This is to certify that the

thesis entitled

DEFOLIATION AND PHYSICAL PROPERTIES
OF SUGAR BEETS

presented by

Hasan Alizadeh

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Engineering

Larry J. Segerlind
Major professor

Date February 14, 1978

O-7639

DEFOLIATION AND PHYSICAL PROPERTIES
OF SUGAR BEETS

By

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A DISSERTATION

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

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1978

ABSTRACT

DEFOLIATION AND PHYSICAL PROPERTIES OF SUGAR BEETS

By

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Using a compound pendulum as the impact device, the mechanical behavior of sugar beet petioles (variety US H20) under impact was studied. The petioles were impacted at four different locations and the impact energy required to remove the petioles and the efficiency of defoliation (percent removal of the petioles) were determined.

Experimental results showed that a maximum number of petioles were removed when impacted close to the crown and in tangential direction (designated as location D). A higher impact energy was required for this location. Approximately 24 joules was sufficient to defoliate a beet using an impact velocity of 2.45 meters per second. The total impact force required to remove the foliage was determined to be 440 newtons.

The relation of the beet temperature, the total dissolved sugar of the root and other important environmental factors (the air and soil temperatures in the field, the air and petioles moisture contents) with the impact behavior of the petioles were investigated. The variation of these quantities during the 1976 sugar beet harvesting season in Michigan, U.S.A. was also studied.

Hasan Alizadeh

The study indicated that beet temperature had the highest correlation with the impact energy and the efficiency of defoliation. The petiole turgidity was a factor affecting their response to impact.

A design criteria for a mechanical defoliator was developed and the results of the laboratory tests on a prototype model were promising.

Separate tests on the beet root were conducted. The apparent modulus of elasticity, maximum shear stress, Poisson's ratio and the type of the failure of cylindrical samples were studied. Three different sample sizes taken from two perpendicular directions were used. The influence of total dissolved sugar and other environmental factors, as indicated above, were analyzed and the variation of the measured parameters during the harvesting season are presented.

Average values of 11.531 megapascals, 1.250 megapascal and 0.39 were determined for the apparent modulus of elasticity, maximum shear stress and Poisson's ratio, respectively. The experimental results on the beet roots showed that the values of apparent modulus of elasticity and maximum shear stress are not dependent on the sample size and loading orientation except smaller size (designated as A) which had different values of apparent modulus of elasticity for the two perpendicular directions. Poisson's ratio was not a function of sample orientation but different sample sizes showed significant differences. The values of Poisson's ratio during the harvesting season remained relatively constant, while the apparent modulus of elasticity and maximum shear stress had an increasing trend. The root samples failed along the plane making approximately 45 degrees with the axial loading direction.

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and

Aghdas

ACKNOWLEDGMENTS

The author sincerely appreciates the guidance and close cooperation of his major professor, Dr. Larry J. Segerlind and the assistance of Dr. George J. Hogaboam in sugar beet crop preparation and constructive information on the beet crop. Equally, his gratitude is extended to Dr. Chester J. Mackson and Dr. George H. Martin for their counseling.

The author is also indebted to the Iranian people from which, through a scholarship, this graduate program was made possible.

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LIST OF SYMBOLS

A	Impact location	—
A	Area	m^2
A_d	Pendulum drop angle	degree
A_r	Pendulum rise angle after impact	degree
B	Impact location	—
C	Impact location	—
c	Chain batch	—
cm	Length	centimeter
Cos	Cosine	—
°C	Temperature	degree Celsius
c_1, c_2, c_3	Numerical values given to the petiole response, zero, one-half and one, respectively	—
D	Impact location	—
D	Distance between the beet rows	m
d	Disc	—
d_{max}	Maximum diameter of beet	mm
E	Energy	J
E_d	Apparent modulus of elasticity	Pa
E_1	Energy loss due to rotation of the defoliator	J
E_2	Energy loss due to translation of the defoliator	J
E_d	Efficiency of defoliation	decimal

$\bar{E}_d$	Total mean efficiency of defoliation (average of means of four locations)	decimal
E_i	Impact energy	J
$E_{i(m)}$	Modified impact energy	J
$\bar{E}_i$	Total mean impact energy (average of means of four locations)	J
F	Force	N
F_c	Centrifugal force	N
G	Shear modulus of elasticity	Pa
g	Gravity acceleration	$9.8\ m/s^2$
H	Disc thickness	mm
h	Height	mm
I_o	Mass moment of inertia about o	$N \cdot m \cdot s^2$
J	Energy	joule
K	Bulk modulus of elasticity	Pa
kg	Mass	kilogram
L	Distance of beets in the row	m
L	Length of beet samples	mm
M	Mass	kg
M_1, M_2	Mass of the disc and a batch of chain, respectively	kg
MPa	Pressure	megapascal
M_t	Total mass of the defoliator	kg
m	Length	meter
mm	Length	millimeter
m·s	Time	millisecond
N	Force	newton
N_t	Total number of tests for each impact location each day	--

P	Period of pendulum free oscillation	s
pCb/N	Transducer sensitivity	picocoulombs per newton
r	Distance between the impact center and the center of rotation of the pendulum	m
rpm	Angular velocity	revolution per minute
r_a	Distance from the centroid of the chain to the disc center	m
r_g	Distance from the center of gravity of the pendulum to the center of rotation	m
r_1	Disc radius	m
s	Time	second
Sin	Sine	--
T	Temperature	°C
V_f	Defoliator forward linear velocity	m/s
V_i	Linear velocity of the pendulum at impact point	m/s

Subscripts

A	impact location
a	apparent
a	average
B	impact location
C	impact location
D	impact location
d	defoliation
d	drop
g	center of gravity

i	impact	
i(m)	modified impact	
j	impact locations A, B, C or D	
max	maximum	
o	center of rotation	
r	rise	
rr	radial direction	
zz	vertical direction	
ΘΘ	circumferential direction	

Greek symbols

ω	Angular velocity	rad/s
Δ	Difference	--
Π	3.14	--
ε	Strain	--
σ	Normal stress	Pa
τ_{max}	Maximum shear stress	Pa
ν	Poisson's ratio	--

I. INTRODUCTION

The sugar beet (Beta Vulgaris L.) has to be topped or defoliated before it is delivered to the processing plant for the extraction of sugar. Improper defoliating or topping is one of the major losses of sugar in the beet processing industry.

Defoliation consists of removing the foliage of the beet plant with rotating steel and rubber flails. Conventional defoliators have the flails hinged radially to rotating drums. The beet petioles are ruptured from the beet by the impact of the rotating flails, Figure 1. Different types of defoliators have been developed to defoliate the sugar beet. Conventional defoliators leave behind beets which are partially defoliated, inverted and with crown cut-offs.

The beet petioles are struck from different locations and directions by the defoliator during harvest. The objectives of this study were to investigate the behavior of the beet petioles when impacted and to study the material properties of the beet root. The overall objective was to develop defoliator design criteria based on the mechanical properties of the petioles and beet which would reduce the problems associated with the conventional defoliators.

The work reported in this thesis consists of six major parts:

1. The apparatus and instrumentation used in conducting the experiments.

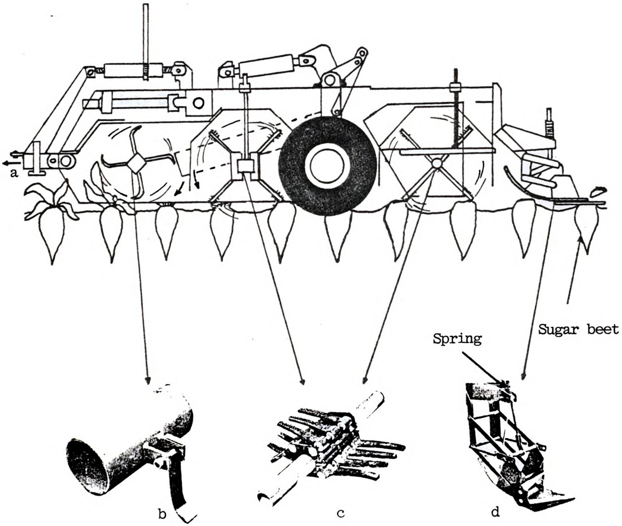


Figure 1. Different Sections of a Conventional Defoliator (Hesston model).

a - complete defoliator
b - steel flail
c - rubber flails
d - scalper unit (optional)

2. The experimental methods and procedures used during the 1976 sugar beet season in East Lansing, Michigan (USA).
3. The development of necessary theoretical relations to analyze the test results.
4. The analysis and discussion of the experimental results.
5. Development of a defoliator design criteria.
6. A discussion of the material properties of the beet root (variety US H20).

II. REVIEW OF LITERATURE

The literature concerning the development of beet topping and defoliating are reviewed herein along with the test methods employed to study the mechanical damage of biological products subjected to impact.

Alizadeh (1976) reported that the topping of sugar beets has been accomplished in many different ways. It has ranged from manual topping to complete mechanization in the industrialized countries. The beets are either topped while they are in the ground or held in the topping machine. This report which contains an inclusion of references on topping and defoliation, shows no extensive studies on the mechanical properties of the beet crown and petioles under the impact of the topping (cutting and beating) unit in the development of the topping mechanisms.

The removal of the crown of the sugar beet introduces severe storage and yield losses (Cole, 1976; Dilley et al., 1968; Francia, 1975; Fort and Stout, 1944; Mason, 1952; Strooker, 1962; Wyse, 1973). Incomplete defoliation creates storage problems and reduces the percentage of sugar extraction during processing because of the higher impurities and lower percentage of sugar (Akeson, 1973; Akeson et al., 1974; Zielke, 1970). These problems cost the sugar beet industry millions of dollars annually (Vosper et al., 1976; Tanner, 1973; British Sugar Beet Review, 1976).

Akeson (1973) and Cole (1976) reported that storage losses can be reduced by only defoliating but not cutting the beet crown. The slight increase in the tonnage of the harvested beets does not greatly affect the quality of the beet. The defoliation of sugar beet involves impacting one body, the beet, with another, a flail. Goldsmith (1960) indicated that solutions for impact problems are obtained for only simple geometrical configurations because of the complexity of the impact phenomena. He gave several solutions involving spheres and cylinders with flat plate loadings.

Different methods have been utilized to investigate the response of the agricultural products under impact loading utilizing the principles of conservation of mass, conservation of momentum and a mechanical energy balance. Simple drop tests, pendulum and a rotating impact arm have been employed in the impact testing of fruits and vegetables. The pendulum has been a popular device for applying an impact load (Bittner et al., 1967; Fluck and Ahmed, 1973; Horsfield et al., 1976; Mohsenin and Goehlich, 1962; Mohsenin, 1970; Srivastava et al., 1976). Parameters such as impact energy, impact force and impulse in combination with force-time or force-displacement relations have been obtained using the pendulum impact device. These quantities are usually related to the damage resistance characteristics of the tested material.

III. EXPERIMENTAL APPARATUS

The apparatus that was constructed to impact the petioles is discussed herein along with the instrumentation used in combination with the impact apparatus. The instruments employed in determining other parameters are also identified and discussed.

A compound pendulum was constructed to perform the experiments. The pendulum, Figure 2, consisted of a steel impact arm, a ball bearing, a protractor, an adjustable marker and a force transducer located under the impact element.

The dimensions of the impact arm are given in Figure 3. The mass of the arm was 0.975 kg, and it was 0.45 m long. The angle of rotation was read from the protractor with the aid of an indicator as well as being recorded on a graph.

The impact velocity of the pendulum was measured and compared with the theoretical value as given by equation (5). The results are shown in Figure 4.

The theoretical values of the impact velocity at zero potential energy was determined as follows. The linear impact velocity, V_i, is related to the angular velocity, ω, by

$$V_i = r\,\omega \tag{1}$$

where r is the distance between the impact center and the center of rotation. The value of V_i was calculated using the relationship

$$M\,g\,h = \frac{1}{2}\,I_O\omega^2 \tag{2}$$

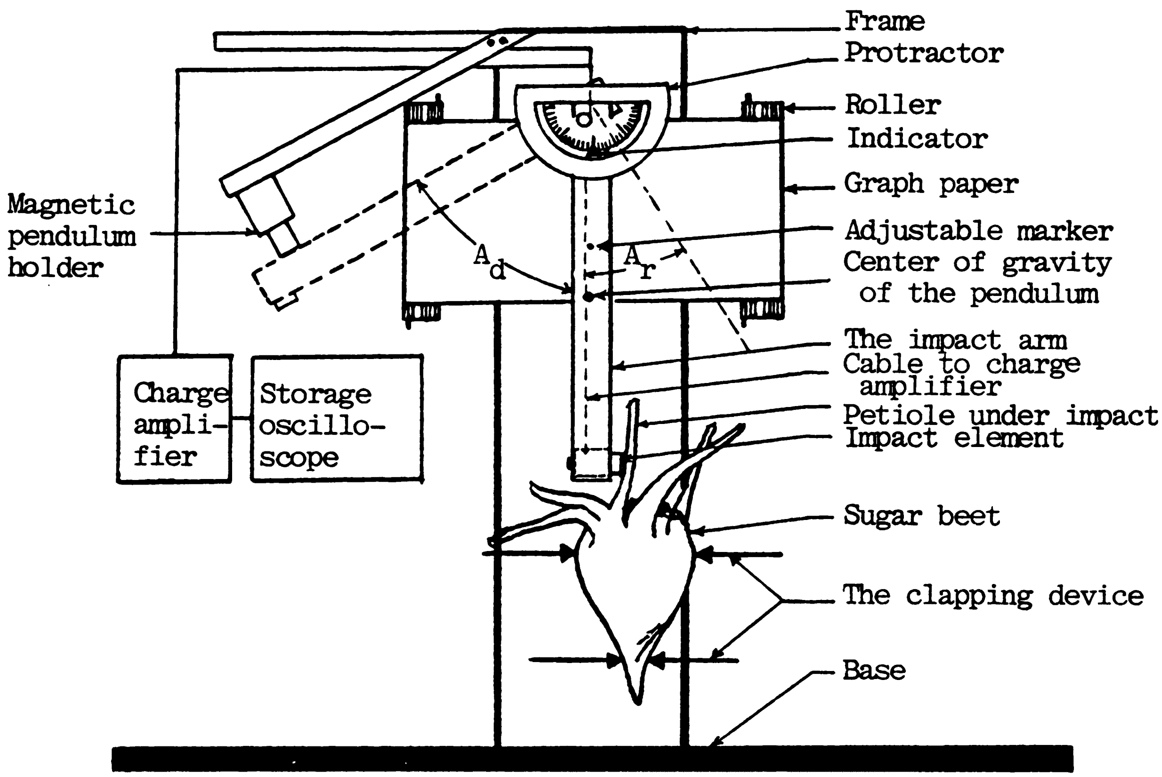


Figure 2. The Schematic Diagram of the Instrumentation.

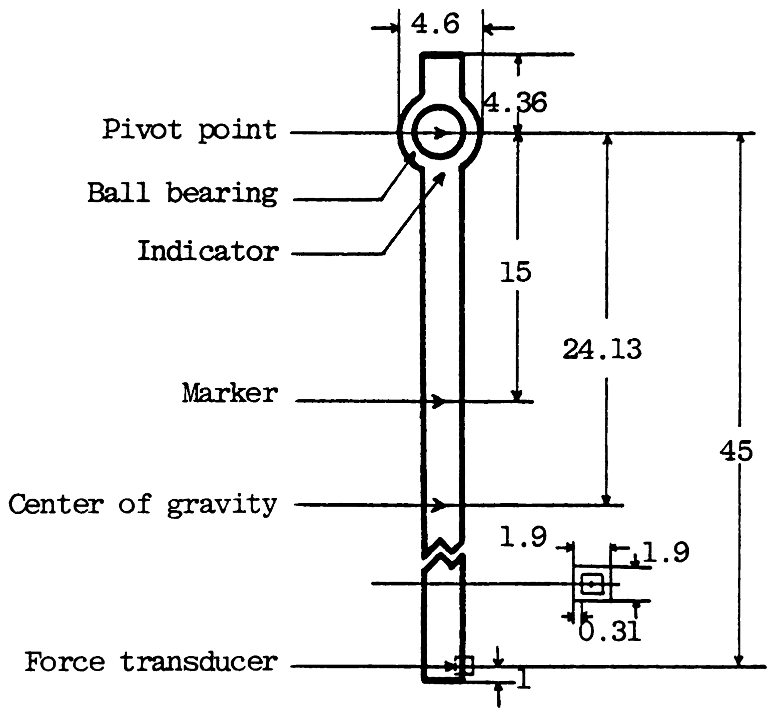


Figure 3. The Schematic Diagram of the Impact Arm.
(All distance values are centimeters.)

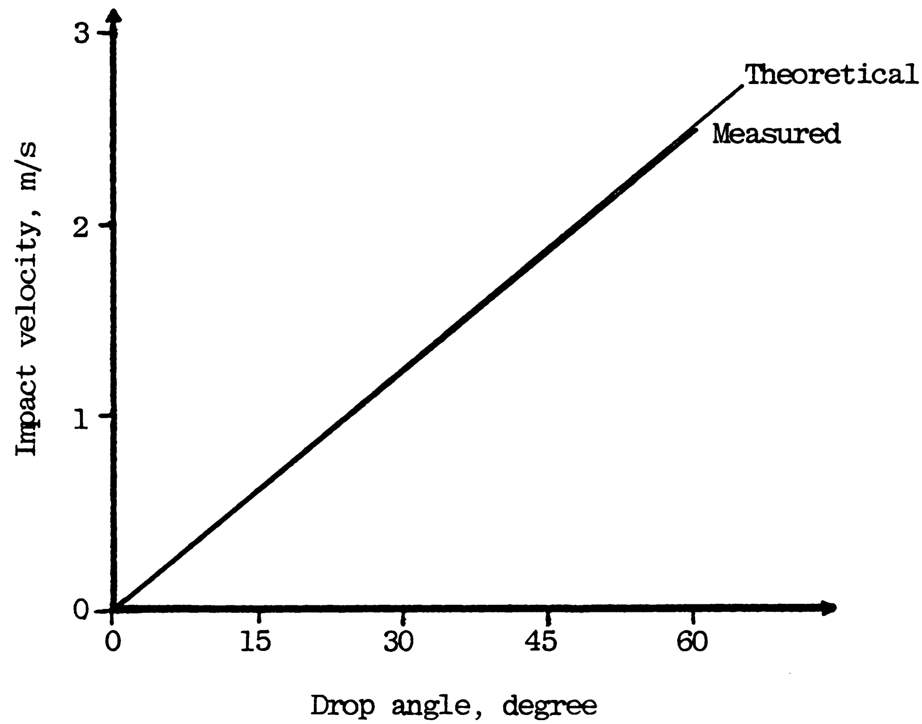


Figure 4. Comparison of Theoretical and Measured Impact Velocities.

where

M = mass of the pendulum

g = drop height of the pendulum which from the geometry, Figure 2, is given by

$$h = r_g\ (1 - \text{Cos}\ A_d) \qquad (3)$$

where r_g and A_d are the distance from the center of gravity of the pendulum to the center of rotation and the drop angle of the pendulum, respectively. The mass moment of inertia, I_o, about point o, the center of rotation is:

$$I_o = \frac{P^2\ Mg\ r_g}{4\Pi^2} \qquad (4)$$

where P is the small amplitude free oscillation period of the pendulum. Replacing h and I_o of equation (2) with equations (3 and 4), and substituting it in equation (1) for ω, the linear impact velocity at the impact point becomes

$$V_i = \left[\frac{8\ \Pi^2\ \ r^2}{P^2}\ (1 - \text{Cos}\ A_d)\right]^{1/2} \qquad (5)$$

The pendulum was calibrated for different drop angles to determine the effect of air, bearing and marker resistance on the operation. The calibration results are shown in Figure 5.

The impact signals were sensed by a Kistler Model 912 quartz force transducer with a charge sensitivity of 10.83 PCb/N (pico columb per newton). The force transducer was protected against any side contacts. The signals were picked up by a Kistler 121 M(5) cord, amplified and

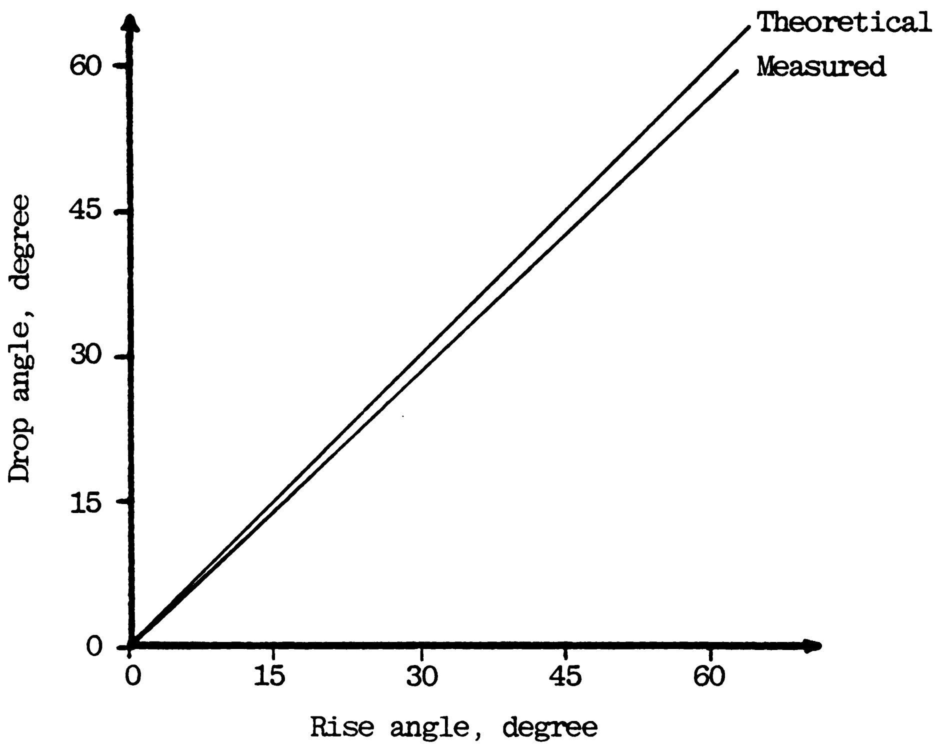


Figure 5. Calibration of the Pendulum for the Effect of Air, Marker and Bearing Resistance.

displayed on an oscilloscope screen.

The charge amplifier was a Kistler Model 504D Dial-Gain, with ranges of 4.448 to 22.24 kilonewton per volt and transducer sensitivity of .224 to 2.24 pCb/N. A tektronix type 549 storage oscilloscope was used to display and store the signals. Pictures were taken from the stored signals using a Hewlett Packard Model 196 A oscilloscope camera.

The approximate velocity at impact was measured using two electromagnetic pickups installed 40 mm apart. The magnetic pickups were connected to a Beckman Model 6040 A electronic counter.

The air temperature was measured with a thermometer having a resolution of 1 degree Centigrade. The internal beet temperature was measured by inserting the same thermometer to the center of the beet once it had been pierced.

The moisture content of the petioles was measured using a Precision Scientific oven Model 625 which dried the petioles at 105 °C for 26 hours.

The percent of the total dissolved sugar of the beets was measured by an AO Model 10406 refractometer with a scale division of 0.1 and an accuracy of 0.05 percent.

IV. METHOD AND PROCEDURE

Certain assumptions were made when designing the experiments of this investigation because the beets were tested under laboratory conditions rather than in the field. The assumptions were justified on the basis of observations and the testing time.

The assumptions were as follows:

1. The change in turgidity of the beet petioles during the testing period was assumed insignificant. It took approximately five minutes to return from the sugar beet field and fifteen minutes to perform the tests on the petioles.
2. The petioles selected for impacting were considered to have a uniform size. The petioles located at the center of the crown were smaller and weaker than those on the outer edges. These petioles along with cracked petioles were not used in the experiment.
3. The clamping of the beet was assumed to provide a support similar to that of the ground. The resistance of the petioles to impact was low and no vibration or movement of the beet during the impact was visible.

Each day during the Michigan sugar beet harvesting season, October 12 through November 10, one beet was carefully removed using a shovel and taken to the laboratory.

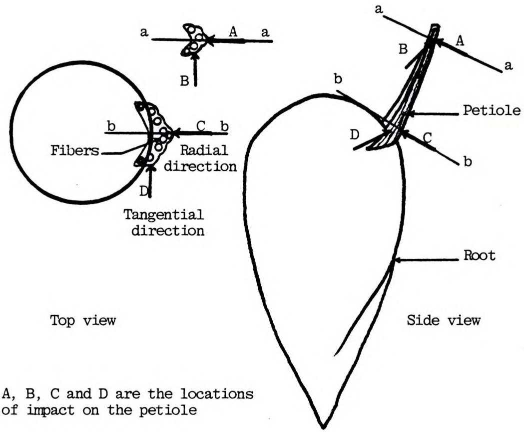
The sugar beets were hand cleaned to remove extra soil and any debris and leafy parts which would have obstructed the tests were eliminated. There was always more than enough petioles left to conduct the experiments. A thermometer was inserted into the pierced beet to determine its temperature.

The beet with a petiole in position for impact was fixed in a vise, Figure 2. Four locations A, B, C and D involving two different distances along the petiole were impacted, Figure 6. Radially oriented locations, A and C, were perpendicular to the tangential load application locations, B and D, respectively. Locations A and B were 127 mm away from the crown of the beet, and locations C and D 25.4 mm. The petioles became thinner beyond the 127 mm location, and were too flexible to break under an impact load. The lower level of 25.4 mm was a minimum because the impact arm made contact with the beet crown and other petioles below this point.

The tests at the different locations were performed using different petioles of a single beet to eliminate differences between beets and to reduce the time between measurements.

Once the beet was clamped in the desired position, the pendulum was raised 60 degrees from the zero potential energy position and released. The 60 degrees drop angle gave an optimum impact (determined in preliminary studies by impacting the petioles for different pendulum drop angles). The 60 degrees was an optimum drop angle because higher than that caused the pendulum to break or bend all of the petioles and less than that caused no damage on most of the larger petioles.

The rise angle was recorded and impact signal was stored on the oscilloscope screen. The tested petiole was manually removed if it had not been ruptured at each location. Five tests, each on a separate petiole



A, B, C and D are the locations of impact on the petiole

Figure 6. The Impacting Locations of the Sugar Beet Petiole.

were conducted at each location and observations of the petiole before and after impact were recorded.

The impacted petioles generally responded one of three ways:

1. No damage: No crack or failure was observed on the petiole after impact.
2. Cracking: The petioles were cracked to different depths and at different levels. Heavy cracks which caused the petioles to hang from the beet crown were regarded as complete failure and classified in 3 below, Figure 7.
3. Failure: The petioles were completely separated from the beet crown.

The mass of the beet root was measured after all the petioles were removed to determine the total foliage mass and prepared for the testing of the beet root for its material properties.

The temperature and percent of total dissolved sugar of the tested beets were measured daily for possible correlation with the experimental results. The moisture content of the tested petioles, air and soil temperatures in the field were also determined daily.

a. Petiole cracking due to impact from location D.

b. Petiole cracking due to impact from location C.

Figure 7. Cracking of the Petioles from Different Locations.

V. RESULTS AND DISCUSSION

The results of the experimental study of the effect of impact location on the failure of petioles is presented herein along with a discussion of how the results varied during the harvesting season.

1. The Response Behavior of Petioles

The observed force-time curves for all impact locations, exhibited two common characteristics first, a linear rise to a peak force, second, some intermediate peaks after the highest peak. Examples of the curves are given in Figures 8, 9 and 10. Assuming the highest peak occurred where the petiole failed by complete breakage, by bending after cracking or by bending without any detectable damage. The characteristics of the impact diagrams can be explained as follows.

The absence of an intermediate peak before the maximum force occurred because the petiole flesh, which contains thin longitudinal fibers on the impacted side, Figure 6, has less resistance to impact than the fibers. The first intermediate peak after the highest peak is due to the slight resistance of the skin facing opposite to the impacted side.

In the case of complete breakage, where the petiole broke from the base, the secondary peak after the highest peak was not as apparent as in the case of no damage or the crack mode of failure. This seems to be due to rapid and once over failure of the whole petiole which is associ-

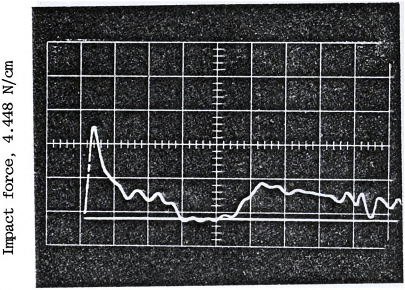


Figure 8. Impact Force-Time Signal for a Completely Failed Petiole from Location B.

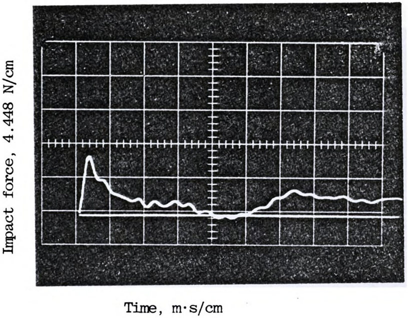
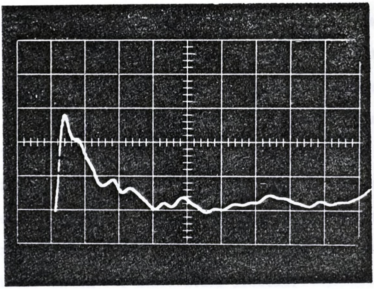


Figure 9. Impact Force-Time Signal for a Cracked Petiole from Location B.

Impact force, 4.448 N/cm



Time, m·s/cm

Figure 10. Impact Force–Time Signal for an Undamaged Petiole from Location B.

iated with a sharp decrease of the peak force after the failure of the petiole.

2. Determination of the Peak Impact Force

The peak impact force for petioles which broke at location D were obtained from the force-time impact curves. An average value of 11 N per petiole was determined. This average included 100 test results with a standard deviation of 3.3. An average of 8 N, with a standard deviation of 2.5, was obtained for petioles which did not fail or were slightly damaged. The average force required to tear off all leaves of a beet is given by Kanafojski and Karwowski (1972) to be 450 N. The average number of petioles on a crown is approximately 40. A total force of nearly 440 N would be required to remove the petioles using the results of this study. The amount of applied force would be greater if the impactor contacted the beet crown and the soil along with the petioles during the defoliation process.

The speed at which the petioles were impacted, 2.45 m/s, affected the amount of force required to flail the petioles. Fluck and Ahmed (1973) found that as the impact velocity increased the peak force was increased. Higher stress levels or impact energy were necessary for impact damage than for slow or static loading damage.

3. Efficiency of Defoliation

To analyze the response of the petioles to impact in terms of the percentage of removal, an efficiency of defoliation, E_d, was defined.

This efficiency was defined as the percentage of the petioles on a single beet which cracked or failed completely under the impact load at a velocity of 2.45 m/s. The efficiency of defoliation is independent of the impact energy and is defined by

$$E_{dj} = \frac{n_1 c_1 + n_2 c_2 + n_3 c_3}{N_t} \tag{6}$$

where

j = impact location A, B, C or D, Figure 6.

E_d = the efficiency of defoliation for a single beet and a specific location,

$$0 \leq E_d \leq 1$$

N_t = the total number of petioles impacted at a location (five)

n_1, n_2 and n_3 = the number of undamaged, cracked and totally failed petioles, respectively

c_1, c_2 and c_3 = numerical values given to the petiole response; values of zero, one-half and one, for no damage, cracking and total failure, respectively, were used.

For example, if two petioles broke, two cracked and one was undamaged during a particular test then

$$E_d = \frac{1(0) + 2(1/2) + 2(1)}{5} = 0.6$$

3.1 <u>The effect of impact location on the efficiency of defoliation</u>

Using the method of single-factor analysis of variance and analysis of factor effects (Neter and Wasserman, 1974), the test results showed that there are significant differences in the means of the efficiency of defoliation for different impact locations at a 99.99 percent confidence level, Figure 11. The average values of E_d for locations A, C, B and D were 0.28, 0.484, 0.610 and 1.0, respectively. The difference is highest between locations A and D, and lowest between B and C, with a confidence of 99 percent, Figure 12. These results indicate that the highest percentage of petioles are removed when the petioles are impacted in the vicinity of D. This occurs because D is closest point to the crown and has higher cross sectional area, making the petiole less flexible at this point as compared to the other locations. The higher value of E_{dD} than E_{dC}, which both correspond to efficiency of defoliations at the same cross sectional area, is due to higher area moment of inertia in tangential direction, D, than radial, C.

The petioles and the beet crown are struck at random orientations under field conditions of defoliation at impact velocities in the range of 15 - 30 m/s (4), and it is difficult to determine the response of individual petioles to the impact. As a result of these constraints, the implication of the results thus far and hereafter can only be an approximate description of what may happen under field conditions of defoliation.

3.2 <u>The variation of the efficiency of defoliation for different locations during harvesting period</u>

The efficiency of defoliation for locations A, B and C, as indicated in Figures 13, 14 and 15, varied during the harvesting period. The trend was from a high to a low efficiency during the 30 days of

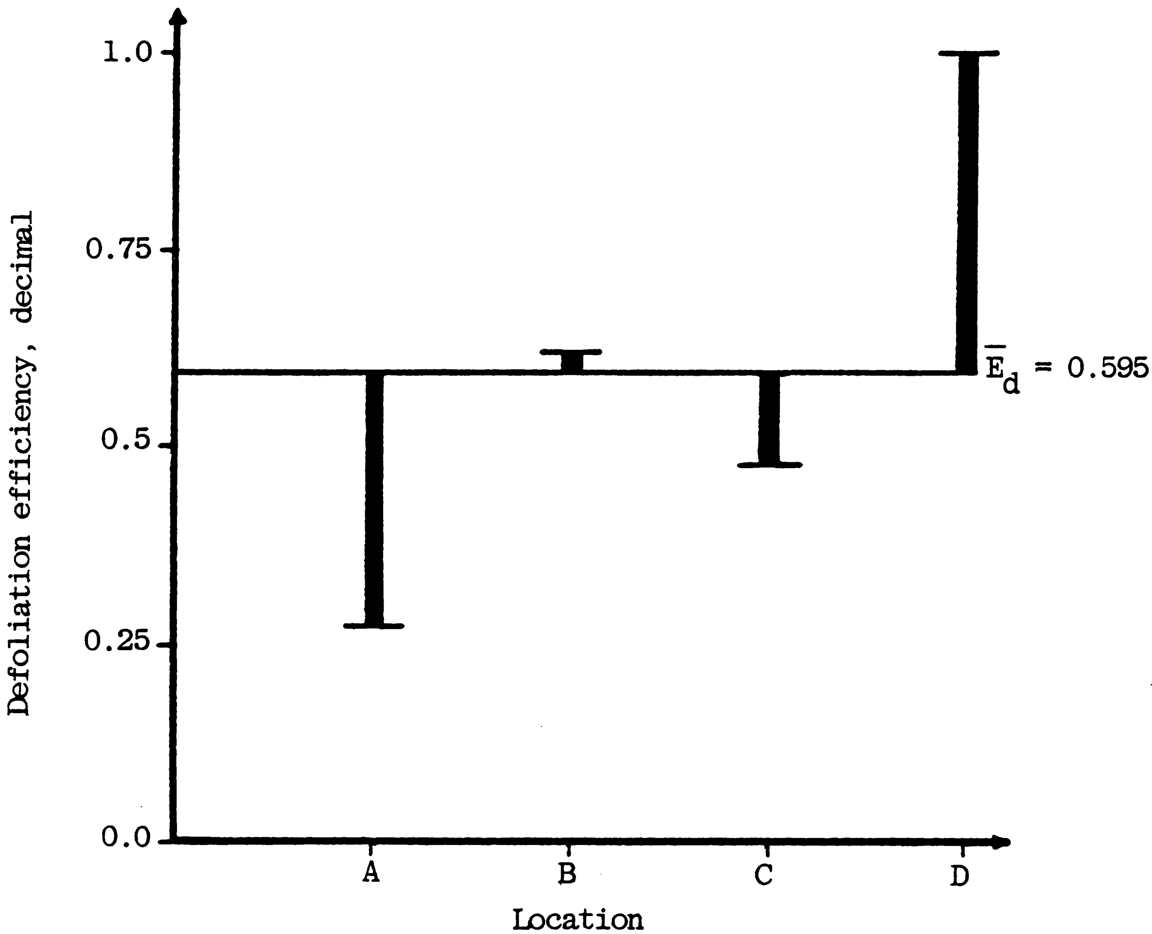


Figure 11. The Mean Defoliation Efficiency Deviations from the Total Mean, $\overline{E}_d$, for the Four Different Impact Locations.

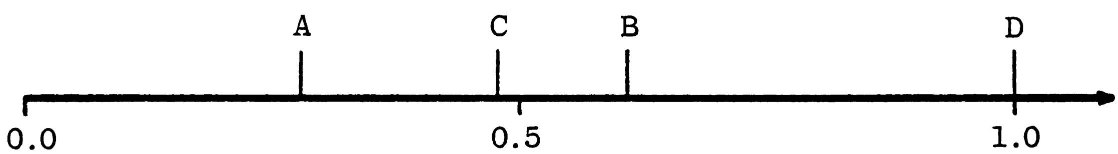


Figure 12. Efficiency of Defoliation Averages Ordered from the Lowest to the Highest for Different Impact Locations, Decimal.

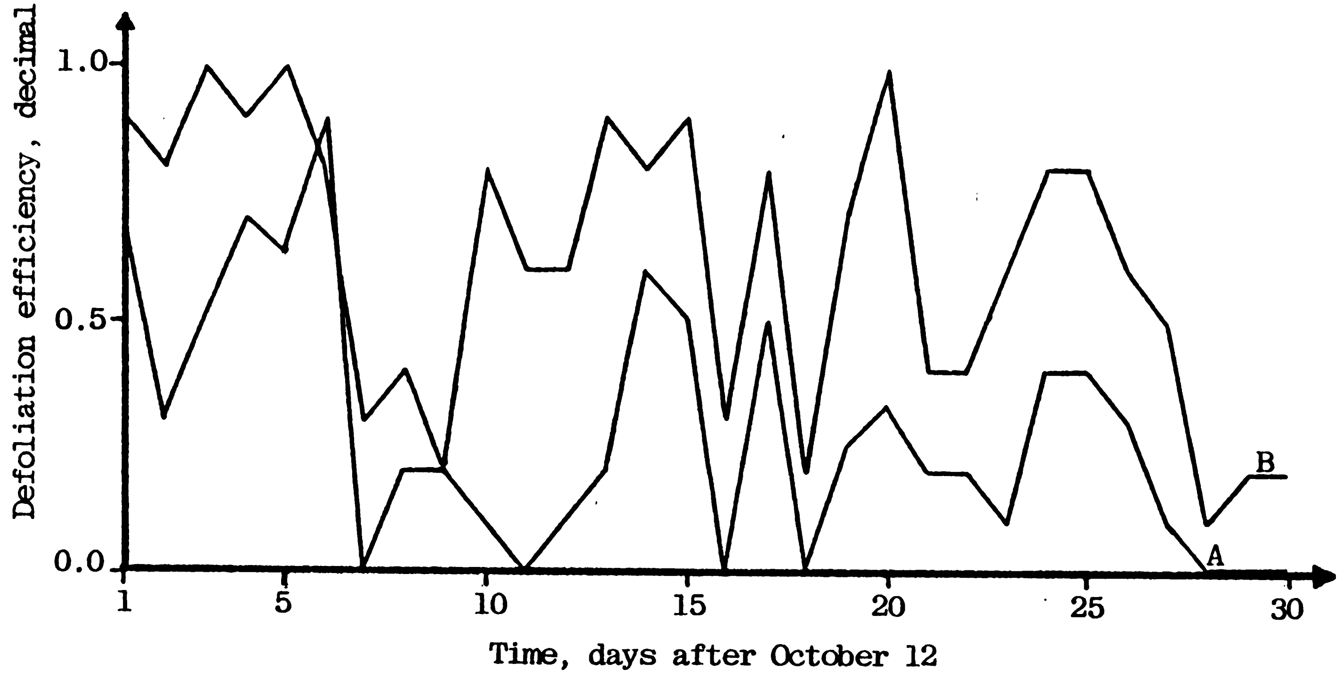


Figure 13. Variation of Defoliation Efficiency, E_d, for Locations A and B during Harvesting Period.

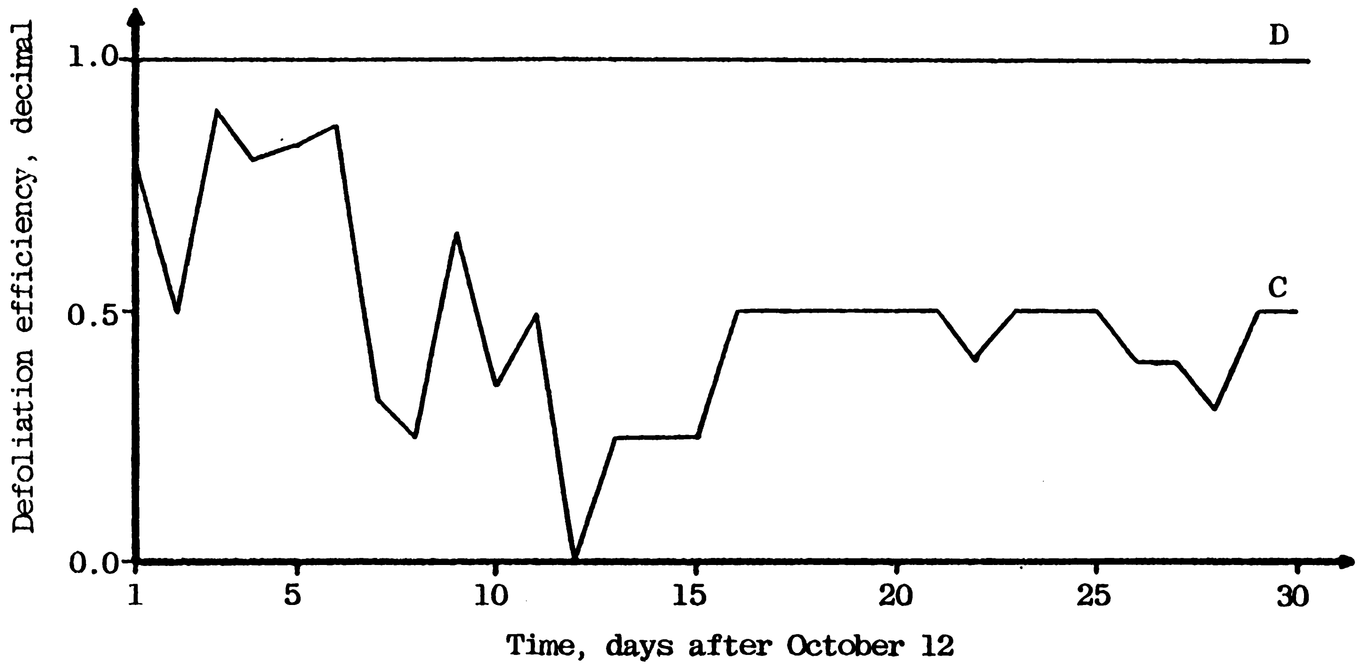


Figure 14. Variation of Defoliation Efficiency, E_d, for Locations C and D during Harvesting Period.

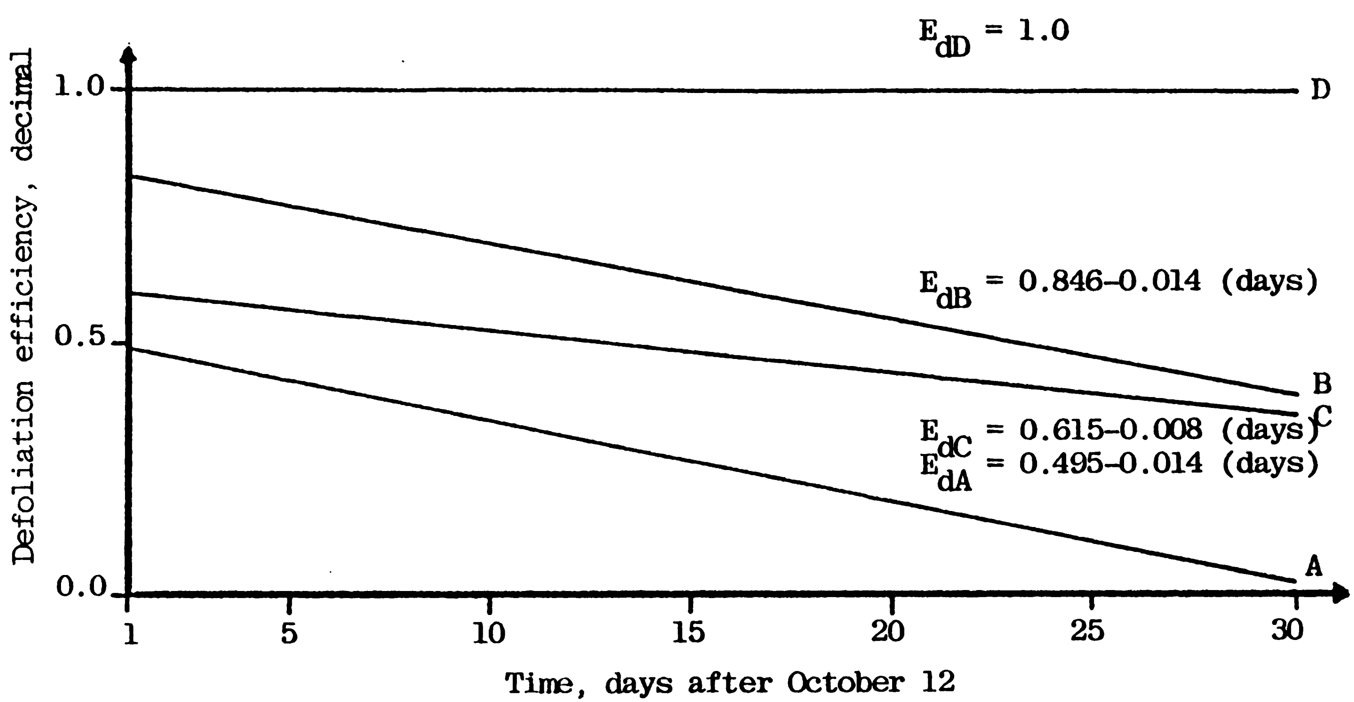


Figure 15. Comparison of Defoliation Efficiency of Four Different Locations with their General Trend during Harvesting Period.

experimentation. All of the trends indicated a high efficiency until approximately October 18. The decrease in E_d for A, B and C was associated with a sharp drop in the beet temperature and the turgidity of the petioles. Even under these conditions the petioles experienced a complete failure when impacted at D. The increased stiffness of the petiole at location D, because of its larger cross sectional area, being closer to the crown and its greater area moment of inertia is believed to be the reason for the higher percentage of defoliation as compared to locations A, B and C.

3.3 The relation of the efficiency of defoliation with the measured parameters

Among the measured parameters, air and soil temperatures in the field, petiole moisture content, total dissolved sugar of the root and beet temperature, the latter had the highest correlation with the efficiency of defoliation with 99 percent confidence. Variation and general trend of these parameters during the harvesting season are shown in Figures 16, 17 and 18. The percent of defoliation at location A versus beet temperature is shown in Figure 19.

It is believed that the higher temperature before October 18 contributed to the turgidity of the petioles which resulted in higher defoliation efficiency. Petiole turgidity, which is related to the water potential of the plant (Merva, 1975), may play a significant role in the way the petioles respond to impact. The more turgid the petioles the higher the defoliation efficiency.

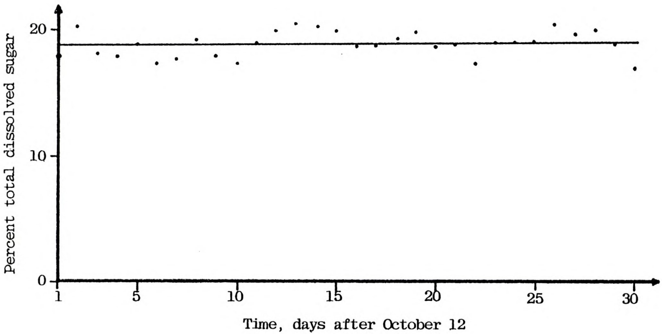


Figure 16. Trend of the Percent of the Total Dissolved Sugar of the Tested Beets during Harvesting Period.

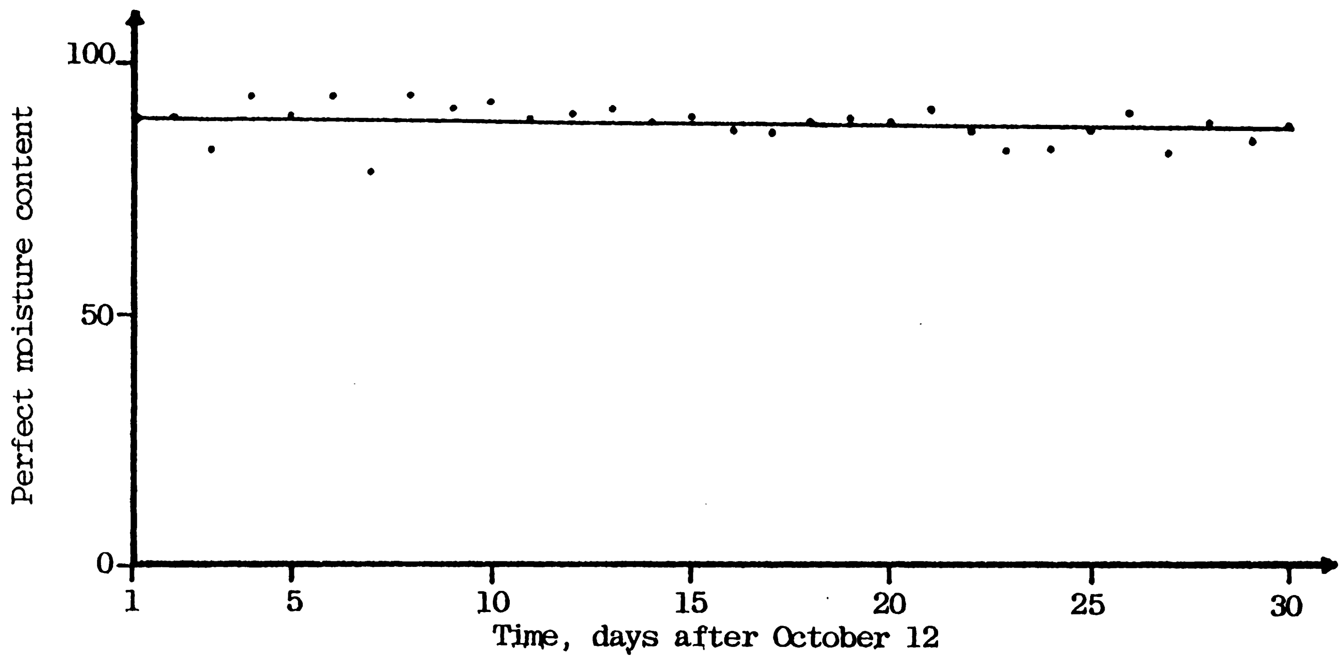


Figure 17. Trend of the Percent of the Moisture Content of the Tested Petioles during Harvesting Period.

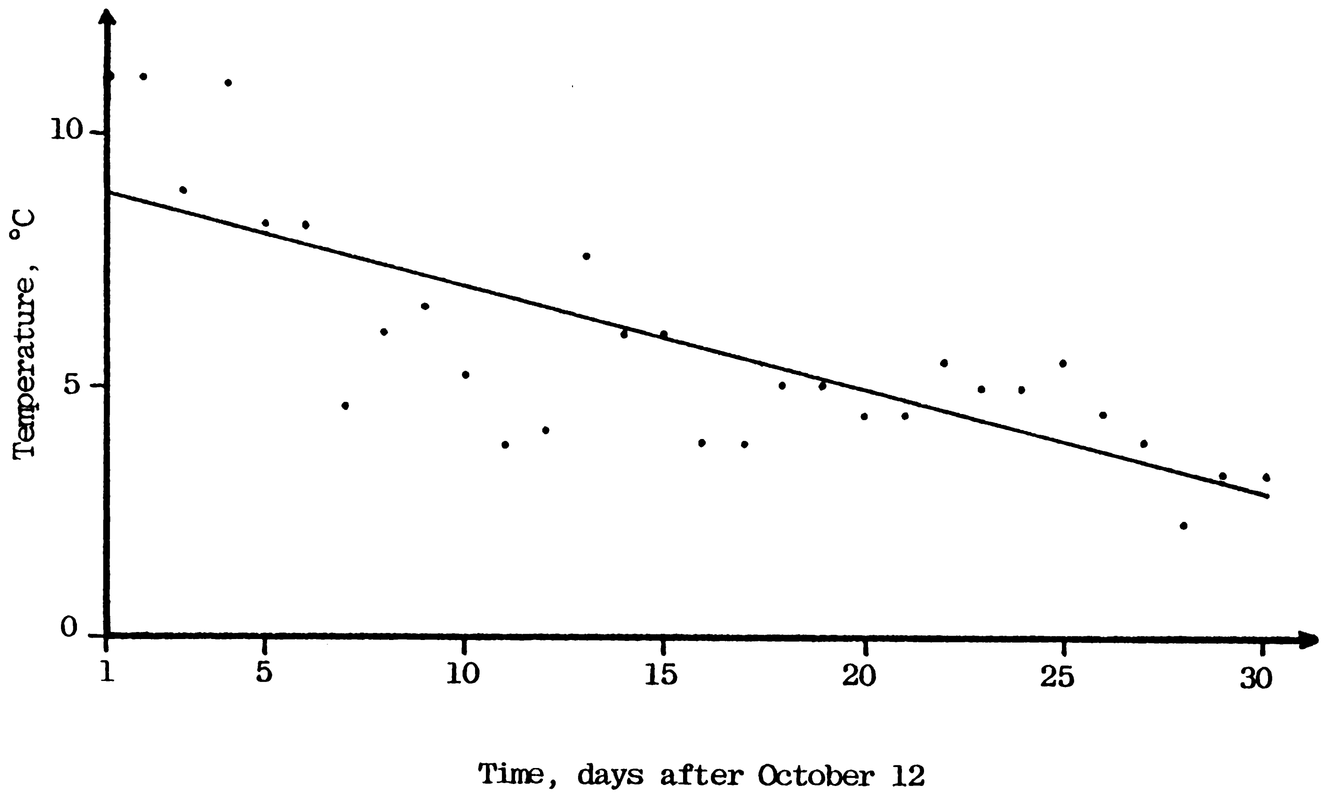


Figure 18. Trend of the Temperature of the Tested Beets during Harvesting Period.

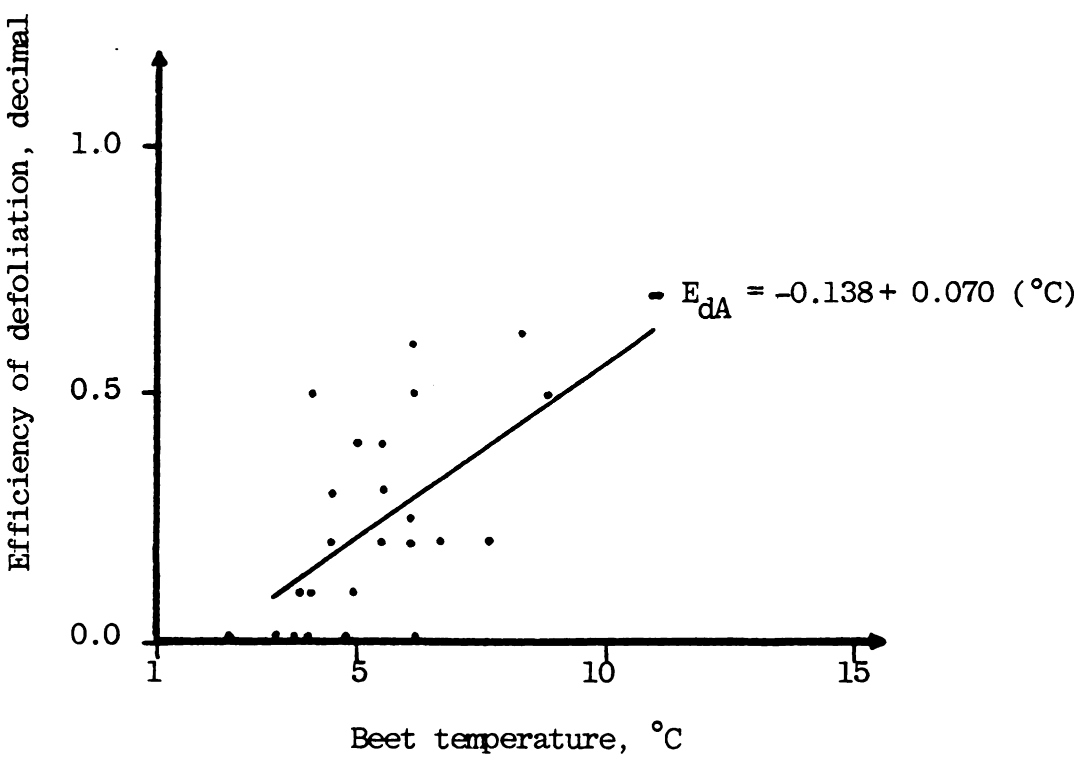


Figure 19. Variation of the Efficiency of Defoliation at A with the Temperature of the Tested Beets.

The effect of other parameters besides beet temperature on E_d can not be completely ignored but they were not judged significant. An equation to describe the relation between the turgidity and temperature remains to be developed.

The importance of temperature on E_d is that a better defoliation can be obtained when the beet is at a proper temperature (in the neighborhood of 10 degrees Celsius in Michigan).

Visual observation of the petioles at extreme temperature conditions is the basis of the following discussion about the upper and lower limits of the E_d - T line, as shown in Figure 19.

When the temperature reaches a level such that the petioles become loose and wilted, the petioles become more difficult to defoliate, thus a sharp drop in the efficiency. On the other hand, a frozen petiole offers a higher turgidity, therefore, breaking without bending or twisting. This implies that the E_d - T line relation is only true for the region as shown in Figure 19. All of the petioles in this study which may have frozen in the field were tested once they had been thawed. This procedure is consistent with field defoliation where frozen petioles thaw during the day.

The turgidity and flexibility with regard to the temperature will be further discussed in considering the impact energy and its variation during the harvesting season in the following section.

Under real field conditions, the temperature affect on defoliation becomes much more significant than those in the laboratory. Freezing and thawing introduces a muddy field which the petioles lie on. This situation makes the defoliation a very difficult operation. The problem is even worse when the petioles are to be collected and fed to

livestock, as it is practiced mainly in Europe. In most cases the harvesting operation has to be stopped until the field condition becomes suitable to operate the defoliator.

4. Impact Energy

The energy absorbed by the petioles during impact was determined using

$$E_i = M\ g\ \Delta h \tag{7}$$

where

E_i = impact energy, $kg{\cdot}m^2/s^2$ (joule)

M = total mass of the pendulum, kg

g = acceleration due to gravity, m/s^2

Δh = difference in the height of the pendulum before and after impact, m

Equation (7) neglects the effects of air and bearing resistance.

From geometry, Figure 2

$$\Delta h = r_g\ (1 - \text{Cos}\ A_d) - r_g\ (1 - \text{Cos}\ A_r) \tag{8}$$

or

$$\Delta h = r_g\ (\text{Cos}\ A_r - \text{Cos}\ A_d) \tag{9}$$

where

r_g = distance between the center of gravity of the pendulum and the axis of rotation, m

A_r = maximum average rise angle of the pendulum after impact, degree

A_d = free drop angle of the pendulum before impact, degree

Substituting (9) into (7) gives the impact energy in terms of the measured variables, A_r and A_d

$$E_{ij} = M\ g\ r_g\ (\text{Cos}\ A_{rj} - \text{Cos}\ A_d),\ j = A, B, C \text{ or } D \qquad (10)$$

Substituting M = 0.975 kg, r_g = 0.2413 m, g = 9.8 m/s^2 and A_d = 60°; (10) simplifies to

$$E_{ij} = 2.3\ (\text{Cos}\ A_{rj} - 0.5) \qquad (11)$$

4.1 The effect of impact location on the impact energy

The experimental results indicated there were differences in the mean values of the impact energy for loctations A, B, C and D, Figure 20, with a confidence coefficient of 0.999. The differences for locations A and B, C and D were not significant at the 99.95 percent confidence level, while at the same level of confidence the differences between A and D, B and C were significant. The insignificant differences between the means for locations A and B or C and D signifies the importance of the turgidity of the petioles in their response to impact assuming turigidity has been the main influencing factor in variation of the efficiency of defoliation for different locations of the petioles.

The insignificant differences in the mean values of E_i for locations A and B is much higher than that of C and D. This is because the only differences in A and B or C and D are in the different orientations of

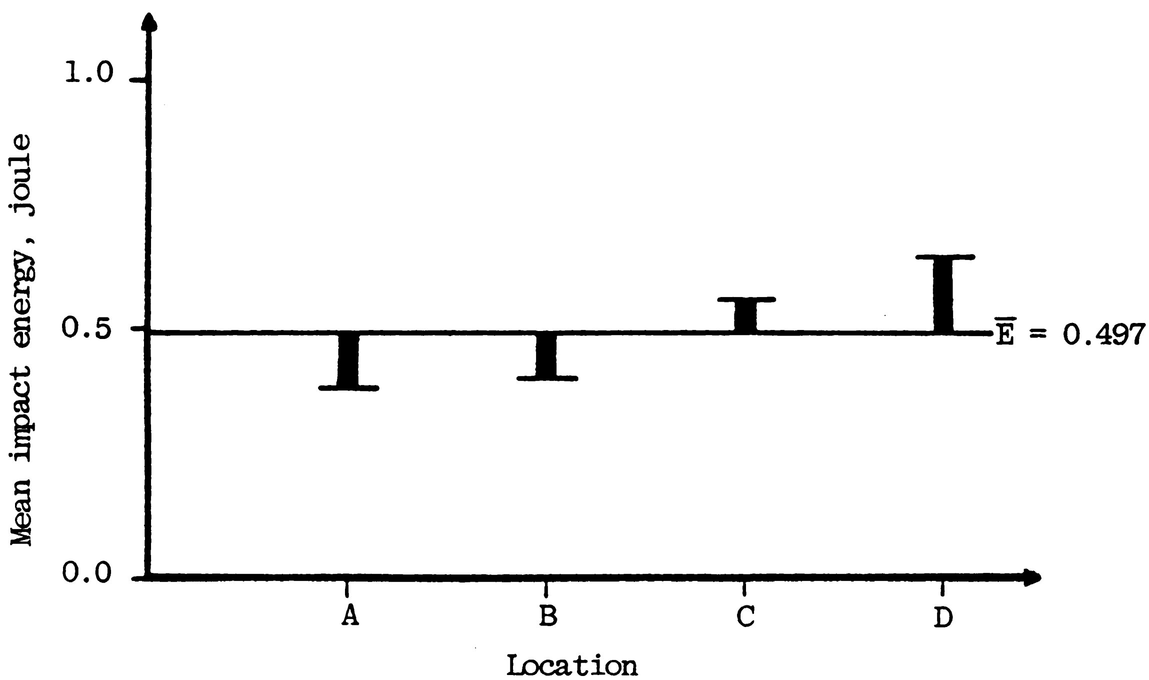


Figure 20. The Mean Impact Energy Deviations from the Total Mean, Ē, for the Four Different Impact Locations.

loading the petioles from the same height, Figure 6. The differences in the width and length of the cross section diminishes in the vicinity of locations A or B.

The above result emphasizes the importance of impacting the petioles from different heights over different orientations. The highest difference existed between locations A and D which were located at different distances from the crown. The same differences were observed in the evaluation of efficiency of defoliation and modified impact energy as will be discussed later. The practicality of this result for a design criteria is very important. It is because the petioles can be defoliated from a desired height, while it would be very difficult to impact them from a specific orientation in the field.

Lower values of impact energy were measured for locations A and B (0.383 and 0.401 joules) than C and D (0.561 and 0.645 joules), location D being the highest, Figure 21. It can be reasoned that locations C and D are stiffer than the other two, therefore, absorbing higher amounts of energy before failing. Locations C and D are less flexible because they are closer to the beet crown and both have larger cross sectional areas than those of A and B (approximately twice as large). The large moment of inertia for the cross section relative to location D than C, may be the reason for the difference in the impact energy.

Greater moment arms for locations A and B suggests that the petioles would break with less impact energy from these locations than C and D. However, the longer moment arms of A and B are associated with higher flexibility. The petioles undergo a large amount of displacement without breakage. The capacity of a petiole to displace without breaking is a characteristic which is closely related to its turgidity and hence, to

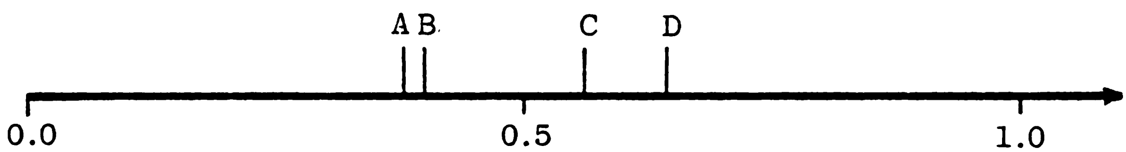


Figure 21. Impact Energy Averages Ordered from the Lowest to the Highest for Different Impact Locations, Joule.

its state of temperature. The higher the capacity to displace or bend without breaking, the lower is the percent of defoliation.

4.2 The variation of the impact energy for different locations during harvesting period

The impact energy varied during the harvesting period. The variations, as shown in Figures 22, 23 and 24, were from the high values to lower values as the harvesting days progressed. The general trend of these variations are presented in Figure 25. The energy corresponding to location D had the smallest variation of the four.

4.3 The relation of the impact energy with the measured parameters

Among the parameters measured total dissolved sugar, air and soil temperatures, petiole's moisture content, air relative humidity and beet temperature, the latter had the highest correlation with the total mean impact energy, $\overline{E}_i$. The relationship between $\overline{E}_i$ and temperature is presented in Figure 26. After approximately October 18 the petioles experienced the freezing and thawing process, their turgidity decreased sharply and they had little resistance to the loading. When struck by the impactor, they were displaced without any major damage, unless they had not been thawed, then they had a form of turgidity created by freezing. Less variation of the impact energy occurred at D than the other locations during the harvesting period. This could be due to a greater stiffness and a minimum displacement without breakage for this impact location.

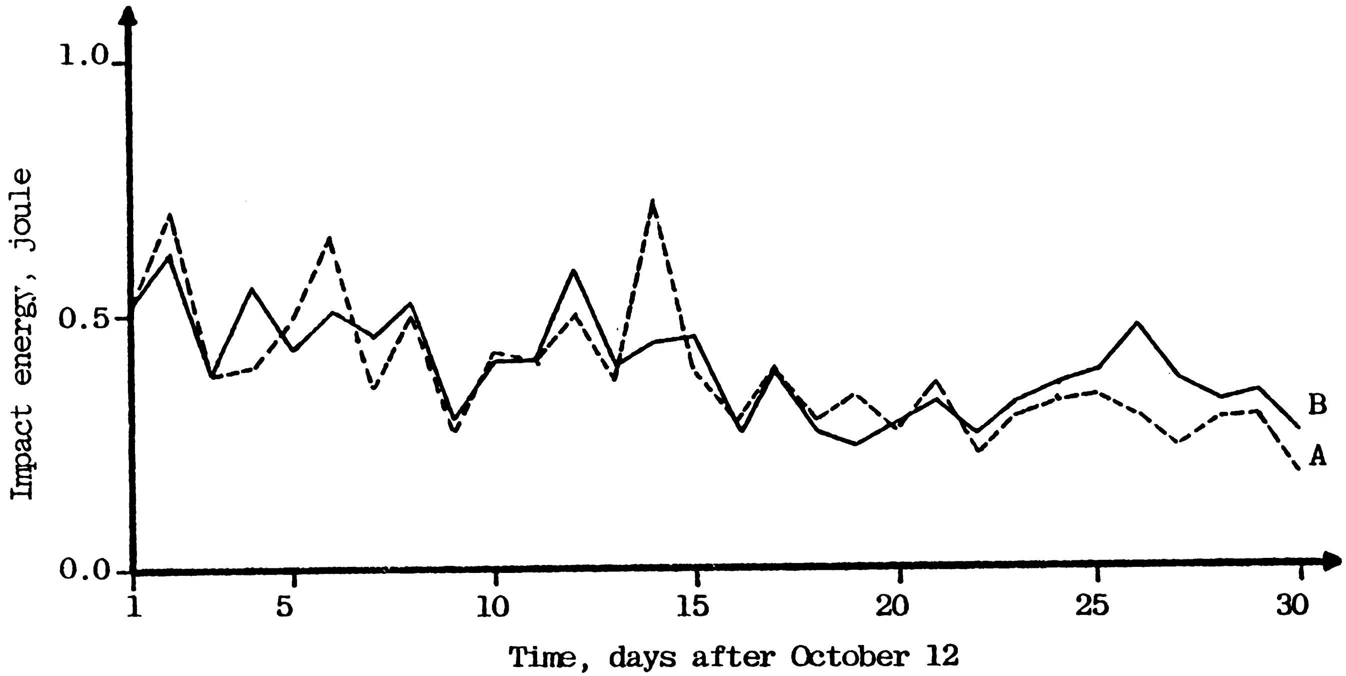


Figure 22. Variation of the Impact Energy, E_i, for Locations A and B during Harvesting Period.

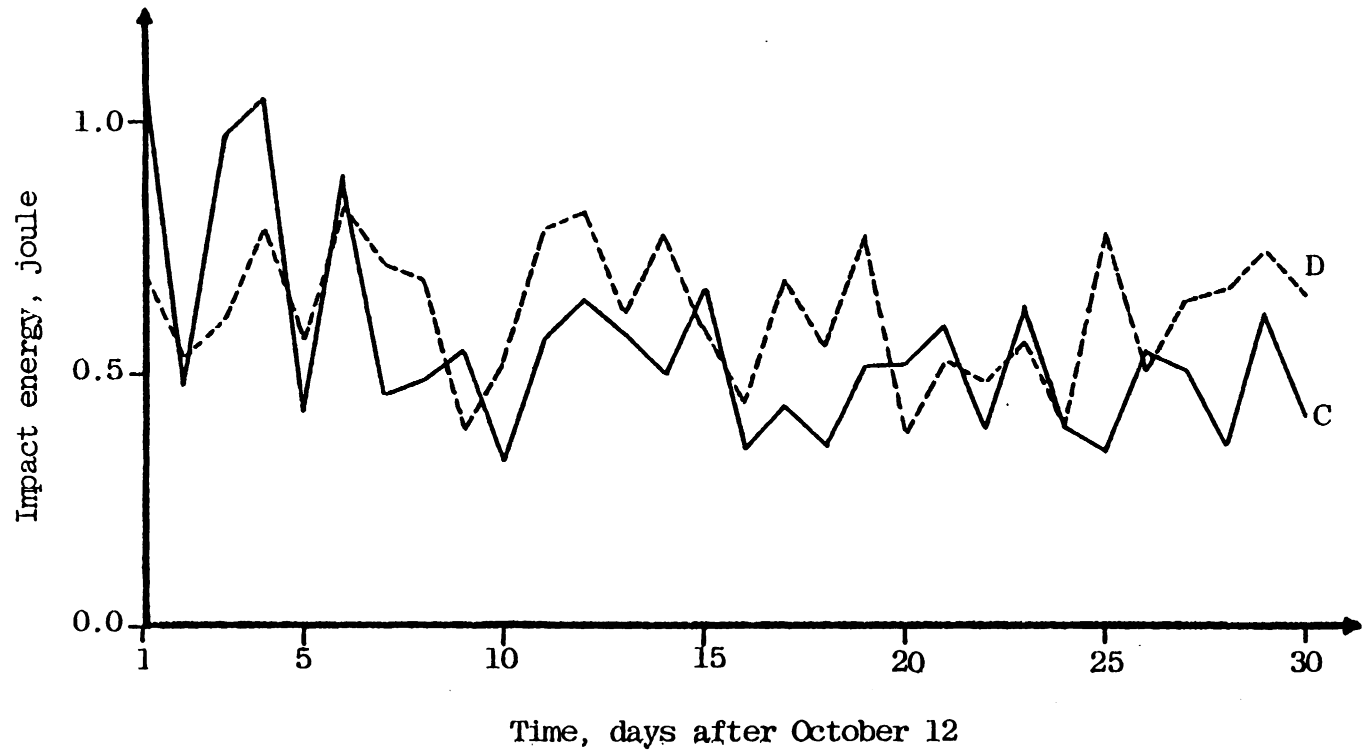


Figure 23. Variation of the Impact Energy, E_i, for Locations C and D during Harvesting Period.

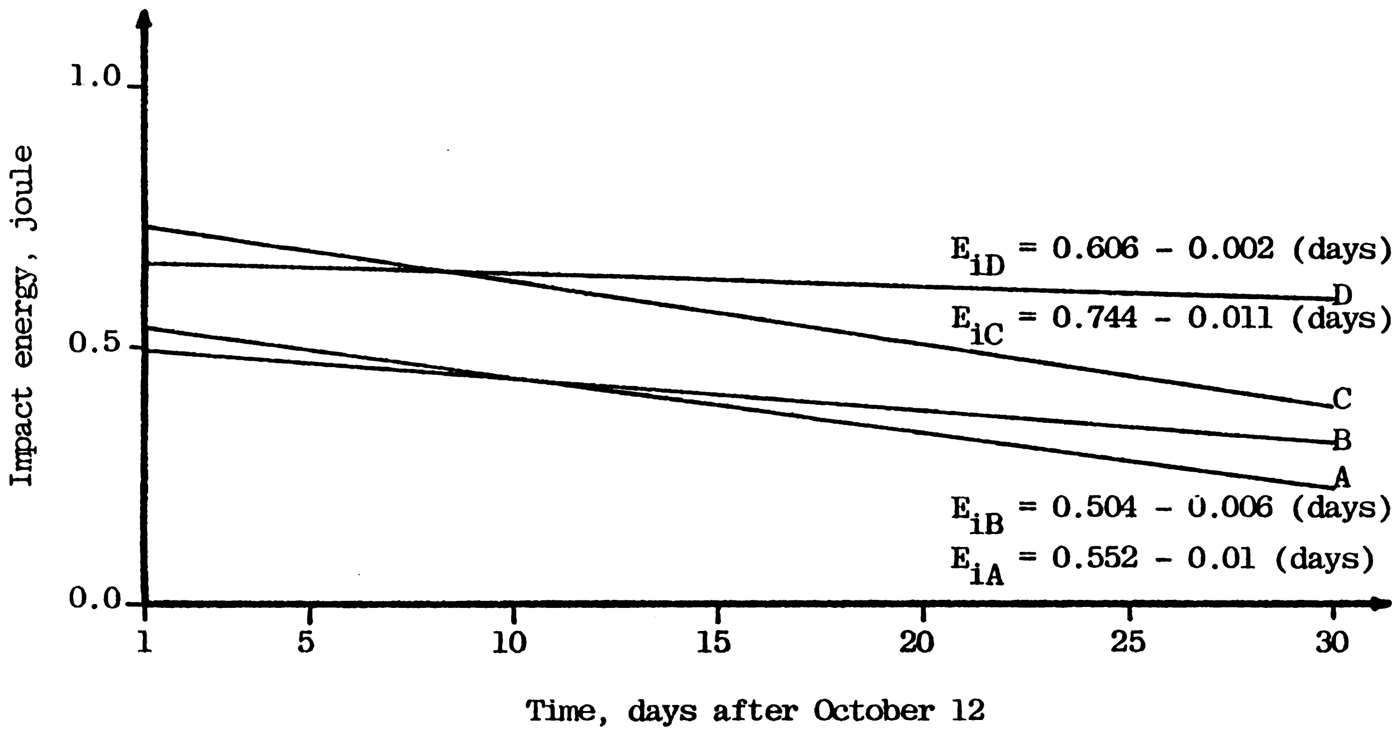


Figure 24. Compariosn of the Impact Energy of Four Different Locations with their General Trend during Harvesting Period.

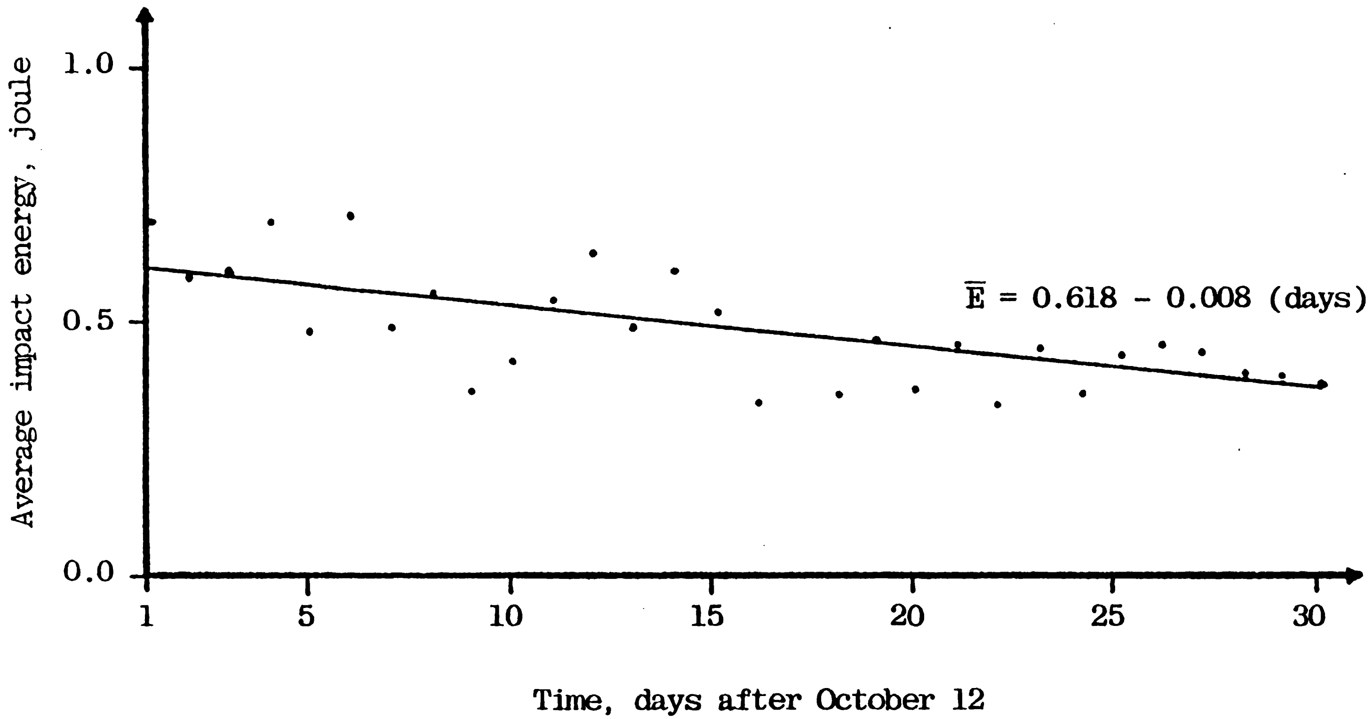


Figure 25. The General Trend of the Average Impact Energy, $\overline{E}_i$, of Locations A, B, C and D during Harvesting Period.

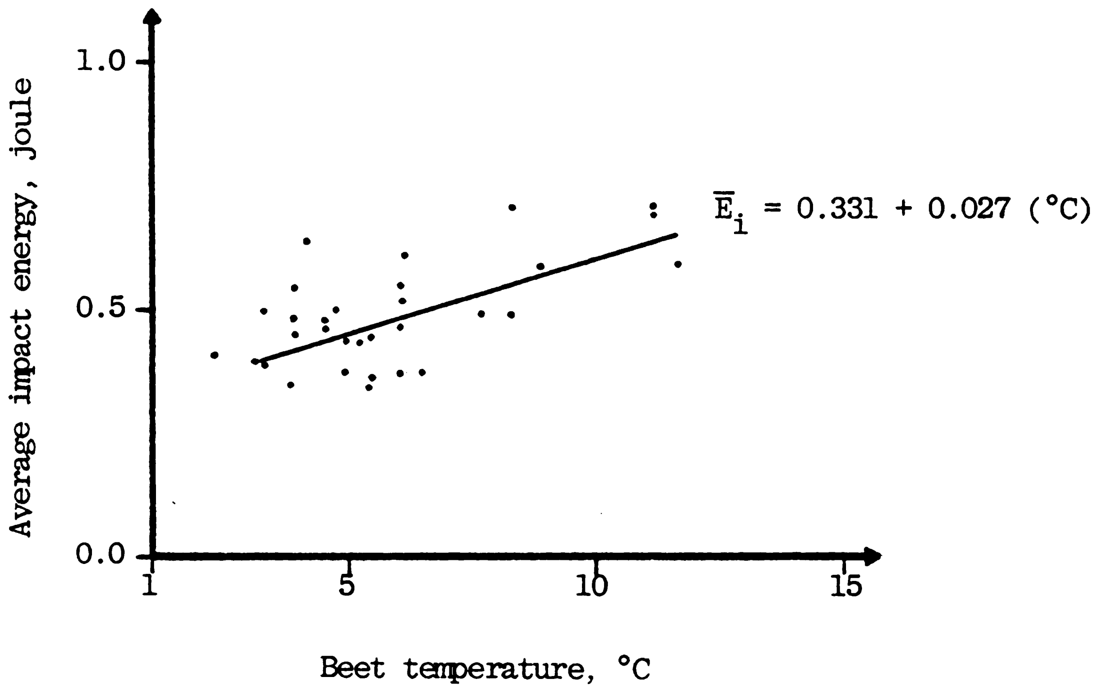


Figure 26. Variation of the Total Mean Impact Energy, $\overline{E}_i$, with the Temperature of the Tested Beets.

The energy-temperature relation, shown in Figure 26, is true only for the range as indicated. Higher temperatures dry the petioles. They can then be removed with less energy. The petioles freeze at lower temperatures producing a form of stiffness requiring greater amounts of energy for their removal.

5. Modified Impact Energy

The impact energy developed earlier, does not give a true picture of the defoliation process. A low impact energy is generally associated with a low efficiency of defoliation because the petiole has deflected and not broken. Thus additional energy would have to be input to complete the defoliation process. An impact energy term which includes the efficiency of defoliation was calculated by multiplying the value of the rise angle, A_r, by E_d. The result was called the modified impact energy, $E_{i(m)}$. The rise angle corresponding to the petiole which was undamaged after impact was considered to be zero because the energy of the pendulum was lost to the displacement of the petiole rather than removing it.

The modified impact energy was obtained by multiplying the A_r of equation (11) in E_d, which resulted

$$E_{i(m)j} = 2.3 \; [\; \mathrm{Cos}\; A_{rj} \;\; E_{dj} - 0.5], \quad j = A, B, C \text{ or } D \qquad (12)$$

5.1 The effect of impact location on the modified impact energy

The results obtained for the modified impact energy indicated that differences exist among the mean values for locations A, B, C and D as shown in Figure 27.

The difference of the modified impact energy between locations A and C was not significant at 99.95 percent confidence level. However, the differences between other locations at the same confidence level were significant as can be seen from Figure 28. The highest modified impact energy occurred at A and lowest at D with the other locations in between.

It would be misleading to justify the differences in the modified impact energy for the four locations without considering the influence of the defoliation efficiency on the impact energy.

As discussed earlier when considering the impact energy, the modified impact energy values for locations A and B should have been much lower because of their higher flexibility, but as was indicated in the analysis of the efficiency of defoliation, location A had the lowest efficiency meaning high rise angles after impact which in turn is an indication of less energy absorption. If the objective is to consider the energy that has caused heavy damage, a break or crack, then the ordering of Figure 28 can be employed. The discussion suggests that it would require less impact energy for location D than the other locations if the breakage of the petioles is the main concern.

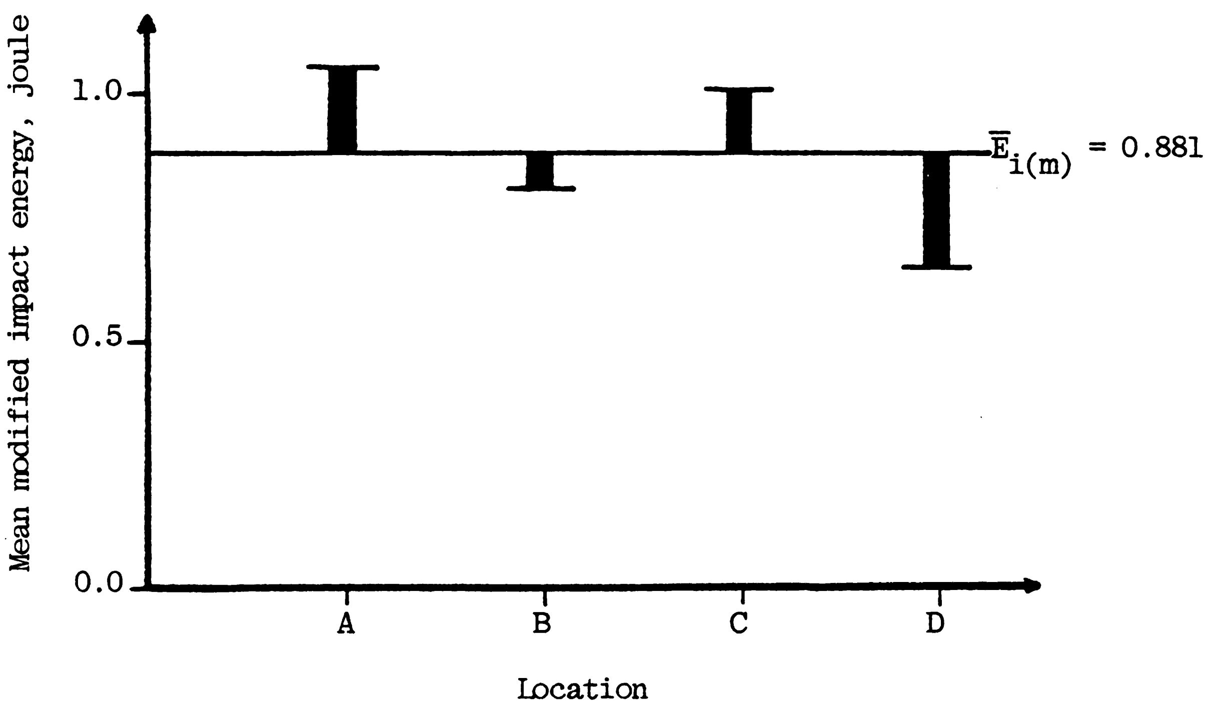


Figure 27. The Mean Modified Impact Energy Deviations from the Total Mean, $\overline{E}_{i(m)}$, for the Four Different Impact Locations.

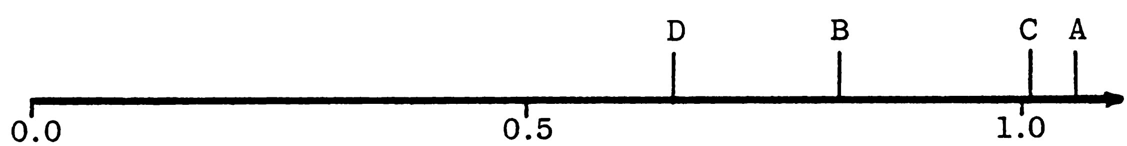


Figure 28. Modified Impact Energy Averages Ordered from the Lowest to the Highest for Different Impact Locations, Joule.

5.2 Variation of the modified impact energy during harvesting period

The values of the modified impact energy varied during the harvesting period, Figures 29 and 30 with their general trend of variation in Figure 31. The results of the modified impact energy, as shown in Figure 31, decreased for locations C and D and increased for locations A and B.

The variations in the values of the impact energy were less than those of modified impact energy for all locations which is due to the contribution of the variation of E_d in equation (12).

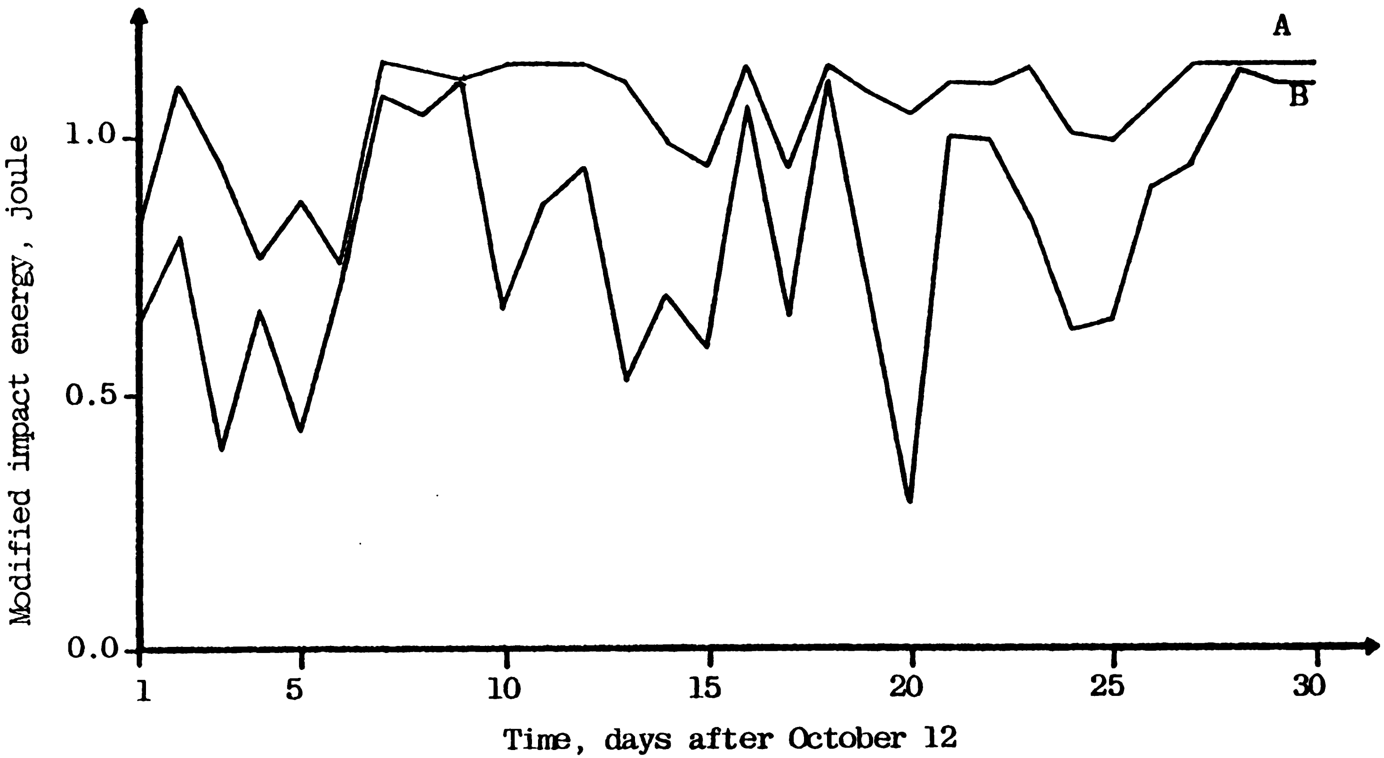


Figure 29. Variation of the Modified Impact Energy, $E_{i(m)}$, for Locations A and B during Harvesting Period.

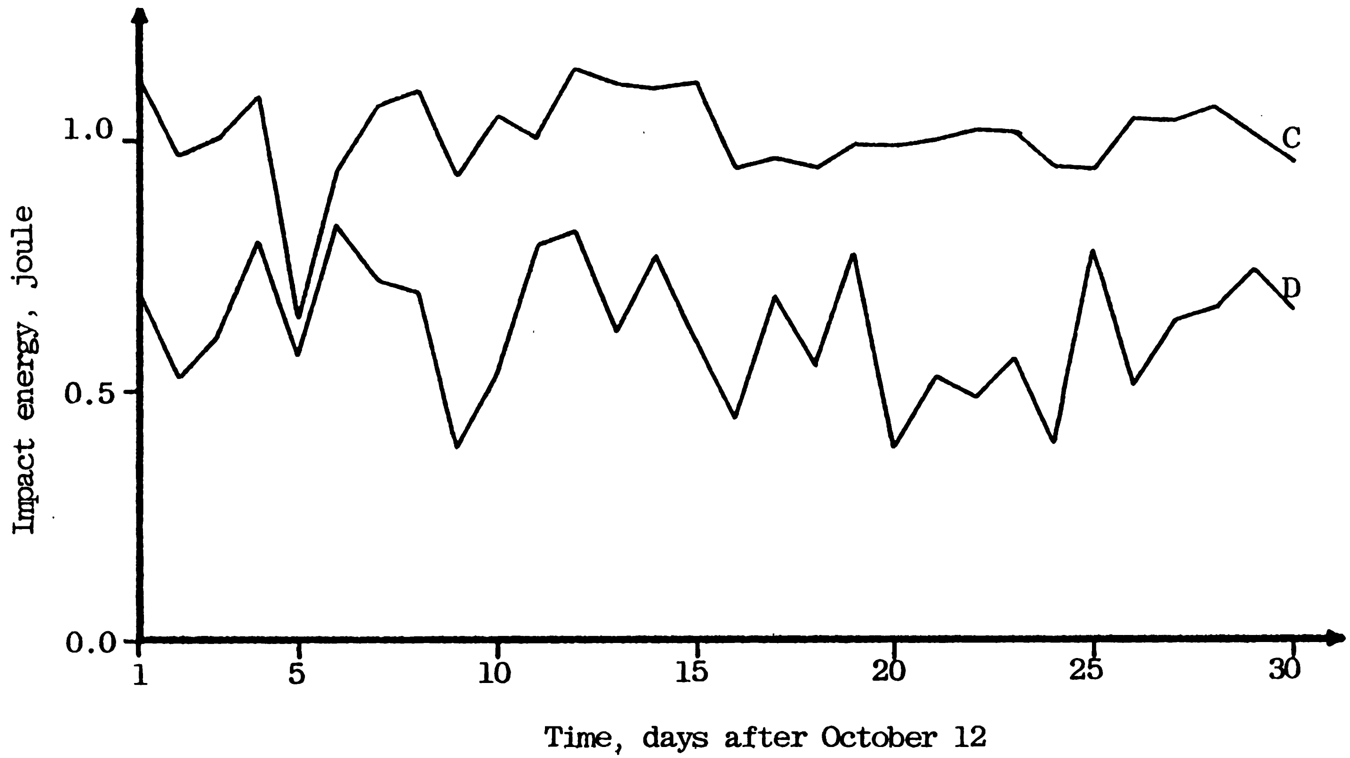


Figure 30. Variation of the Modified Impact Energy, $E_{i(m)}$, for Locations C and D during Harvesting Period.

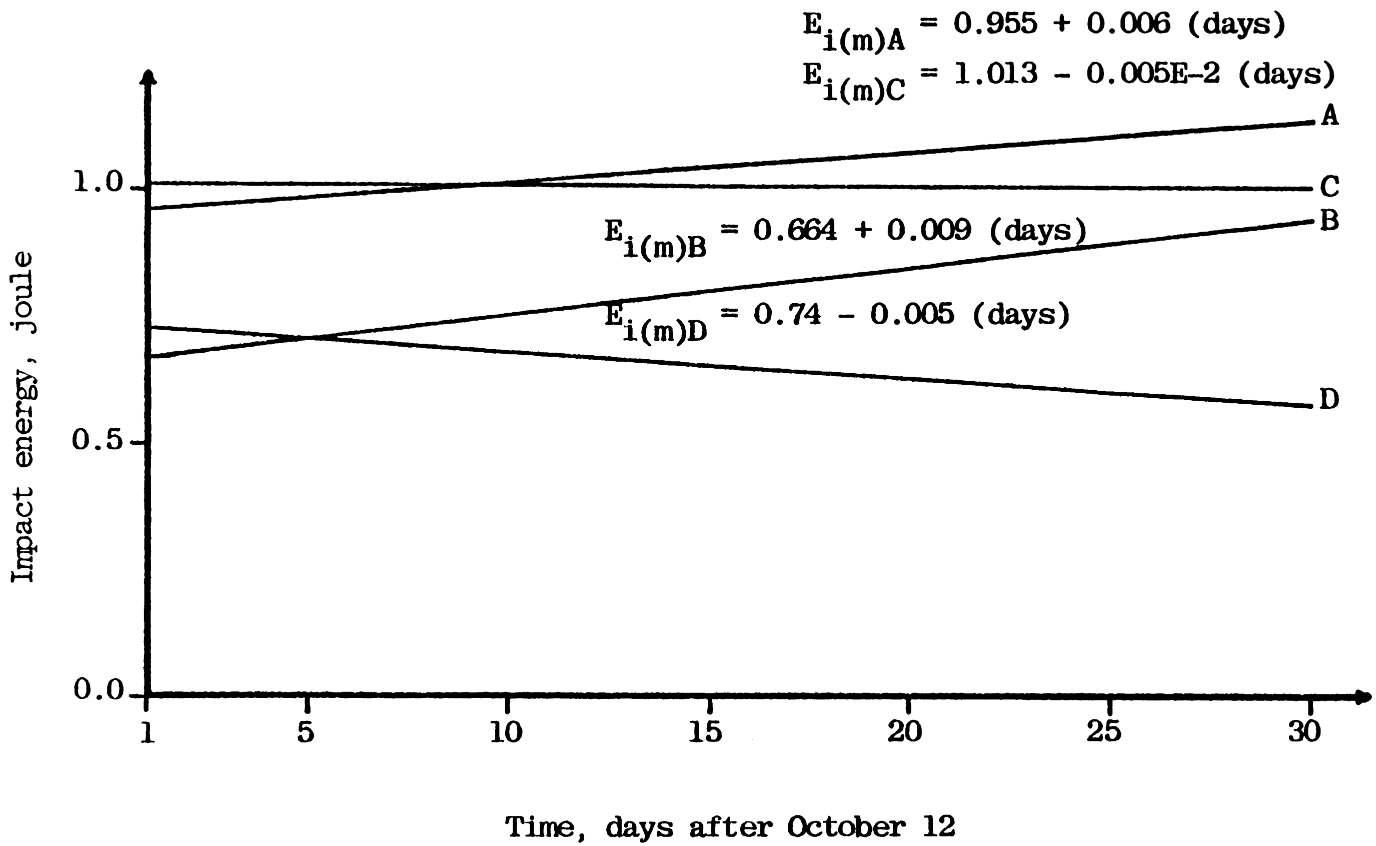


Figure 31. Comparison of the Modified Impact Energy of Four Different Locations with their General Trend during the Harvesting Period.

VI. DEFOLIATOR DESIGN CRITERIA

Sugar beets processing plants around the world require the foliage and a certain portion of the beet crown to be removed before it is delivered to the factory. The requirements on the amount of material removed depends on regional regulations. Crown removal may vary from the lowest leaf scar (25) to the very top portion of the crown. Recent studies in the U.S.A. (7 and 32) indicate that cutting the crown is not desirable because of the exposure of the beet flesh to the environment and the loss of sugar and weight loss during storage.

Conventional defoliators with rubber and steel flails are designed to remove the foliage and some portion of the crown. These defoliators leave behind beets with broken tops, inverted beets and partially defoliated beets all which contribute to the loss of sugar, Figures 32 and 33.

The objective of this discussion is to develop a design criteria for a defoliator which removes the foliage from the crown without breaking the roots.

The design criteria discussed herein was developed assuming average conditions for the beet and foliage. Comparison of economy, efficiency or other factors with the conventional defoliators will have to be made under field conditions. This part is left as a future study.

The laboratory studies showed that a higher percentage of petioles were removed when impacted close to the crown (location D). An impact

Figure 32. Broken Beet and Poorly Defoliated Petioles (Numbers 1 and 2) as Compared to Proper Defoliation (Number 3).

Figure 33. Broken Beet and Poorly Defoliated Petioles by Conventional Defoliators.

force of approximately 11 N with an impact velocity of 2.45 m/s was required to remove an average petiole. The average amount of energy required to remove a petiole was 0.6 joule. A higher percentage of the petioles were removed when they were turgid. These results and constraints will have to be taken into consideration in designing a defoliator.

A rotary disc, d, with a total mass, M_1, radius r_1 and thickness H was devised, Figures 34 and 35. Groups of chains, c, with a total mass M_2 for each group and an average radial distance of r_a from the center of rotation, hinged to the periphery of the disc as the impacting arm. A hollow shaft similar to those in the conventional defoliators could also be used instead of the disc, Figure 36. The preference of the disc over the shaft or vice versa depends on the results of their operation in the field.

The rotating disc can either be carried by a skidder shoe or mounted on a tractor and powered by a hydraulic motor or by the power take-off.

There are three major constraints imposed on the defoliator:

1. An average force of 450 N is required to tear off the petioles of one beet. The range varies between 80 and 700 N (19).
2. The horizontal component of this force which attempts to overturn or rotate the beet should average less than 200 N for crowns greater than 50 mm above the ground level (19).
3. The lower and upper limits of the disc angular velocity are limited by the minimum centrifugal force to keep the chain links nearly straight and by the maximum striking force that the beet root can stand without being damaged. The upper limit depends on the total mass of the rotary mechanism, M_t, the

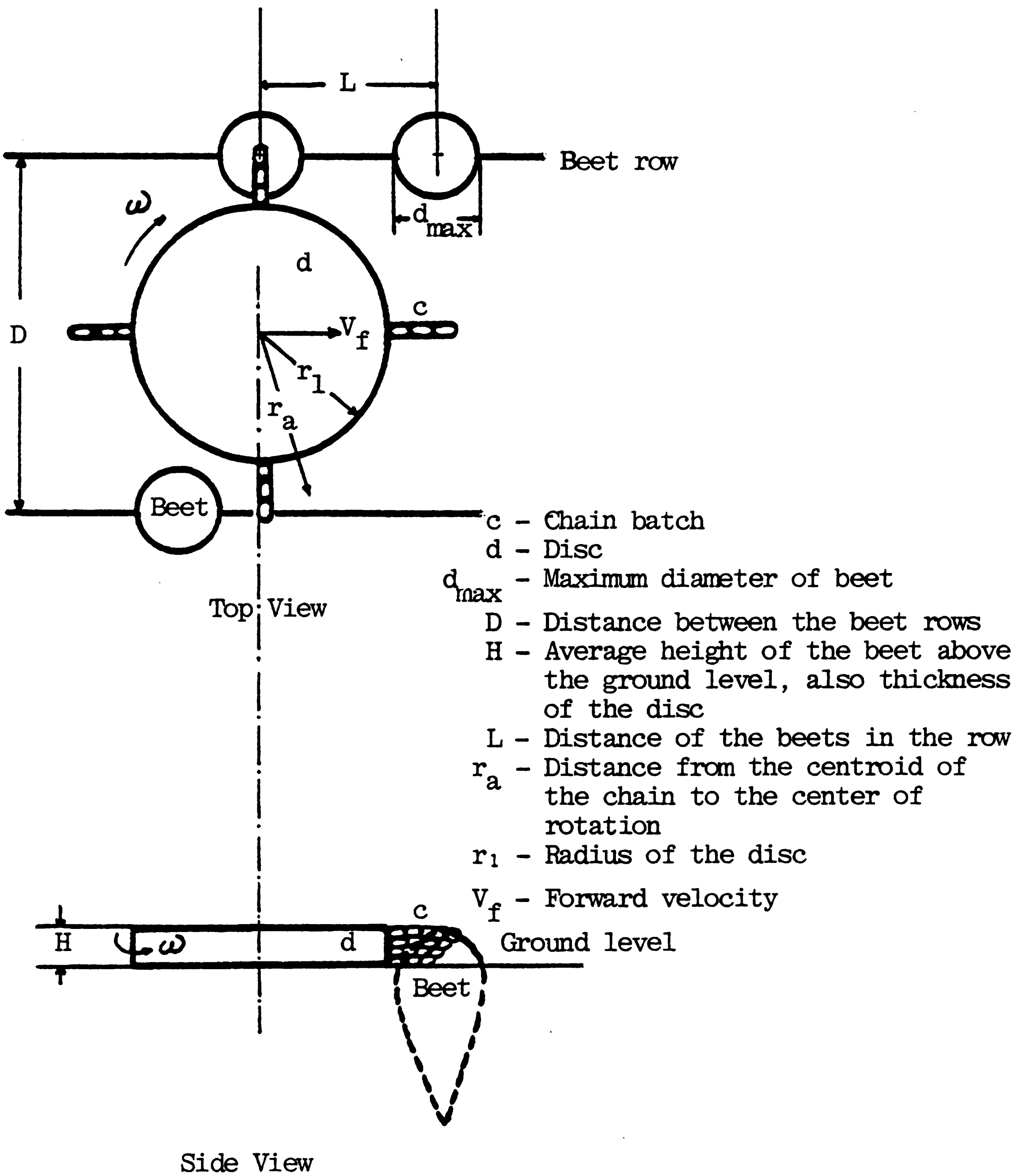
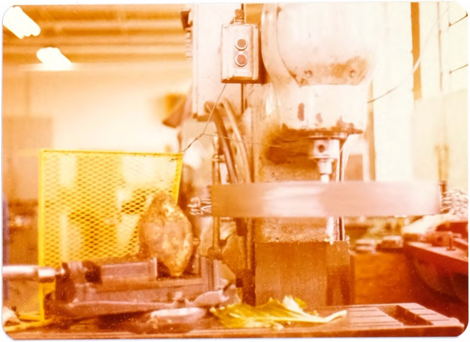


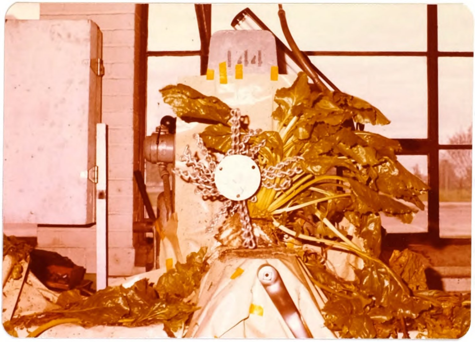
Figure 34. Schematic Diagram of Rotary Defoliator.

a. Before defoliation

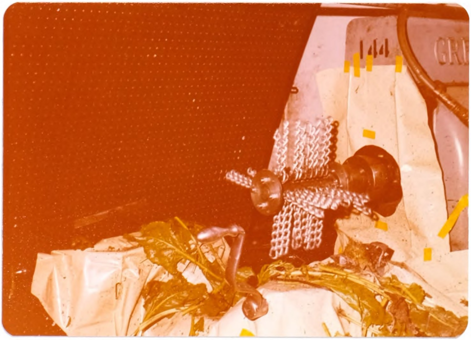


b. After defoliation

Figure 35. The Prototype Model Defoliator using Chain as an Impacting Arm.



a. During defoliation



b. After defoliation

Figure 36. The Prototype Model Defoliator using Chain as an Impacting Arm.

distance from the centroid of the impacting chains to the center of rotation, r_a, and the number of the impacts per unit of time.

An angular velocity of approximately 200 rpm was determined to be the limiting value for the prototype model (M_t = 9.5 kg and r_a = 0.39 m), in order not to break the crown while removing the petioles.

The lower rpm limit (approximately 50 rpm for the prototype model) is determined as follows.

The centrifugal force is equal to mass times the normal acceleration of the disc which is equal to $r_a \, \omega^2$. This force has to be greater than the weight of the chain batch $M_2 g$ in order to keep the chain links nearly straight, thus

$$F_c = M_2 \, r_a \, \omega^2 > M_2 \, g \tag{13}$$

The relation between angular velocity ω and revolution per minute is

$$\omega = \frac{2\Pi \text{ rpm}}{60} \tag{14}$$

Replacing (14) for ω in (13) gives

$$\text{rpm} > \frac{60}{2\Pi} \left(\frac{g}{r_a}\right)^{1 \; 2} \tag{15}$$

where

F_c = centrifugal force, N

M_2 = mass of a batch of chain, kg

r_a = distance from the centroid of the chain batch to the center of rotation

rpm = revolution per minute

g = acceleration due to gravity = 9.8 m/s^2

ω = angular velocity, rad/s

The kinetic energy of the rotating disc at the impact surface is

$$E = E_1 + E_2 \tag{16}$$

$$E = \frac{1}{2} M_t \, r_a^{\,2} \, \omega^2 + \frac{1}{2} M_t \, V_f^{\,2} \tag{17}$$

where

E = kinetic energy of rotating mass at a distance r_a from the center of disc rotation, joule

E_1 = energy loss due to rotation of the defoliator, joule

E_2 = energy loss due to translation of the defoliator, joule

M_t = total mass of the defoliator, kg

V_f = forward velocity of the defoliator, m/s

The energy stored in the disc will have to overcome the energy loss due to the removal of the petioles (an average 24 joules per beet) and the energy loss due to the friction of the chain against leaves (the kinetic coefficient of friction of steel against leaves and beet top was determined to be in the range of 0.6 to 0.7 (19)). Energy will also be lost because of the contact of the defoliator with the ground and vibration of the mechanism.

Beets were held by hand and by a vise in the path of the impacting chain arms in the laboratory tests of the prototype defoliators, Figures 35 and 36. The horizontal defoliator, Figure 35, had a higher total mass and greater vibration compared to the vertical defoliator, Figure 36. The horizontal defoliator, however, left less remnants of petioles on the crown after defoliation. Defoliation process was observed for different disc angular velocities and impacts per unit of time concerning the mechanism shown in Figure 35.

Impact velocity, impact per unit of time and the mass of the chain batch were the determining factors in removal of the petioles. With the disc angular velocity 200 rpm and 0.2 kg chain mass the petioles were removed without severely damaging the beet in approximately 10 seconds. Increasing any of these factors caused crown damage in the form of skinning, flesh removal and breakage.

VII. SOME PHYSICAL PROPERTIES OF THE SUGAR BEET ROOT

A sugar beet experiences mechanical loadings beginning with defoliation and ending when it is processed. The resulting damage can be external or internal. External injuries as recorded by Precht et al. (1976) can occur as crown cut-off, root tip breakage, existence of a gash on one side, cut-off chips from the other side and overall skinning. All of these injuries contribute to the loss of sugar. Internal damage, not evident to the eye, such as crushed or cracked tissues may also exist.

There has been very little work performed on determining the basic mechanical properties of the sugar beet such as its modulus of elasticity, Poisson's ratio and the type of failure under loading. These are essential information in determining the relationships describing the failure characteristics of sugar beet under loading.

Equations that have been developed to score sugar beet injury resulting from free fall weight tests do not provide an understanding of the type of the failure or the stress level developed within the material.

The objective of the following experiments was to determine some of the mechanical properties of the sugar beet root for different loading orientations and sample sizes. The properties which are determined were the apparent modulus of elasticity, Poisson's ratio and the average maximum shear stress at failure for a cylindrical sample.

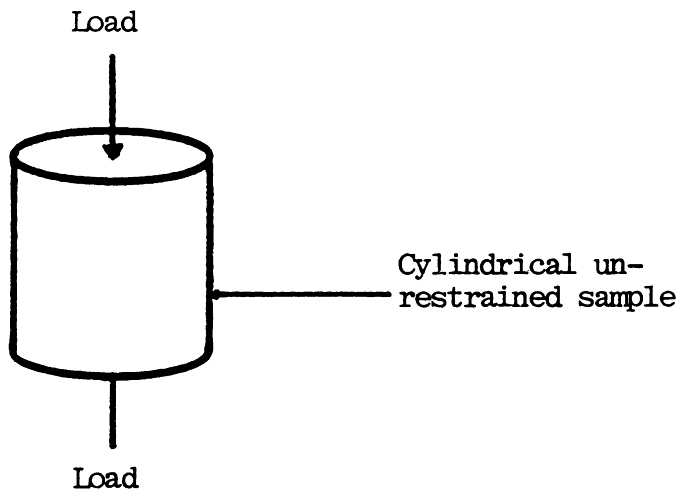
1. Instrumentation

Three dies with spacer plugs, as shown in Figure 37, for three different size samples were constructed. The samples were prepared as needed. Four samples were cut by a sharp blade for each size from two orthogonal directions. Two of the samples were loaded while restrained (in a die), and the other two loaded while unrestrained. All the loadings were applied using an Instron testing machine with a load cell of maximum capacity of 889.6 N which was calibrated using standard weights. The cross head speed of the Instron was 0.84 E-3 m/s.

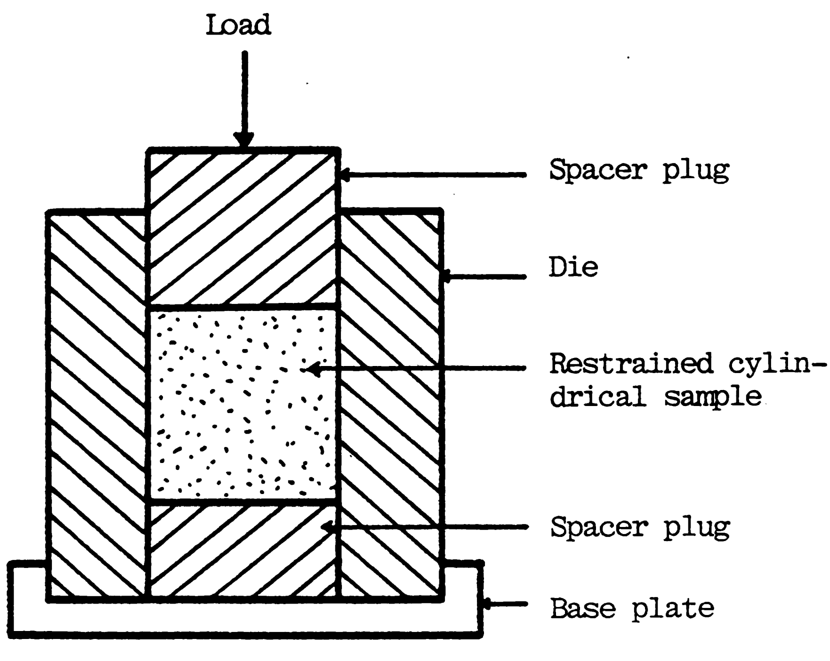
2. Method and Procedure

Tests were performed each day, from October 8 until November 10. All tests were conducted on one beet; the same used in the defoliation studies.

Samples were taken from the middle part of the root (variety US H20). Three different size samples were taken from each of two perpendicular cross sections of the root, Figure 38. The samples were cylindrical in shape with diameters and lengths of 12.7 and 12.7 mm, 19.05 and 19.05 mm, 25.4 and 25.4 mm, respectively. These samples were designated as A, B and C. The two orientations from which the samples were cut were vertical and horizontal. The orthogonal directions were chosen because of apparent difference in the orientations of the fibers as shown in Figure 38.



a. Unrestrained



b. Restrained

Figure 37. Axial Loading of Unrestrained and Restrained Beet Samples.

Figure 38. The Orthogonal Directions of Load Application.

The measured parameters were the compressive force that caused failure of the sample, the apparent modulus of elasticity, E_a, and the Poisson's ratio, ν, for different orientations and sizes of the beet samples.

The apparent modulus of elasticity was determined from the slope of the force-deformation curve at a level where the curve was approximately linear, Figure 39. The stress was obtained by dividing the compressive force by the original cross sectional area of the sample and the strain was determined by dividing the deformation by the original length of the sample. Utilizing the Hooke's law (stress in a bar in tension or compression in the linear elastic region is equal to corresponding strain times by a constant of proportionality known as the modulus of elasticity), the ratio of the stress to the corresponding strain resulted in apparent modulus of elasticity.

Different methods have been employed by the previous investigators to determine Poisson's ratios of agricultural products (Hughes and Segerlind, 1972 and Mohsenin, 1970). Because of simplicity, the die test method presented by Hughes and Segerlind for apples, peaches and potatoes, it was utilized in this study to obtain Poisson's ratio.

In this method the cylindrical samples of material are loaded axially one unrestrained and the other restrained in a die as shown in Figure 37.

The slopes of load-deformation curves at a certain stress level where the curves were approximately linear, provided a measure of ν.

Assuming the specimens as elastic and isotropic material, for an unrestrained sample in polar coordiantes, the triaxial stress equations are

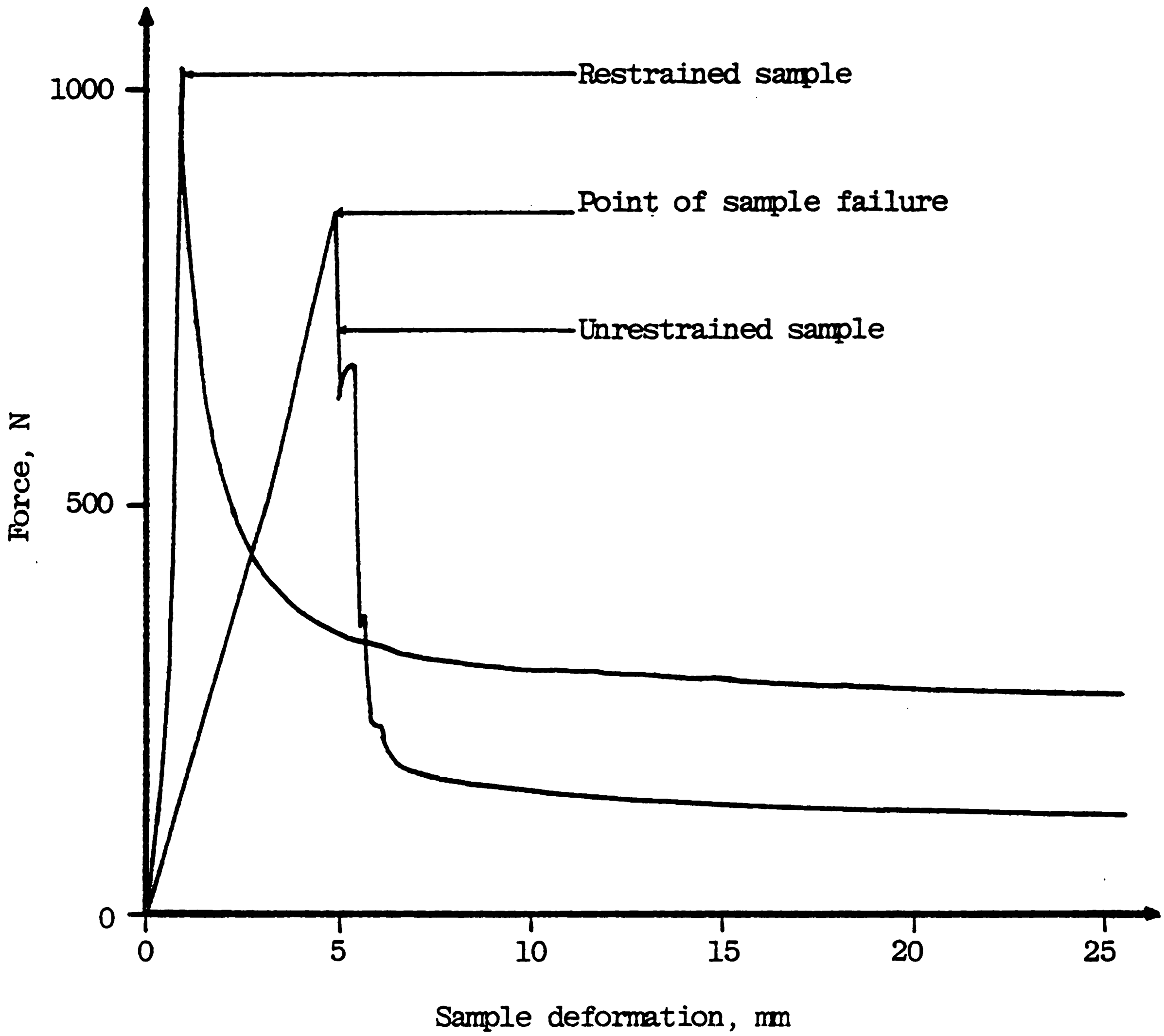


Figure 39. Typical Load-Deformation Curves for Cylindrical Samples of Sugar Beet Root.

$$\varepsilon_{zz} = \frac{\sigma_{zz} - \nu\,(\sigma_{rr} + \sigma_{\Theta\Theta})}{E} \tag{18}$$

$$\varepsilon_{\Theta\Theta} = \frac{\sigma_{\Theta\Theta} - \nu\,(\sigma_{rr} + \sigma_{zz})}{E} \tag{19}$$

$$\varepsilon_{rr} = \frac{\sigma_{rr} - \nu\,(\sigma_{\Theta\Theta} + \sigma_{zz})}{E} \tag{20}$$

where

ε_{zz}, ε_{rr}, $\varepsilon_{\Theta\Theta}$ and σ_{zz}, σ_{rr}, $\sigma_{\Theta\Theta}$ are strains and stresses in vertical, z, radial, r, and circumferential, Θ, directions, respectively.

For a restrained sample, the strains in Θ and r directions become zero. Therefore, equations (18), (19) and (20) when combined, for this case, lead to the following stress-strain relation

$$E\,\left(\frac{\varepsilon_{zz}}{\sigma_{zz}}\right) = \left(1 - \frac{2\,\nu^2}{1 - \nu}\right) \tag{21}$$

where

ν = Poisson's ratio

E = modulus of elasticity, and is equal to

E $= \frac{\sigma}{\varepsilon} = \frac{P/A}{\Delta L/L}$, Pa

P = axial compressive load, N

A = original cross sectional area of the sample, m^2

ΔL = deformation corresponding to the load P, m

L = initial length of the sample, m

To determine the value of ν from equation (21) the values of E and $\frac{\varepsilon_{zz}}{\sigma_{zz}}$ were determined from the slopes of the load-deformation curves,

Figure 39. The slope of the unrestrained curve at a point where it was approximately linear, yielded the value of E_a and the inverse of the slope of the restrained curve, at the same point, gave the value of $\frac{\varepsilon_{zz}}{\sigma_{zz}}$.

For an elastic and isotropic material E and ν are related to shear modulus of elasticity, G, and bulk modulus of elasticity, K, by

$$G = \frac{E}{2(1 - \nu)} \tag{22}$$

$$K = \frac{E}{3\ (1 - 2\nu)} \tag{23}$$

The maximum compressive stress was determined by dividing the compressive force at failure by the original cross sectional area of the sample, from which the maximum shear stress was obtained using the following equation

$$\tau_{max} = \frac{1}{2}\,\sigma_{zz} \tag{24}$$

The above equation is obtained using the three dimensional Mohr's circle for the uniaxial loading.

3. Summary of the Results

The average values of apparent modulus of elasticity, Poisson's ratio and maximum shear stress for 200 samples were determined to be E_a = 11.531 MPa, ν = 0.39 and τ_{max} = 1.250 MPa, respectively.

There were insignificant differences in the mean values of E_a and τ_{max} for different loading directions and sample sizes except size A which had different values of apparent modulus of elasticities for the two perpendicular directions. This comparison was at a 0.999 confidence coefficient. At the same level of confidence the two orthogonal directions had insignificant differences in the mean values of Poisson's ratio, however, different sample sizes showed significant differences.

Observations on the sample failure for different sample sizes and loading directions indicated a common type of failure. The samples failed along the plane making approximately 45 degrees with the axial loading direction, Figure 40. This type of failure indicates that the material has failed in shear along the plane on which the shear stress had a maximum value.

The results of variations of the daily average values of E_a, ν and τ_{max} during the harvesting season as shown in Figures 41, 42 and 43, respectively, indicated that the variation of Poisson's ratio during harvesting period was insignificant, while the change in the values of E_a and τ_{max} for the same period was significant. The values of E_a, ν and τ_{max} are tabulated in Tables 1, 2 and 3.

The values of E_a had an increasing trend, which means the material became stiffer as the time progressed. Also, the values of τ_{max} had an increasing trend.

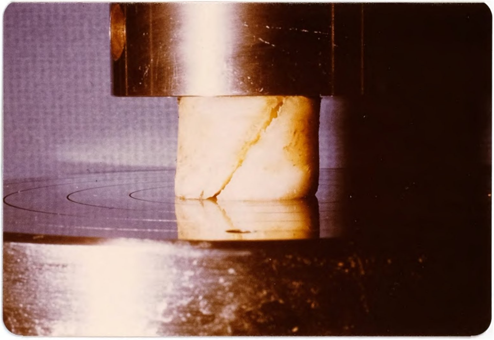


Figure 40. Failure of Cylindrical Sample under Axial Loading.

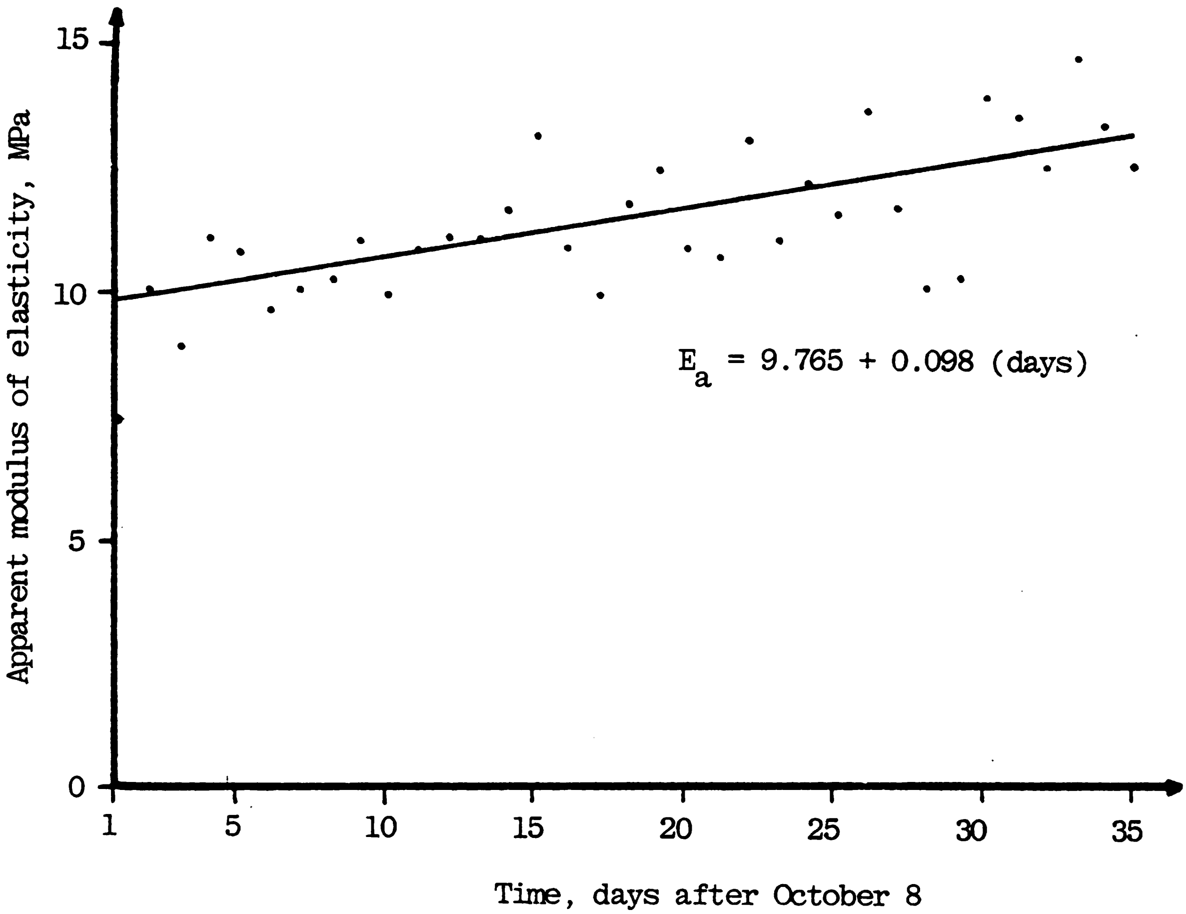


Figure 41. The Trend of Variation of Apparent Modulus of Elasticity of Sugar Beet during Harvesting Season.

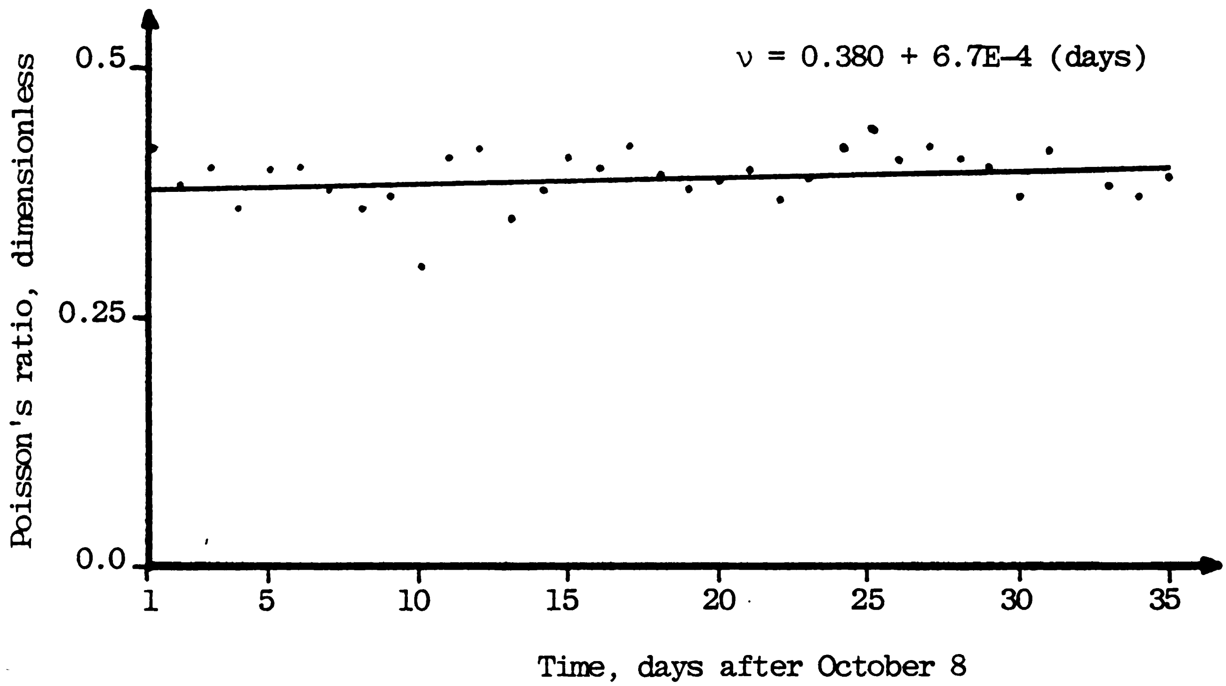


Figure 42. The Trend of Variation of Poisson's Ratio of Sugar Beet during Harvesting Season.

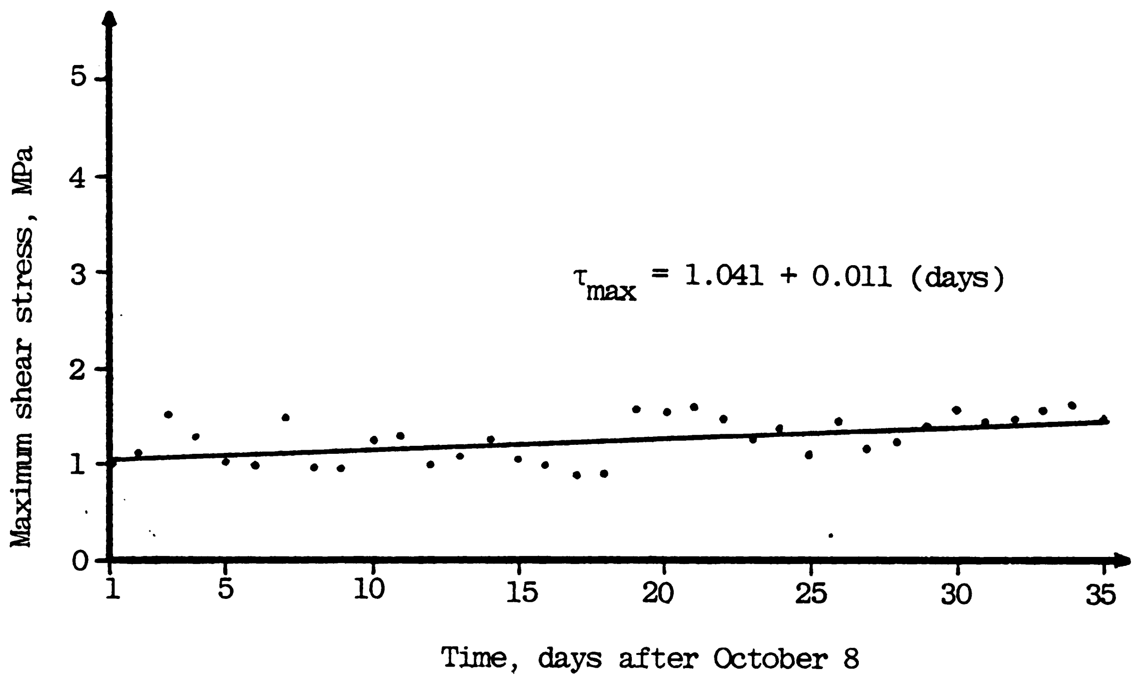


Figure 43. The Trend of Variation of Maximum Shear Stress of Sugar Beet Samples during Harvesting Season.

Table 1. Tabulation of the values of apparent modulus of elasticity for different sizes and orientations of the sugar beet samples, starting October 8 as number 1, MPa.

Sample size[1]	A		B		C	
Loading orientation[2]	V	H	V	H	V	H
Test Number						
1	8.778	7.980	—	—	4.877	7.980
2	11.705	10.328	—	—	7.480	10.973
3	10.328	9.754	—	—	4.620	10.973
4	11.434	10.973	—	—	11.161	10.364
5	9.754	10.328	—	—	10.973	12.541
6	10.328	9.754	—	—	8.778	9.754
7	9.241	10.973	—	—	7.980	12.541
8	11.705	10.328	—	—	9.754	9.754
9	10.973	9.241	—	—	14.631	9.754
10	12.541	11.705	8.360	9.754	6.753	10.973
11	9.241	8.360	11.705	10.641	12.541	12.541
12	10.328	10.328	9.754	11.705	12.541	12.541
13	13.506	13.507	10.641	14.631	21.947	17.557
14	13.506	9.754	16.721	9.754	9.754	10.973
15	9.241	9.241	8.361	19.262	7.980	14.631
16	9.754	7.315	10.641	9.004	10.973	17.557
17	10.973	10.328	10.641	11.705	7.315	8.778
18	12.541	10.328	13.005	13.005	10.973	10.973
19	11.705	9.754	14.631	11.705	12.541	14.631
20	10.973	11.705	7.803	9.754	12.541	12.541
21	10.329	8.778	9.004	9.004	14.631	12.541
22	13.506	12.541	10.641	9.741	17.557	14.631
23	9.754	9.241	9.004	19.508	9.754	9.754
24	12.541	10.328	9.004	13.005	12.541	17.557
25	13.505	10.378	11.705	8.361	14.631	10.973
26	12.541	10.973	13.005	11.705	21.947	12.541
27	11.705	10.973	9.754	10.641	12.541	14.631
28	10.328	10.328	9.754	9.754	10.973	9.754
29	12.541	9.241	9.754	13.005	9.754	7.981
30	14.631	10.328	13.005	13.005	14.631	17.557
31	12.541	11.705	14.631	11.705	17.557	12.541
32	11.705	9.754	13.005	14.631	14.631	10.973
33	14.631	13.505	14.631	16.721	10.973	17.557
34	14.631	11.705	11.705	16.721	12.541	12.541
35	11.327	11.705	11.147	12.321	14.631	13.505

[1]The sizes A, B and C correspond to the cylindrical samples with diameters and lengths of, 12.7 and 12.7 mm, 19.05 and 19.05 mm, 25.4 and 25.4 mm, respectively.
[2]V and H are vertical and horizontal loading directions, respectively.

Table 2. Tabulation of the values of Poisson's ratio for different sizes and orientations of the sugar beet samples, starting October 8 as number 1, dimensionless.

Sample size[1]	A		B		C	
Loading orientation[2]	V	H	V	H	V	H
Test number						
1	0.45	0.40	—	—	0.40	0.42
2	0.33	0.43	--	--	0.30	0.45
3	0.45	0.43	—	--	0.41	0.31
4	0.40	0.41	--	—	0.34	0.31
5	0.44	0.41	—	—	0.36	0.39
6	0.38	0.37	—	--	0.46	0.37
7	0.41	0.37	—	—	0.39	0.37
8	0.41	0.44	—	—	0.21	0.37
9	0.40	0.45	—	—	0.25	0.40
10	0.47	0.33	0.39	0.25	0.17	0.22
11	0.39	0.42	0.44	0.44	0.36	0.39
12	0.42	0.44	0.45	0.44	0.31	0.44
13	0.40	0.31	0.36	0.45	0.29	0.27
14	0.45	0.39	0.41	0.43	0.33	0.30
15	0.42	0.46	0.42	0.39	0.37	0.39
16	0.44	0.45	0.42	0.45	0.29	0.35
17	0.44	0.46	0.46	0.44	0.39	0.35
18	0.42	0.41	0.37	0.37	0.35	0.42
19	0.41	0.45	0.39	0.41	0.23	0.39
20	0.39	0.45	0.45	0.41	0.31	0.31
21	0.48	0.45	0.44	0.40	0.25	0.36
22	0.42	0.34	0.42	0.43	0.35	0.25
23	0.47	0.46	0.45	0.25	0.28	0.45
24	0.44	0.48	0.47	0.43	0.31	0.41
25	0.42	0.43	0.48	0.46	0.43	0.42
26	0.34	0.45	0.45	0.41	0.39	0.41
27	0.46	0.47	0.41	0.37	0.44	0.34
28	0.46	0.46	0.41	0.45	0.30	0.40
29	0.44	0.41	0.41	0.43	0.37	0.34
30	0.43	0.43	0.37	0.45	0.25	0.30
31	0.44	0.43	0.42	0.44	0.35	0.44
32	0.45	0.48	0.37	0.42	0.46	0.45
33	0.43	0.44	0.39	0.31	0.34	0.35
34	0.46	0.46	0.44	0.31	0.23	0.31
35	0.45	0.44	0.42	0.39	0.33	0.32

[1]The sizes A, B and C correspond to the cylindrical samples with diameters and lengths of 12.7 and 12.7 mm, 19.05 and 19.05mm, 25.4 and 25.4 mm, respectively.
[2]V and H are vertical and horizontal loading directions, respectively.

Table 3. Tabulation of the values of maximum shear stress for different sizes and orientations of the sugar beet samples, starting October 8 as number 1, MPa.

Sample size[1]	A		B		C	
Loading orientation[2]	V	H	V	H	V	H
Test number						
1	0.825	1.053	—	—	1.097	1.141
2	1.062	1.062	—	—	0.992	1.931
3	1.615	1.537	—	—	1.281	1.698
4	1.382	1.483	—	—	1.104	1.163
5	0.912	1.141	—	—	0.833	1.141
6	1.018	1.053	—	—	0.967	0.790
7	1.579	1.544	—	—	1.360	1.470
8	1.176	1.053	—	—	0.820	0.816
9	1.000	1.141	—	—	0.899	0.746
10	1.351	1.492	1.248	0.995	1.163	1.240
11	1.457	1.501	1.112	1.209	1.163	1.229
12	0.860	0.921	1.092	1.097	0.790	1.042
13	1.141	1.141	1.092	1.170	1.064	0.943
14	1.123	1.079	1.209	1.287	1.141	1.471
15	0.895	0.983	0.995	1.172	0.932	1.251
16	0.921	0.983	0.975	1.014	0.976	0.987
17	1.035	1.070	0.858	1.131	0.557	0.592
18	0.842	0.930	0.897	0.839	0.878	0.838
19	1.597	1.615	1.424	1.521	1.624	1.481
20	1.422	1.457	1.482	1.521	1.571	1.712
21	1.667	1.474	1.443	1.580	1.514	1.580
22	1.430	1.571	1.295	1.521	1.349	1.624
23	1.334	1.316	1.287	1.073	1.240	1.459
24	1.343	1.176	1.424	1.209	1.744	1.668
25	1.053	1.109	1.073	0.936	1.229	1.196
26	1.193	1.404	1.151	1.619	1.426	1.679
27	1.272	1.158	1.092	0.975	1.053	1.295
28	1.369	1.316	1.112	1.326	1.631	1.185
29	1.193	1.316	1.151	1.272	1.152	1.338
30	1.773	1.913	1.443	1.424	1.351	1.431
31	1.562	1.509	1.365	1.560	1.246	1.338
32	1.611	1.702	1.502	1.248	1.492	1.387
33	1.632	1.615	1.287	1.580	1.624	1.606
34	1.667	1.702	1.619	1.541	1.646	1.524
35	1.439	1.492	1.502	1.248	1.525	1.343

[1]The sizes A, B and C correspond to the cylindrical samples with diameters and lengths of 12.7 and 12.7 mm, 19.05 and 19.05 mm, 25.4 and 25.4 mm, respectively.
[2]V and H are vertical and horizontal loading directions, respectively.

VIII. CONCLUSIONS

The following conclusions were derived from this study:

1. There were intermediate peaks in the force-time curves after failure of the petioles (the highest peak). No intermediate peak was found before the failure. It was thought that the skin of the petiole opposite to the impacting side to be responsible for the secondary peaks.
2. Four different locations on the petioles were impacted. Each location responded differently to the impact.
3. When the petioles were struck close to the crown and in tangential direction (designated as location D), a maximum number of petioles failed (100 percent efficiency of defoliation). A higher impact energy was required for this location than the other locations.
4. The percent removal of the petioles and the energy necessary to remove them varied during the harvesting season, with a decreasing trend from the beginning to the end of the season.
5. Approximately 24 joules of energy was sufficient to defoliate an average beet. The petioles were removed by applying about 440 newtons of impact force per beet, with an impact velocity of 2.45 m/s. Higher impact velocities will be necessary if the crown is impacted also (as occurs under normal field operations).

6. Among the measured parameters (total dissolved sugar, air and soil temperatures, air and petiole moisture contents) the beet temperature had the highest correlation with the percent of the removal of the petioles and the impact energy to remove the petioles.
7. Visual observation indicated that turgidity of the petioles was an important factor affecting their mechanical behavior. A higher efficiency of defoliation was obtained when the petioles were turgid and stiff.
8. A higher percentage of the petioles were removed for all impact locations before overnight freezing and daytime thawing occurred in the field.
9. A rotary design criteria, using chain links as impact elements, was designed and a prototype model was made and tested in the laboratory. The results regarding the foliage removal were promising. Further study on the field tests of the suggested design has been recommended.
10. The apparent modulus of elasticity, E_a, maximum shear stress, τ_{max}, and Poisson's ratio, ν, of the beet roots were determined for three different sizes of cylindrical samples in two orthogonal directions. The average values of E_a, τ_{max} and ν for 200 samples were evaluated to be 11.531 MPa, 1.250 MPa and 0.39, respectively.
11. All samples regardless of size and loading orientation failed in shear along the plane making approximately 45 degrees with the axial loading direction.

12. There were insignificant differences in the mean values of E_a and τ_{max} for different loading directions and sample sizes except size A which had different values of apparent modulus of elasticities for the two perpendicular directions.

13. Poisson's ratio was not a function of sample orientation but different sample sizes showed significant differences.

14. The change in the values of ν during the harvesting season was insignificant, while the values of E_a and τ_{max} had an increasing trend.

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