PARTICLE SEPARATION IN A PNEUMATIC CONVEYING SYSTEM

By

RICHARD WILBUR WHITNEY

Bachelor of Science

Kansas State University

Manhattan, Kansas

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CONVEYING SYSTEM

THESIS APPROVED:

Jay G Porterfield
Thesis Adviser

Lawrence O. Roth

N N Durham
Dean of the Graduate College

PREFACE

The work reported in this study was conducted under Project S-1130 of the Oklahoma Agricultural Experiment Station, "Mechanization for the Harvesting and Production of Horticultural Crops". The major purpose for this study was to evaluate and predict the effectiveness of an in-line pneumatic separator equipped with an energy dissipating backstop for use with agricultural and related materials.

I am especially grateful to Professor Jay G. Porterfield, who served not only as my thesis adviser, but also as a source of encouragement and guidance.

I wish to thank Professor E. W. Schroeder, Head of the Agricultural Engineering Department, and Associate Professor Larry O. Roth who served on the advisory committee. I especially thank Dr. Roth for his assistance and advice concerning photographic procedures employed in this study.

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CHAPTER I

INTRODUCTION

Pneumatic conveying systems are capable of transporting materials with various physical characteristics. The conveyed material can consist of a combination of particles which are to be separated into various fractions. Generally, the separation of certain fractions from the conveyed mass involves the withdrawal of material from the air stream, the separation into fractions, and the re-entry into the air stream of those fractions which are to continue in transport. This procedure results in a loss of energy in deceleration and acceleration of the material, as well as involving mechanisms for withdrawal, re-entry, and separation. This study is to examine a separation device which does not require withdrawal to effect separation.

Statement of Problem

It was the purpose of this study to investigate the effect of various energy dissipating materials in an in-line separator of the aspirating column type and to mathematically predict the percent of a given fraction of particles separated in terms of the system parameters.

Objectives

The objectives of this study were to:

1. Establish relationships among system parameters, particle

aerodynamic characteristics, and percent particle separation for an in-line separator.

2. Develop equations for predicting the number of particles separated as percent of total.
3. Evaluate the effect on performance of the separation system of various energy dissipating backstops within the separator.
4. Extend the use of the prediction equation to include separation of agricultural materials under continued mass flow.

The first three objectives were achieved in Part One. Part Two involved the evaluation of the system operating with continued mass flow.

Limitations

1. Four sizes of separation chambers and inlet pipes were used.
2. Spherical plastic balls were used as test particles for Part One. Eleven sizes from one-eighth to seven-eighths inch in diameter were used.
3. Twelve air flow rates were used. They varied from 8.0 to 26.1 cubic feet per second.
4. Particle density varied from 52.3 to 134.5 pounds per cubic foot. Seven densities were investigated.
5. Mass feed rates varied from 0.0197 to 0.732 pounds per second. Eight feed rates were used.
6. Barometric pressure, air temperature, and relative humidity were not controlled during the tests.
7. Three grains, soybeans, wheat, and sorghum, were used in Part Two.

8. Two separator inlet sizes, two separator chamber sizes, two air flow rates, and one backstop were used in Part Two.
9. The angle of the inlet tube was held constant at 70° with the vertical.

CHAPTER II

REVIEW OF LITERATURE

A particle, introduced into a fluid stream, is acted on by a drag force which depends on the physical characteristics of the particle, the fluid properties, and the relative velocity between the particle and moving fluid. Separation is effected when the drag force is sufficient to translocate some particles away from others which have drag forces of lesser magnitude or which are heavier in weight.

Leniger (1) states that the behavior of spherical particles of up to 100 microns in air, and up to slightly more than 100 microns in water can be predicted by Stokes' Law. According to Stokes' Law, the rate of movement of a particle in a static fluid is proportional to the square of the particle diameter and inversely proportional to the viscosity of the fluid. This is true if a laminar flow is assumed to exist and that resistance is due only to friction of the fluid on the particle. A transition range exists where the Reynolds Number of the particle is between one and one thousand. Both frictional- and shape-resistance exists for free falling particles of up to 2.5 mm in air and up to 4 mm in water within the transition range. Above these sizes, the resistance factor of 0.43 holds and the rates of fall can be calculated by Newton's Law. Newton's Law implies that the rate of fall is proportional to the square root of the diameter and independent of viscosity. It is assumed that turbulence exists and the resistance due to friction is insignificant while that due to shape is significant. In most cases the transition range occurs at some location within the separator which means that neither Stokes' Law nor Newton's Law can completely describe what occurs within the separator. The drag coefficient depends upon the Reynolds Number and Reynolds Number likewise depends upon the unknown relative velocity.

Lapple and Shepherd (2) reported a relationship between the Reynolds Number and the drag coefficient. The equations presented are:

$$V = (Re) \times (U)/(D \times G) = (2g^2M\ (Gp - G)/(C\ A\ Gp\ G))^{1/2} \quad (2.1)$$

and

$$C\ Re^2 = (2gWD^2G\ (Gp-G))/(U^2A\ Gp). \quad (2.2)$$

where

V = relative velocity   M = particle mass

C = drag coefficient

Re = Reynolds Number

g = gravitational acceleration

W = particle weight

D = average particle diameter

G = fluid specific weight

Gp = particle specific weight

U = viscosity of fluid

A = particle projected area

From Equation 2.2, CRe^2 is calculated and a plot of CRe^2 versus Re for a specific particle shape is used to obtain steady state values for C. For a changing velocity, only incremental solutions of 2.1 can be used.

Wadell (3,4) derived a relationship from existing data on spheres between Reynolds Number and drag coefficient C. It was found that the relationship ($C^{1/2} = 0.63 + 4.8/Re^{1/2}$) fits the curve closely for all values of Reynolds Number.

Methods for Determining Equivalent Diameters of Irregular Shaped Particles

Most investigators dealing with drag coefficients have used some specific value for particle diameter. The diameter of an irregularly shaped object, however, presents some difficulty.

Dallavalle (5) states that any irregular shaped particle can be equated to a suitable regular shape. Two methods which he gives are the volume-displacement method, and the use of Newton's or Stokes' Laws. For the displacement method, the volume is determined by displacement and this volume is equated to the volume of a hypothetical sphere having an equivalent diameter. The nominal diameter is given by the relationship ($Dn = (6 \times \text{volume of particle})^{1/3}$).

Using either Stokes' Law or Newton's Law, depending upon the size of particle, the time required for the particle to fall past two fixed points in a particular medium is observed. From this the average velocity may be determined. Since either law relates the diameter of the particle to its velocity in any given medium, the equivalent diameter can be obtained.

Wadell (6) developed a measurement termed degree of circularity ¢.

$$¢ = C'/C$$

C' is the circumference of a circle having the same cross-sectional area as the particle (a camera-lucida image), and C is the actual perimeter of the cross section. It was shown that when movement of irregular shapes through a fluid medium is considered, the degree of circularity of these figures can be correlated with resistance to flow and Reynolds Number.

Houston (7) presented a method of estimating the volume of a particle which could be used to determine the equivalent diameter. A value termed the criterion area was correlated with the actual volume of the particle. The criterion area is defined as the arithmetic average of the projected areas taken along three mutually perpendicular axes. The particle was allowed to assume a natural rest position on a horizontal plane with the viewing axes forming an angle of 35 degrees 16 minutes with the horizontal plane. Measurements were made using potatoes, lemons, and carrots. A relationship for the criterion area Ac and volume was then derived.

$$Ac = KV^{2/3}$$

K is a dimensionless constant related to the typical shape of the body. The value of K for the various objects was:

Lemons - 1.24

Potatoes - 1.38

Carrots - 1.76

The associated probable error in volume for each was found to be 3.7 percent, 8.3 percent, and 6.5 percent, respectively.

Factors Relative to the Quality of Separation

Wessel (8) states that an ideal separation of 100 percent selectivity is present whenever all granule parts smaller than the desired dividing particle are present in the fine fraction and all granule parts larger than the dividing particle are in the coarse fraction. This ideal separation is not attainable by any pneumatic classifying system, however. The so-called Tromp Curve is sometimes employed for the description of system performance and for determining which particles will be separated. The probabilities of separating given classes are determined and these are plotted (Figure 1) against fluid velocity. An estimate of the percents of the various classes within the separated mixture can be made from the Tromp Curve which is approximated by a straight line passing through 0 percent and 100 percent selectivity. The slope of the Tromp Curve is a graduator relating to the selectivity of a separation system.

A curve similar to the probability curves of Figure 1 is obtained when percent of particles lifted by an air stream is plotted against air velocity for a given class of particles. Brown and Reed (9) made tests to determine the air velocity required to lift oats, wheat, and corn. The grain was distributed in a single layer on a screen at the inlet of a vertical duct. Figure 2 shows the results of their study. The materials began to be lifted at the following velocities: For oats, 685 feet per minute; for wheat, 986 feet per minute; and, for corn, 1070 feet per minute. Complete movement of the grains occurred at 1050, 1300, and 2000 feet per minute, respectively.

Wessel (8) has presented the following as the most important factors governing the fineness of classification by gravity sifting:

1. The Reynolds Number as defined by a combination of the physical characteristics, both of the particle and the air system. A limited fluctuation of particle size

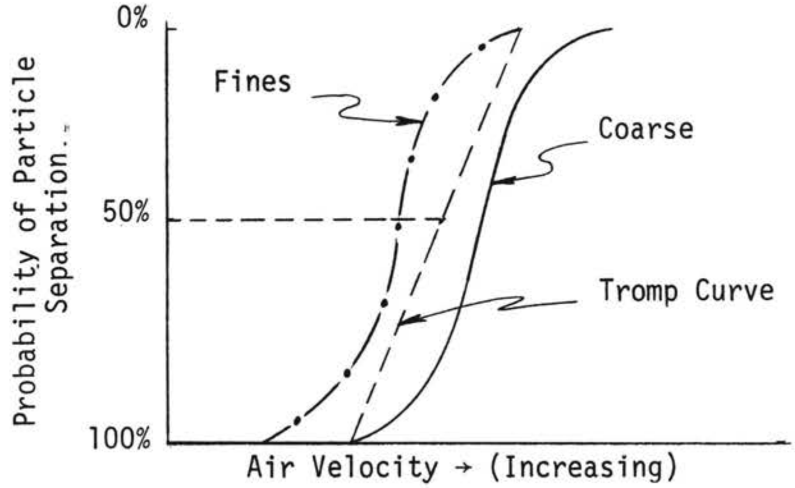

Figure 1. Probability of Particle Separation Versus Air Velocity for Two Classes of Particles Showing The Tromp Curve

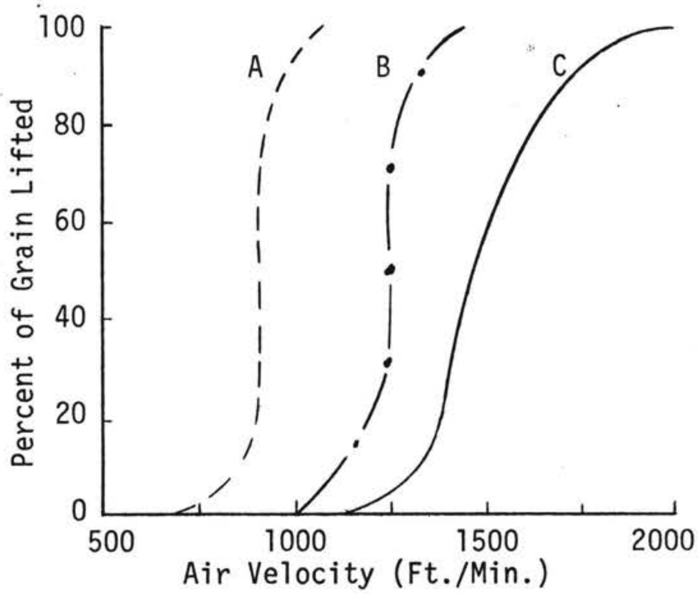

Figure 2. Percent of Grain Lifted Versus Air Velocity (Ft./Min.) for Oats (A), Wheat (B), and Corn (C)

produces a considerable change in terminal velocity for the Stokes Region (Figure 3). Much less fluctuation in terminal velocity is effected by particle size variation in the Newtonian Range where velocity is proportional to the square root of the diameter.

2. Air flow behavior. Turbulence produces random particle movement within a separator which results in less than ideal separation. Wall effects and required air velocities which are high enough for particle conveyance insure turbulent conditions for most separators.
3. The length of time which the particles are in the separation zone.
4. The rate of dispersion of the material immediately upon entering the separation zone.
5. The concentration of particles in the separation zone.

Physical Configurations of Pneumatic Separators

Leniger (1) has assembled diagrams of various types of separators which include diverse principles and methods of pneumatic separation.

Figure 4 shows a method of winnowing. A controlled flow of material is introduced at some point above a continuous uniform flow of air. As the air acts upon the material during free fall, a gradation from light to heavy is produced. The fractions are collected along the lower portion of the air duct.

When air passes through a thin layer of falling material as shown in Figure 5, the inertia of the particles plays an important role. Operation of this type of pneumatic separator depends upon the time

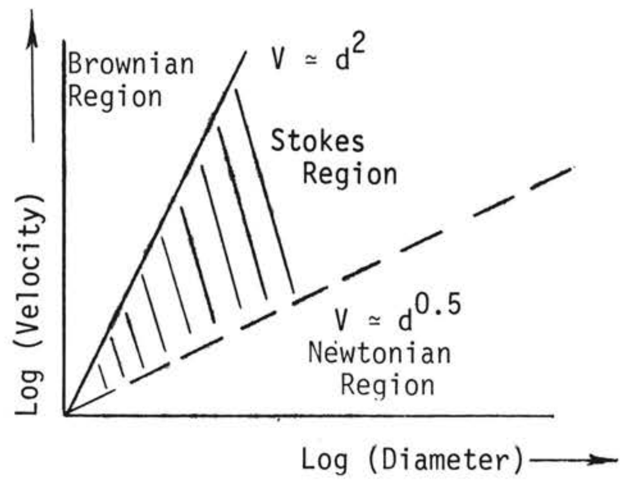

Figure 3. Plot of Particle Relative Velocity Versus Particle Diameter Showing The Stokes and Newtonian Regions

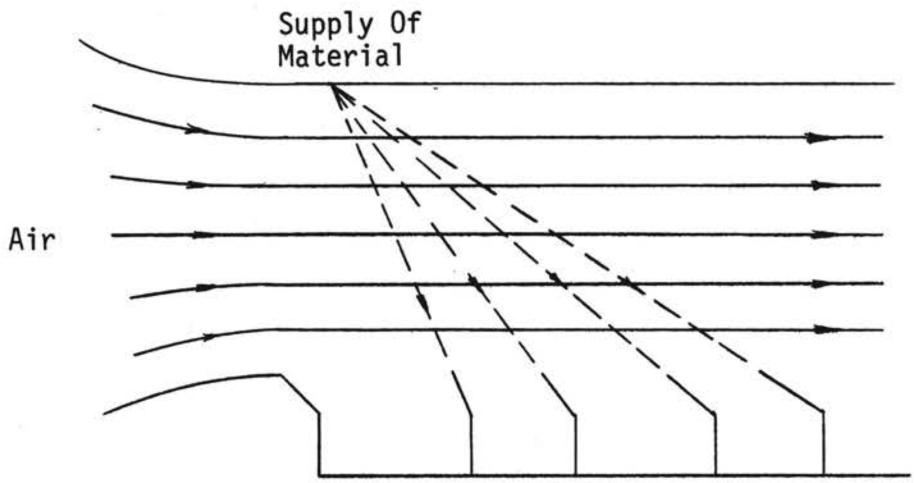

Figure 4. Classification by Means of a Uniform Horizontal Air Flow

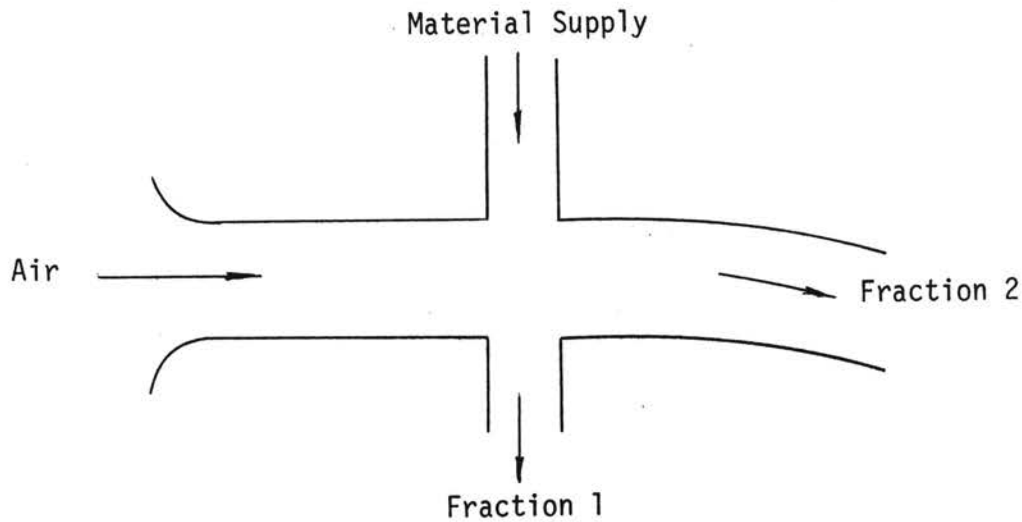

Figure 5. Classification by Means of Passing Air Through a Falling Thin Layer of Material

of fall of the particles in the air stream. The lighter particles end up as Fraction 2, the heavier particles, as Fraction 1.

Figure 6 shows an apparatus in which material is introduced into a rising column of air. The air carries the fine particles (Fraction 2) over the top as the coarse particles (Fraction 1) drop to the collector below. As in the apparatus of Figure 5, difficulty arises in obtaining uniform air flow.

The separators in Figures 7 and 8 are basically different from those shown in Figures 4 through 6. The separators heretofore mentioned have not used centrifugal force as an aid to separation whereas those of Figures 7 and 8 do. Such separators are used for particles of small diameters.

Leniger (1) states that the air and material flow is so complicated in a cyclone separator that a sharp separation (defined by selectivity previously) cannot be accomplished. Variations in cyclone separator design (Figure 7) are, therefore, used to overcome this characteristic. Material is fed onto a rotating disc which distributes the particles by centrifugal force into an air stream produced by the ventilating fan. Coarse particles fall into the inside bin while lighter particles are carried through the ventilator and are deposited into the outer container.

Figure 8 shows a device in which particles are introduced tangentially into a two-dimensional spiral air current in a flat, cylindrical box. Coarse particles are removed at the periphery as fine ones are carried out with the air. Two forces influence the path of the particles. K_1 is proportional to the square of the tangential component of the air velocity and to the mass of the

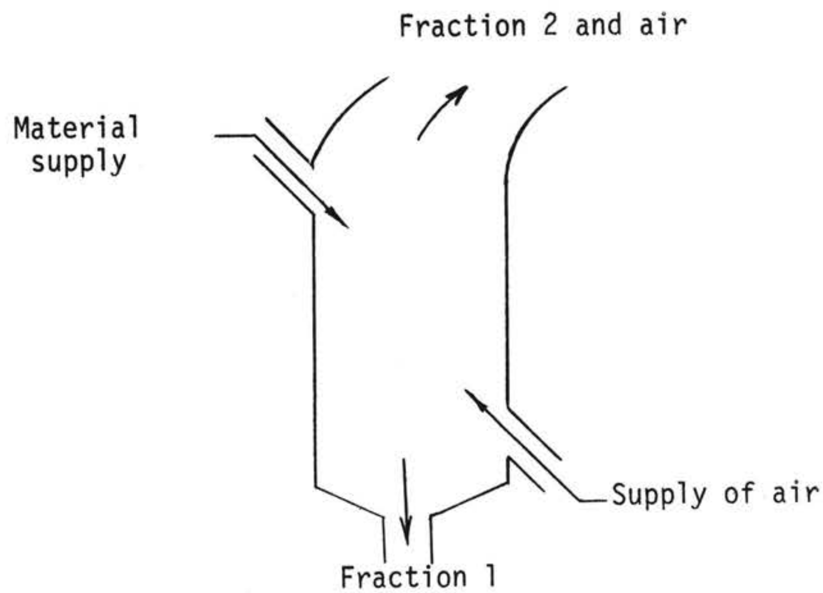

Figure 6. Classification into Two Fractions by Means of Dropping Material Through A Rising Air Column

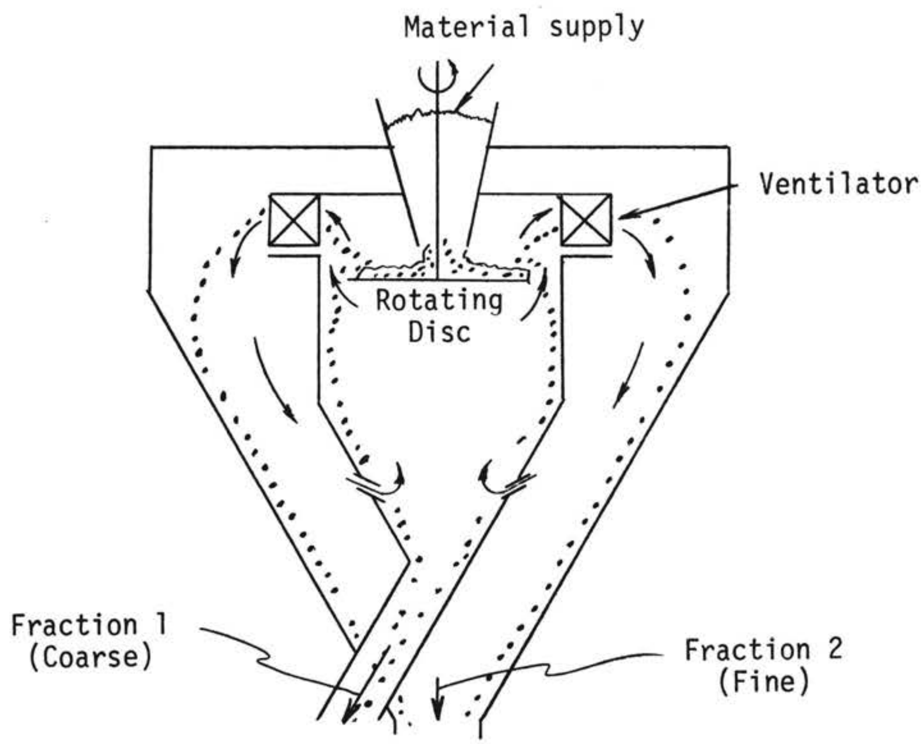

Figure 7. Separation by Means of a Rotating Disc and Ventilator

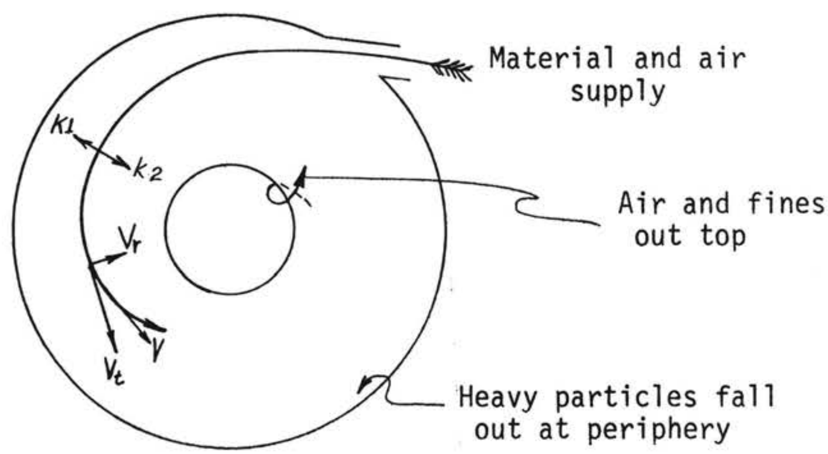

Figure 8. Separation by Means of a Spiral Air Current in a Flat Cylindrical Box

particle. K_2 is proportional to the diameter of the particle and to the radial component of the air current. Particles with a greater rate of fall move radially outward while particles with a lower rate of fall move inward.

Another type of pneumatic separation is that of collision which depends upon particle inertia. When the direction of the air current is suddenly changed, such as by placing obstacles in the air path, a portion of the conveyed mass will collide with these obstacles and be deposited on them. Figure 9 shows various types of apparatus used for collision separation. Particles up to 50 microns can be removed from the air stream with flow rates up to 20 meters per second (1). A disadvantage of this type separator is high head loss; however, collision separators can be used as in-line separators, thus avoiding the necessity of removing the non-separated fraction.

Van Der Kolk (10), reporting on separation of dust from gas, describes a modified cyclone which has two instead of three dimensional flow (Figure 10). The air dust mixture is introduced tangentially through a bend just ahead of the separation chamber. The bend causes a nearly clean air current to form along the outer wall at A. Centrifugal force of the coarse particles cuases them to move to the outside at B and be deposited as Fraction 1. The lighter material is carried into the tighter spiral and out the exit at C as Fraction 2.

Slaymaker (11) describes a gravity table, so called for its separation principle. Particles of varying density are fed over a porous table through which air is blown. An air velocity great enough to cause floatation of portions of the particles is used. The tendency is for stratification to occur with the heaviest particles near the

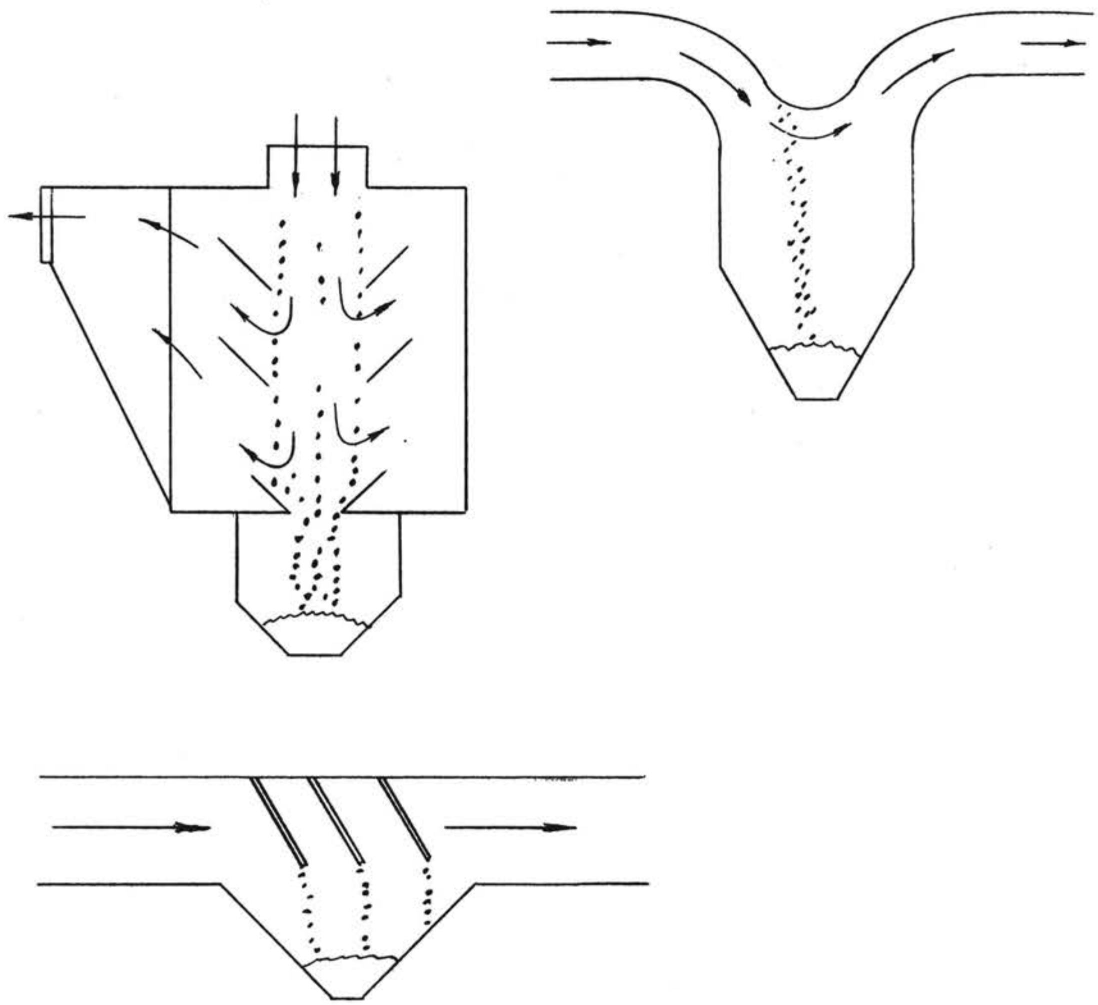

Figure 9. Diagrams of Apparatus for Separation of Particles by Collision

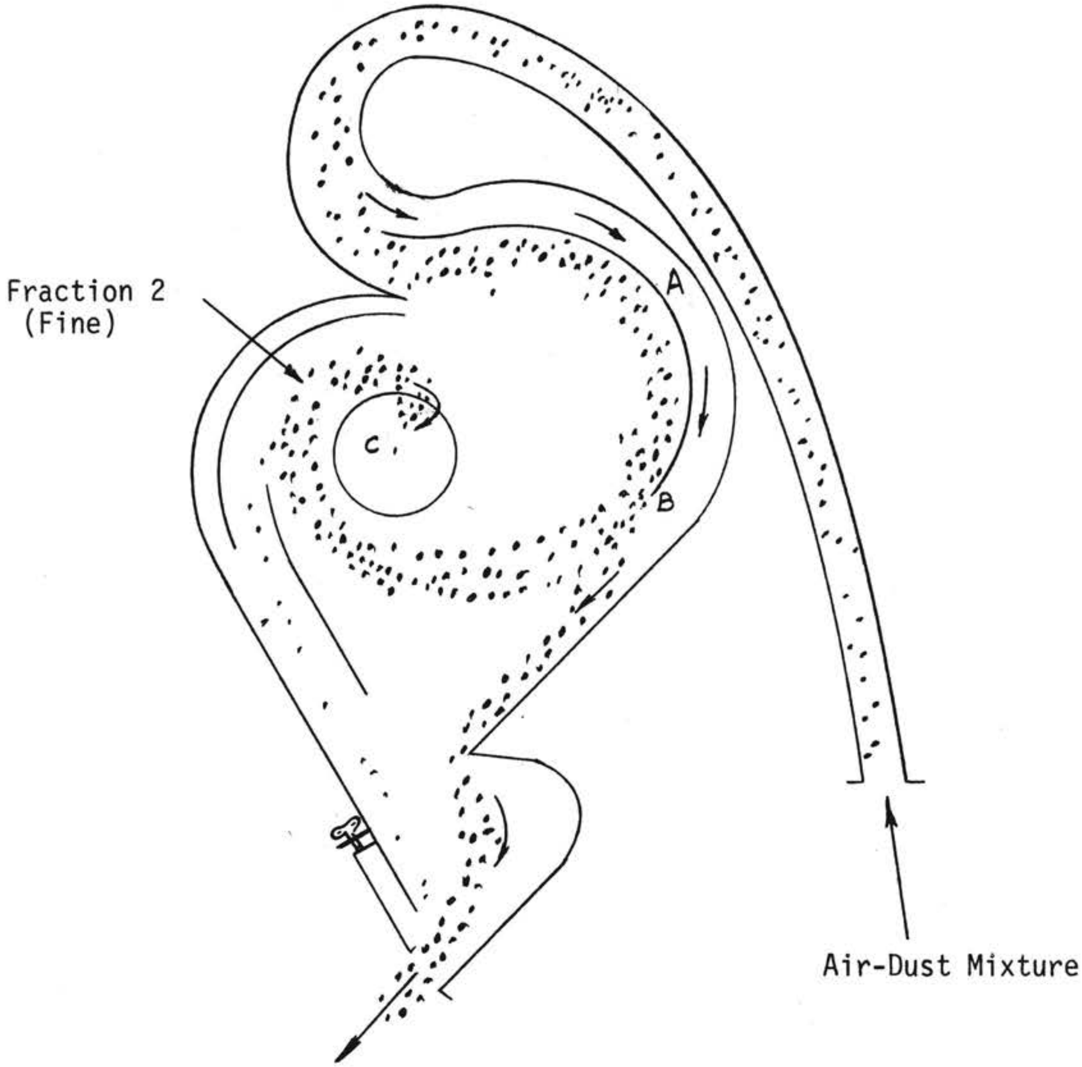

Figure 10. Cyclone Sifter in Which the Main Flow Follows a Flat Spiral Inwards

bottom. When the table is oscillated properly, the heavy stock will climb the conveyor before the light stock thus grading the particles from light to heavy along the table.

Experimental and Commercial Pneumatic Separators

The basic concept of separation by terminal velocities has been developed and used by various manufacturers of separation equipment. One example is a separator produced by the Superior Separator Company (12). This company makes a separator (Figure 11) in which material is introduced mechanically into an inclined chamber. The construction of the chamber is such that the cross-sectional area increases in the upward direction. As the material enters, air is passed upward through the separator. Slits are provided along the lower side of the sloping chamber so that as material reaches its respective terminal velocity and drops to the lower side, it falls through the slits into receiving bins.

Kirk and Hudspeth (13) designed and built a vertical air duct, 12 inches by 14 inches in area and 30 inches high (Figure 12), which was used as a separation chamber. A fan, capable of producing up to 2500 feet per minute air velocity through the chamber, was located at the bottom of the duct. As green bolls and cotton were fed into the chamber at the top by a mechanical feeder, the green bolls fell to the bottom while the cotton was carried by the air stream up and out of the chamber.

Harmon (14) describes the separator shown in Figure 13. As material is fed into the chute, the light seed, splits, broken seed,

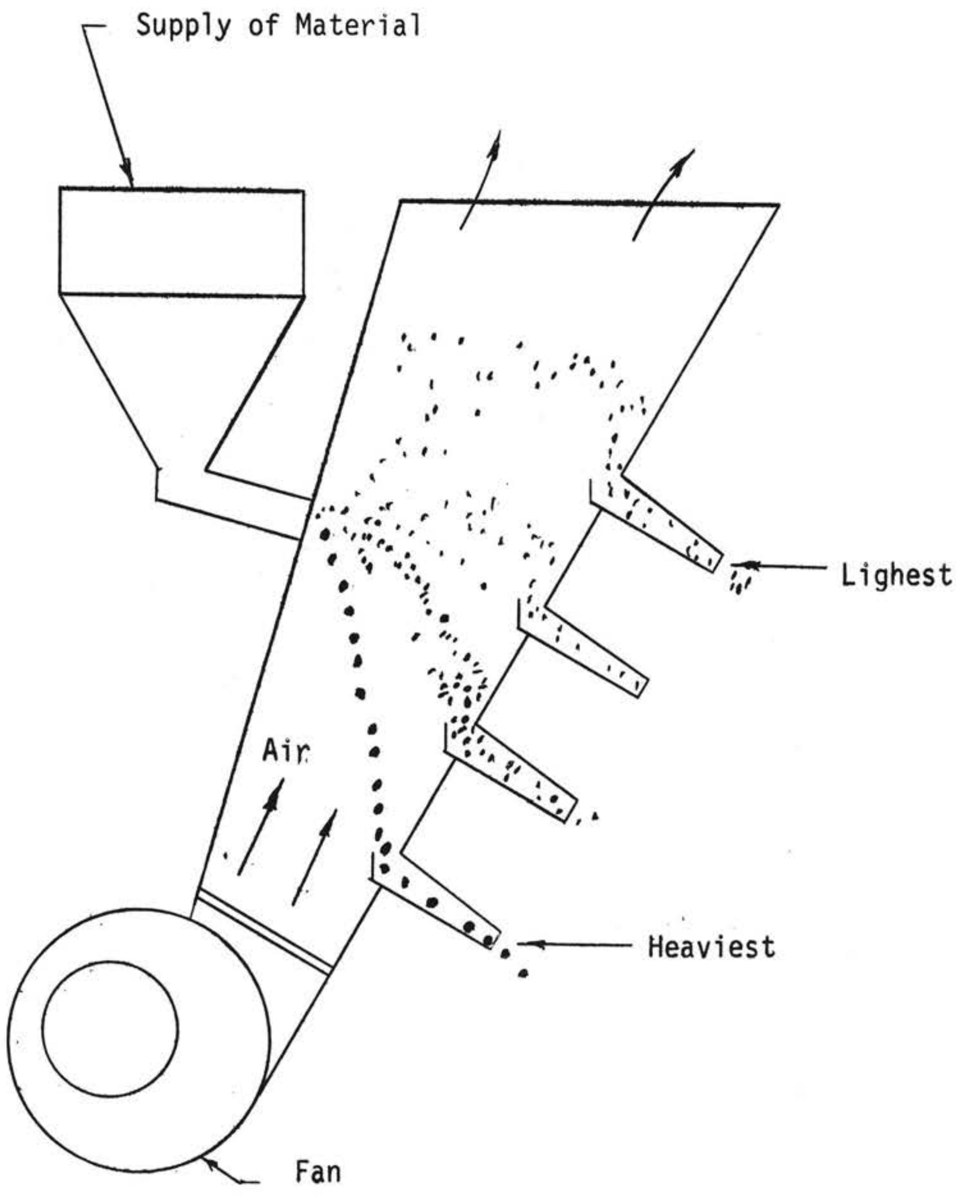

Figure 11. Schematic Diagram of a Separator Which Classifies by Means of Terminal Velocity (Superior Separator Company)

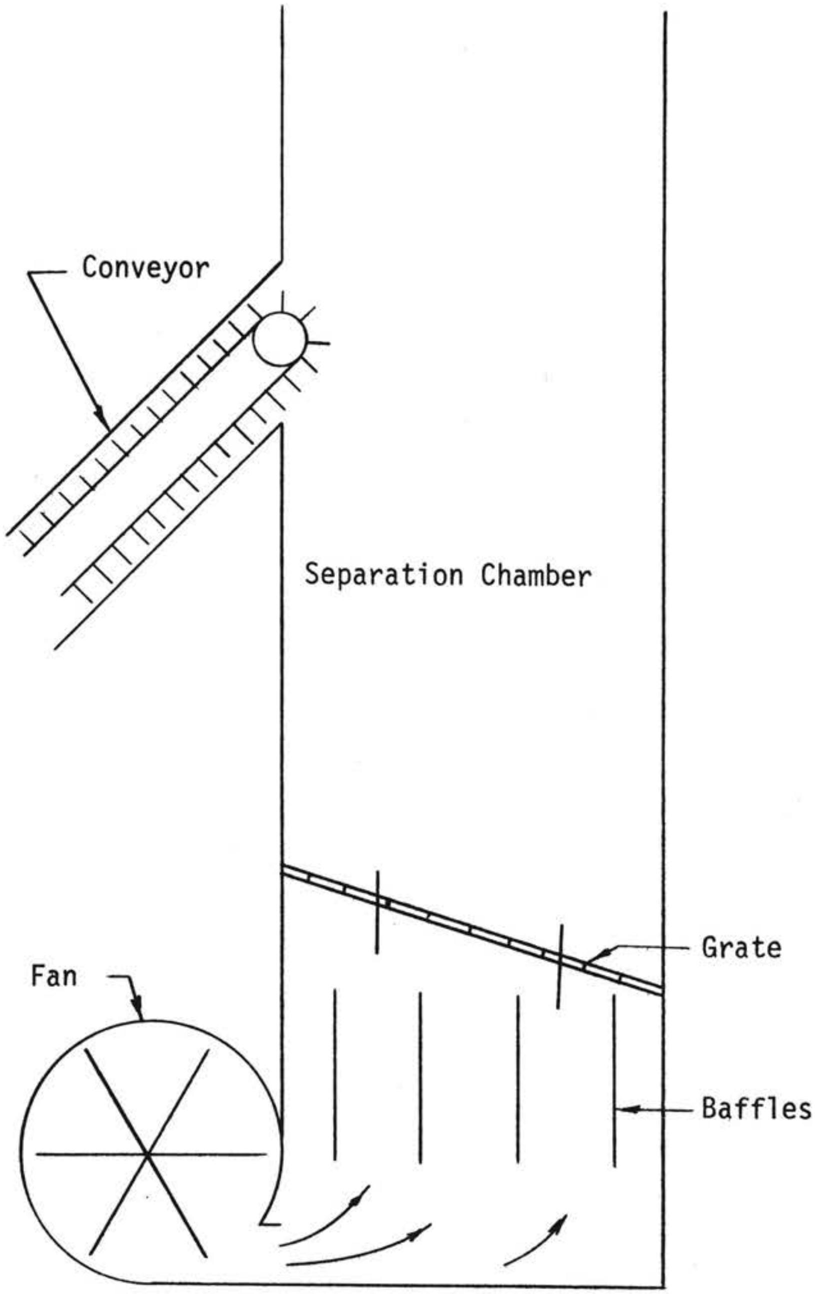

Figure 12. Schematic Diagram of a Green Boll Separator for Cotton Stripper Harvesters

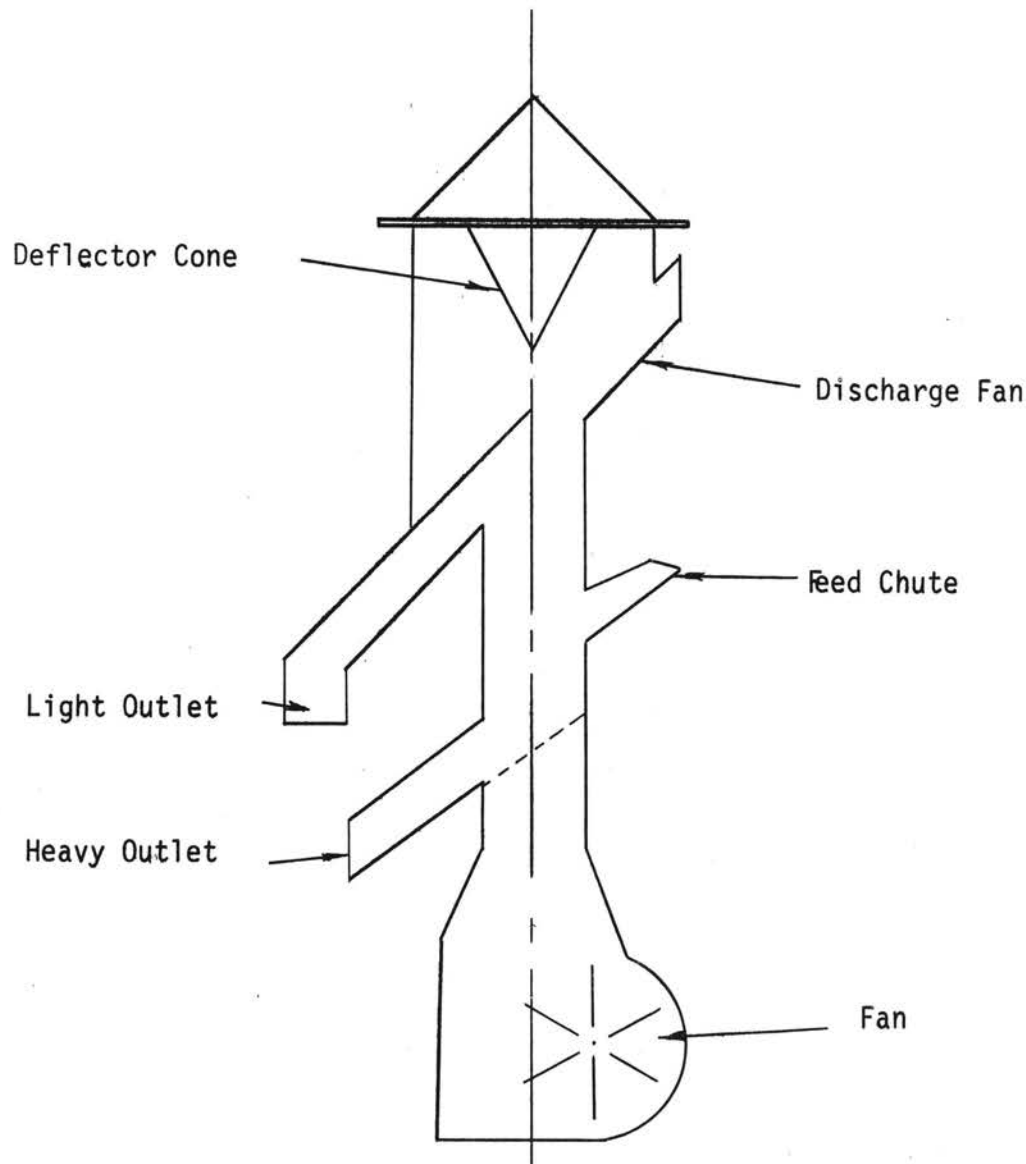

Figure 13. Schematic Diagram of an Aspirating Type Separator Which Classifies into Two Fractions

etc. are lifted by the air in the column. The cone at the top diverts this light material out to the discharge pan. The heavy seed drops against the air flow until it is deflected by the inclined screen out the heavy seed discharge.

The Meyer Machine Company (15) manufactures a line of pneumatic separators which use the separating principle described in Figure 10. Material is fed into an air stream created by a fan located at the bottom of the separator (Figure 14). Heavier particles fall to the lower chute and are discharged as Fraction 1 while the light particles are carried upward. The light material is conveyed into the modified cyclone separator at the top where they are moved by centrifugal force to the outside and fall as Fraction 2. The air exits at the center opening.

Figure 15 shows a green boll separator which is used on the Long (16) cotton harvester. Separation is described as being accomplished in three stages. The first occurs as the cotton leaves the augers. The second stage occurs as the bolls and cotton are carried up the chute suspended in the air stream. Gravity causes bolls to drop into the conveying belt. The final stage occurs as the cotton makes a bend in the flow path. Inertia of the green bolls forces them into a cushion which dissipates their energy. The green bolls then drop into the box below. The remaining cotton is conveyed to the basket.

During a harvesting test with the Long cotton harvester, in which approximately one bale of cotton was harvested, 94.7 total pounds of material were collected in the green boll trap. Of this material, 74.6 percent was burrs and bolls with little or no cotton; the remainder was clean seed cotton.

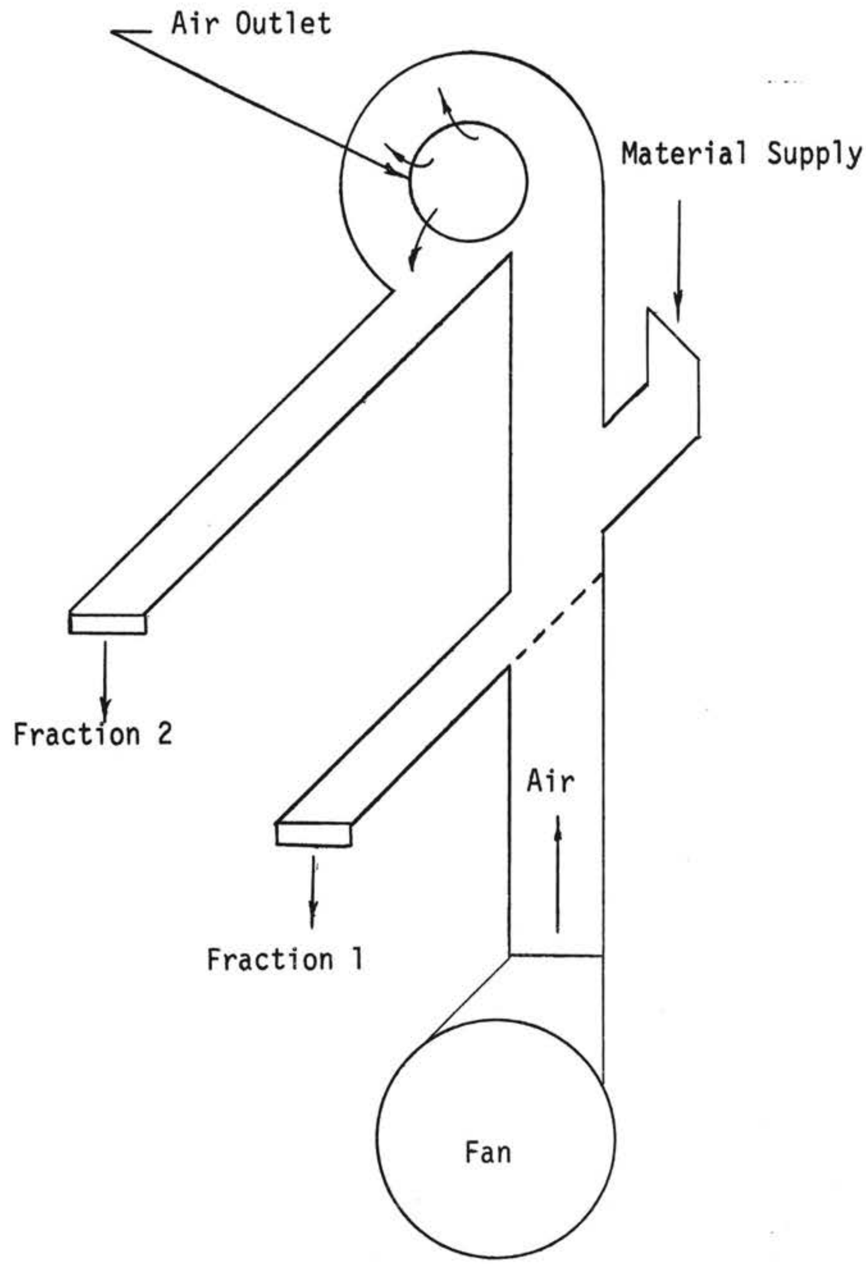

Figure 14. A Separator Which Uses a Modified Cyclone Outlet to Separate Fine Particles (Meyer Machine Company)

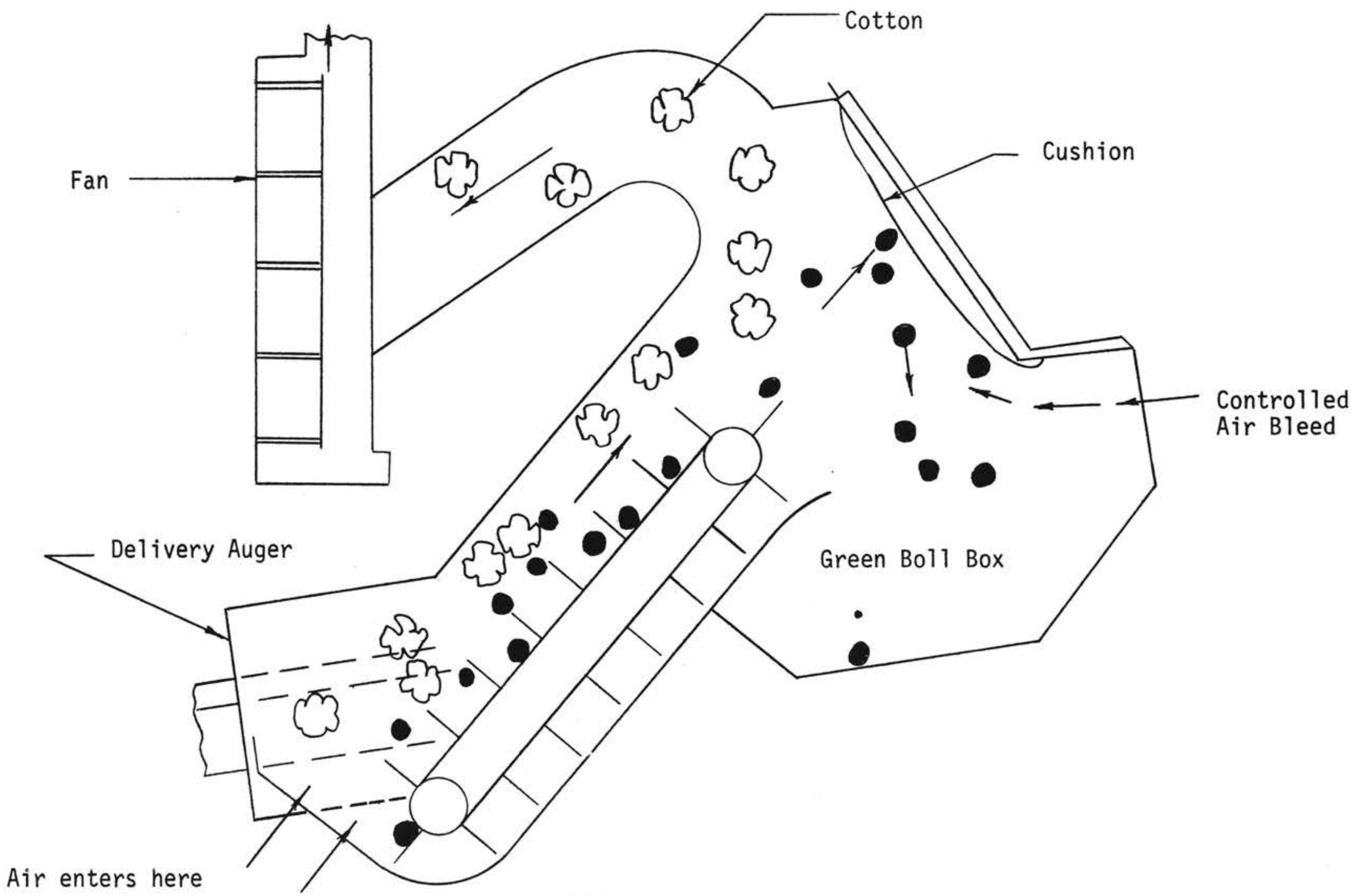

Figure 15. Diagram of Green Boll Separator Used on the Long Cotton Harvester

Figure 16 shows a belt grader which was built and tested by the Oklahoma State University Agricultural Engineering Department for use as a cotton seed cleaner and grader (17). Two belts, approximately six feet long, were operated at a lineal speed of 3400 feet per minute. The belts were arranged such that as seed was fed between the opposing belt faces, it was accelerated and discharged at about belt speed. Acid delinted seed, not graded previously, was used in the tests.

Figure 17 shows the results of the 1957 tests. The heaviest seed was thrown the farthest. It was thought that the larger quantity of seed in the first distance, compared to the second distance from the grader, might be due to an incomplete acceleration of the seed.

Figure 18 shows the results of tests conducted with the belt grader operated at a lineal speed of 4250 feet per minute (18). Each space represents 5 feet of lineal distance from the belt discharge.

Results from the two year's work indicate that the belt grader will grade the seed on the basis of specific gravity but not according to size.

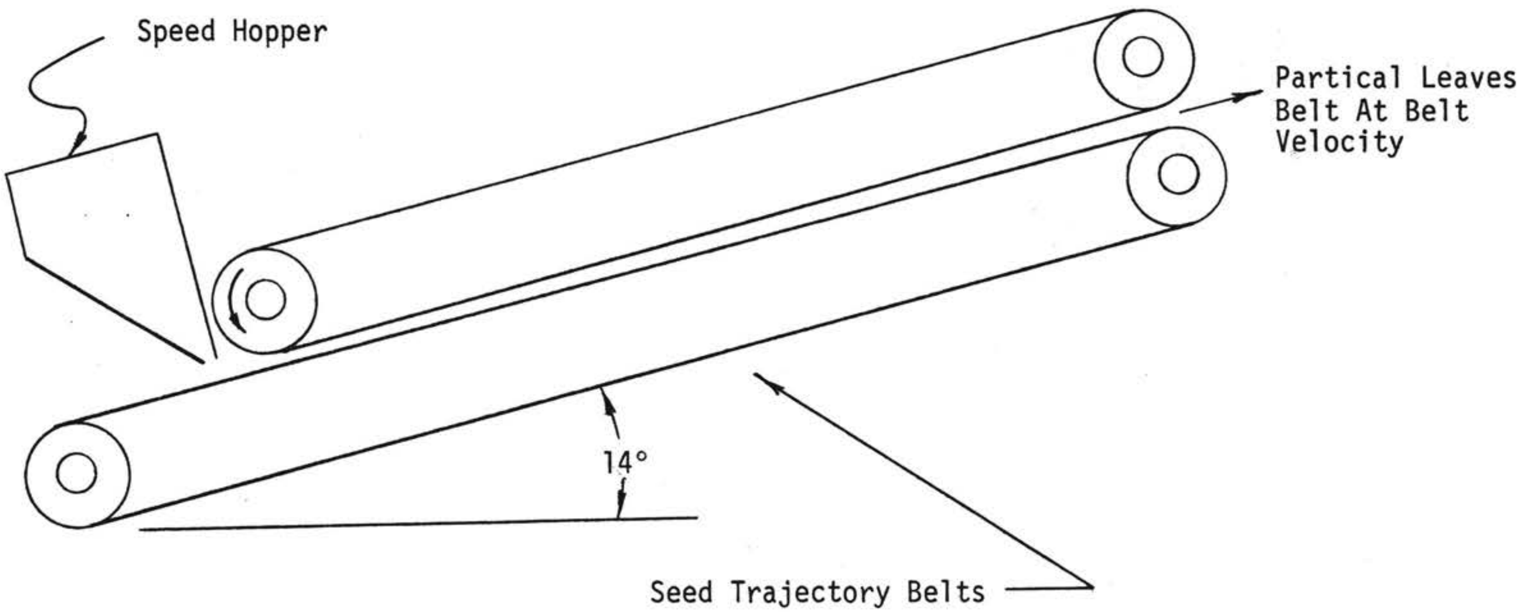

Figure 16. Belt Grader Built and Tested by Oklahoma State University Agricultural Engineering Department

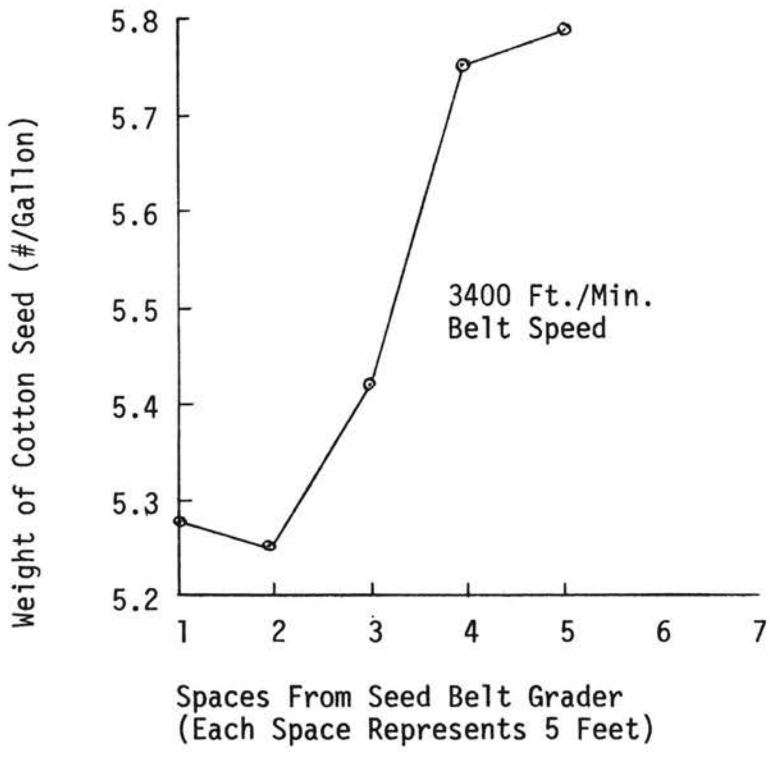

Figure 17. Results of Belt Grader Tests (1957)

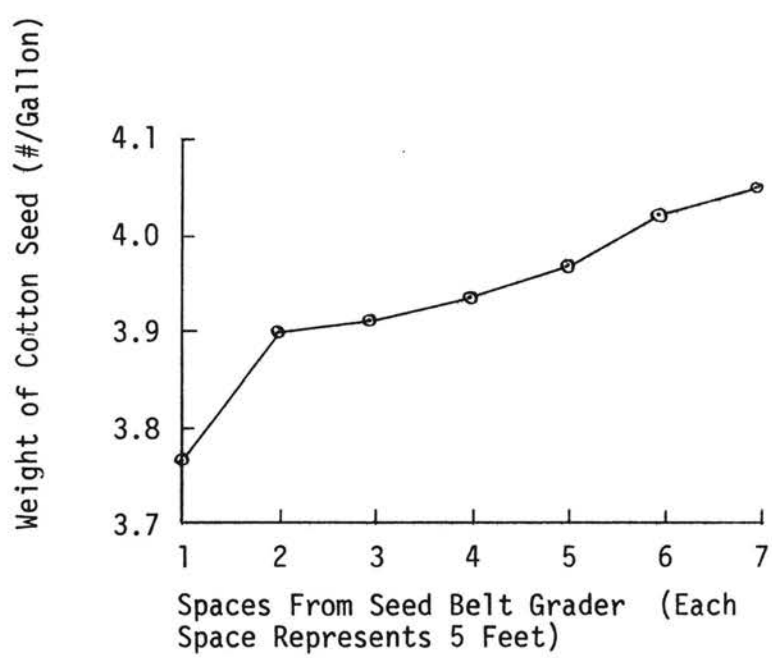

Figure 18. Results of Belt Grader Tests (1958)

CHAPTER III

THEORY

Principles of Pneumatic Separation

Material is transported in a pneumatic conveyor by the effect of aerodynamic drag. The force produced by drag is dependent upon various factors, but of primary concern is the relative velocity between the conveying medium and the conveyed particle. The force required to move particles along horizontal sections is less than that required for vertical conveying; however, the particle velocity in the horizontal section must be high enough to maintain the material in suspension (19). Stoppages and stratification of the conveyed material will be the result of too low air velocity. The operational theory of the separator used for this study is based both upon the effect of low air velocity and the collision principle as stated by Leniger (1).

The action of the separator used for this study is described as follows: Particles are conveyed into the separator through the inlet duct (Figure 19). As the particles enter the chamber, they are either lifted by the air as it is forced upward by the deflector, or they collide with the opposite wall due to their momentum. If the particles are light enough to be carried upward, they move through the separator with the air. If they are heavy enough to collide with the wall, they may be carried upward or they may lose energy from ricocheting within

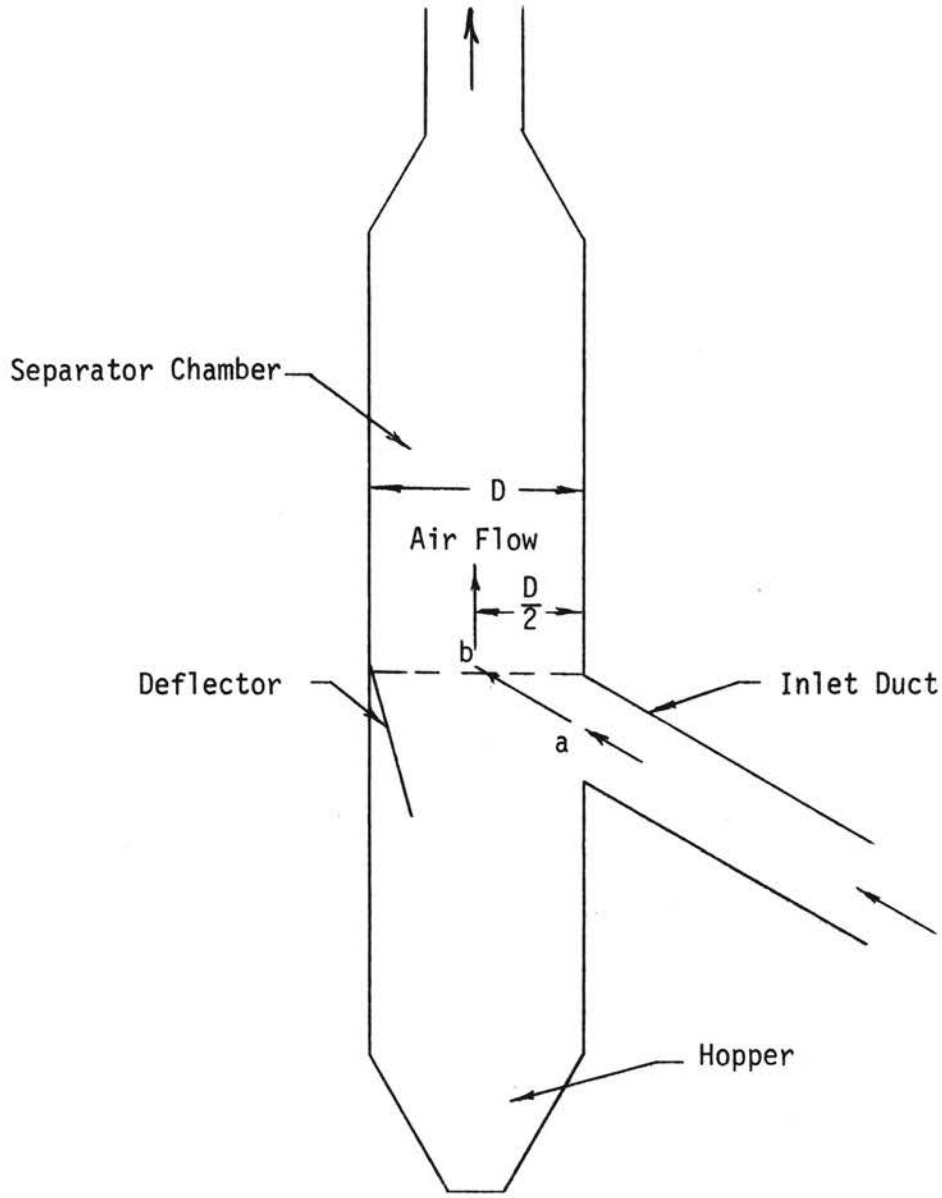

Figure 19. Schematic of Separator Used for Particle Motion Analysis

the separator and drop to the hopper below. The actual path of the particles depends upon various parameters both of the separation system and of the particles.

Particle Motion in a Separator

The following assumptions were made to allow an analytical evaluation of particle motion within the separation chamber:

1. The air flow pattern within the separator was assumed as shown in Figure 19. Flow was assumed parallel with the inlet duct center line in the inlet duct. The flow from the inlet duct exit to the dashed line, drawn horizontally through the deflector hinge point, was assumed parallel to Line ab. Point a was located at the intersection of the inlet duct center line with the separator wall. Point b was located at the intersection of the separation chamber center line with the dashed horizontal line, previously defined. Above the dashed line, the flow was assumed parallel with the separation chamber center line.
2. Particles entering the separator were assumed to have reached the terminal velocity as governed by the air flow rate and size of entry duct.
3. The entering path of particles into the separation chamber was assumed parallel with the inlet duct center line.
4. The relative velocity between the air and particles was assumed equal to the air velocity in the separator

chamber. (Air velocity was actually much greater than particle velocity after impact.)

5. The angle of rebound was assumed equal to the angle of incidence.

Equations of motion for a particle moving in a vertical plane within the separator were written using an initial velocity as computed from equations set forth by Crane and Carleton (20), and direction of the particle and air as assumed. Figure 20 is a free body diagram of a particle within the separator.

The equations were, for the horizontal component of acceleration:

$$\frac{d^2x}{dt^2} = \frac{F}{M} = -\frac{R \cos B}{M} \qquad (3.1)$$

and for the vertical component of acceleration

$$\frac{d^2y}{dt^2} = \frac{F}{M} = (g) \times \left(\frac{(P_p - P_f)}{P_p}\right) + \frac{R \sin B}{M} \qquad (3.2)$$

where

M = mass of the particle (lbs. mass)

P_p = density of the particle (lbs./ft.^{3})

V = velocity of the particle (ft./sec.)

V_y = vertical component of particle velocity (ft./sec.)

W = weight of particle (lbs.)

F = force (lbs.)

g = gravitational acceleration (ft./sec.^{2})

P_f = density of air (lbs./ft.^{3})

V_x = horizontal component of particle velocity (ft./sec.)

R = drag force of air on particle (lbs.)

B = angle whose tangent is V_y/V_x (degrees)

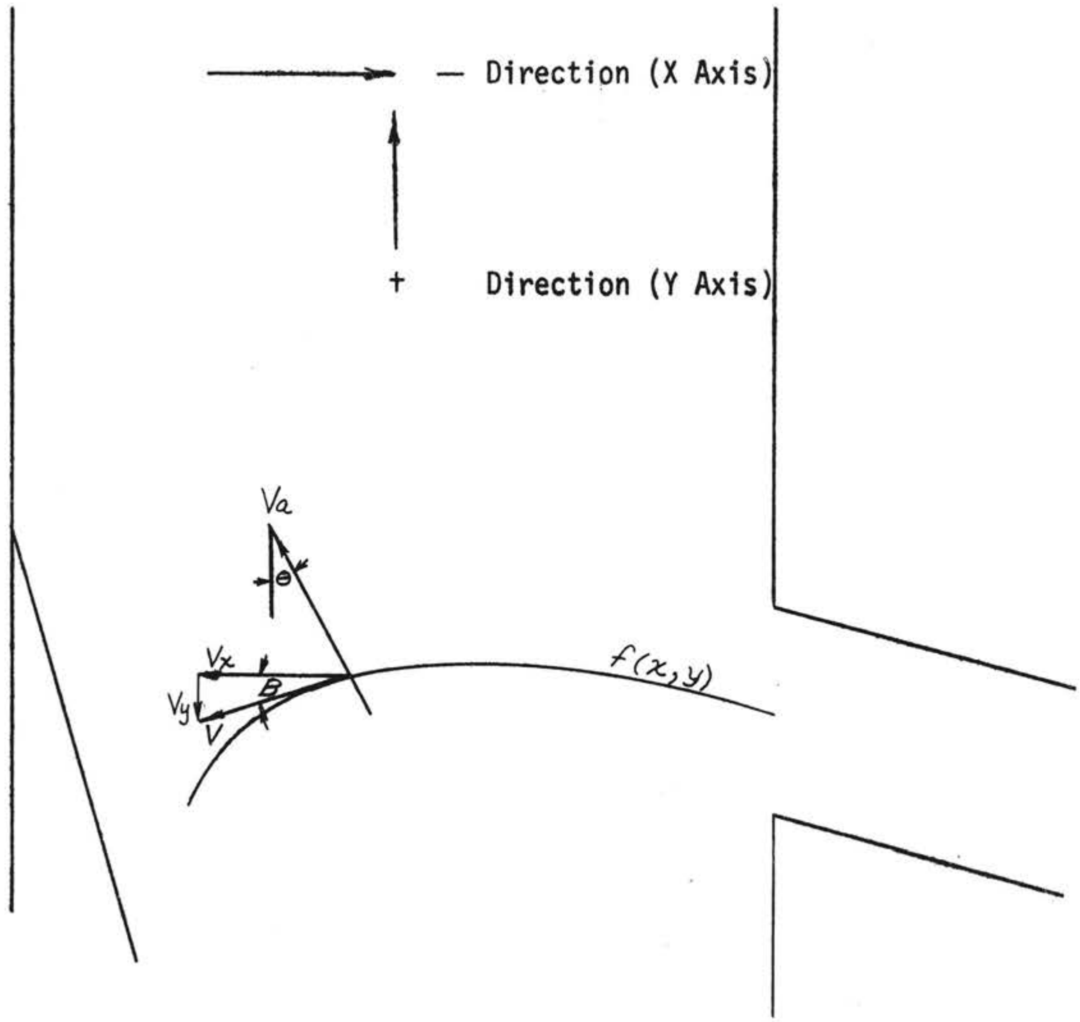

Figure 20. Velocity Diagram of Particle Within Separator

The drag force, R, was found by using the relationships

$$R = (\frac{1}{2g})(P_f)(V_o)(C_r)(A), \qquad (3.3)$$

$$V_o = (V-V_a)[(\frac{V_x}{V})(\sin \Theta) - (\frac{V_y}{V})(\cos \Theta)] \qquad (3.4)$$

and

$$C_r = (0.63 + \frac{4.8}{R_e^{0.5}})^{0.5}. \text{ (Refs. 3, 4, and 19)} \qquad (3.5)$$

where

A = projected area of particle (ft.^{2})

V_o = the relative velocity between the particle and passing air (ft./sec.)

V_a = velocity of the air (ft./sec.)

Θ = angle which the air flow direction makes with the vertical (degrees)

C_r = drag coefficient

R_e = Reynolds Number

The Reynolds Number is given by $((P_f)(V_o)(Dia)/U_a))$ where Dia equals diameter of particle in feet and U_a equals the viscosity of air expressed in pound-seconds per square feet.

When a particle strikes the wall, energy is lost and the particle must assume a new velocity and direction. Using relationships adapted from work by Chancellor (21), a new velocity and direction of the particle was computed. Chancellor suggests that the energy given up by a particle when it impacts a flat surface is of two parts. Part One is that of sliding against friction, here termed E_f, and Part Two, that of partial inelastic rebound, termed E_r. The two losses are given by

$$E_f = \frac{W}{g} [(V \cos \gamma)^2 - V_m^2], \qquad (3.6)$$

$$V_m = \frac{V}{2} [-fk \sin \gamma \pm \sqrt{(fk \sin\gamma)^2 + 4 \cos^2\gamma}],$$

and

$$E_r = \frac{MV^2 k \sin^2\gamma}{2} . \quad (3.7)$$

where

V_m = mean velocity parallel to plane during impact period (ft./sec.)

k = coefficient of energy loss caused by deformation 1 - [coefficient of restitution]^2

f = coefficient of friction of particle material on wall

γ = angle which wall makes with path of particle at time of impact (degrees)

A digital computer was programmed to calculate the entrance velocity, the Reynolds Number, and the drag coefficient (22). Using time increments of 0.002 second, a change of velocity was determined for the time interval. By algebraically adding the product of the velocity and the time increment to the previous location, the velocity, direction, and the location 0.002 second later was determined. A new value for R_e and C_r was then found and the procedure repeated until the trajectory of the particle during flight was traced.

Figure 21 represents the theoretical trajectory of a spherical particle with a projected area of 0.00172 square foot, a diameter of 0.047 foot, weight of 0.01 pound, friction coefficient of 0.433, and an energy loss upon impact of 70 percent. The separator width and length was assumed as 0.833 foot, the deflector angle equal to 10 degrees, inlet angle with the vertical equal to 80 degrees, and an air flow of 33.3 cfs. The solid line is the theoretical trajectory calculated for the particle when entry was made at the lower portion of

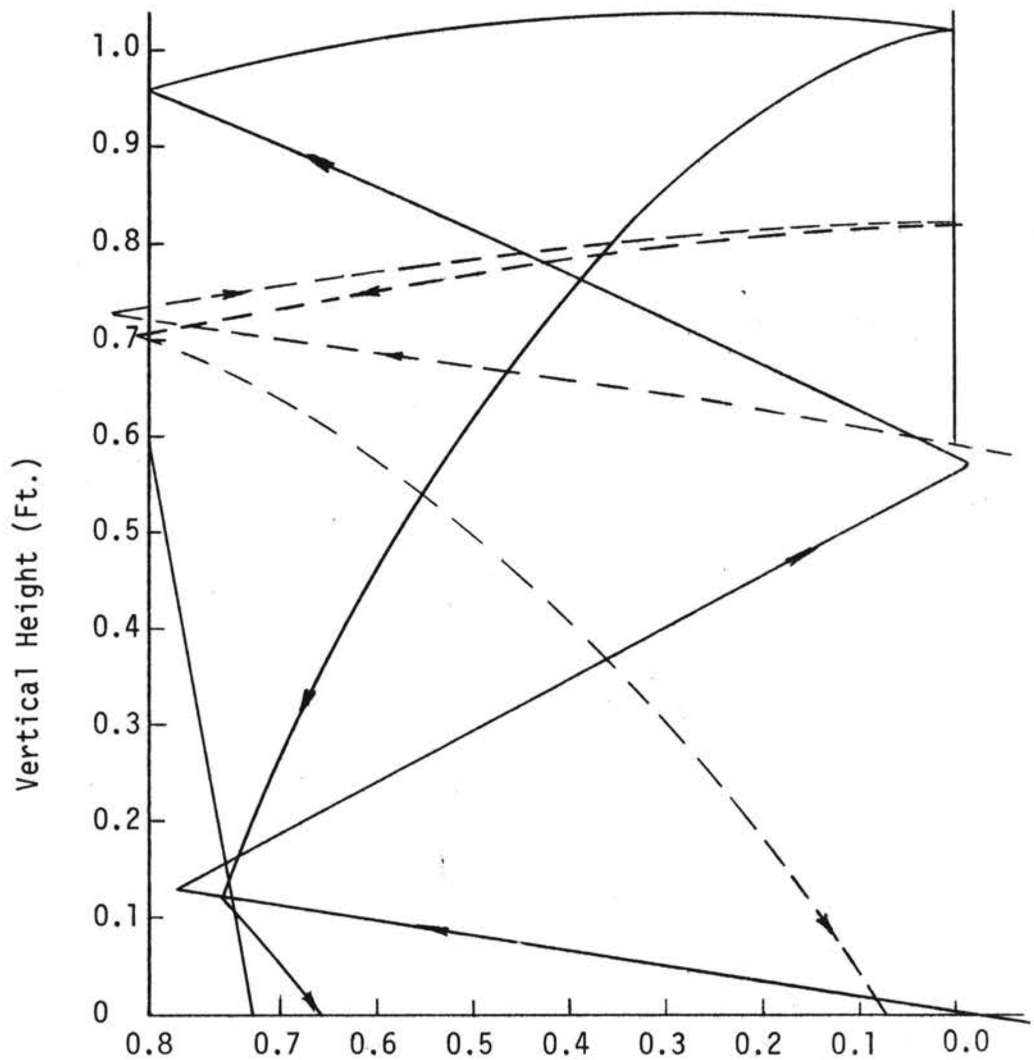

Figure 21. Theoretical Trajectory of a Particle Within Separator

the inlet tube. The dashed line represents the path when entry was at the top of the inlet opening.

It was hypothesized that if all kinetic energy was lost by a particle due to impact with the separator wall, its direction after impact would depend only upon the particle aerodynamic properties and the relative air velocity.

The separator, shown in Figure 19 and discussed in the theoretical treatment previously, was altered by replacing the deflector with an energy dissipating backstop. Figure 22 shows a diagram of the test separator. A complete discussion of the apparatus is in Chapter IV.

Dimensional Analysis

When a number of variables are to be evaluated, it is desirable to simplify the test procedure yet satisfy the objectives as set forth in the experiment design. Dimensional analysis is sometimes useful for this purpose for it permits one to combine the important parameters of an experimental system into dimensionless ratios and use these ratios as variables.

Dimensional analysis is based on the relationships that exist among the units of variables. Qualitative rather than quantitative relationships are obtained through use of dimensional analysis; however, when experimental procedures are used, quantitative results and accurate prediction equations can be obtained (23).

Specifically, the procedure is to form dimensionless ratios called Pi terms from the variables which define the system under study. There is no unique set of Pi terms, although some which are formed may be better from an experimental standpoint than others. The Pi terms

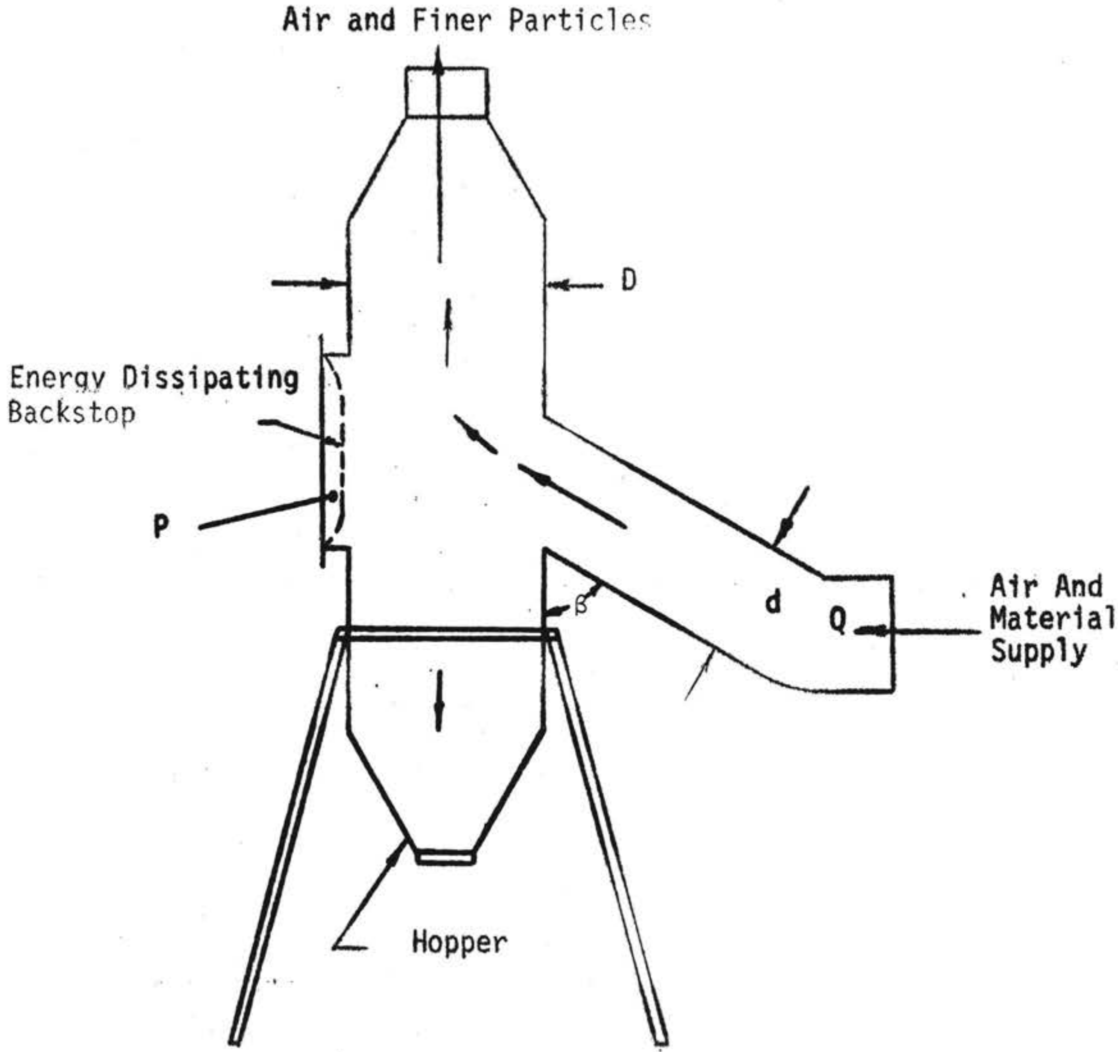

Figure 22. Cross Section of Test Separator

are then arranged so that all the Pi terms but one are held constant. Each Pi term is varied in turn to yield a relationship with the quantity being observed. This relationship is called a component equation. Such equations are obtained for each Pi term. The final prediction equation which defines the system is obtained by combining the component equations. Murphy (23) has outlined the procedure for combining the component equations by either multiplication or addition depending upon the form of the component equations.

Selection of Basic Quantities

The variables which are thought to define the system under study are tabulated in Table I. Those variables which describe the separator are shown in Figure 22.

The Pi terms which were formed from the variables are as follows:

$$\text{Pi } 1 = \text{Per}$$

$$\text{Pi } 2 = \frac{Q^2 Ne}{GD^5}$$

$$\text{Pi } 3 = \frac{Dia^3 \; Pa^2 \; Ne \; G}{Ua^2}$$

$$\text{Pi } 4 = \frac{P_p}{P_a}$$

$$\text{Pi } 5 = \frac{d^3 \; Pa^2 \; Ne \; G}{Ua^2}$$

$$\text{Pi } 6 = \frac{d}{D}$$

$$\text{Pi } 7 = \frac{R \; Ne}{D \; Ua}$$

TABLE I

BASIC PARAMETERS OF THE PHYSICAL SYSTEM

No.	Symbol	Parameter	Dimensions
1	Per	Percent of total entering particles of a single description which are separated.	0
2	B	Angle entry duct makes with vertical degrees.	0
3	D	Separation chamber width dimension. Ft.	L
4	d	Inlet duct width dimension. Ft.	L
5	Dia	Particle diameter. Ft.	L
6	P_p	Density of particle. Lbm./Ft.^{3}	ML^{-3}
7	Pa	Density of air. Lbm./Ft.^{3}	ML^{-3}
8	R	Mass feed rate. Lbm./Sec.	MT^{-1}
9	Q	Air volume flow rate. Ft.^{3}/Sec.	L^3T^{-1}
10	P	Net static pressure behind impact canvas. Lbf./Ft.^{2}	FL^{-2}
11	G	Gravity field strength. Lbf./Lbm.	FM^{-1}
12	Ua	Absolute viscosity of air. Lbf.-Sec./Ft.^{2}	FTL^{-2}
13	Ne	Newtons Second Law coefficient. Lbf./Lbm.-Ft./Sec.^{2}	$FM^{-1}L^{-1}T^2$

$$\text{Pi } 8 = \frac{P^2 \text{ Ne D}}{\text{Ua}^2 \text{G}}$$

$$\text{Pi } 9 = \text{B}$$

Discussion of Pi Terms

Pi 1 represents the percent separated which was the dependent quantity.

Pi 2 is similar to the Froude Number.

Pi 3 and Pi 5 are hybrids composed of Reynolds Number and the Froude Number.

Pi 4 and Pi 6 are ratios of density and length dimensions.

Pi 7 is a Reynolds Number and was found to be relatively insignificant for some tests within the range through which it was varied.

Pi 8 represents a combination of inertia, viscous, and gravity forces.

Pi 9 is an angle and was not varied throughout the tests. Therefore, the angle of the entry duct is a condition for the prediction equation's validity.

CHAPTER IV

APPARATUS, EQUIPMENT, AND MATERIALS

The separator used for this study consisted of three parts, the inlet duct, the separation chamber, and the energy dissipating backstop.

Inlet Ducts

The four sizes of inlet ducts which were used are shown in Figure 23. These were square in cross-section, each having a square to round 7-inch diameter transition at the inlet end. The sizes used were 5.0, 5.2, 5.7, and 6.0 inches. Each duct was 36 inches long. One end had a connecting flange which fastened the ducts to the separation chamber at an angle of 20° below the horizontal.

Separation Chambers

Four, square in cross-section, separation chambers were constructed with widths of 5.3, 5.6, 6.1, and 6.4 inches respectively (Figure 24). Each chamber was fitted with a hopper at the bottom and a transition from square to 7-inch diameter round opening at the top. A framed opening was made in the side of the chambers opposite the entrance duct. The various energy dissipating backstops were fastened to these frames. The overall height of the chambers was 17 inches excluding the transitions and collectors.

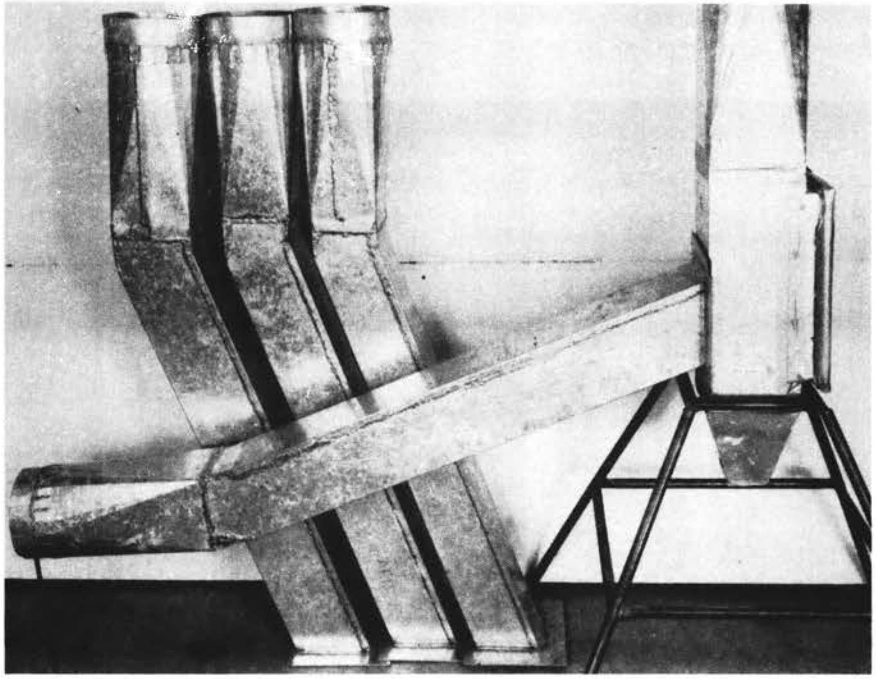

Figure 23. The Four Sizes of Inlet Ducts Used on Separators

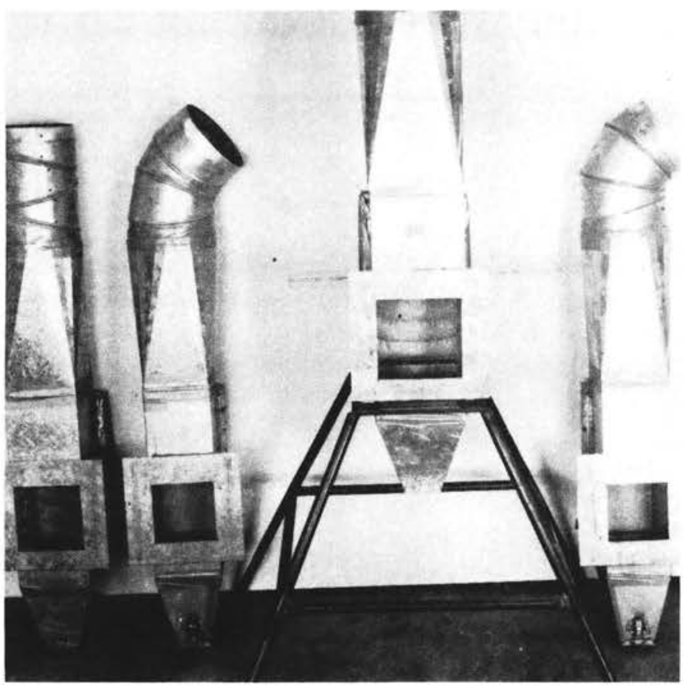

Figure 24. The Four Separation Chambers Used for Tests

Backstops

Six backstops were constructed for each of the four separation chambers. They were 13 inches long and as wide as the separation chambers to which they were mounted. Canvas, carpet, denim, closed cell gasket material, polyurethane foam, and vinyl sponge were used as shock absorbing materials.

The canvas backstop (No. 1 in Figure 25) consisted of a 13-inch chamber width by 2-inch sheet metal box which mated with the framed opening in the separation chamber. Fifteen ounce treated canvas was placed between the chamber frame and the metal box. The box and the frame were bolted together with the canvas between as a diaphram. An adjustable opening was made in each box to allow pressure variation behind the canvas. Atmospheric pressure provided the means of obtaining a pressure differential across the canvas since the pressure inside the separator was less than atmospheric.

Another backstop was made of nylon carpet with a one-eighth-inch foam rubber backing (No. 2, Figure 25). The carpet was glued to three-eighths-inch plywood which was mounted over the separation chamber frame with the carpet facing inward.

Two layers of denim cloth were sewn so as to leave compartments. Corn meal was used to fill these compartments (No. 3, Figure 25) thus forming a sort of "bean bag" which was mounted on three-eighths plywood and used as a backstop.

The remaining backstops were of polyurethane foam (No. 5, Figure 25) and Hi-Car Vinyl Sponge (No. 6, Figure 25), obtained from the Durable Products Company of Chicago, and closed cell gasket material (No. 4, Figure 25) numbered 411-N manufactured by the Industrial

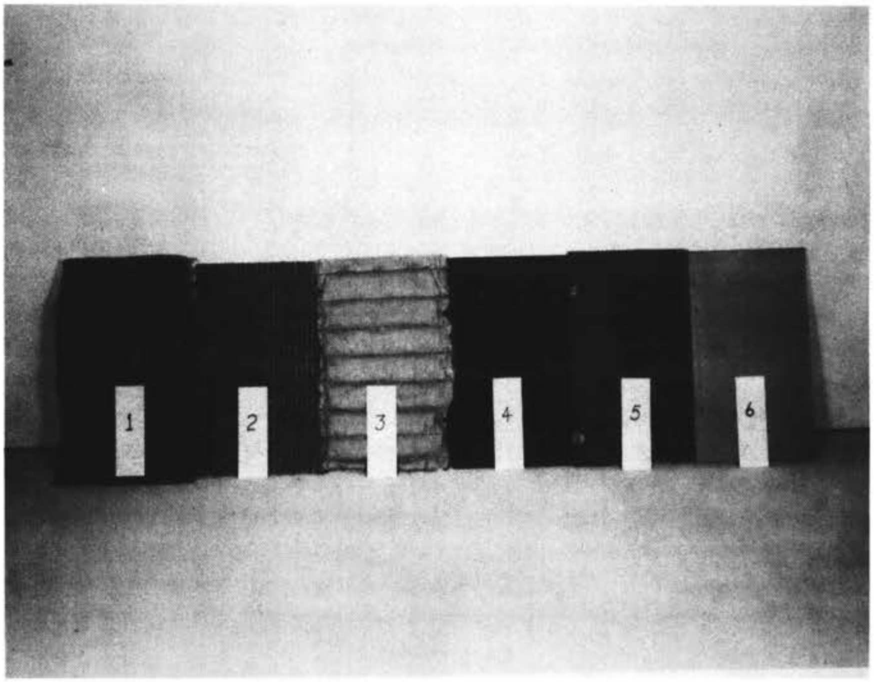

Figure 25. The Six Energy Dissipating Back-
stops Used on Separators

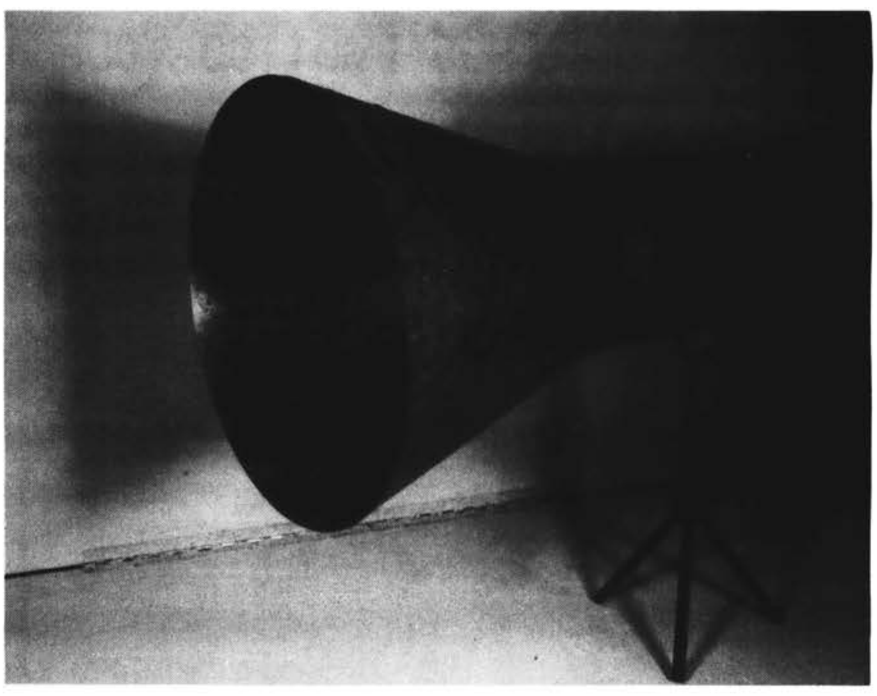

Figure 26. A Conical Inlet to Lower Head Loss At
Air Entrance

Gasket and Packing Company, Inc., Oklahoma City. A half-inch thick sheet of each of these materials was cut to size and glued to three-eighths plywood.

Piping and Fan

Twenty-five feet of 7-inch diameter galvanized sheet metal pipe was connected to the inlet duct of the separator to permit air flow measurement and feeding particles into the system. A conical inlet (Figure 26) was used to lower head loss at the air entrance.

A Bayley Ex-226 material handling fan was used to move air through the system. The fan inlet was connected by 7-inch pipe to the transition on the separation chamber (Figure 27). A one-eighth-inch mesh screen was soldered in the pipe in front of the fan entrance. Particles which passed through the separator were caught by this screen. They were taken out by means of a spout located beneath the screen. An adjustable damper (Figure 28) in the fan outlet duct permitted variation in the air flow with constant fan speed.

Apparatus for Air Flow Measurement

Air flow measurement was made with a pitot-static tube and manometer. The pitot tube was located 20 pipe diameters from the inlet in a straight section of pipe for proper air flow around the pitot tube. Three-sixteenths latex hose connected the pitot with the manometer.

The manometer (Figure 29) consisted of a container with tubing connections at top and bottom, an etched fluid level tube, an Ames dial, and an adjusting screw. The manometer was connected such that the

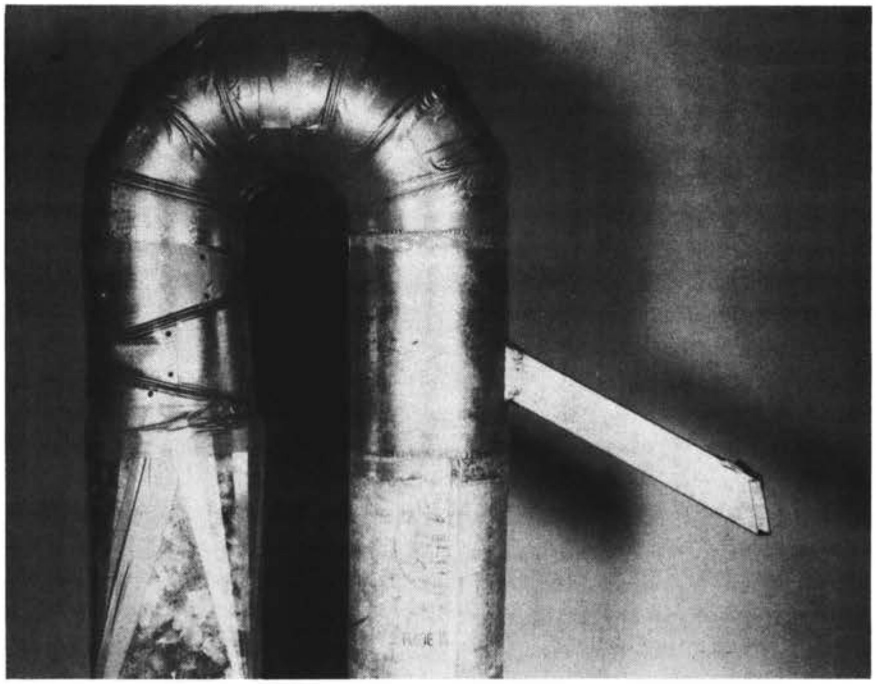

Figure 27. The Separator-Fan Connecting Pipe With Particle Removal Spout

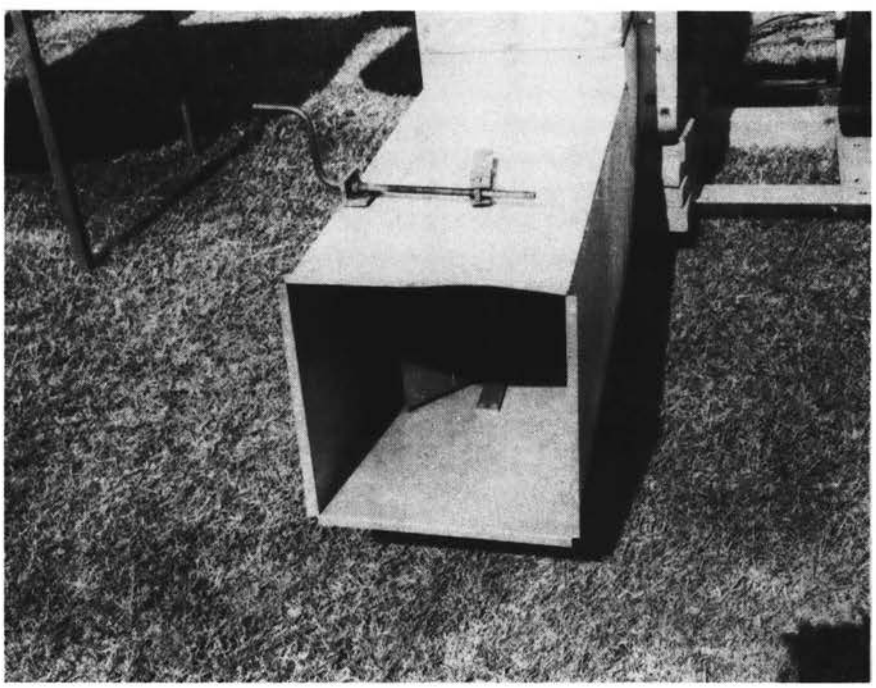

Figure 28. Adjustable Damper in the Fan Exit Duct

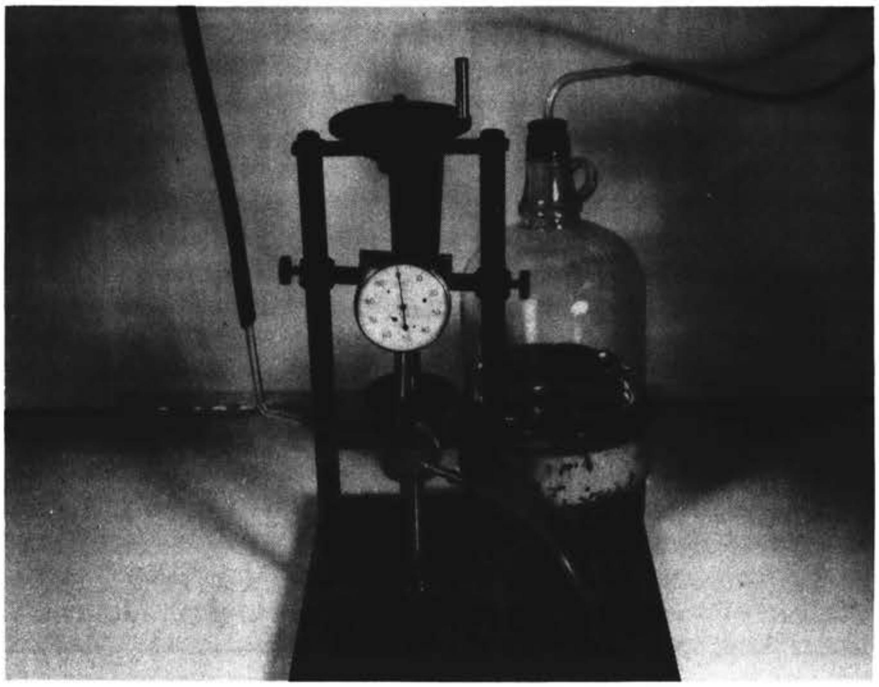

Figure 29. Manometer for Measuring Pitot-Static Tube Pressure

level of the fluid in the indicating tube was proportional to the velocity head at the pitot location in the pipe. The adjusting screw moved the indicator tube vertically. The Ames dial measured this movement from a predetermined position. The indicating tube angle was adjustable to permit increased sensitivity in positioning the level mark at the fluid level.

Adjustment of the manometer was accomplished by moving the indicator to the level of the fluid with no air flow and adjusting the Ames dial to zero. The level of the fluid could then be measured as it varied by adjusting the indicator to fluid level and reading the Ames dial. Methanol with specific gravity of 0.7567, was the manometer fluid used.

Air velocity at the tip of the pitot tube was given by the following equation (19):

$$V = 18.3 \sqrt{P/\text{Gamma}} \qquad (4.1)$$

where

V = Air velocity in ft./sec. at the pitot tube tip.

P = Velocity pressure measured in inches of water.

Gamma = Air density in lbs./ft.^{3}.

With methanol in the manometer, the height of the fluid level increases above that of water, water being heavier than methanol. Equation 4.1 becomes

$$(V = 18.3 \sqrt{.7567\ P/\text{Gamma}})$$

where P is in inches of methanol.

The pitot tip was located at the center of the 7-inch pipe at the maximum velocity position. The velocity monitored by the pitot was, therefore, the maximum and not the average. A traverse of the pipe at the pitot tube location was made to determine the velocity profile. Appendix A-I shows the plot of this traverse for several air flow rates. The area beneath each curve was measured and the average height computed. This average height was divided by the height of the curve at the center of the pipe to obtain a decimal coefficient. Appendix A-II shows a plot of these coefficients for the various air flow rates. The number selected as the coefficient for air flow measurements was 0.92, as most of the tests were conducted with air flows between 17 and 27 cfs.

A 7040 computer was programmed to compute a table of required manometer settings for several air densities and air flow rates. Appendix A-III shows the relationships used for computing the table as well as a portion of the table.

Appendix A-IV includes part of a table relating air density, barometric pressure, relative humidity, and air temperature. The mathematical relationships used to obtain the table are also included. Values for air density were determined from this table and used in calculating the required manometer reading for a given air flow rate.

A hygrothermograph was used to measure the ambient air temperature and relative humidity. Barometric pressure readings were obtained from the local radio station.

Plastic Balls

Plastic balls with densities ranging from 52.3 to 134.5 pounds per cubic foot and diameters from 1/8 to 7/8 inches were obtained from several companies. These balls (Figure 30) were used as particles in Part One of this study.

Each ball was identified by number and weighed in a Mettler Analytical Balance to the nearest ten thousandth gram. The diameter was measured to the nearest ten thousandth inch with a micrometer.

The 7040 computer was programmed to compute the terminal velocity for each ball using the method reported by Lapple and Shepherd (2). Tables were formed which gave the weight of the balls in pounds, Reynolds Number at constant ambient conditions, terminal velocity in feet per second, and density in pounds per cubic feet. An example of these tables is presented in Appendix B-I. Some balls were omitted due to large variations in terminal velocity. The procedure used to determine which balls were omitted is presented in Chapter V.

Ball Feeder

One of the requirements of the experiment design was that the ball feed rate be varied in a controlled manner. Figure 31 shows the apparatus used to accomplish this requirement.

A variable speed drive was used to turn a spur gear. The gear was mounted directly above a track in which a sliding rack gear was placed. A plunger was fastened to one end of the rack. Plastic balls were placed in a tube placed directly in front of the plunger and mounted on the side of a section of inlet duct. A spring clip at the duct end of the tube prevented the balls being sucked into the system prematurely.

As the rack was manually slid into mesh with the rotating spur gear, it was forced to slide down the track at a speed equal to the

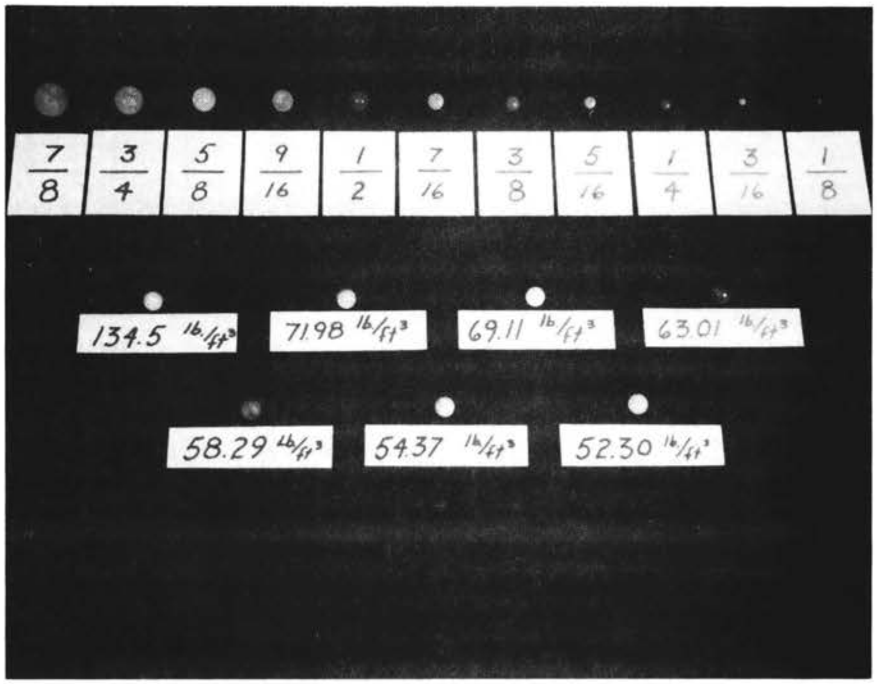

Figure 30. Plastic Balls Used as Particles

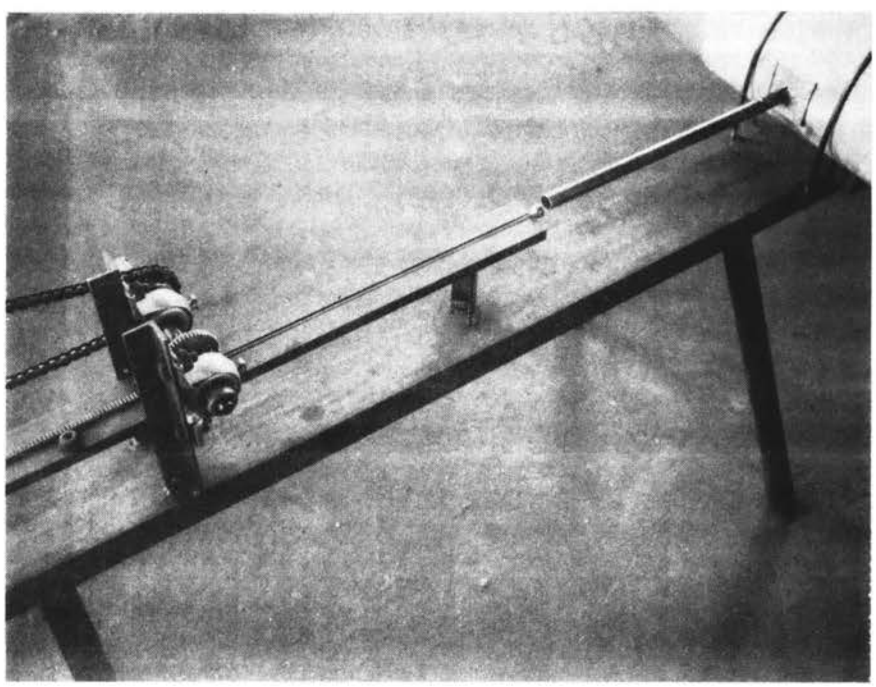

Figure 31. Ball Feeding Apparatus

peripheral speed of the gear. The balls in the tube were forced past the spring clip and into the system by the plunger.

Various sizes of tubes were used to match the ball diameters, and several plunger ends were made to assure smooth operation of the plunger in the tubes. Figure 32 shows the tubes and plunger ends.

Apparatus for the Measurement of the Coefficient of Restitution of Plastic Balls on Backstops

Figure 33 shows the apparatus used to determine the coefficient of restitution of the various plastic balls on the energy dissipating backstops. A device was constructed to drop plastic balls from various heights onto the backstops fastened horizontally to the base. Two parts of a stadia rod were fastened upright, one on either side of the backstop, in the plane in which the balls were dropped. A small vacuum pump was used to hold the balls until they were to be dropped.

Each ball was coated with a thin layer of fluorescent shellac which permitted illumination of the ball by ultraviolet radiation. The camera was fitted with a filter designed to absorb the visible and ultraviolet radiation from the lamp. The room was darkened prior to photographing, thus excluding much of the visible light.

The rebound paths of the balls were photographed by illuminating the rebound area with ultraviolet light, dropping the balls, and opening the camera shutter for the duration of the first bounce. The height of rebound was measured directly by reading the stadia rods at the side (Figure 34). The test data including the coefficients of restitution for selected balls on all of the backstops is presented in Appendix C-I.

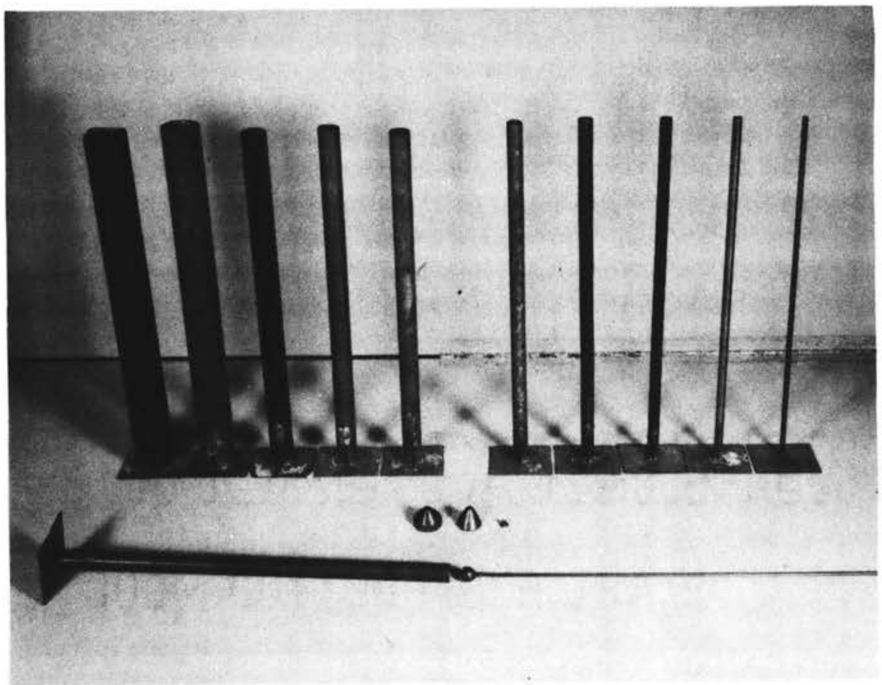

Figure 32. Ball Tubes and Plunger Ends

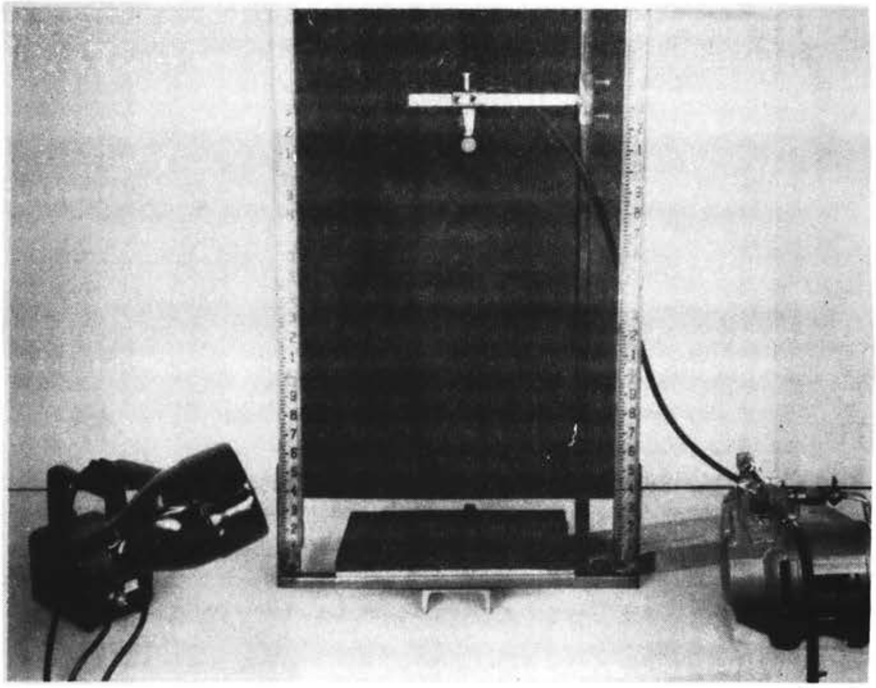

Figure 33. Apparatus for Measuring Coefficient of Restitution of Balls on Backstops

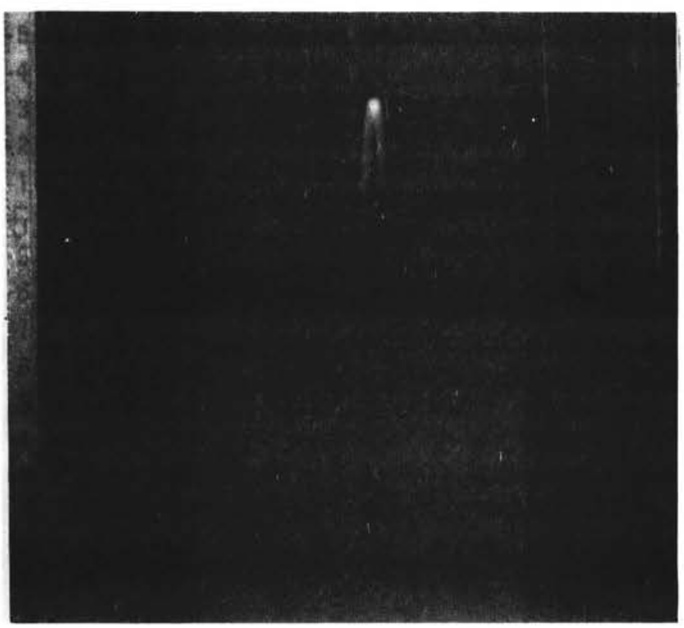

Figure 34. Photograph of the Rebound Path of Ball Dropped on Backstop

Agricultural Materials

Wheat, sorghum, and soybean seed were selected for tests involving continued mass flow. Each seed was graded to size with a roll grader (Figure 35) driven by a variable speed drive. Four samples were taken at random from the graded material and each placed in a volume measuring manometer. The volumes thus obtained and the corresponding weights were used to compute the material density.

Two seed mixtures were formed with the graded seed. The "three-material mixture" consisted of wheat, sorghum, and soybeans. The "two-material mixture" was composed of only wheat and soybeans. Different lots of wheat were used for each mixture. Table II gives the volume, weight, and density for each sample.

TABLE II

VOLUME, WEIGHT, AND DENSITY OF SEED SAMPLES

Sample No.	Volume $In.^3$	Weight Grams	Density $Lbs./Ft.^3$
Wheat (Three-Material Mixture)			
1	1.36	31.68	89.2
2	1.36	31.57	88.5
3	0.96	23.28	92.2
4	1.02	23.84	89.6
Average			
Wheat (Two-Material Mixture)			
1	2.72	61.99	86.6
2	3.41	77.79	86.8
3	2.46	55.25	85.5
4	1.79	40.05	85.7
Average			86.1
			89.8

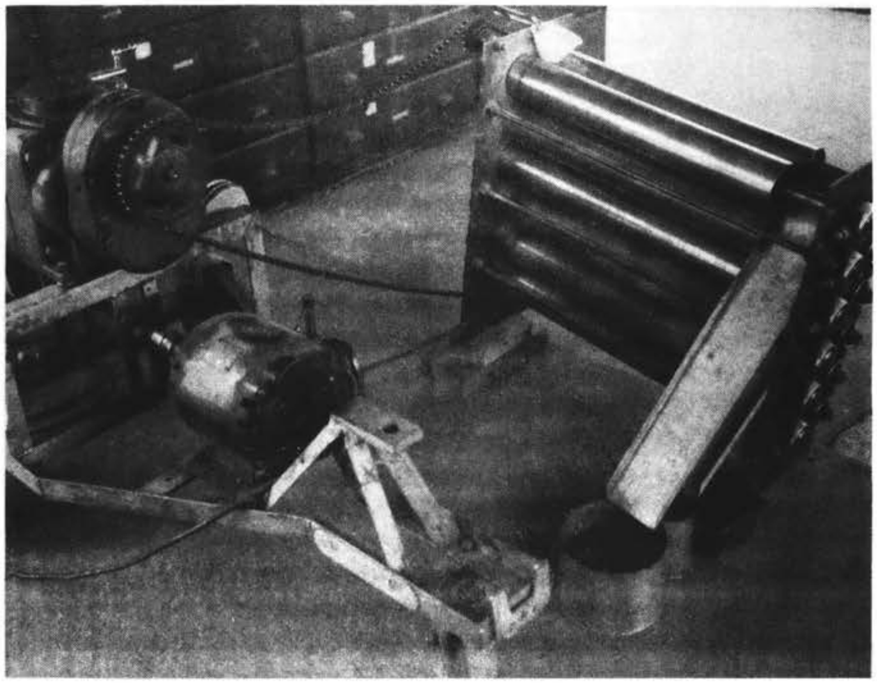

Figure 35. Roll Grader Used for Sizing and Sorting Agricultural Materials

TABLE II (Continued)

Soybeans

Sample No.	Volume $In.^3$	Weight Grams	Density $Lbs./Ft.^3$
1	1.47	31.91	82.8
2	1.44	30.94	81.5
3	1.64	32.90	76.5
4	0.93	20.13	82.6
Average			80.8
		Sorghum	
1	1.45	31.02	81.9
2	1.81	40.18	84.2
3	1.45	32.62	85.6
4	1.85	40.87	83.9
Average			83.9

Ten samples of 20 seeds for soybeans and 100 seeds for sorghum and wheat were drawn at random from the graded material and measured for volume (Appendix B-II). The average volume per seed was then found by division and the equivalent diameter computed as outlined by Dallavalle (5). Table III gives the average volume and equivalent diameter for each seed group.

TABLE III

AVERAGE SEED VOLUME AND EQUIVALENT DIAMETER

	Average Volume ($In.^3$)	Equivalent Diameter (Ft.)
Wheat (Three-Material Mixture)	0.00166	0.0123
Wheat (Two-Material Mixture)	0.00151	0.0119
Soybeans	0.00687	0.0197
Sorghum	0.00127	0.0112

Volume Measuring Manometer

Figure 36 shows the volume measuring manometer used for determining bulk volume. Material is placed in the chamber and the removable end sealed. Turning the hand crank closes the bellows forcing air into the chamber and raises the mercury column. The pressure, and thus the mercury differential, is proportional to the free space within the chamber since a constant volume differential is produced by the bellows. The procedure followed to measure grain volume is in Chapter V. A calibration curve with calibration procedure is in Appendix A-V.

Vibratory Feeder

The vibratory feeder shown in Figure 37 was used to meter the seed into the entrance feeder. It consists of a small storage bin and funnel positioned above a vibrating trough. Feed rate was varied by either raising the funnel with respect to the trough or by varying the amplitude of trough vibration. A potentiometer was used to vary the amplitude. Calibration data and calibration procedure for the feeder is in Appendix A-VI.

Entrance Feeder

Figure 38 shows the apparatus used to feed the seeds into the system. A hopper was constructed and mounted on a section of 7-inch pipe. The ball feeder frame was modified and used as the support structure. A rotating seal, constructed of 1/8-inch belting flaps mounted on a 3/4-inch shaft permitted the seed to be fed into the system without appreciable air leakage. The seal was rotated by a

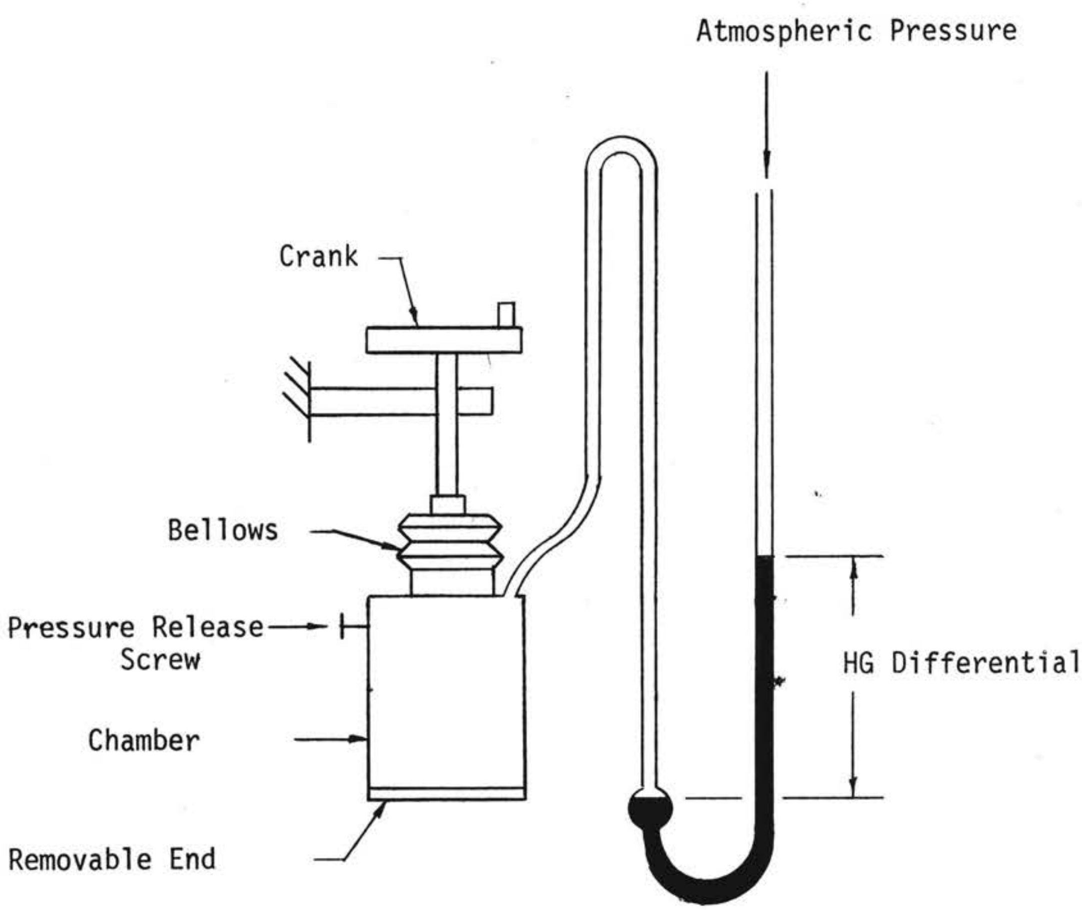

Figure 36. Volume Measuring Manometer

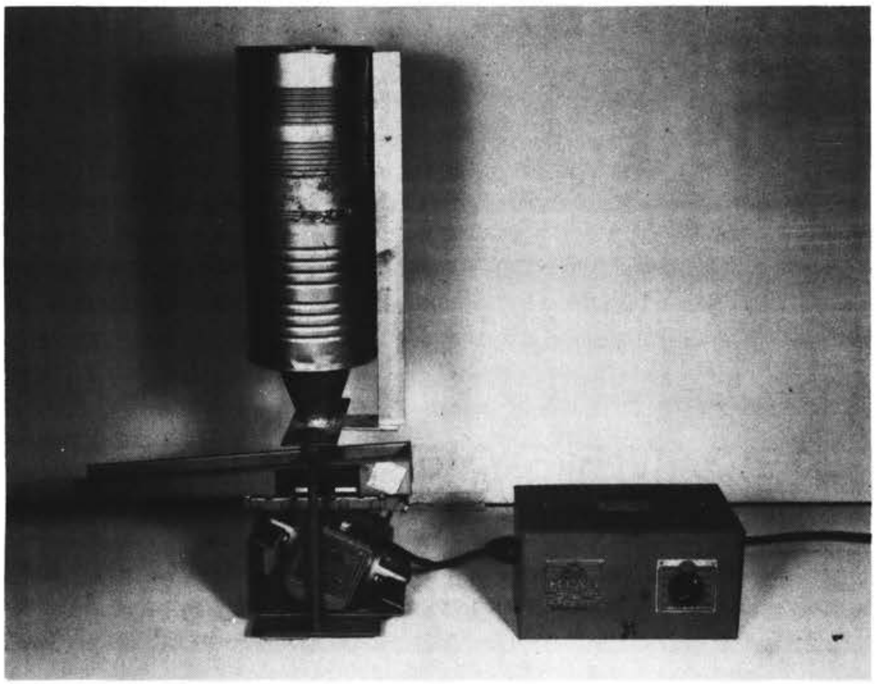

Figure 37. Vibratory Feeder

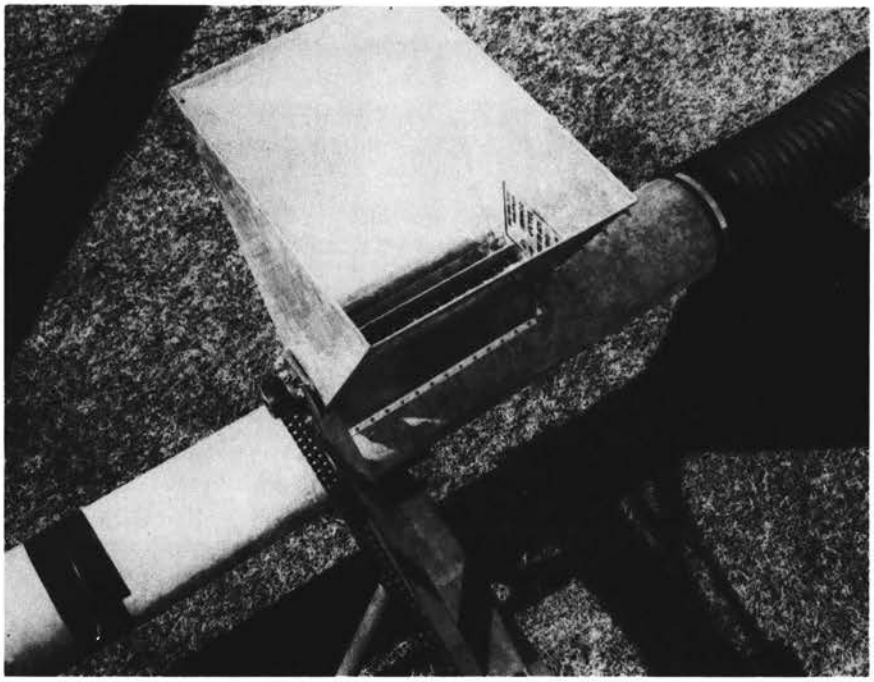

Figure 38. Entrance Feeder

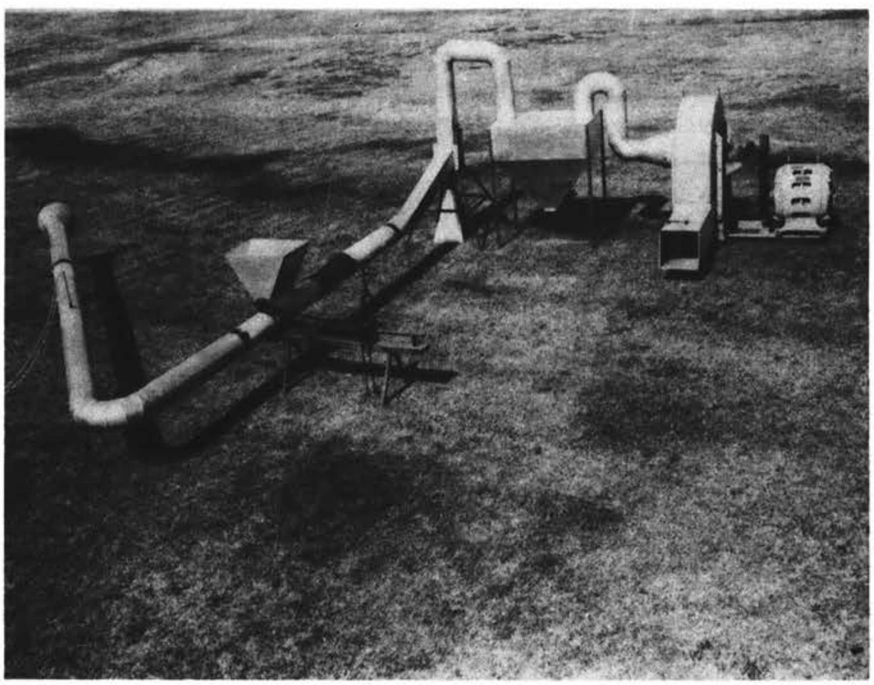

Figure 39. Complete Separating System Showing the Collection Tank

variable speed drive. Rotation was about 100 rpm, sufficient to give uniform feeding at the three metering rates of the vibratory feeder.

Collection Tank

During continued mass flow, the ball removal screen and spout were replaced with the collection tank shown in Figure 39. A screen was fastened over the exit pipe to prevent seed loss through the fan.

CHAPTER V

PROCEDURE

This study was divided into two parts, each part having a specific objective. The first objective sought was that of predicting the percent separated of a given description of balls in terms of the system parameters as set forth in Table I of Chapter III. The experiment schedule followed for Part One is given in Table IV.

The second part of this study involved separation of agricultural material with continued mass flow. The experiment schedules for Part Two are given in Tables V and VI.

Randomization and Experimental Procedure for Part One

In theory it would have been desirable to completely randomize the order of the Pi terms and their respective levels; however, this was not practical. The following randomization procedure was used for Part One:

1. The order of energy dissipating backstops was randomized.
2. The order of the Pi terms for each backstop was randomized.
3. The order of levels for each Pi term was randomized.

The tests were conducted according to the experiment schedule (Table IV) with Pi 9 held constant at 70 degrees. Four observations were made for each level of the Pi terms.

TABLE IV

EXPERIMENT SCHEDULE FOR PART ONE

Pi 1	Pi 2	Pi 3	Pi 4	Pi 5	Pi 6	Pi 7	Pi 8
Observed Response	114.36	$0.035 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	52.30/Pa	$2.25 \times [\frac{Pa^2}{Ua^2} \times 10^{-3}]$	0.9376	$1.399 \times 10^{-3}/Ua$	$0.0930/Ua^2$
	144.83	$0.118 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	54.37/Pa	$2.55 \times [\frac{Pa^2}{Ua^2} \times 10^{-3}]$	0.8988	$3.496 \times 10^{-3}/Ua$	$0.1348/Ua^2$
	178.73	$0.285 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	58.29/Pa	$3.33 \times [\frac{Pa^2}{Ua^2} \times 10^{-3}]$	0.8231	$6.993 \times 10^{-3}/Ua$	$0.1573/Ua^2$
	216.09	$0.547 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	63.01/Pa	$3.89 \times [\frac{Pa^2}{Ua^2} \times 10^{-3}]$	0.7820	$10.56 \times 10^{-3}/Ua$	$0.2397/Ua^2$
	257.47	$0.940 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	69.11/Pa			$14.05 \times 10^{-3}/Ua$	$0.3033/Ua^2$
	302.30	$1.51 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	71.98/Pa			$17.55 \times 10^{-3}/Ua$	$0.3745/Ua^2$
	350.57	$2.24 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$	134.50/Pa			$21.05 \times 10^{-3}/Ua$	$0.4531/Ua^2$
	402.30	$3.19 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$				$24.54 \times 10^{-3}/Ua$	$0.5393/Ua^2$
	457.47	$4.39 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$					
	516.66	$7.57 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$					
	579.31	$12.1 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$					
	645.40						

Note: Each Pi term was varied independently with the others held constant as follows:

Pi 2 = 516.66

Pi 3 = $2.25 \times [\frac{Pa^2}{Ua^2} \times 10^{-6}]$

Pi 4 = 63.14/Pa

Pi 5 = $2.25 [\frac{Pa^2}{Ua^2} \times 10^{-3}]$

Pi 6 = 0.9376

Pi 7 = $1.399 \times 10^{-3}/Ua$

Pi 8 = $0.239/Ua^2$

A preliminary test run was made with the canvas backstop as the energy dissipator. An analysis of variance of the response of Pi 1 due to varying Pi 8 indicated no significant differences in the value of Pi 1. The pressure behind the canvas was, therefore, held constant at about 0.8 inches of water for the duration of the tests with the canvas as backstop.

Procedure Used in Conducting a Test for Part One

The test schedule was carried out for all six energy dissipating backstops described in Chapter IV. A set of component equations were formed for each backstop using the least squares method. Prediction equations were then determined for each backstop.

The following procedure was followed in conducting the tests of Part One:

1. The separator and accessories were set up according to the experiment schedule.
2. All equipment was started and allowed to operate until it was warmed to operating temperature. (Fan, feeder motor, and hygrothermograph).
3. The ambient air temperature, relative himidity, and barometric pressure were observed and the air density computed.
4. The manometer was set at the desired value for scheduled air volume rate.
5. The fan exit adjustment was varied until the manometer setting of procedure number four was accomplished.
6. All adjustments were checked against the schedule. If correct, 20 balls were fed into the system at the scheduled rate.

7. The balls were then retrieved from the collectors and the number in the separator hopper recorded. The 20 balls were fed in again until four observations were recorded.
8. Steps three through seven were repeated according to the experiment schedule until the schedule was completed.
9. The steps one through eight were repeated for each energy dissipating backstop.

Randomization and Experimental Procedure for Part Two

Part Two of this study involved investigation of prolonged mass flow of agricultural material through the separator. Mixtures of wheat, grain sorghum, and soybeans were fed into the system at 6, 12, and 18 pounds per minute. Six mixtures of wheat, grain sorghum, and soybeans (Table V) and four mixtures of wheat and soybeans (Table VI) were used for the tests. The tests were conducted in randomized block fashion. Tables V and VI show the random order in which the individual tests were made.

Separator parameters were held constant for all tests within each group of mixtures. A separator chamber width of 6.1 inches, an inlet duct width of 5.0 inches, and an air flow rate of 10.6 cubic feet per second were used for tests with the three-material mixtures. For the two-material mixture tests the separator width was 6.4 inches, the inlet duct was 6.0 inches, and the air flow rate was 11.0 cubic feet per second. The "bean bag" backstop was used for both mixtures.

Close agreement between those tests replicated (Tables V and VI and Appendix C-V) and their respective counter parts was considered as evidence indicating little need for complete replication.

TABLE V

EXPERIMENT SCHEDULE FOR PART TWO

(Three-Material Mixture)

Test No.	Material	Percent of Total Wt.	Feed Rate
1	Soybeans(A)	10%	18#/Min.
	Sorghum(B)	35%	
	Wheat(C)	55%	
2	A	10%	12#/Min.
	B	55%	
	C	35%	
3	A	35%	18#/Min.
	B	10%	
	C	55%	
4	A	35%	12#/Min.
	B	10%	
	C	55%	
5	A	55%	12#/Min.
	B	10%	
	C	35%	
6	A	10%	6#/Min.
	B	55%	
	C	35%	
7	A	35%	6#/Min.
	B	10%	
	C	55%	
8	A	10%	12#/Min.
	B	35%	
	C	55%	
9	A	10%	18#/Min.
	B	55%	
	C	35%	
10	A	55%	18#/Min.
	B	10%	
	C	35%	

TABLE V (Continued)

Test No.	Material	Percent of Total Wt.	Feed Rate
11	A	55%	12#/Min.
	B	35%	
	C	10%	
12	A	35%	6#/Min.
	B	55%	
	C	10%	
13	A	10%	6#/Min.
	B	35%	
	C	55%	
14	A	55%	6#/Min.
	B	35%	
	C	10%	
15	A	35%	12#/Min.
	B	55%	
	C	10%	
16	A	35%	18#/Min.
	B	55%	
	C	10%	
17	A	55%	18#/Min.
	B	35%	
	C	10%	
18	A	55%	6#/Min.
	B	10%	
	C	35%	

Test numbers 4, 17, and 18 were replicated.

TABLE VI

EXPERIMENT SCHEDULE FOR PART TWO

(Two-Material Mixture)

Test No.	Material	Percent of Total Wt.	Feed Rate
1	Soybeans(A) Wheat(B)	80% 20%	6#/Min.
2	A B	40% 60%	18#/Min.
3	A B	20% 80%	12#/Min.
4	A B	40% 60%	6#/Min.
5	A B	60% 40%	6#/Min.
6	A B	60% 40%	18#/Min.
7	A B	60% 40%	12#/Min.
8	A B	80% 20%	12#/Min.
9	A B	80% 20%	18#/Min.
10	A B	20% 80%	6#/Min.
11	A B	20% 80%	18#/Min.
12	A B	40% 60%	12#/Min.

Test numbers 1, 3, 8, 9, 10, and 11 were replicated.

Procedure for Conducting a Test in Part Two

The tests of Part Two were conducted in the following manner:

1. The separator was assembled as described previously and the air flow adjusted.
2. A seed mixture was poured into the vibrator feeder and the feeder set to the proper feed rate as scheduled.
3. The entrance feeder was started as well as the separator fan and a short period of time allowed for warm-up.
4. The vibrator feeder was started and the seed metered into the system for a period of approximately 45 to 50 seconds duration.
5. All equipment was turned off and the remaining seed removed from the feeder hopper.
6. The "separated" and "collected" fractions were removed, bagged, and labeled.
7. Steps 2 through 6 were repeated for all succeeding scheduled tests.

The above procedure was used for both mixtures. All tests were later separated into the seed groups and each group weighed. The original data collected from the tests of Part Two is presented in Appendix C-V.

Procedure Used to Control Ball Size and Density

The tables presented in Appendix B show the physical data considered for the plastic balls. The average diameter, density, and terminal velocity was computed for each density group. A maximum allowable deviation from the average terminal velocity was computed and all values exceeding this range were omitted.

Maximum and minimum manometer readings were observed at 17 cubic feet per second and 25 cubic feet per second air flow rates. These values were used in a variation of Equation 4.2:

$$\Delta V = V_1 - V_2 = 18.3 \left(\sqrt{\frac{0.7567P_1}{\gamma}} - \sqrt{\frac{0.7567P_2}{\gamma}} \right) \tag{5.1}$$

where

ΔV = velocity change (ft./sec.)

V_1 = maximum velocity (ft./sec.)

V_2 = minimum velocity (ft./sec.)

P_1 = maximum pressure (inches of methanol)

P_2 = minimum pressure (inches of methanol)

γ = air density (pounds per cubic foot)

ΔV was multiplied by 0.92 to give the change in average velocity and one-half of this value was used as the allowable deviation from the mean terminal velocity. $\pm$ 0.40 foot per second was used for polystyrene balls and $\pm$ 0.63 foot per second was used for the remaining balls.

Procedure Used to Measure Seed Volume

The procedure used to determine wheat, grain, sorghum, and soybean volume was as follows:

1. Four random samples were taken for each grain from the test material.
2. The volume manometer cup was filled with the grain being measured and placed in position with the bellows compressed.

3. The pressure release screw was closed and the cup cover plate clamped sufficiently tight to cause the manometer differential to be 1.2 mm of H_g.
4. The pressure release was opened and the bellows opened to the maximum.
5. The pressure release was closed and the bellows compressed to the maximum causing the H_g level to rise. The H_g differential was read with the bellows completely compressed.
6. The grain volume was read from the calibration curve (Appendix A-V). This procedure was repeated for each sample.

CHAPTER VI

PRESENTATION AND ANALYSIS OF DATA

The following is a numerical evaluation of the system variables as they were used in their respective Pi terms. The values of the individual Pi terms are given for each level used in the tests.

$$\text{Pi } 2 = Q^2 Ne/GD^5$$

Constant values of 0.0312 lbf./lbm. - ft./sec.^{2} and 32.16 ft./sec.^{2} were used for Ne and G respectively. The Pi term was varied by changing the value of Q. The values of Pi 2 are presented in Table IV.

$$\text{Pi } 3 = \frac{Dia^3 Pa^2 NeG}{Ua^2}$$

Constant terms Ne and G as given for Pi 2, and Ua equal to 0.03×10^{-5}, were used for Pi 3. Pa, the air density, was not controlled but was recorded for each test (Appendix C-III). The average air density was used in computing the various values of Pi 3 for the component equations. Dia was varied to give the following values of Pi 3:

2,146.857	137,398.900
7.237.976	195,670.700
17,481.550	269,277.200
33,552.310	464,334.600
57,658.450	742,199.200
92,621.550	

$$Pi\ 4 = Pp/Pa$$

The average of Pa for all tests of Pi 4 was used in the computation of Pi 4. Pi 4 was varied by changing material densities. Values were:

703.903	930.148
731.763	968.775
784.522	1810.229
848.048	

$$Pi\ 5 = \frac{d^3 Pa^2 NeG}{Ua^2}$$

Pi 5 differs from Pi 4 in the length parameter only. Pi 5 was varied by changing the inlet duct dimensions. The values of Pi 5 were as follows:

1.3801×10^8	2.0426×10^8
1.5641×10^8	2.3861×10^8

$$Pi\ 6 = d/D$$

Pi 6 was held constant for changes in Pi 5 by varying D. The ratios of Pi 7 and Pi 8 also were held constant by varying R and P, respectively. Values of Pi 6 are presented in Table IV.

$$Pi\ 7 = \frac{RNe}{DUa}$$

The feed rate, R, was varied in Pi 7 to control the Pi term values. Ne and Ua were constant. The values of Pi 7 were as follows:

4,663.33	46,833.33
11,653.33	58.500.00
23,310.00	70,166.67
35,200.00	81,800.00

$$Pi\ 8 = \frac{P^2 NeD}{Ua^2 G}$$

Pi 8 was varied through a range of values from 1.033×10^{12} to 5.992×10^{12} for the canvas backstop. From analysis of variance, it was concluded that no significant changes in Pi 1 were effected by varying Pi 8. Thus, Pi 8 was held approximately constant at 2.663×10^{12} for the duration of testing with the canvas backstop. Pi 8 was not applicable to any other backstop.

Pi 9 = B

B was the angle of the inlet duct centerline measured from the vertical. This was held constant for all tests at 70 degrees.

After the experimental work for Part One was completed, a Fortran program was written for the IBM 7040 computer to process the raw data. Data recorded for the tests were punched in cards and used as input for the program. The processed data are presented in Appendix C-II. In all but two tests, the percents represent the separated fraction of 20 balls passed through the system. Pi 3 Test 1 of Bean Bag and Closed Cell backstops are the exceptions. Nineteen balls were used due to previous losses.

Presentation of Component Equations

The component equations were found with an existing Fortran computer program which makes use of the least squares method of fitting polynomial models to data. Three models were chosen and the coefficients for these models found for each component equation data set. The models were:

$$\text{Pi } 1 = C_1 + C_2 \text{ Pi N}$$

$$\text{Pi } 1 = C_1 + C_2 \text{ Pi N} + C_3(\text{Pi N})^2$$

and

$$Pi\ 1 = C_1 + C_2\ Pi\ N + C_3(Pi\ N)^2 + C_4(Pi\ N)^3$$

The highest order polynomial was chosen for all component equations. R^2, the percent variation in Pi 1 accounted for by knowing Pi X (X = 2 through 7), was used as a basis for the choice of model.

Table VII gives the coefficients of the component equations for all Pi terms and for all backstops as computed from the original data of Appendix C-II.

The component equations are plotted in Figures 40, 41, 42, 43, and 44.

The curves of Figure 40, Pi 1 versus Pi 2, have approximately a 45 degree slope. According to Wessel (8), the slope of the "Tromp" curve, to which these curves are related, is an indication of the separator's selectivity. Selectivity is defined as the ability to separate one material from another. The steeper the curve, the better the selectivity and the smaller the amount of overlap of the separated fractions. The best selectivity is indicated for the system with the carpet backstop.

The sensitivity of the separator to particle diameter is indicated by the plot of Pi 1 versus Pi 3 (Figure 41). For values of Pi 3 between 10,200 and 140,000, particle diameter has a large influence on percent separation. The polyurethane foam, Hi-Car, and carpet backstops have slightly steeper slopes in this region than the other three. All of the Pi 3 values represent Reynolds Numbers of over 1,000, indicating system operation in the range where shape and size of particle is significant but where viscosity is not.

The effect of particle density on percent separation is shown in Figure 42. An increase in density caused an increase in separation for all backstops. No experimental data were taken for values of Pi 4

TABLE VII

COEFFICIENTS FOR COMPONENT EQUATIONS

$$\text{Model Pi } 1 = C_1 + C_2 \text{ Pi N} + C_3(\text{Pi N})^2 + C_4(\text{Pi N})^3$$

R^2 = Percent Variation in Pi 1 Accounted for by Knowing $P_i N$

N	Backstop	C_1	C_2	C_3	C_4	R_2
2	Canvas	0.82395×10^{2}	0.22033	-0.71078×10^{-3}	0.38773×10^{-10}	0.911
	Carpet	0.37426×10^{2}	0.81671	-0.29154×10^{-2}	0.24906×10^{-5}	0.938
	Polyurethane Foam	0.78205×10^{2}	0.38758	-0.18013×10^{-2}	0.16689×10^{-5}	0.886
	Closed Cell	0.66633×10^{2}	0.45793	-0.16834×10^{-2}	0.13061×10^{-5}	0.920
	Bean Bag	0.85405×10^{2}	0.19036	-0.65853×10^{-3}	0.38977×10^{-6}	0.901
	Hi-Car	0.43882×10^{2}	0.73053	-0.26111×10^{-2}	0.22722×10^{-5}	0.921
3	Canvas	0.45405×10^{-1}	0.45540×10^{-3}	-0.91086×10^{-5}	0.61992×10^{-15}	0.880
	Carpet	0.74985×10^{-2}	0.16906×10^{-3}	0.72593×10^{-10}	-0.21727×10^{-15}	0.933
	Polyurethane Foam	-0.19590×10^{-1}	0.21959×10^{-3}	0.72624×10^{-10}	-0.28272×10^{-15}	0.940
	Closed Cell	-0.43250×10^{1}	0.38149×10^{-3}	-0.87944×10^{-9}	0.71639×10^{-15}	0.873
	Bean Bag	0.71880×10^{2}	0.37563×10^{-3}	-0.68240×10^{-9}	0.41299×10^{-15}	0.855
	Hi-Car	-0.11205×10^{-1}	0.28745×10^{-3}	-0.24570×10^{-9}	0.42202×10^{-15}	0.950
4	Canvas	0.27640×10^{-3}	-0.87831	0.94276×10^{-3}	-0.28283×10^{-6}	0.866
	Carpet	-0.11989×10^{4}	0.35265×10^{1}	-0.32247×10^{-2}	0.92003×10^{-6}	0.886

TABLE VII (Continued)

N	Backstop	C_1	C_2	C_3	C_4	R^2
	Polyurethane Foam	-0.47278×10^{3}	0.13576×10^{1}	-0.11718×10^{-2}	0.32680×10^{-6}	0.862
	Closed Cell	0.30588×10^{3}	-0.92368	0.92507×10^{-3}	-0.26343×10^{-6}	0.854
	Bean Bag	-0.41236×10^{3}	0.13199×10^{1}	-0.11981×10^{-2}	0.34647×10^{-6}	0.692
	Hi-Car	-0.45563×10^{3}	0.13184×10^{1}	-0.11332×10^{-2}	0.31669×10^{-6}	0.878
5	Canvas	0.12623×10^{4}	-0.17030×10^{-4}	0.73660×10^{-13}	-0.10025×10^{-21}	0.852
	Carpet	0.63072×10^{3}	-0.80053×10^{-5}	0.30672×10^{-13}	-0.32002×10^{-22}	0.852
	Polyurethane Foam	0.11162×10^{4}	-0.16996×10^{-4}	0.84480×10^{-13}	-0.13562×10^{-21}	0.747
	Closed Cell	0.11357×10^{4}	-0.16395×10^{-4}	0.76106×10^{-13}	-0.11172×10^{-21}	0.725
	Bean Bag	0.41261×10^{4}	-0.66294×10^{-4}	0.35029×10^{-12}	-0.60332×10^{-21}	0.709
	Hi-Car	0.13040×10^{4}	-0.18504×10^{-4}	0.84975×10^{-13}	-0.12509×10^{-21}	0.815
6	Canvas	0.27540×10^{4}	-0.69620×10^{4}	0.46374×10^{4}	-0.29755×10^{3}	0.932
	Carpet	-0.21322×10^{4}	0.65091×10^{4}	-0.66830×10^{4}	-0.23548×10^{4}	0.692
	Polyurethane Foam	0.36426×10^{3}	-0.45650×10^{3}	-0.54910×10^{3}	0.69961×10^{3}	0.859
	Closed Cell	0.42013×10^{2}	0.25630×10^{4}	-0.62437×10^{4}	0.37472×10^{4}	0.677
	Bean Bag	-0.13571×10^{4}	0.76764×10^{4}	-0.12185×10^{5}	0.59875×10^{4}	0.316
	Hi-Car	-0.12085×10^{4}	0.41338×10^{4}	-0.49642×10^{4}	0.21110×10^{4}	0.838

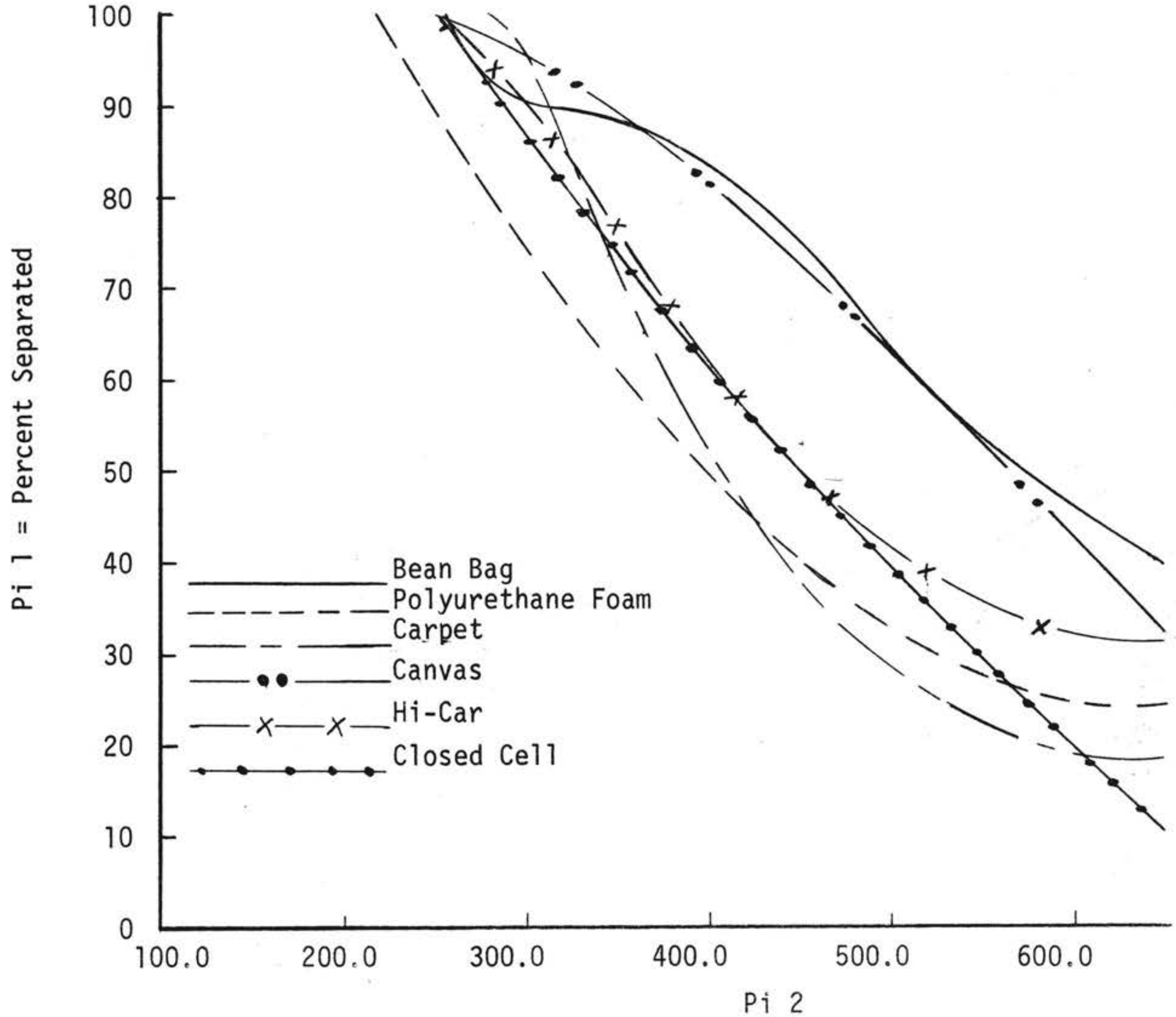

Figure 40. Pi 1 Versus Pi 2

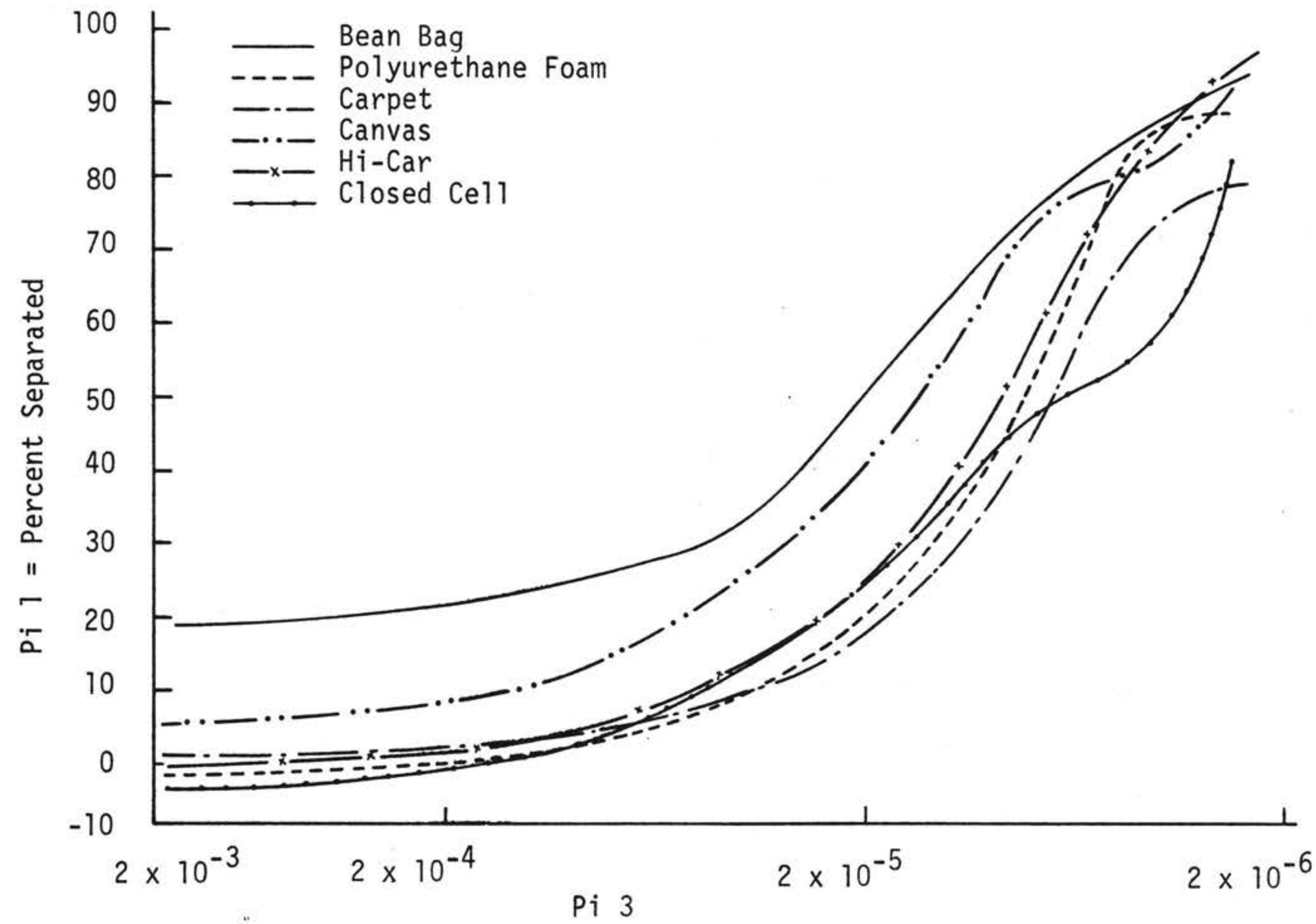

Figure 41. Pi 1 Versus Pi 3

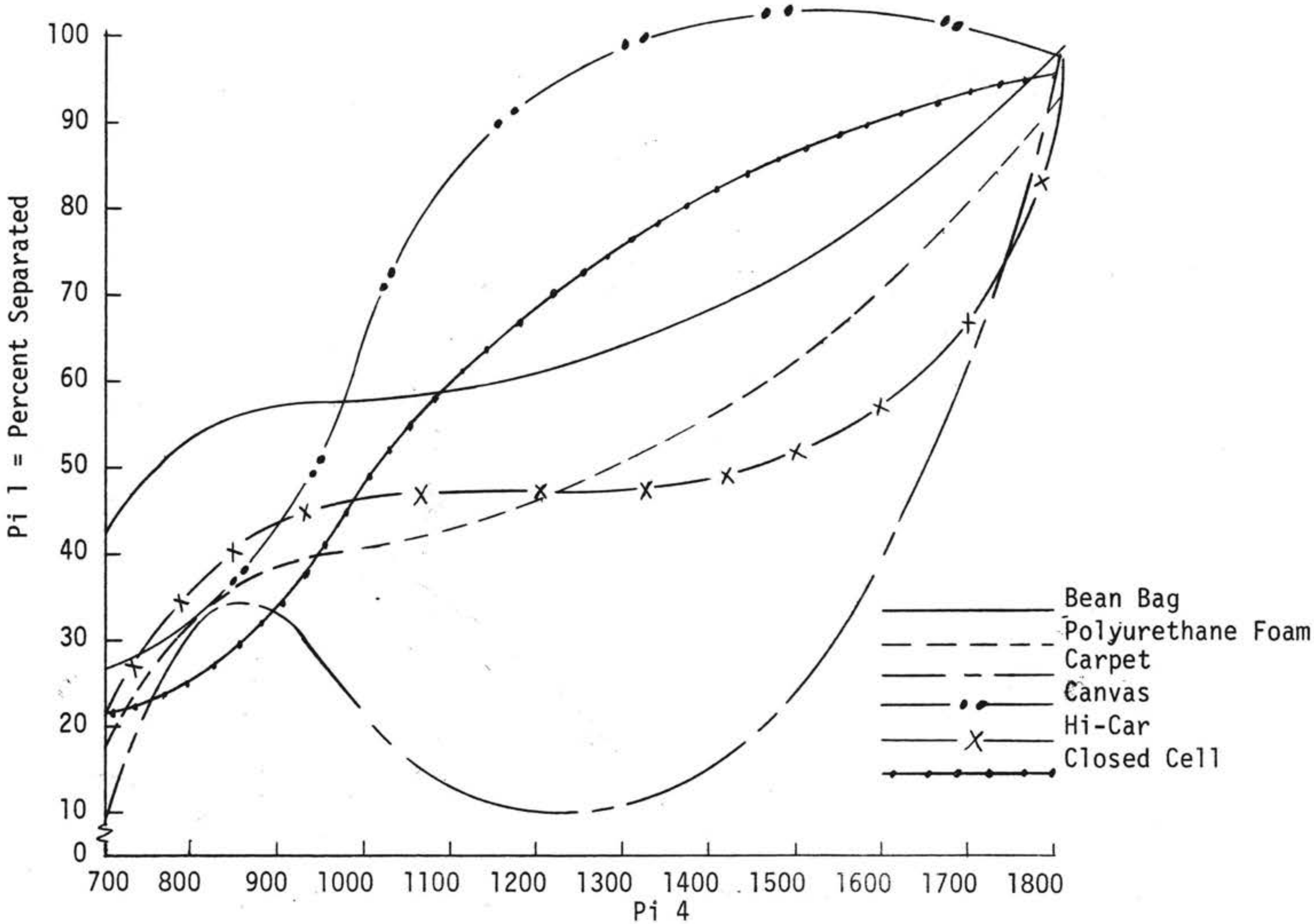

Figure 42. Pi 1 Versus Pi 4

between 960 and 1800; therefore, very little importance should be placed on this portion of the curves. In every case, the curves end with percent separation values between 90 and 98 percent at Pi 4 equal to 1810. An experimental observation was made at Pi 4 equal to 1810.

The results indicate that increased density caused increased separation.

Percent separation was highest for both extremes of inlet duct size (Figure 43). The lower percent separation for values of Pi 1 between 1.6 and 2.1 may possibly be due both to air flow phenomena within the separator and to backstop effects. The reasonable result of enlarging the inlet duct would seem to be the slowing of the entering air and, thus, the particle velocity. This would be expected to result in increased separation as reflected by the curves between Pi 5 equal to 1.8 and 2.3. On the other hand, decreasing the inlet duct size would increase inlet velocities thus decreasing the percent of particles retained by the separator. This was not the case within the investigated range of Pi 5. (Reasons for the relative large values of Pi 1 at Pi 5 equal to 2.3861×10^8 are not known; however, insufficient evidence exists for disregarding it.)

The plot of Pi 1 versus Pi 6 (Figure 44) presents somewhat the same phenomena as Pi 1 versus Pi 5. Increases in separator chamber width resulted in decreased percent separation for bean bag, closed cell, and canvas backstops between Pi 6 equal to 0.78 and 0.85. Percent separation was increased for values beyond 0.85. Separation was increased by enlarging the chamber size for polyurethane foam, Hi-Car, and carpet backstops throughout the range of Pi 6.

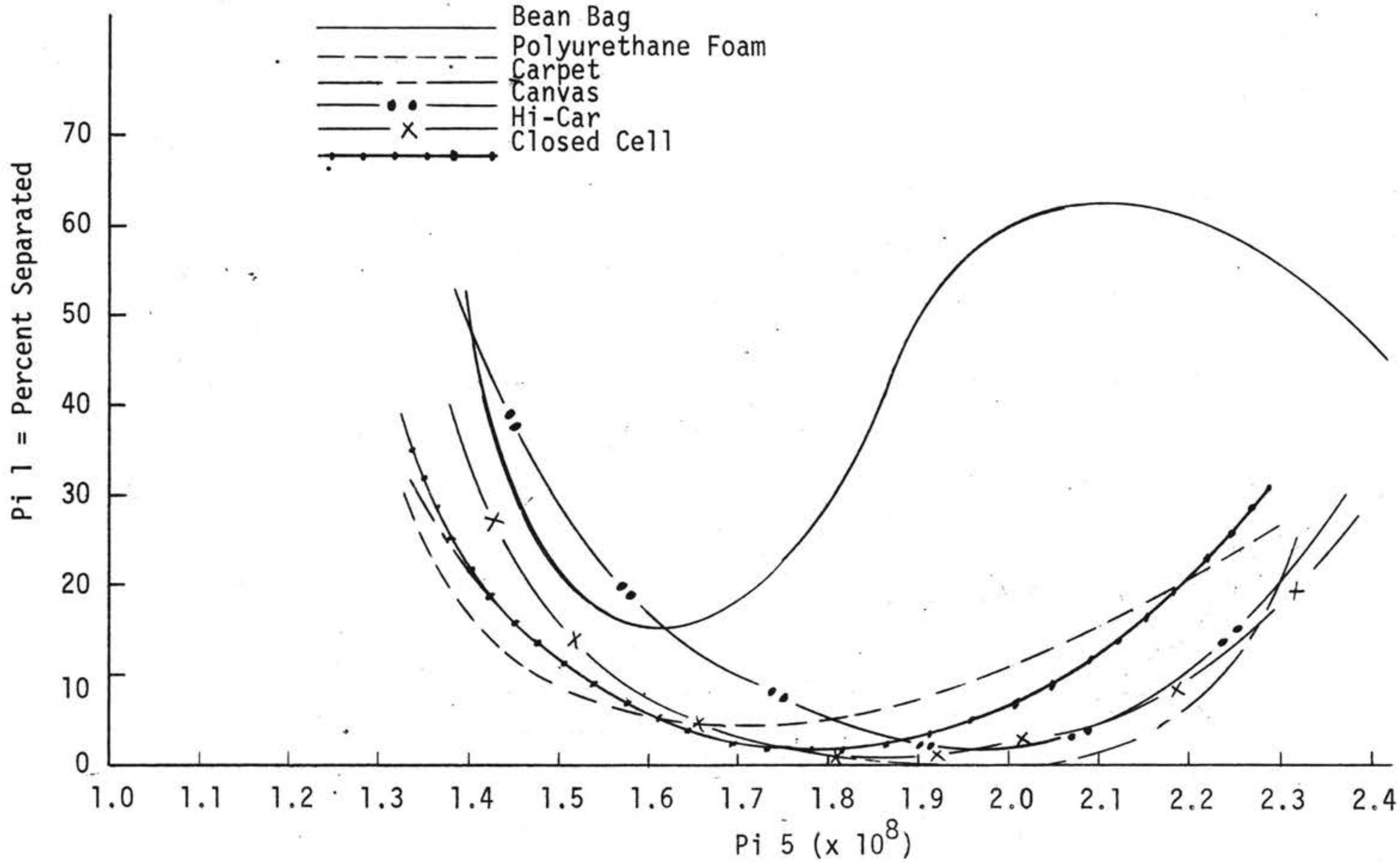

Figure 43. Pi 1 Versus Pi 5

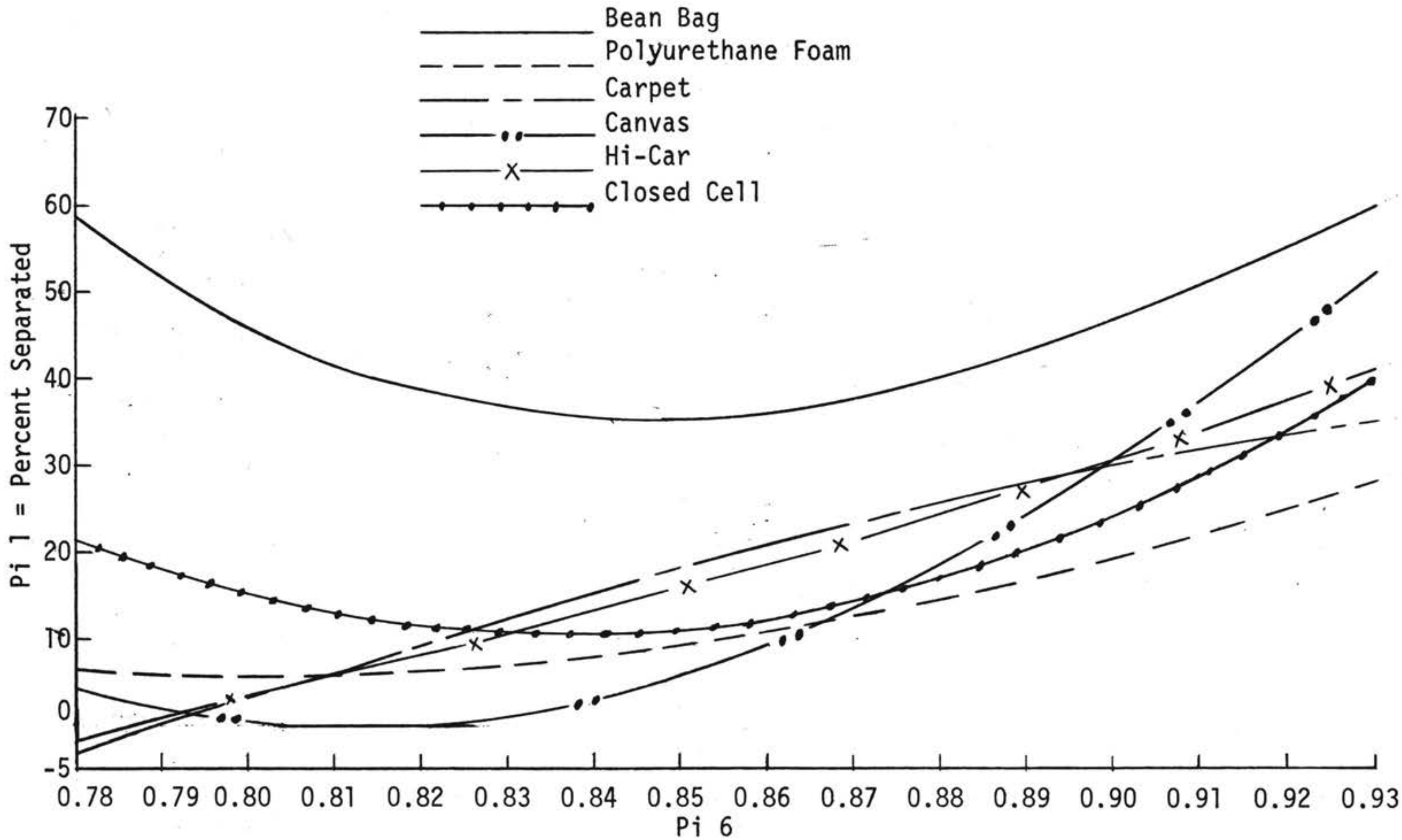

Figure 44. Pi 1 Versus Pi 6

An "F" test at the 95 percent level indicated no significant difference in Pi 1 for changes in Pi 7 within the range through which Pi 7 was varied. No plot of Pi 1 versus Pi 7 was made and Pi 7 was not included in the data used for computing the prediction equations.

Discussion of Backstop Coefficient of Restitution

A major portion of this study involved investigation of the effect of various energy dissipating backstops on separator performance. Six different backstops were used in the separator for each of the varied parameters. Figures 40 through 44 show the relative effect on system performance of these backstops.

The coefficient of restitution, defined as the square root of the ratio of height of rebound to height of drop, was used as an indicator of energy absorption capacity of the backstops. A low coefficient represents a high degree of energy absorption capacity. A series of tests were made to determine the effect on the coefficient of restitution by ball diameter, drop height, and ball density. Four diameters, 1/8, 1/4, 1/2, and 7/8 inches, densities of 54.37, 58.29, 63.01, 69.11, and 134.5 pounds per cubic foot, and drop heights of 12, 30, 42, and 48 inches were investigated for the carpet backstop. The data from these tests are presented in Appendix C-I.

Figures 45, 46, and 47 show the effect of the varied parameters on the coefficient of restitution. Each parameter was varied individually with the others held constant. Diameter of 1/2 inch, density of 63.01 pounds per cubic foot, and drop heights equal to 48 inches were the constant values.

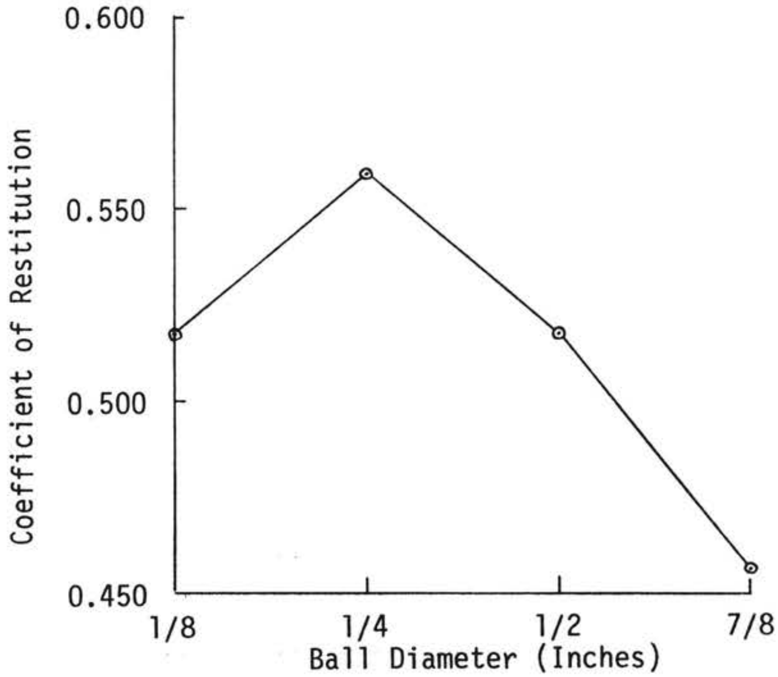

Figure 45. Coefficient of Restitution Versus Ball Diameter

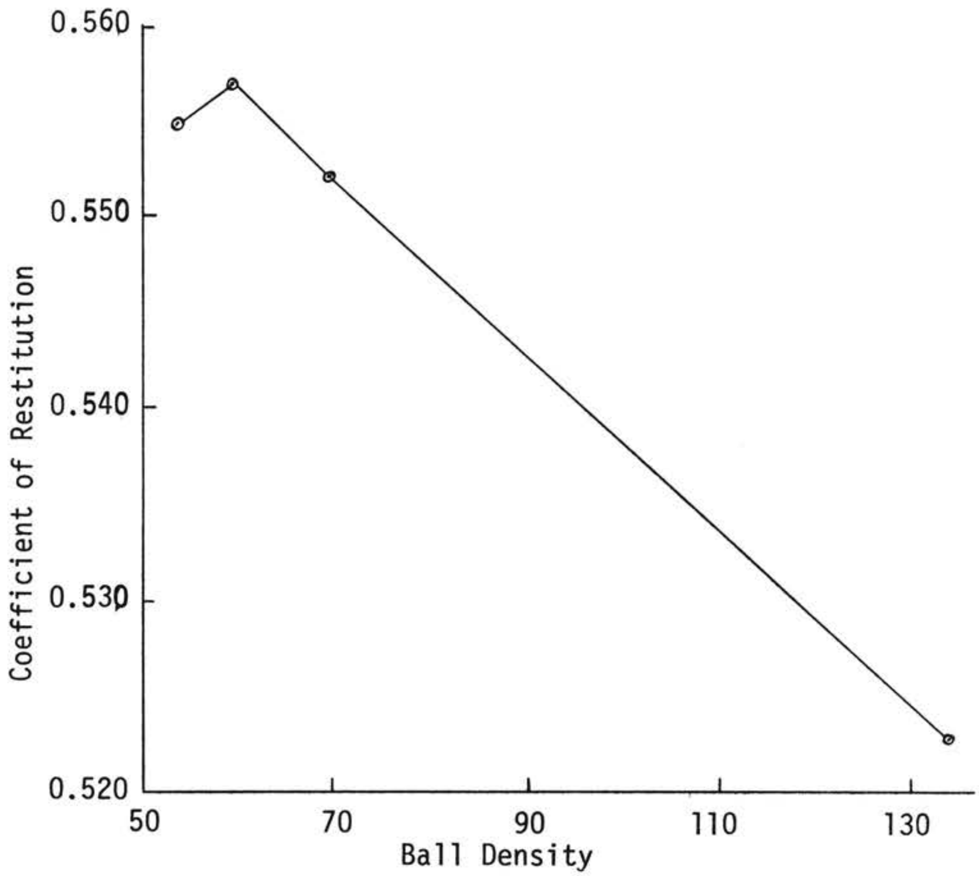

Figure 46. Coefficient of Restitution Versus Ball Density

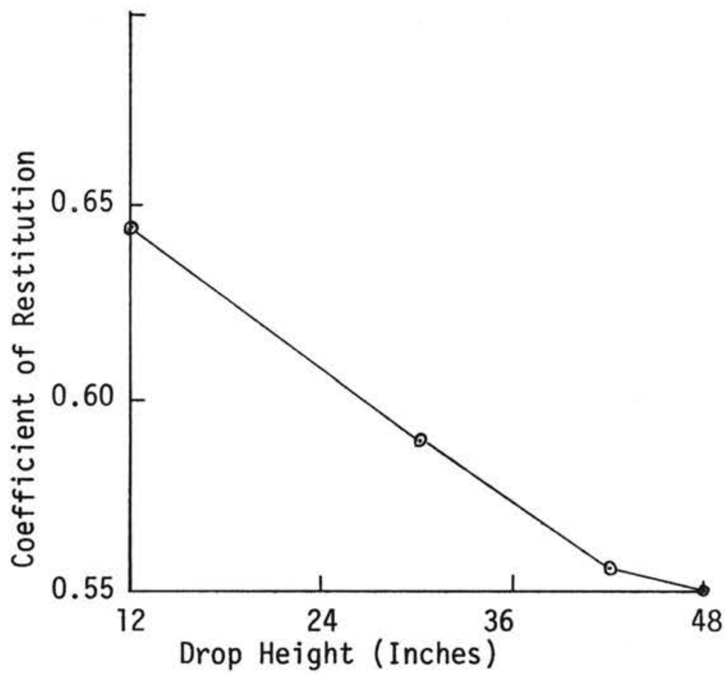

Figure 47. Coefficient of Restitution Versus Drop Height

Generally, increases in impact energy, regardless of the method by which it was achieved, resulted in decreases in the coefficient of restitution. Two exceptions to this were the 1/8-inch diameter test (Figure 45) and the test where ball density was 54.37 pounds per cubic foot (Figure 46). The carpet layer evidently absorbed the energy of these balls and was a better energy absorber than was the foam rubber backing. This conclusion is further substantiated by the higher coefficient of restitution obtained for the 1/4-inch balls and the 58.29 pounds per cubic foot density. At these conditions, the foam rubber backing was depressed and released more of the impact energy to the balls than did the carpet or the plywood. For the larger and for more dense balls, the general trend was a reduction in the coefficient of restitution for increases in impact energy. It is expected that the other plywood backed backstops would show the same trend as did the carpet backstop, but likely at different values of impact energy. The canvas backstop would be expected to respond differently.

Figure 48 shows the relative energy absorbing capacities of the backstops. The bean bag and the canvas backstops had the highest energy absorbing capacity. Percent separation was highest for the bean bag and canvas backstops as shown by the component equation plots (Figures 40 through 44), thus indicating a possible relationship between separator performance and backstop coefficient of restitution.

The conclusion follows that particle inlet velocity, particle density, and particle diameter all have an effect on the performance of a plywood-backed energy dissipator such as those used in this study. No attempt was made to investigate all of the backstops in detail nor were these variables, as such, made a part of the prediction equation.

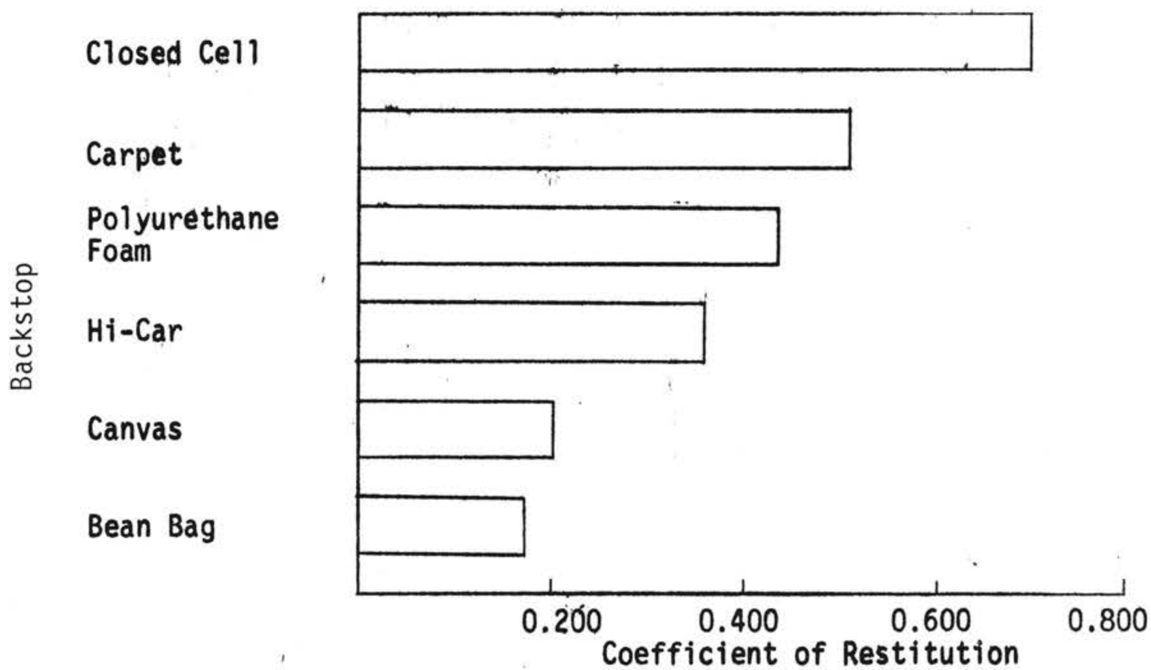

Figure 48. Relative Values of Backstop Coefficient of Restitution

Instead, a prediction equation for each backstop was found which includes within its scope the particular backstop characteristics.

Development of the Prediction Equations

A polynomial model of cubic order was selected for the prediction equations. Approximately 85 percent of the variation in Pi 1 was accounted for by knowing the values of the independent variables in the cubic model.

A quadratic model was also selected and a least squares fit computed for it. The values of R^2 generally were as good as for the cubic model; therefore, the second order polynomial was selected as the prediction equation model. The coefficients of the prediction equations for each backstop are presented in Table VIII.

Prediction Equation Test

During the experimental work, four sets of system parameters were selected as tests for the prediction equations. The system parameter values, with the corresponding Pi term values, are presented in Table IX. Twenty samples of 20 balls each were fed into the separator. The percents separated for the samples, within each parameter set, and for each backstop are presented in Appendix C-IV. The mean percent separated was computed, and a 95 percent confidence interval found for the means.

An evaluation of prediction equation accuracy was made by substituting the Pi term values of the check tests into the corresponding prediction equation. The equation was solved for the percent separated and this value compared with the actual percent separated.

TABLE VIII

COEFFICIENTS OF THE PREDICTION EQUATIONS

Model: $\text{Pi } 1 = C_0 + C_1\text{Pi } 2 + C_2(\text{Pi } 2)^2 + C_3(\text{Pi } 3) + C_4(\text{Pi } 3)^2 + C_5 \text{ Pi } 4 + C_6(\text{Pi } 4)^2 + C_7(\text{Pi } 5) + C_8(\text{Pi } 5)^2 + C_9 \text{ Pi } 6 + C_{10}(\text{Pi } 6)^2$

Coefficients	Canvas	Carpet	Bean Bag	Closed Cell	Polyurethane Foam	Hi-Car
C_0	0.7074903×10^4	-0.2177634×10^4	0.1605879×10^4	0.3319413×10^4	0.49599616×10^4	0.1200802×10^3
C_1	-0.3534610	-0.8175235	-0.6083180	-0.5475573	-0.1012164	-0.7543079
C_2	0.1787109×10^{-3}	0.6337891×10^{-3}	0.4941406×10^{-3}	0.3388672×10^{-3}	$-0.6640625 \times 10^{-2}$	0.6293945×10^{-3}
C_3	0.3354472×10^{-3}	0.2299675×10^{-3}	0.2906323×10^{-3}	0.2381630×10^{-3}	0.2906331×10^{-3}	0.3041784×10^{-3}
C_4	$-0.3138189 \times 10^{-9}$	$-0.1657551 \times 10^{-9}$	$-0.2237026 \times 10^{-9}$	$-0.1900518 \times 10^{-9}$	$-0.2737530 \times 10^{-9}$	$-0.2446494 \times 10^{-9}$
C_5	0.2672030	0.5034808×10^{-1}	0.8617333×10^{-1}	0.7044071×10^{-1}	0.1074816	0.1522900
C_6	$-0.8248895 \times 10^{-4}$	0.8303023×10^{-5}	$-0.8114114 \times 10^{-5}$	$-0.9979755 \times 10^{-6}$	$-0.2420432 \times 10^{-4}$	$-0.3453040 \times 10^{-4}$
C_7	$-0.7710648 \times 10^{-5}$	$-0.4792611 \times 10^{-5}$	$-0.3737293 \times 10^{-5}$	$-0.4450780 \times 10^{-5}$	$-0.2334325 \times 10^{-5}$	$-0.5260562 \times 10^{-5}$
C_8	$0.2007578 \times 10^{-13}$	$0.1303283 \times 10^{-13}$	$0.1013780 \times 10^{-13}$	$0.1230075 \times 10^{-13}$	$0.5939907 \times 10^{-14}$	$0.1371708 \times 10^{-13}$
C_9	-0.1528710×10^5	0.6259661×10^4	-0.2943185×10^4	-0.6630649×10^4	-0.1101147×10^5	0.7685885×10^3
C_{10}	0.9006748×10^4	-0.3502964×10^4	0.1799921×10^4	0.3874185×10^4	0.6364154×10^4	-0.2934506×10^3
R^2	0.870	0.870	0.845	0.842	0.721	0.895

TABLE IX

SYSTEM PARAMETER VALUES USED FOR PREDICTION EQUATION TESTS

Parameter Set 1

Parameter	Value		Pi Term	
Q	21.6	cfs	2	443
Dia	0.0417	ft.	3	136,000
P_p	134.5	$lbs./ft.^3$	4	1,805
d	0.434	ft.	5	154,000,000
D	0.505	ft.	6	0.87
R	0.107	lbs./sec.	7	21,950
P_a (Average)	0.0745	$lbs./ft.^3$		

Parameter Set 2

Parameter	Value		Pi Term	
Q	14.0	cfs	2	343
Dia	.0208	ft.	3	16,600
P_p	63.14	$lbs./ft.^3$	4	854
d	0.5	ft.	5	233,000,000
D	0.505	ft.	6	0.99
R	0.0125	lbs./sec.	7	2,560
P_a (Average)	0.0740	$lbs./ft.^3$		

Parameter Set 3

Parameter	Value		Pi Term	
Q	19.0	cfs	2	335
Dia	0.0417	ft.	3	133,700
P_p	134.5	$lbs./ft.^3$	4	1,820
d	0.417	ft.	5	133,000,000
D	0.444	ft.	6	0.940
R	0.75	lbs./sec.	7	175,000
P_a (Average)	0.0739	$lbs./ft.^3$		

Parameter Set 4

Parameter	Value		Pi Term	
Q	15.0	cfs	2	214
Dia	0.0313	ft.	3	56,200
P_p	63.14	$lbs./ft.^3$	4	856
d	0.434	ft.	5	146,000,000
D	0.444	ft.	6	0.979
R	0.402	lbs./sec.	7	9,360
P_a (Average)	0.0742	$lbs./ft.^3$		

The values predicted by the prediction equations were found unacceptable when compared with the check data. Average percent error of the predicted from the observed values varied from 75 percent for the "bean bag" backstop to 393 percent for the polyurethane foam backstop. Other prediction equation models were tried for the "bean bag" backstop until a satisfactory prediction equation was obtained. The task of determining the prediction equations for all backstops was beyond the scope of this study.

The following prediction equation model was determined for the "bean bag" backstop:

$$\text{Pi } 1 = -749.3652 - 0.1054 \text{ Pi } 2 + 0.29347 \times 10^{-3} \text{ Pi } 3 - 0.29095 \times 10^{-9}(\text{Pi } 3)^2 + 0.027425 \text{ Pi } 4 - 0.24486 \times 10^{-5} \text{ Pi } 5 + 0.65833 \times 10^{-14}(\text{Pi } 5)^2 + 2309.878 \text{ Pi } 6 - 1312.180(\text{Pi } 6)^2$$

Approximately 70 percent of the variation in Pi 1 was accounted for by knowing the values of the independent variables.

Comparison of predicted values with the check data presented in Appendix C-IV disclosed an average percent error of 9 percent. This figure represents the relative amount of deviation from the 95 percent confidence interval placed on the check data means.

Adaptation of Prediction Equation to Continuous Mass Flow

A necessary part of this study was that of modifying the separator prediction equations to allow prediction of the percent separation for continued mass flow conditions. To determine the modified prediction equations for all of the backstops would have been beyond the scope of this study. Therefore, only one prediction equation was modified. Likewise, only two separator set-ups were used to obtain the mass flow data.

Data was taken for two- and three-material mixtures. Wheat, soybeans, and sorghum grain were mixed as presented in Tables V and VI. Feed rates of 6, 12, and 18 pounds per minute, and mixtures of 10, 35, and 55 percent of total weight for the three-material mixtures were tried. For two-material mixtures, 20, 40, 60, and 80 percent of total weight was used. Detailed discussion of the test procedure is presented in Chapter V.

Separator and system parameter values during the tests were as follows:

	Two Materials	Three Materials
Separator chamber size	6.399 inches	6.079 inches
Inlet duct size	6.0 inches	5.0 inches
Backstop	Bean Bag	Bean Bag
Air density	0.0732 lbs./ft.^{3}	0.0732 lbs./ft.^{3}
Air flow rate	11.0 ft.^{3}/sec.	10.65 ft.^{3}/sec.
Average wheat equivalent diameter	0.0119 ft.	0.0123 ft.
Average wheat density	86.1 lbs./ft.^{3}	89.8 lbs./ft.^{3}
Average soybean equivalent diameter	0.0197 ft.	0.0197 ft.
Average soybean density	80.8 lbs./ft.^{3}	80.8 lbs./ft.^{3}
Average sorghum grain equivalent diameter		0.0112 ft.
Average sorghum grain density		83.9 lbs./ft.^{3}

The observed data for the two- and three-material mixtures is presented in Appendix C-V. Eighteen tests for the three-material mixtures and 12 tests for the two-material mixtures were run. Tests 4, 17 and 18 for the three-material mixtures and 1, 3, 8, 9, 10 and 11 for the two-material mixtures were replicated. The percent separated for each mixture is presented in Tables X and XI.

The mixtures of seed were passed through the system and the various fractions removed, separated, and weighed. Soybeans were separated by screening. Some difficulty was experienced while attempting to separate the sorghum grain from the wheat. Although the wheat and sorghum grain had been roll graded prior to mixing, a noticeable quantity of wheat terminated in the sorghum grain and vice versa. The corrected weight of each fraction was determined by hand separating a 0.1 pound sample of the mixtures. The percent of wheat and the percent of sorghum grain in the sample was thus obtained. These percents were used to correct the weight of the fractions. Corrected weights were used in all calculations dealing with the percent separated.

The amounts of wheat and sorghum grain which passed through the separator into the collector were estimated. The procedure used to estimate the weights of these fractions was as follows:

1. The wheat separated by the system was weighed.
2. The total weight of all material fed into the separator was determined.
3. The amount of wheat fed into the system was found by taking the product of the percent of wheat in the original mixture and the total weight of all material fed into the system.
4. The weight of wheat in the collector was estimated by subtracting the weight of wheat separated from the weight fed in.
5. This procedure was repeated for sorghum grain.

TABLE X

PERCENT OF MATERIAL SEPARATED FOR THE THREE-MATERIAL MIXTURE

Test No.	Percent Soybeans Separated	Percent Sorghum Separated	Percent Wheat Separated
Rep. 1			
1	45.30	34.35	39.35
2	36.85	32.20	35.00
3	44.55	30.15	36.50
4	43.40	51.65	55.80
5	43.50	31.20	37.70
6	38.90	42.80	23.40
7	38.85	33.30	34.85
8	44.30	30.90	39.70
9	49.45	35.50	40.40
10	49.05	39.90	43.60
11	43.10	31.00	40.90
12	39.90	29.10	39.20
13	38.90	28.10	35.70
14	38.60	27.35	34.70
15	43.25	31.10	26.90
16	45.65	27.00	61.40
17	45.00	31.20	37.70
18	35.85	28.60	32.40
Rep. 2			
4	39.80	34.25	51.25
17	44.90	27.50	48.50
18	35.50	22.50	21.70

TABLE XI

PERCENT OF MATERIAL SEPARATED FOR THE TWO-MATERIAL MIXTURES

Test Number	Percent Soybeans Separated	Percent Wheat Separated
1	71.5	50.0
2	76.5	52.4
3	72.8	51.3
4	74.1	50.9
5	70.0	52.0
6	74.0	51.5
7	74.0	51.4
8	72.5	51.3
9	75.2	51.6
10	71.1	50.8
11	73.9	51.3
12	72.6	51.0
Rep. 2		
1	72.5	51.0
3	77.8	53.2
8	74.0	52.0
9	75.8	51.7
10	76.4	37.6
11	73.5	51.2

The procedure was verified by comparing the estimated with the actual values. The collected material (that which was not separated) of three tests, randomly selected from each feed rate group, was separated to obtain the actual values. The estimated and actual values are presented in Table XII. The average percent error was 3.7 for wheat and 2.3 for sorghum grain.

TABLE XII

COMPARISON OF ACTUAL AND ESTIMATED VALUES OF PERCENT MATERIAL COLLECTED

Test	Percent Wheat Collected			Percent Sorghum Collected		
Number	Estimated	Actual	Percent Error	Estimated	Actual	Percent Error
12	39.2	36.0	8.9	29.2	30.3	3.6
13	35.7	36.0	0.8	28.1	28.6	1.8
17	37.6	37.0	1.6	31.3	31.8	1.6
	Average		3.7			2.3

Figures 49 and 50 show the relative effect on percent separation of increasing feed rate. The curves represent averages of all mixtures for each material. In all cases, except that of sorghum grain in the three-material mixture tests, increasing feed rate tended to increase separation. The influence of feed rate on separation, as expressed by the mass flow data, is in contrast with the results of Part One where no significant change was produced by varying feed rate.

It is suggested that as the system loaded up, energy losses were increased, both within the conveyor pipe and within the separation chamber. This energy loss supplemented the action of the energy dissipating backstop, thus effecting increased separation. The feed rates of Part One were not sustained; therefore, the loading effect could not

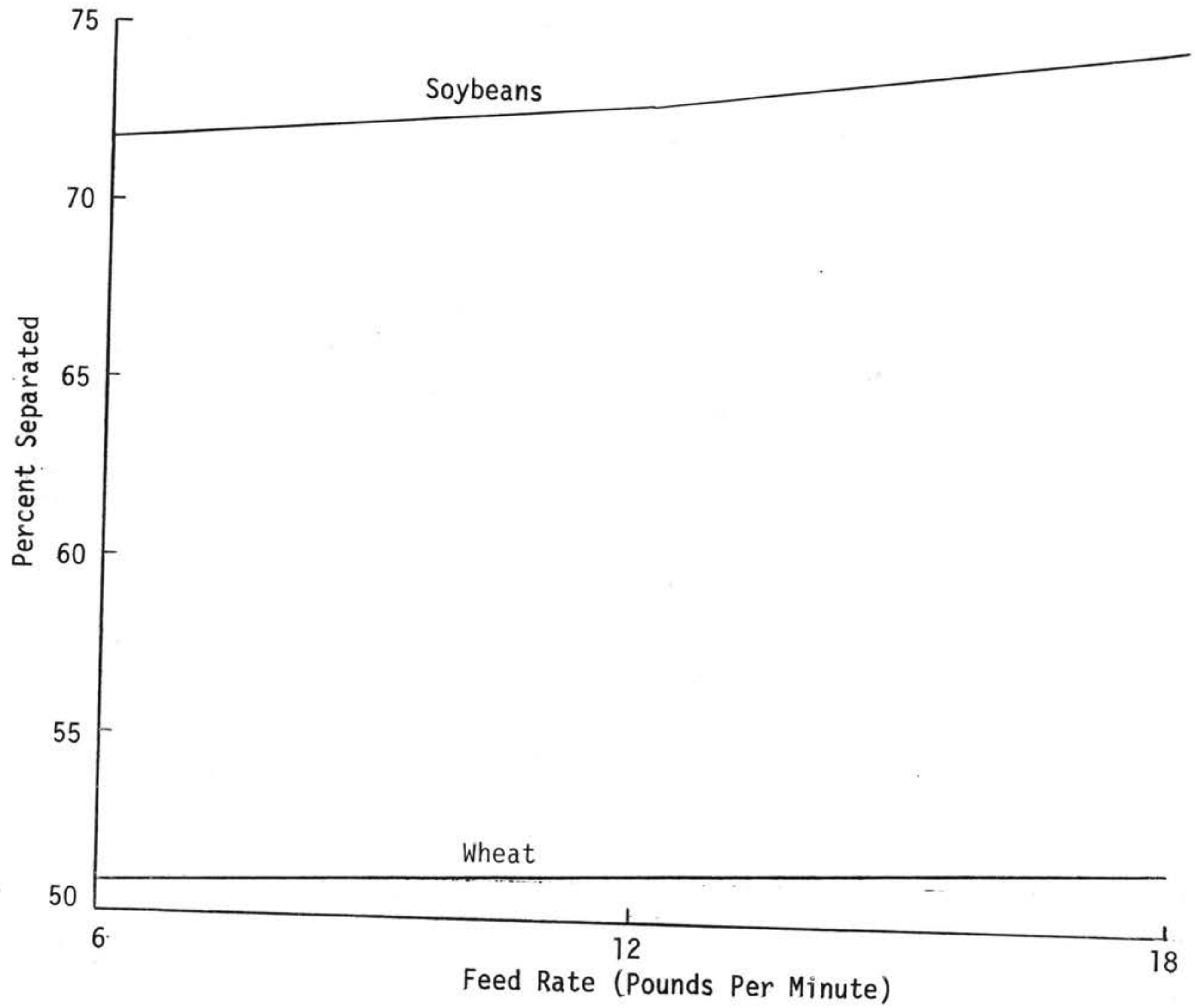

Figure 49. Percent Separation Versus Feed Rate (Two-Material Mixture)

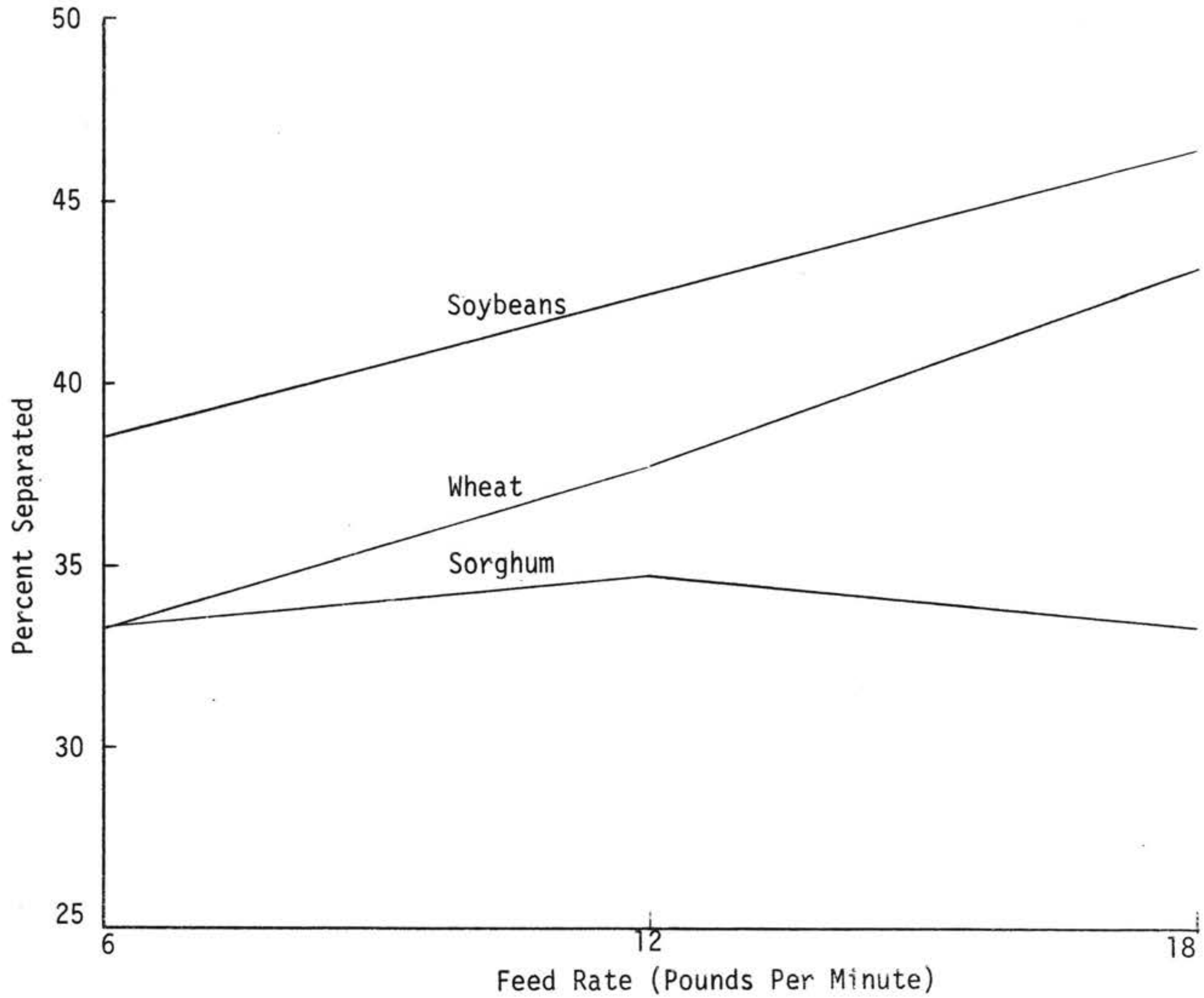

Figure 50. Percent Separation Versus Feed Rate (Three-Material Mixture)

occur. Interparticle rebound, especially at the higher feed rates, likely contributed to the energy losses and possibly to the degree of randomness with which separation occurred.

Figure 51 illustrates the slight fluctuations in percent separation which were produced by varying mixture concentrations. The maximum observed variation in percent separation for wheat was 4 percent at 6 pounds per minute feed rate. For soybeans, the maximum was 8 percent, also at 6 pounds per minute. There was even less variation in the three-material mixtures brought about by concentration changes.

Development of the Modified Prediction Equation

It was hypothesized that the percent separation of a given material class under continued mass flow is a function of feed rate, the percent of total weight which the given material class represents, and the percent separation as forecast by the prediction equation of Part One. Written in equation form,

$$P_{mf} = f(R, P_{ct}, Pi\ 1)$$

where

P_{mf} = Percent separation of given material under continued mass flow

R = Feed rate of total mixture, lbs./sec.

P_{ct} = Percent of total weight which the given material class represents

and

Pi 1 = Predicted value for percent separation as computed by Part One prediction equation.

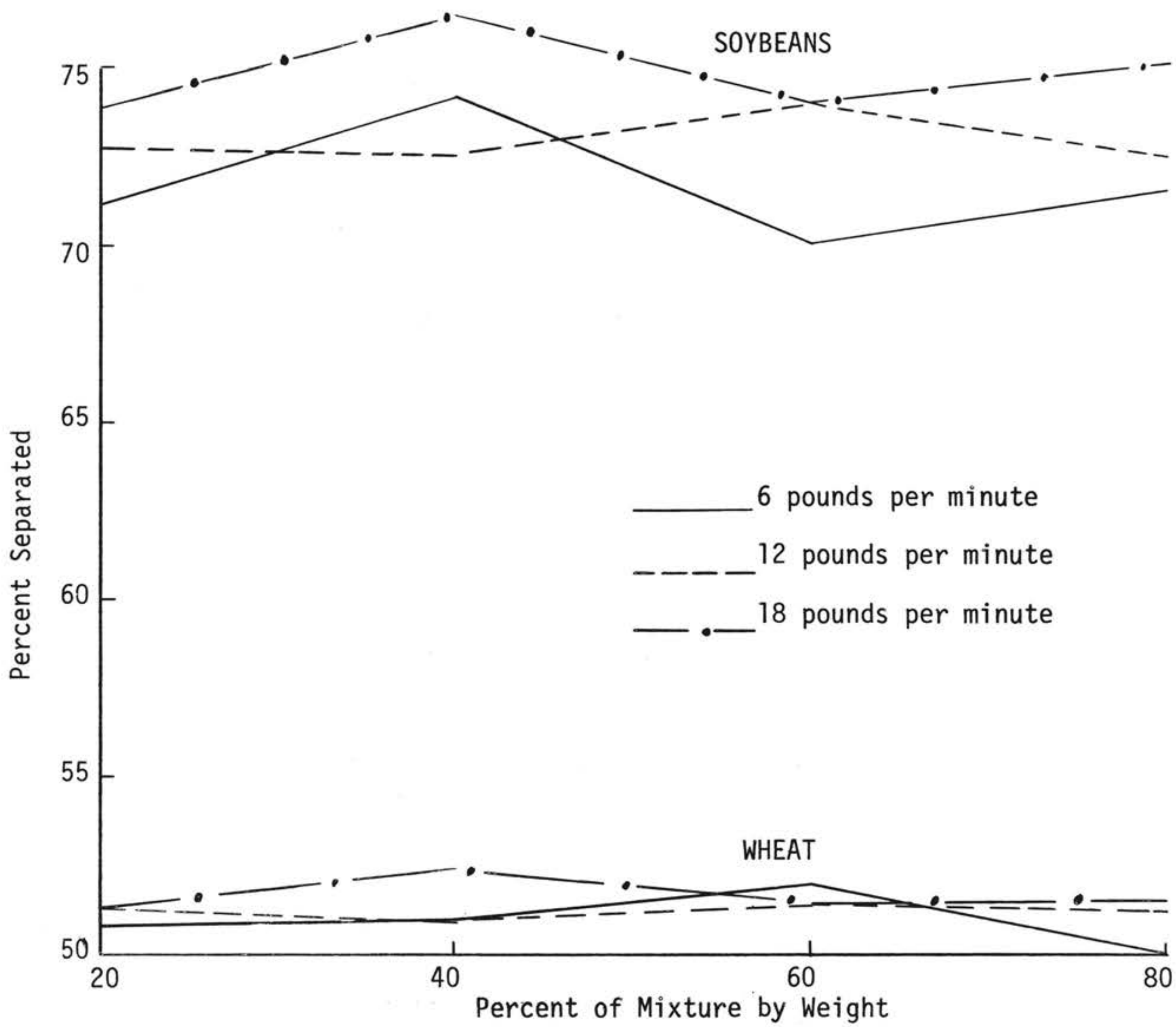

Figure 51. Percent Separation Versus Percent of Mixture by Weight

This hypothesis was based on the assumption that all variables which affect separation are included in the prediction model. The system parameters are represented by Pi 1, the feed rate by R, and a characteristic of the material mass is included as the percent of total weight. A possible weakness in the hypothesis is that the material mass is not characterized as to particle size nor as to number of classes. Conceivably, a mixture could be made of very small dense balls and large low density balls. Separation of this type of mixture would very likely result in something other than the predicted values, since the equation was determined for a range of diameters and densities found in values for agricultural seeds. Accordingly, it was further assumed that the modified prediction equation would be applicable only to materials with dimensions and densities within the range investigated.

Figures 49, 50, and 51 indicate that the effect of feed rate is approximately linear, while the effect of percent of total weight of the mixture is not.

Eight models were investigated for the modified prediction equation. They were as follows:

$$P_{mf} = C_0 + C_1 R + C_2 P_{ct} + C_3 Pi\ 1$$

$$P_{mf} = C_0 + C_1 R + C_2 P_{ct} + C_3 Pi\ 1 + C_4 (Pi\ 1)^2$$

$$P_{mf} = C_0 + C_1 R + C_2 P_{ct} + C_3 (P_{ct})^2 + C_4 Pi\ 1$$

$$P_{mf} = C_0 + C_1 R + C_2 P_{ct} + C_3 (P_{ct})^2 + C_4 Pi\ 1 + C_5 (Pi\ 1)^2$$

$$P_{mf} = C_0 + C_1 R + C_2 R^2 + C_3 P_{ct} + C_4 Pi\ 1$$

$$P_{mf} = C_0 + C_1 R + C_2 R^2 + C_3 P_{ct} + C_4 Pi\ 1 + C_5 Pi\ 1^2$$

$$P_{mf} = C_0 + C_1 R + C_2 R^2 + C_3 P_{ct} + C_4 P_{ct}^{\ 2} + C_5 Pi\ 1$$

$$P_{mf} = C_0 + C_1R + C_2R^2 + C_3P_{ct} + C_4P_{ct}^2 + C_5Pi\ 1 + C_6Pi\ 1^2$$

Originally, all data of both the two- and three-grain mixtures were used in determining coefficients for the above models. None was satisfactory due to large variation in the predicted values. The two mixtures were then analyzed separately; however, very little improvement was achieved. Finally, data for the individual grains were analyzed.

The modified prediction model which best predicted the observed values was,

$$P_{mf} = C_0 + C_1R + C_2P_{ct} + C_3(P_{ct})^2 + C_4Pi\ 1$$

where

C_0, C_1, C_2, C_3, and C_4 represent constant coefficients.

Table XIII shows the coefficient values obtained for each modified prediction equation.

The average percent error listed in Table XIII represents the average error in predicted percent separated one would expect to obtain through the use of the respective prediction equation. The average error values indicate that both decreases in grain size and increases in number of size classes produce larger prediction error. This is hypothetically caused by increased randomness within the separator and less differentiation in aerodynamic properties. The effects of random collision within the separator are multiplied by the addition of a third particle class.

The modified prediction equation would be useful in predicting the amount of a particular size class which would be separated from a mixture of size classes by a given set of separator parameters.

TABLE XIII

COEFFICIENT VALUES FOR THE MODIFIED PREDICTION EQUATIONS

$$P_{mf} = C_0 + C_1R + C_2P_{ct} + C_3P_{ct}^2 + C_4Pi \; 1$$

Identification	C_0	C_1	C_2	C_3	C_4	Avg. % Error
Soybeans (2-grain)	24.898	0.1847	-0.06301	0.00048	0.6863	1.9
Wheat (2-grain)	22.961	0.2500	0.12778	-0.00160	0.3341	3.7
Soybeans (3-grain)	16.789	0.6855	0.00657	-0.00022	0.2248	4.1
Sorghum (3-grain)	27.820	0.21527	-0.4925	0.00718	0.10621	11.5
Wheat (3-grain)	834.970	0.9434	-0.8810	0.01402	-10.574	14.6

CHAPTER VII

SUMMARY AND CONCLUSIONS

The objectives of this study were to: (1) Establish relationships among system parameters, particle aerodynamic characteristics, and percent particle separation for an in-line separator, (2) Develop equations for predicting the number of particles separated as percent of total, (3) Evaluate the effect on performance of the separation system of various energy dissipating backstops within the separator, and (4) Extend the use of the prediction equation to include separation of agricultural materials under continuous mass flow. In Part One, plastic balls of various densities and diameters, were pneumatically conveyed through an in-line separator equipped with an energy dissipating backstop. Twelve air flow rates, 11 ball diameters, 7 ball densities, 4 inlet duct diameters, 4 separator chamber diameters, and 6 energy dissipating backstops were investigated. System variables were organized into nine dimensionless parameters (Pi terms). The values of the dimensionless parameters with the respective resulting percent separation values were analyzed to give the coefficients of a prediction equation polynomial model. The effect of each of the energy dissipating backstops was studied.

Part Two involved continuous mass flow through the system. Two material mixtures were used to determine the relationship of system parameters required to predict the percent separation of a given size class from the total mass by the separator. Soybeans, sorghum and wheat were combined into two separate mixtures. One mixture consisted of soybeans and wheat, the other of soybeans, sorghum, and wheat. Feed rates of 6, 12, and 18 pounds per minute were used. Seven concentrations within the total mixture were investigated for each grain. These were 10, 35, 55, 60, 40, 20, and 80 percent.

A modified prediction equation in the form of a polynomial for each grain within each mixture was determined. The equations developed were functions of percent of total mixture, feed rate, and Pi 1, the predicted percent separated by the corresponding system prediction equation determined in Part One.

Conclusions

1. An in-line pneumatic separator of the type used for this study has inherent characteristics which produce randomness in separation. Accuracy in predicting percent separation of a given size class is, therefore, inhibited. Results indicate that this difficulty is reduced as the values of the particle aerocynamic properties become more diverse.
2. Entrance velocity, particle density, and particle diameter affect the performance of plywood backed energy dissipators such as those used for this study. The greatest percent separation occurred with the use of backstops having the largest capacity for energy absorption.
3. Under continuous mass flow, feed rate affects percent separation of a given size class more than does the percent concentration. Higher feed rates produce increased separation within certain limits.

4. Percent separation of a given size class can be predicted with limited accuracy using those prediction equations presented in this study provided that the system parameter ranges of these tests are not exceeded and that particles of similar aerodynamic properties are used.

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APPENDIX A

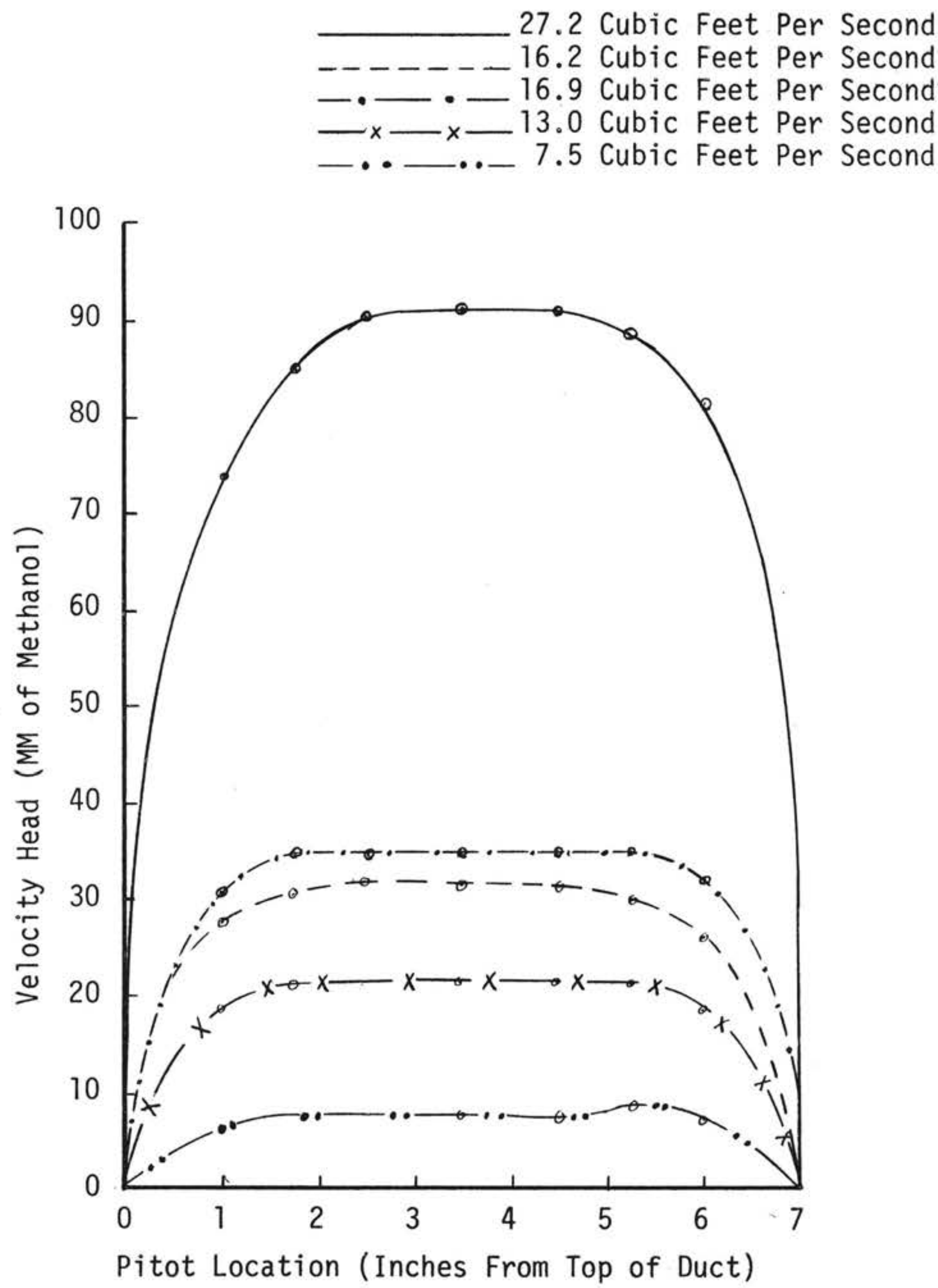
TABLES AND CURVES PERTAINING TO AIR FLOW MEASUREMENT

CALIBRATION CURVE FOR VOLUME MEASURING MANOMETER

CALIBRATION DATA FOR VIBRATOR FEEDER

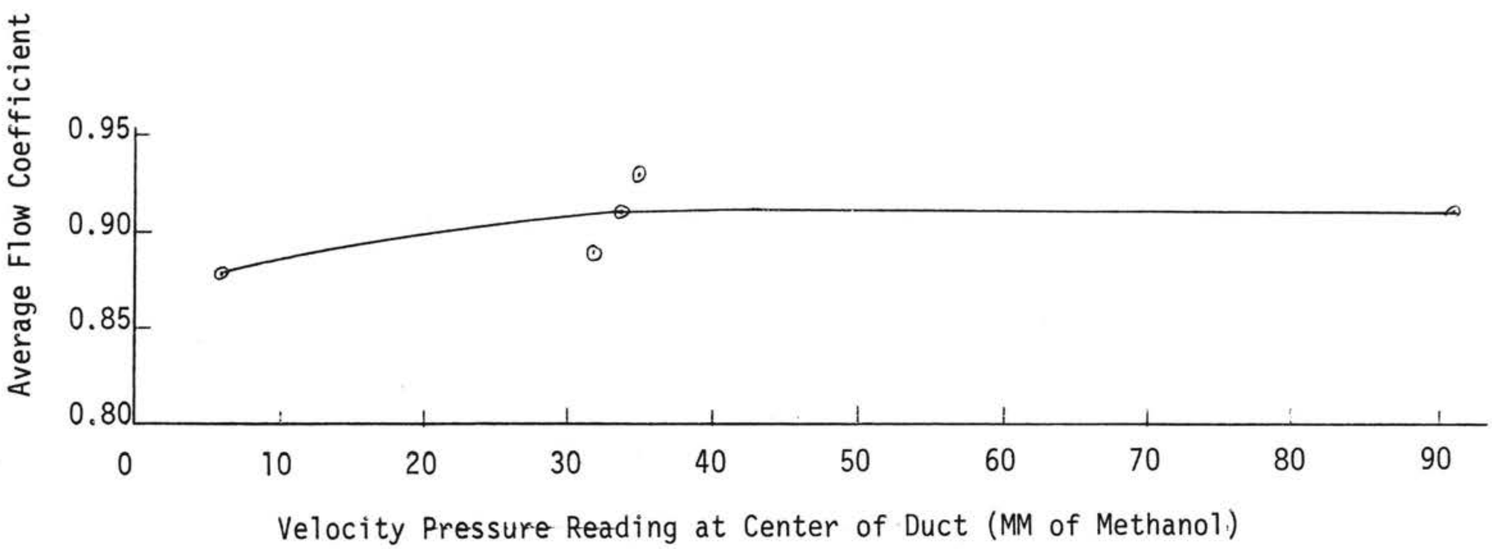
APPENDIX A-I

VELOCITY PROFILE IN 7-INCH DUCT FOR VARIOUS AIR FLOW RATES



APPENDIX A-II

PLOT OF VELOCITY PRESSURE VERSUS AVERAGE FLOW COEFFICIENT FOR VARIOUS AIR FLOW RATES



APPENDIX A-III

The following table relates air density, manometer reading, and air flow rates. The relationships used for the computations are derived as follows:

The rate of air flow through the system is given by

$$Q = 3.14 \times \frac{d^2}{4.0} \times V \times \text{Coef.}$$

where

Q = air flow through the pipe in cfs

d = diameter of the pipe at the pitot tip location in ft.

V = velocity at the center of the pipe in ft./sec.

and

Coef. = the coefficient used to relate the average velocity and the velocity at the center of the pipe

Substituting 0.92 for the coefficient, 0.583 feet for d, and (18.3 x $\sqrt{\frac{.7567\ P}{\text{gamma}}}$) (Chapter IV) for V, the equation becomes

$$Q = 3.92 \sqrt{\frac{P}{\text{gamma}}}$$

where P = velocity pressure in inches of methanol (manometer setting) and gamma = air density in lbs./ft.^{3}

APPENDIX A-III (Continued)

VALUES OF MANOMETER READINGS FOR VARIOUS AIR FLOW RATES AND AIR DENSITIES (PARTIAL TABLE)

C.F.S.	Air Density lbs./ft.^{3}	Manometer Setting In. of Methanol	C.F.S.	Air Density lbs./ft.^{3}	Manometer Setting In. of Methanol
8.00	0.0625	0.26	9.00	0.0625	0.33
8.00	0.0630	0.26	9.00	0.0630	0.33
8.00	0.0635	0.26	9.00	0.0635	0.33
8.00	0.0640	0.27	9.00	0.0640	0.34
8.00	0.0645	0.27	9.00	0.0645	0.34
8.00	0.0650	0.27	9.00	0.0650	0.34
8.00	0.0655	0.27	9.00	0.0655	0.35
8.00	0.0660	0.27	9.00	0.0660	0.35
8.00	0.0665	0.28	9.00	0.0665	0.35
8.00	0.0670	0.28	9.00	0.0670	0.35
8.00	0.0675	0.28	9.00	0.0675	0.36
8.00	0.0680	0.28	9.00	0.0680	0.36
8.00	0.0685	0.28	9.00	0.0685	0.36
8.00	0.0690	0.29	9.00	0.0685	0.36
8.00	0.0695	0.29	9.00	0.0695	0.37
8.00	0.0700	0.29	9.00	0.0700	0.37
8.00	0.0705	0.29	9.00	0.0705	0.37
8.00	0.0710	0.29	9.00	0.0710	0.37
8.00	0.0715	0.31	9.00	0.0715	0.38
8.00	0.0720	0.31	9.00	0.0720	0.38
8.00	0.0725	0.30	9.00	0.0725	0.38
8.00	0.0730	0.30	9.00	0.0730	0.38
8.00	0.0735	0.30	9.00	0.0735	0.39
8.00	0.0740	0.30	9.00	0.0740	0.39

APPENDIX A-IV

VALUES OF AIR DENSITY FOR VARIOUS AIR TEMPERATURES, BAROMETRIC PRESSURES, AND RELATIVE HUMIDITIES (PARTIAL TABLE)

Air Temperature °F	Station Barometric Pressure In. HG	Relative Humidity Percent	Air Density lbs./ft.^{3}
81.0	29.0	0.20	0.0709
81.0	29.0	0.25	0.0709
81.0	29.0	0.30	0.0708
81.0	29.0	0.35	0.0708
81.0	29.0	0.40	0.0707
81.0	29.0	0.45	0.0707
81.0	29.0	0.50	0.0706
81.0	29.0	0.55	0.0706
81.0	29.0	0.60	0.0705
81.0	29.0	0.65	0.0705
81.0	29.0	0.70	0.0704
81.0	29.0	0.75	0.0704
81.0	29.0	0.80	0.0703
81.0	29.0	0.85	0.0703
81.0	29.0	0.90	0.0702
81.0	29.0	0.95	0.0702

The following equations were used to compute air density values for the above table (24).

Air density (lbs./ft.^{3} of mixture) equals Wa plus Wv where Wa is the pounds of dry air contained in a cubic foot of saturated or partly saturated air and Wv is the pounds of water vapor contained in a cubic foot of air-vapor mixture. Wa and Wv are found as follows:

$$Wa = \frac{b - eh}{346.5 + 0.7535t}$$

and

$$Wv = \frac{ehs}{346.5 + 0.7535t}$$

then

$$Wa + Wv = \frac{b + eh\ (s - 1)}{346.5 + 0.7535t}$$

where

h = relative humidity expressed as a decimal

b = barometric pressure in inches of mercury

e = vapor pressure of water in inches of mercury at dry-bulb temperature t

t = dry-bulb temperature, deg. F.

s = specific weight of water vapor

APPENDIX A-V

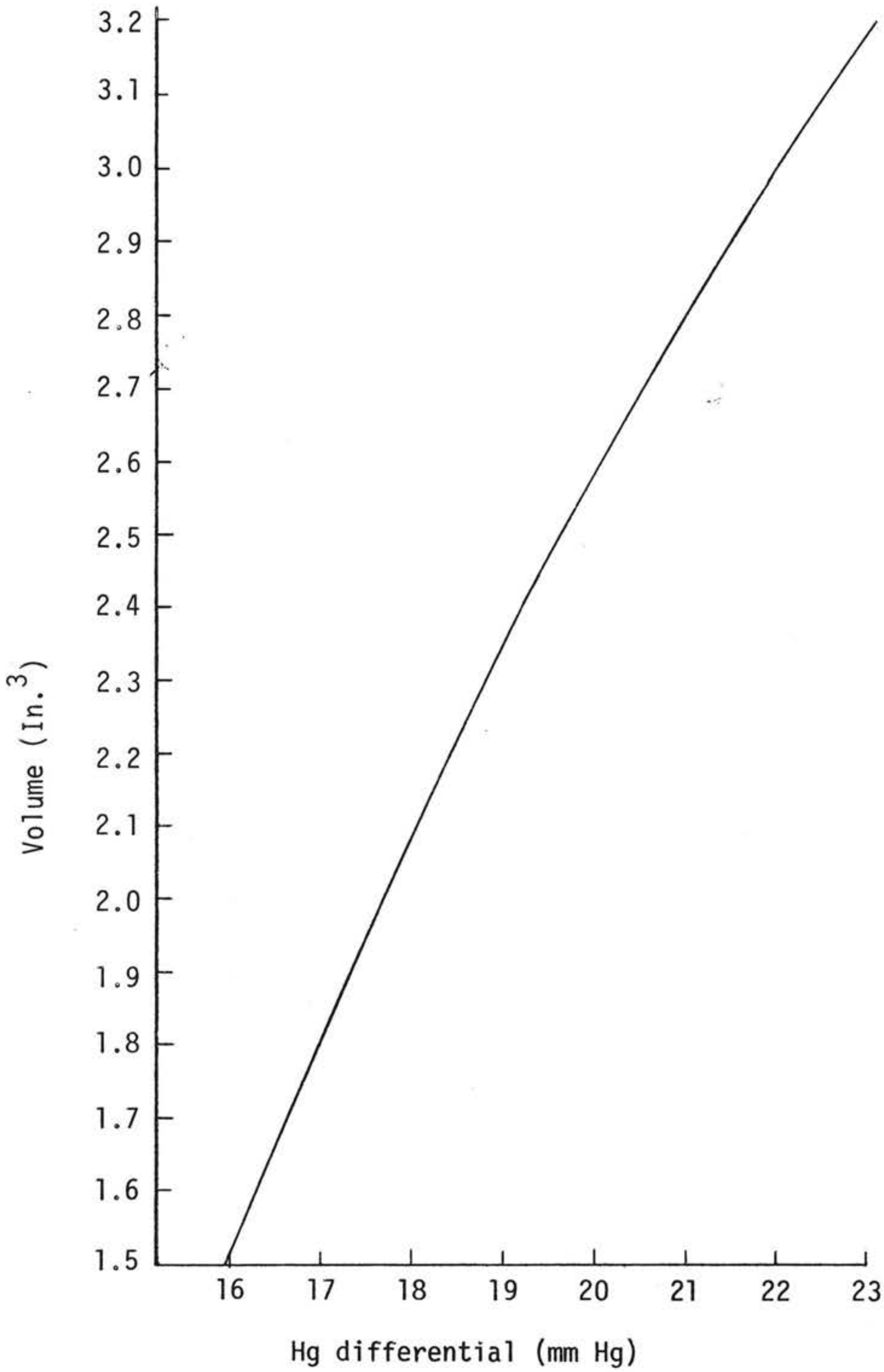
VOLUME MEASURING MANOMETER CALIBRATION

The procedure used to calibrate the volume measuring manometer is as follows:

1. Various discs of known volume were placed in the manometer chamber (Figure 34). The discs were calibrated in terms of percent of total volume and were of such values that steps of 5 percent from 0 to 100 were possible.
2. The bellows were closed with the pressure release screw open. The pressure release was then closed and the chamber cap tightened until 1.2 mm. Hg differential was read. The pressure was released and the bellows opened to the maximum.
3. The pressure release was closed and the bellows compressed to the maximum. The Hg differential was read.
4. The procedure of 1 through 3 was repeated for the various calibration discs and the Hg differential read.
5. The volume values were found by multiplying the percent of volume by the chamber volume. Chamber volume was 4.32 cubic inches.

The portion of the calibration curve which was used for this study is presented in the following figure.

APPENDIX A-V (Continued)



CALIBRATION CURVE FOR VOLUME MEASURING MANOMETER

APPENDIX A-VI

VIBRATOR FEEDER CALIBRATION

The vibrator feeder was observed to meter at different rates for changes in either material concentrations or number of material classes in the mixture. Calibration procedure was, therefore, limited to experimentally determining the dial setting for a desired rate of flow for a given mixture. All of the dial positions were determined and then an attempted resetting was made. The actual feed rates obtained for the two settings and the percent error from the desired feed rate values are presented in the following table:

APPENDIX A-VI (Continued)

VIBRATOR FEEDER CALIBRATION DATA

Three-Material Mixture

Dial Setting	Feed Rate Lbs./Min.	Percent of Material In Mixture by Wt. Soybeans	Sorghum	Wheat	Trial #1	Trial #2	Average Percent Error From Desired
1		55	35	10	5.96	5.82	-1.833
2		35	55	10	6.02	6.07	0.992
3		55	10	35	6.05	6.12	1.417
4	6	10	55	35	6.04	6.00	0.334
5		35	10	55	6.01	6.15	1.333
6		10	35	55	5.96	5.88	-1.333
		Average Overall Percent Difference					0.152
7		55	35	10	11.96	11.92	-0.500
8		35	55	10	12.04	12.02	0.250
9		55	10	35	12.04	11.90	-0.251
10	12	10	55	35	11.97	11.86	-0.709
11		35	10	55	12.06	12.20	1.082
12		10	35	55	11.99	11.90	-0.458
		Average Overall Percent Difference					-0.264
13		55	35	10	18.02	18.10	0.333
14		35	55	10	18.07	17.95	0.055
15		55	10	35	17.96	17.80	-0.667
16	18	10	55	35	18.00	18.16	0.445
17		35	10	55	17.99	18.10	0.250
18		10	35	55	18.01	18.10	0.306
		Average Overall Percent Difference					0.361

APPENDIX A-VI (Continued)

Two-Material Mixture

Dial Setting	Feed Rate Lbs./Min.	Percent of Material In Mixture by Wt. Soybeans	Wheat	Trial #1	Trial #2	Average Percent Error From Desired
19		20	80	5.98	6.22	1.667
20		40	60	5.93	6.04	-0.500
21	6	60	40	6.02	6.10	1.000
22		80	20	5.96	6.02	-0.167
		Average Overall Percent Difference				0.417
23		20	80	11.92	11.94	-0.583
24		40	60	11.95	12.03	-0.083
25	12	60	40	12.00	11.93	-0.292
26		80	20	12.00	11.91	-0.375
		Average Overall Percent Difference				-0.334
27		20	80	17.90	18.04	-0.167
28		40	60	18.06	18.08	0.389
29	18	60	40	18.02	18.07	0.250
30		80	20	17.94	17.76	-0.834
		Average Overall Percent Difference				-0.091

APPENDIX B

SIZE AND DENSITY CONTROL OF PLASTIC BALLS (SAMPLE TABLE)

INDIVIDUAL SEED VOLUME AND EQUIVALENT DIAMETER

APPENDIX B-I

BALL SIZE AND DENSITY CONTROL
(Sample Table)

Polystyrene Five Sixteenths Inch

Ball	Diameter (Ft.)	Weight (Lbs.)	Reyn. No.	CRE2	Ter. Veloc. (Ft./Sec.)	Density (Lbs./Ft.^{3})
1	0.0259	0.000598	8426.7	29277567.4	48.495	65.17
2	0.0260	0.000603	8461.5	29525472.5	48.633	65.47
3	0.0259	0.000598	3422.2	29245279.8	48.500	65.23
4	0.0260	0.000602	8452.4	29460832.7	48.612	65.46
5	0.0259	0.000598	8425.2	29266848.1	48.518	65.28
6	Ball Omitted					
7	0.0260	0.000600	8441.8	29385213.8	48.489	65.04
8	0.0260	0.00602	8455.4	29482303.5	48.582	65.32
9	0.0260	0.000600	8437.3	29352828.9	48.447	64.90
10	0.0259	0.000600	8435.8	29342239.8	48.532	65.26
11	0.0260	0.000601	8446.3	29417533.7	48.499	65.05
12	0.0259	0.000600	8440.3	29374592.1	48.558	65.33
13	0.0261	0.00604	8469.0	29479001.7	48.489	64.84
14	0.0259	0.000599	8432.8	29320671.5	48.514	65.21
15	0.0260	0.000603	8458.4	29503643.6	48.491	64.93
16	0.0259	0.000598	8426.7	29277632.2	48.526	65.30
17	0.0259	0.000598	8426.7	29277632.2	48.526	65.30
18	0.0259	0.00599	8432.8	29320671.5	48.514	65.21
19	0.0260	0.00601	8443.3	29396095.5	48.544	65.25
20	0.0260	0.000600	8441.8	29385083.5	48.426	64.79
21	0.0260	0.000601	8447.8	29428350.3	48.523	65.13
22	0.0259	0.000595	8407.1	29137600.1	48.491	65.30
23	Ball Omitted					
24	0.0260	0.000600	8435.8	29342207.3	48.516	65.19
25	0.0259	0.000600	8437.3	29353023.9	48.540	65.23
Corrected	0.0260			Overall Average	48.378	

APPENDIX B-II

INDIVIDUAL SEED VOLUME AND EQUIVALENT DIAMETER

Wheat (Three-Material Mixture)

Sample No.	Volume For 100 Seeds ($In.^3$)	Average Volume Per Seed ($In.^3$)
1	0.170	0.00170
2	0.160	0.00160
3	0.160	0.00160
4	0.160	0.00160
5	0.160	0.00160
6	0.160	0.00160
7	0.180	0.00180
8	0.170	0.00170
9	0.180	0.00180
10	0.160	0.00160
Average		0.00166

Wheat (Two-Material Mixture)

Sample No.	Volume For 100 Seeds ($In.^3$)	Average Volume Per Seed ($In.^3$)
1	0.158	0.00158
2	0.158	0.00158
3	0.141	0.00141
4	0.151	0.00151
5	0.141	0.00141
6	0.141	0.00141
7	0.151	0.00151
8	0.151	0.00151
9	0.158	0.00158
10	0.158	0.00158
Average		0.00151

APPENDIX B-II (Continued)

Soybeans

Sample No.	Volume For 100 Seeds ($In.^3$)	Average Volume Per Seed ($In.^3$)
1	0.150	0.0075
2	0.130	0.0065
3	0.130	0.0065
4	0.140	0.0070
5	0.150	0.0075
6	0.140	0.0070
7	0.140	0.0070
8	0.140	0.0070
9	0.130	0.0065
10	0.123	0.0062
Average		0.00687

Sorghum

Sample No.	Volume For 100 Seeds ($In.^3$)	Average Volume Per Seed ($In.^3$)
1	0.145	0.00145
2	0.123	0.00123
3	0.123	0.00123
4	0.127	0.00127
5	0.140	0.00140
6	0.123	0.00123
7	0.123	0.00123
8	0.123	0.00123
9	0.123	0.00123
10	0.117	0.00117
Average		0.001267

APPENDIX C

COEFFICIENT OF RESTITUTION DATA

ORIGINAL DATA, PART ONE

OBSERVED AIR DENSITIES

CHECK DATA OF PART ONE

ORIGINAL DATA, PART TWO

APPENDIX C-I

TEST DATA FOR THE MEASUREMENT OF THE COEFFICIENT OF RESTITUTION

OF PLASTIC BALLS ON BACKSTOPS

Test No.	Ball Name	Ball Density	Ball Dia.	Surface	Drop Ht. (In.)	Rebound Ht. Correction	Rebound Ht. (In.) 1	2	3	Avg.	Coefficient Of Restitution*
1.1	Polystyrene	63.14 lbm./ft.^{3}	1/8"	Carpet	48	-1.26 in.	15.30	12.90	12.96	13.70	0.537
1.2	Polystyrene	63.14 lbm./ft.^{3}	1/4"	Carpet	48	-1.26 in.	15.30	15.66	15.54	15.50	0.570
1.3	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	13.86	13.86	13.68	13.80	0.538
1.4	Polystyrene	63.14 lbm./ft.^{3}	7/8"	Carpet	48	-1.26 in.	10.26	10.32	10.14	10.22	0.463
2.1	Polyethylene	54.37 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	14.58	14.94	14.58	14.70	0.555
2.2	Blue Stripe Polyethylene	58.29 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	14.82	14.82	14.82	14.82	0.557
2.3	Orange Nylon	69.11 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	14.58	14.46	14.58	14.51	0.552
2.4	Teflon	134.50 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	12.96	13.02	13.14	13.05	0.523
3.1	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	5.10	5.04	4.74	4.96	0.645
3.2	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	10.56	10.62	10.02	10.38	0.590
3.3	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	14.7	14.82	14.82	14.78	0.556
4.1	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Carpet	48	-1.26 in.	14.7	14.10	14.64	14.42	0.550
4.2	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Polyurethane Foam	48	-1.56 in.	9.48	9.06	8.58	9.04	0.435
4.3	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Closed Cell	48	-1.62 in.	22.98	23.70	22.98	23.22	0.697
4.4	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Hi-Car	48	-1.56 in.	6.18	6.12	6.00	6.10	0.358
4.5	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Bean Bag	48	-1.80 in.	1.44	0.90	1.56	1.30	0.165
4.6	Polystyrene	63.14 lbm./ft.^{3}	1/2"	Canvas	48	-1.80 in.	1.98	1.92	1.80	1.90	0.198

*Coefficient of Restitution = $\sqrt{\frac{\text{Rebound Height}}{\text{Drop Height}}}$

APPENDIX C-II

ORIGINAL DATA OF PART ONE

Test Series for Canvas Backstop

PI 2 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		100.00	100.00	100.00	100.00
2		100.00	100.00	100.00	100.00
3		100.00	100.00	100.00	100.00
4		100.00	100.00	100.00	100.00
5		100.00	100.00	95.00	100.00
6		95.00	95.00	100.00	100.00
7		95.00	85.00	75.00	95.00
8		75.00	75.00	95.00	90.00
9		70.00	85.00	50.00	65.00
10		55.00	70.00	45.00	75.00
11		35.00	45.00	60.00	50.00
12		35.00	35.00	25.00	35.00

PI 3 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		20.00	5.00	15.00	20.00
2		15.00	10.00	15.00	15.00
3		0.00	10.00	0.00	0.00
4		20.00	15.00	10.00	5.00
5		20.00	10.00	10.00	5.00
6		40.00	50.00	55.00	65.00
7		65.00	60.00	75.00	50.00
8		55.00	70.00	55.00	65.00
9		60.00	80.00	60.00	65.00
10		95.00	85.00	75.00	80.00
11		100.00	90.00	95.00	90.00

APPENDIX C-II (Continued)

PI 4 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		35.00	30.00	35.00	25.00
2		30.00	20.00	15.00	35.00
3		10.00	25.00	35.00	20.00
4		40.00	40.00	40.00	60.00
5		65.00	50.00	50.00	35.00
6		60.00	45.00	50.00	45.00
7		95.00	100.00	95.00	100.00

PI 5 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		40.00	65.00	50.00	55.00
2		25.00	5.00	20.00	20.00
3		5.00	5.00	0.00	0.00
4		30.00	25.00	45.00	20.00

PI 6 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		60.00	55.00	65.00	60.00
2		25.00	10.00	20.00	35.00
3		0.00	10.00	0.00	5.00
4		0.00	5.00	0.00	0.00

APPENDIX C-II (Continued)

PI 7 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		55.00	70.00	65.00	45.00
2		70.00	55.00	55.00	70.00
3		55.00	45.00	50.00	40.00
4		65.00	60.00	55.00	50.00
5		55.00	50.00	65.00	55.00
6		55.00	55.00	65.00	60.00
7		70.00	65.00	55.00	45.00
8		70.00	60.00	50.00	50.00

APPENDIX C-II (Continued)

Test Series for Carpet Backstop

PI 2 VARIED

TEST NO	SAMPLE NO 1	2	3	4
	PERCENT SEPARATED			
1	100.00	100.00	100.00	100.00
2	100.00	100.00	100.00	100.00
3	100.00	100.00	100.00	100.00
4	100.00	100.00	100.00	100.00
5	100.00	100.00	100.00	100.00
6	90.00	100.00	75.00	100.00
7	95.00	70.00	85.00	70.00
8	65.00	50.00	60.00	35.00
9	25.00	30.00	35.00	15.00
10	25.00	35.00	30.00	25.00
11	20.00	30.00	30.00	15.00
12	10.00	20.00	25.00	10.00

PI 3 VARIED

TEST NO	SAMPLE NO 1	2	3	4
	PERCENT SEPARATED			
1	0.00	0.00	0.00	5.00
2	0.00	5.00	5.00	5.00
3	0.00	10.00	0.00	0.00
4	0.00	0.00	0.00	5.00
5	15.00	20.00	10.00	15.00
6	15.00	5.00	15.00	15.00
7	35.00	45.00	45.00	15.00
8	30.00	25.00	25.00	20.00
9	40.00	55.00	50.00	45.00
10	65.00	80.00	70.00	75.00
11	75.00	80.00	80.00	80.00

APPENDIX C-II (Continued)

PI 4 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		15.00	20.00	10.00	15.00
2		5.00	15.00	10.00	10.00
3		40.00	5.00	40.00	35.00
4		25.00	30.00	50.00	50.00
5		30.00	20.00	25.00	30.00
6		45.00	20.00	30.00	15.00
7		100.00	95.00	100.00	100.00

PI 5 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		25.00	40.00	20.00	40.00
2		10.00	10.00	15.00	5.00
3		0.00	0.00	0.00	0.00
4		25.00	25.00	20.00	30.00

PI 6 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		45.00	40.00	25.00	25.00
2		20.00	50.00	20.00	50.00
3		0.00	15.00	0.00	5.00
4		0.00	0.00	0.00	0.00

APPENDIX C-II (Continued)

PI 7 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		20.00	45.00	30.00	40.00
2		20.00	25.00	25.00	35.00
3		15.00	30.00	20.00	25.00
4		25.00	20.00	35.00	25.00
5		40.00	45.00	20.00	25.00
6		30.00	35.00	25.00	25.00
7		25.00	20.00	45.00	30.00
8		50.00	35.00	30.00	30.00

APPENDIX C-II (Continued)

Test Series for Bean Bag Backstop

PI 2 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		100.00	100.00	100.00	100.00
2		100.00	100.00	100.00	100.00
3		100.00	100.00	100.00	100.00
4		95.00	100.00	100.00	100.00
5		100.00	100.00	100.00	100.00
6		95.00	95.00	90.00	75.00
7		90.00	95.00	90.00	95.00
8		90.00	75.00	75.00	70.00
9		85.00	65.00	85.00	75.00
10		50.00	70.00	50.00	65.00
11		45.00	60.00	50.00	40.00
12		35.00	50.00	25.00	50.00

PI 3 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		15.00	25.00	42.05	42.05
2		15.00	20.00	25.00	25.00
3		10.00	10.00	15.00	15.00
4		25.00	15.00	10.00	25.00
5		30.00	40.00	40.00	40.00
6		65.00	50.00	55.00	60.00
7		60.00	65.00	70.00	80.00
8		70.00	55.00	60.00	55.00
9		80.00	80.00	55.00	85.00
10		85.00	95.00	90.00	85.00
11		90.00	90.00	85.00	95.00

APPENDIX C-II (Continued)

PI 4 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		30.00	35.00	60.00	25.00
2		55.00	60.00	50.00	55.00
3		55.00	30.00	70.00	45.00
4		50.00	70.00	60.00	55.00
5		35.00	70.00	35.00	60.00
6		75.00	60.00	55.00	60.00
7		100.00	100.00	100.00	100.00

PI 5 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		40.00	55.00	65.00	50.00
2		10.00	5.00	35.00	15.00
3		75.00	55.00	55.00	65.00
4		40.00	20.00	55.00	60.00

PI 6 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		50.00	65.00	70.00	50.00
2		70.00	45.00	50.00	60.00
3		20.00	35.00	45.00	40.00
4		65.00	65.00	60.00	60.00

APPENDIX C-II (Continued)

PI 7 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		65.00	65.00	60.00	60.00
2		75.00	65.00	45.00	60.00
3		75.00	60.00	70.00	95.00
4		60.00	70.00	55.00	50.00
5		70.00	80.00	50.00	55.00
6		55.00	50.00	65.00	50.00
7		65.00	60.00	45.00	65.00
8		65.00	70.00	60.00	75.00

APPENDIX C-II (Continued)

Test Series for Closed Cell Backstop

PI 2 VARIED

TEST NO	PERCENT SEPARATED SAMPLE NO 1	2	3	4
1	100.00	100.00	100.00	100.00
2	100.00	100.00	100.00	100.00
3	100.00	100.00	100.00	100.00
4	100.00	100.00	100.00	100.00
5	95.00	95.00	100.00	100.00
6	90.00	95.00	90.00	90.00
7	95.00	70.00	80.00	90.00
8	40.00	40.00	75.00	50.00
9	30.00	45.00	50.00	55.00
10	40.00	15.00	30.00	45.00
11	25.00	25.00	45.00	40.00
12	0.00	10.00	5.00	10.00

PI 3 VARIED

TEST NO	PERCENT SEPARATED SAMPLE NO 1	2	3	4
1	0.00	10.55	5.25	0.00
2	0.00	0.00	5.00	0.00
3	0.00	0.00	5.00	5.00
4	0.00	0.00	0.00	0.00
5	5.00	10.00	5.00	0.00
6	30.00	40.00	30.00	0.00
7	45.00	35.00	35.00	20.00
8	25.00	25.00	55.00	40.00
9	55.00	70.00	45.00	65.00
10	50.00	55.00	55.00	40.00
11	80.00	70.00	85.00	90.00

APPENDIX C-II (Continued)

PI 4 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		15.00	45.00	30.00	25.00
2		5.00	15.00	25.00	15.00
3		5.00	35.00	10.00	25.00
4		30.00	35.00	40.00	40.00
5		40.00	30.00	40.00	40.00
6		50.00	30.00	25.00	55.00
7		100.00	100.00	95.00	90.00

PI 5 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		35.00	45.00	45.00	30.00
2		15.00	10.00	10.00	10.00
3		5.00	10.00	5.00	0.00
4		30.00	30.00	30.00	35.00

PI 6 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		50.00	35.00	35.00	50.00
2		35.00	25.00	15.00	35.00
3		5.00	10.00	5.00	5.00
4		15.00	30.00	10.00	35.00

APPENDIX C-II (Continued)

PI 7 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		35.00	35.00	15.00	25.00
2		45.00	10.00	45.00	20.00
3		20.00	20.00	20.00	25.00
4		20.00	25.00	25.00	35.00
5		35.00	40.00	20.00	20.00
6		15.00	15.00	15.00	30.00
7		35.00	20.00	30.00	35.00
8		35.00	40.00	40.00	20.00

APPENDIX C-II (Continued)

Test Series for Polyurethane Foam Backstop

PI 2 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		100.00	100.00	100.00	100.00
2		100.00	100.00	100.00	100.00
3		100.00	100.00	100.00	100.00
4		95.00	100.00	100.00	90.00
5		95.00	95.00	90.00	100.00
6		75.00	70.00	85.00	100.00
7		35.00	75.00	35.00	45.00
8		40.00	35.00	60.00	60.00
9		45.00	45.00	35.00	35.00
10		55.00	20.00	35.00	35.00
11		20.00	35.00	15.00	15.00
12		15.00	40.00	15.00	30.00

PI 3 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		0.00	0.00	0.00	0.00
2		0.00	0.00	10.00	0.00
3		0.00	5.00	0.00	5.00
4		0.00	10.00	0.00	5.00
5		5.00	15.00	5.00	0.00
6		0.00	15.00	10.00	25.00
7		55.00	35.00	25.00	25.00
8		35.00	35.00	40.00	35.00
9		75.00	50.00	45.00	70.00
10		90.00	85.00	70.00	90.00
11		90.00	85.00	85.00	95.00

APPENDIX C-II (Continued)

PI 4 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		5.00	35.00	30.00	10.00
2		30.00	5.00	35.00	15.00
3		35.00	20.00	30.00	30.00
4		45.00	50.00	35.00	30.00
5		45.00	40.00	20.00	40.00
6		40.00	45.00	50.00	30.00
7		95.00	90.00	100.00	90.00

PI 5 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		35.00	30.00	35.00	20.00
2		5.00	15.00	10.00	5.00
3		10.00	0.00	15.00	15.00
4		35.00	25.00	20.00	25.00

PI 6 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		25.00	35.00	25.00	35.00
2		25.00	20.00	20.00	10.00
3		5.00	5.00	5.00	10.00
4		10.00	5.00	5.00	5.00

APPENDIX C-II (Continued)

PI 7 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		10.00	30.00	20.00	30.00
2		20.00	40.00	35.00	30.00
3		20.00	30.00	30.00	35.00
4		55.00	35.00	20.00	45.00
5		25.00	30.00	65.00	35.00
6		40.00	35.00	40.00	35.00
7		40.00	30.00	35.00	20.00
8		25.00	35.00	15.00	35.00

APPENDIX C-II (Continued)

Test Series for Hi-Car Vinyl Sponge Backstop

PI 2 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		100.00	100.00	100.00	100.00
2		100.00	100.00	100.00	100.00
3		100.00	100.00	100.00	100.00
4		100.00	100.00	100.00	100.00
5		95.00	100.00	100.00	100.00
6		100.00	100.00	95.00	90.00
7		90.00	75.00	90.00	70.00
8		65.00	50.00	65.00	55.00
9		45.00	25.00	35.00	55.00
10		35.00	55.00	40.00	35.00
11		30.00	45.00	40.00	35.00
12		55.00	30.00	25.00	35.00

PI 3 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		0.00	0.00	0.00	0.00
2		5.00	0.00	0.00	0.00
3		0.00	0.00	5.00	0.00
4		0.00	5.00	5.00	10.00
5		20.00	30.00	5.00	10.00
6		25.00	30.00	30.00	25.00
7		35.00	35.00	50.00	35.00
8		50.00	40.00	25.00	60.00
9		50.00	60.00	45.00	60.00
10		85.00	95.00	70.00	95.00
11		90.00	95.00	95.00	95.00

APPENDIX C-II (Continued)

PI 4 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		25.00	30.00	5.00	25.00
2		30.00	30.00	20.00	25.00
3		30.00	15.00	45.00	50.00
4		25.00	50.00	50.00	35.00
5		40.00	55.00	35.00	50.00
6		40.00	45.00	50.00	50.00
7		90.00	95.00	100.00	100.00

PI 5 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		45.00	30.00	30.00	55.00
2		10.00	0.00	10.00	20.00
3		5.00	5.00	5.00	0.00
4		30.00	30.00	30.00	20.00

PI 6 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		50.00	45.00	35.00	35.00
2		20.00	40.00	25.00	50.00
3		0.00	5.00	0.00	10.00
4		0.00	0.00	0.00	0.00

APPENDIX C-II (Continued)

PI 7 VARIED

TEST NO	SAMPLE NO	PERCENT SEPARATED 1	2	3	4
1		45.00	40.00	55.00	40.00
2		40.00	35.00	25.00	60.00
3		40.00	35.00	55.00	25.00
4		20.00	20.00	35.00	40.00
5		30.00	35.00	35.00	40.00
6		50.00	55.00	50.00	50.00
7		50.00	50.00	40.00	45.00
8		40.00	35.00	40.00	45.00

APPENDIX C-III

AIR DENSITY VALUES OBSERVED DURING TESTS

Canvas Backstop
(Air density in lbs./ft.^{3})

Test No.	Pi 2	Pi 3	Pi 4	Pi 5	Pi 6	Pi 7
1	0.0756	0.0728	0.0741	0.0740	0.0775	0.0726
2	0.0755	0.0730	0.0741	0.0734	0.0775	0.0738
3	0.0755	0.0728	0.0740	0.0737	0.0775	0.0738
4	0.0755	0.0728	0.0740	0.0740	0.0775	0.0726
5	0.0758	0.0728	0.0740			0.0738
6	0.0755	0.0728	0.0740			0.0726
7	0.0758	0.0728	0.0740			0.0738
8	0.0755	0.0728				0.0738
9	0.0756	0.0728				
10	0.0755	0.0733				
11	0.0758	0.0728				
12	0.0754					

Average air density = 0.0742 lbs./ft.^{3}

Carpet Backstop
(Air density in lbs./ft.^{3})

Test No.	Pi 2	Pi 3	Pi 4	Pi 5	Pi 6	Pi 7
1	0.0711	0.0754	0.0712	0.0722	0.0746	0.0745
2	0.0710	0.0750	0.0718	0.0719	0.0746	0.0746
3	0.0712	0.0754	0.0715	0.0722	0.0746	0.0743
4	0.0711	0.0750	0.0715	0.0719	0.0746	0.0743
5	0.0711	0.0750	0.0716			0.0743
6	0.0711	0.0750	0.0715			0.0743
7	0.0711	0.0753	0.0715			0.0743
8	0.0712	0.0755				0.0743
9	0.0709	0.0750				
10	0.0717	0.0751				
11	0.0717	0.0750				
12	0.0712					

Average air density = 0.0733 lbs./ft.^{3}

APPENDIX C-III (Continued)

Bean Bag Backstop
(Air density in lbs./ft.^{3})

Test No.	Pi 2	Pi 3	Pi 4	Pi 5	Pi 6	Pi 7
1	0.0750	0.0746	0.0760	0.0760	0.0766	0.0740
2	0.0750	0.0740	0.0767	0.0754	0.0760	0.0737
3	0.0750	0.0746	0.0760	0.0753	0.0767	0.0737
4	0.0753	0.0740	0.0760	0.0760	0.0763	0.0740
5	0.0753	0.0746	0.0760			0.0737
6	0.0753	0.0746	0.0764			0.0740
7	0.0750	0.0740	0.0760			0.0737
8	0.0750	010746				0.0737
9	0.0750	0.0740				
10	0.0750	0.0750				
11	0.0753	0.0740				
12	0.0750					

Average air density = 0.0750 lbs./ft.^{3}

Closed Cell Backstop
(Air density in lbs./ft.^{3})

Test No.	Pi 2	Pi 3	Pi 4	Pi 5	Pi 6	Pi 7
1	0.0718	0.0760	0.0725	0.0710	0.0712	0.0720
2	0.0718	0.0760	0.0725	0.0710	0.0712	0.0720
3	0.0718	0.0760	0.0725	0.0710	0.0712	0.0720
4	0.0718	0.0768	0.0725	0.0716	0.0713	0.0720
5	0.0718	0.0768	0.0725			0.0720
6	0.0718	0.0768	0.0725			0.0720
7	0.0718	0.0756	0.0725			0.0720
8	0.0719	0.0756				0.0720
9	0.0718	0.0763				
10	0.0719	0.0758				
11	0.0719	0.0758				
12	0.0719					

Average air density = 0.0729 lbs./ft.^{3}

APPENDIX C-III (Continued)

Polyurethane Foam Backstop
(Air density in lbs./ft.^{3})

Test No.	Pi 2	Pi 3	Pi 4	Pi 5	Pi 6	Pi 7
1	0.0720	0.0748	0.0745	0.0720	0.0720	0.0720
2	0.0720	0.0756	0.0745	0.0720	0.0720	0.0720
3	0.0720	0.0756	0.0745	0.0720	0.0720	0.0720
4	0.0720	0.0748	0.0745	0.0720	0.0720	0.0720
5	0.0720	0.0756	0.0745			0.0720
6	0.0720	0.0748	0.0745			0.0720
7	0.0720	0.0748	0.0745			0.0720
8	0.0720	0.0756				
9	0.0720	0.0748				
10	0.0720	0.0748				
11	0.0720	0.0754				
12	0.0720					

Average air density = 0.0731 lbs./ft.^{3}

Hi-Car Backstop
(Air density in lbs./ft.^{3})

Test No.	Pi 2	Pi 3	Pi 4	Pi 5	Pi 5	Pi 7
1	0.0738	0.0747	0.0742	0.0745	0.0745	0.0748
2	0.0742	0.0747	0.0742	0.0745	0.0745	0.0748
3	0.0729	0.0744	0.0742	0.0748	0.0745	0.0749
4	0.0738	0.0742	0.0742	0.0750	0.0745	0.0750
5	0.0729	0.0744	0.0742			0.0752
6	0.0742	0.0747	0.0742			0.0749
7	0.0729	0.0744	0.0742			0.0747
8	0.0720	0.0744				0.0747
9	0.0738	0.0747				
10	0.0733	0.0753				
11	0.0738	0.0747				
12	0.0735					

Average air density = 0.0743 lbs./ft.^{3}

APPENDIX C-IV

CHECK DATA FOR ESTABLISHING PREDICTION EQUATION ACCURACY*

Canvas Backstop

	PARAMETER SET 1	PARAMETER SET 2	PARAMETER SET 3	PARAMETER SET 4
	45.00	45.00	80.00	25.00
	55.00	25.00	65.00	35.00
	40.00	45.00	55.00	15.00
	60.00	35.00	80.00	20.00
	50.00	20.00	85.00	5.00
	45.00	45.00	75.00	0.00
	50.00	25.00	90.00	10.00
	50.00	35.00	60.00	15.00
	25.00	30.00	90.00	20.00
	45.00	40.00	90.00	20.00
	60.00	20.00	75.00	0.00
	55.00	40.00	90.00	25.00
	60.00	20.00	100.00	20.00
	55.00	25.00	90.00	10.00
	40.00	35.00	80.00	15.00
	45.00	35.00	85.00	0.00
	45.00	35.00	65.00	5.00
	50.00	35.00	90.00	20.00
	45.00	20.00	70.00	15.00
	55.00	25.00	90.00	5.00
MEAN=	48.75	31.75	80.25	14.00

95 PERCENT CONFIDENCE INTERVAL FOR MEANS =

MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
44.81	52.69	27.64	35.86	74.60	85.90	9.53	18.47

*Tabular values represent percent separated (Pi 1)

APPENDIX C-IV (Continued)

Carpet Backstop

	PARAMETER SET 1		PARAMETER SET 2		PARAMETER SET 3		PARAMETER SET 4	
	70.00		15.00		75.00		10.00	
	65.00		5.00		75.00		5.00	
	50.00		10.00		80.00		10.00	
	70.00		15.00		90.00		20.00	
	45.00		25.00		65.00		5.00	
	45.00		5.00		80.00		25.00	
	65.00		20.00		85.00		15.00	
	45.00		15.00		60.00		10.00	
	50.00		15.00		100.00		5.00	
	40.00		5.00		85.00		10.00	
	70.00		15.00		80.00		30.00	
	60.00		20.00		60.00		5.00	
	55.00		25.00		75.00		10.00	
	40.00		5.00		85.00		10.00	
	55.00		25.00		85.00		15.00	
	55.00		25.00		85.00		10.00	
	55.00		25.00		75.00		5.00	
	55.00		5.00		85.00		10.00	
	65.00		15.00		80.00		15.00	
	50.00		5.00		90.00		25.00	
MEAN=	55.25		14.75		79.75		12.50	
95 PERCENT CONFIDENCE INTERVAL FOR MEANS =								
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
	50.66	59.84	11.07	18.43	75.10	84.40	9.06	15.94

APPENDIX C-IV (Continued)

Bean Bag Backstop

	PARAMETER SET 1	PARAMETER SET 2	PARAMETER SET 3	PARAMETER SET 4
	70.00	40.00	95.00	35.00
	85.00	35.00	100.00	45.00
	80.00	25.00	90.00	35.00
	60.00	25.00	85.00	35.00
	80.00	20.00	85.00	40.00
	65.00	40.00	95.00	45.00
	80.00	30.00	90.00	15.00
	80.00	30.00	90.00	55.00
	90.00	45.00	80.00	30.00
	75.00	25.00	80.00	30.00
	80.00	35.00	90.00	35.00
	70.00	30.00	90.00	35.00
	75.00	30.00	100.00	65.00
	90.00	30.00	85.00	35.00
	85.00	30.00	90.00	45.00
	80.00	30.00	100.00	45.00
	75.00	25.00	95.00	35.00
	55.00	20.00	95.00	30.00
	95.00	10.00	85.00	25.00
	90.00	30.00	85.00	35.00
MEAN=	78.00	29.25	90.25	37.50

95 PERCENT CONFIDENCE INTERVAL FOR MEANS =

MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
73.17	82.83	25.59	32.91	87.36	93.14	32.49	42.51

APPENDIX C-IV (Continued)

Closed Cell Backstop

PARAMETER SET 1	PARAMETER SET 2	PARAMETER SET 3	PARAMETER SET 4
40.00	15.00	75.00	30.00
40.00	20.00	90.00	20.00
50.00	5.00	85.00	20.00
40.00	10.00	95.00	30.00
45.00	10.00	85.00	15.00
45.00	15.00	85.00	15.00
65.00	20.00	85.00	20.00
50.00	10.00	80.00	15.00
65.00	25.00	70.00	40.00
60.00	15.00	70.00	25.00
60.00	10.00	55.00	35.00
40.00	10.00	90.00	30.00
55.00	20.00	90.00	35.00
60.00	10.00	80.00	15.00
50.00	15.00	80.00	35.00
60.00	15.00	90.00	25.00
65.00	10.00	80.00	35.00
55.00	15.00	90.00	35.00
55.00	15.00	90.00	10.00
45.00	20.00	75.00	45.00

MEAN= 52.25 14.25 82.00 26.50

95 PERCENT CONFIDENCE INTERVAL FOR MEANS =

MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
48.06	56.44	11.94	16.56	77.55	86.45	21.88	31.12

APPENDIX C-IV (Continued)

Polyurethane Foam Backstop

	PARAMETER SET 1	PARAMETER SET 2	PARAMETER SET 3	PARAMETER SET 4
	60.00	5.00	95.00	15.00
	35.00	10.00	80.00	10.00
	60.00	15.00	95.00	5.00
	55.00	20.00	80.00	10.00
	75.00	25.00	95.00	15.00
	85.00	20.00	70.00	10.00
	75.00	0.00	85.00	30.00
	65.00	15.00	95.00	20.00
	70.00	0.00	85.00	10.00
	80.00	5.00	85.00	15.00
	70.00	10.00	80.00	15.00
	75.00	10.00	90.00	20.00
	75.00	20.00	90.00	10.00
	65.00	15.00	80.00	10.00
	75.00	20.00	90.00	15.00
	75.00	10.00	85.00	15.00
	70.00	15.00	90.00	20.00
	45.00	25.00	85.00	5.00
	50.00	25.00	90.00	15.00
	60.00	20.00	80.00	20.00
MEAN=	66.00	14.25	86.25	14.25

95 PERCENT CONFIDENCE INTERVAL FOR MEANS =

MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
60.14	71.86	10.59	17.91	83.13	89.37	11.48	17.02

APPENDIX C-IV (Continued)

Hi-Car Backstop

PARAMETER SET 1	PARAMETER SET 2	PARAMETER SET 3	PARAMETER SET 4
40.00	30.00	85.00	30.00
35.00	10.00	65.00	25.00
40.00	30.00	60.00	20.00
65.00	35.00	75.00	25.00
60.00	25.00	85.00	5.00
45.00	20.00	65.00	35.00
60.00	35.00	80.00	20.00
50.00	25.00	85.00	5.00
70.00	40.00	80.00	10.00
40.00	20.00	70.00	35.00
50.00	35.00	70.00	20.00
75.00	35.00	70.00	15.00
45.00	30.00	85.00	20.00
60.00	30.00	90.00	10.00
45.00	30.00	65.00	15.00
70.00	25.00	75.00	40.00
50.00	35.00	70.00	15.00
75.00	25.00	75.00	25.00
30.00	25.00	75.00	20.00
70.00	20.00	80.00	25.00
MEAN= 53.75	28.00	75.25	20.75

95 PERCENT CONFIDENCE INTERVAL FOR MEANS =

MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
47.22	60.28	24.66	31.34	71.34	79.16	16.24	25.26

APPENDIX C-V

ORIGINAL DATA OF PART TWO

Three-Material Mixture Tests

Test Number	Soybeans Separated (Lbs.)	Wheat Separated (Corrected) (Lbs.)	Sorghum Separated (Corrected) (Lbs.)	Total Wt. Separated (Lbs.)	Soybeans Collected (Lbs.)	Wheat Collected (Estimated) (Lbs.)	Sorghum Collected (Estimated) (Lbs.)	Actual Total Wt. Collected (Lbs.)
Rep. I								
1	0.80	3.53	1.81	6.14	0.97	5.44	3.46	10.87
2	0.42	1.27	1.76	3.45	0.72	2.36	3.72	7.48
3	2.70	3.40	0.51	6.61	3.36	4.90	1.18	10.30
4	1.66	2.15	0.33	4.14	2.17	1.70	0.31	5.26
5	2.61	1.40	0.33	4.34	3.38	2.32	0.73	6.29
6	0.21	0.60	0.82	1.64	0.33	1.97	1.11	3.23
7	0.68	0.93	0.16	1.77	1.07	1.74	0.33	3.08
8	0.51	2.33	1.18	4.02	0.64	3.69	2.64	6.91
9	0.88	2.40	3.28	6.56	0.90	3.54	6.06	10.42
10	4.61	2.33	0.61	7.55	4.79	3.02	0.92	7.73
11	2.64	0.45	1.19	4.28	3.49	0.65	2.65	6.69
12	0.71	0.18	0.77	1.66	1.07	0.28	1.88	3.16
13	0.21	0.96	0.48	1.65	0.33	1.73	1.23	3.24
14	1.10	0.17	0.47	1.74	1.75	0.32	1.25	3.18
15	1.73	0.41	1.88	4.02	2.27	0.69	4.17	6.98
16	2.76	1.05	2.53	6.35	3.29	0.66	6.86	10.73
17	4.26	0.64	1.86	6.76	5.19	1.06	4.11	10.28
18	0.99	0.56	0.14	1.69	1.77	1.17	0.35	3.24
Rep. 2								
4	0.97	1.94	0.37	3.86	2.35	1.85	0.71	6.96
17	4.27	0.82	1.62	6.61	5.25	0.87	4.28	10.25
18	0.97	0.58	0.11	1.66	1.76	2.09	0.38	3.19

APPENDIX G-V (Continued)

Two-Material Mixture Tests

Test No.	Soybeans Separated (Lbs.)	Wheat Separated (Lbs.)	Soybeans Collected (Lbs.)	Wheat Collected (Lbs.)	Total Soybeans Fed Into System (Lbs.)	Total Wheat Fed Into System (Lbs.)
Rep. 1						
1	2.86	0.46	1.17	0.46	4.03	0.92
2	5.17	5.24	1.70	4.76	6.77	10.00
3	1.66	4.39	0.62	4.17	2.28	8.56
4	1.49	1.38	0.64	1.33	2.13	2.71
5	2.06	1.06	0.81	0.98	2.87	2.04
6	7.66	3.43	2.68	3.24	10.34	6.67
7	4.91	2.19	1.74	2.08	6.65	4.27
8	6.44	1.07	2.44	1.02	8.88	2.09
9	10.30	1.73	3.39	1.62	13.69	3.35
10	0.81	2.65	0.33	2.57	1.14	5.22
11	2.62	6.92	0.93	6.57	3.55	13.49
12	3.25	3.26	1.23	3.14	4.48	6.40
Rep. 2						
1	2.90	0.51	1.08	0.49	3.98	1.00
3	1.78	4.56	0.51	4.00	2.29	8.56
8	6.43	1.06	2.26	0.98	8.69	2.04
9	10.31	1.71	3.28	1.60	13.59	3.31
10	0.78	1.09	0.24	1.81	1.02	2.90
11	2.59	6.88	0.94	6.55	3.53	13.43

VITA

Richard W. Whitney

Candidate for the Degree of

Master of Science

Thesis: PARTICLE SEPARATION IN A PNEUMATIC CONVEYING SYSTEM

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Miami County, Kansas, November 1, 1938, the son of Wilbur and Helen Whitney.

Education: Graduated from Kansas State University in 1961 with a Bachelor of Science Degree, majoring in Agricultural Engineering; completed the requirements for the Master of Science Degree from Oklahoma State University in May, 1967.

Professional Experience: During college worked one summer for the U.S.D.A., A.R.S. After graduation employed as Temporary Instructor in the Agricultural Engineering Department at Kansas State University, 1961-1962; Instructor at Oklahoma State University in the Agricultural Engineering Department, 1962-1967

Professional Organizations: Member of the American Society of Agricultural Engineers; Engineer-in-Training in Kansas.