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This report also considers alternatives to conventional wastewater collection methods currently used by the Navy and focuses on: (a) compatibility with general terrain, (b) reduction of pipe size, (c) equipment and installation costs, and (d) operational manpower requirements.

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INTRODUCTION

The Civil Engineering Laboratory (CEL) has been tasked by the Naval Facilities Engineering Command (NAVFAC) to develop design criteria for vacuum wastewater transfer systems.

The wastewater generated by temporary, remote Naval activities requires effective management to prevent waste accumulation in operational complexes and industrial areas. Operational requirements at remote bases are such that wastewater transport and collection systems must be rapidly installed and operated in a fail-safe, cost-effective manner. Furthermore, it is imperative that this goal be met without subordinating the resources allocated for the primary mission.

Current pollution abatement technology for transporting and collecting liquid wastewaters includes:

- Traditional gravity methods
- Conventional pressure-system approaches
- Newly developed vacuum collection techniques

The most attractive alternative of the three cited candidates in meeting the remote Naval base requirements is that of vacuum-operated sanitation systems for collecting liquid wastes. This approach provides rapid, low-cost installation; is unrestrained, within limitations, by local topography; and allows for assembly of the transport piping without maintaining a standard grade requirement (i.e., minimum 1/4-in. slope/linear ft).

Vacuum systems allow for the collection of wastewaters into a common collection system while servicing a number of wastewater generating sources. This provides a cost-effective solution in applications where a network of series interconnected lift stations are required since vacuum systems can utilize parallel connected (wagon wheel configured) transport mains that represent independent collection systems/collection stations. When compared to low pressure sewer systems, vacuum applications become attractive because the reduced pretreatment requirements (such as grinding or maceration) decrease overall operation and maintenance (O&M) costs.

The most attractive asset possessed by a vacuum sewer system lies in its inherent fail-safe capabilities. Benefits, not encountered in conventional or pressure systems, include:

1. Reduced groundwater and potable water supply contamination resulting from leakage since the negative (or vacuum) pressure forces leakage into - rather than out of - the wastewater transport piping.

2. O&M requirements are decreased because vacuum sewer systems are aerobic; gravity and pressure sewer systems are generally anaerobic.*

In the past, design failures with vacuum systems have resulted from the improper assessment of vacuum lift requirements and the failure to provide appropriate capacity vacuum and wastewater discharge pumps.

This report focuses primarily on the development of design criteria for vacuum collection of wastewaters generated from multiple sources (such as toilets, kitchens, laundries, and showers) and transported in a single, common transport main. Although special purpose vacuum system applications are addressed to a limited extent, further research and development will be required to insure reliable, cost-effective operations of such systems in Navy applications.

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*An anaerobic condition typically produces a septic wastewater that is difficult to treat because of the increased production of such sewer gases as methane and hydrogen sulfide.

BACKGROUND

The vacuum sewage transfer concept, based upon the utilization of air as the primary wastewater transport medium, was introduced in Sweden in 1959 (Ref 1). In such systems, air is used to displace the water required in cleaning, flushing, and transport activities. The literature reports the vacuum collection process as the entrapment of waste material in a small quantity of flushing water that is propelled toward the vacuum receiving tank by a differential pressure (i.e., vacuum and atmospheric air) existing across the mixture of solids, liquids, and air. The literature and design manuals further go on to say that during this phase of wastewater transport, this mixture is formed into a small packet (or "slug") of liquid waste that is rapidly propelled down the pipeline, gradually deforming. This results from the unbalanced forces of pipe friction and gravity acting on the slug. As a result, slug deformation allows air to flow around and through the slug, reducing the driving force required for its movement. As slug movement slows, it further deforms, and eventually stops. To minimize the detrimental effects of slug deformation on wastewater transport, slug reformation traps were installed at specified intervals enabling gravity to assist in the slug reformation process. Rebuilding the slug serves to reestablish the differential pressure across the solid-liquid mixture and thus provides a mechanism for transferring the slug to the next trap.

Preliminary testing and subsequent experience have shown that a system design based on these conceptual assumptions is inadequate because of the inability of a liquid to support a shear force and remain intact as a slug, even for very short periods of time. This fundamental discrepancy has historically been compensated for by the use of large quantities of air for the transport of small volumes of wastewater.

The vacuum waste transfer concept has been reported to be a flexible transport process capable of being applied in the following configurations:

1. A single-pipe system where only vacuum toilets are connected to a vacuum sewer system (i.e., black-water system)(Ref 1)

2. A single-pipe system in parallel with the other where gray water sources (shower, laundry, and kitchen types of wastewaters) are connected to a vacuum sewer system (i.e., dual-pipe black- and gray-water system) (Ref 1)

3. A single-pipe system combining black and gray wastewater into a common transfer main, using conventional fixtures along with gravity-fed intermediate holding and storage tanks (Ref 1)

The first two configurations have been in use in the Bahamas and throughout Europe since 1965 (Ref 2) and have been installed in elementary schools, housing developments, and apartment complexes.

After several years of operation and maintenance, engineering efforts conducted by the Ministry of Works in Nassau, Bahamas, to further develop vacuum system technologies were discontinued. The unresolvable problems were: (1) frequent system bog-down or operation failure and (2) solids deposition within the transport mains. Excessive resources were reportedly being consumed by O&M; therefore, no future vacuum collection sewage installations were foreseen. Future efforts were to include reverting back to conventional gravity-type sewer systems until O&M problems with vacuum systems could be resolved.

Most commercial vacuum wastewater collection system installations have been of the first configuration - single-pipe, black-water system. Actually, the use of these systems in these applications, usually small-scale, is not representative of vacuum transport and collection since in most instances the transport mains are very short (less than 500 feet), the amount of water in the pipeline is minimal, and the collection tank is typically at a lower elevation than the wastewater source. In these applications, the pipeline remains open (empty) so vacuum can be available to those parts of the system requiring pneumatic energy for vacuum valve/component operation. In this configuration, wastewater flows in a gravity-assist mode, and the wastes and wastewaters are essentially carried by large volumes of air as discrete particles of mist and solids.

In 1970, the Jered Company, National Homes, Inc., and Colt Industries began commercializing these configurations in the United States. They placed major emphasis on vacuum system hardware and component development. One of their first efforts was a test demonstration of a single-pipe, black-water system in the Marine barracks at Annapolis, Md., in 1972 (Ref 3). This demonstration produced some satisfactory results. Although a number of mechanical problems with valves, piping, etc., were resolved, the effort provided no fundamental design criteria or performance standards that could serve as a basis for design.

Colt Industries distributes prefabricated vacuum wastewater collection systems and miscellaneous vacuum-operated components and valves. Their market consists primarily of small-scale recreational vehicles, railroad cars, 26-foot mobile restrooms, and Marine installations for ferry boat service (Ref 4). Here, too, the primary functions of the vacuum energy are to drive the air that assists in cleaning, provide a mechanism for operating the essential vacuum valves, and maintain a mini-flush water-consumption condition.

The Mobility Equipment Research and Development Center (MERDC), Fort Belvoir, Va., and the Naval Ship Research and Development Center (NSRDC), Annapolis, Md., are primarily concerned with test and evaluation of black-water systems for shipboard installation. These systems represent conservative designs and generally depend on the assistance of gravity for flow between decks. The solids are essentially transported by the flow of large volumes of air.

The Canadian Ministry of Transportation and the Royal Canadian Navy are currently using vacuum systems in mobile trailer parks and aboard their Navy destroyers (Ref 4). These installations are of the Colt Industries type and generally represent duplications of black-water systems found in Sweden and the Bahamas. The standard installation practice with these types of systems is to design the vacuum power supplies oversized; these assist gravity to attain reliable system operation. The large quantities of power consumed per gallon of waste transported may be of little significance in a water-short area that expends tremendous power reserves to generate the required quantities of flushing water.

The third configuration (i.e., single-pipe, black and gray water) came to the United States via Vacuum Technology, Inc., in 1970 (Ref 5). A number of large-scale operational installations have been made in housing developments in the eastern portion of the United States; the most significant of these is Lake of the Woods, located in Orange County, Va. The builder of this installation was successful in obtaining a permanent permit from the State Water Control Board in 1970 to operate the system The remaining developments were held in a temporarily accepted status pending the completion of performance evaluations prior to rendering a permanent acceptance. The Lake of the Woods system is currently undergoing major redevelopment because of its failure to reliably transport and collect wastewater in accordance with its design. Instead, the system became hydraulically overloaded and failed to perform before the housing development was even one-third complete. The remaining developments of this type were found to be in various stages of completion at the end of the last review conducted by CEL.

As a result of a growing public interest and requirements for engineering development, the Environmental Protection Agency (EPA) began investigating existing vacuum systems in the United States to identify the operational and design problems encountered in large-scale (pipeline lengths > 1,000 feet) and rolling-terrain applications. It has requested that CEL provide research and development reports as technology transfer support material in this evaluation.

Because of EPA's involvement and a general growing interest in vacuum sewer system application, operation, and maintenance, the AirVac Division of National Homes recently expanded its major marketing objective of hardware development. It increased its engineering staff with major proponents of vacuum systems from the Bahamas and placed a substantial portion of its engineering efforts on design criteria development of vacuum sewage transfer systems.

Problems historically associated with poor performance of vacuum wastewater collection systems are derived from the lack of design criteria. These problems can be represented as:

1. A failure to identify the fundamental principles surrounding the hydraulic/pneumatic characteristics of vacuum wastewater collection
2. The aura of complexity accompanying three-phase flow (liquid, solids, and air)

The most frequent failures associated with vacuum system performance have resulted from:

1. Inadequate power allocations for fully-loaded system operation
2. Lack of understanding of the terrain and system elements that form the basis for assessing lift requirements
3. Quantification of the relationships of vacuum reserve tank capacity to that of system lift requirements
4. Sizing the vacuum discharge pumps without recognizing their functions
5. High potential for solids and grease deposition in the transport line

DISCUSSION

The purpose of this report is to present the results of recent research and testing of vacuum wastewater transfer systems conducted by CEL to facilitate the development of design criteria.

Vacuum transport and collection of wastewater begins when liquid waste enters a transport pipe through an admittance valve. The wastewater is rapidly propelled by atmospheric air toward a vacuum storage/wastewater collection tank. This dual-purpose tank is both level-controlled and vacuum-pressure controlled to insure that it will not become filled with either air or wastewater. A wastewater discharge pump connected to the bottom of this tank completes the vacuum transfer cycle when it is actuated by a level control switch that transfers the collected wastewater to a treatment or disposal site. The wastewater transfer pump essentially performs the functions of collecting and transporting the wastewater. The vacuum pump serves only to remove the low pressure air from the system so that the suction side of the wastewater collection/transport pump remains primed and does not become air-locked.

The interrelationships of these concepts have been evaluated and analyzed with the assistance of an experimental test facility and are developed in the body of this report.

EXPERIMENTAL TEST FACILITY

An experimental vacuum wastewater transfer/collection system was designed by CEL and installed at the Naval Air Station, Point Mugu, Calif. This test site was to allow testing of the performance of system configurations and developing design criteria to support reliable wastewater transport and collection. As a result, this facility has undergone testing, evaluation, and extensive modifications since 1973. The original test facility consisted of three independent transport mains of 2-, 3-, and 4-in.-diam plastic pipe, each of which was about 1,100 feet in length and accommodated a net lift of 10.5 feet.

Each vacuum main could be supplied from three independent or combined sources:

1. One thousand-gallon tank representing shower, laundry, and kitchen wastes as derived from Point Mugu's sewer

2. Three vacuum toilets connecting directly to the vacuum main

3. Three mini-flush gravity toilets discharging into a level-controlled interface/storage tank

Test and analysis identified the need to modify the system from time-to-time to enable development of standard practices for predicting (1) transport phenomena (air/water/solids ratios) and (2) the relative impact of various hydraulic configurations on wastewater transport efficiencies. Since the initial system installation, the test facility has been modified to include methods for evaluating the following configurations and capabilities:

1. Two-in.-diam transport main with vacuum toilets loading into clear plastic pipe undergoing repeating elevation changes. The total cumulative lift is 32 feet over a horizontal distance of 100 feet, while the total net lift is only 12 feet over the same horizontal distance.

2. Three-in.-diam transport main more than 2,100 feet long with multiple source loading (i.e., nine tanks) attached to the transport piping at 100-foot intervals. The net system lift is 15 feet.

3. Four-in.-diam transport main 1,100 feet long that incorporates 300 feet of clear plastic sections. The slug reformation traps in this entire run have been removed. Net system lift requirements in this transport main are approximately 10.5 feet.

This report presents the results obtained from test and evaluation of the basic and modified system configurations and identifies essential design criteria to be considered for reliable vacuum system operation.

Vacuum System Energy Requirements

The practical action of the vacuum pump is to discharge the low-pressure air admitted to the system while a preset vacuum is maintained. The wastewater discharge pump must be designed to transport all the wastewater while working against the preset suction head in the vacuum reserve tank. The interrelationships between these two pumps have been examined to illustrate their independent and combined effects on the vacuum transport and collection process.

When the vacuum pump in steady-state condition removes 1 cu ft of low-pressure air from the vacuum reserve tank, an equivalent volume of low-pressure air or liquid is drawn into the vacuum reserve tank from the transport/collection system. When the wastewater discharge pump removes 1 cu ft of water from the tank, an equivalent volume of air and water mixture is drawn into the tank.

This description is presented to show that the "suction energy" expended by the vacuum pump in discharging 1 cu ft of low-pressure air is more than the suction energy expended by the discharge pump in discharging 1 cu ft of wastewater since the vacuum pump essentially gathers low-pressure air, compresses it to atmospheric pressure, and discharges it from the system. In other words, under steady-state conditions, equal amounts of air or water mixtures are transported equal distances along the pipeline by the discharge of either (1) a cubic foot of water or (2) a cubic foot of low-pressure air. It is concluded, therefore, that the relative quantity of energy required to operate the vacuum pump (as compared to the wastewater discharge pump) is independent of the pipeline's configuration. The absolute value of this energy, however, does change if either the pipeline's configuration or the relative proportions of air and wastewater in the transported mixture are changed.

The air-to-water ratio is the quantity most likely to vary in a fixed installation. Furthermore, it represents a major influence in the amount of energy required to transport the wastewater. The air-to-water ratio of the flowing mixture varies over a large range (both with time and throughout the system).

The theoretical significance of the air-to-water ratio in the transported mixture, measured in terms of energy, can be illustrated by the relationships that follow.

With the assumpton that the energy required to maintain a working vacuum while transporting and collecting liquid waste is proportional to the amount of air and wastewater collected,

$$E = k\bar{A}$$

where E = energy in watt-hours
k = proportionality constant
$\bar{A}$ = $A + W$
A = cubic feet of low-pressure air entering the collection tank
W = cubic feet of wastewater entering the collection tank

Since the primary objective of a vacuum transport/collection system is to transport and collect wastewater (transporting air being incidental to the process), it is more appropriate to express this relationship in terms of the energy required to transport a unit of wastewater; i.e.,

$$\frac{E}{W} = \frac{k\bar{A}}{W}$$

but

$$\bar{A} = A + W$$

Therefore,

$$\frac{E}{W} = \frac{k(A + W)}{W}$$

and

$$\frac{E}{W} = k + k\frac{A}{W}$$

setting

$$y = \frac{E}{W} \text{ and } x = \frac{A}{W}$$

$$y = k + kx \qquad (1)$$

This implies that the energy required to transport and collect a unit of wastewater is directly proportional to the air-to-water ratio plus a constant. Equation 1 further implies that the relationship of the energy required to transport or collect wastewater is linear with respect to the air-to-water ratio. Figure 1 illustrates the experimental confirmation of the relationship between energy and air-to-water ratios.

In the experiment, 50 gallons of liquid waste were injected into a 4-in.-diam transport main, and the air and energy necessary to collect the wastewater 1,114 feet downstream in the vacuum collection tank were measured.

Prior to each test injection of wastewater, the system's vacuum level was stabilized at 18 inches of mercury. Each 50 gallons of waste admitted to the 4-inch system was followed by approximately 30 seconds of air.

Vacuum pump energy was measured with a watt-hour meter, and the number of gallons of wastewater entering the collection tank were obtained by measuring level changes in the calibrated wastewater collection tank. The volume of air required to transport the wastewater was monitored at the vacuum pump's exhaust port. These two measurements were used to establish the energy per gallon of waste required to transport and collect various quantities of air and water mixtures over a distance of 1,100 feet while undergoing a net lift of 10.5 feet.

The experiment was repeated with 50-gallon loadings into a 3-in.-diam transport main under the same test conditions of system vacuum level and amounts of air. The results of this test showed that more energy per gallon of wastewater transported 1,114 feet was required than was previously required in the 4-in.-diam system test.

Decreasing the 50-gallon loadings to the 3-in.-diam transport main with each injection to 20 gallons produced (1) a corresponding decrease in the resulting friction losses and (2) a transport efficiency (energy consumed per gallon transported) consistent with the 4-in.-diam transport main's performance.

The 3-in.-diam system experiment was repeated with 20-gallon loadings and compared with the results of the 50-gallon, 4-in.-diam test. The results of this testing are shown in the experimental results of Figure 1 and summarized in Tables 1 and 2.

A regression analysis of the experimental data provides the following comparable empirical relationship between the energy required to transport wastewater and the air-to-water ratios required to support this process.

$$\frac{E}{W} = 0.07\frac{A}{W} + 0.07 \qquad (2)$$

One standard deviation (σ) of E/W as determined from the experimental data was:

$$\sigma = \pm 0.07$$

The relative effect of changing the diameter size of the transfer lines from 3 inches to 4 inches and the manner of introducing air at the wastewater generation point were observed to be insignificant when compared to the effect of changing the air-to-water ratio.

Figure 1 indicates that the most efficient vacuum wastewater transfer/collection system results from keeping as much air out of the system as possible. Operation of a system with no air (full bore) is difficult to attain operationally. It has been found that sewage transportation and collection utilizing a negative pressure (vacuum) is very susceptible to gas and air accumulation within the transport main because of air leakage into the system and because of dissolved air in the wastewater. For example, at atmospheric pressure the amount of air that may be dissolved in water is about 2.9% by volume at 32°F and about 1.9% by volume at 77°F. The solubility of air in water is inversely proportional to temperature and directly proportional to pressure; thus, the solubility of air in water is doubled at a pressure of 15 psig and halved at -7 psig (i.e., 15 inches of mercury vacuum) (Ref 6,7,8).

Another factor to be considered is that, under certain terrain conditions, injection of controlled amounts of atmospheric air into the system's vacuum transport piping may become desirable to blow accumulated wastewater from the line. This may be considered the equivalent of going beyond the theoretical 34-foot vertical lift limitation associated with a solid column of water.

Hydraulic Failures

In practice, leakage or other uncontrolled additions of air or gases into a vacuum system results in a reduced vacuum. Although a reduced vacuum can support liquid waste movement, liquid transport often results at a very low flow rate (i.e., inches per minute instead of feet per second). Low flow rate conditions tend to reduce system transport capacity, causing wastewater overflows at the source and solids deposition or grease buildups within the pipeline. The occurrence of wastewater transport at very low flow rates (e.g.. < 2 ft/sec) is commonly referred to as "bog-down."

As wastewater transport rates decrease because of insufficient pressure differentials, the vacuum transport main approaches a bog-down condition; small quantities of air, but not enough to move the liquid, flow through the wastewater toward the vacuum reserve tank. This is shown in Figure 2. This air, depending on pipe configuration and geometry, may migrate toward the vacuum reserve tank very slowly. During this time, usually on the order of hours, the accumulated wastewater remains untransported, blocking the pipeline by isolating or preventing the transfer of sufficient vacuum reserves to upstream areas for the operation of flush valves and initiation of wastewater transport when the system is opened to the atmosphere.

Maintaining System Vacuum

To support effective vacuum wastewater collection, the system's primary mover - the vacuum - must be maintained at a level sufficient to offset the total lift requirements and to support wastewater transfer.

Because of maintenance obligations and power costs, the vacuum level is generally maintained over a range. This practice eliminates numerous pump cycles resulting from an oversized pump trying to maintain a specific vacuum and avoids long-running cycles associated with a smaller or undersized pump trying to "catch-up."

Because of power demands and other factors, maximum vacuum pump capacity should be no more than twice the system demand (Ref 9). For example, in a 75-cfm system (i.e., 13 vacuum toilet flushes per minute) this criterion calls for a 150-cfm vacuum pump. This pump size would require a 10-hp power source that would draw approximately 35 amperes of current in a 220-volt circuit. Increasing the vacuum pump size to 250 cfm (more than three times the system's demand) would require 50 amperes of current during system operation. In addition to high steady-state current requirements, starting current surges of up to 600% can be expected each time the vacuum pump cycles (Ref 9). Because of the motor's inability to dissipate the heat associated with large current surges, numerous pump cycles may result in serious motor damage. Therefore, maximizing vacuum pump performance in terms of vacuum pump off-time is an important factor to consider. Pump motor sizes less than 30 hp are limited to a duty cycle of approximately 20 starts per hour; larger pump motors have a maximum frequency limitation of around five starts per hour.

Vacuum Reserve Tank

One method of minimizing the pump cycling requirement is to incorporate an appropriately sized vacuum reserve tank to act as a buffer to resist system vacuum level fluctuations. This would provide for longer periods of system operation between vacuum pump start-ups. One method for determining the appropriate capacity of this reserve is to apply control volume concepts and the principles of continuity to the air or vacuum portion of the system's collection station in the following manner.

Let Q_i represent the average volumetric flow rate of air entering the collection tank as a result of leakage and system usage and Q_o the volumetric flow rate of air leaving the system when the vacuum pump is operating. Therefore, for a vacuum system to maintain a given vacuum level under steady-state conditions, the amount of air being evacuated from the system must be equal to the amount of air entering the system. Mathematically, this is expressed as:

$$Q_i = K Q_o \tag{3}$$

where K is the ratio of the time the pump is on to the total time (the time the pump is on, T_1, plus the time the pump is off, T_2). The total time is represented by the quantity $T_1 + T_2$. Therefore,

$$K = \frac{T_1}{T_1 + T_2}$$

Because the number of times a vacuum pump motor may be started per hour is dependent upon its size, the frequency of system cycling becomes an operational limiting factor. Since frequency, f, is defined as the reciprocal of time, the K term becomes:

$$K = T_1 \frac{1}{T_1 + T_2} = T_1 f$$

and from Equation 3

$$Q_i = T_1 f Q_o \tag{4}$$

This relationship provides a method of evaluating system operation in terms of mass (air and water) flow rates, pump sizing requirements, and system cycling limitations. For example, in the 75-cfm Q_i system, th vacuum pump discharge capacity, Q_o, and the pump cycling requirements can be determined by using Equation 4, after pump running time criteria has been identified. Using a pump running time of 3 minutes out of every 12 (the pump is off three times longer than it is on) produces:

$$T_1 = 3 \text{ min}$$

$$f = \frac{1}{12} = 0.0833 \text{ min}^{-1}$$

and

$$Q_o = \frac{Q_i}{T_1 f} = 300 \text{ cfm}$$

Evaluating these results in terms of allowable starts per hour yields a frequency of 5 starts per hour which is the maximum limit for ratings above 30 hp.

The primary purpose of a vacuum reserve tank is to buffer fluctuations in available system vacuum and minimize the impact of pump cycling by providing longer periods of system operation before a pump turn-on is required. This relationship can be described by a state equation, PV = NRT, that characterizes the interrelationships of system pressure, vacuum reserve tank capacity, and pump cycling.

In this equation:

P = system pressure in atmospheres
V = volume of vacuum reserve tank in liters
N = vacuum reserve capacity in moles
R = universal gas constant (1-atmopshere/$^{\circ}$K-moles)
T = absolute temperature

Since the vacuum system reserve capacity is dependent upon operational vacuum requirements, this capacity can also be expressed as the volumetric flow entering the control volume during the vacuum pump's off-time.

$$N = T_2 Q_i \qquad (5)$$

This expression also represents the total amount of air or wastewater that enters the system when the operational pressure varies from its low point, P_1, to its high value, P_2.

At standard temperature and pressure conditions there are 22.4 l/mole and 28.31 l/cu ft. These conversion factors allow the units of the variables in Equation 5 to be adjusted consistently with the requirements of the basic equation of state. Rearranging and substituting this expression into the basic equation of state produces Equation 6.

$$V = \frac{T_2 (Q_i) RT}{P_1 - P_2} \qquad (6)$$

Equating the vacuum reserve tank to a control volume and evaluating this relationship in terms of the principles of continuity, the interrelationship of the various parameters of interest can be identified.

In applications where the vacuum pump capacity, Q_o, is larger than the rate at which the air and wastewater enter the system, Q_i, Q_i will be evacuated from a given vacuum reserve volume, V, at a rate that will maintain a given operational vacuum. Conversely, when a desired operational pressure has been identified, the appropriate reserve capacity that will enable the maintenance of this criteria in terms of system loading and minimum pump cycling can be determined.

Evaluating the criteria affecting the parameters of this derived expression will be necessary in determining the limitations associated with reliable vacuum system operation and identifying the potential marginal performance conditions encountered in existing operational vacuum systems.

The pressure term, P, in the derived expression is primarily dependent upon the system head requirements. The pump running time and input flow rate depend upon the pump's size and wastewater generation sources, which are also dependent on flow rate requirements.

Maintaining the initial assumptions of system flow rate under steady-state conditions determines the minimum vacuum pump capacity and, hence, the horsepower requirements to drive the vacuum pump. This criteria establishes the maximum number of pump cycles the system can tolerate per hour. The combination of the pump's capacity and its associated duty cycle provide the basis for determining the "pump-off" time.

System Head Requirements

In experimental testing, the air and water in the transport main separated as a result of the general system configuration and local terrain conditions. The positive sloping portions of the pipeline have been observed to consistently fill with wastewater; the negative sloping portions become filled with air. This hydraulic behavior requires that the total system design head include the cumulative elevation changes as derived from the positive sloping segments of the transport piping. This is opposed to the net elevation change utilized in full pipe flow system design. Thus, the lower design limit of the vacuum range (i.e., lowest vacuum or largest absolute pressure) must be larger than the maximum cumulative static head as measured in feet of water plus the required energy to provide sufficient wastewater transport while overcoming the pipe friction losses resulting from dynamic flow conditions.

Since the flow of wastewater in a vacuum transfer system also includes the management of entrained air, the transfer of this resulting air and water mixture is often referred to as two-phase flow. Although actual applications of a vacuum wastewater transfer system deal with three-phase mixtures of solids, liquids, and air, the solids portion of the wastestream has been historically neglected. This neglect has often resulted in many system failures because the wastewater flow rates were low enough, resulting from too many friction losses, to allow solids to deposit, thus plugging the pipeline.

It has been shown by the inventor, A. B. Electrolux Corp., and others, that the friction factors associated with two-phase flow systems are higher than those associated with a network flowing in a full pipe condition (Ref 11). The values of the resulting two-phase friction factor have been identified as a function of the air-to-water ratio of the transported two-phase mixture. It has been further shown that the friction factor is also a function of the transport piping's slope (Ref 12). Low friction factors have been identified with horizontal and vertical pipe runs while higher loss values have been identified with a pipe sloped at an angle of 45 degrees. Research conducted by others has shown the friction factor associated with a horizontal pipe was nearly the same as those tested vertically. It is concluded, therefore, that a vacuum system designed to lift must also include the appropriate friction loss factor's association with the characteristics of the lift.

The upper limit of a system's operational vacuum range is generally determined by the power costs and operational efficiencies associated with cost-effective vacuum pump operation.

Vacuum pumps in general display a performance curve similar to centrifugal wastewater pumps. They operate more efficiently at lower vacuums than they do at higher vacuums. As a result, it may require the same amount of energy to build a vacuum level from 18 inches to 24 inches of mercury as was required to bring a particular system from a 0-inch to an 18-in.-of-mercury vacuum level. Also, in applications where high vacuums are required (i.e., > 20 inches of mercury), the effects of excessive (i.e., > 24 feet of water) suction heads present substantial cavitation problems to the impellers of centrifugal wastewater-handling pumps (Ref 13). These pumps are used in conjunction with the dual-purpose, vacuum-reserve, wastewater-collection tank. The suction lift requirements that must be adhered to by any type of pump suitable for handling sewerage or wastewater are generally defined by the cavitation coefficient, δ.

The term δ is defined as the net positive suction head available (NPSHA) divided by the total pump head, H, per stage (Ref 14).

$$\delta = \frac{NPSHA}{H}$$

This term is specified by the manufacturer, or it can be easily determined in the field by following guidelines set forth by the Hydraulic Institute Procedures.

Vacuum Pump and Reservoir Sizing

With a minimum amount of system leakage, the volumetric flow rate of air entering the system is a predetermined quantity since it is directly proportional to the number and type of wastewater sources serviced (i.e., showers, kitchens, laundry, water closets). In order to support steady-state vacuum system performances, the net result of this term should not be larger than the vacuum pump's capacity.

The vacuum reserve tank volume, V, and vacuum pump's off time, T_2, are the remaining quantities to be evaluated in the previously derived Equation 6:

$$V = \frac{T_2 \, Q_i \, RT}{P_1 - P_2}$$

Since T_2 is a function of pump size and cycle frequency, Q_i is proportional to the type and number of wastewater sources serviced, RT is treated as a constant, and $P_1 - P_2$ is determined by total system head requirements. The vacuum reserve tank capacity, V, can be determined, based on the system's application.

After the initial values of T_2 and V have been established, a cost-effective determination of these parameters can be made, based upon economic considerations. A procedure for performing this analysis can be conducted as follows.

With the capital costs associated with a specified range of vacuum pump capacities and vacuum reserve tanks as determined initially, these costs are plotted as a function of capacity. This is illustrated in Figure 3. Curve A represents the costs associated with various sized vacuum tanks. The point a_1 illustrates a tank capacity sufficiently low enough to yield a negligible impact on vacuum system transport/collection performance (continuous vacuum pump operation); a_2 represents the point at which the tank becomes large enough to require internal structural supports for higher operational vacuums. Although structural supports will assist in preventing a tank collapse, solids/debris fouling precludes using structural members in sewage or wastewater applications.

Curve B demonstrates the capital cost investments required for different sizes of vacuum pump capacities.

Term b_2 corresponds to a system configured to operate without a vacuum reserve tank representing a vacuum pump operating in a nearly continuous run mode. This point corresponds to the volumetric flow rate out of the system - Q_o being equal to Q_i, the volumetric flow rate into the system while b_1 illustrates an operational condition that utilizes an oversized vacuum pump. This corresponds to a condition where a large capacity vacuum pump is used to meet system requirements in short-run cycles, producing the previously discussed cycling restrictions associated with high starting currents and excessive steady-state electrical circuit requirements.

The graphical summation of curves A and B produces curve C. This resulting curve represents the total combined capacity requirements of the vacuum pump and the vacuum reserve tank. The minimal point of curve C (C_1) illustrates the minimum cost required to accommodate the two parameters simultaneously. Therefore, for a given application, where Q_i, R, T, and the mean vacuum level are defined, an optimum vacuum pump and reserve tank size can be selected that supports the specified operational requirements for the application.

Although the criteria associated with management of vacuum and air in the vacuum collection station have been identified, critical considerations must be given to these parameters in terms of how they support their assigned function and the management of the vacuum-collected wastewaters.

Figure 1 suggests that one of the most important factors associated with vacuum system operation and performance is that of Q_i, the volumetric flow rate of atmospheric air entering the system. Therefore, mechanisms that control the admission of air into vacuum system operation should be investigated and understood before operational system designs are attempted.

Air Admission Effects on Vacuum System Performance

The concept of liquid slug flow frequently considered in the design of a system requires that each quantity of wastewater entering the transport main must be followed by a deliberate quantity of atmospheric air. This sequence is designed to maintain a pressure difference across the liquid slug until it has been disintegrated. To evaluate this transport process, extensive analysis with video tape and clear plastic pipe have been conducted.

Experimental test and evaluations have shown that a liquid "slug" rapidly changes in shape and flow pattern. This primarily results from the fact that fluids cannot support a shear. The observed progressive states of two-phase flow (liquid and gas) are illustrated in Figure 4. These observed flow patterns have also been identified by others (Ref 11, 12, and 15 through 18).

The following describes the sequence of the flow pattern changes. Liquid waste was injected into the pipeline in the form of a slug (a volume of waste followed by atmospheric air). Since fluids cannot support a shear, however, the driving force of the atmospheric air began to accelerate the slug's deformation. Distortion was continuous, rapidly progressing to the annular and misty flows shown in Figure 4. After the slug had broken up, the air began rushing across the surface and through the mist of the deforming slug, neutralizing the driving differential pressure. As the slug's deformation neared completion, the liquid began to collect in the lower portion of the conduit, gravity draining to the system's hydraulic low points; thus, initiating the stratified flows shown in Figure 4.

Subsequent slug loading produced the same class of flow patterns, resulting in gradual wastewater accumulation throughout the transport main. This buildup continued with each additional slug injection until approximately 35% of the transport main volume was occupied by liquid waste.

At this point a steady-state hydraulic transport configuration was established. The air-to-water ratio reached an equilibrium within the total pipeline and the gallons of wastewater injected gradually became equal to the quantity of wastewater collected in the vacuum reserve tank. The mechanism for wastewater transport in this configuration was maintained by controlling the volume of air, Q_1, admitted to the system with each additional slug injection. The air rushed across the surface of the liquid creating the wavy stratified regime shown in Figure 4. This regime occupied approximately a 3-foot section of pipe (so-called slug flow) that moved along the pipe as a wave to transporting about 2 gallons of wastewater per wave to the vacuum reserve/wastewater collection tank.

These observations indicate that admission of air to the system causes varying flow patterns and multiple friction factors that lead to an energy-intensive wastewater transport operation.

Air Admission and Control Criteria

A variety of methods exist for introducing wastewater into vacuum wastewater collection systems. In combined systems, the most popular method is to level-control a wastewater holding tank in conjunction with an admittance valve near the tank's bottom for admitting wastewater followed by atmospheric air to the vacuum-operated pipeline.

The holding tank can be configured with either a vertical bottom discharge or a horizontal bottom tank discharge. In each configuration the wastewater's level activates a valve admitting liquid waste into the transport main followed by a volume of atmospheric air.

In a holding tank configuration with a vertical bottom tank discharge, vortexing began as the wastewater level neared the tank's bottom. This reduced the tank's liquid discharge rate by about 40%. This reduced flow rate resulted from the simultaneous introduction of atmospheric air and wastewater.

System operation with measurable amounts of vortexing have reduced system transport capacity, lowered net system flow rates, and required shorter horizontal transport distances for a given air-to-water ratio. As a result, a testing program was initiated to assess the characteristics of vortexing as it relates to cylindrical holding tanks.

Tests were run with a 1,000-gallon, 5-ft-diam tank connected to a 4-inch vacuum main under a 20-inches-of-mercury vacuum. The tank was evacuated, and vortexing occurred as the liquid level dropped to within about 1 foot of the tank's bottom. This occurred at a ratio of liquid depth to the tank diameter of 0.2.

With use of the same initial conditions (20-inches-of-mercury vacuum and 4-in.-diam transport main), tests were run on a 55-gallon, 2-ft-diam tank. As this tank was evacuated, vortexing again occurred as the water level dropped to a ratio of liquid depth to tank diameter of 0.2. The wastewater discharge configuration utilizing horizontal bottom discharge was also tested for vortexing; no measurable vortexing was observed. As a result, this configuration was selected for use in determining the hydraulic transport capacity of transport mains with different diameters.

The test procedure used to evaluate the holding tank with a horizontal bottom discharge configuration consisted of measuring the time needed to discharge 50 gallons of liquid waste from a 55-gallon tank into 2-, 3-, and 4-in.-diam transport mains.

In the 4-in.-diam transport main tests, the wastewater inlet valve remained open for approximately 30 seconds after the introduction of 50 gallons of liquid waste. In this mode of operation, a steady-state condition (i.e., gallons of wastewater introduced being equal to gallons of wastewater collected at the vacuum reserve tank) did not occur until about 350 gallons of wastewater had accumulated in the 4-in.-diam transport main. After a steady-state condition was achieved, the vacuum transfer process moved the liquid waste over the 1,100-foot pipeline at an average rate of approximately 12 ft/sec.

Identical testing was conducted with the 2- and 3-in.-diam transport mains utilizing 50-gallon loadings, followed by approximately 30 seconds of atmospheric air. The initial results of these tests are summarized below:

Slug Size (gal)	Transport Main Diameter (in.)	Local Vacuum (in. of Hg)	Time for Liquid Entry (sec)
50	2	18	30
50	3	18	9
50	4	18	4

In steady-state system operations, 50 gallons of injected wastewater produced 50 gallons of output from the transport piping. The transfer rates were substantially reduced by changing the size of the transport piping as shown. The 3-inch transport main achieved an approximate 5-ft/sec velocity for 50-gallon injections over the 1,100-foot length of pipeline while the 2-inch transport main produced a steady-state transfer rate of about 0.6 ft/sec over the 1,100-foot distance.

The data further show that doubling the transport main diameter significantly alters wastewater injection time. Although wastewater input times depend, to a large extent, upon the input air-to-water ratios (and subsequent wastewater accumulations in the transport line), the data have been empirically found to obey the following mathematical relationship for wastewater injections of 50-gallon slugs into 2-, 3-, and 4-in.-diam transport mains.

$$T = 225\ d^{-2.907}$$

where T = time of entry of 50 gallons into a vacuum-operated transport main in seconds

d = diameter of the transport main in inches

This expression demonstrates the potential for predicting wastewater input times for transport mains of different diameters. Such a predictive tool will be useful in calculating system size limitations in terms of the number and size of separate, wastewater sources (holding tanks) that can be incorporated into a system design. This allows some degree of assurance that the system can perform without bog-down and sewage overflow conditions.

Because of the measurable differences in the wastewater transport performance of the 2-, 3-, and 4-inch lines, the pressure drop across their discharge openings - orifice discharge coefficients, C - was estimated. The 2-, 3-, and 4-in.-diam orifices were time-volume tested as above with the transport line disconnected and the tank discharging freely to the atmosphere.

The C values obtained from these test results compared to theoretical hydraulics as follows (Ref 19):

Diameter (in.)	C Experimental	C Theoretical
2	0.539	0.596
3	0.529	0.596
4	0.512	0.596

These coefficients were then used to compute the head loss across the orifice while discharging into the transport main:

$$h = \frac{v^2}{(C^2)(2g)}$$

where C = discharge coefficients

v = average velocity entering the line in ft/sec

g = 32.17 ft/sec^2

h = head loss in feet of water

For example, 50 gallons discharging into a 4-inch line in 4 seconds (19-ft/sec velocity) shows a head loss at the point of discharge of:

$$h = \frac{19^2}{0.512^2(64.34)} = 21.4 \text{ feet}$$

The initial head in the drum was an average of 2.5 feet, providing a net waterhead requirement of 18.9 feet to be supplied by the vacuum in order to attain the measured velocity of 19 ft/sec. This is equivalent to 16.6-inches-of-mercury vacuum, indicating that very little vacuum was required for overcoming the friction loss that results from flowing wastewater through the system at this rate. As the data indicate, there are considerable differences in the transport velocities and head losses associated with the 2-, 3-, and 4-inch pipelines.

As a result of experimental testing, it was determined that the 50-gallon slug loading of a 3-in.-diam line had to be reduced to about 20 gallons in order to obtain the same steady-state transport velocity exhibited by the 50-gallon loading of the 4-inch transport main. The loading on the 2-inch transport main had to be reduced to about 6 gallons in order to obtain the same transport velocity as the 50-gallon, 4-inch line loading.

The impact of transport main diameter on steady-state wastewater transport velocity is nominally attributed to the friction head loss resulting from the wetted pipe area. For example, 50 gallons of liquid waste occupies about 76 linear feet in a 4-inch line, wetting an equivalent area of about 69 sq ft; 50 gallons occupies more than 307 linear feet of 2-inch line and wets an equivalent area of about 160 sq ft of pipe. An analysis of this data further demonstrates that the injected air required to transport the wastewater is consuming a significant proportion of the vacuum available to operate the system.

Vacuum Systems in Network Applications

Preliminary testing and experimentation have been conducted to explore vacuum system transport technology in network applications where multiple wastewater sources are serviced by a single common transport main. In this application, multiple source integration often results in the transfer mains instead of unidirectional transport of liquid wastes to the collection tank. In addition, as the wastewater and atmospheric air passes or enters a lateral transport junction, local vacuum pressure approaches zero (i.e., atmospheric pressure) at that point. This results from the liquid waste movement changing a static head into a dynamic velocity head. Since the local working pressure is reduced, nearby vacuum components are forced into an intermittent mode of operation. As the liquid slug deforms and leaves the junction, vacuum is restored, and the service lateral again becomes operational.

For conventional black-water systems utilizing more than one adjacent vacuum fixture, this intermittent period (system dead time) is approximately 2 seconds and is attributed to small loading volumes and rapid slug deformation.

Conventional vacuum system dead time is variable since the delay is a function of component location, loading size, and slug deformation time, which in turn is largely dependent on transport main diameter. For a constant slug loading of 2 quarts per injection, slug deformation time will decrease as the transport main diameter is increased.

A 2-quart slug in a 2-in.-diam transport main occupies 3 linear feet while the same size slug in a 3- or 4-in.-diam line occupies 1.25 or 0.75 foot, respectively. Doubling the transport main diameter with identical load conditions reduces the effective slug size by 75%.

This slug length reduction will allow more rapid deformation and will therefore proportionally reduce system dead time. Conversely, keeping the pipe diameter constant while increasing the system loading lengthens the slug and its deformation time. While this provides greater transport effectiveness, this method of operation causes a longer system dead time in multiple source applications and implies a need for intermediate storage and sequencing if continuous system operation is desired.

Another factor to be considered when minimizing system dead time with small slug loading is that of water hammer, the vibratory effects of which are imparted to the vacuum transport main.

When injecting liquid waste into an evacuated transport main across a pressure gradient of 15 inches of mercury, high stresses are subjected to the transport main in local areas of direction change. Under identical small loading conditions from vacuum toilets, peak accelerations of 6, 17, and 29 g at a frequency of 40 cps in the vertical, lateral, and transverse directions, respectively, have been observed at a 45-degree sanitary elbow approximately 15 feet from the point of slug injection. Large slug loading of 50 gallons and slow-acting, electrically operated, ball valves have reduced vibration and water hammer effects: static head has been converted to velocity head over longer time frames, resulting in lower total external forces.

An alternative to the conventional method of vacuum wastewater transfer is the use of large slugs to reduce transport line losses, thereby increasing liquid waste transport capabilities. Careful consideration of multiple source implementation of conventional vacuum transfer systems is necessary, however, because these differential pressure devices typically operate on principles of first-come, first-served. Operation of collection stations under these conditions gives priority to the tanks closest to the vacuum source. Such a multiple source collection mode presents a special class of problems. Loading rates throughout the network will vary, thus requiring intermediate storage for wastewater sufficiently removed from the primary collection station.

In this regard, the intermediate collection tank size must, in part, be based upon detention and transportation time criteria that does not allow discharge of septic, vacuum-collected sewage to the treatment plant facility.

Additionally, if the transport main length compared to slug size is large, deformation characteristics of the waste packets nearly always result in partially filled vacuum transport mains. Unless these lines are horizontal, waste will collect at the system's low points, and air will collect at the high points of the main. This configuration often results in intermediate pressure gradients within the vacuum main that cause a buffering action to occur between the vacuum pump and the local vacuum-operated fixture. Since the internal piping volumes are fixed and the entrapped liquid is easily moved, the generalized gas law equations (PV = NRT) apply to the resulting volumes when varying pressures are applied. Under steady-state conditions such a configuration results in oscillating liquids and varying pressures until the internal pressure gradients are equalized.

CEL has developed an approach to utilizing a vacuum as the primary driving potential. In this concept, which varies from standard vacuum applications, atmospheric air is kept from entering the system's piping, and the differential working pressure is continuously maintained outside the transport main.* This mode of operation allows predictable events to occur with time because there are no intermediate flow regimes under varying loading conditions. Steady-state conditions are nearly idealized and lend themselves to accurate modeling and analysis by Hardy-Cross pipe network methods (Ref 20). These methods are based on iteration processes and convergence techniques and are highly suitable for digital computer investigations.

CEL has successfully used this tool to assist in evaluating an experimental, vacuum, waste transfer system with full pipe flow that

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*In this configuration the transport piping is maintained in a full pipe flow condition. When a wastewater source is emptied, the admittance valve is opened to allow atmospheric pressure to force the wastewater into the collection piping and is closed just prior to complete tank evacuation and the subsequent admission of air to the transport piping. This practice supports full pipe flow conditions, predictable system head losses, and much lower friction factors than those encountered with two-phase mixtures of air and wastewater.

accommodates loading by 500 men. The general system layout is based on Bureau of Yards and Docks Drawing no. 816511 contained in Reference 21.

The experimental model basically operates according to principles associated with a continuous pressurized medium. This method keeps the pressure gradient external to the transfer main, alleviates intermediate flow regimes caused by air-deforming liquid slug packets, and establishes a flow pattern with a predictable single-phase friction factor.

DESIGN OF A MULTIPURPOSE VACUUM WASTEWATER COLLECTION SYSTEM

In design of a sewage transport/collection system, the number of people the system will serve must be assessed early; the maximum projected population is required. After the population and the types of communities are determined, a base or camp layout such as that in Reference 21 will assist in identifying the types, locations, and sources of wastewater to be handled.

Characterization of these sources can then be conducted in terms of the quantities and qualities of wastewater expected. Based on operational requirements and routine activities, the wastewater generation rate (50 gal/capita/day) can be projected and a diurnal curve constructed. Reference 22 states, "Domestic water use can be attributed to six major functions or areas"; these include: (1) toilet/sanitary wastes, (2) sink, (3) garbage disposal, (4) bath/shower, (5) dishwasher, and (6) washing machine.

In a multipurpose vacuum collection system, the wastewater is transported in a single common transport main. Generally, gravity is used to collect the wastewater in an intermediate storage tank from the generation point. This tank should be level-controlled, feeding the vacuum transport main directly when the intermediate wastewater level reaches a predetermined point.

Because of septicity and solids handling constraints, the intermediate storage tank size should allow an average detention time of about 1 hour. This tank should incorporate a conical or tapered bottom with horizontal discharge to support effective solids removal with minimal vortexing for transport to the vacuum collection station where the effluent can be discharged to the appropriate treatment or disposal areas.

In the functional design of a sanitary sewer system, the hydraulics associated with wastewater transport generally present standard or conventional types of problems. The solids and entrapped air associated with vacuum collection systems, however, present a different class of problems. Standard sewage design practices dictate a liquid velocity of at least 2 ft/sec to prevent solids from depositing in the transport main.

A more limiting factor is associated with the removal of entrained or trapped gases to prevent the equivalence of an air-locked pipeline as is found in pressure-type systems. It has been shown that the minimum wastewater velocity required to remove air or gases is 3.5 ft/sec in a 4-in.-diam transport main undergoing negative slopes of up to 60 degrees (Ref 23). The upper limit on the wastewater transport velocity has been established at 10 ft/sec because of conduit scouring (Ref 10). Since a full bore type of vacuum system incorporates a very low air-to-water ratio within the transport main, a full pipe flow configuration is assumed.

With wastewater velocity constraints set at a range of 3.5 to 10 ft/sec, Hazen-Williams hydraulic modeling can be utilized to calculate the head loss characteristics associated with high friction factors experienced with small diameter pipe. The 4-in.-diam limitation is derived from increased capital costs associated with larger diameter pipe. For example, a 6-in.-diam plastic pipe costs about twice as much per linear foot as the 4-in.-diam plastic pipe.

Utilizing the assumptions of full pipe flow, a given pipe size, and a range of wastewater flow velocities, Hazen-Williams-derived criteria can be utilized as a tool to identify the potential head losses and friction factors associated with a particular base or camp layout in terms of flow capacity.

Recalling that total dynamic head (TDH) in feet is equal to the sum of the head losses (H_L) resulting from friction, static head, and velocity head, the following equation can be written:

$$TDH = VH + SH + FH$$

where VH = velocity head in feet ($V^2/2g$)
SH = static head (cumulative elevation in feet)
FH = friction losses (H_f) in ft/ft

Since a perfect vacuum has a limited theoretical lift capacity of 34 feet, the available vacuum level (i.e., 26 feet for all practical purposes) represents the TDH available to transport and collect wastewater. If the system is designed to lift, this requirement reduces the TDH available to transport the liquid waste (illustrated graphically in Figure 5). As a result, the basic head loss relationship can be rewritten as follows:

$$TDH - SH = VH + FH$$

The VH term, $V^2/2g$, is on the order of 1 foot of head since the velocity is constrained to between 3.5 and 10 ft/sec.

By setting y = TDH - SH, the initial expression can be approximated by the following:

$$y \approx 1 + FH \approx H_f$$

$$H_f = \frac{H_L}{1\ ft}$$

where the total loss can be found by

$$H_f = \frac{H_L}{1\ ft} \text{(length in feet, L)}$$

and

$$y \approx \frac{H_L}{1 \text{ ft}} (L)$$

By use of the initial assumption of low air-to-water ratios or full pipe flow, Hazen-Williams calculations give a good approximation for values of H_f when rigid 4-in.-diam plastic pipe is utilized as a vacuum transport main, flowing full of wastewater (Figure 6). Operation is maintained within the velocity constraints mentioned earlier.

Given a particular application and an accompanying topographical map for determining the cumulative lift requirements, SH, a vacuum range can be determined in terms of transport velocity and line length. For instance, a 4-in.-diam line approximately 1,200 feet long requires a vacuum of about 20 inches of mercury to lift about 10 feet and still guarantee a transport velocity of 3.5 ft/sec. Having established system vacuum range limitations, the previously derived relationship,

$$V = \frac{T\ (R)(T_2)(Q_i)}{P_1 - P_2}$$

can be utilized to determine the preliminary values of V and T_2.

Evaluating the economic tradeoff relationships between vacuum reserve tank volume and vacuum pump capacity (consistent with Figure 3) will enable the appropriate class of components to be selected in terms of their intended application.

The vacuum-reserve/wastewater-collection tank is a dual-purpose tank. It is level-controlled, enabling the upper portion to be used as a vacuum reserve tank and the lower portion, as a wastewater storage tank that transfers the collected wastewater to the treatment or disposal site.

Incorporating this type of tank instead of two separate components will reduce capital and O&M costs. Such a tank will provide a mechanism that allows the wastewater discharge pump to simultaneously restore the system to its maximum vacuum and also discharge the collected wastewater to the appropriate treatment or disposal area. This method of operation allows the vacuum pump to function as a fail-safe device. After the vacuum pump establishes the system's initial maximum vacuum with the collection tank nearly empty (maximum volume), its primary mission becomes that of removing air and vaporized gases that have leaked into or entered the system.

Because the wastewater discharge pump provides a dual function in steady-state system operation, its sizing and control mechanisms are critical. This pump must be able to adequately handle continuous system peak flow rates. For populations up to about 5,000, a peak-to-average wastewater flow rate of 4 to 1 can be utilized (Ref 24). The level controls must be such that the sewage pump is set to initiate pumping when the wastewater level in the vacuum reserve/wastewater collection tank has risen sufficiently to reduce the tank volume and, hence, the vacuum in the reservoir to a predetermined system minimum. At this point (approximately 2-hour detention time) the collected wastewater's level should initiate the wastewater discharge pump at a rate that equals the system's peak flow rate. For design, this capacity should support a peak flow rate while working against a high system suction head. This pumping rate should be maintained until the collected wastewater level reaches a point that produces a volume of evacuated tank that creates the maximum required system vacuum.

When this level is attained, the wastewater pump should stop pumping and allow sufficient wastewater to remain in the collection tank to maintain an effective prime so the wastewater discharge pump does not become air-locked.*

Since the level-control approach requires use of the system's design operational vacuum limits in terms of collection tank volume, the intermediate points between the values corresponding to minimum system vacuum (high water point) and maximum system vacuum (low collected

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*Prevention of a wastewater discharge pump air-lock condition also requires a check valve to be installed in this pump's discharge line.

wastewater point) can serve as calibration and check points for the maintenance of this alignment for subsequent reliable system performance. If, for instance, a maintenance check reveals the wastewater level in the collection tank is inconsistent with the required vacuum (e.g., from air leakage producing a lower system vacuum than the waterline should produce), the vacuum pump could be energized until the appropriate vacuum was restored and the system returned to an automatic mode of operation.

CONCLUSIONS

1. There are three basic and distinct vacuum collection system configurations, each possessing its own fundamental design requirements.

(a) A single-pipe system where only vacuum toilets are connected to a vacuum sewer system (i.e., black-water system) (Ref 1).

(b) A single-pipe system in parallel with item (a) where gray-water sources (shower-, laundry-, and kitchen-type wastewaters) are connected to a vacuum sewer system (i.e., dual-pipe black- and gray-water system) (Ref 1).

(c) A single-pipe system combining the two types of wastewater into a common transfer main using conventional fixtures along with gravity-fed intermediate holding or storage tanks (Ref 1).

2. The variation in the fundamental design requirements depends upon the types and kinds of wastewater sources (e.g., kitchens, showers, urinals) serviced.

3. The transport efficiency of a vacuum wastewater collection system is a function of the system's operating air-to-water ratio.

4. A critical element in the design of a vacuum wastewater transport system is control of the amount of atmospheric air admitted to drive the wastewater to the collection point.

5. The rate of wastewater transport in a vacuum system under steady-state conditions is also a function of the transport main diameter and its piping configuration.

6. Vacuum system performance is affected less by changing the transport main diameter or its configuration than it is by altering the operational air-to-wastewater ratio.

7. Vortexing can produce about a 40% decrease in vacuum wastewater transfer rate. This effect can be minimized, however, by placing the discharge port on the side of the holding tank.

8. The total design head required to support vacuum wastewater transport must include the total head (measured in feet of water) resulting from the cumulative (as opposed to net) positive sloping portions of the transport pipe line.

9. In network applications, as the wastewater and atmospheric air enters or passes a lateral transport junction, local vacuum pressure approaches zero or atmospheric pressure at that point.

10. The varying hydraulic friction factors resulting from the flow of wastewater and air in a common transport main with measurable air-to-wastewater ratios are not subject to conventional hydraulic analysis.

11. Standard hydraulic design data for fluid discharge through an orifice while admitting wastewater (not mixtures of air and water) to a vacuum collection system can be utilized to account for head-loss coefficients across the inlet to the transport line.

12. Vacuum wastewater collection systems designed to operate at very low air-to-water ratios (essentially no air) appear to behave as low

pressure, full pipe flow systems; operate more efficiently than those configured with measurable air-to-water ratios; and lend themself to standard hydraulic analysis.

RECOMMENDATIONS

The research efforts reported herein are not considered complete since these findings apply primarily to multipurpose vacuum collection systems that operate with very low air-to-water ratios. Operational problems associated with vacuum systems operating with measurable air-to-water ratios (i.e., 10 to 60) include: (1) varying hydraulic friction factors resulting from mixtures of air and wastewater, (2) limited suction lift capability, and (3) decreased wastewater collection efficiency in network application because of lateral transport mains.

It is recommended, therefore, that research testing and experimentation continue in the area of vacuum system applications where medium or high values of operational air-to-water ratios are required.

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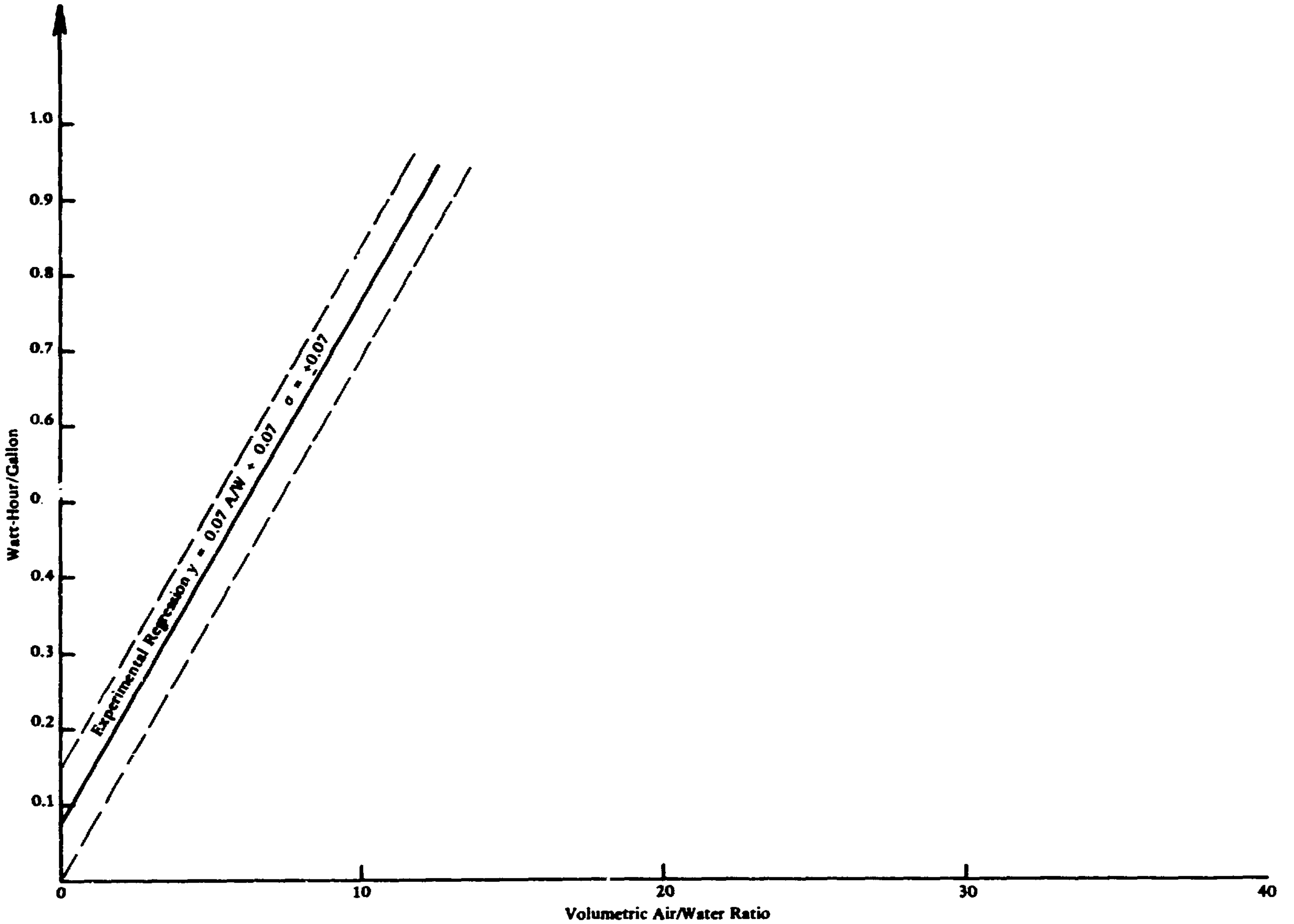
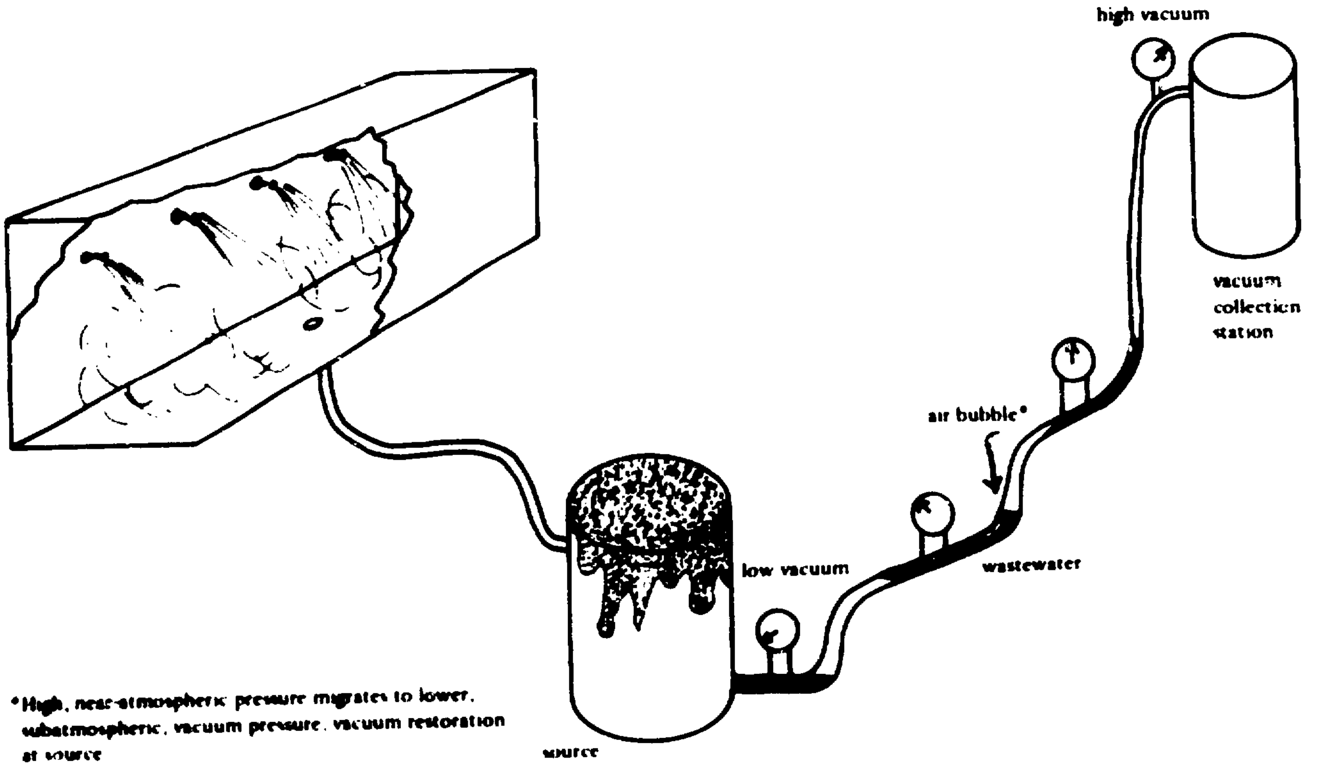


Figure 1. Energy requirements to support vacuum transport and collection 1,100 feet with net elevation changes of 10.5 feet.



*High, near-atmospheric pressure migrates to lower, subatmospheric, vacuum pressure, vacuum restoration at source

Figure 2. Vacuum collection system hydraulic failure (i.e., bog down).

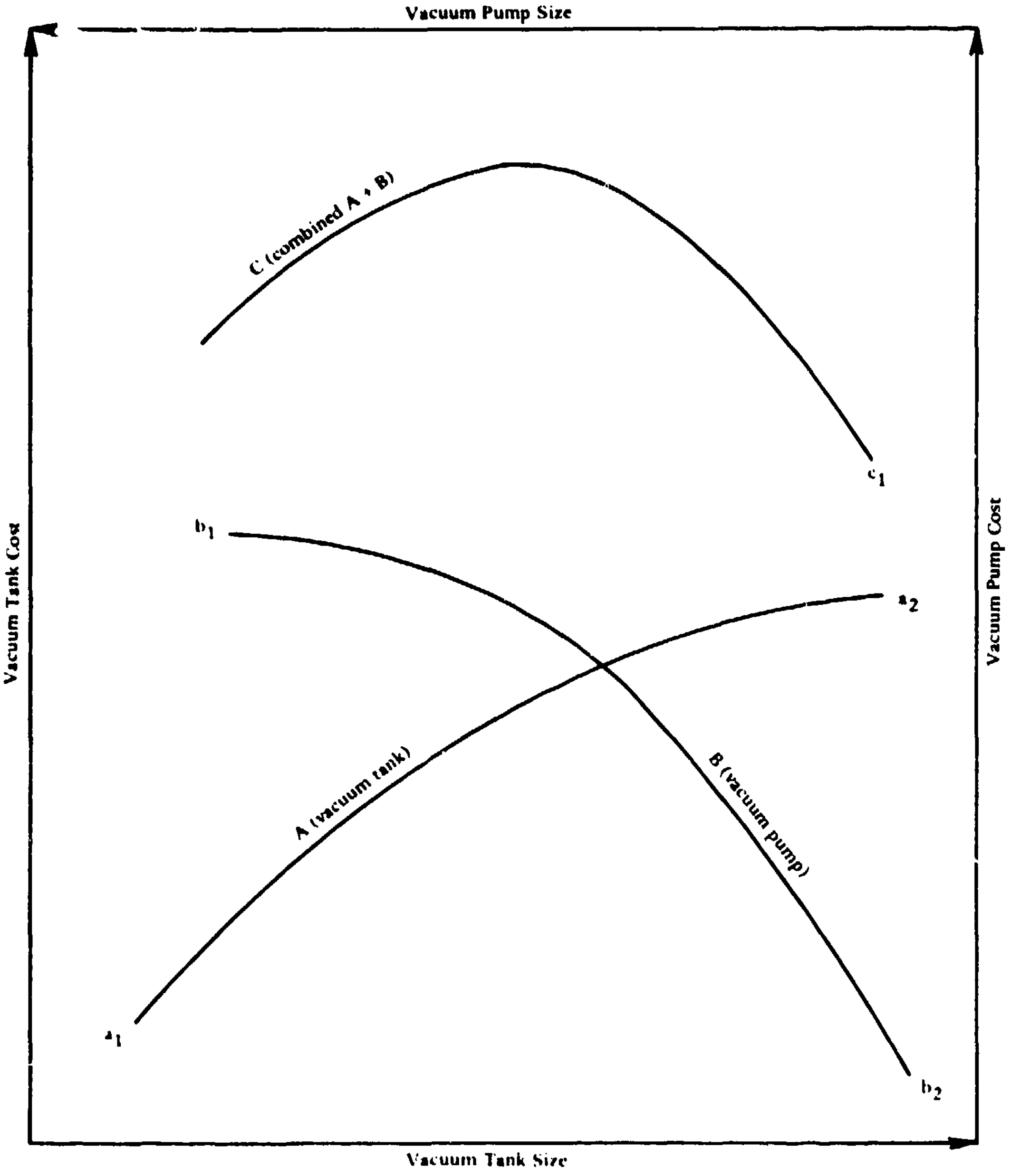


Figure 3. Sizing vacuum pumps and vacuum tanks.

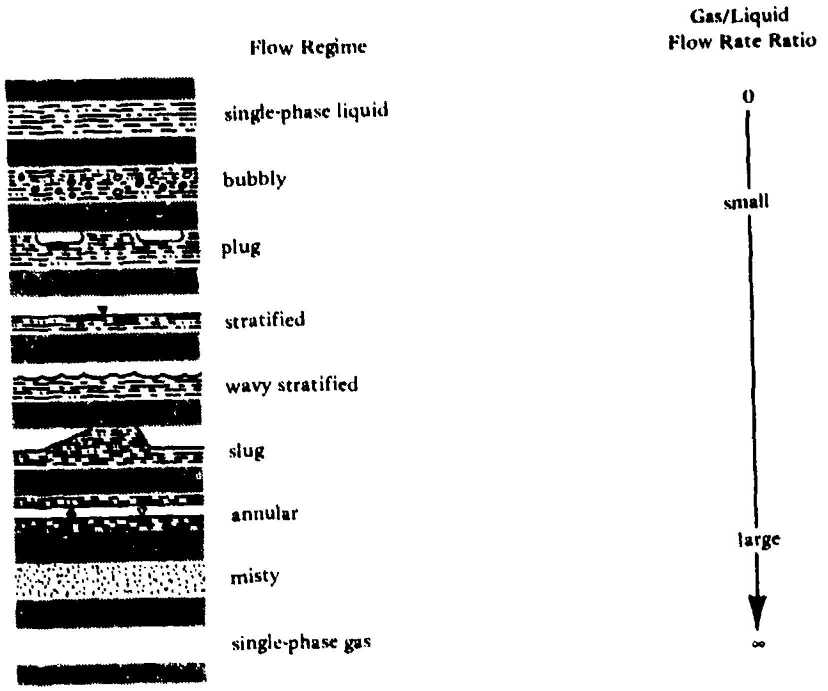


Figure 4. Two-phase flow regimes.

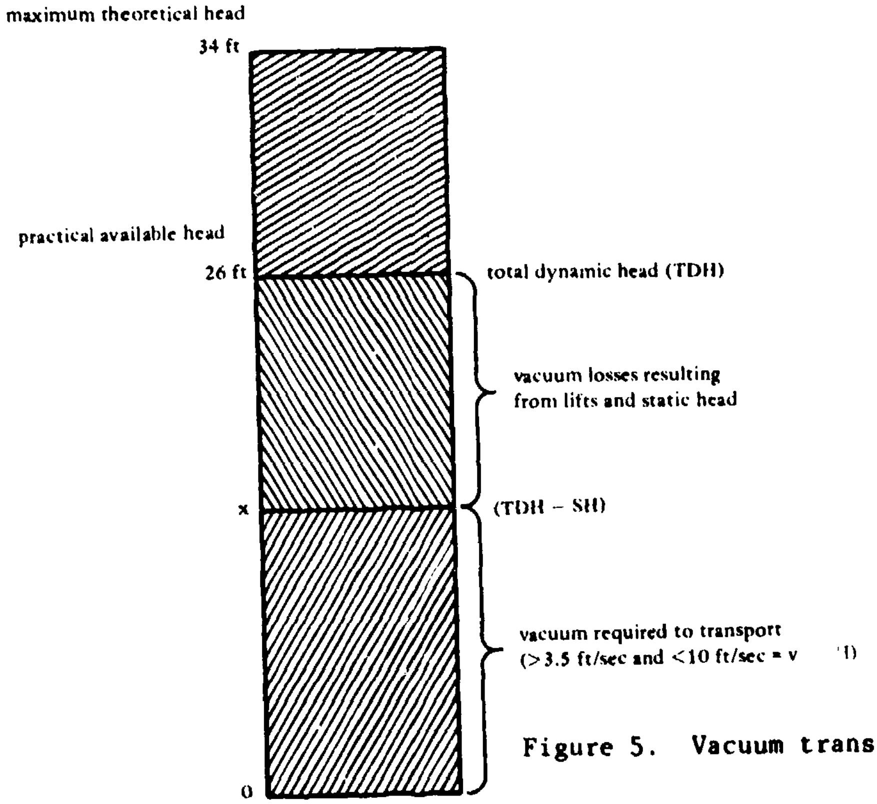


Figure 5. Vacuum transport limitations.

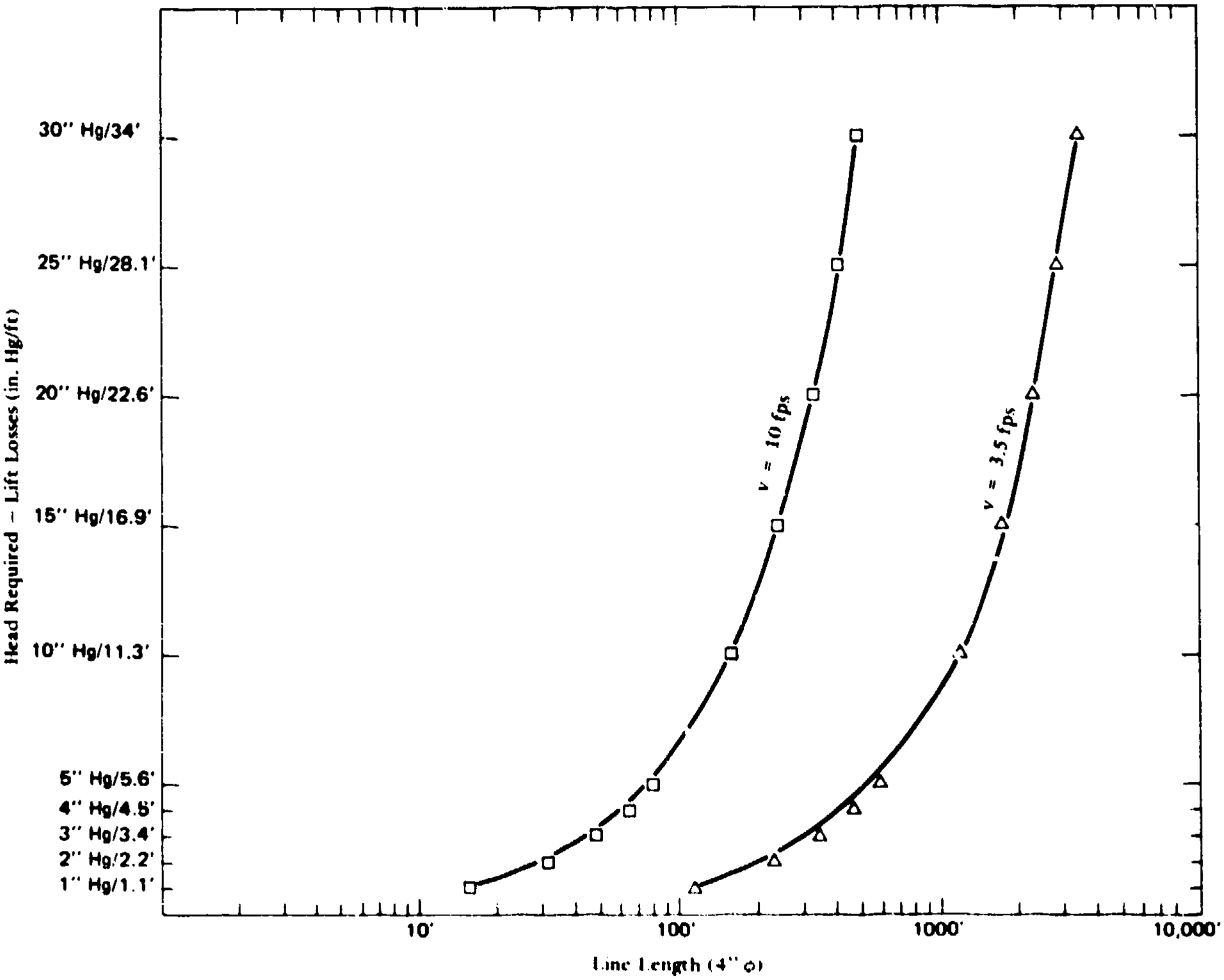


Figure 6. Head required for minimum lift losses versus line length for 4-in.-diam pipe.

Table 1. Performance of a 4-Inch Vacuum Transport Main

[50-gallon injections, main 1,114 feet long]

Test Injection	Vacuum Reserve (in. Hg)	Local Vacuum (in. Hg)	Liquid Input Time (sec)	Air Time (sec)	Liquid Collected (gal)	Vacuum Pump Running Time (min)	Air Volume (cu ft)[a]	Air-to-Water Ratio for x-Axis	Energy Consumption (watt)	Transport Effectiveness (watt-hr/gal) for y-Axis
1	19	18.1	4	30	69.7	5.35	434	46	223	3.20
2	19.2	18.5	4	37.2	4.5	1.41	116	194	12	13.11
3	19.5	15	4.2	21.8	56.2	1.50	117	16	62	1.10
4	19	18	4.6	24.4	49.5	1.58	124	19	66	1.33
5	20	14.8	4.4	20.8	101.2	2.41	186	14	100	0.99
6	19.5	19.2	4.0	28.3	52.8	1.50	117	17	62	1.17
7	16	14.8	5.0	32	10.1	2.0	165	122	83	8.22
8	17	17	4.0	33	83.2	2.23	174	16	93	1.12
9	20	17.5	4.0	33	62.9	2.40	191	23	99	1.57
10	19	18.2	4.8	29	54	2.66	214	30	111	2.18
11	19	19.0	4.2	30	43.8	2.40	193	33	99	2.26

[a] Example of how figures in last four columns are derived. Sample is taken from test injection no. 1, with following constants:

$y = 0.672\,x + 0.0564$ and $\sigma = \pm 0.0402$

Air Volume $\frac{835\ \text{ft}^3}{\text{min}}(5.35\ \text{min}) - 69.7\ \text{gal}\left(\frac{1\ \text{ft}^3}{7.48\ \text{gal}}\right) = 434\ \text{ft}^3$

Air/Water Ratio $\frac{\text{air}}{\text{water}} = \frac{434.0}{9.31} = 46.61$

Energy Consumption Calculation. $41.6\left(\frac{\text{watt-hr}}{\text{min}}\right)(5.35\ \text{min}) = 222.56$ watts

Transport Effectiveness $\frac{222\ \text{watt-hr}}{69.7\ \text{gal}} = 3.19\,\frac{\text{watt-hr}}{\text{gal}}$

Table 2. Performance of 3-Inch Vacuum Transport Main

[20-gallon injections, main 1,114 feet long]

Test Injection	Local Vacuum (in. Hg)	Air Time (sec)	Liquid Collected (gal)	Vacuum Pump Running Time (min)	Air Volume (cu ft)[a]	Air-to-Water Ratio for x-Axis	Energy Consumption (watt)	Transport Effectiveness (watt-hr/gal) for y-Axis
1	15	30	15.75	1.33	108	51.5	55.3	3.51
2	14-1/2	30	8.9	1.13	92	78.4	47.0	5.28
3	12-1/2	30	28.1	1.33	106	28.4	55.3	2.32
4	13-1/2	30	18	1.25	101.3	42.2	52	2.89
5	12-1/2	30	22.5	1.31	105	35.2	54.49	2.42
6	13-1/2	30	20.25	1.18	95.2	35.2	49.0	2.42
7	13	30	24.75	1.25	100.4	30.4	52	2.10
8	16	30	16.87	2	163.7	72.7	83.2	4.93
9	17-1/2	30	14.62	1.73	141.6	72.6	71.9	4.92
10	16-1/2	30	16.8	1.10	89.06	39.7	45.76	2.72
11	15	30	15.75	1.33	108.2	51.5	55.3	3.51

[a] Constants:

$y = 0.0644\,x + 0.2198$ and $\sigma = \pm 0.0945$

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