EFFECTS OF PLATE SPEED AND CELL CLEARANCE ON THE METERING ACCURACY OF A HORIZONTAL PLATE, METERING DEVICE

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PREFACE

The work reported in this thesis was conducted as a part of State Project 802, "Development of Improved Machines and Methods for Seedbed Preparation, Planting, and Early Weed Control in Cotton Production", of the Oklahoma Agricultural Experiment Station. One of the objectives of this project is to evaluate the performance of graded seed in presently available planters and to modify present planters to exploit the unique physical dimensions of cotton seed. This investigation was made to obtain basic performance data on horizontal plate, seed metering devices that may be used to improve and refine the metering devices now used to meter cotton seeds.

The author is grateful to Professor Jay G. Porterfield, the thesis advisor, for making the necessary arrangements to carry out this study, for his invaluable encouragement and counsel during the study, and for his appropriate comments and suggestions in the writing of this thesis.

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CHAPTER I

INTRODUCTION

This investigation was initiated to study the performance characteristics of horizontal plate, seed metering devices.

Although horizontal plate, seed metering devices have been used for many years on row crop planters for metering corn, cotton, peanuts, sugar beets and other large seeded crops, the development of these devices has been primarily through a " cut and try " method. The present metering devices are becoming inadequate due to the demand for faster planting speeds along with the greater metering accuracy required for precision planting. Further improvements and refinements of these devices are hampered by a lack of theoretical and empirical design information of the basic elements involved. The establishment of the basic relationships and evaluation of each of the factors involved will provide the necessary design information to improve and refine these devices to meet present and future demands.

Because of the many factors to be investigated and the limited time for the thesis project, this study has been limited to developing the equipment, evaluating techniques, and to evaluating just one of the factors. The work reported herein is but a small part of the total information needed. Many subsequent studies could be made, utilizing the apparatus and techniques developed for this study.

CHAPTER II

OBJECTIVES

The objectives of this study were to:

1. Develop the apparatus and techniques of evaluating the factors affecting the metering accuracy[1] of a horizontal plate, metering device.
2. Establish the relationship between metering accuracy and plate speed with varying amounts of cell clearance[2] for a horizontal plate, metering device.

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[1]Metering accuracy may be used synonymously with per cent cell fill and is defined as the total number of seeds collected divided by the total number of cells passing the discharge point.

[2]Cell clearance refers to the size of cell with respect to the seed. It is the amount a seed cell is larger than the seed. Cell clearance will be expressed as a percentage of the diameter of the seed used.

CHAPTER III

REVIEW OF LITERATURE

A. Basic Concepts

A horizontal plate, seed metering device consists essentially of a seed plate rotating in a horizontal plane with a number of seed cells on the edge or near the edge of the plate. Seed flow into the cells is encouraged by the force of gravity and may be aided by various seed orientation devices on the moving plate and or on the stationary parts of the unit. A seed cutoff device is used to limit the number of seeds per cell and reduce seed damage, and a seed knockout device is used to insure positive unloading of the cells at the discharge point.

The desired performance of a horizontal plate, seed metering device would feature a high metering accuracy or per cent cell fill relatively independent of cell speed with a minimum amount of seed damage. Each of the following factors may exert an influence on the performance and must be evaluated for a particular metering condition (1):

1. Size of seed cell relative to seed.
2. Shape of seed cell relative to seed.
3. Orientation of seed relative to seed cell.
4. Distance seed cell is exposed to seed.
5. Type of cutoff and knockout device used.
6. Depth of seed above seed plate.
7. Speed of seed cell relative to seed.
8. Time seed cell is exposed to seed.
9. General shape of seed.

10. Variation in seed size and shape.

11. Surface characteristics of seed.

12. Density of seed.

The first eight of these factors are related to the metering device while the other factors are properties of the seeds. Little is known of the variation in density and surface characteristics of seeds. The variation in seed size and shape may be considerable, but can be minimized by a system of careful grading, screening, sorting or measuring. Although the shapes of the different crop seeds commonly metered with this type of device vary widely, they may be classified into three basic shapes according to their dimensional variation. Spherical seeds such as sorghum, soybeans, and sugar beets vary in only one dimension. Cotton and peanuts, being somewhat cylindrical vary in two dimensions, diameter and length. Corn seeds have variation in all three dimensions of length, width and thickness. Establishment of the basic relationships in terms of these three shape factors would provide useful information necessary to improve the performance from this type of seed metering device.

B. Development of the Horizontal Plate, Metering Device

The basic elements of the horizontal plate, metering device were concieved and developed during the latter half of the nineteenth century (2). Most of the devices developed during this period were hill dropping devices designed to meter a number of seeds in the same seed cell. These devices had rather poor metering characteristics due to inadequate design and construction of the seed plates and seed orienting devices and due to the lack of any system of seed sizing or grading. Developments in recent years have been primarily in refining the basic elements and adapting the devices to meter different types of crop seeds.

Considerable attention has also been given to grading of seeds particularly as the concept of single seed metering for high speed precision planting has developed (3).

In the development of precision sugar beet planting equipment, both the seeds and elements of the metering device were studied. Bainer (4) developed processes of modifying the seed as to size and shape to make them more suitable for precision drilling. He found that seeds so processed could be graded to size ranges of 2/64 to 3/64 inch. Results of tests with metering devices indicate that the seed diameter and seed thickness to insure proper cell fill, should approach the smaller dimensions of the size range to minimize multiple cell fill and seed damage. Some of the basic relationships were established by Barmington (5) in tests with commercial sugar beet planters. He suggests that 1/64 inch cell clearance is larger than needed especially when the seed contains high percentages of the smaller size fractions. Barmington found that a small increase in the plate cell size apparently increased the percentage of cell fill very rapidly when the seed contains a small per cent of the smaller sizes. The per cent cell fill was found to decrease very rapidly with an increase in plate cell speed for all metering devices tested. Reducing the seed plate thickness to the dimensions of the smaller size fractions was found to decrease the per cent cell fill appreciably over the speed range. Most of the commercial planters tested showed a tendency toward minimum seed damage at a plate speed that gave 100 per cent or slightly less than 100 per cent cell fill.

Calibration tests of horizontal plate cotton planters by Schroeder et al (6) showed that seed plates with larger cells resulted in less variation in cell fill over a range of plate speeds. The cell fill was found to be most consistant when graded cotton seed of a particular size was selected to be used with a particular seed cell size. These tests were made using seed plates that were designed to meter more than one seed per cell. Autry (7) used different sizes and shapes of seed cells to produce accurate cell fill for metering delinted cotton seed, but made no mention of the cell size in relation to the seed size.

Tests on corn planters were made by Reed (8) and Sjogren (9) to determine the influence of some factors on the accuracy of seed drop. Reed found that of the three shapes of kernels used (large, broad, round; long, narrow, peg-shaped; intermediate between other two) the large round kernel was the most difficult to drop with accuracy. Both reported that a system of grading the seed was necessary for increased accuracy and pointed out the necessity of selecting plates to fit the seed. In both series of tests the performance of the round hole plates was inferior to either the edge selection or flat selection plates. Over the speed range tested, Sjogren found that lower accuracy accompanied the higher speeds and that the round hole type plates were more sensitive to speed than the edge selection plate. He also reported that the accuracy of drop due to the amount of seed in the hopper depended largely upon the treatment of the seed. When graded or sized seed was used, little difference was noted in the accuracy of drop for different amounts of seed in the hopper.

A survey of some machines used to count tablets and capsules for the pharmaceutical industry showed only a few machines to use rotating disks with cells as the counting devices. The design of these devices is essentially a trial and error procedure to arrive at a cell size that will accurately meter the tablets or capsules. The speed of the counting cells is held quite low to maintain the desired accuracy. Hence the counting rate of an individual machine is relatively low. High counting rates are obtained by combining a number of devices to make one larger machine.

CHAPTER IV

APPARATUS AND EQUIPMENT

A. General Test Conditions

In order to accomplish the objectives set forth in this study, a set of test conditions was established to fix the design of the test apparatus and to evaluate the relationship between metering accuracy and linear cell speed for varying amounts of cell clearance.

The test conditions selected are grouped as constant factors and variable factors as follows:

Constant Factors

1. Seed shape. Spherical objects used as seeds.
2. Spherical cast phenolic plastic balls used as seeds to reduce size variation.
3. Seed plate cell of cylindrical shape with axis in a vertical plane.
4. Seed plate thickness to allow only one ball per cell.
5. Number of cells per plate and diameter of plate.
6. Depth of balls above seed plate at start of test.
7. No stationary or moving parts specifically to aid in orienting balls to cell.
8. Constant distance of cell exposure to seed hopper.
9. Non-yielding cutoff device to prevent multiple cell fill and a suitable knockout device to insure positive cell unloading.

Variable Factors

1. Linear cell speed variation from 0 to 150 feet per minute.

2. Cell clearances of 10, 20, 30, 40, and 50 per cent of the ball diameters.

3. Two ball sizes of 1/4 inch and 3/8 inch diameter.

B. Design and Development of Apparatus

The apparatus was designed so that it could be used to evaluate any of the basic factors. To accomplish this, the following design requirements were established.

1. Ease of changing seed plates.
2. Variable seed plate speed.
3. Support for orientation, cutoff, and knockout devices.
4. Count the cells passing the discharge point for a given time interval.
5. Collect a sample with the device in operation
6. Similiar dimensions and physical shape as existing devices.

The basic apparatus developed to meet these requirements is shown in figures 1, 2, and 3. The basic unit consisted of a stationary hopper bottom 8-1/16 inches in diameter that was supported by four legs 15 inches long. The hopper bottom had a notch cut in its edge to provide an unloading area for the seed cells and a 2-1/4 inch diameter hole bored in the center through which the seed plate drive shaft extended. The seed plate drive shaft was mounted vertically in two self aligning pillow block ball bearings. The bearings were attached to a mounting bracket that was attached to the underside of the hopper bottom. The top of the seed plate drive shaft was threaded and near the top was a two inch diameter plate support collar and a one inch diameter seed plate centering plug. The seed plate drive shaft was positioned vertically so that the top of the plate support collar and the top of the hopper bottom plate

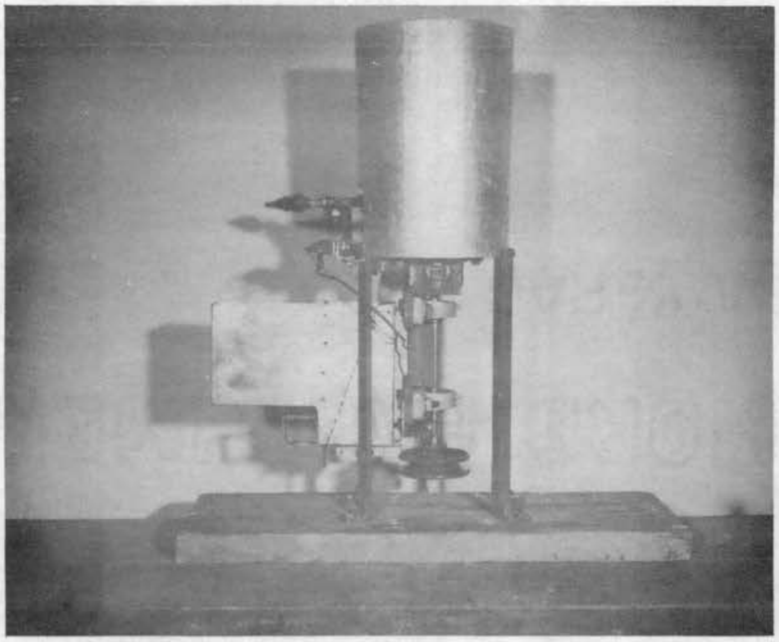


Figure 1. Side view of apparatus with sample container in pre-sample position.

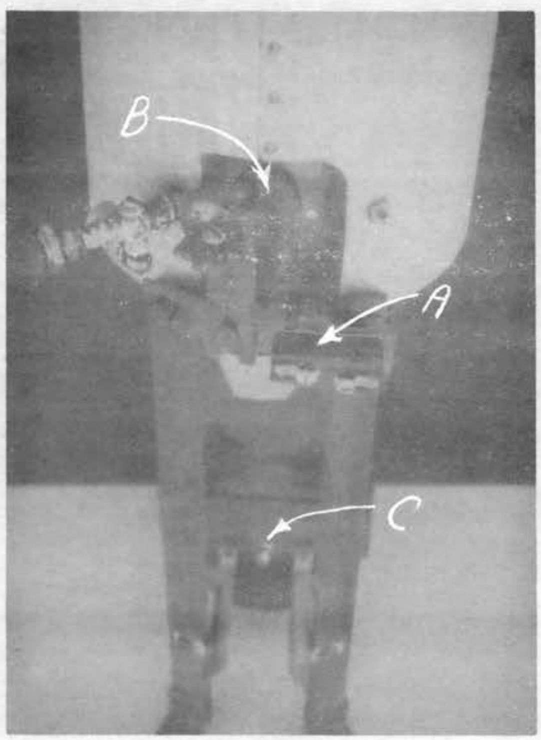


Figure 2. Front view of apparatus showing counting switch (A), air knockout (B) and sample switch (C).

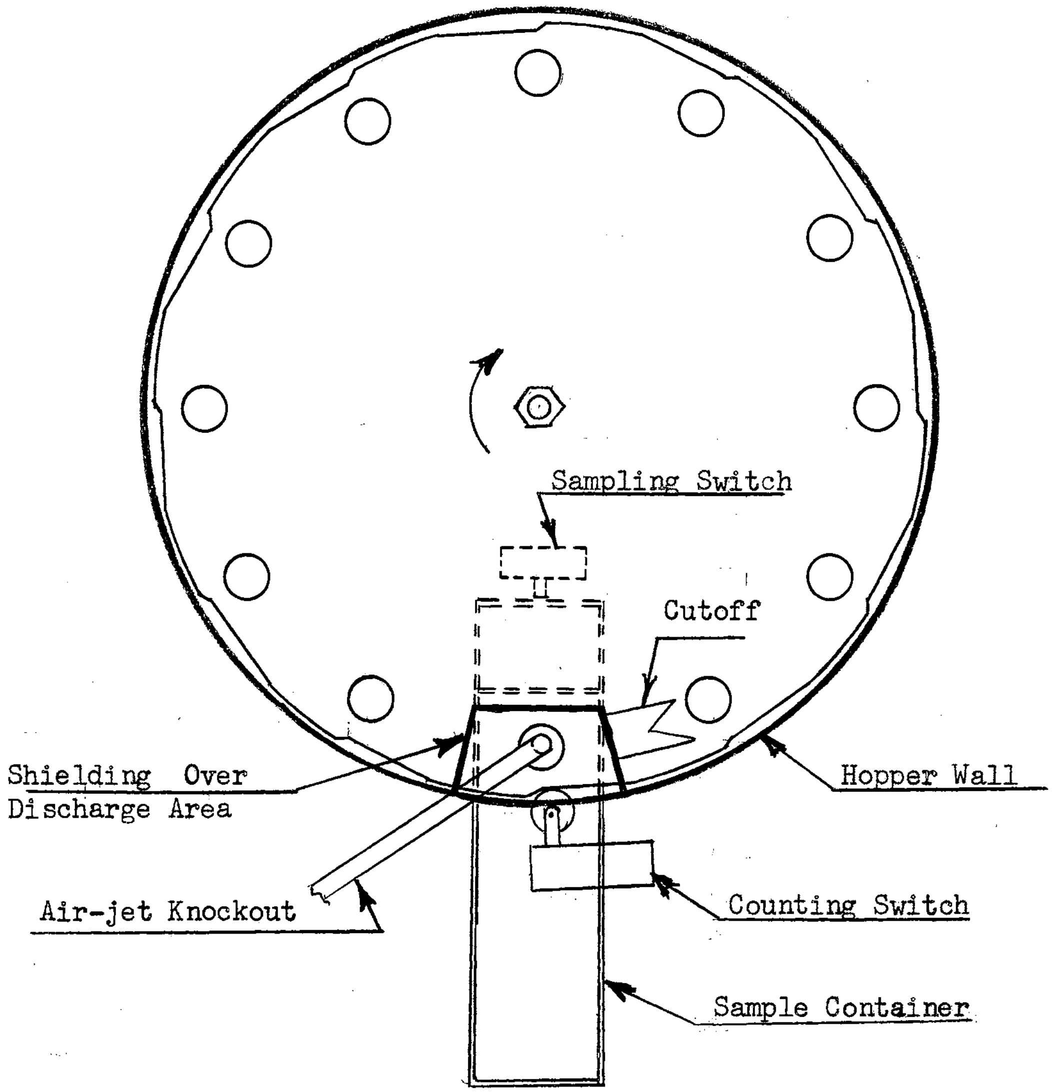


Figure 3. Diagram of apparatus with sample container in pre-sample position and with sample switch open.

were even. The seed plates fitted over the centering plug and were attached to the drive shaft by a flat washer and nut. The hopper fitted around the hopper bottom and was held in place by the leg attaching bolts. A hole cut in the hopper at the discharge point allowed positioning of the knockout device over the seed cells. The knockout, sampling switch and counting switch were mounted on adjustable brackets. Two guides attached to the legs supported the sample container. A tapered discharge spout attached to the hopper bottom plate guided the discharged balls into the sample container. Removable shielding attached inside the hopper covered the discharge area and provided a support for the cutoff device. Power was supplied to the drive shaft through a quarter turn Vee belt drive using a Westinghouse oil gear hydraulic torque converter. An airjet type knockout was selected to unload the cells. The nozzle tip consisted of an 1/8 inch hydraulic grease fitting with the check ball and spring removed. Air under pressure was supplied by a portable air compressor and controlled by a valve near the nozzle tip.

Counting and timing of the seed cells was done electrically. The wiring diagram for the circuit is shown in figure 4 . A single pole, single throw, snap action counting switch actuated by milled notches on the periphery of the seed plate opened and closed the circuit each time a cell passed the discharge point. The cell counts were recorded by a Veeder Root series B-1205 reset magnetic counter. Time was indicated by a Telechron self starting electric clock connected in the counting circuit. A single pole, single throw, snap action sampling switch actuated by the sampling container started and stopped the magnetic counter and clock simultaneously. The sampling container had two compartments which facilitated the taking of samples with the apparatus in operation. A

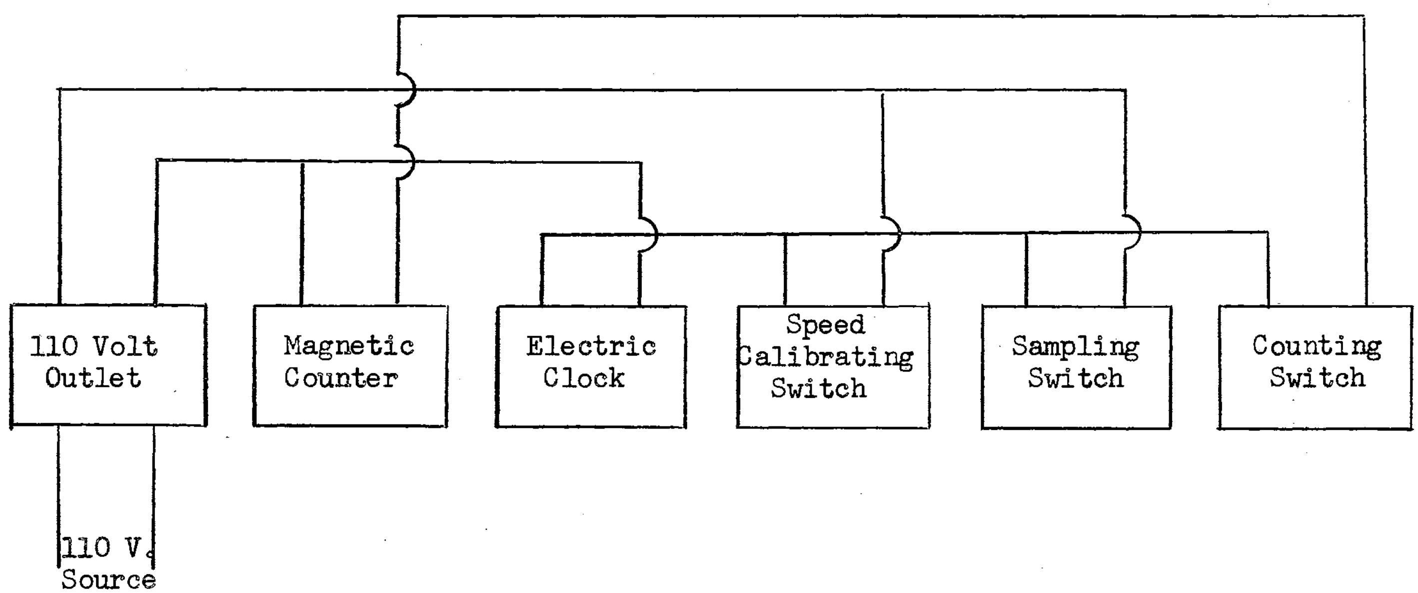


Figure 4. Wiring diagram of counting circuit

single pole, single throw, calibrating switch in the circuit permitted checking the plate speed before a test was started. Because there were 12 cells in each plate and each cell was counted, the revolutions per minute of the plate could rapidly be checked by noting the number of counts recorded on the counter over a five second interval. The linear speed of the cells was determined using the cell circle diameter of seven inches.

The samples were rapidly counted using a counting board. The counting board consisted of a shallow box with 500 spaced depressions in the box bottom. A sheet metal lid facilitated emptying the board after each sample was counted. The completed apparatus and test layout is shown in figure 5.

Several additions to the basic apparatus were necessary to adapt it to the test conditions selected. The seed plates were made eight inches in diameter and fitted in the hopper with 1/32 inch clearance between the plate edge and the hopper wall. Twelve equally spaced round holes were bored in the plates on a seven inch diameter circle. The cells were not beveled or tapered. The sharp edge caused by the boring operation was removed with emery cloth. Notches were milled on the plate edge near each cell to actuate the counting switch. The cell clearances for the different plates were made 10, 20, 30, 40, and 50 per cent of the ball diameter. A set of five plates was made for each of the two ball sizes selected. Complete dimensions of the seed plates are as shown in figure 7. The plate thickness was made 20 per cent larger than the ball diameter. This permitted only one ball to be completely in a cell and less than 50 per cent of a second ball to be in the same cell for the largest cell clearance.

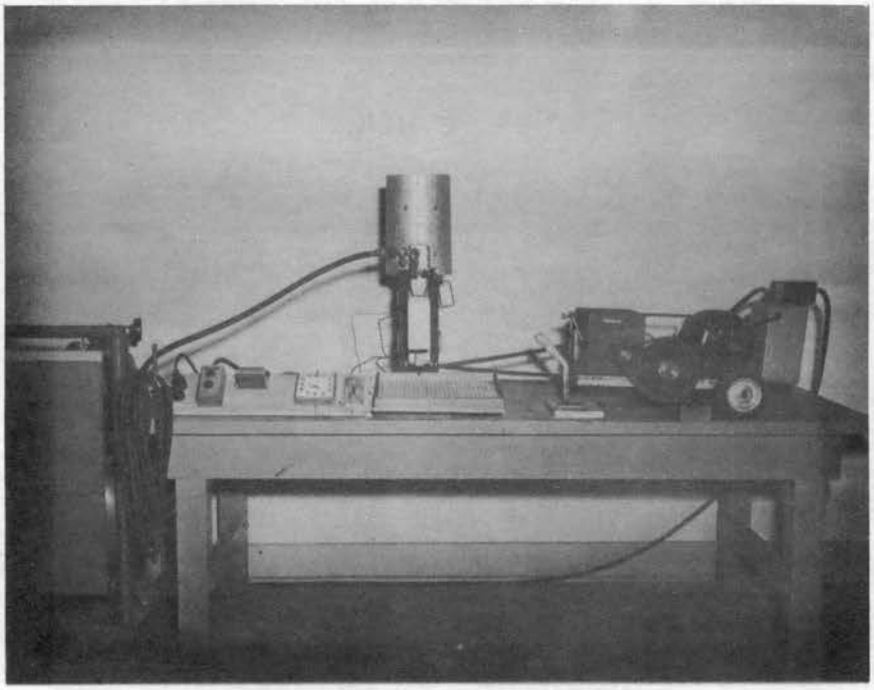


Figure 5. Apparatus layout used during tests.

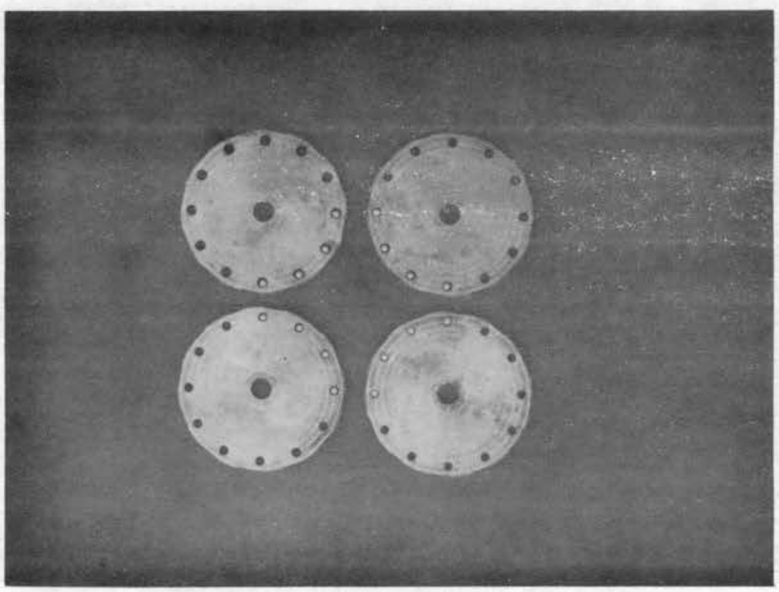


Figure 6. Seed plates used with 3/8 inch balls.

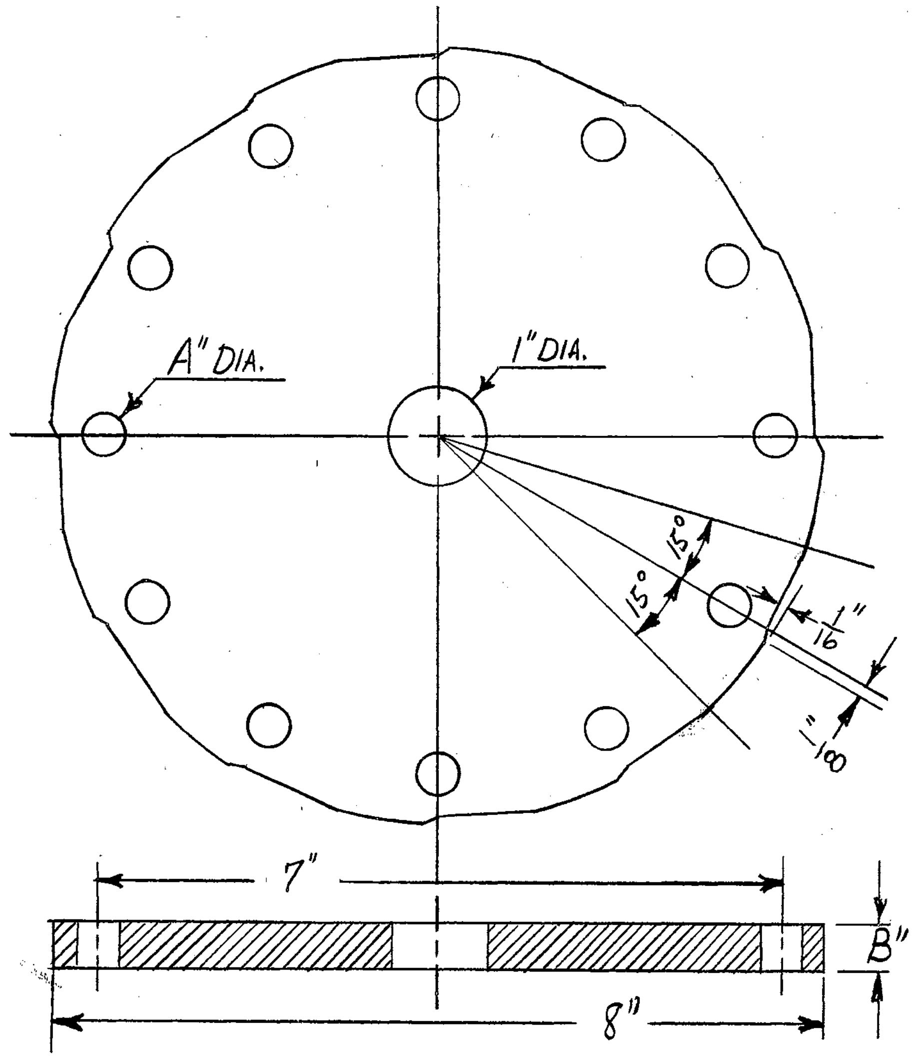


Plate No.	Ball Size	Cell Clearance (% Ball Dia)	A	B
1	1/4	10	0.275	0.300
2	1/4	20	0.300	0.300
3	1/4	30	0.325	0.300
4	1/4	40	0.350	0.300
5	1/4	50	0.375	0.300
6	3/8	10	0.4125	0.450
7	3/8	20	0.4500	0.450
8	3/8	30	0.4875	0.450
9	3/8	40	0.5250	0.450
10	3/8	50	0.5625	0.450

Figure 7. Seed plate dimensions.

The non-yielding type cutoff device was developed during preliminary tests with the apparatus. The device consisted of a vee notched piece of sheet metal sliding on the top of the seed plate and positioned so the notch tip was 1/8 inch off the centerline of the cell circle. The vee notch was aided by a spring loaded ball arrangement working through the bottom of the seed cell at the cutoff point as shown in figure 8 . The combined action of both of these devices provided the necessary lifting action on the second ball in each cell to remove it from the cell. The vee notch, being beveled and positioned off the cell centerline, rejected a ball at the cutoff point that was less than 50 per cent in the cell and injected a ball into the cell that was over 50 per cent in the cell. The vee notch cutoff was attached to the shielding covering the discharge area. Because of the space occupied by the shielding and cutoff, 15 per cent of the length of the cell circle was covered. The inside of the hopper is shown in figure 9 .

C. Preliminary Operation

Preliminary tests were made with the apparatus to establish a test technique and to check the operation and reliability.

Frequent jamming of the apparatus occured using the plates with cell clearance 50 per cent of the ball diameter. This occured because the cells were large enough to allow the second ball to be approximately 50 per cent in a cell and because the lifting action of the spring loaded ball at the bottom of the cell could not raise the second ball far enough for the vee notch to reject it. For this reason further work with the plates having a cell clearance of 50 per cent of the ball diameter was discontinued. The cutoff device operated satisfactorly for the other plates although occasional jamming occured when a ball was approximately

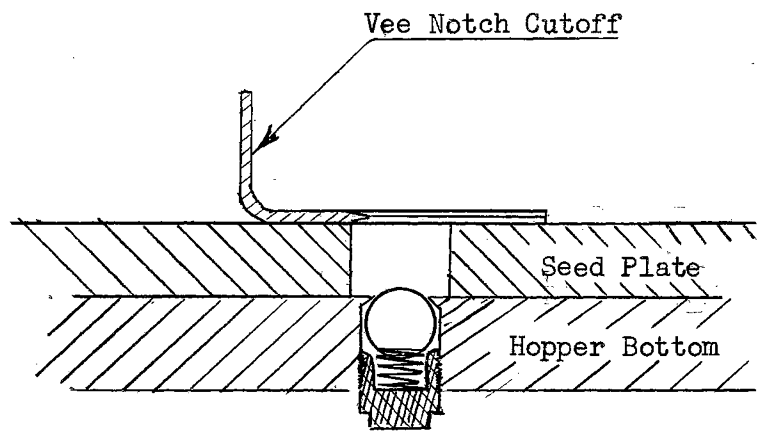


Figure 8. Diagram of spring loaded ball arrangement at the cutoff point.

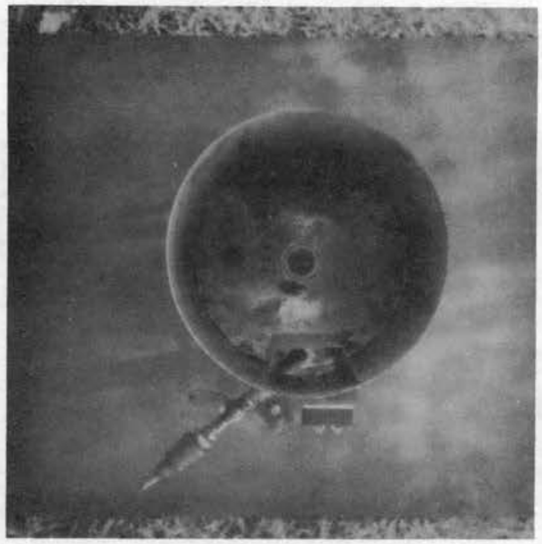


Figure 9. View showing inside of hopper with 15 percent of cell circle covered. Seed plate rotates in a clockwise direction. Note cutoff vee notch to the right side of the shield.

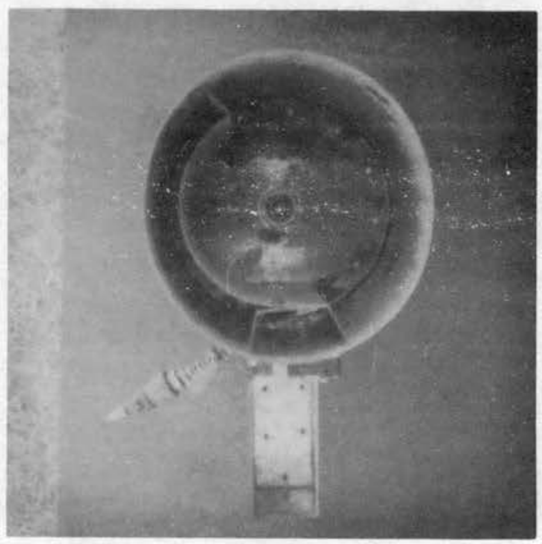


Figure 10. View showing inside of hopper with 50 percent of cell circle covered.

50 per cent in an empty cell at the discharge point. The frequency of jamming for this cause was not deemed serious enough to warrent further development of the cutoff device. When jamming occured during a test, the test was rerun.

Careful adjustment of the air from the air jet knockout was necessary because of the air turbulence set up over the seed plate. Too large an air stream from the nozzle tip impinging on the seed plate just before the knockout point caused the ball in a cell to be lifted partially out of the cell and be wedged between the nozzle tip and the cell wall. Too small an air stream did not provide sufficient knockout action.

Because of the nature of the electrical counting system, one or two extra counts per sample could have been recorded by the counter. The extra counts would be caused by either the counting switch being open when the sampling switch was closed or by the counting switch being closed when the sampling switch was opened. This chance error in counting, however, could be reduced to a negligible value by merely enlarging the sample size.

The maximum rated counting speed of the magnetic counter was 1000 counts per minute. Because the seed cell plate had twelve cells and each cell was counted, the maximum rotative speed of the seed plate should have been 83.3 revolutions per minute. Operation above this speed would have overloaded the counter and resulted in inaccurate counting.

It was found that the speed of the plate could be varied in approximately five revolutions per minute increments with the lower speed about 20 revolutions per minute and the highest about 80 revolutions per minute.

CHAPTER V

PROCEDURE

A. Design of Experiment

The statistical aspects of conducting the tests were considered in order to obtain data that would be accurate and statistically reliable.

The controlled variables for the study were cell clearance, ball size and plate cell speed. Four clearances and two ball sizes were selected for study with each combination tested over the speed range of the apparatus. A study of the testing technique showed that the least amount of seed plate changing would involve running all of the speeds for a particular plate and ball size before changing to another plate. In preliminary work with the apparatus it was found that the speed could be varied in approximately five revolutions per minute increments which would give a total of twelve speeds over the range. It was also found that the speeds could not be repeated with sufficient precision to fit into a statistical design where speed would be one of the treatments. Upon these bases a completely randomized factorial design was selected with cell clearance and ball size as the main treatments. A minimum of three replications for each treatment combination were selected. The speeds for each treatment combination were selected to be run at random. A sample size of 500 cells was selected to hold the chance counting error to less than one per cent.

B. Test Technique

The technique used to conduct the tests was as follows:

1. Install seed plate and shielding, adjust cutoff, attach air

knockout and fill hopper to desired level with balls.

2. Turn on air to knockout.
3. With sample container in pre-sample position start apparatus and adjust to the desired speed using the speed calibration switch to check the speed.
4. Reset the magnetic counter to zero.
5. To start test pull sample container from pre-sample position to sample taking position.
6. At the end of the test interval, push sample container to pre-sample position stopping the counter and clock.
7. Stop apparatus.
8. Record counter reading and time interval.
9. Count and record sample.
10. Refill hopper to desired level.
11. Start with step two above and repeat procedure for each speed before changing plates.

C. Specific Test Conditions

The specific conditions under which the tests were conducted are as follows:

1. Spherical cast phenolic plastic balls nominal 1/4 inch and 3/8 inch diameter used in place of seeds. The balls have a real specific gravity of about 1.25 and a size variation as shown in the appendix. The average size of the smaller balls was 0.243 inch and of the larger balls was 0.364 inch.
2. The seed plate thickness was 20 per cent larger than the ball diameter for both ball sizes.
3. Each plate had 12 equally spaced cells on a seven inch circle.

The outside diameter of the plates was eight inches. The cells were round and were not beveled or tapered. Plate cell clearance was 10, 20, 30, and 40 per cent of ball diameter for both ball sizes. Measured variation in cell size for each plate is shown in the appendix.

4. Depth of balls in hopper was approximately six inches.
5. The shielding and cutoff device covered 15 per cent of the plate cell circle.
6. Plate speed was varied from 20 to 80 RPM in approximately 5 RPM increments.
7. Each test of such a length as to permit a minimum of 500 cells to pass the discharge point.

D. Supplementary Investigation

An investigation was conducted to determine the effect of cell exposure distance upon metering accuracy. This investigation was made to see if reducing the cell exposure distance would simulate cell speeds higher than obtainable with the original apparatus. The higher cell speeds were desired to supply additional information on the reaction of the metering accuracy as speeds were increased beyond the range of the apparatus. The cell exposure distance was changed by shielding the cells inside the hopper. The two exposure distances used for this investigation were with the cell circle 50 per cent and 62.5 per cent covered. All other test conditions were the same as for the other tests.

CHAPTER VI

PRESENTATION AND ANALYSIS OF DATA

A complete set of data was obtained with the seed plate cell circle 50 per cent covered in the supplementary tests. These data are presented for comparison with data where the seed plate cell circle was 15 per cent covered.

A statistical analysis of the data obtained is shown in tables II and IV. The numbers in tables I and III are averaged over speed.

The effect of seed plate cell speed and cell clearance on cell fill is shown graphically in figures 11, 12, 13, and 14 . The curves shown were visually fitted to the data. A family of curves of the form $y = e^{a - bx}$ were first fitted to the data using the method of least squares. These curves did not fit the data below the speeds that produced 100 per cent cell fill. Attempts were made to fit a family of curves of the form $y = e^{-x^2}$ to the data using the method of least squares. This equation did not provide reasonable fits to some of the data despite the similiarity in the general shape of the data and the equation.

The effect of total cell clearance on cell fill over the speed range tested is shown in figures 15 and 16.

The effect of total cell clearance on the highest cell speed that would produce 100 per cent cell fill is shown in figure 17. The total cell clearances in figures 15, 16, and 17 are based on the average ball and plate cell size.

The results of the supplementary test showing the effect of the amount of cell circle coverage is presented graphically in figures 18 and 19 . The curves shown represents one trial over the speed range for each amount of cell circle coverage.

The original data obtained from conducting all tests are included in the appendix. Some of the slower speeds were not tested in the series with 50 per cent of the cell circle covered. In these tests the highest speed that produced 100 per cent cell fill was found and the tests were initiated from this point. Previous test work showed that at slower plate speeds the cell fill remained constant at 100 per cent.

TABLE I

EFFECT OF BALL SIZE AND CELL CLEARANCE ON PER CENT CELL FILL WITH 15 PER CENT OF CELL CIRCLE COVERED (CELL FILL AVERAGED OVER SPEED)

Ball Size	Replication	Cell Clearance (% of Ball Diameter) 10	20	30	40
	1	50.4	72.7	95.2	97.3
1/4	2	53.5	71.7	94.9	98.6
	3	48.7	69.8	93.2	98.2
Mean		50.9	71.4	94.4	98.0
	1	74.4	95.3	98.1	99.7
3/8	2	73.9	91.4	98.4	99.8
	3	72.5	91.5	97.4	99.8
Mean		73.6	92.7	98.0	99.8

TABLE II

ANALYSIS OF VARIANCE OF PER CENT CELL FILL WITH 15 PER CENT OF CELL CIRCLE COVERED

Source of Variation	df	ss	ms	F
Total	23	6585.78		
Treatments	7	6554.02		
Balls (B)	1	912.67	912.67	459.78*
Clearances (C)	3	5072.91	1690.97	851.87*
B x C	3	568.44	189.48	95.46*
Error	16	31.76	1.99	

* Significant above 99 per cent confidence level

TABLE III

EFFECT OF BALL SIZE AND CELL CLEARANCE ON PER CENT CELL FILL WITH 50 PER CENT OF CELL CIRCLE COVERED (CELL FILL AVERAGED OVER SPEED)

Ball Size	Replication	Cell Clearance (% of Ball Diameter)			
		10	20	30	40
1/4	1	29.4	54.4	80.1	91.3
	2	28.8	52.6	80.5	88.1
	3	32.0	49.2	78.2	91.1
Mean		30.1	52.1	79.6	90.2
3/8	1	55.0	80.3	89.9	96.5
	2	54.8	79.7	86.3	95.8
	3	57.9	77.7	82.2	95.2
Mean		55.9	79.2	86.1	95.8

TABLE IV

ANALYSIS OF VARIANCE OF PER CENT CELL FILL WITH 50 PER CENT OF CELL CIRCLE COVERED

Source of Variation	df	ss	ms	F
Total	23	10919.58		
Treatments	7	10850.14		
Balls (B)	1	1594.14	1594.14	367.31*
Clearances (C)	3	8629.86	2876.62	662.82*
B x C	3	626.14	208.71	48.09*
Error	16	69.44	4.34	

* Significant above 99 per cent confidence level

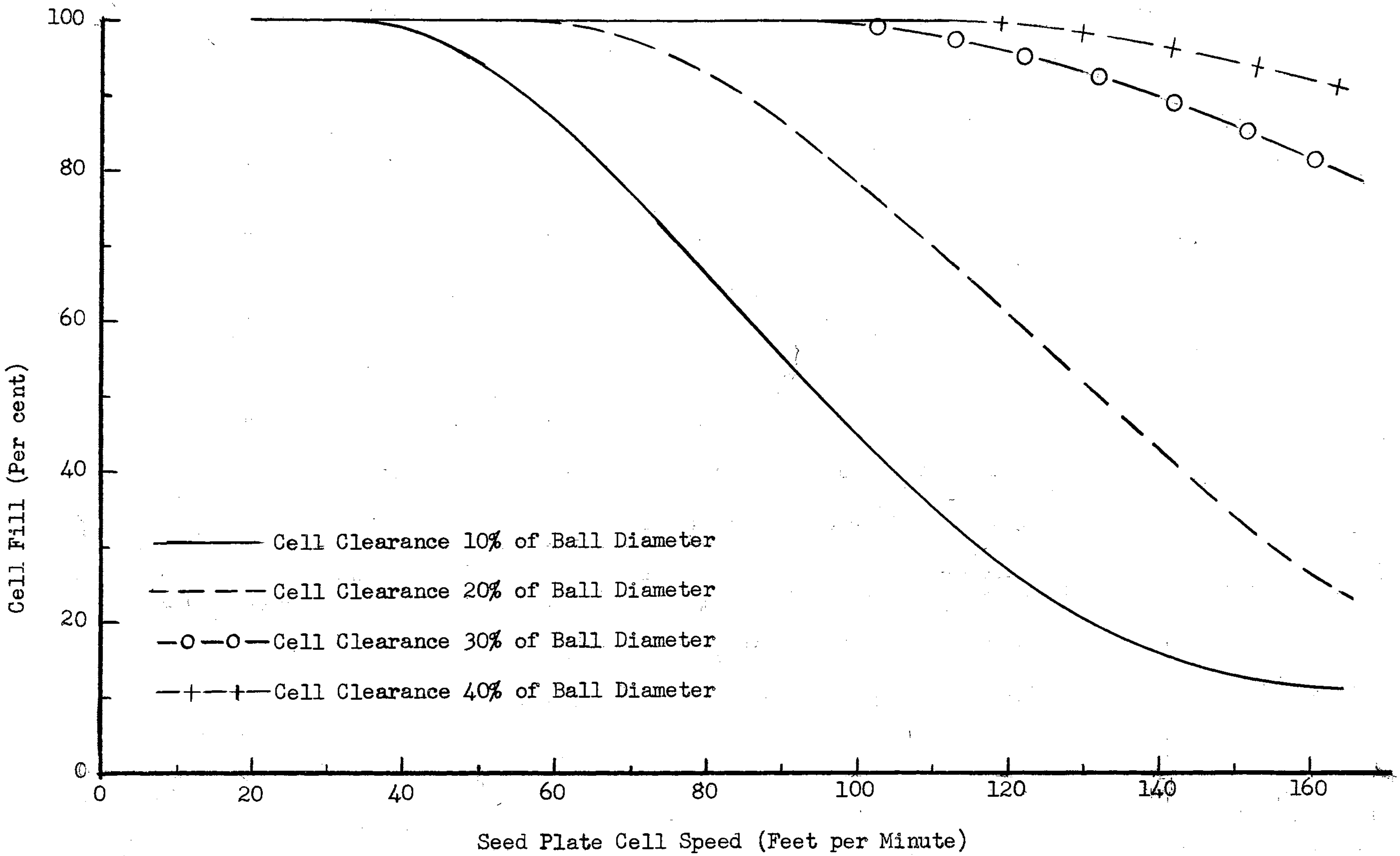


Figure 11. The effect of cell speed on cell fill with 1/4 inch balls and 15 per cent of the cell circle covered.

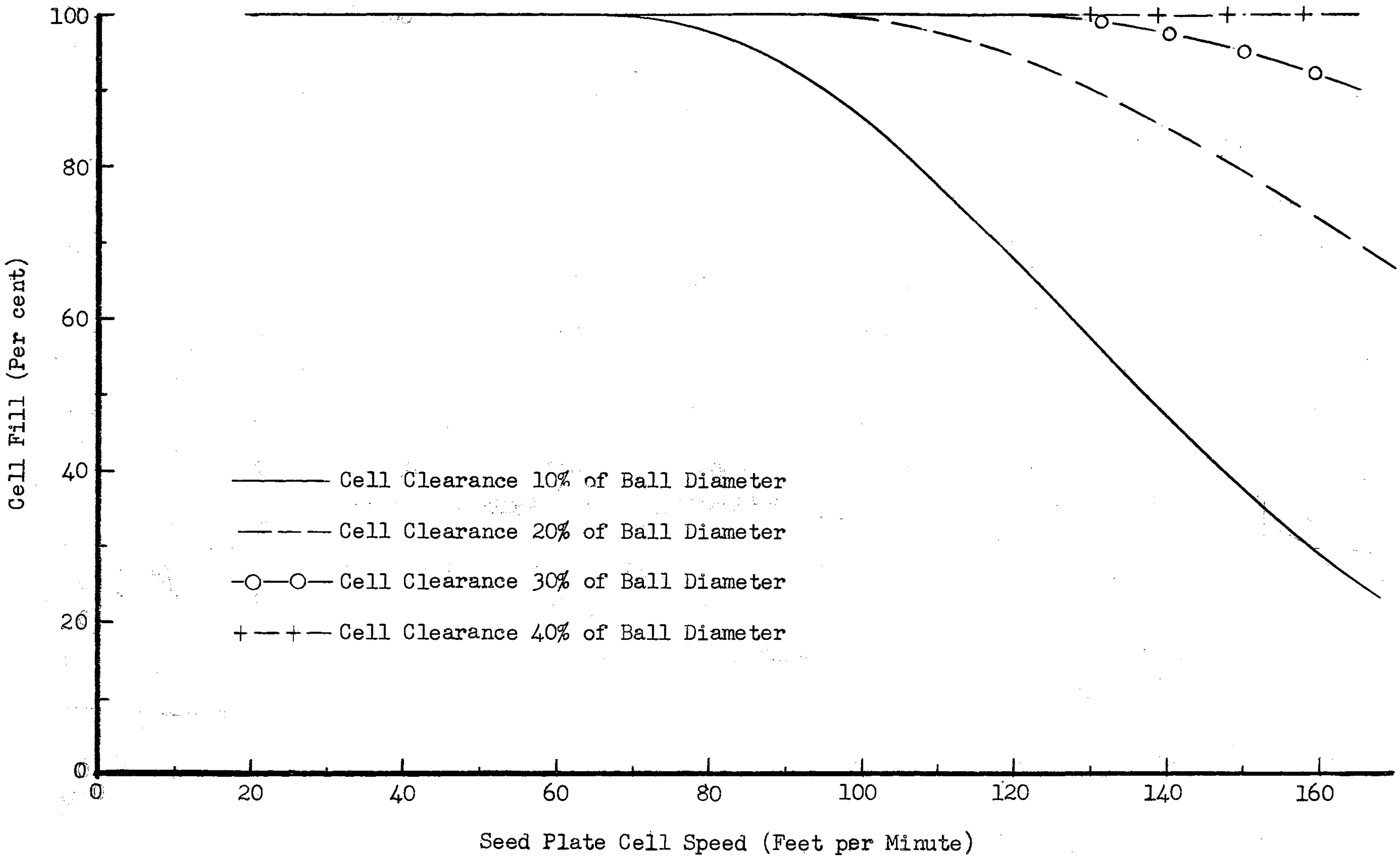


Figure 12. The effect of cell speed on cell fill with 3/8 inch balls and 15 per cent of the cell circle covered.

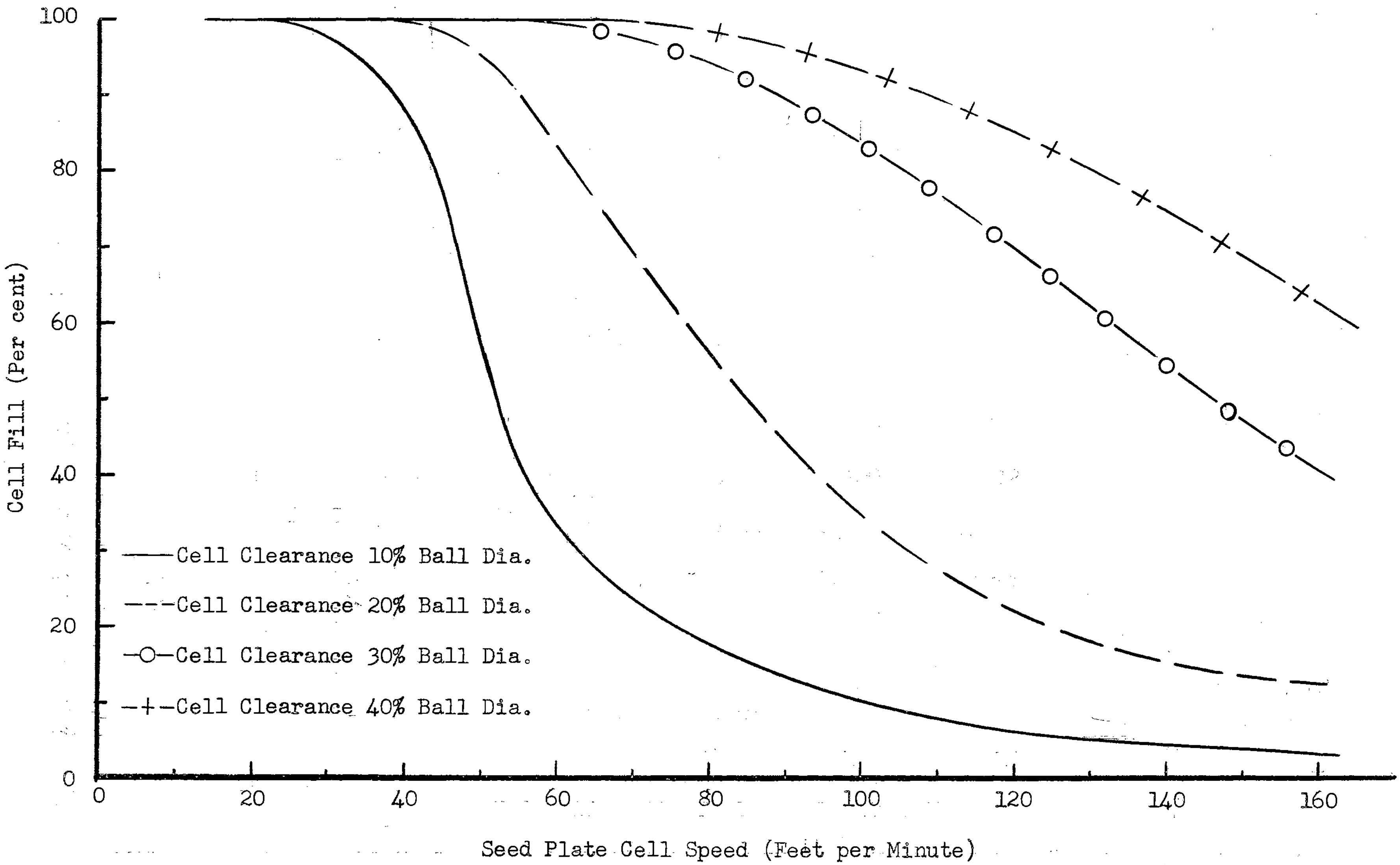


Figure 13. The effect of cell speed on cell fill with 1/4 inch balls and 50 per cent of the cell circle covered.

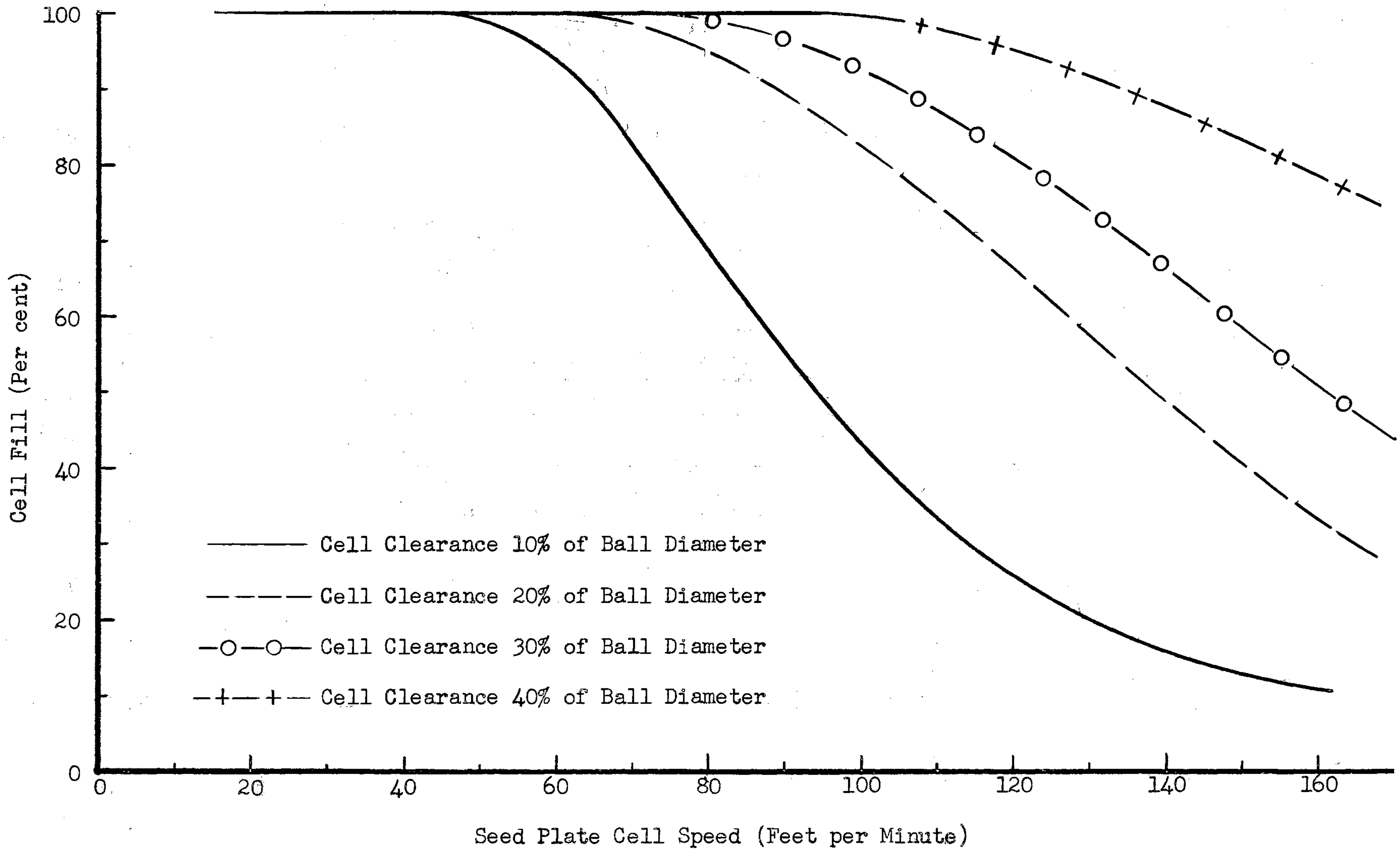


Figure 14. The effect of cell speed on cell fill with 3/8 inch balls and 50 per cent of the cell circle covered.

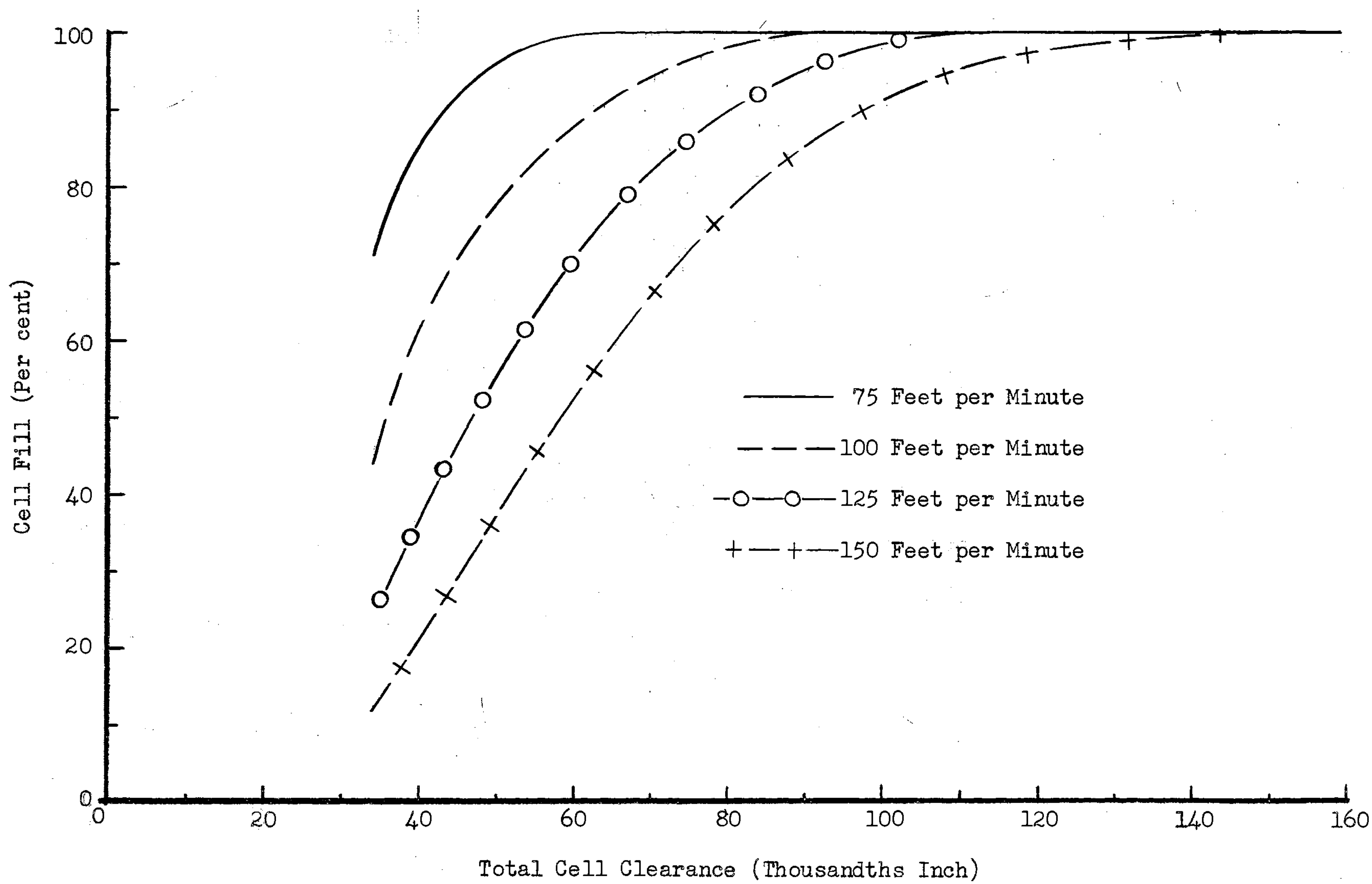


Figure 15. The effect of total cell clearance on cell fill with 15 per cent of the cell circle covered for different plate speeds.

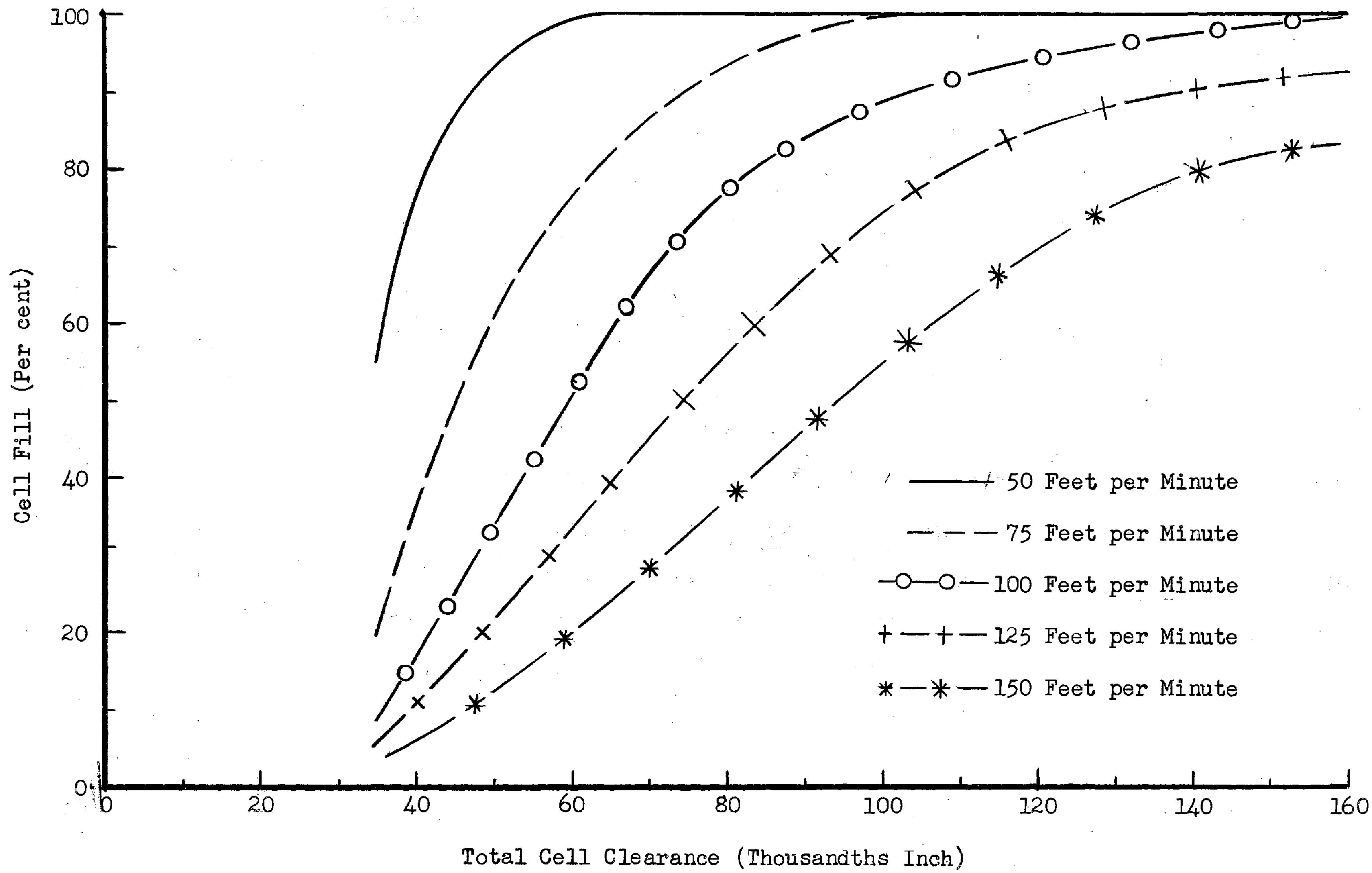


Figure 16. The effect of total cell clearance on cell fill with 50 per cent of the cell circle covered for different plate speeds.

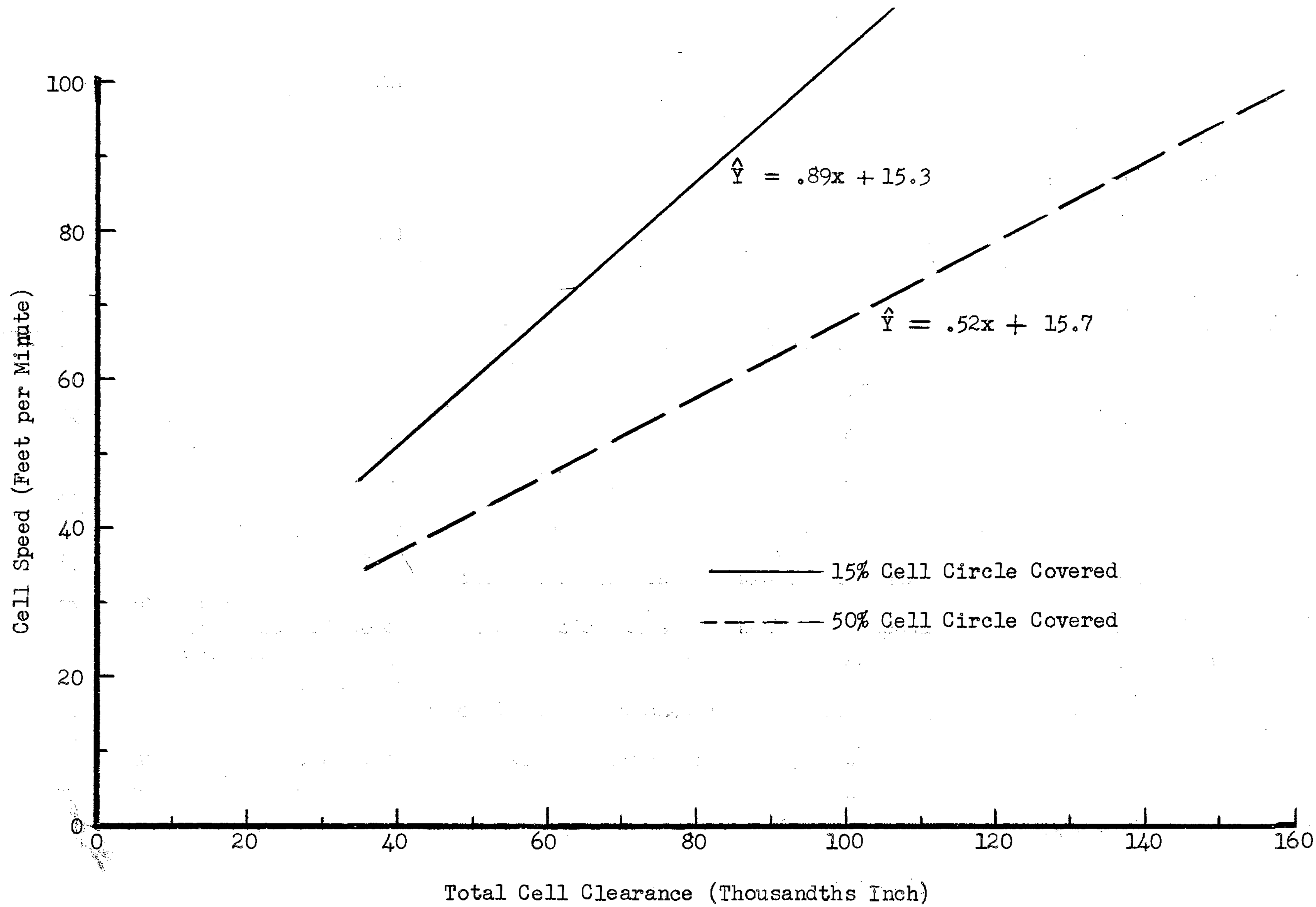


Figure 17. The effect of total cell clearance on the highest speed that will produce 100 per cent cell fill.

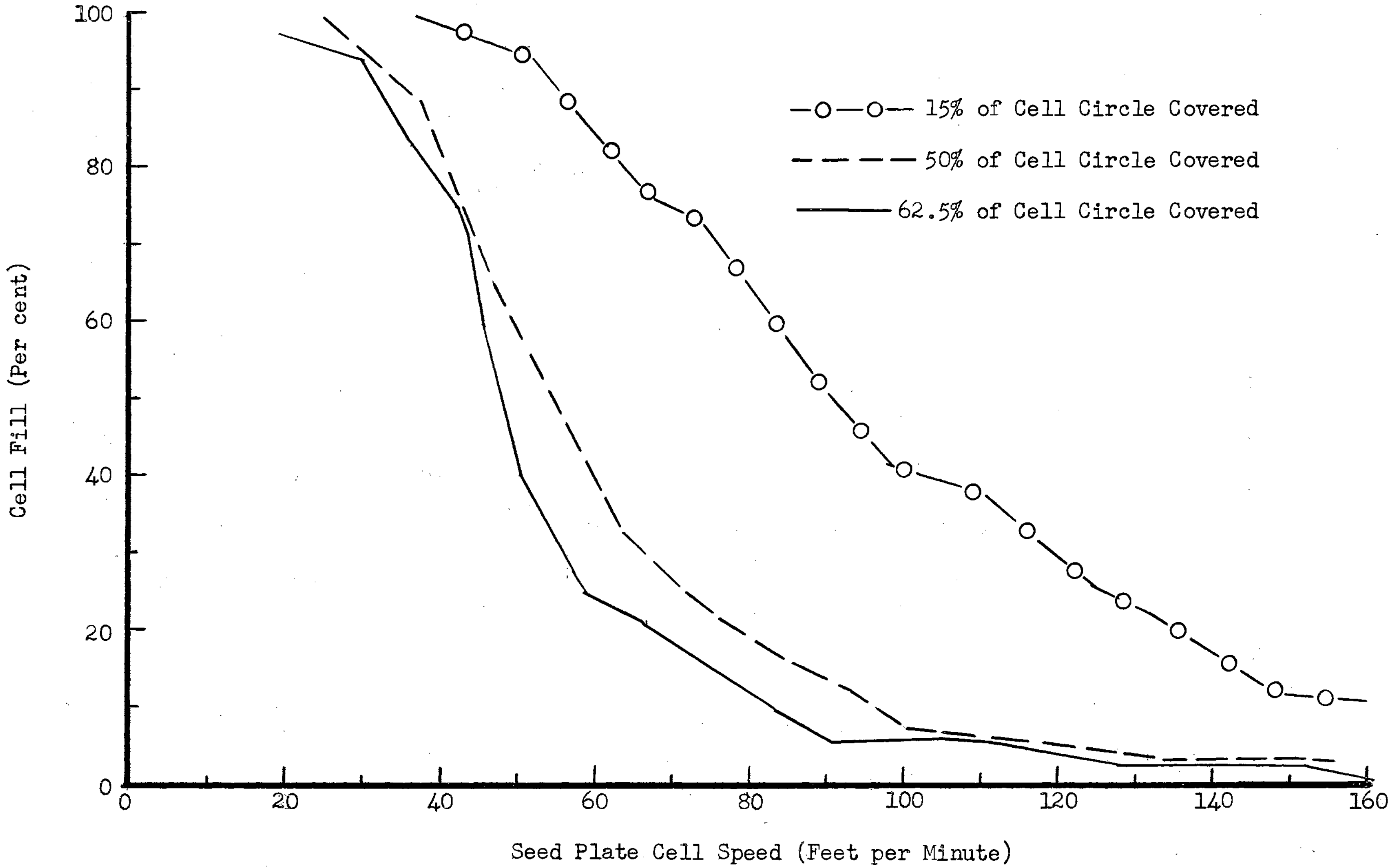


Figure 18. The effect of cell circle coverage using 1/4 inch balls and a 10 per cent cell clearance.

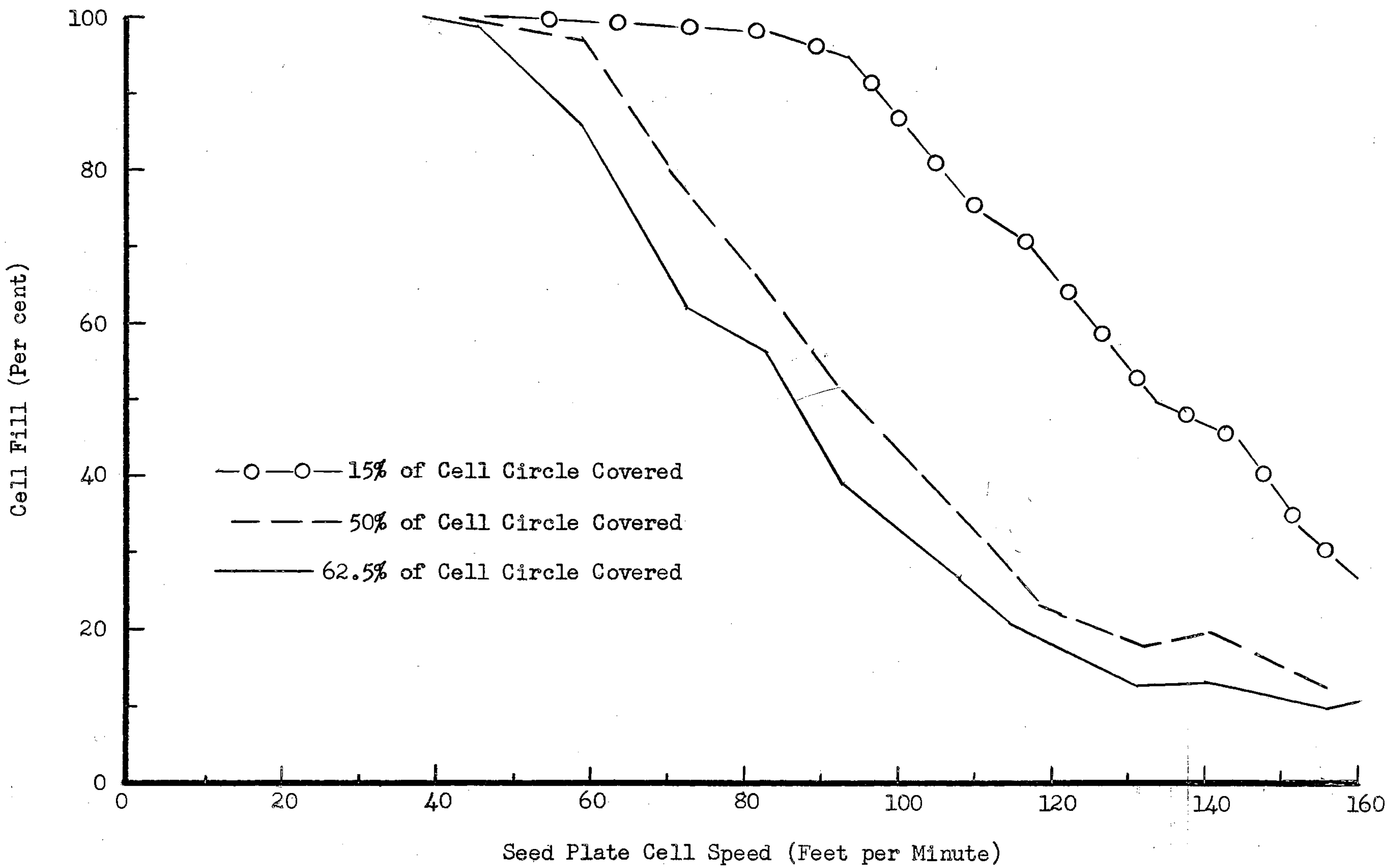


Figure 19. The effect of cell circle coverage using 3/8 inch balls and a 10 per cent cell clearance.

CHAPTER VII

DISCUSSION OF RESULTS

A. Results of Tests

A statistical analysis was made on the data to examine the significance of the treatments. The analysis of variance of the data is presented in tables II and IV. The analysis of variance shows a significant difference in the data above the 99 per cent confidence level for all treatments. The significant differences in the data due to ball size and due to the interaction between ball size and cell clearance may be attributed to the fact that the total cell clearances are different for the two sizes of balls when expressed as a per cent of the ball diameter. Both ball sizes produced comparable results when operated with the same amount of total cell clearance and followed the same pattern over the speed range as shown in figures 15 and 16 when expressed on a total clearance basis.

The effects of cell speed and cell clearance on cell fill are presented graphically in figures 11, 12, 13, and 14. These data show the larger cell clearances to extend the range of high cell fill accuracy as speed is increased. The larger cell clearances are also less sensitive to speed change as evidenced by the flatter slope of the curves of the large clearances. All of the curves appear to have the same general shape of double curvature, although the curves for the large clearances have not been extended as far as the others due to the speed limitation of the test apparatus. Sufficient information is not known about the motion of the balls in the hopper relative to the cell movement to explain the flattening out of the curves at high cell speeds. This flattening effect became more pronounced, however, as more of the cell circle was covered. Because the equations used in the curve fitting did not fit the data, no physical significance could be attached to the equations or equation constants that would aid in explaining these effects. The conditions limiting the cell fill would seem to be the opportunity of orientation of the ball to the cell, the time that is required for orientation and the action of the forces that may tend to prevent or slow the ball from entering a cell when properly oriented.

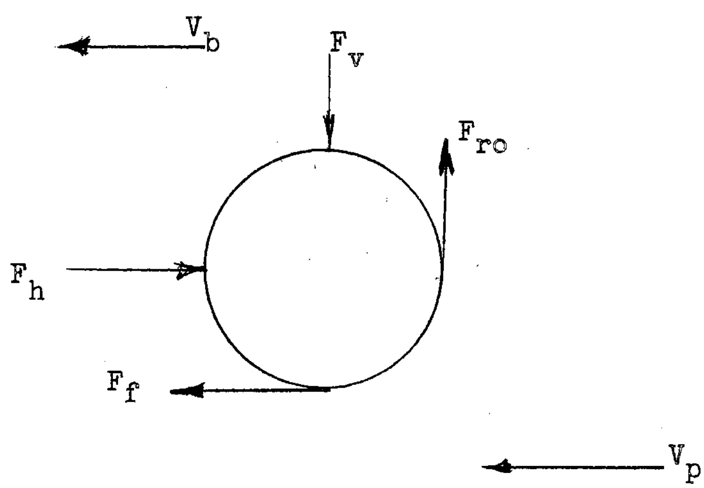
The time required for a seed to fall into a cell did not seem to be an important factor influencing cell fill. Approximately 0.031 second was required for a 3/8 inch ball to free fall a distance of one half of its diameter. At the maximum speed of the test apparatus, a cell would move 0.95 inch during 0.031 second. With the cell circle 50 per cent covered, eleven inches of exposure distance of the balls to the cells was available. The time of ball fall into a cell should not affect the metering accuracy except where a ball starts to fall into a cell at a point 0.95 inch or less from the cutoff device.

Results of the supplementary tests are shown in figures 18 and 19. These tests indicate that increasing the cell circle coverage decreases the metering accuracy and makes the metering accuracy more sensitive to speed over the lower speed range and less sensitive to speed over the higher speed range. When the cell circle was 62.5 per cent covered, the test apparatus could not be operated slow enough to obtain 100 per cent cell fill. Because of the change in the general slope of these curves, different amounts of cell circle coverage did not exactly simulate higher speeds of operation.

B. Force Analysis of Seed in Hopper

This analysis is presented in order to bring out some of the possible force actions and reactions that may tend to aid or hinder a seed in moving into a seed cell in a seed plate. The statements included in this analysis are made without benefit of experiment for proof.

The following is a force diagram in a tangential vertical plane of a seed in contact with a seed plate:



Where:

V_b = Velocity of Seed

V_p = Velocity of Seed Plate

F_f = Frictional Force Between Seed and Seed Plate

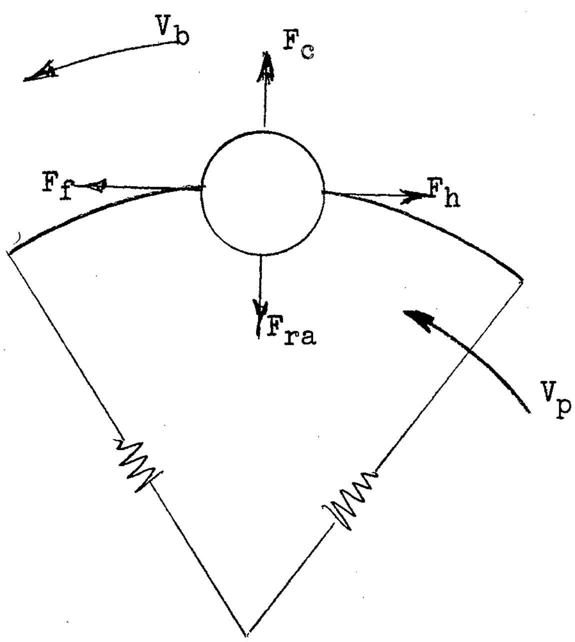
F_{ro} = Summation of Friction Retarding Forces of Rotation

F_h = Horizontal Component of Retarding Forces

F_v = Vertical Component of Weight Producing Forces

The velocity of the seed may be equal to the plate velocity at low plate velocities, but will probably be less than the plate velocity at high plate velocities. The amount of seed rotation about its own axis will depend upon the amount of contact with other seeds and upon the coefficients of friction between the seeds and between the seed and seed plate. If the sum of the frictional rotation retarding forces were equal to or less than the rotation producing forces, the seed would either slip on the seed plate or revolve about its own axis with a backspin motion.

A force diagram in the horizontal plane is shown as follows:



Where:

V_b = Velocity of Seed

V_p = Velocity of Seed Plate

F_f = Frictional Force Between Seed and Seed Plate

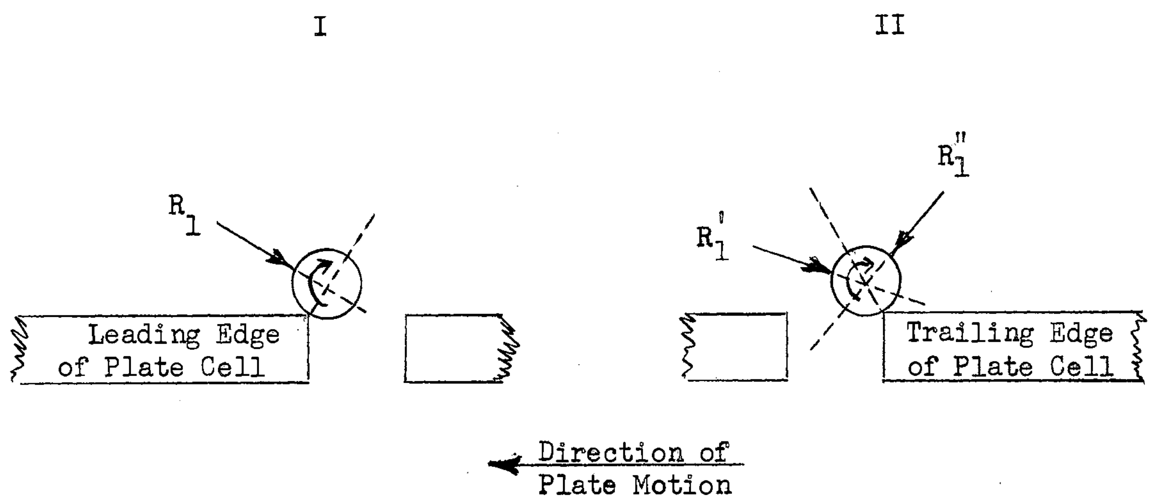
F_h = Horizontal (Tangential) Component of Retarding Forces

F_c = Centrifugal Force (mrw^2)

F_{ra} = Radial Component of External Forces

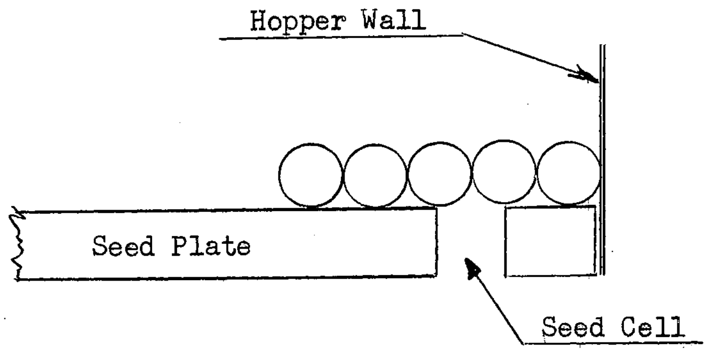
The possibility of radial movements exists in this condition depending upon the speed of seed, mass of seed and magnitude and direction of the radial forces. Radial movement of the seed may aid in orienting the seed to a cell.

Two conditions of impending cell fill are shown in the following diagram:



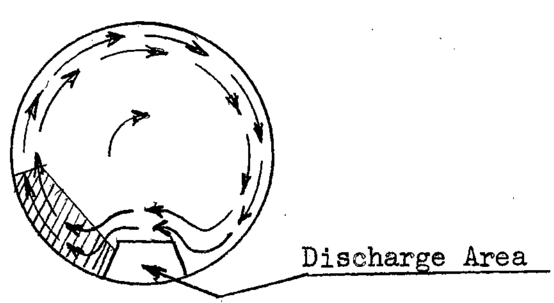
When a seed is moving over the leading edge of a cell as in condition I, the resultant of the horizontal and vertical resisting forces will help the seed into the cell. Backspin of the seed is also an aid in this condition. In condition II, any backspin would not help a seed into a cell. Depending upon the direction of the resultant (R_1) of the horizontal and vertical resisting forces with respect to the edge of the cell, the seed may be helped in or out of the cell.

An arrangement of seeds with respect to a cell is shown in the following diagram in a radial vertical plane:



The condition as shown in this diagram may exist when the seed cell is at or near the edge of a seed plate. If the resultant of the radial forces is directed either toward or away from the hopper wall, no radial seed movement is possible unless one or more of the seeds moves vertically or horizontally with respect to the other seeds. With layers of seeds around and over the ones shown in the diagram, the movement of a seed is made more difficult and seed orientation to the cell is hampered. The amount of radial seed movement necessary for cell fill to occur from this condition depends on the cell and seed sizes. Little or no radial movement of the seed on the seed plate is suspected except at points near the cutoff and discharge area.

The following diagram is presented to show a suspected path of seed movement around the hopper next to the seed plate as the seeds move with the plate:



In this diagram, radial seed movement is seen to occur in two places; toward the center of the hopper at the cutoff point and toward the hopper wall after passing the shielding that covers the discharge area. No radial movement is assumed around the rest of the hopper wall due to the apparent lack of forces or reactions that would tend to produce radial movement. A small proportion of the cell filling may occur at the cutoff point because of the time element involved. The radial movement necessary to cause complete seed orientation with the cell may occur at too small a distance before cutoff to allow time for a seed to drop into a cell. The shaded area on the diagram shows the area where the majority of the cells are expected to be filled. The length of this area would depend upon the shape of the shielding covering the discharge area as well as the plate cell size and relative speed of the seed and plate cells.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The apparatus and a technique of evaluating the individual factors involved in metering have been established. The apparatus was designed to allow variation of each of the factors separately and to evaluate each factor quantitatively.

This investigation was conducted under a particular combination of metering conditions and the results will apply only to these conditions. However, when subsequent studies are made on other factors the results of this study will form a basis for comparison and become an aid in measuring the effects of other factors.

The following conclusions were made from this investigation under the test conditions previously stated:

1. An increase in plate cell speed was accompanied by a decrease in cell fill after a certain speed was reached. This speed was related to the amount of cell clearance.
2. Increasing the amount of cell clearance increased the highest speed at which 100 per cent cell fill occured.
3. An increase in cell clearance made the metering accuracy less sensitive to speed changes.
4. The cell fill became almost independent of speed using the 1/4 inch balls and a cell clearance of 10 per cent of the ball diameter when the cell speed was fast enough to result in the cell fill being less than 15 per cent.
5. A decrease in the cell exposure distance in the hopper appeared

to produce the same effects as reducing the total cell clearance.

6. Decreasing the cell exposure distance in the hopper did not simulate operation at higher speeds.

Since this study was carried out using originally developed apparatus and techniques, two suggestions are offered that will be of benefit to consider for future studies:

1. Use a speed changing device where speed could be varied in more exact increments with repeatability.
2. The size variation of the cast phenolic plastic balls was greater than desired. The use of balls made of nylon would reduce the size variation as nylon balls are commercially available and can be furnished with less size variation.

Several questions confronting the author that arose during the investigation are proposed for subjects of future study:

1. A study of the motion of the balls in the hopper next to the seed plate to determine the general movement of the balls relative to the cells.
2. To determine the importance of radial seed movement as an aid in obtaining high cell fill accuracy.
3. To determine if the majority of cell filling occurs in the area immediately past the discharge area.
4. To determine whether stationary or moving seed orientation devices are more effective in guiding a ball to a cell.
5. To determine whether the speed of the cell or the distance a cell is exposed in the hopper is the more important factor in metering accuracy.

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APPENDIX

DATA SHEET 1

MEASUREMENT OF PLATE CELLS

Cell No.	Ball Size 1/4				Ball Size 3/8			
	Nominal Cell Diameter							
	.275	.300	.325	.350	.4125	.4500	.4875	.5250
1	.278	.298	.329	.352	.412	.449	.492	.524
2	.278	.298	.330	.352	.410	.452	.487	.523
3	.278	.300	.330	.352	.413	.447	.488	.525
4	.278	.299	.329	.352	.413	.455	.488	.524
5	.276	.299	.328	.352	.412	.449	.486	.529
6	.276	.299	.329	.352	.414	.450	.485	.523
7	.277	.299	.329	.352	.415	.448	.496	.518
8	.278	.300	.329	.351	.413	.447	.487	.520
9	.278	.298	.329	.351	.410	.448	.487	.524
10	.278	.299	.330	.351	.412	.447	.487	.523
11	.278	.299	.330	.351	.415	.448	.486	.523
12	.278	.297	.330	.351	.414	.447	.487	.523
Mean	.278	.299	.329	.352	.413	.449	.488	.523

DATA SHEET 1A

DIMENSIONS OF PLASTIC BALLS

1/4 Inch Balls*

.243	.242	.241	.242	.238	.241	.242	.248	.239	.249
.250	.239	.241	.243	.239	.245	.239	.248	.241	.239
.244	.240	.238	.240	.244	.241	.243	.246	.241	.242
.247	.240	.244	.243	.239	.239	.244	.251	.240	.247
.246	.242	.244	.239	.239	.244	.251	.243	.248	.243
.244	.247	.245	.242	.241	.245	.241	.240	.238	.243
.249	.243	.244	.241	.242	.240	.240	.241	.246	.243
.247	.242	.243	.239	.239	.247	.242	.246	.243	.246
.242	.239	.242	.238	.241	.240	.240	.240	.241	.239
.250	.241	.243	.241	.240	.242	.241	.246	.243	.243

Mean = .243

Range = .238 - .251

3/8 Inch Balls*

.363	.364	.364	.365	.363	.366	.365	.360	.363	.360
.365	.365	.365	.364	.365	.362	.363	.365	.363	.363
.366	.363	.364	.363	.364	.362	.364	.361	.364	.361
.362	.362	.362	.364	.365	.364	.361	.363	.363	.364
.362	.364	.365	.370	.363	.363	.365	.364	.365	.362
.365	.364	.364	.367	.363	.362	.364	.365	.362	.365
.363	.365	.363	.362	.364	.364	.363	.364	.362	.362
.365	.364	.364	.361	.365	.362	.363	.364	.363	.364
.365	.363	.364	.365	.363	.365	.366	.362	.364	.364
.363	.362	.365	.364	.364	.361	.361	.363	.364	.361

Mean = .364

Range = .360 - .367

*Sample of 100 drawn at random from lot

DATA SHEET 1B

ORIGINAL DATA FROM TESTS

3/8" Ball - 10% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	120	505	504	21.0	38.6	99.8
2	110	523	522	23.8	43.6	99.8
3	75	510	509	34.0	62.3	99.8
4	65	495	495	38.1	69.8	100.0
5	55	526	512	47.8	87.6	97.3
6	50	520	492	52.0	95.3	94.6
7	45	520	419	57.8	105.9	80.6
8	40	507	340	63.4	116.1	67.1
9	35	515	248	73.6	134.8	48.2
10	35	543	236	77.6	142.2	43.5
11	30	505	160	84.2	154.2	31.7
12	30	543	163	90.5	165.9	30.0
			Replication II			
1	120	490	489	20.4	37.4	99.8
2	100	509	509	25.5	46.6	100.0
3	80	505	503	31.6	57.8	99.6
4	70	529	523	37.8	69.2	98.9
5	60	549	537	45.8	83.8	97.8
6	50	514	484	51.4	94.2	94.2
7	45	537	404	59.7	109.3	75.2
8	40	512	359	64.0	117.3	70.1
9	35	512	255	73.1	134.0	49.8
10	35	552	245	78.9	144.5	44.4
11	30	500	168	83.3	152.7	33.6
12	30	536	125	89.3	163.7	23.3
			Replication III			
1	125	505	504	20.2	37.0	99.8
2	105	514	514	24.5	44.9	100.0
3	70	505	504	36.1	66.1	99.8
4	65	510	507	39.2	71.9	99.4
5	50	520	469	52.0	95.3	90.2
6	50	517	474	51.7	94.7	91.7
7	45	530	401	58.9	107.9	75.7
8	40	545	351	68.1	124.8	64.4
9	35	521	258	74.4	136.4	49.5
10	35	557	235	79.6	145.8	42.2
11	30	513	149	85.5	156.7	29.0
12	30	546	155	91.0	166.8	28.4

DATA SHEET 1B--CONTINUED

3/8" Ball - 20% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	120	509	509	21.2	38.9	100.0
2	100	503	502	25.2	46.1	99.8
3	75	511	511	34.1	62.4	100.0
4	65	517	516	39.8	72.9	99.8
5	55	515	513	46.8	85.8	99.6
6	50	505	503	50.5	92.5	98.6
7	45	525	520	58.3	106.9	99.0
8	40	496	490	62.0	113.6	98.8
9	35	503	480	71.9	131.7	95.4
10	35	531	480	75.9	139.0	90.4
11	30	495	405	82.5	151.2	81.8
12	30	530	423	88.3	161.9	79.8
			Replication II			
1	135	519	519	19.2	35.2	100.0
2	105	509	508	24.2	44.4	99.8
3	80	533	531	33.3	61.0	99.6
4	70	525	525	37.5	68.7	100.0
5	60	525	524	43.8	80.2	99.8
6	55	546	544	49.6	91.0	99.6
7	45	519	507	57.7	105.7	97.7
8	40	512	477	64.0	117.3	93.2
9	40	563	511	70.4	129.0	90.8
10	35	543	446	77.6	142.2	82.1
11	30	505	351	84.2	154.2	69.5
12	30	538	349	89.7	164.3	64.9
			Replication III			
1	120	515	514	21.5	39.3	99.8
2	100	497	496	24.9	45.5	99.8
3	75	508	507	33.9	62.1	99.8
4	70	533	532	38.1	69.8	99.8
5	50	496	494	49.6	90.9	99.6
6	50	497	495	49.7	91.1	99.6
7	45	536	517	59.6	109.1	96.5
8	40	531	505	66.4	121.6	95.1
9	40	565	484	70.6	129.4	85.7
10	35	552	452	78.9	144.5	81.9
11	30	510	375	85.0	155.8	73.5
12	30	543	363	90.5	165.9	66.9

DATA SHEET 1B--CONTINUED

3/8" Ball - 30% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	140	494	494	17.6	32.3	100.0
2	110	493	492	22.4	41.1	99.8
3	75	495	494	33.0	60.5	99.8
4	70	519	518	37.1	67.9	99.8
5	55	512	511	46.5	85.3	99.8
6	55	556	554	50.5	92.6	99.6
7	50	555	554	55.5	101.7	99.8
8	40	515	513	64.4	118.0	99.6
9	40	566	556	70.8	129.7	98.2
10	33	483	470	73.2	134.1	97.3
11	30	493	469	82.2	150.6	95.1
12	30	528	469	88.0	161.3	88.8
			Replication II			
1	120	516	516	21.5	39.4	100.0
2	105	517	516	24.6	45.1	99.8
3	75	495	495	33.0	60.5	100.0
4	65	519	518	39.9	73.2	99.8
5	55	536	534	48.7	89.3	99.6
6	50	547	546	54.7	100.2	99.8
7	45	536	535	59.6	109.1	99.8
8	40	521	519	65.1	119.3	99.6
9	40	583	575	72.9	133.6	98.6
10	30	488	475	81.3	149.0	97.3
11	30	504	480	84.0	153.9	95.2
12	30	545	498	90.8	166.5	91.4
			Replication III			
1	135	496	495	18.4	33.7	99.8
2	100	494	494	24.7	45.3	100.0
3	85	518	518	30.5	55.8	100.0
4	60	482	481	40.2	73.6	99.8
5	55	505	504	45.9	84.1	99.8
6	50	508	506	50.8	93.1	99.6
7	45	509	506	56.6	103.6	99.4
8	40	530	526	66.3	121.4	99.2
9	35	524	513	74.9	137.2	97.9
10	35	546	514	78.0	142.9	94.1
11	30	528	487	88.0	161.3	92.2
12	30	535	462	89.2	163.4	86.4

DATA SHEET 1B--CONTINUED

3/8" Ball - 40% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	125	505	505	20.2	37.0	100.0
2	100	504	503	25.2	46.2	99.8
3	75	518	518	34.5	63.3	100.0
4	65	503	501	38.7	70.9	99.6
5	50	476	475	47.6	87.2	99.8
6	50	517	516	51.7	94.7	99.8
7	45	521	520	57.9	106.1	99.8
8	40	499	497	62.4	114.3	99.6
9	35	505	503	72.1	132.2	99.6
10	35	534	530	76.3	139.8	99.3
11	30	507	503	84.5	154.9	99.2
12	30	542	538	90.3	165.5	99.3
			Replication II			
1	130	503	503	19.3	35.5	100.0
2	100	495	495	24.8	45.4	100.0
3	75	527	527	35.1	64.4	100.0
4	65	501	500	38.5	70.6	99.8
5	60	540	539	45.0	82.5	99.8
6	55	549	548	49.9	91.5	99.8
7	45	542	540	60.2	110.4	99.6
8	40	529	527	66.1	121.2	99.6
9	35	515	515	73.6	134.8	100.0
10	35	534	533	76.3	139.8	99.8
11	30	506	504	84.3	154.5	99.6
12	30	548	545	91.3	167.4	99.5
			Replication III			
1	145	504	504	17.4	31.8	100.0
2	110	513	512	23.3	42.7	99.8
3	75	498	498	33.2	60.8	100.0
4	65	481	481	37.0	67.8	100.0
5	55	525	525	47.7	87.5	100.0
6	50	499	499	49.9	91.4	100.0
7	45	512	512	56.9	104.2	100.0
8	40	496	495	62.0	113.6	99.8
9	40	556	555	69.5	127.4	99.8
10	35	539	538	77.0	141.1	99.8
11	35	586	583	83.7	153.4	99.5
12	30	524	519	87.3	160.0	99.0

DATA SHEET 1B--CONTINUED

1/4" Ball - 10% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	120	507	506	21.1	38.7	99.8
2	120	511	510	21.3	39.0	99.8
3	70	492	419	35.1	64.4	85.2
4	70	526	437	37.6	68.9	83.1
5	55	521	337	47.4	86.8	64.7
6	50	511	278	51.1	93.6	54.4
7	45	538	211	59.8	109.5	39.2
8	40	491	131	61.4	112.5	26.7
9	35	503	108	71.9	131.7	21.5
10	35	544	129	77.7	142.4	23.7
11	35	584	83	83.4	152.9	14.2
12	30	532	66	88.7	162.5	12.4
			Replication II			
1	130	497	497	19.1	35.0	100.0
2	125	508	506	20.3	37.2	99.6
3	90	513	482	28.5	52.2	94.0
4	70	512	389	36.6	67.0	76.0
5	65	525	383	40.4	74.0	73.0
6	55	539	280	49.0	89.8	51.9
7	50	537	220	53.7	98.4	41.0
8	40	484	182	60.5	110.9	37.6
9	40	544	141	68.0	124.6	25.9
10	40	581	123	72.6	133.1	21.2
11	35	566	67	80.9	148.2	11.8
12	30	537	56	89.5	164.0	10.4
			Replication III			
1	140	503	501	18.0	32.9	99.6
2	115	517	515	22.5	41.2	99.6
3	70	495	368	35.4	64.8	74.3
4	70	523	408	37.4	68.5	78.0
5	55	513	279	46.6	85.5	54.4
6	50	484	268	48.4	88.7	55.4
7	45	521	181	57.9	106.1	34.7
8	45	566	174	62.9	115.2	30.7
9	40	566	93	70.8	129.7	16.4
10	35	522	90	74.6	136.7	17.2
11	35	575	75	82.1	150.5	13.0
12	30	535	57	89.2	163.4	10.7

DATA SHEET 1B—CONTINUED

1/4" Ball - 20% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	125	504	503	20.2	36.9	99.8
2	110	505	503	23.0	42.1	99.6
3	75	512	508	34.1	62.5	99.2
4	70	511	502	36.5	66.9	98.2
5	55	509	481	46.3	84.8	94.5
6	55	531	454	48.3	88.5	85.5
7	45	544	383	60.4	110.8	70.4
8	40	514	309	64.3	117.7	60.1
9	40	554	301	69.3	126.9	54.3
10	35	539	222	77.0	141.1	41.2
11	35	583	224	83.3	152.6	38.4
12	30	534	169	89.0	163.1	31.6
			Replication II			
1	145	499	499	17.2	31.5	100.0
2	120	509	509	21.2	38.9	100.0
3	85	511	509	30.1	55.1	99.6
4	70	501	493	35.8	65.6	98.4
5	60	516	481	43.0	78.8	93.2
6	50	503	420	50.3	92.2	83.5
7	50	568	402	56.8	104.1	70.8
8	45	558	345	62.0	113.6	61.8
9	40	544	281	68.0	124.6	51.7
10	35	516	227	73.7	135.0	44.0
11	30	499	142	83.2	152.4	28.5
12	30	520	147	86.7	158.8	28.3
			Replication III			
1	120	516	515	21.5	39.4	99.8
2	100	496	495	24.8	45.4	99.8
3	75	509	506	33.9	62.2	99.4
4	70	532	515	38.0	69.6	96.8
5	60	564	485	47.0	86.1	86.0
6	50	527	437	52.7	96.6	82.9
7	45	539	356	59.9	109.7	66.0
8	40	523	304	65.4	119.8	58.1
9	40	565	309	70.6	129.4	54.7
10	35	528	196	75.4	138.2	37.1
11	30	507	152	84.5	154.9	30.0
12	30	541	145	90.2	165.2	26.8

DATA SHEET 1B--CONTINUED

1/4" Ball - 30% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	125	499	498	20.0	36.6	99.8
2	95	498	497	26.2	48.0	99.8
3	75	524	523	34.9	64.0	99.8
4	65	515	514	39.6	72.6	99.8
5	60	551	550	45.9	84.1	99.8
6	50	516	513	51.6	94.6	99.4
7	45	538	527	59.8	109.5	98.0
8	40	525	510	65.6	120.3	97.1
9	35	520	489	74.3	136.1	94.0
10	35	537	493	76.7	140.6	91.8
11	30	506	436	84.3	154.5	86.2
12	30	537	414	89.5	164.0	77.1
			Replication II			
1	135	505	504	18.7	34.3	99.8
2	110	519	518	23.6	43.2	99.8
3	80	526	525	32.9	60.2	99.8
4	70	508	507	36.3	66.5	99.8
5	60	529	527	44.1	80.8	99.6
6	50	535	527	53.5	98.0	98.5
7	45	544	534	60.4	110.8	98.2
8	40	519	497	64.9	118.9	95.8
9	40	577	546	72.1	132.2	94.6
10	35	529	479	75.6	138.5	90.5
11	30	506	424	84.3	154.5	83.8
12	30	532	417	88.7	162.5	78.4
			Replication III			
1	120	520	519	21.7	39.7	99.8
2	100	499	498	25.0	45.7	99.8
3	75	514	513	34.3	62.8	99.8
4	70	528	527	37.7	69.1	99.8
5	55	550	544	50.0	91.6	98.9
6	50	508	504	50.8	93.1	99.2
7	45	547	526	60.8	111.4	96.2
8	40	513	487	64.1	117.5	94.9
9	35	513	470	73.3	134.3	91.6
10	35	544	476	77.7	142.4	87.5
11	30	510	399	85.0	155.8	78.2
12	30	538	390	89.7	164.3	72.5

DATA SHEET 1B--CONTINUED

1/4" Ball - 40% Total Cell Clearance - 15% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	120	500	499	20.8	38.2	99.8
2	100	485	484	24.3	44.4	99.8
3	70	499	498	35.6	65.3	99.8
4	70	509	507	36.4	66.6	99.6
5	55	510	509	46.4	85.0	99.8
6	50	504	502	50.4	92.4	99.6
7	45	538	533	59.8	109.5	99.1
8	40	525	516	65.6	120.3	98.3
9	35	505	496	72.1	132.2	98.2
10	35	524	499	74.9	137.2	95.2
11	30	506	469	84.3	154.5	92.7
12	30	534	456	89.0	163.1	85.4
			Replication II			
1	130	499	498	19.2	35.2	99.8
2	115	528	527	23.0	42.1	99.8
3	75	504	502	33.6	61.6	99.6
4	70	541	539	38.6	70.8	99.6
5	60	528	525	44.0	80.6	99.4
6	50	525	523	52.5	96.2	99.6
7	45	541	535	60.1	110.2	98.9
8	40	515	511	64.4	118.0	99.2
9	40	560	552	70.0	128.3	98.6
10	35	533	517	76.1	139.5	97.0
11	35	581	566	83.0	152.1	97.4
12	30	525	494	87.5	160.4	94.1
			Replication III			
1	140	499	498	17.8	32.7	99.8
2	105	503	502	24.0	43.9	99.8
3	80	494	493	30.9	56.6	99.8
4	65	506	506	38.9	71.3	100.0
5	55	499	498	45.4	83.1	99.8
6	55	536	535	48.7	89.3	99.8
7	45	521	517	57.9	106.1	99.2
8	40	509	509	63.6	116.6	100.0
9	40	567	560	70.9	129.9	98.8
10	35	523	504	74.7	136.9	96.4
11	30	501	474	83.5	153.0	94.6
12	30	542	489	90.3	165.5	90.2

DATA SHEET 1B--CONTINUED

3/8" Ball - 10% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2						
3	95	500	499	26.3	48.2	99.8
4	75	513	481	34.2	62.7	93.8
5	60	512	356	42.7	78.2	69.5
6	55	543	299	49.4	90.5	55.1
7	45	516	185	57.3	105.0	35.9
8	45	542	202	60.2	110.4	37.3
9	40	544	132	68.0	124.6	24.3
10	35	513	102	73.3	134.3	19.9
11	35	558	74	79.7	146.1	13.3
12	30	530	58	88.3	161.9	10.9
			Replication II			
1						
2	110	514	513	23.4	42.8	99.8
3	90	513	511	28.5	52.2	99.6
4	80	526	492	32.9	60.2	93.5
5	60	508	338	42.3	77.6	66.5
6	55	533	284	48.5	88.8	53.3
7	50	539	221	53.9	98.8	41.0
8	45	542	191	60.2	110.4	35.2
9	40	537	114	67.1	123.0	21.2
10	35	523	76	74.7	136.9	14.5
11	35	541	94	77.3	141.6	17.4
12	30	500	80	83.3	152.7	16.0
			Replication III			
1						
2						
3	105	501	500	23.9	43.7	99.8
4	80	520	503	32.5	59.6	96.7
5	65	511	398	39.3	72.0	77.9
6	60	538	354	44.8	82.2	65.8
7	50	507	260	50.7	92.9	51.3
8	45	547	173	60.8	111.4	31.6
9	40	521	119	65.1	119.3	22.8
10	40	576	102	72.0	131.9	17.7
11	35	538	105	76.9	140.8	19.5
12	30	511	62	85.2	156.1	12.1

DATA SHEET 1B--CONTINUED

3/8" Ball - 20% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2						
3	100	490	489	24.5	44.9	99.8
4	75	512	511	34.1	62.5	99.8
5	65	505	497	38.8	71.2	98.4
6	55	515	473	46.8	85.8	91.8
7	50	529	428	52.9	96.9	80.9
8	45	541	407	60.1	110.2	75.2
9	40	526	368	65.8	120.5	70.0
10	35	500	305	71.4	130.9	61.0
11	35	544	266	77.7	142.4	48.9
12	30	531	199	88.5	162.2	37.5
			Replication II			
1						
2						
3						
4	80	507	506	31.7	58.1	99.8
5	70	519	511	37.1	67.9	98.5
6	60	495	480	41.3	75.6	97.0
7	55	526	472	47.8	87.6	89.7
8	50	532	420	53.2	97.5	78.9
9	40	499	319	62.4	114.3	63.9
10	40	548	294	68.5	125.5	53.6
11	35	531	239	75.9	139.0	45.0
12	30	512	152	85.3	156.4	29.7
			Replication III			
1						
2						
3	95	507	506	26.7	48.9	99.8
4	75	534	531	35.6	65.2	99.4
5	65	525	515	40.4	74.0	98.1
6	55	514	473	46.7	85.6	92.0
7	50	537	448	53.7	98.4	83.4
8	45	552	397	61.3	112.4	71.9
9	40	570	317	71.3	130.6	55.6
10	35	523	298	74.7	136.9	57.0
11	35	583	232	83.3	152.6	39.8
12	30	521	185	86.8	159.1	35.5

DATA SHEET 1B--CONTINUED

3/8" Ball - 30% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2						
3	95	510	510	26.8	49.2	100.0
4	75	514	511	34.3	62.8	99.4
5	65	508	506	39.1	71.6	99.6
6	55	511	506	46.5	85.1	99.0
7	50	553	524	55.3	101.3	94.8
8	45	541	496	60.1	110.2	91.7
9	40	512	439	64.0	117.3	85.7
10	35	514	389	73.4	134.6	75.7
11	35	548	367	78.3	143.5	67.0
12	30	510	337	85.0	155.8	66.1
			Replication II			
1						
2						
3						
4	75	511	511	34.1	62.4	100.0
5	65	526	526	40.5	74.1	100.0
6	55	518	510	47.1	86.3	98.5
7	50	549	517	54.9	100.6	94.2
8	40	527	402	65.9	120.7	76.3
9	40	558	405	69.8	127.8	72.6
10	40	576	438	72.0	131.9	76.0
11	35	574	346	82.0	150.3	60.3
12	30	502	289	83.7	153.3	57.6
			Replication III			
1						
2						
3						
4	70	538	538	38.4	70.4	100.0
5	60	515	511	42.9	78.6	99.2
6	55	543	524	49.4	90.5	96.5
7	46	509	453	55.3	101.4	89.0
8	40	531	410	66.4	121.6	77.2
9	35	517	358	73.9	135.3	69.2
10	35	549	314	78.4	143.7	57.2
11	30	508	272	84.7	155.2	53.5
12	30	539	241	89.8	164.6	44.7

DATA SHEET 1B--CONTINUED

3/8" Ball - 40% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2						
3						
4	75	529	529	35.3	64.6	100.0
5	65	518	515	39.8	73.0	99.4
6	55	534	533	48.5	89.0	99.8
7	50	537	535	53.7	98.4	99.6
8	45	553	535	61.4	112.6	96.7
9	40	527	505	65.9	120.6	95.8
10	35	506	460	72.3	132.5	90.9
11	35	548	495	78.3	143.5	90.3
12	30	528	453	88.0	161.3	85.8
			Replication II			
1						
2						
3						
4						
5	65	507	506	39.0	71.5	99.8
6	55	512	511	46.5	85.3	99.8
7	50	544	539	54.4	99.7	99.1
8	45	556	543	61.8	113.2	97.7
9	40	529	507	66.1	121.2	95.8
10	35	510	466	72.9	133.5	91.4
11	35	550	476	78.6	144.0	86.5
12	30	511	404	85.2	156.1	79.1
			Replication III			
1						
2						
3						
4						
5	65	510	509	39.2	71.9	99.8
6	55	535	529	48.6	89.1	98.9
7	50	522	517	52.2	95.7	99.0
8	45	559	536	62.1	113.8	95.9
9	40	528	480	66.0	121.0	90.9
10	35	520	472	74.3	136.1	90.8
11	35	537	466	76.7	140.6	86.8
12	30	516	411	86.0	157.6	79.7

DATA SHEET 1B--CONTINUED

1/4" Ball - 10% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1	180	501	493	13.9	25.5	98.4
2	125	516	454	20.6	37.8	88.0
3	100	526	330	26.3	48.2	62.7
4	75	523	172	34.9	63.9	32.9
5	65	515	123	39.6	72.6	23.9
6	55	512	80	46.5	85.3	15.6
7	50	514	57	51.4	94.2	11.1
8	45	542	39	60.2	110.4	7.2
9	40	535	23	66.9	122.6	4.3
10	35	518	15	74.0	135.6	2.9
11	35	578	19	82.6	151.3	3.3
12	30	510	15	85.0	155.8	2.9
			Replication II			
1	185	509	506	13.8	25.2	99.4
2	130	515	481	19.8	36.3	93.4
3	95	500	302	26.3	48.2	60.4
4	75	512	143	34.1	62.5	27.9
5	65	501	94	38.5	70.6	18.8
6	55	507	48	46.1	84.5	9.5
7	50	555	70	55.5	101.7	12.6
8	45	535	36	59.4	108.9	6.7
9	40	504	32	63.0	115.5	6.3
10	35	505	17	72.1	132.2	3.4
11	35	544	19	77.7	142.4	3.5
12	30	519	16	86.5	158.5	3.1
			Replication III			
1	230	510	505	11.1	20.3	99.0
2	130	506	487	19.5	35.7	96.2
3	105	519	362	24.7	45.3	69.7
4	80	523	173	32.7	59.9	33.1
5	70	534	141	38.1	69.9	26.4
6	60	545	98	45.4	83.2	18.0
7	50	513	52	51.3	94.0	10.1
8	45	551	47	61.2	112.2	8.5
9	40	538	33	67.3	123.2	6.1
10	35	505	44	72.1	132.2	8.7
11	35	545	26	77.9	142.7	4.8
12	30	507	19	84.5	154.9	3.7

DATA SHEET 1B--CONTINUED

1/4" Ball - 20% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2	130	498	497	19.2	35.1	99.8
3	105	518	515	24.7	45.2	99.4
4	80	527	446	32.9	60.4	84.6
5	65	506	313	38.9	71.3	61.9
6	60	538	323	44.8	82.2	60.0
7	55	553	218	50.3	92.1	39.4
8	45	522	168	58.0	106.3	32.2
9	40	532	131	66.5	121.9	24.6
10	40	574	115	71.8	131.5	20.0
11	35	566	101	80.9	148.2	17.8
12	30	520	67	86.7	158.8	12.9
			Replication II			
1						
2	130	508	506	19.5	35.8	99.6
3	105	513	497	24.4	44.8	96.9
4	80	516	421	32.3	59.1	81.6
5	70	522	344	37.3	68.3	65.9
6	55	529	235	48.1	88.1	44.4
7	50	514	227	51.4	94.2	44.2
8	45	536	181	59.6	109.1	33.8
9	40	517	138	64.6	118.4	26.7
10	35	506	80	72.3	132.5	15.8
11	35	551	71	78.7	144.2	12.9
12	30	506	49	84.3	154.5	9.7
			Replication III			
1						
2	130	510	510	19.6	35.9	100.0
3	95	524	495	27.6	50.5	94.5
4	70	512	383	36.6	67.0	74.8
5	65	528	307	40.6	74.4	58.1
6	50	500	171	50.0	91.6	34.2
7	50	538	172	53.8	98.6	32.0
8	45	545	148	60.6	111.0	27.2
9	40	524	125	65.5	120.0	23.9
10	40	565	86	70.6	129.4	15.2
11	35	543	82	77.6	142.2	15.1
12	30	510	81	85.0	155.8	15.9

DATA SHEET 1B--CONTINUED

1/4" Ball - 30% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2						
3	90	514	513	28.6	52.3	99.8
4	70	503	500	35.9	65.8	99.4
5	65	541	525	41.6	76.3	97.0
6	50	508	447	50.8	93.1	88.0
7	50	552	439	55.2	101.2	79.5
8	40	519	376	64.9	118.9	72.4
9	40	554	378	69.3	126.9	68.2
10	40	599	343	74.9	137.2	57.3
11	35	550	303	78.6	144.0	55.1
12	30	514	227	85.7	157.0	44.2
			Replication II			
1						
2						
3						
4	75	517	516	34.5	63.2	99.8
5	60	534	499	44.5	81.6	93.4
6	55	547	462	49.7	91.1	84.5
7	50	527	445	52.7	96.6	84.4
8	45	549	391	61.0	111.8	71.2
9	40	520	352	65.0	119.1	67.7
10	35	527	330	75.3	138.0	62.6
11	35	549	312	78.4	143.7	56.8
12	30	519	237	86.5	158.5	45.7
			Replication III			
1						
2						
3						
4	75	503	502	33.5	61.4	99.8
5	65	507	491	39.0	71.5	96.8
6	55	502	454	45.6	83.6	90.4
7	50	522	398	52.2	95.7	76.2
8	45	531	372	59.0	108.1	70.1
9	40	519	296	64.9	118.9	57.0
10	35	510	286	72.9	133.5	56.1
11	35	551	266	78.7	144.2	48.3
12	30	512	226	85.3	156.4	44.1

DATA SHEET 1B—CONTINUED

1/4" Ball - 40% Total Cell Clearance - 50% of Cell Circle Covered

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Plate Cell Speed Ft./Min.	Cell Fill (%)
			Replication I			
1						
2						
3						
4	70	503	502	35.9	65.8	99.8
5	65	517	516	39.8	72.9	99.8
6	55	534	526	48.5	89.0	98.5
7	50	534	519	53.4	97.9	97.2
8	45	554	498	61.6	112.8	89.9
9	40	523	468	65.4	119.8	89.5
10	35	520	399	74.3	136.1	76.7
11	35	560	421	80.0	146.6	75.2
12	30	531	364	88.5	162.2	68.5
			Replication II			
1						
2						
3						
4	70	511	511	36.5	66.9	100.0
5	65	524	518	40.3	73.9	98.9
6	50	510	486	51.0	93.5	95.3
7	50	543	503	54.3	99.5	92.6
8	40	497	415	62.1	113.9	83.5
9	40	540	426	67.5	123.7	78.9
10	35	515	380	73.6	134.8	73.8
11	35	564	408	80.6	147.7	72.3
12	30	519	322	86.5	158.5	62.0
			Replication III			
1						
2						
3						
4	85	507	506	29.8	54.6	99.8
5	75	528	526	35.2	64.5	99.6
6	65	531	527	40.8	74.9	99.2
7	55	535	520	48.6	89.1	97.2
8	50	545	516	54.5	99.9	94.7
9	45	561	489	62.3	114.2	87.2
10	40	525	431	65.6	120.3	82.1
11	35	545	384	77.9	142.7	70.5
12	30	536	336	89.3	163.7	62.7

DATA SHEET 1B--CONTINUED

Trial No.	Time of Test (sec)	Counter Reading	Balls in Sample	Plate Cell Speed RPM	Ft./Min.	Cell Fill (%)
3/8" Ball - 10% Total Cell Clearance - 62.5% of Cell Circle Covered						
1	120	508	504	21.2	38.8	99.2
2	100	494	489	24.7	45.3	99.0
3	80	515	444	32.2	59.0	86.2
4	65	514	318	39.5	72.5	61.9
5	60	542	306	45.2	82.8	56.5
6	50	507	198	50.7	92.9	39.1
7	45	531	141	59.0	108.1	26.6
8	40	502	104	62.8	115.0	20.7
9	40	574	71	71.8	131.5	12.4
10	35	537	70	76.7	140.6	13.0
11	30	513	51	85.5	156.7	9.9
12	30	540	63	90.0	164.9	11.7
1/4" Ball - 10% Total Cell Clearance - 62.5% of Cell Circle Covered						
1	240	503	488	10.5	19.2	97.0
2	155	507	476	16.4	30.0	93.9
3	130	514	428	19.8	36.2	83.3
4	110	505	375	23.0	42.1	74.3
5	110	523	375	23.8	43.6	71.7
6	105	522	312	24.9	45.5	59.8
7	90	500	199	27.8	50.9	39.8
8	80	502	137	31.4	57.5	27.3
9	80	517	126	32.3	59.2	24.4
10	70	511	106	36.5	66.9	20.7
11	60	546	53	45.5	83.4	9.7
12	50	496	29	49.6	90.9	5.8
13	45	517	30	57.4	105.3	5.8
14	45	553	31	61.4	112.6	5.6
15	40	559	14	69.9	128.1	2.5
16	30	453	10	75.5	138.4	2.2
17	35	581	16	83.0	152.1	2.8
18	30	527	2	87.8	161.0	0.4

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