Flotation and Conveying Air Velocities for Processed Monogerm Sugar Beet Fruits[1]

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Received for publication August 3, 1964

The handling and processing of sugar beet fruits is becoming increasingly mechanized. Little basic information is available relative to the physical and mechanical properties of the sugar beet fruit which can be used in engineering design. With an increase in mechanization, there is a greater demand for basic engineering information. This research concerns flotation (terminal velocity) and conveying velocities as well as some observations on the orientation of the sugar beet fruit in a vertical air stream.

Materials and Methods

A 1-hp electric motor with a centrifugal forward-curved blade fan connected to a 4-inch (outside diameter) horizontal aluminum irrigation pipe was used as the air-flow system. A stainless steel orifice plate and a venturi tube were installed in series in the pipe. Flange, vena contracta and pressure taps were located in relation to the orifice plate as recommended by Eckman[3]. These permitted three pressure-differential readings to be taken with each rate of flow. A separate measurement was taken with the venturi tube.

A plenum chamber, 24 × 36 × 30 inches outside dimensions, constructed from ¾-inch plywood was installed at the end of the pipe. Sheet metal baffles were used to diffuse the air currents in the chamber. Steel sleeves (2½ inches outside diameter and 6 inches long) with air-sealing flanges were used to connect the chamber with the observation tubes which consisted of 2½-inch (outside diameter) clear acrylic plastic pipe polished on both interior and exterior surfaces. An air-flow control unit with a seed retainer was used on the exhaust end of the tubes.

Flotation velocities were determined in the vertical tube (50 inches long). Conveying velocities were determined in the

[1] Cooperative investigation of the Michigan Agricultural Experiment Station and the Crops Research Division, Agricultural Research Service, U. S. Department of Agriculture. Approved for publication as Journal Article #3363, Michigan Agricultural Experiment Station.

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[3] Eckman, Donald P. 1958. Industrial Instrumentation. John Wiley & Sons, Inc., New York.

horizontal tube (17.5 feet long). The respective velocities are average velocities over the cross-sectional area of the tube. All joints and connections in the air-flow system were airtight.

Sugar beet fruits used in this research were of the (SL 126ms $\times$ SL 128) ms $\times$ SP 5822-0 monogerm variety[4]. This is a commercial variety with a high germination capability. The fruits were hand processed, sized into 1/64-inch diameter classes, equilibrated (68 F and 43.9% relative humidity) and individually weighed before the tests were run. Sizing was done with sheet metal sieves having round punched holes of the sizes indicated. Length and thickness dimensions of the fruits were not determined.

The limits of the terminal or flotation velocities for a certain size-group were determined by placing the fruits on a screen at the bottom of the vertical tube. Before the fan was started, the air-flow control was closed completely. A micromanometer was used to measure air pressure differentials. The control device was opened slowly until the first fruit was carried into the seed retainer. A complete set of readings was taken. The air-flow control was then opened until the last fruit was ejected from the vertical observation tube and another complete set of readings was taken. The foregoing procedure was repeated five times. The average of the first set of readings was used to determine the flotation velocity for the lightest fruit, while the average of the second set was used to calculate the flotation velocity of the heaviest fruit in the given size-group.

Conveying velocities were determined by injecting the fruits of a given size-group into the horizontal conveying tube. A hole was drilled in the plastic tubing approximately 4 feet from the plenum chamber. Sugar beet fruits could not be dropped into the conveying tube, because of a positive air pressure inside the tube. Therefore, the hole was threaded to accept a cartridge device made from 3/8-inch steel pipe. Fruits were injected into the system by 1) controlled injection allowing individual fruit dispersion in the air stream, 2) sudden injection of the entire size-group and 3) fruits placed on the bottom of the conveying tube while system was shut down. A wire plunger in the cartridge device was used to control the injection rate for the first two methods. If the fruits did not convey at a preset air-flow rate, they were removed and the flow rate was increased by intervals of 1 foot per second until they were conveyed.

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[4] Kindly supplied by the West Coast Beet Seed Company, Salem, Oregon.

Results

The number of fruits in each group, the total weight, the mean weight per fruit and the standard deviation of the fruits for each size-group are recorded in Table 1. The weights of the individual fruits in any size-group approach a normal distribution. Hence 68.27% of the observations should be within one standard deviation of the mean, 95.45% within two standard deviations and 99.73% within three standard deviations. A study of each group revealed that only the lightest fruit in the 9/64-inch group and the heaviest fruit in both the 11/64- and 12/64-inch groups were more than three standard deviations removed from the mean. When the fruits in each group were divided by equal weight intervals into approximately 12 subgroups, the weight interval containing the mean weight had the largest number of fruits in every case with only one exception (Table 2). In this exceptional case, the weight interval containing the most fruits was immediately below the one containing the mean weight, and the mean weight was the lowest value in its weight interval.

Table 1. — Size, mean weight, and standard deviation for hand-processed sugar beet fruits of (SL 126ms × SL 128)ms × SP 5822-0 hybrid variety.

Fruit diam. inches	No. of fruits	Total weight grams	Mean weight grams	Standard deviation grams
7/64	90	.7296	.0081	.0016
8/64	96	.9500	.0099	.0018
9/64	128	1.6039	.0125	.0017
10/64	127	1.8711	.0147	.0021
11/64	85	1.5126	.0178	.0023
12/64 or larger	96	2.0638	.0215	.0031

Maximum and minimum fruit weights in each size-group are plotted against fruit size in Figure 1. Observations which may be made are 1) for the first three size-groups, the heaviest fruit in a given group was nearly three times the weight of the lightest fruit in that same group, 2) for the last three size-groups, the heaviest fruit in a given group was about twice the weight of the lightest fruit in that same group and 3) considering the fruits in all size-groups, the heaviest fruit had nearly seven and one-half times the weight of the lightest fruit. For the groups with the larger size fruits, the span between the heaviest and the lightest fruits became greater. The plotted points represent extreme values and the weights of all other sugar beet fruits used in this research are represented by values in the shaded area. The mean value of each size-group is plotted as a heavy dot. These, in general, are close to the center of the

Table 2. — The weight distribution of hand-processed (SL 126ms × SL 128)ms × SP 5822-0 variety sugar beet fruits after subdivision into size-groups.

Size	Weight interval (grams × 10⁻¹) 35 to 44	45 to 54	55 to 64	65 to 74	75 to 84	85 to 94	95 to 104	105 to 114	115 to 124	125 to 134	135 to 144	145 to 154	155 to 164	165 to 174	175 to 184	185 to 194	195 to 204	205 to 214	215 to 224	225 to 234	235 to 244	245 to 254	255 to 264	265 to 274	275 to 284	285 to 294	295 to 304	305 to 314
7/64	1	7	7	13	25*	17	14	5	1																			
8/64		2	2	5	8	16	25	23	10	4	0	1																
9/64			1	0	0	2	6	26	27	26	25	9	5	1														
10/64								4	14	20	21	24*	15	15	5	7	1	1										
11/64										4	0	8	10	15	18	16	3	6	2	2	0	0	1					
12/64 or larger												1	1	6	6	8	13	17	18*	3	8	5	2	2	4	1	0	1

*Subgroup containing mean weight

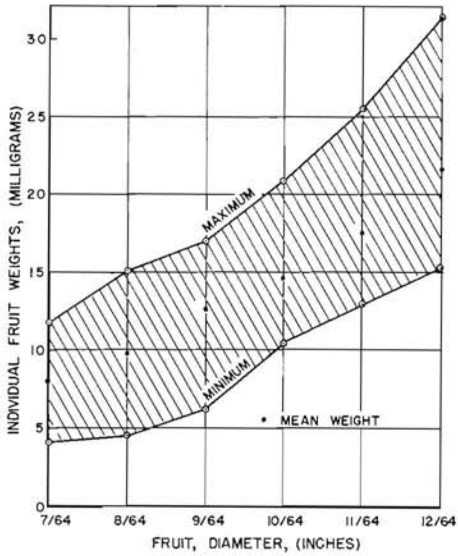

Figure 1.—Maximum and minimum individual weights of (SL 126ms × SL 128)ms × SP 5822-0 hybrid variety hand-processed sugar beet fruits plotted against fruit size.

weight span for their respective size-groups. For the larger fruits, the dots are below the mid-point of the weight span, thus indicating that there were only a few unusually heavy fruits in the group.

The span of flotation velocities for each size-group is illustrated in Figure 2. Only a slight increase in air velocities was necessary as the size of the fruit diameters increased. The maximum and minimum values plotted represent averages of the average values calculated from the flange, vena contracta and pressure tap readings, all used with the 2-inch orifice plate.

Velocities required to convey horizontally the fruits for the different methods of injection are plotted in Figure 3. The least velocity (23 to 24 fps) was required when the fruits were injected at a rate which permitted each fruit to be individually dispersed in the air stream as it fell across the diameter of the conveying tube. Each plotted point (Figure 3) for this injection method represents the air velocity which successfully conveyed the size-group in ten successive trials. The heavier or more dense fruits tended to lodge in the tube, but the lighter fruits had a scouring effect and helped to move the heavier fruits along.

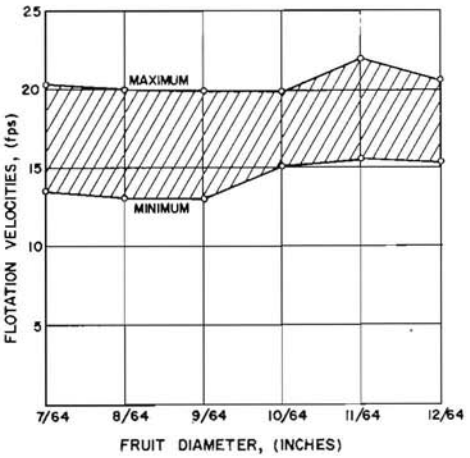

Figure 2.—Maximum and minimum air velocities required for the flotation of hand-processed sugar beet fruits of (SL 126ms × SL 128)ms × SP 5822-0 hybrid variety.

When the sugar beet fruits of a given size were injected as a group, a higher velocity was required to convey them through the tube. The greater the total weight of the fruits injected, the greater was the air velocity necessary to sufficiently disperse and accelerate the fruits while they were falling across the diameter of the conveying tube. Each plotted point for this method of injection represents ten successive trials in which the respective size-groups were successfully conveyed.

Fruits placed into the conveying tube with no air flowing required the greatest air velocity to dislodge and convey them through the tube. In this case, the stationary fruits supported each other in the static condition. The lowest air velocity in the conveying tube was around the tube perimeter, so the flow rate in the tube had to be increased until the perimeter velocity was sufficiently high to give the sugar beet fruits their initial acceleration. Each plotted point for this method represents five successive trials in which the size-groups were successfully conveyed.

The recommended conveying velocity of 38 fps is developed in the discussion section of this report.

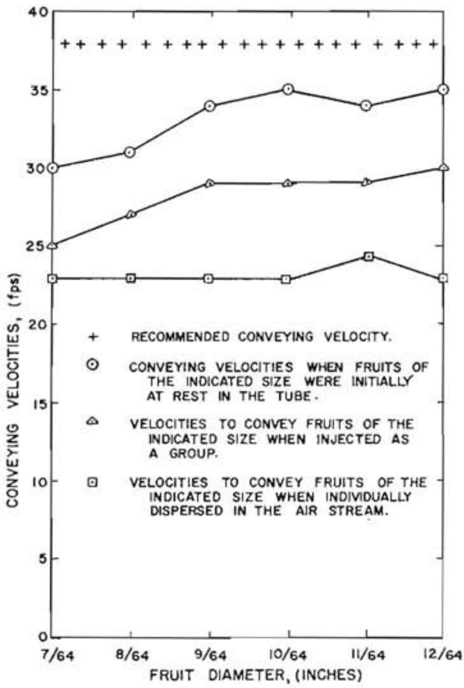

Figure 3.—Velocities required to convey horizontally hand-processed (SL 126ms × SL 128)ms × SP 5822-0 hybrid variety sugar beet fruits of the size indicated.

Discussion

Air-flow equipment

Accurate air-flow measurement presents a problem even with modern instrumentation. Considerable time and effort was spent in the design and construction of an orifice meter and a venturi tube. The objective was to use these devices in the same air stream and then from their pressure differential readings to calculate air volumes which would coincide. The orifice was machined from an 0.08-inch stainless steel plate. The venturi tube was constructed from 26-gage galvanized sheet metal. A piece of heavy-duty steel pipe was machined to the appropriate slopes and throat diameter to give a precision throat section.

A 0.50 diameter ratio (orifice diameter/inside pipe diameter) was used in the calculations. The air-flow system developed less than 2 inches H_2O maximum static pressure. Therefore, the air could be considered as an incompressible fluid and the equation as shown below was used to determine the orifice flow.

$$V = K_0 \sqrt{2vg\,(p_1 - p_2)} \qquad (1)$$

Where

V = velocity of fluid flowing in the pipe, fps
K_0 = over-all flow coefficient
v = specific volume of air, ft^3/lb
g = 32.2 ft/sec^2
$(p_1 - p_2)$ = pressure difference across orifice plate, lbs/ft^2

The over-all flow coefficient is composed of two constants.

$$K_0 = K'_0 \; B^2 \qquad (2)$$

Where

K'_0 = orifice-flow coefficient as listed by Eckman
B^2 = $(d/D)^2$ = (diameter ratio)^2

To select the proper K'_0, the Reynolds number must be known. The Reynolds number is directly proportional to the volume of flow and may be calculated as shown below.

$$R = \frac{4\rho q}{\pi \mu B D} \qquad (3)$$

Where

ρ = density of flowing fluid, lbs/ft^3
q = flow rate, ft^3/sec
μ = absolute viscosity of flowing fluid, lbs/ft-sec
D = pipe diameter, ft

The velocity (V) and the over-all flow coefficient (K_0) were the only unknowns which remained after a pressure-differential reading was taken. The actual velocity was determined by first assuming a velocity. This permitted the calculation of a Reynolds number and hence the selection of an orifice-flow coefficient (K'_0). If the assumed velocity was considerably different from the calculated velocity, another velocity assumption was made by which a more appropriate K'_0 could be selected and hence a closer agreement could be reached between the actual and the assumed velocities.

The same equation with a different over-all flow coefficient was used to determine the flow through the venturi tube. The flow coefficient was calculated as shown below,

$$K_0 = \frac{CB^2}{\sqrt{1 - B^4}}$$

where "C" is designated by Eckman as a discharge coefficient having values between 0.90 and 1.0 depending upon the Reynolds number involved. Values of "C" used in this research ranged between 0.956 and 0.971.

The three velocities calculated from pressure differentials across the orifice plate were in good agreement. These varied from 1% at the higher velocities to 3% at the lower velocities when calculated as shown below for a given flow.

$$\frac{(\text{Max. velocity} - \text{Min. velocity})\ 100}{\text{Minimum velocity}} = \text{Percent variation}$$

When results from the venturi tube were included, the variation reached a maximum of 4% for the span of velocities between 10 and 29 fps in the observation tube. The venturi tube readings were consistently higher than those for the orifice plate. Construction requirements permitted the orifice plate to be machined to greater precision than could be attained in the construction of the venturi tube. Therefore, the average of the three velocities calculated from the differential readings across the orifice plate was used to determine the flotation velocities. Assuming the true velocity to lie somewhere within the range of maximum and minimum velocities determined for a given air flow, the final value used should be within ± 5% of the true air velocity. Since good agreement existed among the velocities calculated from the three different tap arrangements, only the pressure tap readings for the orifice plate were used to determine the conveying velocities.

Fruit preparation and handling

The sugar beet fruits used in this research were first hand-processed and then screened to sizes of 7/64, 8/64, 9/64, 10/64, 11/64 and 12/64-inch or larger. Fruits smaller than 7/64-inch were discarded. The proportion of fruits in each category does not represent the proportion of each size-group in an ordinary seed sample. To get a number of fruits of size 12/64-inch or larger, a large sample was initially used. Thereafter some of the fruits of intermediate size were randomly removed. The distribution of fruit weights in any size-group should be representative of the distribution in any other group of the same size and number of fruits.

The empty intervals in Table 2 generally indicate that the sample sizes used were not large enough to accurately represent the fruit populations in the various size-groups. The number of fruits in each size-group is, however, considered sufficiently large to represent definite trends.

Fluid flow characteristics

Air flow in the observation tubes was turbulent. Such flow exists whenever the value of Reynolds number exceeds 4000.

The Reynolds number for the observation tubes was calculated by the following equation:

$$R = \frac{DV\rho}{\mu}$$

Where

R = Reynolds number
D = inside tube diameter, ft
V = average air velocity, ft/sec
ρ = density of air, lbs/ft^3
μ = air viscosity, lbs/ft-sec

For an average velocity of 20 ft/sec and an air density of 0.075 lbs/ft^3, the Reynolds number was calculated to be 21,800. For an average velocity of 35 ft/sec, it was 38,000. These are relatively low values, since in commercial practice Reynolds numbers of one million or greater may be encountered.

Under stable conditions, the velocity for both turbulent or streamlined flow in a tube or pipe is highest at the center and decreases as the tube perimeter is approached. The velocity at the tube surface is actually zero. The flow in a layer immediately adjacent to the tube perimeter is streamlined. The thickness of this layer is dependent upon the velocity of the flowing fluid. The higher the velocity, the thinner will be the layer of streamlined flow.

The first fruit ejected from the vertical observation tube in each of the smaller size-groups was possibly an empty fruit. Its ejection required less velocity than did fruits containing seeds. The last fruit remaining in the tube floated around the tube perimeter in a vertical interval for practically indefinite periods. Nothing remained in the tube which would temporarily destroy the aerodynamic equilibrium of the fruit and hence no disturbance caused it to move into the center air stream to be ejected into the seed retainer. As air flow was increased, the flotation level of the fruit was raised, thereby indicating that the flotation velocity at the tube perimeter had moved up the tube to the new level at which the fruit was being suspended. Air flow increases were necessary until the fruit reached a level approximately 1-foot distant from the tube exit where flow conditions became sufficiently unstable to eject the fruit.

Fruit orientation

An individual fruit of normal configuration does not necessarily twist and spin in a turbulent air stream. Many individual fruits were observed to float around the tube perimeter in the cap-up position for periods of several minutes. When numerous fruits were placed into the system, they tended to strike each other in the oscillation process and thereby disrupted the aerodynamic equilibrium position of an individual fruit.

Previous research by Kunze, Snyder and Hall[5] has indicated the sugar beet seed to be most sensitive to damage when the fruit is impact-loaded on its cap. From the foregoing observations, the individual fruit in a free fall would position itself with its cap up and hence would impact on its butt, but it would be impacted on its cap by succeeding falling fruits.

Terminal velocities

The terminal velocity of a sugar beet fruit is the highest velocity that such a fruit will attain while falling through still air for an infinite distance; or conversely, the terminal velocity is that air velocity which is necessary to suspend a sugar beet fruit in a vertical air stream. In this research, terminal velocity is defined as that velocity which was necessary to extend the elliptical flotation path of the fruit just beyond the 4-foot length of the observation tube.

If a single layer of fruits was observed in the base of the tube as the air-flow control was slowly opened, the fruits could be seen to orient themselves in the position of cap up. They became airborne as the air flow was increased. The air stream beyond the screen formed a velocity gradient. As the air moved up the tube, the velocity in the center increased but that around the tube perimeter decreased. This phenomenon caused the fruit to move up in the center of the observation tube and to drop down when it moved out to the tube perimeter. The air speed at the center was greater than the terminal velocity for the given fruit, while the air speed at the tube perimeter was less than the terminal velocity. As the fruit at the tube perimeter dropped, it encountered an increasingly higher velocity which halted its downward motion. Then, if it moved into the center of the tube once more, its elliptical flotation path was repeated.

The time that a fruit remained in the center stream was variable. Generally the oscillations of a fruit were less than 2 feet in height. Thus with a given air flow, a fruit may have oscillated in the 2-foot section immediately above the screen. A slight increase in air flow was necessary to make that same fruit oscillate in the 1- to 3-foot section of the tube since the center velocity was still increasing but the velocity at the perimeter of the tube at the 1-foot level was then sufficiently high to suspend

[5] Kunzo, O. R., F. W. Snyder and C. W. Hall, Impact Effects on Germination and Seedling Vigor of Sugar Beets. J. Am. Soc. Sugar Beet Technol. 13(4): 341-353. 1965.

the fruit. An additional increase in air flow caused the fruit to oscillate toward the top of the tube with the possibility of being ejected into the seed-retainer.

Conveying velocities

Velocities required to convey a given size-group of fruits were somewhat dependent upon the method by which the fruits were injected into the system. Fruits which were initially at rest in the horizontal tube before the air flow was started required the highest conveying velocity. The lowest velocity was required for fruits which were individually dispersed in the conveying air stream.

Conveying velocities were generally higher than flotation velocities. For this research, a conveying velocity was defined as that velocity which conveyed all the sugar beet fruits of a given size-group through the horizontal tube. The *lowest* conveying velocities (Figure 3) were about 3 fps higher than the highest flotation velocities, or nearly 50% higher than the *average* flotation velocities (Figure 2) for the respective size-groups. The lowest conveying velocity was in effect an average conveying velocity since fruits which conveyed readily would strike and accelerate other fruits which were tending to lodge in the tube. A 50% increase above the flotation velocity of a sugar beet fruit was sufficient to convey it. For example, fruits which required flotation velocities of 16 to 18 fps required minimum conveying velocities of 24 to 27 fps. Fruit sample sizes in this research were necessarily limited and thereby created the possibility that extreme conditions were not encountered. Maximum flotation velocities of slightly over 22 fps were measured. Velocities of 25 fps should be sufficient for the flotation of any hand-processed sugar beet fruits. Conveying velocities should be based on maximum flotation velocities. Then with a 50% increase in this flotation velocity, the recommended conveying velocity would be 38 fps.

In working with coffee fruits, Eschenwald and Hall[6] considered the conveying air velocity to be 30 fps greater than the flotation velocity. When their results for green coffee fruits, ripe fruits, fresh pulp and pulped washed beans were studied, the conveying velocities ranged from 46 to 58 percent above the flotation velocities. The results here are in good agreement with the work on coffee beans when conveying velocities are considered to be a certain percentage greater than flotation velocities.

[6] Eschenwald, Adolfo and Carl W. Hall, 1961. Air-Flotation, Pneumatic Conveying Velocities, and Airflow Relationships for Coffee Fruits and Coffee Beans. The Journal of Agriculture of the University of Puerto Rico. 45(4): 319-331.

The earlier work by Kunze, Snyder and Hall has indicated that germination and seedling vigor of sugar beet seeds can be reduced when fruits are impact-loaded (using a steel sphere) with as little as 25 gram-centimeters of impact-energy. Experimental results and theoretical calculations showed that a sugar beet fruit weighing 12.5 milligrams and traveling at a velocity of 70 fps would have an impact energy of about 29 gram-centimeters. A single application of this impact energy reduced root and shoot growth of the seedling by 15 to 20 percent.

When an air velocity of 38 fps is used to convey sugar beet fruits, the fruit never attains this velocity because of friction. However, if a sugar beet fruit weighing 12.5 milligrams attained this velocity and was impacted against a stationary object, its impact-energy would be only 8.6 gram-centimeters. This is well below the energy-level of impact-loads which have been found to be detrimental to the seed. In contrast fan manufacturers recommend air velocities in excess of 70 fps for conveying inert materials of similar densities.

Summary and Conclusions

Sugar beet fruits of the (SL 126ms × SL 128) ms × SP 5822-0 hybrid variety were hand-processed, sized and equilibrated at 68°F and 43.9% relative humidity. The fruits were individually weighed before a given size-group was subjected to either flotation or conveying tests. Ambient air was used in the air-flow system to determine flotation (terminal) and conveying velocities.

Fruits of the same size had a two- to three-fold weight variation. Unsized fruits 7/64 inch or larger in diameter had as much as a seven and one-half fold variation in weight. Larger diameter fruits generally required a slightly higher flotation velocity than did smaller diameter fruits.

Experimental results indicated that flotation velocities varied from a minimum of 13.2 fps to a maximum of 22.1 fps. The span of flotation velocities for any given size-group was only slightly less. A velocity of 25 fps should, in general, be adequate to suspend any hand-processed sugar beet fruits in an air stream.

An individual sugar beet fruit of normal configuration tends to float in an air stream with the cap of the fruit facing up. Twisting and spinning of the fruit is induced by collisions with other fruits in the air stream.

Horizontal conveying velocities were generally higher than flotation velocities. Minimum conveying velocities were dependent upon the method of injecting the fruits into the air stream. The lowest velocity (23 to 24 fps) was required when fruits were individually dispersed in the air stream. The highest velocity (30 to 35 fps) was required when the fruits were initially at rest in the conveying tube before the air-flow was started. Air velocities of 38 fps should be adequate to convey fruits horizontally in a tube. No tests were run with elbows in the system.

Previous work by the authors has indicated that germination and vigor of sugar beet seeds may be reduced when fruits are subjected to impact-loads of 25 gram-centimeters. If a fruit (12.5 milligrams) attained a velocity of 38 fps, it would have an impact-energy of 8.6 gram-centimeters. This is well below the 25 gram-centimeter energy level which is detrimental.