START

FLUIDIZED

CONVEYING

OF SEED

Technical Bulletin No. ~~1350~~ 1315

Agricultural Research Service

UNITED STATES DEPARTMENT OF AGRICULTURE

Preface and Acknowledgments

This investigation was conducted at Corvallis, Oreg., over a period of about 5 years by the Agricultural Engineering Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Oregon Agricultural Experiment Station, Oregon State University.

Preliminary work included fluidizing tests of seed and the construction and evaluation of several low-velocity pneumatic conveying arrangements for seeds. One transport system, which showed the desired combination of easy cleanability and no seed damage, was studied in some detail and is reported here.

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U.S. DEPARTMENT OF AGRICULTURE
Agricultural Research Service

ERRATA

United States Department of Agriculture Publication

"Fluidized Conveying of Seed" was erroneously numbered

Technical Bulletin 1350.   The correct number is

Technical Bulletin 1315.

February 1965

Fluidized Conveying of Seed

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SUMMARY

Seed-processing research has been conducted since 1954 at Corvallis, Oreg., by the Agricultural Engineering Research Division of the U.S. Department of Agriculture in cooperation with the Oregon Agricultural Experiment Station at Oregon State University. Efforts have been directed toward improved operation of existing equipment and the evolution of new techniques or machinery for improving efficiency in seed processing.

The investigation reported here deals with the seed-handling phase of processing and describes the development, testing, and potential of a special pneumatic system called dense-phase or fluidized conveying. Seed movement in this operation consists of aerated seed slugs that form, move, dissipate, and re-form in a cyclical manner throughout the pipe run. The slugs show a high degree of mobility or fluidity.

According to the literature, dense-phase transport of solids has received little or no attention. However, it offers several unique advantages for seed handling. Easily damaged seed can be transported at low velocities without lowering germination; small-diameter conveying lines can be employed to provide simple, flexible installations; and excellent cleanout is possible since remaining seed can be purged from the run by increased airflow.

Dense-phase transport of crimson clover was evaluated in a 56-foot run of 1⅝-inch diameter tubing by operating at different capacity levels and determining such performance data as pressure, power, air volume, air velocity, seed velocity, solid-air ratio, and seed damage. These factors were compared to their counterparts in lean-phase transport (typical pneumatic conveying) conducted in the same system.

It was found that the ordinary concepts of fluid flow are not directly applicable to dense-phase conveying, probably because this form of material transport is classified best in a region between true fluid flow and movement of a solid. (As an example, the average pressure drop per foot of conveying run decreases with increase in conveying capacity.)

Auxiliary airflow bypassing the airlock proved very important. In a special study where conveying capacity was held constant, pressure and power requirements were reduced about 50 percent with increased amounts of auxiliary air. However, seed velocity increases under these conditions, which could be a limiting factor with easily damaged seed.

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A special formula based on seed germination measures was devised to rate severity of the clover-conveying trials even though no damage, as such, was evident. Computed severity indexes reveal that severity was less for dense-phase than for lean-phase conveying and only slightly greater than for controls (not conveyed).

All clover transported in this system showed greater normal germination than controls because hard seeds were stimulated into germination. Total germination (normal-plus-hard seed) was essentially unchanged.

Additional damage trials with beans showed that damage increased with seed velocity in the lean-phase trials but that all measures of damage for the dense-phase condition studied were either lower than or near the minimum values for the lean-phase range examined.

Generally speaking, fluidized or dense-phase transport as defined here seems entirely feasible for conveying free-flowing seeds at low velocity through flexible, small-pipe systems without damage.

INTRODUCTION

Seed Handling

Handling of seed during cleaning, treating, and storing is a major part of seed processing. Seed may be handled as few as three times in a one-machine, farm seed-cleaning plant or more than a dozen times in plants equipped with a full line of processing and treating equipment. Generally, seed is handled less in multistory buildings than in single-story buildings. In the former, seed is elevated to storage bins located high above the ground so the seed can flow by gravity through several machines placed in series below the bins. In single-story buildings, seed must be elevated each time it passes through a machine.

Requirements for efficient seed handling vary with the type of operation and seed purity, but in all seed processing—and particularly certified seed—it is important to have a system that will elevate and convey seed without damage and mixing, that can be cleaned and inspected easily between lots, and that has suitable capacity to fit into a processing sequence.

The seed industry uses many methods of seed handling, which range from handling sacks by hand to automatic pushbutton-controlled pneumatic systems. Handling methods generally used can be divided into two classes: (1) mechanical and (2) pneumatic. Mechanical operations include manually handling sacks and moving with a hand-truck, mechanical conveying equipment such as screw augers, belts, bucket elevators, and forklift trucks with pallets or tote boxes. Pneumatic operations include various systems operating above or below atmospheric pressure.

A good feature of mechanical conveyors is the relatively low power required for operation. The chief objection to many mechanical units is their inability to be cleaned thoroughly between seed lots, which may cause mixing or contamination of seeds. This is a serious matter when the seed being handled has strict purity requirements as do certified seed and seed specially bred for disease resistance, insect resistance, and high yield.

Properly designed pneumatic systems offer the advantage of easy,

effective cleanout between lots since pneumatic systems can be purged with air as needed. However, a disadvantage of pneumatic conveying is damage to some seeds caused by their striking conveying pipe elbows and cyclones while traveling at the high velocity required to convey the seeds in the airstream.

The Fluidizing Process

In an effort to find a handling method that would prevent seed damage and mixing, a survey was made of conveying systems used in other industries. A pneumatic system called fluidized conveying employed by the flour, cement, ceramic, and chemical industries offered encouraging possibilities. Reportedly, this system moved fine particles in a fluidized state at low velocity with high solid-to-air ratios. In this sense, fluidized refers to a mass of solid particles permeated with air and showing fluidlike properties.

The phenomenon of a fluidized bed can be demonstrated readily with a small container having a porous membrane at the bottom. When air is introduced through the bottom, a contained mass of solid particles expands and acts, to a large extent, like a liquid. The upper surface becomes level, air bubbles rise through the particles and burst, and the fluidized bed permits objects to sink that would remain on the surface without aeration of the mass.

Many references in the literature point out that the main use of fluidizing has been in the field of chemical engineering, particularly in petroleum-cracking processes to obtain gasoline and other products (3, 13, 20, 37).[1] Its value here is to provide fluidized beds of catalyst, which accelerate chemical reactions, improve heat-transfer properties between oil vapor and catalyst, and yield uniform temperature distribution in the process. Outside the petroleum industry, the fluid-bed technique has been used to good advantage in many fields such as roasting ores and calcining limestone (14, p. 14), drying wheat (23, p. 625), drying easily damaged potato granules (26, p. 232), and feeding fissionable fuel in nuclear reactors (37, p. 41).

The application of fluidizing to pneumatic transport of materials has received less attention and has been restricted primarily to finely ground particles like powders. Within the cracking units, fluidized catalyst is recirculated from regenerator to reactor (14, p. 11). In the ceramics industry, fluidized clay has been transported at solid-air ratios of 100:1 (19, p. 367), and a British system reports fluidized conveying of powders and chemicals in a batch process over long distances (10, p. 181). Powdered coal was moved at solid-air ratios of 200:1 through a 58-foot run (2, p. 1838), and some flour-conveying systems employed a type of fluidized transport (38, p. 80). Fluidized conveying of wheat has been reported, but air velocities employed were relatively high—near that required for conventional conveying (22, p. 349).

A special use of fluidizing in material transport employs an air chamber and porous membrane, like canvas, as the bottom of a conveying trough tilted slightly from the horizontal. Air passing up through the membrane fluidizes the product, which then flows downhill by gravity (20, p. 12).

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[1] Italic numbers in parentheses refer to Selected References, p. 40.

Since most of the published fluidization work and applications deal with materials of small particle size, tests with seeds were undertaken by the U.S. Department of Agriculture in cooperation with the Oregon Agricultural Experiment Station. Results have shown generally that coarse products like agricultural seeds can be fluidized, but not as effectively as powders. Also, a pneumatic transport system for seeds has been developed that shows characteristics of fluidized conveying; namely, low solids velocity, high solid-air ratio, and a flowing seed mass that possesses a large degree of mobility or fluidity.

Many seed-conveying trials were conducted in small-diameter pipes ($\frac{1}{2}$, 1, and $1\frac{5}{8}$ inches), but all can be classified as either dense-phase or lean-phase conveying. In dense-phase trials, the seed flows at a low velocity in a loosely compacted, aerated mass that fully occupies the pipe in some parts of the run and moves in recurrent slug form in other parts. Seed movement in lean-phase trials is similar to ordinary pneumatic transport of solids; that is, air and seed velocities are relatively high, and concentration of seed in the airstream is low.

According to the literature, pneumatic transport of solids in the dense phase as defined here has received little or no attention. In fact, the onset of "slugging" or blocking in transport lines usually is cause for concern since it defines a limiting condition for most pneumatic conveying. Figure 1 illustrates the narrow working range between blockage and damage, as discussed by Segler (*31, p. 71*), which is a limitation of ordinary pneumatic conveying. In contrast, the dense-phase conveying reported here not only opens up much of the so-called blockage area for transport purposes but also locates the operation in a region of the graph farther removed from damage.

Scope of This Investigation

This investigation consisted of the design, construction, and test evaluation of a pneumatic seed conveyor that would—

1. Convey easily injured seed at a relatively low velocity without damage.
2. Be capable of easy and thorough cleanout.
3. Possess conveying capacity great enough to supply seed-processing machines.
4. Offer continuous rather than batch flow.
5. Provide simple, flexible transport runs.
6. Eliminate need for cyclones at end of run.

Fluidized or dense-phase transport of seed appeared to meet all these requirements; therefore, it was studied in some detail. Engineering performance data were obtained, first to evaluate the seed-handling potential of such a system, and second to form a basis for making design recommendations for other similar systems. In most cases, companion trials of lean-phase transport were conducted in the same system for comparison. The results have been used to establish the interrelations of capacity, power requirement, air pressure, airflow, seed velocity, solid-air ratio, and seed damage.
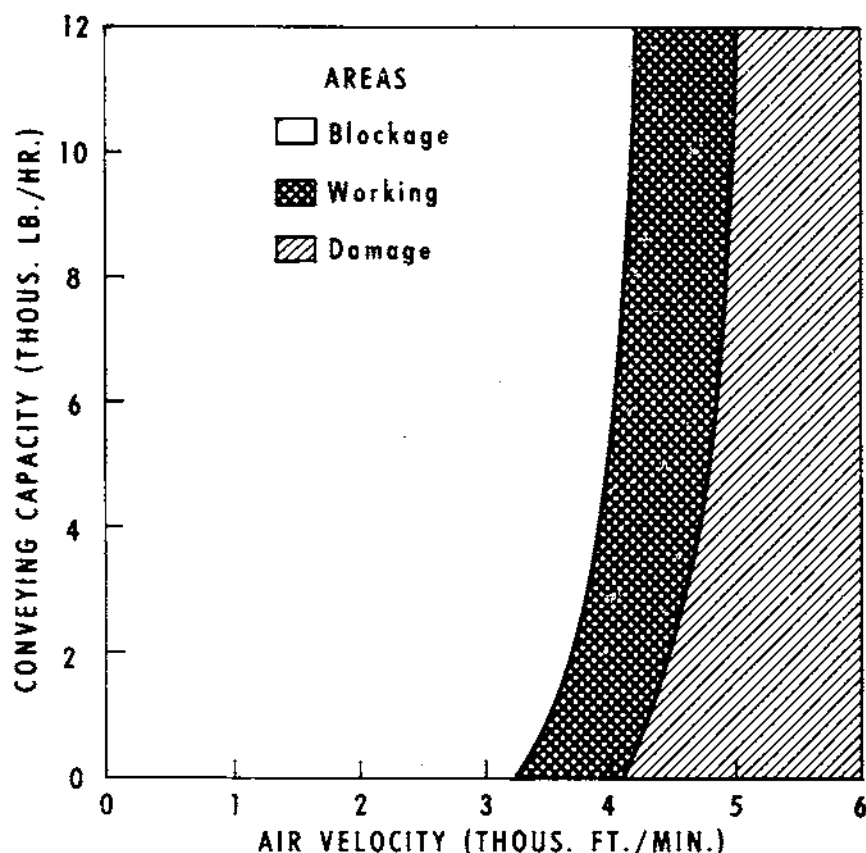
FIGURE 1.—The safe working area in ordinary pneumatic conveying. From Segler (*31, p. 71*).

EQUIPMENT AND MATERIALS

Air and Power Supply

Conveying air was supplied by a rotary, positive-displacement blower. Typically, blowers of this type deliver a low volume output against relatively high pressures; compared to centrifugal and propeller fans, blower output varies only slightly with pressure change. The unit employed showed a rating of 42 c.f.m. at 7 p.s.i.g. when operating at 1,200 r.p.m.

Since it was important that air supply be constant in replicated trials, blower speed was measured by stroboscope and tachometer and controlled with a variable sheave transmission.

The blower was driven with "B" section belts by a 5-h.p., 220-volt electric motor. Actual power requirements for the blower drive were determined with an industrial analyzer, which measured electrical power with a polyphase wattmeter.

Conveying air from the blower was divided and supplied to the transport run through two lines, as shown in figure 2. The main line
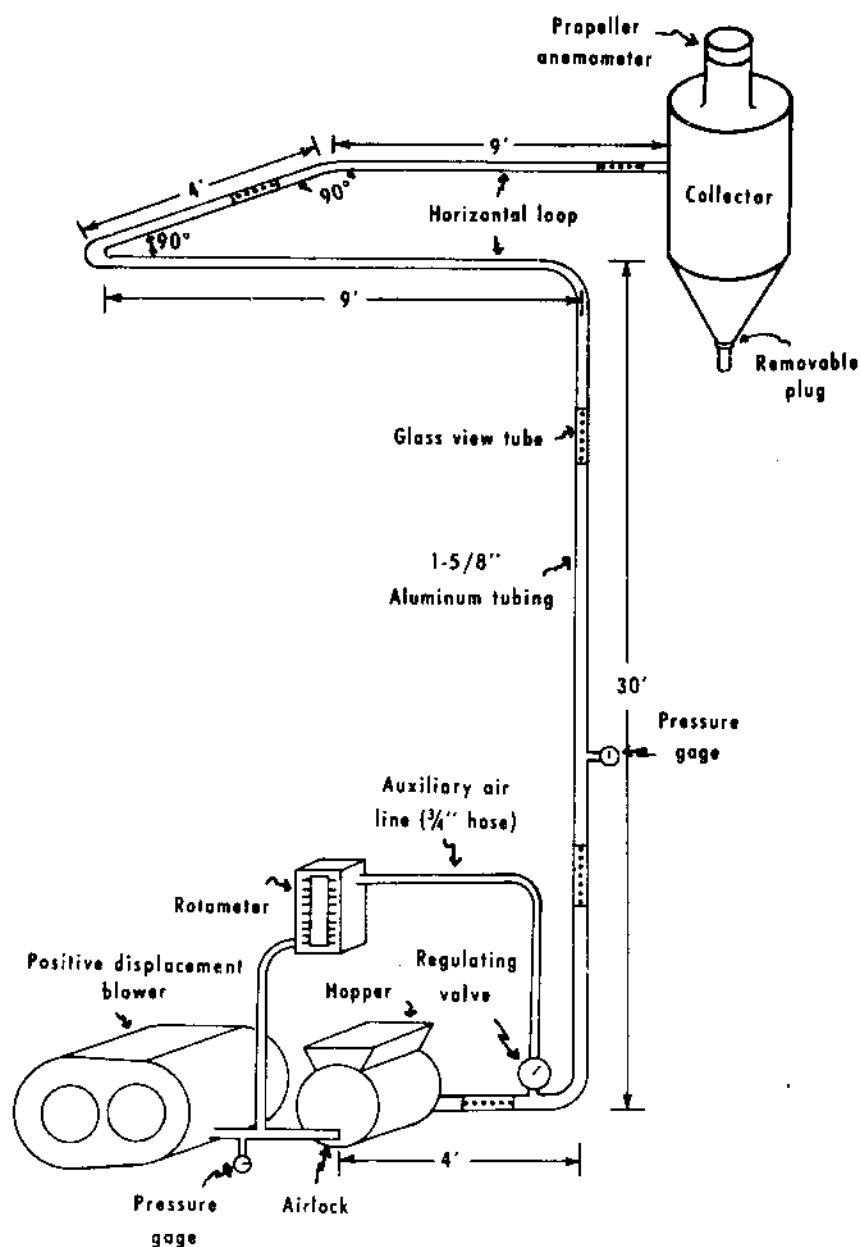
FIGURE 2.—Schematic sketch of USDA fluidized seed conveyor.

led to the airlock and consisted of 1½-inch pipe in which a check valve was located to prevent any seed backup into the blower. An auxiliary line composed of ¾-inch rubber hose bypassed the airlock and supplied air to the conveying line through a rotameter at a point 3 feet downstream from the airlock. A ¾-inch gate valve was located in the auxiliary line to control air flow and was equipped with a circular scale to show the opening of the valve shaft in degrees.

Seed Supply and Transport

Seed was supplied to the conveying line by a rotary airlock (sometimes called a star feeder). An airlock or some other type of air-sealing unit is needed when a product is to be introduced continuously into relatively high-pressure atmosphere. Various schemes are used to accomplish this kind of solids feeding (27), but rotary airlocks probably are most common because they are simple, readily available, and effective at pressure differentials up to 10 p.s.i. All airlocks leak some air in operation because of necessary clearances between rotor and housing and because each compartment traps and exhausts high-pressure air. The unit in this study had 12 vanes and was of "blow-through" construction where the supply air passes through the bottom section of the lock. With the use of a speed reducer, the airlock rotation was fixed at 42 r.p.m. for all trials.

In dense-phase conveying, a hopper feeding the airlock was kept full so that the seed head was reasonably constant and so that ample seed stock was available for the characteristic surge cycling typical of feeding as well as actual transport. In lean-phase conveying, the hopper discharge was metered to the airlock as a means of regulating solid-air ratio.

The conveying run was 56 feet of 1⅝-inch aluminum tubing including four 90° elbows of 12-inch radius. At five points in the run, short sections of glass tubing were inserted to provide visibility, as shown in figure 3. All joints were butted and held by radiator hose and clamps.

Air Measurement

Velocity and volume measurements of the conveying air required special techniques because air movement through the system was relatively slow and pulsating.

Air velocity was determined at the outlet of the seed collector after seed had dropped from the airstream. A propeller anemometer was used to measure pulsating airflow because it provided a cumulative reading over the test period from which an average figure could be computed. Inaccuracy of the anemometer that might be expected at low readings was minimized by recalibrating it several times against a sensitive heated-thermocouple unit in low-velocity air movement.

Air velocity at the collector outlet was used to compute the total volume of air actually transporting the seed. This air volume also provided a means of computing air velocity in the 1⅝-inch transport line which could not be measured directly because of entrained seed. (Air volume and velocity are based on gross pipe areas.)
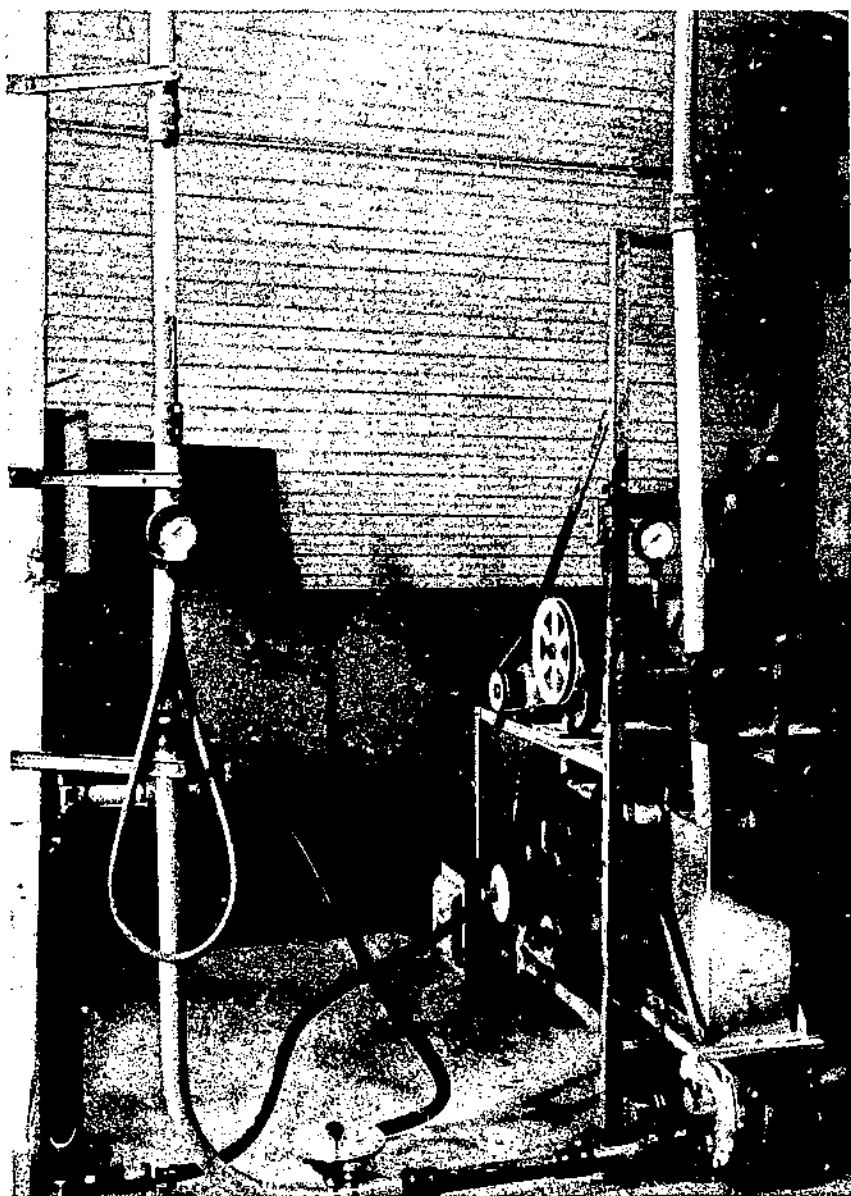
FIGURE 3.—USDA fluidized seed conveyor, showing blow-through rotary airlock, auxiliary air introduction, and part of the 56-foot run of 1⅝-inch transport line.

The portion of the total conveying air that was supplied through the auxiliary air line was measured by using a rotameter equipped with a linear scale. A large-capacity unit was employed to minimize the amplitude of float cycling due to pulsating flow. Since rotameter readings tend to be high under these conditions, the rotameter was calibrated against the heated thermocouple and also against the propeller anemometer in pulsating flow (*1, p. 5*).

A pressure gage and a thermometer were used to determine air characteristics at the rotameter and system discharge so that airflow measurements could be corrected to standard pressure-temperature conditions and thereby be compared sensibly. All air volumes are reported as standard cubic feet per minute (s.c.f.m.).

A sling psychrometer was used to determine ambient air conditions.

Conveying Capacity and Materials Transported

To determine conveying capacity, seed transported in a measured time interval was collected and weighed to the nearest tenth of a pound on a small platform scale.

Most of the conveying tests were conducted with a high-quality lot of crimson clover that showed an initial germination of 93.2 percent. High germination was desirable because this would indicate a lot that was uniform and that should show damage readily. Additional seed damage trials were conducted with navy beans (California Small Whites) that had an initial germination of 93.8 percent. Other types of seed handled in brief conveying trials were lotus, red clover, vetch, beets, parsnips, Alta fescue, peas, and large garden beans. Peas and lentils for foodstuffs also were transported.

Seed Damage

In a study of seed damage, fractions of the high-quality lots were dyed, mixed with carrier seed for conveying trials, and transported to the collector. The seed lot then was cup sampled as it was run out of the collector and was reduced further in a chaffy grass splitter to about one-fourth pound. All dyed seeds (whole and pieces) were removed from this quantity by hand and weighed by analytical balance. Seed germination tests were conducted in high-humidity cabinets with temperature control.

PROCEDURE

Test procedures were prepared and followed for dense-phase conveying trials, lean-phase conveying trials, constant capacity tests, seed velocity determinations, and seed damage evaluations. Three men composed the test crew. Two were stationed at the feed end of the system (ground level), one was located at the discharge of the run (third floor), and communication was maintained by intercoms.

Dense-Phase Conveying

Seed transport in the dense phase was obtained by providing a stockpile of seed in the hopper feeding the airlock so that seed was available

as needed for the surge flow typical of this operation.   Four levels of conveying capacity were provided by varying the valve setting in the auxiliary air line, and four or six replicated trials were carried out at each capacity level.   Blower speeds were brought to 1,100 r.p.m. (unloaded) before each run.   Items measured during the run were seed transported, time of run, electrical-power consumption, line air pressure, air velocity at the collector discharge, auxiliary air valve opening, and auxiliary airflow.   These quantities were used to compute conveying capacity; horsepower; velocity, volume, and weight of conveying air; solid-air ratio; and percentage of total conveying air that was auxiliary.

Lean-Phase Conveying

The procedure for lean-phase trials was similar to that for dense-phase except that the different levels of conveying capacity were obtained by varying the rate of introducing seed to the system, and no auxiliary air was used.   Four replicated trials were conducted at each capacity level, and blower speeds were standardized at 1,400 r.p.m. (unloaded) before each run.

Constant Capacity, Variable Air Tests

A special study of dense-phase conveying was conducted where different airflow rates were employed while capacity was held constant at 1,500 ($\pm$65) pounds per hour.   Blower speeds and auxiliary air valve settings were adjusted to provide different auxiliary airflow rates as indicated by the rotameter.   Four replicated trials were carried out at each condition of airflow, and the same readings were made as described in the procedure for dense-phase conveying.

Seed Velocity Determinations

Average seed velocity in the conveying line was determined by a procedure outlined by Segler ($31, p. 159$), which requires knowledge only of conveying capacity and the seed weight per foot of run.   Then, by a simple mathematical relation:

$$V_s = \frac{C}{W_L}$$ where V_s = seed velocity, in feet per minute
   C = conveying capacity, in pounds per minute
   W_L = seed weight per foot of run, in pounds per foot

Also, $W_L = \frac{W_T}{L}$ where W_T = total seed weight in run, in pounds
   L = length of run, in feet

So, $$V_s = \frac{CL}{W_T}$$

Conveying capacity was determined by measuring time and weighing transported seed in each trial; length of run was fixed in all trials at 56 feet.   The total weight of seed in the line at any instant was found by abruptly diverting the supply air to atmosphere through a special relief valve, and then collecting and weighing the seed thus deposited in the line.

Seed Damage Evaluations

Seed damage tests for crimson clover were carried out in conjunction with the dense- and lean-phase conveying trials, and separate damage tests were conducted for beans.

Clover test lots were made up so that about 10 percent of the conveyed stock was dyed, high-germination seed. At a given capacity level, three replications were obtained with the same carrier lot by adding red seed first, then green, and finally violet. After the first replicated trial, the transported lot was sampled and red seed extracted as described earlier. Green seed then was added for the second replication and extracted for analysis, as was violet seed for a third replication. This procedure was repeated for each of four capacity levels in the dense-phase trials and four in the lean-phase trials. An analysis of red seed remaining in the carrier lot after three replications made it possible to determine the cumulative effect of repeat passes through the system.

No breakage was evident in these trials with crimson clover; therefore, damage and conveying severity were evaluated only in terms of seed germination.

An additional damage study was conducted with beans where deliberate efforts were made to induce seed damage at some operating levels. Air velocity was varied from low to the highest possible in this system, feed rate was low, and a metal impact plate was fixed in the collector so that all beans struck it. The same scheme, blending a small quantity of dyed, high-germination seed with a carrier lot and then extracting the colored seed for evaluating damage, was used. One condition of dense-phase and five conditions of lean-phase conveying were examined, and each condition was replicated twice. Transported lots were cup sampled and then split further on the chaffy grass divider. About 500 colored beans and fragments were analyzed finally for breakage and germination.

Seed samples were taken before conveying, after passage through the airlock, and after the complete conveying process, in an effort to measure the portions of the total damage due to airlock action and to actual transport.

RESULTS AND DISCUSSION

Dense-Phase Operation

Dense-phase conveying results for crimson clover are summarized in table 1, and illustrate how performance varied when the auxiliary air valve was opened. As seen in figure 2, the auxiliary valve was in an air line that bypassed the airlock, which allowed high-pressure air to be supplied directly to the seed-conveying line.

Figure 4 presents some of the data for dense-phase conveying. The capacity and airflow trends are similar, showing an increase in value with auxiliary air valve opening. A leveling-off tendency indicates that greater valve openings become increasingly less effective. The pronounced likeness of the auxiliary and total air curves is reasonable since at all test conditions auxiliary airflow represented 70 percent or more of the total airflow. ("Total" flow refers to air

TABLE 1.—*Results of dense-phase conveying tests with crimson clover at four capacity levels* [1]

Conveying capacity		Seed in system [2]	Seed velocity	Power	Air velocity	Total air volume [3]	Air weight	S/A ratio (pounds seed per minute: pounds air per minute)	Auxiliary air		Pressure at blower outlet	Pressure drop per foot [5]
Pounds per hour	Pounds per minute								Valve opening	Percentage of total [4]		
		Lb.	*F.p.m.*	*Hp.*	*F.p.m.*	*S.c.f.m.*	*Lb. per min.*		*Degrees*	*Pct.*	*P.s.i.g.*	*P.s.i.g.*
338	5.6	15.9	20	3.9	365	5.3	0.38	14.7:1	250	72	7¾	0.138
891	14.9	11.1	75	3.6	685	9.9	.71	20.9:1	320	100	7	.125
1,527	25.5	7.9	185	3.3	1,340	19.3	1.40	18.3:1	450	83	6¼	.112
1,713	28.6	6.7	252	3.0	1,700	24.5	1.77	16.2:1	720	88	5½	.098

[1] Averages of 4 to 6 replications.
[2] Total seed in system at any instant.
[3] Air doing the conveying; corrected to standard pressure-temperature conditions.

[4] By volume, corrected to standard pressure-temperature conditions.
[5] Average linear pressure drop over whole run.

doing the actual conveying and does not include leakage through the airlock.)

Similar capacity trends might have been obtained if total air were increased by means other than opening the auxiliary air valve. However, even though higher blower speed tended to increase blower output, it also produced a greater pressure differential across the airlock which, in turn, caused more air leakage and feeding difficulties. Since the airlock imposed limitations at the higher operating pressures, it proved desirable to bypass a substantial amount of the air around the airlock. This technique effectively lowered system pressures, reduced air leakage and power requirements, and improved feeding characteristics—all without sacrifice in conveying capacity. Because of its demonstrated importance, introduction of auxiliary air was studied later in more detail. (See figs. 7 and 8.)
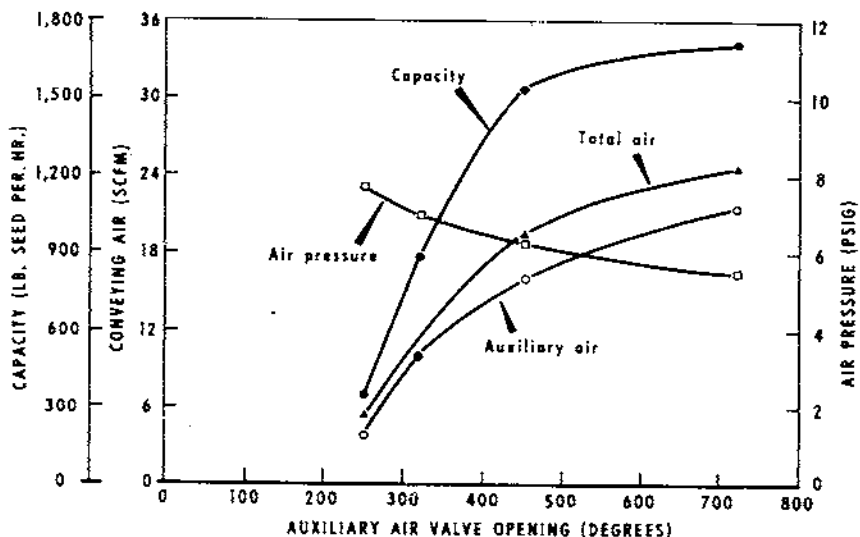
FIGURE 4.—Effect of auxiliary air valve opening in dense-phase conveying of crimson clover. Each point is an average of 4 or 6 replications.

Additional performance data for dense-phase conveying of crimson clover are presented in figure 5. When capacity increased as shown, air pressure and power requirement dropped, seed velocity increased, and solid-air ratio climbed to a maximum and then decreased. The tendency for pressure to drop as capacity increased is noteworthy because it departs from the usual pattern in pneumatic conveying. (This phenomenon is discussed later in connection with fig. 8, and a more complete power-capacity relation is shown in fig. 12.)

Since an increase in air rate was associated with an increase in capacity, it is reasonable that seed velocity, too, should increase as indicated in figure 5. Actual values of seed velocity, however, are relatively low—250 f.p.m. and below.

Solid-air calculations reflect the amount of solids handled per unit amount of air. As used specifically in this study, the solid-air (S/A) ratio indicates the pounds of seed per minute transported by 1 pound

of air per minute. Since these are weight rates (constant mass flow), the air component in any one test setup is unaffected by pressure and temperature changes that occur as air moves from the high-pressure region (blower output) to atmosphere (pipe discharge). Air weight itself was calculated by using the specific volume of air at the pipe discharge which was essentially at standard conditions.

FIGURE 5.—Some performance characteristics in dense-phase conveying of crimson clover. Each point is an average of 4 or 6 replications.

The distinct hump in the S/A-ratio curve in figure 5 is likely due to the fact that flow in the dense-phase trials began with a "slugged" or packed pipe. At this time when the seed mass was very dense, a relatively small movement of solids occurred at a given airflow rate. (Seed velocities are low, as shown.) This tends to produce a low S/A figure, as indicated for the minimum-capacity trial. At a larger airflow rate, the seed mass became less dense, or more fluidlike in its flow properties, and the solids rate increased more proportionately than the air rate, thus producing a greater S/A figure. At the higher capacity levels, the dense-phase concept of seed transport in a mass is less applicable because the "slugs" of seed are faster moving, more permeated by air, and not as sharply defined. Resistance to airflow is lower, and air rates increase more readily than solids rates. This suggested interrelation of solids and air rates is supported by the slopes of the capacity and air curves in figure 4, where capacity appears to climb more sharply than air at first and also levels off more rapidly than air as the auxiliary valve is opened more.

From a practical standpoint, figure 5 indicates that the best operating condition is at the highest capacity level examined, because power requirements and pressures are least at this point. A possible limitation here is seed velocity-damage considerations; however, these velocities, although highest for the dense-phase transport, were not great enough to damage the clover test lots. (Velocity-damage rela-

tions for crimson clover, beans, and other seeds are discussed in a separate section.)

Lean-Phase Operation

For direct comparison with dense-phase conveying, lean-phase trials were carried out in the same system. Lean-phase transport is similar to typical pneumatic conveying, particularly in terms of higher seed velocities. Different capacity levels were obtained by varying the rate of introducing seed to the system, and test results are summarized in table 2. No auxiliary air was used in these trials and blower speed was held essentially constant. The only changes in air rate were those caused by varying resistance to airflow that took place as seed-introduction rates were changed.

Some of the data for the lean-phase trials are presented in figure 6, in which the same coordinates are used as in figure 5. A comparison
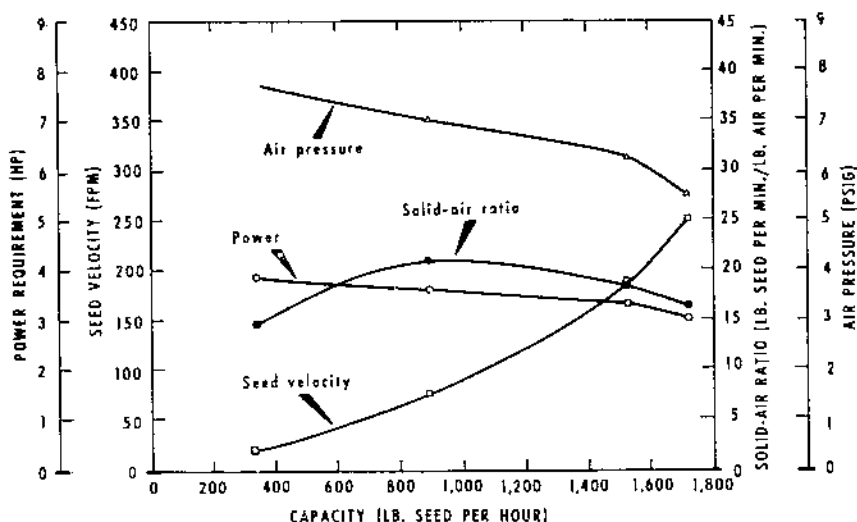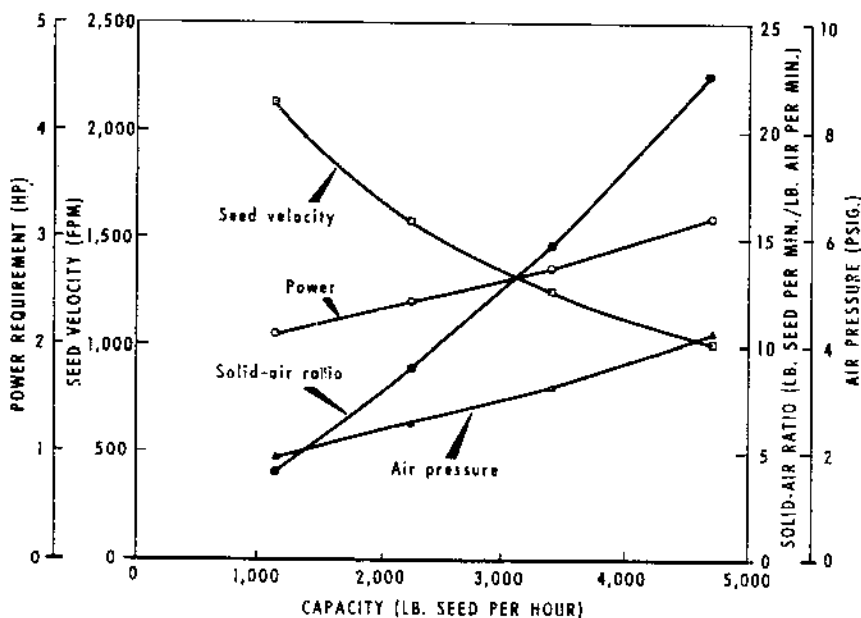

FIGURE 6.—Some performance characteristics in lean-phase conveying of crimson clover. Each point is an average of 4 replications.

of the two plots shows opposite trends for pressure, power, and seed-velocity curves. In the lean-phase transport (fig. 6), pressure and power increase with capacity, as might be expected. The indicated rise in S/A ratio also is logical because, as the solids-flow rate increased, the airflow rate decreased. This is different from dense-phase transport (figs. 4 and 5), where both solids rates and air rates increased with capacity. (More information on pressure variations and airflow rates for lean-phase conveying is presented in figure 9. Also, a power-capacity relation is shown in fig. 12.)

Since the data in table 2 for lean-phase conveying were obtained by starting with an arbitrary airflow and an uncharged system, the

TABLE 2.—*Results of lean-phase conveying tests with crimson clover at four capacity levels* [1]

Conveying capacity		Seed in system [2]	Seed velocity	Power	Air velocity	Total air volume [3]	Air weight	S/A ratio (pounds seed per minute: pounds air per minute)	Pressure at blower outlet	Pressure drop per foot [4]
Pounds per hour	Pounds per minute									
		Lb.	*F.p.m.*	*Hp.*	*F.p.m.*	*S.c.f.m.*	*Lb. per min.*		*P.s.i.g.*	*P.s.i.g.*
1,125	18. 8	0. 48	2, 125	2. 1	4, 400	63. 3	4. 64	4. 1:1	1⅛	0. 034
2,225	37. 1	1. 27	1, 585	2. 4	3, 960	57. 0	4. 17	8. 9:1	2½	. 045
3,365	56. 1	2. 40	1, 255	2. 7	3, 640	52. 4	3. 84	14. 6:1	3¼	. 058
4,695	78. 3	4. 16	1, 015	3. 2	3, 265	47. 0	3. 45	22. 7:1	4¼	. 076

[1] Averages of 4 replications.
[2] Total seed in system at any instant.
[3] Air doing the conveying; corrected to standard pressure-temperature conditions.
[4] Average linear pressure drop over whole run.

measured air velocities at a given seed-introduction rate probably were greater than needed simply to convey seed at that rate.   For example, air velocity dropped to 3,265 f.p.m. for the maximum-capacity trial, but was still great enough to sustain seed movement.   This points out that lesser capacities also could have been accommodated at 3,265 f.p.m. although measured air velocities for lower capacities were greater. However, lean-phase operation at this low velocity was unstable, approaching the slugged condition of dense-phase operation.   Seed velocity in the lowest capacity trial was the highest observed for conveying clover (2,125 f.p.m.).   A comparable figure for flax seed at the same capacity was determined by Wood and Bailey (*35*, *p. 153*) to be about 2,500 f.p.m.   (An air-speed velocity relation is presented in fig. 10.)

Dense-Phase Conveying at a Constant Capacity Level and Variable Airflow Rates

Since adjustment of the auxiliary air valve had proved critical in dense-phase conveying, it was examined in a separate study which is summarized in table 3.   Capacity was held nearly constant at 1,500± 65 pounds per hour, and the auxiliary valve setting and blower speeds were varied as needed to obtain a series of auxiliary airflow rates.

The pressure curve (fig. 7) decreases logically with increases in auxiliary air because the air rate was increased by opening the auxiliary valve and thereby lessening the restriction to airflow in this line. The greater auxiliary flow tended to move seed out of the vertical riser and to lower the total system resistance, thereby encouraging more total airflow.   (Total air is not shown in fig. 7, but it would exhibit the same trend, essentially, as auxiliary air, since auxiliary air represented 70 percent or more of the total airflow in all trials.)
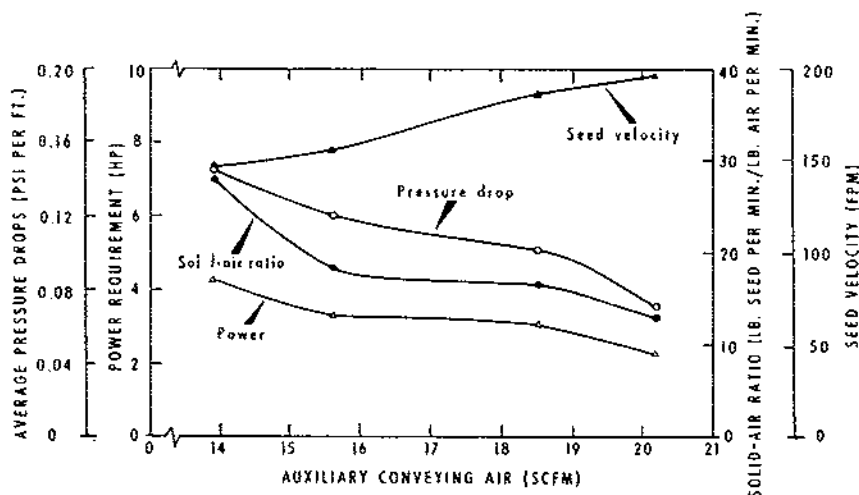
FIGURE 7.—Constant capacity, variable air travels (1,500±65 pounds per hour) in dense-phase conveying of crimson clover.   Each point is an average of 4 replications.

TABLE 3.—*Results of dense-phase conveying tests with crimson clover at a constant capacity level and variable airflow rates* [1]

Conveying capacity		Seed in system [2]	Seed velocity	Power	Air velocity	Total air volume [3]	Air weight	S/A ratio (pounds seed per minute: pounds air per minute)	Auxiliary air		Pressure at blower outlet	Pressure drop per foot [5]
Pounds per hour	Pounds per minute								Valve opening	Percentage of total [4]		
		Lb.	*F.p.m.*	*Hp.*	*F.p.m.*	*S.c.f.m.*	*Lb. per min.*		*Degrees*	*Pct.*	*P.s.i.g.*	*P.s.i.g.*
1,555	25.9	9.9	147	4.3	890	12.8	0.928	27.9:1	360	100	8½	0.152
1,435	24.0	8.5	158	3.4	1,250	18.0	1.305	18.4:1	450	87	6¾	.120
1,535	25.4	7.6	187	3.1	1,460	21.0	1.522	16.7:1	540	88	6	.107
1,485	24.8	7.0	198	2.3	1,800	25.9	1.878	13.2:1	(⁶)	78	4	.072

[1] Averages of 4 replications.
[2] Total seed in system at any instant.
[3] Air doing the conveying; corrected to standard pressure-temperature conditions.
[4] By volume, corrected to standard pressure-temperature conditions.
[5] Average linear pressure drop over whole run.
[6] Full; also, main supply restricted some.

Less resistance to airflow meant smaller power requirements, as shown in figure 7, and later in figure 11. Seed velocity increases because total conveying air rate (and therefore air velocity) increases as auxiliary air increases.

Solid-air ratios might be expected to drop with auxiliary air as indicated because the solids-flow rate remained nearly constant while airflow rates increased.

The characteristic S-shape of the power, pressure, and S/A curves can be explained, partially at least, by the fact that the actual conveying capacity was not exactly the same for all tests. For example, in the second trial actual capacity (at 15.6 s.c.f.m.) was less than 1,500 pounds per hour, and in the third trial more than 1,500 pounds per hour. Figure 7 shows that in the S/A curve, to cite one case, a higher second point and lower third point would have produced an S/A plot more nearly linear with auxiliary air.

The general similarity in shape of the curves for power, pressure, and S/A ratio suggests that power and pressure values for a test condition are influenced strongly by the S/A ratio of that condition. In a larger sense, this S/A relation may be thought of, generally, as a density index or a measure of induced fluidity in the seed mass. With this in mind, the highest S/A values of the study indicate relatively low fluidity or mobility of the seed mass, and low S/A values suggest great fluidity and easy movement of the seed. Such an analysis is supported by the trends shown in figure 7, where the fourth trial (at 20.2 s.c.f.m.) produced seed movement so readily that it approached lean-phase conveying.

The practical value of figure 7 is to illustrate that best operating conditions for a given capacity involve the largest amounts of auxiliary air that can be tolerated. This means lower operating costs, less air leakage, and better feeding conditions. However, a possible limitation is high seed velocity with resultant damage, and possible "breakover" into lean-phase conveying where velocity-damage problems are more likely.

Pressure Drops in Dense- and Lean-Phase Conveying

In any conduit through which a fluid is flowing, there is a continuous loss of head or pressure. The pressure-drop characteristic was examined for dense-phase conveying of crimson clover and is presented in figure 8. When auxiliary air was introduced as shown, the average pressure drop per foot of conveying run decreased with increase in capacity. This is opposite to the usual pressure-capacity relation expected in typical pneumatic transport and to the results for lean-phase conveying shown in figure 9.

The ordinary concepts of fluid flow are not directly applicable to dense-phase conveying because this form of material transport probably is classified best in a region between fluid flow and the movement of a solid. In typical slug flow of dense-phase conveying, the seed movement is not continuous but follows an irregular cycle where slugs of seed are forming, moving, and dissipating throughout the pipe run. Actual movement takes place when air pressure builds up enough to impart momentum to any slug. This pneumatic propelling force acts only for a short time because pressure drops rapidly

as the slug is moved downstream. However, pressure again builds up as new slugs form, and cycle recurs in the form of repeated pneumatic boosts.
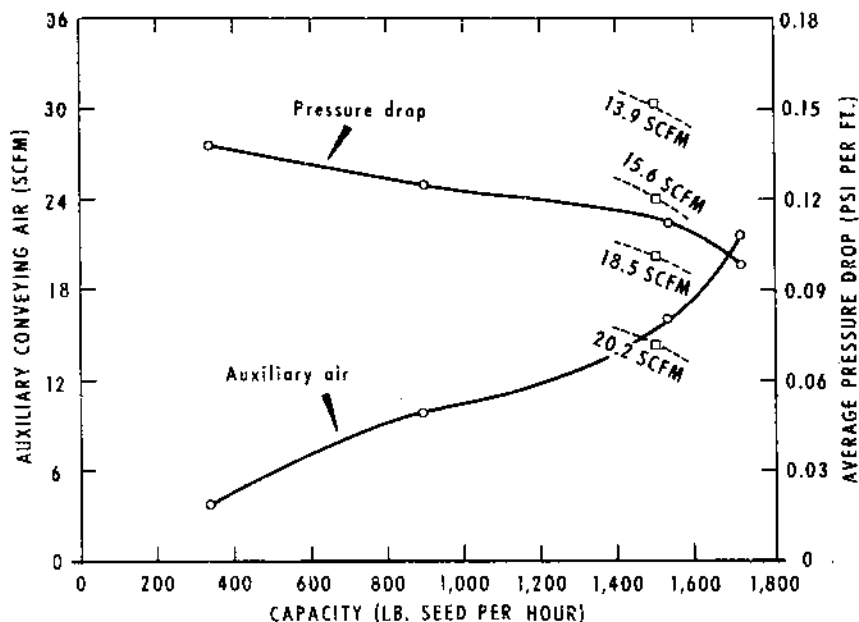

FIGURE 8.—Pressure-capacity relations in dense-phase conveying of crimson clover. Each point is an average of 4 or 6 replications. Square points are pressure drops from constant capacity tests (fig. 7).
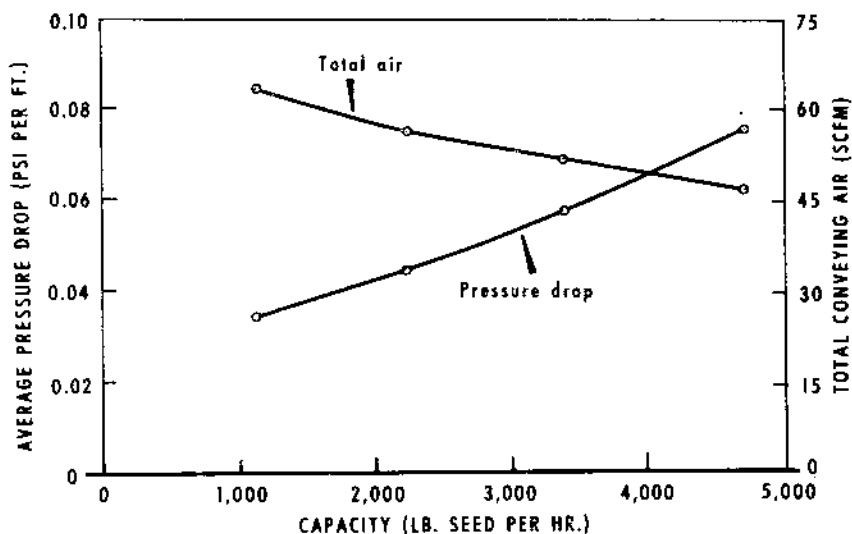

FIGURE 9.—Pressure-capacity relations in lean-phase conveying of crimson clover. Each point is an average of 4 replications.

If the seed slugs in dense-phase conveying were definite and non-changing in character, the typical slug flow might be analyzed from a friction standpoint, with some justification, as though each slug represented a solid cylinder. On this basis, seed movement would take place when the static friction of a stationary seed plug was overcome by the application of pneumatic force. Once started, the seed plug would continue in motion until kinetic friction exceeded the moving force.

However, the seed slug is not a solid, unchanging substance. It contains an appreciable amount of void space and can be permeated readily by air. The effects of air bleeding through the seed mass are to decrease bulk density, "lubricate" the mass, and produce a degree of fluidity. Because of this fluidity, the seed slug is a mobile, changing thing that shows some characteristics of both a solid and a fluid.

The reduction of pressure drop with increase in capacity (shown in fig. 8 for dense-phase conveying) is logical when it is realized that the seed movement can begin from a slugged condition. When this happens, initial capacity figures will be low; and since resistance to airflow through the dense seed mass is relatively great, maximum system pressures will be high. When introduction of auxiliary air is increased, the seed mass becomes less dense (more fluidlike) and is easily permeated by air. Since seed can now flow more readily, capacity increases while resistance to airflow decreases, as shown in figure 8.

At the upper levels of capacity, the pressure-drop curve falls off more sharply—an indication that the "break-over" point is being approached where dense-phase conveying changes to lean flow and where pressures are generally lower. Also in this region, auxiliary air rates climb steeply—an indication that seed charge in the line is decreasing. (This is reflected too, in the decreasing S/A ratio of fig. 5.) Total airflow, if plotted, again would show the same trend as auxiliary air.

The pressure-capacity relation suggested in figure 8 is influenced greatly by rate of auxiliary airflow. The plotted square points represent pressure drops per foot obtained in four operating conditions of the constant capacity, variable air test shown in table 3. These pressure-drop figures are included in figure 8 to emphasize that any of these square point values, or others, might have been obtained (all at the fixed capacity of 1,500 pounds per hour) depending on the amount of auxiliary air introduced. If the same type of auxiliary air study had been performed at each capacity level shown in figure 8 (as it was for 1,500 pounds per hour), a family of pressure-drop curves could have been plotted somewhat as illustrated by the short dashed lines, each of which represents a different auxiliary airflow. The slopes of these curves are not known, but each would pass through one of the square points shown. The conclusion to be drawn here is that different pressure-capacity relations can be obtained by employing different auxiliary air rates, all at a fixed capacity. Each point of the pressure-drop curve in figure 8 applies only to the auxiliary air rate indicated at that capacity.

To provide the lowest possible pressure drop per foot at any capacity level, it is advisable to operate with the highest auxiliary-air rate that can be tolerated. The limiting air rate again will be dictated by

possible "break-over" into lean-phase conveying and resultant high-velocity seed-damage considerations.

Figure 9 represents a relation of average lineal pressure drop, total airflow, and capacity in lean-phase transport of crimson clover. The increase in pressure drop (or head loss) with increase in capacity is typical of ordinary pneumatic conveying and conforms generally to the laws of fluid friction. The Darcy-Fanning equation for turbulent fluid flow states:

$$h_f = \frac{fL}{D} \frac{V^2}{2_g}$$

where: h_f = head loss, in feet
   f = friction coefficient, dimensionless
   L = pipe length, in feet
   V = velocity, in feet per second
   D = internal pipe diameter, in feet
   g = acceleration of gravity = 32.17 feet per second^2

The friction coefficient, f, is a function of Reynolds number which depends in part upon the viscosity of the fluid being considered. When seeds in varying amounts are entrained in a moving airstream, the effect is to change the apparent viscosity makeup of the flowing seed-air mixture. As a result, friction coefficients also will change and might be expected to vary in the same general fashion as solid-air ratios. This thought is supported by the fact that an increase in S/A ratio was accompanied by an increase in pressure drop over the whole system, as shown in figures 6 and 9. A related point here is that greater amounts of seed in the system act as added restrictions to airflow.

Data in figure 9 were obtained by fixing the blower speed initially, then varying the seed-introduction rate. The indicated drop in airflow is reasonable since more seed in the system (higher S/A ratio) tends to reduce air velocity and volume from the standpoint of seed-acceleration requirements. Also, as the S/A ratio increased, the blower slowed down slightly and was called upon to operate at greater pressures. Both factors reduce blower output.

Figure 9 shows that the airflow rate decreases as pressure increases. This appears to contradict the general law pertaining to system characteristic curves, which states that resistance to airflow in a system varies directly as the square of the volume flow (another form of the Darcy-Fanning equation). However, the data in figure 9 do not contradict this concept because each capacity level represents a different S/A ratio, viscosity, and friction coefficient. As a result, four system characteristic curves could be established where each is appropriate for a given capacity and would demonstrate the typical parabolic increase in pressure with volume flow. In this way, each seed-introduction rate produces a new system characteristic. The plotted pressure drops in figure 9 can be thought of then as single points, each from a different system characteristic curve.

An interesting speculation is the combined effect of seed density, S/A ratio, shape, and texture on the viscosity makeup of a seed-air mixture. Once this is known, flow properties and pressure drops can be predicted for any seed-handling problem. The work reported

here includes a brief study of one part of the viscosity picture—that of S/A ratio for crimson clover.

The practical value of figure 9 is to show pressure-capacity relations for lean-phase conveying that are opposite in trend to the results for dense-phase conveying (fig. 8), and to suggest the lowest airflow rates that will transport crimson clover seed in the lean phase.

Seed and Air Velocities in Dense- and Lean-Phase Conveying

The influence of air velocity on seed velocity for both dense- and lean-phase conveying trials are presented in figure 10 to provide a graphic comparison of the two methods. In both, seed velocity increases with increase in air velocity, but the rate of change in the lean phase is much greater, as noted by relative slopes of the curves. Also, seed velocity and air velocity are much less for dense- than for lean-phase conveying.
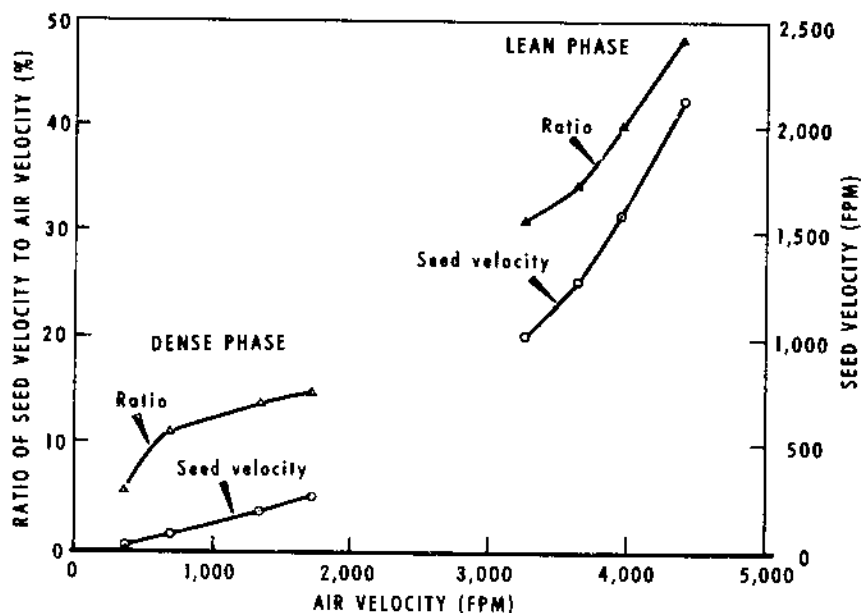
FIGURE 10.—The influence of air velocity on seed velocity in dense- and lean-phase conveying of crimson clover. Each point is an average of 4 or 6 replications.

There is a suggestion that the seed-velocity curves might have been continuous had greater velocities been attempted in dense-phase trials, or lesser velocities in lean-phase trials. However, either action would have involved operating in an unstable region. The lowest measured seed velocity shown for lean-phase conveying (1,000 f.p.m.) checks well with a vertical choking velocity of about 900 f.p.m. determined by Zenz for rape seed (*36 (6), p. 136*). Zenz also noted that horizontal settling velocity was identical to vertical choking velocity for particles of uniform size but much greater for particles of mixed size.

Ratios of seed velocity to air velocity are plotted for both dense- and lean-phase conveying. The ratios for dense phase are much lower, and the curve appears to be leveling off, whereas ratios for lean phase are increasing. In lean-phase conveying, the ratios show that average seed velocity ranges from about 31 to 48 percent of the air velocity, but it is not known if the seeds had stopped accelerating in the 56-foot run employed here. These figures are interesting because of the varying estimates that have been made of this "slippage" factor. Richardson and McLeman (*30, p. 263*) found values of about 72 to 81 percent for 0.04-inch coal particles. With flax seed, Wood and Bailey (*35, p. 161*) determined a figure of 50 percent for low seed-air concentration and 20 percent for high seed-air concentration. Segler (*31, p. 103*) worked with wheat and found grain velocity was about one-third of the air velocity.

In the velocity comparisons shown in figure 10, results for lean-phase conveying likely are more accurate than those for dense-phase conveying because all velocities discussed here are averages, and the dense phase includes a wide range of seed motion—in some cases the seed even drops momentarily against the airflow in the vertical run.

Power Requirements in Dense- and Lean-Phase Conveying

Power-pressure relations of dense- and lean-phase conveying trials are presented together in figure 11, and both methods show the same trend—that power requirements increase linearly with air pressure for the particular range of capacity and auxiliary air studied. One of the dense-phase plots (the constant capacity, variable air investi-

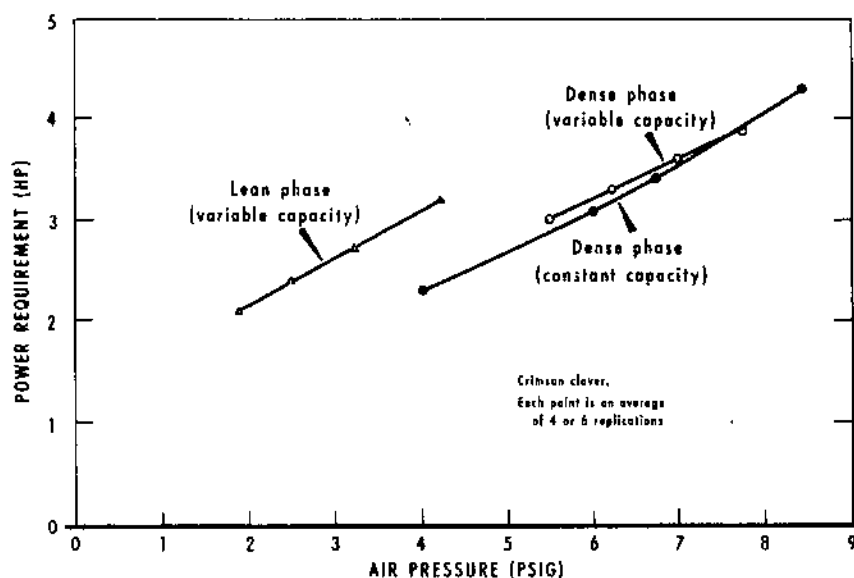FIGURE 11.—Power-pressure relations in variable capacity and constant capacity trials in dense- and lean-phase conveying of crimson clover. Each point is an average of 4 or 6 replications.

gation) compares the power-pressure data shown in figure 7. Here the pressure range is greater, but the same general trend of linearity is evident except for the maximum pressure point, which suggests a proportionately greater power requirement when the seed mass is very dense.

The rate of power increase for all trials is nearly the same, as indicated by the slope of the curves. Generally, dense-phase conveying shows greater pressure and power requirements than does lean-phase conveying except at 4 p.s.i., which was near the point of "breaking over" into the lean phase. As shown, power and pressure characteristics of this dense-phase test condition fell nicely within the ranges for the lean phase.

The lean-phase and variable dense-phase plots represent only the power and pressure figures associated with a given test condition, regardless of capacity.

The main value of figure 11 is to show that power requirements generally increase steadily with system pressure in both lean- and dense-phase conveying.

Power requirements for dense-phase and lean-phase conveying are shown on a unit-conveying basis in the curves in figure 12, which are elaborations of the power curves in figures 5 and 6, respectively.
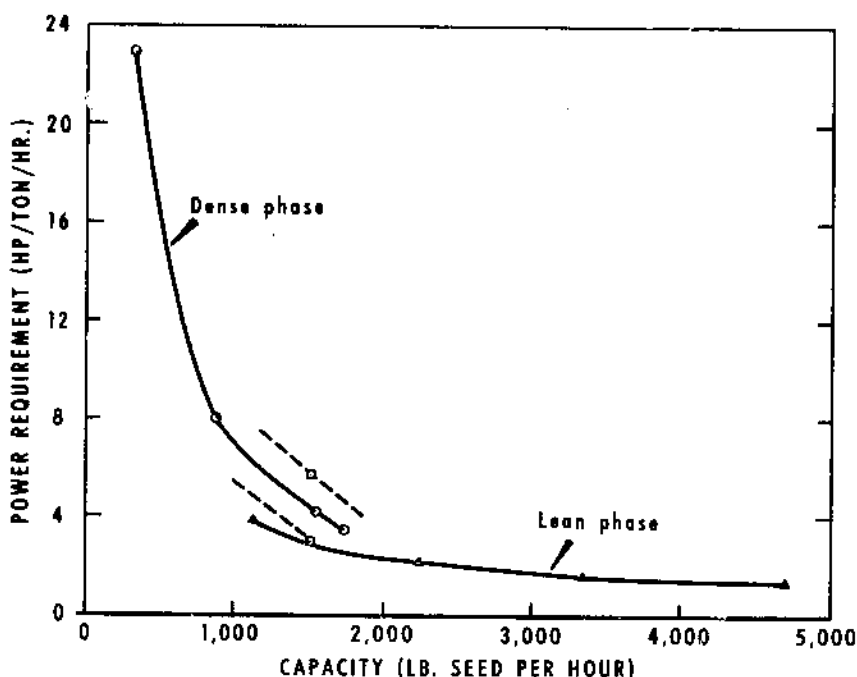

FIGURE 12.—Relations of power requirements and conveying capacity in dense- and lean-phase conveying of crimson clover. Each point is an average of 4 or 6 replications. Square points represent range of dense-phase power requirements from constant capacity test (fig. 7).

Power requirements (horsepower per ton per hour) for low-capacity trials in dense-phase conveying are high because the seed mass is very dense and little auxiliary air is being used to fluidize the seed load in the vertical riser. This is an extreme condition where the flow approaches the movement of a solid rather than a fluid, as discussed earlier. Capacities, therefore, are low and power requirements high, and the combination of these two factors results in the high horsepower per ton per hour figures plotted.

The power requirements for dense-phase conveying drop sharply with increased capacity as introduction of auxiliary air is stepped up. In contrast, power requirements drop slowly with increased capacity in lean-phase conveying and, generally, power requirements are less than in the dense phase.

There is a suggestion that the two curves are nearly continuous even though each represents a different conveying method. Continuity, in a sense, may be possible here because the largest capacity figure shown for dense-phase conveying represented a maximum condition of auxiliary airflow beyond which the operation probably would have "broken-over" into lean-phase conveying.

Again taking advantage of the constant-capacity dense-phase data of figure 7, it is possible to compute power-requirement figures for different auxiliary air rates, all at a fixed capacity. The square points shown in figure 12 represent the range found for 1,500 pounds per hour. In effect, this means that a family of power curves could be established and drawn, as discussed earlier in connection with figure 8, if a series of auxiliary air rates had been studied at the various capacity levels. The dashed lines through the square points in figure 12 suggest curve slopes that might have been obtained. The family-of-curves concept also seems to verify the possible continuity of dense- and lean-phase curves.

The value of figure 12 is to present a direct comparison of power requirements for the two methods on a unit-conveying basis and to illustrate the marked beneficial effect of introducing auxiliary air in dense-phase conveying.

Seed Damage

Many research studies have pointed out that mechanical damage to seed can readily lower or weaken germination. The damage may occur at any point in the harvesting, cleaning, or handling process, and in some seed lots, germination loss can reach prohibitive levels.

According to Harter (*17, p. 371*), thresher injury in beans may produce up to 30 percent abnormal germination. Brown and Toole (*8, p. 91*) point out that mechanical injury in handling may cause serious breaks in the seed embryo, which prevent normal development of the seedling. Moore (*24, p. 22*) suggests that mechanical damage, even before it reduces germination appreciably, causes seed to lose vigor and show other signs of weakness. Justice (*18, p. 161*) indicates that seedling abnormality may be a secondary effect of fungi attack through lesions and breaks induced by severe mechanical action. Moore (*25, p. 8*) also cites an indirect effect—that of premature seed aging.

Asgrow (*4, p. 22*) determined that germination decreased significantly when beans were dropped 1 foot (repeated drops) or 3 feet

(single drop) upon a metal plate. The Seed Testing Laboratory at Oregon State University has observed that damage in fine fescue crops has increased in recent years and that this has resulted in lower germination and more rapid deterioration in storage (28).

Seed damage frequently is associated with pneumatic conveying and should be considered in evaluating any system. In a comprehensive study of pneumatic grain conveying, Segler (31, p. 71) suggests that conveying should take place in a limited but distinct region of velocities between damage and blockage areas. Goss and Jones (16, p. 20) studied airlifts handling alfalfa and concluded that air velocities over 3,000 f.p.m. would damage seed. In another study of airlift damage Asgrow (4, p. 35) found that bean damage was cumulative in repeated passes through one system.

Because of its importance in efficient pneumatic conveying, seed damage was investigated in several phases reported here and was made up of drop tests, brief conveying trials, and extensive conveying studies with crimson clover and beans.

Drop Tests

Preliminary to the study of actual conveying damage, various kinds of seed that typically show damage in seed testing were dropped from a 12-foot height upon wood, metal, rubber, concrete, and seed surfaces. In some tests, drops were repeated. Kinds of seed tested were crimson clover, lotus, subterranean clover, hairy vetch, tall oatgrass groats, and orchardgrass groats. Germination tests were performed immediately and again after two storage periods of 16 months and 5 years. Storage was in an enclosed, unheated space.

A comparison of germination figures for the dropped lots and companion control lots (not dropped) showed no significant differences immediately or after 16 months' storage. After 5 years' storage the legumes again showed no differences, but the two dropped grass seed lots decreased more in germination than did their controls. The tall oatgrass groats showed germination figures of 38 percent (dropped) and 57 percent (controls), whereas the orchardgrass groats showed 53 percent (dropped) and 62½ percent (controls). Although differences are indicated, they were evident only in lots dropped seven times. On the basis of the results of all the drop tests, it must be concluded that significant mechanical damage did not occur.

Brief Conveying Trials

Various kinds of seed were conveyed pneumatically through small-diameter pipe of the USDA experimental conveyor in either dense- or lean-phase flow, or both, and resulting damage was evaluated in terms of germination and breakage. Table 4 summarizes details of the test operations, some of which reflect only single observations. The data indicate, broadly, that seed lots transported in the dense-phase trials show little or no damage. Airlock damage also can be seen in some trials, but, as discussed later, this can be reduced with proper airlock selection or design.

Extensive Conveying Studies With Crimson Clover

Seed breakage was not evident in any of the conveying trials conducted with crimson clover, so possible damage was evaluated by

TABLE 4.—*Seed damage in brief lean-phase and dense-phase conveying test with various seeds and foodstuffs*

Items conveyed and type of conveying	Conveying run			Passes	Through airlock	Breakage [1]		Germination	
	Pipe diameter	Elbows (90° 12″R)	Length			Conveyed	Controls	Conveyed	Controls
Seed:	*Inches*	*Number*	*Feet*	*Number*		*Percent*	*Percent*	*Percent*	*Percent*
Beans (Top Crop):									
Lean-phase_____	1	2	53	1	Yes_____	0.3	0.2	69	76
Do_____	1	2	53	3	Yes_____	1.1	.2	61	76
Do_____	1	2	53	5	Yes_____	2.3	.2	57	76
Dense-phase_____	1	2	53	1	Yes_____	.3	.2	75	76
Do_____	1	2	53	3	Yes_____	.2	.2	79	76
Peas (Green Scotch):									
Dense-phase_____	1⅝	2	38	1	No_____	--------	--------	59	54
Do_____	1⅝	2	38	1	Yes_____	--------	--------	48	54
Peas (Whole Alaska):									
Dense-phase_____	1⅝	2	38	1	No_____	--------	--------	92	92
Do_____	1⅝	2	38	1	Yes_____	--------	--------	90	92
Beets:									
Dense-phase_____	1⅝	4	56	1	Yes_____	3	1	--------	--------
Lean-phase_____	1⅝	4	56	1	Yes_____	2	1	--------	--------
Parsnips: Lean-phase___	1⅝	4	56	1	Yes_____	2	1	--------	--------
Foodstuffs:									
Peas (Yellow and Green):									
Dense-phase_____	1⅝	4	56	1	Yes_____	5	1	--------	--------
Lentils:									
Lean-phase_____	1⅝	4	56	1	Yes_____	3	1	--------	--------
Do_____	1⅝	4	56	1	No_____	1	1	--------	--------

[1] Approximate percentage by weight.

germination tests on representative samples from the four dense-phase trials and the four lean-phase trials discussed earlier. Summarized results are shown in table 5.

TABLE 5.—*Seed damage and conveying severity in dense-phase and lean-phase conveying tests with crimson clover* [1]

Test condition	Seed velocity	Normal germination	Hard seed	Abnormal germination	Dead seed	Severity index No.[2]
	Feet per minute	*Percent*	*Percent*	*Percent*	*Percent*	
Dense phase____	20	85.3	7.0	6.7	1.0	1.09
	75	86.0	8.0	5.3	.7	.78
	185	83.7	9.0	6.3	1.0	.83
	252	85.7	7.7	5.7	1.0	.89
Lean phase____	2,125	88.0	5.3	5.3	1.3	1.21
	1,585	86.3	6.0	7.7	0	1.24
	1,255	87.3	3.7	6.7	1.7	2.00
	1,015	89.3	3.7	6.0	1.0	1.70
Controls_____	_____	83.8	9.4	5.8	1.1	.76

[1] Average of 3 replications for dense-phase and lean-phase trials, and 8 for controls.

[2] Severity index No. $= \dfrac{1 + (\text{Abnormal germination} + \text{Dead seed})\%}{1 + (\text{Hard seed})\%}$

Normal germination and hard seed together reflect potential good seed, and this measure is essentially the same in all dense-phase and lean-phase trials. For additional comparison, these figures can be plotted on a velocity scale, as shown in figure 13, which then gives the impression that a straight line can be fitted to the points. The line deviates only slightly from the horizontal, so on this basis, normal-germination-plus-hard seed appears unaffected by seed velocity. The straight line is dashed between the highest velocity dense flow and the lowest velocity lean flow because this region is unstable from a conveying standpoint and is another example of the discontinuity discussed earlier.

In all cases, the conveyed material appears as good as the controls, and little or no seed damage is evident. Abnormal-germination-plus-dead-seed count is not shown directly, but it also remained constant, essentially. This is so because a seed subjected to a germination test must fall in one of these two classifications, which together equal 100 percent: normal-germination-plus-hard seed, or abnormal-germination-plus-dead seed. The lack of change in abnormal-germination-plus-dead seed is perhaps a more direct indication that damage did not occur.

However, even though the normal-germination-plus-hard-seed figures remained constant, the hard-seed component for lean-phase lots was less than for dense-phase lots. This suggests that the conveying action, in some cases, served to scarify hard seeds and make them germinable, but was not severe enough to damage seed. An interesting implication is that some mechanical severity may be tolerable in a conveying action, and perhaps even desirable, if it stimulates hard seed into normal germination. Since degree of severity apparently is
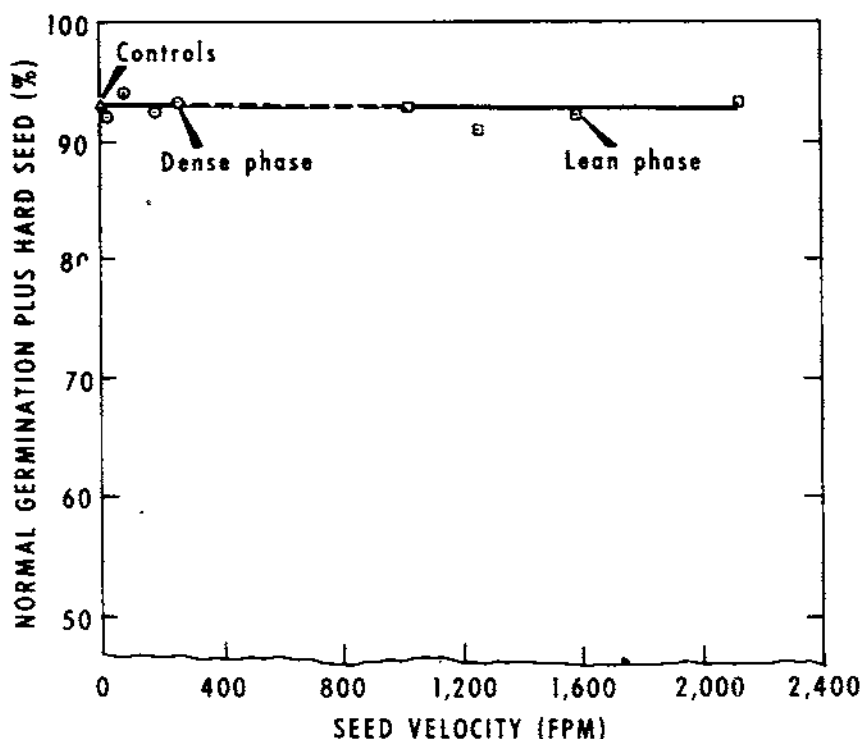
FIGURE 13.—Comparison of dense- and lean-phase conveying of crimson clover in terms of seed germination. Each point is an average of 3 replications except controls, which is an average of 8.

important, the following formula was devised to evaluate the conveying trials of this study in terms of relative mechanical severity:

$$\text{Severity index No.} = \frac{1 + (\text{Abnormal germination} + \text{Dead seed})\%}{1 + (\text{Hard seed})\%}$$

Where: abnormal, dead, and hard seed figures are percentages by number as determined in standard seed germination procedures.

The formula arises from an analysis of a seed's response when subjected to a mechanical action. There are four possible responses: (1) If the action is severe enough, seeds that otherwise would germinate normally may show abnormal germination or be killed (numerator of the formula will increase). (2) If the action is severe enough, hard seed may be caused to germinate normally or abnormally (denominator will decrease). (3) If the action is less severe, abnormal-germination-plus-dead-seed percentages may not change (numerator will be unchanged). (4) If the action is less severe, hard seed percentages may not change (denominator will be unchanged). Since the numerator must either increase or stay the same, and the denominator must decrease or stay the same, the calculated index number

then must increase or stay the same for seed lots subjected to a mechanical action.

The formula reveals several other things. The numerator actually is an expression of seed damage, so it follows that damage is a special form of severity as defined here and might logically be considered an extreme form. Also, a mechanical action that changes any of the three germination measures of the formula will increase the severity index number. The index number increase, then, can be the result of damage (if the numerator increases) or the result of hard seed reduction (if the denominator decreases), or both. The arbitrary figure 1 appears in numerator and denominator to provide positive numbers and a rational condition, mathematically, when the abnormal-germination-plus-dead-seed figure or hard seed content is zero.

The formula does not include a term for normal germination of seed because the result of a mechanical action cannot be predicted for this measure. (Normal germination can increase if hard seeds are caused to germinate normally, but it can decrease if normal seeds are killed or caused to germinate abnormally.) However, the formula senses any change in normal germination because such change must appear in the form of revised values for abnormal, dead, or hard seed.

As calculated by the formula, the severity index number will indicate any damage (numerator change) or any hard seed reduction (denominator change), or both. However, a limitation is that these changes must be due to a mechanical action.

The formula has an immediate application in rating the conveying trials of this study, but it also may have general value as a tool for evaluating severity in other seed-handling operations. Therefore, if the severity index number is computed for seed lots before and after exposure to various mechanical actions, a comparison of the index numbers will indicate relative severity of these actions whether or not seed has been damaged.

As applied to the conveying trials reported here, the severity index numbers should provide a means of comparing the dense-phase and lean-phase operations at severity levels less than those associated with seed damage. Such knowledge is considered valuable because damage potential varies according to kind of seed, moisture content, and conveying system. A comparative rating of dense- and lean-phase conveying trials under the low-damage conditions of these tests should help predict results at other conditions more conducive to seed damage.

Severity index numbers were calculated and are shown in table 5. All dense-phase values are less than lean-phase values, indicating that dense-phase conveying is less severe. In fact, most index numbers for dense-phase trials are only slightly greater than for the controls.

Also, as plotted in figure 14, severity index numbers tend to increase generally as seed velocity increases. Again, the line is dashed between the two conveying methods, indicating discontinuous data. This trend is less definite when the dense-phase grouping and the lean-phase grouping are considered alone. The highest index number for dense-phase conveying occurred when the flow pattern was very dense and the seed movement was lowest of all tests. Under these conditions, seed may suffer enough airlock injury to explain the higher figure. (Airlock effects supporting this thought are discussed later in connection with bean damage.)
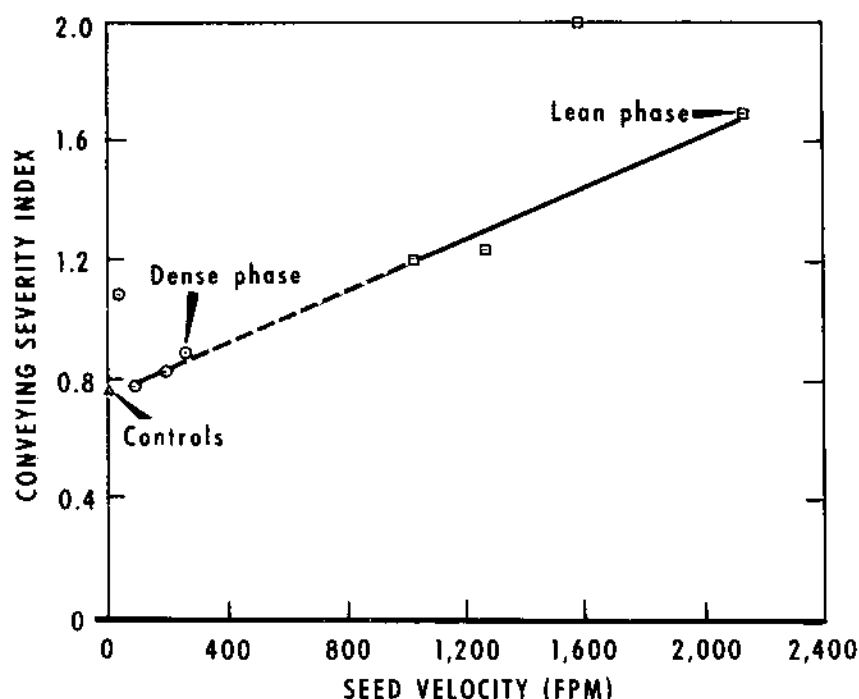
FIGURE 14.—Comparison of conveying severity for dense- and lean-phase conveying of crimson clover.   Each point is an average of 3 replications except controls, which is an average of 8.

The greatest index number for lean-phase conveying at 1,600 f.p.m. appears high, and no logical explanation for this is known.   If plotted, each of the three replicates for this condition would fall above the line as drawn.

A similar trend line would be obtained for these trials if only hard seed reduction was considered because little if any damage occurred (numerator change in the index formula).   However, hard seed reduction alone is not a complete index of severity since seed damage can occur without changing hard seed count.

The overall value of figure 14 is to suggest that conveying severity increases with seed velocity; and when a transport action is severe enough to cause damage, this effect can be reduced by lowering velocity.

Another evaluation of severity is presented in figure 15, which shows hard seed, normal germination, abnormal-germination-plus-dead seed, and severity index numbers for several groups of conveying trials. For comparison, the same measures are included for controls.

This plot compares dense-phase conveying, as a whole, with lean-phase conveying on both one-pass and three-pass bases.   The groups have been arranged, from left to right, in order of increasing index number and decreasing hard seed count.   The relative positions of groups resulting from this arrangement are interesting.   Controls show the lowest index number, dense-phase conveying is intermediate,

and lean-phase conveying shows the highest index numbers. Within the dense- and lean-phase classifications, index numbers are higher for each three-pass group than for the one-pass groups.

CRIMSON CLOVER
■ Hard seed (%)
▨ Germination, normal (%)
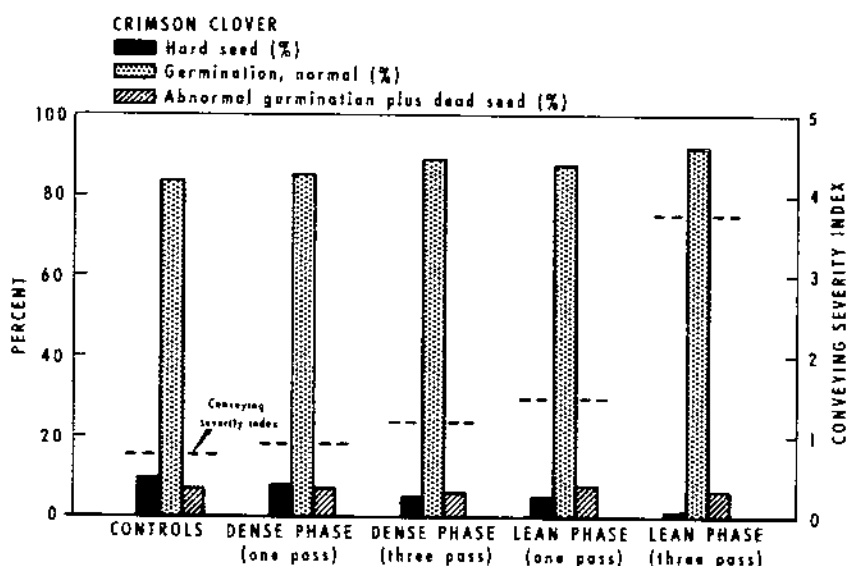▨ Abnormal germination plus dead seed (%)

Figure 15.—Seed germination and conveying severity in various trials in dense- and lean-phase conveying of crimson clover. Controls are averages of 8 determinations; one pass, 12 determinations; three pass, 2 determinations.

Figure 15 reveals that the increase in severity index number is mainly the result of progressive decrease in hard seed—this is so because abnormal-germination-plus-dead-seed values (damage) change very little. The drop in hard seed nearly equals the increase in normal germination. The normal germination bars could not increase much in these trials because there was relatively little hard seed in the original test lot. Conveying trials should be more informative with seed lots like lotus and dichondra, whose hard seed content may be 50 percent or more.

Since hard seed content decreased, as shown, to 1 percent at the conveying condition of maximum severity, it is interesting to speculate what might have happened if conveying conditions had been even more severe. A reasonable guess is that seeds otherwise germinating normally would have been killed or forced to germinate abnormally (seed damage). Continuing this hypothetical chain of events on the bar graph of figure 15, increasing conveying severity first would cause the black bars to decrease until nonexistent, while the dotted bars increased in like amounts. Then, when severity was great enough, the dotted bars would decrease, while the diagonal bars increased in like amount, showing the presence of seed damage. So, the optimum conveying for largest amount of normally germinating seed would be that condition whose severity was great enough to reduce hard seed content to zero, but not high enough to cause seed damage.

The main value of figure 15 is to rate the relative severity of different conveying trials by use of the index number, and to show that increasing severity can reduce hard seed content and thereby increase normal germination without damaging seed.

Extensive Conveying Studies With Beans

The lean-phase conveying described here has been characterized by air and seed velocities considerably greater than for dense-phase conveying. As a result, seed damage would appear more likely in lean-phase conveying. However, a good comparison of damage differences between the two methods in one physical system proved difficult to obtain. Crimson clover was not damaged in dense-phase conveying, but neither was it damaged in companion lean-phase trials (fig. 13). However, when conveying trials were rated according to their severity, dense-phase trials appeared less severe (figs. 14 and 15).

In another attempt to obtain a damage comparison, conveying trials were conducted with beans because of their damage susceptibility. Small beans were chosen as a test lot to facilitate passing through the airlock used, but this size probably provided a relatively strong bean. When thrown against concrete, the test beans did not break as readily as did larger types. A second reason for conveying beans was to evaluate airlock breakage with a larger product than crimson clover, which had shown no breakage.

Dense-phase trials with beans were carried out at one arbitrarily selected operating level, and lean-phase trials were conducted at five levels, including the condition of greatest seed velocity possible with the USDA experimental system. Dense-phase results are discussed later. Lean-phase results are summarized in table 6 and are plotted in figure 16, where all curves are relative damage measures of a sort. The breakage curve indicates damage that is extensive enough to be visible readily; the abnormal-germination-plus-dead-seed curve reflects damage present in the seed lots but not necessarily visible; and the normal-germination-plus-hard-seed curve is a measure of potentially good seed that apparently is undamaged physiologically. Each

TABLE 6.—*Seed damage and breakage in lean-phase conveying tests with beans* [1]

Test condition	Seed velocity	Normal germination	Hard seed	Abnormal germination	Dead seed	Visible breakage [2]
	Feet per minute	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Lean-phase_____	2, 265	73. 5	1. 0	22. 5	3. 0	1. 62
	1, 660	82. 7	. 5	15. 5	1. 3	. 70
	1, 445	83. 5	. 3	15. 0	1. 2	. 59
	960	89. 7	1. 2	7. 8	1. 3	. 49
	650	91. 0	. 5	7. 0	1. 5	. 40
Controls_____	_____	93. 4	. 4	4. 0	2. 2	_____

[1] Average of 2 replications with California small white navy beans for lean-phase trials, and 4 for controls.
[2] Percentage by weight of beans showing absence of some part of cotyledon when viewed without magnification.

curve shows the same type of trend—that increased velocity is related to greater seed damage.

It is entirely reasonable that the normal-germination-plus-hard-seed curve should fall off, as indicated, in the same amount that the abnormal-germination-plus-dead-seed curve increases because, together, the curve ordinate values must equal 100 percent.
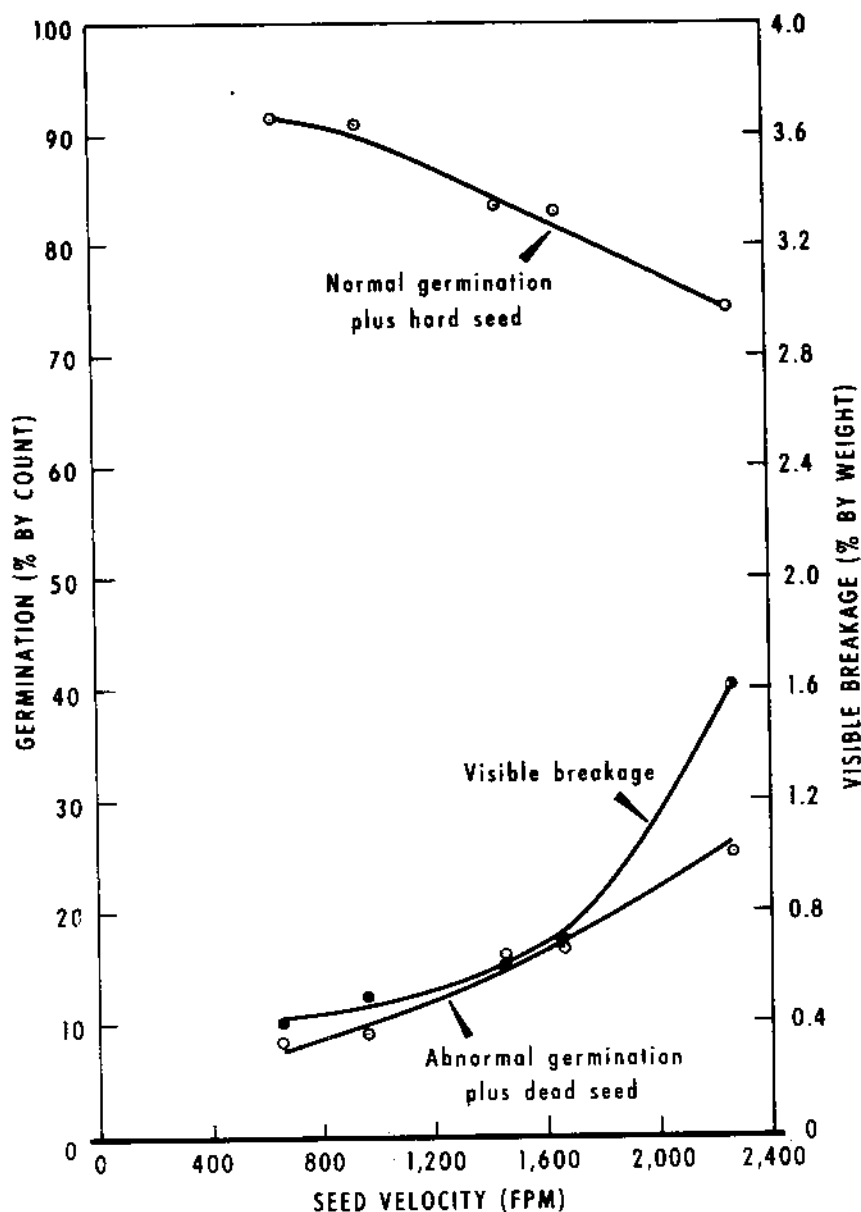

FIGURE 16.—Effect of seed velocity on seed damage in lean-phase conveying of dry beans (California small white). Each point is an average of 2 replications.

Capacities for each lean-phase test in this damage study were kept low purposely to make best use of the limited amount of uniform, high-quality test sample and to insure high seed velocity when desired. Lean-phase capacities, held as nearly constant as possible using a vibrator feeder, were 245 (±15) grams per minute, and dense-phase capacities were about 24 pounds per minute.

Breakage, as it is considered here, includes beans that show any part of a cotyledon missing when inspected without magnification. This means that reported breakage values tend to be slightly greater than would be determined by standard purity procedures in seed-testing laboratories, which stipulate that a seed portion representing more than half of the original unit must be considered a whole seed. The particular basis selected for this test appeared to offer a more exact measurement of actual seed breakage. After the amount of breakage was determined, broken beans larger than half of the original unit were returned to the test samples so that standard selection and germination procedures could be carried out.

In any event, breakage values were relatively low, as indicated in figure 16, with four out of five tests showing 0.70 percent or less. Samples analyzed for breakage were relatively small (about 70 grams), so sampling error is a possible limitation in interpreting the breakage results. However, the deviation between replications was very small, and the original test material showed a low initial breakage figure, implying a test lot of uniform initial breakage. The breakage curve is mainly important not for its specific values but because it shows generally low figures and that breakage tends to increase with seed velocity.

Actually, breakage figures for beans are made up of three components: initial (present in test lot as received); airlock (induced in passage through airlock); and transport (attributed to the actual conveying). Of these components, initial is common to the stock used for all trials, so any differences in total breakage figures for dense-phase and lean-phase conveying must be assigned to airlock plus transport effects.

An analysis of breakage components appears in table 7. The total breakage value for dense-phase conveying is 1.55 percent (two replications at one test condition), as compared to lean-phase values ranging from 0.40 to 1.62 percent. Although total breakage for dense-phase conveying thus appears to equal the highest values for lean-phase conveying, a substantial amount of this breakage is airlock effect, as shown in table 7. Airlock effect in dense-phase is greater (about four times) than in lean-phase. In dense-phase conveying, each compartment of the airlock tends to operate with a nearly full load but to discharge only a small part of this load in any one revolution. As a result, some seeds are tumbled many times at or near the shearing edges of the airlock. In addition, the lower air-seed velocities of dense-phase conveying keep the seed at the shearing edges longer as seeds move from the airlock to the pipe. Both actions provide more opportunity in dense-phase transport for seed to be caught between rotor and housing of the airlock and thus be sheared or crushed.

If airlock effects are discounted, the remaining breakage (that can be attributed to transport) ranges from 0.13 to 1.35 percent for the lean-phase velocities shown in figure 16. On the same basis, dense-

TABLE 7.—*Seed breakage in dense-phase and lean-phase conveying tests with beans* [1]

Breakage due to—	Dense-phase conveying	Lean-phase conveying
	Percent	*Percent*
Airlock	1. 03	0. 27
Transport	. 52	. 13–1. 35
Total	1. 55	. 40–1. 62

[1] Average of 2 replications with California small white navy beans. Values are percentage by weight of beans showing absence of some part of cotyledon when viewed without magnification and include some initial breakage.

phase breakage was 0.52 percent. Generally speaking, breakage was relatively low in all trials. Where airlock action might be a serious consideration, it can be minimized by using an airlock equipped with flexible wiper strips at the blade edges and by installing another flexible strip at the airlock feed to level each compartment load below the shearing point of the lock housing and thereby reduce shearing of seed.

A similar breakdown on abnormal-germination-plus-dead-seed figures for dense- and lean-phase conveying also indicates greater airlock effects for dense-phase conveying. A total figure of 10 percent was determined for abnormal-germination-plus-dead seed in dense-phase conveying to compare with the lean-phase values shown in figure 16. When transport effects again are considered, the value for dense-phase conveying becomes 2.5 percent as compared to a range for lean-phase of 3.2 to 20.2 percent.

With reference to normal-germination-plus-hard seed, a total figure of 90 percent was determined for dense-phase conveying which compares favorably with the range for lean-phase flow of 74.5 to 91.5 percent shown in figure 16.

In analyzing velocity–damage relations, it is possible to relate the measured bean velocities shown in figure 16 to impact velocities that might be calculated for drop trials. For example, if beans had been included in the preliminary drop tests (12-foot height) described earlier, the impact velocity would have been:

where: $v = \sqrt{2gh}$ (neglecting air resistance)
v = impact velocity, in feet per second
h = drop height, in feet
g = acceleration of gravity, in feet per second^2

Then: $v = \sqrt{2(32.2)12}$
$= \sqrt{772.8}$
$= 27.8$ f.p.s. or 1,668 f.p.m.

As shown in figure 16, a velocity of 1,668 f.p.m., equivalent to a 12-foot drop, would lower normal-germination-plus-hard seed to about 82 percent. For general interest, it is also possible to calculate drop heights with impact velocities that equal the range of seed velocities shown in figure 16 for lean-phase conveying. With the

same velocity formula as above, only solving now for "h" in a velocity range of 650 to 2,265 f.p.m. (10.8 to 37.8 f.p.s.) :

$$h = \frac{v^2}{2\,g}$$

$$= \frac{(10.8)^2 \text{ to } (37.8)^2}{2(32.2)}$$

$$= \frac{116.6 \text{ to } 1,428.8}{64.4}$$

$$= 1.8 \text{ to } 22.2 \text{ ft.}$$

In comparison, the drop-height equivalent for dense-phase conveying (at an average velocity of 161 f.p.m.) is 0.1 foot.

The main value of figure 16 is to show that seed damage (abnormal-germination-plus-dead seed) increases as seed velocity increases in lean-phase conveying and that visible breakage also increases with velocity, but that actual breakage values are relatively low in all cases. Also, a comparison of the lean-phase values as given in figure 16 with dense-phase values shows that all damage measures for dense-phase conveying either are lower than for lean-phase or are near the low end of the range shown for lean-phase conveying.

CONCLUSIONS

Preliminary fluidizing trials, dense-phase and lean-phase conveying tests with crimson clover, and seed damage studies with crimson clover and beans warrant the following conclusions:

1. Small legume seeds like the clovers and alfalfa can be fluidized but not as effectively as powders.

2. A pneumatic conveyor for seeds was developed that shows characteristics of fluidized conveying—namely, low seed velocity, high seed-air ratio, and a flowing seed mass that has a large degree of mobility or fluidity.

3. Flow pattern in dense-phase conveying consists of aerated slugs of seed that form, move, dissipate, and re-form throughout the pipe run.

4. Ordinary principles of fluid flow are not entirely applicable to dense-phase operation because fluidity of the seed slug places it in a classification between true fluid flow and movement of a solid.

5. Dense-phase operation departs from usual concepts of pneumatic conveying in that pressures and power requirements drop as conveying capacity increases.

6. Flow pattern in lean-phase conveying involves a high-velocity seed movement typical of ordinary pneumatic transport.

7. Lean-phase conveying was found to conform generally to laws of fluid friction inasmuch as pressure drop increased as conveying capacity increased, which suggests that variable seed-air ratios change viscosity makeup of flowing seed-air mixtures.

8. Auxiliary airflow bypassing the air lock has proved very important in dense-phase conveying since it lowers operating pressures, reduces power requirements, and facilitates feeding of seed to the system.

9. In all dense-phase operations, auxiliary airflow represented 70 percent or more of the total conveying air.

10. Greatest seed velocities observed in dense-phase conveying were 250 f.p.m., and in lean-phase conveying, 2,125 f.p.m.

11. In lean-phase flow, the air-velocity range used for transport was 3,250 to 4,400 f.p.m., and seed velocities ranged from 31 to 48 percent of the air velocities.

12. Greatest solid-air ratio of the study was 28:1 dense-phase conveying.

13. In both dense- and lean-phase conveying, power requirements increased linearly with air pressure for the capacities and auxiliary air rates studied.

14. Conveying 1,700 pounds per hour in the dense phase required about 3½ horsepower per ton per hour; the same capacity in the lean phase required about 2½ horsepower per ton per hour.

15. Certain legumes dropped from a 12-foot height upon metal and concrete surfaces showed the same germination as undropped control lots after 5 years' storage.

16. The following formula was devised to rate severity of conveying trials in this study and may have general value as a research tool to evaluate severity in other seed-handling operations whether or not damage, as such, occurs:

$$\text{Severity index} = \frac{1 + (\text{Abnormal germination} + \text{Dead seed})\%}{1 + (\text{Hard seed})\%}$$

17. No difference was found in damage measures of dense- or lean-phase operation and controls (not conveyed) for crimson clover, but severity for dense-phase was less than for lean-phase conveying and only slightly greater than for controls.

18. All crimson clover transported in dense- and lean-phase conveying showed greater normal germination than controls because of reduction in hard seed content. However, total germination (normal-plus-hard seed) remained the same in all trials.

19. Optimum conveying for the largest amount of normally germinating seed would be that condition where severity is great enough to reduce hard seed content to zero but not great enough to cause seed damage.

20. Damage in beans transported in lean-phase conveying increased as seed velocity increased, but total breakage was relatively low in all cases.

21. All damage measures for dense-phase transport of beans either are lower than or near the minimum values of the range found for lean-phase transport.

22. Dense-phase conveying was unsuited for seeds that bridge easily, like large grass seeds, and material of varying particle size, like ground feed. However, such products are handled readily in this system by lean-phase operation.

23. Finally, fluidized or dense-phase transport of seed as described here is entirely feasible as a means of conveying free-flowing seeds at

low velocity without damage through flexible, small-pipe systems in ample quantity to supply processing machines.

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