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Hydraulic Transport of Potatoes

ABSTRACT

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Measured headlosses for potatoes transported in 9.5-inch-diameter horizontal and vertical pipes were compared with mathematically predicted headlosses. Measured and predicted headlosses agreed well when the predictions were made with equations that had been developed for the heterogeneous flow of sand and coal particles. Flow profiles were analyzed for potatoes transported in metal flumes with various cross sections and slopes. Manning roughness coefficient could be estimated with a form of an equation published for the heterogeneous flow of sand. Potato concentrations were varied and potato handling rates were varied from 780 to 1,800 pounds per minute in the trials conducted. Design criteria for pipelines and flumes were developed.

KEYWORDS: drag coefficient, fluming, hydraulic transport, Manning coefficient, open channel flow, pipelining, potato

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SYMBOLS

A	Cross-sectional area of a pipe or flume (ft^2)
B	Flume bottom width (in)
c	Concentration of particles in a mixture with water (volume of particles/unit volume of mixture)
C_D	Drag coefficient
C_T	Transport concentration for a vertically flowing mixture (volume of particles in a length of pipe/total volume of mixture in that length of pipe)
d	Diameter or nominal diameter of a conveyed particle (ft)
D	Pipe diameter or flow depth (ft)
D_c	Critical depth for most efficient channel flow (ft)
D_h	Hydraulic depth = cross-sectional area of flowing fluid divided by free-surface width (ft)
E	Elevation in vertical pipelining (ft)
f	Friction factor (dimensionless)
g	Acceleration due to gravity (ft/sec^2)
H	Total head for flume (ft water)
H_E	Pumping head in vertical pipelining (ft water)
H_H	Pumping head for horizontal pipelining (ft water)
H_{TOT}	Total pumping head in a pipeline system (ft water)
hp	Horsepower
i_m	Headloss for flow of a fluid-particle mixture (ft water/ft pipe)
i_w	Headloss for flow of water (ft water/ft pipe)
K	Coefficient (dimensionless)
L	Length of horizontal pipe in a pipeline system (ft)
$\underline{n}$	Exponent (dimensionless)

n	Roughness coefficient (sec/ft$^{1/3}$)
n_m	Roughness coefficient obtained by using Manning formula (sec/ft$^{1/3}$)
n_w	Roughness coefficient for clear water (sec/ft$^{1/3}$)
N_{RE}	Reynolds number - RV/v
N	Exponent (dimensionless)
Q	Volume flow rate of fluid-particle mixture (ft^3/sec)
R	Hydraulic radius = cross-sectional area of flowing fluid divided by wetted perimeter (ft)
s	Specific gravity of conveyed material (dimensionless)
S	Hydraulic energy gradient = flume slope with uniform flow (ft/ft)
T	Width of channel at water surface (ft)
V	Mean velocity of fluid or a mixture (ft/sec)
V_c	Critical flow velocity (ft/sec)
V_D	Critical deposit velocity (ft/sec)
V_P	Velocity of a conveyed particle (ft/sec)
V_s	Settling velocity, or slip velocity, of a particle in water (ft/sec^2)
V_{sh}	Hindered settling velocity of a particle in a pipe (ft/sec)
Z	Elevation change for flume (ft)
v	Kinematic viscosity (ft^2/sec)
ϕ	Angle between flume side and vertical (degrees)

HYDRAULIC TRANSPORT OF POTATOES

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INTRODUCTION

The term "hydraulic transport" refers to the process of conveying solid materials by water flowing through a flume or pipeline. When this process occurs in an open channel, it is called fluming; when it occurs in a pipe, it is called pipelining. In open channel flow the liquid stream is not completely enclosed by solid boundaries and thus has a free surface subjected only to atmospheric pressure. In pipe flow the fluid completely fills the pipe and has no free surface.

Four types of flow are often considered in horizontal, hydraulic transport:

1. Homogeneous suspension, in which particles and fluid are uniformly mixed;

2. Heterogeneous suspension, in which mixing is not uniform across the flow area;

3. Saltation with a heterogeneous suspension or a sliding bed;

4. Saltation and a stationary bed. (Saltation is a type of movement in which the particles descend to the bottom of the flume or pipe, rise because of the lift of the fluid velocity gradient around them, and then descend again while simultaneously being propelled horizontally by the flowing fluid.)

These types of flow patterns occur successively with decreasing velocity for any given particle concentration and are discussed in detail by Newitt et al. (17) and Charles (2).

Hydraulic transport is especially convenient for moving solids, such as agricultural products, that require washing. Since the density of most agricultural produce is near that of water, suspending them in a moving stream is fairly easy. Sugar beets and potatoes are two products for which pipelining or fluming is frequently used to serve as a means both of washing and conveying.

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Handling potatoes with flowing water apparently began concurrently with early types of potato processing. In the 1870's, starch factories in Maine used flowing water to transport potato stocks from holding bins to grinding machines. Edgar (6) credits a potato packing plant in Torrington, WY, with the first use of fluming for handling table stock potatoes in 1942. In Florida and in Maine, the first such use was in 1954. Across the country, interest in washing potatoes for market and the rapid development of the potato processing industry spurred expansion of fluming as a method of conveying potatoes.

Although hydraulic transport has been used by the potato industry to convey table stock potatoes from storage to the packingline and convey potatoes from place to place onsite at processing plants just prior to processing, there has been much reluctance to use hydraulic transport to (a) convey processing stock out of storage for shipment to processing plants not located onsite (b) convey seed potatoes at any time, and (c) convey any type of potatoes into long-term storage. This reluctance is based on concerns about the transport fluid becoming contaminated with bacteria and fungi which can cause serious potato quality deterioration (4, 11, 24). In 1965, however, it was shown that seed potatoes are not always adversely affected when handled in water (26), and later research has indicated the potential for handling all types of potatoes in water at any time through the use of additives for controlling bacteria and fungi (22). Also, a laboratory study has shown that even french-fry strips--that is, a processing product--could be transported by water (16).

More recently, the use of water for transporting potatoes has been expanded to include vertical as well as horizontal movement. Pumps have been developed which elevate potato-water mixtures in pipes to the required levels in packinghouses and processing plants. This development offers the possibility of completely integrated hydraulic-transport systems using a combination of flumes and pipelines.

The first significant research on transporting solids in pipes was reported by Blatch (1) and involved sand and water mixtures. Fowkes and Wancheck (7) reported on hydraulic transport of 2-inch by 0.5-inch coal in a 6-inch-diameter pipe, and Worster and Denny (27) discussed transport of 1.5-inch-diameter coal in a 6-inch pipe. These were the only sources of information on transport of particles that approximate the size and specific gravity of potatoes. Lack of engineering data for designing large systems and the fact that most previous work on hydraulic transport does not relate to agricultural products resulted in the research on pipelining and fluming potatoes in the large quantities reported in this bulletin.

Mechanics of Flow

Vertical Transport

Whenever the direction of fluid flow is upward, a particle which is heavier than the fluid slips back against the flow of fluid. As the fluid flows past, a drag force is exerted on the particle, resulting from impingement of the fluid on the particle and friction between the fluid and the particle. A single particle in an infinite volume of fluid with no boundary effects on the fluid (infinite fluid) will be in equilibrium (that is, will not slip) when the forces exerted upon it by the moving fluid equal the buoyant weight of the particle. The equilibrium fluid velocity, often called slip or settling velocity, V_s,[1/] required on a large particle such as a potato is (14)

$$V_s = \sqrt{\frac{4}{3}\frac{gd}{C_D}(s - 1)} \qquad [1]$$

The drag coefficient, C_D, is a dimensionless number whose value depends on particle shape, surface roughness, turbulence level, Reynolds number, and other parameters.

In addition to the drag coefficient, the concentration of particles in a pipe markedly influences the rate of settling. The term "hindered settling velocity" is used to describe this actual rate of settling. When a particle falls in a vertical pipe or other narrow vessel, the displaced fluid flows upward around the particle, decreasing the settling velocity below that for a fall in an infinite fluid (27). Such a decrease may occur when agricultural products such as potatoes are pipelined, because particle size may be large in relation to pipe diameter. Maude and Whitmore (15) have shown that hindered settling velocity, V_{sh}, is given by

$$V_{sh} = V_s (1 - c)^{\underline{n}} \qquad [2]$$

The exponent, _n_, is a function of particle shape, size distribution, and Reynolds number and has the values 4.65 and 2.32 for Reynolds numbers less than 1 and greater than 1,000, respectively. This _n_ is not related to roughness coefficient.

If the drag force exceeds the buoyant weight of the particles, the particles are accelerated upward until they reach a velocity equal to the fluid velocity minus the hindered settling velocity. For a given flow rate of particles through a system, the portion of the cross-sectional area of the pipe occupied by particles is inversely proportional to their velocity. As particle velocity increases, greater cross-sectional area

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1/ See list of symbols on page ii.

becomes available for the flowing fluid, which then decreases in velocity. Because of the decrease in fluid velocity the drag force on the particles decreases, and they subsequently slow down. This slowing down increases particle concentration in the cross-sectional area, and fluid velocity is forced to increase again. Finally, an equilibrium will be achieved such that the particles progress at a steady velocity without further changes in concentration. The height at which this equilibrium is achieved may be considerable in pneumatic transport (that is, transport by compressed air) but is fairly short in hydraulic transport (25). The latter is especially true of a material, such as potatoes, whose specific gravity is close to that of water. The equilibrium particle velocity will be given by

$$V_p = V - V_{sh} \qquad [3]$$

Headlosses in Vertical Transport

Headlosses for vertical, heterogeneous flow have been investigated by a number of workers, including Durand and Condolios (5), Gilbert (8), and Newitt et al. (18). All found that the actual friction component of headloss for mixtures utilizing water as the transport fluid is the same as that for clear water. The actual head change per unit length of pipe in excess of static lift (i_m) is equal to friction head plus a static head term that relates the concentration and the density of the solid particles present in the pipe:

$$i_m = i_w + c\ (s - 1) \qquad [4]$$

When equation 4 is applied to vertical flow, it is important to use the actual concentration of particles in the pipe rather than the delivered concentration.

When mixture velocity is less than five times the hindered settling velocity, actual transport concentration, C_T, can be estimated by comparing the mean velocity of flow with the probable particle velocity in the following equation (15):

$$C_T = c \frac{V}{(V - V_{sh})} \qquad [5]$$

This is only an approximation, since a higher transport concentration causes a higher fluid velocity for a given rate of solids delivery.

When particle-hindered settling velocity is significant in relation to mean flow velocity, the length of the acceleration zone may be significant. If it is, the vertical flow analysis described by Smith and O'Callaghan (25) is recommended, because it allows analysis of the two-phase flow in this zone.

In any hydraulic transport system involving both horizontal and vertical pipes, the mean conveying velocity will normally be at least five times the hindered settling velocity. Use of the delivered concentration in equation 4 is appropriate in this case.

Horizontal Transport

Whenever particles with hindered settling velocities greater than 0.01 foot per second are conveyed horizontally, they tend to fall toward the bottom of the pipe (5, 17). This tendency affects flow conditions in the pipe by causing an uneven fluid-velocity distribution from the bottom to the top of the pipe's cross section. If the horizontal conveying velocity is high in relation to the hindered settling velocity, the particles will be carried in suspension by the turbulent flow of the fluid. But should the velocity decrease, the particles will be deposited in a bed at the bottom of the pipe, initially forming a sliding bed. The deposition will continue until equilibrium is reached for the particular flow mixture. The lowest velocity for particle transport is called the critical deposit velocity, and it is dependent on pipe diameter and particle density. If the flow rate of the mixture falls below this critical deposit velocity, more and more material will be deposited in the bed until the pipe is finally blocked.

Durand and Condolios (5) and Newitt et al. (17) gave the critical deposit velocity in water for particles over 0.1 inch in diameter as

$$V_D = 1.33 [2g D (s-1)]^{0.5} \qquad [6]$$

In our tests, reported later, potatoes with a specific gravity of 1.070 being carried in water in a 12-inch-diameter pipe had a critical deposit velocity of approximately 2.8 feet per second. In a 9.5-inch-diameter pipe, it was 2.5 feet per second.

Headlosses in Horizontal Transport

Typical conveying velocity and headloss relationships for horizontal conveying are shown in figure 1.

This figure shows that at high velocities the headloss curves for the various mixtures are parallel and higher than the headloss curve for clear water. However, as the mean velocity decreases, the conveyed particles tend to move to the bottom of the pipe and their velocity decreases below the average velocity of the water; then the headloss decreases for each mixture but

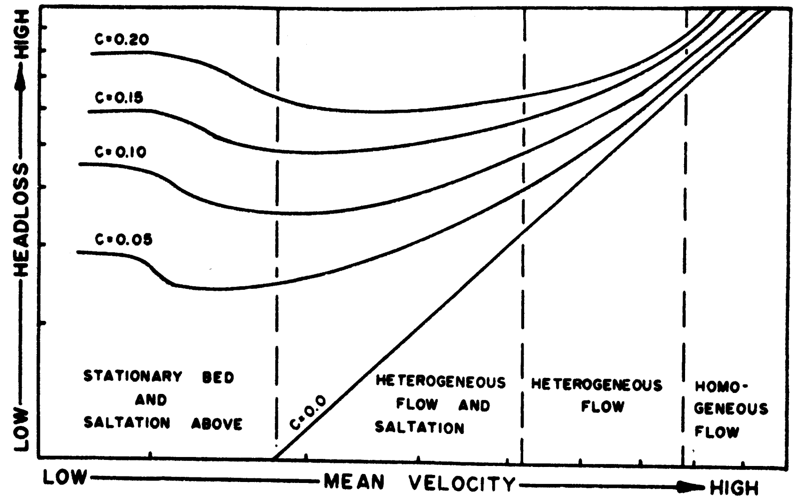


Figure 1.
Typical conveying velocity and headloss relationships in horizontal pipelining: curved lines represent solids-water mixtures of different concentrations (c), and straight line represents clear water.

at a slower rate than the rate for clear water. The headloss for each mixture continues to decrease as mean velocity decreases until the critical deposit velocity is reached. At that point, the headloss rises rapidly as a bed is built up in the pipe, leaving less of the cross section available for flow.

The most economical point for operation is at the critical deposit velocity, because headlosses--and therefore power requirements--are lowest. However, a slight change in the flow condition at this point can cause rapid buildup of a bed and subsequent blockage of the pipe. Most pipelines are operated in the saltation and heterogeneous flow range so that no material is deposited at the bottom of the pipe.

Durand and Condolios (5) investigated the pipelining of sands in the heterogeneous flow range. More than 300 tests over a wide range of particle and pipe sizes were used to develop an empirical equation describing headloss under the conditions of heterogeneous flow. That equation has been refined to the following form:

$$i_m = i_w + 81ci_w \left[\frac{gD}{V^2} \quad \frac{(s-1)}{\sqrt{C_D}} \right]^{1.5} \qquad [7]$$

Durand and Condolios (5) found that particles greater than 2 mm in diameter apparently had no effect on headlosses in water. This phenomenon concerning particle size was confirmed by tests with gravel ranging in nominal diameter from 2 to 100 mm and is postulated to apply to all other materials regardless of their specific gravity. When conveying mixtures contain particles of different sizes, the presence of fine particles is found to decrease headlosses substantially. This effect is always found if the fine material remains in suspension.

Inclined pipes generally provide more difficult conveying conditions than either vertical or horizontal pipes. Some workers have treated the situation as horizontal flow, with an elevation term added to the equations for horizontal headloss (27).

Experimental Procedures and Apparatus

Since most previous work on hydraulic conveying covered materials of a very different particle size and specific gravity than those of agricultural products, the applicability of previously gained information to the pipelining of potatoes had to be determined experimentally.

Potato Samples

Katahdin, Russet Burbank, and Kennebec varieties of potatoes were used in the experiments. Potato samples were obtained by separating a field run sample with a spool-type sizer set to divide the potatoes at the 2.25-inch intermediate-axis dimension. All tubers that did not pass between the sizing spools at this setting were used as a "coarse" particle sample and those that passed through formed the "fine" particle sample.

Drag Coefficients

Since Russet Burbank and Kennebec potatoes are not of a readily defined geometric shape, drag coefficients were determined experimentally by allowing individual potatoes to fall freely in a 12-foot-long, 12-inch-diameter cylinder containing water. During the determinations, the falling potatoes were observed to very quickly orient themselves with their maximum cross section perpendicular to the direction of fall in the fluid; so the effective diameter of each potato was based on this projected area.

Since Katahdin potatoes are roughly spherical, the average of the measured maximum and minimum dimensions for a sample of 100 potatoes was used as an estimated effective diameter. The drag coefficient for this variety was determined experimentally.

Pipeline System

A 9.5-inch-diameter pipeline was fabricated to allow measurements of headlosses under various flow conditions and to

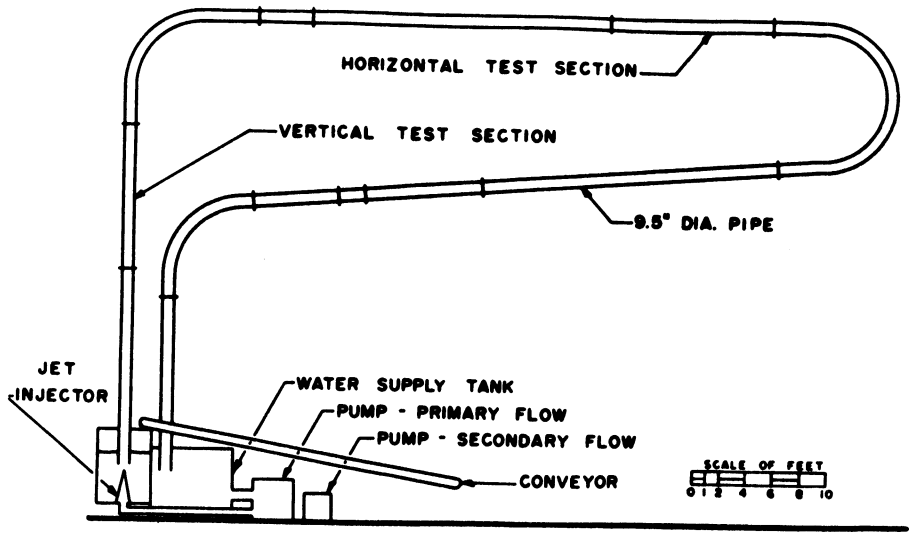


Figure 2.
Arrangement of pipelining test system.

determine the effects of pipelining on potato quality. Figure 2 illustrates the arrangement of the pipeline system for these tests. The straight sections of the pipeline consisted of steel pipe. The bends in the pipeline were constructed with transparent acrylic plastic so that flow patterns could be observed.

An irrigation pump was used to deliver water through a 4.5-inch-diameter jet into the open end of the vertical leg of the pipeline. Under the influence of this jet, secondary water from an injector tank was drawn upward into the pipeline. Approximately 40 percent of the water in the pipeline entered as secondary water from the injector tank. The system discharged into the supply tank and, once primed, operated almost as a siphon, with the irrigation pump supplying only sufficient energy to overcome friction in the line.

The potatoes were fed into the injector tank with a calibrated feed conveyor until the desired quantity was introduced. They then entered the pipeline with the secondary water and were recirculated. In operation, the system contained approximately 2,500 pounds of potatoes.

Headlosses were measured simultaneously in vertical and horizontal sections of the pipeline. Headlosses in the vertical pipe were measured over an 11.4-foot section beginning 13 feet from the injector end of the the line. Headlosses were measured over a 9.9-foot length in the horizontal section commencing 30 feet from the 90° bend.

At each pressure measurement location, four taps were drilled 90° apart around the pipe circumference. These were connected to mercury manometers that contained water over the mercury. Connecting lines were purged between every run.

Commercial orifice plates with bypass rotameters were installed in the supply line to the irrigation pump and in the delivery line from the secondary pump to measure water flow rates. Both plates were over 20 pipe diameters away from obstructions or bends. However, as the conveying water became fouled with soil and starch grains, the rotameters gave erratic readings. To overcome this problem, pressure gauges were installed in parallel with the rotameters and were calibrated against the rotameter readings with clean water flow in the system. The calibrated pressure gauges were used to indicate the water flow rate during the actual test runs.

Almost 600 test runs were made with the three varieties of potatoes at delivery rates of up to 30 pounds per second. To determine the effect of potato size on headloss, approximately half of the runs were made with the separated coarse and fine samples of field run potatoes. The remaining half of the runs were made with the full range of potato sizes in the sample.

Mechanical Damage

Single-Passage Tests. Prelilminary damage evaluation was done by removing 20-pound samples from each new batch of potatoes after one passage through the entire pipelining system. One passage consisted of pickup from the sump, travel along two 12-foot-long mechanical conveyors, injection into the pipe, travel through 160 feet of pipeline, and return to the sump.

Damage was evaluated by submerging the potatoes in a catechol solution. Skinned areas and bruised areas (flesh damage) were indicated by discoloration from the catechol (19). The U.S. Number 1 Grade standard was used for damage level criteria.

Multipassage Tests. To gain detailed knowledge of the damage which might occur during long distance pipelining, a number of tests were made with each variety at a mean flow velocity of 8 feet per second and a potato flow rate of approximately 20 pounds per second (a delivered concentration of 8 percent). A quantity of mixed-size potatoes sufficient to average one passage through the system per minute (that is, 2,500 pounds) was used for each test. The system was operated continuously, and 20-pound samples were withdrawn after 1, 2, 5, and 10 minutes of operation. These periods of operation were roughly equivalent to 1, 2, 5, and 10 passes through the system. The samples were evaluated for damage as described for the single-passage tests.

Curve Fitting Technique

A least-squares, linear-regression curve-fitting procedure was used to plot and analyze the data.

Discussion of Results

Drag Coefficients

The drag coefficient for Kennebec potatoes, which might be described as blocky prolate spheroids, averaged 1.3. The coefficient for Russet Burbank potatoes, which have a long cylindrical shape, averaged 1.2. These figures agree closely with Hallee's figures (9) obtained by suspending potatoes in a vertical airstream. The average drag coefficient for Katahdin potatoes, which are roughly spherical, was 0.85. Very few potatoes in these tests had settling velocities greater than one foot per second in clear water. Large variations in coefficients were found.

Rouse (23) showed that the drag coefficient is 0.50 for spheres and 0.74 for long cylinders oriented perpendicular to turbulent flow at a Reynolds number of 1×10^5. This number is close to the Reynolds number for our test conditions. Ellipsoids, which may roughly approximate the shape of a long potato, were shown by Rouse (23) to have a possible drag coefficient of 0.80 at the above Reynolds number. Our tests with potatoes indicate that common geometric shapes do not realistically represent the three most common potato shapes.

Vertical Transport

Flow velocities in the pipeline system were adjusted so that mean flow velocities in the horizontal section were maintained above 4 feet per second to prevent deposition. Based on equation 6, with $s = 1.070$ and $D = 9.5$ inches, the critical deposit velocity is 2.5 feet per second; hence, the system was operated at 1.6 V_D for the horizontal section.

For the vertical section, with $d = 3$ inches (the largest diameter of the potatoes) and $C_D = 1.3$, the hindered settling velocity is 0.76 feet per second based on equation 1. Since the velocity of the system--4 feet per second--was almost five times the unhindered settling velocity of the largest potatoes used in the experiments, no correction for slip was required in the concentrations value (see page 4) used in the vertical transport calculations. The measured rate of headloss along the

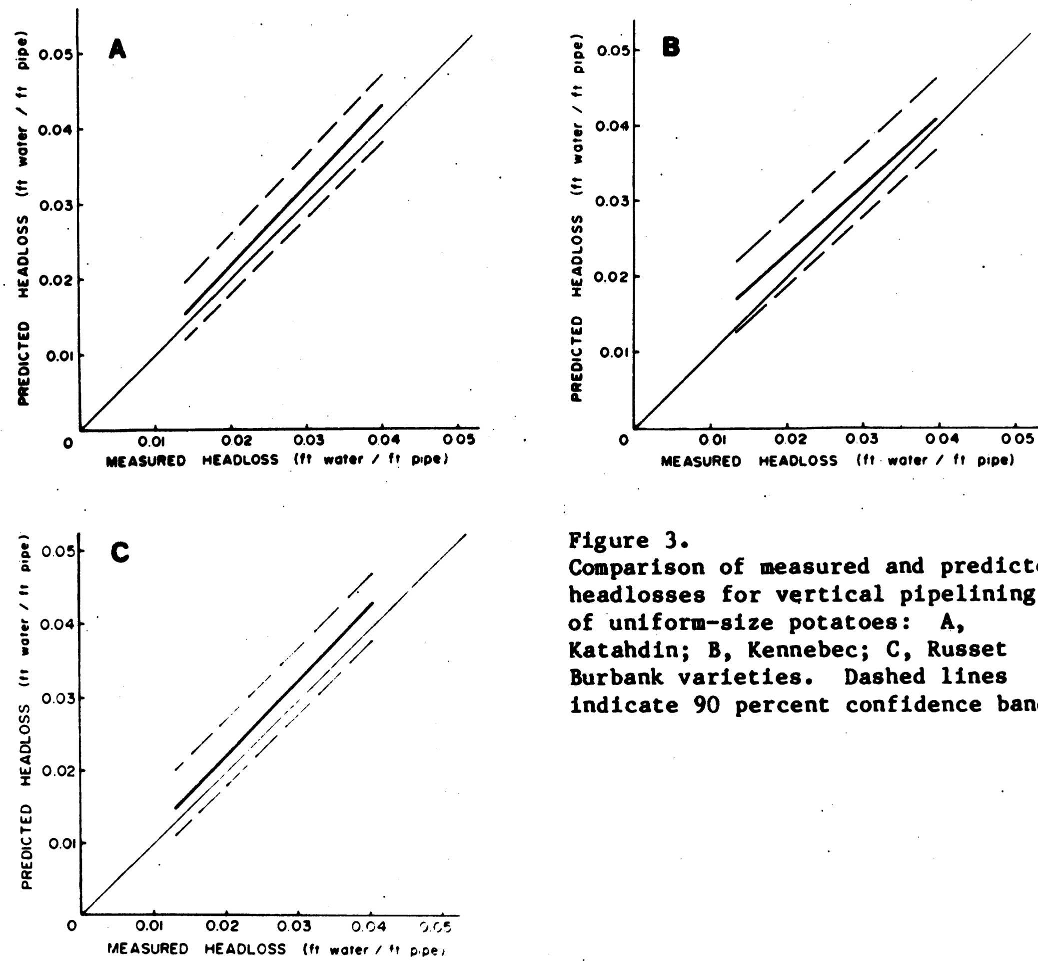
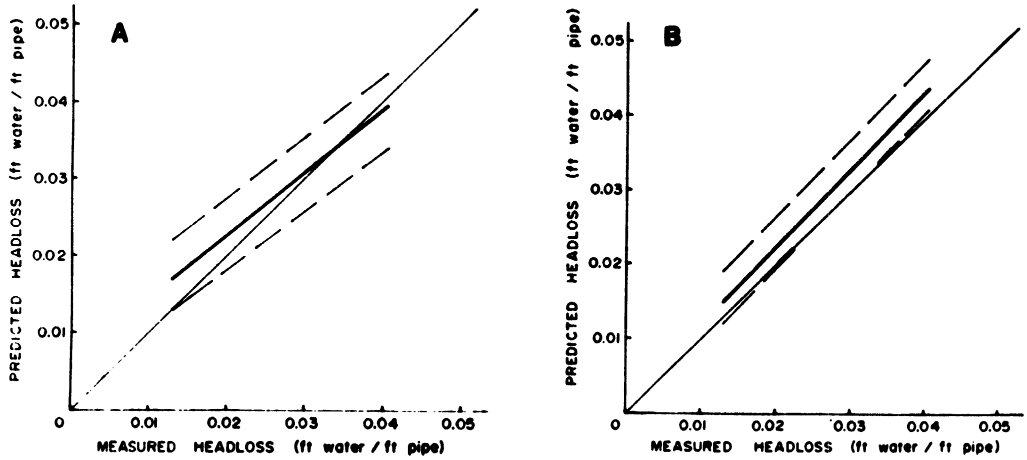


Figure 3.
Comparison of measured and predicted headlosses for vertical pipelining of uniform-size potatoes: A, Katahdin; B, Kennebec; C, Russet Burbank varieties. Dashed lines indicate 90 percent confidence band.

11.4-foot, vertical test section was compared with the headloss predicted by equation 4. The relationships between the measured and predicted headloss values for the samples of sized potatoes are shown in figure 3. Figure 4 shows the relationships for samples of mixed-size potatoes.

As shown by the positions and slopes of the regression lines in each figure except, perhaps, figure 4C, measured and predicted headlosses agreed closely. For the mixed-size Russet Burbank potatoes (fig. 4C), the predicted headlosses were low at the low velocities and tended to be high at the higher velocities. This discrepancy may have been due to interference between moving potatoes, which tends to upset their normal orientation in the pipe. The more irregular the tuber shape, the more a change in orientation will affect the conveying characteristics of the potato.



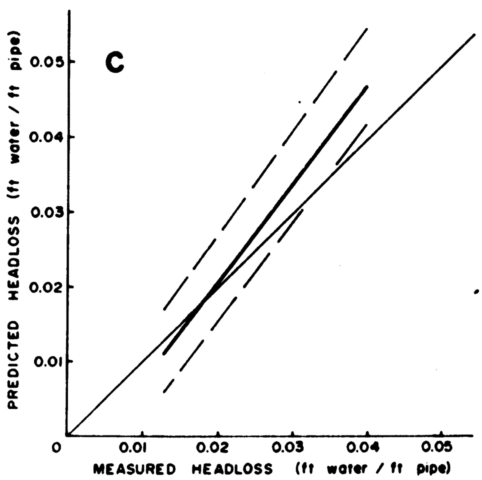


Figure 4.
Comparison of measured and predicted headlosses for vertical pipelining of mixed-size potatoes: A, Katahdin; B, Kennebec; C, Russet Burbank varieties. Dashed lines indicate 90 percent confidence band.

Horizontal Transport

The measured headlosses from the 9.9-foot horizontal section of pipe, which represented steady-state conditions, were compared with headlosses predicted with equation 7. The results are shown in figures 5 and 6. The match between the predicted and measured values was, again, reasonably close.

As with vertical conveying, the greatest discrepancies in position and slope of the regression lines occurred for the mixed-size Russet Burbank potatoes and were due to the tendency of the predicted headlosses to be high at the high velocities. Again, this tendency was thought to have been due to the irregular shape of the potato. These deviations for horizontal

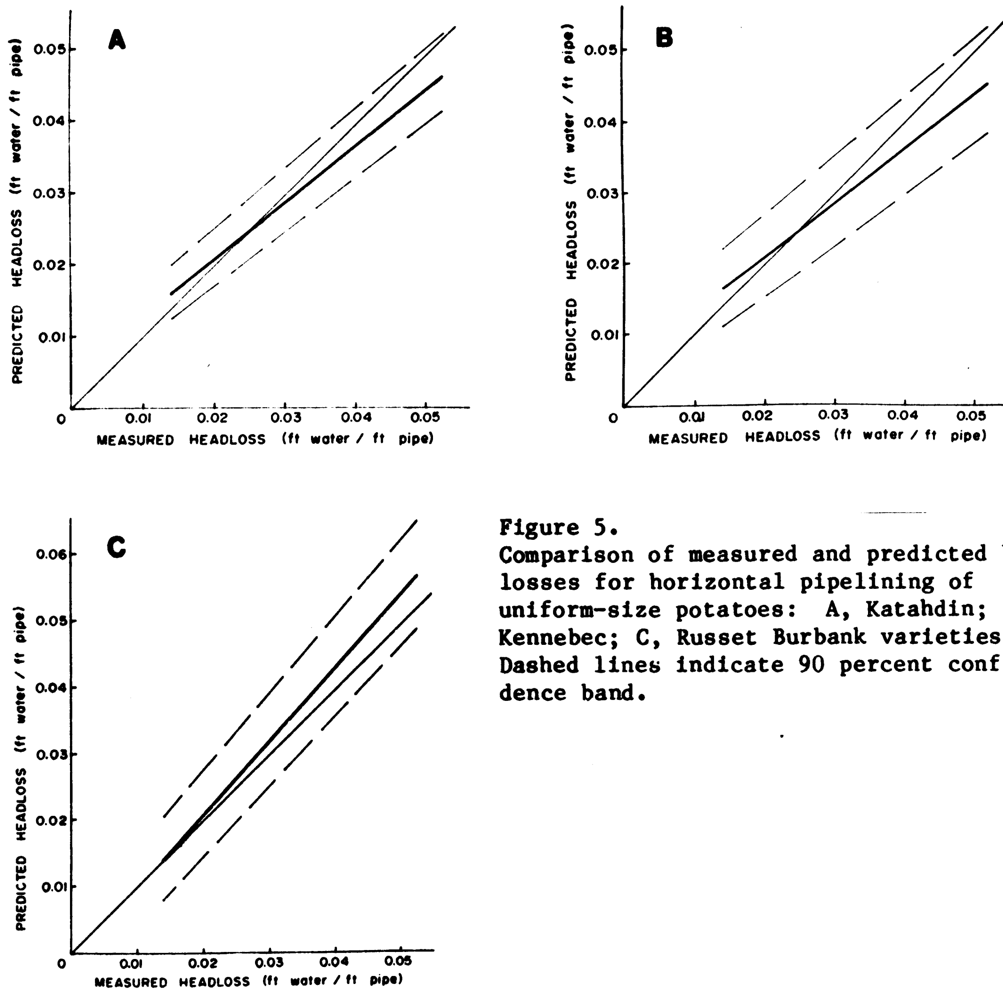
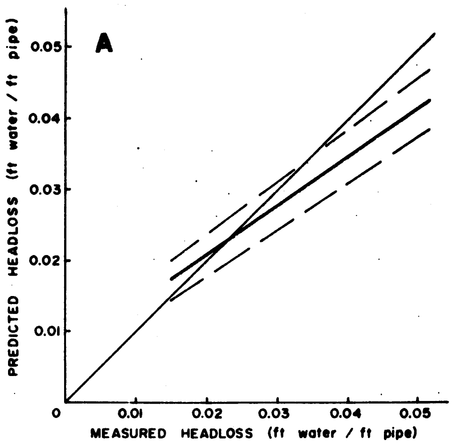
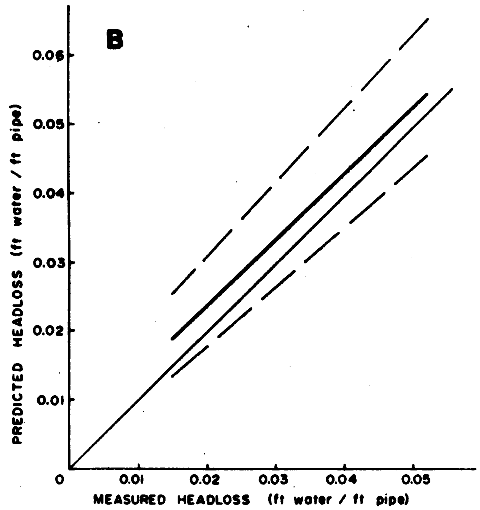


Figure 5.
Comparison of measured and predicted headlosses for horizontal pipelining of uniform-size potatoes: A, Katahdin; B, Kennebec; C, Russet Burbank varieties. Dashed lines indicate 90 percent confidence band.

flow of mixed-size Russet Burbank potatoes may be considered equivalent to an accuracy of ± 40 percent, the accuracy reported for other empirical data fits (28). A second set of headloss predictions made by a computer simulation method coincided almost exactly with those made with equation 7, so no particle-to-particle momentum transfer appears to have occurred with samples of mixed-size potatoes.

The difficulties of making precise headloss predictions for the horizontal pipelining of irregularly shaped particles are well documented (5, 28). Since the predicted headlosses for Russet Burbank potatoes were generally high, we considered it safe to use equation 7 in designing a system for horizontally pipelining potatoes.





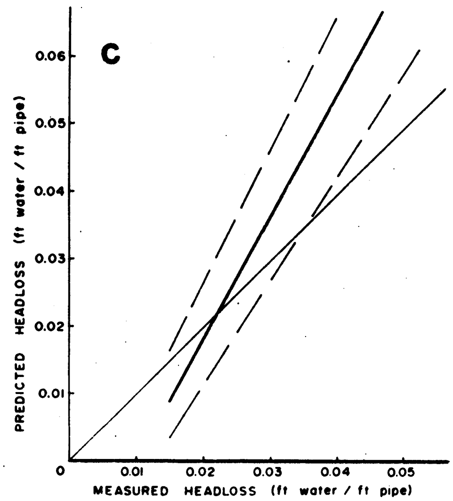


Figure 6.
Comparison of measured and predicted headlosses for horizontal pipelining of mixed-size potatoes: A, Katahdin; B, Kennebec; C, Russet Burbank varieties. Dashed lines indicate 90 percent confidence band.

Mechanical Damage

For the single-passage tests, in which potaotes were evaluated after one passage through the entire pipelining system, no flesh damage was found on any potato and skin damage was always less than 2 percent of the tuber surface area.

For the multipassage tests, the results (fig. 7) indicated that damage from pipelining potatoes at 8 feet per second for distances up to 500 feet (3 passes) would not exceed the 5 percent U.S. No. 1 grade tolerance. This amount of damage is less than that reported for single-time dry handling methods (12).

Many of the samples ultimately spent over 5 hours in the pipeline system, which is equivalent to their being conveyed almost 10 miles, and none was skinned more than 50 percent.

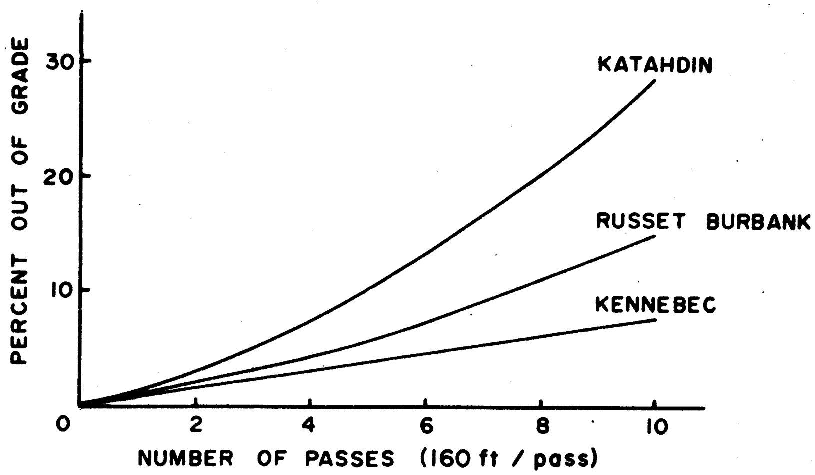


Figure 7.
Percentage of potatoes that exceed the U.S. No. 1 grade tolerance of 5 percent flesh damage after being pipelined.

Conclusions and Recommendations

Conclusions

1. For vertical hydraulic conveying of potatoes at velocities greater than 4 feet per second, steady-state conditions of flow were attained very quickly and the rate of headloss was approximated by equation 4:

$$i_m = i_w + c\ (s-1)$$

2. For horizontal conveying of potatoes at velocities greater than 4 feet per second, the rate of headloss for steady-state conditions was approximated by equation 7:

$$i_m = i_w + 81ci_w \left[\frac{gD}{V^2} \quad \frac{(s-1)}{\sqrt{C_D}} \right]^{1.5}$$

3. Conveying potatoes at mean velocities of 4 to 12 feet per second in smooth pipes resulted in very little damage to tubers other than some superficial skinning.

4. Potatoes were successfully conveyed at 160 percent of the critical deposit velocity.

Recommendations

1. The minimum internal diameter of the pipe should be at least 9 inches. As a rough rule, the pipe diameter should be at least twice the nominal diameter of the largest particle to be conveyed. While 9 inches is not double the length of the longest potato likely to be found, careful observations of flow in the 9.5-inch pipeline successfully used during the experimental work indicated that a 9-inch minimum recommendation is reasonable.

2. The minimum mean flow velocity in the horizontal section should be about 5 feet per second. To avoid deposition of potatoes at the pipe bottom and the subsequent possibility of pipe blockage, a mean design velocity of 5 feet per second (or approximately double the critical velocity if the pipe is greater than 15 inches in diameter) is suggested. This is based on our observations of flow conditions in transparent plastic pipe sections (data not shown). If a system consists of only vertical pipes, a slightly lower velocity may be used.

3. The maximum mean flow velocity should not exceed 10 feet per second. At mean velocities greater than 10 feet per second, headlosses are rather high. Also, observations (data not shown) in transparent plastic pipe sections indicated that at higher velocities potatoes tended to slide along the wall of the pipe at bends in the pipeline, with an accompanying increase in chance for damage.

4. The maximum delivered concentration of potatoes should be 15 percent by volume. This concentration value may be exceeded for large-diameter pipes but represents a safe value for small-diameter installations because the danger of blockage is proportionately greater.

Designing a Pipelining System

Although giving detailed procedures for designing a pipeline system is beyond the scope of this report, some basic steps can be given. Therefore, these steps, along with two examples to illustrate their application, are given in this section. This information should be useful to the researcher in making preliminary design and feasibility studies for a potato pipeline.

Design Steps

1. Determine the capacity required of the system in hundredweight (cwt) of potatoes per hour.

2. Fix the concentration desired, with $c = 0.15$ maximum.

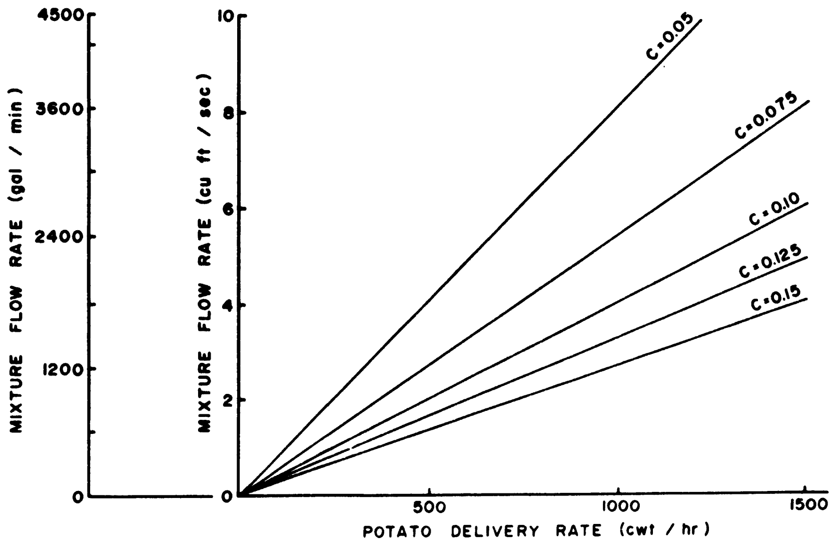


Figure 8.
Relationship of potato delivery rate and total flow rate for various concentrations of potatoes (s = 1.070) in water.

3. Calculate the volume flow rate--

$$Q\ (ft^3/sec) = \frac{\text{cwt potatoes/hr}}{2{,}246 \times s \times c}$$

Figure 8, which was developed for potatoes with a specific gravity of 1.070, may be used to obtain the volume flow rate in cubic feet per second or in gallons per minute.

4. Calculate the minimum pipe diameter to give 10 feet per second maximum velocity (minimum limit is 9 inches internal diameter)--

$$D_{min}\ (ft) = \sqrt{Q \times 0.127}$$

5. Calculate the maximum pipe diameter to give the minimum velocity of 5 feet per second--

$$D_{max}\ (ft) = \sqrt{Q \times 0.255}$$

Figure 9 gives the limiting pipe diameters for flow rates of normal mixtures.

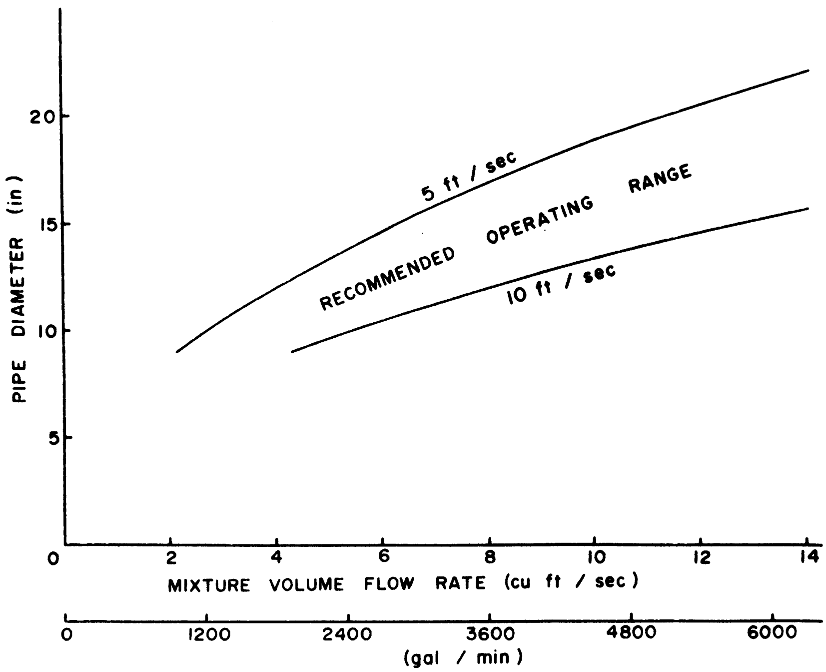


Figure 9.
Pipe diameters for potato pipelining.

6. Select a pipe diameter. The choice of any particular diameter within the above limits will depend on a number of factors, including a balance of operating and installation costs. A smaller diameter pipe will be lower in initial cost but will mean higher conveying velocities, higher headlosses, and greater power consumption.

7. Calculate the mean conveying velocity--

$$V\ (\text{ft/sec}) = \frac{1.27 \times Q}{D^2}$$

8. Calculate the clean-water-friction headloss--

$$i_w\ (\text{ft water/ft pipe}) = \frac{fV^2}{2gD}$$

The value of f for turbulent flow in smooth steel pipes will be approximately 0.02.

9. Calculate the headlosses and total them.

(a) Elevation head (the vertical pipelining distance plus the friction losses in vertical sections converted to head)--

$$H_E = E + Ei_m$$

where $i_m = i_w + c\ (s-1)$

(b) Friction head for horizontal flow--

$$H_H = L \left[i_w + 81 c i_w \left(\frac{gD}{V^2} \quad \frac{(s-1)}{\sqrt{C_D}} \right)^{1.5} \right]$$

(c) Total head--

$$H_{TOT} = H_E + H_H$$

10. Calculate the pump horsepower required--

$$hp = 0.25\ Q\ H_{TOT}$$

This figure allows for a pumping efficiency of approximately 60 percent.

By following these design steps, the head, delivery, and power requirements for the pump can be approximated for any particular application. A range of designs is possible for each situation. In selecting the best combination of pipe size, conveying velocity, solids concentration, and other design parameters, both the mechanical and economic viewpoints should be considered.

Very few pumps can handle potatoes without causing damage. For elevations of up to 15 feet and short pipelining distances, a jet injector, as used in the experimental apparatus, may be useful. For higher lifts or long pipelines, a special potato pump is desirable.

Detailed design work for actual installations should be carried out by an experienced engineer, but the following examples serve to illustrate the basic technique and enable comparisons to be made with other handling methods.

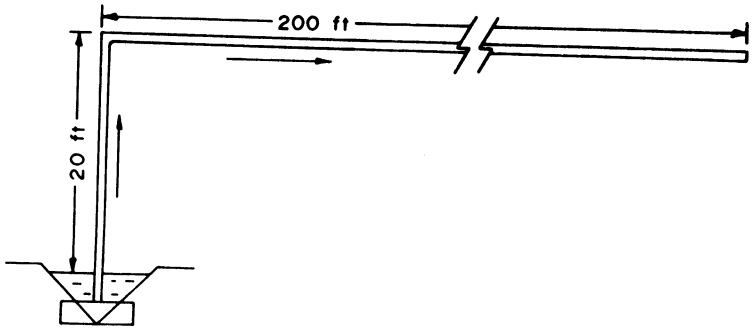


Figure 10.
Arrangement of pipeline system for example 1.

Example 1

The desired delivery of potatoes through the system shown in figure 10 is 1,200 hundredweight per hour. The requirements for the system can be estimated by using the following design steps:

1. Capacity--1,200 hundredweight per hour.

2. Concentration. Try c = 0.15.

3. Volume flow rate. From figure 8 for 1,200 hundredweight per hour at 0.15 concentration of solids, Q = 3.35 cubic feet per second or 1,500 gallons per minute.

4. and 5. Range of suitable pipe diameters. From figure 9, the range is 9 to 11 inches.

6. Selection of pipe diameter. Because 9 inches is at the minimum and the concentration (0.15) is high, try 10 inches, that is, 0.833-foot diameter.

7. Mean conveying velocity--

$$V = \frac{1.27\ Q}{D^2} = \frac{1.27 \times 3.35}{(0.883)^2} = 6.25 \text{ ft/sec}$$

8. Clean-water-friction headloss--

$$i_w = \frac{fV^2}{2gD} = \frac{0.02 \times (6.25)^2}{2 \times 32.2 \times 0.833} = 0.0146 \text{ ft water/ft pipe}$$

9. Headlosses--

(a) $H_E = E + E\,[i_w + c\,(s-1)]$

$= 20 + 20\,[0.0146 + 0.15\,(1.070 - 1.0)]$

$= 20 + 0.5$

$= \underline{20.5 \text{ ft water}}$

(b) $$H_H = L\left[i_w + 81 c i_w \left(\frac{gD\,(s-1)}{V^2\,\sqrt{C_D}}\right)^{1.5}\right]$$

$$= 200\left[0.0146 + 81 \times 0.15 \times 0.0146 \left(\frac{32.2 \times 0.83 \times 0.07}{(6.25)^2 \times \sqrt{1.0}}\right)^{1.5}\right]$$

$= 200\,(0.0146 + 0.00177)$

$= \underline{3.3 \text{ ft water}}$

(c) $H_{TOT} = H_E + H_H = 20.5 + 3.3 = \underline{23.8 \text{ ft water}}$

In this example of a short pipeline with a low mean velocity and a large lift, the elevation head represents approximately 85 percent of the total head.

10. Pump horsepower required--

$hp = 0.25 \times Q \times H_{TOT} = 0.25 \times 3.35 \times 23.8$

$= \underline{20 \text{ approx.}}$

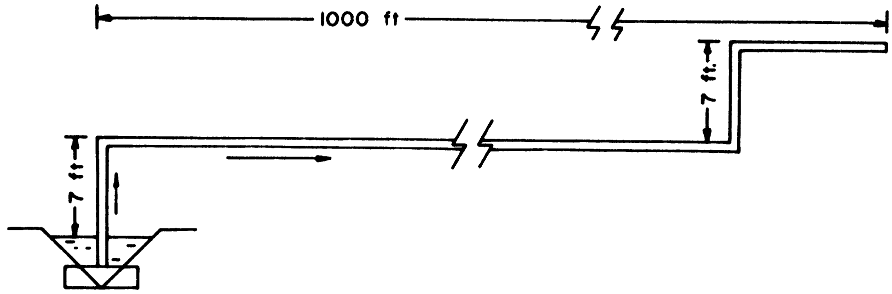


Figure 11.
Arrangement of pipeline system for example 2.

Example 2

The desired delivery rate of potatoes through the pipeline shown in figure 11 is 900 hundredweight per hour. The concentration is limited to c = 0.1, as the pipeline is being fed by a long flume system (see pages 33-34). The return water will be used in the flumes, and a minimum total volume of water in the system is desired.

The design steps are as folows:

1. Capacity--900 hundredweight per hour.

2. Concentration--c = 0.10 maximum.

3. Volume flow rate. From figure 8 for 900 hundredweight per hour at 0.10 concentration of solids, Q = 3.75 cubic feet per second or 1,680 gallons/per minute.

4. and 5. Range of suitable pipe diameters. From figure 9, the range is 9 to 11.5 inches.

6. Selection of pipe diameter. Select 9 inches (0.75 feet) to minimize the total water requirement of the system.

7. Mean conveying velocity--

$$V = \frac{1.27 \times Q}{D^2} = \frac{1.27 \times 3.75}{(0.75)^2} = 8.47 \text{ ft/sec}$$

(Note that since the minimum pipe size was limited by the 9-inch-minimum-diameter recommendation, the velocity is less than 10 feet per second).

8. Clean-water-friction headloss--

$$i_w = \frac{fV^2}{2gD} = \frac{0.02 \times (8.47)^2}{2 \times 32.2 \times 0.75} = 0.03 \text{ ft water/ft pipe}$$

9. Headlosses--

(a) $H_E = E + E\,[i_w + c\,(s-1)]$

$= 14 + 14\,[0.03 + 0.01\,(1.070 - 1)]$

$= 14 + 0.5$

$= \underline{14.5 \text{ ft water}}$

(b) $$H_H = L\left[i_w + 81ci_w\left(\frac{gD}{V^2}\ \frac{(s-1)}{\sqrt{C_D}}\right)^{1.5}\right]$$

$$= 1{,}000\left[0.03 + 81 \times 0.1 \times 0.03\left(\frac{32.2 \times 0.75 \times 0.07}{(8.47)^2 \times \sqrt{1.0}}\right)^{1.5}\right]$$

$= 1{,}000\,(0.03 + 0.00088)$

$= \underline{30.9 \text{ ft water}}$

(c) $H_{TOT} = H_E + H_H = 14.5 + 30.9 = \underline{45.4 \text{ ft water}}$

As velocities increase and as horizontal sections become longer, the proportion of total head represented by elevation head decreases.

10. Pump horsepower required--

$hp = 0.25 \times Q \times H_{TOT} = 0.25 \times 3.75 \times 45.4$

$= \underline{43 \text{ (approx.)}}$

Mechanics of Flow

Theoretically, the cross-sectional shape of a channel affects the velocity of the fluid it carries, because the shape determines the ratio of the cross-sectional flow area to the wetted perimeter (hydraulic radius R) and, thus, the relative surface area exposed to frictional forces.

Table 1 (see appendix B for all tables) shows the relative efficiencies (based on hydraulic radius-area ratios) of flumes with ideal, equal-area cross sections.

Of the noncircular cross sections listed in table 1, those for the semihexagon and the trapezoid with 1:2 side slope are theoretically the most efficient. In general practice, trapezoidal or rectangular flumes have been used because they are easiest to construct. However, the effects of the cross-sectional area of flumes may not be the same in the transport of potato-water mixtures as in the transport of clear water. For example, friction losses for potatoes will tend to be greater on the flume bottom, due to more contact, than on the sides. For such mixtures this factor would tend to favor a much-deeper-than-wide section than theoretical considerations might indicate.

The slope, S, of the channel determines the amount of energy imparted to the water by gravity, and the roughness coefficient, n, indicates the resistance to flow. These two variables can be related to velocity by the classic Manning formula (13):

$$V = \frac{1.486}{n_m} R^{2/3} \ S^{1/2} \qquad [8]$$

Potatoes often move in open channel flumes by saltation. Our field observations indicate that mean water velocities near 5 feet per second cause potatoes to be almost continuously waterborne (heterogeneous flow) and that velocities below 1.2 feet per second allow tubers to sink to the bottom of the flume and travel largely by sliding.

The only published work on fluming potatoes (6) deals with low-velocity flow that causes potatoes to be transported as a sliding bed at the bottom of the flume. We therefore undertook a study to provide data on fluming potatoes at velocities ranging from those allowing saltation to those allowing heterogeneous flow.

Experimental Procedures and Apparatus

Flume System

Fluming trials were conducted with 200-foot-long sheet-metal flumes. Field run lots of Russet Burbank and Kennebec varieties were studied. Known quantities of water and potatoes were simultaneously fed into a lateral flume to yield the desired water-to-potato concentration by volume. This lateral flume intersected the main test flume at a right angle. The main flume discharged into a reservoir, from which water was recirculated (pumped) back to the lateral flume.

Water flow rates were determined by taking gauge pressures in the pump discharge pipe and then determining the pump output based on pump calibration curves. Potato flow rates were determined by uniformly introducing a known weight of potatoes during the test interval.

Flume slope was determined with an engineer's level and a stadia rod. Slopes of 1 inch per 12 feet and 1 inch per 15 feet were studied.

A trapezoidal cross section which had a 10-inch bottom width, an 18-inch top width, and a 16-inch depth was used as one test shape. A rectangular cross section 12 inches wide by 18 inches deep was also tested.

Tables 6 and 7 give further information on the number of trials conducted and the variables tested.

Depth and Velocity Profiles

Calibrated, recording-type float devices were installed at 10-foot intervals along the test flume to measure flow depths.

With the known volume of flow, velocity profiles were computed from the flow depth and cross-sectional-area relationship for each flume shape being tested (see appendix A, sample 1, for calculations). These profiles and computed values were used as a basis for comparing the effects of the input variables being tested.

Mechanical Damage

Dyed samples of stored potatoes were placed in the flume system and recovered during the various runs to evaluate potato damage for three intersection angles (45°, 60°, and 90°) between the lateral (supply) flume and the main flume. The dyed tubers that were recovered were treated with a catechol solution so that any bruising or skinning could be readily observed (19).

For injury comparison, individual potatoes from the samples were rated from 1 (no discernible injury) to 6 (sufficiently damaged to prevent them from meeting U.S. No. 1 grade specifications). An injury index was computed for each sample by summing the products of the percentage of tubers in each classification multiplied by the numerical class rating. The smaller the index, the less the degree of damage. The number of dyed, bruise-free potatoes were counted and a percentage was calculated.

Potatoes at 45° and 60° F pulp temperature were transported in both 45° and 60° F water to determine if water temperature affected bruising. The transport time in the flume was about 30 seconds.

Curve Fitting Techniques

Concentration ratios were related to average mixture velocities using least-squares, linear-regression curve-fitting procedures. Damage index data were represented with a freehand curve fit.

Discussion of Results

Flow Conditions

The maximum flow rate of 29 pounds of potatoes per second was achieved with the Kennebec variety, at a flume slope of 1 inch per 12 feet and a potato concentration of about 18.5 percent (table 6). A slightly lower rate, 26 pounds per second, was achieved with Russet Burbank variety at a concentration of about 17 percent. Velocities near the test-flume inlet ranged from 3.0 to 4.8 feet per second. The discharge velocities were approximately 2.8 to 4.6 feet per second for an approximate 10 percent concentration, 2.0 to 3.0 feet per second for a 12.5 percent concentration, and 1.0 to 1.5 feet per second for a 16.7 percent concentration.

As shown in figure 12, the flow depth fluctuated, indicating apparent wave action. This apparent wave action may have been due to a saltation type flow characterized by the potatoes alternately sliding along the flume bottom then being bouyed up. This action may also indicate that the flume was inclined at less than critical slope and that gradually varying flow was occurring (13).

The data indicate that the decrease in velocity (increase in flow depth) was greatest between the 5-foot and the 35-foot sections. Apparently the flow made the transition from less than critical to greater than critical depth within the first 35 feet of flume (see appendix A, sample 3, for critical depth calculation procedure).

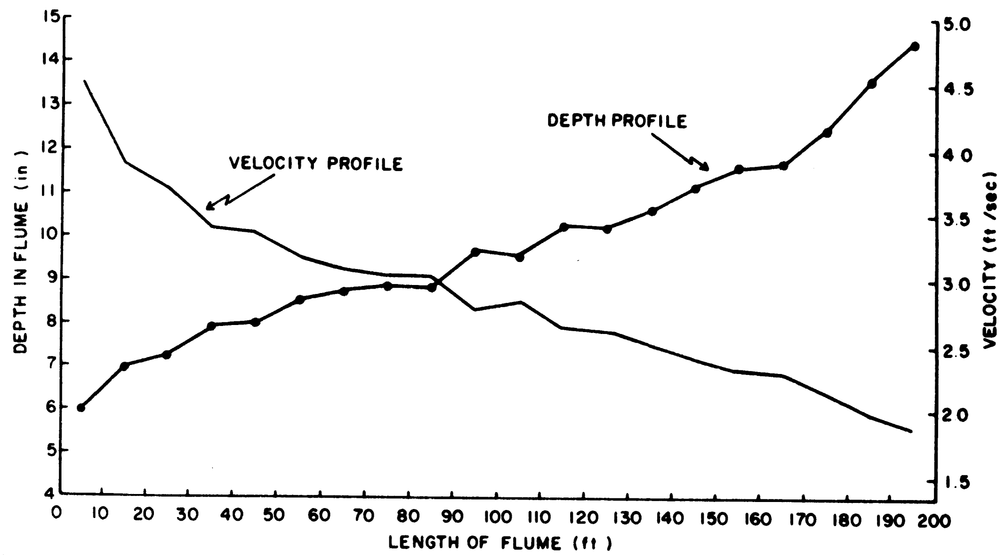


Figure 12.
Typical measured-depth and computed-velocity profiles for 12-in-wide rectangular flume transporting Kennebec variety potatoes at 0.165 concentration (vol. to vol.) in water.

Computer analysis of the flow data (table 7) indicated that hydraulic gradients reversed a number of times beyond the 135-foot station. Therefore, flow analysis comparisons were made with data for the 35-foot through 135-foot stations.

Figures 13 and 14 illustrate the effect of potato concentration on mixture velocity. The 75- to 85-foot reach was selected as an example, since it was midway between the 35- and 135-foot stations.

During the trials the Russet Burbank potatoes seemed to flow slower and closer to the bottom of the flume than the Kennebec potatoes when the flume slope was 1 inch per 15 feet and the mixture concentration was over 10 percent. However, of the trial data--which were highly variable--only those for the rectangular flume bore out this indication. Plots for the 195-foot station were generally similar to the corresponding plots in figures 13 and 14. Quite likely, the Russet Burbank potatoes at 13.7 percent concentration moved as a sliding bed in the rectangular flume when the flume slope was 1 inch per 15 feet.

Regardless of the flume slope or cross-sectional shape, the velocity loss along the flume was lowest for potato concentrations in the 9 to 10 percent range. Table 2 shows the results for several trials.

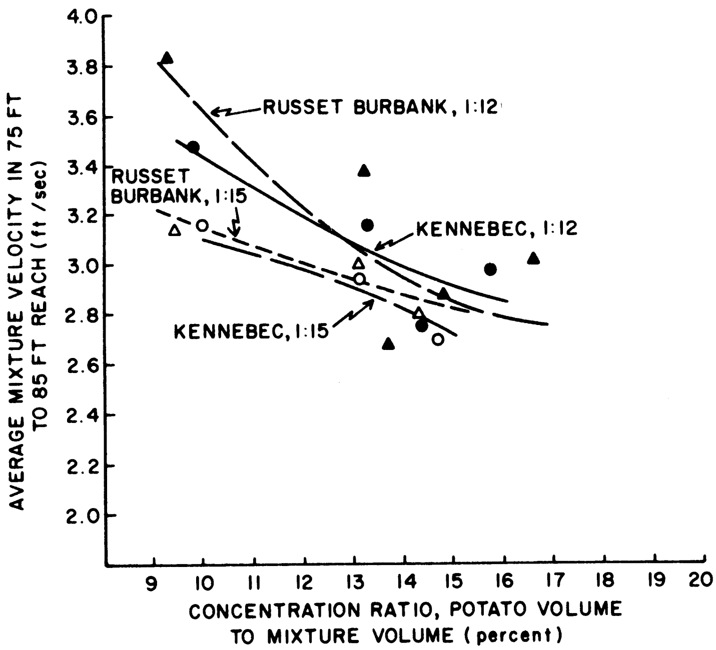


Figure 13.
Effect of potato concentration on velocity of transport in a trapezoidal flume, with a 10-in-wide bottom and 1:4 side slope, at flume slopes of both 1 in:12 ft and 1 in:15 ft for Kennebec (solid and open circles) and Russet Burbank variety potatoes.

The velocity differences indicate that Russet Burbank potatoes may offer slightly more resistance to flow in an open channel than Kennebec potatoes. The specific gravity of the Russet Burbank potatoes exceeded that of Kennebec by 0.004 to 0.008 and may have had some influence. However, the elongated shape of the Russet Burbank potato may have had more influence. Similar varietal effects were found in the pipeline work (see fig. 5B and 5C). These data on fluming indicate that a velocity of about 4 feet per second is needed to maintain uniform flow for potatoes with specific gravities in the 1.080 to 1.090 range. This velocity is about twice the value predicted by equation 6.

Manning Roughness Coefficient

In the Manning formula, equation 8, the factor n_m accounts for friction effects. A mean n_m for the entire 100-foot test section was calculated for each trial, based on calculated n_m's from equation 8 for each 10-foot reach between the 35-foot and 135-foot stations (see appendix A, sample 2, for calculation procedure). Results from trial 32, one of the trials with the most uniform flows for the 12-inch rectangular flume, are shown in table 3.

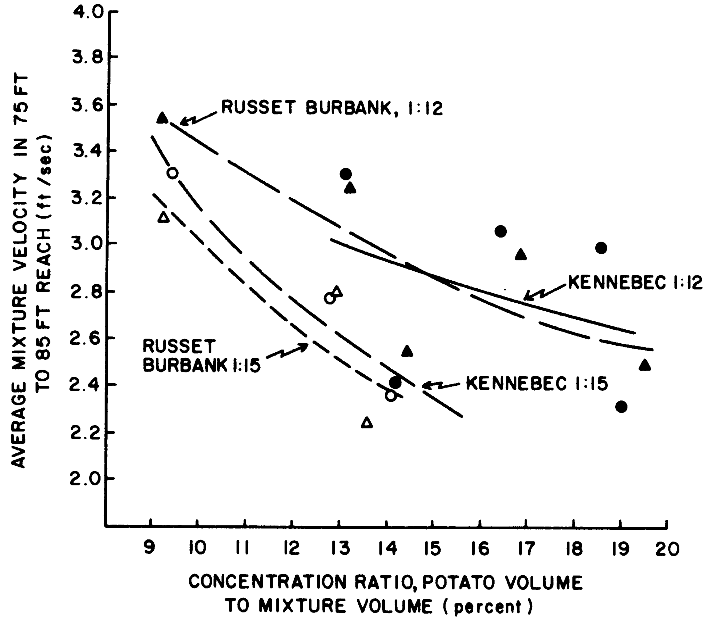


Figure 14.
Effect of potato concentration on velocity of transport in a 12-in rectangular flume at flume slopes of both 1 in:12 ft and 1 in:15 ft for Kennebec (solid and open circles) and Russet Burbank variety potatoes.

Values of n_m were predicted, based on the means of variables that were related, by using the following equations (17):

$$n = n_w + c(s-1) \qquad [9]$$

$$n = n_w + Kcn_w \left[\frac{gD_h}{V^2} \; \frac{(s-1)}{\sqrt{C_D}} \right]^N \qquad [10]$$

Equation 10 is a general form of equation 7. The ratio n_m/n was calculated for each trial and then averaged for each flume type (table 4).

Equation 9 greatly overestimated n_m. Equation 10 with the coefficients K = 121 and N = 1.5 safely approximated n_m values calculated from trial data. Equation 10, as used with the preceding values for K and N, was discussed by Newitt et al. (17) for various flow conditions.

Flume Slope

As indicated by figures 13 and 14 and shown by the data in table 2, a flume slope of 1 inch per 12 or 15 feet was generally not sufficient to maintain a constant velocity as mixture concentrations were increased above approximately 10 percent. A flume slope of 1 inch per 12 feet with concentrations of less than 10 percent may have approached conditions that allowed fairly uniform flow rates for the 10-inch trapezoidal flume (table 2). This slope was not sufficient to maintain uniform flow in the 12-inch rectangular flume at the less-than-10-percent concentrations tested.

Flume Cross Section

As indicated in table 2, the 10-inch trapezoidal flume roughly maintained the mixture velocity for the test concentrations that were less than 10 percent. The velocity decreased in the 12-inch rectangular flume for all concentrations tested, regardless of slope. These results are consistent with the relative efficiencies shown in table 1.

The results reported herein are applicable to flumes flowing quite full. If the flume is expected to be filled to widely different capacities over time, an elliptical cross section, with the major axis vertical, should be considered (3). This shape will allow flow velocities to (a) remain high enough to prevent blockage from potatoes when the flume is flowing at low capacity and (b) remain low enough to prevent excessive wear of the channel surface when the flume is flowing at high capacity. A similar awareness that a tapered-bottom flume would be desirable may have prompted the previous recommendation (6) that a trapezoidal flume be used.

Hydraulic Jump

The hydraulic jump is an abrupt rise in water surface which may occur in an open channel when water flowing at high velocity is retarded (13). During this decrease in velocity, kinetic energy (velocity) is converted to potential energy (stream depth). In this transition some energy is lost in the form of turbulence; hence, some transport capability is lost.

When the water surface is at the lower depth (lower stage flow), the water is flowing at supercritical velocity. When the water surface is at the higher depth (upper stage flow), the water is flowing at subcritical velocity. Critical velocity, V_c, occurs at critical depth, D_c, the depth at which maximum discharge per unit of energy occurs; and these are related as follows:

$$D_c = \frac{Vc^2}{g} \qquad [11]$$

As the water depth increases from less than critical to greater than critical depth, the hydraulic jump may be observed.

Critical velocity can be estimated by using the following equation from King (13) to obtain required flow area, A:

$$\frac{A^3}{T} = \frac{Q^2}{g} \qquad [12]$$

Using A, D_c may be determined (see appendix A, sample 3).

Hydraulic jump may be difficult to evaluate unless special channel designs are used to measure it. Wave action may make the jump difficult to detect. A sharp decrease in calculated energy gradient, H, along a channel indicates the occurrence of a hydraulic jump.

The average headloss per foot, S, which is the hydraulic energy gradient, was calculated for each 10-foot reach for each test. The fluctuations of S along the channel for a constant channel slope suggested changes in type of potato flow rather than a hydraulic jump phenomenon. The potatoes in most tests were probably going through transitions between sliding bed, saltation, and heterogeneous flow.

Hydraulic jump could be of concern if the flume slope changes from steep to shallow or if the flume discharge becomes submerged. Under either condition the mixture velocity may be reduced to the extent that the potatoes completely settle, stop sliding, and form a blockage.

In the present trials, supercritical velocities, that is, flows at less than critical depth, were from 5.0 to 5.8 feet per second and subcritical velocities were 3.8 to 4.3 feet per second. The critical velocity for potato-water mixtures would thus appear to be in the order of 4.3 to 5.0 feet per second. For clear water flowing at 4.3 feet per second, the calculated or theoretical critical depth would be approximately 6 inches.

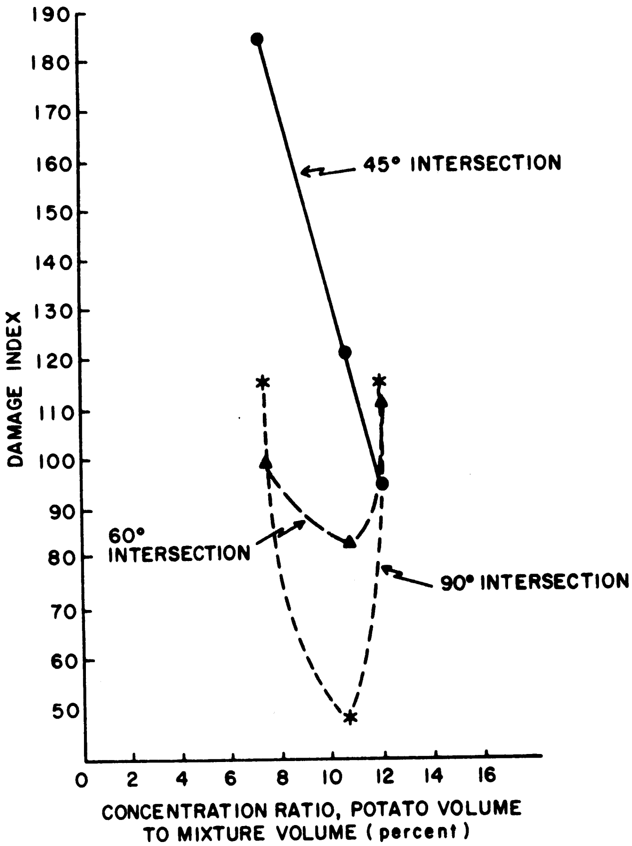


Figure 15.
Damage due to flume intersection angle at various mixture concentrations. Mixture velocity ranged from 2.83 to 4.33 ft/sec.

Mechanical Damage

As indicated in figure 15 and table 5, there was no consistent trend relating intersection angle and damage index. The 10.7-percent concentration consistently resulted in the lowest damage index except when the intersection angle was 45°. At the two lowest concentrations, the 60° and 90° intersection angles caused less damage than the 45° angle.

From a construction standpoint, a 90° lateral (bin) flume is the most direct route to a main flume, thus requiring the shallowest bottom-grade cut to maintain slope. Also, the damage data suggest that a 90° intersection is acceptable.

The data also indicate that a 10.7-percent concentration causes much less damage than a 7.4- or 12.0-percent concentration at a 90° intersection.

The average flow velocities of 3.8 to 4.3 feet per second are close to the minimum pipeline velocity of 4 feet per second, which caused little damage in pipelines flow (see page 14).

No effects of water temperature on bruising were observed for the 30-second transport time used.

Conclusions and Recommendations

Conclusions

1. The Manning roughness coefficient, n_m could be estimated for open channel conveying of potatoes with the relationship

$$n = n_w + 121\ cn_w \left[\frac{gD_h}{V^2}\ \frac{(s-1)}{\sqrt{C_D}}\right]^{1.5}$$

2. A slope of 1 inch per 12 feet and mixture concentrations of less than 10 percent maintained uniform flow in the 10-inch trapezoidal flume.

3. A slope of 1 inch per 12 feet and mixture concentrations of less than 10 percent did not maintain a uniform flow in the 12-inch rectangular flume.

4. With a concentration of approximately 10 percent, the 90° lateral-to-main-flume intersection was the most feasible from both a damage and construction standpoint.

Recommendations

1. The minimum flume width should be 10 inches. No blockage, due to long potatoes, was observed in the trapezoidal flume with the 10-inch bottom or the 12-inch rectangular flume. These minimum flume-width dimensions should allow sufficient clearance to handle any potato variety. The maximum dimension on most varieties will not exceed 4 to 6 inches. Russet-type varieties may occasionally reach 8 inches as a maximum length. Trapezoidal flumes with an 8-inch bottom have been used with the typically smaller varieties.

2. The recommended concentration is 10 percent volume to volume. This concentration caused little damage at flume intersections and gave the most uniform flows in flumes with slopes of 1 inch per 12 feet and 1 inch per 15 feet.

   Potatoes at higher concentrations, from 10 through 19 percent, were transported without blockage in flumes having these two slopes, but moved as a sliding bed. If the slope or other conditions are not uniform, the chance of blockage is greater for potatoes at these high concentrations than at a concentration of 10 percent. In field designs, concentrations of 14 percent are often used for runs that do not exceed approximately 100 feet.

At a concentration of 10 percent, 10 cubic feet of mixture would contain 9 cubic feet of water and 1 cubic foot of potatoes.

3. The minimum mean flow velocity should be 1.6 feet per second. Observations indicated sliding bed conditions at a flow velocity of approximately 1.2 feet per second. Since this type of flow may be blocked relatively easily, a velocity of 1.6 feet per second is suggested as a minimum for design purposes. This has been successfully used in field designs and should reduce the chance of discharge conditions causing problems upstream.

4. The maximum mean flow velocity should be 4.0 feet per second. This velocity maintained uniform flow conditions in our tests and allowed heterogeneous flow. Obtaining higher velocities would necessitate greater slopes and increased construction costs. Also, damage might increase.

5. The minimum flume slope should be 1 inch per 15 feet. Test data indicated that this slope is sufficient to maintain flows for concentrations from 9 to 19 percent for up to 195-foot runs, which were the limits of our tests conditions. At concentrations of approximtely 16 to 19 percent, mean flow velocities were reduced to the sliding bed range after 185 feet of travel. Our suggested guideline for field design is that bin flumes can have a slope of 1 inch per 15 feet if the runs are less than 50 feet. For these short runs, the combination of the original sluicing momentum and flume slope apparently imparts more energy than is needed to overcome frictional losses.

6. The maximum flume slope should be 1 inch per 12 feet. Tests indicated that a slope of 1 inch per 12 feet will prevent sliding bed conditions in runs up to 195 feet long with potato concentrations of less than 19 percent. However, the pattern of decreasing velocity indicated that a sliding bed condition would develop at longer distances. If concentrations are maintained at approximately 10 percent, fairly uniform flows should be maintained at this slope for any practical distance.

Designing a Fluming System

Design Steps

1. Determine the capacity required of the system in hundredweight of potatoes per hour.

2. Select the concentration desired. Suggested values are c = 0.10 for the main flume and c = 0.14 for the lateral (bin) flume.

3. Calculate volume of flow in bin flume.

4. Determine bin flume dimensions.

5. Calculate volume of flow in main flume.

6. Determine main flume dimensions.

7. Determine grade lines for bin flume and main flume.

8. Determine volume of water sump must hold.

9. Determine volume of soil sump must hold.

10. Determine sump dimensions.

Example

1. Desired capacity is 1,200 hundredweight (cwt) per hour.

2. Bin flume--c = 0.14, assumed length is 100 feet; main flume c = 0.10, assumed length is 200 feet.

3. Volume of flow in bin flume, Q.

   Volume of potatoes (s = 1.070)

$$\frac{1{,}200 \text{ cwt}}{\text{hr}} \times \frac{1 \text{ hr}}{3{,}600 \text{ sec}} \times \frac{1 \text{ ft}^3}{(1.070)\ 62.4 \text{ lb}}$$

$$\times \frac{100 \text{ lb}}{1 \text{ cwt}} = 0.499 \text{ ft}^3/\text{sec}$$

   Volume of water

$$c = \frac{\text{vol. potatoes}}{\text{vol. potatoes} + \text{vol. water}} = 0.14$$

$$0.14(0.499) + 0.14(\text{vol. water}) = 0.499$$

$$\text{Vol. water} = 3.065 \text{ ft}^3/\text{sec} \times 7.48 \text{ gal/ft}^3$$

$$= 22.9 \text{ gal/min}$$

$$Q = 0.499 + 3.065 = 3.56 \text{ ft}^3/\text{sec.}$$

4. Bin flume dimensions. Assume design velocity of 1.6 feet per second. This will reduce excavation needed, since a slope of 1 inch per 15 feet will allow this velocity to be attained.

$$\text{Flume area} = \frac{\text{mixture flow volume}}{\text{mean velocity}} = \frac{3.56}{1.6} = 2.23 \text{ ft}^2$$

Assume rectangular flume with width (B) equal twice the depth (D)

$$BD = 2.23 \text{ ft}^2 \times 144 \text{ in}^2/\text{ft}^2$$

$$(2D)D = 2.23 \times 144$$

$$D = \sqrt{\frac{2.23 \times 144}{2}} = 12.7 \text{ inches}$$

$$B = 2D = 25.34 \text{ inches}$$

Allowing for 2-inch freeboard (4 to 6 inches if stones are being handled with potatoes), overall depth at farthest upstream location is 15 inches; use 24-inch nominal width.

5. Volume of flow in main flume, Q.

Volume of potatoes is 0.499 ft^3/sec

Volume of water (concentration reduced to 10 percent)

$$c = 0.10 = \frac{0.499}{\text{vol. water} + 0.499}$$

$$\text{vol. water} = 4.491 \text{ ft}^3/\text{sec} = 33.60 \text{ gal/sec}$$

$$Q = 0.499 + 4.491 = 4.990 \text{ ft}^3/\text{sec}$$

Note that an additional 1.426 cubic feet per second or 10.67 gallons per second of water is needed in excess of that supplied by the bin flume. Usually this supplementary water is added at the farthest upstream end of the main flume.

6. Main flume dimensions. Assume design velocity of 4 feet per second to ensure uniform flow. This will require a slope of 1 inch per 12 feet.

$$\text{Flume area} = \frac{Q}{4.0} = \frac{4.99}{4.0} = 1.25 \text{ ft}^2$$

Again, use rectangular flume

$$2D^2 = 1.25$$

$$D = 0.79 \text{ ft} = 9.5 \text{ in}$$

$$B = 2D = 19.0 \text{ in}$$

Allowing 2 inches of freeboard, depth at farthest upstream location in main flume would nominally be 12 inches; use 19-inch width.

7. Grade lines for flume system. With the floor surface at the upstream end of a lateral (bin) flume as a reference, the following grades would be needed:

From step 4, the bottom of the bin flume farthest upstream would be 15 inches below the floor surface (with 2-inch freeboard included).

The 100-foot bin flume (step 2), with a slope of 1 inch per 15 feet (step 4), would have a discharge grade that would be

15 in + 100 ft x 1 in/15 ft = 21.7 in, or nominally 22 inches below the reference floor surface.

However, a 4-inch drop might be used to impart additional energy at the bin-to-main-flume intersection (21). Then, the grade of the main flume at the farthest bin flume would be nominally 26 inches below the reference floor surface.

The 200-foot main flume (step 2) with a slope of 1 inch per 12 feet (step 5) would have a discharge grade of

26 in + 200 ft x 1 in/12 ft = 42.67 in, or nominally 43 inches below the reference floor surface.

8. Volume of water sump must hold.

From bin flume (step 4)--2.23 ft^2 x 100 ft = <u>223 ft^3</u>

From main flume (step 6)--1.25 ft^2 x 200 ft = <u>250 ft^3</u>

From water supply pipe system--assuming 300 ft of pipe to supply bin flume, 200 ft of pipe to supply main flume, and 8 in diameter pipe--

$$\text{Vol.} = \frac{\Pi\, d^2}{4} \times \text{length} = \frac{\Pi(8/12)^2}{4}$$

$$\times\ 500\ \text{ft} = 174\ \text{ft}^3.$$

Total volume = 223 + 250 + 174 = 647 ft^3

9. Volume of soil sump must hold. Assume soil is 2 percent by volume of incoming potatoes and one cleanout is done per 10-hour day.

$$\frac{1{,}200\ \text{cwt}}{\text{hr}} \times 10\ \text{hr} \times \frac{1\ \text{ft}^3}{0.42\ \text{cwt potatoes}} \times 0.02 = 570\ \text{ft}^3$$

10. Sump dimensions.

Total capacity needed (below main flume discharge)

Water (step 8)	=	647 ft^3
Soil (step 9)	=	570 ft^3
Total	=	1,217 ft^3

Possible sump dimensions could be

8 ft deep x 12 ft wide x 12.6 ft long

Bottom of this size sump would be

(8 ft + 43 in/12 in) = 11.6 ft below the reference floor surface.

References (10, 21) discuss design guidelines that have been successfully used in the field.

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APPENDIX A. SAMPLE CALCULATIONS

Sample 1

Calculation of water-potato-mixture velocity (trial 32, 35-foot station, rectangular channel)

$D = 6.40 \text{ in} = 0.533\text{-ft flow depth}$

$B = 12.0 \text{ in} = 1.00\text{-ft width}$

$A = B \times D = 0.533 \times 1.00 = 0.533 \text{ ft}^2 \text{ flow area}$

$$Q = \left[\frac{\text{potatoes lb/min}}{62.4 \text{ lb/ft}^3 \times s} + \frac{\text{gal}}{\text{min}} \times \frac{0.134 \text{ ft}^3}{\text{gal}}\right] \frac{1 \text{ min}}{60 \text{ sec}}$$

$$= \left[\frac{783}{62.4 \times 1.080} + 850 \times 0.134\right] \frac{1}{60} = 2.09 \text{ ft}^3/\text{sec}$$

$$V = \frac{2.09}{0.533} = 3.92 \text{ ft/sec}$$

Sample 2

Calculation of mean flow parameters for a 10-foot reach (trial 32, 35-foot to 45-foot reach, slope is 1 inch per 12 feet)

At 35-foot station:

$D_{35} = 6.40 \text{ in}$ $\qquad V_{35} = 3.92 \text{ ft/sec}$

Z_{35} = elevation above flume discharge based on 200 feet total flume length

$$Z_{35} = (200 - 35) \frac{1/12}{12} = 1.15 \text{ ft}$$

$$H_{35} = \text{total head at 35-foot station} = \frac{V^2{}_{35}}{2g} + Z_{35} + D_{35}$$

$$= \frac{(3.92)^2}{64.4} + 1.15 + 0.533 = 1.97 \text{ ft}$$

$$R_{35} = \text{hydraulic radius} = \frac{0.533 \times 1.00}{2 \times 0.533 + 1.00} = 0.258 \text{ ft}$$

At 45-foot station:

$$D_{45} = 6.70 \text{ in} = 0.558 \text{ ft}$$

$$Q = 2.09 \text{ ft}^3/\text{sec}$$

$$A_{45} = 0.558 \times 1.00 = 0.558 \text{ ft}^2$$

$$V_{45} = \frac{2.09}{0.558} = 3.75 \text{ ft/sec}$$

$$Z_{45} = (200 - 45)\,\frac{1/12}{12} = 1.08 \text{ ft}$$

$$H_{45} = \frac{(3.75)^2}{64.4} + 1.08 + 0.558 = 1.86 \text{ ft}$$

$$R_{45} = \frac{0.558 \times 1.00}{2 \times 0.558 + 1.00} = 0.264 \text{ ft}$$

Mean Flow Conditions for 35- to 45-foot reach:

$$V_m = \frac{V_{35} + V_{45}}{2} = \frac{3.92 + 3.75}{2} = 3.84 \text{ ft/sec}$$

$$R_m = \frac{R_{35} + R_{45}}{2} = \frac{0.258 + 0.264}{2} = 0.261 \text{ ft}$$

S = hydraulic slope = change in total head per foot of

$$\text{flume length} = \frac{H_{35} - H_{45}}{10} = \frac{1.92 - 1.85}{10} = 0.0060$$

n_m = mean roughness for 10-foot reach

Rearranging equation 8

$$n_m = \frac{1.486\, R_m{}^{2/3} S^{1/2}}{V_m} = \frac{1.486(0.261)^{2/3}(0.0060)^{1/2}}{3.84}$$

$$n_m = 0.0124$$

Sample 3 Calculation of critical flow depth (trial 26)

Reference (13) indicates critical depth can be found by solving equation 12 for A and then solving for depth.

$Q = 2.85\ ft^3/sec$

T = water surface width = rectangular flume width

= 12 in = 1.00 ft

$$A^3 = \frac{(2.85)^2\ (1.00)}{32.2} = 0.252\ ft^6$$

$A = 0.632\ ft^2$

$D_c = 0.632/1.00 = 0.632\ ft = 7.59\ in$

As indicated in the data of table 7, flow depth went from 7.25 inches at the 45-foot station to 7.75 inches at the 55-foot station. This may indicate a transition from lower stage to upper stage flow in this 10-foot reach. A hydraulic jump may have occurred in this 10-foot reach.

Table 1.
Relative efficiencies of flumes with ideal equal-area cross sections1/

Cross-sectional shape	$R/\sqrt{A}$ 2/	Efficiency relative to semicircle (%)
Semicircle	0.399	100
Semihexagon	.380	95
Trapezoid, 1:2 side slope ($\tan \phi = 0.5$)	.380	95
Trapezoid, 1:4 side slope ($\tan \phi = 0.25$)	.372	93
Rectangle	.354	89
Square	.333	83
Previously recommended trapezoidal bin flume (6), with 8-in bottom and 1:4 side slope	.333	83

1/ Flume with ideal cross section has the least wetted perimeter for given flow area, that is, greatest hydraulic radius, R. This section will be such that center of semicircle inscribed within it will coincide with midpoint of the water surface. For tapezoid bottom, width = 2 x flow depth x ($\sec \phi - \tan \phi$). For rectangle bottom, width = 2 x flow depth (3).

2/ $R/\sqrt{A}$ is dimensionless ratio which can be applied directly in calculation of hydraulic radius, R, for a specific section: that is, for a 100-in^2 area, R for the semicircular section is $0.399 \times \sqrt{100}$ or 3.99 in.

Table 2.
Changes in calculated velocities along flumes transporting potatoes at low concentrations

Trial No.	Variety	Flume slope (in/ft)	Conc. vol/vol (%)	Flume bottom width (in)[1/]	Velocity at indicated station (ft/sec) 35 ft	135 ft	Velocity change (%)
11	Russet Burbank	1/12	9.75	10	3.89	3.98	+ 3
20	Russet Burbank	1/15	9.35	10	3.66	3.13	-16
26	Russet Burbank	1/15	9.17	12	3.60	2.87	-19
32	Russet Burbank	1/12	9.23	12	3.94	3.43	-13
14	Kennebec	1/12	9.75	10	3.76	3.65	- 5
22	Kennebec	1/15	9.97	10	3.60	3.30	- 8
28	Kennebec	1/15	9.35	12	3.83	3.14	-18

1/ 10-in flume is trapezoidal, with 1:4 side slope; 12-in flume is rectangular.

Table 3.
Measured flow depths and calculated flow parameters used to obtain mean n_m for trial 32 1/

Station reach (ft)	Flow depth (ft)	Mean hydraulic radius, R_m (ft)	Mean velocity, V_m (ft/sec)	Mean hydraulic slope, S (ft/ft)	Manning roughness coefficient n_m (sec/ft$^{1/3}$)
25-35	0.533	0.257	3.94	0.0069	0.0126
35-45	.558	.261	3.83	.0065	.0128
45-55	.608	.269	3.58	.0054	.0127
55-65	.617	.275	3.41	.0066	.0150
65-75	.596	.274	3.44	.0078	.0160
75-85	.583	.271	3.54	.0074	.0151
85-95	.593	.270	3.55	.0066	.0142
95-105	.568	.269	3.60	.0077	.0151
105-115	.600	.269	3.58	.0059	.0133
115-125	.625	.275	3.41	.0059	.0142
125-135	.592	.274	3.43	.0083	.0166
				Mean	.0143

1/ Russet Burbank potatoes flumed at 0.0923 conc. in 12-in rectangular flume.

Table 4.
Accuracy[1/] of equations 9[2/] and 10[3/] for predicting Manning n_m in trials showing near-uniform flow conditions

Equation and coefficients	Flume type			
	10-in Trapezoid		12-in Rectangle	
	Mean	SD	Mean	SD
Equation 9	0.74	0.03	0.74	0.01
Equation 10				
K = 66, N = 1.0	1.19	.04	1.16	.04
K = 81, N = 1.5	1.17	.04	1.14	.04
K = 121, N = 1.5	1.12	.04	1.09	.05

1/ Accuracy indicated by ratio n_m/n, where n_m = Manning roughness coefficient calculated from trial results.

2/ $n = n_w + c(s - 1)$.

3/ $n = n_w + K\, c n_w \left[\frac{gD_h}{V^2} \; \frac{(s - 1)}{\sqrt{C_D}} \right]^N$.

Table 5.
Damage data for 3 potato concentrations and 3 angles of intersection between lateral and main flume

Concentration (c) and angles	Average velocity (ft/sec)[1/]	Damage index	Bruise free (%)
c = 7.4%			
45°	3.58 (3.17/4.00)	184.0	43.0
60°	3.92 (4.00/3.83)	99.4	64.4
90°	3.58 (3.33/3.83)	115.0	65.9
c = 10.7%			
45°	4.00 (3.33/4.67)	121.0	60.7
60°	4.08 (3.67/4.50)	83.3	70.0
90°	4.17 (3.67/4.67)	48.5	81.4
c = 12.0%			
45°	4.08 (2.83/4.33)	95.1	70.3
60°	3.67 (3.67/3.67)	111.1	57.2
90°	4.08 (3.67/3.83)	115.2	59.6

[1/] First velocity in parenthesis is near inlet of lateral flume; second velocity in parenthesis is at discharge from lateral flume.

Table 6.
Test conditions for trials with 10-inch trapezoidal flume and 12-inch rectangular flume

Flume and trial No.	Potato var.[1/]	Supply rate Potato (lb/sec)	Supply rate Water (gal/sec)	Conc. (%)	Slope (in/ft)
Trapezoidal flume					
11	RB	13.2	14.2	9.29	1/12
12	RB	19.6	14.2	13.20	1/12
13	RB	60.0	14.2	14.77	1/12
14	K	13.8	14.2	9.75	1/12
15	K	19.7	14.2	13.30	1/12
16	K	23.9	14.2	15.75	1/12
17	RB	13.0	9.0	13.66	1/12
18	RB	16.3	9.0	16.56	1/12
19	K	13.7	9.0	14.39	1/12
20	RB	13.3	14.2	9.37	1/15
21	RB	19.4	14.2	13.07	1/15
22	K	14.2	14.2	9.97	1/15
23	K	19.3	14.2	13.12	1/15
24	RB	13.6	9.0	14.26	1/15
25	K	14.0	9.0	14.68	1/15
Rectangular flume					
26	RB	13.0	14.2	9.17	1/15
27	RB	18.9	14.2	12.82	1/15
28	K	13.2	14.2	9.35	1/15
29	K	18.7	14.2	12.75	1/15
30	RB	12.9	9.0	13.64	1/15
31	K	13.3	9.0	14.09	1/15
32	RB	13.1	14.2	9.23	1/12
33	RB	19.5	14.2	13.17	1/12
34	RB	26.0	14.2	16.86	1/12
35	K	19.2	14.2	13.10	1/12
36	K	25.2	14.2	16.45	1/12
37	K	29.0	14.2	18.55	1/12
38	K	13.5	9.0	14.24	1/12
39	K	19.1	9.0	19.04	1/12
40	RB	13.7	9.0	14.40	1/12
41	RB	19.7	9.0	19.45	1/12

[1/] Varieties: RB = Russet Burbank, K = Kennebec.

Table 7.
Flow depths (inches) for trials 11-25, run with a 10-inch trapezoidal flume and trials 26-41 run with a 12-inch rectangular flume

Flume and trial No.	Fluming distance (feet)																			
	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175	185	195
Trapezoidal flume																				
11	6.70	6.80	7.00	6.30	6.50	6.50	7.10	6.80	6.60	6.90	7.10	6.70	6.60	6.40	7.00	7.00	6.80	6.10	4.60	5.40
12	7.30	7.00	7.20	7.20	6.75	6.90	7.50	8.10	7.50	7.90	8.20	8.00	8.20	7.90	8.80	8.90	8.90	8.95	9.15	8.80
13	6.60	6.60	7.10	7.30	7.00	7.25	7.80	9.00	9.10	9.80	9.40	8.80	9.90	10.40	12.10	12.20	12.75	12.70	13.20	15.10
14	7.10	6.70	6.90	6.80	6.60	6.80	7.00	7.50	7.20	7.40	7.20	7.20	7.00	7.10	7.40	7.00	6.90	6.50	4.40	5.60
15	7.00	6.80	7.10	7.00	7.10	7.00	7.80	8.30	8.20	8.30	8.30	9.00	8.80	8.50	9.30	9.20	9.40	9.70	10.30	10.80
16	7.00	6.80	7.20	7.10	7.00	7.30	7.90	9.00	8.80	9.70	9.20	10.00	9.80	9.80	11.40	11.50	11.60	12.30	12.60	14.00
17	4.30	4.90	6.00	5.50	5.50	5.90	6.40	6.45	6.50	6.60	7.20	7.20	8.30	7.60	8.50	8.70	9.60	10.35	11.15	11.45
18	4.50	5.10	5.80	5.20	5.50	5.30	5.40	5.80	6.20	6.30	6.60	6.90	7.20	8.20	9.00	10.40	12.20	12.25	14.00	15.00
19	5.00	5.80	6.00	5.70	5.90	5.75	6.30	6.36	6.30	6.10	6.50	6.50	6.70	6.75	6.75	6.80	6.90	7.60	7.95	7.50
20	6.90	6.90	6.80	7.20	6.85	6.90	7.35	8.00	7.90	8.15	8.20	8.20	7.90	8.15	9.10	8.70	8.70	8.80	8.70	8.70
21	6.90	6.90	6.90	7.50	7.00	7.30	7.50	8.80	8.40	9.20	8.90	9.70	9.30	9.65	11.50	11.50	12.00	12.20	13.15	14.00
22	7.00	7.00	6.90	7.40	7.00	7.00	7.60	8.40	7.60	7.90	7.90	8.00	7.60	7.80	8.30	8.25	8.00	8.00	7.10	5.40
23	6.90	6.90	7.10	7.50	7.00	7.30	7.80	9.00	8.50	9.00	9.40	9.60	9.80	9.40	11.30	11.30	11.40	12.00	12.00	13.40
24	4.90	5.30	5.40	5.70	5.75	5.75	6.10	6.20	6.30	6.50	6.70	7.00	7.30	7.60	8.30	8.80	9.60	10.45	11.10	12.25
25	4.90	5.40	5.80	5.85	5.85	6.00	6.40	6.50	6.45	6.20	6.90	7.10	7.40	7.40	8.30	8.40	9.00	9.70	10.50	10.90
Rectangular flume																				
26	5.41	5.90	6.75	7.16	7.25	7.75	7.70	7.95	8.05	8.35	8.30	8.43	8.67	8.75	8.80	8.93	8.95	8.95	8.90	9.25
27	5.60	6.73	6.90	7.92	7.89	8.30	8.85	9.23	9.36	9.63	9.84	10.25	10.65	10.84	11.20	11.48	11.50	12.20	12.75	14.65
28	5.25	6.00	6.30	6.80	7.02	7.35	7.45	7.60	7.54	7.70	7.67	8.03	7.96	8.02	8.22	8.25	8.10	8.20	8.45	9.20
29	5.35	5.95	6.93	7.58	7.85	8.72	8.90	9.15	9.55	9.93	10.20	10.92	10.85	11.00	11.35	11.75	12.07	12.58	12.97	14.35
30	4.28	4.30	5.48	6.05	6.35	5.78	7.17	7.35	7.60	8.22	8.14	8.85	9.20	9.55	9.80	10.25	10.60	11.32	12.05	12.95
31	4.20	4.83	5.46	6.14	6.50	6.63	6.85	7.03	7.18	7.60	7.73	8.55	8.61	8.74	9.06	9.20	9.50	10.25	10.80	11.95
32	5.40	5.55	6.30	6.40	6.70	7.30	7.40	7.15	7.00	7.11	6.82	7.20	7.50	7.10	6.27	7.32	7.10	7.03	7.52	7.10
33	5.20	6.10	6.68	7.12	7.60	7.90	7.89	8.08	8.00	8.18	8.40	8.95	8.66	9.15	9.50	10.00	10.04	10.75	11.90	12.68
34	5.70	6.50	7.27	7.95	7.91	8.71	9.22	9.12	9.35	10.15	10.27	11.00	11.31	11.77	12.38	12.75	13.20	14.08	15.15	18.00
35	5.75	6.82	7.05	7.40	7.66	8.05	8.10	8.00	7.82	8.10	7.95	8.35	8.60	8.55	8.54	8.80	8.65	8.60	8.95	8.95
36	6.00	6.95	7.28	7.95	8.00	8.52	8.75	8.90	8.85	9.72	9.56	10.30	10.25	10.65	11.20	11.65	11.72	12.50	13.65	14.50
37	5.77	6.40	6.97	7.30	7.74	8.42	8.90	9.00	9.23	9.75	9.97	10.30	10.70	10.95	12.25	13.00	14.11	15.00	16.00	18.00
38	4.55	5.15	5.50	5.90	6.52	6.68	6.95	7.00	6.90	7.27	6.93	7.56	7.60	7.82	7.76	7.92	8.23	8.75	9.05	9.75
39	4.10	5.10	5.75	6.44	6.70	7.20	7.54	7.50	7.85	8.35	8.56	9.12	9.40	9.95	10.50	11.35	11.80	12.90	13.93	15.15
40	4.00	4.75	5.10	5.68	5.98	6.50	6.62	6.55	6.70	6.75	6.75	7.30	7.29	7.41	7.87	8.55	8.60	8.75	9.30	10.05
41	3.85	4.65	5.30	5.66	5.95	6.88	6.92	7.05	7.22	7.90	8.15	8.85	9.20	9.95	10.80	11.70	12.62	13.95	14.90	18.00

NOTES

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