DEVELOPMENT AND ANALYSIS OF THE ROLLING-COMPRESSING WAFERING PROCESS

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Joseph Molitorisz

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DEVELOPMENT AND ANALYSIS OF THE

ROLLING-COMPRESSING WAFERING PROCESS

By

Joseph Molitorisz

AN ABSTRACT OF A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1964

Approved H. F. McColly
Carl W. Hall

ABSTRACT

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Recognizing the potential of wafering in the mechanization program of modern agriculture, the Agricultural Engineering Department at M.S.U. for several years conducted basic research in this field.

The activities covered problems such as:

1. The basic study of pelletability of grasses and legumes.
2. The development of several devices to make wafers or pellets.
3. Handling and drying studies.
4. Feeding trials.

Considering the usually unfavorable weather conditions in many parts of our country during the hay making season, the research activities were directed to the wafering of crops at a wide range of moisture content and also to the wafering of a variety of crops, including grasses and legumes. The "hay-in-a-day" idea which is so desirable in many states is one of the main objectives in the work. The losses of feed value during the making of hay directed the attention to the study of methods to process hay at higher moisture content and with minimum handling. Each step in moving hay at moisture content below 25 per cent (wb) results in additional loss of the most valued parts of alfalfa, the leaves.

The results of the research work proved that a wide variety of both grasses and legumes can be wafered at practically any moisture content up to fresh-cut condition without any additives or binding agents. The wafers retain their shape in handling, can be dried with conventional dryers, can be handled with properly-selected equipment and, most important, are acceptable to animals, both heifers and milking cows.

Wafering can be developed in two directions serving identical purposes:

1. To produce low-density wafers for which the specific density is about 20-30 lb/ft^3. These wafers can be made in various sizes and are acceptable for direct feeding and mechanical handling.
2. To produce high-density wafers for which the specific density is about 30-50 lb/ft^3. For this product an extra grinding process (probably hammer mill) might be necessary before feeding.

Both low- and high-density pellets can be made of the same crop but the more efficient utilization of storage space is provided by the high-density product, which, in some cases, could justify the additional grinding. The other factor to be considered is that lower density wafers have a higher drying rate. The higher density wafers have better durability characteristics which can be important in a large-scale, mechanized operation. All these factors must be considered carefully when farm application is studied.

One of the limiting factors for the capacity is the power consumption.

The experimental results proved that a power consumption of 6 to 8 hp-hr per ton of hay is possible. The reduced power consumption can reduce the price of the machine by using the tractor as a power source, without an auxiliary engine. The optimum moisture content of hay for wafering was found to be from 25 percent to 40 percent (wb). With crushed hay of that moisture content, the field losses are small, the power consumption is low and artificial drying is justified.

The matter of the proper structure for wafers is the critical factor. The term "structure" stands for the physical strength of the wafers, which is the function of many variables such as: the length of the stems and the arrangement of stems in the wafers. Density is not necessarily the major factor.

The feeding trials with heifers and milking cows did not indicate significant increase in dry-matter consumption nor in milk or butterfat production. Some variations were experienced as the result of differences in hay quality, size and shape of wafer, but even in similar conditions the reaction of the animals varied (1).

In general, we can conclude that wafering has its place in the modern, mechanized agriculture. The making of wafers in field operation--not restricted to a certain type crop at some critical condition--is an important step toward this goal.

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CHAPTER I

INTRODUCTION

In the process of reducing the volume of a constant mass, an increase in its density results. For a porous medium, the density change does not necessarily mean a change in the basic structural material but rather a change in the volume of the void spaces within the structure.

In order to produce the desired reduction in the volume of a material, stresses have to be applied on its boundary surfaces. The mechanical properties of the material are determining factors for the total energy input to attain the desired volumetric change.

Most of the crops in consideration for this particular process are in a complex mechanical state, effected by biological, physiological and physical factors and almost invariably, are in the state of transformation during the process.

Alfalfa, for example, may be processed in its high moisture content state and as a result of the applied stresses on the boundary surfaces its relatively "solid dry" appearance and elasto-visco-plastic characteristics, may be transformed into an almost liquid state losing its elasto-plastic characteristics, and behaving as a quasi-viscous material.

Other extreme condition for alfalfa might be the "bone dry" state when viscous properties do not exist.

In the general concept of high density self-contained hay packages, two distinct groups are considered:

Pellets: Made of compressed forages whose constituent elements (leaves and stems) have been sized by grinding (2).

Wafers: Made of compressed forages without sizing or with sizing by chopping or similar process (2).

The term specific density will be referred to as the weight of a unit volume of the body of a single piece of processed product composed of numerous constituents (stems, leaves, solids, and liquids).

The term bulk density will be referred to as the weight of a unit volume of the plurality of single bodies of the processed product in random state.

This study in concerned with a compression process which is relatively independent of the moisture-content of the forage crops, allowing the wafering of a variety of long forages at wide range of moisture content.

CHAPTER II

LITERATURE REVIEW

The attempts to convert loose fibrous agricultural crops into dense packages for economical handling and storage originated from the early part of this century. Stationary and mobile balers were invented and commercially used to make bales of hay and straw. The development of the pelleting and wafering process is, however, relatively new. It was introduced in the United States in 1929. Pelleting of ground hay has been done by stationary mills which used rollers to force the ground material through tapered holes in a die. The concept of pelleting and wafering of forages was studied and developed by several researchers. Professor H. D. Bruhn and his associates at the University of Wisconsin discovered that long hay could be compressed into stable wafers. This discovery was the by-product of research on hay-drying when mechanical compression was tried to reduce moisture content of wet hay. The year was 1953. The reported result indicated that alfalfa hay at about 20 percent moisture content when compressed at 3,000 pounds per square inch retained the shape of the compression chamber and possessed adequate strength to sustain handling stresses.

Similar results were reported by Professor H. F. McColly and his associates. James L. Butler (1958) studied the energy requirement to compress whole alfalfa hay in a hydraulically operated piston-cylinder device. Page L. Bellinger (1960) reported his studies on the pelletability of forages.

The first commercially available field wafering machine was reported by the Lundell Manufacturing Company (1960). The principle of the machine was based on the "open-ring die" design (13).

Another commercial wafering machine was produced by the Vaughan Manufacturing Company, Incorporated (1961). This machine is basically a plunger unit with a plurality of piston-cylinder compression mechanism. Researchers from the University of Illinois gave accounts on their work on pelleting (1961) by extrusion process (14). The University of California at Davis reported the results of a study on formation of hay wafers with impact load (15).

Professor H. F. McColly and the author invented the rolling-compressing wafering process in 1959. This thesis is part of the analysis of this process.

CHAPTER III

COMPARATIVE ANALYSIS OF THE SIGNIFICANCE OF THE STRUCTURAL, MECHANICAL AND GEOMETRICAL CHARACTERISTICS OF BALED AND WAFERED FORAGES

Both bales and wafers are compressed packages of loose forages. While bales are not self contained in the sense that a binding agent (wire or string) is necessary to retain the desired shape of the package, wafers do not need any foreign binding agent and thus are self contained.

The essential difference between the significance of the structural, mechanical and geometrical characteristics of the two packages is that bales are stored and handled in compressed state but when offered to the animals, the binding agents are removed and the loose state of the constituent forage restored. The geometry and density of bales are therefore merely factors for the convenience in handling storage and machine capacity without the involvement of the animal factor.

Analyzing wafers from the same point of view, we find that structurally they have to be built to possess adequate mechanical strength, durability for handling and storage. However, they either should be destroyable by the animals for consumption or if in the very high density state, an additional loosening process should be considered. Geometrically, wafers have to be designed to satisfy the requirement for mechanical handling, durability, and animal acceptance.

Size, shape, structure and mechanical properties are closely interrelated factors in making forage wafers. Neither of these properties are determining factors by themselves.

The term physical structure is applied to describe the following conditions:

a. Size of the constituent elements (length of stems)

b. Orientation and relative arrangement of the stems and fibers

c. The stem-leaf ratio.

In the study of the mechanical properties of wafers, the most important besides the conventional tensil compressive and shear strength is the total energy that is required to destroy them.

Factors Effecting the Quality and Physical Properties of Forages

Grasses and legumes are different in their physical and chemical compositions. Even within the various groups of the above species, significant differences can be found. These physical differences would include:

a. Length of the stems

b. Coarseness of the stems

c. Tensile strength of the fibers

d. Moisture content

e. Stem-leaf ratio

The Composition of the common forages shows significant differences not only with varieties and stage of maturity but also with geographical location. Table I is a collection of information of the composition of some important roughages.

TABLE I. AVERAGE COMPOSITION OF ROUGHAGES[1]

	Total Dry Matter %	Protein %	Fat %	Fiber %	Minerals %	
Alfalfa	90.5	15.4	1.6	28.5	8.3	Dry
Early Bloom	22.5	4.6	0.7	5.8	2.1	Green
Alfalfa	90.5	12.9	2.1	31.8	7.4	Dry
Past Bloom	29.3	3.6	0.7	11.9	2.2	Green
Alfalfa and	89.2	11.8	2.0	32.5	6.2	Dry
Bromgrass Pasture	22.5	4.8	0.8	5.3	2.2	Green
Bluegrass	89.4	8.2	2.8	29.8	6.5	Dry
Pasture	30.2	5.5	1.2	7.6	2.5	Green
Bromgrass	88.8	10.4	2.1	28.2	8.2	Dry
Pasture	30.0	4.2	1.3	9.0	2.1	Green
Grasses	89.0	7.0	2.5	30.9	5.5	Dry
Mixed	30.8	3.0	1.3	10.6	1.8	Green
Pasture Grasses and						Dry
Legumes - Northern States	22.0	5.0	0.9	4.8	1.9	Green
Pasture Grasses and						Dry
Legumes - Southern States	25.1	3.8	0.8	6.7	2.5	Green
Pasture Grasses	90.0	3.3	1.8	34.1	6.3	Dry
Western Plains	35.0	3.5	0.9	11.1	2.6	Green
Pasture Grasses Mature	90.0	4.6	2.3	31.9	5.9	Dry
Western Plains	65.0	2.6	1.1	22.9	4.2	Green
Sudan Grass	89.4	8.8	1.6	28.0	8.1	Dry
	23.4	1.9	0.4	8.4	2.4	Green

[1]Morrison, Frank B., Feeds and Feeding (Ithaca, New York: Morrison Publishing Company, 1957). (9)

CHAPTER IV

COMPARATIVE ANALYSIS OF SOME KNOWN WAFERING DEVICES

The commonly known processes to compress forages or other fibrous materials into wafers for livestock feed can be divided into three categories:

a. Closed bottom plunger or ram devices (10)

b. Open bottom plunger or ram decives (10)

c. External or internal roller devices (10)

These processes require pressures usually in excess of 3,000 lbs/sq. in. and are limited to crops with low moisture content, generally below 25 percent wet basis.

To characterize the above processes, the stress diagrams of the forage material in the corresponding devices are shown on Figures 1 and 2.

The stress distribution in the bodies of the masses on Figures 1 and 2 is affected by the moisture content of the processed material. Conditions may exist when the compressed material under these stresses changes from an unsaturated, relatively dry state, into a partly or fully saturated state.

Two distinct groups of conditions may exist for saturated states:

a. Drained, where both the permeable properties of the material and the boundary conditions of the compression chamber allow the discharge of the free liquids without considerable pressure (11).

b. Undrained where the boundary conditions of the compression chamber do not allow the discharge of the free liquids (11).

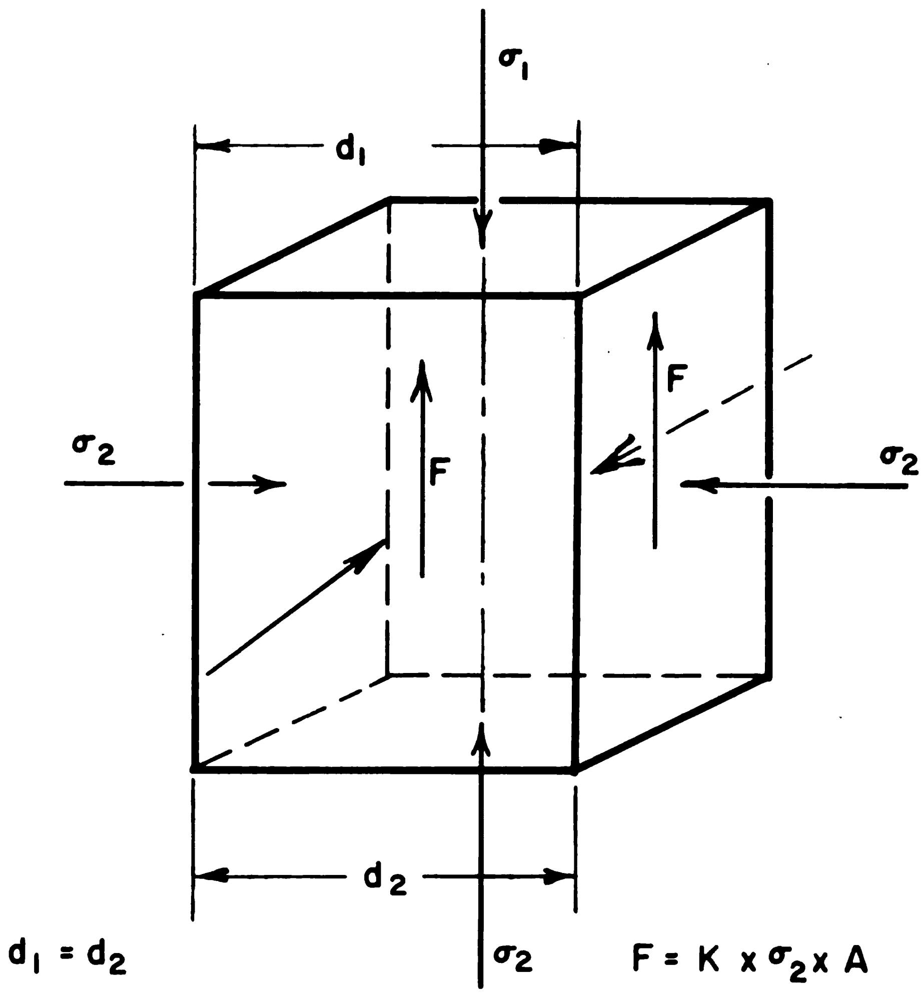


FIGURE 1. STRESS DIAGRAM FOR A CLOSED BOTTOM COMPRESSION CHAMBER

σ_1 = Major principle stress exerted by the plunger
σ_2 = Minor principle stress exerted by the lateral boundary of the chamber
σ_3 = Major principle stress exerted by the closed bottom of the chamber
K = Friction coefficient
F = Frictional force
A = Surface area of the lateral boundaries.

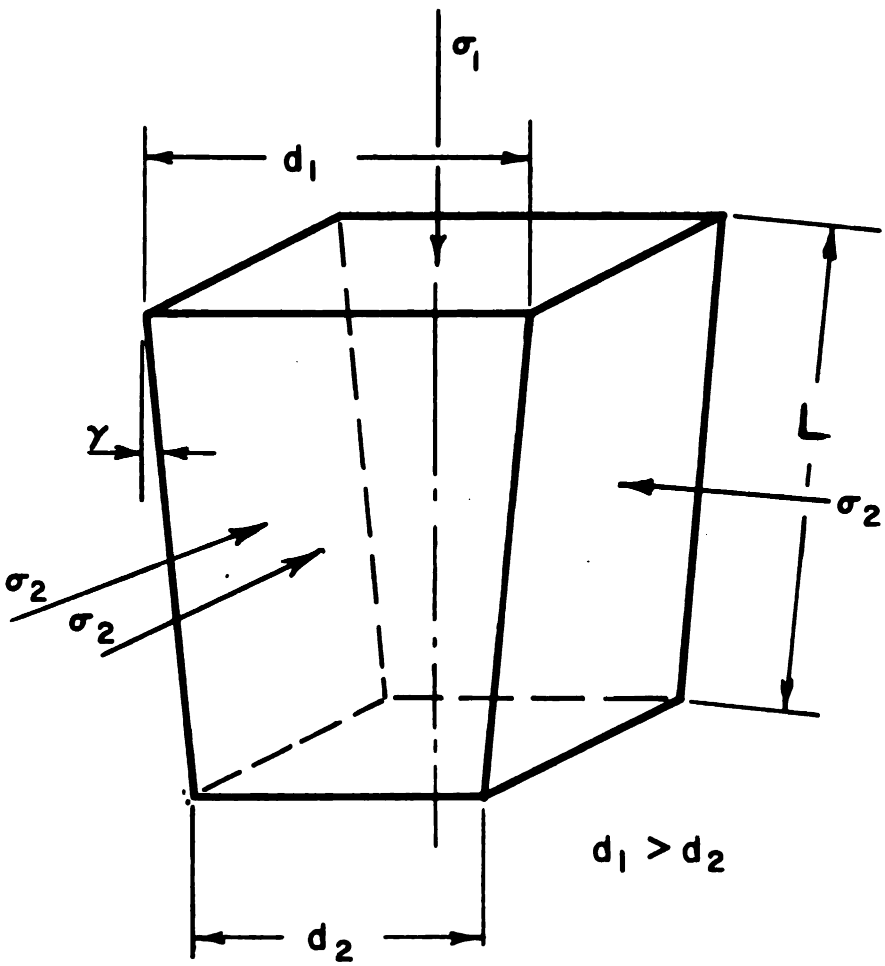


FIGURE 2. STRESS DIAGRAM FOR AN OPEN BOTTOM COMPRESSION CHAMBER

σ_1 = Major principle stress exerted by the plunger

σ_2 = Minor principle stress exerted by the converging lateral boundaries of the chamber.

CHAPTER V

STRESS ANALYSIS FOR LOW MOISTURE CONTENT MEDIUM IN A CLOSED AND OPEN BOTTOM COMPRESSION CHAMBER

For this part of the analysis, the moisture content of the processed forage is assumed at a level where even under high stresses, no freewater can be extracted. This level is found usually below 20 percent moisture content.

If the major principle stress exerted by the plunger or ram is σ_1 then the equation for the state of stress can be written as:

$$\sigma_1 = \Sigma\sigma_R$$

Where σ_R = reactive stresses

$$\sigma_R = \sigma_3 + F$$

Where $F = \sigma_2 \times K \times A$

See Figure 1.

For the open bottom plunger device, the state of stresses can be expressed as (see Figure 2):

$$\sigma_1 = \Sigma\sigma_R = \Sigma(\sigma_{R1} + \sigma_{R2})$$

$$\sigma_{R1} = \sigma_2 \sin\Upsilon$$

$$\sigma_{R2} = \sigma_2 \times K$$

Thus:

$$\sigma_1 = \sigma_2 (\sin\Upsilon K)$$

Where:

$$\text{Sin}\,\Upsilon = \frac{D_1 - D_2}{2\,1}$$

Because of the absence of the reaction force at the bottom, the cohesive properties of the compressed medium play a very important role in the process.

CHAPTER VI

STRESS ANALYSIS FOR HIGH MOISTURE CONTENT MEDIUM IN A CLOSED AND OPEN BOTTOM COMPRESSION CHAMBER

For this phase of the analysis, the moisture content in the processed medium is assumed at a level where under certain external stress liquids can be extracted from it.

In writing the equation for the stress equilibrium, the presence of the extracted liquid has to be included.

$$\sigma_1 = \Sigma \sigma_R$$

Where: σ_1 = Major principal stress

σ_R = Reactive stresses

Using the closed end plunger device, it is found that under the action of the exerted principal stresses, the previously unsaturated loose material turns into a saturated state, changing its complex elasto-plastic structure into viscous liquid state. The equation for equilibrium is now in the form of:

$$\sigma_1 = \bar{\sigma} + U\ (1-a)$$

Where:

σ_1 = Total external principal stress

$\bar{\sigma}$ = Effective stress

U = Hydrostatic pore water pressure

a = Contact area between solid particles

If drained conditions would prevail "U" would be the function of the permeability of the compressed medium. The stress equilibrium equation could be then expressed as:

$$\sigma_1 = \bar{\sigma} + U_t$$

If t = time is sufficiently long then $U \longrightarrow 0$ therefore

$$\sigma_1 = \bar{\sigma}$$

The stress equilibrium for undrained conditions might be written as:

$$\sigma_1 = \bar{\sigma} + U$$

Where "U" is not the function of time, but rather the function of σ_1.

CHAPTER VII

FUNCTIONAL ANALYSIS OF THE ROLLING-COMPRESSING WAFERING APPARATUS

The rolling-compressing wafering device is basically an open bottom compression chamber with the distinction that both the major and minor principle stresses are exerted by the lateral boundary surfaces. The major principle stresses are transaxial and perpendicular to the direction of flow of the material under process, while the minor principle stresses are acting in the axial direction providing the forces to induce the axial flow.

The lateral boundaries are cylindrical surfaces arranged radially to form a chamber as shown on Figure 3.

The cylindrical rollers are bearing supported to allow rotation but are restricted from axial movement. Their axis of rotation is adjustable relative to the longitudinal axis of the confined chamber. They may be in parallel or in a torsional configuration as shown on Figures 4 and 5.

Each roller is externally powered and rotating in the same direction with identical peripheral velocities. In contrast to a closed end type compression device, the axial expansion of the processed material is restricted only by the frictional forces on the roller's surfaces, and by the mutual adhesion and interlocking of the composite fibers. Therefore, the "minor principle stresses" may be considered as internal stresses rather than external ones.

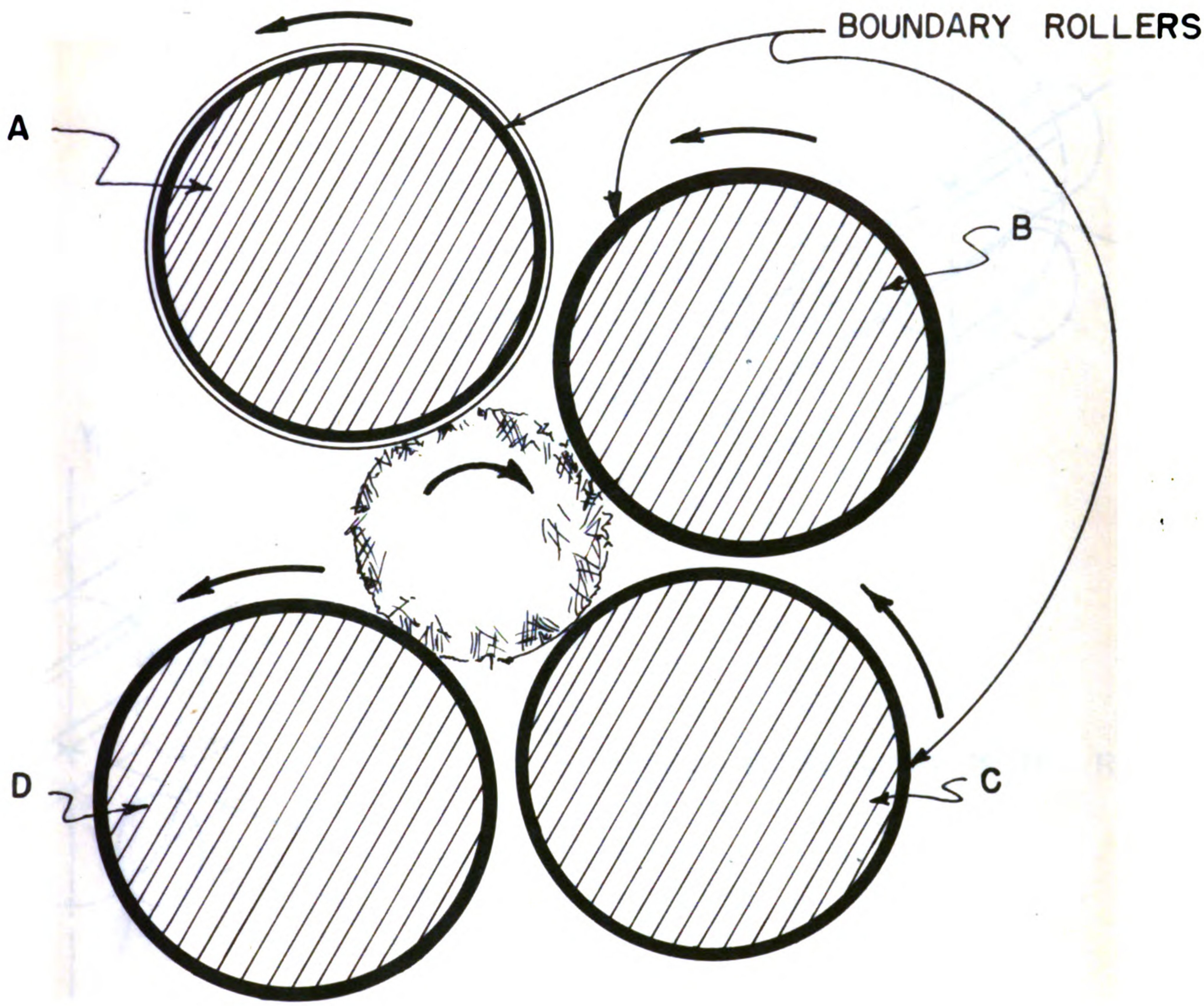


FIGURE 3. CROSS-SECTIONAL DIAGRAM OF THE COMPRESSION CHAMBER OF THE ROLLING WAFERING APPARATUS

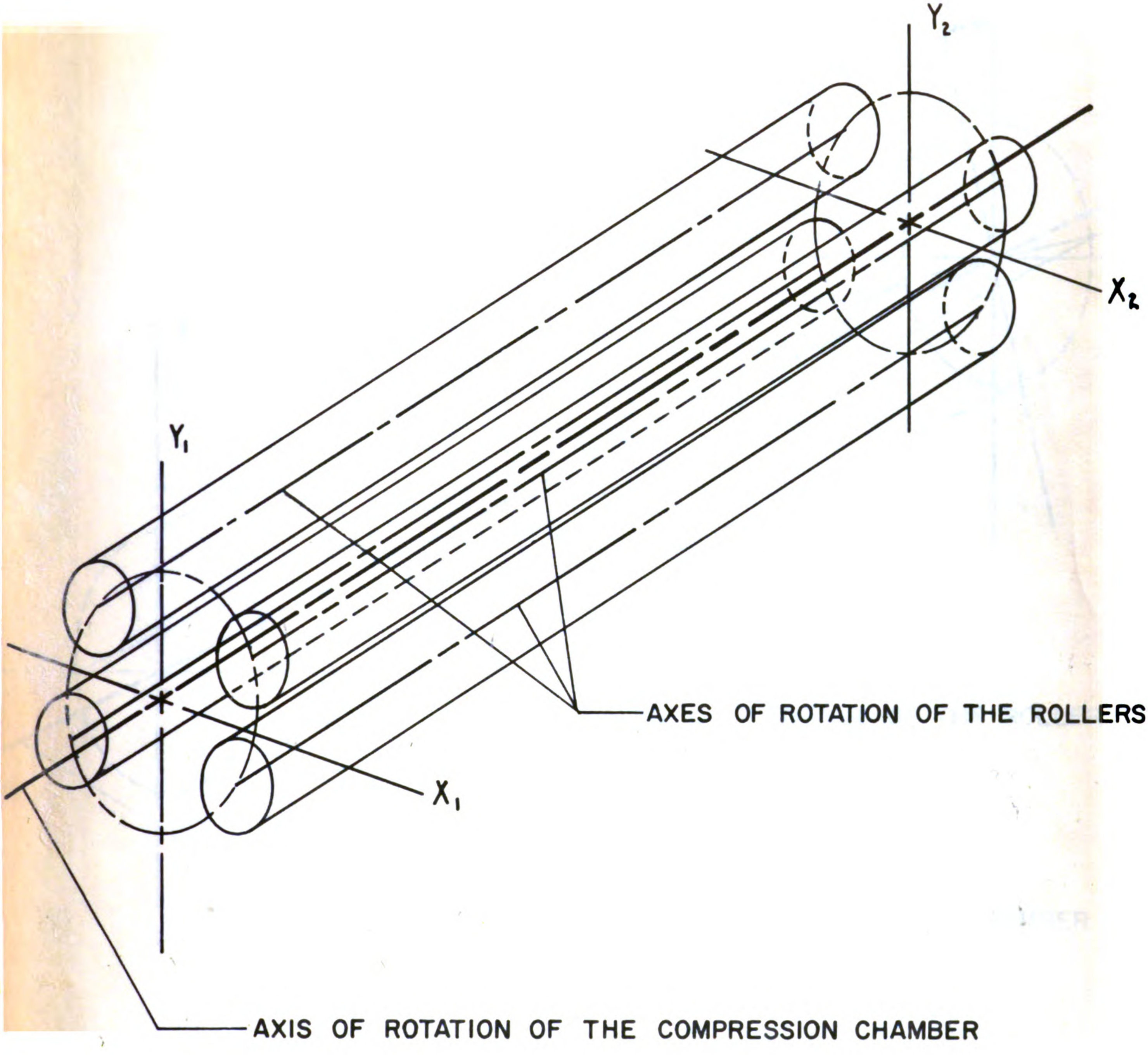


FIGURE 4. DIAGRAM OF THE RELATIVE POSITIONS OF THE AXES OF ROTATION IN THE PARA-AXIAL CONFIGURATION

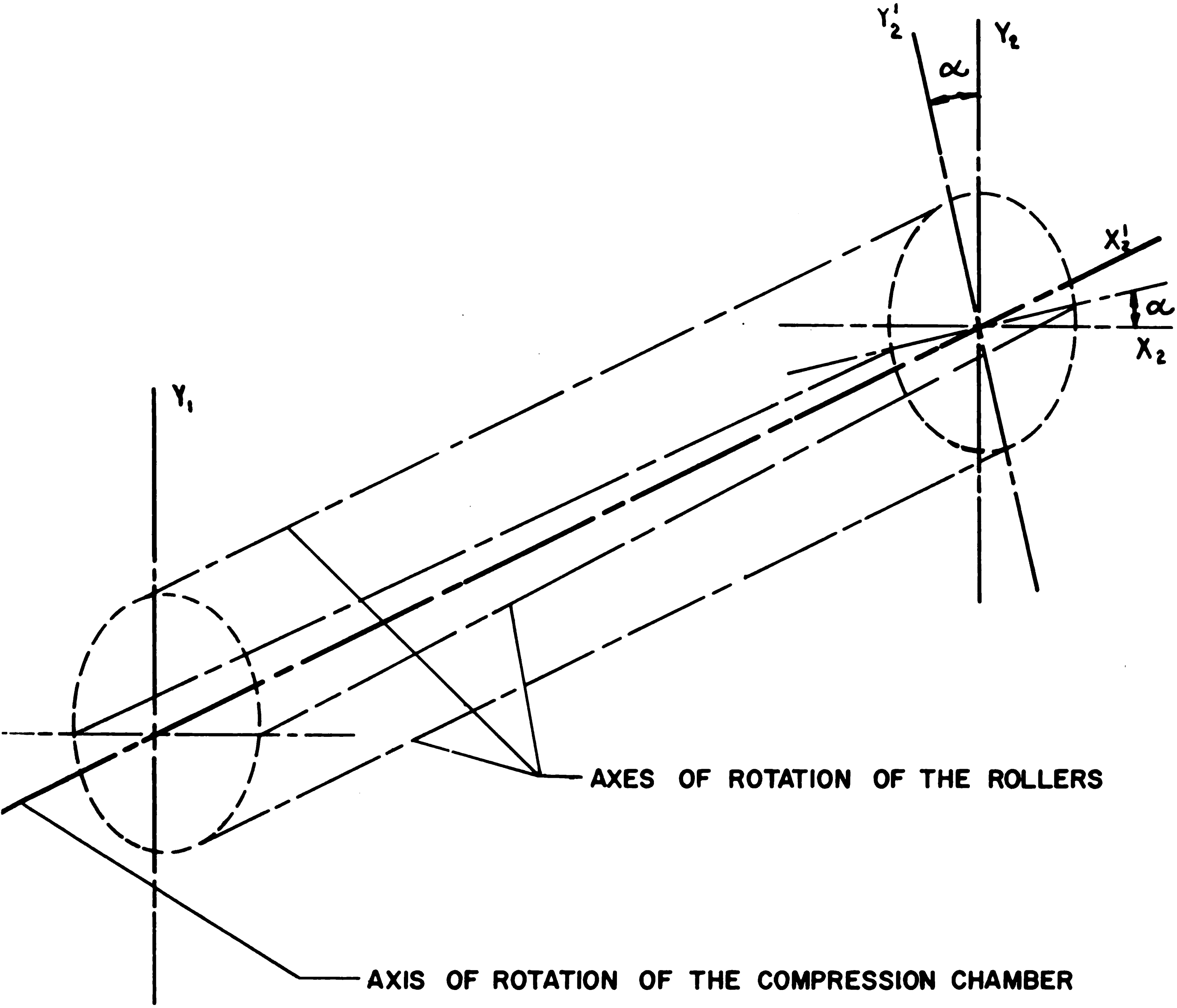


FIGURE 5. DIAGRAM OF THE RELATIVE POSITIONS OF THE AXES OF ROTATION IN THE TORSIONAL CONFIGURATION

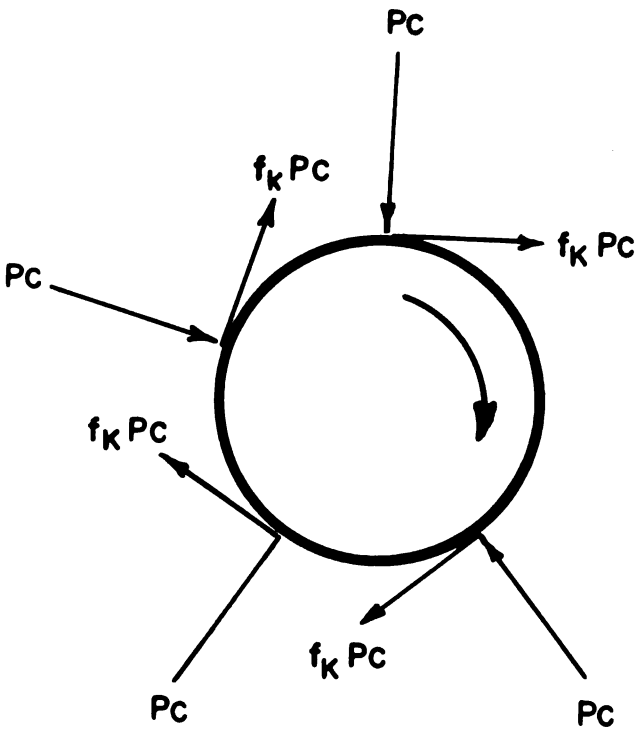
The application of this wafering process is restricted to materials composed of relatively long fibrous bodies having adhesive or interlocking properties to provide the conditions for the internal stresses.

If a mass of fibrous compressible material is placed in the chamber under the stresses transmitted by the boundary rollers, the acting forces may be illustrated by the transaxial force diagram of Figure 6. Figures 7 and 8 are free-body diagrams of the material in the chamber. The stresses for the para-axial configuration of the roller system are shown on Figure 7. The major principle stresses are illustrated by the radial vectors. The magnitude of these stresses is determined by the physical state of the material under process. At this configuration of the system no axial forces are acting.

It was one of the objectives of the development of the rolling compressing wafering device to provide a mechanism for continuous intake-compression and discharge without applying reciprocating mechanical elements.

The axial configuration shown on Figure 5 provides the conditions to resolve the peripheral frictional forces into axial and tangential components.

The free-body diagram on Figure 8 illustrates the system of the acting forces. The radial forces represent a force field which can be approximated by the surface of a torsional belt. This force field is transaxial to the axis of rotation of the corresponding roller and to the axis of rotation of the compression chamber.



P = COMPRESSION RADIAL FORCE
C = COMPRESSIBILITY FACTOR OF THE HAY
f_K = COEFFICIENT OF FRICTION

FIGURE 6. TRANSAXIAL FORCE DIAGRAM OF THE ROTATING MATERIAL IN THE CHAMBER SHOWING THE RESULTANT STRESSES EXERTED BY THE ROLLERS

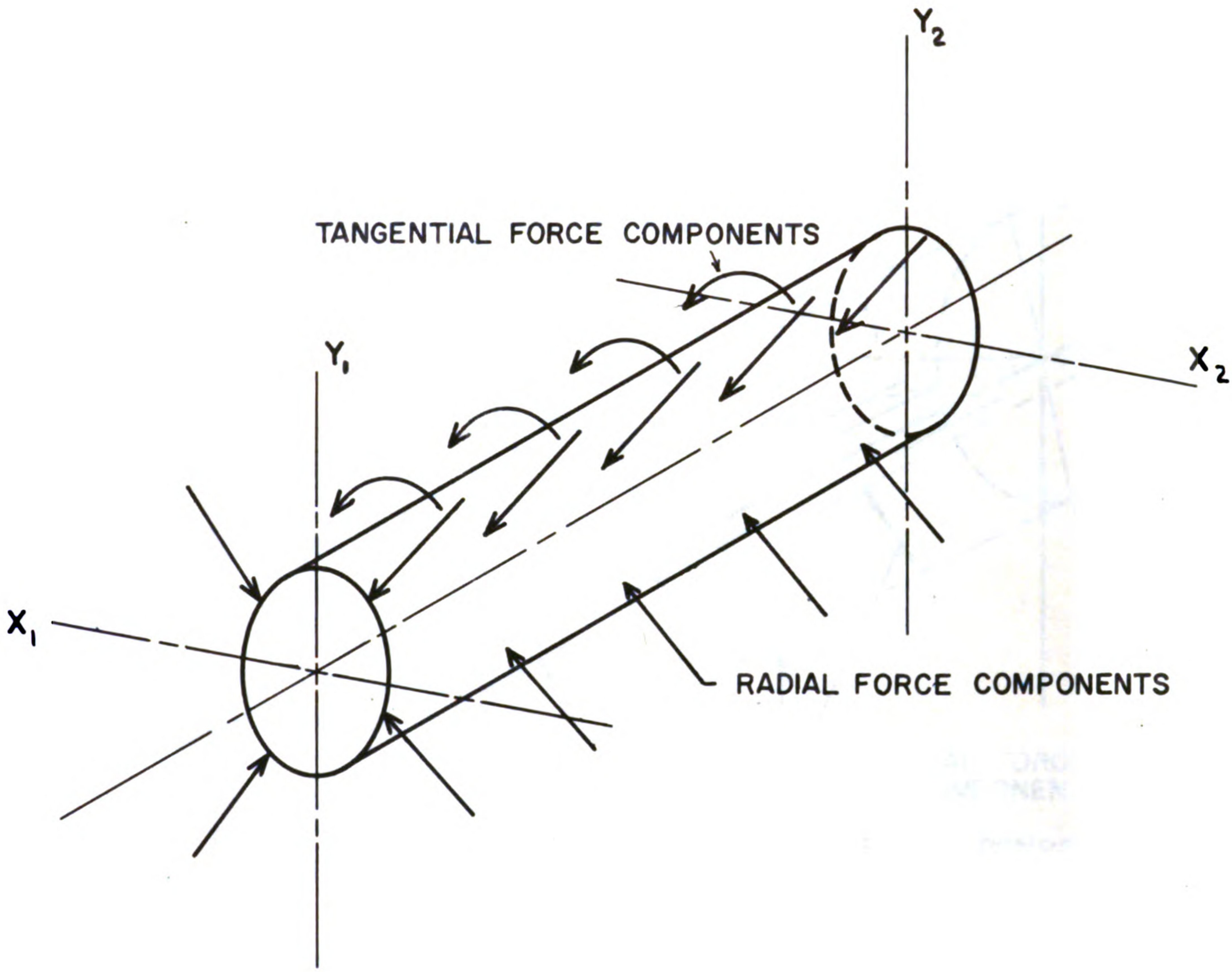


FIGURE 7. THREE-DIMENSIONAL FREE BODY DIAGRAM FOR THE PARA-AXIAL CONFIGURATION

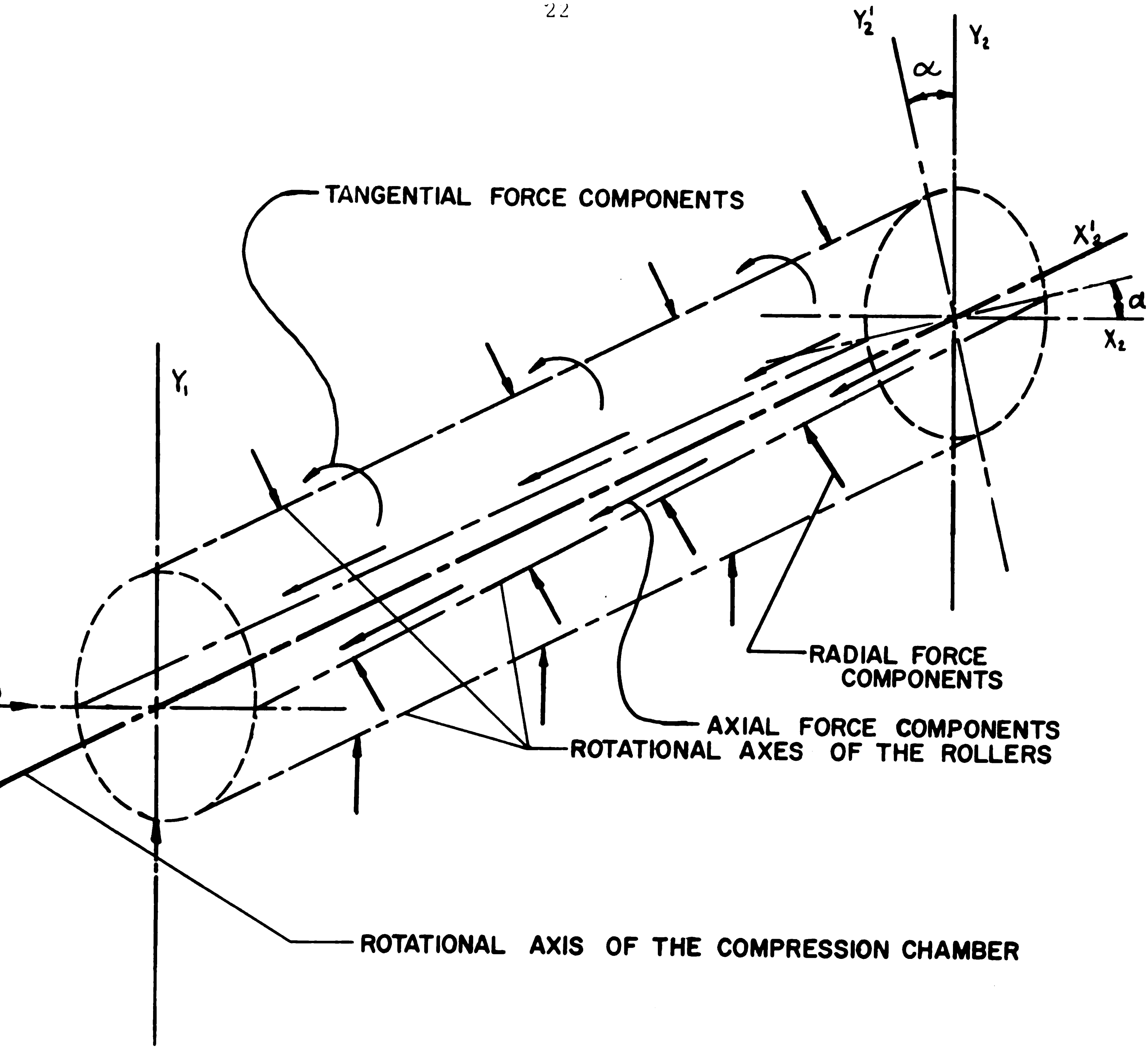


FIGURE 8. THREE DIMENSIONAL FREE BODY DIAGRAM FOR THE TORSIONAL CONFIGURATION

Due to the torsional configuration of the system the tangential frictional forces are resolved into two components; one which is tangential inducing the angular displacement, the other the axial inducing the linear displacement of the material in the chamber.

The relationships between the two component is the function of the torsional angle "α" between the Y_2 and Y_2' axes. If $\alpha = o$ Y_1 and Y_2 are complanar parallel axes thus in the axial force components will be **zero**. Under this conditions the material in the chamber will suffer only angular displacement.

If, however, $\alpha \neq o$ then Y_1 and Y_2' are not coplanar parallel axes, therefore the rollers exert both tangential and axial forces inducing both angular and linear displacement of the material in the chamber.

Assuming the ideal frictional transfer of forces when the kinetic friction coefficient $f_k = 1$ the induced axial velocity can be expressed as follows:

$$V_a = V_t \times \sin \beta$$

where

V_a = axial velocity of the material in the chamber

V_t = peripheral velocity of the roller

β = torsional angle

This expression is illustrated on Figure 9.

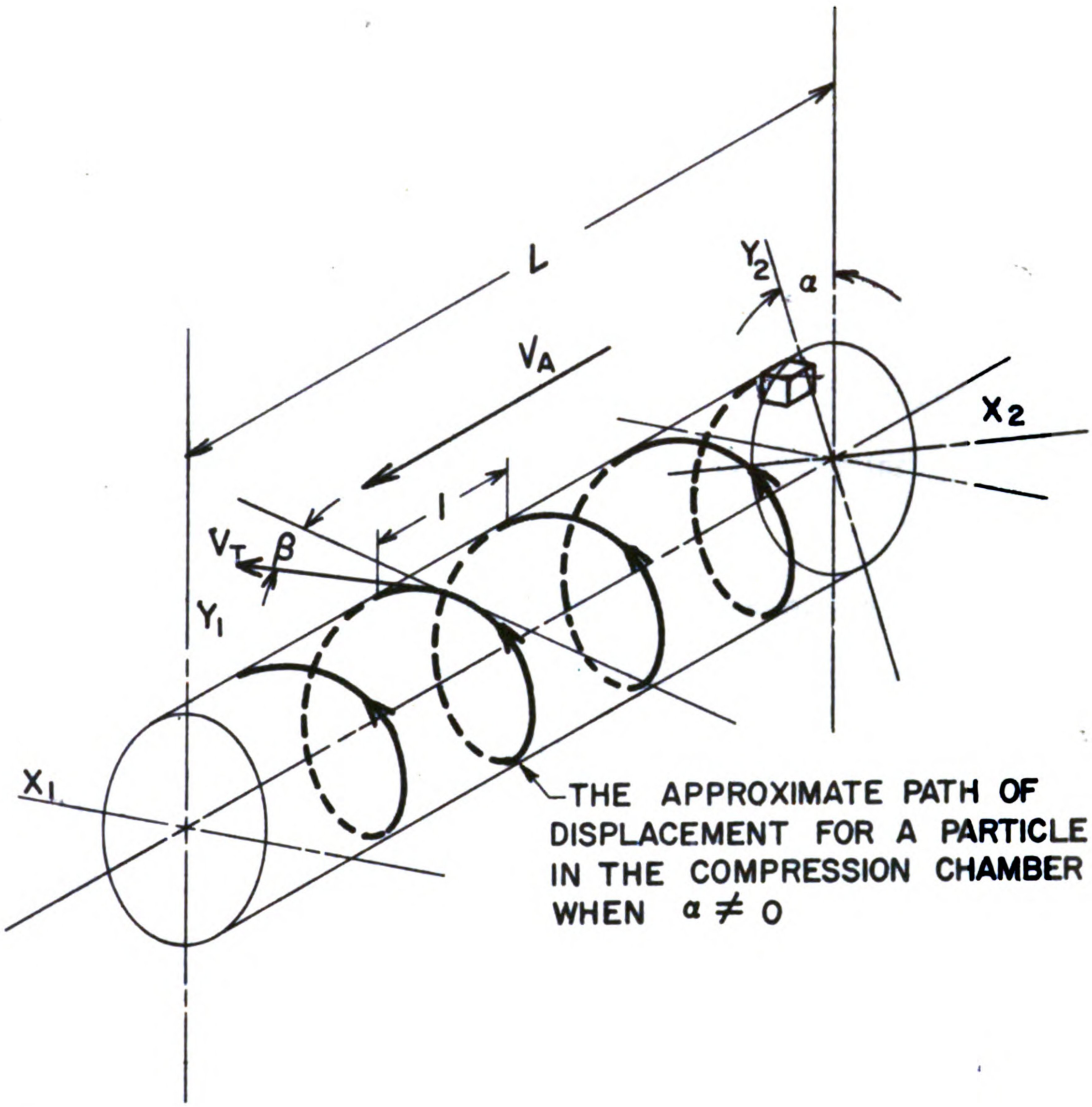


FIGURE 9. DIAGRAM OF THE PERIPHERAL FRICTION FORCES

Similarly the angular velocity can be expressed as

$$V_r = V_t \times \cos \beta$$

where

V_r = angular velocity of the material in the chamber

The magnitude of the torsional angle β has a significant role in the device. By adjusting it the linear or axial velocity of the processed material can be varied which effects the total work or energy input, determining the final density of the product.

The compression chamber of the device is confined by the cylindrical rollers which are arranged adjacent to each other but without providing a continuous boundary surface. There is an interspace between each pair of rollers to eliminate frictional losses of energy.

One of the characteristics of the device is that in spite of these open interspaces material cannot leave the chamber through them. This phenomenon is illustrated on Figure 10 where two adjacent rollers are shown. The radii of the rollers are identical, thus

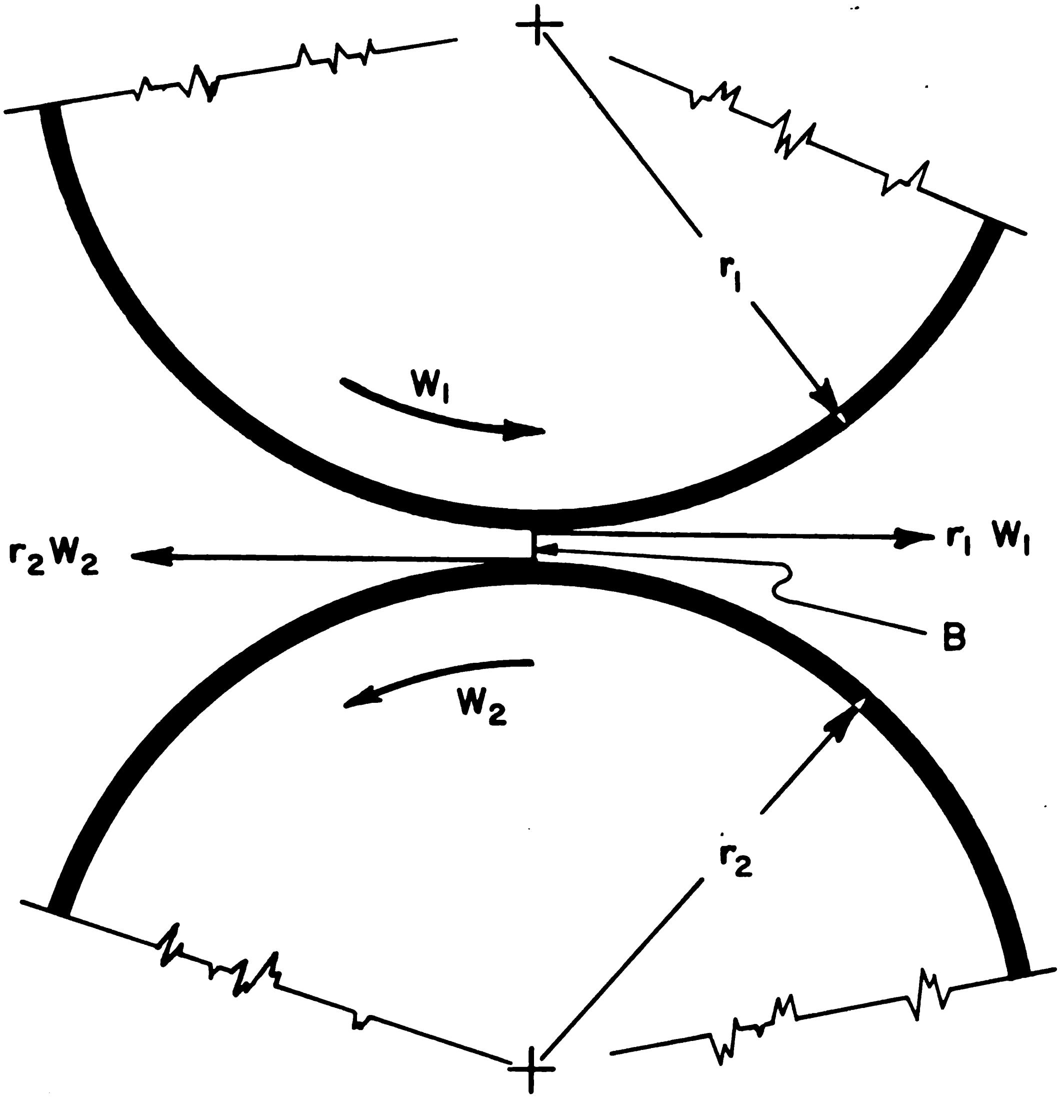
$$r_1 = r_2$$

The angular velocities are also the same, both in magnitude and direction, therefore

$$\omega_1 = \omega_2$$

The peripheral velocities at the interspace are illustrated by the two vectors which are equal in magnitude but opposite in directions. This can be expressed by the equation:

$$\overrightarrow{r_2\omega_2} = \overrightarrow{-r_1\omega_1}$$



W = ANGULAR VELOCITY

r = RADIUS OF THE ROLLERS

$W_1 = W_2$ AND $r_1 = r_2$

$W_1 r_1 = W_2 r_2$

FIGURE 10. VECTOR DIAGRAM OF THE COUNTER ACTING FRICTION FORCES AT THE INTER-SPACES BETWEEN THE ADJACENT ROLLERS

The significance of this equation can be readily recognized if it is considered that all agricultural crops processed by this device are fibrous but discontinuous materials composed of several structural elements which prior or during the process may become separated from each other and would tend to adhere to the roller's surfaces following their direction of motion and leaving the chamber through the open interspaces.

Observing the diagram on Figure 10 and recalling the equation for the peripheral velocities it can be seen that the discharge of the loose particles is prevented by the counter-acting rotating surfaces and they are forced to continue the rotational motion with the bulk of the material.

In actual operation a small amount of particles may leave the chamber through the interspaces because of the difference in the friction conditions on the rollers' surfaces. However, the amount of this material is insignificantly small and can be returned into the chamber with the inflowing new material.

The rolling-compressing wafering process requires the continuous feeding of the loose material into the compression chamber. It is also required that the incoming material become wrapped around the partially rolled-compressed rotating mass. To satisfy these requirements the interspace between one of the pairs of rollers is increased to allow substantial amounts of material to enter this area where the tangential velocity vectors of the rotating mass and of one of the rollers have the same directions. These two rotating surfaces serve as feeding means by drawing the interwoven mass of the fibrous material into the chamber.

To illustrate the rolling process a continuous, long, elasto-plastic porous belt is used. This similatude may be applied by considering that the stream of continuously incoming fibrous forage material is composed of a plurality of stems and leaves with mutual-adhesion and interlocking characteristics, possessing elasto-visco plastic properties both individually and also in their random state.

For the simplicity of the analysis the initial position of the volume elements in the subsequent layers is chosen along the transaxial straight line connecting the two boundary surfaces.

Figure 11 represents the condition at which the radial major principle stresses are negligible causing no deformation in the cylindrical shape of the wrapped layers.

If only the tangential forces are acting, the marked elements of the successive layers would suffer a displacement along a circular path. If the torsional angle $\alpha \neq 0$ a three dimensional displacement of the marked elements would take place on a spiral shaped path with constant radius along the longitudinal axis of the compression chamber.

At steady-state operating conditions when the major principle stresses are sufficiently great the originally cylindrical cross section of the rotating mass is deformed to an elliptic-spiral configuration with variable major-minor axis ratios. These ratios are decreasing in the subsequent layers toward the centroidal axis of the body. Figure 12 illustrates the condition when the marked elements are still in their initial radial position but under the compressive major principle stresses.

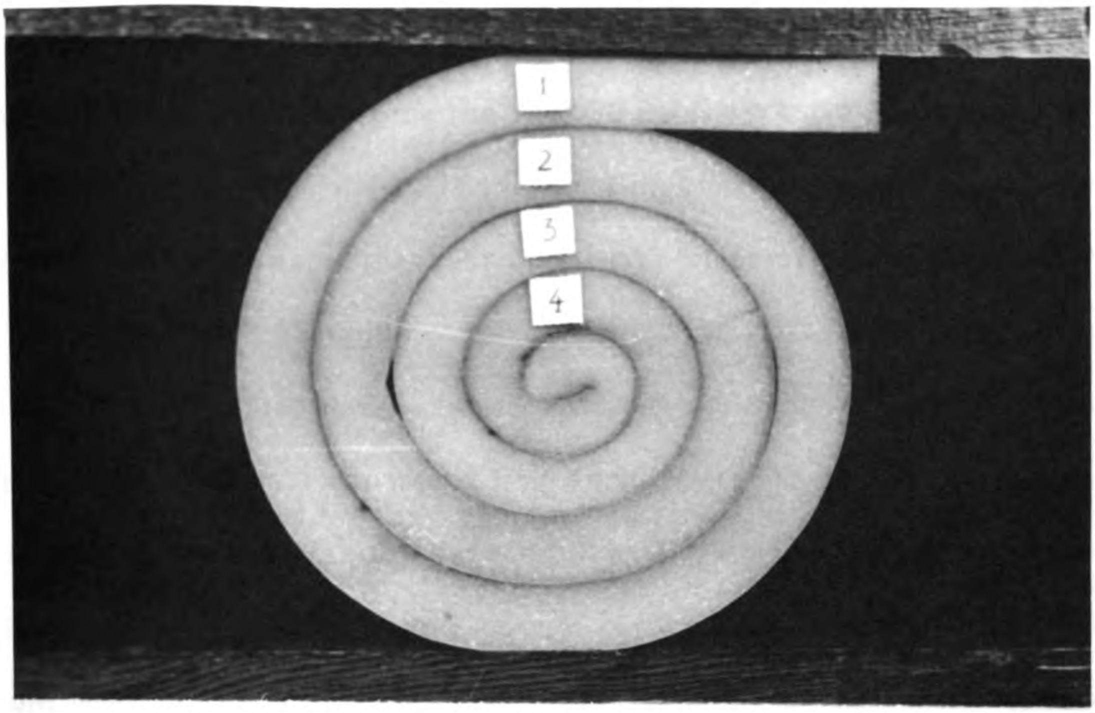


FIGURE 11. ILLUSTRATION OF THE ROLLED LAYERS WHEN THE RADIAL STRESSES ARE VERY SMALL

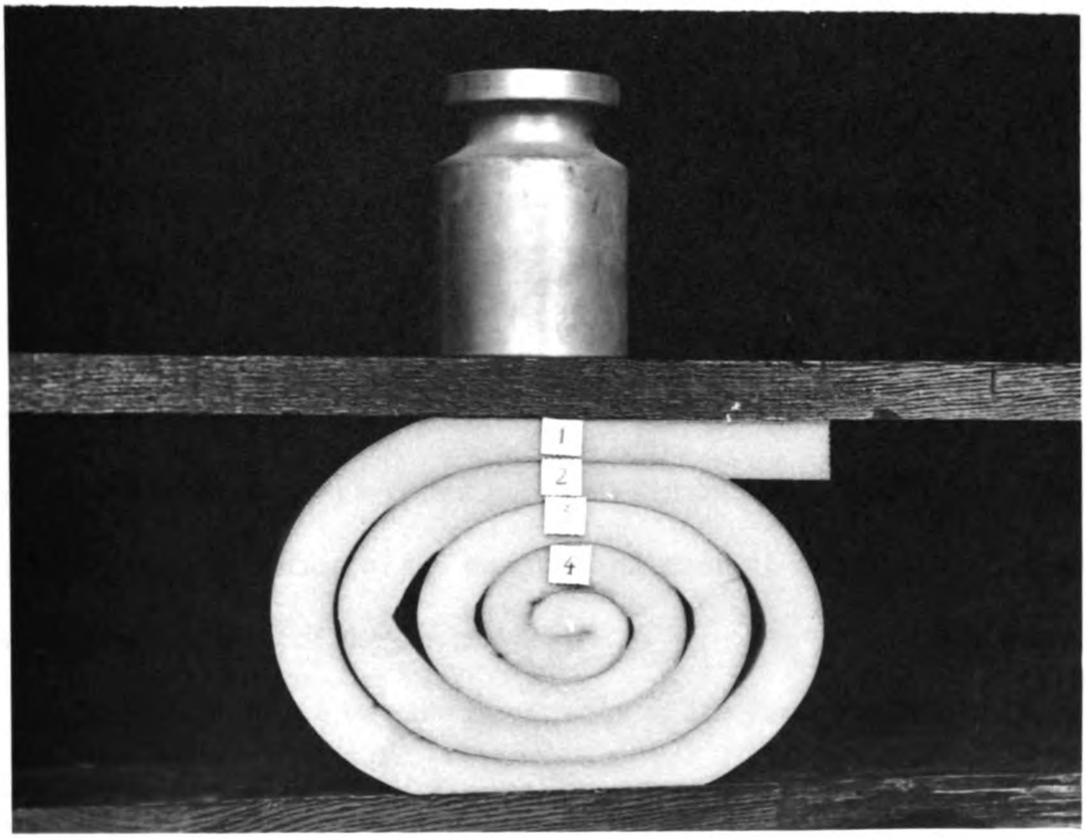


FIGURE 12. DEFORMATION OF THE ROLLED LAYERS WHEN ACTED UPON BY THE RADIAL STRESSES

For each layer of this figure a gradual increase in the length of the radius can be observed during the first 90 degree rotation.

The increase in the radii is the function of the geometry of the boundary conditions as well as of the mechanical properties of the processed material.

Considering the angular displacement of the marked elements it can be seen that, as they leave the radial stress zone the layers can expand and become relatively separated from each other. This separation results in a reduction in the friction between them allowing the differential angular velocities which during the subsequent revolutions provide the gradual "tight wrapping" of the layers. Figures 13 and 14 illustrate the "wrapping" action demonstrating the change in the relative position of the elements. Experiments with models indicated that if a curve is drawn connecting the marked element after a number of revolutions, a logarithmic spiral is obtained. This positional relationship between the elements is effected by several factors.

The transfer of the torque to induce the rotation in the chamber is a frictional function, therefore, the maximum torque transfer takes place at the maximum radial stress zones. The magnitude of the radial stresses, however, is the function of the density and strength of the material, and also of the geometry of the chamber.

On Figures 4 and 5 two configurations of the axes of the boundary rollers were illustrated. The para-axial configuration of Figure 4 demonstrated that the "diameter" of the compression chamber is constant along

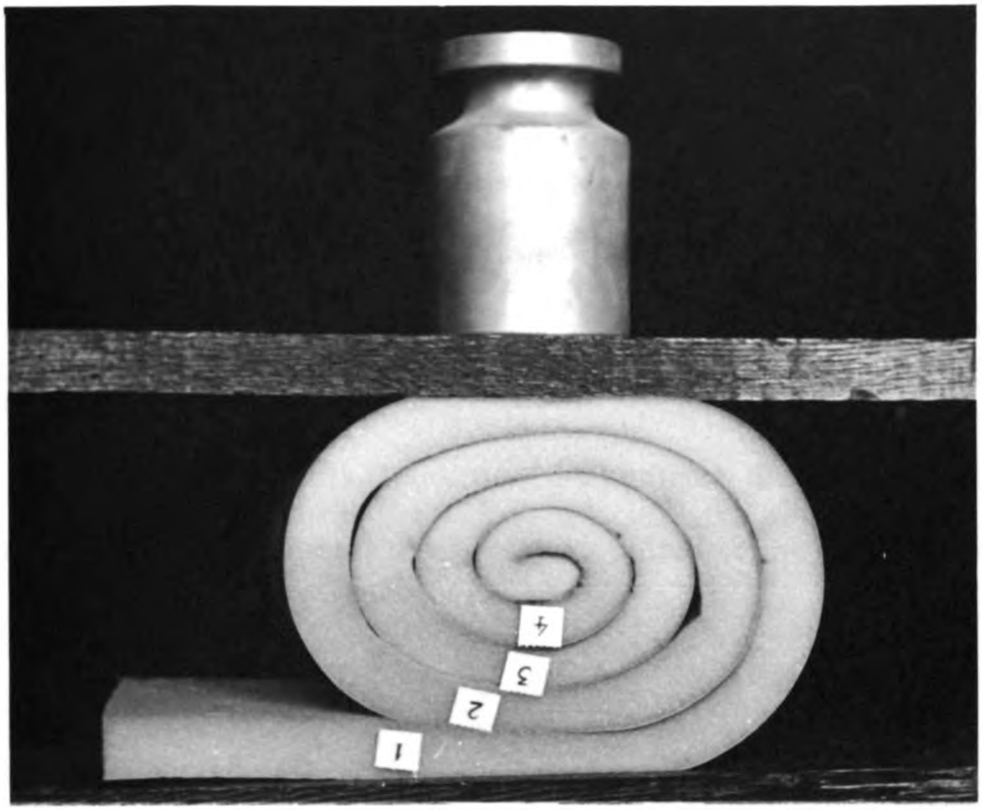


FIGURE 13

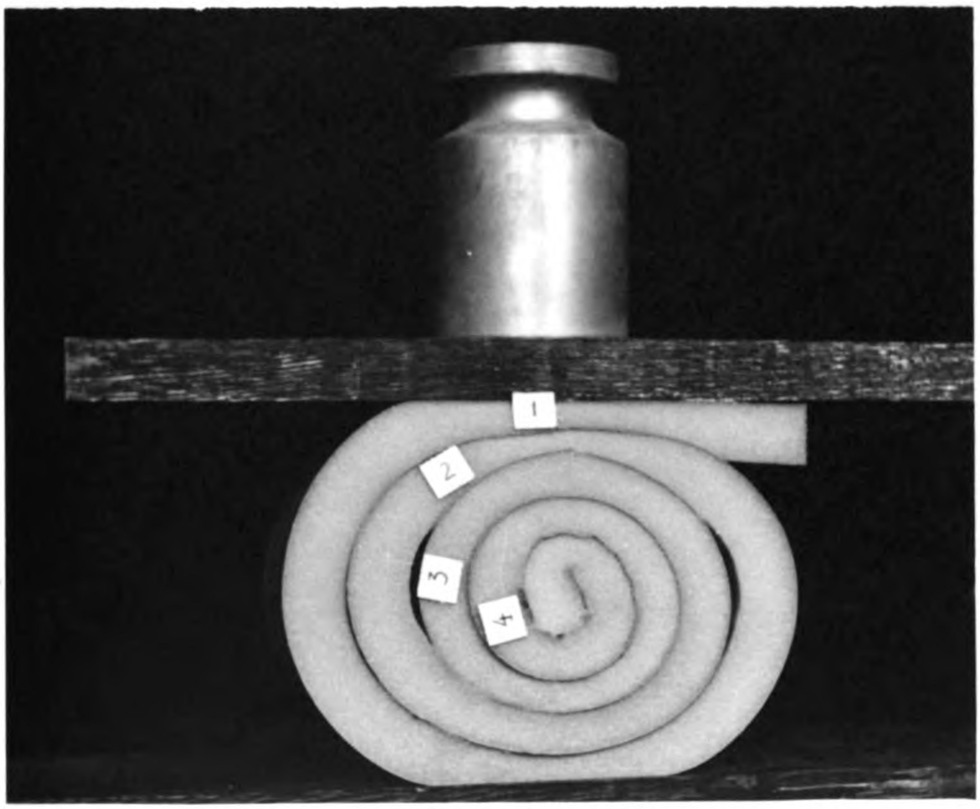


FIGURE 14

CHANGE IN THE RELATIVE POSITIONS OF THE MARKED POINTS OF THE SUBSEQUENT LAYERS DURING THE ROLLING PROCESS its axis. The torsional configuration is shown on Figure 15. Because of the geometry of the system in this configuration, the "diameter" of the chamber is not constant along its axis. Due to the torsional displacement of the bearing plates the "cross-section" of the chamber is described by a hyperboloid. Figure 16 is a demonstration of this geometrical shape when the torsional angle α is large.

It can be seen from this figure that the minimum diameter and consequently the maximum radial stresses are applied at the midpoint of the chamber.

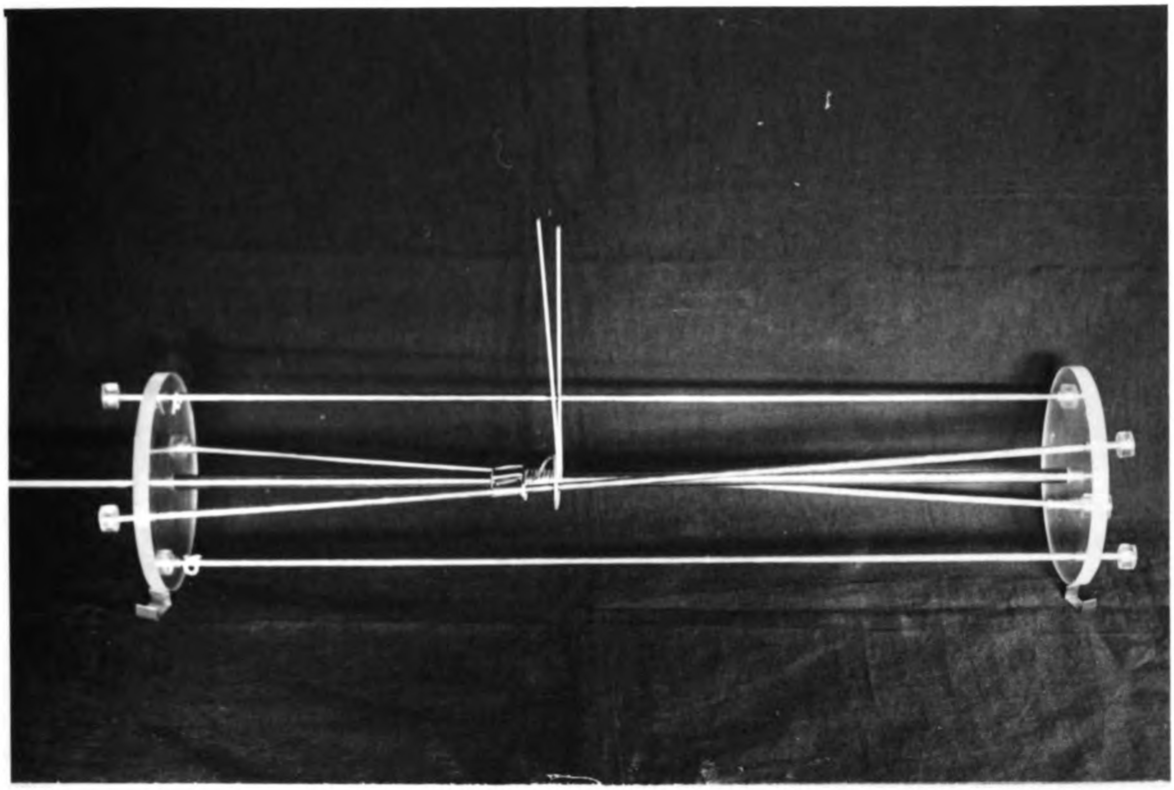


FIGURE 15. THE TORSIONAL CONFIGURATION OF THE ROTATIONAL AXES AND ANGLE β

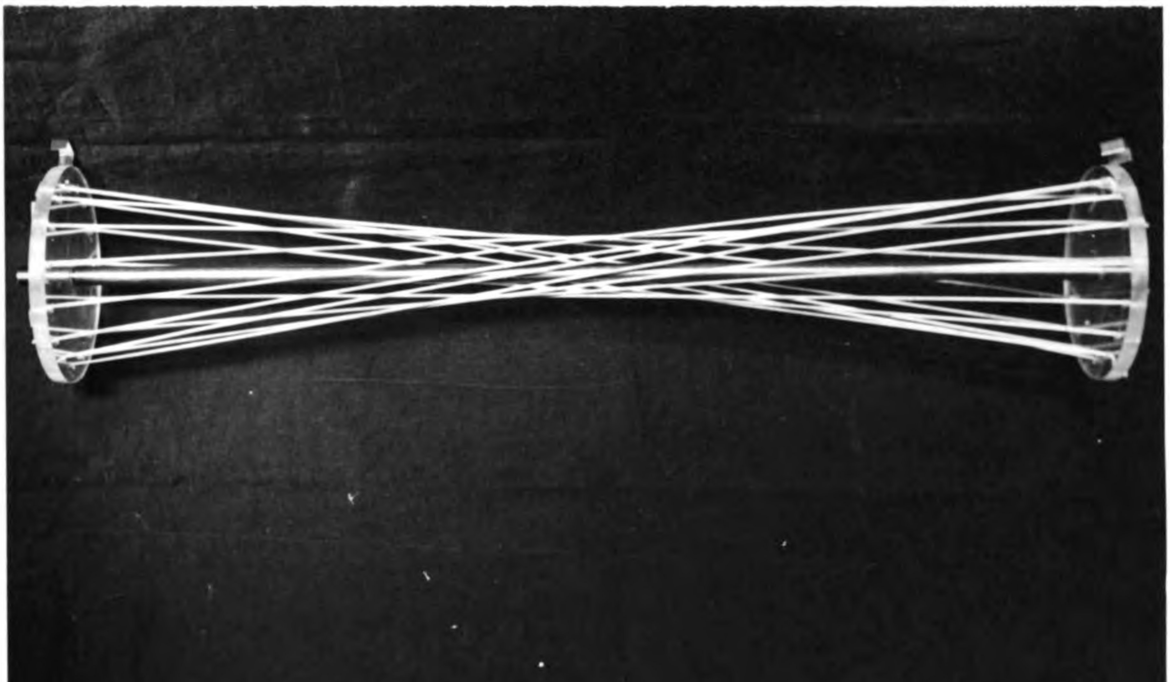


FIGURE 16. THE HYPERBOLOIDAL BODY OF THE COMPRESSION CHAMBER WHEN THE TORSIONAL ANGLE α IS LARGE

CHAPTER VIII

STRESS ANALYSIS OF THE ROLLING-COMPRESSING WAFERING PROCESS

From the functional analysis of the device it could be derived that the magnitude of the radial stresses must be large enough to cause the elliptic deformation in the layers and also to produce the normal stresses which are necessary for the transfer of the tangential and axial forces. If, however, these external stresses exceed the shear strength of the fibrous material, a shear failure may develop interrupting the continuity of the operation.

To analyze the shear characteristics of some typical agricultural forage crops their mechanical properties have to be considered:

Adhesion. It varies not only with the moisture content and variety of the forages but also with the "consolidation" pressure which is a stress that was exerted on the material prior to the wafering process. The adhesive shear strength is contributed by the natural adhesives of the crop. Its effectiveness depends on the total contract surface area between the composite elements which in terms is the function of the compressive stresses.

It has to be noted that the adhesive components of the shear strength is independent of the length of the composite fibers. Chopped or sized forages can be compressed into dense self-contained pellets in plunger or ram type devices. For these packages the shear strength is provided by the natural adhesives only.

The adhesive shear strength is very much moisture dependent, therefore, it may be small or practically negligible for high moisture-content crops.

Experiments with alfalfa hay indicated that leaves in general have better adhesive properties as compared to the stems of the crop. It was also found that besides the intensity of the normal stresses temperature had significant effect on them. "Welding" of alfalfa leaves could be demonstrated at relatively small normal stresses, about 200 to 300 pounds per square inch, when the temperature of the stress surfaces was raised to about 250 degrees Fahrenheit.

The shear-strength-moisture content relationships for sized alfalfa hay when compressed into wafers under 3,000 pounds per square inch is illustrated on Figure 17. The curve clearly shows the rapid decrease in adhesion as moisture content increases.

A second component of the shear strength of compressed forages is provided by the interwoven state of the randomly arranged plurality of composite fibers. Its intensity is effected by the orientation of the stems relative to each other and to the direction of the applied shear stresses. This physical property is not significantly effected by moisture content and may be considered as a cohesive function.

Both the adhesive and cohesive components are characteristics of the forage materials independent of the applied normal stresses.

The third shear stress component is directly the function of the normal stresses and of the physical condition of the forage.

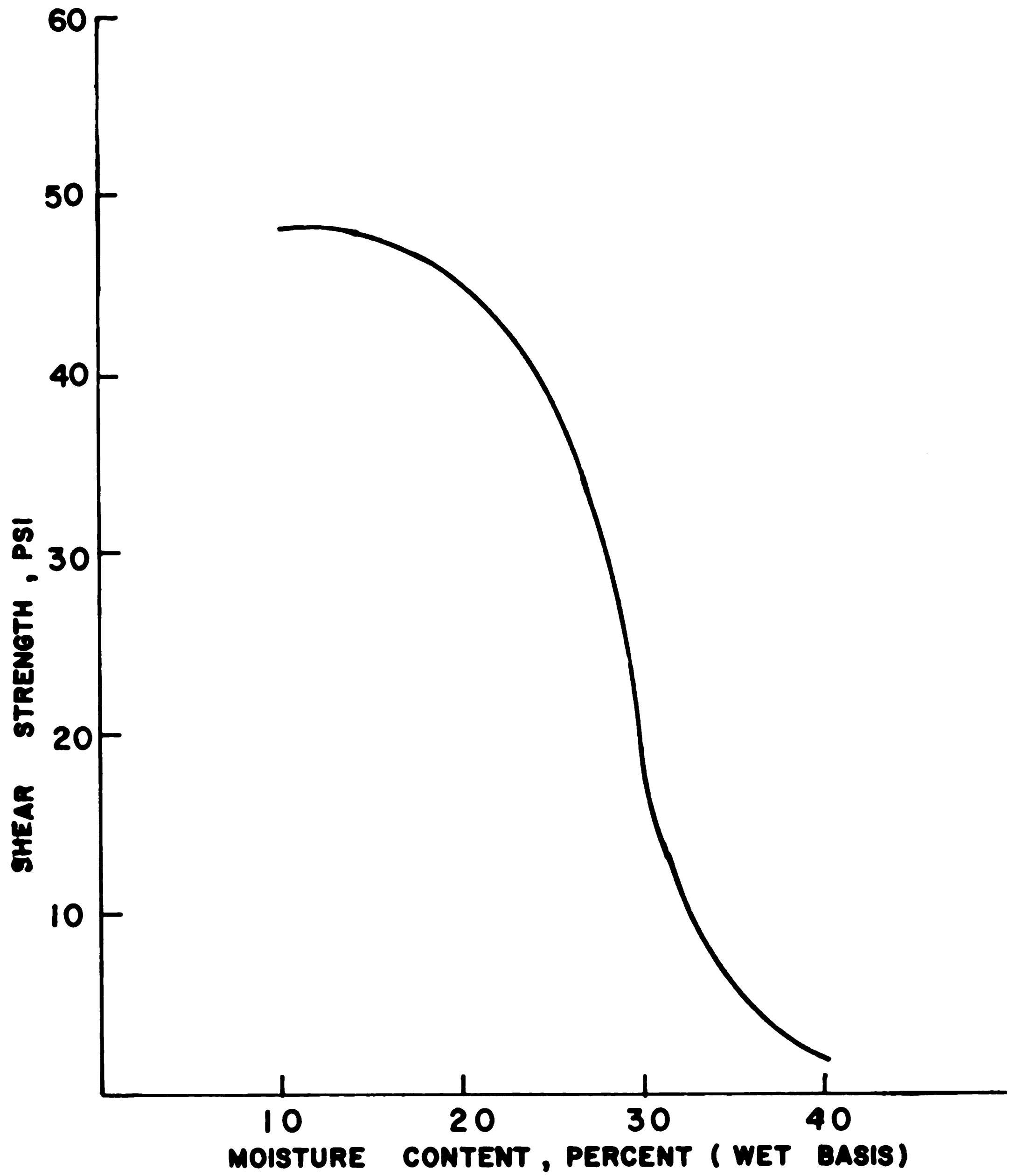


FIGURE 17. SHEAR STRENGTH V.S. TO MOISTURE CONTENT FOR CHOPPED ALFALFA HAY PELLETS MADE AT 3000 PSI PRESSURE

The coulomb's equation applied in soil mechanics to describe the shear strength of a soil medium has the form as follows:

$$s = c + \sigma \tan \phi \qquad (11)$$

Where

s = The shear strength of the soil

c = Cohesive component of the shear strength which is not the function of the normal stresses

σ = Applied normal stress

ϕ = The angle of the shear envelope.

To describe the shear strength of forage materials this expression may be applied in an expanded form of:

$$s = a + c + \sigma \mu$$

Where

s = Shear strength of the compressed forage

a = The adhesive component of the shear strength

c = Cohesive component

σ = Normal stress

μ = Moisture dependent coefficient

The moisture dependency of the third component can be explained by observing the lubricating effect of the liquids or juices extracted from the body of the crop under the applied normal stresses. It has to be considered that the permability of the compresses mass determines the rate of drainage of these juices, therefore, this third component has time elements also.

It is an important characteristic of this wafering process that the three contributing shear strength components are functioning independently at the various stages of the process, thus making it possible to form wafers at wide range of moisture contents.

In order to determine the resistance of a roller moving on the compressible forage mass, the forces acting against the roller have to be defined.

The rollers are driven, when a moment (M) is imposed upon them in the direction of motion. They have the tendency to slide relative to the forage mass in the chamber, depending upon the physical conditions of the material and the magnitude of the applied torque. Figure 18 gives an illustration of this state of stress. The frictional part of the tangential forces (dF) on an arbitrarily chosen elementary contact area (dA) will oppose the motion. Form the geometry, the elementary normal force (dN) passes through the center of the roller. By adding (dN) to (dF) the resultant (dR) is obtained which acts at α angle relative to (dN). When the internal shear strength of the forage mass is greater than the external interface friction α refers to the friction between the rollers and forage mass. When the internal shear strength is smaller than the interface friction force, α refers to the angle of internal friction. In other words, the smaller value of the friction angle between roller and forage or the internal friction angle of the forage will be assigned to α, depending on whether slip on the contact surface or within the hay mass is most likely to occur.

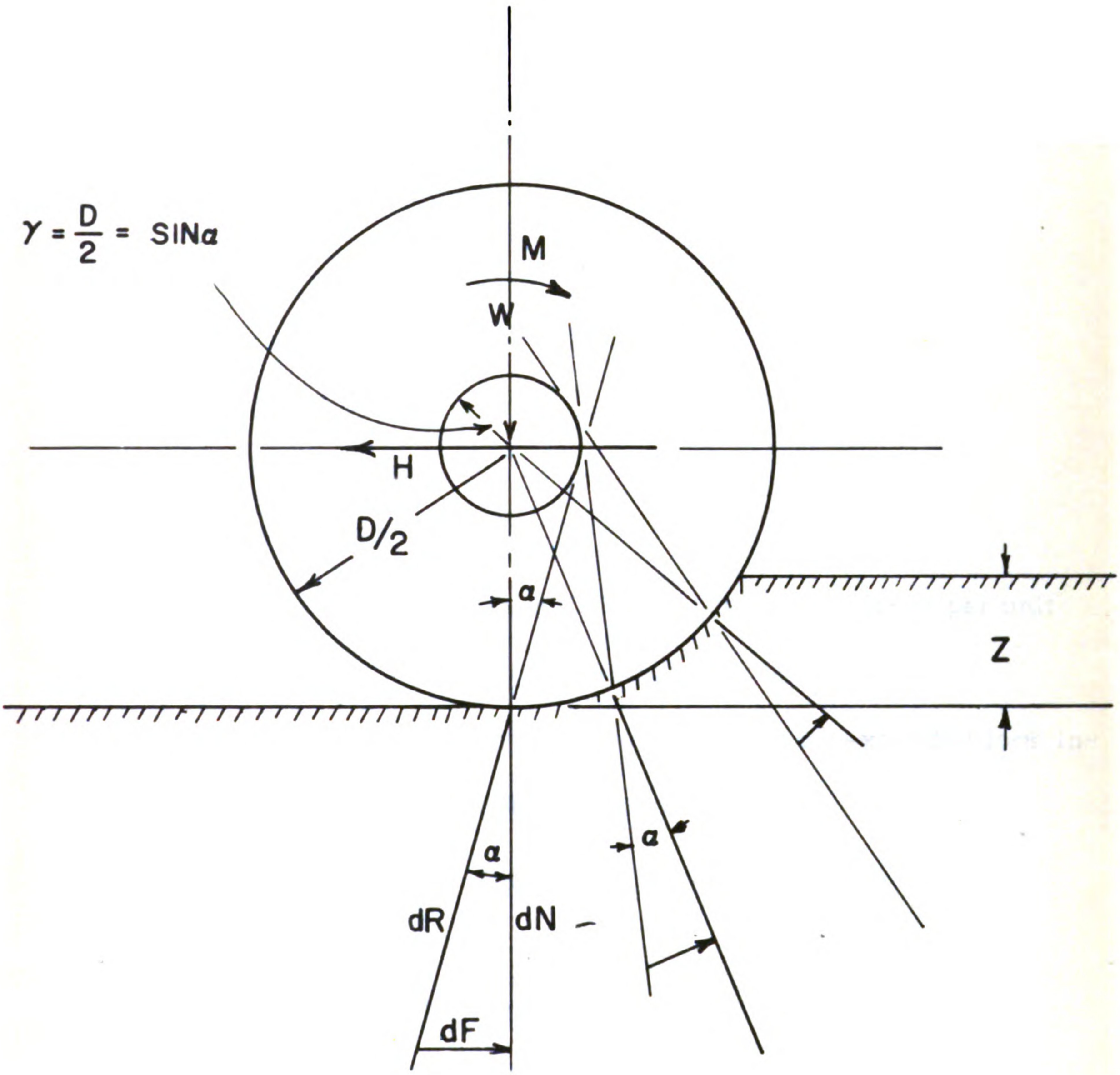


FIGURE 18. DIAGRAM OF THE STRESSES EXERTED BY A ROLLER ON THE ROTATING MATERIAL IN THE CHAMBER

Constructing (dR) at several locations along the contact area and assuming that α is constant along the contact length, it can be shown that the resultants will be tangent to a circle of radius.

$$r = \frac{D}{2} \sin \alpha$$

For soils with cohesive properties the effect of cohesion along the contact area is expressed as:

$$K = AC$$

Where

K = Cohesive force

A = Ground contact area

C = Cohesive stress

Cohesion for soils is defined as: The shearing resistance per unit area when the normal compressive stress is equal to zero.

The above formula for forages may be applied in an expanded form including both the cohesive and adhesive components.

$$F_{ac} = A(a+c)$$

Where

F_{ac} = Adhesive and cohesive force

A = Contact area between roller and forage

a = Adhesive stress

c = Cohesive stress.

The equation for the equilibrium of the force system acting on the rollers may be written as follows:

$$\Sigma M_O = M - rR - F_{ac}\frac{D}{2} = O \qquad (12)$$

The summation of the vertical forces may be expressed as

$$\Sigma F_V = W - R \cos(\alpha - \beta) - Z_o \, b \, ac \qquad (12)$$

Where

W = The normal force transmitted by the rollers

Z_o = Vertical compaction

b = The projection of the contact area.

The summation of the horizontal forces may be written as:

$$\Sigma F_h = R \sin(\alpha - \beta) - H + \sqrt{DZ_o - Z_o^2} \, bac \qquad (12)$$

Where

H = Motion resistance

When β is known in the above equations the remaining unknowns can be determined.

This derivation for the rolling resistance has severe limitations because it is based on the assumption that the bearing surface of the forage mass is a straight surface. Another limitation that may be considered is that the elastic properties were neglected.

CHAPTER IX

ANALYSIS OF THE RELATIONSHIPS BETWEEN THE DIAMETRICAL-RATIO AND STRESS DISTRIBUTION

In the actual configuration of the wafering device the rotating forage mass has a finite diameter which is in the neighborhood of the diameter of the rollers. It is therefore more realistic to analyze the stress conditions on the basis that the forage mass in the chamber is a compressible wheel which is driven by rigid wheels through surface friction.

The frictional part of the tangential forces (dF) acting on the arbitrarily chosen elementary contact area (dA) induces the rotational motion. The normal force (dN) is also transmitted on the elementary contact area, however, it does not pass through the rotational axis of the mass in the chamber but rather it acts as a counter-acting torque. Figure 19 is a diagram of this force system.

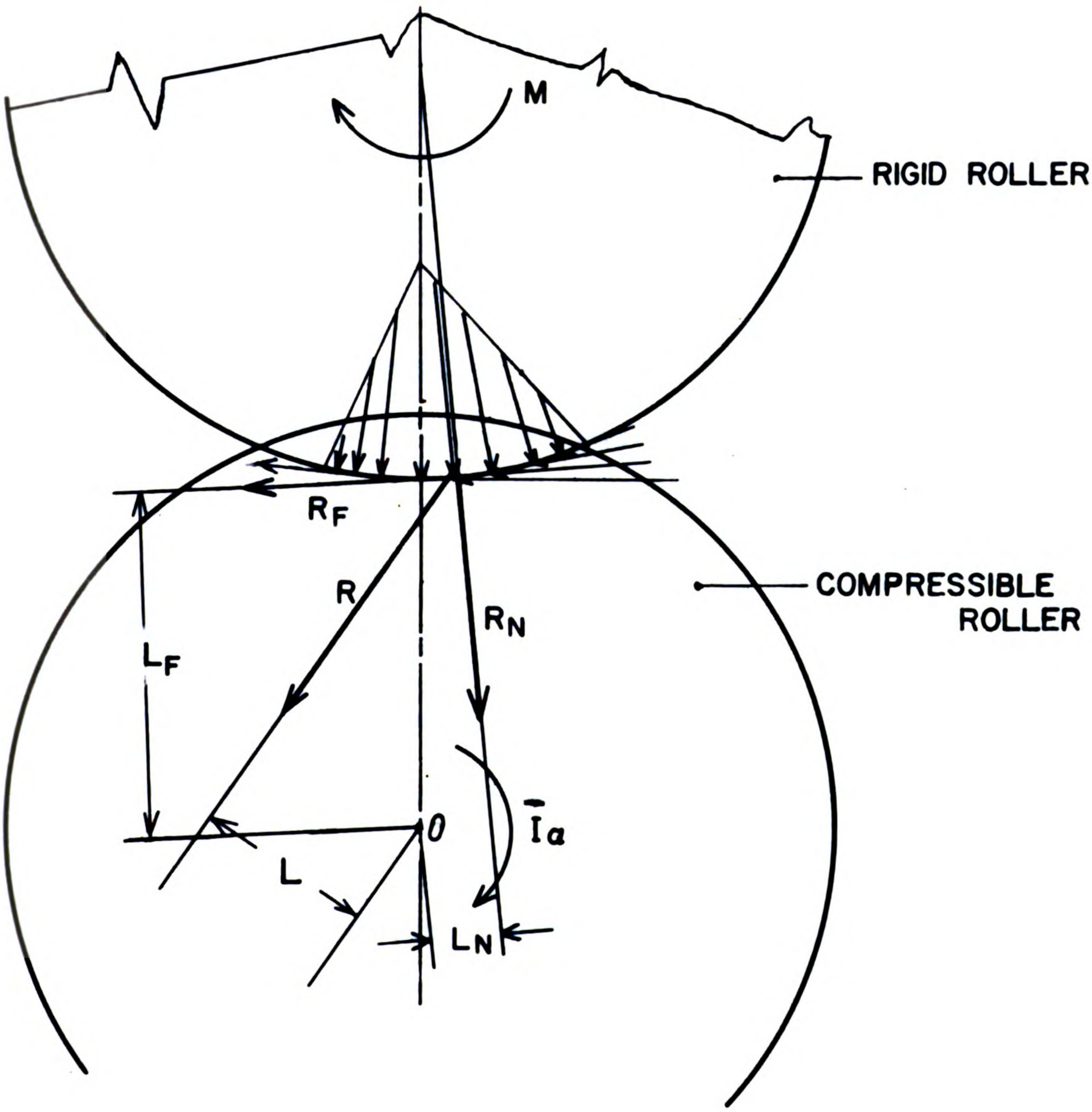
If R_F is the resultant of the tangential forces acting at a distance L_F from the rotational axis of the forage the torque can be expressed as:

$$M_F = R_F L_F$$

Similar expression can be used for the resultant of the normal or radial stresses acting at a distance L_N from the rotational axis. Therefore:

$$M_N = R_N L_N$$

Where L_F is the radius of the rotating forage mass in the chamber at the radial stress zones. Because of the elastic characteristics of the forages



R_V = RESULTANT OF THE NORMAL STRESSES
R_F = RESULTANT OF THE FRICTIONAL STRESSES
R = RESULTANT OF R_F AND R_V

FIGURE 19. MOMENT DIAGRAM OF THE SYSTEM

and the non-cylindrical shape of the chamber the magnitude of the radius varies from its minimum at the stress zones to its maximum at the zones between the adjacent rollers where no radial stress is applied.

The moment arm for the radial force is L_N which can be expressed in terms of the distance between the axes of rotation of the roller and of the forage mass. Therefore:

$$L_N = \left[\frac{D+D_o}{2}\right] \sin \beta$$

Where

D = Diameter of the roller

D_o = The minimum diameter of the forage mass

β = The angle measured from the straight line connecting the rotational axes of the corresponding roller and rotating forage mass. This angle is a variable effected by several factors as: the density of the forage mass, the diametrical relationship between the rollers and the rotating mass, the magnitude of the applied normal stress and also by the angular velocity of the elastic forage body.

Since the boundaries of the chamber are provided by a plurality of rollers the equilibrium equation for the moment at steady-state operation can be written as follows:

$$\curvearrowleft\!+ \; M_o = \Sigma -R_N L_N + \Sigma R_F L_F = O$$

An additional negative torque or moment component may be considered which is produced by the force that is required to draw the loose material into the compression chamber through the feeding interspace between one of the pairs of rollers.

It is obvious from the moment equation that the continuity of the process can be assured only if $R_F L_F$ is greater than $R_N L_N$. When the negative moment $R_N L_N$ is greater the rotation of the mass is not maintained and either slippage between the roller and forage mass or shear failure within the forage mass may take place. Considering these two failure conditions the moment equation may be rewritten in the following form:

$$\circlearrowleft\!+\; M_o = \Sigma(-R_N L_N + R_{F_S} L_{F_S} + R_{F_I} L_{F_I}) = 0$$

Where

R_{F_S} = The resultant of the tangential frictional forces acting on the periphery of the rotating mass

R_{F_I} = The resultant of the internal tangential frictional forces acting within the body of the forage mass

L_{F_S} and L_{F_I} are the corresponding torque or moment arms.

The external resultant R_{F_S} is effected by the adhesive or frictional relationships between the two surfaces. Therefore it may be considered as a parameter in the design of the rollers' surface.

The internal resultant R_{F_I} is determined by the physical properties of the material acted upon by the induced stresses.

As a consequence of the above conditions there are two failure patterns in this wafering process:

a, an external failure when

$$R_N L_N > R_{F_S} L_{F_S}$$

b, an internal failure when

$$R_N L_N > R_{F_I} L_{F_I}$$

Either of these failures can stop the rotation of the forage mass depending upon the relative values of $R_{F_S}L_{F_S}$ and $R_{F_I}L_{F_I}$. Both the external and internal friction stresses are effected by the physical condition of the material. The presence of free liquids reduces the mutual adhesion as well as the surface friction, therefore, the probability of failure is greater for high moisture content crops especially when the permeability or drainage conditions are unfavorable.

In order to reduce the probability of failure the negative component of the equilibrium equation $R_N L_N$ should be kept at the possible minimum. Since R_N must be large enough for sufficient frictional transfer of the tangential forces the reduction in the magnitude of the moment arm L_N is necessary. The proper diametrical-ratio between the rollers and the chamber may serve this purpose.

Figure 20 illustrates the stress conditions for two diametrical ratios:

$$\frac{D_H}{D_1} = 1 \text{ and } \frac{D_H}{D_2} = 0.5$$

Where

D_H = Diameter of the chamber or the minimum diameter of the rotating mass

D_1 and D_2 = Diameters of the rollers

If Z_o (which is the radial deformation of the forage mass under the stresses) is identical for both diametrical ratios, it can be seen that the stress area is greater for the larger diameter roller. Consequently, the line of action of the resultant force is at a longer distance from the rotational axis of the chamber.

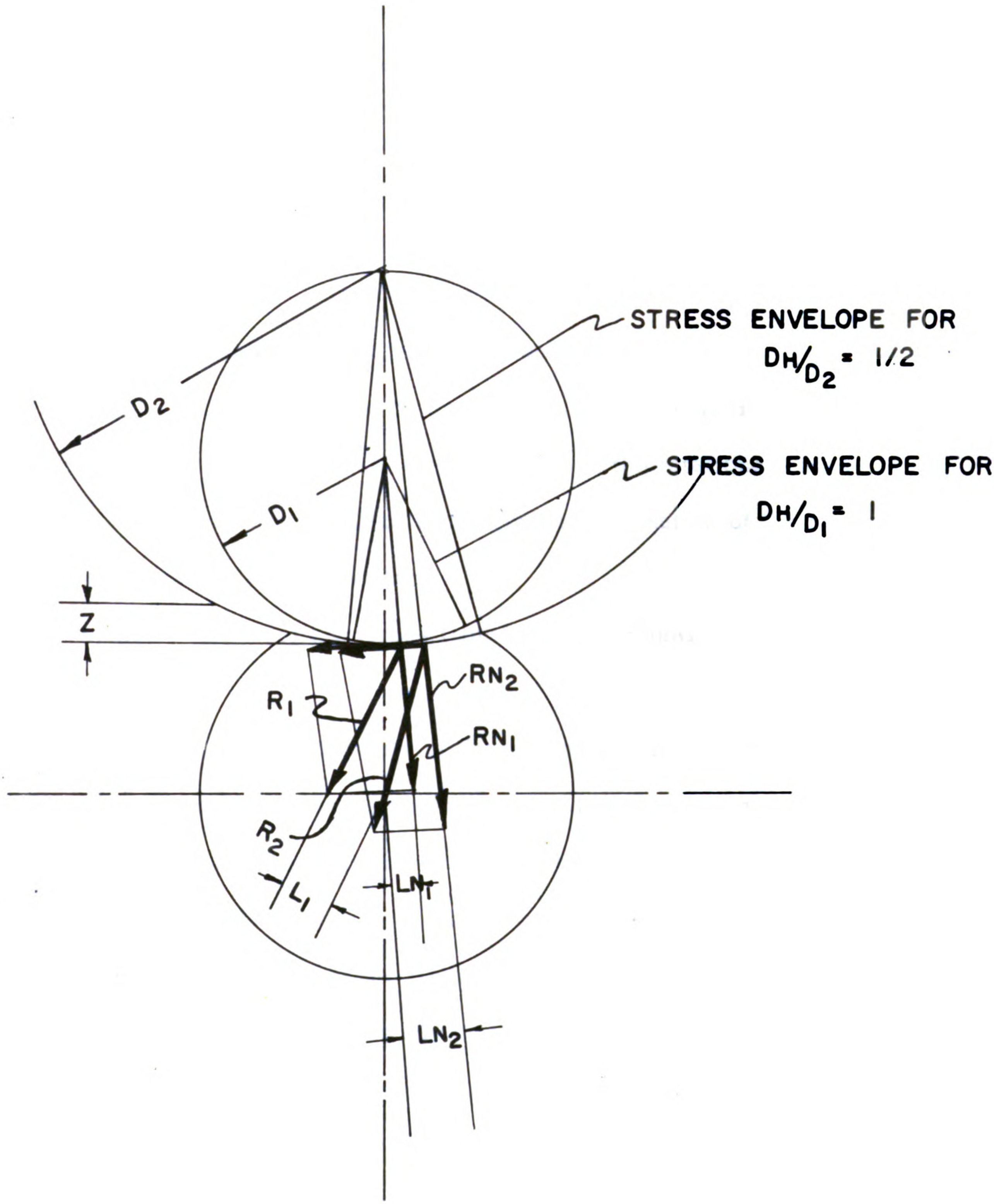


FIGURE 20. DIAGRAM OF THE ACTING MOMENT VS. DIAMETRICAL RATIO

Since both the magnitude and the moment arm of the resultant of the normal stresses increases with the increase of the roller's diameter the value of the diametrical-ratio should be at the possible maximum.

The graphical summation of the tangential and radial resultant forces is shown on Figure 20. On this diagram R_1 is the resultant force for the greater diametrical ratio. It is acting on the forage mass at L_1 distance from the axis of rotation in a positive direction.

R_2, which is the resultant force for the smaller diametrical ratio, is shown at the state of stress when it passes through the rotational axis of the forage body. For this condition of the forces the rotation of the forage body is pending or may actually stop.

The system of the rsultant forces induced by the plurality of rollers is shown on Figure 21.

The density of the rolled wafers is determined by the physical properties of the fibrous material and by the energy absorbed in the process.

Among the several physical properties moisture content is probably the most important. It effects the soluble adhesives which are major factors in the shear strength of the product. The external or internal transfer of the torques depends greatly on the lubricating effect of the extracted liquids. The rolling wafering process can be considered as a drained process because of the non-continuous boundary surfaces. It is also interesting to note that the radial compressive stresses in combination with the rotation of the material in the chamber function as a "hose

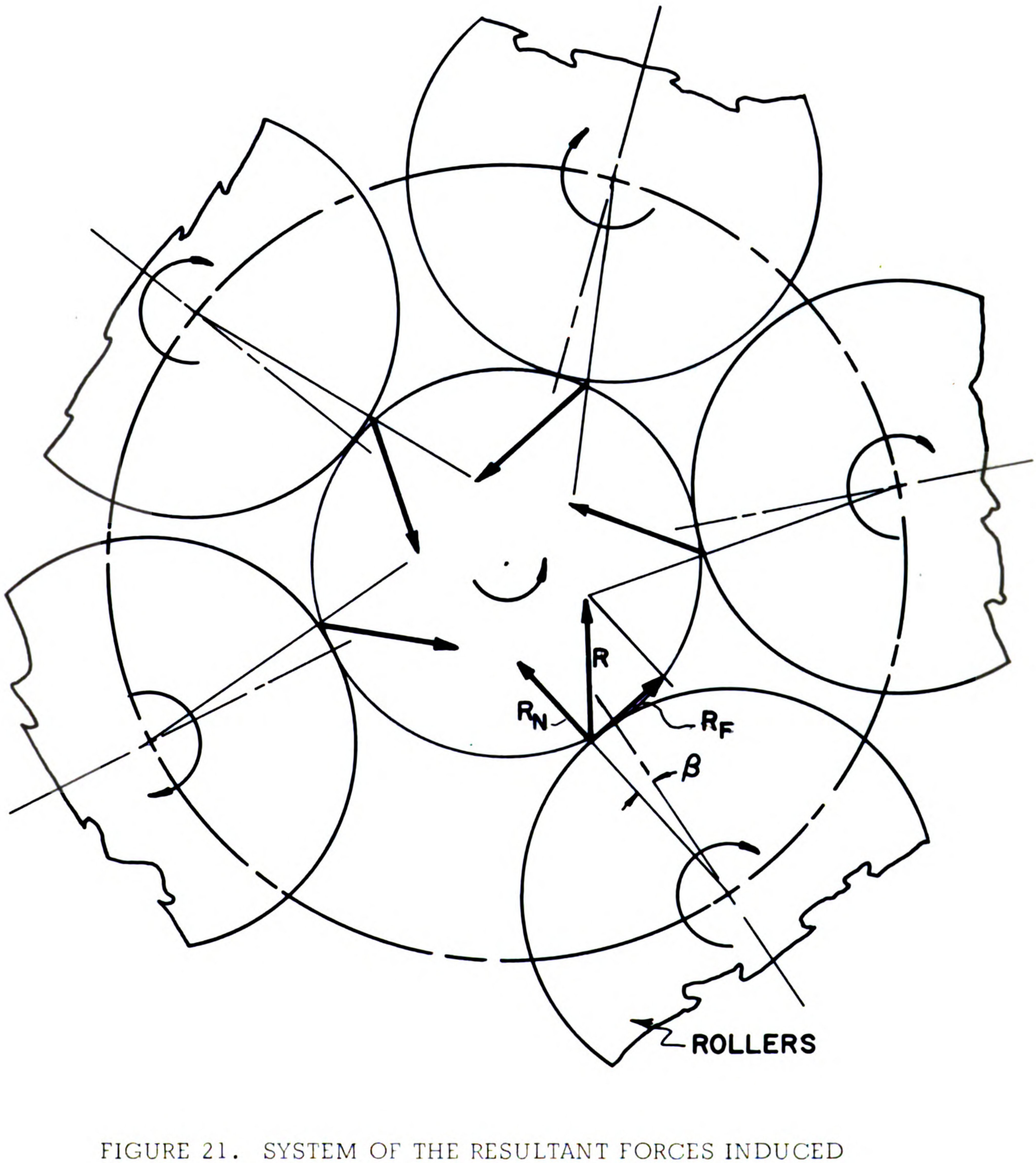


FIGURE 21. SYSTEM OF THE RESULTANT FORCES INDUCED BY THE PLURALITY OF ROLLERS

type pump" forcing the free liquids from the internal section of the wafer body toward the periphery where they can be discharged.

The total energy consumption of the process has to be divided into two groups: the energy which is absorbed by the material in form of work and the energy which is dissipated in form of heat and other losses.

The useful energy input is determined by the material's properties, by the magnitude of the applied stresses and by the time period of the stress application. The magnitude of the stresses can be considered as the function of two factors: the strength of the material to sustain these stresses and the means of supporting the rollers. Because of the gradual build-up of the density of the wafer in the chamber the analysis of the stress requirements is important.

At the feeding zone of the machine which is the first half length of the chamber where the newly incoming loose material begins to wrap around the rotating partially compressed fibers, the normal stresses cannot be near as high as in the second half of the chamber toward the discharge end. The subsequent deformation of the rolling mass under the radial stresses gradually tightens the layers until the strength of the wafer's body is great enough to sustain the stresses without further deflection.

In the design of the device the suspension of the rollers should be made to allow the adjustment of the magnitude of the radial stresses in order to have some control over the final density of the wafers.

The length of the chamber is also a factor to determine the total energy input. The longer the chamber the more gradual the rolling process can be. This aspect must be considered for high moisture content crops and for those materials with small shear strength.

Any excessive work on the material during the process will cause damage either in form of destroying the fibers or generating heat which may reach the combustion temperature.

CHAPTER X

STRUCTURAL ANALYSIS OF THE ROLLED WAFERS

The rolling-compressing wafering process fully utilizes the adhesive and interlocking or cohesive properties of the fibrous crops, thus it may be considered as a relatively moisture independent process.

The three dimensional configuration of an individual stem within the body of a wafer is illustrated on Figure 22. The conical spiral is the result of the simultaneous angular and axial displacement of the rotating mass during the wrapping of the continuously incoming loose forage material. The angle "Z" is therefore the function of the ratio of the angular and linear displacement. This conical configuration is shown on Figure 23 which is the photo of a rolled wafer after the removal of some of the outer layers.

To demonstrate the basic structural differences between wafers made of long hay with a plunger type device and those made with the rolling process Figure 24 is presented. Wafer no. 1 was made with a plunger device. The zig-zag pattern of the stems' configuration is the result of the axially applied compressing force on the axially oriented stems. For this wafer the only significant binding component is the mutual adhesion of the stems and leaves. Its axial tensil strength is small and the elastic properties of the composite elements cause excessive expansion.

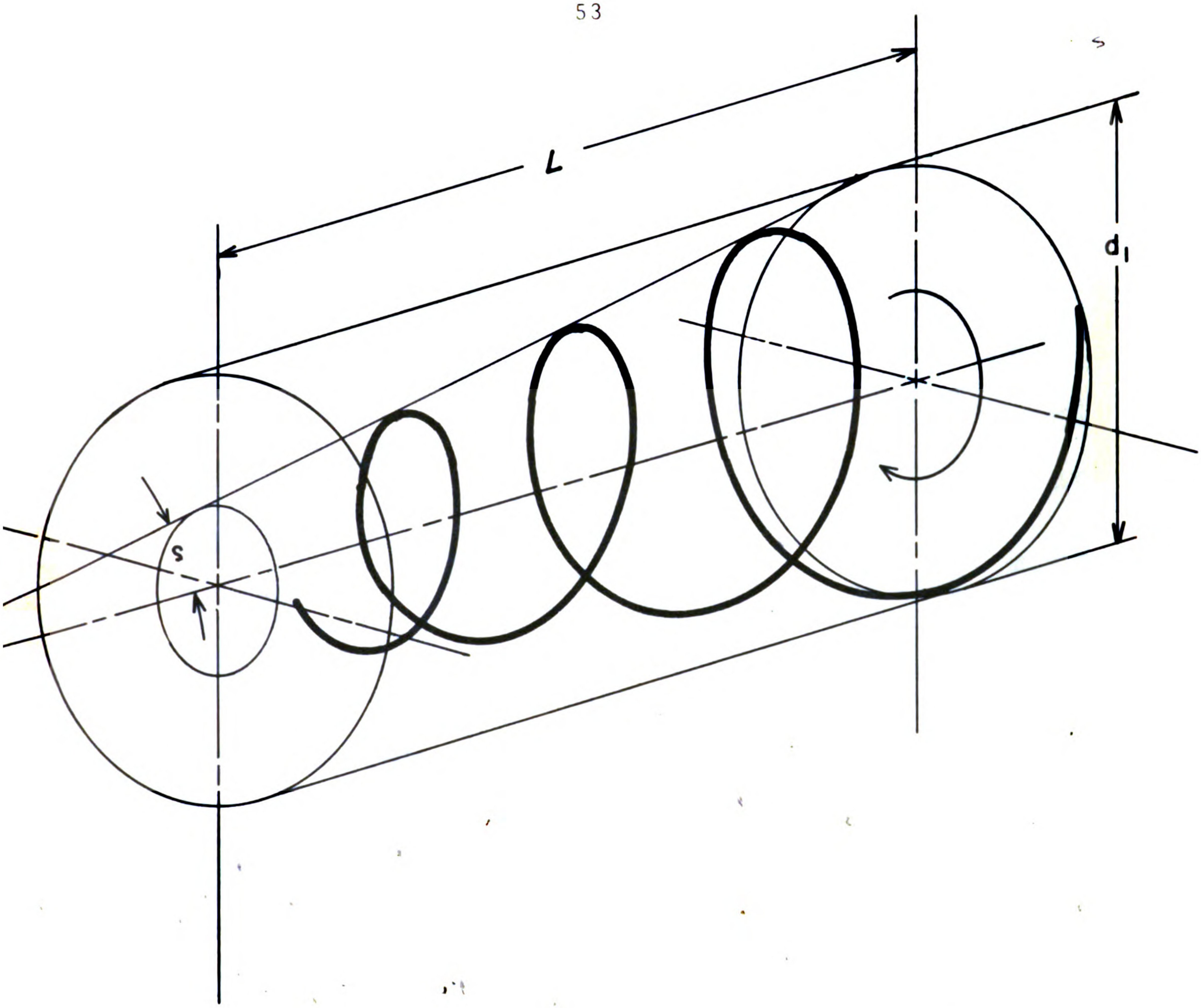


FIGURE 22. THREE DIMENSIONAL CONFIGURATION OF A STEM WITHIN THE BODY OF A ROLLED WAFER

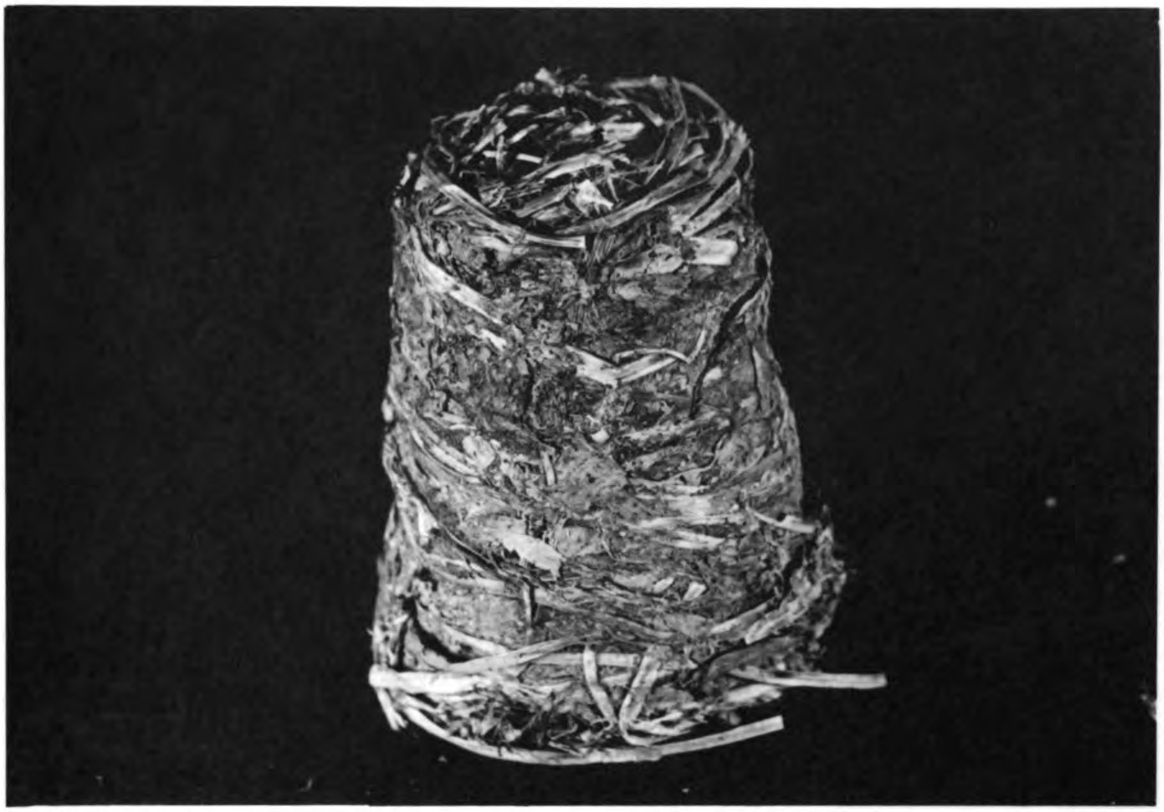


FIGURE 23. PHOTO OF A ROLLED WAFER AFTER THE REMOVAL OF SOME OF THE OUTSIDE LAYERS

FIGURE 24. ILLUSTRATION OF THE BASIC STRUCTURAL DIFFERENCES BETWEEN WAFER MADE WITH:
1. PLUNGER DEVICE, 2. ROLLING APPARATUS,
3. PLUNGER DEVICE WITH PREORIENTED HAY

Wafer no. 2 was made with the rolling process clearly showing the wrapped arrangement of the stems. Rolled wafers made of high moisture content alfalfa hay may have a "hairy surface" because of the not tightly wrapped loose stems.

Wafer no. 3 was made with a plunger-type device but prior to the application of the compressive stress the stems were arranged in a loosely wrapped bundle. This wafer exhibited a superior stability relative to wafer no. 2 in spite of its higher moisture content. The better stability was the result of the interlocking arrangement and proper orientation of the stems.

The factors effecting the structural quality of rolled wafers may be listed as follows:

a, the length of the composite stems. The rolling wafering process cannot be successfully applied to crops or other fibrous material if the length of the stems or fibers is not at least 1.5 times the diameter of the wafer. It is, however, possible to wafer the mixture of long and sized stems if the length of the long fibers satisfy the 1.5D requirement and compose at least 50 percent of the mixture. It was also found that certain fibrous materials could be wafered with shorter length, however, these fibrous products possessed unusual adhesive properties.

b, coarseness of the stems, which plays an important role in the cohesive or interlocking properties. Some grasses exhibited excellent cohesion while having little or no adhesion, making the wafering possible.

c, the stem-leaf ratio plays an important role at high moisture content where the adhesive properties of the leaves had little or no binding effect. For low moisture content legumes the adhesives in the leaves were significant binding agents.

The effectiveness of the adhesive and cohesive binding properties of the wafers was tested by the measurement of the dimensional changes in the wafers' bodies after the process. The reference or initial dimensions were the "diameter" of the chamber and the length of the wafer to which the continuous hay bar was sliced during the rolling process.

The observed changes were small as recorded on Figure 31.

The durability of dried wafers was tested on the tumbling chute, which was designed by Mr. Bellinger in 1960. Each tested wafer was tumbled ten times in the chute and the change in its weight was recorded. Regardless of the conditions of the forage material at the time of wafering, the weight loss during the testing cycle was small, about 4.8 percent of the initial weight. The wafers were dryed to 18 percent moisture content (wet basis).

Similar results were obtained when wafers prior to drying were tested. The dry matter separation was about 5 percent. However, these wafers had a "hairy" appearance after testing. It is therefore essential to apply the possible minimum handling of the wafers before the drying process.

For a comparative analysis of the moisture-content-density relationships for alfalfa hay wafers made with a plunger type device and those made with the rolling process, some data are plotted on Figure 25.

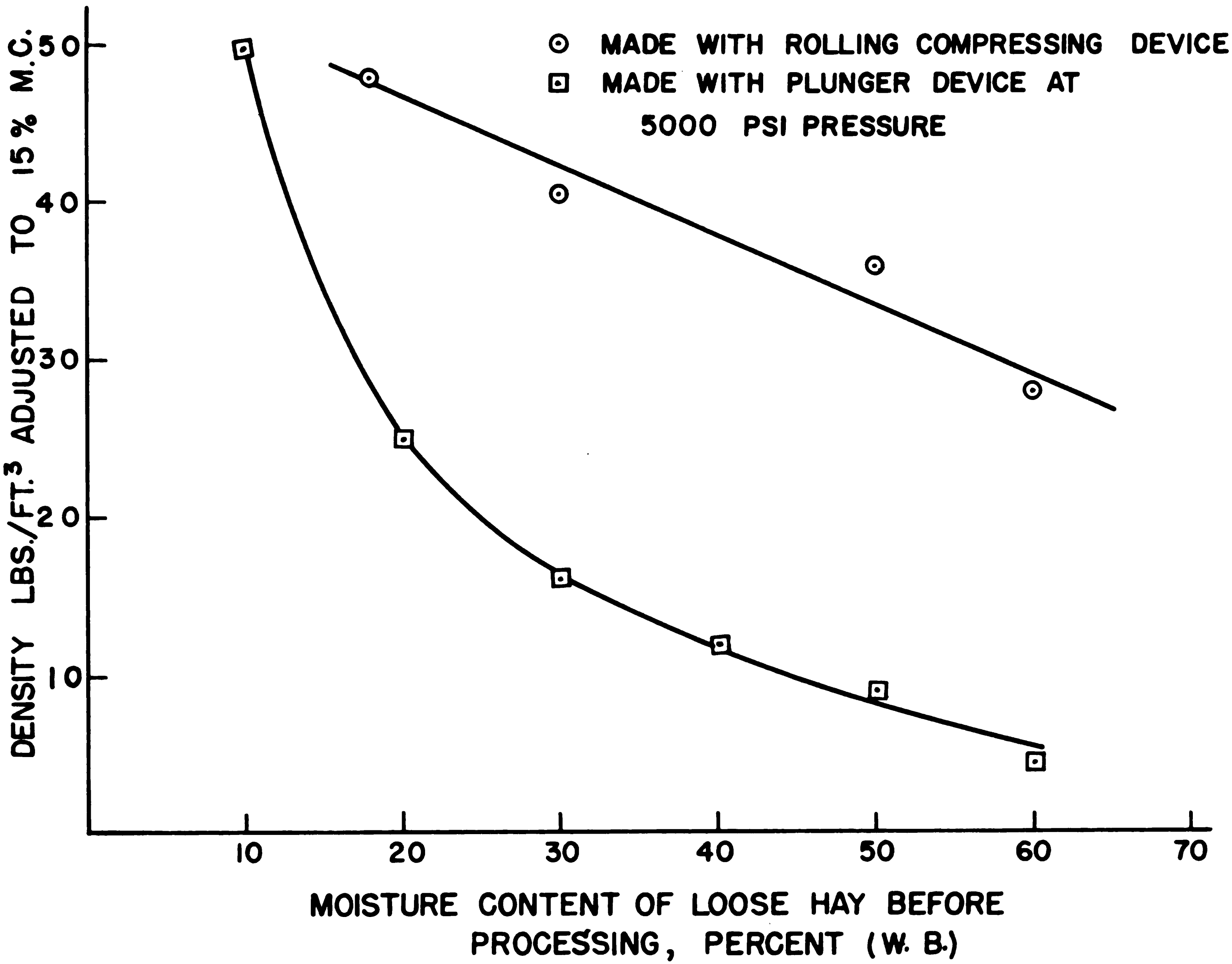


FIGURE 25. DENSITY VS. MOISTURE CONTENT FOR WAFERS MADE WITH ROLLING AND PLUNGER DEVICE

CHAPTER XI

DESIGN AND OPERATION OF THE EXPERIMENTAL ROLLING-COMPRESSING APPARATUS

Three basically identical experimental devices were constructed for the analysis of the process:

The first device, shown on Figure 26, had a 27-inch long four-roller compression chamber. The rollers were powered by a three horsepower electric motor through a v-belt drive. The power was transmitted to the individual rollers by a roller chain drive. The peripheral velocity of the roller was the same. The chamber diameter was approximately 1.5 inches. The rollers had no radial adjustment but the bearing plates could be adjusted to obtain the torsional angle. The theoretical rotational speed of the material in the chamber was 320 revolutions per minute.

To provide controlled feeding an oscillating feeding table was attached to the rolling unit. The table was powered through an excentric crank drive with a two-inch stroke at 85 cycles per minute. The protruding curved fins on the table's surface forced the fibers through the feeding area which was restricted by stationary fingers.

The actual feeding of the machine was limited to the feeding zone which is approximately half of the total length of the chamber. The other section of the chamber was necessary to the gradual density build up. If the whole chamber length is used for feeding, the surface of the wafers is

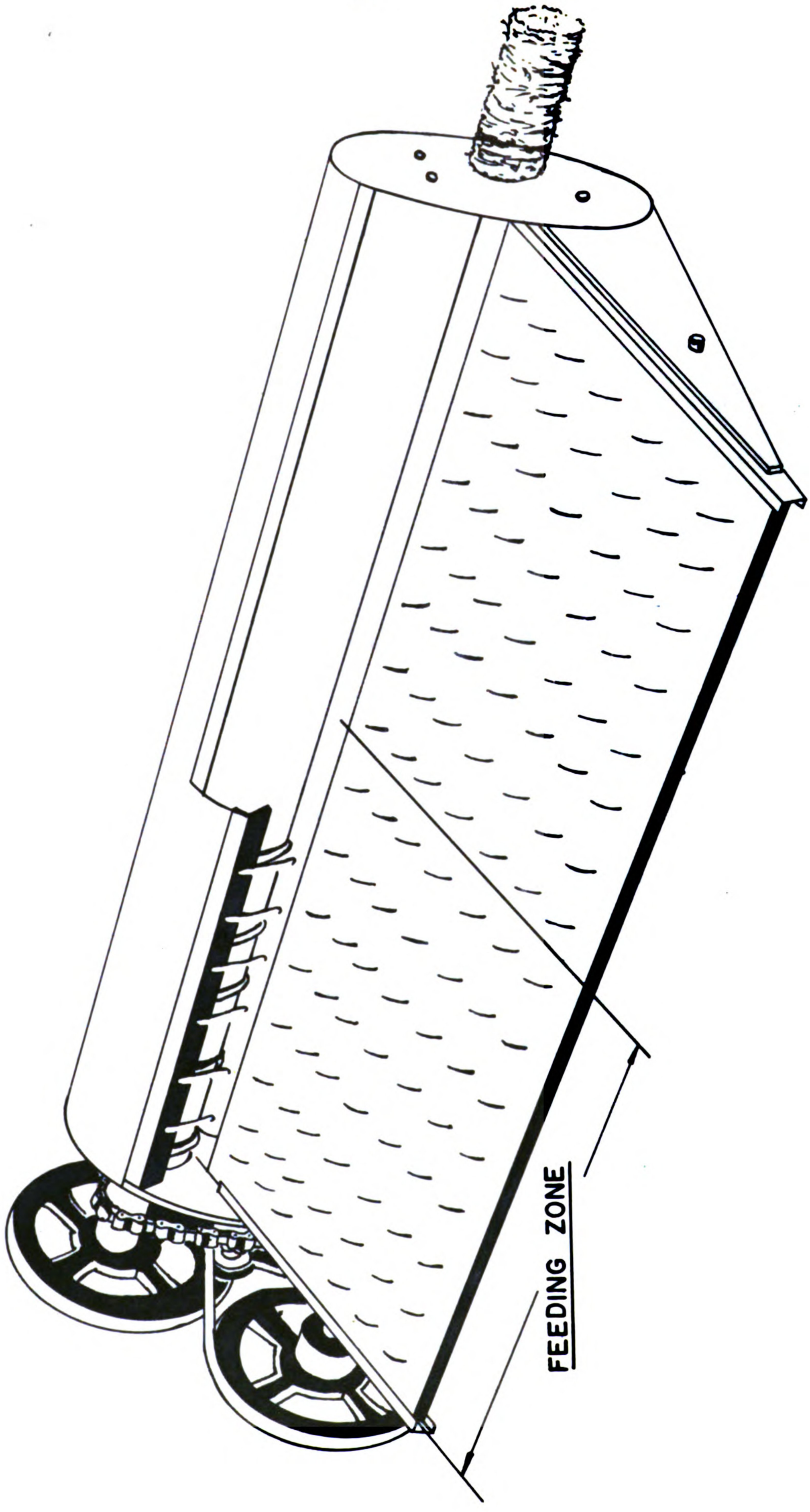


FIGURE 26. DIAGRAM OF THE FIRST ROLLING-COMPRESSING WAFERING APPARATUS

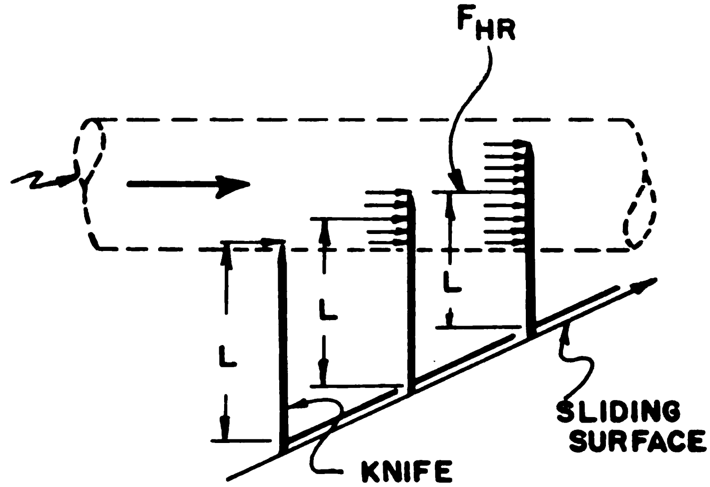
not well formed and the loosening or unwrapping of the outside layers might take place. The rollers were made of steel tubing with relatively smooth surfaces. One of the rollers was later modified by welding a spiral shaped edge on it to provide more positive driving.

The structural weaknesses of the first apparatus were apparent, therefore no attempts were made to produce large quantities of wafers with it.

The slicing of the continuous wafer bar was done by the self powered apparatus shown on Figure 27. It consists of a frame to support the sprockets with the chain. The cutting knives were mounted on the chain links. The rotating and axially moving bar of the compressed forage exerts the force F_{HR} on the rear surfaces of the knives propelling the chain. The cutting edges of the knives penetrated the forage bar while it was rotating and sliced the bar to the desired length which depends upon the spacing of the knives on the chain.

The second device, shown on Figure 28 was designed for experimental field work, therefore it was mounted on the three-point-hitch of a tractor. It was powered from the power-take-off through a planetary gear system.

The length of the chamber was 28 inches long with 1.6 inch diameter. The rollers were made of solid cold rolled steel bar with 3 inches diameter. The adequate structural strength of the device allowed extensive testing. Similarly to the first unit, no radial adjustment of the rollers was possible. The diametrical-ratio of this apparatus was 0.535 as compared to the first device with 0.653 ratio.



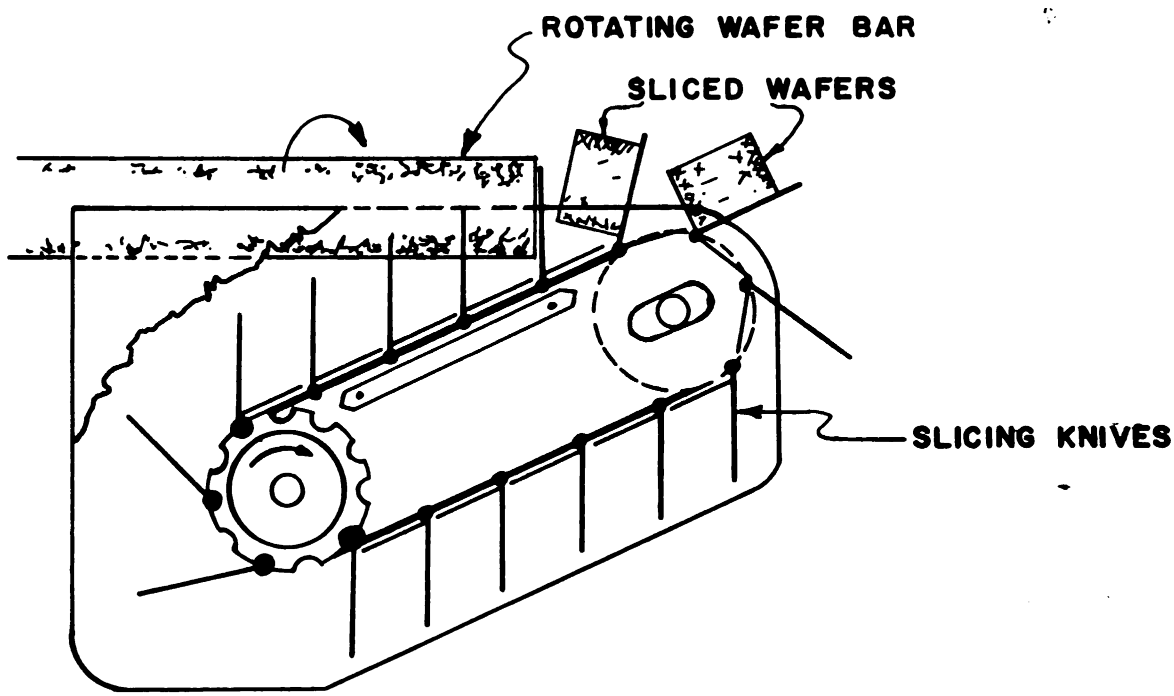


FIGURE 27. SLICING DEVICE FOR THE ROLLING WAFERING APPARATUS

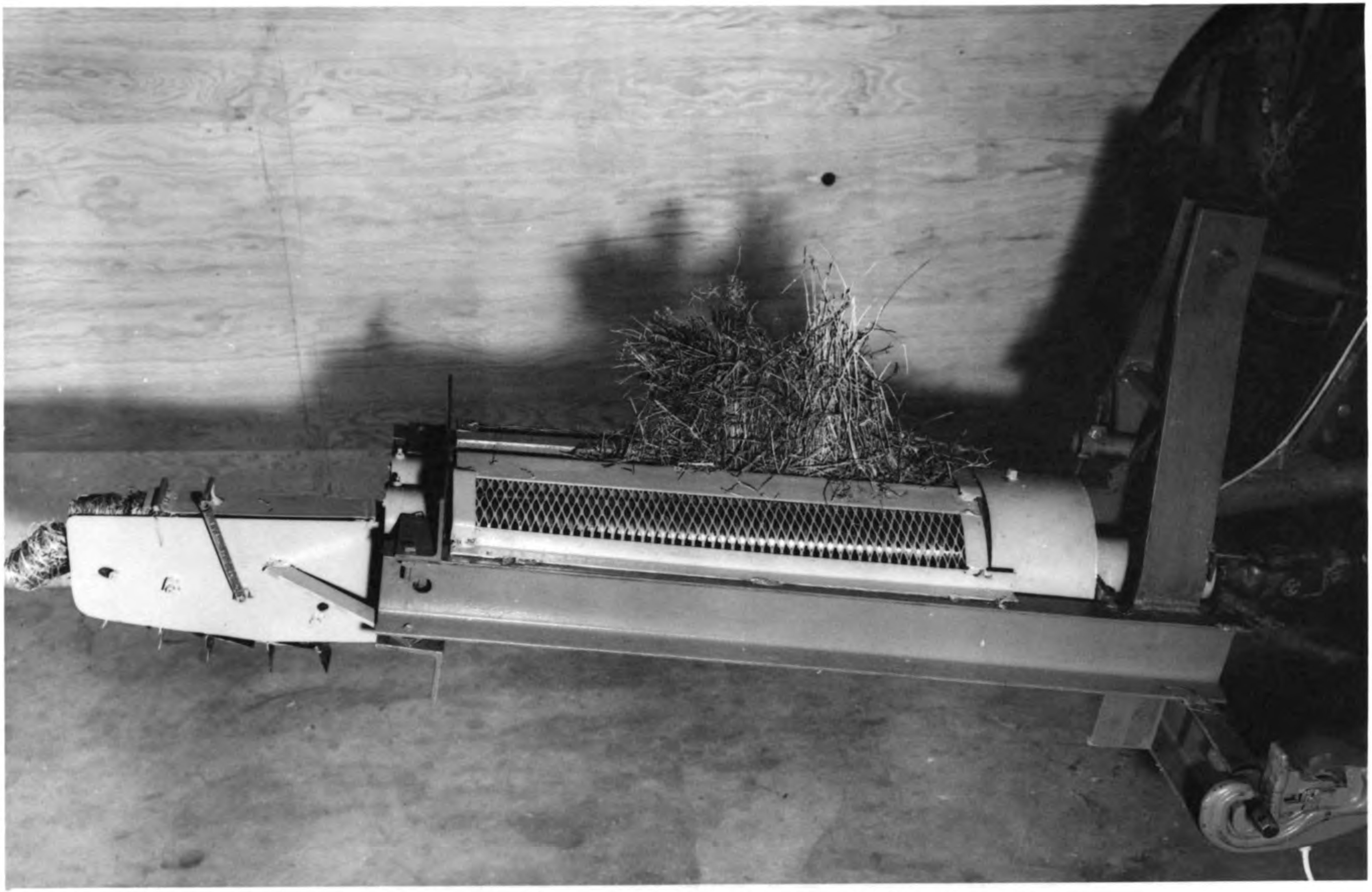


FIGURE 28. TRACTOR-MOUNTED ROLLING WAFERING APPARATUS

The third apparatus had a 27 inch long compression chamber with 2-1/8 inches maximum diameter. The diametrical-ratio was 0.92. The rollers were driven by an electric motor with variable speed and were adjustable both radially and torsionally. The purpose of the radial adjustment by compressive springs was to maintain the radial stresses at a nearly constant magnitude.

The increased diametrical ratio improved the performance of the apparatus. Considerable reduction in heat generation could be observed. The larger wafer diameter increased the capacity consiberably.

The second device was later modified by adding a frusto-conical section to the main drive shaft which entered the compression chamber. It provided positive drive for the internal section of the rotating forage bar and also functioned as the continuation of the dense core of the material in the feeding area. The modified design is shown on Figure 29.

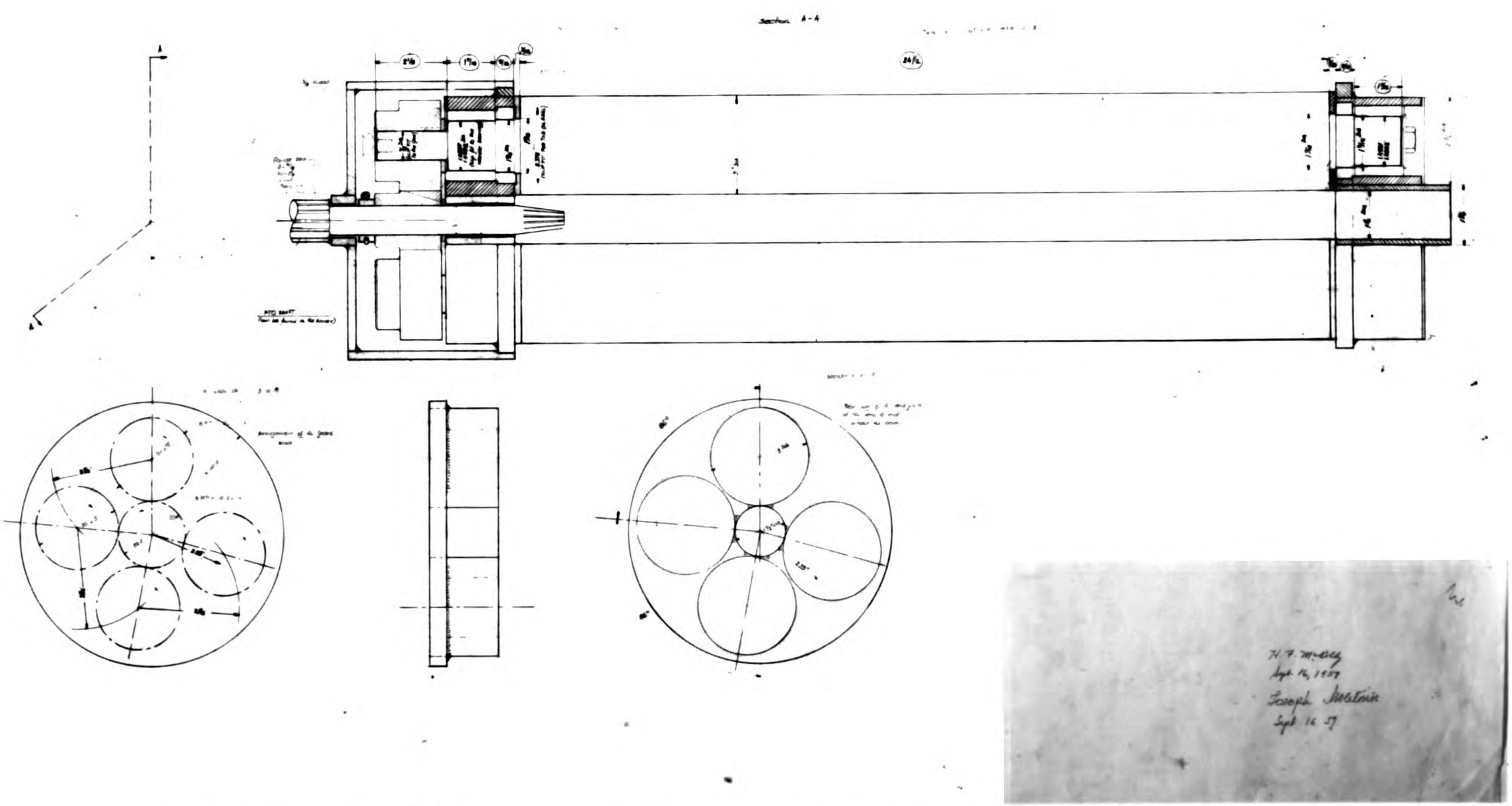


FIGURE 29. DESIGN OF THE MODIFIED TRACTOR-MOUNTED WAFERING APPARATUS

CHAPTER XII

SUMMARY

One limitation in the broader application of the wafering process to agricultural forage crops was the moisture content. In the pelleting and wafering of chopped or long hay by piston or ram devices the main binding elements are the natural adhesives of the crop. These adhesives are mostly water soluble gums and sugars, therefore, their effectiveness largely depend on the water content of the forage.

The fibrous characteristics of most grasses and legumes provided a different concept for wafering, where the binding elements are not restricted to the adhesives. The moisture independent interlocking of the composite stems and the wrapping of the fibers in a rolling process made it possible to wafer high moisture crops. These self-contained packages possess excellent durability, can be made in different sizes at various densities. It also became possible to wafer those forage crops without adequate adhesive properties.

The rolling wafering device is a relatively simple mechanism without the need of reciprocating components. It provides a continuous process whose capacity can be increased to a commercially acceptable level. The power requirements are relatively low and for a properly designed and constructed field machine the energy consumption is expected to be equal to the baling machines.

The rolled wafers are accepted by the animals. Feeding trials indicated no change in butterfat or milk production. A slight increase in dry matter consumption was experienced when good quality hay wafers at 20 to 28 pounds per cubic foot density were fed. At higher densities the application of some loosening process may be necessary prior to feeding.

In general, the results of this research study indicated the definite advantage of this process over the conventional plunger or die wafering process.

Figure 30 illustrates a rolled wafer.

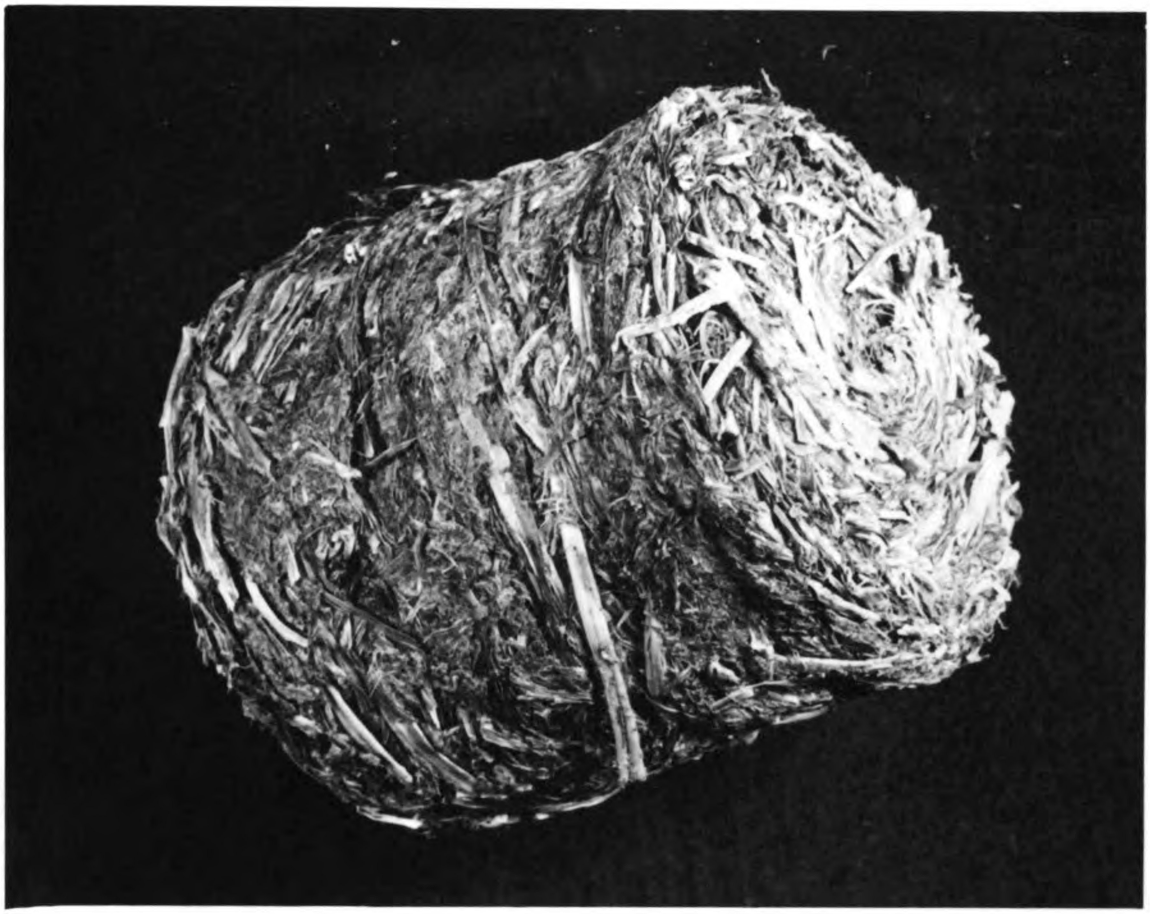


FIGURE 30. PHOTO OF A ROLLED WAFER

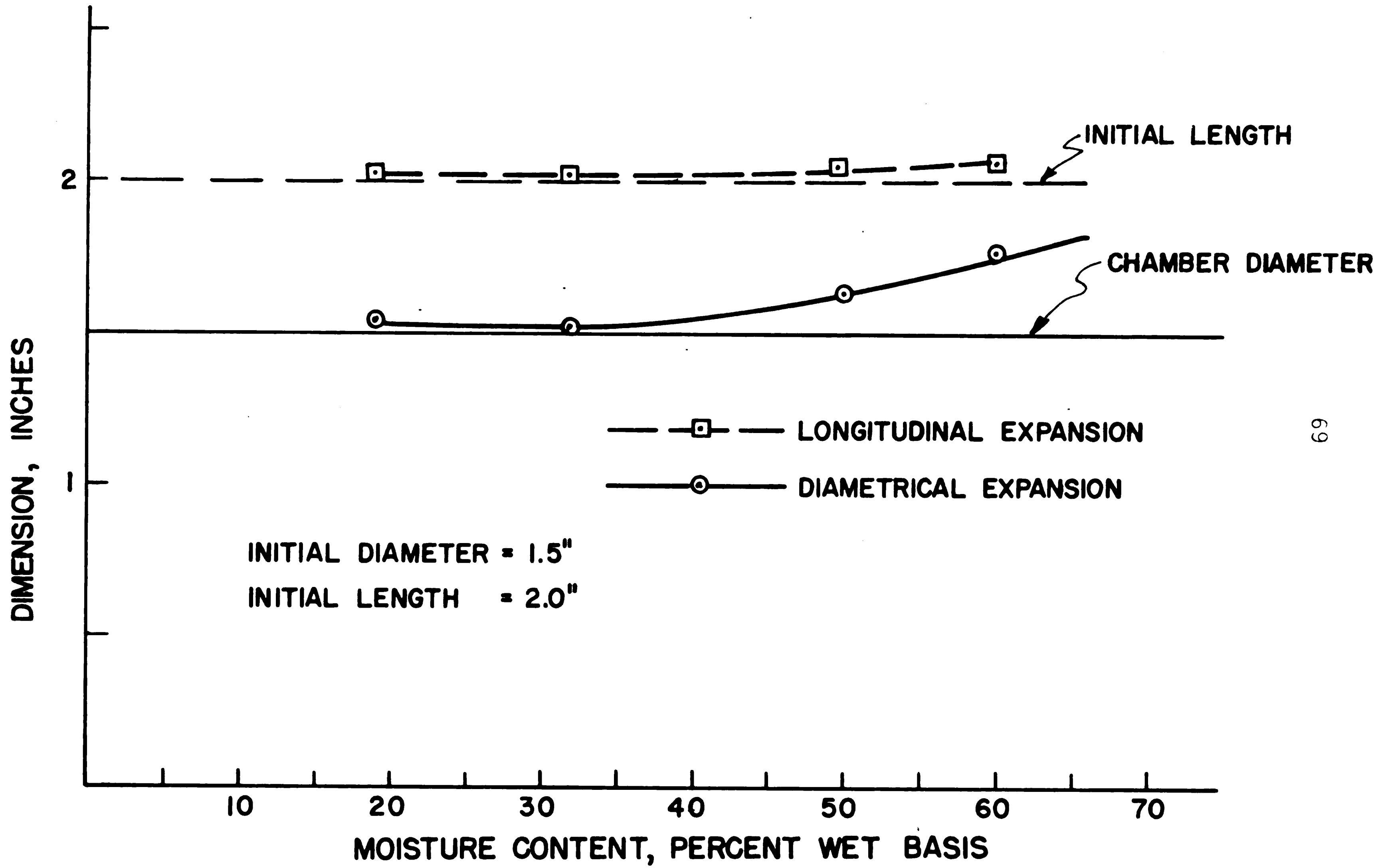


FIGURE 31. DIMENSIONAL CHANGES OF ROLLED ALFALFA WAFERS VS. MOISTURE CONTENT

CHAPTER XIII

CONCLUSIONS

As the result of the observations and data collected during these research studies the following conclusions are presented:

1. The forming of self-contained packages of agricultural or other fibrous materials is possible by the rolling wafering process.
2. The durability and strength of the rolled wafers is provided not only by the adhesive effect of the natural gums and other chemical constituents but also by the interlocking and wrapping of the individual fibers or stems.
3. The moisture independent binding factors make it possible to apply the rolling process to fibrous materials at wide range of moisture content and also to fibrous materials without adhesive characteristics.
4. The nature of the process requires a relatively simple mechanism. The continuous flow of the material through the machine is provided without reciprocating components. It is therefore possible to reduce the power requirements to a commercially acceptable level.
5. The rolled wafers are acceptable for animal feeding.

CHAPTER XIV

SUGGESTIONS FOR FURTHER STUDY

In order to gain more knowledge about the rolling process and of the rolled wafers, the following suggestions are submitted:

1. Study of the rheological properties of agricultural forage crops before and after the wafering process.
2. Experimental and theoretical analysis of the stresses during the wafering process, in order to obtain the required parameters for the development of the apparatus.
3. Investigation of the drying and handling characteristics of the rolled wafer at various geometrical configurations.
4. Conduct extensive feeding trials to determine the optimum size and density of the wafers.

REFERENCES

1. J. Molitorisz (1960-61). Project Report on "Hay Pelleting." Michigan State University, Department of Agricultural Engineering.

2. H. F. McColly (1964). "What's Happening in Hay Wafering." Michi- State University publication.

3. H. D. Bruhn (1955). "Pelleting Grain and Hay Mixtures," Agricultural Engineering Journal, 36, 330-331.

4. H. D. Bruhn (1957). "Engineering Problems in Pelletized Feeds," Agricultural Engineering Journal, 38, 522-525.

5. H. D. Bruhn, A. Zimmerman, and R. P. Niedermeier (1958). Developments in Pelleting Forage Crops. Paper presented at winter meeting of ASAE.

6. J. B. Butler (1958). "Factors Effecting the Pelleting of Hay." Unpublished Ph.D. thesis, Michigan State University, East Lansing, Michigan.

7. P. L. Bellinger (1960). "Energy Requirements for Pelleting Whole Alfalfa Hay and Preliminary Studies of Durability and Animal Acceptance of Pellets and Wafers." Unpublished M.S. thesis, Michigan State University, East Lansing, Michigan.

8. H. F. McColly and J. Molitorisz (1960). "Crop Pelleter, Description of a Patentable Idea." Unpublished paper prepared for patent application.

9. F. B. Morrison (1957). Feeds and Feeding. (Ithaca, New York: Morrison Publishing Company.)

10. J. B. Dobie (1960). "Production of Hay Wafers," Agricultural Engineering Journal, June.

11. K. Terzaghi (1943). Theoretical Soil Mechanics. (New York: Wiley Publishing Company.)

12. E. Hegedus (1962). A Preliminary Analysis of the Force System Acting on a Rigid Wheel. U. S. Army Ordnance Tank-Automotive Command, Detroit, Michigan

13. V. J. Lundell and D. O. Hull (1960). Developing and Engineering a Field Wafering Machine. Paper presented at the 1960 winter meeting, American Society of Agricultural Engineers.

14. D. R. Vaughan and R. W. Johnson (1961). Development of a Field Pelleter. Paper presented at the 1961 annual meeting, American Society of Agricultural Engineers.

15. William Chancellor (1961). Formation of Hay Wafers with Impact Loads. Paper presented at the winter meeting of ASAE.