

SOME PHYSICAL PROPERTIES OF STRAWBERRIES RELATED TO DESIGN OF  
A SELECTIVE HARVESTER

BY

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# ABSTRACT

A fruit selection tool, which could be used as a component of a selective strawberry harvesting system, was designed and tested. Design was based upon physical and rheological properties of the Northwest variety of strawberries which is commonly grown in British Columbia.

Fruit retention force was measured as a function of time over the harvest season. Three rheological parameters, linear limit, bioyield point and tangent modulus, were calculated from force-deformation curves obtained from flat plate loading tests. These parameters were used to evaluate fruit quality and its variation over the harvest season.

Correlations among quality parameters, fruit retention force and fruit surface colour indicated that colour could be used as an accurate indicator of fruit quality and fruit maturity. Fruit surface colour was, therefore, used as the selection parameter controlling the fruit selection tool.

Subjective and objective colour measurements were made. Relative reflectance curves for strawberry surface were obtained from a Unicam automatic recording spectrophotometer by scanning a 2.54 cm. diameter surface of the fruit at fast speed. Spectrum variables obtained from the reflectance curves were used for objective colour evaluation and maturity assessment. The relative reflectances at various wavelengths had good correlation with surface colour, the highest being that between reflectance at 525 nanometers and percent surface

red colour. Maturity ratio for strawberries was calculated from reflectance curves and was established as the ratio of reflectances at 650 nm to 525 nm. Maturity ratio best represented the surface colour and was used to define fruit ripeness.

An electronic system was designed and used to measure maturity ratio and to identify fruit maturity. Tests conducted on this system in the laboratory indicated a minimum response time of 0.166 seconds per fruit. The influence of illumination and its geometry were also investigated.

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# TERMINOLOGY

CIE	Commission Internationale de L'Eclairage
D	Day of the harvest
FRF	Fruit retention force
F/W	Ratio of fruit retention force to weight of strawberry
I	Current in amperes
IVR	Index of variance in reflectance
LL	Linear limit
M <sub>R</sub>	Maturity ratio
n	Sample size
nm	Nanometer
P	Probability level; $(1 - \alpha)$ , where $\alpha$ is the level of significance
r	Simple correlation coefficient
R.F.	Reflectance factor
R <sub>p</sub>	Percent red colour of the berry surface
S	Sensitivity of the electronic instrument
Sy	Standard error of estimate of y
Y	Bioyield point
Ø	Angle between the initial linear portion of the force-deformation curve and the deformation axis

## 1. INTRODUCTION

Strawberries are about a 1 1/2 million dollar annual crop in the lower mainland of British Columbia. About 80 percent of the crop goes to the processing plants and the remaining 20 percent is sold to the fresh fruit market, (7)<sup>1</sup>.

In recent years farmers have been handicapped by adverse economic conditions and repeated labour shortages during the harvesting period. High labour and production costs do not provide for profitable returns. Most of this increased cost is incurred during the harvesting period. This popular fruit could soon be priced out of the market if some mechanical means of cheaply harvesting the strawberry are not evolved.

### 1.1 Purpose of the Research

In view of the above problem it was proposed to design a selective harvesting tool. A criteria based on the physical properties or surface colour characteristics was to be evolved to decide the quality of fruit which would then be used in the design of a harvesting system. Since the Northwest variety of strawberries are the most popular variety grown in British Columbia, the results discussed in this study are limited to this variety.

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<sup>1</sup> Number in parentheses refer to references listed in the literature cited.

## 2. REVIEW OF LITERATURE

Until recently mechanical harvesting of fruit and vegetable crops was limited to a very few types. Because of increasing labour shortage and increased production costs the emphasis has been to harvest every crop mechanically in a short span of time. A number of research organizations have been engaged in various aspects of fruit harvesting mechanization (3, 8, 22, 27, 37).

### 2.1 Present Harvesting Systems

Present harvesting systems can be classified into three main classes:

#### 1. Once-over harvesting systems (regenerative plants).

The crop under this class mature all at the same time. The complete plant may be removed from the soil to facilitate processing under controlled conditions. The plant regenerates itself every year. Under this class fruit and plant damage can be tolerated to a large extent. This method is widely used for harvesting sugar cane and tomatoes.

#### 2. Once-over harvesting (non-regenerative plants)

This system is essentially the same as the previous one except that plants do not regenerate every year and hence excessive plant damage can not be tolerated to avoid adversely affecting the yield the following year. The plant, in this case, is not harvested along with the fruit for processing. This method is widely used for harvesting grain crops.

### 3. Selective harvesting system.

This system is used where the fruit do not ripen all at the same time. Ripe fruits are harvested over an extended period of time during the harvesting season. The machine, harvesting such crops, must be able to distinguish between ripe and unripe fruit. The plants may or may not be regenerative and hence the machines are designed to suit the particular requirement. Damage to the plant and unripe fruit can not be tolerated. These machines have been used for cotton, mushrooms (32) and tomatoes (37) for example.

Various mechanical means are employed to sever the fruit from the plant system. In any case fruit separation may be achieved by applying a force greater than the fruit retention force. Fruit separation may be achieved by applying tension, shear, inertia or impact force or torsional force. Strawberry harvesting machines have been designed without any consideration to fruit or plant properties (3,8).

For selective harvesting of fruits, some criteria, based on the properties of the fruit, are usually decided upon as the basis by which the ripe and unripe fruits can be discriminated. This criteria could be based upon rheological properties, physical properties or colour of the fruit.

#### 2.2 Application of Colourimetric Methods

Although, the use of colourimetric techniques in design of harvesting machines has been very limited, these

techniques have long been used for processing and grading purposes.

Stephenson (37) used the colour of tomatoes as the deciding criteria for selective harvesting of tomatoes. The tomatoes were illuminated by an illuminant and the reflectance of the tomato surface was measured at two wavelengths by photocells. The photocells were arranged in parallel to get uniform response from an irregularly shaped tomato. The amount of current flowing out of the circuit was used as a measure of the maturity of the fruit.

Surface colour has also been used as a criterion for grading lemons (35), tomatoes (20), and prunes (9) according to their maturity.

Heron et al. (20) used reflectance at three wavelengths 528 nm, 671 nm and 730 nm to classify tomatoes. While working on the method to make separation by measuring reflectance at one point on the surface, they found that variation in the reflectance intensity about the surface of a tomato is not significantly large. They obtained 92.98% correct classification by making reflectance measurements at one point. But the sample size was too small to justify results for larger samples.

Hoover and Dennison (23) used a Hunter colour-difference meter with "Rd" circuit to evaluate colour of strawberries. They found out that there was no difference in the "b" value but the "a" value increased steadily with increase in surface redness. This method of colour evaluation is, however, limited in scope unless it can be related to



some known reproducible standards to be utilized in the design of a harvesting system.

Gaffney and Jahn (19) devised a colour measuring system for grading tomatoes using reflectance at two wavelengths. Reflectance measurements made at two wavelengths, at 540 nm as measuring wavelength and 590 nm as reference wavelength gave good classification. Since the measurements were made by a stationary machine, the system was cumbersome for field operations and also uneconomical.

Powers et al. (35) while working on the development of a lemon grader used "Index of variance in reflectance" IVR as the criteria for colour measurement of lemons:

$$\text{where, IVR} = \frac{R_1 - R_2}{R_2} \quad [1]$$

$R_1$  = Reflectance at 6780A (678 nm)

$R_2$  = Reflectance at 7200A (720 nm).

This index enables one to classify lemons into five distinct colour catagories.

### 2.3 Study of Present Strawberry Harvesters

A number of organizations have been engaged in the development of strawberry harvesters.

Oregon State University (3) developed a self propelled, once over strawberry harvesting machine. The machine consisted of two hollow picking reels with spring-steel fingers. These fingers stripped all the berries as it moved through the crop row.

A University of Arkansas group (3) developed a

commercial harvesting unit. The machine used "air suction" to raise the berries from the ground so that aluminum fingers could strip them from the plant.

Hughes and Rickson (3) designed a tractor mounted strawberry harvester using the principle of forced air to lift the berries. The harvesting was accomplished by stripping the berries with picking fingers.

Strawberry harvesters have also been developed by the University of Iowa, University of Tennessee and University of Illinois. All these machines have been experimental units only and improvement in the designs are still underway.

#### 2.4 Colorimetry

Colorimetry has been widely used in paint, dye and the textile industry and lately in petroleum and the petrochemical industry. The application of colorimetry to fruit and vegetables is comparatively a recent innovation. Moreover, the application to the fruit industry is not very efficient. This is because the nature of the problem is different. In the paint and dye industry one set of measurements is often enough to establish colour of the entire batch and even on a continuous process the change in colour is gradual. Hence, apparatus that should quickly adjust to large changes is not required. In the fruit and vegetable industry, however, the colour of each fruit must be separately determined, usually in a fraction of a second. Successive measurements may lie at the extremes of the measuring range.

### 3. ANALYSIS OF PHYSICAL PROPERTIES AND COLOUR MEASUREMENT.

This chapter presents the physical properties and the rheological characteristics of the strawberry fruit. The methods employed to measure individual characteristics are also discussed. These properties are essential for determining the behaviour of the fruit to the applied machine forces. Various components of the machine employed in handling and storage are designed on the basis of these characteristics.

#### 3.1 The Strawberry Plant and Fruit

Before the harvesting system or machine can be designed it is necessary to have a knowledge of physical and morphological characteristics. A knowledge of these characteristics are necessary to achieve a rational design.

The strawberry is a perennial herb of the genus *Fragaria* and family *Rosaceae*. Strawberries are propagated by removing runners, which form naturally, and setting them into new fields. In many cases a new planting is made every year, produces fruit the following year and is then plowed under. However, two annual crops may be produced from one planting. The strawberry is grown in solid beds or matted rows. When grown in rows, the crop rows are spaced 1.2 M apart. Fully mature, the crop row is about 0.66 M wide and about 0.33 M high, (Figures 1a, 1b). As the berries mature they get heavier and sag down and are hidden under the dense foliage (Figure 2).



Figure 1a. A typical strawberry field

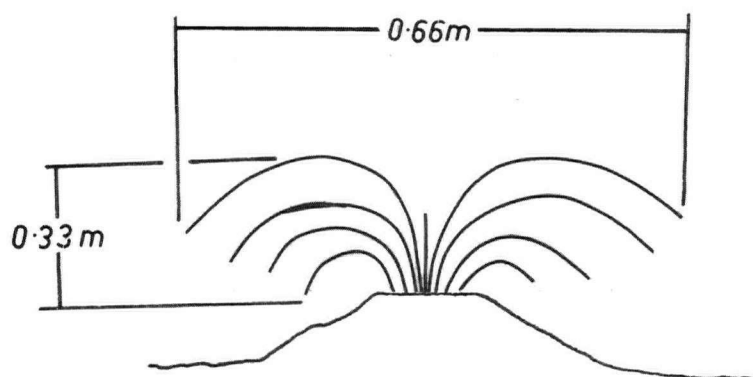


Figure 1b. A typical strawberry plant

The strawberry is a juicy, edible and aggregate fruit. Strawberry fruit can best be described as conical but the shape changes with variety. The strawberry changes its colour from green to red as it ripens. The ripe strawberry is bright red in colour on the surface and yellow achenes (seed) are attached. The fruit is attached to the plant system at the pith (Figure 3). The pith area becomes soft, fluffy and hollow when the berry ripens and the fruit attachment force decreases.

Almost all the harvesting is achieved by hand picking. Since the crop matures over an extended period of time the picking is scheduled every two or three days. When picked with machine, the complete plant is stripped. This causes extensive damage to the plant and hence new plantings are done every year.

### 3.2 Fruit and Plant Distribution

The number of plants were counted per foot (0.3 M) at six different places on each of six rows (18 months old) selected for the study. A metal wire frame 1' x 2' x 1' (0.33 x 0.66 x 0.33 M) was used to count the distribution of fruit across the row. The fruit distribution was also counted at 36 feet (12 M) of row at 36 places.

The number of berries were counted between the four successive 3 inch (7.6 cm) sections about the row center line. All the fruits were contained within the 1 foot (0.33 M) of the plant height and hence no attempt was made to find the fruit distribution along the height of the plant.

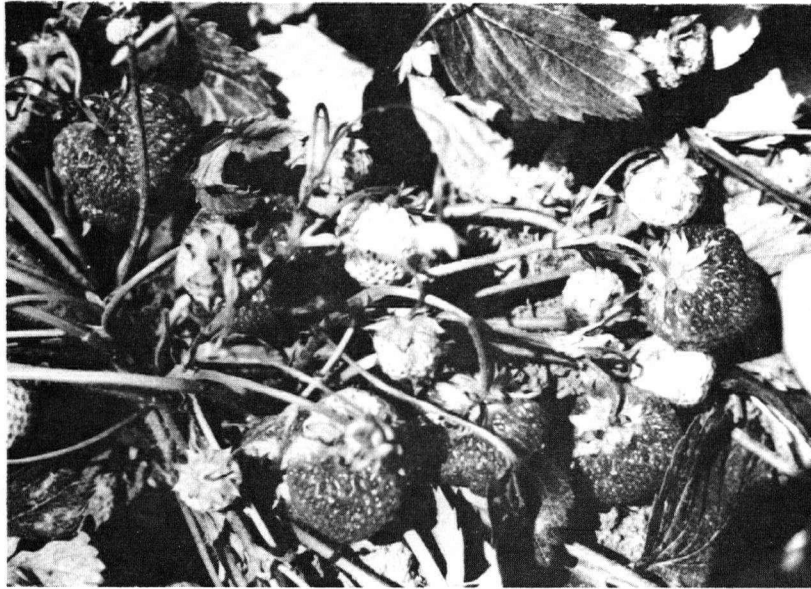


Figure 2. Strawberry plant showing berries hidden under dense foliage

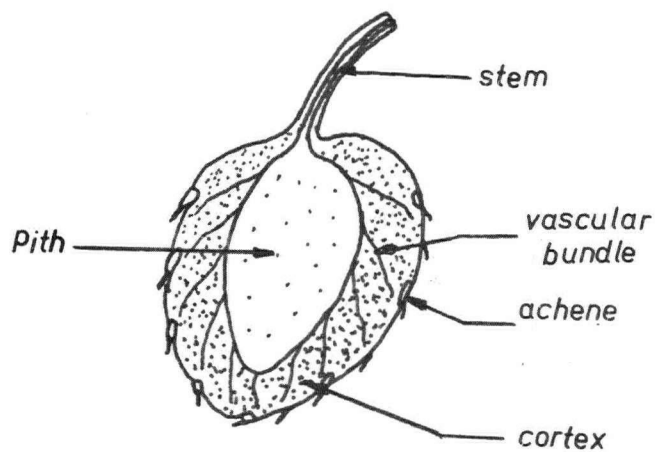


Figure 3. Cross-section view of a strawberry

Results obtained from 36 observations showed that plant distribution (number of plants) per foot (30 cm) of the row was  $21 \pm 5$ . Figure 4 shows the cumulative frequency fruit distribution curve across the row width. This figure indicates that 60 percent of the berries are located within 15 cm of the row centerline and to pick 85 percent of the berries, row slices 22.5 cm thick about the row centerline should be harvested, and to harvest 100 percent of the crop the entire row width of 60 cm should be harvested.

### 3.3 Fruit Size and Weight

Strawberry weight and size are important from the point of view of a picking reel design, finger spacings and conveyor capacities.

The weight of the individual strawberry was measured on a Mettler H-16 type chemical balance. A sample of 172 berries was used to find average weight of strawberry fruit. In the 1970 harvest season the mean weight of strawberry was  $11.08 \pm 4.15$  gms. Janick (24) found the average weight of strawberry to be 14.2 gms.

It was found that average weight of ripe berries did not change significantly over the harvest season. For the 1970 season the simple regression of Z on X gave the following equation:

$$Z = 12.34 - 0.22 X \quad [2]$$

$$n = 112, \quad r = 0.258, \quad S_y = 3.914$$

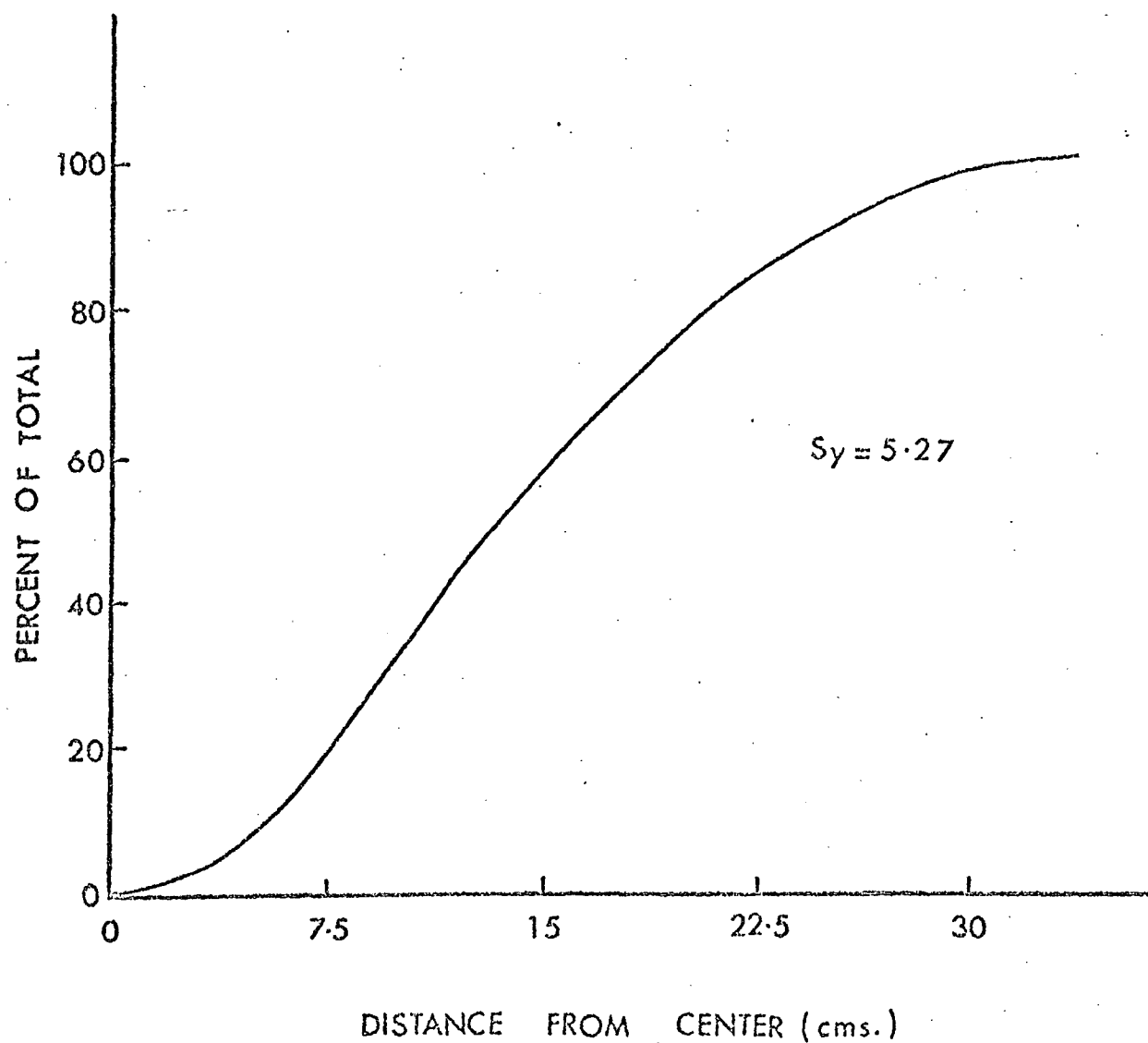


FIGURE 4. Cumulative frequency fruit distribution curve per foot (30 cm.) of strawberry crop measured about the center of the row.



where  $Z$  = Mean weight per berry in gms,

$X$  = Day of harvest

$$1 \leq X \leq 10$$

The above relation indicates that ripening time is independent of berry weight and equal number of heavy and light berries can be expected on the first day of harvest.

The shape of the strawberry is not consistent and can not be described. But most of the Northwest variety of strawberries can best be described as conical (Figure 5). From the design point of view the height and maximum and minimum diameter of strawberry are most important variables. The measurements, diameter and height, were made with hand calipers. Figure 5 shows the typical shape of a strawberry fruit and the statistical correlation of the physical dimensions is given in Table I.

TABLE I  
CORRELATION MATRIX FOR PHYSICAL DIMENSIONS  
OF STRAWBERRIES

	FRF	Weight.	Height	Mean Dia.
Mean	667.8 gms.	12.3 gms.	2.260 cms.	2.015 cms.
Std.Deviation	$\pm 236.7$	$\pm 4.8$	$\pm 0.404$	$\pm 0.565$
FRF	1.0			
Weight	0.286	1.0		
Height	0.282	0.054	1.0	
Mean Dia.	0.383	0.445	0.746	1.0

From the table the mean diameter is  $2.02 \pm 0.56$  cm and mean height of strawberry is  $2.26 \pm 0.40$  cm. Test conducted by

Janick (24) on 144 strawberries of miscellaneous varieties indicated a variation in average strawberry diameter from a minimum of 1.90 cm. to a maximum of 4.06 cm.

### 3.4 Fruit Retention Force

Fruit retention force (FRF) was defined as the force required to remove the fruit from the petiole. The FRF was measured by a Chatillon type DPP1 hand dynamometer (Figure 6) (capacity 1140 gms). Measurements were made with the dynamometer mounted on a surveyor's tripod as shown. The fruit stem was held in a spring loaded clamp and the jaws of the clamp were coated with silicon carbide paper to avoid slipping. A strawberry was held in a 1 cm slotted brass ring of 5 cm diameter. The dial was set to zero and tension force was applied by tightening the screw. As the stem broke or the fruit detached, the fruit detachment force was read on the dial. Since the fruit was held vertically the weight of fruit was added to the fruit detachment force to get fruit retention force (FRF). The dial was then reset to zero to test the next sample.

For the 1970 harvest season, the mean FRF for 112 ripe berries was  $667.8 \pm 236.7$  grams. Hoag and Hunt (22) in tests conducted during 1963 and 1964 on six different varieties (Stelemaster, Vermillion, Red Glow, Sparkle, Sure crop and Midway) found that the mean picking force of different varieties of strawberries was significantly different at the 5% level of significance. For 1963 the range of picking force was a maximum of 1155 grams for

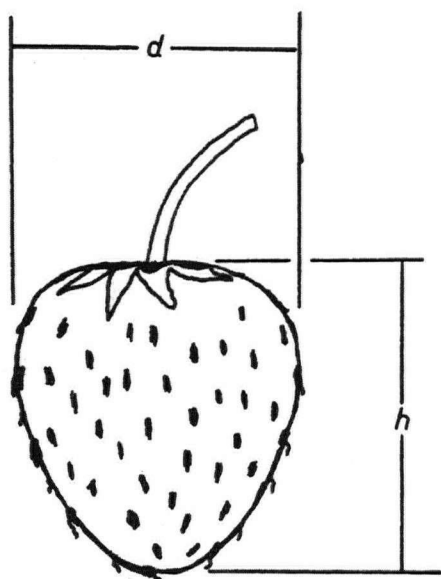


Figure 5. A typical strawberry fruit

a. THE STRAWBERRY

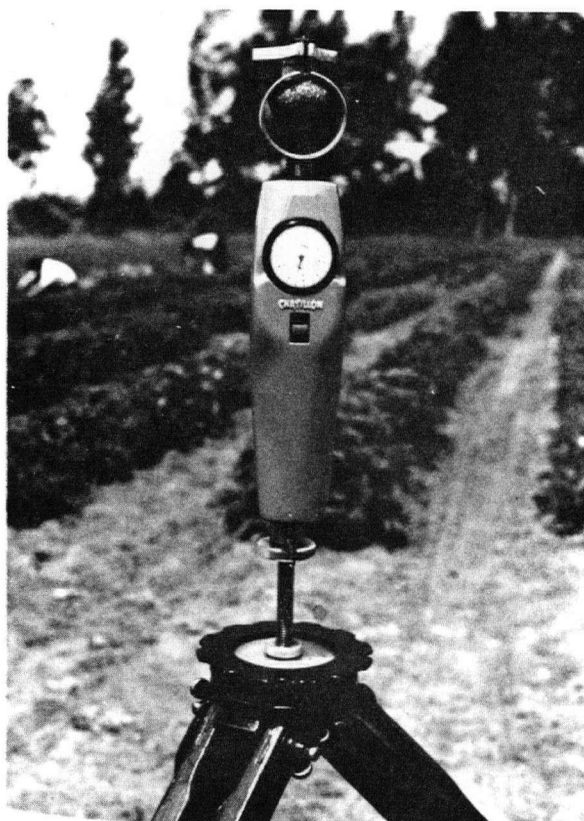


Figure 6. Hand dynamometer mounted on surveyor's tripod and strawberry held in the holder

Vermillion to a minimum of 266.5 grams for the Sure crop variety of strawberries.

Figure 7 shows the variation of mean fruit retention force for ripe or ready to pick berries over the harvest period. Ready to pick berries are those having 80% or more surface redness. The figure indicates that mean FRF for the ripe berries decreases as the harvest season progresses. The equation of the line of simple regression indicating the relation between the two variables is:

$$\text{FRF} = 867.3 - 32.7 D \quad [3]$$

$$n = 112$$

$$S_y = 215.7$$

$$r^2 = 0.122$$

where  $\text{FRF}$  = Fruit retention force in gms,  
 $D$  - Day of harvest for  $1 \leq D \leq 10$ .

Coefficient of correlation between the fruit retention force and day of harvest gave a value of -0.349.

### 3.5 F/W Ratio

The F/W ratio is the ratio of fruit retention force to the weight of an individual berry. This ratio was measured for a sample of 172 berries. The maturity of the strawberries ranged from totally green berries to over-ripe berries. Mean F/W ratio over the entire harvest period was found to be  $71.36 \pm 24.26$ . The analysis of data gave the following equation for simple regression of F/W on day of harvest:

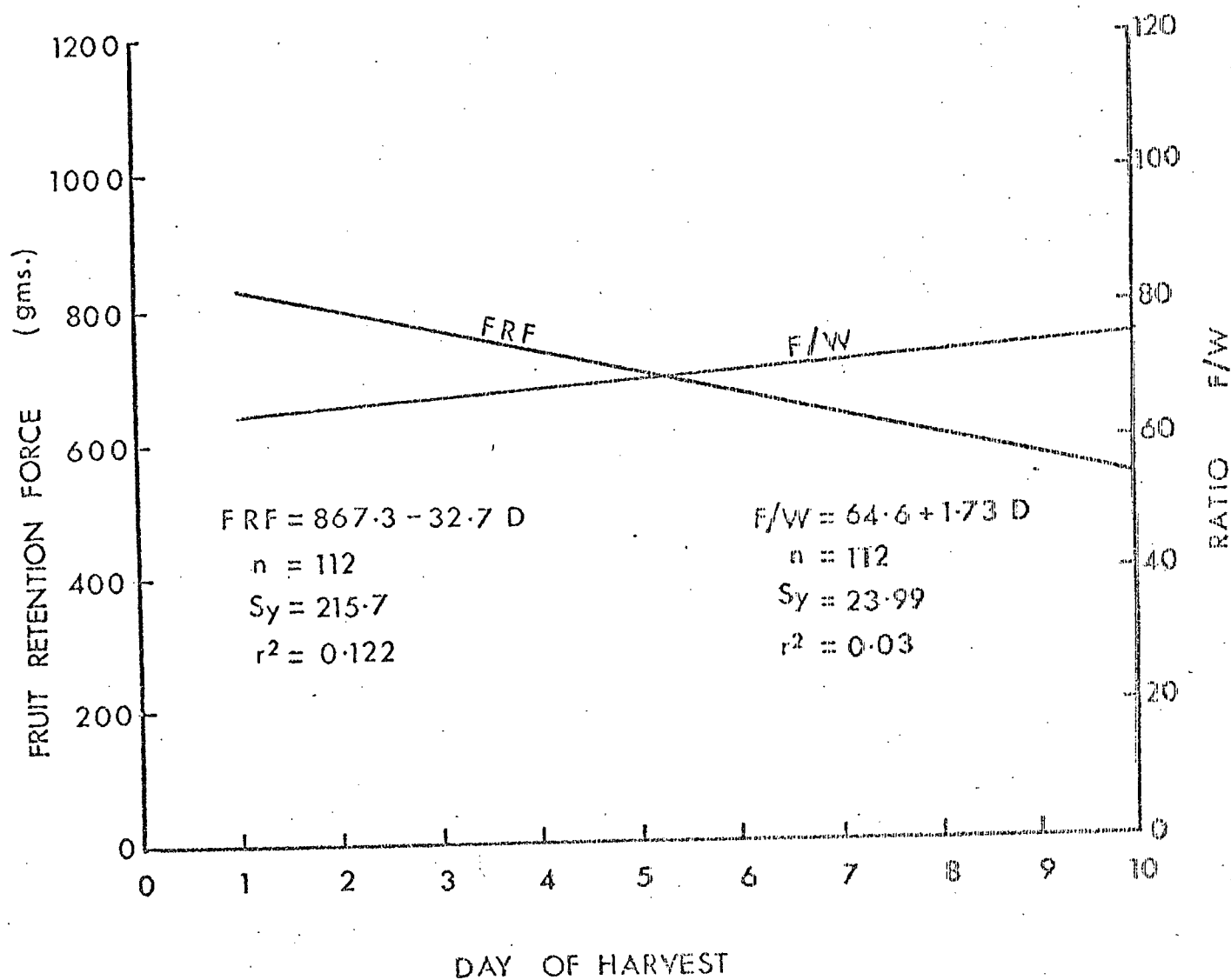


FIGURE 7. Least square simple regression of fruit retention force and F/W ratio on day of harvest.

$$F/W = 64.6 + 1.73 D \quad [4]$$

$$n = 112$$

$$S_y = 23.99$$

$$r^2 = 0.030$$

Equations [3] and [4] have been illustrated in Figure 7.

### 3.6. Rheological Properties

Increasing demand for a better end product together with the delicate and soft skin structure of strawberries demand a better knowledge of their significant physical properties for better handling. Strawberries must undergo various kinds of mechanical, optical and electrical treatment before the product reaches the consumer or processing unit from the farm. It is essential, therefore, to understand the behaviour and response of strawberries when subjected to such treatments so that a machine handling and processing operation can be designed for maximum efficiency and better quality of end product. Moreover, rheological characteristics can also be utilized as apparent maturity indicators and quality evaluations.

A table model Instron tester (Figure 8) was used to obtain force-deformation curves for strawberries, ranging in maturity from totally green to over ripe strawberries. To obtain the critical values of rheological parameters, berries were placed in an upright position, as shown in Figure 9, and compressed between two flat plates at a loading rate of 2 centimeters per minute. A typical force-deformation curve obtained from these tests is shown in Figure 10.

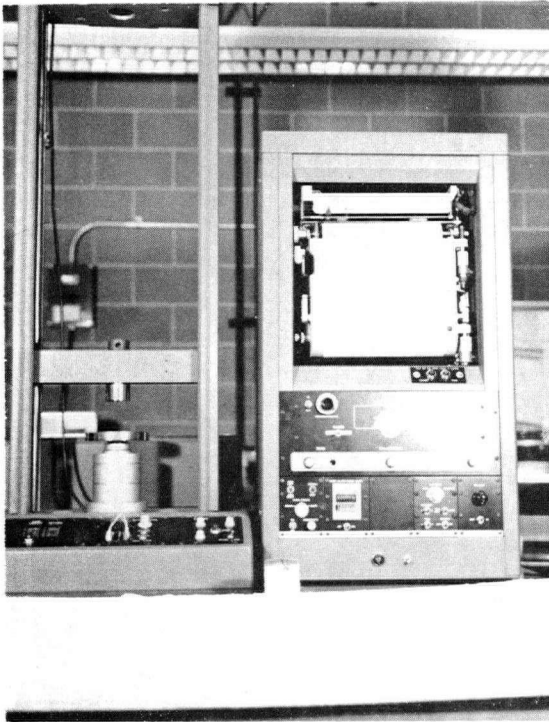


Figure 8. Instron loading machine

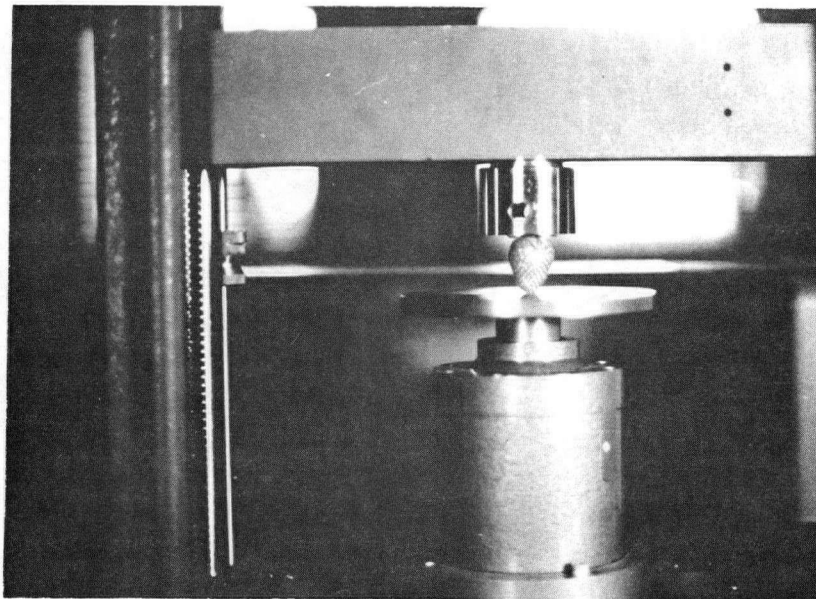


Figure 9. Orientation of strawberry compressed between two flat plates.

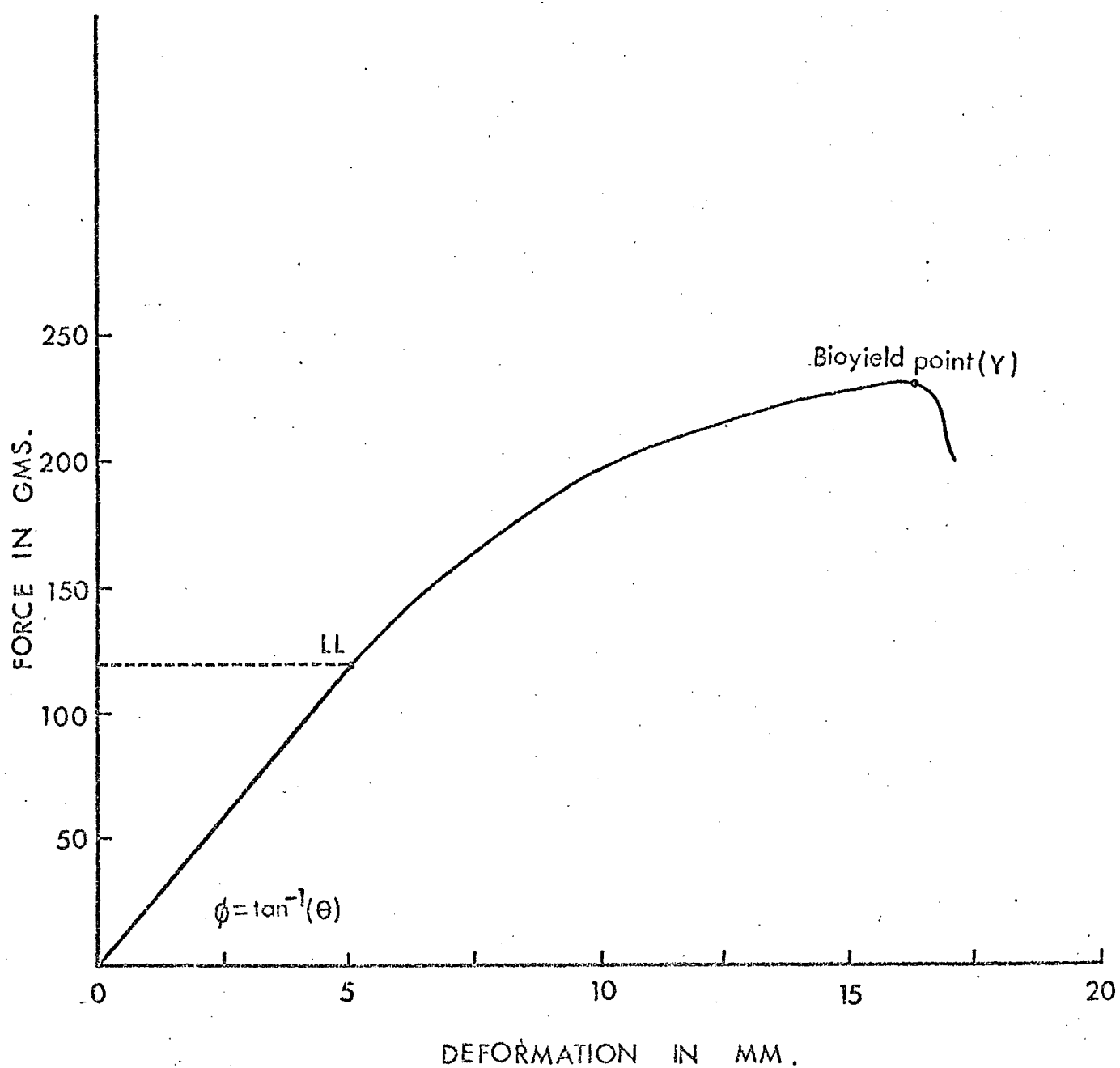


FIGURE 10. Typical force-deformation curve for strawberry subjected to loading between two flat plates at a rate of 2 cm. per minute.



From these curves the values of linear limit (LL) or the minimum load when load-deformation curve becomes non-linear, bioyield point (Y) or maximum load beyond which force decreases or remains constant with increase in deformation, and tangent modulus ( $\theta$ ), or the slope of the force-deformation curve, were measured. Correlation coefficients of linear correlation between rheological parameters and FRF and F/W were calculated to find significance of rheological characteristics on fruit retention force and F/W ratio. The correlation coefficients among these variables are shown in Table II.

TABLE II  
CORRELATION MATRIX FOR RHEOLOGICAL PROPERTIES

	FRF	F/W	Lin.Lmt.	BYP.	Tan.Mod
Mean	667.8	71.36	49.97	116.6	1.622
Std.Deviation	$\pm 236.70$	$\pm 24.26$	$\pm 26.10$	$\pm 47.70$	0.65
FRF	1.00				
F/W	0.41	1.00			
Lin.Lmt.	0.26	0.00	1.00		
BYP.	0.42	0.25	0.47	1.00	
Tan.Mod.	0.41	0.26	0.28	0.75	1.00

The FRF had the highest coefficient of correlation of 0.423 with bioyield point (Y), (significant at  $P \leq 0.05$ ). Least square simple regression of FRF on bioyield resulting from a sample of 118 strawberries is:

$$\text{FRF} = 504.8 + 2.0 Y \quad [5]$$

$$n = 118$$

$$S_y = 208.6$$

$$r^2 = 0.178$$

where FRF = Fruit retention force in gms,

Y = Bioyield point in gms.

The above result is illustrated in Figure 11. It can be derived from the above results that an increase in bioyield point is consistent with the increase in fruit retention force. The mean value of bioyield point for 30 ripe strawberries on the first day of harvest was 126.1 gms, whereas on the last day (tenth) of harvest season, the value was 78.1 gms. It shows that there is a marked decrease in the value of bioyield point of ripe strawberries as the harvest season progresses. Hence the fruit harvested on the last day of the harvest season is more susceptible to mechanical damage and bruising than those harvested on previous days.

It may also be derived from the results in the previous table that the ratio of fruit retention force to weight of the berry ( $\frac{F}{W}$ ) is not better than FRF in indicating rheological parameters as might have first been expected.

### 3.7 Fruit Quality Evaluation

The quality of strawberries can be evaluated by surface colour, size or firmness. In the processing units quality is evaluated manually by feeling the berries in between the fingers. In order to commercialize the process

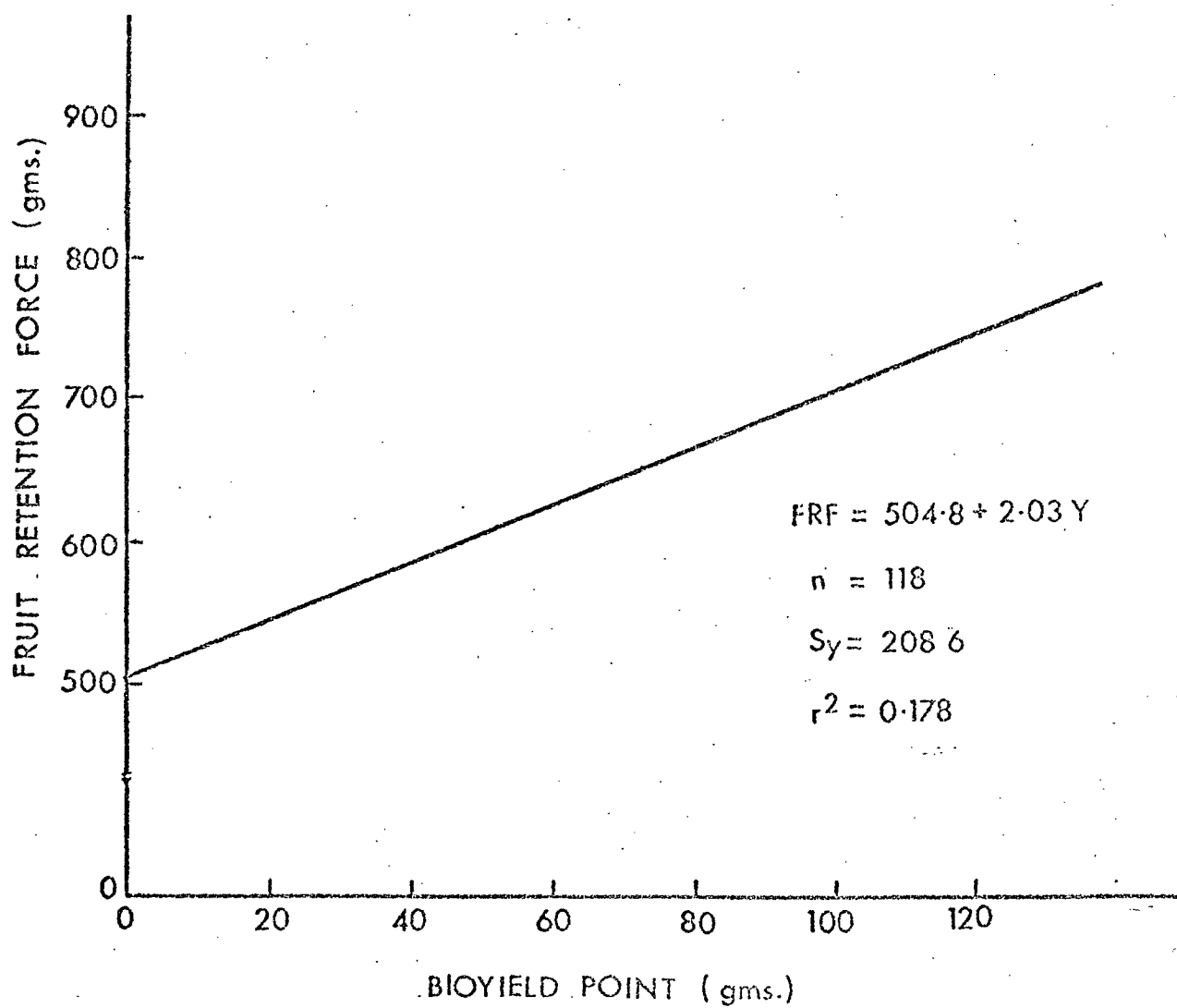


FIGURE 11. Least square simple regression of fruit retention force on bioyield point.

the mechanical or electronic sorter has to make the decisions; and the rheology of the fruit provides the obvious solution to replace the manual operation. Since the bioyield point, which is the point when the skin starts rupturing, is a destructive test, it is not desirable for quality evaluation. Therefore, to define quality of strawberries, tangent modulus seems to be a better parameter. Tangent modulus, which is a measure of fruit behaviour in response to applied mechanical force until the initial cell rupture occurs in the fruit, is also a non-destructive test. Moreover, this is probably the criteria measured by manually compressing the strawberry between the fingers. Hence, the tangent modulus can be used as an indicator of fruit quality. The simple regression of FRF on tangent modulus is:

$$\text{FRF} = 644.7 + 59.6 \theta$$

$$n = 118$$

$$S_y = 226.8$$

$$r^2 = 0.410$$

where FRF = Fruit retention force gms,

$\theta$  = Tangent modulus.

Although complete design of harvesting and handling equipment requires knowledge of the behaviour of strawberries to shock loading, vibration, heat and many other types of treatments, the force-deformation characteristics provide most of the essential data. The analysis of force-deformation characteristics,

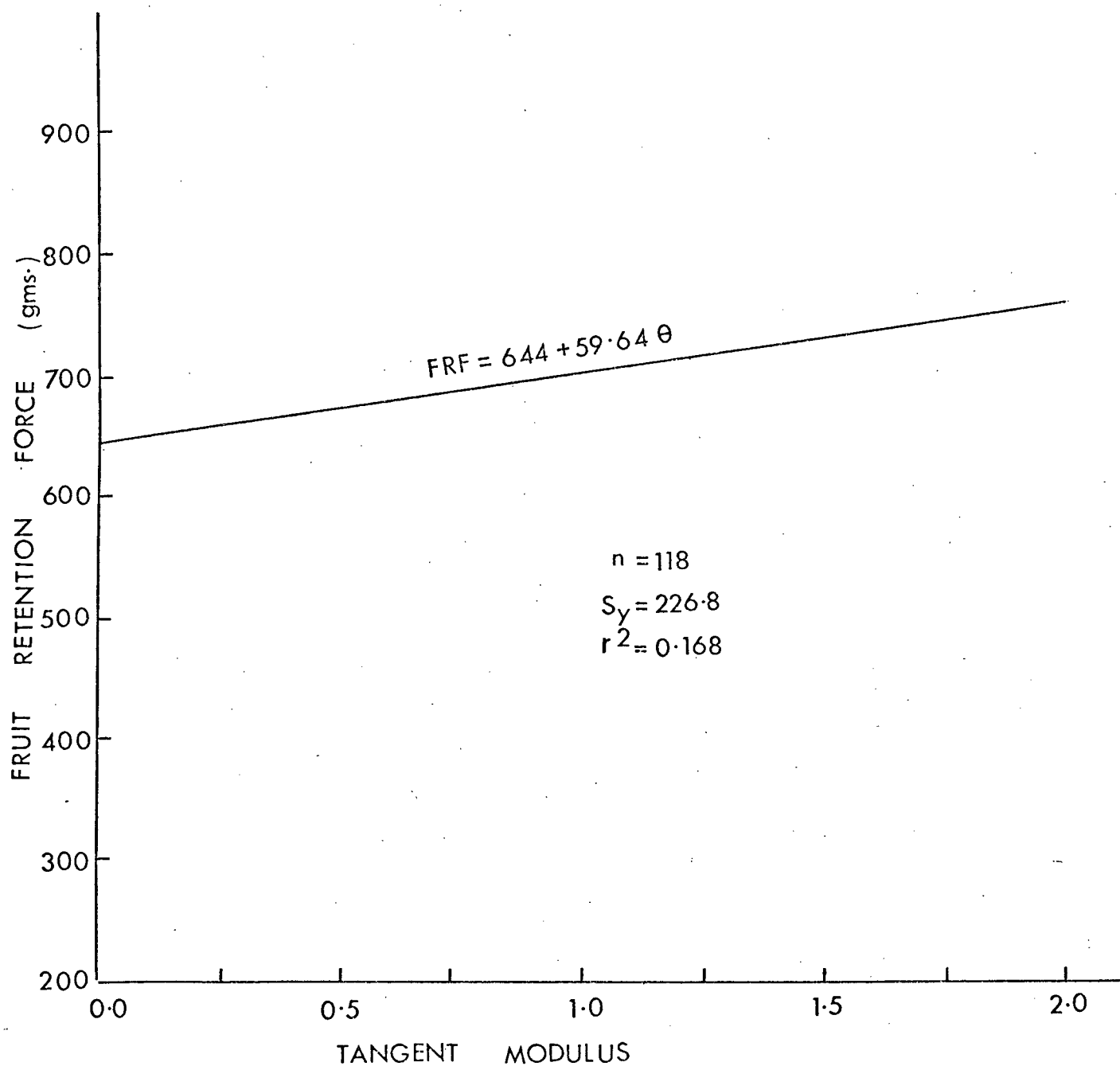


FIGURE 12. Least square simple regression of FRF on Tangent Modulus.

apart from the above three measured parameters, provide knowledge of parameters which can be used in the design of strawberry stripping mechanisms, conveying systems, hopper storage and even further treatments in the processing operations.

### 3.8 Colour Evaluation and Maturity of Fruit

Normally fruit ripeness is judged on the basis of surface redness and picking and sorting is carried out by visual colour judgement. If berries are to be picked mechanically, or processed on a continuous processing operation, some suitable colour criteria is needed for quick and accurate colour evaluation which indicates the ripeness of the berry. Therefore, to find the colour criteria for the design of a suitable selective harvesting system, the reflectance spectrum of the berry surface was analyzed.

### 3.9 Subjective Colour Evaluation

Subjective colour determinations were made on a sample of 118 strawberries over a 10 day harvest period. A value of zero percent red was given to a totally green strawberry, 100 percent to a completely red and ready to pick strawberry and 120 percent to that which was over-ripe and becoming deep red in surface colour (Figure 13). Appropriate values of percent surface red colour were given to partially red coloured strawberries. A typical sample of strawberries of Northwest variety are shown in Figure 13.

### 3.10 Spectral Characteristics

The visual or subjective colour measurements were compared with the spectral characteristics of the strawberry surface. These results were then used in the design of an electronic colour detector.

A Unicam automatic spectrum recorder (Figure 14) was used to obtain the relative reflectance curves of the strawberry surface. A 2.54 cm diameter surface from the lower portion of each strawberry was held in a metal holder (Figure 15), covered with saran wrap, and scanned over the visible spectrum (400 nm\* to 700 nm) on the fast speed of the Unicam. The spectrophotometer was calibrated for 100 percent reflectance on a magnesium oxide surface (reflectance factor\*\* 0.97). Spectral analyses were carried out on 118 samples over the 1970 harvest season. The relative reflectance curves plotted by the instrument were recorded on a logarithmic scale (Figure 16). These curves were converted into normal curves and plotted on an arithmetic scale. Figure 17 shows typical relative reflectance curves for totally green, ready to pick and over-ripe strawberries.

The simplest way to discriminate strawberries as to colour is to characterize its reflectance curve by a single measurement of reflectance. It may be assumed that any one peculiarity in the reflectance properties of straw-

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\* 1 nanometer (nm) =  $1 \times 10^{-9}$  meters.

\*\* Is the ratio of reflected light to incident light.

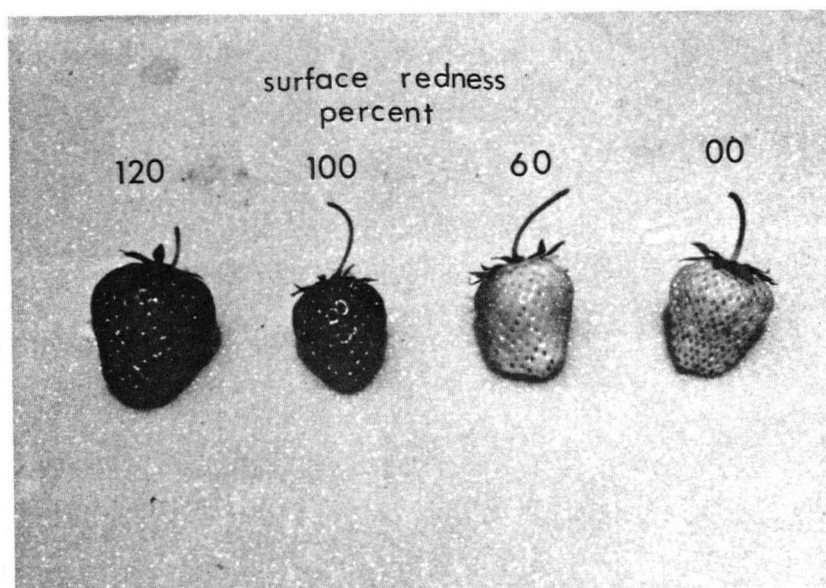


Figure 13. Typical strawberry sample of varying surface redness

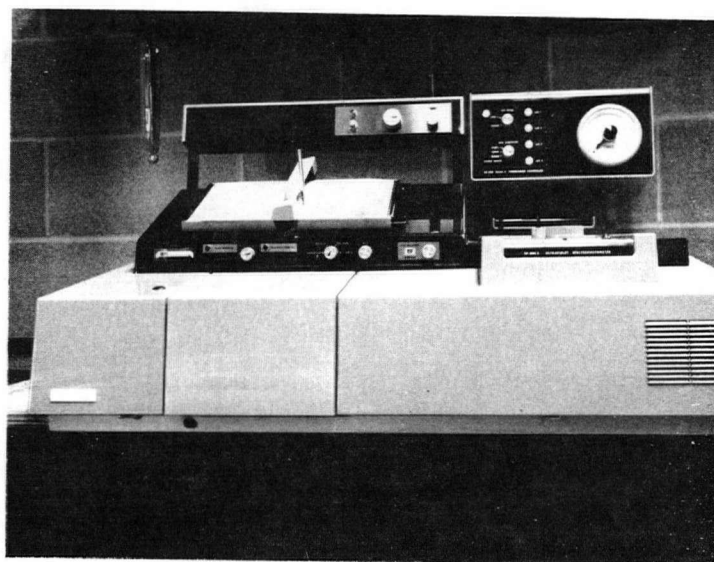


Figure 14. Unicam automatic recording spectrophotometer



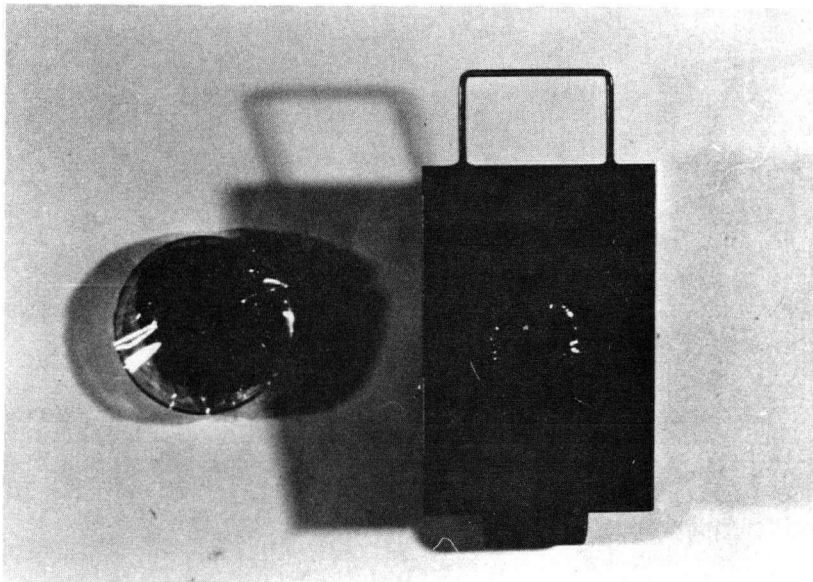


Figure 15. Strawberry surface held in sample holder

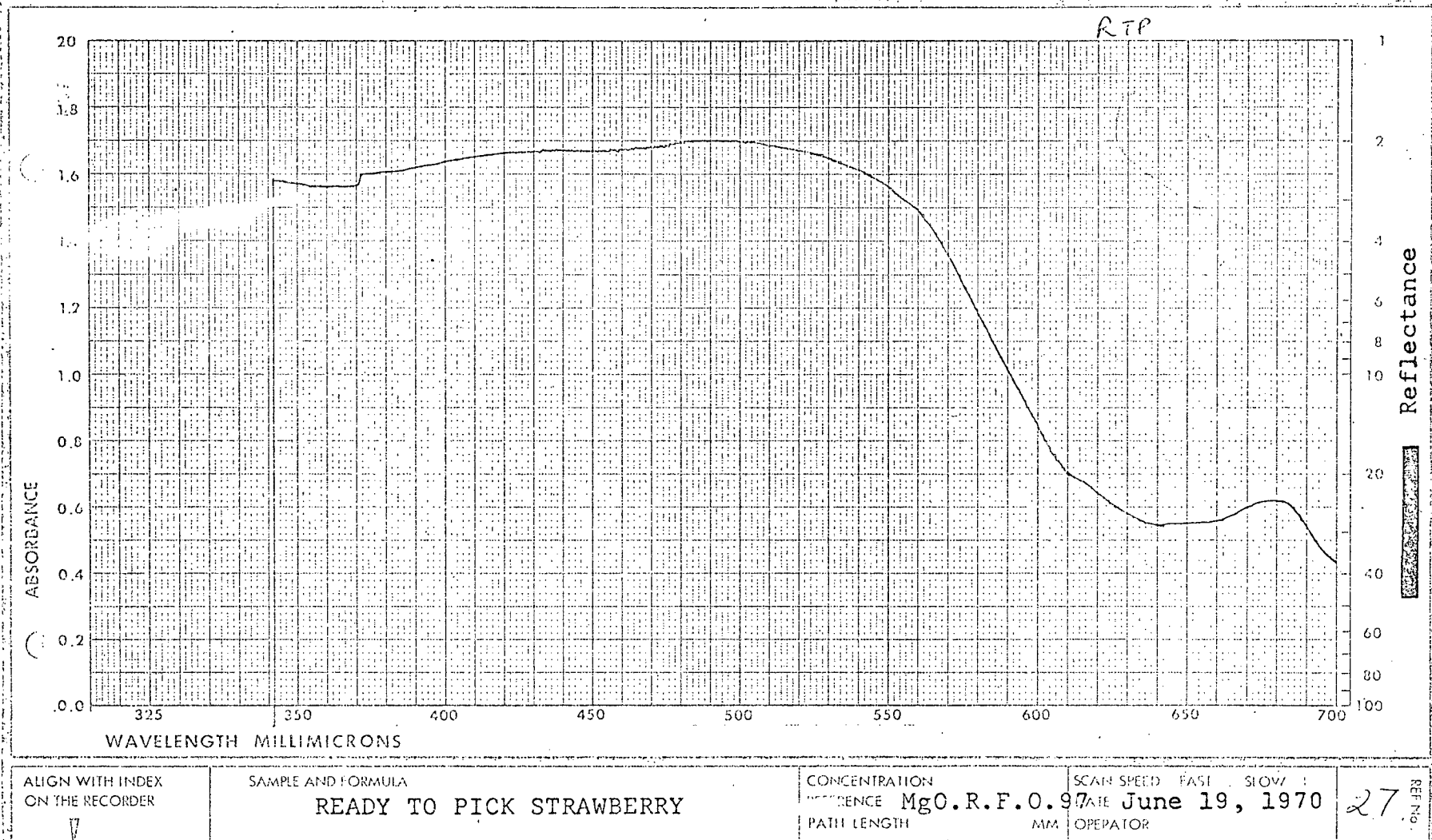


FIGURE 16. A typical relative reflectance curve for a strawberry surface recorded on the logarithmic scale.

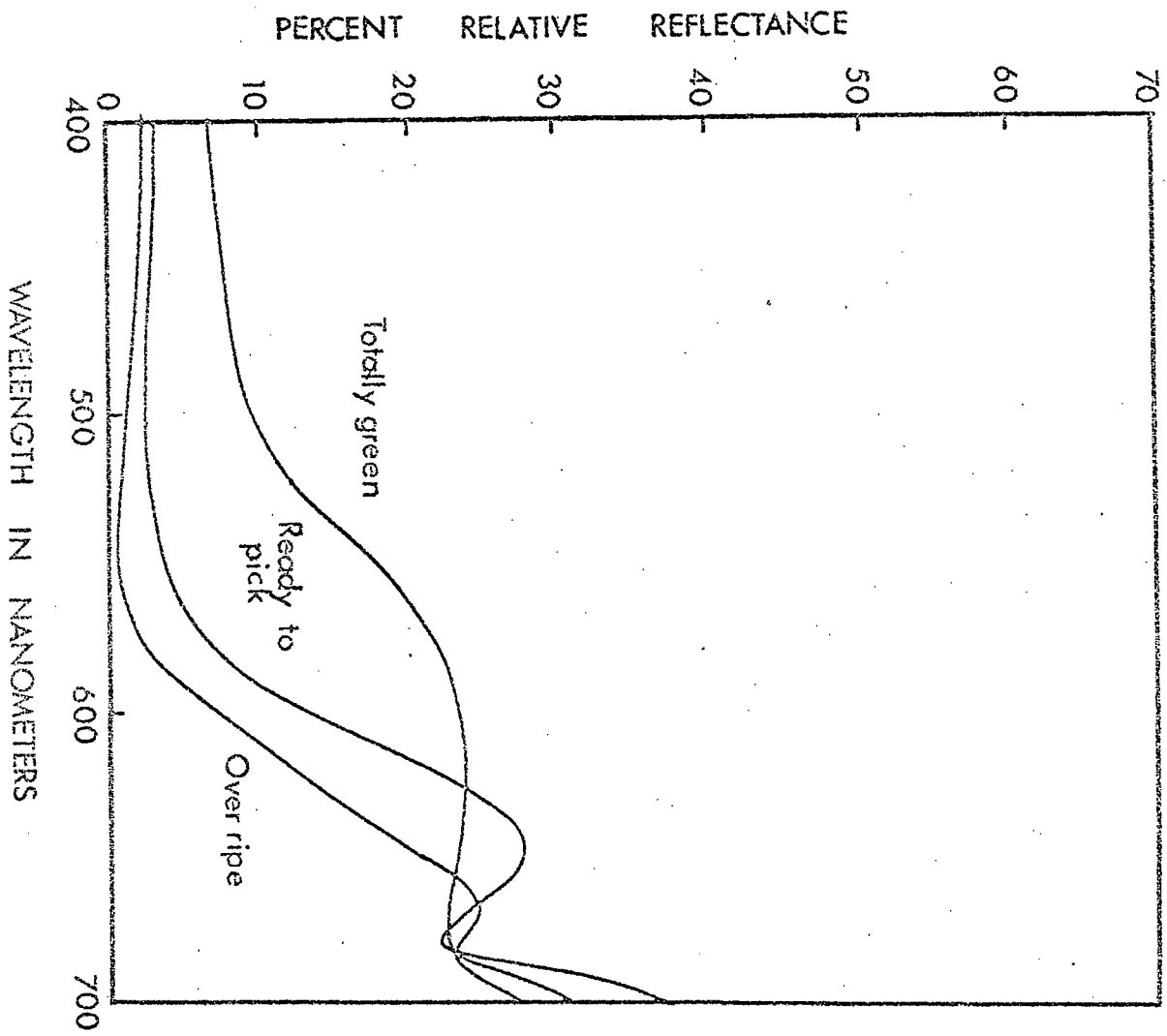


FIGURE 17. Typical spectral reflectance curves for totally green, ready to pick (100% red) and over ripe strawberries plotted on an arithmetic scale.

berries is characteristic of all the strawberries. Hence, colour measurements of fruit can be confined only to one or more narrow regions of the spectrum where such anomalies are known to occur. It is evident that this measurement should be made in the region of the spectrum where change in reflectance between consecutive colour classes is greatest. In this respect the results shown in Figure 17 are of particular significance since the relative reflectance up to 520 nm does not change significantly over the range of berry ripeness; and from the 650 nm wavelength and above, the difference in relative reflectance is once again insignificant over the berry ripeness. However, there is a sharp difference between the relative reflectances over the 520 nm to 650 nm range and berry ripeness.

The wavelength which best represents the surface colour could be found by correlating the reflectances at different wavelengths with the visual colour judgements. Eight wavelengths were selected and reflectances at these wavelengths were correlated with the visual colour evaluations. The analysis indicates that the highest correlation coefficient was  $-0.740$  at 525 nm wavelength. The negative value of correlation coefficient indicates that reflectance at 525 nm (green region of the spectrum) decreases as the surface red colour increases or the berry matures. The simple regression of reflectance at 525 nm on visual evaluation of percent surface redness for 118 samples gave the following equation:

$$R_{525} = 17.16 - 0.17 R_p \quad [7]$$

$$n = 118$$

$$S_y = 27.33$$

$$r^2 = 0.551$$

where  $R_{525}$  = Percent relative reflectance at 525 nm,

$R_p$  = Percent surface redness.

The highest correlation of visual colour evaluation with that of reflectance in the red region of the spectrum was 0.562 at 630 nm wavelength.

To measure the reflectance at 525 nm for the colour measuring system, the fruit can be illuminated with light restricted to a narrow band of wavelengths in the vicinity of 525 nm. A portion of light reflected is intercepted by a photocell. The resulting photoelectric current is proportional to the reflectance of the berry. The current magnitude is also influenced by factors other than strawberry reflectance. These functional relationships can be expressed by:

$$I = SR \quad [8]$$

where  $I$  is the photoelectric current,

$R$  is the percent strawberry reflectance,

$S$  is the sensitivity of the system.

The component  $S$  comprises such quantities as photocell sensitivity, intensity of illumination, berry shape and size, location and orientation of berry with respect to illuminant

and photocell, surface roughness, gloss, and wetness.

Although the electronic measurement of surface reflectance of berries at this wavelength would give a reasonably good evaluation of berry ripeness, it would, however, incorporate many errors caused by variables represented by S, and variation in instrument response at different reflectances. Therefore, if measurements of surface reflectances are made at one wavelength, inaccuracies caused by measurements would be inconsistent for different levels of reflectances.

This method might, nevertheless, be useful if the variation in R between consecutive reflectances of various berries were very great in comparison to the variation in the factors represented by S. And, again, because of heterogeneous mixture of green and red colour for different berries even of the same level of maturity, this method is impractical for discriminating berries according to their colour.

### 3.11 Colour Criteria

Another quantity proposed as a criterion of colour is the ratio of reflectance at two selected wavelengths. This colour criterion whose measured value is independent of instrument sensitivity has long been used in colorimetry. The ratio of reflectances at two wavelengths, called the reflectance ratio, was computed for each berry for a number of possible combinations, e.g.  $\frac{600}{500}$ ,  $\frac{640}{550}$ ,  $\frac{650}{530}$  .....etc.

Out of all the reflectance ratios for each berry, one reflectance ratio was required to represent the surface colour. This was determined by statistically comparing all reflectance ratios for each berry with each berry's surface colour. The reflectance ratio for all the berries which gave the highest correlation coefficient was considered to best represent the surface colour and was called the maturity ratio.

### 3.12 Maturity Ratio

The maturity ratio has been established as the ratio of reflectances at 650 nm and 525 nm. It is a good indicator of strawberry ripeness and can be used effectively to define maturity of the fruit. In the present study it would be used to define quality for harvesting purposes.

Analysis indicated that the maturity ratio increases with the increase in surface redness. Figure 18 shows the relation between maturity ratio and percent surface redness of strawberries. The simple regression indicating the relation between the two values is:

$$Mr = -1.76 + 0.11 Rp \quad [9]$$

$$n = 118$$

$$Sy = 29.05$$

$$r^2 = 0.493$$

where Mr = Maturity ratio,

Rp = Percent surface redness.

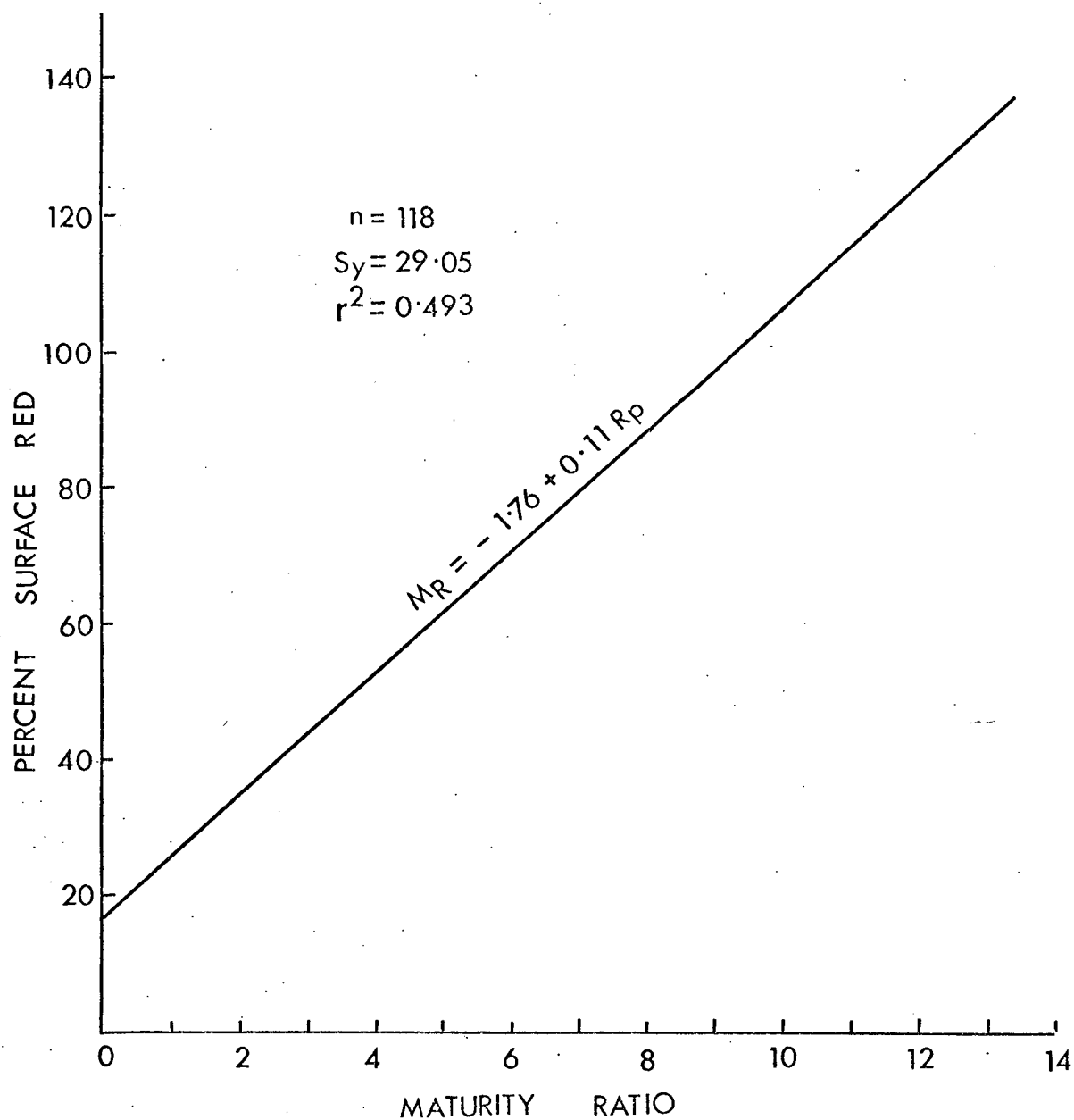


FIGURE 18. Least square simple regression of maturity ratio on percent surface red.



It can be derived from the above relation that as the fruit ripens the value of maturity ratio increases. Almost all the strawberries from green to over-ripe have maturity ratios ranging between 0 to 10. Negative correlation between maturity ratio and reflectance at 525 nm wavelength indicates the percent green colour on the surface decreases as the maturity ratio increases. Simple correlation among maturity ratio, FRF, F/W, percent surface redness and BYP are given in Table III.

TABLE III  
CORRELATION MATRIX FOR SPECTRAL AND  
RHEOLOGICAL PROPERTIES

	Lin.Lmt.	BYP.	525 nm	650 nm	Maturity Ratio	Tan. Mod.	Percent Red	Day
Lin.Lmt.	1.0							
BYP.	0.47	1.0						
nm-525	0.14	0.54	1.0					
nm-650	0.20	0.00	-0.06	1.0				
Maturity Ratio	-0.18	-0.47	-0.76	0.24	1.0			
Tan.Mod.	0.28	0.76	0.57	-0.06	-0.44	1.0		
Percent Red	-0.19	-0.57	-0.74	-0.05	0.70	-0.51	1.0	
Day	-0.27	-0.27	0.14	-0.44	-0.21	-0.05	-0.01	1.0

The bioyield point and tangent modulus have poor correlation with maturity ratio. The value of tangent modulus decreases as the maturity ratio increases further confirming

the fact that the berry becomes softer as it ripens. The decreased value of bioyield point with increasing ripeness (increased value of maturity ratio) shows that the berry becomes increasingly susceptible to mechanical damage.

In quality control operations the colour of products is usually evaluated in CIE (Commission Internationale de L'Eclairage) variables. Because of high prices of sophisticated spectrophotometers the measurements in colour variables are made on less expensive equipment such as a Hunter Colour Difference Meter or Hitachi Perkin-Elmer Spectrophotometer. These variables can, however, be converted into CIE standards for comparison. A study carried out on a limited number of samples show (Table IV) that CIE  $x$ ,  $y$  and  $z$  values have good correlation with the surface redness value of a strawberry.

TABLE IV  
CORRELATION MATRIX FOR CIE COLOUR VARIABLES  
OF STRAWBERRY SURFACE

	Percent Surface Red	Y-value	CIE-x	CIE-y
Percent Surface Red	1.00			
Y-value	0.893	1.00		
CIE-x	0.874	-	1.00	
CIE-y	0.870	-	-	1.00

Studies carried out by Hoover and Dennison (23) on a Hunter Colour Difference Meter with an 'Rd' circuit to

measure the colour of strawberries, showed that correlation between surface redness and 'a' value was significantly high. They suggested that 'a' value which is indicative of red pigment in the strawberries could be used effectively for quality control. But any evaluation of colour of strawberries by a method such as above is limited in scope unless it can be related to some known reproducible standards. Moreover, the CIE values and the Hunter Colour Difference Meter variables are not justified for colour evaluation of partially ripe or even ripe berries because the colour of the strawberry is not uniform over the entire berry surface.

#### 4. DESIGN OF COLOUR MEASURING SYSTEM

This chapter discusses the design of a colour detection system. The optical and operational design considerations which affect the performance of the system, the electronic circuitry and instrumentation of the system have also been discussed.

##### 4.1 Theory of Design

It has been established that maturity ratio is a measure of fruit ripeness and any discrimination between the ripe and unripe strawberries can be made based on the value of maturity ratio. In order to divide the strawberries between two categories, mature (ready to pick) and immature (not ready to pick), one value of maturity ratio has to be selected. This value which marks the dividing line between mature and immature berries was called maturity coefficient. The separation was achieved by comparing the subjective colour determinations made on the strawberry colour and value of maturity ratio obtained from relative reflectance curves.

The mature berries were established as those berries having 80 percent or more surface redness. The berries were separated allowing different values of the maturity ratio to be the maturity coefficient and separating the mature and immature berries. The berries with a maturity ratio higher than the maturity coefficient are to be picked and berries with the maturity ratio lower than the maturity coefficient are to be rejected. These results were then compared to the visual colour judgement and the maturity

coefficient that would give the minimum loss of berries was found. The lost berries included the immature berries having a value of maturity ratio more than the maturity coefficient, and the mature berries having a value of maturity ratio less than the maturity coefficient. Figure 19 shows the percent berries lost by considering different values of maturity coefficients. The percent lost berries decreases with selection of increasing value of maturity coefficient until the value reaches 4.5. Higher values give increasing loss of berries. A sample of 118 berries gave a minimum loss of 10 percent at a maturity coefficient of 4.5.

The selective separation of strawberries would thus be achieved in this system by making reflectance measurements at 650 nm and 525 nm wavelengths and where the reflectance ratio is equal to, or greater than 4.5, the berry is ripe and ready to pick.

The purpose of the system is to measure a value of reflectance coefficient and to obtain a corresponding mechanical response.

#### 4.2 Colour Discriminator

The accuracy of manual picking is adequate enough for commercial purposes. It is questionable, then, whether even a small investment would be justified solely for increased precision. The problem, therefore, is one of reducing costs while maintaining accuracy of picking approximately at the same level as that of hand picking.

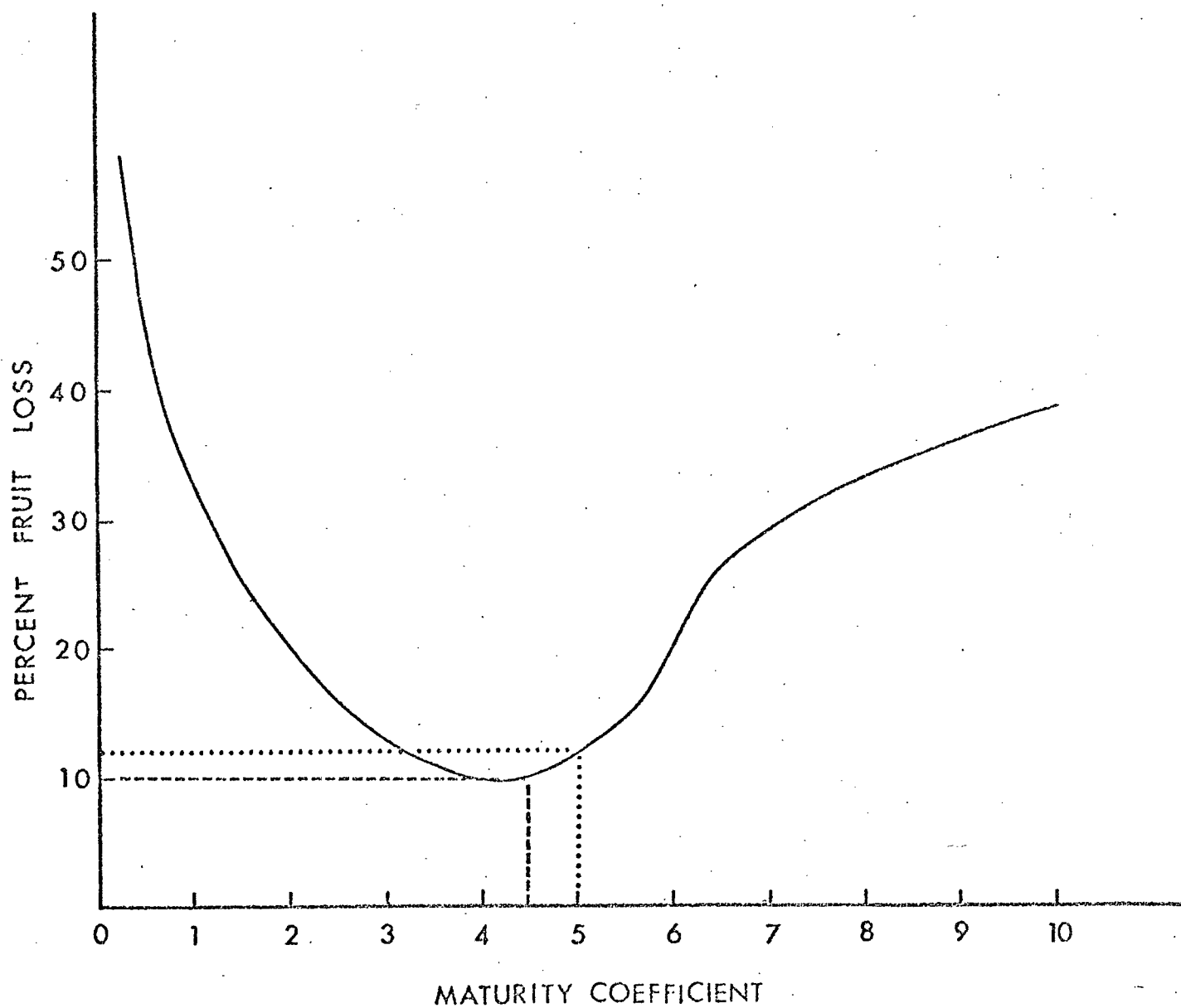


FIGURE 19. Showing the theoretical loss distribution by selecting different values of maturity coefficient.

In a harvesting machine, detection of colour is one of the many operations in a sequence which includes, picking, orientation, detecting, harvesting, conveying, storing and hauling. If any operation should interrupt for a short period of time, all of them must stop. The continuity of operation is thus of great importance.

The distribution of strawberries over the row indicates a total of 144 berries per foot (0.33 M). Even though it might be possible to design a colour sensor to handle full flow of berries, it would be questionable whether such a machine is advisable. It would be better to divide the flow among two or more sensors mounted on the same machine so that temporary failure of one sensor does not interrupt the whole operation.

The colour of strawberries is far from uniform. Even the riper fruits are blotchy and might have patches of green colour. Although, to view the entire berry surface colour would be uneconomical, the essential criterion for an efficient colour detecting system would be to view as much surface area as is economically possible. The geometry of alignment of photodiodes, angle of viewing and distance of photodiode from the berry surface would be important in this context.

In commercial operations the strawberries may be wet, covered with mud, too little or too much illumination or sunshine. It is desirable therefore, that the system is

capable of adjustment for operation under these conditions.

All kinds of adverse field conditions can be expected during the machine operation. The requirements call not only that the machine be rugged and compact but also that it perform efficiently and accurately during actual operation.

#### 4.3 The Optical Requirements

To simulate manual sorting by an electronic system some of the basic optical criteria have to be considered while measuring reflectance. The components, namely illuminant, object and detector are essential considerations in any colour measuring operation.

##### 4.3.1 The Illuminant

The reflectance of a surface is the percentage of incident light reflected by it. The efficiency of a system requires that there is enough reflected light so that small changes in illumination do not adversely affect the performance. Although, too intense an illumination might cause a shift in hue.

The illuminant should provide illumination of the same colour temperature over an extended period of operation. The illuminant whose spectral distribution changes due to long operation time are not suitable for colour measurement. Illuminants like fluorescent light or mercury lamps are also not suitable for such operations.

The illumination provided must be uniform. This becomes all the more important in the case of strawberries



because of their non-uniformity in surface colour. The illuminant should illuminate the entire surface of the strawberries. It is preferable, but not essential that the incident light should be straight and parallel. With present day devices this is not difficult. An illuminant equipped with focussing lens would be reasonably sufficient for the purpose.

The orientation of the illuminant with respect to the object has considerable effect on the measured reflectance. While measuring diffuse reflectance the object is illuminated from an angle of  $45^\circ$  to the surface of the object.

#### 4.3.2 The Object

The surface of the object should be level and smooth while measuring diffuse reflectance. Although such a condition is ideal, the quality of strawberries cannot be sacrificed. Moreover, the purpose here is not colour specification but evaluation of berry quality. Therefore, all the colour evaluations would be comparative and not absolute.

Since continuity of operation is important, each berry must move past the field of illuminant and the viewing field of the detector, and must be within the viewing range of detector for the time during which measurements are made.

#### 4.3.3 The Detector

Of all the three components in colour detection,

the colour detector is most important. The uniformity of operation requires that detector response be consistent, at least, over the range of spectrum in which the measurements are made.

The economy of operation requires that the detector should have the least possible response time. A slow response detector could slow down the operation of the entire equipment thereby seriously reducing the capacity and increasing the cost.

The detector, in this case, should preferably be small and rugged. Too big a detector would cause congestion at the detection head of the machine. Because the machine has to operate in adverse field conditions it is essential to have a detector which would not be affected by shocks and other mechanical hindrances.

The detector should have a wide angle of view so that the entire object can be viewed. To measure diffuse reflectance the detector must be aligned at  $90^\circ$  to the surface of the object. The detector must also be accurate since even a small variation in performance could cause significant loss in performance efficiency.

#### 4.4 The Design of Optical Apparatus

Analysis has indicated that the maturity ratio is a function of reflectance at 650 nm and 525 nm. It is evident therefore that the reflectances at these wavelengths should be measured simultaneously and with equipment of the same sensitivity. This was done by illuminating the straw-

berries with one illuminant and measuring the reflectances with two photodiodes of the same sensitivity. The details of photodiodes are discussed later in the chapter.

The optical apparatus used for the purpose is shown in Figure 20. The illumination was provided by a 12 V tungsten lamp (colour temperature 2854°K). The lamp was of fixed intensity and could be operated on AC or DC voltages. A focussing lens was mounted in front to focus the light on the object. The reflected light was filtered through two narrow band interference filters. Since filters of exact specification were not available, filters with a close approximation were used. In the prototype, two available Balzer interference filters with peak transmission at 640 nm and 540 nm and with 9 nm half band width were used to make measurements at these wavelengths. The filtered reflectances were intercepted by two Hewlett-Packard #HP 5082-4205 pin photodiodes. The photodiodes were preferred over the traditional photo tubes because of their compactness, portability and efficiency. The photodiodes had a response time of less than one nanosecond. Other specifications for the photodiodes are given in Appendix A. Because of highly directional sensitivity of the photodiodes, their axis has to be within  $\pm 1.0$  degrees of the direction of reflected light.

#### 4.5 The Electronic Apparatus

To evaluate the suitability of the system an

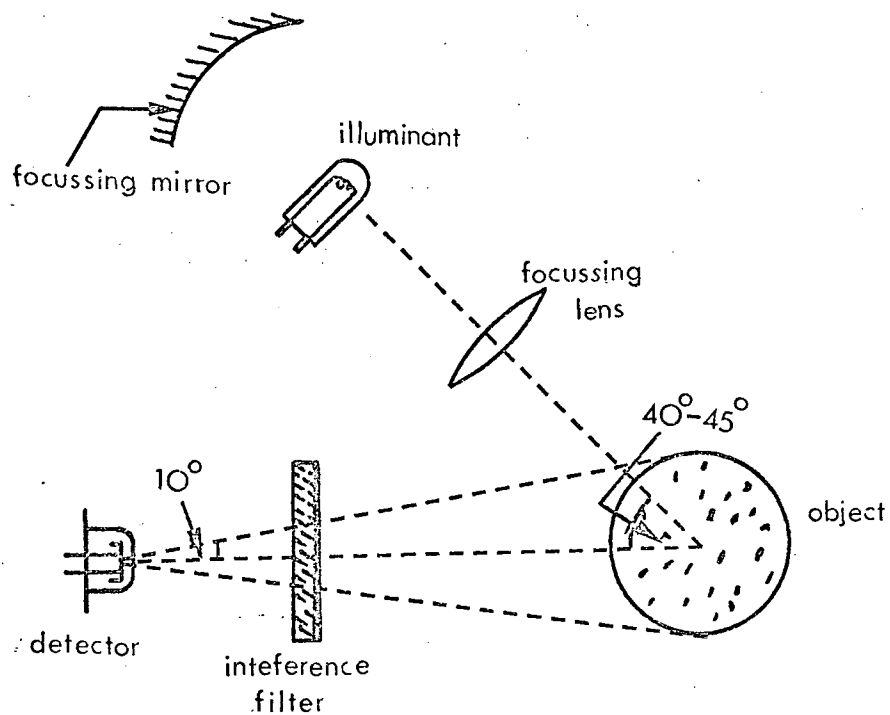


FIGURE 20. Optical apparatus for colour measuring system.

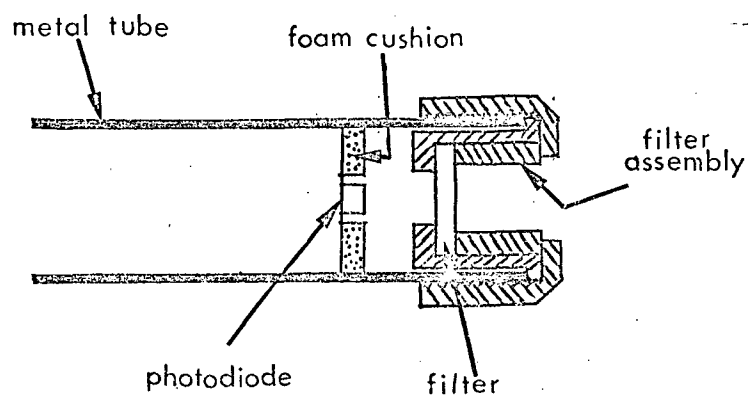


FIGURE 21. Cross sectional view of the filter-probe assembly. (Not to scale).

experimental apparatus was tested in the laboratory. The tests were limited to the operational efficiency, the speed of performance, and the effect of different parameters on performance of the system.

The electronic apparatus consisted of four primary components namely, the colour sensor or probe, amplifier, voltage comparator, and the electronic switch or solenoid.

#### 4.5.1 The Probe

The probe assembly consisted of interference filter, the pin photodiode and the probe circuitry. The construction of filter assembly and probe circuitry is shown in Figure 21 and 22. The probe casing was formed from 1/16 inch (1.5 mm) copper tube of 25 mm diameter. The filter was held in a rubber holder at one end of the probe. The photodiode was held behind the filter on a plexiglass mount. Foam padding was used to cushion the photodiodes. The probe circuit was obtained from Hewlett-Packard application notes 915 (21).

#### 4.5.2 Amplifier

The amplifier (Figure 23) was modified from a circuit suggested by Hewlett-Packard (1967) for use with pin photodiodes. The photodiodes, field effect transistor, and 10 Meg  $\Omega$  resistor were mounted with the probe circuit. The three leads which are separated from ground by high impedance were kept short to minimize pickup. The amplifier was mounted on a perforated circuit board and enclosed in a

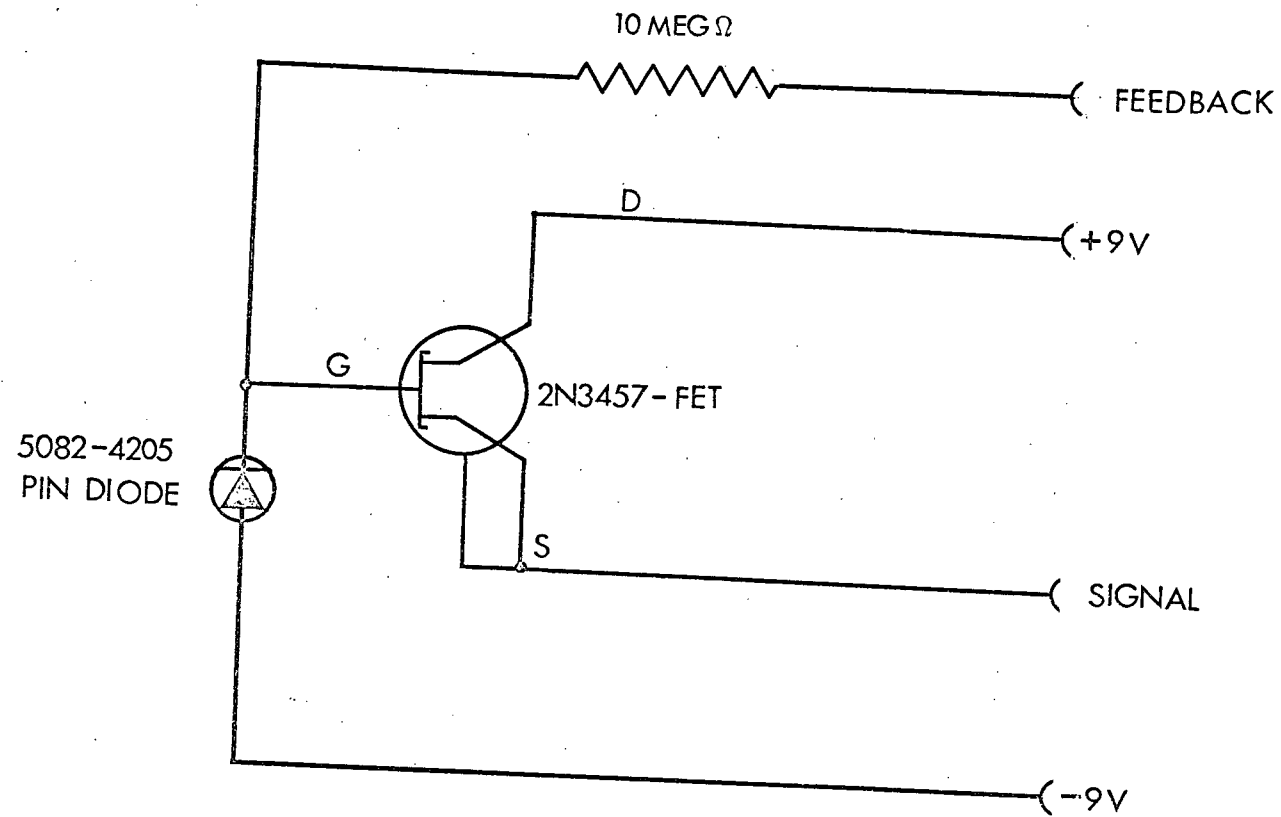


FIGURE 22. Circuit diagram for probe assembly

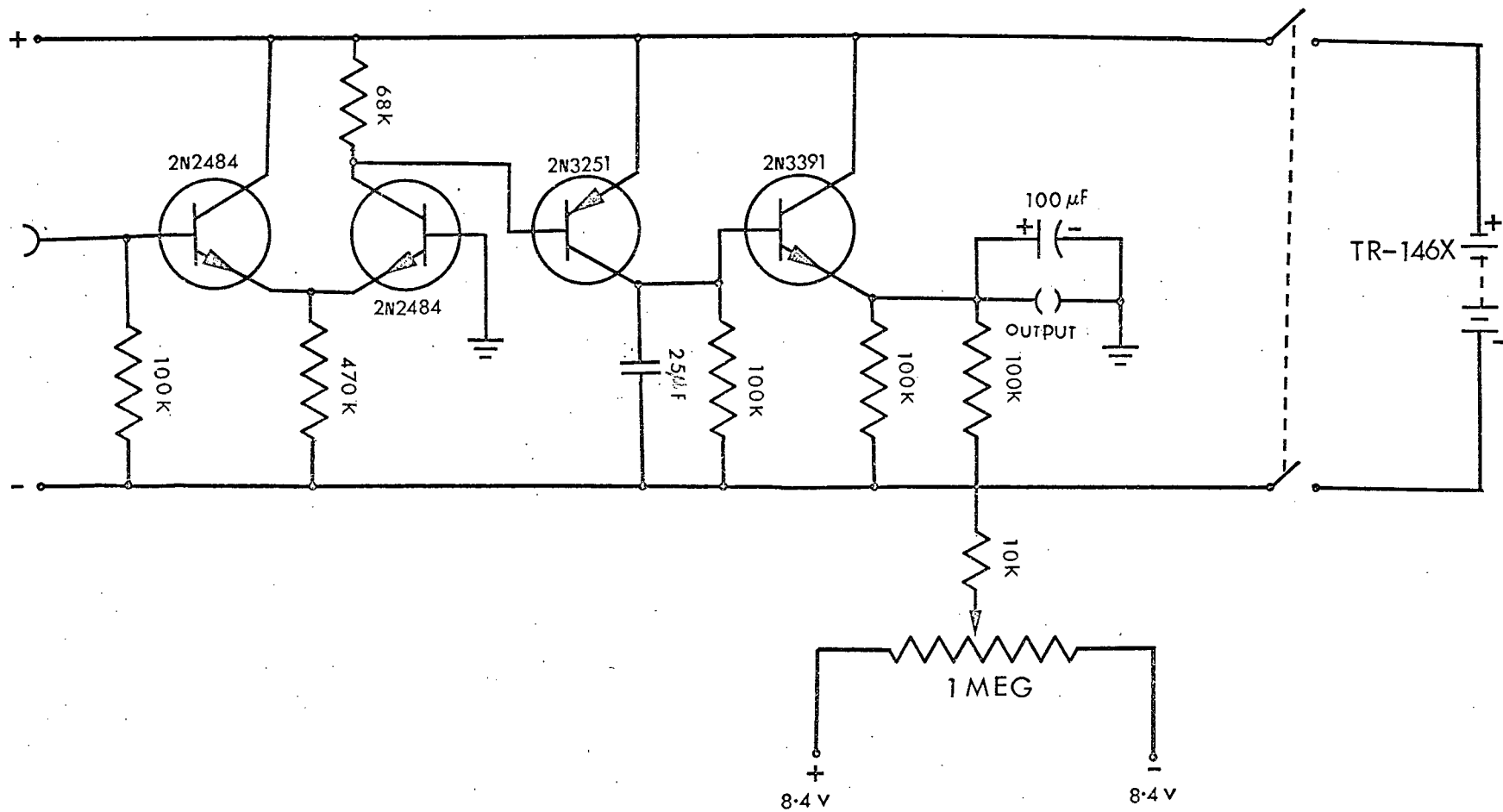


FIGURE 23. Circuit diagram for signal amplifier

metal casing.

#### 4.5.3 Voltage Comparator

The purpose of the comparator was to get a mechanical response at the solenoid corresponding to the maturity ratio measurements made by the probes. The circuit diagram for the voltage comparator is shown in Figure 24. The current flowing through the individual probe is proportional to the reflectance at which the measurements are being made by that probe. The signal voltage  $E_R$  obtained from the 640 nm measuring probe (red colour region of the spectrum) was read on a digital voltmeter. This voltage was reduced to one-fifth,  $E_R/5$ , of the original value by a 10-turn potentiometer. The signals from the probe measuring reflectance at 540 nm (green colour region of spectrum),  $E_G$ , was compared with the output signal of a potentiometer by opposing currents from each probe. The resulting signal was fed into a zenor diode which in turn controlled the signal at the solenoid.

#### 4.5.4 The Solenoid

The solenoid was the component used to obtain the mechanical response corresponding to the measured value of maturity ratio. The current flow in the solenoid was controlled by a zenor diode in the comparator. If the measured value of maturity ratio is more than 5 (maturity coefficient), the solenoid would come to 'close' position, but if the measured value of maturity ratio is less than 5 the solenoid would remain in 'open' position.



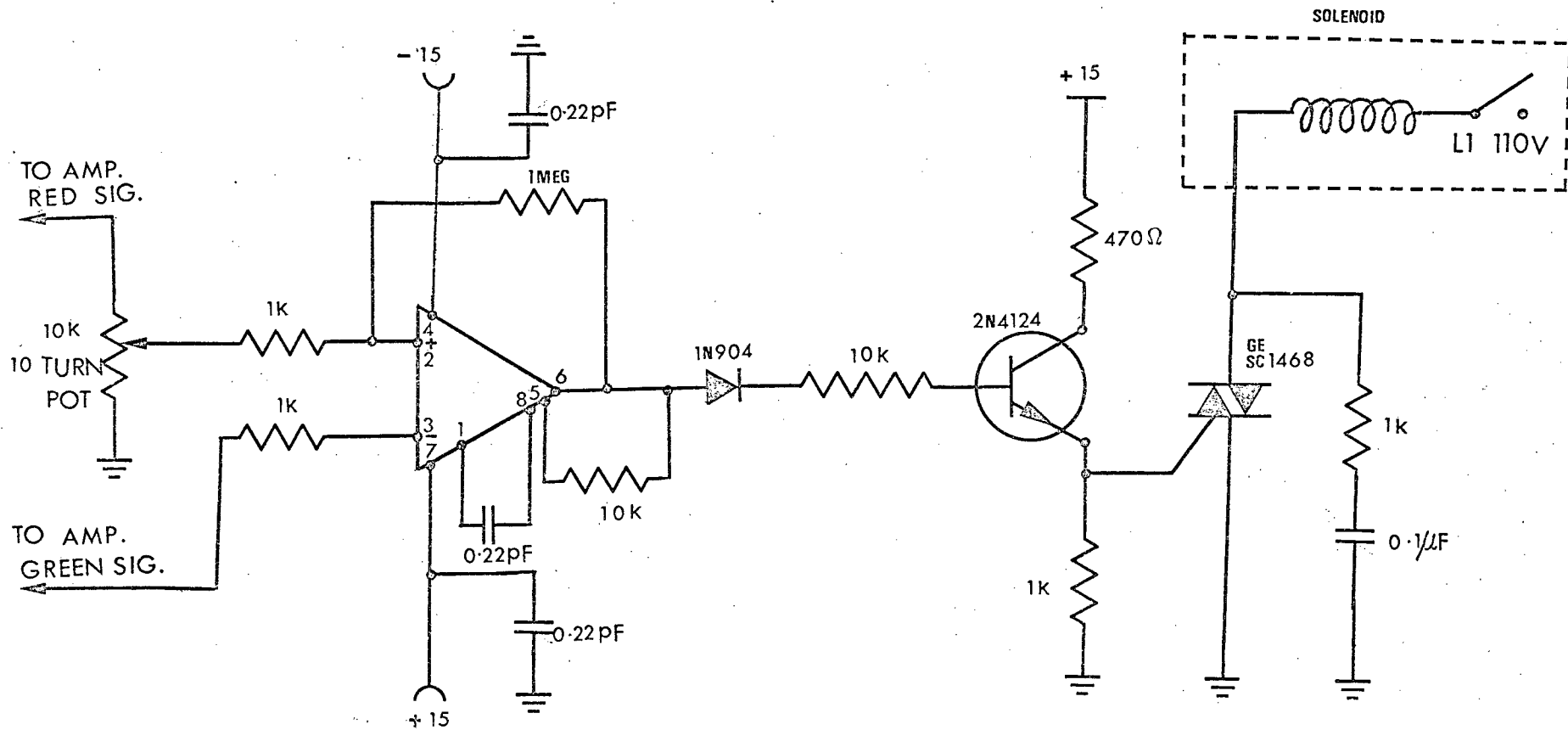


FIGURE 24. Schematic diagram for voltage comparator and solenoid

#### 4.6 The Test Results

An experimental set-up shown in Figures 25 and 26 was used to test the electronic system. A circular disc, painted with black matte paint on its periphery, was rotated by a variable speed motor. Strawberries were placed in 12 equispaced holes along the periphery of the disc. Each berry in the hole was illuminated from the top by a 12V tungsten lamp, as it passed under the viewing field of two photodiodes. The electronic system was zeroed for reflectance from a black surface. As the berries passed under the photodiodes, the reflectance was measured by photodiodes at an angle between  $40^{\circ}$  -  $45^{\circ}$  to the berry surface, arranged in three dimensional symmetry about the strawberry.

##### 4.6.1 Speed of Response

The maximum speed of response was measured at the solenoid by increasing the speed of rotation of the disc until the solenoid would no longer respond to the signal change. The maximum response time obtainable from the components used was 0.166 seconds per strawberry. This time was limited by the solenoid response to the maturity ratio signal (electrical). Although such a response is low for the economical performance of a harvesting system, the speed can be increased by using a faster response solenoid or different transducer.

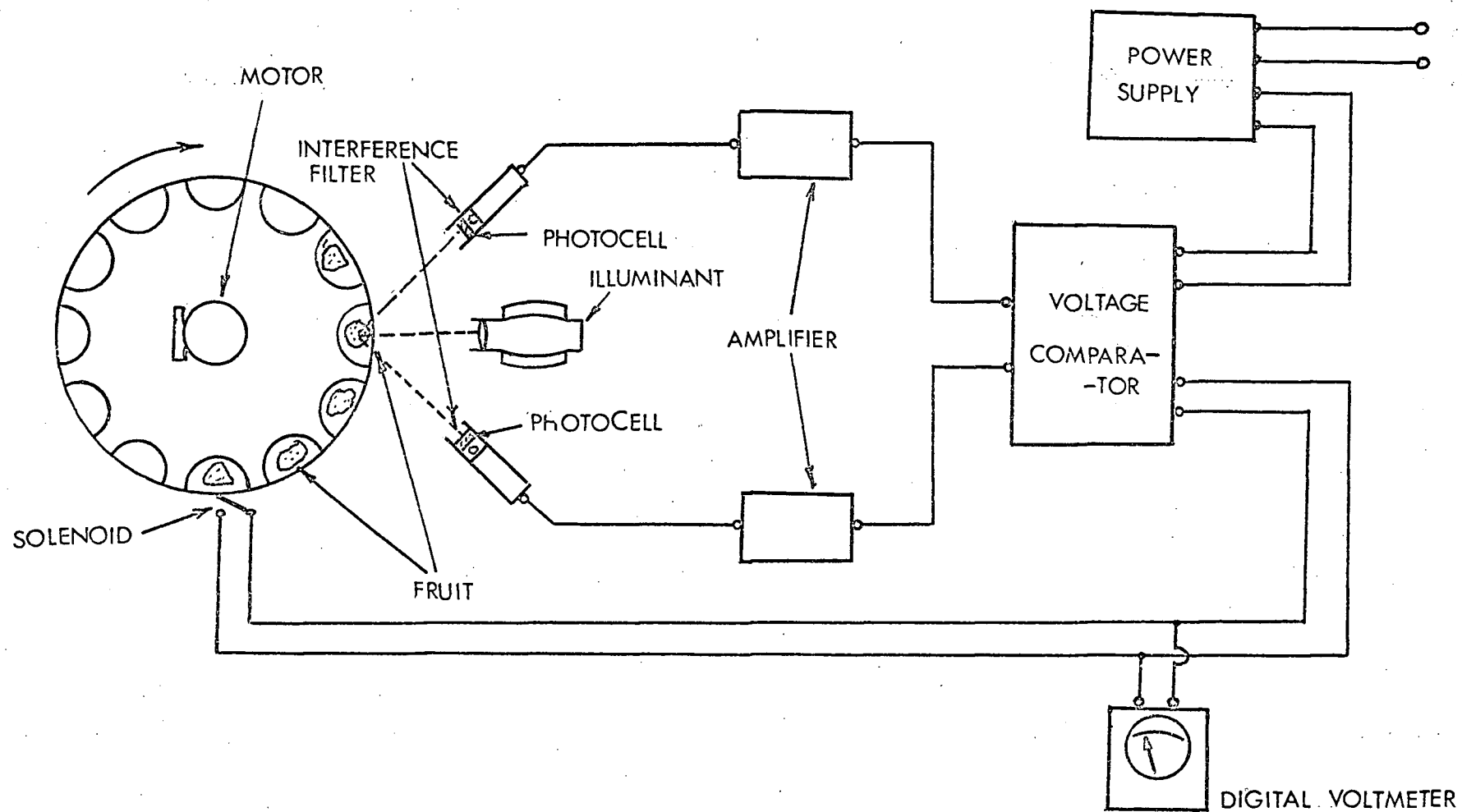


FIGURE 25. Schematic diagram of experimental arrangement for testing colour discriminator equipment.

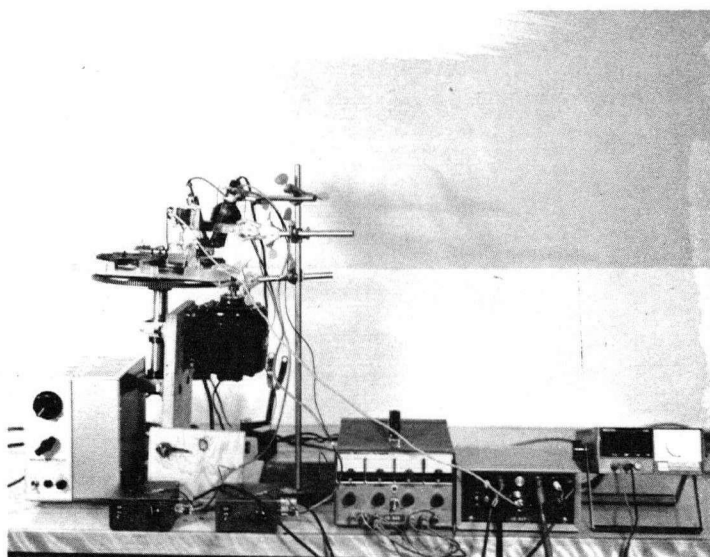


Figure 26. General view of the experimental equipment for testing colour discriminator equipment.

#### 4.6.2 Surface and Illumination Conditions

A number of strawberries freshly picked from the field were tested under the system. The shape and surface and surface conditions have no effect on the performance of the system. The system performed satisfactorily under laboratory conditions and all the samples could be identified by the electrical signal, giving a 100 percent performance. The fluorescent and stray light had no effect on the performance but direct sunlight causes a shift in the value of measured maturity ratio. The signal produced by each fruit was found independent of the surface conditions within the limits of the accuracy of measurements. Although it seems probable that surface conditions do to some extent affect the signal, any change in output is masked by the noise level. An effect of this magnitude is unimportant in commercial operations of this kind. The results of tests conducted in the 1971 season are given in Table V.

TABLE V. Results of the tests conducted on the electronic colour detection system for performance efficiency using Northwest variety of strawberries.

	Total berries	No. of lost berries unripe accepted or ripe rejected	Percent loss
Not ready to pick	207	52	25
Ready to pick	177	25	14.4
Total	384	77	20

#### 4.6.3 The Angle of Illumination and Detection

The angle of viewing had no effect when the measurements were confined between  $10^\circ$  to  $60^\circ$  from the incident illumination on the strawberry surface. But the maximum output signal was obtained when the reflectance was measured at an angle between  $40^\circ$  to  $45^\circ$  from the incident illumination.

#### 4.6.4 The Instrument Stability

The system was tested for its stability by comparing the results performed on the same samples at two different times. A sample of 24 strawberries were tested just after switching on the system and the same samples were tested after several hours. There was no appreciable shift in the signals to justify the effect of "warm up" period. The system is therefore capable of performing accurately without having to wait for long warm up periods.

## CONCLUSIONS

Tests performed on the Northwest variety of strawberries indicate that the following conclusions can be drawn:

1. The mean fruit-retention force of ripe strawberries decreases as the harvest season progresses.
2. The fruit-retention force decreases and the surface redness increases as the berry ripens. Both of these characteristics are a good measure of berry ripeness.
3. The rheological properties of the strawberries obtained from the force-deformation curves are good indicators of fruit quality. The bioyield point had the highest correlation with FRF. These parameters can be effectively used in the design of fruit handling components in the harvesting machine.
4. The relative reflectance at 525 nm (green coloured region of spectrum) decreased and relative reflectance at 640 nm (red coloured region of spectrum) increased as the berry ripens.
5. Maturity ratio is an excellent indicator of berry ripeness and could be used in place of visual colour evaluations. It can effectively be used as a deciding parameter for a selective strawberry harvester. This criteria can also be used for separating ripe and unripe berries or for grading the berries in a processing plant.

## SUGGESTIONS FOR FUTURE WORK

Although the results of the tests conducted on the strawberries give a fairly good knowledge of the fruit behaviour to applied machine forces, further study should be carried out on the strawberries to investigate the effects of such operations as impact loading, bruising due to friction with the conveyors and variation in the physical parameters of various varieties of strawberries.

The performance of the electronic system to differentiate between the ripe and unripe strawberries should be investigated with a prototype of the harvester in actual field conditions. Since the speed of response of the solenoid may be lower for economical operation of the harvesting machine, different transducers should be tried to get optimum response speed.



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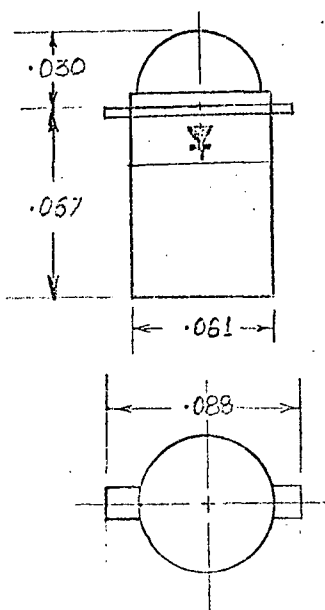
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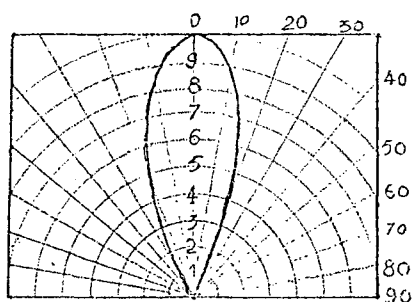
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## APPENDIX A

## PIN PHOTODIODE (SERIES HP 5082-4200) SPECIFICATIONS



Dimension in inches

Relative directional sensitivity  
of pin photodiode

Optical and electrical characteristics at 25°C

Sensitive area	...	$3 \times 10^{-3} \text{ cm}^2$
Diameter	...	0.254 mm.
Speed of response	...	<1 nanosecond.
Series resistance	...	50 $\Omega$ .