AN EXPERIMENTAL AUGER-BOOM-TYPE FERTILIZER DISTRIBUTOR
WITH
AUTOMATIC CONTROL

by

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Thesis submitted to the Graduate Faculty of the
Virginia Polytechnic Institute
in candidacy for the degree of
MASTER OF SCIENCE
in
Agricultural Engineering

May, 1964
Blacksburg, Virginia

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ABSTRACT

Central-hopper spreaders are widely used to apply dry fertilizer. Uniformity of distribution is severely limited by the centrifugal-fan and boom-type distributors used on these spreaders.

The purpose of this study was to investigate the application of automatic control principles to an experimental auger-boom-type distributor. To facilitate the use of automatic controls, a distributor of special design was developed. It consisted of an auger conveyor with a U-shaped cross section. Eighteen discharge openings were located on 6-inch centers along its length. Small compartments at the location of each opening, agitators on the auger flighting, and a control slide along the length of the boom, controlled the discharge from the boom. The control system consisted of a flow-level detector at the outboard end of the boom and a controller and linear actuator to operate the control slide.

Basic performance characteristics of the distributor were measured on a laboratory test stand using manual-remote control. Coefficients of variation for discharge patterns along the length of the boom varied from 4.63 to 12.22 percent under various combinations of auger speed, discharge opening size, and boom inclination. Discharge rate was more sensitive to opening size than auger speed. Regression coefficients and tests of independence indicated that discharge rate was not greatly influenced by fertilizer flow level. Minor segregation of dry-blended fertilizers was noted.

In tests with automatic control, errors in slide position were corrected. However, slow oscillation of the slide occurred after the initial correction. An improved flow-level detector and controller are needed for acceptable field performance of the system.

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INTRODUCTION

Several types of distribution equipment are used to apply the large quantities of commercial fertilizer needed for economical production of farm crops. Distribution equipment for liquid fertilizer sprays the fertilizer on the soil surface or injects it into the soil. With fertilizer in dry form, application practices also include both surface and subsurface application. Special distributors which provide row application or other detailed placement are required for some crops and soils. Under a wide range of conditions, however, broadcast application of fertilizer on the soil surface is satisfactory, and more economical.

Broadcast spreaders for dry fertilizer have two types of hopper arrangements, and may be classified on that basis. Wide-hopper spreaders meter fertilizer all along the hopper width and width of swath coverage is limited to the width of the hopper. Central-hopper spreaders, on the other hand, discharge a metered amount of fertilizer into some mechanisms to distribute the material laterally across a swath width which is usually greater than the width of the hopper.

Several factors have contributed to recent increased use of central-hopper spreaders. Transport width can be held to acceptable limits for highway use without decreasing the swath width and without unduly limiting hopper capacity. A large effective swath width, and elimination of stops to refill hoppers, both contribute to high field efficiency. The adaptability of central-hopper spreaders to both the transport function and the field spreading function uniquely qualifies this type for trailer or truck mounting to handle bulk fertilizer. The low cost of dry granular, bulk fertilizer has stimulated the use of equipment capable of handling it efficiently, such as truck and trailer mounted central-hopper spreaders.

The basic distributor configurations used for central-hopper spreaders are the centrifugal fan and the boom. The centrifugal distributor is simpler and more compact. The boom type employs augers or conveyor chains to mechanically move material laterally across the swath. Openings along the length of the boom provide for distribution across the swath. The positive action of boom-type distributors is needed for finely pulverized fertilizer which cannot be thrown satisfactorily with centrifugal-type distributors.

Serious problems of non-uniform application with both centrifugal and boom-type distributors have been noted by numerous observers. Smith (1) found that total wheat yields, as well as wheat yield variations within fields, are sometimes caused by lack of uniform fertilizer application with these distributors. Cunningham (2) found that the coefficient of variation of distribution patterns with central-hopper spreaders exceeded those of liquid fertilizer sprayers and wide-hopper spreaders. He also noted that some dry-blended fertilizers were severely segregated by the action of centrifugal and boom-type distributors. Investigations by Hoffmeister (3) and Maxwell (4) also identified the distributors as the principal source of the problem, rather than the metering equipment used on the hoppers.

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*Numbers in parenthesis refer to the Bibliography

Because boom-type distributors may be designed to operate on the principle of positive fertilizer control, this type was selected as the object of research and experimentation. Without positive control, segregation of some ingredients in dry blends probably cannot be eliminated. Also application of this principle is necessary to reduce effects of wind and irregular field topography.

REVIEW OF LITERATURE

The first patent for an auger-boom-type distributor was issued in 1903 to Kessler (5). This patent describes the basic components of present commercial boom-type distributors.

In 1925, McGuiness (6) applied for a patent for an auger conveyor mounted on a dump truck for the purpose of spreading sand on tarred roads. This was the first idea of using a truck to increase the application capacity of the spreader.

In view of the difficulty in obtaining uniform distribution along the length of the boom, an auger boom with the discharge openings in a helical pattern was designed by Richey (7) in 1943. Control plates were used to provide the different opening sizes.

An early design and a later modification of a well known distributor are described in two patents by Rosselet in 1941 and 1946 respectively (8) (9). These patents also describe the feeding system of the hopper to the auger boom distributors.

The configuration of this auger-boom design used at the present time consists of a 3-1/8-inch-diameter steel tube, 111 inches long, containing a series of slots spaced at 6-inch intervals. These slots are angled 55 degrees with the horizontal and the top of the inboard slot is 1/2-inch above a horizontal diametral plane with the top of succeeding slots located on a 0.73 degree helix. An auger rotates within the tube, carrying the fertilizer along the length of the boom to the outboard end which is open to prevent fertilizer accumulation. A 4-inch-diameter steel tube is also used for booms designed for higher application rates. This boom is constructed similarly to the 3-inch one except the discharge slots are located at same level.

An investigation of the factors which affect non-uniform distribution was conducted by Shaver (10). From the results of the single-discharge tests of his study, an important fact concerning the discharge and the flow level of the fertilizer was noted. The discharge from each opening is a function of the fertilizer flow level at that segment. The flow levels decrease gradually from the inboard end to the outboard end. The helical arrangement of the opening slots are used to compensate for the flow level differences.

The principle of grain discharge through openings as described in the Agricultural Engineers' Handbook (11) may be applied to the fertilizer discharging from the boom-type distributor. The principle states that the flow of the grain is independent of the head as long as the openings are flowing full. A discharge opening in a commercial auger-boom flows full only for an instant previous to the auger flighting passing over the opening.

An idea of keeping a portion of the total head of fertilizer constantly over each opening was studied experimentally by Bolt (12). In his experiment an enlarged ring section in the tube was used at the location of each opening. With this ring, an added head of fertilizer piled above each opening to keep the openings flowing full at all times during operation. This portion of fertilizer head also reduced the effect of flow level differences for each opening. Agitators were used to prevent bridging of fertilizer in the ring. The opening slot at the bottom of the ring was controlled by a shutter with different opening sizes. The results of tests with four of these rings indicated reasonably uniform distribution.

OBJECTIVES

The basic objective of this study was to investigate the application of automatic control principles to the design of a boom-type fertilizer distributor. Special requirements for automatic control indicated need for a distributor of unique design. The sequence of the investigation was established by the following subordinate objectives:

1. To design and develop an experimental boom-type distributor which is suited to both automatic and manual-remote control.
2. To investigate the influence of discharge opening size, flow level, operating speed, and inclination on performance of the experimental distributor.
3. To apply principles of automatic control in designing and testing a control system for the experimental distributor.

DESIGN AND CONSTRUCTION OF THE EXPERIMENTAL DISTRIBUTOR

Design of the Boom and Auger

The experimental design was based on a series of 18 identical compartments. Each compartment was U-shaped in cross section with a 2-1/2-inch radius at the bottom. Total height of the section was 5-1/2 inches. Each compartment was one-inch thick and a discharge opening slot was located in the bottom as shown in Figure 1. The compartments were 6-inch on centers. The connecting part between each compartment was a 4-1/2-inch-long U-tube with its top at the same level as the compartment, but one-inch smaller elsewhere. All the compartments and connecting tubes were welded together and two pieces of 7/8 by 3/16-inch flat iron were used on both sides of the boom to strengthen the entire assembly.

The inboard* and outboard ends were designed similarly to commercial auger-boom distributors to facilitate attachment to test equipment and auger drive sockets.

An auger with a nominal 4-inch pitch was used for this boom. As shown in Figure 1, paddle-shaped agitators, 7/8 inches long, were welded on the auger flighting at the location of each compartment. These agitators passed the center of the discharge opening of the compartment to prevent bridging of fertilizer. Since the pitch of the auger was not an integral number of inches, the agitators formed a spiral around the auger. This was designed to prevent the simultaneous

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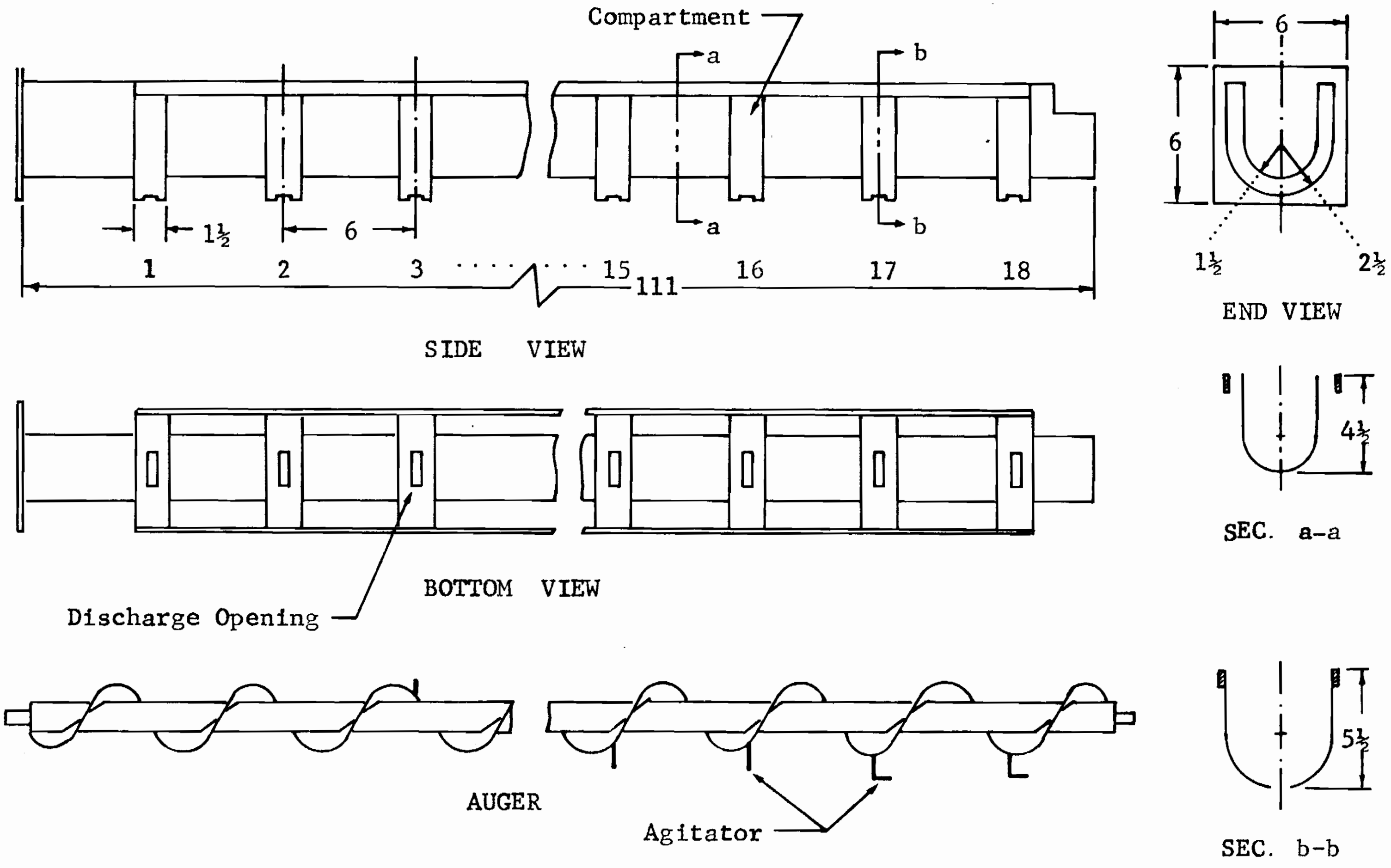
*The inboard end of a boom is the end which receives the fertilizer.



All dimensions are in inches.

Figure 1 Experimental Boom and Auger.

engagement of all agitators with fertilizer and consequent cyclical loading of the auger driving mechanism.

For automatic control purposes, compartments 17 and 18 as designated in Figure 1, were chosen as error detector locations. Special construction for these two compartments was designed to utilize the existence of fertilizer head in each compartment to operate small paddle switches. A principle of interference was used to generate force to operate the switches. A 1/4-inch-diameter shaft was extended into each compartment, and on respective ends of this shaft a friction leaf and a pushing arm were fastened as illustrated in Figure 2. The friction leaf was hook-shaped and its lower surface cleared the agitator by 1/16 inches. The agitator in these compartments was Z-shaped in configuration, one inch horizontally, and 7/8 inches vertically as shown in Figure 1 and 2. When the fertilizer head was sufficiently high to be picked up by the agitator, a force would be transmitted to the friction leaf due to interference through the fertilizer particles. This force was used to rotate the shaft and cause the pushing arm to press on a microswitch*. The other end of the pushing arm was bent upward to limit the shaft rotation. Bearings and compression springs were used to smooth the rotating action of the shaft. Detail construction is illustrated in Figure 2.

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*Model 1SMI manufactured by the Minneapolis-Honeywell Corp.

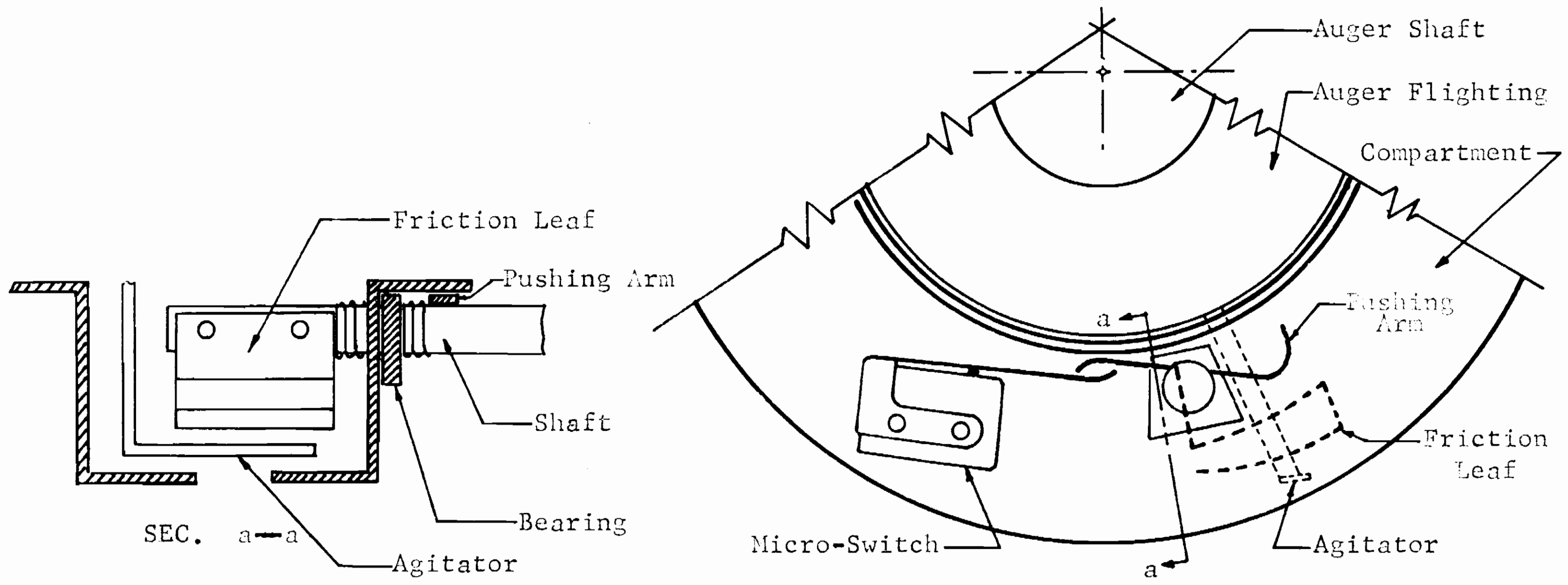

Full Scale

Figure 2 Paddle-Switch Construction for the Automatic Control System.

Design of the Opening-Size Control Mechanism

A U-shaped control slide, 115 inches long, was formed from a 24-gage metal sheet to fit the bottom of the boom. This slide, shown in Figure 3, is fastened to the boom by a set of tension springs so that it can slide longitudinally. Steel blocks were welded on both sides of compartments 4, 10, and 16 for the purpose of guiding the control slide.

A steel end plate was used on the outboard end of the slide. Two bearing brackets were fastened to this plate to provide a means for the actuator shaft.

The linear actuator is fastened to the outboard end of the boom by two arms as shown in Figure 4. The shaft of the linear actuator controls the movement of the slide through a displacement of 3 inches. Triangular shape openings were cut in the bottom of the slide, at 6-inch intervals. The 3-inch travel of the slide, and the slide openings provided a means for adjusting discharge rate from zero to a maximum value.

The discharge openings on the boom were cut with an end milling machine. They are 1-9/16-inch long, 3/8-inch wide and have round ends. The triangular openings on the control slide were cut with a sabre saw to the dimensions shown in Figure 5. The discharge opening size is expressed as a linear displacement of the control slide with respect to the edge of a guiding block on the boom. A stainless steel rule was attached on the slide rim, as shown in Figure 5, to give the readings.

In order to give greater physical significance to the slide position, a curve given in Figure 6 was constructed to express the relationship of true opening size in square inches to the linear position.

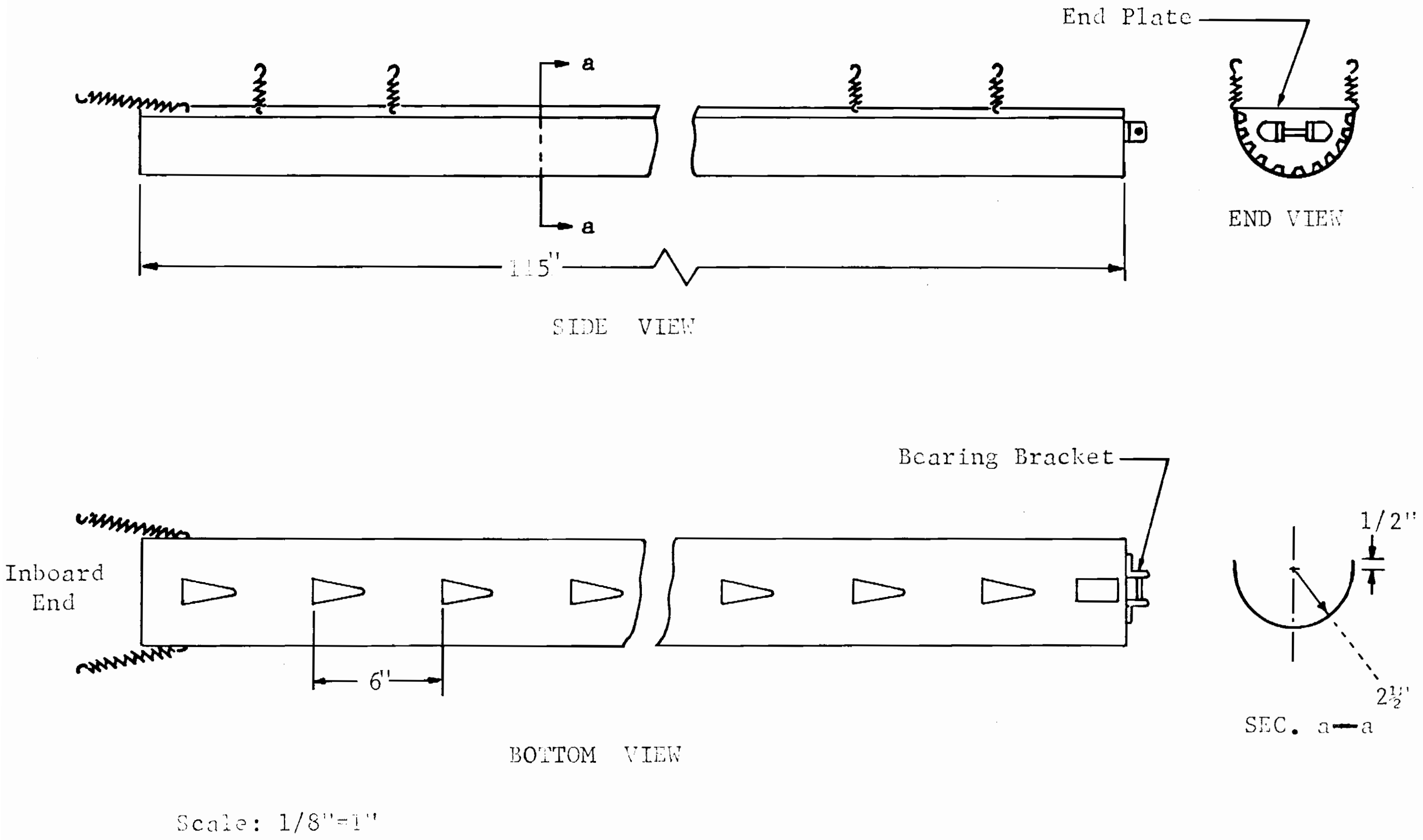
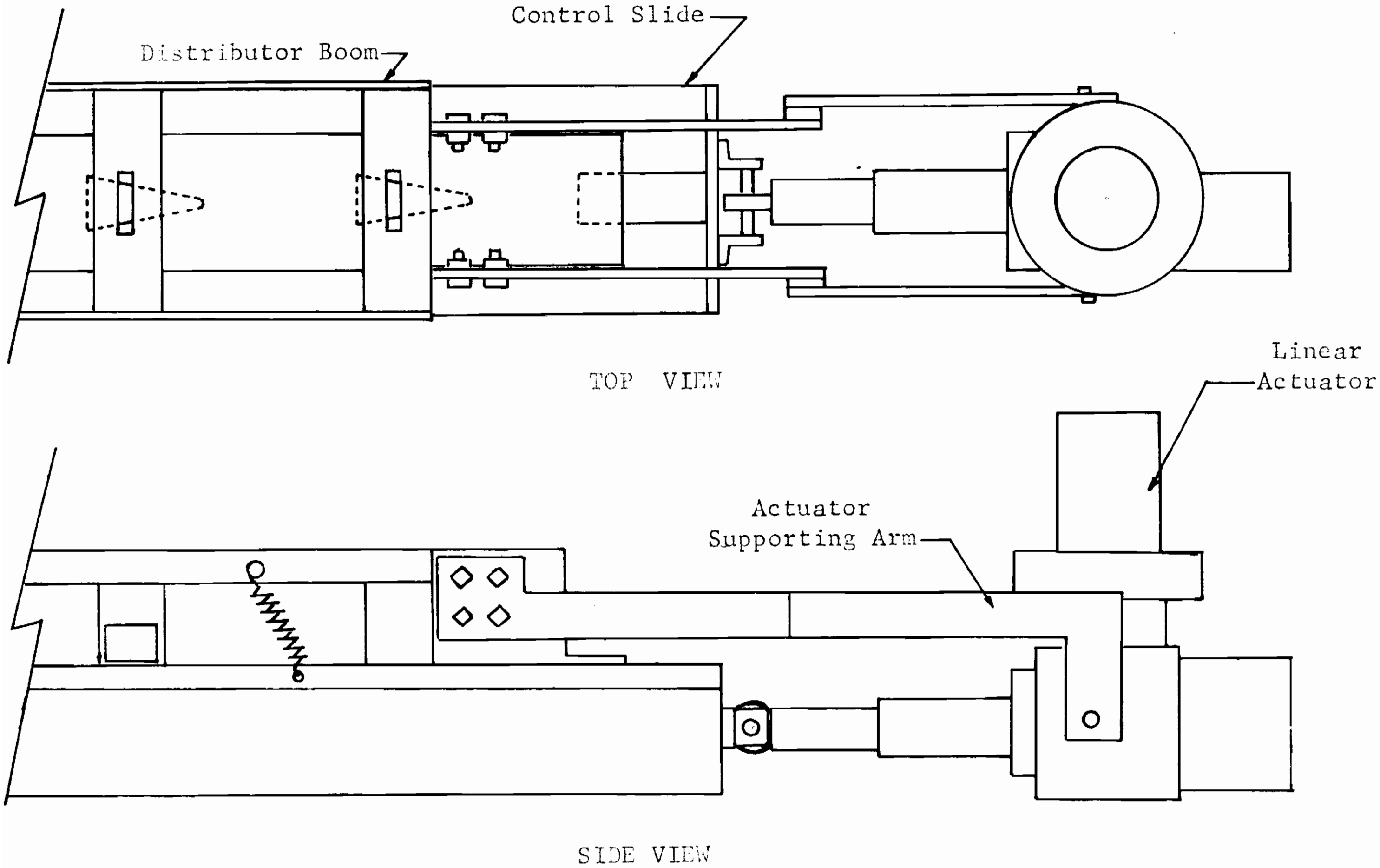
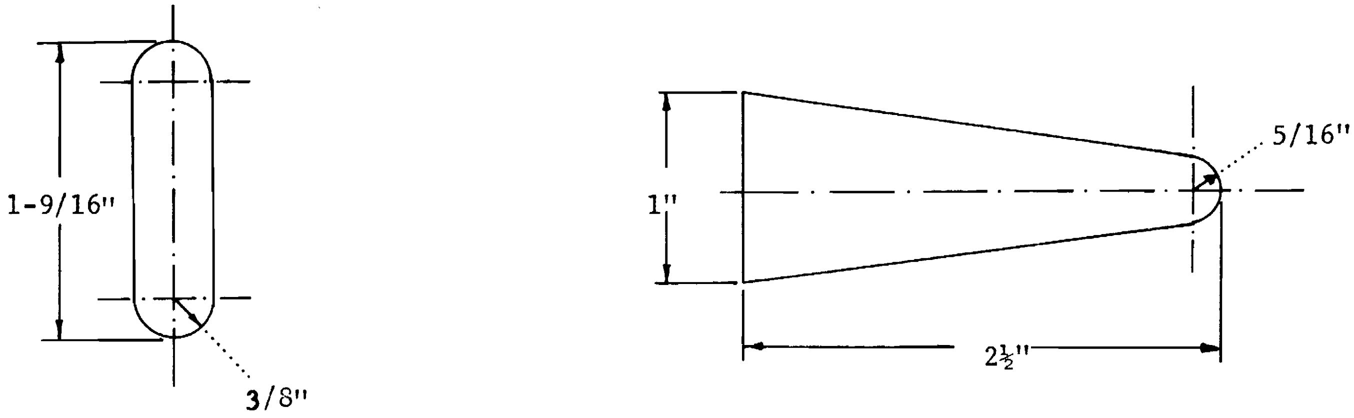


Figure 3 Discharge-Opening Control Slide.



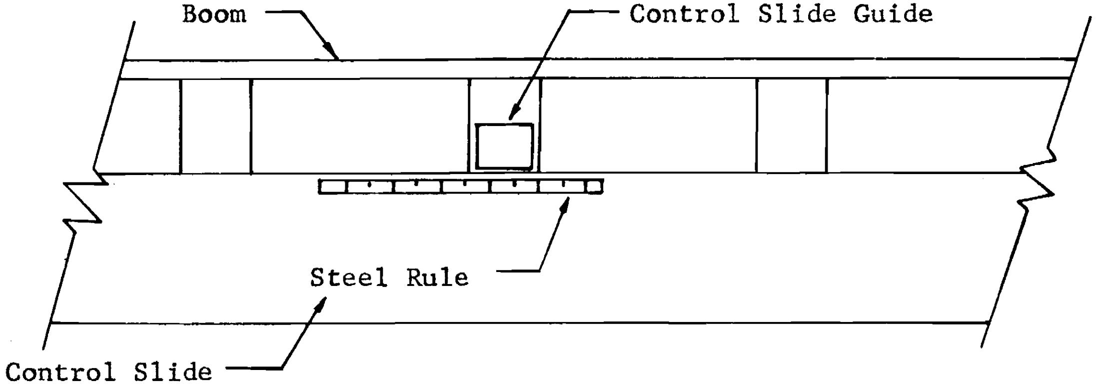
Scale: 1/4''=1''

Figure 4 Slide Control Mechanism.



Boom Opening

Control Slide Opening



Slide Position Indication

Scale: 1/4"=1"

Figure 5 Boom and Slide Opening Configuration.

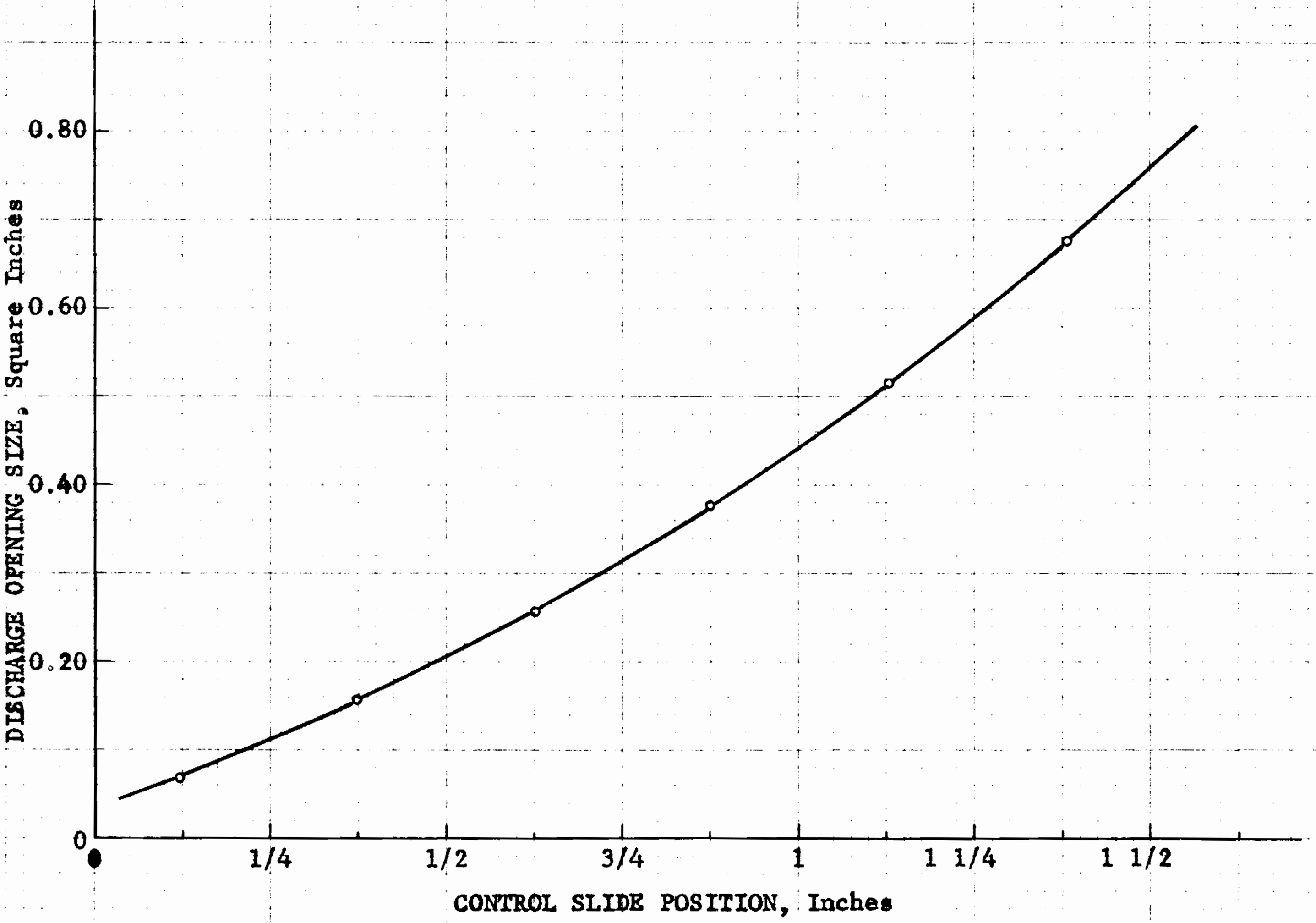


Figure 6 Control-Slide Calibration Curve.

At the inboard end, the control slide was pulled by two tension springs which helped the actuator motion in one direction and also prevented tipping effects caused by the strong push of the actuator.

Design of the Remote Control Circuit

There were three different electrical power requirements for the entire experiment. They were 110 volts a-c, 6 volts d-c and 24 volts d-c. Six volts d-c was obtained by center tapping the 24-volt d-c source.

The circuit diagram in Figure 7 shows the whole electrical arrangement for the remote control and for distributor test stand operation. All the switches and instruments were mounted in a control panel.

The sample collecting system used was designed by Shaver (10). A wattmeter was added to examine the power used by the motor which operated a variable speed drive* and in turn operated the auger. The linear actuator motor was controlled by a double-throw, spring-loaded switch for slide movement in either direction.

This circuit was also used in automatic control tests to preset the control slide position.

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*Model 100V400 M, manufactured by Zero-Max Company, Minneapolis, Minnesota.

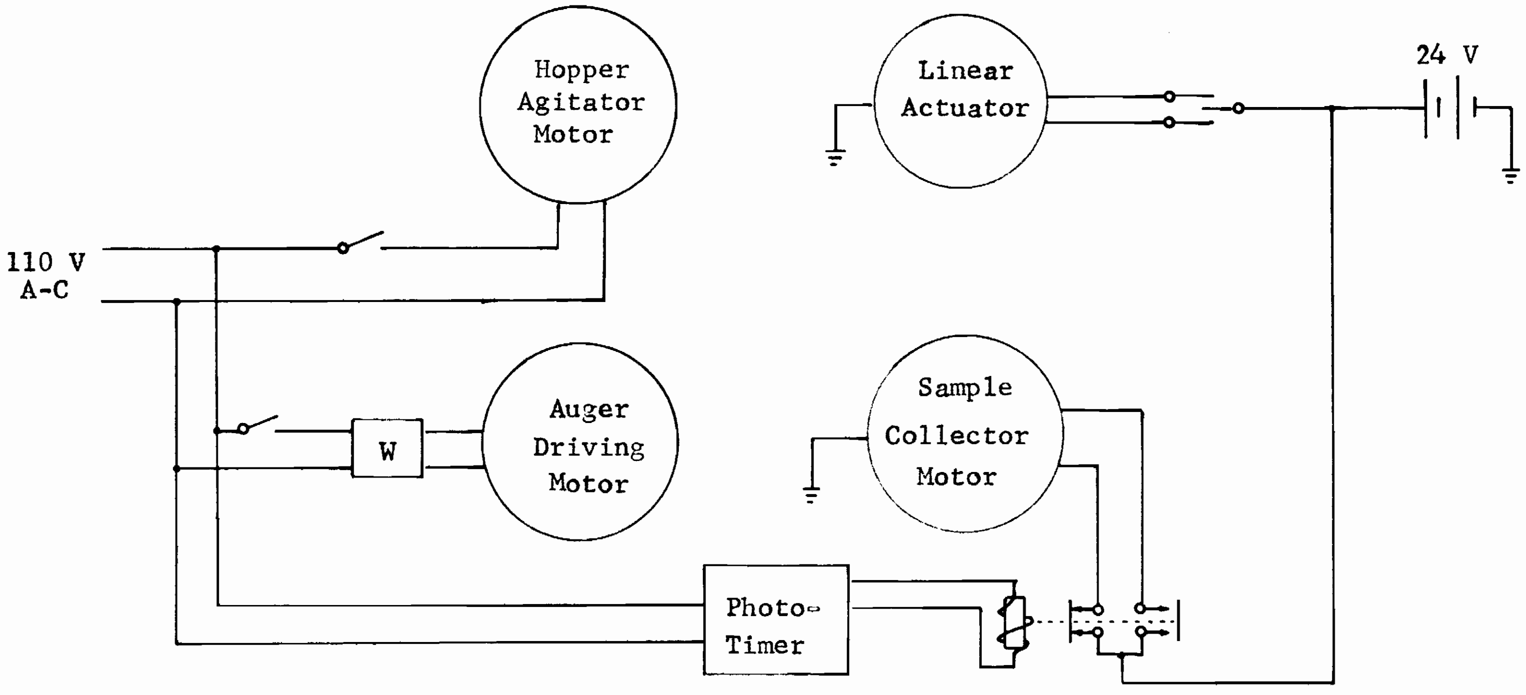


Figure 7 Remote Control and Distributor Test Stand Circuit.

DESIGN OF THE AUTOMATIC CONTROL SYSTEM

The basic principles of a closed-loop or feedback control system were used in the design of the control system for the experimental distributor. A block diagram in Figure 8 shows the elements of a basic feedback system. Typical time response curves for this system are also shown in the figure. The analogy of the experimental boom control system to the theoretical system is shown in Table 1. Because of the difficulties in designing a proportional error detector in the small space of a boom compartment, micro-switches and relays were used. According to feedback control theory (13), such a system is classified as a relay-type or pulse-type control system. In a relay-type system, the full power of the motor is applied as soon as the error signal is large enough to operate the relay. A relay-type feedback control system is non-linear and readily produces oscillations. A delay-time circuit was used to minimize this difficulty.

Design of the Experimental Controller

The error detector of the distributor control system was designed to give a series of on-off signals from the micro-switches. These signals operated relays. The polarity and period of the relay operation depended upon the on-off performance of the micro-switches. To limit the sensitivity of the control, a time-delay system was used, consisting of time-delay relays TDR 1 and TDR 2, and a relay, R_3, as shown in Figure 10. The purpose of this time-delay system was to divide the long on-off period of the relay action time into shorter periods of actuator operation. This was obtained by adjusting the

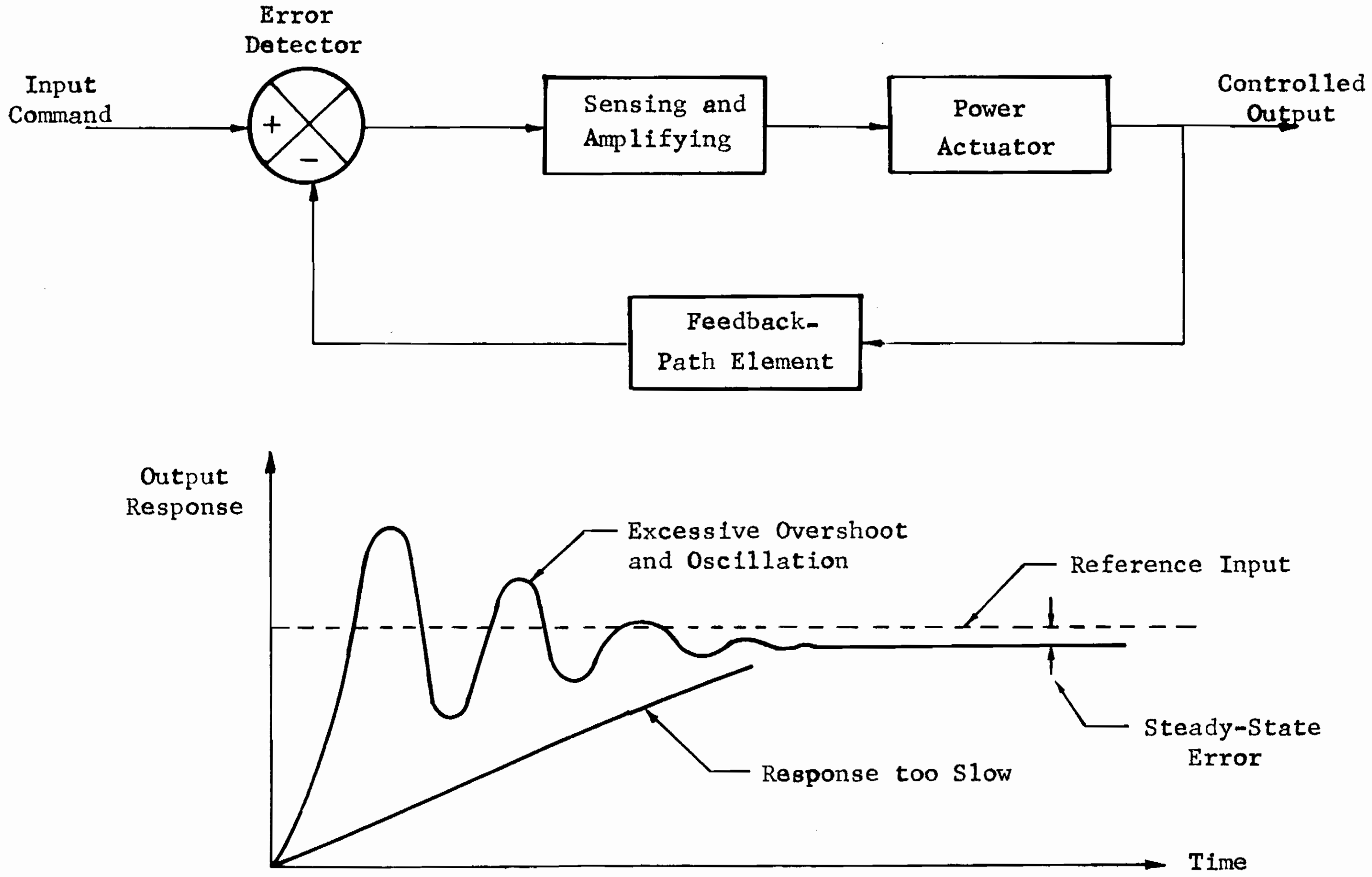


Figure 8 Block Diagram and Typical Response Curves for a Feedback Control System.

Table 1 - Analogy of the Experimental Boom-Type Distributor Control System to Theoretical Feedback Control

Theoretical Feedback Control Units	Experimental Boom-Auger Spreader Control Units
Input command	Flow level of the fertilizer input
Error detector	Head of fertilizer in compartments 17 and 18 and the two micro-switches
Sensing and amplifying elements	Sensing and time delaying elements
Power actuator	Linear actuator
Controlled output	Slide position or discharge opening size
Feedback path units	Moving slide causing flow level change

delay time of TDR 1 and TDR 2. The periodic-rectangular waves shown in Figure 9 is the anticipated typical output signal of this part of the system. The length of the delay-time on TDR 1 and TDR 2 was defined as delay-time and on-time respectively for the control system. The difference in these two time intervals, which was defined as off-time, gave the control system a non-response period during which the microswitches could not operate the actuator. By adding this delay-time system, the error detector signal was modified to supply step-correction to the control slide on the distributor.

To eliminate probable high frequency switching of relays R_1 and R_2 due to agitator rotation, an R-C circuit was used to provide a time constant for each delay coil equal to the minimum expected rotative speed of the auger. With this delay-time, the relay would remain energized until periodic signals from the microswitches, having the frequency of the agitator, ceased. The R-C circuit design is shown in Figure 10 near the location of microswitches MS_1 and MS_2. The resistors r_1 and r_3 were used to limit inrush currents carried by the microswitch contacts. To record the performance of the control system, a two-channel recorder was used. Channel 1 of the recorder was used to indicate the off-time intervals and channel 2 was used to record the output signal which operates the power actuator. A relay R_4, was used to identify the polarity of signals during the recording process.

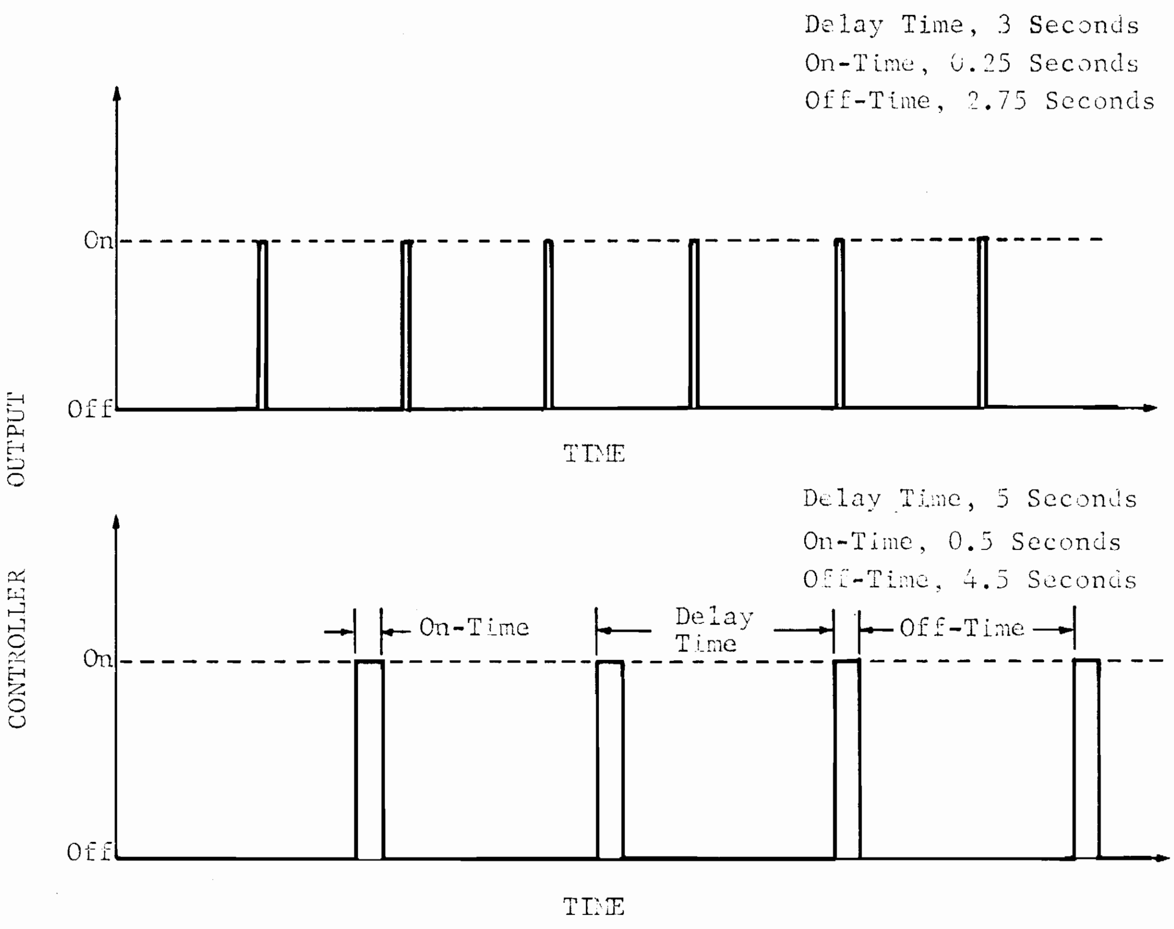
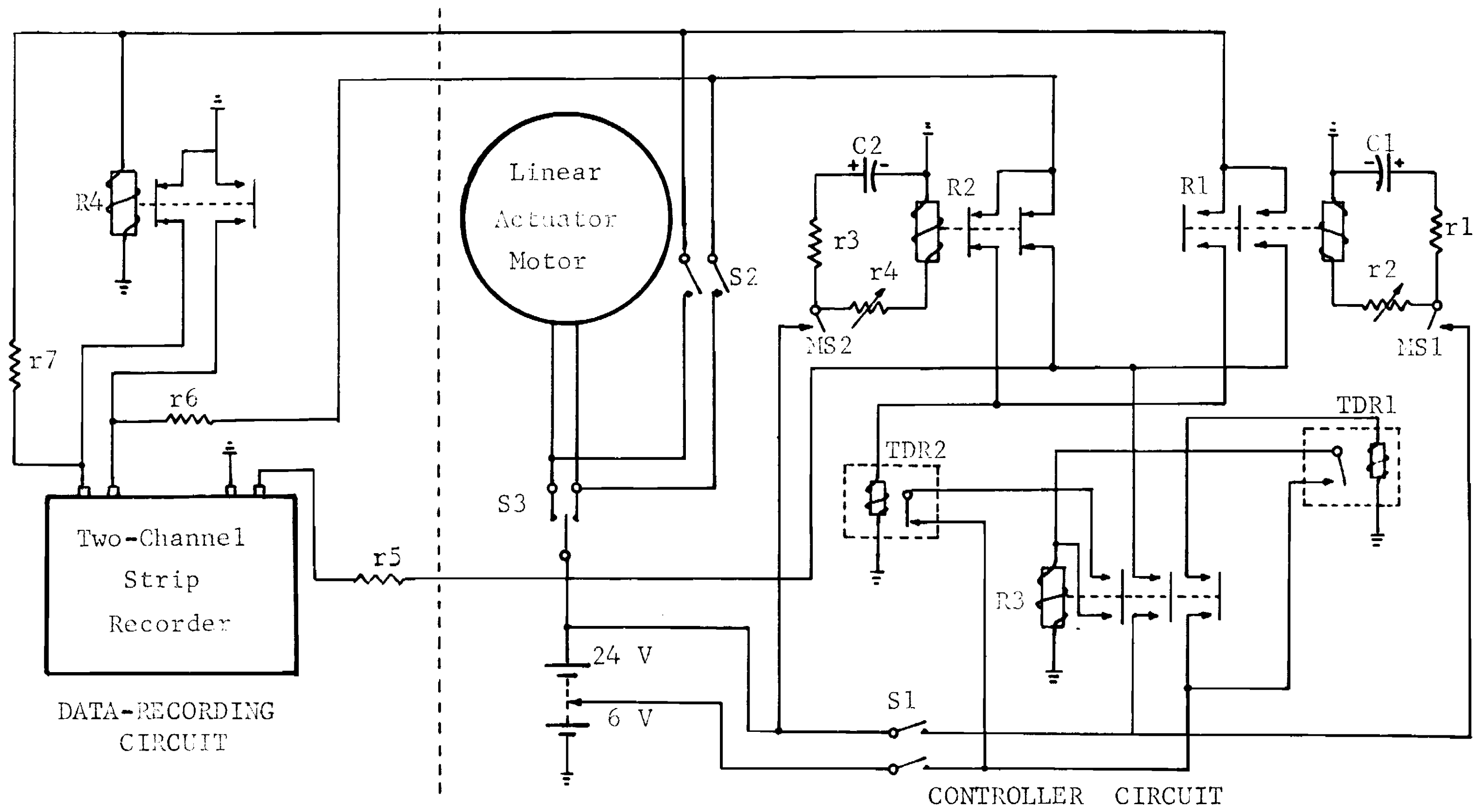


Figure 9 Periodic Square-Wave Function for the Controller.



TDR1- Pneumatic type. Agastat Model DFW22

TDR2- Pneumatic type. Agastat Model DFW12

C1= 500 Mfd
C2= 300 Mfd
r1= r3= 5 Ohms
r2= 5K
r4= 10K
r5= r6= r7= 4K

Figure 10 Automatic Control and Recording Circuits for the Experimental Auger-Boom-Type Distributor.

Expected Design Performance

The control system must handle three different situations as follows:

1. Compensation for insufficient discharge-opening size.
2. Compensation for excessive discharge-opening size.
3. Equilibrium.

In the first situation, the fertilizer in the boom would tend to flow excessively from the outboard end of the distributor. Compartments 17 and 18 would be full. The fertilizer head in these two compartments would make MS_1 and MS_2 operate and charge the capacitors C_1 and C_2, of the R-C circuits and energize relays, R_1 and R_2. Since R_1 is normally open and R_2 is normally closed, only R_1 would be closed. At the same time, current flow from the 6-volt source through the contacts of TDR 1, which is closed when there is no current flow, would energize R_3. Through the contacts of R_3 and R_1, the coils of TDR 1 and TDR 2 would be energized and start a cycling, on-off operation. The relay R3 would follow this pattern and operate the actuator periodically. The movement of the actuator increases the opening size by moving the slide and thereby compensating for the excessive flow level at the end of the boom.

In the second situation, fertilizer would not reach the last two compartments. In this case, MS_1 and MS_2 remain in the off position. The normally closed relay, R_2, is closed and conducts current to the second lead of the actuator, and the slide closes the discharge openings. The reduction of the discharge opening would cause the flow level to increase at the outboard end of the boom.

For the equilibrium condition, compartment 17 would contain fertilizer, but compartment 18 would be empty. In this case, MS_2 would close, but MS_1 would remain open. Therefore, both relays, R_1 and R_2, would be open and no current would flow to the actuator. This is the situation that the control system always seeks to achieve.

Theory of System Performance

To determine the influence of auger speed, auger pitch, actuator speed, and compartment capacity; the following theoretical model was analysed. The symbols used in the analysis are:

E = initial error in flow level at $x = X$, lbs per auger pitch

L = flow level at any point along the length of the boom, lbs per auger pitch

L_o = flow level at the inboard end, lbs per auger pitch

p = auger pitch, ft

n = auger speed, rpm

q_o = initial discharge rate along the boom, lbs per ft per min

q = discharge rate along the boom, lbs per ft per min

s = actuator speed, ft per min

t = time, min

T = definite time, min

x = length measured along the boom axis, ft

X = total boom length, ft

C = capacity of the compartments, lbs per ft of boom length

k = discharge constant, lbs per min per ft of boom length per ft of control slide opening

$y = st$ = change of control slide position from initial position, ft

In developing the mathematical model, the following assumptions were used:

np = auger conveying speed

npT = displacement of fertilizer along the boom during time period, T

$q_o + kst$ = discharge rate at time t

For a slide position that provides discharge openings of insufficient size, all compartments in the boom are filled and a positive flow-level error, E, is assumed to exist initially at the end of the boom. The flow level at any point, x, along the boom at time t, is governed by the following differential equation:

$$\frac{dL}{dx} = \frac{-q_o}{n} - \frac{kst}{n}, \quad \text{since } dx = npdt, \quad \frac{dL}{dt} = - pq_o - pkst$$

Eq. 1 (a)

The integral of the equation between the limits $L = L_i$, $t = 0$ to $L = L_f$, $t = T_1$ is:

$$L_f - L_i = - pq_oT_1 - \frac{pksT_1^2}{2} \qquad \text{Let } L_f = 0, \text{ then } L_i - pq_oT_1 = E$$

$$\text{So that } E = \frac{pksT_1^2}{2} \quad \text{and } T_1 = \sqrt{\frac{2E}{pks}}$$

Eq. 1 (b)

Where T_1 = time required to reduce the flow level at a given point, x, along the boom by an amount E from its initial steady-state level when $T_1 \leq x/np$

Upon elimination of E, discharge from compartment 18 continues until its capacity is exhausted. The time, T , required to empty compartment 18 is influenced by continued control slide movement, since the dead space for the system is not reached until the end of this period.

$$T_2 = \frac{C}{q_o + ksT_1 + \frac{ksT_2}{2}}$$

Applying the quadradic formula, this becomes:

$$T_2 = \sqrt{\left(\frac{q_o}{ks} + T_1\right)^2 + \frac{2C}{ks}} - \left(\frac{q_o}{ks} + T_1\right) \qquad \text{Eq. 2 (a)}$$

During period T_2 the flow level will diminish to zero at other locations near the outboard end of the boom. At time $T_1 + T_2$, flow level will be zero for all $x > x_2$. Two different conditions, (I) and (II), are involved in determining x_2.

(I) If $x_2 > (T_1 + T_2)\,np$, the initial flow level before T_1 and T_2 was already on the initial steady-state flow level curve. In this case, Eq. 1 (a) is employed and its integral will be:

$$L_f - L_i = - pq_o t - \frac{pkst^2}{2} \Bigg|_{T_1}^{T_1 + T_2}$$

Let $L_f = 0$, and $L_i = (X - x_2 + T_2 np)\,\frac{q_o}{n}$

Then $x_2 = X - \frac{npks}{2q_o}\,(2T_1\,T_2 + T_2{}^2)$ Eq. 2 (b)

(II) If $x_2 < (T_1 + T_2)\,np$, then the following differential equation will be employed:

$$\frac{dL}{dt} = -\left[pq_o + psk\,\left(T_1 + T_2 - \frac{x_2}{np}\right)\right] - pkst$$

The integral of the above equation between the limits 0 to $\frac{x_2}{np}$ will be:

$$L_f - L_i = -\left[pq_o + psk\,\left(T_1 + T_2 - \frac{x_2}{np}\right)\right] \frac{x_2}{np} - \frac{psk}{2}\left(\frac{x_2}{np}\right)^2$$

Eq. 2 (c)

Let $L_f = 0$ but $L_i = L_o$ Therefore,

$$x_2 = n\left[\frac{pq_o}{sk} + p(T_1 + T_2)\right] + n\sqrt{\left[\frac{pq_o}{sk} + p(T_2 + T_1)\right]^2 - \frac{2L_o p}{sk}}$$

Eq. 2 (d)

After compartment 18 is exhausted, the following two cases may result:

A. $X - x_2 < 1/2$ ft

B. $X - x_2 > 1/2$ ft

For case A, if $X - 1/2 > (T_1 + T_2 + T_3'')\, np$ and T_3'' = time required to bring the flow level to zero at compartment 17, the following equation applies:

$$\frac{dL}{dt} = -\, pq_o - ksp(T_1 + T_2) \qquad \text{Eq. 3 (a)}$$

But $L_f = 0$ and $L_i = \left[1/2 - (X - x_2) + T_3''\, np\right] \frac{q_o}{n}$

$$\text{Therefore } T_3'' = \frac{1/2 - (X - x_2)}{ksp\ (T_1 + T_2)}\left(\frac{q_o}{n}\right) \qquad \text{Eq. 3 (b)}$$

After T_3'', an additional time period $T_4'' = T_2$ is required to exhaust compartment 17. Eq. 3 (a) integrated between appropriate limits becomes:

$$\left[X - 1/2 - x_4 + T_2\, np\right] \frac{q_o}{n} = pq_o T_2 + ksp(T_1 T_2 + T_2^2)$$

$$\text{Therefore } x_4 = X - 1/2 - \frac{nksp}{q_o}\ (T_1 T_2 + T_2^2) \qquad \text{Eq. 3 (c)}$$

Where $L = 0$ for all $x > x_4$.

If $X - 1/2 < (T_1 + T_2 + T_3'')\, np$, Eq. 2 (c) applies and we have

$$L_o = \left[pq_o + pks\left(T_1 + T_2 + T_3'' - \frac{X - 1/2}{np}\right)\right]\left(\frac{X - 1/2}{np} - T_3''\right) +$$

$$\left[pq_o + psk(T_1 + T_2)\right] T_3'' \qquad \text{Eq. 3 (d)}$$

T_3'' can be obtained by solving the above quadradic equation.

In case B, and if $X - 1/2 > (T_1 + T_2 + T_3'')\,np$, assume $T_2'' = T_2 - T_2'$

Where T_2'' = time required for the flow front to recede from compartment 17 to x_2, T_2' = time required for the front to recede from compartment 18 to 17.

Substituting $X - x_2 = 1/2$ in Eq. 2 (b) or Eq. 2 (d), T_2' is obtained. In this case, before the compartment 18 is exhausted, compartment 17 starts to exhaust also. Let T_3' = time required to exhaust compartment 17, then T_3' can be calculated by using the equation:

$$C = \left[q_o + ks(T_1 + T_2') + \frac{ksT_2''}{2}\right] T_2'' + \left[q_o + ks(T_1 + T_2)\right] (T_3' - T_2'') \qquad \text{Eq. 4 (a)}$$

Equation 2 (b) with new limits:

$$X - x_3 = \frac{n}{q_o}\; ks(T_1T_3 + T_2T_3) \qquad \text{Eq. 4 (b)}$$

Where $T_3 = T_3' - T_2''$ = time required to complete the exhausting of compartment 17. After the flow level in compartment 17 is exhausted, an additional time interval, T_4 is required before the flow front recedes to a minimum x position and starts to advance toward the outboard end of the boom. Assume x_4 is this minimum position. The following integral equation gives the relationship between T_4 and x_4 for $x_4 > (T_1 + T_2 + T_3 + T_4)np$

$$\int^{o} (x_3 - x_4 + T_4\, np)\,\frac{q_o}{n}\; dL = \int_o^{T_4} -\left[pq_o + ks(T_1+T_2)\right] dt + \int_o^{T_4} pkstdt$$

$$x_3 - x_4 = \left[\frac{pksn}{q_o}\;(T_1+T_2)\right] T_4 - \frac{pksn}{q_o}\;\frac{T_4^{\,2}}{2} \qquad \text{Eq. 4 (c)}$$

T_3'' can be obtained by solving the above quadradic equation.

In case B, and if $X - 1/2 > (T_1 + T_2 + T_3'')\,np$, assume $T_2'' = T_2 - T_2'$ Where T_2'' = time required for the flow front to recede from compartment 17 to x_2, T_2' = time required for the front to recede from compartment 18 to 17.

Substituting $X - x_2 = 1/2$ in Eq. 2 (b) or Eq. 2 (d), T_2' is obtained. In this case, before the compartment 18 is exhausted, compartment 17 starts to exhaust also. Let T_3' = time required to exhaust compartment 17, then T_3' can be calculated by using the equation:

$$C = \left[q_o + ks(T_1+T_2') + \frac{ksT_2''}{2} \right] T_2'' + \left[q_o + ks(T_1+T_2) \right] (T_3' - T_2'') \qquad \text{Eq. 4 (a)}$$

The position of the flow front after period T_3' is given by the following equation which is similar to Equation 2 (b):

$$x_3 = X - \frac{npks}{q_o} (T_1T_3+T_2T_3) \qquad \text{Eq. 4 (b)}$$

Where $T_3 = T_3' - T_2''$ = time required to complete the exhausting of compartment 17. After the flow level in compartment 17 is exhausted, an additional time interval, T_4, is required before the flow front recedes to a minimum x position and starts to advance toward the outboard end of the boom. Assume x_4 is this minimum position. The following integral equation gives the relationship between T_4 and x_4 for $x_4 > (T_1 + T_2 + T_3 + T_4)np$

$$\int_{(x_3-x_4+T_4np)\frac{q_o}{n}}^{o} dL = \int_o^{T_4} - \left[pq_o+ks(T_1+T_2) \right] dt + \int_o^{T_4} pkstdt$$

$$x_3 - x_4 = \left[\frac{pksn}{q_o} (T_1+T_2) \right] T_4 - \frac{pksn}{q_o} \frac{T_4^2}{2} \qquad \text{Eq. 4 (c)}$$

In order to find the minimum value for x_4, differentiation of x_4 with respect to T_4 is required.

$$\frac{dx_4}{dt_4} = \frac{npks}{q_o}(T_1 + T_2) - \frac{npks}{q_o} T_4 = 0 \qquad T_4 = T_1 + T_2$$

Substituting this in Eq. 4 (b):

$$x_4 = x_3 - \frac{npks}{q_o} \; \frac{(T_1 + T_2)^2}{2} \qquad \text{Eq. 4 (d)}$$

After the flow front recedes to x_4 it advances toward the outboard end and to compartment 17 which stops the slide closing action of the actuator.

Let T_5 be the time required for the flow front to move from x_4 to compartment 17 at position X - 1/2. The flow during this time must fill the depleted capacity along this interval, $X - 1/2 - x_4$. If A pounds of fertilizer occupy a length of the boom, y, downstream from x_4 and if $y = np\,(T_5 - t) - (X - 1/2 - x_4) + x$ Eq. 5 (a)

then this amount of fertilizer is required to fill the depleted capacity and to provide discharge along the length, y. The differential equation relating these factors is:

$$y\,(q_o - kst)\,dt + cdx + d\,A = 0 \qquad \text{Eq. 5 (b)}$$

Where

$$A = \left\{ \left[npT_5 - (X - 1/2 - x_4) \right] \frac{q_o}{n} - pq_o t + \frac{pskt^2}{2} - \frac{q_o y}{2n} \right\} \frac{y}{p}$$

The differential equation expressed in terms of x and t is:

$$\left(\frac{kst^2}{2} - \frac{q_o x}{np} + c\right) dx + \left(q_o x - \frac{npskt^2}{2}\right) dt = 0 \qquad \text{Eq. 5 (c)}$$

Where $c = q_o t - kst^2/2$ until $c = C$

When the flow front has advanced to compartment 17, and slide closing action ceases, a similar differential equation applies:

$$(ksT_5 - \frac{q_o x}{np} + c)\ dx + (q_o x - npksT_5)\ dt = 0$$

Finally when the flow front reaches compartment 18 during the next time period, T_6, opening of the slide commences and a maximum flow level occurs before the influence of the slide opening action is effective. Then the rate at which the flow level rises is:

$$\frac{dL}{dt} = pksT_5 - pkst \qquad \text{Eq. 6}$$

This shows that the maximum flow level occurs at $T_7 = T_5$ provided $X > np(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7)$

The analysis shows that time required to correct errors in flow level is inversely proportional to the square root of the auger pitch, and actuator speed. However, changes in discharge rates resulting from the controlling action increase in proportion to the square root of actuator speed, making high speeds undesirable. The analysis also shows that capacity increases the time required to correct errors.

TEST PROCEDURES

The test stand used for the experimental distributor is described by Shaver (10). It served to support the fertilizer feeder, experimental distributor, and the auger driving system. The test stand included a fertilizer sample collector which consisted of a frame and 19 pairs of one-quart plastic cups. The complete arrangment is shown in Figure 11. An end-support frame, shown in detail in Figure 12, was designed to reduce vibration of the boom during operation. Arms extended from the test stand were used to support the middle part of the boom. The end support frame accommodated a range of slopes of plus or minus 10 percent.

The entire experimental arrangement is shown in Figure 11, including the remote control panel in the foreground. The experimental automatic controller was located along side the remote control panel as shown in Figure 13.

Tests for Basic Distributor Characteristics

The purpose of the tests was to measure the uniformity of the distribution from the experimental distributor and to study relationships among flow level, auger speed, and control slide position necessary for satisfactory distribution. Tests were scheduled with three feeding rates and four auger speeds as shown in Table 2. Three replications were used for each condition with the order of testing completely randomized.

A standard testing procedure was developed. Each test run was started with the feeder hopper 5/6 full and with the distributor control slide closed. The feeder was then adjusted to give a certain rate of

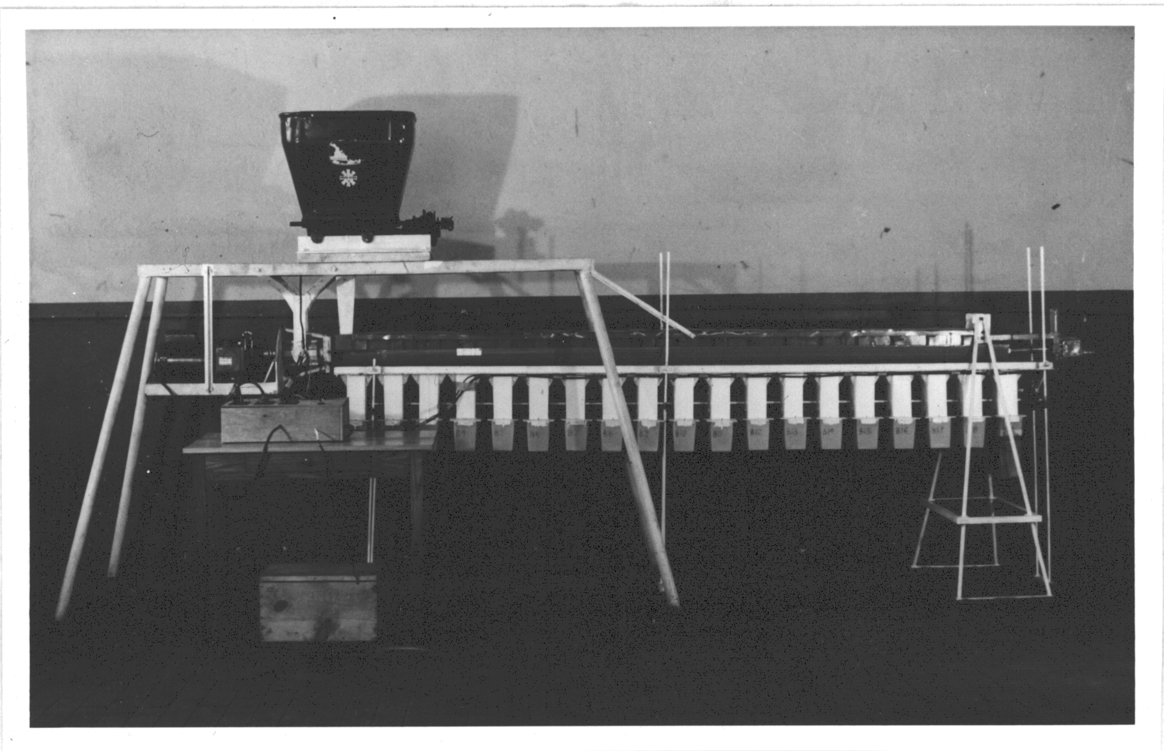


Figure 11 - Test Stand With Distributor in Level Position

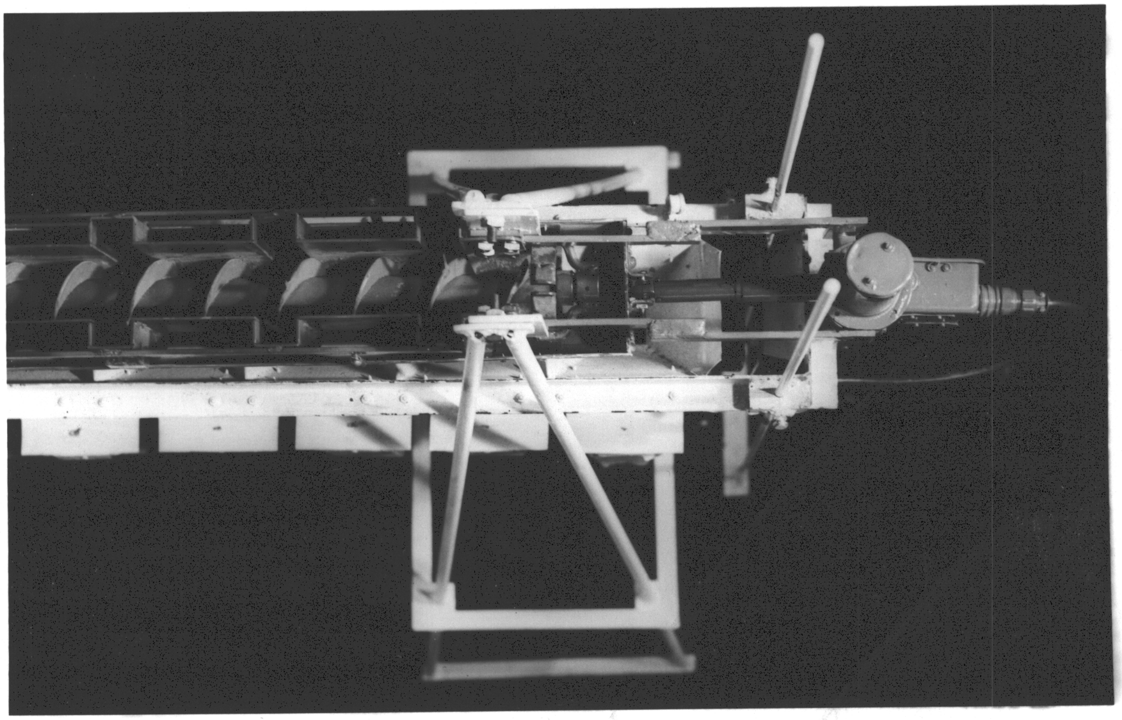


Figure 12 - End Support Frame for Distributor

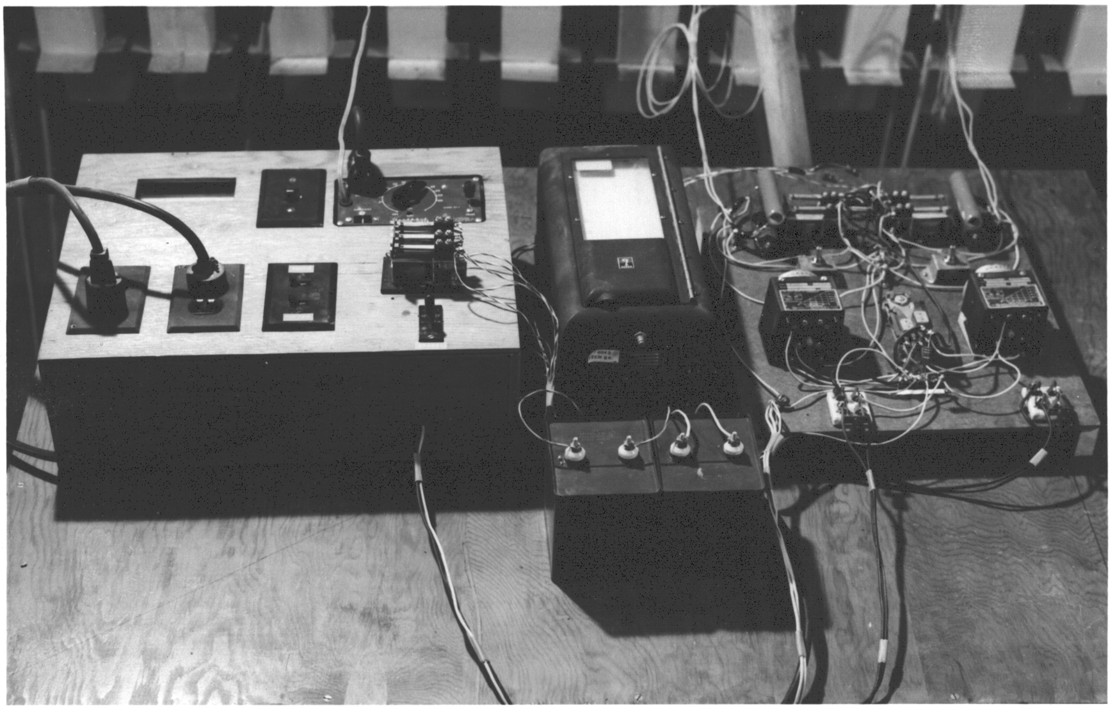


Figure 13 - Control Panels for Remote and Automatic Control System

Table 2 - Basic-Distributor-Characteristics Testing Schedule

Auger Speed	Nominal Hopper Feeding Rate		
	25 lbs/min.	54 lbs/min.	76 lbs/min.
100 rpm	12, 1, 27	13, 16, 18	-- -- --
200 rpm	2, 8, 24	3, 9, 11	33, 26, 31
300 rpm	5, 23, 20	6, 10, 32	7, 15, 19
400 rpm	4, 14, 28	21, 22, 30	17, 29, 25

discharge based on previous calibration of the feeder. Next, the auger-drive was adjusted to give the particular speed designated for the test. Using the remote-control switch, the slide position was adjusted so that the end discharge was approximately twice the amount from other discharge openings. After equilibrium was reached, following this adjustment, samples were collected with the collector unit over a 20-second period. The auger speed, slide position, discharge weight from each opening, and wattmeter reading were recorded after each test run. The three variables, flow level, slide position, and auger speed, were studied to provide the information for basic characteristics of the experimental boom distributor.

Supplemental tests were used to investigate the influence of boom inclination on performance. Inclinations of plus and minus 10 degrees were studied. The testing arrangement for a downward or minus inclination is shown in Figure 14. The specific conditions for these tests were auger speed, 200 rpm, and feeder rate, nominally 25 pounds per minute. These were used in the previous level tests, to simplify comparison.

Granular phosphate was used for the tests. Fertilizer was used only once, and not recycled through the distributor. Physical properties of the phosphate were determined from composite samples of four subsamples; one subsample was drawn from each 200 pounds used. Particle size distributions and other physical properties are shown in Table 7, Appendix III.

Figure 14 - Test Arrangement With Boom Inclined Downward

Particle segregation caused by the distributor was tested using dry-blends composed of ingredients with dissimilar physical properties. Two kinds of blended material were used. They were granular phosphate-granular potash and granular phosphate pesticide. Both materials were mixed in a concrete mixer. The ratio for phosphate-potash combination was one to one by weight for phosphate-pesticide, two to one. The highest auger speed of the previous tests, 400 rpm, was employed to provide conditions conducive to maximum segregation. U. S. Sieves No. 12 and No. 14 were used to separate fine and large particles of each sample from the discharge openings and indicate the degree of segregation caused by the distributor.

Tests With Automatic Control

To investigate the performance of the control system, steady-state and dynamic tests were designed. For the steady-state tests, the control slide was started manually to a position near the correct setting for a certain fertilizer feeding rate as determined from the basic tests. The automatic control system was then placed in operation. The output signals of the control system were shown on the recorder. When the actuator changed its direction of movement during the data recording period, the slide position was also recorded. Continuous filling of the fertilizer feeder was required to complete 4 to 5 cycles of control slide movement for each test. A 20-second sample was taken during the testing process in order to check the feeding rate supplied to the distributor. Tests with three auger speeds and with different delay-time combinations were scheduled as shown in Table 3.

Table 3 - Testing Schedule for the Automatic Control System

Test No.	Nominal Feeding Rate lbs per min.	Auger Speed rpm	Signal On-Time sec.	Signal Off-Time sec.	Slide Movement for Each Period, inches
1	25	100	0.25	3	1/16
2	25	200	0.25	3	1/16
3	25	300	0.25	3	1/16
4	25	200	0.20	4	3/64
5*	25	200	0.20	4	3/64

*Dynamic test starting with a slide setting of 3/4 inches or a slide error of 3/4 - 1/2 = 1/4 inches.

For dynamic testing, the control slide was set to a position 1/4-inch greater than the correct position found from the earlier basic tests. This dynamic test would indicate the ability of the system to compensate for this error. Fertilizer was recycled through the distributor because of the large quantity needed.

EXPERIMENTAL RESULTS

The overall action of the experimental boom distributor and its automatic control system coincided closely with expected performance. The fertilizer carried by the auger filled each compartment sequentially. By constantly maintaining a portion of the head over each opening with the compartmented construction, distribution patterns were relatively uniform. Though the performance of the control system would not be acceptable for commercial use, the design was of value in examining the feasibility of the principle.

All the fertilizer and pesticide materials used were sampled and analyzed in groups according to the test number. Their bulk densities, moisture contents, and particle sieve analysis are listed in Table 7, Appendix III.

Basic Distributor Characteristics

The basic characteristics of the experimental distributor were determined primarily during level operation. Results of supplementary tests with inclined operation and with blended materials are presented individually.

Level operation

The weights of the samples collected along the length of the boom are given in Table 5, Appendix I. From these data, the flow level which corresponded to each compartment could be calculated with the following formula:

$$X_i = \frac{(Y_t - Y_s) \cdot 3}{P \cdot R}$$

Where:

X_i = flow level at the i-th compartment, lbs/pitch

Y_t = total discharge from the boom, lbs/20 sec.

Y_s = summation of the discharge from compartments 1 through i, lbs/20 sec.

R = auger speed, rpm

P = number of pitch lengths per auger revolution, pitches/rev.

Lines of regression of the flow level versus discharge were plotted in Figures 15, 16, 17, and 18 for each auger speed. The coefficient of variation for each test was also calculated to evaluate the uniformity of distribution. The weights of samples from compartments 1 and 18 were consistently higher than from adjacent compartments. This was due to inaccuracy in the construction. The end discharge fluctuated from test to test because of small variations in feeding rate and auger speed. In order to analyze more accurately the influence of flow level, discharge from compartments 1 and 18 and the end discharge were omitted in calculating the parameters for the regression lines. All regression values are shown in Table 6, Appendix II.

The coefficient of variation denotes the degree of nonuniformity of discharge rates. Values varied from 4.63 percent to 12.22 percent. These values were lower than those observed by Cunningham (14) for commercial booms, and indicates improved uniformity with the experimental distributor. Test for independence showed that the influence of flow level on discharge rate was significant.

A similar distribution pattern was observed for every test. This was caused by inaccurate construction of the boom, auger, and control

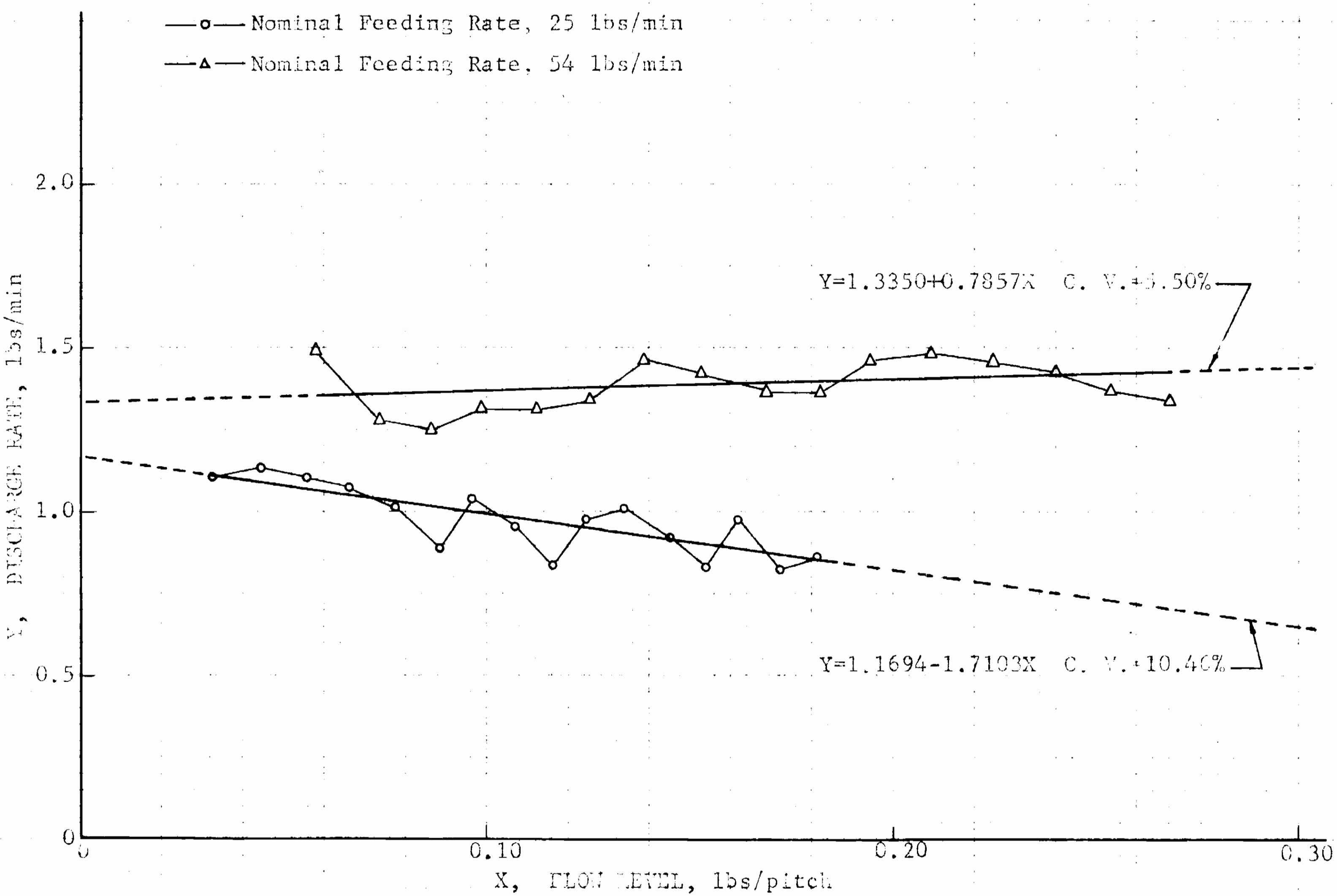


Figure 15 Influence of Flow Level on Discharge Rate, 100 rpm.

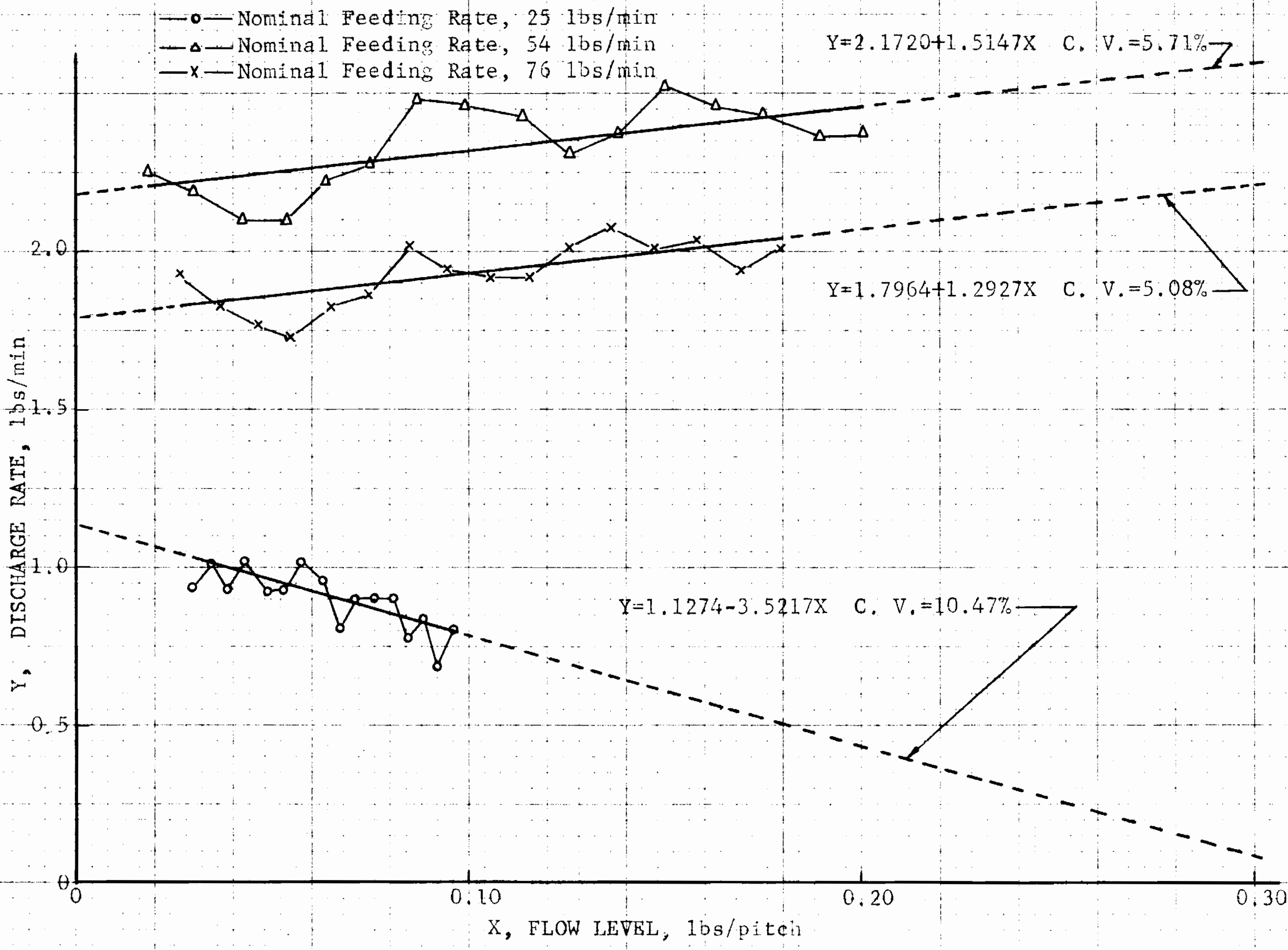


Figure 16 Influence of Flow Level on Discharge Rate, 200 rpm.

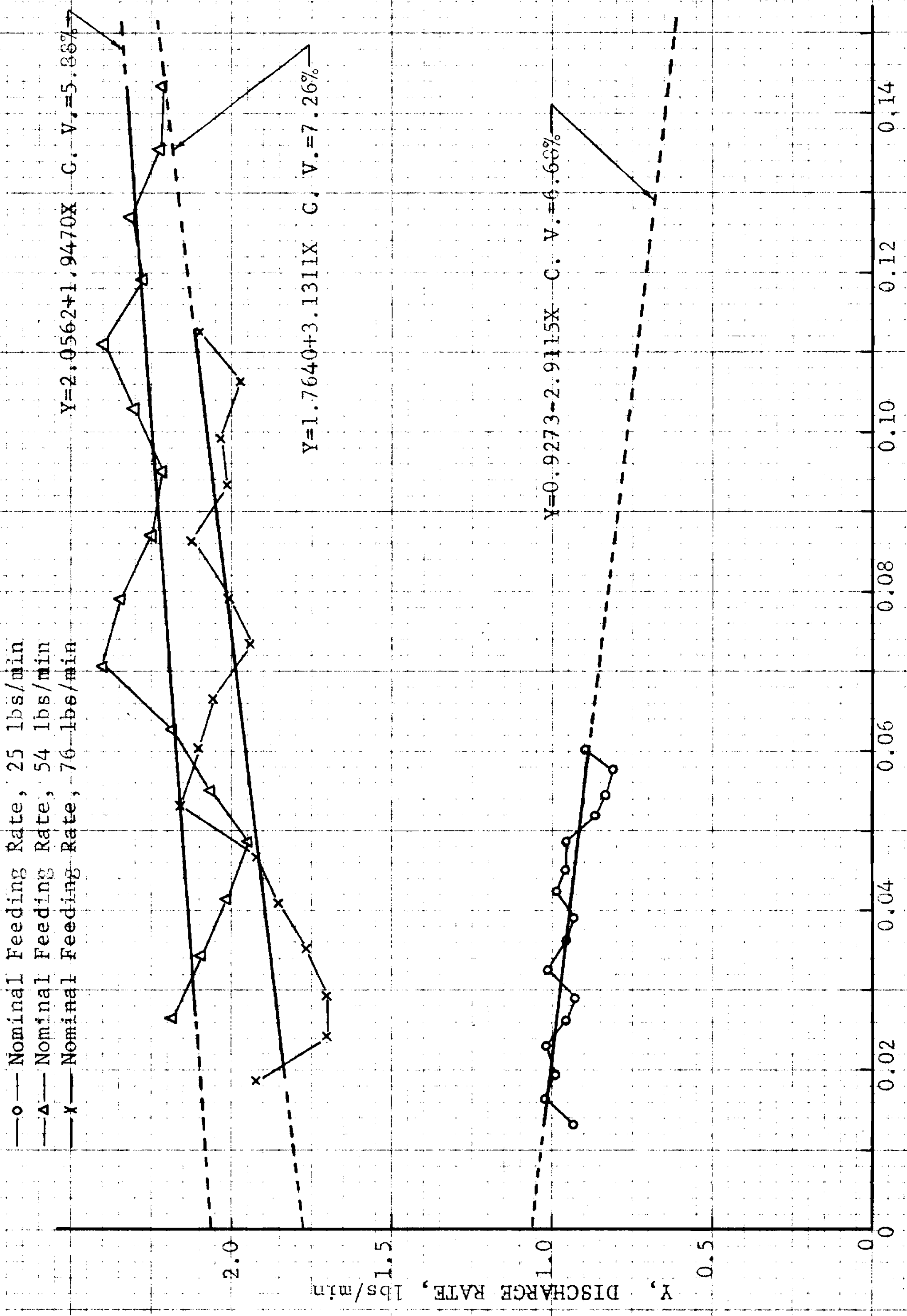


Figure 17 Influence of Flow Level on Discharge Rate, 300 rpm.

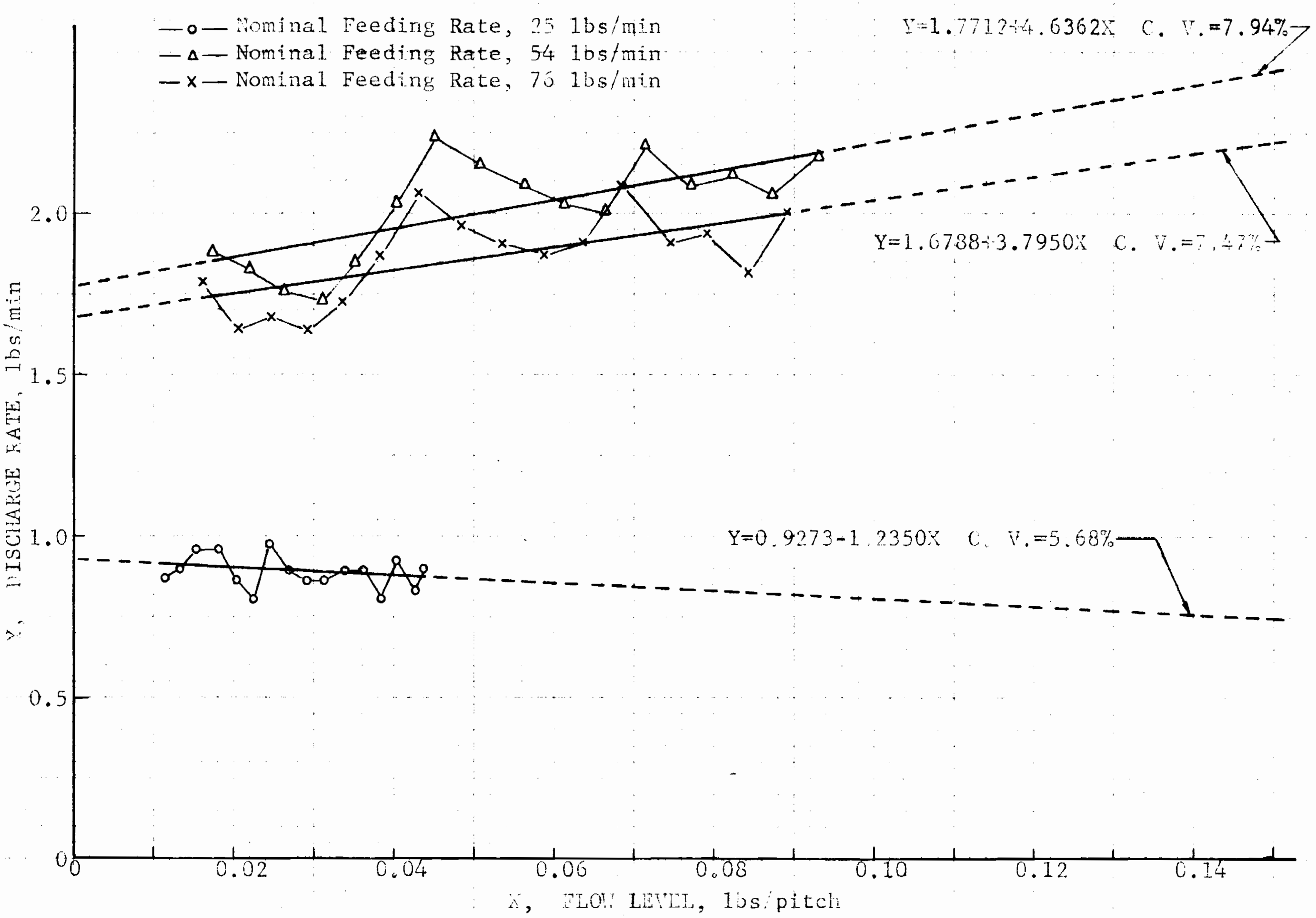


Figure 18 Influence of Flow Level on Discharge Rate, 400 rpm.

slide. Table 9, Appendix III shows the difference among discharge opening sizes for the compartments. Improved distribution should be possible through the use of precise manufacturing techniques.

Particular trends in the regression of flow level on discharge rate were noted. The slope of the regression line was influenced by the discharge opening size. When the feeding rate was low and discharge openings small, the slope was negative. When the rate was increased, slope was slightly positive. The negative slope was believed to be caused by bridging effects when the opening size was small. This effect was more pronounced with large fertilizer heads that accompanied high flow level and resulted in the negative slope of the regression. With high feeding rate and large opening size, increased flow levels caused greater discharge rates and positive regression coefficients.

After a careful study of the basic data, a set of curves showing the influence of opening size on discharge rate was constructed and are presented in Figure 19. From these curves, the mean discharge rate appeared to be influenced by the auger speed only within a certain range of opening sizes. When the opening sizes were beyond this range, the effect of the auger speed was small. The largest influence occurred between 3/4-inches and 1-3/8-inches and with an auger speed of 200 rpm. to 300 rpm. The effect of auger speed between 300 rpm and 400 rpm was small and similar for all opening sizes. Since the discharge rate was affected more by slide position than by auger speed, a separate auger-driving system would simplify the controlling factors in operation.

Another set of relationships are shown in Figure 20. These were obtained by crossplotting from the basic curves of Figure 19. The

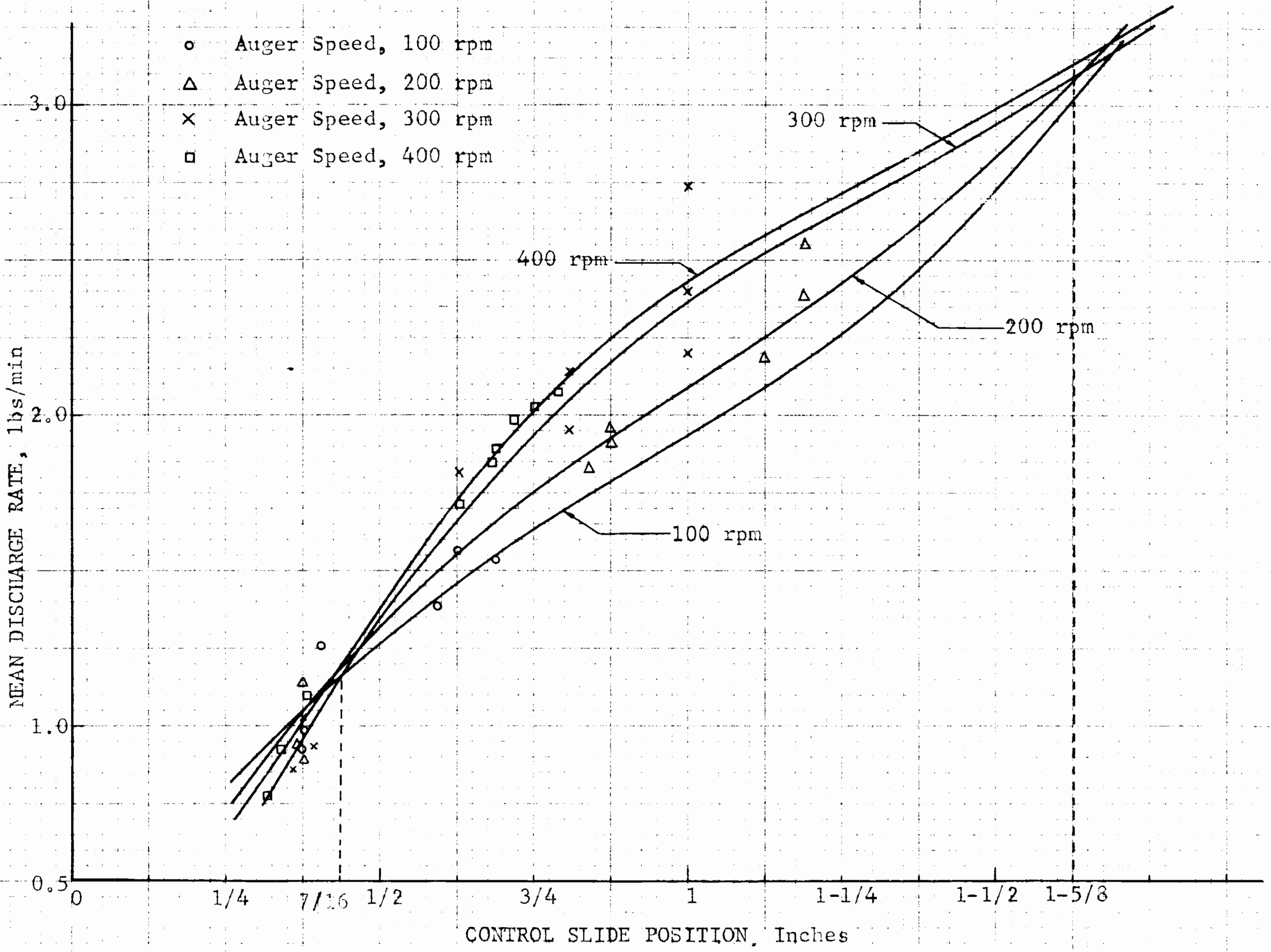


Figure 19 Influence of Slide Position on Mean Discharge Rate.

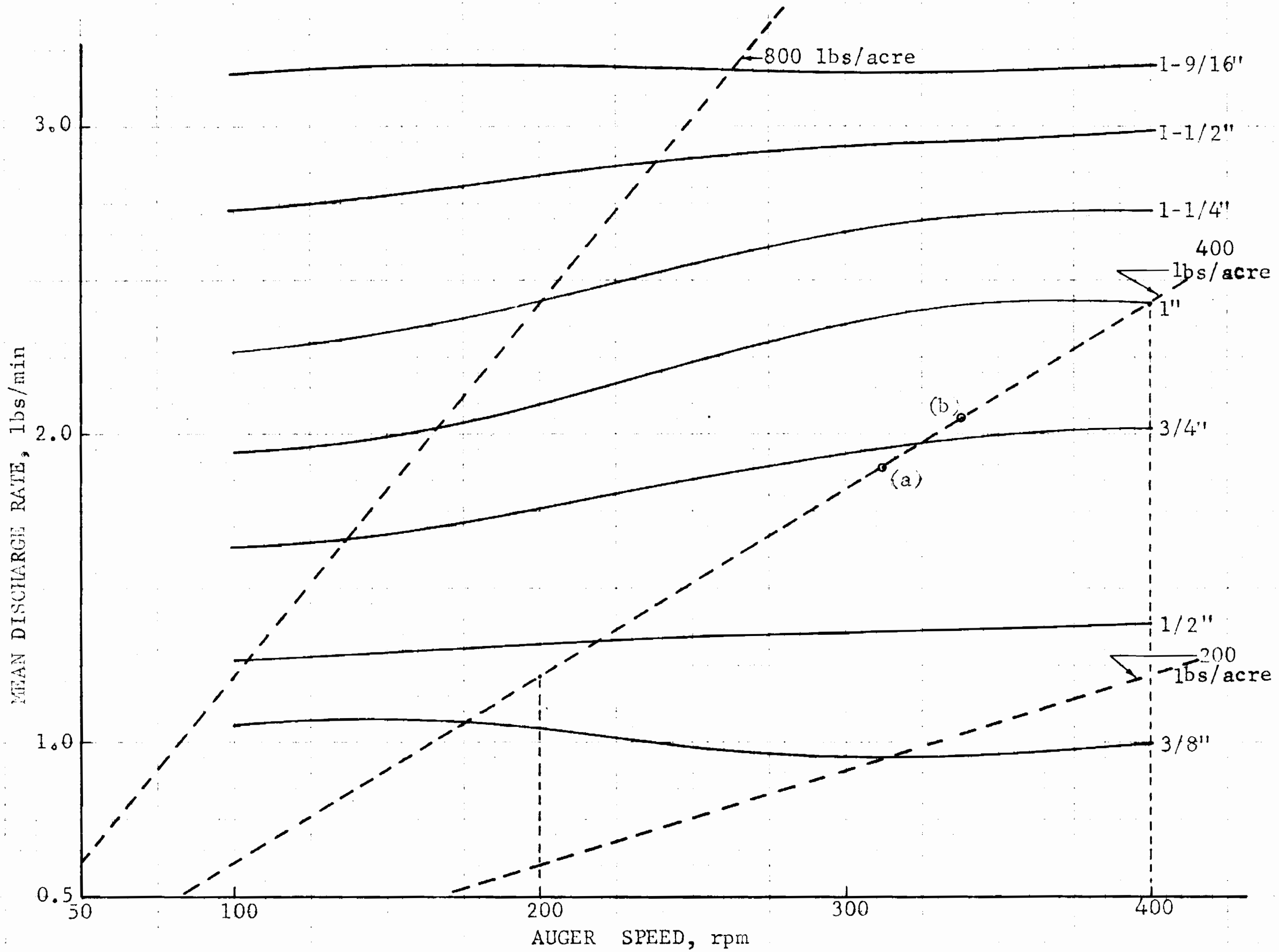


Figure 20 Influence of Auger Speed on Mean Discharge Rate.

result of crossplotting shows the relationship between mean discharge rate and auger speed for each opening size. On the same chart, ideal feeder curves were plotted by assuming that the feeding rate from the hopper was directly proportional to the ground speed of the distributor. The auger,in this case, was assumed to be ground driven with a speed of 400 rpm at 6 miles per hour of ground speed.

The intersections of these two sets of curves shown in Figure 20 indicate the different combinations of the mean discharge rate, auger speed, and control slide position that provide certain fertilizer field application rates. For instance, a 400 pound-per-acre application rate is obtained at 200 rpm, with a 7/16-inch opening slide position while at 400 rpm, a one inch opening is required.

From this chart, the range of control slide movement needed to compensate for changes in operating speed, or other conditions, could be found. This is important in automatic control system design. For example, suppose a change of ground speed caused a 25 rpm change in auger speed, as shown by point (a) and point (b) in Figure 20. The control slide should move between 23/32 inches and 25/32 inches in order to compensate for the variation in speed and give a constant rate of 400 pounds per acre.

Inclined operation

A 200 rpm auger speed and a 25 pound per minute nominal feeding rate were used for both upward and downward inclined tests. Samples from each discharge opening were collected and weighed. Weights are given in Table 5, Appendix I. Based on the data obtained, two lines of regression for each inclined-condition were plotted as shown in Figure 21. It appeared that the slope of the regression lines and the shape of the distribution patterns were quite similar to those with level operation. The small coefficients of variation of the test showed that inclined operation did not adversely affect uniformity of distribution.

Segregation of dry blends

The sample weights from tests with blended material are given in Table 8, Appendix III. Sieve analysis was employed to test for particle segregation effects. Figure 22 illustrates the particle-size distribution along the length of the boom based on the percentage of material retained on a particular sieve. The relatively uniform percentage distribution of the tests for each blended material reflected a small particle-size-segregation effect. A comparison of the coefficients of variation determined from these tests and those determined by Cunningham (2) for a commercial boom-type distributor is shown in Table 4.

Automatic Control System Stability

The strip chart records for tests with the control system in operation provided data for the position diagram for the control slide shown in Figure 23. These curves expressed the movement of the control slide with respect to the operating time of the automatic control system. The actual shape of the curve was a stepped-curve because of the periodic operation of the actuator by the controller. For simplification, straight lines were used to construct the curves.

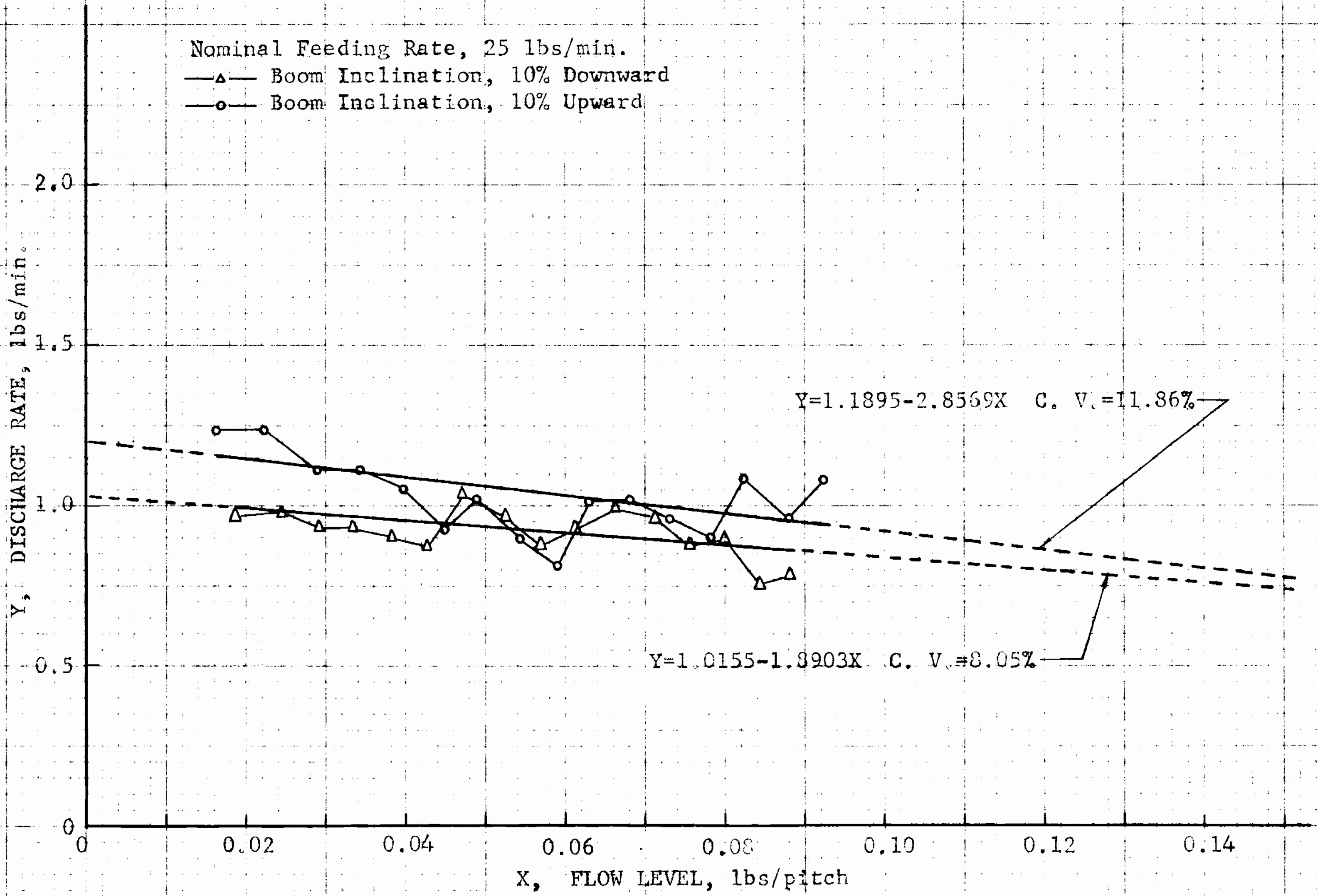


Figure 21 Influence of Flow Level on Discharge Rate with Inclined Boom, 200 rpm.

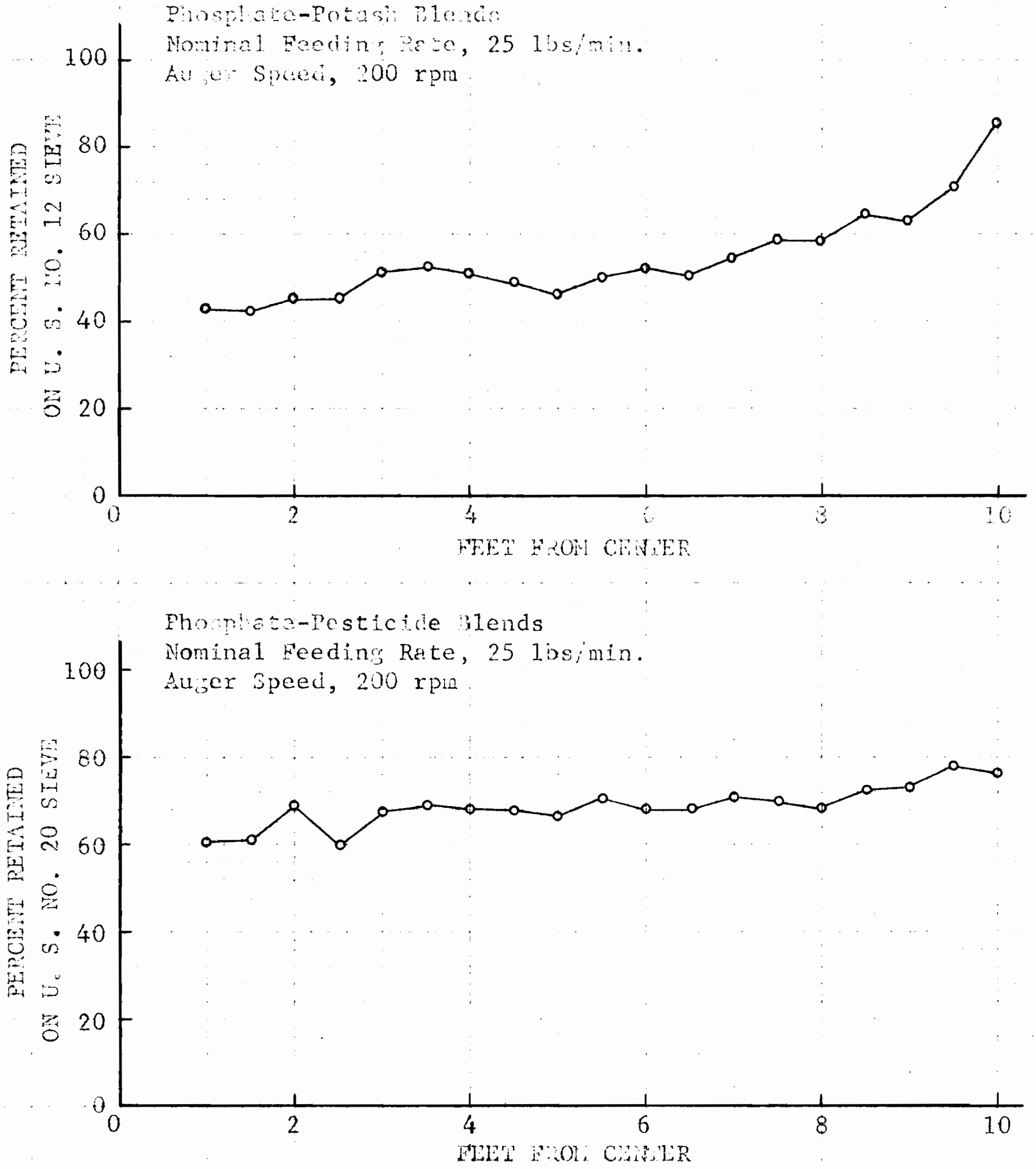


Figure 22 Segregation of Dry Blends.

Table 4 - Coefficients of Variation for Distribution of Blended Materials[a]

Distributor	Materials Used	Total Pattern	Phosphate	Potash	Pesticide
Experimental Boom	Phosphate[b]	6.00	21.00	9.43	----
Experimental Boom	Phosphate and Pesticide	4.86	5.70	----	13.72
Commercial Boom	Phosphate[c] and Potash	18.80	27.10	12.90	----

[a] Values expressed as percentages.
[b] Segregation analysis based on an estimation from the result of sieve analysis.
[c] Segregation analysis based on chemical analysis.

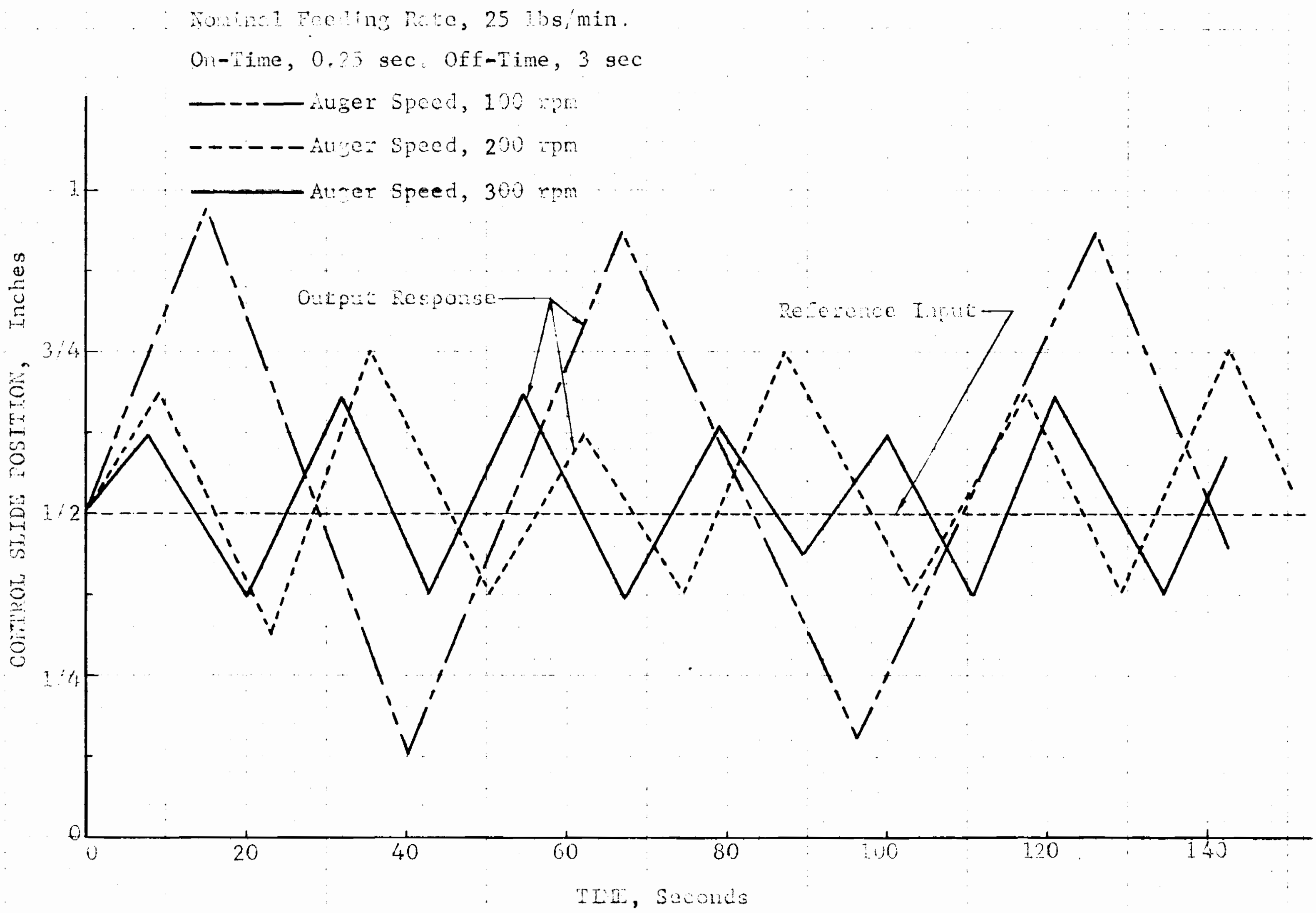


Figure 23 Oscillation Curves for Steady-State Response.

Three saw-tooth oscillation curves, shown in Figure 23, illustrated the response of the control system for three different auger speeds and with no initial error in opening size. The large amplitude of the curves indicates overshoot in the controlling action of this system. The overshoot was reduced by increasing the auger speed, but the response still did not coincide exactly with the reference input corresponding to a 1/2-inch-opening size. The reason for the oscillation appeared to be inadequate design of the error detector components.

Two curves in Figure 24 show the effect of changing the delay-time of the controller. It appeared that increased off-time and decreased on-time caused the response curve amplitude to be reduced but elongated its period.

The response curve plotted in Figure 25, shows the characteristic of the control system in compensating for a control-slide-error setting of plus 1/4 inches. The response curve dropped lower than its normal position because of the error-setting, then, it recovered and oscillated as in the tests with steady conditions after only two complete cycles. This showed that the control system used for the experimental distributor had an error-compensating characteristic, but that an undesirable oscillation persisted.

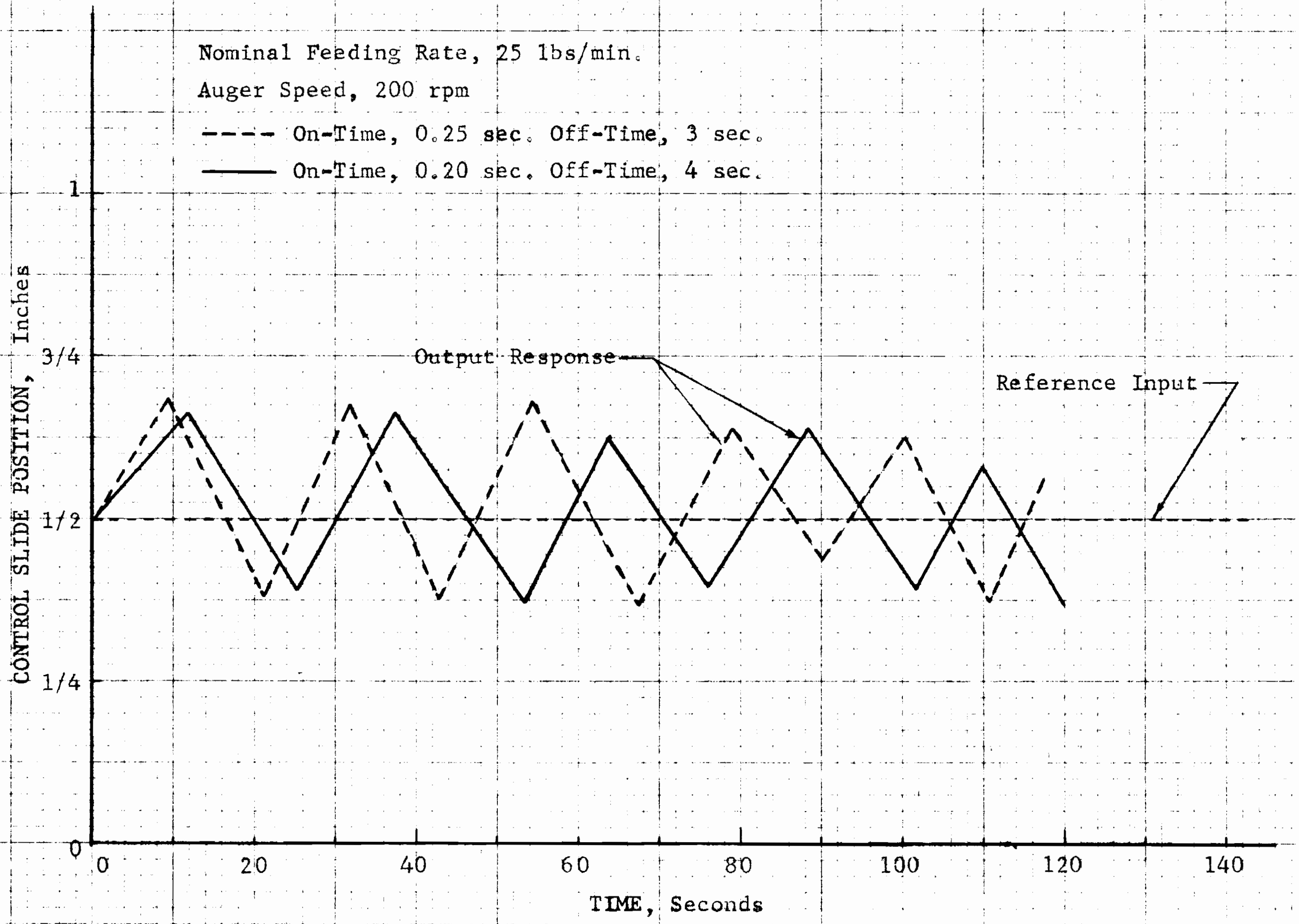


Figure 24 Influence of Delay Time on Steady-State Oscillation.

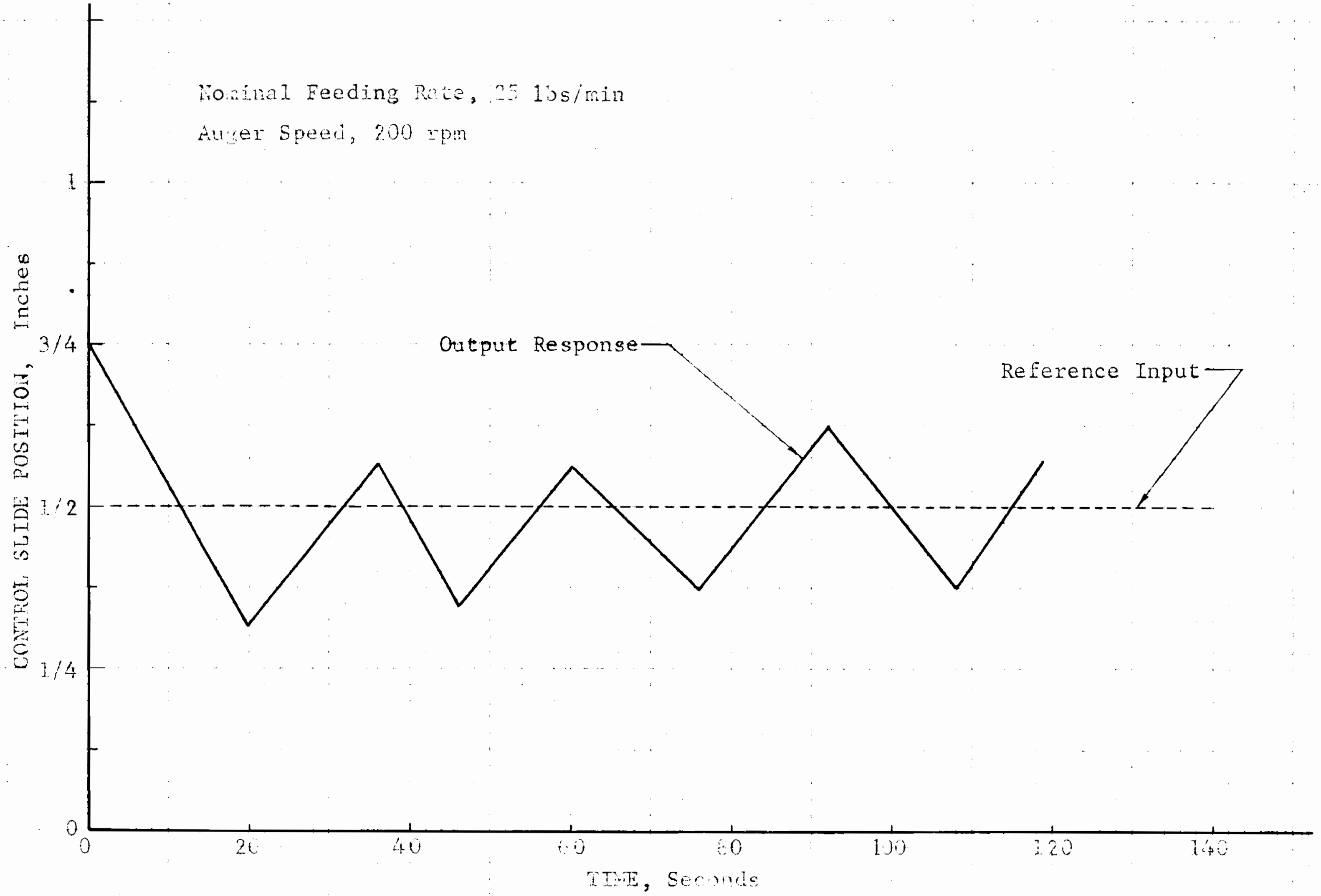


Figure 25 Error Compensation Test with a Slide Position Error of 1/4 Inches.

SUMMARY AND CONCLUSIONS

Central-hopper spreaders provide the most economical means for applying dry fertilizer on many farms. Previous investigations of both the centrifugal and boom-type distributors used on these spreaders show that design improvements are needed for more convenient operation and more uniform distribution.

The objective of this study was to investigate the application of remote and automatic control principles to an experimental boom-type distributor. While many farm machines require human observation and adjustment to compensate for operating variables and maintain satisfactory performance, examples of successful application of automatic control principles are numerous. For example, automatic draft control on most farm tractors adjusts implement depth to provide constant draft, and automatic combine-header controls are available to maintain a constant preset cutting height.

The control system developed for the experimental distributor consisted of a flow-level detector at the outboard end of the distributor boom, and a relay-type controller and linear actuator to control the size of discharge openings along the boom. The boom consisted of an auger conveyor with a U-shaped cross section. Eighteen discharge openings were located on 6-inch centers along its length. Small compartments at the location of each opening and agitators on the auger flighting were designed to provide uniform distribution.

Tests to determine basic performance characteristics of the experimental distributor with manual-remote control were conducted on a laboratory test stand. The following conclusions were drawn from the test results:

1. Coefficients of variation for discharge patterns along the length of the boom were small for all combinations of auger speed, discharge opening size, and boom inclination. The coefficient values ranged from 4.63 to 12.22 percent.
2. Discharge rate was not greatly influenced by fertilizer flow level in the boom. Regression coefficients ranged from plus 1.8295 to minus 1.7103. With small discharge openings, greater discharge occurred at low flow levels. This appeared to be due to the tendency of fertilizer to bridge when discharge openings were small.
3. Auger speed had little influence on discharge rate, particularly between 300 and 400 rpm. With opening sizes of 7/16 and 1-5/8 inches, the entire speed range tested of 100 to 400 rpm, had negligible influence.
4. Boom inclinations to simulate side slopes of plus and minus 10 percent, had little influence on uniformity of distribution. Coefficients of variation in these tests ranged from 6.74 to 11.86.
5. Action of the experimental distributor caused minor segregation of dry blended fertilizer and fertilizer-pesticide blends. Based on a sieve analysis, the variation of the particle distribution was less than 20 percent of the discharge from each opening in the test of fertilizer-pesticide blends.

Tests using the automatic control system were also conducted on the laboratory test stand. Conclusions from results of these tests are:

1. The control system designed for the experimental distributor was marginally stable. Slow oscillations of the control slide occurred after initial correction of a position error. The oscillation frequency was about three cycles per minute and the amplitude of oscillation was close to 1/4 inches of the control slide displacement.
2. Increased auger speed and longer off-time of the controller reduced the amplitude of oscillation. Longer off-time also decreased the frequency.

A theoretical model of the experimental distributor and control system was analysed mathematically. Integral control involving constant velocity control slide correction was assumed. This mode of control corresponds exactly to the one employed in the experimental system when on and off times for the controller are adjusted to values that are small compared with time required for correction. The following conclusions were drawn from the results of the analysis:

1. Time required to correct an error in flow level is proportional to the square root of the error, and inversely proportional to the square root of the product of auger pitch and actuator speed.
2. The change in discharge rate from the distributor during correction of a flow level error is proportional to the square root of the product of the error, auger pitch, and actuator speed.
3. Time required to correct a flow level error increases with increased compartment capacity.

RECOMMENDATIONS

Since a relay or pulse type of feedback control system is nonlinear and is very complicated to analyse mathematically, the application of simulation techniques are apropos. By using an appropriate simulation, the effect of the performance of every part in the control system could be easily investigated.

A proposed analog computer simulation diagram is shown in Figure 26. It was developed from the basic block diagram of the feedback control system.

To apply simulation techniques, two characteristic relationships are needed. They are:

Relationship 1:	Relationship between the fertilizer level change in compartment 17 and the discharge opening size of this compartment.
Relationship 2:	Influence of the control slide change to the flow level change in compartment 17.

To simplify the derivation of the above relationships, the following assumptions may be made:

1. Assume that compartments 17 and 18 are combined together as a single but larger compartment and the micro-switches MS1 and MS2 are mounted at different levels.
2. Assume that the feeding rate and the auger speed are maintained constant with respect to time.
3. Assume the relays used in the system are ideal and without dead zone and hysteresis effect.
4. Assume that no other factors influence the system operation except the main controlling factors. These are auger speed, fertilizer feeding rate, and discharge opening size.

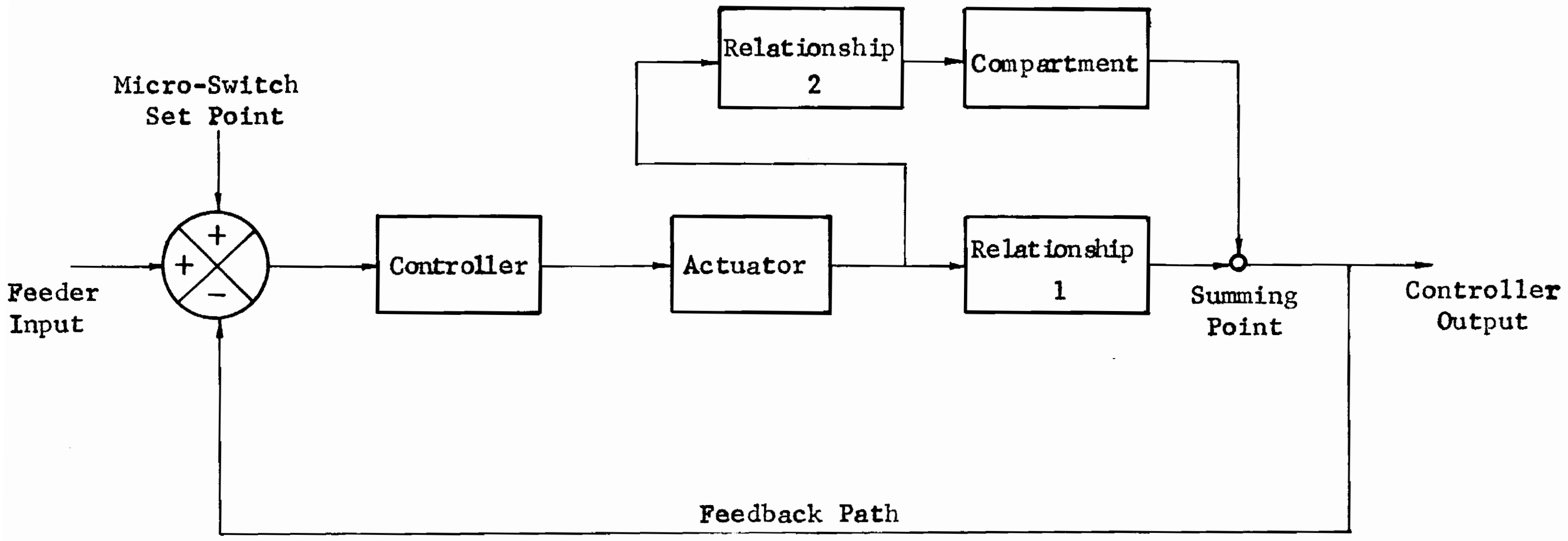


Figure 26 Analog Computer Simulation Diagram for the Control System.

Possible analog computer components to simulate the elements shown in Figure 26 are the following:

Error Dector: Simulated with two potentiometers and a diode. The potentiometers represent the set point of the micro-switches and the fertilizer feeding rate.

Controller: Simulated with two diodes, a relay, and a simple time-constant circuit.

Actuator: Simulated by a pulse-wave voltage generator and two relays.

Compartment: Simulated by a simple time-constant circuit.

Relationship 1: Generated by an arbitrary function generator.

Relationship 2: Also generated by an arbitrary function generator.

Summing Point: Simulated with a summing amplifier.

Appropriate time and magnitude scaling would be very important and proper simplification may be used when any transfer function turns out to be non-linear. A strip recorder or an oscilloscope could be used to investigate characteristic performance of any point in the control system.

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ACKNOWLEDGEMENTS

The author wishes to express his deepest appreciation to Dr. F. M. Cunningham for his guidance, assistance, encouragement, and inspiration liberally given throughout the research and writing of this thesis. He wishes, also, to thank the remaining faculty members of the Agricultural Engineering Department for their many services and helpful suggestions.

Appreciation is also expressed to Even-Spread Mfg. Co., Owensville, Ohio, for their help in the construction of the experimental boom and auger.

The author is indebted to Southern States Cooperative, Richmond, Virginia, for supporting this research project.

Finally, the author extends his sincere thanks to Mrs. Marion Price for her care and interest in typing this thesis.

VITA

Edmund Yee-Su Chao, son of Woo-Kuo Chao and Mr. Chiang-Tau Chao, was born on January 24, 1938, at Chungking, China. He is the youngest son in a family of four girls and five boys. He attended elementary schools at Chungking and Nanking, China. He finished his secondary and high school education at Taipei, Taiwan, China. After four years attendance at the National Taiwan University, he was awarded the Bachelor of Science Degree in Agricultural Engineering in June, 1960.

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He enrolled in the Virginia Polytechnic Institute, Department of Agricultural Engineering in September, 1962. His major field is Farm Power and Machinery. From February, 1963, he became a research assistant in the Department. He married the former Jane Shen of Chungking, China, on February 8, 1964, in a service at the Methodist Church in Blacksburg, Virginia.

His major professor is Dr. F. M. Cunningham and his course advisor is Prof. U. F. Earp.

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Edmund Y. S. Chao

APPENDIX I

Table 5 - Data From Basic-Distributor-Characteristic Tests

Discharge Opening	Discharge Rate, pounds per 20 seconds									
	Test Number									
	12	1	27	13	16	18	2	8	24	3
1	0.34	0.25	0.31	0.60	0.61	0.54	0.40	0.30	0.31	0.93
2	0.29	0.43	0.27	0.52	0.52	0.45	0.32	0.27	0.26	0.87
3	0.28	0.43	0.24	0.52	0.52	0.46	0.29	0.32	0.21	0.86
4	0.33	0.48	0.28	0.56	0.55	0.48	0.34	0.28	0.28	0.89
5	0.28	0.40	0.26	0.55	0.56	0.49	0.32	0.26	0.26	0.92
6	0.31	0.45	0.31	0.57	0.58	0.50	0.36	0.30	0.30	0.93
7	0.34	0.47	0.30	0.55	0.55	0.49	0.37	0.30	0.31	0.89
8	0.33	0.43	0.30	0.51	0.53	0.46	0.37	0.30	0.29	0.87
9	0.28	0.37	0.26	0.52	0.51	0.46	0.37	0.27	0.28	0.87
10	0.32	0.44	0.28	0.52	0.53	0.48	0.40	0.32	0.31	0.87
11	0.35	0.46	0.35	0.53	0.55	0.49	0.44	0.34	0.33	0.88
12	0.30	0.40	0.32	0.46	0.50	0.45	0.39	0.31	0.30	0.81
13	0.34	0.42	0.31	0.47	0.48	0.44	0.42	0.31	0.31	0.76
14	0.36	0.39	0.33	0.46	0.47	0.44	0.44	0.34	0.34	0.77
15	0.37	0.37	0.34	0.46	0.47	0.42	0.42	0.32	0.32	0.77
16	0.38	0.37	0.34	0.46	0.46	0.43	0.42	0.34	0.33	0.83
17	0.37	0.42	0.33	0.55	0.54	0.50	0.43	0.32	0.33	0.82
18	0.45	0.48	0.40	0.64	0.64	0.60	0.52	0.38	0.39	0.94
End	0.67	2.60	0.64	1.33	1.45	1.36	1.37	1.62	1.12	2.08
Total	6.69	10.33	6.17	10.78	11.02	9.94	8.39	7.11	6.58	17.56
Mean Feeding Rate, lbs/min	20.07	30.99	18.51	32.34	33.06	29.82	25.17	21.33	19.74	52.68
Auger Speed, rpm	100.0	100.5	97.0	100.0	94.4	99.5	206.6	204.0	204.0	196.5
Slide Position inches	3/8	13/32	3/8	11/16	5/8	19/32	3/8	3/8	3/8	1-3/16

Table 5 (Continued) - Data From Basic Distributor-Characteristic Tests

Discharge Opening	Discharge Rate, pounds per 20 seconds									
	Test Number									
	9	11	4	14	28	5	23	20	6	10
1	0.87	0.77	0.44	0.31	0.26	0.37	0.32	0.31	1.00	0.82
2	0.79	0.70	0.38	0.30	0.25	0.35	0.30	0.28	0.96	0.74
3	0.79	0.70	0.44	0.28	0.25	0.31	0.27	0.27	0.93	0.74
4	0.81	0.74	0.44	0.31	0.26	0.36	0.28	0.29	0.92	0.77
5	0.82	0.74	0.37	0.27	0.22	0.31	0.29	0.30	0.94	0.76
6	0.84	0.76	0.40	0.30	0.26	0.34	0.32	0.27	0.97	0.80
7	0.79	0.72	0.39	0.30	0.25	0.34	0.32	0.31	0.89	0.77
8	0.77	0.70	0.39	0.29	0.25	0.35	0.33	0.31	0.89	0.74
9	0.81	0.73	0.37	0.29	0.25	0.32	0.31	0.29	0.94	0.75
10	0.82	0.74	0.40	0.30	0.26	0.35	0.32	0.31	0.96	0.78
11	0.83	0.74	0.42	0.33	0.28	0.38	0.34	0.34	0.97	0.80
12	0.76	0.69	0.37	0.27	0.25	0.32	0.31	0.30	0.90	0.73
13	0.74	0.67	0.38	0.29	0.25	0.35	0.32	0.31	0.87	0.69
14	0.70	0.63	0.37	0.32	0.28	0.36	0.34	0.32	0.89	0.65
15	0.70	0.65	0.35	0.32	0.26	0.35	0.33	0.31	0.80	0.67
16	0.73	0.70	0.36	0.30	0.28	0.34	0.34	0.33	0.81	0.70
17	0.75	0.73	0.36	0.29	0.26	0.33	0.31	0.32	0.84	0.73
18	0.83	0.85	0.38	0.36	0.30	0.40	0.37	0.38	0.99	0.86
End	0.32	1.64	0.54	1.13	0.53	1.32	0.98	1.01	1.20	1.68
Total	14.47	14.60	7.55	6.56	5.20	7.55	6.70	6.56	17.67	15.18
Mean Feeding Rate, lbs/min.	43.41	43.80	22.65	19.68	15.60	22.65	20.10	19.68	53.01	45.54
Auger Speed, rpm	191.3	200.3	405.6	395.4	401.0	296.0	302.3	313.7	294.6	284.4
Slide Position, inches	1-3/16	1-1/8	3/8	11/32	5/16	3/8	3/8	3/8	1	1

Table 5 (Continued) - Data From Basic Distributor-Characteristic Tests

Discharge Opening	Discharge Rate, pounds per 20 seconds								
	Test Number								
	32	7	15	19	33	26	31	21	22
1	0.80	0.86	0.75	0.63	0.72	0.71	0.72	0.73	0.76
2	0.75	0.82	0.70	0.59	0.67	0.66	0.67	0.70	0.74
3	0.72	0.74	0.66	0.55	0.65	0.65	0.64	0.65	0.68
4	0.73	0.77	0.68	0.58	0.68	0.68	0.68	0.68	0.72
5	0.76	0.77	0.67	0.58	0.67	0.66	0.66	0.68	0.71
6	0.78	0.82	0.71	0.60	0.69	0.68	0.71	0.71	0.76
7	0.72	0.75	0.67	0.57	0.67	0.65	0.67	0.65	0.67
8	0.71	0.75	0.65	0.55	0.64	0.64	0.65	0.66	0.68
9	0.75	0.80	0.69	0.56	0.64	0.64	0.66	0.67	0.71
10	0.76	0.80	0.70	0.58	0.65	0.65	0.67	0.68	0.72
11	0.79	0.82	0.72	0.61	0.67	0.67	0.69	0.70	0.74
12	0.72	0.73	0.64	0.56	0.62	0.62	0.65	0.63	0.67
13	0.67	0.69	0.62	0.54	0.61	0.60	0.62	0.59	0.62
14	0.64	0.63	0.59	0.53	0.58	0.58	0.59	0.57	0.58
15	0.65	0.60	0.57	0.52	0.59	0.58	0.60	0.57	0.58
16	0.68	0.62	0.57	0.53	0.61	0.59	0.61	0.58	0.59
17	0.71	0.65	0.64	0.57	0.64	0.62	0.65	0.61	0.62
18	0.82	0.78	0.77	0.68	0.75	0.74	0.75	0.73	0.76
End	1.03	1.06	1.13	2.58	0.92	0.89	0.58	2.48	2.40
Total	14.19	14.46	13.13	12.91	12.67	12.48	12.47	14.27	14.71
Mean Feeding Rate, lbs/min.	42.57	43.38	39.39	38.73	38.01	37.44	37.41	42.81	44.13
Auger Speed, rpm	290.8	311.0	311.2	285.7	188.7	216.8	208.1	392.8	400.5
Slide Position, inches	1	13/16	13/16	5/8	7/8	27/32	7/8	23/32	3/4

Table 5 (Continued) - Data From Basic Distributor-Characteristic Tests

Discharge Opening	Discharge Rate, pounds per 20 seconds									
	Test Number									
	30	17	29	25	34a/	35a/	36a/	37b/	38b/	39b/
1	0.76	0.72	0.65	0.70	0.77	0.67	0.46	0.36	0.31	0.36
2	0.73	0.66	0.61	0.67	0.47	0.50	0.36	0.28	0.26	0.32
3	0.69	0.62	0.57	0.61	0.45	0.39	0.32	0.29	0.25	0.30
4	0.71	0.65	0.60	0.65	0.44	0.40	0.36	0.35	0.30	0.35
5	0.70	0.65	0.59	0.64	0.36	0.33	0.30	0.32	0.29	0.32
6	0.74	0.69	0.64	0.70	0.36	0.32	0.32	0.35	0.32	0.36
7	0.67	0.63	0.58	0.64	0.34	0.31	0.34	0.37	0.33	0.38
8	0.68	0.62	0.58	0.63	0.30	0.28	0.34	0.37	0.31	0.36
9	0.70	0.64	0.59	0.64	0.37	0.23	0.27	0.33	0.29	0.31
10	0.72	0.65	0.61	0.66	0.29	0.25	0.30	0.36	0.32	0.35
11	0.75	0.67	0.64	0.69	0.35	0.27	0.34	0.39	0.34	0.38
12	0.68	0.60	0.57	0.63	0.30	0.26	0.31	0.35	0.29	0.34
13	0.62	0.55	0.52	0.58	0.32	0.30	0.35	0.35	0.30	0.35
14	0.58	0.55	0.51	0.55	0.36	0.32	0.37	0.36	0.31	0.35
15	0.59	0.55	0.50	0.56	0.35	0.32	0.37	0.36	0.31	0.36
16	0.61	0.55	0.52	0.55	0.41	0.37	0.42	0.36	0.33	0.36
17	0.63	0.57	0.53	0.60	0.41	0.38	0.42	0.37	0.32	0.36
18	0.76	0.71	0.65	0.70	0.56	0.54	0.52	0.43	0.38	0.42
End	1.54	1.75	1.65	1.35	0.17	0.65	0.59	0.63	1.18	0.28
Total	13.86	13.03	12.11	12.75	7.28	7.09	7.06	6.98	6.50	6.61
Mean Feeding Rate, lbs/min.	41.58	39.09	36.33	38.25	21.84	21.27	21.18	20.74	19.50	19.83
Auger Speed, rpm	398.4	385.2	401.5	382.6	199.0	200.2	201.5	211.7	201.5	201.5
Slide Position, inches	27/32	21/32	5/8	21/32	13/32	3/8	3/8	13/52	3/8	13/32

a/ Inclined-upward tests.
b/ Inclined-downward tests.

APPENDIX II

Table 6 - Statistical Analysis of the Basic-Distributor Tests[a]

Test No.	Line of Regression[b]			Test of Independence	Coefficient of Variation
	$\hat{\beta}$	$\hat{\alpha}$	Equation	t_o	
12	-1.7103	0.9984	Y=0.9984-1.7103X	-4.6161*	10.46
13	0.3109	0.4599	Y=0.4599+0.3109X	2.6347	7.65
1	0.2883	0.3675	Y=0.3675+0.2883X	2.1043	8.34
27	-0.5841	0.3628	Y=0.3628-0.5841X	-5.0791*	11.02
16	0.2619	0.4710	Y=0.4710+0.2619X	2.6454	6.88
18	0.1234	0.4450	Y=0.4450+0.1234X	1.2989	5.50
2	-1.5688	0.4935	Y=0.4935-1.5688X	-8.1284*	12.22
8	-1.1739	0.3758	Y=0.3758-1.1739X	-5.6437*	10.47
24	-1.2794	0.3700	Y=0.3700-1.2794X	-5.2867*	11.32
9	0.5049	0.7240	Y=0.7240+0.5049X	3.2785*	5.71
3	0.5916	0.7674	Y=0.7674+0.5916X	3.7923*	6.13
11	0.2773	0.6954	Y=0.6954+0.2773X	1.6216	4.93
4	1.0000	0.3592	Y=0.3592+1.0000X	6.8493*	7.05
14	-0.4117	0.3091	Y=0.3091-0.4117X	-0.9802	5.68
28	-0.9166	0.2758	Y=0.2758-0.9166X	-3.1606*	5.84
5	-0.2195	0.3507	Y=0.3507-0.2195X	-0.7035	5.65
23	-0.9705	0.3504	Y=0.3504-0.9705X	-4.0269*	6.68
20	-1.0689	0.3417	Y=0.3417-1.0689X	-4.0797*	6.58
6	0.8659	0.8275	Y=0.8275+0.8659X	3.8145*	5.95
10	0.6490	0.6842	Y=0.6842+0.6490X	2.4961	5.88

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a/ Formulas used for statistical calculation are derived by Brownlee (15).
b/ Calculations are based on pounds per 20 seconds.
c/ t-distribution test at $\alpha =$ 1 percent, $t_{\alpha/2} = 2.977$.
*Indicates significant dependence.

Table 6 (Continued) - Statistical Analysis of the Basic-Distributor Tests

Test No.	Line of Regression			Test of Independence	Coefficient of Variation
			Equation	t_o	
32	0.6984	0.6698	Y=0.6698+0.6984X	2.5676	6.11
7	1.6149	0.6246	Y=0.6246+1.6149X	4.0372*	10.23
15	0.4750	0.5267	Y=0.5267+0.4750X	2.3284	4.63
33	0.4309	0.5988	Y=0.5988+0.4309X	3.3146*	5.08
26	0.5665	0.5846	Y=0.5846+0.5665X	3.7516*	5.30
31	0.4352	0.6129	Y=0.6129+0.4352X	2.8821	5.05
21	1.5421	0.5530	Y=0.5530+1.5421X	4.4569*	7.46
22	1.8295	0.5648	Y=0.5648+1.8295X	4.1579*	8.86
30	1.5454	0.5904	Y=0.5904+1.5454X	3.8060*	7.94
17	1.5897	0.5303	Y=0.5303+1.5897X	4.4405*	7.78
29	1.4603	0.5022	Y=0.5022+1.4603X	3.5019*	7.79
25	1.2650	0.5596	Y=0.5596+1.2650X	3.0853*	7.47
34[a]	0.8045	0.3206	Y=0.3206+0.8045X	1.2872	16.61[c]
35[a]	1.1617	0.2654	Y=0.2654+1.1617X	1.4612	20.96[c]
36[a]	-0.9523	0.3965	Y=0.3965-0.9523X	-2.5259	11.86
37[b]	-0.7906	0.3894	Y=0.3894-0.7906X	-3.2804*	8.43
38[b]	-0.6301	0.3385	Y=0.3385-0.6301X	-2.6927	8.05
39[b]	-0.4408	0.3687	Y=0.3687-0.4408X	-2.1192	6.74

[a] Inclined-upward tests.

[b] Inclined-downward tests.

[c] Mechanical fit of control slide to boom was disturbed, data not typical.

APPENDIX III

Table 7 - Physical Properties of Materials Used

Material Specification	Sample No.	Bulk Density lbs/ft^3 Loose Fill	Bulk Density lbs/ft^3 Compact Fill	Moisture Content, percent dry basis	Sieve Analysis, percent retained U. S. Sieve Number 8	12	16	20	30	Pan
60% Phosphate[a]	1	71.16	73.25	3.88	18.75	28.12	34.61	11.94	3.60	2.92
"	2	72.20	74.12	3.38	15.98	27.33	36.80	12.37	3.52	3.88
46% Phosphate[b]	3	63.95	65.33	4.27	10.71	51.63	34.12	3.17	0.19	---
"	4	63.33	65.76	4.95	12.61	53.74	30.62	2.61	0.15	---
"	5	63.73	66.00	4.59	11.72	53.42	31.46	3.17	0.19	---
"	6	62.68	66.45	4.34	11.91	52.45	31.91	3.30	0.29	---
60% Potash[c]	7	70.00	75.00	1.28	36.32	39.88	10.50	6.81	3.09	3.33
10% Pesticide[d]	8	37.20	40.10	10.87	0.00	0.00	0.00	23.60	56.00	20.40

[a] Granular phosphate manufactured by Tennessee Valley Authority.
[b] Granular phosphate manufactured by American Cyanamid Company.
[c] Granular potash manufactured by Tennessee Valley Authority.
[d] Granular pesticide manufactured by Stauffer Chemical Company.

Table 8 - Particle Segregation for Dry Blends

Discharge Opening	Phosphate-Potash Blended Ratio 1:1 by Wt.			Phosphate-Pesticide Blended Ratio 2:1 by Wt.		
	Total Sample,	Percentage Retained		Total Sample,	Percentage Retained	
	lbs/20 sec.	U. S. Sieve 12	Pan	lbs/20 sec.	U. S. Sieve 20	Pan
1	0.39	41.76	58.24	0.43	60.99	39.01
2	0.42	42.73	57.27	0.41	61.45	38.55
3	0.39	44.38	55.62	0.37	68.98	31.02
4	0.41	46.70	53.30	0.40	59.91	40.09
5	0.34	50.97	49.03	0.33	67.82	32.18
6	0.38	51.51	48.49	0.40	69.45	30.55
7	0.38	52.67	47.33	0.38	68.27	31.73
8	0.38	50.27	49.73	0.38	68.18	31.82
9	0.36	49.28	50.72	0.35	66.78	33.22
10	0.38	52.20	47.80	0.37	70.78	29.22
11	0.42	54.95	45.05	0.40	68.46	31.54
12	0.35	55.36	44.64	0.35	68.17	31.83
13	0.35	58.55	41.45	0.37	71.17	28.83
14	0.35	61.99	38.01	0.38	70.06	29.94
15	0.34	61.25	38.75	0.38	69.22	30.78
16	0.36	67.23	32.77	0.39	72.75	27.25
17	0.32	67.78	32.22	0.34	73.37	26.63
18	0.38	76.23	23.77	0.43	78.72	21.28
End	0.70	87.28	12.72	0.75	76.30	23.70
Coefficient of Variation[a/] (Percent)	6.00	9.43	21.00	4.86	5.70	13.72

[a/] All coefficients of variation based on samples from compartments 2 through 17.

Table 9 - Difference Between Actual Opening Sizes From Indicated Size

Discharge Opening	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Difference Actual Minus Indicated in 1/64ths of Inches	0	-1	0	0	0	0	-1	-1	-1	0	+1	0	0	+1	0	0	0	+2