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I am submitting herewith a dissertation written by George Takyi Owirodu entitled "Theoretical Analysis and Evaluation of a Parallel Belt Sheller for Mature Green Soybeans." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Engineering.

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THEORETICAL ANALYSIS AND EVALUATION OF A PARALLEL BELT
SHELLER FOR MATURE GREEN SOYBEANS

A Dissertation

Presented for the

Doctor of Philosophy

Degree

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George Takyi Owirodu

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ABSTRACT

Previous study of an experimental parallel-belt sheller indicated some potential for use of such mechanism in shelling mature green vegetable soybeans. The major drawback of the existing mechanism was the excessive damage done to the shelled beans. Dynamical analysis of the system was made to determine the shelling force and identify the source of the forces responsible for bean damage. The existing mechanism was modified and evaluated. Belt material, shelling length, relative belt speed and belt spacing were found to affect shelling and bean quality. Bean damage was affected by soybean cultivar. Generally the performance of the modified sheller was no better than the original experimental parallel belt sheller. On the basis of bean quality, the performance of the new design is considered unsatisfactory.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION	1
Background and Statement of the Problem.	1
Objectives	2
II. REVIEW OF LITERATURE	3
III. THEORETICAL ANALYSIS OF PARALLEL BELT GREEN SOYBEAN	
SHELLER.	5
Definitions and Assumptions.	5
Dimensional Analysis	8
Theoretical Analysis	9
Dynamic analysis	9
Belt force and energy requirements	10
Shelling force	20
Mode of failure of pod	23
Bean kinematics.	28
IV. MODIFICATIONS OF THE PARALLEL BELT SHELLING UNIT	46
The Parallel Belt Sheller.	46
Sheller Modifications.	46
V. EXPERIMENTAL METHODS	52
Background	52
Preparation of Soybeans.	54
Equipment.	55
Testing Procedure.	56

CHAPTER	PAGE
Description of Test	56
Data Analysis	58
VI. DISCUSSION OF RESULTS	59
Belt Material	59
Top Belt Inclination Results.	64
Shelling Length Results	64
Other Results	69
Relative belt speed	69
Computation of power requirements for the sheller . .	69
Belt spacing.	72
Soybean cultivars	75
Sheller modifications performance results	76
VII. SUMMARY AND CONCLUSIONS	80
BIBLIOGRAPHY.	82
APPENDICES.	86
APPENDIX A. SHELLER DATA FOR 1976.	87
APPENDIX B. SHELLER DATA FOR 1977.	95
VITA.	105

LIST OF FIGURES

FIGURE	PAGE
1. Schematic of Parallel Belt Sheller Showing Major Sections . .	6
2. Schematic Diagram of the Sheller-pod System	11
3. Free Body Diagram of Top Belt	12
4. Free Body Diagram of Bottom Belt.	13
5. Free Body Diagram of Soybean Pod.	21
6. Suture of a Soybean Pod	24
7. Soybean Pod Failure by Longitudinal Sliding	26
8. Soybean Pod Failure by Transverse Sliding	27
9. Couple Acting on a Pod.	29
10. Bean Motion	31
11. Positioning Chute for Bean Collection	37
12. Bean Motion upon Discharge from the Sheller	38
13. The Original Experimental Parallel Belt Sheller	47
14. Schematic of the Components and Operation of the Parallel Belt Sheller.	48
15. Schematic of Sheller with Inclined Top Belt	50
16. Schematic of Sheller with Reduced Shelling Length	51
17. Factorial Experiment Design for the Sheller	53
18. Percent Shelling Versus Belt Material	60
19. Percent Bean Damaged Versus Belt Material	61
20. Percent Good Beans Versus Belt Material	62
21. Percent Beans with Damaged Coats Versus Belt Material	63

FIGURE	PAGE
22. Percent Shelling Versus Belt Inclination.	65
23. Percent Bean Damaged Versus Belt Inclination.	66
24. Effect of Shelling Length on Mature Green Soybean Shelling. .	67
25. Effect of Shelling Length on Quality of Shelled Bean.	68
26. Effect of Belt Relative Speed on Mature Green Soybean Shelling.	70
27. Effect of Belt Relative Speed on Quality of Shelled Bean. . .	71
28. Effect of Belt Spacing on Mature Green Soybean Shelling . . .	73
29. Effect of Belt Spacing on Quality of Shelled Bean	74
30. Performance of Modified Sheller on Shelling	77
31. Bean Damage Caused by Modified Shellers	78

NOMENCLATURE

A	Projected area of bean particle
a	Acceleration
c	Constant or constant of integration
d	Belt spacing
e	Belt mass per unit length
e_1	Top belt mass per unit length
e_2	Bottom belt mass per unit length
F	Force
F_1	Top belt frictional force
F_2	Bottom belt frictional force
g	Acceleration due to gravity
h	Parallel belt sheller height measured from the ground level to the surface of the bottom belt
l	Parallel belt shelling length
m	Mass of soybean bean
m_1	Mass of top belt
m_2	Mass of bottom belt
N	Normal force or reaction
N_1	Normal force on pod due to top belt
N_2	Normal force on pod due to bottom belt
Q_s	Generalized total Lagrangian force
Q_{x_1}	Generalized Lagrangian force along X_1 axis
Q_{x_2}	Generalized Lagrangian force along X_2 axis
q_s	Generalized Lagrangian co-ordinate

r	Radius of pulley
T	Total kinetic energy of sheller-pod system
T_1	Kinetic energy of top belt
T_2	Kinetic energy of bottom belt
μ	Coefficient of friction of belt surface
μ_1	Coefficient of friction of top belt
μ_2	Coefficient of friction of bottom belt
V	Total potential energy of sheller-pod system
V_1	Potential energy of top belt
V_2	Potential energy of bottom belt
W	Weight of pod or bean
X	Co-ordinate axis (abscissa)
$\dot{x}$	Velocity along x-axis
x_1	Co-ordinate for top belt
x_2	Co-ordinate for bottom belt
x_3	Co-ordinate for pod
$\ddot{x}$	Acceleration along x-axis
y	Co-ordinate (ordinate)
$\dot{y}$	Velocity along y-axis
$\ddot{y}$	Acceleration along y-axis

CHAPTER I

INTRODUCTION

I. BACKGROUND AND STATEMENT OF THE PROBLEM

The importance of soybeans as a highly nutritive crop is very well documented (6, 19, 27, 31). Because of problems associated with processing, very small amounts of soybeans are consumed as a green vegetable. Mechanization of green soybean shelling is needed to stimulate increased use of the crop, to induce large scale production of vegetable-type soybeans, and to encourage commercial processing. The mechanisms developed over the years for shelling beans have not been successful in shelling mature green soybeans because of their low shelling capacity and excessive damage to the beans.

In an attempt to overcome these problems, an experimental parallel-belt sheller was designed (19). The system employed the shear force developed by the relative motion of two parallel belts for shelling. The experimental mechanism was constructed, tested and its performance compared to two existing bean shellers. The results of the test indicated that shelling green soybeans by the parallel belt principle is possible and that the mechanism had potential for greater shelling capacity than presently-used shellers. The current design, however, caused excessive damage to the shelled bean, even under optimum operating conditions.

II. OBJECTIVES

The objectives of this study were:

1. To analyze the forces acting on the soybean during and after shelling and identify the source of forces which cause bean damage.
2. To conduct an evaluation of the parallel-belt sheller with respect to the following factors: heat treatment of green soybean pods, belt spacing, belt speed, belt type or material (surface characteristics and hardness), top belt inclination, shelling length, and bean variety (bean shape).
3. To improve upon the current design of the sheller for greater shelling capacity and minimum bean damage.

CHAPTER II

REVIEW OF LITERATURE

An extensive discussion of the theory of shelling and the development of shelling mechanisms are given by Owirodu (19). This discussion included a review of the original papers of many researchers in this field.

Lamp, et al. (12) and Arnold, et al. (1) defined and described the process of bean shelling as getting the bean out of the pod, without damage, by overcoming the forces which restrain it. Mitchell, et al. (17) and Collins, et al. (6) in separate studies noted that, in shelling green beans, the magnitude of the restraining forces is reduced by subjecting the green pods to a brief heat treatment in water.

Information concerning the development of shelling mechanisms is found extensively in the literature under the headings of disc shellers, cylinder and concave threshers, roller shellers and parallel belt shellers. Since the parallel belt sheller is the main concern of this study, the other shellers will not be considered here.

The most significant work with respect to belt shellers is that of Gordon (8). He followed the design of an old army huller used in 1918 to build a small double-belt mechanism for shelling dry castor beans. The machine consisted of two parallel belts which travelled in the same direction but at different speeds. The top belt moved slower than the bottom belt and the castor beans were shelled between the belts as a result of their abrasive action due to the differential speed.

The shelling efficiency of Gordon's device was reported as 72% with 2% cracked beans and an average capacity of 675 pounds of shelled beans per hour per foot of belt width. Gordon's mechanism, however, was bulky and required a considerable amount of space in addition to large capacity cleaning and separating devices.

Walker, et al. (31) improved upon Gordon's design and built a similar but smaller mechanism for shelling dry soybeans. They used their mechanism for a further investigation of the parallel belt principle for shelling. The results of the study indicated that shelling was affected by numerous factors including the moisture content of the pod and orientation of the pod with respect to the direction of belt travel. Shelling declined with high moisture content and with pod length oriented perpendicular to the direction of belt travel. Shelling length and belt speed were also found to affect shelling significantly. Bean shelling was found to increase with increase in shelling length and relative belt speed. Unlike the other type of shellers, pod feeding to the parallel belt sheller was found to present no difficulty. Under the best operating conditions, the mechanism was reported to produce over 95% shelling of dry soybeans with minimum bean damage.

The high shelling capacity of the parallel belt sheller coupled with the low bean damage and ease of pod feeding prompted its consideration for further study, development and application to shelling green soybeans.

CHAPTER III

THEORETICAL ANALYSIS OF PARALLEL BELT GREEN SOYBEAN SHELLER

I. DEFINITIONS AND ASSUMPTIONS

Shelling is the process of removing the bean from the pod.

Bean damage as used in this study refers to any disfiguring of the shelled bean resulting from cracked seed coat, split seed and broken cotyledons.

Output material is a convenient term used to refer to the output product of the parallel belt sheller. The output product consists of unshelled pods, empty or shelled pods, split beans, shelled undamaged beans, broken beans, seed coats and seed germ.

The dynamic analysis of the sheller-pod system as considered in this study is categorized into the following sections:

1. Bean pod feeding;
2. Bean shelling process;
3. Bean output after shelling.

During the feed process, heat treated mature green soybean pods are fed to the intake end of the sheller. This end is indicated by A in Figure 1. At the intake end the top belt has no effect on the pods and no shelling takes place. In Figure 1, B indicated the part of the mechanism where shelling takes place. The pods come between the top and bottom belts moving at different speeds. Forces developed as a result of pod-belt contact cause pod failure and subsequent liberation of the beans.

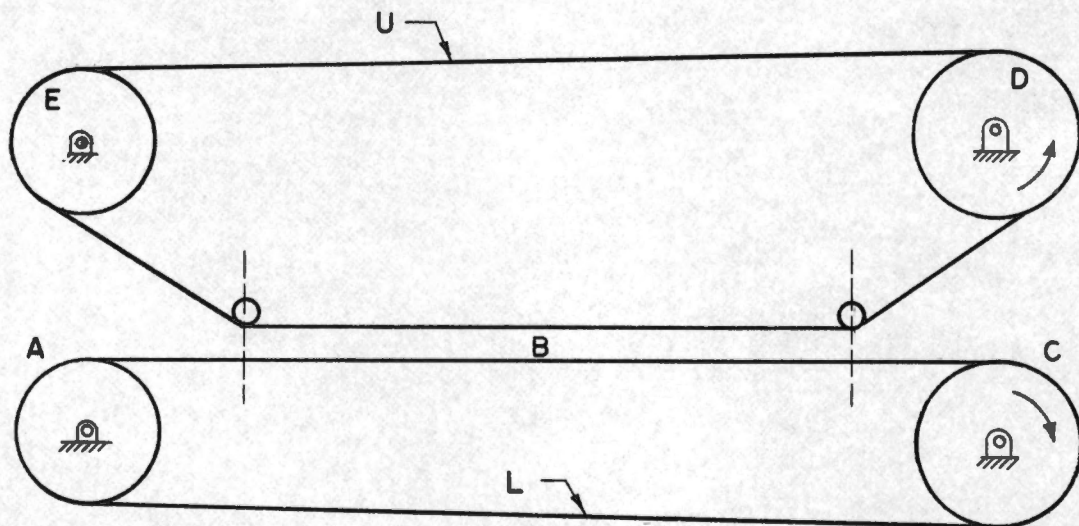


Figure 1. Schematic of parallel belt sheller showing major sections.

- A. Input.
- B. Shelling region.
- C. Output.
- D. Drive pulley.
- E. Idler drive.
- L. Bottom belt.
- U. Top belt.

The shelled beans, empty pods and unshelled pods enter region C, the output section of the sheller where the output material is collected.

It is necessary to make the following important assumptions before proceeding with the force analysis.

1. At the sheller intake end, the soybean pod is at rest relative to the bottom belt. This means that the pod has no velocity relative to the belt. It lies on the bottom belt and moves with it.
2. The top and bottom belts move at different velocities. Thus when the pod comes between them, the high speed belt accelerates the pod and maintains it in dynamic equilibrium. It is the frictional force of the high speed belt that causes the pod to move against the opposing frictional force of the low speed belt.
3. After shelling, the output material made up of various components with different velocities leave the shelling region. Some components of the output material, mainly the undamaged and damaged beans and unshelled pods, escape from the shelling region with the velocities acquired during shelling. The remainder of the output material consisting mainly of empty pods, broken beans and bean coats remain on the bottom belt and occasionally on the top belt. These components remain attached to the surface of the belts until they can escape or fall due to the force of gravity.

For this study, dynamic analysis will be attempted only for sections B and C of the sheller as shown in Figure 1.

II. DIMENSIONAL ANALYSIS

The prediction equation for determining the shelling force was made by the application of the theory of dimensional analysis and the Buckingham Pi theorem (18). The general expression for the shelling force was derived as follows:

$$F/b = f\left(\frac{t}{d}, \frac{A}{\ell^2}, \mu, \frac{N}{mg}, \frac{\sigma t}{mg}, \frac{V^2}{g\ell}, \frac{N}{b}, \frac{d}{\ell}\right), \quad (1)$$

where

A = area of contract of pod with belt surface,

b = belt tension,

d = spacing between belts,

F = shelling force,

f = function,

g = acceleration due gravity,

ℓ = shelling length of sheller,

m = mass of pod,

N = normal force on pod,

t = characteristic length of pod,

V = relative velocity of top and bottom belts,

σ = adhesive force at suture, and

μ = coefficient of friction between belt and pod.

Thus Equation (1) indicates that the shelling force is a function of the quantities listed above. From previous experimental results (19) it is known that the shelling force depends largely on velocity, coefficient of friction of belt, adhesive force at suture, shelling space and normal force on the pod. Equation (1) could therefore be simplified to

$$F = f'(d, V, \mu, \sigma, N). \quad (2)$$

However, it should be noted that the normal force, N , comes into play only when there is contact between the pod and the belts. Thus N is a function of the distance between the top and bottom belts, d . Therefore, only one of those parameters can be included in the equation (2). Excluding d and rewriting equation (2)

$$F = f''(V, \mu, \sigma, N). \quad (2a)$$

Thus, dimensional analysis gives a prediction of the shelling force as being a function of the velocity, coefficient of friction, suture adhesive force, and normal force.

III. THEORETICAL ANALYSIS

Dynamic Analysis

The parallel belt sheller employs the shear action produced by the relative motion of two belts in shelling green soybeans. The

sheller-pod system is shown in diagramatic form in Figure 2. The dynamic analysis of the system is divided into two parts. First, the belt is considered to determine the forces responsible for the belt motion and also to determine the energy requirements of the shelling mechanism. Second, the source and action of the shear force responsible for shelling will be determined.

Belt force and energy requirements. The top and bottom belts of the parallel belt sheller are driven by independent drive pulleys each operated by a hydraulic motor. The Lagrange's equation and the other laws of dynamics (9, 14, 15) will be applied to determine the equations of motion of the belts. Free body diagrams of the belts are shown in Figures 3 and 4. First consider the top belt shown in Figure 3. When a belt passes over a rough pulley, the tension in the belt on the two sides of the pulley will differ (14). Assume that there is friction between the pulley and belt and the pulley is rotating counterclockwise as shown in Figure 3. The frictional force F_t acting to oppose the motion of the pulley is clockwise. This same frictional force acts on the belt in an opposite or counterclockwise direction. This causes the belt tension S_{t_1} on the bottom side of the pulley to be greater than the tension S_{t_2} on the other side in order to hold both S_{t_2} and F_t in equilibrium (9, 14). By the equilibrium of forces principle (14) the above relationship can be expressed mathematically as

$$S_{t_1} = S_{t_2} + F_t$$

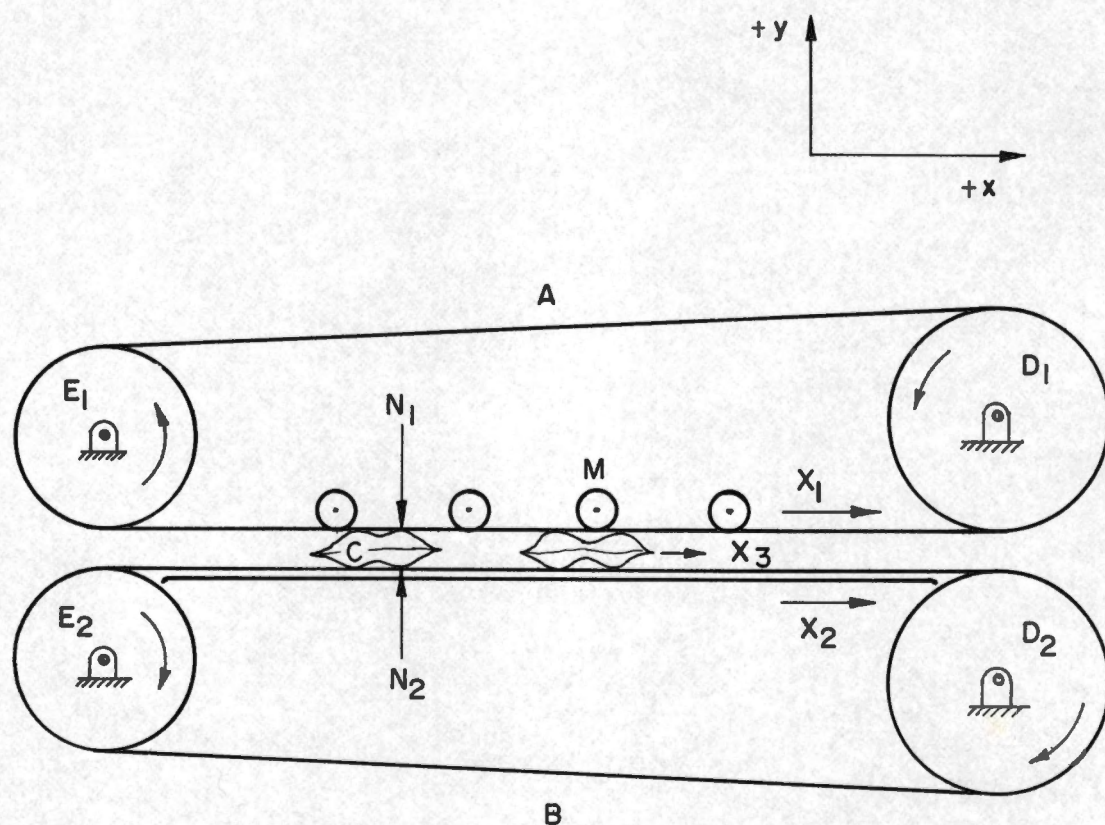


Figure 2. Schematic diagram of the sheller-pod system.

- | | |
|------------------|---|
| A. Top belt. | X_1 co-ordinate describing motion of A. |
| B. Bottom belt. | X_2 co-ordinate describing motion of B. |
| C. Soybean pod. | X_3 co-ordinate describing motion of C. |
| D. Drive pulley. | |
| E. Idler drive. | |
| M. Roller. | |

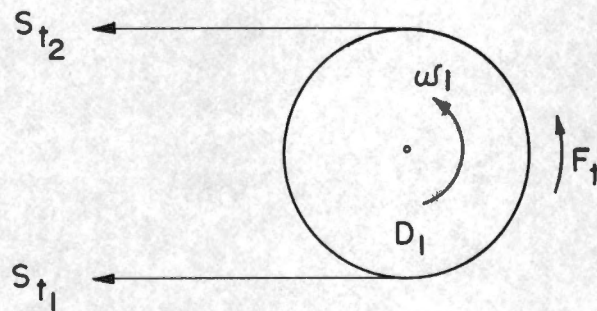


Figure 3. Free body diagram of top belt.

D. Drive pulley.

F_t . Top belt force.

S_{t_1} . Tension in the tight section of top belt.

S_{t_2} . Tension in the slack section of top belt.

ω_1 . Angular speed of top pulley.

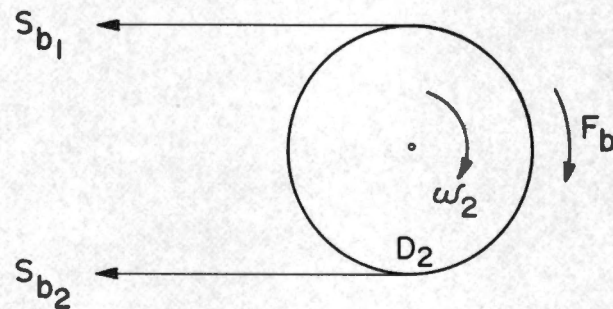


Figure 4. Free body diagram of bottom belt.

D. Drive pulley.

F_b . Bottom belt force.

S_{b1} . Tension in the tight section of bottom belt.

S_{b2} . Tension in the slack section of bottom belt.

ω_2 . Angular speed of bottom pulley.

which can be simplified to

$$F_t = S_{t_1} - S_{t_2}. \quad (3a)$$

The external force acting on the top belt to keep it in motion is therefore F_t . By a similar analysis, the external force acting on the bottom belt can be found to be F_b which is also a frictional force with direction as shown in Figure 4. The magnitude of the forces F_t and F_b can be determined by the application of Lagrange's equation of motion (9), which is

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_s} \right) - \frac{\partial T}{\partial q_s} + \frac{\partial V}{\partial q_s} = Q_s, \quad (3b)$$

where

$$T = T_1 + T_2, \quad (4)$$

and

$$V = V_1 + V_2. \quad (4)$$

Now

$$T_1 = 1/2 m_1 \dot{x}_1^2 = 1/2(e_1 L_1) \dot{x}_1^2, \quad (5)$$

$$T_2 = 1/2 m_2 \dot{x}_2^2 = 1/2(e_2 L_2) \dot{x}_2^2, \quad (6)$$

where

L_1 = length of top belt, and

L_2 = length of bottom belt.

Equations (5) and (6) may be substituted into Equation (3) to obtain

$$T = 1/2(e_1 L_1) \dot{x}_1^2 + 1/2(e_2 L_2) \dot{x}_2^2. \quad (7)$$

When Equation (7) is differentiated with respect to belt velocity along each co-ordinate axis and the result differentiated with respect to time, the following results are obtained:

$$\frac{\partial T}{\partial \dot{x}_1} = (e_1 L_1) \dot{x}_1, \quad (8)$$

and

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{x}_1} \right) = (e_1 L_1) \ddot{x}_1. \quad (9)$$

Also

$$\frac{\partial T}{\partial x_1} = 0. \quad (10)$$

Similarly,

$$\frac{\partial T}{\partial \dot{x}_2} = (e_2 L_2) \dot{x}_2, \quad (11)$$

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{x}_2} \right) = (e_2 L_2) \ddot{x}_2, \quad (12)$$

and

$$\frac{\partial T}{\partial x_2} = 0. \quad (13)$$

Since both belts are fixed, they are assumed to have no potential energy. Therefore $V_1 = V_2 = V = 0$, and hence

$$\frac{\partial V}{\partial x_1} = \frac{\partial V}{\partial x_2} = 0. \quad (14)$$

The total external force acting on the belt system is given as

$$Q_s = Q_{x_1} + Q_{x_2},$$

where

$Q_{x_1} = F_t$, the force generated as a result of the top belt and pulley interaction, and

$Q_{x_2} = F_b$, the force generated as a result of the bottom belt and pulley interaction.

The Lagrange's Equation (3b) is stated with respect to the x_1 co-ordinate as

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{x}_1} \right) - \frac{\partial T}{\partial x_1} + \frac{\partial V}{\partial x_1} = Q_{x_1}. \quad (15)$$

When Equations (9), (10) and (14) are substituted into Equation (15), the following equation is obtained:

$$(e_1 L_1) \ddot{x}_1 = F_t. \quad (16)$$

Similarly,

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{x}_2} \right) - \frac{\partial T}{\partial x_2} + \frac{\partial V}{\partial x_2} = Q_{x_2} \quad (17)$$

and when Equations (12), (13) and (14) are substituted into Equation (17), the following equation is obtained:

$$(e_2 L_2) \ddot{x}_2 = F_b. \quad (18)$$

Equations (16) and (18) indicate that the belt force is a function of the belt mass and acceleration. During shelling, the belt velocities are maintained constant. The accelerations $\ddot{x}_1$ and $\ddot{x}_2$ represent the rates at which the top and bottom belt velocities are increased to bring them from rest to their respective constant operating velocities $\dot{x}_1$ and $\dot{x}_2$. Thus $\ddot{x}_1$ and $\ddot{x}_2$ are only startup accelerations for the sheller. If accelerations $\ddot{x}_1$ and $\ddot{x}_2$ are assumed constant, the following definitions can be made:

$$\ddot{x}_1 = \frac{\dot{x}_1}{t_1}, \quad (19)$$

and

$$\ddot{x}_2 = \frac{\dot{x}_2}{t_2} \quad (20)$$

where t_1 and t_2 are the times it takes for the top and bottom belts to reach velocities $\dot{x}_1$ and $\dot{x}_2$, respectively, when starting from rest. When Equations (19) and (20) are substituted into Equations (16) and (18) the following results are obtained:

$$F_t = (e_1 L_1) \frac{\dot{x}_1}{t_1}, \quad (21)$$

and

$$F_b = (e_2 L_2) \frac{\dot{x}_2}{t_2}. \quad (22)$$

The power required to operate the top and bottom belts may be determined from the following formula (19):

$$\text{Power} = \text{Force} \times \text{Velocity},$$

or

$$P = P_1 + P_2,$$

or

$$P = F_t \dot{x}_1 + F_b \dot{x}_2, \quad (23)$$

where

P_1 = power required to operate the top belt,

P_2 = power required to operate the bottom belt, and

P = total power required for operating both belts.

When Equations (21) and (22) are substituted into Equation (23), the expression for total power is obtained as follows:

$$P = \left(e_1 L_1 \frac{\dot{x}_1}{t_1} \right) \dot{x}_1 + \left(e_2 L_2 \frac{\dot{x}_2}{t_2} \right) \dot{x}_2,$$

or

$$P = e_1 L_1 \frac{\dot{x}_1^2}{t_1} + e_2 L_2 \frac{\dot{x}_2^2}{t_2}. \quad (24)$$

Since the top and bottom belts were of equal length, Equation (24) can be simplified by making the following substitution:

$$L = L_1 = L_2.$$

Hence

$$P = L \left\{ \frac{e_1 \dot{x}_1^2}{t_1} + \frac{e_2 \dot{x}_2^2}{t_2} \right\}. \quad (25)$$

The expression for determining the power requirements of the sheller is therefore given by Equation (25). This is the maximum power required to start the sheller. Once the sheller is up to operating speed, the operating power is less than the maximum power.

Shelling force. The force which causes the soybean to be shelled is generated by the relative motion of the top and bottom belts. When a pod is placed between the moving top and bottom belts such that there is contact between the soybean pod and the belts, the friction between each belt and the pod gives rise to a frictional force. These frictional forces, F_1 and F_2 , along with the normal forces N_1 and N_2 , act on the soybean pod as shown in the free body diagram in Figure 5. The expressions for the frictional forces can be derived by the application of the laws of friction (9, 14) as follow:

$$F_1 = \mu_1(-N_1) = -\mu_1 N_1, \quad (26)$$

$$F_2 = \mu_2 N_2, \quad (27)$$

where

μ_1 = kinetic coefficient of friction between the top belt
and a soybean pod, and

μ_2 = kinetic coefficient of friction between the bottom belt
and a soybean pod.

It should be noted that the frictional forces come into existence only when there is a relative motion between the top and bottom belts. When the two belts have the same velocity, no frictional

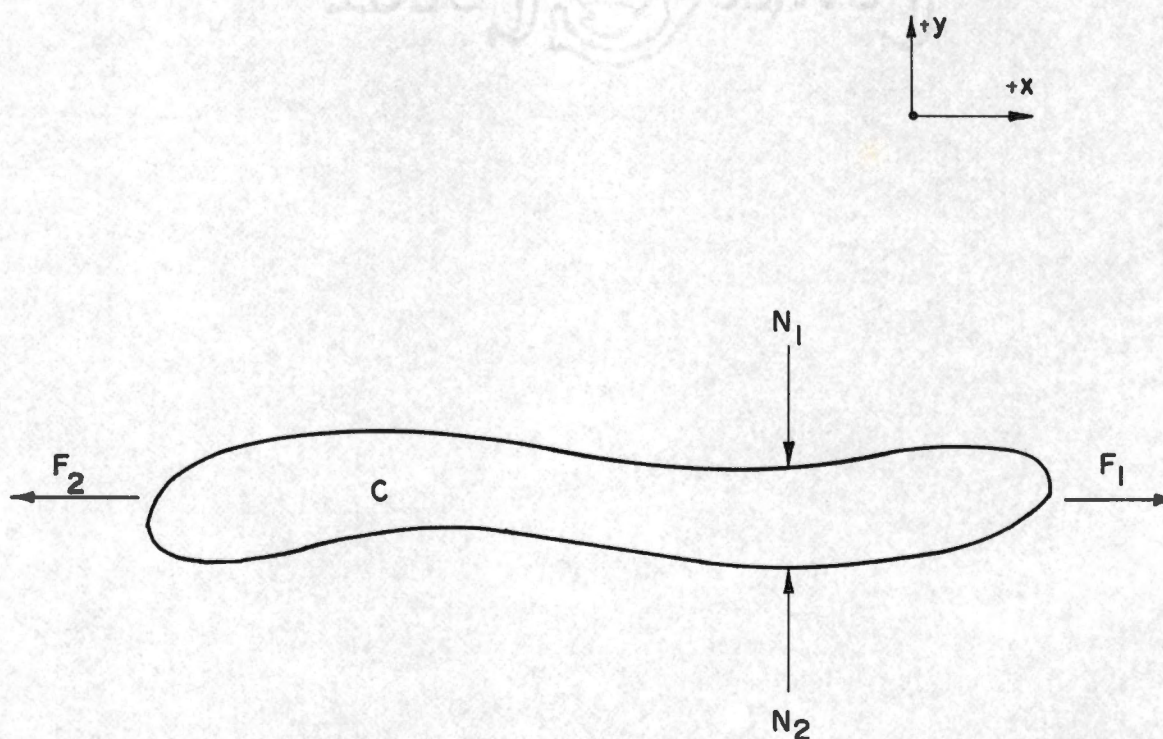


Figure 5. Free body diagram of soybean pod.

C. Soybean pod.

F_1 . Frictional force between belt A and pod C.

F_2 . Frictional force between belt B and pod C.

N_1 . Normal reaction of belt A and rollers M on pod C.

N_2 . Normal reaction of belt B and wooden support on pod C.

forces come into operation, hence there is no shelling (19). By defining the resultant force F acting on a pod as

$$F = F_1 + F_2, \quad (28)$$

an expression for F can be obtained by substituting Equations (26) and (27) into Equation (28) as follows:

$$F = -\mu_1 N_1 + \mu_2 N_2,$$

or

$$F = \mu_2 N_2 - \mu_1 N_1. \quad (29)$$

The force F is the effective force which stresses the soybean pod and causes the pod cover to fail in liberating the beans. The force F is therefore the shelling force. The shelling force also depends on the relative motion of the belts. The magnitude of the shelling force is determined mainly by the magnitude of the relative velocities of the belts as well as the coefficient of friction and the contact pressure between the belts and the soybean pod.

The foregoing analysis was made with respect to a single soybean pod. In practice, several soybean pods are fed to the sheller for shelling. The magnitude of the shelling force also depends on the number of pods being shelled. The total shelling force F_R generated by the sheller is thus given by the following expression:

$$F_R = nF, \quad (30)$$

where

F = shelling force acting on a single pod, and

n = number of soybean pods being shelled.

Mode of Failure of Pod

It is important to make the following assumptions before considering how a soybean pod could fail under the action of the shelling force:

1. The weakest part of the pod is the suture which is the line of attachment of the two halves of the pod enclosing the beans. This is shown in Figure 6.
2. The suture is further weakened by moist heat treatment.
3. The equilibrium position adapted by the pod is that at which a plane containing the longitudinal section is horizontal and passes through the suture.
4. Before and during shelling the bean pod can assume one of the following positions:
 - a. Pod length in the direction of belt motion;
 - b. Pod length perpendicular to the direction of belt motion;
 - c. Pod in any position between (a) and (b).

As previously indicated, shelling occurs only when the bean pod is between, and contacted by, the top and bottom belts.

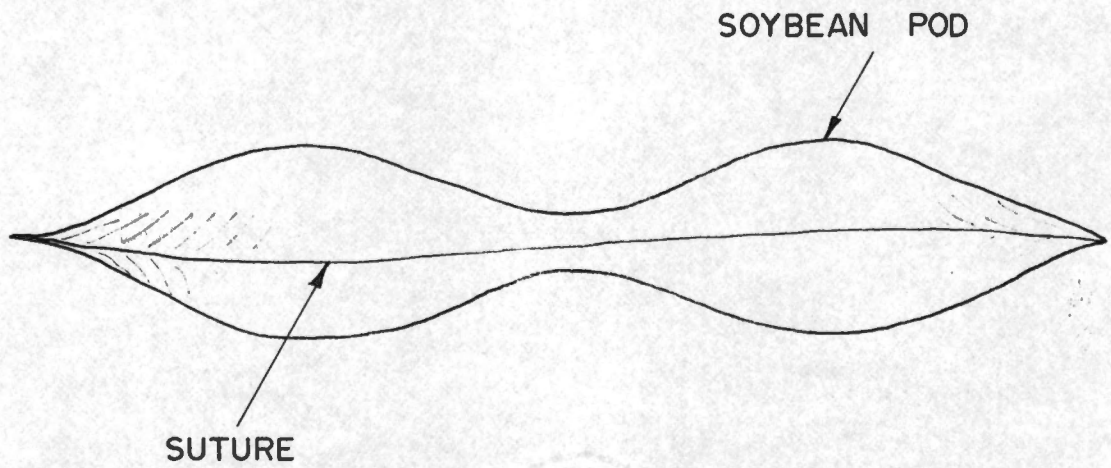


Figure 6. Suture of a soybean pod.

Pod failure can occur in a number of ways depending on the pod position as defined under assumption (4) above:

1. With the pod in position (4a),
either the upper or lower half of the pod cover can slide over the other along the suture under the action of the shelling force as shown in Figure 7.
2. With the pod in position (4b),
failure can occur along the suture as shown in Figure 8.
3. With the pod in position (4c),
the mode of action of the forces F_1 and F_2 may result in a longitudinal twisting of the pod such that the beans are squeezed out through failure points developed in the suture or from a split in the pod cover.

In the case of failure mode 1. and 2. the stress on the pod tends to be uniform. Since the surface area along the suture is very small the shelling stress can be large. With regards to failure mode 3., pod stress tends to be uneven and the part of the pod cover that tends to be most stressed gives way.

Shelling might not occur because of the following reasons:

1. Inadequate contact of the top and bottom belts with bean pod. This may result from the fact that pods fed to the sheller are not of the same size or thickness.
2. When the shelling force is zero. That is when the frictional forces F_1 and F_2 are equal. This sets up a

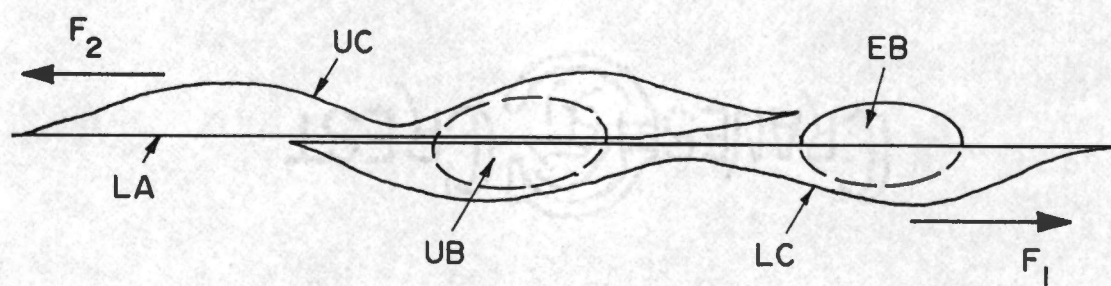


Figure 7. Soybean pod failure by longitudinal sliding.

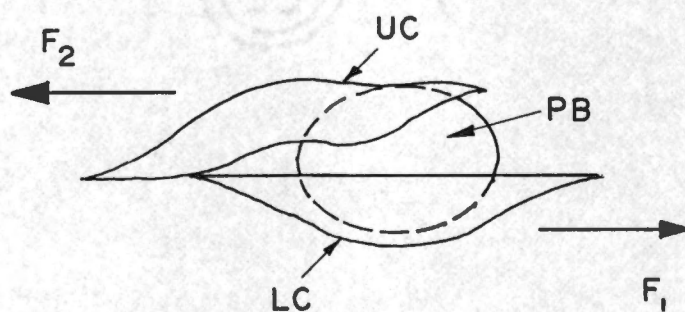


Figure 8. Soybean pod failure by transverse sliding.

EB. Exposed bean.

LA. Line of attachment or suture.

LC. Lower pod cover.

PB. Partially exposed bean.

UB. Unexposed bean.

UC. Upper pod cover.

couple on the bean pod, if pod length is perpendicular to belt travel, as shown in Figure 9. In such a situation the pod rolls between the moving belts.

3. Inadequate stressing of the pod by the available shelling force due to tougher pod cover and stronger suture.

Bean damage may be caused by the following:

1. Inadequate belt spacing;
2. Excessive normal force on the shelled bean;
3. Non-uniform application of shelling force causing pod twisting and bean damage;
4. Belt surface rubbing against the shelled bean and damaging the bean coat;
5. Excessive shelling force causing bean split by sliding one cotyledon over the other during shelling;
6. Rolling of a flat bean causing bean damage; and
7. Bean impacting on a hard surface after shelling and during collection.

Bean Kinematics

The output material as it leaves the sheller assumes some form of motion before it is collected. Two forms of motion were observed. In one case some components of the output material flew out immediately upon release from the shelling part of the sheller. Otherwise the output material remains on the bottom belt until it can escape from the belt as it moves around the pulley.

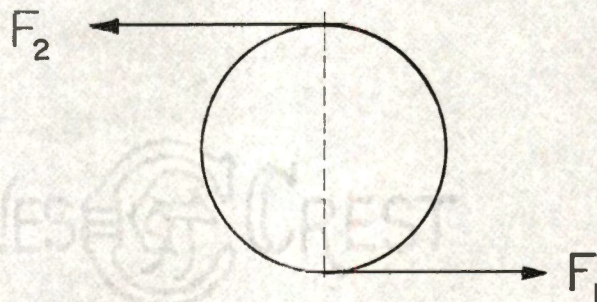


Figure 9. Couple acting on a pod.

For the purpose of collection and separation of the output material, it is necessary to analyze the two forms of motion. For the analysis only the bean component of the output material would be considered. The bean will be considered as a particle. The analysis of the latter form of bean motion will be considered first.

First assume a bean of mass m resting on top of a smooth pulley of radius r as shown in Figure 10. The point at which the bean leaves the pulley could be determined if it is assumed that the bean starts to move from rest. The free body diagram shown in Figure 10 indicates the forces acting on the bean. These are the plane reaction N , along the radius and the weight mg . Applying Newton's laws of motion (9, 15), the equations of motion can be found by summing forces along the radius and the tangent:

$$\Sigma F_r = -N + mg \cos \theta = mr\omega^2, \quad (31)$$

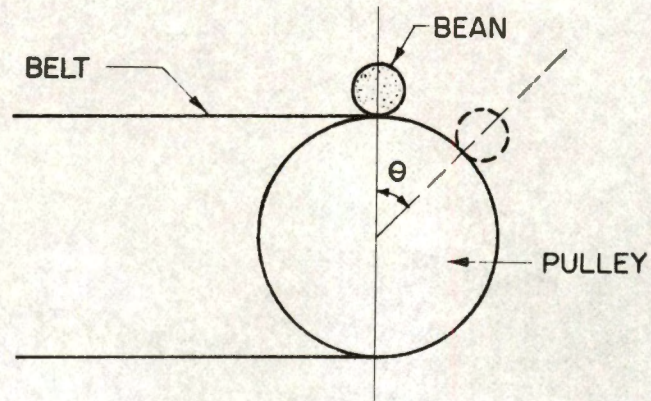
and

$$\Sigma F_t = mg \sin \theta - f = mr\alpha. \quad (32)$$

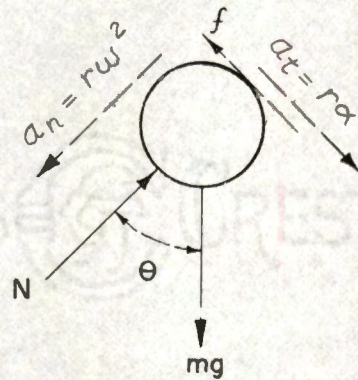
For a solution a third equation is necessary. This is the one which expresses a relationship among θ , ω and α . Now

$$\omega = \frac{d\theta}{dt}, \quad (33)$$

and



(a)



(b)

Figure 10. Bean motion.

- a. Acceleration.
- f. Frictional force due to belt surface.
- g. Acceleration due to gravity.
- N. Normal reaction.
- θ . Angular displacement at any time t .
- ω . Angular speed.
- α . Angular acceleration.

$$\alpha = \frac{d\omega}{dt}. \quad (34)$$

When dt is eliminated from Equations (33) and (34), the following is obtained:

$$\alpha d\theta = \omega d\omega. \quad (35)$$

From equation (32),

$$\alpha = (mg \sin \theta - f)/mr. \quad (36)$$

Substituting Equation (36) into (35) yields

$$\left(\frac{mg \sin \theta}{mr} - \frac{f}{mr} \right) d\theta = \omega d\omega.$$

Upon integrating this becomes

$$\int_0^\theta \left(\frac{g \sin \theta}{r} - \frac{f}{mr} \right) d\theta = \int_0^\omega \omega d\omega,$$

which yields

$$\left(-\frac{g \cos \theta}{r} - \frac{f\theta}{mr} \right) \Big|_0^\theta = \frac{\omega^2}{2},$$

or

$$- \frac{g \cos \theta}{r} - \frac{f\theta}{mr} + \frac{g}{r} = \frac{\omega^2}{2} .$$

This can be written in a simplified form:

$$\frac{g}{r} (1 - \cos \theta) - \frac{f\theta}{mr} = \frac{\omega^2}{2} . \quad (37)$$

At the point of departure from the pulley, the normal reaction N is zero. Equation (31) now becomes

$$mg \cos \theta = mr\omega^2 ,$$

or

$$\frac{g}{r} \cos \theta = \omega^2 . \quad (38)$$

Replacing ω^2 in Equation (37) by its value in Equation (38) yields

$$\frac{g}{r} (1 - \cos \theta) - \frac{f\theta}{mr} = \frac{g}{2r} \cos \theta$$

which could be rewritten

$$\frac{g}{r} - \frac{g}{r} \cos \theta - \frac{g}{2r} \cos \theta = \frac{f\theta}{mr} ,$$

or

$$g - \frac{3}{2} g \cos \theta = \frac{f\theta}{m},$$

or

$$1 - \frac{3}{2} \cos \theta = \frac{f\theta}{mg}. \quad (39)$$

Using Taylor's series expansion (11):

$$\cos \theta = 1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \dots, \quad -\alpha < \theta < \alpha$$

truncating after two terms,

$$\cos \theta = 1 - \frac{\theta^2}{2}. \quad (40)$$

When Equation (40) is substituted into Equation (39) this becomes

$$1 - \frac{3}{2} \left(1 - \frac{\theta^2}{2}\right) = \frac{f\theta}{mg},$$

or

$$\frac{3\theta^2}{4} - 1/2 = \frac{f\theta}{mg},$$

which can be written in standard quadratic form as

$$3\theta^2 - \frac{4f\theta}{mg} - 2 = 0. \quad (41)$$

The general solution to Equation (41) is

$$\theta_{1,2} = -\frac{4f}{mg} \pm \sqrt{\left(\frac{4f}{mg}\right)^2 + 24} . \quad (42)$$

If the belt is smooth f can be assumed negligible, then Equation (39) simplifies to

$$1 - \frac{3}{2} \cos \theta = 0 ,$$

or

$$\cos \theta = \frac{2}{3} ,$$

and

$$\theta = \cos^{-1} \frac{2}{3} = 48.2^\circ . \quad (43)$$

It could be inferred from the results of the derivation that the point at which the bean leaves the belt, and for that matter the pulley, is independent of the size or radius of the pulley. This point is given as the value of θ in Equation (43) for a smooth belt. For a rough belt θ has the value given by Equation (42), which indicates that θ is dependent on belt surface friction.

This means that during the collection of the output material, a chute or a conveying mechanism has to be positioned no less than

48° from the vertical of the pulley as shown in Figure 11, in order to take advantage of the free motion.

The other form of motion which the bean particle assumes as it is propelled out of the sheller is assumed similar to the motion of a projectile shown in Figure 12. Suppose the bean is in equilibrium at point B during the flight; then by the equilibrium of forces principle (15)

$$\Sigma F_y = 0, \quad (44)$$

and

$$\Sigma F_x = 0. \quad (45)$$

Summing forces in the y-direction and neglecting air resistance

$$\Sigma F_y = F_y - W, \quad (46)$$

and applying equation (44)

$$\Sigma F_y = F_y - W = 0,$$

but $F_y = 0$ since the only force acting is the weight of the bean.

Hence $\Sigma F_y + W = 0$, and if $W = mg$ then

$$\Sigma F_y + mg = 0.$$

But $\Sigma F_y = m\ddot{y}$. Therefore

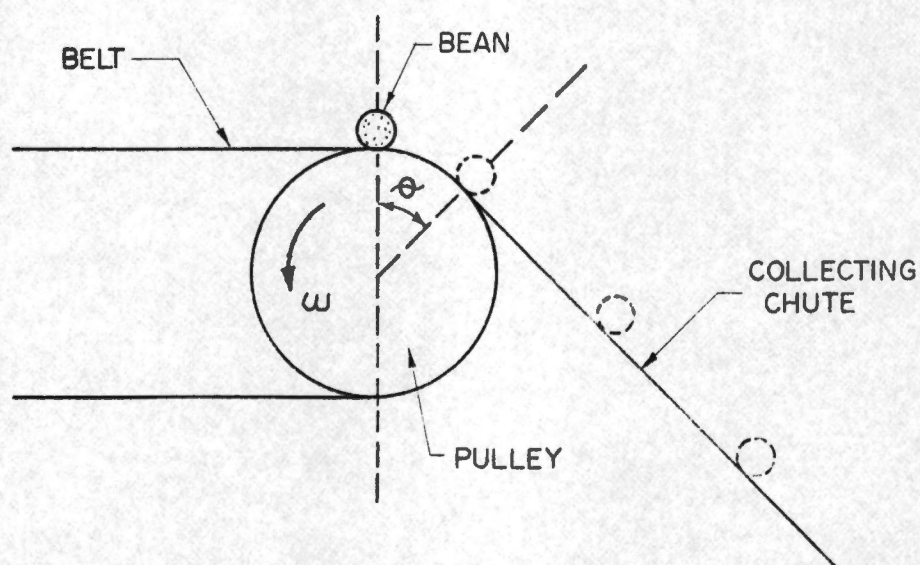


Figure 11. Positioning chute for bean collection.

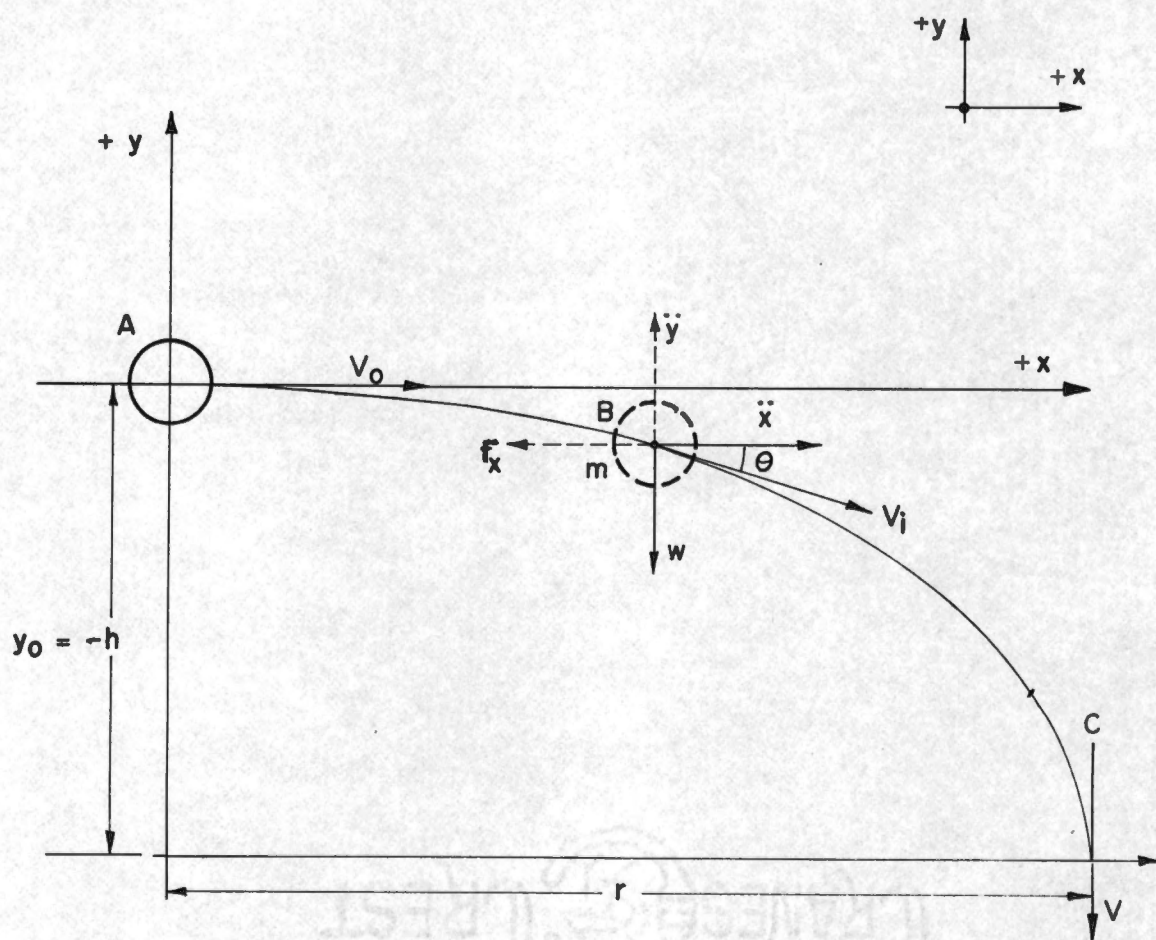


Figure 12. Bean motion upon discharge from the sheller.

$$\ddot{m}\dot{y} + mg = 0$$

$$\ddot{m}\dot{y} = -mg.$$

Hence

$$\ddot{y} = -g. \quad (47)$$

Similarly, summation of forces in x-direction gives

$$\Sigma F_x = -F_x + \dot{m}\ddot{x},$$

and by Equation (45)

$$\Sigma F_x = -F_x + \dot{m}\ddot{x} = 0,$$

or

$$-F_x + \dot{m}\ddot{x} = 0.$$

But $F_x = 0$, therefore

$$\dot{m}\ddot{x} = 0$$

since the mass of the bean is not zero, $m \neq 0$. Then

$$\ddot{x} = 0. \quad (48)$$

The path of the bean can be determined by integrating Equations (47) and (48) with respect to time t , and eliminating t ,

$$\ddot{y} = -g$$

$$\dot{y} = -gt + c_1, \quad (49)$$

where c_1 is a constant which can be determined by substituting the initial conditions $\dot{y} = y_0$, $t = t_0 = 0$ into Equation (49), and

$$\dot{y}_0 = -g(0) + c_1.$$

Hence,

$$c_1 = \dot{y}_0. \quad (50)$$

Thus Equation (49) becomes

$$\dot{y} = -gt + \dot{y}_0. \quad (51)$$

Integrating Equation (51) with respect to time,

$$\text{and} \quad \int \dot{y} = \int (-gt + \dot{y}_0),$$

$$y = -\frac{gt^2}{2} + \dot{y}_0 t + c_2. \quad (52)$$

Now c_2 can be determined with initial conditions

$$y = y_0 = -h, \quad t = 0, \quad \dot{y} = \dot{y}_0$$

substituted into Equation (52) which yields

$$y_0 = \frac{g(0)^2}{2} + \dot{y}_0(0) + c_2.$$

Hence,

$$c_2 = y_0 = -h. \quad (53)$$

When Equation (53) is substituted into (52)

$$y = -\frac{gt^2}{2} + \dot{y}_0 t + y_0. \quad (54)$$

Now $\dot{y}_0 = V_i \sin \theta$ from Figure 12 and $y_0 = -h$; therefore Equation (54) becomes

$$y = -\frac{gt^2}{2} + (V_i \sin \theta)t - h. \quad (55)$$

Similarly, integrating both sides of Equation (48) with respect to time,

$$\dot{x} = \dot{x}_0,$$

and

$$\dot{x} = c_3, \quad (56)$$

where c_3 is determined by substituting the initial conditions $\dot{x} = \dot{x}_0$ and $t = t_0 = 0$ into Equation (56). Hence

$$c_3 = \dot{x}_0. \quad (57)$$

When Equation (57) is substituted into (56)

$$\dot{x} = \dot{x}_0. \quad (58)$$

When Equation (58) is integrated with respect to time,

$$\int \dot{x} = \int \dot{x}_0,$$

or

$$x = \dot{x}_0 t + c_4, \quad (59)$$

where c_4 is determined by substituting the initial conditions:

$$x = \dot{x}_0, \quad t = 0$$

into Equation (58) and

$$c_4 = x_0 - \dot{x}_0(0) = x_0. \quad (60)$$

Hence Equation (58) becomes

$$x = \dot{x}_0 t + x_0. \quad (61)$$

Now from Figure 12, page 38, $\dot{x}_0 = V_i \cos \theta$, $x_0 = 0$, and when substituted Equation (61) gives

$$x = (V_i \cos \theta)t. \quad (62)$$

To determine the path of the bean, t is eliminated between Equations (55) and (62).

From Equation (62)

$$t = \frac{V_i \cos \theta}{x}. \quad (63)$$

Substitute Equation (63) into (55) to obtain

$$y = -\frac{g}{2} \left(\frac{V_i \cos \theta}{x} \right)^2 + (V_i \sin \theta) \left(\frac{V_i \cos \theta}{x} \right) - h.$$

This simplifies into

$$y = -\frac{g}{2} \frac{V_i^2 \cos^2 \theta}{x^2} + \frac{V_i^2 \sin \theta \cos \theta}{x} - h. \quad (64)$$

Equation (64) is the equation of a parabola, therefore the path followed by the bean as it leaves the sheller is parabolic.

The time of travel of the bean is the time it takes the bean to fall a height h . The time is determined by substituting $y = -h$ into Equation (55) to obtain

$$-h = -\frac{gt^2}{2} + (V_i \sin \theta) t - h,$$

and

$$\frac{gt^2}{2} = (V_i \sin \theta)t.$$

Hence

$$\text{time, } t = \frac{2V_i \sin \theta}{g}. \quad (65)$$

The range of the bean is determined using Equation (62)

$$x = (V_i \cos \theta)t,$$

but t is given by Equation (65), so by substitution

$$x = (V_i \cos \theta) \frac{2V_i \sin \theta}{g},$$

or

$$\text{bean range, } r = x = \frac{2V_i^2 \cos \theta \sin \theta}{g}. \quad (66)$$

Equations (64), (65) and (66) are of practical importance in the design of a collector for the output material. Equation (66) gives the maximum span of the collecting structure. The speed V_0 of the bean as it leaves the sheller, that is, when $\theta = 0$, is estimated

by the mean of the top and bottom belt speeds. Equation (64) enables the shape of the collecting structure to be determined. The suggested shape is parabolic.

CHAPTER IV

MODIFICATIONS OF THE PARALLEL BELT SHELLING UNIT

I. THE PARALLEL BELT SHELLER

The experimental parallel belt sheller unit used for this study is shown in its original design form in Figures 13 and 14. It consisted of two parallel belts which moved in the same direction but at different speeds. The top belt had a constant speed while the bottom belt speed was variable. Both belts were of identical dimensions and made of neoprene and fabric.

Each belt was independently driven by a variable speed hydraulic motor attached to a drive pulley and powered by an independent hydraulic power supply operated from a tractor power take-off. Belt tension and alignment were maintained by two side-mounted, self-aligning take-up units which aligned the idler pulleys at the opposite end of the unit from the drive pulleys. Design details of the parallel belt sheller are given by Owirodu (19).

II. SHELLER MODIFICATIONS

It was necessary to modify the mechanism in order to study the effect of new operating parameters in addition to making a detailed evaluation of previously studied parameters. The sheller was designated differently after each modification for identification purposes.

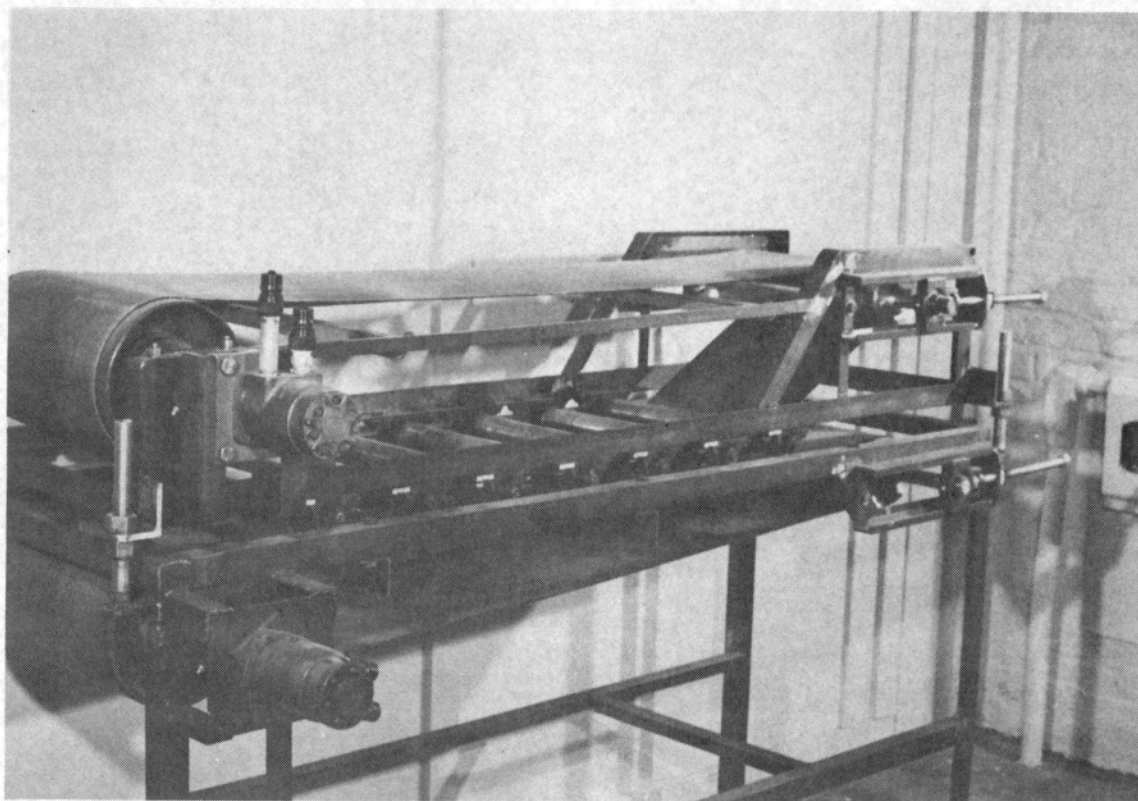


Figure 13. The original experimental parallel belt sheller.

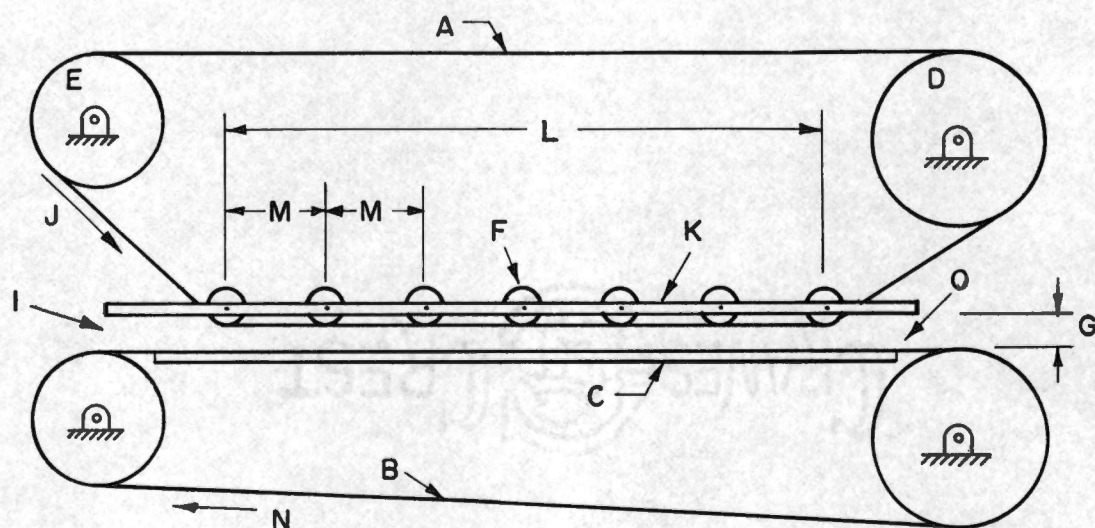


Figure 14. Schematic of the components and operation of the parallel belt sheller.

- | | |
|------------------|-------------------------------------|
| A. Top belt. | I. Intake of sheller. |
| B. Bottom belt. | J. Direction of top belt travel. |
| C. Wooden board. | K. Rack bearing rollers. |
| D. Drive pulley. | L. Shelling length. |
| E. Idler drive. | M. Roller spacing. |
| F. Rollers. | N. Direction of bottom belt travel. |
| G. Belt Spacing. | O. Outlet of sheller. |

Sheller one referred to the original shelling mechanism with top and bottom belts of identical dimensions and material. The belts were parallel with a shelling length of 0.914 meters.

Sheller two was similar to sheller one except that the top belt was replaced by another belt of the same dimensions but different material. The new belt had a rough surface as opposed to the smooth surface characteristics of the original belt.

Sheller three was identical to sheller one but the top belt was inclined at an angle of five degrees to the horizontal bottom belt as shown in Figure 15. This change made it possible for the effect of top belt inclination on shelling to be studied.

Sheller four had identical features to sheller one except that two rollers were removed to shorten the shelling length to 0.610 meters as shown in Figure 16. With this modification the effect of shelling length on sheller performance was determined.

Sheller five was similar to sheller four; however, the shelling length was reduced further to 0.3048 meters by removing two more rollers.

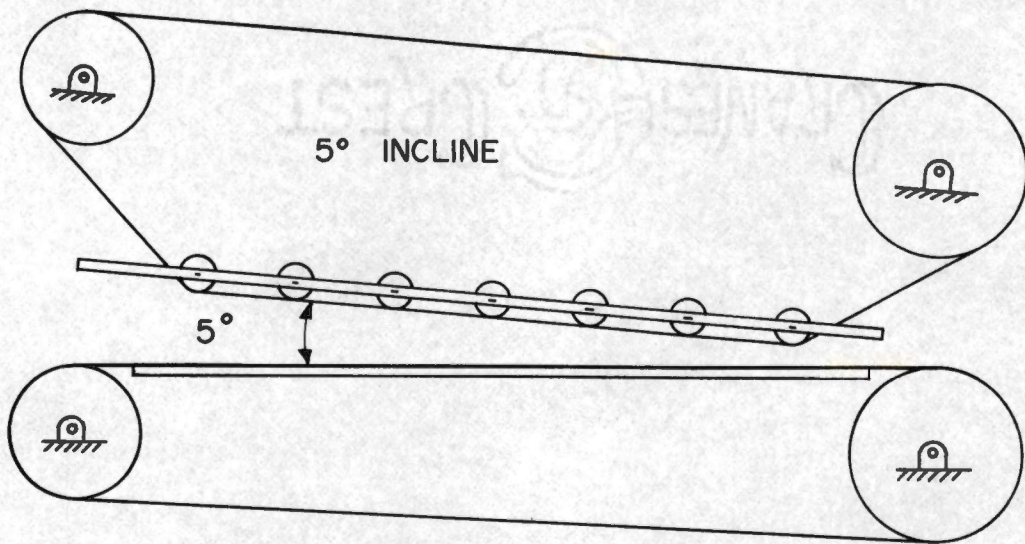


Figure 15. Schematic of sheller with inclined top belt.

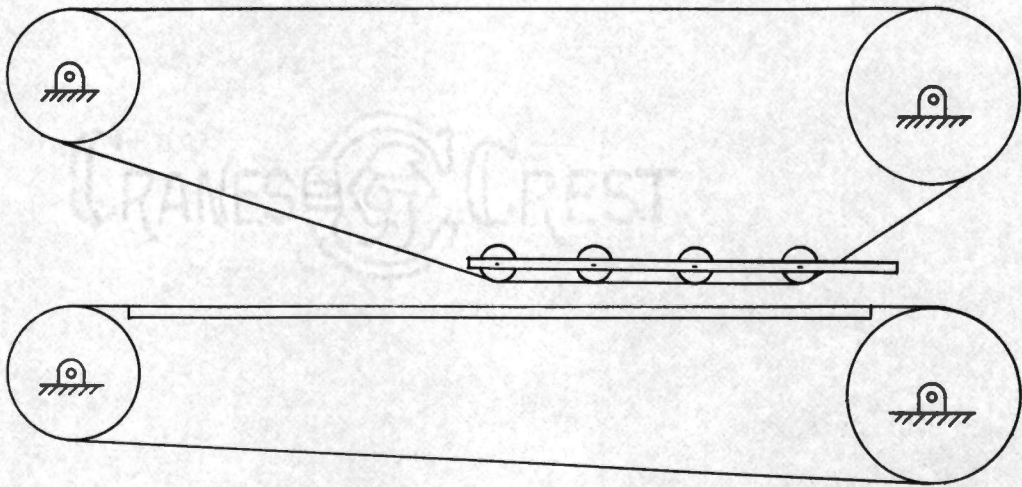


Figure 16. Schematic of sheller with reduced shelling length.

CHAPTER V

EXPERIMENTAL METHODS

I. BACKGROUND

The experimental parallel belt sheller was used to investigate the effects on the shelling of green soybeans of four factors in addition to the factors studied in a previous work (19). The new parameters were belt material, soybean cultivar, top belt inclination and shelling length. These factors were maintained constant in the previous experiment while the influence on shelling of other factors (belt speed, belt spacing, heat treatment and pod orientation) were being measured. Heat treatment and pod orientation were not considered in this experiment because their effects had been established (19). Effective shelling occurred when soybean pods were heated for three minutes in water at 90° C (6, 19). Pod orientation was found to have no effect on shelling (19).

A factorial experiment design was used for the experiment. This experiment design made it possible for the effects of each of the factors on shelling to be investigated in the same experiment. The experiment consisted of three replications, two types of belts, three shelling lengths, two top belt inclinations, three soybean cultivars, three belt speeds and six belt spacings for a total of 286 tests. A sketch of the experiment plan is presented in Figure 17.

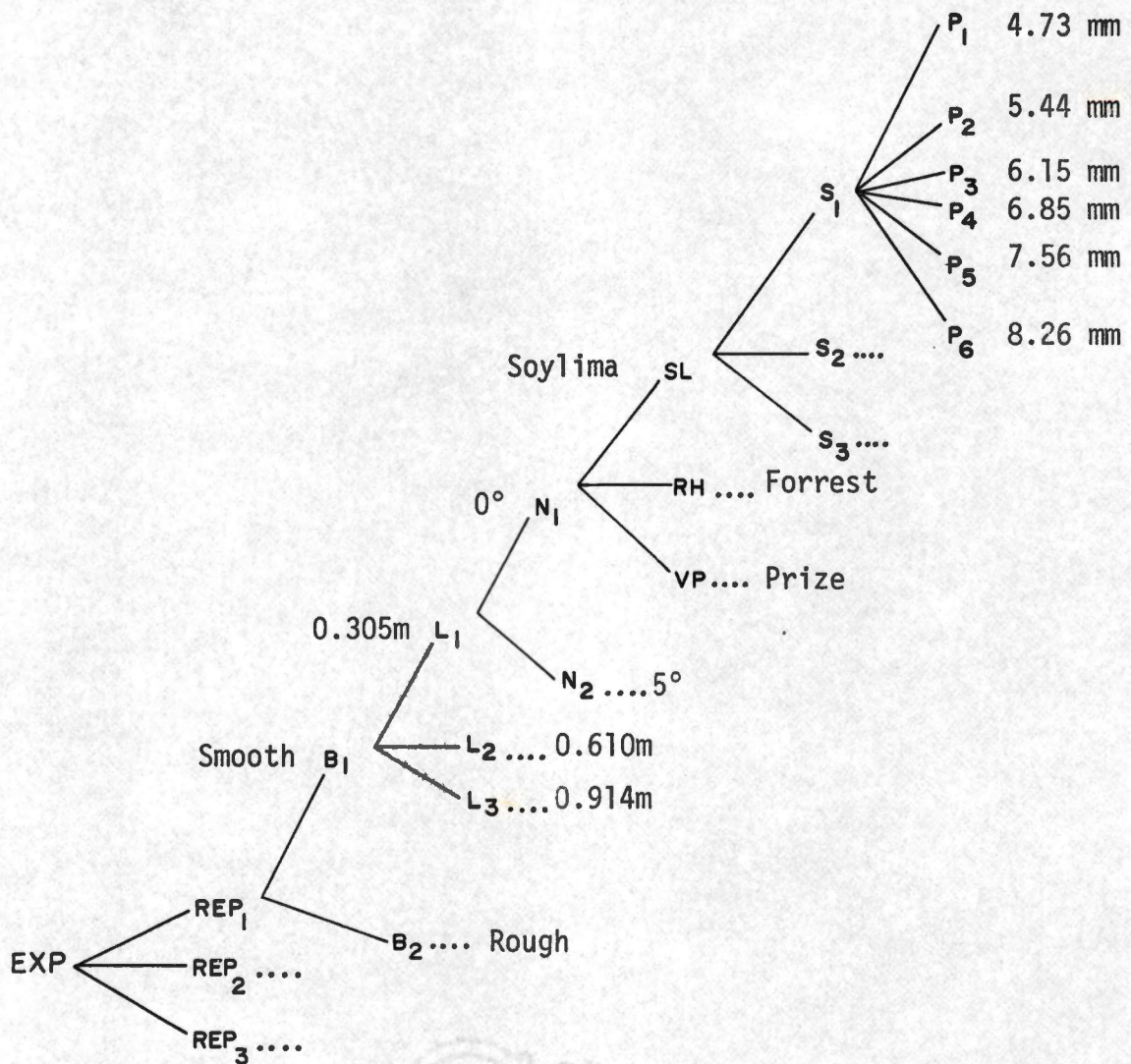


Figure 17. Factorial experiment design for the sheller.

EXP Experiment.

$S_1 = 73 \text{ m/min}$

REP Replication.

$S_2 = 85 \text{ m/min}$

B Top belt.

$S_3 = 97 \text{ m/min}$

L Shelling length.

N Top belt inclination.

S Belt speed.

P Belt spacing.

The four response variables measured during the tests were the percentage of pods that shelled completely, the percentage of pods that did not shell or that partially shelled and the quality index of the shelled beans. The bean quality index was measured in terms of percentage of shelled beans that were not damaged, hitherto noted as "perfect beans," percentage of shelled beans with damaged seed coat but intact cotyledons, hereafter noted as "imperfect beans" and percentage of shelled beans with split and broken cotyledons as a group and described under the general term "miscellaneous."

II. PREPARATION OF SOYBEANS

About 4.5 kilograms of each cultivar of mature green soybeans were used for the entire experiment. The soybean cultivars included the soylima, which was used consistently throughout the entire study, and some field cultivars, such as the Prize and Forrest, depending on which was available during the growing season. The soybean names used were local designations to distinguish between cultivars since their actual scientific names are unknown. For this study, the soybean cultivars were put under two main categories according to bean shape; the round and flat bean types.

The soylima is a late maturing cultivar with physical characteristics similar to the Japanese variety, Hato. It belongs to the flat bean category.

The Prize and Forrest are early maturing soybeans with round, short, hairy pods and round beans.

All the soybean cultivars were obtained from the University of Tennessee Agricultural Experiment Station at Knoxville, Tennessee.

The mature green soybean plants were collected by hand and conveyed to the laboratory for pod removal just before the tests. Harvesting was normally done late in the morning just before the test runs. Beans which were not used on the same day were discarded.

Samples of pods were taken at random, placed into cotton bags and heated for three minutes in water at 90° C before shelling.

III. EQUIPMENT

Auxilliary equipment employed during the tests consisted of a tractor, hydraulic power supply, strobe-tachometer, mercury thermometer, an electric stove, a stop watch and a measuring scale.

The hydraulic power supply which was used to drive the hydraulic drive motors of the sheller consisted of a Hydreco Model 19 PL 190036 hydraulic pump which was driven by the PTO of a Massey Ferguson Model 265, 65-HP tractor on which the unit and associated controls for the independent flow circuits were mounted.

The strobe-tachometer was used to measure the speed of the rotating parts of the sheller.

A 0-110° C range centigrade mercury thermometer was utilized to measure the temperature of the water in which the pods were heated. The water was heated by a portable electric stove. The time of heat treatment was measured by a stop watch.

IV. TESTING PROCEDURE

The procedure used during each test was as follows:

1. 100 gram samples of freshly harvested soybeans were taken at random, placed in cotton bags, and heated for three minutes in water at 90° C. The pods were then emptied from the bags and allowed to cool to room temperature.
2. The appropriate level of each of the experimental factors was selected and the sheller was set accordingly.
3. Samples of the heat treated pods were run through the sheller. The pods were hand fed one after another. The output material from the sheller was collected, separated into the various fractions, weighed and the appropriate data recorded.
4. Three replications of each test were made.

V. DESCRIPTION OF TEST

The factorial experimental plan employed in this study made it possible for the effects of six factors on shelling to be investigated in the same experiment. The following factors were studied in three replications at the following levels: two belt materials (smooth and rough); three shelling lengths (0.305, 0.610, and 0.914m); two top belt inclinations (0° and 5°); three soybean cultivars (soylima, Prize, and Forrest); three bottom belt speeds (73, 85 and 97 m/mins); one top belt speed (122 m/min, producing the corresponding relative belt speeds of 49, 37, and 25 m/mins); and six belt spacings (4.93, 5.68, 6.34,

7.05, 7.75 and 8.46 mm). No changes were made in the roller spacing during the entire experiment.

A typical test was designated as Rep₁ B₁ L₁ N₁ SL S₁ P₁ as shown in Figure 17. This means that for replication one of that test the sheller was set with a smooth top belt, at 0.305 m shelling length, 0° top belt inclination, to shell soylima cultivar, at 73 m/mins belt speed and 4.73 mm belt spacing. Another test could be designated Rep₂ B₂ L₁ N₂ VP S₁ P₃. For simplicity, this test is not shown on the experiment plan in Figure 17; however, it could be easily derived. The tests were run randomly.

The results of each test are presented in Appendix A and Appendix B. For instance, in Appendix A a test result is designated as observation one (OBS. 1). This indicates a test where the sheller was set with the smooth top belt, at 0.305 m shelling length, shelling soylima cultivar, for replication one, at 73 m/mins bottom belt speed and 6.85 mm belt spacing. The results were: 2.08% unshelled soybean pods, zero percent good shelled beans, 1.38% of shelled beans with damaged seed coat and 92.48% of shelled beans with split and broken cotyledons and empty bean covers. The term "mach 1" represented the sheller version one. This term accounted for the top belt inclination factor which was not indicated as a separate column in the appendix.

The performance tests for the five versions of the sheller were included in the same experiment. Sheller one (indicated as "mach 1" in observation number one in Appendix A) referred to the original mechanism with smooth top belt, 0° belt inclination, and 0.914m

shelling length. In determining the performance of sheller one all test results containing "mach 1" in the data in Appendix A and Appendix B were used in the data analysis. Similar explanation applied to the other sheller versions.

VI. DATA ANALYSIS

The Statistical Analysis System (SAS, 1976) (28) installed at the University of Tennessee Computing Center was employed to perform a statistical analysis on the test data. The analysis of variance (ANOVA), means, and plot procedures of the SAS were extensively used in the analysis of data. Computer programs used for the analysis can be found in the SAS Manual (28).

CHAPTER VI

DISCUSSION OF RESULTS

I. BELT MATERIAL

The results of the belt material tests are shown in Figures 18 through 21. The smooth belt produced a greater shelling than the rough belt as shown in Figure 18. There was a difference of about 24% in the amounts of soybean pods shelled. An analysis of variance results indicated that the effect of belt material and surface characteristics on shelling capacity was statistically significant.

The percentage damage (based upon the number of shelled beans) caused by both belts were about the same. This effect is shown in Figure 19.

The effect of belt surface characteristics did not appear to influence, to any great extent, the amount of good beans produced during shelling. This effect is shown in Figure 20.

The rough belt tended to cause more damage to bean coats than the smooth one; Figure 21 shows this effect.

These results were found to hold true for all cultivars of the soybeans used in the study. The results also point to the inference that the shelling capacity of the sheller and the amount of bean coat damage were affected by the type of top belt material used. It was found that the smooth belt shelled 16% more beans than the rough one shelled.

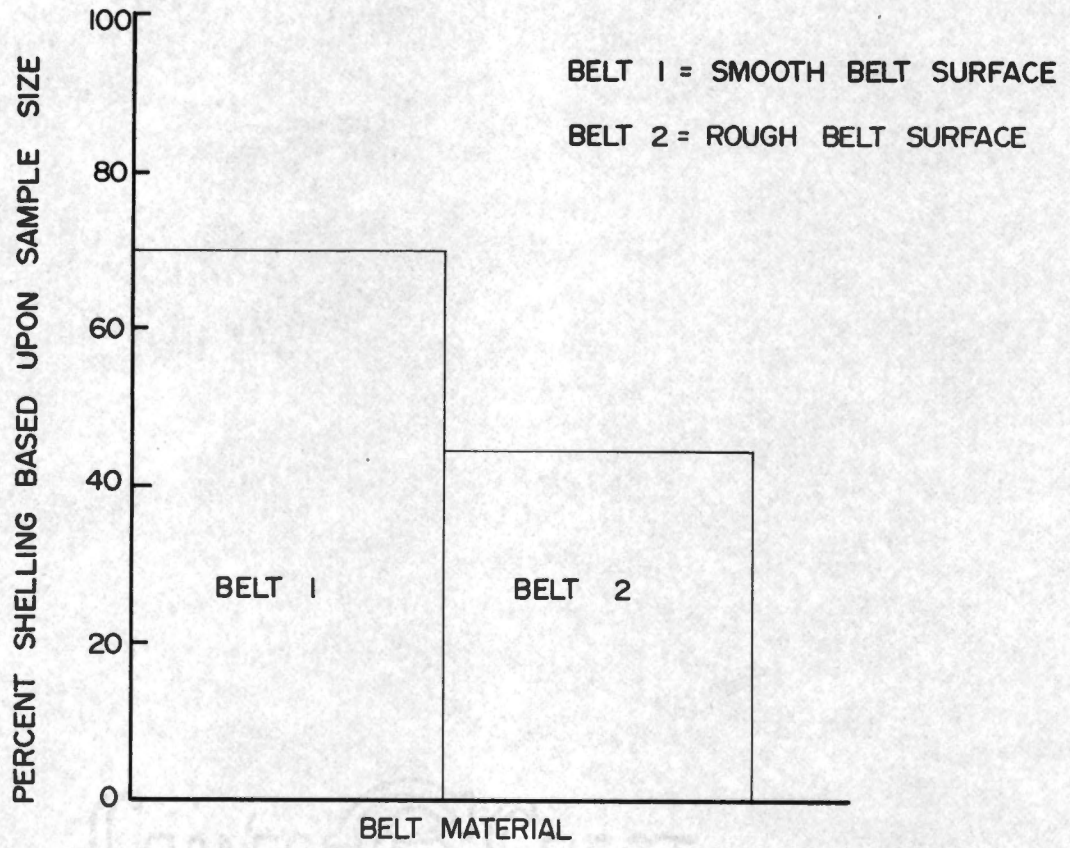


Figure 18. Percent shelling versus belt material.

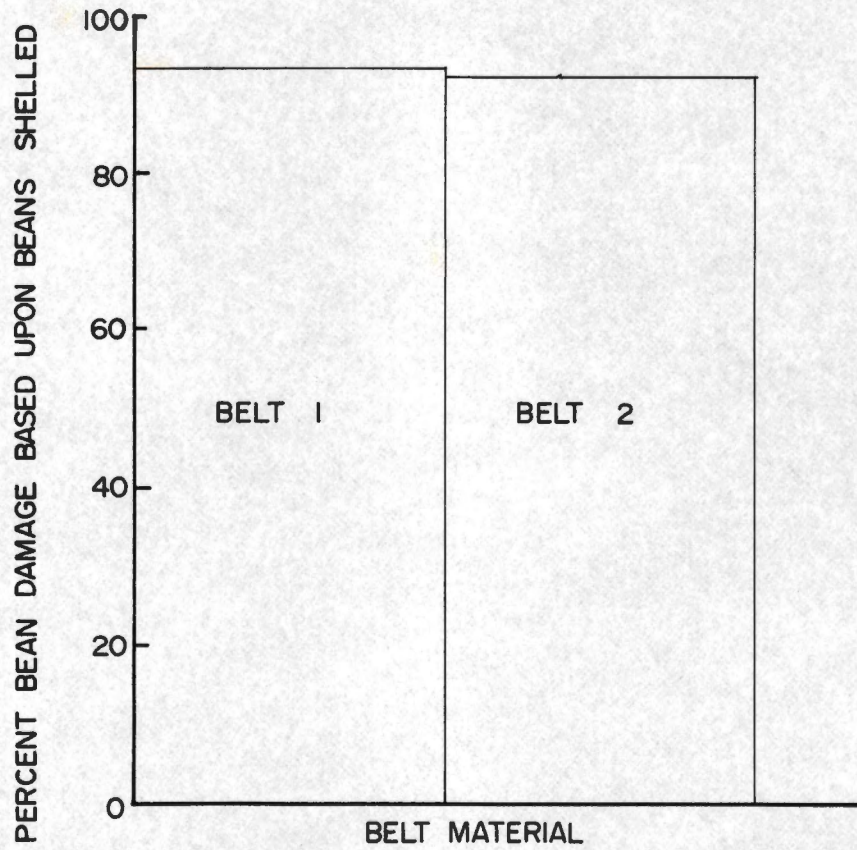


Figure 19. Percent bean damaged versus belt material.

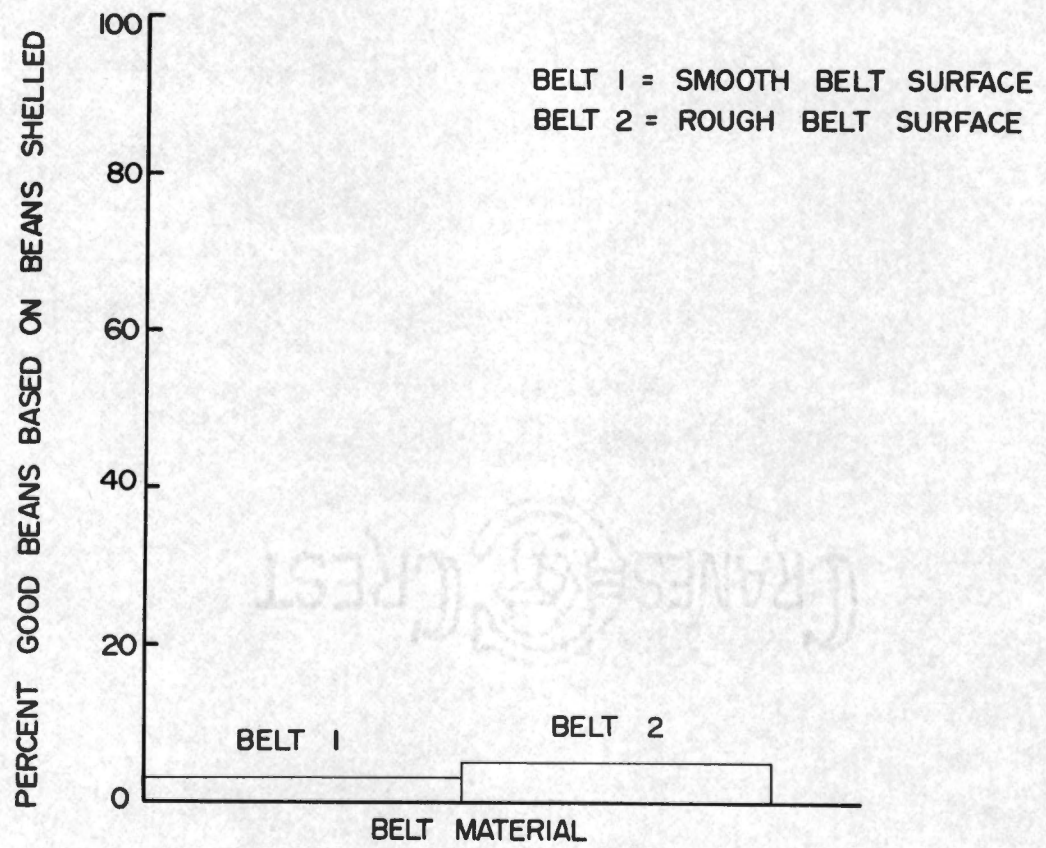


Figure 20. Percent good beans versus belt material.

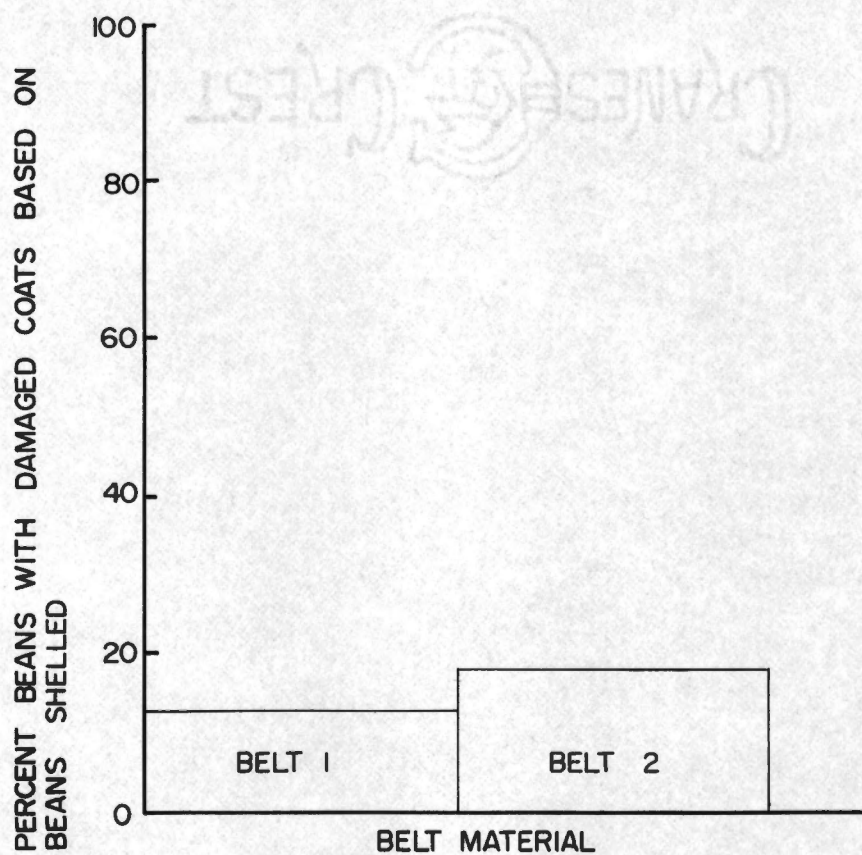


Figure 21. Percent beans with damaged coats versus belt material.

II. TOP BELT INCLINATION RESULTS

The top belt inclination test results are shown in Figures 22 and 23. These figures show that inclination of the top belt did not produce any noticeable difference as far as capacity of the sheller and bean damage were concerned.

The results of analyses of variance indicated no significant effect of top belt inclination on either shelling or bean damage. From these results, it may be inferred that a five degree top belt inclination did not affect shelling.

III. SHELLING LENGTH RESULTS

Results of the shelling length tests are shown in Figures 24 and 25. Shelling was increased when the shelling length was increased from 0.305 to 0.610 meters; however, further increases in the length caused a decline in shelling. This effect is indicated in Figure 24. It was found that bean damage increased proportionately with the shelling length. Bean quality was also found to increase with shelling length; however, quality declined for lengths greater than 0.610 meters. Figure 25 shows that though shelling was highest at a shelling length of 0.610 meters, bean coat damage was also at a peak at that length. Results of analysis of variance indicated that shelling length had a significant effect on shelling capacity and bean damage.

The results were found to be true for all cultivars of the soybeans used in the study. It may be concluded that shelling length affected the shelling capacity of the sheller and the quality of the shelled beans.

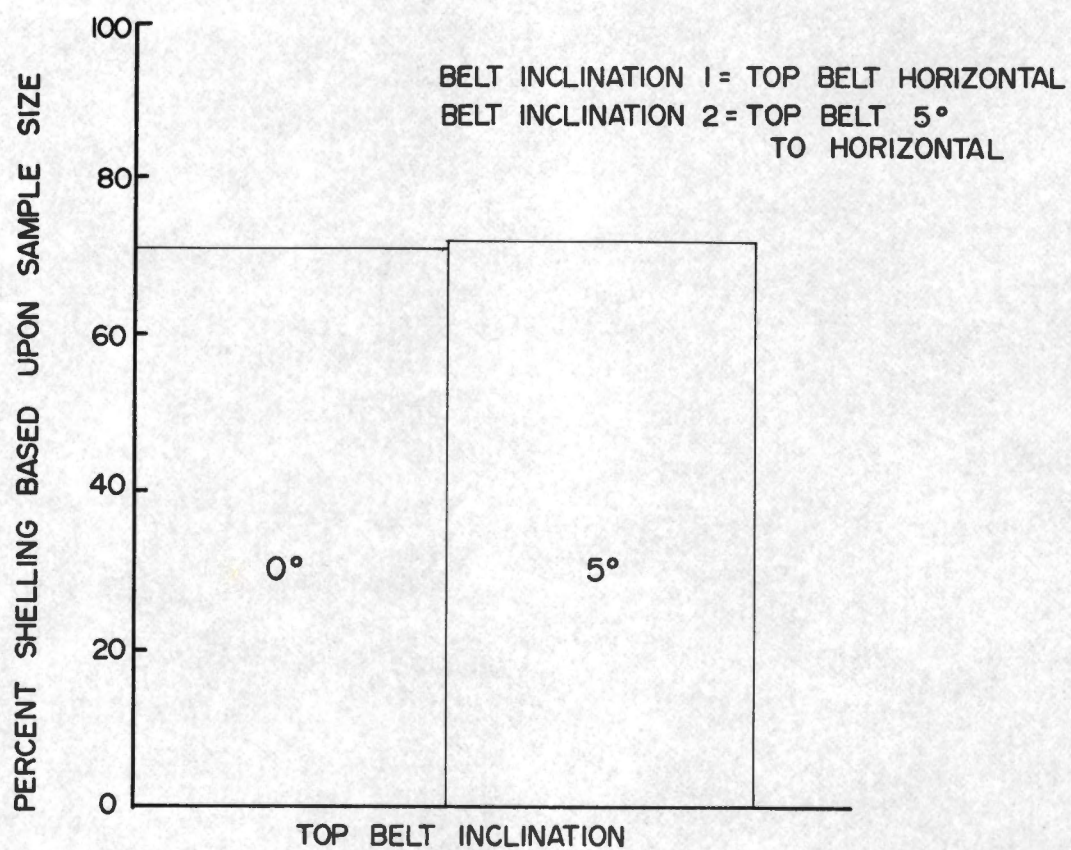


Figure 22 Percent shelling versus belt inclination.

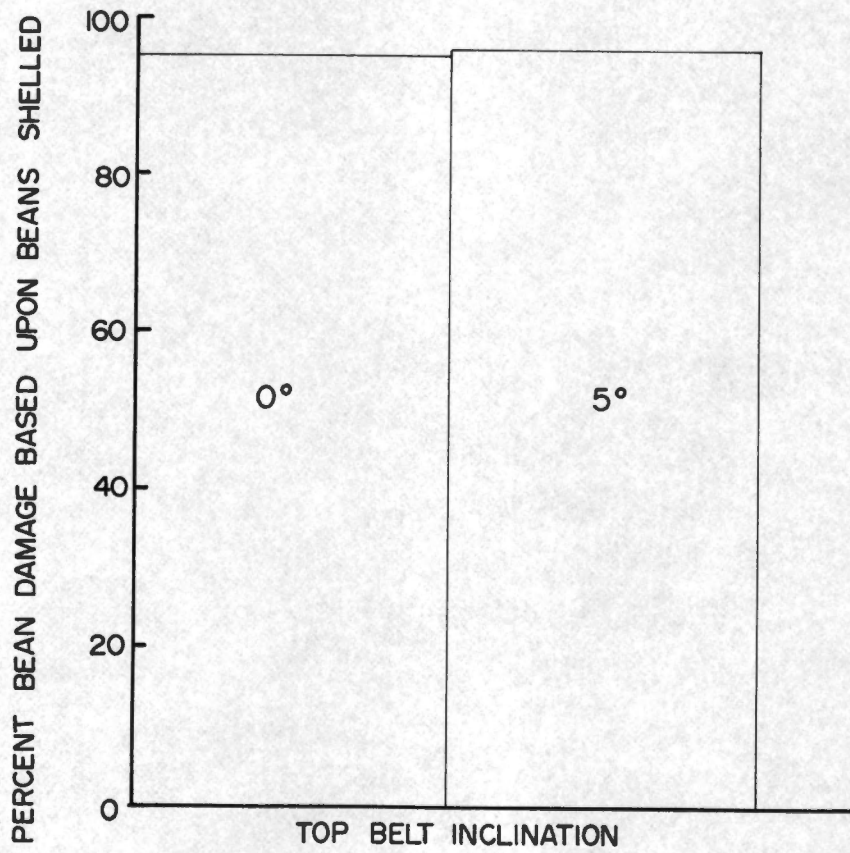


Figure 23. Percent bean damaged versus belt inclination.

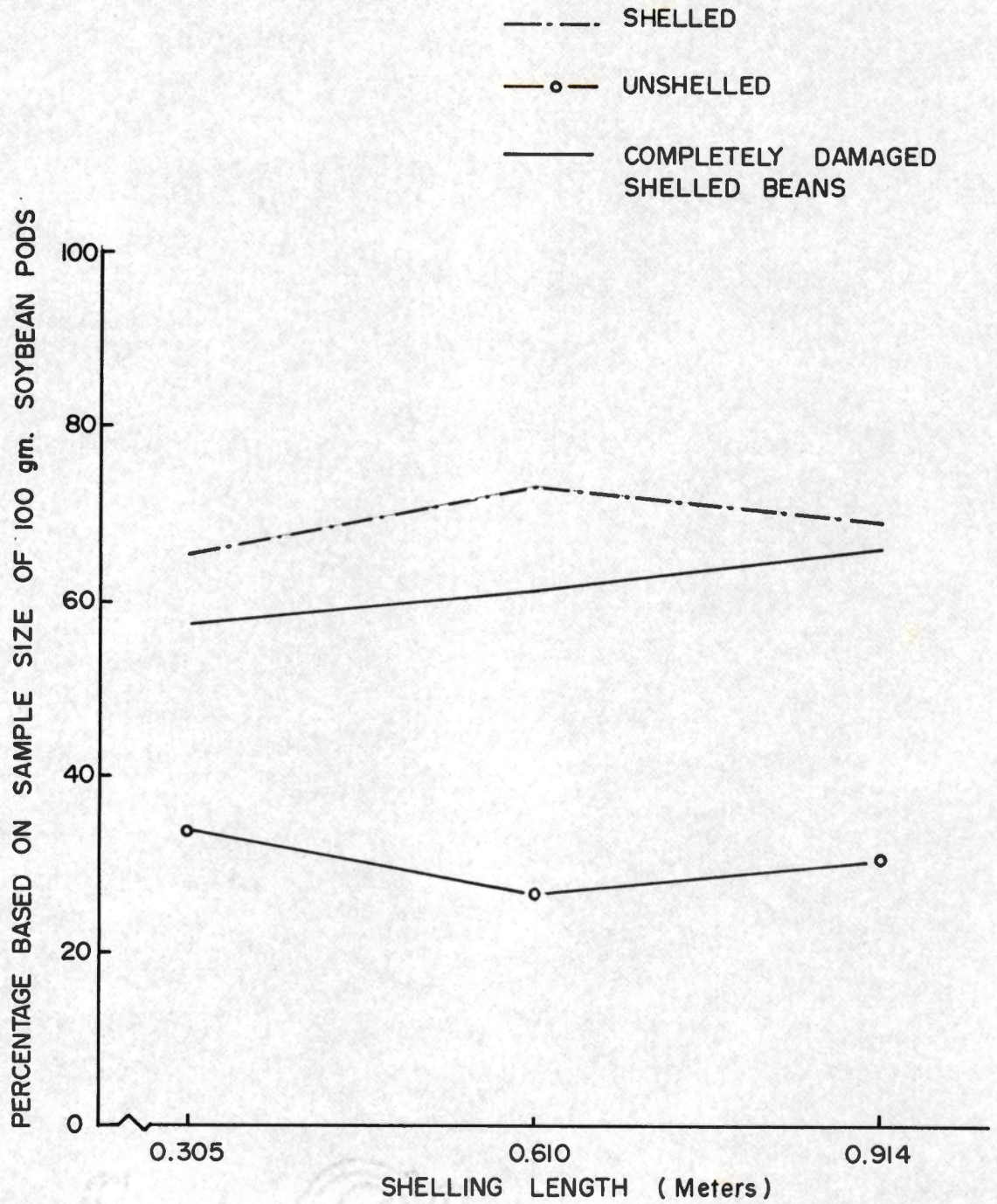


Figure 24. Effect of shelling length on mature green soybean shelling.

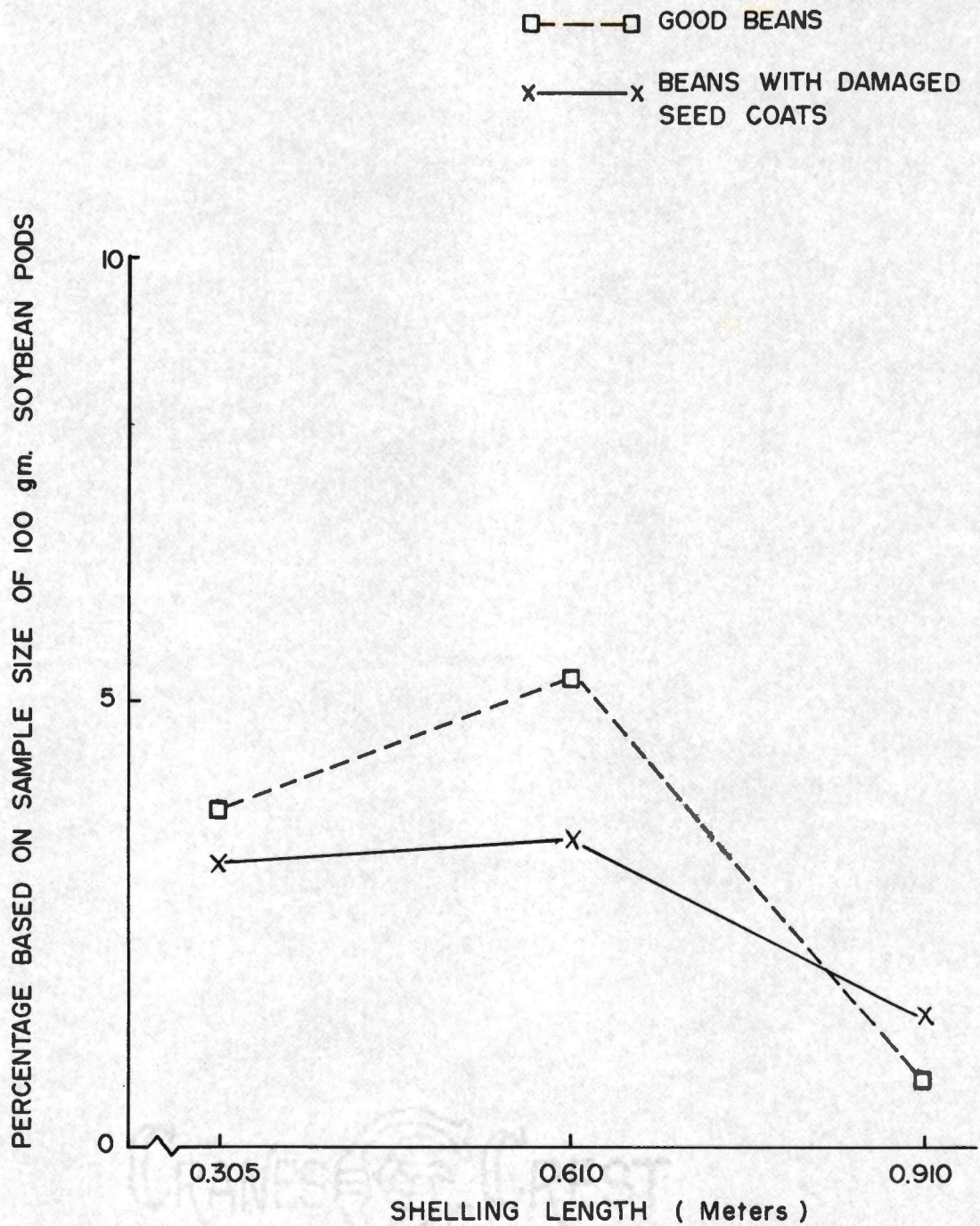


Figure 25. Effect of shelling length on quality of shelled bean.

IV. OTHER RESULTS

Relative Belt Speed

The effects of belt relative speed considered over all other operating factors are shown in Figures 26 and 27. These figures show that, generally, shelling increased with increase in relative belt speed. The rate of increase, however, declined with high relative speeds. Bean damage followed the same pattern as shelling. Bean quality, as shown in Figure 27, also appeared to increase with relative speed to a peak at 37 meters per minute and declined thereafter. Bean coat damage, however, increased with increase in relative belt speed. The optimum relative belt speed was found to be 37 meters per minute.

Results of an analysis of variance indicated that relative belt speed had a significant effect on the capacity of the sheller and the quality of shelled beans.

The foregoing results are in agreement with results obtained in a previous study (19).

Computation of Power Requirements for the Sheller

The power required for starting the sheller can be determined by applying Equation (25) in Chapter III. This is the power required to overcome the total inertia of the mechanism. For the same top and bottom belt materials, the maximum power, P , is given as

$$P = Le \left\{ \frac{\dot{x}_1^2}{t_1} + \frac{\dot{x}_2^2}{t_2} \right\}. \quad (67)$$

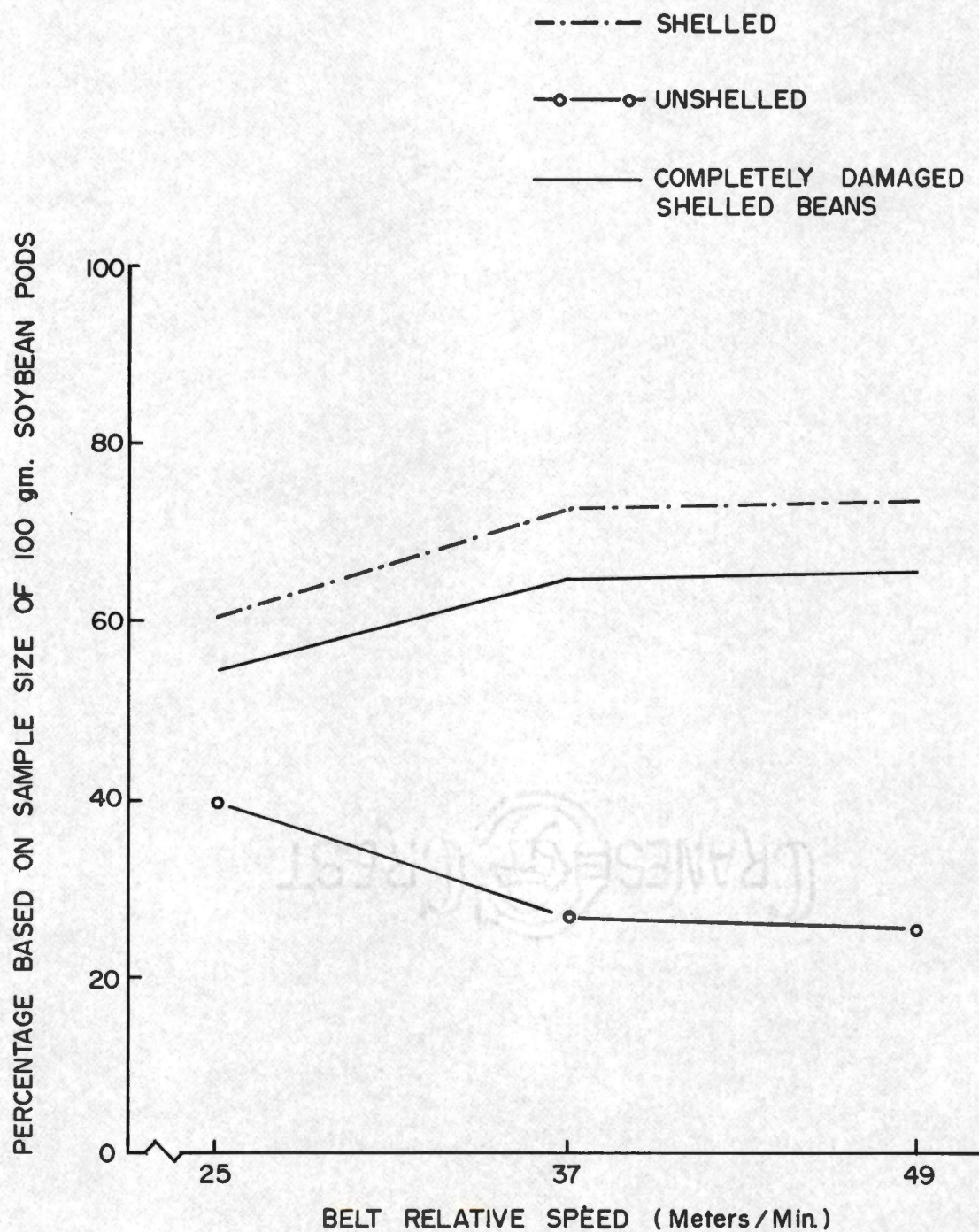


Figure 26. Effect of belt relative speed on mature green soybean shelling.

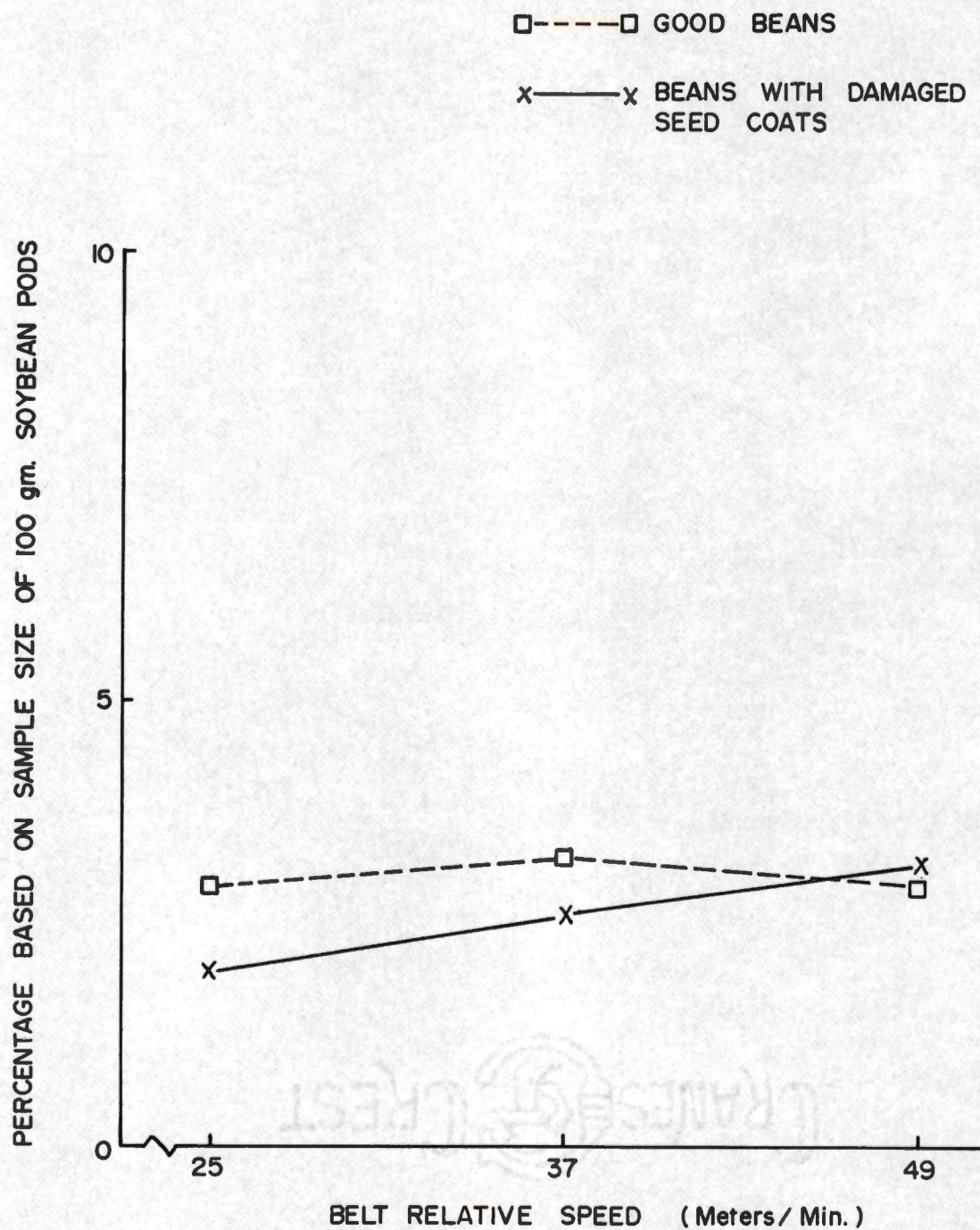


Figure 27. Effect of belt relative speed on quality of shelled bean.

When $L = 3.835\text{m}$, $t_1 = 8 \text{ secs}$, $t_2 = 10 \text{ secs}$, $\dot{x}_1 = 122\text{m/mins}$, and $\dot{x}_2 = 85 \text{ m/mins}$ are substituted into Equation (67), the following result is obtained:

$$P = 2.752e \text{ Watts.} \quad (68)$$

For the smooth belt with $e = 0.94 \text{ kg/m}$, the maximum power required was found to be 2.587 watts.

Belt Spacing

The effects of belt spacing considered over all other operating factors are shown in Figures 28 and 29. Generally, shelling decreased with increase in belt spacing as shown in Figure 28. The optimum range of belt spacing depended on the soybean cultivar. Bean damage also showed a decrease with increase in belt spacing. Figure 28 also shows a close relationship between shelled and damaged beans. The explanation for this is that percent bean damage appeared to form a constant proportion of percent beans shelled.

Figure 29 indicates that bean coat damage tended to decrease with increase in belt spacing. Percent good beans showed an erratic response to belt spacing.

Results of an analysis of variance indicated that belt spacing had a significant effect on shelling and quality of shelled beans.

The results obtained in the present study conformed to those in a previous study (19).

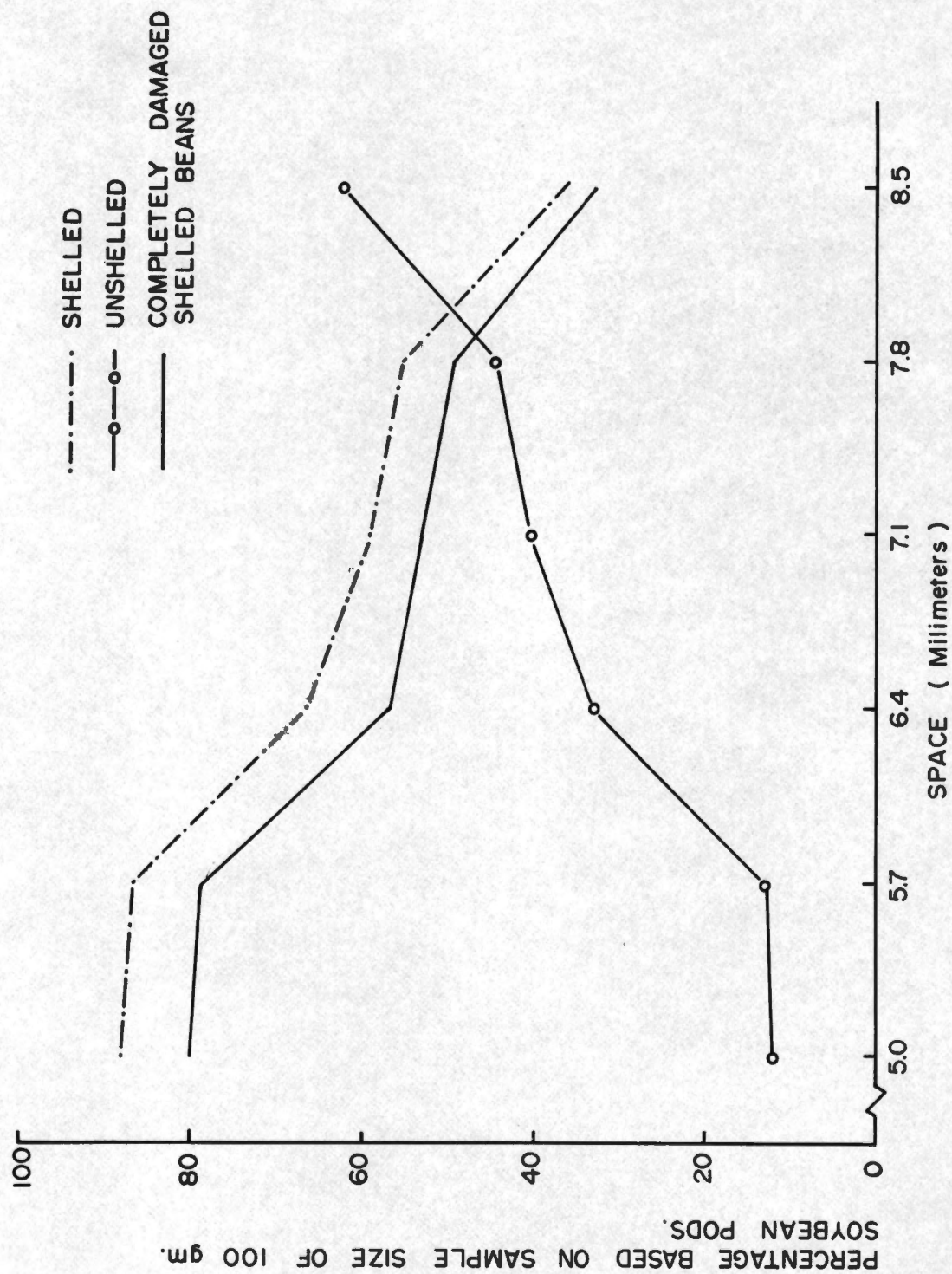


Figure 28. Effect of belt spacing on mature green soybean shelling.

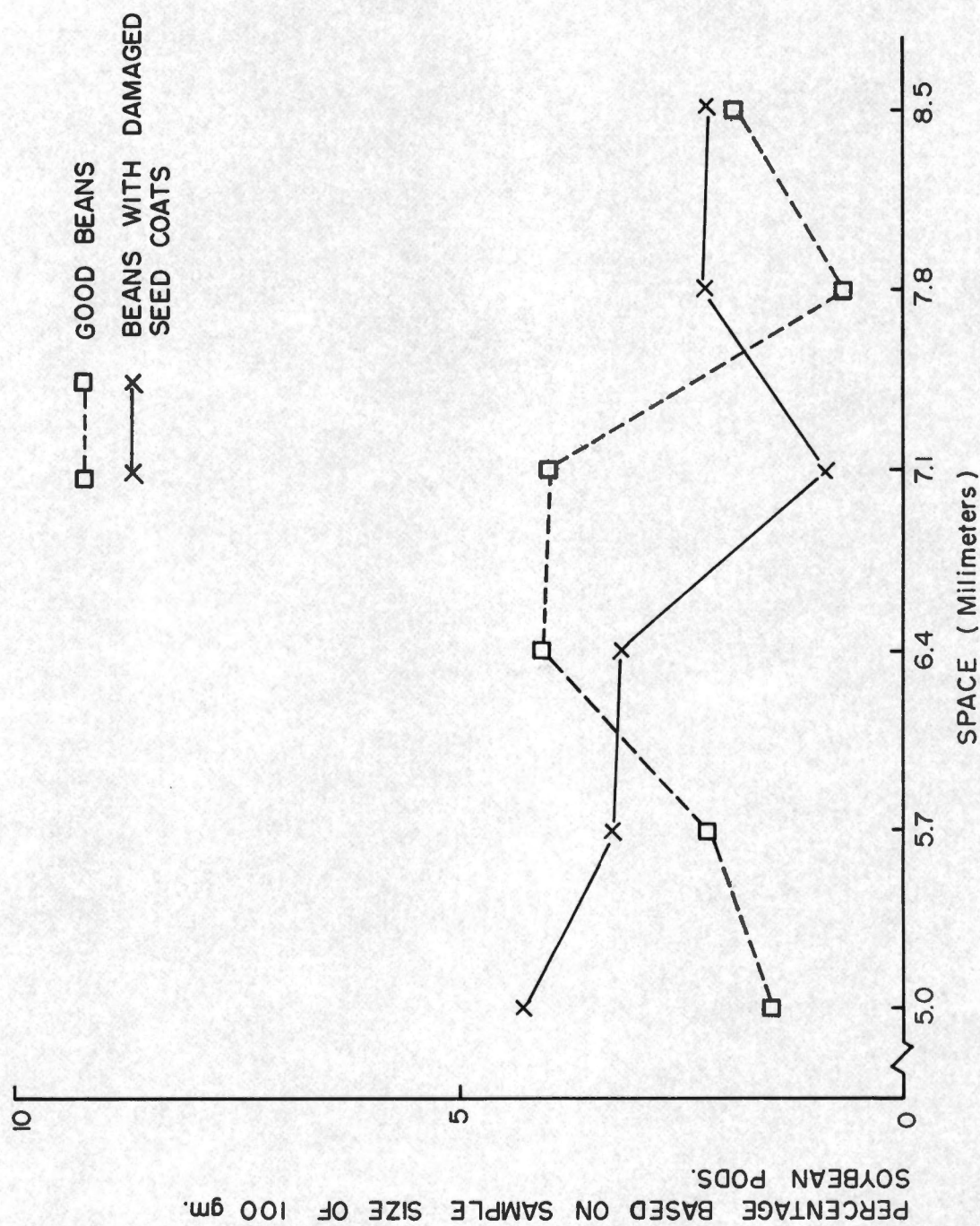


Figure 29. Effect of belt spacing on quality of shelled bean.

The results also seemed to agree with the theoretical analysis. By Equation (34) in Chapter III, the shelling force is a frictional force proportional to the coefficient of friction, μ , between the belt and soybean pod, and also proportional to the normal reaction, N , of the belt on the pod. Since the coefficient of friction between a particular belt material and soybean pod is constant, the shelling force could be increased only by increasing the normal force. Manipulating the belt spacing was equivalent to changing the magnitude of the normal force. The effect of decreasing the belt spacing was to increase the contact pressure between the belts and the pod. This resulted in an increase in the normal force and hence the shelling force. An increase in the belt spacing had the effect of decreasing the belt-pod contact pressure and thus the shelling force. These results therefore explain the effect of belt spacing on shelling and bean quality.

The optimum spacings for all cultivars of soybeans used in the study were found to lie between 5.66 and 7.75 millimeters.

Soybean Cultivars

Three soybean cultivars were used for the entire study of the design and performance of the experimental parallel belt sheller. The soylima, a flat vegetable soybean, was used as the standard of comparison. The other two round field soybean cultivars, Prize and Forrest, were used when either one or both of them were available during test season.

Results of a previous study (19), considering only the Forrest and soylima cultivars, showed that the sheller performed better with Forrest cultivar than the soylima. During that test an average of 76% shelling or partial shelling was obtained with the Forrest cultivar as compared to 56% for the soylima. Less bean damage was also noticed with Forrest than the soylima cultivar.

The results of the present study did not show much difference, with respect to shelling, among the cultivars used including the soylima. However, total bean damage and bean coat damage were much lower for the round field cultivars than the flat cultivar.

Results from the analysis of variance indicated that soybean type had no significant effect on shelling; however, it had a significant effect on bean damage. The results of the present and previous studies point to the conclusion that though the amount of shelling did not appear to depend on the soybean cultivar, bean damage did. Less bean damage was observed with the round soybean cultivars than the flat one (19).

Sheller Modifications Performance Results

The performance of the five versions of the sheller design are shown in Figures 30 and 31. Figure 30 shows that the shelling performance of sheller versions 1, 3, 4 and 5 were about the same. However, the performance of sheller 2 was much lower. Recalling, sheller 2 had identical design as sheller 1, the original design, except the top belt had a rough surface and the bottom belt surface was smooth just as all the other sheller versions. The other versions had a smooth top belt.

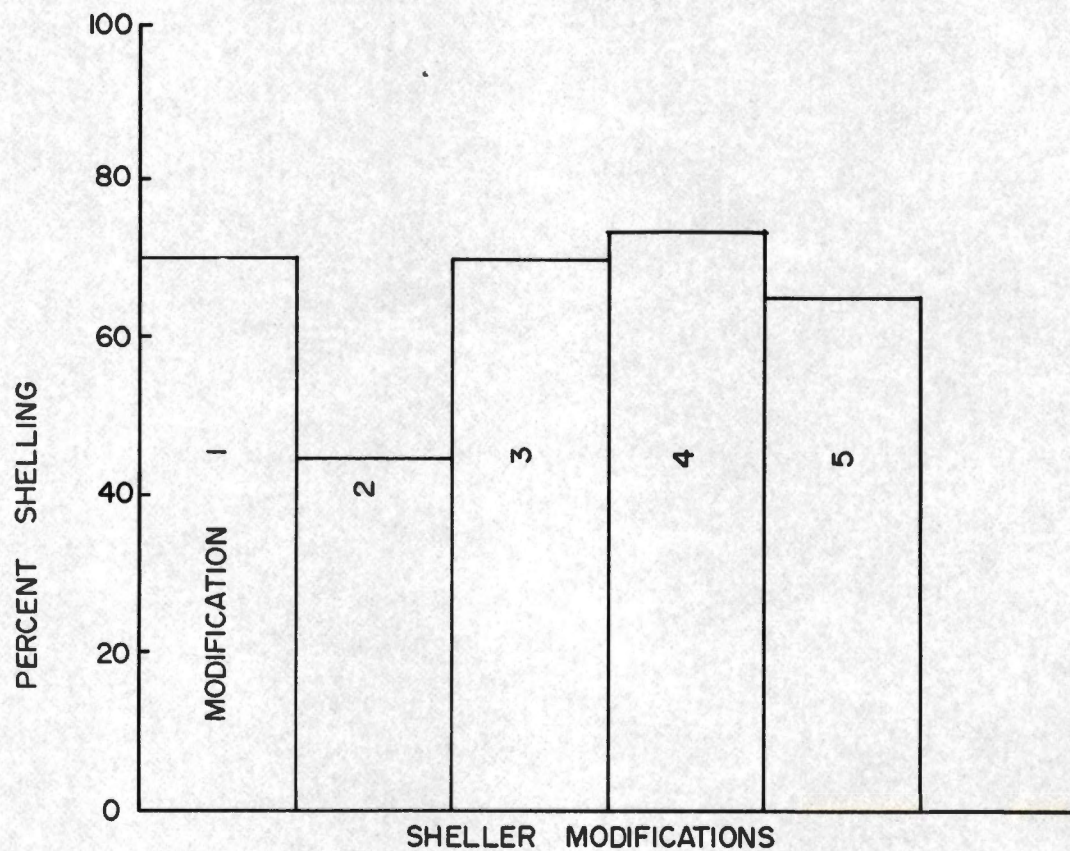


Figure 30. Performance of modified sheller on shelling.

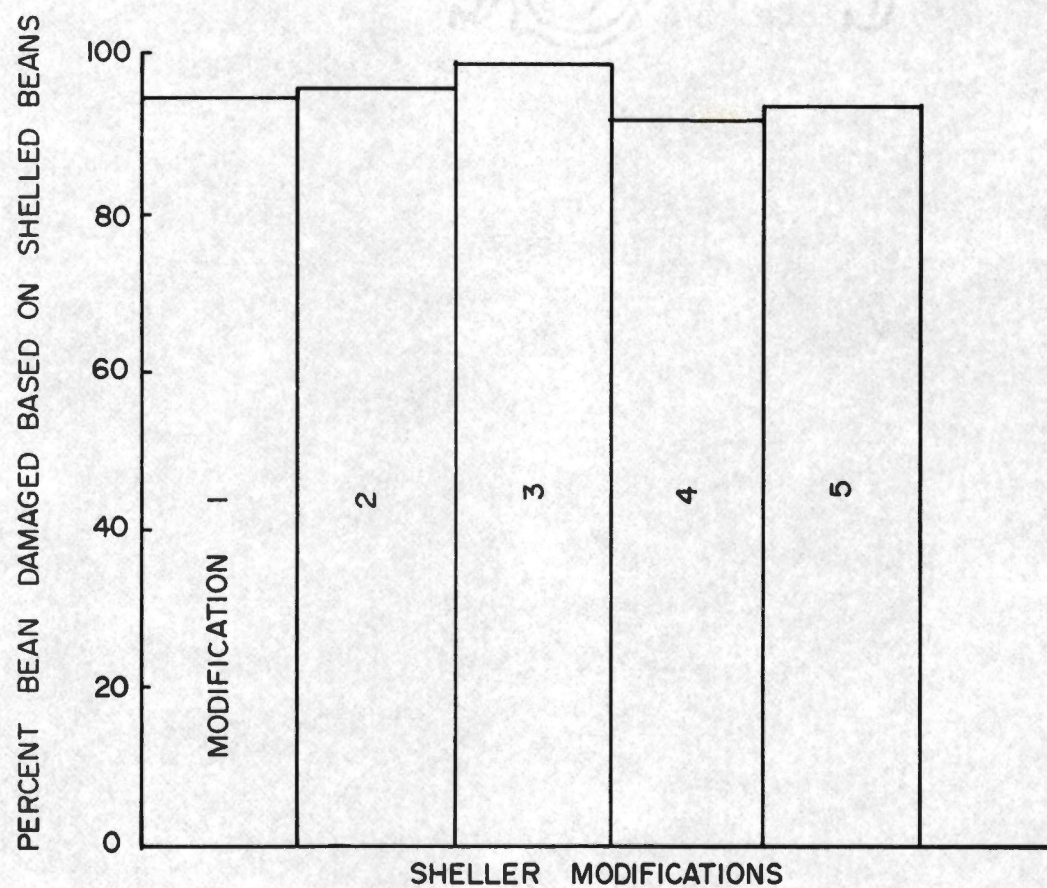


Figure 31. Bean damage caused by modified shellers.

According to Figure 31, all versions of the sheller caused almost identical amounts of bean damage. Sheller 4 produced the highest shelling and caused the minimum bean damage compared to the others.

Considering the sheller performance over all design versions, operating factors and soybean types, it produced 69.2% shelling, 62.1% total bean damage, 2.6% bean coat damage and 3.1% good beans. Thus, of the total beans shelled, 92% were damaged and only 8% were good beans.

CHAPTER VII

SUMMARY AND CONCLUSIONS

An experimental parallel belt sheller was designed, constructed and evaluated in a previous study to determine its suitability for shelling mature green vegetable soybeans (19). Results of the study indicated some potential for use of such a mechanism. It was necessary therefore to conduct a further investigation on the sheller to study the other factors which were not studied previously but which seemed to affect the sheller performance. Although the original sheller performed well it did cause a high degree of damage to the shelled beans.

The excessive bean damage caused concern and in an attempt to isolate the causes and take measures to minimize the damage the present study was undertaken.

Though the effects of new factors were ascertained, the general results of this study were not too different from the previous one.

Belt material was found to affect the shelling capacity of the sheller. The smooth belt performed better than the rough one. However, total bean damage did not appear to reduce with the surface characteristics of the belt. Moreover the rough belt did more damage to the bean coats than the smooth one.

Neither shelling nor bean damage was found to be affected by top belt inclination within the range of 0 to 5 degrees.

The shelling length test showed conclusively that the shelling capacity of the sheller and the quality of the shelled bean were affected by the shelling length.

Relative belt speed was found to affect the shelling capacity of the sheller and the bean quality. This result confirmed the findings of a previous study (19) concerning the effect of belt speed.

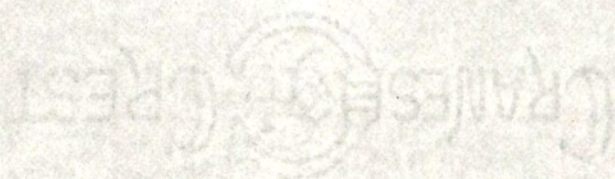
For belt spacing, results of the present study as well as the previous indicated it to have a significant effect on shelling and bean quality. The smaller the spacing, the higher the shelling and the lower the bean quality were.

Soybean cultivars did not appear to affect percent shelling but did affect bean damage. Shelled bean quality was found to be higher for the round soybean cultivars than for the flat one.

The sheller versions with smooth identical top and bottom belt material were found to out perform the rough top belt version. All versions of the sheller caused almost the same amount of bean damage. The sheller version which performed best was the one with smooth identical top and bottom belt material and 0.610 meters shelling length.

On the whole the best sheller version did not perform any better than the original experimental parallel belt sheller. On the basis of bean quality, the performance of the new design, resulting from this study, is very unsatisfactory.

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APPENDICES

APPENDIX A

SHELLER DATA FOR 1976

The experimental data collected in 1976:

NOTATION

Belt	1 = Smooth top belt
	2 = Rough top belt
Length	1 = 0.914 meters shelling length
Mach	1 = Original sheller design
Rep	1 = Replication 1
	2 = Replication 2
	3 = Replication 3
Space	1 = 4.73 mm belt spacing
	2 = 5.44 mm belt spacing
	3 = 6.15 mm belt spacing
	4 = 6.85 mm belt spacing
	5 = 7.56 mm belt spacing
	6 = 8.26 mm belt spacing
Speed	1 = 73 meters per min
	2 = 85 meters per min
	3 = 97 meters per min
Type	SL = Soylima cultivar
	VP = Prize cultivar

TABLE 1

Experimental Data for 1976 (Based on 100 gram Weight of Soybean Sample Size)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
1	1	1	1	SL	1	1	1	2.08	0.00	1.38	92.48
2	1	1	1	SL	1	1	2	0.00	0.64	7.28	87.85
3	1	1	1	SL	1	1	3	10.41	5.78	25.35	54.96
4	1	1	1	SL	2	1	1	2.28	0.00	0.00	92.18
5	1	1	1	SL	2	1	2	0.00	0.00	0.00	95.08
6	1	1	1	SL	2	1	3	29.60	5.68	13.28	46.58
7	1	1	1	SL	3	1	1	0.00	1.38	0.63	94.38
8	1	1	1	SL	3	1	2	0.00	0.66	8.18	86.37
9	1	1	1	SL	3	1	3	24.81	3.28	20.08	45.28
10	1	1	1	SL	1	1	1	0.00	1.55	0.00	91.68
11	1	1	1	SL	1	2	2	4.05	0.00	10.20	79.28
12	1	1	1	SL	1	2	3	24.38	0.00	16.92	55.88
13	1	1	1	SL	2	2	1	0.00	4.28	0.00	90.68
14	1	1	1	SL	2	2	2	5.70	0.70	12.19	78.12
15	1	1	1	SL	2	2	3	30.58	7.73	14.78	43.28
16	1	1	1	SL	3	2	1	0.00	0.71	0.00	94.68
17	1	1	1	SL	3	2	2	1.76	0.00	5.68	89.38
18	1	1	1	SL	3	2	3	38.18	6.33	11.12	41.08
19	1	1	1	SL	1	3	1	0.00	0.71	0.00	94.38
20	1	1	1	SL	1	3	2	11.11	0.65	14.38	69.90

TABLE 1 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
21	1	1	1	SL	1	3	3	66.36	2.98	2.56	26.03
22	1	1	1	SL	2	3	1	0.00	0.00	0.00	91.38
23	1	1	1	SL	2	3	2	16.38	0.38	5.58	74.20
23	1	1	1	SL	2	3	3	58.08	5.68	5.98	27.58
25	1	1	1	SL	3	3	1	0.00	1.28	0.00	97.18
26	1	1	1	SL	3	3	3	64.75	6.68	5.28	19.60
27	1	1	1	SL	3	3	2	12.98	2.13	12.68	67.98
28	1	2	1	SL	2	1	1	15.55	0.56	6.90	76.99
29	1	2	1	SL	2	1	2	14.11	3.16	18.14	60.00
30	1	2	1	SL	2	1	3	64.08	3.08	6.88	24.28
31	1	2	1	SL	1	1	1	16.88	0.48	7.61	71.70
32	1	2	1	SL	1	1	2	23.31	2.48	14.62	55.76
33	1	2	1	SL	1	1	3	63.00	4.00	6.80	31.20
34	1	2	1	SL	3	1	1	9.88	0.00	11.14	73.58
35	1	2	1	SL	3	1	2	25.18	2.93	17.58	48.88
36	1	2	1	SL	3	1	3	65.23	3.95	4.98	23.90
37	1	2	1	SL	1	2	1	23.05	0.67	0.00	62.31
38	1	2	1	SL	1	2	2	57.34	0.62	4.62	35.19
39	1	2	1	SL	1	2	3	94.20	1.28	0.00	4.10
40	1	2	1	SL	2	2	1	2.92	0.70	9.13	82.05

TABLE 1 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
41	1	2	1	SL	2	2	2	77.80	1.08	4.28	14.90
42	1	2	1	SL	2	2	3	89.38	0.00	0.81	9.28
43	1	2	1	SL	3	2	1	13.21	0.70	5.50	85.42
44	1	2	1	SL	3	2	2	60.30	0.90	4.40	34.80
45	1	2	1	SL	3	2	3	90.00	0.80	0.69	6.00
46	1	2	1	SL	2	3	1	39.92	0.00	6.71	52.48
47	1	2	1	SL	2	3	2	81.82	0.00	3.03	14.41
48	1	2	1	SL	2	3	3	86.93	0.78	3.19	8.63
49	1	2	1	SL	1	3	1	55.63	0.00	6.19	37.45
50	1	2	1	SL	1	3	2	64.88	4.39	4.21	26.08
51	1	2	1	SL	1	3	3	67.00	2.10	7.28	22.98
52	1	2	1	SL	3	3	1	42.00	0.00	6.51	51.49
53	1	2	1	SL	3	3	2	70.42	3.58	7.11	23.10
54	1	2	1	SL	3	3	3	74.26	1.40	5.20	16.00
55	1	1	1	VP	2	1	4	14.68	2.45	12.58	67.35
56	1	1	1	VP	2	1	5	31.65	0.78	11.78	52.36
57	1	1	1	VP	2	1	6	32.08	2.48	12.89	49.66
58	1	1	1	VP	2	1	4	35.92	2.99	10.09	47.20
59	1	1	1	VP	1	2	4	28.08	0.84	7.01	61.51
60	1	1	1	VP	1	2	5	34.68	3.31	11.28	47.58

TABLE 1 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
61	1	1	1	VP	1	2	6	57.08	5.18	5.28	31.28
62	1	1	1	VP	1	2	1	58.68	2.20	4.95	33.68
63	1	1	1	VP	1	3	4	25.32	1.98	18.11	51.18
64	1	1	1	VP	1	3	5	38.51	0.99	9.42	47.78
65	1	1	1	VP	1	3	6	30.18	4.56	11.54	53.85
66	1	1	1	VP	1	3	2	56.76	3.28	4.11	33.28
67	1	1	1	VP	2	2	4	20.81	0.78	12.28	62.08
68	1	1	1	VP	2	2	5	25.92	3.52	15.68	53.58
69	1	1	1	VP	2	2	6	48.98	1.89	10.72	37.38
70	1	1	1	VP	2	2	3	63.71	0.81	5.08	28.08
71	1	1	1	VP	3	3	4	25.32	1.98	18.10	51.18
72	1	1	1	VP	3	3	5	35.51	0.99	9.42	47.78
73	1	1	1	VP	3	3	6	30.18	4.56	11.54	53.85
74	1	1	1	VP	3	3	4	56.76	3.28	4.11	33.28
75	1	1	1	VP	3	1	4	0.00	0.00	0.00	99.10
76	1	1	1	VP	3	1	5	20.58	1.86	15.29	58.58
77	1	1	1	VP	3	1	6	32.03	2.80	15.04	46.73
78	1	1	1	VP	3	1	3	34.28	0.98	8.81	51.83
79	1	1	1	VP	3	2	4	12.11	0.70	9.40	74.78
80	1	1	1	VP	3	2	5	23.36	6.72	14.98	55.18

TABLE 1 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
81	1	1	1	VP	3	2	6	53.38	2.78	10.68	31.78
82	1	1	1	VP	3	2	1	61.21	3.38	9.58	23.30
83	1	1	1	VP	3	3	4	13.29	2.48	13.28	67.93
84	1	1	1	VP	3	3	5	33.48	0.81	12.08	51.38
85	1	1	1	VP	3	3	6	33.18	1.78	6.68	56.99
86	1	1	1	VP	3	3	2	75.47	0.97	4.28	18.78
87	1	1	1	VP	2	3	5	42.18	3.33	5.78	46.68
88	1	1	1	VP	2	3	6	39.28	1.78	13.32	42.38
89	1	1	1	VP	2	3	3	68.18	1.21	3.78	25.05
90	1	1	1	VP	2	3	6	30.68	4.68	6.83	53.48
91	1	2	1	VP	1	1	4	11.34	0.60	11.18	75.88
92	1	2	1	VP	1	1	5	34.43	0.63	17.28	45.22
93	1	2	1	VP	1	1	6	50.98	4.24	12.28	30.88
94	1	2	1	VP	1	1	4	67.18	6.80	7.21	18.08
95	1	2	1	VP	2	1	4	13.31	0.63	14.93	69.15
96	1	2	1	VP	2	1	5	21.78	6.28	15.13	54.58
97	1	2	1	VP	2	1	6	35.95	3.08	13.68	44.46
98	1	2	1	VP	2	1	5	46.93	3.31	15.73	31.38
99	1	2	1	VP	3	1	4	13.78	1.78	10.08	69.80
100	1	2	1	VP	3	1	5	21.08	7.70	26.48	51.68

TABLE 1 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
101	1	2	1	VP	3	1	6	49.58	6.88	7.68	34.48
102	1	2	1	VP	3	1	1	68.28	4.68	5.73	19.84
103	1	2	1	VP	1	2	4	12.28	3.18	15.98	66.88
104	1	2	1	VP	1	2	5	39.60	4.08	16.29	38.88
105	1	2	1	VP	1	2	6	48.33	3.22	12.73	35.38
106	1	2	1	VP	1	2	2	75.51	2.48	6.01	15.10
107	1	2	1	VP	2	2	4	13.00	4.00	16.00	60.00
108	1	2	1	VP	2	2	5	35.68	4.28	12.80	45.63
109	1	2	1	VP	2	2	6	62.78	4.81	9.01	22.65
110	1	2	1	VP	2	2	3	82.53	3.35	3.51	8.69
111	1	2	1	VP	3	2	4	23.61	2.58	12.52	54.93
112	1	2	1	VP	3	2	5	55.78	4.20	11.38	26.81
113	1	2	1	VP	3	2	6	63.88	6.08	7.28	20.70
114	1	2	1	VP	3	2	4	73.35	3.18	3.10	19.48
115	1	2	1	VP	1	3	4	58.61	0.62	10.92	29.53
116	1	2	1	VP	1	3	5	77.08	0.62	4.53	14.70
117	1	2	1	VP	1	3	6	84.28	0.96	4.61	8.11
118	1	2	1	VP	1	3	3	94.28	1.48	1.43	3.30
119	1	2	1	VP	2	3	4	56.13	1.28	6.78	33.32
120	1	2	1	VP	2	3	5	64.93	0.71	4.28	28.56

TABLE 1 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
121	1	2	1	VP	2	3	6	85.68	0.98	3.28	8.78
122	1	2	1	VP	3	3	5	98.08	0.48	0.28	2.78
123	1	2	1	VP	3	3	4	56.13	1.28	6.78	33.32
124	1	2	1	VP	3	3	5	77.78	1.43	9.48	16.97
125	1	2	1	VP	3	3	6	85.51	0.60	4.78	7.78
126	1	2	1	VP	3	3	6	96.00	0.98	1.72	2.23

APPENDIX B

SHELLER DATA FOR 1977

The experimental data collected in 1977:

NOTATION

Belt	1 = Smooth top belt
Length	1 = 0.914 meters shelling length
	2 = 0.610 meters shelling length
	3 = 0.305 meters shelling length
Mach	3 = Sheller 3
	4 = Sheller 4
	5 = Sheller 5
Rep	1 = Replication 1
	2 = Replication 2
	3 = Replication 3
Space	1 = 4.73 mm belt spacing
	2 = 5.44 mm belt spacing
	3 = 6.15 mm belt spacing
	4 = 6.85 mm belt spacing
	5 = 7.56 mm belt spacing
	6 = 8.26 mm belt spacing
Speed	1 = 73 meters per minute
	2 = 85 meters per minute
	3 = 97 meters per minute

Type SL = Soylima cultivar
 RH = Forrest cultivar
 VP = Prize cultivar

TABLE 2
Experimental Data for 1977 (Based on 100 grams Weight of Soybean Sample Size)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
1	5	1	3	SL	1	3	3	54.8	2.7	5.6	36.7
2	3	1	1	SL	1	1	5	8.3	0.0	5.5	83.5
3	4	1	2	SL	1	2	3	48.1	3.7	6.7	38.7
4	4	1	2	SL	1	1	2	11.5	1.6	6.3	77.0
5	4	1	2	SL	3	3	3	0.0	0.0	0.0	95.8
6	4	1	2	SL	2	1	2	15.0	1.7	6.8	75.5
7	4	1	2	SL	3	1	3	26.4	0.7	9.6	60.3
8	5	1	3	RH	1	3	3	20.5	4.8	0.0	73.7
9	5	1	3	RH	3	3	3	23.3	8.6	0.0	66.1
10	5	1	3	SL	2	2	2	32.7	2.1	11.0	52.7
11	5	1	3	SL	1	2	1	9.5	3.8	2.6	83.8
12	3	1	1	SL	3	3	4	46.7	0.0	0.0	55.7
13	3	1	1	SL	1	3	6	86.1	0.0	0.0	17.1
14	3	1	1	SL	3	2	5	33.9	1.5	4.1	62.1
15	3	1	1	SL	2	1	4	4.1	0.0	2.8	90.9
16	5	1	3	RH	2	1	2	9.2	2.1	0.0	85.7
17	5	1	3	RH	3	2	3	17.3	3.9	0.0	77.0
18	3	1	1	SL	3	1	4	1.5	0.0	4.5	92.9
19	3	1	1	VP	3	1	2	8.2	0.2	1.5	86.8
20	5	1	3	SL	3	3	3	70.0	2.1	0.0	29.0

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
21	4	1	2	SL	2	3	3	36.8	2.1	8.2	52.2
22	3	1	1	SL	2	2	5	28.8	2.2	2.9	66.0
23	3	1	1	SL	1	1	4	13.9	0.0	1.4	83.7
24	3	1	1	SL	3	1	5	14.1	0.7	5.5	78.1
25	3	1	1	SL	3	3	1	33.6	1.5	8.2	58.8
26	3	1	1	SL	3	2	6	60.0	3.5	1.9	35.2
27	3	1	1	SL	2	2	4	26.7	0.0	1.1	72.8
28	3	1	1	SL	2	3	4	30.6	0.3	0.0	73.8
29	3	1	1	SL	2	1	5	10.7	0.3	7.4	79.2
30	3	1	1	SL	2	3	5	58.5	0.0	2.0	42.7
31	5	1	3	RH	3	3	3	63.9	5.4	0.0	30.2
32	3	1	1	SL	3	3	5	69.9	0.0	1.8	31.7
33	3	1	1	SL	1	2	5	49.2	1.1	2.2	48.8
34	3	1	1	SL	1	3	4	53.1	0.0	0.0	49.0
35	5	1	3	SL	3	2	2	21.0	2.9	7.8	67.1
36	3	1	1	SL	3	2	4	14.4	0.0	5.5	81.6
37	3	1	1	SL	2	3	6	81.7	0.0	0.0	21.5
38	5	1	3	SL	1	3	4	50.0	7.7	0.0	40.3
39	3	1	1	SL	1	2	4	38.7	0.0	0.0	61.9
40	3	1	1	SL	1	1	6	54.5	0.3	3.1	39.2

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
41	5	1	3	RH	2	3	2	6.0	2.6	0.0	89.5
42	5	1	3	RH	1	3	2	5.4	2.2	0.4	91.4
43	5	1	3	RH	3	3	2	5.3	2.9	2.0	87.9
44	3	1	1	SL	2	1	6	30.7	1.7	7.2	61.4
45	5	1	3	SL	3	3	2	32.5	4.0	9.1	54.4
46	5	1	3	SL	2	2	2	36.1	4.2	3.3	54.9
47	3	1	1	SL	3	6	6	80.1	0.9	0.0	22.0
48	3	1	1	SL	1	5	5	63.6	0.0	0.5	38.6
49	3	1	1	SL	2	6	6	51.6	5.5	3.3	41.1
50	5	1	3	RH	2	3	3	25.5	6.3	1.5	67.1
51	5	1	3	RH	1	2	3	29.2	4.6	0.0	63.7
52	4	1	2	SL	2	2	2	8.5	5.6	7.5	76.6
53	5	1	3	SL	1	2	3	58.2	1.1	7.3	32.8
54	5	1	3	RH	2	2	3	55.7	6.3	0.0	37.8
55	4	1	2	RH	1	2	2	3.2	4.7	0.1	87.7
56	4	1	2	RH	2	2	4	19.5	9.7	3.2	64.1
57	4	1	2	SL	2	3	2	19.5	4.4	4.5	69.1
58	4	1	2	RH	3	2	4	21.2	8.3	0.4	66.5
59	4	1	2	RH	2	1	3	34.9	12.0	2.9	46.8
60	5	1	3	SL	3	2	3	56.2	2.3	7.7	33.7

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
61	4	1	2	SL	2	1	2	7.9	2.4	4.2	82.0
62	4	1	2	RH	1	3	2	8.1	4.5	1.0	84.0
63	5	1	3	RH	3	2	4	65.5	9.4	0.0	25.7
64	5	1	3	SL	1	1	3	53.5	1.2	10.0	33.7
65	5	1	3	RH	1	2	2	3.6	1.4	0.0	93.5
66	5	1	3	RH	2	2	2	3.6	1.4	0.0	93.5
67	5	1	3	RH	3	2	2	3.6	1.4	0.0	93.5
68	5	1	3	SL	3	1	2	45.4	3.7	4.0	46.8
69	4	1	2	RH	3	2	2	5.8	4.7	2.0	82.3
70	5	1	2	RH	2	3	3	36.5	9.1	0.0	53.0
71	5	1	3	SL	2	2	3	64.5	2.6	4.5	28.8
72	5	1	3	SL	1	3	2	25.8	4.5	11.0	57.8
73	5	1	3	RH	2	3	4	67.5	8.3	0.0	24.3
74	4	1	2	RH	2	1	2	6.5	2.6	1.2	84.1
75	5	1	3	RH	3	1	2	2.2	1.5	0.0	93.3
76	4	1	2	RH	3	3	2	6.8	6.0	1.2	83.0
77	4	1	2	SL	1	3	3	54.8	4.2	2.8	36.0
78	5	1	3	SL	2	3	3	64.8	1.2	3.9	30.7
78	4	1	2	SL	1	3	2	29.6	6.0	5.5	60.0
80	4	1	2	SL	1	1	3	23.3	2.3	12.0	62.0

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
81	4	1	2	SL	3	2	1	0.0	0.0	0.0	99.7
82	5	1	3	SL	1	2	2	23.8	1.9	9.5	63.9
83	4	1	2	RH	3	1	2	10.4	2.9	1.6	80.0
84	5	1	3	SL	1	1	3	77.0	4.3	2.5	18.3
85	4	1	2	SL	3	3	3	51.9	2.6	5.7	38.1
86	4	1	2	RH	2	3	2	18.7	6.4	0.4	72.9
87	4	1	2	RH	1	2	3	28.4	10.0	1.3	56.0
88	4	1	2	RH	2	2	4	53.9	10.0	1.0	33.3
89	5	1	3	RH	1	1	4	64.2	5.2	0.0	30.1
90	5	1	3	RH	1	1	2	2.6	3.2	0.0	91.3
91	4	1	2	RH	1	1	3	11.7	9.2	3.4	72.4
92	5	1	3	SL	2	3	2	30.5	4.5	10.0	50.7
93	4	1	2	RH	3	1	4	42.9	10.0	1.4	44.6
94	5	1	3	SL	1	1	2	39.9	1.9	8.4	47.8
95	4	1	2	RH	1	3	3	36.0	6.7	1.0	54.7
96	4	1	2	RH	2	3	3	33.3	7.0	1.5	56.1
97	4	1	2	RH	1	1	4	63.5	7.0	0.8	27.3
98	4	1	2	RH	3	2	3	28.9	10.0	3.2	54.3
99	4	1	2	RH	2	3	4	67.1	7.3	0.0	24.4
100	5	1	3	SL	1	3	1	6.8	6.9	11.0	75.0

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
101	4	1	2	RH	3	2	4	54.7	11.0	1.0	32.6
102	5	1	2	RH	2	1	4	49.9	8.0	0.0	41.5
103	4	1	2	SL	3	2	3	42.1	1.3	6.6	48.4
104	4	1	2	RH	2	2	2	9.4	2.8	1.5	81.6
105	4	1	2	RH	1	3	4	75.4	5.5	1.0	17.7
106	4	1	2	RH	3	1	3	16.0	7.6	1.1	68.2
107	4	1	2	RH	1	1	2	2.2	4.1	1.9	87.8
108	4	1	2	RH	3	3	4	66.1	7.5	1.2	25.4
109	4	1	2	RH	2	1	3	21.6	9.1	1.4	63.1
110	4	1	2	RH	1	2	4	38.5	8.2	2.6	47.1
111	4	1	2	SL	1	2	2	7.3	1.9	10.0	76.6
112	4	1	2	SL	3	2	2	7.0	2.3	9.3	78.4
113	4	1	1	SL	1	2	6	63.6	3.6	2.3	34.1
114	5	1	3	RH	3	1	3	34.1	6.4	2.6	54.2
115	5	1	3	SL	3	1	3	76.1	3.8	5.8	21.7
116	5	1	3	RH	1	2	4	62.8	5.4	0.0	32.9
117	5	1	3	RH	3	1	4	54.9	7.0	0.0	37.0
118	4	1	2	SL	2	2	3	16.1	3.1	10.0	69.2
119	3	1	1	VP	3	3	3	20.0	0.0	1.0	79.5
120	3	1	1	VP	3	2	3	1.2	0.4	0.0	96.4

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
121	3	1	1	VP	2	2	5	48.7	1.2	1.0	47.8
122	3	1	1	VP	1	3	4	38.0	0.8	0.0	63.1
123	3	1	1	VP	1	2	4	24.1	1.2	0.0	76.4
124	3	1	1	VP	2	2	2	2.8	0.0	0.0	95.4
125	3	1	1	VP	2	2	4	28.3	0.4	0.0	72.6
126	5	1	3	RH	2	2	3	21.3	8.3	0.0	70.5
127	4	1	2	SL	2	1	3	22.3	1.2	10.0	63.9
128	4	1	2	SL	3	3	2	20.8	2.8	7.0	67.0
129	3	1	1	VP	3	3	5	82.5	0.2	0.0	19.1
130	5	1	3	SL	1	1	1	15.7	0.0	4.3	77.0
131	5	1	3	SL	2	1	1	15.7	0.0	4.3	77.0
132	5	1	3	SL	3	1	1	15.7	0.0	4.3	77.0
133	3	1	1	VP	2	3	2	5.7	0.0	0.0	94.1
134	3	1	1	VP	1	3	5	71.4	1.3	0.0	29.1
135	3	1	1	VP	1	3	3	12.8	1.4	0.0	86.5
136	3	1	1	VP	2	3	5	77.0	0.8	0.0	24.1
137	3	1	1	VP	1	2	2	2.7	0.0	0.0	95.5
138	3	1	1	VP	3	3	4	41.3	0.0	0.0	59.8
139	5	1	3	RH	1	1	3	23.2	6.3	1.3	67.2
140	3	1	1	VP	2	2	3	1.8	0.0	0.5	97.6

TABLE 2 (CONTINUED)

OBS	MACH	BELT	LENGTH	CULTIVAR	REP	SPEED	SPACE	UNSHELL.	PERF.	IMPERF.	MISC.
141	3	1	1	VP	2	1	4	0.0	3.5	1.0	92.3
142	3	1	1	VP	1	2	3	1.5	0.6	0.0	95.9
143	3	1	1	VP	3	3	2	6.6	0.0	0.0	94.1
144	3	1	1	VP	3	2	2	0.0	0.0	0.0	99.8
145	3	1	1	VP	2	3	4	33.9	0.0	0.0	66.6
146	3	1	1	VP	2	1	5	54.2	2.0	1.1	39.4
147	3	1	1	VP	3	2	5	3.6	1.3	0.0	50.7
148	3	1	1	VP	1	2	5	39.6	0.2	0.6	56.2
149	3	1	1	VP	1	1	4	40.4	0.7	3.2	53.4
150	3	1	1	VP	3	2	4	21.1	1.1	0.0	77.3
151	3	1	1	VP	3	1	4	48.9	1.1	0.0	48.3
152	3	1	1	VP	3	1	5	47.2	0.0	5.1	46.9
153	3	1	1	VP	2	1	3	17.0	1.0	1.0	78.2
154	3	1	1	VP	1	3	2	3.6	0.0	0.0	96.2
155	3	1	1	VP	2	3	3	0.0	0.0	1.0	98.4
156	3	1	1	VP	1	1	2	5.0	0.2	0.0	91.1
157	3	1	1	VP	3	1	3	10.2	1.6	0.0	83.6
158	3	1	1	VP	2	1	2	5.3	0.0	0.5	90.4
159	3	1	1	VP	1	1	3	13.8	2.5	0.0	81.0

VITA

George Takyi Owirodu was born in Takoradi, Ghana on November 22, 1949. He graduated from Tema Secondary School, Ghana, in June 1968. The following September he entered the University of Ghana, and in June 1962 he received a Bachelor of Science degree in Agricultural Mechanization. He earned a Diploma in Journalism in July 1972. He worked as a journalist with a local paper. He later served as a Mathematics and Physics teacher at the Ghana International School and then as an Economics and Logic teacher at another local school.

He entered the Graduate School of the University of Tennessee, Knoxville, in September 1973. He received the Master of Science degree with a major in Agricultural Engineering in August 1975. While completing his doctoral studies in Agricultural Engineering, he was also pursuing a program toward the degree of Master of Business Administration at the University of Tennessee.