection instead of surface application).

Annual Quantity of Raw Waste:

The annual quantity of raw waste to be treated and disposed of is the predominant factor which determines the size of the operation. It is generally assumed that the larger the size of the treatment facility, the lower the treatment cost per ton of raw waste due to the use of bigger and presumably more efficient equipment. The assumption should hold for the disposal phase of the operation but may not necessarily hold for transportation if the sludge has to be spread over larger disposal areas.

The annual quantity of raw waste also affects the logistics of the transportation phase. While it is possible to haul sludge from small treatment facilities on a regular basis with trucks or tank wagons and keep up with the facility output, it would be logistically impossible to do the same for large treatment facilities such as the Chicago Sewage Treatment Plant. More elaborate handling, storage, and transportation equipment would be needed for larger facilities.

Seasonal Waste Distribution:

The annual load distribution on a treatment facility affects its operation to no small extent. Communities with substantial seasonal variations in their waste output demand more storage and/or treatment capacity of their treatment facilities than their annual output might otherwise indicate. Examples of such communities are small communities with substantial seasonal industries such as food processing, small campus towns with considerable college enrollment, convention centers, etc.

The additional storage spreads peak loads over a period of time, thereby reducing the treatment capacity needed to handle the peak load. On the other hand, the additional treatment capacity would reduce prolonged storage of raw wastes. In either case, the additional storage and/or treatment capacities involve a higher total cost per ton of raw waste.

The choice between additional storage and/or treatment capacities should not be based upon the economic operation of the treatment facility alone. It should take into account the operation of the entire disposal system. Certain transportation modes and disposal methods may not be feasible all year round in many regions of the U. S., such as transportation by barge and sub-sod injection. The use of such transportation or disposal methods would alter the scheduling picture altogether. If the maximum load occurs when the maximum transportation and disposal potential exist, only minimal storage would be needed. As an example, generation of waste by a food processing plant and disposal by sprinkler irrigation on appropriate crops would be generally well matched in season so that no storage might be necessary. On the other hand, a campus town in a northern latitude (low waste output during the summer and frozen ground in the winter) disposing of its sludge by surface spreading or sub-surface injection should have considerable storage.

The choice of specific treatment, transportation, or disposal equipment is affected by the amount of annual use. In general, intermittent use could tolerate equipment with higher running costs if its initial investment is sufficiently lower than what might normally be used. For example, a pipeline used to transport sludge all year round is usually cheaper than trucking because of its lower operating cost, but could be more expensive if used a few days a year. A treatment plant might consider such a pipeline if it is transporting to a single disposal site, but would not if it disposes on numerous small sites each accommodating the plant output for only a few days.

Geographic Location:

Geographic location affects the waste treatment cost through many factors such as the commercial value of the site of the treatment facility, labor cost, power cost, etc. The weather conditions associated with the location can also make certain treatment processes economically feasible in one region and nonfeasible in another. For example, drying sludge in the Southwest might be economically performed with solar radiation but could be uneconomical in humid regions where artificial heating would be needed.

The geographic location also affects transportation and disposal methods and their cost. For example, transportation by barge may not be available in some locations, exposed pipelines might not be tolerated where the freezing risk is high, plow-furrow cover or sub-sod injection are not practical in frozen ground, etc. Furthermore, as discussed above, seasonal and/or intermittent use of such equipment introduces entirely new factors: scheduling and storage.

Total Solids Content:

The concentration of treated sludge is directly related to the treatment processes it undergoes. Generally speaking, the higher the total solids content (TS), the higher the treatment cost per dry ton to produce it. On the other hand, the higher the TS, the lower the amount of sludge which has to be handled, transported, and disposed of and, in general, the lower the transportation and disposal costs. The selection of the extent of the treatment should therefore be based on the economics of the entire system, rather than the treatment aspect only.

The TS of the treated sludge also affects the transportation and disposal methods. For example, slurried sludge might be transported economically by pipeline and disposed of by sprinkler irrigation if its TS is below 8 to 10%. Higher TS tends to rule out sprinkler irrigation in favor of surface irrigation, application by truck or tank wagon, or sub-sod injection. Still higher TS tends to rule out the pipeline in favor of transportation by railroad, truck, etc.

SYSTEM CONSTRAINTS

The disposal system has three types of constraints on the sludge quantities x_j's which flow through its different pathways: internal, external, and feasibility constraints. All constraints must be satisfied at all times. A pathway is the sequence of all treatments, transportation, and disposal processes which raw waste undergoes until it is applied to the soil. It is represented in Figure 26 by the blocks appropriate to these processes and the lines connecting them.

Internal Constraints:

An internal constraint is the functional relationship between the input and output of a block. The input of the *ith* block, q_i, was defined by equation 1. The output of the *ith* block, Q_i, can be similarly expressed,

$$Q_i = \sum_{j=1}^{n} b_{ij}X_j \text{ for } i = 1, 2, \ldots, m$$

where b_{ij} is equal to 1 if j is associated with a line *originating* at the *ith* block, and is equal to zero if the line does not originate there. The functional relationship of the *ith* block can now be expressed as follows:

$$\sum_{j=1}^{n} b_{ij}X_j = F_i \sum_{j=1}^{n} a_{ij}X_j, \quad \text{for } i = 1, 2, \ldots, m \qquad (5)$$

where F_i is the ratio of the total amount of sludge leaving the block to that entering it. It is equal to 1 unless the process represented by the block produces a change in the sludge concentration (that is, TS). Only the principal treatment processes (digestion, thickening, dewatering, and drying produce a substantial change in concentration (an increase in TS; hence, an F_i less than 1), although a slight change in concentration could occur while sludge is stored at the treatment plant or at the disposal site. This change is generally an increase in concentration ($F_i<1$) due to moisture evaporation or seepage, but could also be a reduction in the event of rainfall on open storage facilities. Digestion heat treatment and line stabilization produce substantial changes in the total tons of solids to be handled as well as in the concentration of solids.

External Constraints:

External constraints are functional requirements imposed on the disposal system by the community, the government, the environment, etc., in which it operates. In other words, external constraints are those conditions imposed on the sludge quantities flowing along the various pathways of the system by everything external to the system. For example, the requirement that the treatment plant should have a capacity greater than or equal to a certain figure based on the estimated raw sewage generated by the community is an external constraint. Limits dictated by the capacity of existing treatment plants, or any individual treatment process, are external constraints. Limits set by transportation modes: what may be used and what may not, capacity of those which may be used, frequency of use, etc., are all external constraints. The requirement that the sludge disposed of annually on the soil should not exceed a certain amount per acre, and its frequency of application, are external constraints. Any additional limits on the heavy metal content (or other pollutants) are external constraints. Limits dictated by climate or environment are external constraints.

An external constraint on the amounts of sludge flowing through the pathways of the system may take any one of the following forms:

$$\sum_{j=1}^{n} d_{ij}X_j \ (\leq, \ =, \ \geq) \ P_i \quad \text{for } i = 1, 2, \ldots, m_1 \qquad (6)$$

where P_i is the limit which must be observed (maximum or minimum), d_{ij} is the coefficient of the *jth* variable X_j in the *ith* constraint, and m_1 is the number of external constraints. Unlike internal constraints, the subscript i may not necessarily be associated with the *ith* block, since a block may have none, one, or more than one external constraint imposed on it. The subscript i simply identifies the constraint among all the m_1 external constraints.

Feasibility Constraints:

Assume that a fixed quantity q tons of a given product has to be processed into a final form by process No. 1, process No. 2, or a combination. Let the quantity processed by each process be X_1 and X_2, respectively, and let the processing cost per ton for each process be C_1 and C_2, respectively. The total processing cost Z would be given by

$$Z = C_1X_1 + C_2X_2 \qquad (7)$$

where

$$q = X_1 + X_2 \qquad (8)$$

Assuming further that C_1 is less than C_2, intuition says that the total cost Z would be minimized when the entire quantity q is processed by process No. 1. The optimal solution for X_1 and X_2 would therefore be given by

$$X_1 = q \qquad (9)$$

$$X_2 = 0 \qquad (10)$$

Mathematically speaking, minimizing the total cost Z (equation 7) subject only to the continuity constraint (equation 8) does not lead to the same optimal solution (equations 9 and 10). Since both X_1 and X_2 are algebraic quantities which may assume positive or negative values, more saving would be realized if X_2 is assigned a negative value without violating the continuity constraint (X_1 would be greater than q). In fact, a profit would be realized if X_2 is made sufficiently negative and that profit has no upper limit. This meaningless result was obtained by allowing X_2 to become negative. It would have been avoided and the same optimal solution (equations 9 and 10) would have been mathematically derived if neither variable was allowed to assume a negative value.

The requirement that each variable be greater than or equal to zero is the so-called feasibility condition which must be satisfied at all times. It is expressed for the disposal system as follows:

$$X_j \geq 0 \text{ for } j = 1, 2, \ldots, n \quad (11)$$

MATHEMATICAL MODEL

The mathematical model of the disposal system puts the various concepts which have just been discussed in a quantitative form which lends itself to known optimization techniques. The objective of the analysis is to minimize the cost of the entire disposal system while satisfying all m internal constraints, m_1 external constraints, and the feasibility condition. It is developed in a sufficiently general form in the Appendix that it would still be valid with any deletions from, or additions to, the block diagram (Figure 26). The general model could be summarized as follows:

Minimize the cost function

$$\sum_{j=1}^{N} c_j X_j = z$$

over the region

$$\sum_{j=1}^{N} d_{ij} X_j = P_i \text{ for } i = 1, 2, \ldots, M \quad (12)$$

and

$$X_j \geq 0 \quad \text{for } j = 1, 2, \ldots, N$$

The solution technique of the mathematical model as described by equation 12 depends on the nature of the cost coefficients c_j, and the constraint coefficients d_{ij} and p_i. If these coefficients are constant over a sufficiently long period of time, linear programming techniques could be utilized to select the least expensive treatment, transportation, and disposal system. Detailed discussion of linear programming solution methods for optimizing alternative systems is beyond the scope of this bulletin and is available in textbooks such as Hadley (12). Hadley also discusses several interesting topics such as the maximum change in costs which would not alter the optimal solution pathway. Such aspects of linear programming theory could be used to a great advantage in analyzing the sludge disposal system.

If one or more cost coefficients of a given process change with the amount of sludge processed, or if the constraints on a given process change with the amount of sludge processed, the problem becomes nonlinear and requires the more elaborate nonlinear programming techniques. Such nonlinear cost functions and constraints are more typical of sludge disposal systems. As previously suggested, the cost per ton for many treatment and disposal processes is expected to decrease when more sludge is processed. Many constraint coefficients also change with the amount of sludge processed. A constraint on heavy metal content of sludge disposed of on the soil is likely to specify less heavy metal per ton of sludge (lower d_{ij}) with higher amounts of sludge. Detailed discussion of nonlinear programming techniques is also beyond the scope of this bulletin and is available in specialized textbooks such as Abadie (1), Arrow, *et al.* (3), Boot (6), Dennis (10), and Duffin, *et al.* (11).

If the cost function or the constraints change with time, the solution of the mathematical model would require dynamic programming techniques. This type of a model is associated with systems subject to seasonal variations in costs, storage needs, or constraints. Most disposal methods in the United States would be affected by seasonal temperature variations. Many treatment and transportation methods are also affected. This should emphasize the value of dynamic programming in the solution of sludge disposal models. Detailed discussion of dynamic programming is well beyond the scope of this bulletin and is available in many textbooks such as Bellman (4), Bellman and Dreyfus (5), and Hadley (13).

While the study of linear programming, nonlinear programming, or dynamic programming requires several specialized courses building on a good background in mathematics and computer programming, their use in analyzing sludge disposal systems is fortunately not that difficult. Canned programs are available on most large scale computers which would solve equations (12) using these programming techniques. The instructions for any of these programs explain how the various coefficients (c_j, d_{ij}, and p_i) could be included and how to interpret the final solution format.

APPENDIX
A MATHEMATICAL MODEL FOR THE DISPOSAL SYSTEM

The objective of the mathematical analysis is to minimize the cost of the entire disposal system while satisfying all m internal constraints, m_1 external constraints, and the feasibility conditions. The cost function, the system constraints, and the feasibility conditions were all discussed in the text. The mathematical model can be expressed as follows:

Minimize the cost function,

$$\sum_{j=1}^{n} c_j X_j = z, \tag{13}$$

such that,

$$\sum_{j=1}^{n} b_{ij} X_j = F_i \sum_{j=1}^{n} a_{ij} X_j \quad \text{for } i = 1, 2, \ldots, m \tag{14}$$

$$\sum_{j=1}^{n} d_{ij} X_j \ (\leq, =, \geq)\ P_i \quad \text{for } i = 1, 2, \ldots, m_1 \tag{15}$$

$$X_j \geq 0 \text{ for } j = 1, 2, \ldots, n \tag{16}$$

This mathematical model could further be rearranged to take a more familiar form. First, the inequalities which occur in the external constraints (equation 15) can be converted into equalities through the use of appropriate slack and surplus variables as outlined by Hadley (12). Multiply each constraint with a negative p_i by —1 and reverse the direction of the inequality so that all p_i's would be positive. Arrange the constraints into three groups as follows:

$$\sum_{j=1}^{n} d_{ij} X_j \leq p_i \text{ for } i = 1, 2, \ldots, k_1 \tag{17}$$

$$\sum_{j=1}^{n} d_{ij} X_j \geq p_i \quad \text{for } i = k_1 + 1, \ldots, k_1 + k_2 \tag{18}$$

$$\sum_{j=1}^{n} d_{ij} X_j = p_i \quad \text{for } i = k_1 + k_2 + 1, \ldots, m_1 \tag{19}$$

Define a new variable for each constraint of the first group (equation 17) to take up the *slack* of the left-hand side relative to the right-hand side.

$$X_{n+i} = p_i - \sum_{j=1}^{n} d_{ij} X_j \quad \text{for } i = 1, 2, \ldots, k_1$$

The variable is called a *slack variable* and obviously satisfies the feasibility condition.

$$X_{n+i} \geq 0 \text{ for } i = 1, 2, \ldots, k_1$$

Equation (17) can now be written as

$$\sum_{j=1}^{n} d_{ij} X_j + X_{n+i} = p_i \quad \text{for } i = 1, 2, \ldots, k_1 \tag{20}$$

Similarly a new *surplus variable* could be defined for each constraint of the second group (equation 18) to absorb the surplus in the left-hand side relative to the right-hand side,

$$X_{n+i} = \sum_{j=1}^{n} d_{ij} X_j - p_i \quad \text{for } i = k_1 + 1, \ldots, k_1 + k_2$$

The surplus variable also satisfies the feasibility condition

$$X_{n+i} \geq 0 \text{ for } i = k_1 + 1, \ldots, K_1 + k_2$$

Equation 18 can now be written as:

$$\sum_{j=1}^{n} d_{ij}X_j - X_{n+i} = p_i$$

$$\text{for } i = k_1 + k, \ldots, k_1 + k_2 \quad (21)$$

Defining the total number of variables N to include the original variables as well as the slack and surplus variables,

$$N = n + k_1 + k_2 \quad (22)$$

equations 19, 20, and 21 can be written in one single form as follows:

$$\sum_{j=1}^{N} d_{ij}X_j = p_i \text{ for } i = 1, 2, \ldots, m_1 \quad (23)$$

where the definition of d_{ij} is extended to include $j = n+1, \ldots, N$, as follows:

$d_{ij} = 1$ for $j = n+i$ and $i = 1, 2, \ldots, k_1$

$d_{ij} = -1$ for $j = n+i$ and
and $i = k_1 + 1, \ldots, k_1 + k_2$

$d_{ij} = 0$ for all other values of i and j

Second, noting that the internal constraints (equation 14) can be written as:

$$\sum_{j=1}^{n} (b_{ij} - a_{ij}F_i)\, X_j = 0$$

$$\text{for } i = 1, 2, \ldots, m$$

they could be treated as an extension of the external constraints and described by an extension of equation 23,

$$\sum_{j=1}^{N} d_{m_1 + i,j}\, X_j = p_{m_1 + i}$$

$$\text{for } i = 1, 2, \ldots, m \quad (24)$$

where:

$d_{m_1 + i,j} = b_{ij} - a_{ij}F_i$
for $i = 1, \ldots, m; \quad j = 1, \ldots, n$

$d_{m_1 + i,j} = 0$
for $i = 1, \ldots, m; \quad j = n + 1, \ldots, N$

$p_{m_1 + i} = 0$ for $i = 1, \ldots, m$

The external and internal constraints (equations 15 and 14) can now be expressed as

$$\sum_{j=1}^{N} d_{ij}X_j = p_i \text{ for } i = 1, 2, \ldots, M \quad (25)$$

where:

$$M = m_1 + m \quad (26)$$

Third, extending the cost function (equation 13) to include the slack and surplus variables at a *zero* cost per ton,

$$c_j = 0 \text{ for } j = n + 1, \ldots, N$$

and noting that the slack and surplus variables were shown to satisfy the feasibility condition, the mathematical model (equations 13 through 16) can be expressed in this convenient form:

Minimize the cost function

$$\sum_{j=1}^{N} c_jX_j = z$$

over the region:

$$\sum_{j=1}^{N} d_{ij}X_j = p_i \text{ for } i = 1, 2, \ldots, M \quad (27)$$

and

$$X_j \geq 0 \quad \text{for } j = 1, 2, \ldots, N$$

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