PHYSICAL PROPERTIES OF FRUIT RELATED TO CRACKING

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ABSTRACT

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By

Bernard Robert Tennes

Sweet cherry and tomato growers have experienced problems with fruit cracking under various climatic conditions late in the season. Under certain conditions, rupturing of the fruit skin results in the loss of the entire crop. Much research has been done selecting varieties that are crack resistant. However, a few of the more crack susceptible varieties exhibit outstanding fruit quality with high consumer demand. Thus, growers continue to produce these high quality fruit and accept the risk of crop loss.

The objectives of this investigation were the following: (1) to construct a representative model of the fruit related to past and present research; and (2) to contribute to knowledge of the cause and effect relationships related to fruit cracking by (a) making field observations to determine orientation and location of fruit cracks, (b) analyzing osmotic behavior of the fruit,

(c) studying the water potential characteristic of the sweet cherry tree, and (d) making a stress analysis of the skin of the fruits under various conditions.

From field observation and soak tests the orientation and location of fruit cracking were determined. The effect of bruising on fruit cracking was analyzed. For sweet cherries, puncture determinations were made at nine locations to determine possible differences in the skin's resistance to puncture. Tomato skins were analyzed for both tensile and puncture testing. A significant linear relationship between the puncture and tensile testing was established using a 1/8 inch cylindrical probe.

Determinations of water potential for fruit and leaves of sweet cherry trees were made during a 24 hour period and replicated the following year. Significant variations occurred among the fruit, the leaves, and over the 24-hour period of recording.

The relationship between tensile and puncture tests for tomatoes was established. With this prediction, equation values can be established based on the rapid puncture test that will give an indication of the tensile stress in a fruit skin.

Based on the experimental values obtained for skin stress and the possible internal pressure that can be present in a fruit, the fruit skin cannot be the major factor that prevents fruit cracking. Localized cell

dimensional changes at constant cell and skin volume can be as great as 1.38 times the initial dimension.

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A = Area

A_1 = Area of circle

A_2 = Cross-sectional area of a shell

B = A constant $(\frac{4C.V.}{P})$

C_s = Mole fraction of solvent

D = Diameter of a collenchyma cell under high turgor pressure

Dp = Diameter of probe

Fp = Puncture force

M = Molecular weight

N = Number of moles

P = Bursting pressure for the tomato fruit

R = Gas constant

$S.P.$ = Specific gravity

$S.V.$ = Skin volume of a fruit

T = Temperature in degrees Kelvin

Vw = Molar volume of water

ds_1 = Dimension of element in the meridional direction

ds_2 = Dimension of an element in the direction of the parallel circle

e = Partial vapor pressure of water at temperature T

e_o = Saturated vapor pressure of water at temperature T

$\frac{e}{e_o}$ = Relative humidity

f = Subscript for the final value

i = Subscript for the initial value

ln = Natural logarithm

m = Mass of material

r = Radius of curvature of a section

r_1 = Meridional radius of curvature

r_2 = Radius of curvature of the section perpendicular to the meridian

s = Subscript for solute

SS = Soluble solid content, percent

w = Subscript for solvent

α = Statistical probability of a type 1 error

δ = Side dimensions of a collenchyma cell under turgor pressure

μ = Angstroms

π = 3.14159

ψ = Water potential

σ = Tensile stress of fruit skin

τ = Shear stress of fruit skin

INTRODUCTION

1.1 The Problem

1.1.1 Sweet Cherries

Sweet cherry production for 1970 in the United States was about 121,650 tons (Crop Reporting Board, 1971), valued at about $43.55 million. California produced 25,400 tons, Oregon 40,000 tons, Washington 25,800 tons, and Michigan 21,000 tons (17.3 percent of the national crop).

During some seasons, cracking or splitting of sweet cherries occurs and can cause up to 90 percent crop loss. The estimated annual loss from cracking is $1.3 million nationally and about $252 thousand in Michigan. This problem has been investigated by many researchers and to date no practical and reliably effective solution has been found.

In 1970 eighty growers located in three areas of Michigan were surveyed to define this problem further. These growers estimated that every year 0 to 10 percent of their sweet cherries crack. They reported that cracking occurred after rains which were followed by sunshine, when trees had stayed wet 3 to 4 hours or longer. Cracking occurred from the time cherries started to turn color until

maturity. More mature fruit resulted in a much higher percentage of cracking. A heavier fruit set produced a higher incidence of fruit splitting.

1.1.2 Tomatoes

Tomato production in the United States was 14.07 thousand tons during 1970 (Crop Reporting Board, 1971). California is first in tomato production, Ohio is second, and Michigan ranks seventh. Tomato production has shifted from the eastern states to the western area primarily because of the longer growing season, higher yields, and predictable supply of water.

During some years large losses from cracking occur due to unfavorable climatic conditions that prevail late in the harvest season. This loss has amounted to $18.79 million on a national level and $409.2 thousand in Michigan.

Tomatoes crack similarly to cherries. In the past, cracking of tomatoes was not as important economically as it is now. Previously, handpickers simply did not pick cracked fruit. With the utilization of mechanical harvesters, the cracked fruit is picked, mixed with sand and dirt, and transported with other tomatoes to the processing plant. Furthermore, the methodology of mechanical harvesting tends to enlarge and increase the severity of the crack during the harvest operation.

Nationally, the combined losses for cracking of sweet cherries and tomatoes were $20.09 million. The loss to Michigan's growers resulted in $661.2 thousand annually. These losses for sweet cherries and tomatoes represent only the fruit unsuitable at the field level. Loss to the industry because of lower quality and spoilage in transit and storage is difficult to determine.

1.1.3 Possible Solutions

Horticulturalists have attempted to produce tomato and sweet cherry varieties that have a high level of crack resistance, but, to date, the problem reigns.

Climatic conditions in certain geographic areas can be less conducive to cracking than in other areas. Tomatoes are grown in California where the watering of the commercial field is controlled through irrigation. However, unpredictable rainfalls do occur and result in major crop losses.

In an attempt to alleviate sweet cherry cracking, Michigan fruit growers have utilized such practices as the following: (1) an air blast to remove moisture after rains; (2) SADH [(2,2-dimethylhydrazide) succinic acid] applications; (3) applications of lime, sulphur, or salad oils; (4) reduction of tree vigor by decreasing fertilizer and the application of captan (fungicide); and (5) clean cultivation of the orchard surface instead of a sod. All these methods may or may not alleviate sweet cherry cracking,

but each has proved helpful to some degree for a particular grower. As of now, little that is truly significant can be done to alleviate the problem of fruit and vegetable cracking. Partially effective means of controlling fruit rupture include harvest of mature fruit as soon as possible, maintenance of constant, plentiful soil moisture supply, avoidance of heavy irrigation just prior to harvest, a good fertility program, and selection of varieties resistant to cracking.

To alleviate losses from cracking of cherries and tomatoes preventative measures are essential. Prevention can be prescribed only when the phenomena of cracking is better understood. Therefore, determination of the cause and effect relationships is basic.

1.2 Objectives

The ultimate goal of this study was to enhance knowledge of the cause and effect relationships concerning cracking by studying the physical properties of the fruit structure of tomatoes and cherries.

The objectives of this investigation were the following: (1) to construct a representative model of the fruit related to past and present research; and (2) to contribute to knowledge of the cause and effect relationships related to fruit cracking by (a) making field observations to determine orientation and location of fruit cracks, (b) analyzing osmotic behavior of the fruit,

(c) studying the water potential characteristic of the sweet cherry tree, and (d) making a stress analysis of the skin of the fruit under various conditions.

LITERATURE REVIEW

2.1 Sweet Cherry Cracking

One of the early researchers, Verner (1937), advocated cultural and handling practices to help reduce the heavy losses in cherry fruit cracking. Verner's plan was to systematically harvest the trees in the order in which the fruit ripened. Contemporary fruit pickers refuse to harvest orchards having a light crop during normal years. Thus, spot picking of cherries is not feasible. Furthermore, with the prevalence of mechanical harvesting, selective picking is not economical.

Burtner (1942) and Webb (1947) suggested that growers shake the water from the trees immediately following a rain to reduce the length of time that water surrounds the fruit. From the 1970 survey mentioned, some growers use speed sprayers and helicopters to remove water from the fruit and leaves. There was general consensus that some benefit is obtained.

During the 1942 Oregon season, Burtner (1942) reported that an application of borax to the soil at the rate of thirty pounds to the acre reduced cherry cracking to a negligible amount even during a rainy period near harvest time. A similar effect was observed in a sweet cherry tree row adjacent to an alfalfa field that had an

application of boron. Boron was believed to give elasticity to the plant cell membranes.

Verner and Blodgett (1931) reported that excess soil moisture and faulty irrigation practices have no influence on fruit cracking. Cracking was observed during periods of rain and believed to be caused by direct absorption of the moisture through the skin of the fruit. By using covers to exclude rain from tree branches, they found that cracking was prevented on ripe fruit while severe cracking occurred on the exposed parts of the same tree. Levin, et al. (1959) reported that with fruit soaked in water, the higher the soluble solids, the water is absorbed more quickly into the fruit and extensive cracking will occur. The rate of increase in fruit weight was about 1.8 times greater at 85°F than at 40°F. Levin, et al. (1959) stated that when the sun comes out after a heavy rain there is more cracking in the humid environment. The modulus of elasticity was found to increase as the moisture content decreased. At higher moisture contents the longitudinal section has a higher modulus of elasticity than the transverse section. At lower moisture content the reverse relationship is true.

Wann (1949) found that three factors contribute to fruit cracking: (1) variety; (2) stage of maturity; and (3) the length of rainy periods and local climatic

conditions. Variety differences influence mainly the skin's permeability, skin modulus of elasticity, and soluble solids content at maturity. The water supply can only be controlled in certain arid regions where irrigation is used as the primary moisture supply.

In early experiments, Wann (1949) found cracking to occur primarily because of absorption of water through the fruit skin. Thus, tests were designed to reduce the rate of absorption through the skin by control of external moisture. Various calcium solutions were sprayed on sweet cherry foliage by Verner (1938); these reduced remarkably the susceptibility of fruit to cracking. Because of plant residue and foliage burn, calcium sprays have not been used on commercial trials. Oil sprays have been tried, but have not been successful because of the off flavor the oils reportedly give the fruit. Copper sulfate was reported by Verner (1938) to have good success when applied at 0.1 to 0.25 percent in conjunction with the cherry fruit fly spray. Copper was believed to have a toughening effect on the fruit skin.

2.2 Tomato Cracking

Tomato cracking usually is in the form of a concentric and radial cracks in the skin at the stem end of the fruit. These cracks vary in depth and seem to develop regardless of rainfall as reported by Frazier and Bowers

(1947). When new cracks develop, they are about 0.2 to 0.5 centimeters in length. As a rule these cracks increase linearly from day to day with the development of new cracks. Frazier and Bowers (1947) found no close agreement between volume increase and cracking indices;[1] cracking was the highest near the pink stage of maturity of the fruit. They concluded that cracking results from pressure of locular contents on the ovary wall which tends to make cracking of the skin a localized phenomenon.

Another type of skin cracking also occurs in fruit that ripens during a period of dry weather. Under such conditions high temperature often causes a sudden splitting of the skin either radially or longitudinally about the fruit.

Soil moisture was not found to be in itself a limiting factor. Frazier and Bower (1947) found the main factors that cause tomato cracking to be temperature, wind, humidity, shading, maturity, foliage, size of root system and nutrient availability, particularly calcium. Severity of cracking was found to vary with the year, the soil, the variety, among vines and among fruit on the same vine.

Horticulturists have explored different varieties to determine any that are possibly resistant to radial and concentric cracking. Armstrong and Thompson (1967) concluded that resistance to cracking is a quantitative

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[1]The linear cracking per fruit was measured in centimeters.

characteristic controlled by several to many additive genetic factors. Dominance plays a minor role. They found higher resistance to cracking can be obtained by imposing heavy selection pressure in advanced generations. Thompson (1965) demonstrated that it is possible to select lines with higher levels of crack resistance than found in either of the resistant parents.

Carolus, et al. (1965) found that cracking, predominately radial, is erratic in its occurrence having no trends consistently associated with tomatoes grown under different ASM (Available Soil Moisture) conditions. Cracking is most pronounced during warm years in the fruit from plants receiving natural rainfall. Carolus, et al. (1965) found that low atmospheric stress or low DPD (Diffusion Pressure Deficit) in the plant promotes vegetative growth and fruit enlargement. As ASM falls, the rate of top growth decreases and the fruit contains increasingly higher concentrations of soluble solids. At low ASM, fruit size and rate of enlargement decrease. Carolus, et al. (1965) found high atmospheric stress is associated with high radiation and temperature which results in a high DPD in the plant. Under these conditions, fruit enlargement is rapid at first, but as the DPD increases rapidly with decreasing ASM, the trend is reversed and water may be withdrawn from the fruit to such

an extent that blossom-end-rot develops. Carolus, et al. (1965) found that the tomato fruit is a very sensitive indicator of plant water stress.

Frazier and Bowers (1947) found that it is not necessary for water to be absorbed through the fruit skin to cause cracking, but the mere decrease in transpiration of water from the plant is sufficient to cause expansion and rupture. He also found that fruit near the base of a fruit cluster cracks in a shorter period of time than fruit located further from the main stem. Frazier also reported that plots heavily irrigated throughout the season have more cracking of fruit than plots left continuously dry. Dry treatment followed by continued heavy irrigation produces significantly more cracked fruit and larger cracking indices than heavy irrigation throughout the growing season.

Freeman and Kretchman (1968) reported that as leaf and soil nitrogen increase, cracking also increases. They also found that as the potassium content of the leaves increases, the incidence of cracking decreases. The precise total nitrogen content at which fruit cracking becomes a serious concern was not determined. However, the amount of nitrogen required for maximum yield of fruit would most likely result in considerable fruit cracking.

2.3 Puncture Studies

Frazier (1934) found that most radial cracks occur in the suture of the fruit. Cracking resistance of the suture by puncture is much less than in the cheek region. He concluded that the tissue beneath the skin must play an important role as well as the skin itself. Microscopic examination reveal a fission beneath the crease of the fruit.

Hood and Webb (1968) made puncture tests on tomato fruit at different stages of maturity, which they classified as mature green, starbreaker, pink and ripe. With a 1/4 inch diameter probe and a cross head speed of 10 centimeters per minute, they found that as the percent of reflectance increases the puncture force increases linearly. Voisey and MacDonald (1964) found that the major resistance of the puncture test occurred when the probe penetrated the skin. They used a puncture probe of 0.062 inches in diameter and a head speed of 0.0455 inches/second for their evaluations. Puncture force was about 1.00 pound plus the weight of the fruit.

Johannessen (1949) found that the stem end has less resistance to puncture than the middle, and the blossom end resistance is greater than the middle. Fruit from different plants and fruits from the same plant were found to vary greatly in their resistance to puncture.

Most all the puncture tests were made to determine if there is a difference in resistance to fruit cracking and the magnitude of puncture value. Some attempt was made to determine the strength of the skin. Voisey (1965) indicated that the skin strength at blossom end is the strongest and the weakest at the stem end creases.

TABLE 2.1.--Physical properties of tomato skin reported by Voisey (1965).

Tomato Fruit Cracking Classification	Bursting Pressure (psi)		Tensile Loading (psi)	Modulus of Elasticity (psi)
	Stem End	Blossom End		
Resistant	31	44	1750	11,700
Moderately Susceptible	28	30	1770	10,940
Susceptible	23	31	1750	12,050
Very Susceptible	22	32	1515	11,280

It was found that very susceptible varieties have the highest proportion of linear load extension curves, indicating that time dependent mechanical properties are a major factor governing cracking resistance. Creep properties of the skin were found to be one of the main factors in cracking. An analogy was made with two balloons, one of polyethylene film (resistant variety) and the other of thin steel (crack-susceptible variety). As also reported by others, Voisey (1965) found the effects of firmness are negligible since the load drops to zero

upon skin rupture. Creep tests for three hours with a tensile load lowered the ultimate strength, which resulted in failure.

2.4 Physical Description and Development of Cherries and Tomatoes

Both sweet cherries and tomatoes have a spherical shape with a complex internal structure. About the spherical shape is a viscoelastic membrane called the skin. Esau (1965) described the cherry as being composed of an exocarp or skin, the fleshy mesocarp, and the stony endocarp (Figure 2.1). The exocarp includes the epidermis and several layers of collenchyma cells. The fleshy mesocarp consists of loosely packed parenchyma cells that increase in size from the periphery toward the interior. In growing, the cells change in shape from ovid (with the largest diameter parallel to the surface of the fruit) to cylindrical (with the longest diameter in the radial direction). Voisey (1965) described skin tensile tests as being a portion of a pressurized diaphram. In his opinion skin strength is one of the important components in resistance to cracking.

According to Tukey (1934), there are three stages of pericarp development. A rapid increase in size follows fertilization (stage I). There is a delayed increase during mid-season in which the stony endocarp enlarges (stage II). A second increase in size occurs from

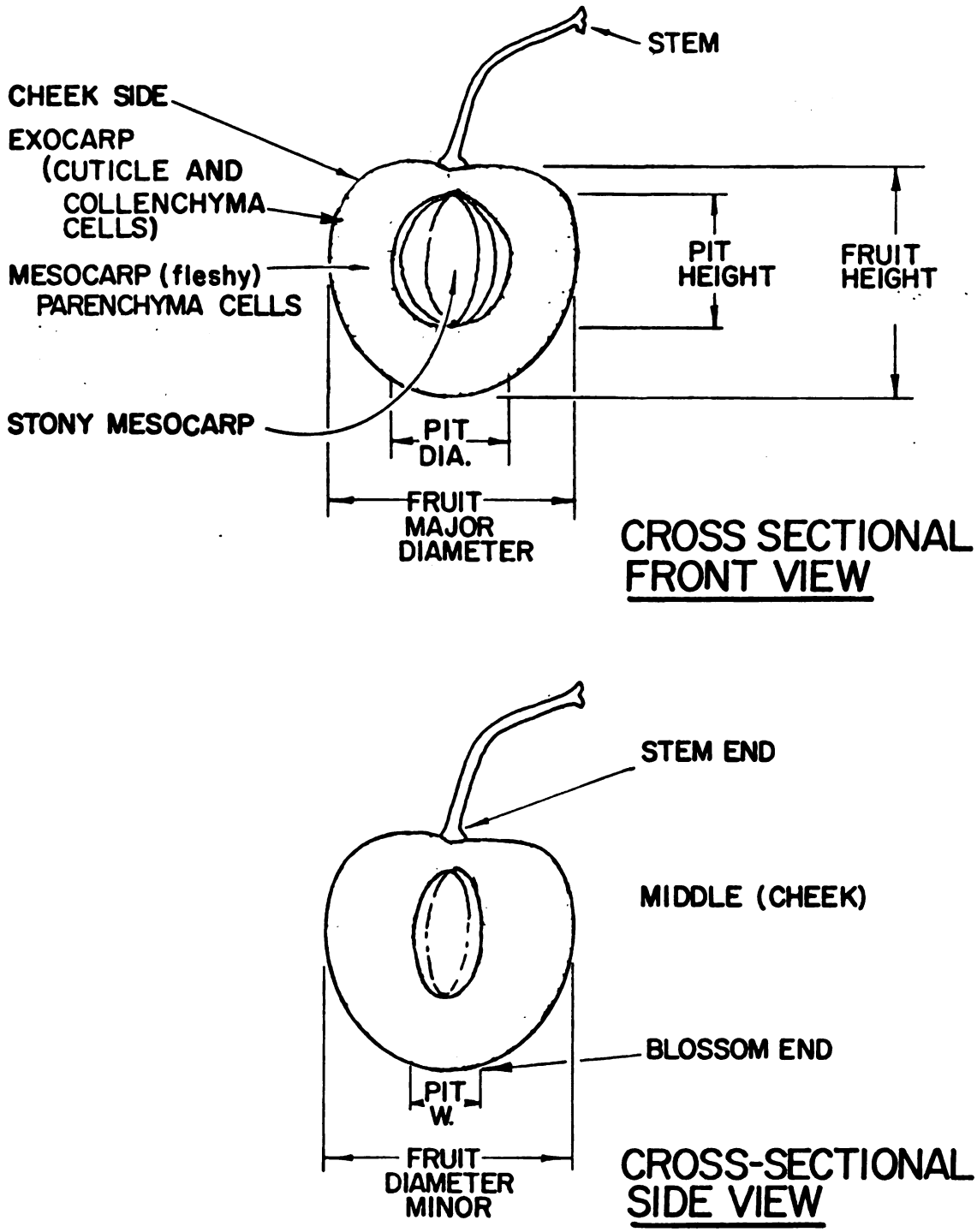


Figure 2.1.--Cross section diagram of sweet cherry fruit (Prunus avium) showing the basic dimensions, structural and cell arrangements.

mid-season until fruit ripening (stage III). The change to the period of delayed growth is abrupt and the duration of this period (stage II) is independent of the rate of growth and the size attained. The increase in size during stage I is primarily because of cell division, whereas the increase during stage III is primarily because of cell enlargement.

Nitsch (1953) stated that a fruit consists of cells with walls, protoplasm, and vacuoles, with the protoplasm constituting the bulk of fruit tissue up to anthesis. As cell division ceases and cell enlargement begins, the relative volume of the protoplasmic fraction tends to decrease, while the cell wall and the vacuole gain in importance. As cell enlargement proceeds, individual cells tend to become spherical and they loosen from each other. Thus, intercellular spaces are formed and lined with relatively thick pectin layers. The cell walls consist of cellulose, hemicellulose, and pectins.

Nitsch (1953) described fruit maturation as follows:

> When maturation commences, the protopectin content of the fruit decreases and pectin is formed. The continuous phase of the young primary wall consists of protopectin in which cellulose strands form only an open lace pattern. As fruit cells enlarge, the volume of the vacuoles increase steadily, being correlated with a large uptake of water. In addition to water, the vacuoles of fruits contain many other compounds such as tannins and pigments.

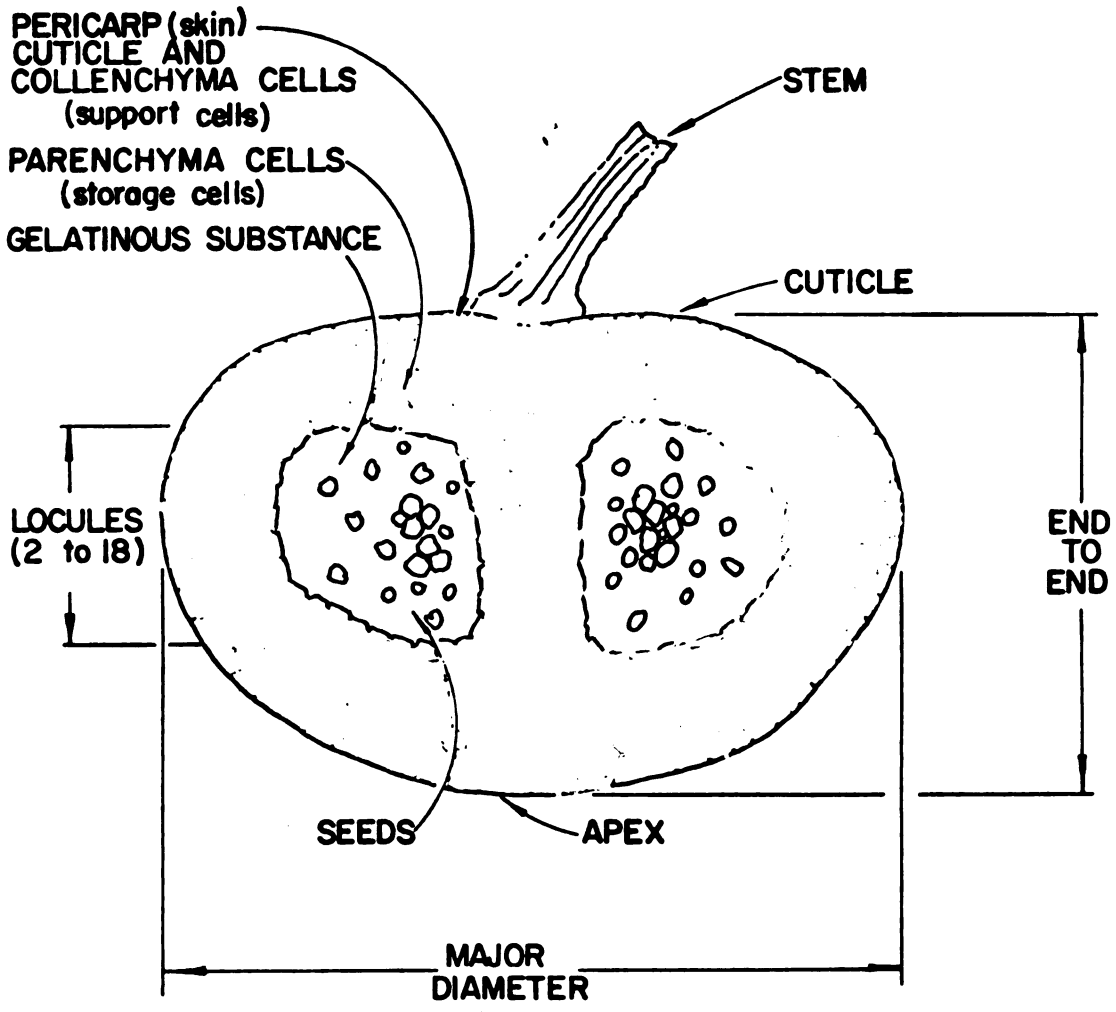
Esau (1965) stated that tannins frequently accumulate in the epidermis and vascular bundles of fruits.

Tomatoes have an exocarp skin consisting of the cuticle and three to four layers of collenchyma cells for support (Figure 2.2). The fleshy mesocarp consists of the cuticle and three or four layers of collenchyma cells for support. The mesocarp is made up of parenchyma cells (storage) and 2 to 18 locules (gelatinous substance and seeds) which make up 15-32 percent of the fruit's weight. The endocarp consists of parenchyma cells with vascular bundles coming from the corky stem and passing down the main part of the fruit and out into the mesocarp. The locules are described as cavities filled with placenta between the ovary walls and cross walls perpendicular to the ovary.

2.5 Stress Analysis of the Cuticle and Attached Layers of Cells

Miles, et al. (1968) analyzed tomatoes as an engineering material by considering contributions of peel, ovary walls, and placenta to the total strength of the fruit. They used a flat-plate compression test to cause failure of the skin and ovary wall. Comparisons were made between tomato fruit and an elastic sphere. Tomatoes were found to have viscoelastic properties.

Their test results indicated failure occurs by skin rupture extending from excessive tensile hoop stresses.



CROSS SECTIONAL SIDE VIEW

Figure 2.2.--Cross section diagram of tomato fruit (Lycopersicon esculentum) from the side showing the basic dimensions, structures, and cell arrangements.

The peel was found to be the single most important component of the tomato related to mechanical strength. The peel acts as a membrane surrounding a mass of more easily deformable material. Removing the peel alters the fruit's mechanical properties more than any other changes made to the fruit. Extracting and injecting fluid changes the fruit's mechanical properties in a predictable fashion. A plot of the log force (flat plate loading) versus log deformation gives a slope of 1 for a natural tomato and 0.95 for an elastic balloon. A tomato behaves similarly to an elastic balloon under flat plate loading. These fruit tend to behave much like a balloon filled with fluid. To analyze this spherical pressure vessel, a description of the skin (shell membrane) and properties is necessary.

2.6 Description of Tomato Cuticle

Bukovac (1970b) stated that the tomato cuticle is between 6 to 10 microns thick. However, he indicated that many surface imperfections of small holes and cracks can be seen in the skin.

In general, the cuticle appears as a thin non-cellular membranous covering with projections extending between the anticlinal walls of epidermal cells. This cutin substance possesses both hydrophilic and hydrophobic properties owing to the presence of polar and non-polar groups.

The composition and the nature of the chemical linkage of the cuticular waxes in the curtin matrix is not fully understood. Bukovac (1970b) described the cuticular wax on the tomato cuticle as a very soft or viscous wax. When viewed on an electronmicrograph, smearing of the epicuticular wax can be done by pressing with a glass slide. Bukovac and Norris (1966) reported the half dissociation value for tomato fruit cuticle to have a pH of approximately 3.2. Thus, there is a possibility that the surface may be negatively charged. It was found that inorganic nutrient ions (Ca^{+2} and SO_4^{-2}) penetrate the isolated tomato fruit cuticle, but to a lesser degree than urea. Yamada, et al. (1965) reported that the rate of penetration of urea through tomato cuticle increases with time. Yamada (1962) hypothesized that the enhanced cuticular permeability with prolonged exposure to urea may be caused by extraction of some cuticular constituent resulting in a cuticle of greater permeability.

Possingham, et al. (1967) discussed the influence of wax levels and wax structure on cuticular transpiration. The waxy components of the cuticle provide the prime barrier to water loss from the plants.

Bukovac (1970a) reported that the coefficient of osymmetry[2] for several compounds penetrating the tomato

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[2]The moisture flux through the skin from the morphological outer to inner surface divided by the moisture flux from morphological inner to outer surface.

fruit cuticle is greater than one favoring penetration toward the inner surface. However, Bukovac (1970a) stated that the data presently available is not sufficiently conclusive to distinguish whether cuticles from different plants behave differently as suggested by reported data or if these differences are related to the experimental technique utilized.

Hall and Jones (1961) showed that brushing the leaf surface disturbs the epicuticular wax and increases the permeability of the cuticle. Levin, et al. (1959) reported that the incidence of sweet cherry cracking is much greater among cherries which have been soaked in water than in unsoaked fruit when the cherries are dropped a fixed distance on to a hard surface. No evaluation was made on the wax structure on the fruit cuticle.

STRESS AND WATER RELATIONSHIPS

3.1 Stress Analysis of Thin Shell

To better understand the stress that contibutes to the ultimate failure and cracking of the fruit skin, stress concepts must be evaluated. Many assumptions must be made regarding the homogeneity of the material inside the fruit and the homogeneity of the external membrane (skin surrounding the internal material). A simple model is assumed to make the initial analysis meaningful and workable. This model consists of a spherical elastic membrane with internal pressure and an opening at the top of the spherical vessel. The membrane (skin) is considered as the main factor responsible for the elasticity of the fruit and impermeable to moisture movement. The internal mass is considered as an incompressible fluid subjected to pressure in excess of atmospheric pressure.

For a membrane vessel with internal pressure, Timoshenko (1948) developed the general equations for a surface of revolution, which is subject to a continuous internal pressure of intensity p. If one assumes that the wall thickness is small compared to the radius of curvature and there are no discontinuities in the meridional curves, stress can be calculated with sufficient accuracy by

neglecting the bending of the wall of the vessel and assuming uniform distribution of the stress throughout the wall thickness.

If one defines the terms for the element on the surface of revolution (Figure 3.1) as the following, equations for the skin stress can be derived. Where;

1 = Tensile stress in the meridional direction (meridional stress),

2 = Tensile stress along the parallel circle (hoop stress),

t = Uniform thickness of membrane,

ds_1 = Dimension of element in meridional direction,

ds_2 = Dimension of the element in the direction of the parallel circle,

r_1 = Meridional radius of curvature,

r_2 = Radius of curvature of the section perpendicular to the meridian.

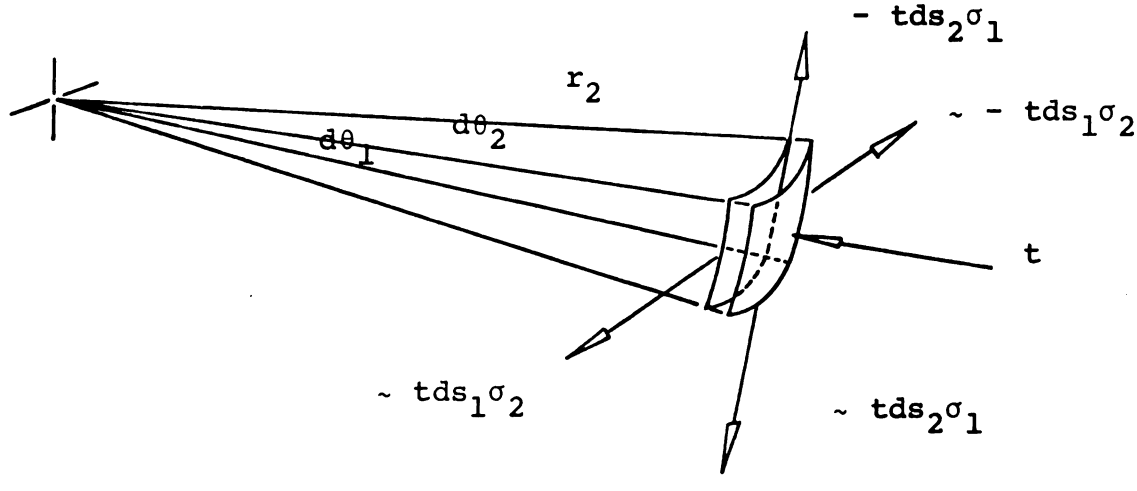


Figure 3.1.--Element on a surface of revolution.

The total forces acting on the sides of the element are $t\sigma_1 ds_2$ and $t\sigma_2 ds_1$ and have a component acting normal to the element equal to;

$$tds_2\sigma_1 d\theta_1 = \frac{t\sigma_2 ds_1 ds_2}{r_1} \tag{1}$$

and

$$tds_1\sigma_2 d\theta = \frac{t\sigma_2 ds_1 ds_2}{r_2}. \tag{2}$$

The sum of these normal components are in equilibrium with internal normal pressure of the vessel element. Thus,

$$\frac{t\sigma_1 ds_1 ds_2}{r_1} + \frac{t\sigma_2 ds_1 ds_2}{r_2} = pds_1 ds_2, \tag{3}$$

or

$$\frac{\sigma_1}{r_1} + \frac{\sigma_2}{r_2} = \frac{p}{t}. \tag{4}$$

From this development of stress related to wall thickness, radius of curvature, and membrane thickness, the spherical vessel can be treated as a special case where

$$r_1 = r_2 = r$$

and

$$\sigma_1 = \sigma_2 = \sigma.$$

Thus, Equation 4 reduces to Equation 5,

$$\sigma = \frac{pr}{2t} \tag{5}$$

From Equation 5, the stress in the skin can be calculated by using the values reported by Bukovac (1970b) for the tomato skin as 6μ minimum and 10μ maximum thickness, the value of p as 30 psi, reported by Voisey (1965) and assuming r = 1.5 inches as an average radius.

For minimum thickness ($6\mu = 2.383 \times 10^{-4}$ inches),

$$\sigma = \frac{pr}{2t},$$

$$\sigma = \frac{30\ (1.5)}{2(2.38 \times 10^{-4})},$$

$$\sigma = 9.4537 \times 10^{4},$$

$$\sigma = 94{,}537 \text{ psi.}$$

For maximum thickness ($10\mu = 3.937 \times 10^{-4}$ inches),

$$\sigma = 57{,}150 \text{ psi.}$$

From this calculation of the skin stress under internal pressure loading, the fruit skin would have to withstand stress up to approximately 47 times greater than the known stress carrying capacity of 1515 psi reported by Voisey (1965).

3.2 Volumetric Analysis of Cell Element

Collenchyma cells are angular in shape as observed under a microscope (Figure 3.2). Upon the addition of water to the cells, the cells take on a round or spherical

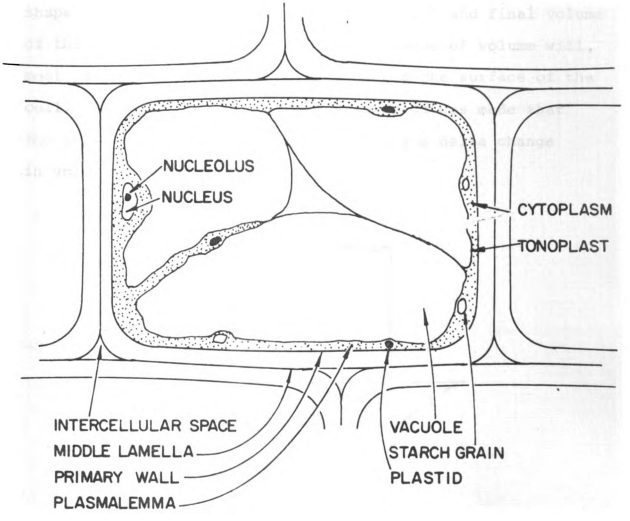


Figure 3.2.--Diagram of a mature collenchyma cell based on a description by Esau (1965), demonstrating the relatively thick walls and the characteristic angular shape.

shape. Assuming the cell is initially a cube and as the cells absorb moisture they change from cubical to spherical shape, the relationship between the initial and final volume of the cell can be determined. This change of volume will most likely occur without an increase in the surface of the cell. For this development the assumption was made that the surface area remains constant during a delta change in volume of the cell.

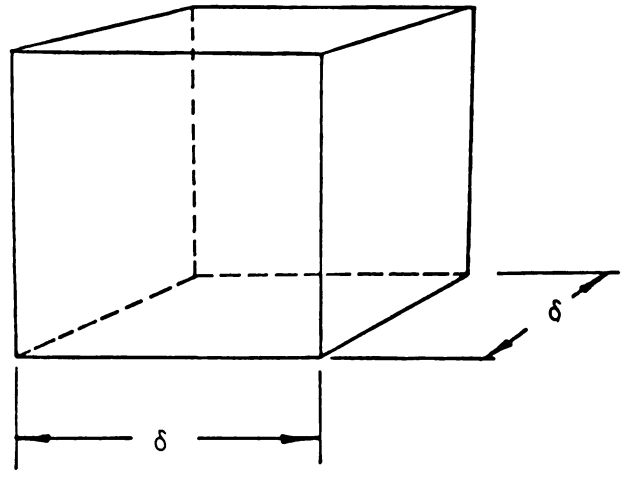


Figure 3.3.--Model of collenchyma cell under low turgor pressure.

where; volume of cell = δ^3, (6)

surface area of cell = 6 δ^2. (7)

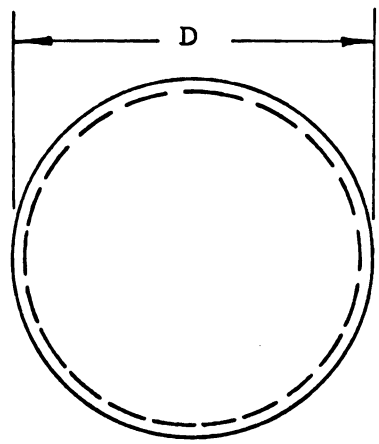


Figure 3.4.--Model of collenchyma cell under high turgor pressure.

where; volume of sphere = $\frac{\pi}{6} D^3$, (8)

surface area of sphere = πD^2.

If one equates the surface area of the spherical cell to the same value of surface area of the cubical cell (Equation 9) which will maintain the minimum free energy of the cell system, one obtains Equation 10.

where; $6\ \delta^2 = \Pi\ D^2$, (9)

$$D^2 = \frac{6\ \delta^2}{\Pi},$$

$$D = \sqrt{\frac{6}{\Pi}}\ \delta,$$

or

$$D = 1.38\ \delta. \tag{10}$$

D equals the diameter of the sphere that has the same surface area as the cube.

Therefore, the increase in the dimension of each unit cell can be 1.38 times the dimensions of the cube if the surface area of the cell is not to be increased.

The ratio of $\frac{D}{\delta}$ was found to equal 1.38. With this ratio in mind, the ratio of the volume of a cube to the volume of a sphere was calculated in Equation 11.

where;

$$\frac{\text{Volume of sphere}}{\text{Volume of cube}} = \frac{\frac{\Pi\ D^3}{6}}{\delta^3}, \tag{11}$$

$$\text{Volume of sphere} = \frac{\Pi}{6}\ (1.38)^3\ \text{Volume of cube},$$

$$\text{Volume of sphere} = 1.38\ \text{Volume of cube}.$$

Thus, the change in volume of the cube to the sphere can be represented directly by the relationship $D = 1.38\ \delta$.

3.3 Fruit Model

How do the cells of a fruit behave? Falk, et al. (1958) measured potato tuber parenchyma and found that Young's modulus was linearly dependent on the turgor pressure of these cells. Thus, they assumed these cells to be liquid-filled with thin elastic membranes. Nilsson,

et al. (1958) constructed a model of the parenchyma cells assuming that each was filled with an incompressible fluid contained by a thin elastic membrane (Figure 3.5). The cell membrane is assumed to be impermeable (for short periods of time) to the internal fluid which exerts pressure out on the cell wall. Thus, the model for a cherry and a tomato fruit becomes an arrangement of cubical or spherical shape cells depending on the turgidity of the cells (Figure 3.6).

3.4 Stress as a Function of Fruit Diameter

The relationship between stress and fruit diameter for a thin wall vessel concept is given in Equation 12;

$$P = \frac{4\ t\sigma}{D}\ , \tag{12}$$

where; P = pressure inside vessel,

t = thickness of vessel wall,

σ = tensile stress in wall,

D = vessel diameter.

If one transposes and solves for D, one obtains Equation 13;

$$D = \frac{4\ t\sigma}{P}\ . \tag{13}$$

If one assumes that the fruit skin maintains a constant cell volume after the fruit has grown to ¼ of its mature size, Equation 14 gives the skin volume;

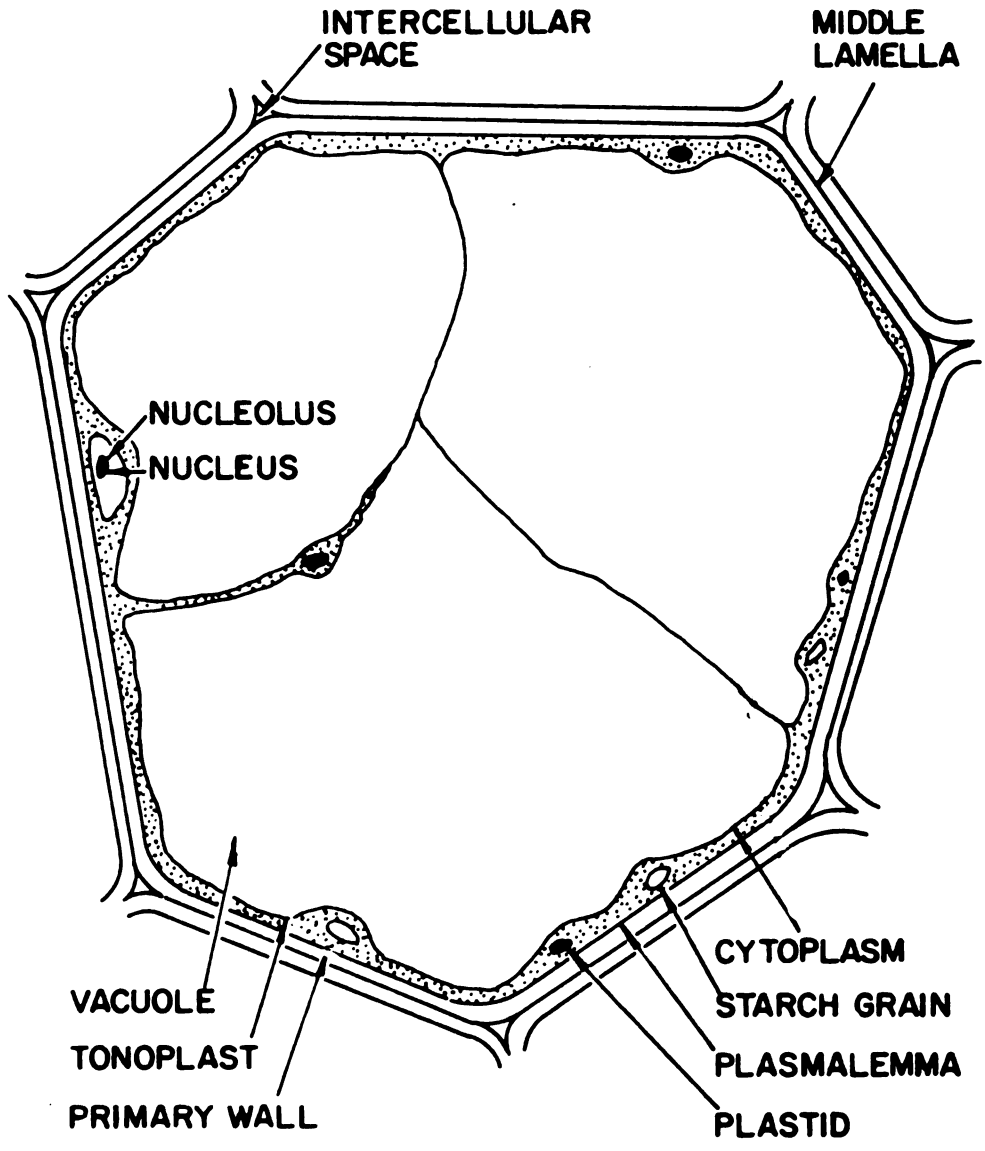
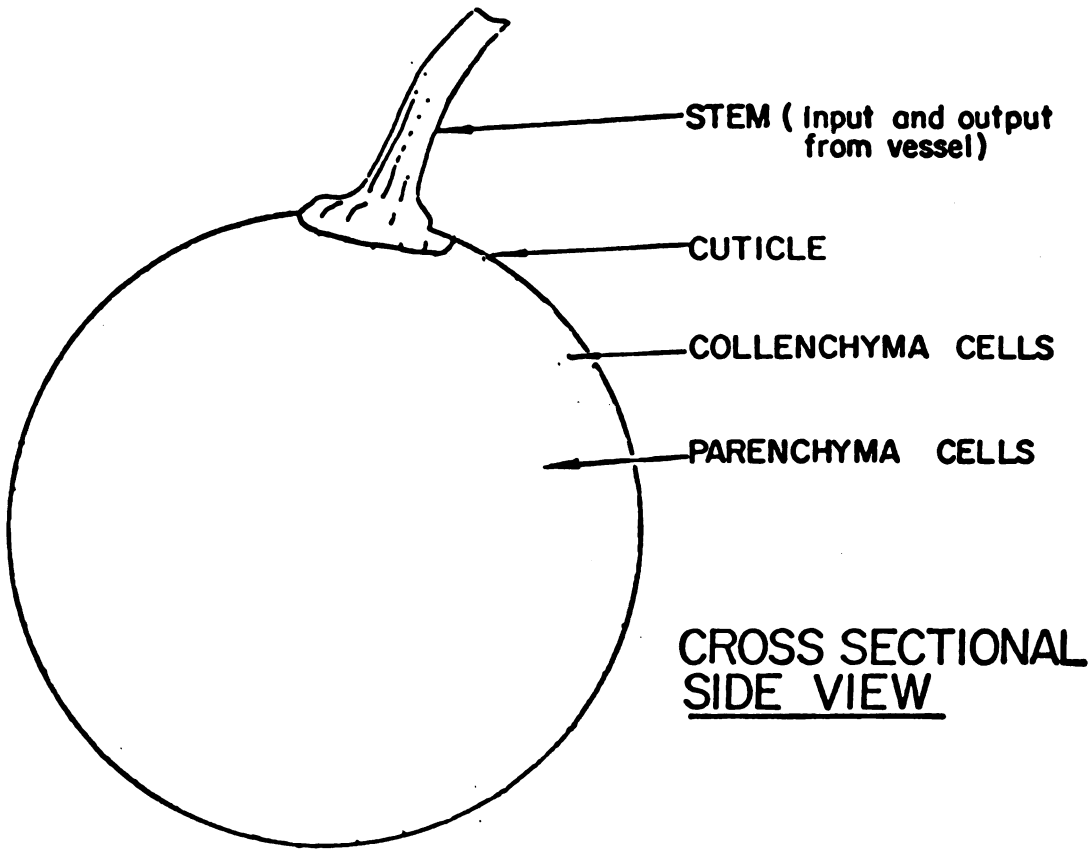


Figure 3.5.--Diagram of a mature parenchyma cell by Ray (1963).



CUTICLE- WAXY SURFACE, IMPERMEABLE TO GAS AND LIQUID. BEHAVES LIKE A VISCOELASTIC MEMBRANE

PARENCHYMA CELLS - SPHERICAL IN SHAPE WITH AN ELASTIC MEMBRANE FILLED WITH AN INCOMPRESSIBLE FLUID AT A PRESSURE (P_2) IN EXCESS OF ATMOSPHERIC PRESSURE. FUNCTION OF CELLS IS STORAGE.

COLLENCHYMA CELLS - ANGULAR TO CUBICAL IN SHAPE WITH THICKER PRIMARY WALL FILLED WITH AN INCOMPRESSIBLE FLUID AT A PRESSURE (P_1) IN EXCESS OF ATMOSPHERIC PRESSURE. FUNCTION OF CELL IS SUPPORT.

Figure 3.6.--A theoretical model for cherry and tomato fruit vessel.

$$SV \text{ (skin volume)} = (\Pi D^2 (t)) = \text{constant.} \quad (14)$$

If one substitutes into Equation 13 for the value t from Equation 14, one obtains Equation 15;

$$D = \frac{4SV\sigma}{\Pi D^2 P},$$

$$D^3 = \frac{4SV\delta}{\Pi P}, \quad (15)$$

where 4, SV, Π and P collectively are assumed to be a constant "B". Thus,

$$D^3 = B\ \sigma. \quad (16)$$

As can be seen in Equation 16, the stress in a fruit skin increases as the cube of the fruit diameter, assuming that the skin maintains a constant volume during the fruit enlargement, and the internal fruit pressure remains constant. Under these assumptions, there is little hope in growing a fruit variety that will have a skin with stress characteristics that will not fail under a sudden fruit enlargement period. Emphasis should be placed on the selection of fruit varieties that have a highly elastic outer fruit protective surface and skin. Thus, substantial fruit enlargement can occur without excessive stress buildup within the skin area. In addition to high elasticity, the skin should have a good moisture barrier to avoid excessive moisture flow occurring from the outside environment to the internal fruit cell complex.

3.5 Major Components of the Fruit Water Potential Gradients

The loss of water by plant tissue results in a water potential gradient being established within the plant system. If the resistance is uniform, the rate the water moves is directly proportional to the affinity (difference or gradient of water potential). This water loss is largely a result of transpiration from the plant during the day. The uptake of this lost water may occur through several different mechanisms within the plant and its environment.

Taylor (1963) constructed a diagram (Figure 3.7) which shows the relative activity of water (ratio of water potential in the system to that of pure free water). Figure 3.7 illustrates the following:

a. The resistance to water flow is less at the root-soil interface. The water potential at the root-soil interface is nearly the same as that within the xylem or leaf tissue. This resistance is accompanied by a moderately high energy barrier that results from the interaction of root colloids with the water.

b. The resistance to moisture flow across the leaf-air interface is normally much higher that in all other portions of the plant environment. This interface has a high energy barrier caused by the vaporization that occurs.

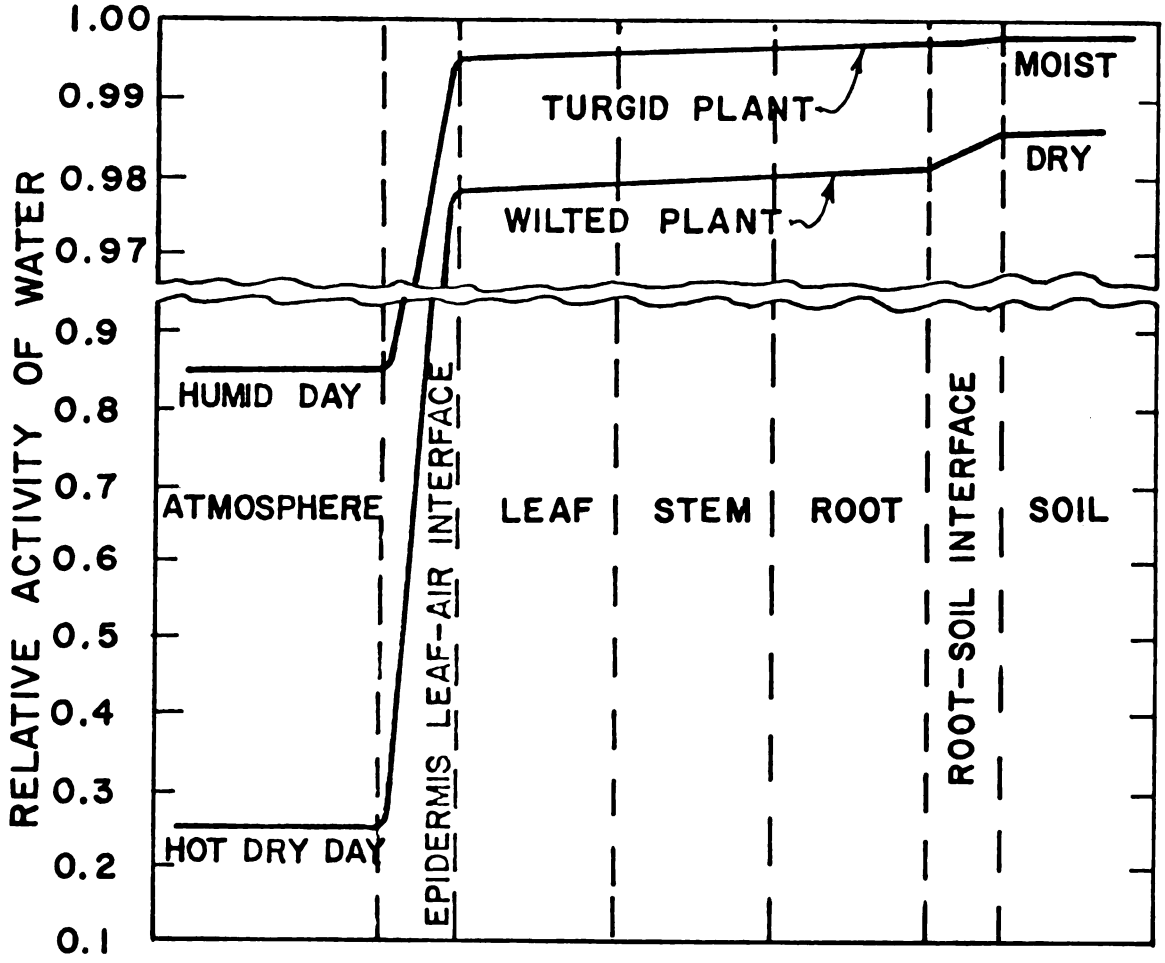


Figure 3.7.--Diagram of the relative activity of water (ratio of water potential in the system to that of pure free water) along the path of supply from soil to air. The potential drop is most rapid where the resistance is highest, at the leaf-air interface. Taylor (1963).

c. The resistance to water flow in the xylem is negligible when the stem is attached to the roots and/or leaves. Flow in the xylem invokes the same molecular mechanism as viscous flow or diffusion.

There are changes in the plant structure that influence the rate of water loss by controlling the resistance to flow at the point where resistance is highest, the plant-air interface. Changes in temperature will affect the water lost from the plant. One of the components of the water potential within the plant system is due to the soluble solid content. By assuming that the resistance to water flow in the xylem is negligible when the stem is attached to the roots and/or leaves, it is implied that resistance to water flow to and from the attached fruit is also negligible.

Under conditions of isothermal equilibrium Kramer (1969) stated the water potential equations to model the free energy status of water in a plant cell as follows;

$$\psi \text{ cell} = \psi_s + \psi_p + \psi_m,$$

where; ψ cell = water potential within the fruit cell,

ψ_s = osmotic potential of the solutes,

ψ_p = internal pressure of the cell,

ψ_m = matrix potential of the cell constitutents

Kramer (1969) further stated that under most conditions the value of ψ_m is very small compared to values of ψ_s and ψ_p and can be considered negligible. Depending on the water stress of the plant and on climatic conditions, the water potential relationships for a plant system could be as follows;

$$\psi air < \psi leaf < \psi xylem < \psi fruit,$$

during periods of high water stress or low relative humidity of the air (water potential values are negative) or conversely,

$$\psi air > \psi leaf > \psi xylem > \psi fruit,$$

during period of low water stress or high humidity of the air. Depending on climatic conditions and/or soluble solid content of the fruit, the fluctuations in ψ_p, the pressure component of the fruit cell water potential will vary since,

$$\psi fruit = \psi_s + \psi_p,$$

where;
$$\psi_s = \frac{RT}{\bar{V}_w} \ln N_w, \tag{17}$$

ψ_p = p = internal pressure of the cell

$$N_w = \frac{1}{1 + \frac{M_w}{m_w} \frac{(m_s)}{(M_s)}} \tag{18}$$

R = gas constant, $82.052 \frac{(cm^3)(atm)}{K^o(mole)}$,

M = molecular weight,

m = mass,

T = temperature in degrees Kelvin,

$\bar{V}_w$ = molar volume of water =

$$18 \frac{(grams)(cm^3)}{(mole)(l)(gram)},$$

$$Nw = \frac{n_w}{n_w + n_s}, \text{ mole fraction of solvent,} \qquad (19)$$

n = number of moles $(\frac{m}{M})$.

Subscripts;

s = solute,

w = solvent.

If one calculates the value of ψ_s for a fruit having a soluble solid content of 16 percent at 20^o centigrade, a value of approximately -26 atmospheres is obtained. Kramer (1969) lists values of leaf water potential for dogwood trees and tomatoes ranging from zero to -40 atmospheres. If one assumes negligible resistance to water flow between the leaf and fruit these values are representative of the fruit cell water potential and one can calculate the value of internal pressure in a fruit cell as;

ψfruit = -20 atm,

ψ_s = -26 atm,

ψ_p = 6 atm.

Under normal climatic conditions (high water stress or low humidity of the air), the internal pressure of the fruit or fruit cells would be approximately 6 atm pressure. If one assumes that a period of prolong precipitation (low water stress or high humidity of the air) can result in a water potential value of approximately -8 atmospheres for the plant and the fruit and, for a short period of time, the value for the osmotic component remains constant at -26 atmospheres, then the value of the pressure component of the water potential must change to maintain equilibrium giving;

$$\psi \text{fruit} = -8 \text{ atm},$$
$$\psi_s = -26 \text{ atm},$$
$$\psi_p = 18 \text{ atm}.$$

Thus during a prolonged period of rain, the internal pressure component of the fruit cell water potential might increase up to 3 times. Therefore, climatic conditions may cause considerable fluctuation in the pressure component of the fruit water potential.

Levin, et al. (1969) reported that values of soluble solid content of the fruit can change from 16 to 18 percent in 4 days. If one assumes the fruit water potential to remain constant at -20 atmospheres for favorable climatic conditions and further assumes that the weather remains stable producing an accelerated ripening

process, the value of the pressure component of the water potential must change to maintain equilibrium giving;

$$\psi fruit = -20 \text{ atm},$$

$$\psi_s = -29 \text{ atm},$$

$$\psi_p = 9 \text{ atm}.$$

During periods of rapid growth and increasing soluble solid content of the fruit, the internal pressure component of the fruit cell water potential might increase up to 50 percent in a 4 day period under these assumptions. Such fluctuations in water potentials could result in fruit cell rupture and/or cracking of the fruit skin.

3.6 Water Potential Gradient Caused by Humidity Fluctuations

The water potential changes in the plant canopy with changes in the relative humidity can be calculated. From Kramer (1969), the equation for calculating the water potential in the atmosphere is given as Equation 20:

$$\Psi_{air} = \frac{RT}{\bar{V}_w} \ln \frac{e}{e_o}, \text{ (atmospheres)}, \qquad (20)$$

where; R, T, and $\bar{V}_w$ are given in Equation 17, and,

e = partial vapor pressure of water at temperature T,

e_o = saturated vapor pressure of water at temperature T,

$\frac{e}{e_o}$ = relative humidity.

From a plot of negative water potential versus the relative humidity (Figure 3.8), temperature has an effect on the water potential as the humidity drops from 100 to a lower value. At a relative humidity of 97 percent, which can occur during rainfall, the difference in water potential from 10 to 40 degrees centigrade temperature results in about 4.166 atmospheres negative water potential difference.

3.7 Fruit Water Potential

Soluble solid content of sweet cherries varies from about 14 to 20 percent, Levin, et al. (1959), which is the range of most interest to Michigan cherry growers.

Molecular weight of fruit sugars has been used by Bedford (1972) as having a molecular weight of 180 grams per mole. Percent soluble solid content has commonly been used by the fruit industry and can be calculated by Equation 21;

$$\text{Percent soluble solids} = SS = \frac{\text{mass of sugar x 100\%}}{\text{mass of sugar + mass of solvent}} . \tag{21}$$

The osmotic potential is listed as in Equation 17;

$$\psi = \frac{RT}{Vw} \quad \ln Nw, \text{ (atmospheres)}, \tag{22}$$

If one substitutes the values for molecular weight quoted above into Equation 18 for M_w and M_s;

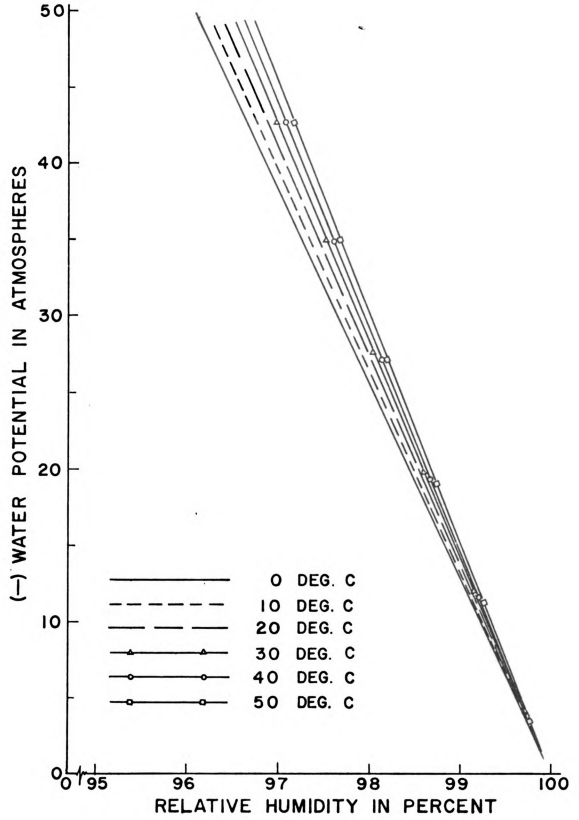


Figure 3.8.--The relationship of water potential (Ψ) to relative humidity ($\frac{e}{e^o}$) at different temperatures.

where; $\frac{m_w}{m_s} = \frac{18}{180} \quad \frac{\text{gram/mole}}{\text{gram/mole}} = 0.1,$

$$N_w = \frac{1}{1 + 0.1(\frac{m_s}{m_w})}$$

From Equation 21, one obtains the relationship between SS and mass of the fruit as;

$$SS = \frac{m_s}{m_s + m_w} .$$

If one solves for m_w, one finds;

$$m_w = m_s \frac{(1 - SS)}{SS} \quad \text{or} \quad \frac{m_s}{m_w} = \frac{SS}{1 - SS} .$$

If one substitutes the value of m_w into Equation 18, one obtains Equation 23;

$$N_w = \frac{1}{1 + 0.1(\frac{SS}{1 - SS})} , \tag{23}$$

$$N_w = \frac{1 - SS}{1 - 0.9\ (SS)} .$$

If one plots the water potential versus the soluble solid content for a molecular weight of 180 and 200, the result illustrates that at a high soluble solid content (18), the effects of molecular weight of 180 versus 200 on the osmotic component of the water potential is approximately 2 atmospheres (Figures 3.9 and 3.10).

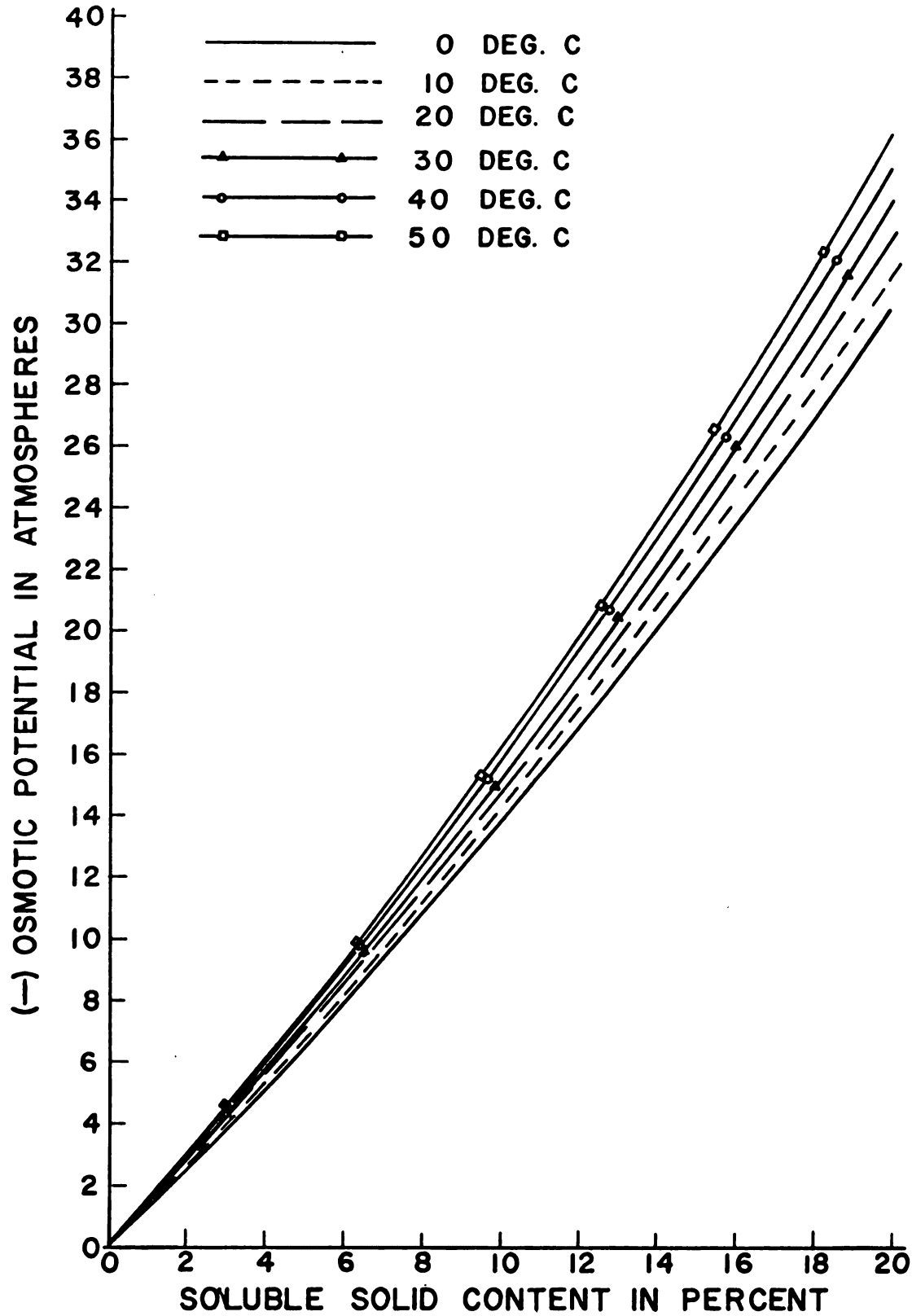


Figure 3.9.--The relationship of soluble solid content to osmotic potential (molecular weight 180) at different temperatures.

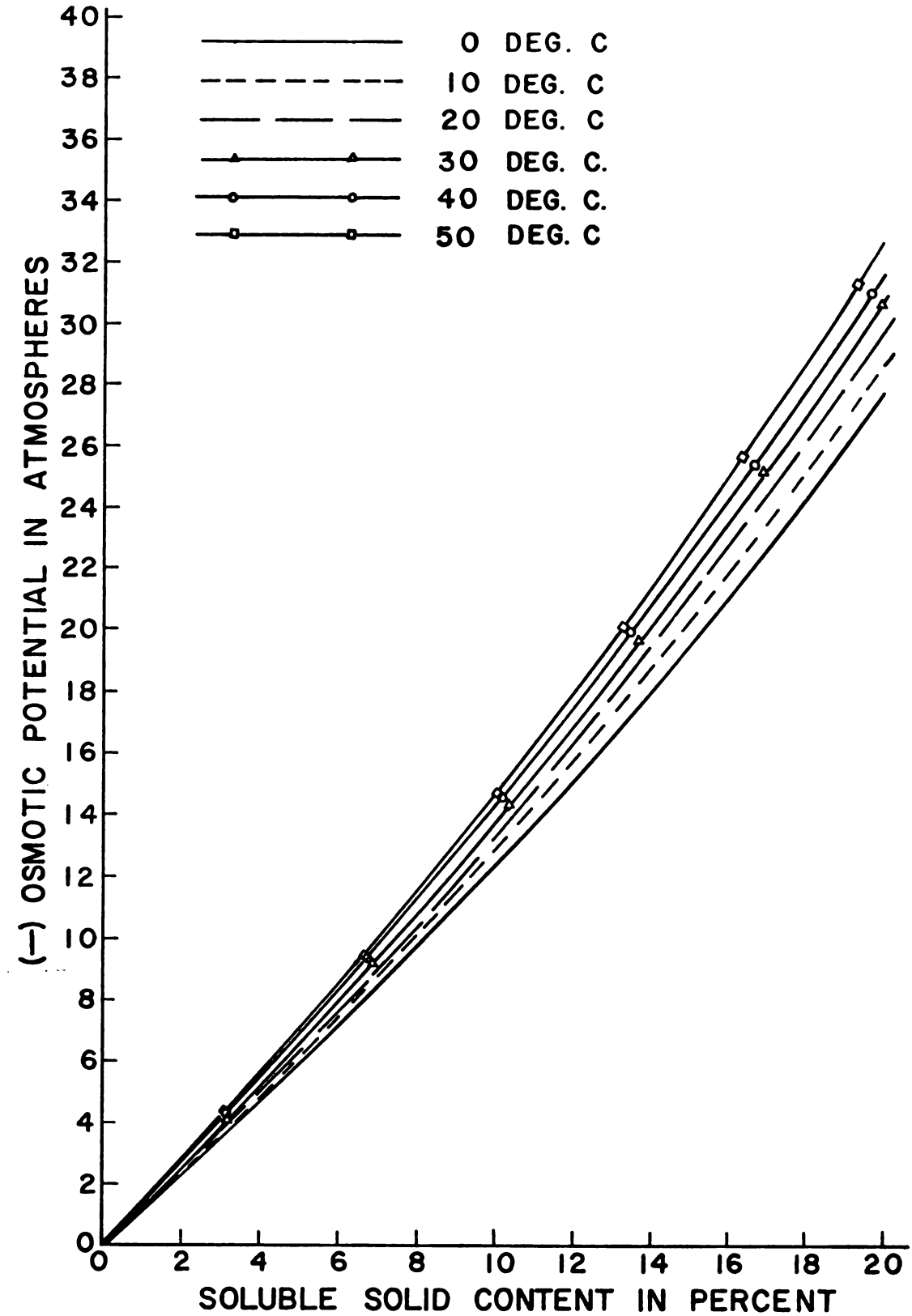


Figure 3.10.--The relationship of soluble solid content to osmotic potential (molecular weight 200) at different temperatures.

The osmotic potential for fruit within the 14 to 20 percent soluble solid content range can go from approximately 22 to 34 atmospheres, or a difference of 11.80 atmospheres at a temperature of 30^{o} centigrade and a molecular weight of 180. At a higher sugar content in the fruit, the temperature effect on the osmotic water potential is very significant, i.e., at 20 percent soluble solid content, the water potential difference between 10 to 40 degrees centigrade is about 3.5 atmospheres. If all other parameters are held constant, the change in temperature from night to day can cause a moisture movement from the fruit environment to the fruit with a potential gradient of 3.5 atm per distance to an available water source. A change of molecular weight from 180 to 200 grams per mole effectively lowers the slope of the lines for osmotic potential at the various temperatures (Figures 3.9 and 3.10).

As the relative humidity drops from 100 to 96, the water potential of the air rises from 0 to about 50 atmospheres (Figure 3.8).

If one plots the relative humidity equations versus the osmotic potential, one can observe that the osmotic component of the water potential at high soluble solid content (18%) is equivalent to a relative humidity of 97.7 percent (Figure 3.11). Relative humidities of this magnitude or higher occur only when precipitation occurs or when the ambient temperature falls below the dew point.

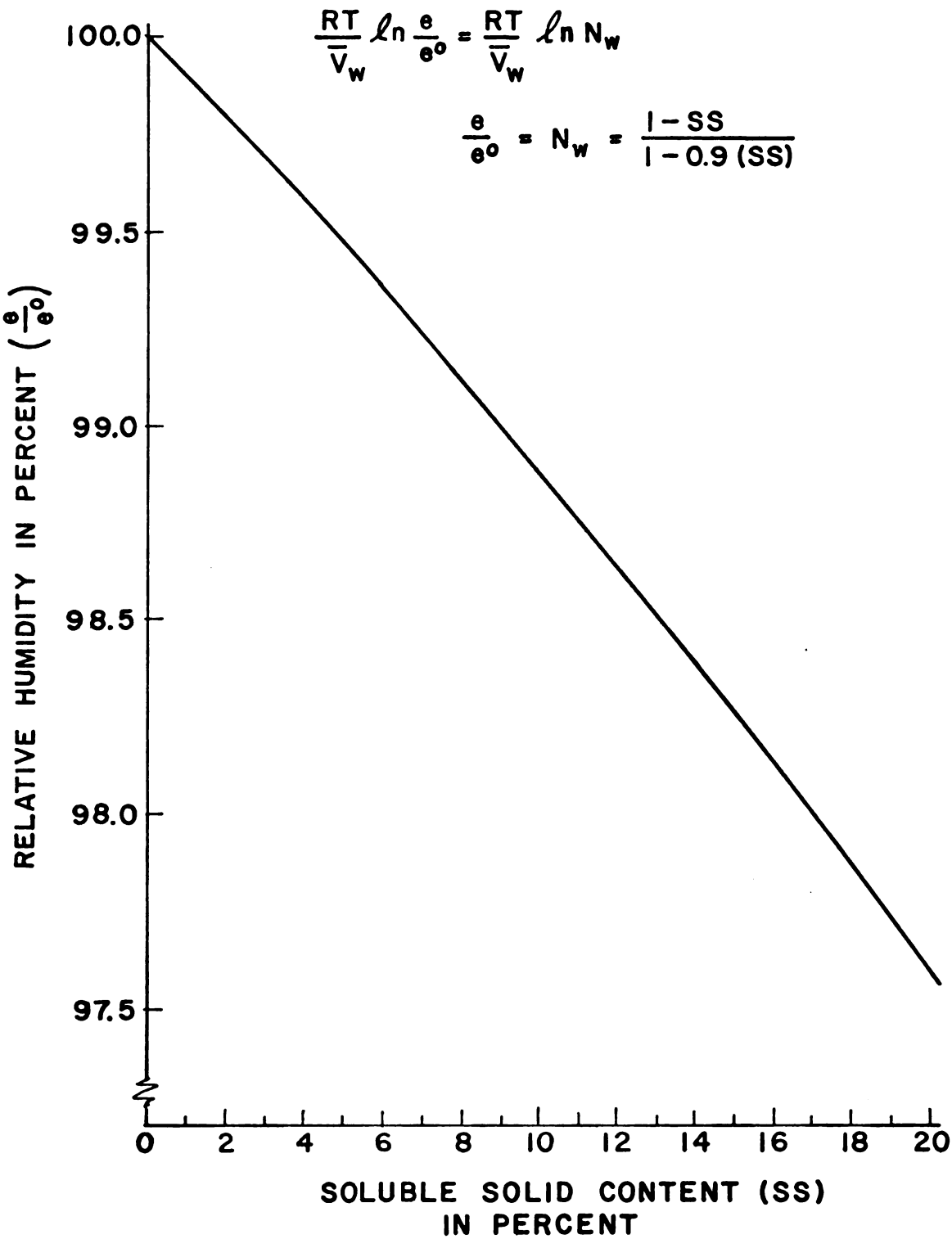


Figure 3.11.--The relationship of soluble solid content to relative humidity (molecular weight = 180).

Thus, the possibility of a water potential gradient caused by high humidity that might produce a sufficient moisture gradient to move into the plant-fruit complex from the atmosphere seems remote.

If one calculates the volume of water taken on by a fruit if the soluble solid content changes 4 percent, an approximate value for the fruit diameter at the lower soluble solid content can be obtained. Taking data from Watt and Merrill (1963), the percent water content for sweet cherries and tomatoes is 80.4 and 93.5 percent, respectively. Using these percentages for water content, the percent of mass of water taken into the fruit can be obtained.

If one takes Equation 21 and substitutes the values of sweet cherry soluble solid content of 18 percent and 80.4 percent water content initially, the decimal fraction of fruit sugars content can be calculated for a unit mass;

$$0.18 = \frac{m_s}{0.804 + m_s} ,$$

$$m_s = 0.1765.$$

One can substitute this value of m_s in Equation 21 for a soluble solid content of 0.14 and m_s value of 0.1765 units of mass since the fruit sugar content will not be lost in the uptake of moisture by the fruit;

$$0.14 = \frac{0.1765}{m_w + 0.1765}$$

$$m_w = 1.0842.$$

Thus the increase in mass of water should be the difference between the two values of 0.2802 units of mass, indicating that the water content can increase approximately 34.8 percent for a change of 4 percent in the soluble solid content of a sweet cherry.

If one makes the same calculation for a unit mass of tomato fruit initially at a soluble solid content of 6 percent and 93.5 percent water content, the increase in the mass of water for a 4 percent decrease in soluble solid content can be calculated by Equation 21;

$$0.06 = \frac{m_s}{0.935 + m_s},$$

$$m_s = 0.0596.$$

If one assumes that the soluble sugar content will remain constant, the new mass of water can be calculated for a 2 percent soluble solid content. The result is;

$$0.02 = \frac{0.0596}{m_w + 0.0596},$$

$$m_w = 2.8910.$$

The percent increase in the mass of water would be the difference between the initial and final values of m_w

divided by the initial value or 209.1 percent. Therefore, for the soluble solid to decrease from 6 to 2 percent, the mass of water must increase 209.1 percent over the initial amount.

As observed in Figure 3.10, the osmotic potential for a change in 4 percent soluble solid for cherries and tomatoes is approximately 8 atm and 4 atm respectively. The osmotic potential change is much less for tomatoes than cherries. As observed from the calculations of percent change in water mass, the cherry changes only 34.8 percent, where the tomato changes 209.1 percent. Thus, it would appear that the tomato can be affected more by osmotic potential than the cherry; this assumes that the water potential of the fruit environment is approximately zero.

3.8 Change in Fruit Diameter Caused by a 4 Percent Change in the Soluble Solid Content

To determine the change in the fruit diameter that resulted in the change in the fruit mass, several assumptions had to be made.

The fruit was assumed to be spherical and any change in the fruit would maintain the spherical relationship. A further assumption was made that the fruit diameter increased proportionally to the required change in the fruit volume that was necessary for the increased fruit mass.

3.8.1 Changes in Diameter for Sweet Cherries

From the calculation in Section 3.7, the increase in initial and final mass of the fruit can be calculated. Tennes, et al. (1969) reported the average Schmidt fresh sweet cherry is equivalent to a sphere having a diameter of 0.883 inches and a specific gravity of 1.094. By further assuming that the fluid is incompressible and the relationship between mass and volume is one to one, then Equation 8 can be written as Equation 24;

$$\frac{m_i}{m_f} = \frac{SP_i}{SP_f} \frac{V_i}{V_f} = \frac{SP_i}{SP_f} \frac{\frac{\pi}{6} D^3_i}{\frac{\pi}{6} D^3_f} \tag{24}$$

where; m = Mass of fruit,
V = Volume of fruit,
D = Diameter of fruit,
SP = Specific gravity.

subscripts; i = initial value,
f = final value.

Values for Equation 24 are;

$m_1 = 0.804 + 0.177$

$m_f = 1.084 + 0.177$

$D_i = 0.883$ inches,

$SP_i = SP_f$,

$\frac{m_i}{m_f} = \frac{D^3_i}{D^3_f}$ (1),

$$D^3f = \frac{m_f}{m_i} D^3i,$$

$$D^3f = \frac{(1.084 + 0.177)}{(0.804 + 0.177)} (0.883)^3,$$

$$D_f = 0.965 \text{ inches.}$$

or a 34.8 percent change in the fruit mass of water should cause an 13.2 percent increase in the fruit diameter.

3.8.2 Changes in Diameter for Tomatoes

For a 4 percent change in soluble solid content, it was calculated in Section 3.6 that the increase in fruit mass due to water was 209.1 percent. Using Equation 23 with the values obtained in this study for tomatoes;

$$m_i = 0.935 + 0.059,$$

$$m_f = 2.891 + 0.059,$$

$$D_i = 2.713 \text{ inches.}$$

Thus, Equation 23,

$$D_f = \frac{(2.891 + 0.059)}{(0.935 + 0.059)} \quad 2.713,$$

$$D_f = 3.920 \text{ inches.}$$

A 209.1 percent increase in the fruit mass should cause a 44.2 percent increase in the tomato's diameter.

EXPERIMENTAL

4.1 General Field Observations

4.1.1 Procedure for Sweet Cherries

First, field tests were conducted during the 1968 sweet cherry season to observe conditions which possibly could cause cracking. Observations were made in commercial orchards to orient the crack location with resepct to the fruit tree. These tests were followed by a test to determine the effect on fruit cracking when the fruit was subjected to the following three different conditions: (1) submerging the fruit in water while still attached to the tree, (2) subjecting the tree foliage to 100 percent relative humidity, and (3) subjecting both the fruit and foliage to 100 percent relative humidity. These environmental conditions were established by placing plastic bags on the fruit trees' limbs to produce the desired treatment effects.

In addition to these on-the-tree tests and observations, samples of fruit were handpicked and administered different bruise levels of 0X, 1X, 2X and 3X (X is the number of times the fruit is dropped from a 3-foot height into a hard plastic laboratory tray). One test lot was punctured in addition to being bruised. After the above

treatments, samples were placed in water at 21.1° centigrade temperature for different time periods. Changes in diameter of the fruit were recorded for the different soak periods and time when cracking occurred. Soluble solid content of the fruit was recorded at the beginning and end of each test.

4.1.2 Discussion of Results

In an attempt to determine the location of the cracked fruit on the tree, observations were made on Schmidt and Napoleon sweet cherry trees in the Grand Traverse, Michigan area. All recorded observations were made on the lower seven feet of the tree canopy or within reaching height from the ground. The observed trees averaged 4 to 6 percent cracked fruit. In approximately 95 percent of the recorded incidents of cracked fruit, the fruit was in a position with the crack oriented away from the tree canopy or outward, and on the outer ends of tree branches. A higher percentage (60-70) of the cracks were in conjunction with a wind-whipped or bruised spot. Cracking occurred more frequently (70 percent of observations) on the windward side of the tree. Of the recorded cracked fruit, 82.8 percent of cracks were located at the apex end of the fruit (Table 4.1).

Several tests were conducted to determine if a significant change in the fruit diameter could occur

TABLE 4.1.--Location of crack on the fruit surface and the average soluble solid content of the cracked fruit.

Location of Crack on the Fruit	Percent of Total Observations
Stem End	0.0%
Cheek	15.3%
Apex	82.8%
Suture	1.9%

while the fruit was still attached to the tree. Two of the tests involved having the cherries in water and 100 percent relative humidity. The tree foliage was subjected to similar conditions in an effort to induce cracking. For the test of 100 percent relative humidity on the tree foliage, there was an increase in the fruit diameter over a period of 24 hours (Table 4.2).

TABLE 4.2.--Average fruit diameter next to foliage subjected to 100 percent relative humidity.

Day	Average Fruit Diameter (inches)
1st	0.740
2nd	0.827

Similar results were obtained when both the tree foliage and fruit were subjected to 100 percent relative humidity conditions (Table 4.3).

TABLE 4.3.--Changes of fruit diameter and soluble solid content with time when foliage and fruit were subjected to 100 percent relative humidity.

Day	Average Fruit Diameter (inches)	Average Soluble Solid Content (percent)
1st	0.866	17.0
2nd	0.884	18.0
3rd	0.892	18.0

4.2 Osmotic Tests for Sweet Cherries

4.2.1 Procedure for Sweet Cherries

A widely used practice by sweet cherry growers is the application of a water solution of sulfur and lime applied with an air blast sprayer in an effort to prevent or reduce cracking. As the fruit matures, a couple of applications are made prior to expected precipitation. Additional applications of 20 pounds of lime per 500 gallons of water are used during and after a rainstorm. These applications of sulfur and lime are made in an attempt to alleviate the cracking of fruit that occurs after rainstorms. Following this idea, spray tests of different concentrations of calcium nitrate, sodium nitrate and

potassium nitrate were applied to sweet cherry trees to the various concentrations of each mentioned chemical.

Of four nitrate levels (1, 2, 3 and 4 molar solutions applied to the tree foliage), it was observed that foliage burning was most severe for the calcium nitrate and sodium nitrate (in some cases, more than 50 percent defoliation). Less damage occurred with potassium nitrate applied at the same levels (less than 10 percent foliage burn). Thus, potassium nitrate was selected and tested.

At Fennville, Michigan, eight sweet cherry trees were treated in their entirety with potassium nitrate solution. Of the three application rates used (4, 8 and 12 molar), all treatments produced severe burning of the tree foliage (10 to 80 percent of surface area). However, the same lower rate (4 molar) applied a month earlier in the season to individual limbs did not produce severe burning.

Like other applied chemical sprays, many other climatic factors influence KNO_3 behavior after application. However, the defoliation caused by burning reduced the spread of brown-rot in the treated trees. No apparent damage was done to the fruit at the different concentrations of these chemicals.

Sweet cherries were handpicked and placed in solutions of calcium nitrate, potassium nitrate and sodium nitrate for periods of 24 hours. Solutions of each

compound were of 0.2, 0.4, 0.6 and 0.8 molar concentrations. Water temperature was maintained at approximately 21.1° centigrade for the 24-hour soak period. Additional soak tests using cane sugar were conducted on fruit treated with ethephon [(2 chlorethyl) phosphonic acid]. Each test was repeated three times.

Some cherry growers believe that the soluble solid content changes during the night, causing water to enter the cherry fruit early in the morning and swelling the fruit until the skin ruptures. Thus, soluble solid content and diameter of cherries were recorded for a 24-hour period for both the 1970 and 1971 cherry seasons. The chemical abscission compound ethephon was included in this evaluation.

It was observed that many of the cracks which occurred in sweet cherries after a wind and rain storm had apparently originated from a bruised area on the fruit surface. Thus, 20 cherries for each sample were handpicked with stems attached and bruised by dropping the fruit a distance of 3 feet onto a plastic laboratory tray 0X, 1X, 2X and 3X times (X is the number of times the fruit was dropped). Each sample of 20 fruit was then placed in water at approximately 21.1° centigrade for 29-hours. The diameters were determined throughout the 29-hour soak period. A second sample of cherries was given the same

bruise damage and then the skins were punctured before soaking.

4.2.2 Discussion of Results

Various concentrations of potassium nitrate, sodium nitrate and calcium nitrate in a water solution for sorting sweet cherries were effective in alleviating cracking. Sweet cherry samples, when placed in water for a 22-hour period, yielded approximately 63 percent cracked fruit. A 0.6 molar solution of potassium nitrate in the storage water reduced the cracking of the fruit to 4 percent (Table 4.4). Thus, a new possibility for field handling of fruit in aqueous solution without serious problems of fruit splitting was found.

TABLE 4.4.--Percent of fruit cracking during a 22-hour soaking period in various solutions.

	Molar Solution of Compound				
	0.0	0.2	0.4	0.6	0.8
KNO_3	63	16	4	4	0
$Ca(NO_3)_2$	63	9	13	14	0
$NaNO_3$	63	32	21	4	-

As seen in Table 4.4, potassium nitrate was more effective in reducing incidence of fruit splitting in a

water solution. Of the three tested compounds, potassium nitrate caused the least foliage burn when sprayed on the foliage. For these reasons, potassium nitrate was selected for further evaluations of spray applications on sweet cherry trees.

The incidence of sweet cherry splitting in a water solution was checked for SADH [(2,2-dimethylhydrazide) succinic acid] treated fruit (Table 4.5). It was found that samples of SADH treated fruit of 1000 and 2000 ppm had higher initial soluble solid content over non-treated fruit taken from the same orchard. This indicated that SADH increased the soluble solid content of sweet cherries. It would be expected that as the sugar content increases the incidence of fruit splitting also increases. The incidence of splitting went from 72 percent for non-treated fruit to 95 percent for fruit treated with 2000 ppm of SADH (Table 4.5). This increased rate of splitting most likely was caused by the increased soluble solid content rather than the applications of SADH.

The same splitting test on fruit treated with a chemical abscission compound (ethephon) resulted in the opposite effect on fruit splitting than was found for SADH treated cherries. Both the treated and check samples of Schmidt cherries were taken from the same orchard and soaked in water and different potassium nitrate

TABLE 4.5.--Percent of fruit cracking during a 24-hour soak period in various potassium nitrate solutions for SADH-treated Schmidt sweet cherries.

Treatment	SS*	Molar Concentration of Solution			
		0.0	0.2	0.4	0.6
Non-treated	15.0	72	49	12	5
SADH 1000 ppm	16.5	76	61	40	12
SADH 2000 ppm	18.5	95	75	17	14

*The initial soluble solid content of the samples.

solutions (Table 4.6). It was found that the soluble solid content for this sample of 100 fruit was the same for both the treated and non-treated fruit. Therefore, it seemed the sample would behave similarly when subjected to soaking tests. However, it was found that ethephon treated fruit had a lower incidence of fruit splitting than the non-treated fruit of the same initial sugar content.

TABLE 4.6.--Percent of fruit cracking during a 24-hour soaking period in various potassium nitrate solutions for ethephon treated Schmidt sweet cherries.

Treatment	SS*	Molar Concentration of Solution			
		0.0	0.2	0.4	0.6
Non-treated	16.0	65	43	13	16
500 ppm ethephon	16.0	61	35	21	3

*The initial soluble solid content of the samples.

A test was conducted to determine the effect of the temperature of a solution in which sweet cherries were held on their percent of cracking. Samples of Napoleon and Schmidt cherries were held at three different temperatures and known sugar ($C_6H_{12}O_6$) content for a 24-hour soak period. Both varieties of fruit were harvested from the same orchard.

The percentage of fruit that cracked decreased as the sugar content of the solution in which the fruit was held increased (Figures 4.1 and 4.2). The Schmidt variety had a lower percentage of fruit cracking than the Napoleon variety when held in the same environment (compare Figure 4.1 with 4.2). The highest percent of cracked fruit occurred at 15.5°C. The lower testing temperature of 4.4°C resulted in fewer fruit cracking. For the Schmidt variety of sweet cherries, the higher soak temperature of 26.6°C did not produce greater fruit cracking than the lower soak temperature of 4.4°C (Figure 4.2).

A plot of the soluble solid content of sweet cherries versus the relationship between time of day for various ethephon treatments was highly variable (Figure 4.3). The average value of soluble solid content was higher for non-treated fruit than for either of the two treatments of ethephon (Table 4.7). The lowest average value obtained for soluble solid content was for the highest concentration of ethephon. Therefore, it appeared for the 1970 data that the soluble solid content of the

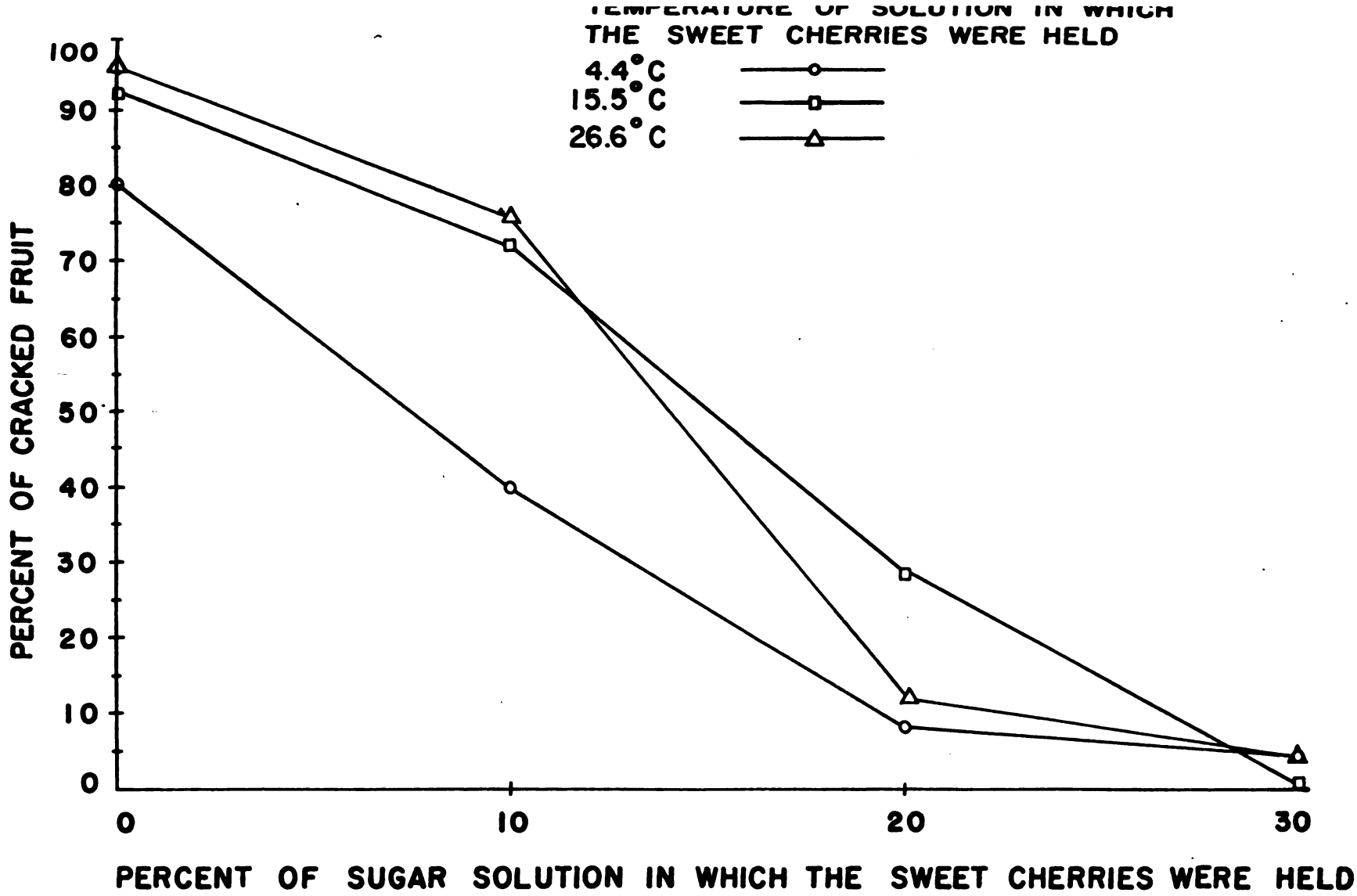


Figure 4.1.--The percent of fruit cracking that occurred after the Napoleon cherries were held for 24 hours in a sugar solution at different temperatures.

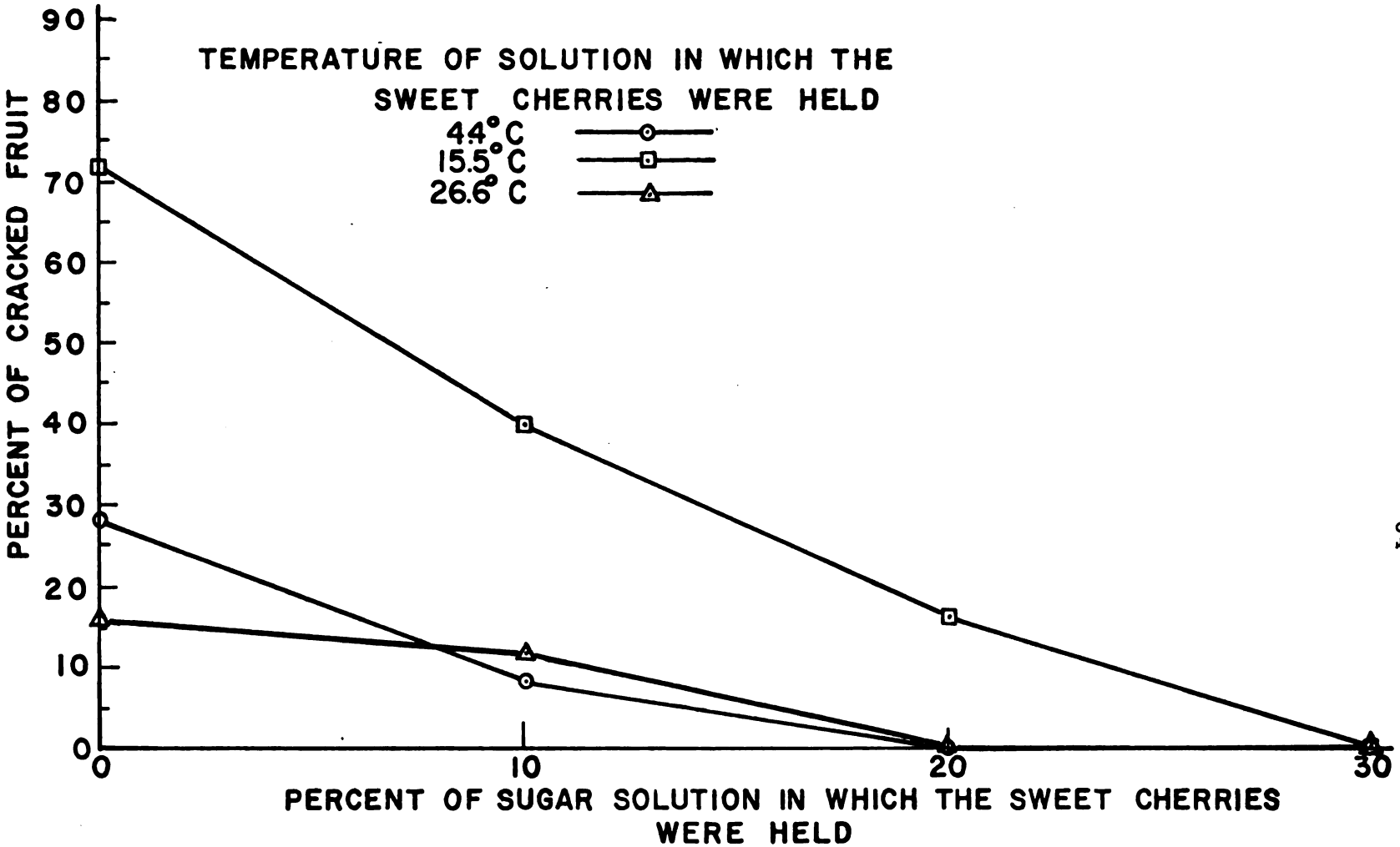


Figure 4.2.--The percent of fruit cracking that occurred after the Schmidt cherries were held for 24 hours in a sugar solution at different temperatures.

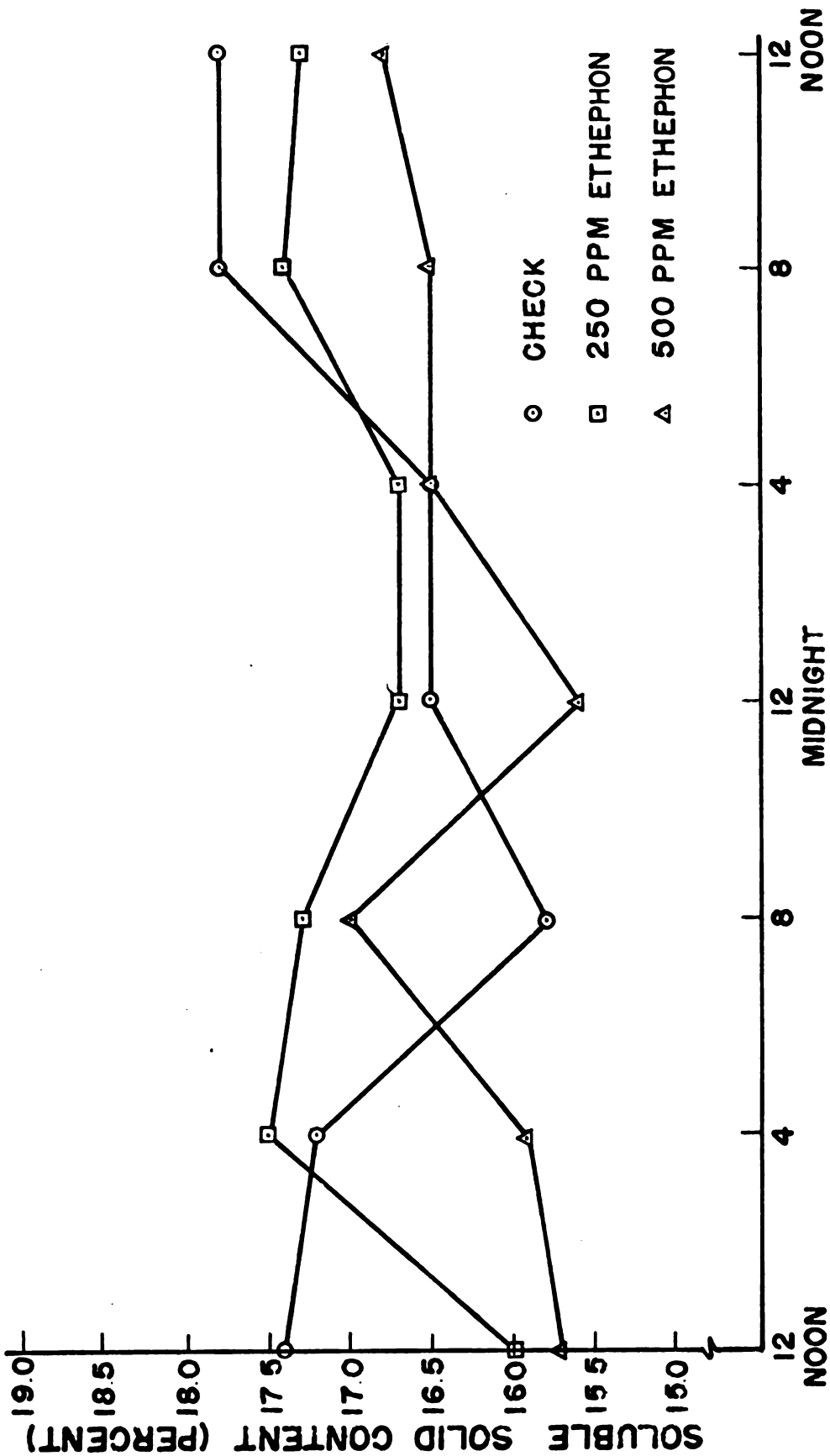


Figure 4.3.--The relationship between time of day and soluble solid content of sweet cherries at various ethephon treatments during the 1970 season.

TABLE 4.7.--Analysis of variance table for soluble solid content of sweet cherries (1970).

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	2	4.60*
Time	6	1.92
Ethephon x time	12	1.28
Remaining error	84	
Total	104	

*α = 0.05
Mean soluble solid content (percent) = 16.77 $\pm$ 1.22 percent
Mean non-treated = 17.02 percent
Mean 250 ppm ethephon = 16.99 percent
Mean 500 ppm ethephon = 16.29 percent

sweet cherries was slightly reduced by increasing levels of ethephon concentrations. Differences among the treatment means were not significant (α = 0.05) by using Tukey's w-procedure for the non-treated and 250 ppm ethephon treatments.

However, the mean value of the high level of ethephon treated fruit for the 1971 tests had a higher soluble solid content than did the check sample (Table 4.8). The type of variation that occurs in the soluble solid determinations indicates other factors not determined responded to ethephon.

TABLE 4.8.--Analysis of variance table for soluble solid content of sweet cherries (1971).

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	1	19.94**
Replication	1	0.01
Ethephon x replication	1	1.73
Time	6	2.10
Ethephon x time	6	2.71
Ethephon x time x replication	6	0.72
Remaining error	118	
Total	139	

** α = 0.01
Mean soluble solid content (percent) = 14.96 $\pm$ 1.32
Mean non-treated = 14.52
Mean 500 ppm ethephon - 15.41

The effect of time on sweet cherry size under the influence of ethephon was plotted for the 1970 season (Figure 4.4). The effect of ethephon on fruit size was highly significant (0.01 level) (Table 4.9). For the 1970 test, time had no effect upon the diameter of the fruit during this 24-hour period. Ethephon treatments caused a reduction of the fruit diameter. This can partially be explained by the fact that, for the 1970 season, soluble solid content for the non-treated fruit was greater than

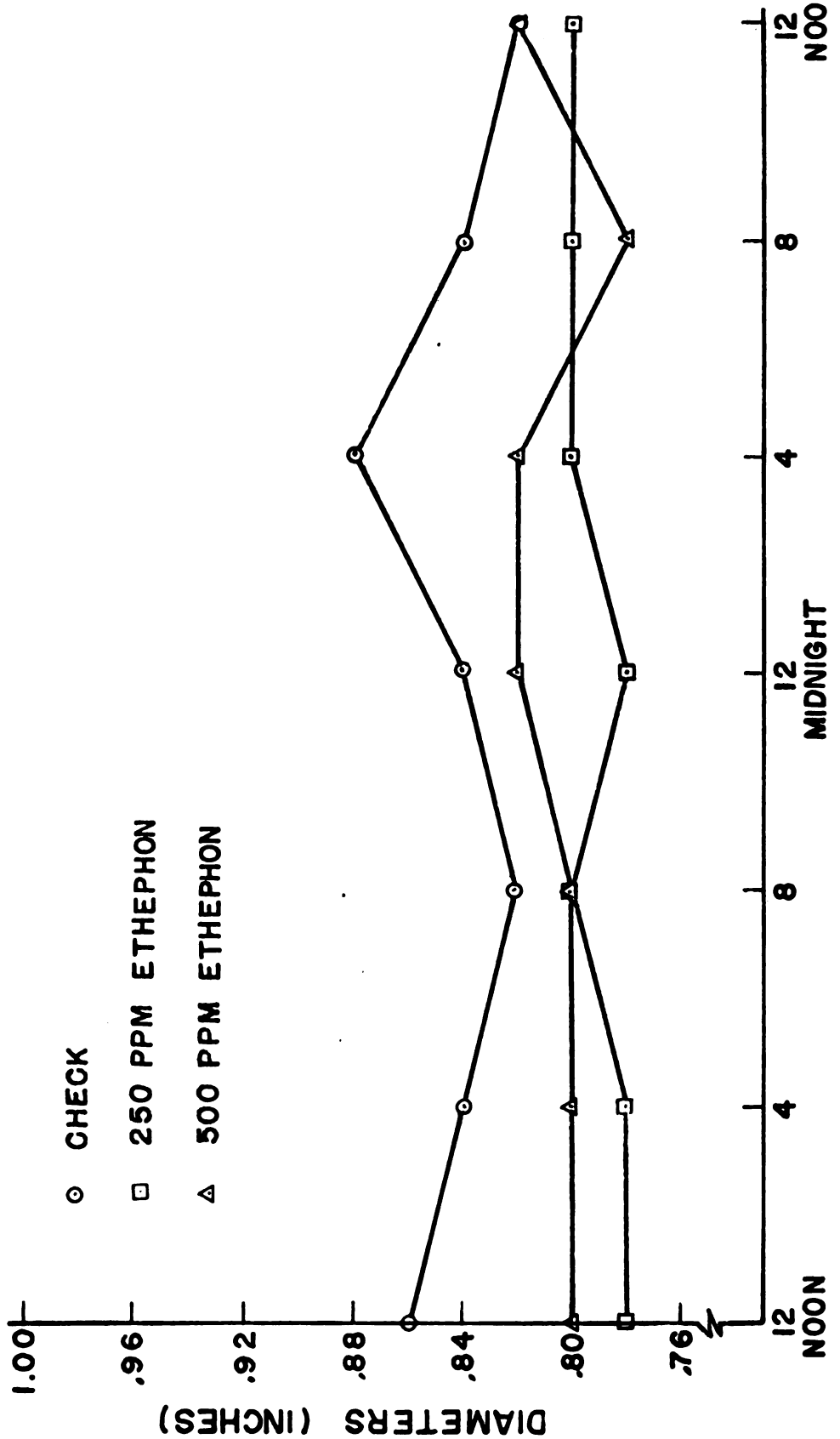


Figure 4.4.--The effect of time on sweet cherry size under the influence of ethephon for the 1970 season.

the treated fruit. With higher soluble solid content of the fruit, the diameter of the fruit would be expected to be higher as reported by Levin, et al. (1969).

TABLE 4.9.--Analysis of variance table for diameter of sweet cherries for the 1970 season.

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	2	27.45**
Time	6	0.48
Ethephon x time	12	1.00
Remaining error	84	
Total	104	

** $\alpha = 0.01$
Mean diameter = 0.815 + 0.041 inches
Mean non-treated = 0.8$\overline{48}$ inches
Mean 250 ppm ethephon - 0.790 inches
Mean 500 ppm ethephon = 0.808 inches

Since there was no significant ($\alpha = 0.01$) difference in fruit diameter between treatments of 250 and 500 ppm of ethephon during the 1970 tests by Tukey's w-procedure, 1971 tests were made with non-treated fruit and 500 ppm of abscission chemical. The fruit diameter variations during a 24-hour period again were found to be highly significant for the chemical abscission material. Many other variables such as the development of an

abscission layer or a higher transpiration rate of the fruit may have an effect on water stress during the day.

When cherries were bruised and then soaked in water, the change in fruit diameter was highly significant for both the varieties and the soak periods (Table 4.10).

TABLE 4.10.--Analysis of variance table for diameter of sweet cherries bruised and soaked in water for 29 hours.

Source of Variance	Degrees of Freedom	F Statistic
Variety (Napoleon and Schmidt)	1	32.20**
Bruise level (0X, 1X, 2X and 3X)	3	1.75
Variety x bruise level	3	0.75
Time	3	9.59**
Bruise level x time	9	0.12
Variety x bruise level x time	9	0.06
Remaining error	611	
Total	639	

Mean cherry diameter (inches) = 0.850 $\pm$ 0.059

Mean diameter of Napoleon cherries = 0.863

Mean diameter of Schmidt cherries = 0.837

Mean diameter of various soak times

Tukey's w-procedure
α = 0.01 , 0.05

Initial = 0.832
5 Hours = 0.848
17 Hours = 0.862
29 Hours = 0.859

**α = 0.01

Tukey's w-procedure--Values connected by α common line are not significant at the indicated levels.

The diameter increase was more rapid for the Schmidt variety during the first five hours of soak than for the Napoleon variety (Figures 4.5 and 4.6). Part of this more rapid swelling of the Schmidt cherry could be attributed to the higher soluble solid content of 17.0 percent for the Schmidts over the lower value of 14.5 percent obtained for the Napoleon fruit.

A second sample of cherries having punctured skin, in addition to being bruised, before soaking yielded significance for variety, bruise level and soak periods (Table 4.11).

Rapid swelling of the Schmidt cherries occurred during the first five hours of soaking (Figure 4.7 and 4.8). Significance obtained for the different bruise levels can be seen readily by the separation of the average values obtained for the fruit diameter for different bruise levels (Figures 4.7 and 4.8).

Part of the decrease in the cherry diameter of higher bruise levels with a punctured skin could be attributed to the loss of cherry juice. Even with a ruptured cherry skin, the change in the fruit diameter was highly significant with soaking periods.

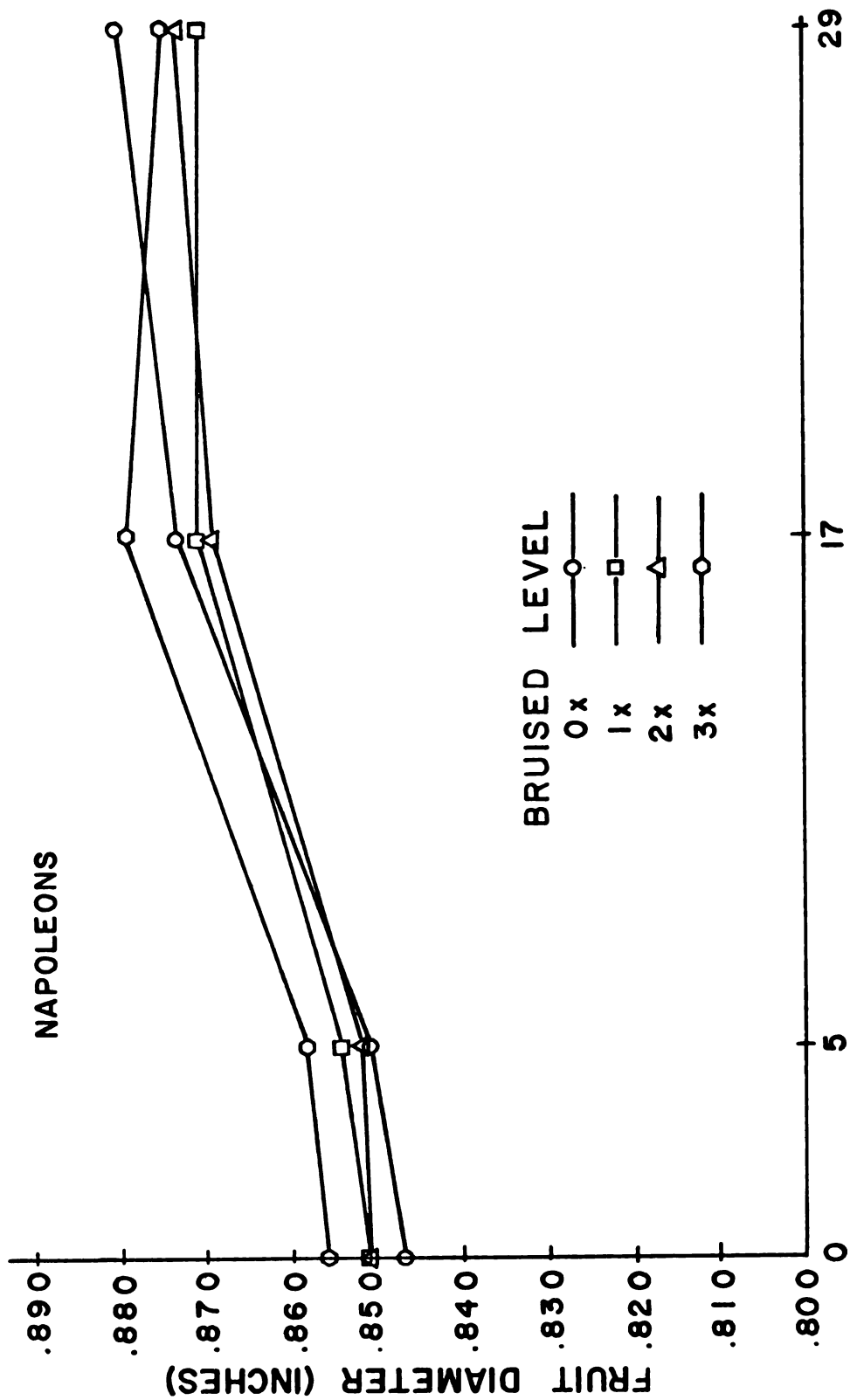


Figure 4.5.--The relationship between bruise levels and fruit diameter of Napoleon cherries when soaked in water for various lengths of time.

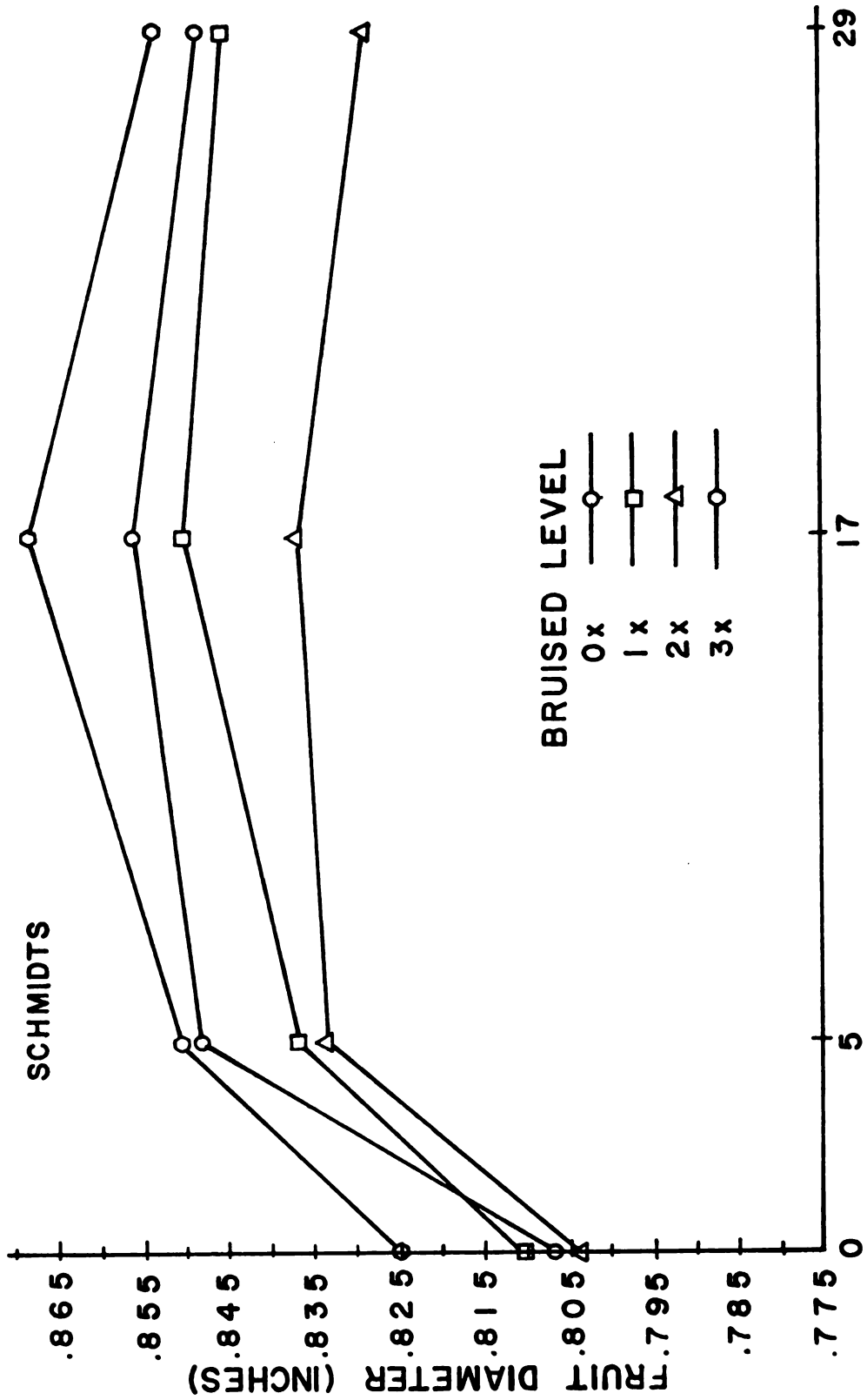


Figure 4.6.--The relationship between bruise levels and fruit diameter of Schmidt cherries when soaked in water for various lengths of time.

TABLE 4.11.--Analysis of variance table for the diameter of sweet cherries bruised, punctured and then soaked in water for 29 hours.

Source of Variance	Degrees of Freedom	F Statistic
Variety (Napoleon and Schmidt)	1	112.47**
Bruise level (0X, 1X, 2X and 3X)	3	15.69**
Variety x bruise level	3	4.54
Time	3	7.68**
Bruise level x time	9	0.06
Variety x bruise level x time	9	0.10
Remaining error	611	
Total	639	

**α = 0.01

Mean cherry diameter (inches) = 0.844 $\pm$ 0.064

Mean diameter of Napoleon cherries

Bruise level = 0.868 Tukey's w-procedure, α = 0.01 and 0.05

1X = 0.889
0X = 0.881
3X = 0.860
2X = 0.840

Mean diameter of Schmidt cherries = 0.820

0X = 0.864
3X = 0.818
1X = 0.813
2X = 0.803

Mean diameter of various soak times

Tukey's w-procedure, α = 0.01, 0.05.

Initial (0) = 0.826
5 Hours = 0.845
17 Hours = 0.856
29 Hours = 0.848

Tukey's w-procedure--Values connected by a common line were not significant at the indicated levels.

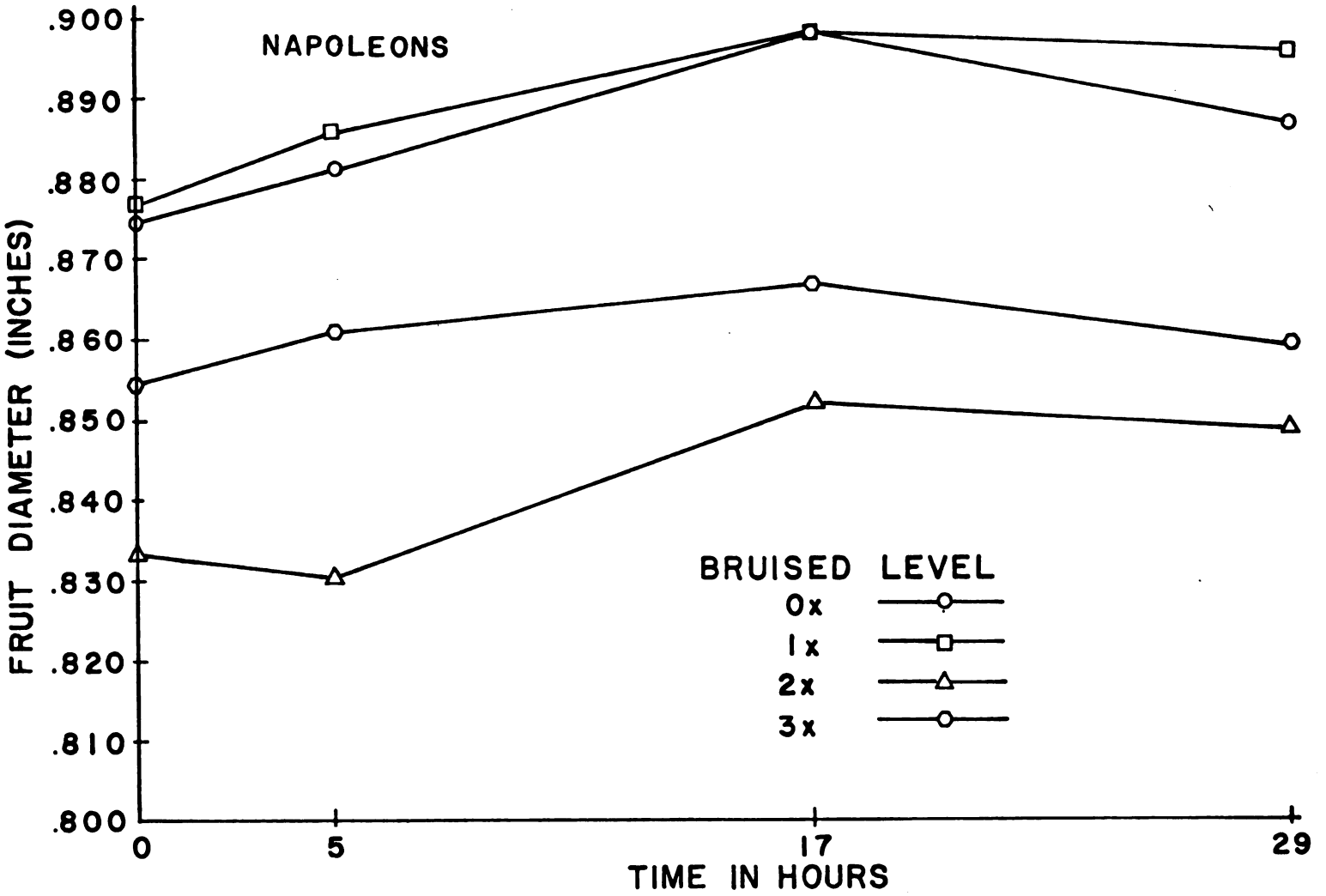


Figure 4.7.--The relationship among bruise levels and fruit diameter when Napoleon cherries are punctured and soaked in water for various lengths of time.

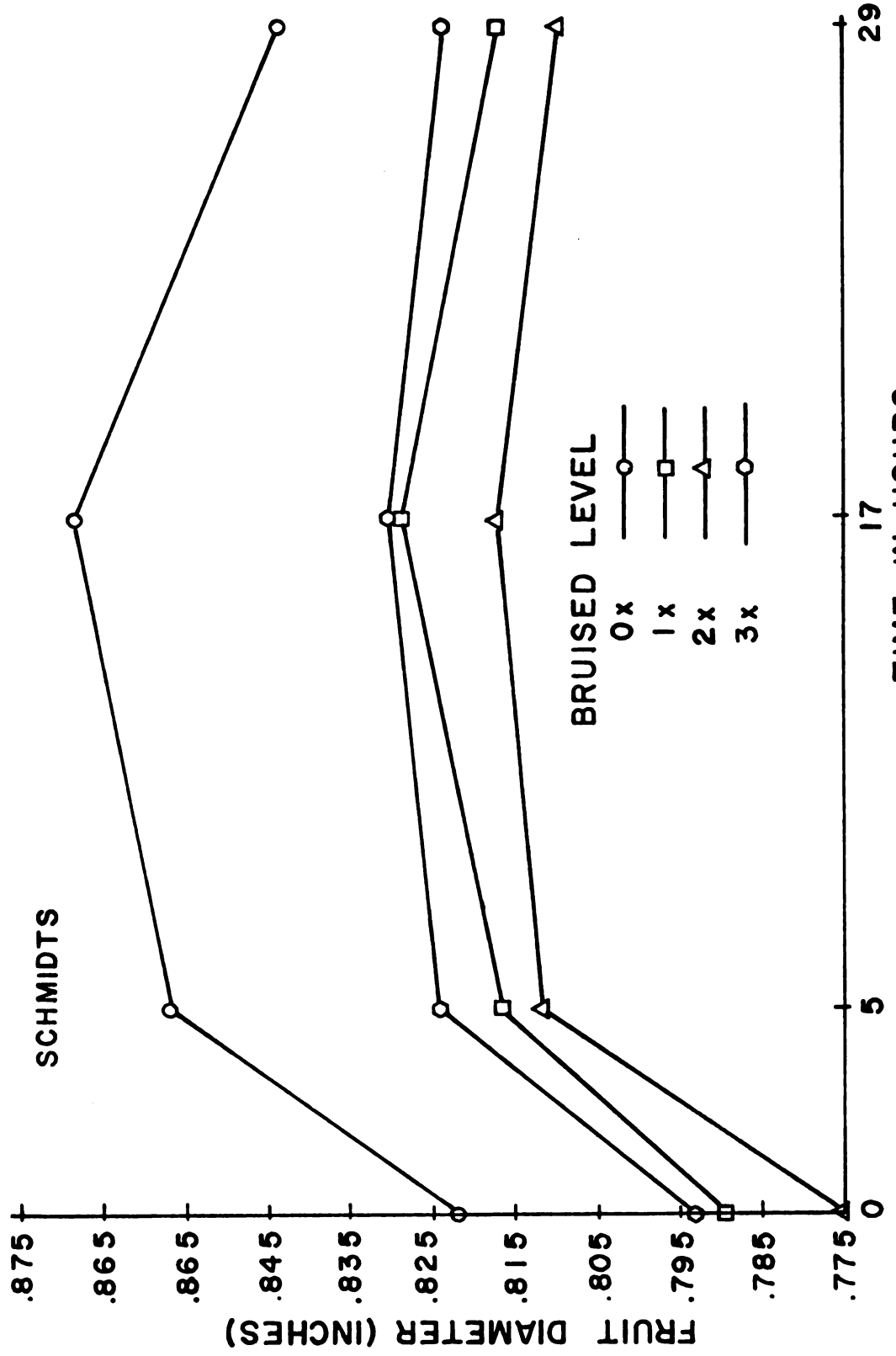


Figure 4.8.--The relationship between bruise levels and fruit diameter when Schmidt cherries are punctured and soaked in water for various lengths of time.

4.3 Water Potential Tests for Sweet Cherries

4.3.1 Procedure for Water Potential Determination

A search of literature did not reveal the use of the pressure chamber for fruit trees. To better understand the moisture relationship of the sweet cherry fruit and foliage, a PMS Instrument Company pressure chamber (Figure 4.9) was obtained for these determinations. According to the operator's manual, a pressure loading rate of 15 to 20 pounds per square inch per second had been used satisfactorily with Douglas-fir samples. Tests were conducted on sweet cherry tree limbs at constant temperature of 21.1° centigrade. The pressure chamber calibration curves for various turn settings on the pressure load rate control valve were found to behave linearly for the different openings of the needle valves (Figure 4.10). The most accurate setting was for 6 turns on the needle valve, giving a pressure chamber load rate of 0.50 seconds per atmosphere. This load rate was much too high to give realistic results from actual fruit placed in the chamber.

To determine the proper setting on the pressure chamber rate control valve, sweet cherry limbs were brought into the laboratory and placed with the cut stems in a water container. Determinations were then performed on both leaves and fruit, removing each from the same

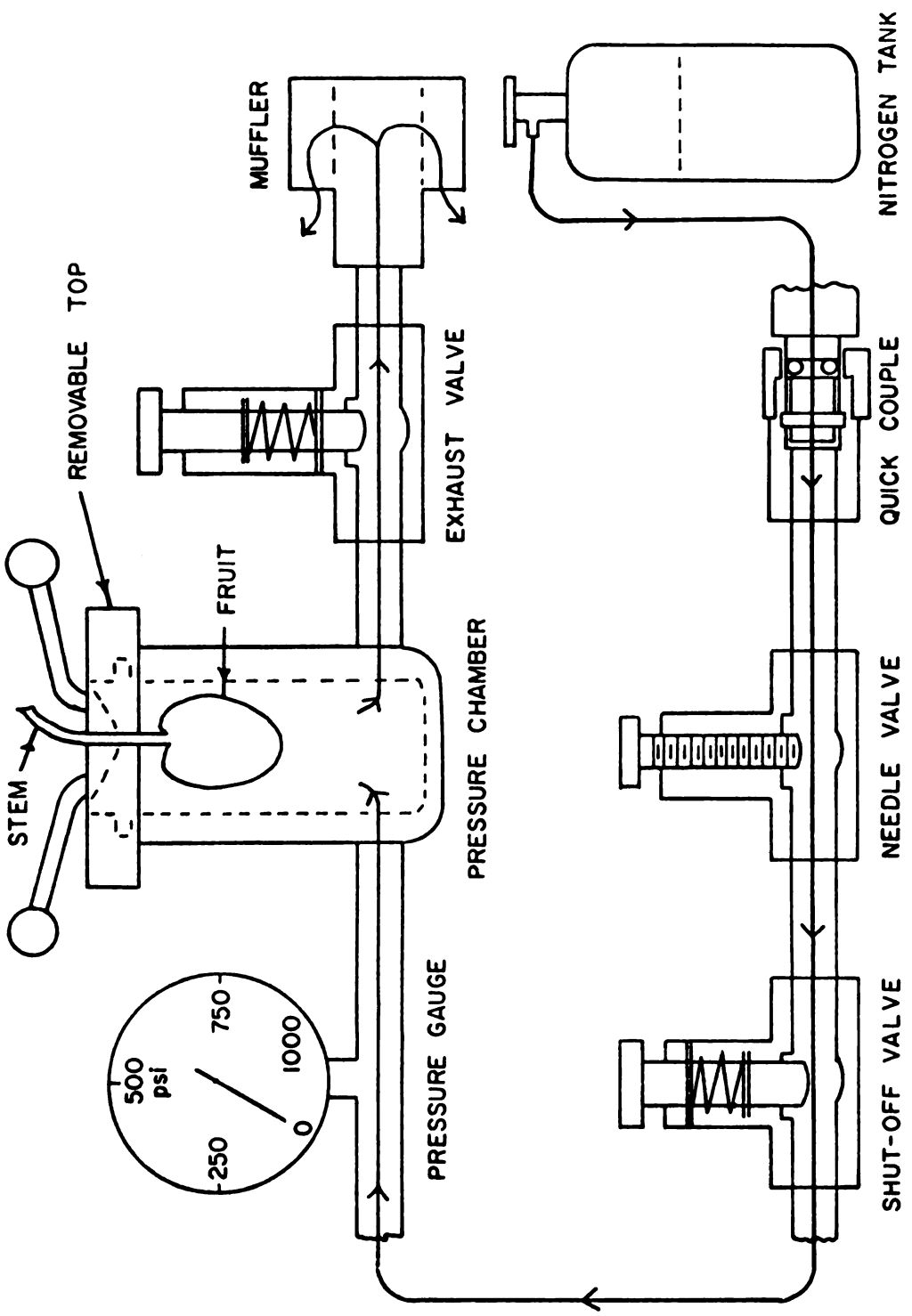


Figure 4.9.--Schematic of PMS Instrument Company's pressure chamber used in water potential determinations of plants.

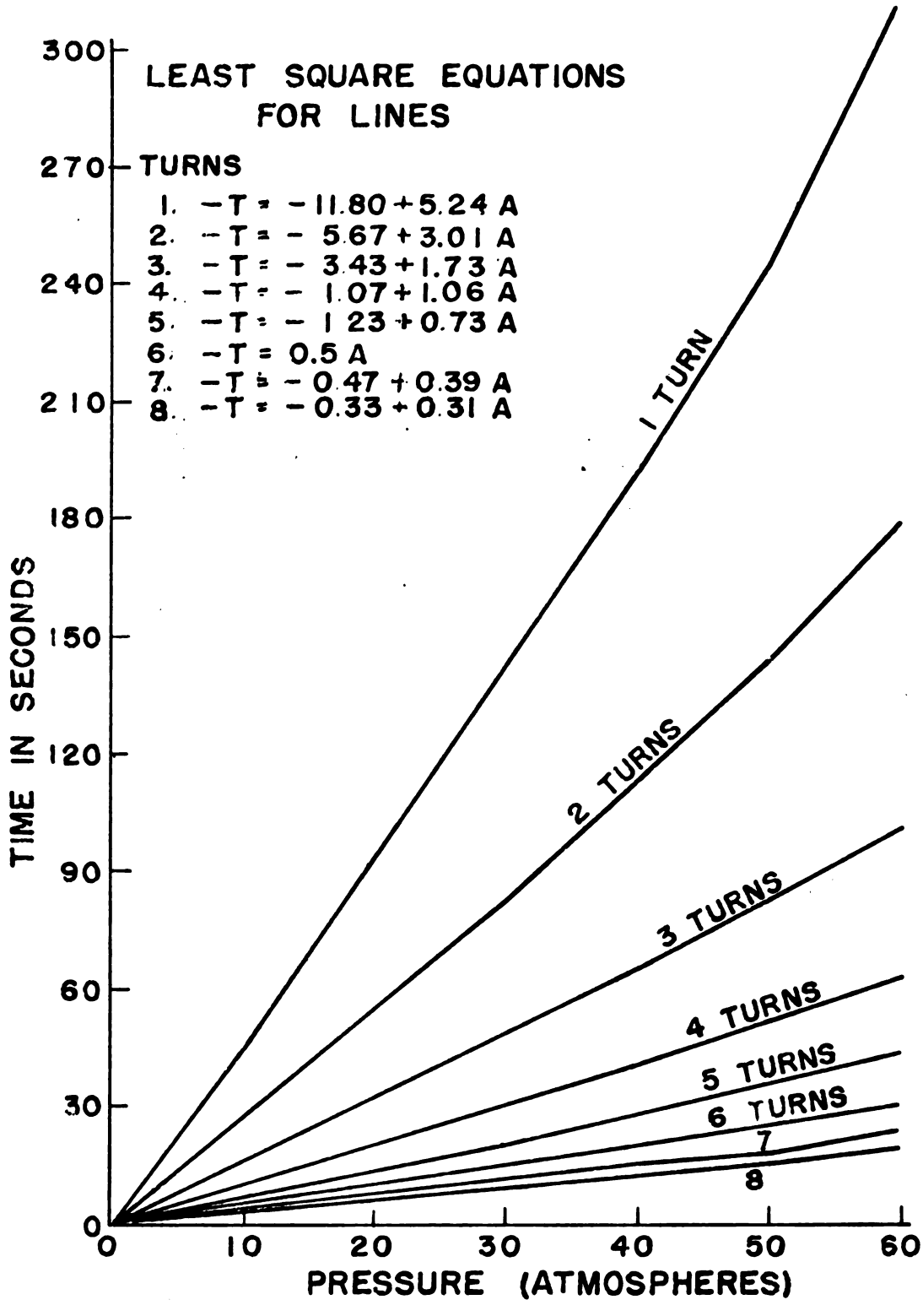


Figure 4.10.--Pressure chamber calibration determinations made for various turn settings on pressure load rate needle valve for the PMS Instrument Company's chamber.

location on the limbs. These determinations involved setting the instruments at 1, 2, 4 and 6 turns on the rate control valve. A good deal of variation did occur within each determination (Figure 4.11). The most important factor in the rate control setting on the pressure chamber was to obtain repeatable and dependable results for both the fruit and the leaves of the fruit tree. The plot for water potential versus 1 to 4 turns on the rate control pressure chamber resulted in a linear relationship. There was a rapid increase of water potential values obtained from 4 to 6 turns on the pressure load rate needle value for both the leaves and fruit determinations. A setting of 2 turns of the pressure chamber rate control valve was selected to give what was considered the most reliable and repeatable results.

Boyer (1967) compared the pressure chamber method of determining plant water stress with more elaborate techniques and found very favorable agreement. Boyer also stated that this is the best and most convenient field method available at that time.

The water potential determinations were made using the pressure chamber method previously described. These determinations were started at 12:00 noon and were taken every 4 hours until 12:00 noon the following day. Water potential determinations were taken on ethephon-treated sweet cherry fruit and leaves over a 24-hour

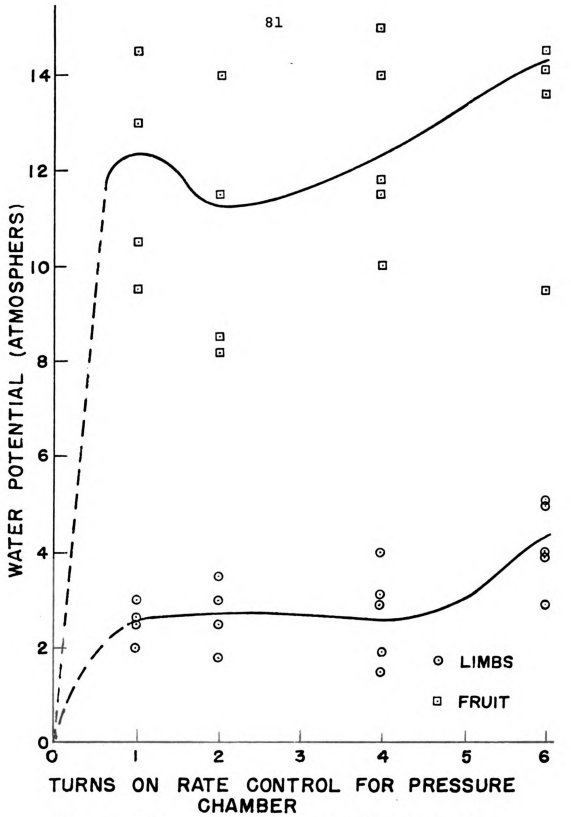


Figure 4.11.--The effects of rates of loading pressure chamber on water potential determination of sweet cherry fruits and leaves.

period for both the 1970 and 1971 cherry seasons. Each sample consisted of five fruit or leaves individually placed in the pressure chamber and the water potential of each specimen was determined. The relative humidity and ambient temperature were recorded by a hydrothermograph.

4.3.2 Discussion of Results

For the 1970 season, the water potential determinations were made on both non-treated fruit and ethephon treated fruit of 250 ppm and 500 ppm. Time had a highly significant effect upon the water potential of the leaves, as well as on the fruit (Figure 4.12). The soluble solid content of the fruit was not affected throughout the 24-hour period of recording. From the analysis of variance, it can be seen that ethephon did not have a significant effect upon the water potential of either the fruit or the leaves (Table 4.12). There was a significant difference ($\alpha = 0.05$) between the fruit and the leaves' water potential values as expected. However, an interaction between ethephon and location was obtained. In other words, the patterns of the values obtained for the water potential for the fruit and the leaves for the different treatments were different. It was found that the water potential for the highest concentration of ethephon was much lower during certain periods of time of day than for the non-treated and lower level of

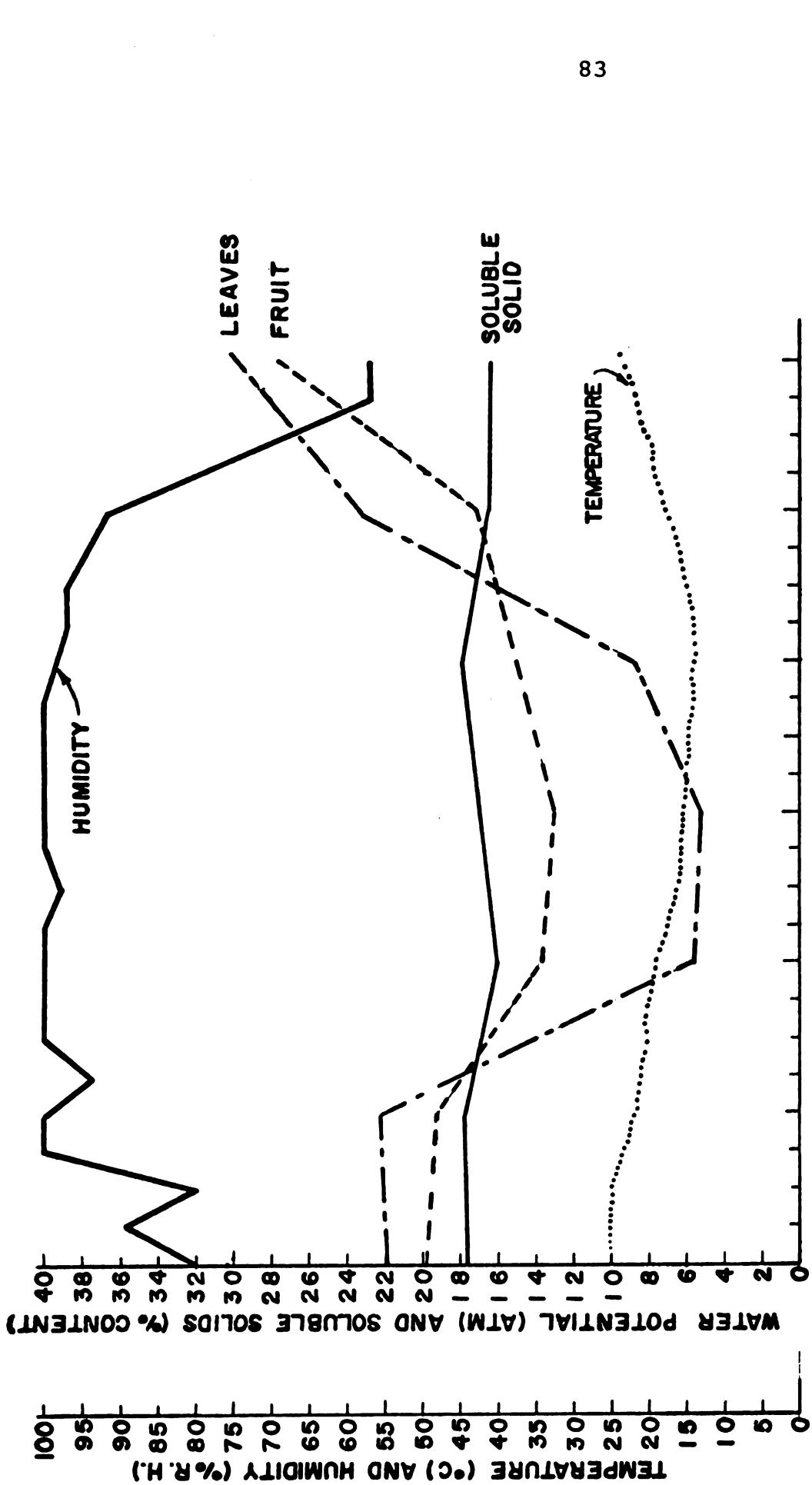


Figure 4.12.--The relationship among temperature, humidity, water potential (fruit and leaves), and soluble solid content for sweet cherries as a function of time throughout a 24 hour period taken during the 1970 season.

TABLE 4.12.--Analysis of variance table for water potential (atm) of leaves and fruit.

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	2	1.98
Location (fruit and leaves)	1	6.09*
Ethephon x location	2	4.41*
Time	6	74.13**
Ethephon x time	12	0.74
Ethephon x location x time	12	0.51
Remaining Error	174	
Total	209	

Mean water potential for sweet cherry fruits and leaves for different times.

	Time (hours)	Water Potential (atm)
7/15/1970	12:00 Noon	23.12
	4:00 PM	20.18
	8:00 PM	10.22
	12:00 Midnight	8.78
	4:00 AM	13.67
	8:00 AM	21.91
7/16/1970	12:00 Noon	29.71

Mean water potential for sweet cherry fruit and leaves for different times listed for Tukey's w-procedure.

Time (hours)	Water Potential (atm)	α 0.01 and 0.05
12:00 Noon (final)	29.71	
12:00 Noon (start)	23.12	|
8:00 AM	21.91	| |
4:00 PM	20.18	|
4:00 AM	13.67	|
8:00 PM	10.22	|
12:00 Midnight	8.78	

**α = 0.01 Mean water potential value = 18.23 $\pm$ 8.55 atm
* α = .05 Mean water potential fruit = 17.40
Mean water potential leaves = 19.05

Tukey's w-procedure--Values connected by a common line were not significant at the indicated levels.

ethephon treated fruit. Many other variables not measured in these tests will be responsible for these variations. The water potential of the leaves of the trees under the various treatments did not result in similar values. As expected from the theoretical development in Section 3.5, the water potential throughout the 24-hour period was highly significant. There was neither interaction between ethephon and time during the period of the test, nor interactions among ethephon, position, and time of the test. In summary, the most significant effects were the difference between the water potential of the fruit and the leaves, and the different effects of ethephon treatment throughout the day on the fruit and the leaves; this verifies the theory in Section 3.5.

During the period of the test, the incidence of cracking was approximately 5 to 10 percent within the orchard. Rainfall occurred during the period of the test and is indicated by 100 percent relative humidity on the graph (Figure 4.12).

For the 1971 season, the water potential determinations were made on non-treated fruit and fruit treated at 500 ppm of ethephon. These determinations were made during a week of relatively stable weather conditions (no rainfall). Under these conditions, the values of water potential obtained for the sweet cherry leaves were consistently less during the 24-hour data collection period

than the values obtained for the fruit (Figure 4.13). With precipitation occurring during the determination period (1970 season), the values of water potential obtained for fruit and leaves fluctuated, giving higher values for the sweet cherry leaves in the daytime period and lower values during the night time period than the values obtained for fruit (Figure 4.12).

The statistical analysis of the 1971 water potential determinations gave significance ($\alpha = 0.01$) being obtained for the time of determination for the sweet cherry fruit (Table 4.13). From this analysis, the abscission chemical compound ethephon did not affect the water potential for sweet cherry fruit.

The analysis of water potential data for the sweet cherry leaves resulted in a significant ($\alpha = 0.01$) effect with time or daily fluctuations (Table 4.14). A less significant ($\alpha = 0.05$) effect was obtained among sweet cherry trees. Thus, the chemically treated fruit does not vary from the non-treated fruit during a daily cycle.

4.4 Puncture Tests for Sweet Cherries

4.4.1 Procedure for Puncture Determinations

Field samples were taken from a commercial fruit orchard and placed in a controlled environment chamber at 4.4, 15.5, and 26.6 degrees centigrade temperature and

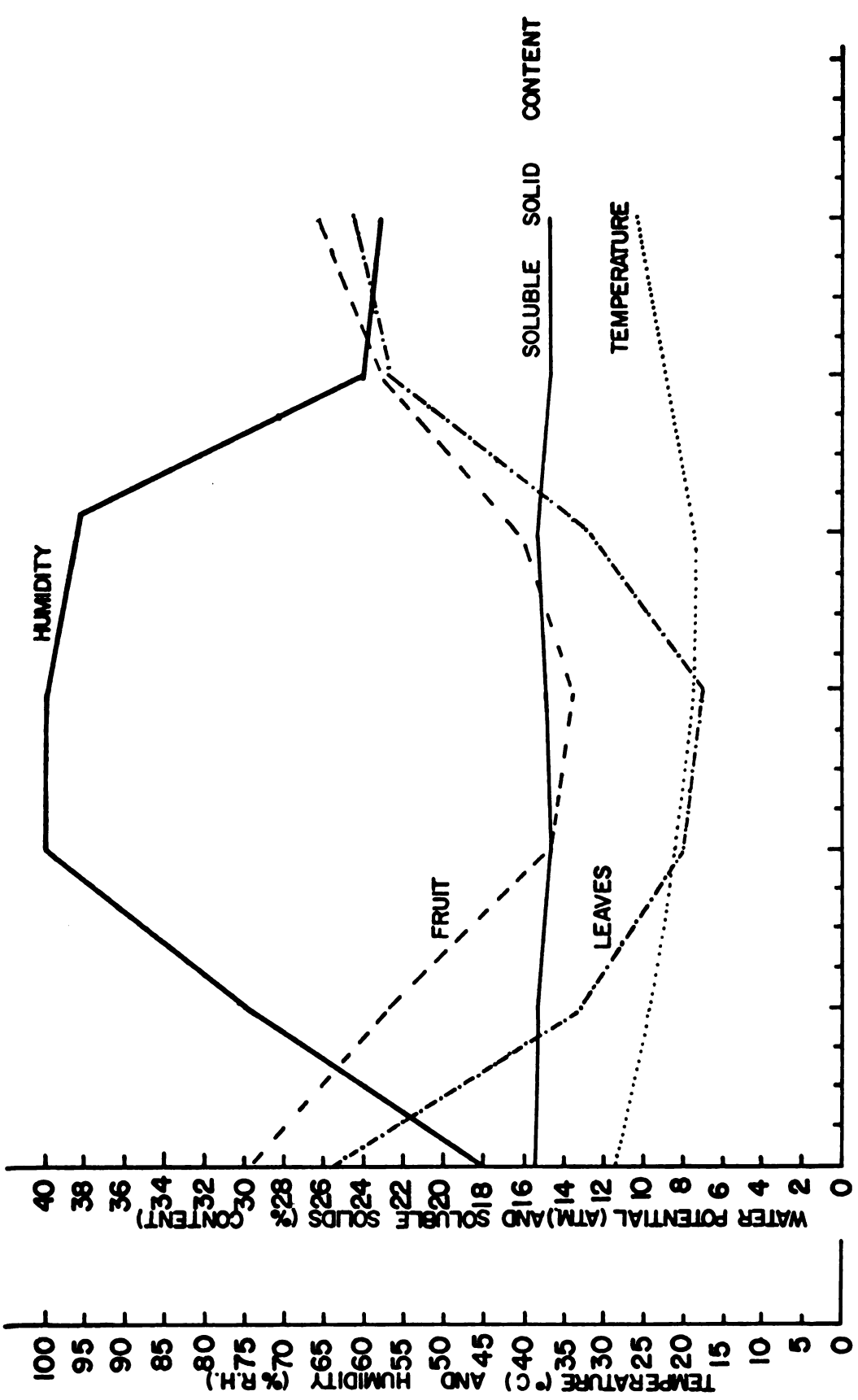


Figure 4.13.--The relationship among temperature, humidity, water potential (fruit and leaves), and soluble solid content for sweet cherries as a function of time throughout a 24 hour period taken during the 1971 season.

TABLE 4.13.--Analysis of variance table for water potential (atm) of sweet cherry fruit (1971).

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	1	0.30
Replication	1	0.78
Ethephon x replication	1	10.63**
Time	6	122.99**
Ethephon x time	6	1.60
Ethephon x time x replication	6	0.69
Remaining error	118	
Total	139	

Mean water potential for sweet cherry fruit for different times.

	Time (hours)	Water Potential (atm)
7/12/1971	3:00 PM	29.95
	7:00 PM	22.83
	11:00 PM	14.83
7/13/1971	3:00 AM	13.40
	7:00 AM	16.00
	11:00 AM	23.08
	3:00 PM	26.20

Mean water potential for sweet cherry fruit for different times listed for Tukey's w-procedure.

Time (hours)	Water Potential (atm)	α 0.01 and 0.05
3:00 PM (start)	29.95	
3:00 PM (final)	26.20	
11:00 AM	23.08	
7:00 PM	22.82	
7:00 AM	16.00	
11:00 PM	14.83	
3:00 AM	13.40	

**α = 0.01 Mean value of fruit water potential = 20.89 + 6.36
Mean value of water potential of check = 21.01
Mean value of water potential of treated = 20.78

Tukey's w-procedure--Values connected by a common line were not significant at the indicated levels.

TABLE 4.14.--Analysis of variance table for water potential (atm) of leaves of sweet cherries (1971).

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	1	2.09
Replication	1	5.14*
Ethephon x replication	1	1.66
Time	6	175.40**
Ethephon x time	6	3.58*
Ethephon x time x replication	6	0.35
Remaining error	118	
Total	139	

Mean water potential for sweet cherry leaves for different times.

	Time (hours)	Water Potential (atm)
7/12/1971	3:00 PM	25.70
	7:00 PM	13.18
	11:00 PM	8.00
7/13/1971	3:00 AM	6.98
	7:00 AM	12.60
	11:00 AM	22.80
	3:00 PM	24.60

Mean water potential for sweet cherry leaves for different times listed for Tukey's w-procedure.

Time (hours)	Water Potential (atm)	α 0.01 , 0.05
3:00 PM (start	25.70	| |
3:00 PM (final)	24.60	| |
11:00 AM	22.80	
7:00 PM	13.48	| |
7:00 AM	12.60	| |
11:00 PM	8.00	| |
3:00 AM	6.98	| |

** α = 0.01 Mean value of leaf water potential = 16.264 + 7.893

* α = 0.05 Mean value of non-treated = 15.936

Mean value of ethephon - 16.593

Tukey's w-procedure--Values connected by a common line were not significant at the indicated levels.

85 percent relative humidity until tested. After being held 24 hours in the controlled environment chamber, each of the 20 fruit were removed and punctured in 9 locations (four punctures at stem end, four punctures at the middle and one puncture at the blossom end), with all punctures starting at the suture and located 90 degrees apart about the fruit stem to apex axis. The puncturing was done with the Instron Universal Tester, using a 0.0625-inch diameter flat-cylindrical probe at a load rate of 0.5 inches per minute.

An attempt was made to remove the cherry skin and make tensile determinations in the apex-stem and circumference directions. Because of the small diameter (less than 1 inch), the attempts to make these tensile determinations were not reproducible or meaningful.

Further attempts were made to simulate sweet cherry cracking using the vacuum immersion method employed by Thompson (1965). This method rendered only partial success in causing splitting of the fruit.

Samples of 20 sweet cherry fruit each were taken and placed in a solution of 0, 10, 20 and 30 percent sugar. The test lots were then held in a temperature chamber at 4.4, 15.5 and 26.6 degrees centigrade for a 24-hour period before two puncture force determinations were made on each fruit cheek. Cracking of the fruit was recorded if it occurred during the soak period.

4.4.2 Discussion of Results

Research results from laboratory puncture tests on sweet cherries indicate that the Schmidt variety had a more significant ($\alpha = 0.05$) correlation coefficient between puncture force and location on the fruit than the Napoleon variety. The correlation between punched locations goes down as the temperature goes up in a 4.4° to 26.6° centigrade range and a constant 85 percent relative humidity. At the 26.6° centigrade temperature, the correlation is significantly less than at the 4.4° and 15.5° centigrade temperatures used in the experiment. The fruit tested at the 4.4° and 15.5° centigrade temperatures had no significant change in correlation between locations.

The analysis of the puncture force on sweet cherries held at 4.4°, 15.5° and 26.6° centigrade and 85 percent relative humidity indicated that there were no significant differences among the puncture forces among the varieties, temperatures and the locations. Therefore, the effects of the varieties tested, the location of the puncture on the fruit and the temperature at which the fruit was held did not affect the values of the puncture forces obtained.

The effect of puncture values on sweet cherries held in different sugar solutions for different lengths of time was analyzed. Significant differences ($\alpha = 0.01$) were found in the puncture force for fruit held in the

different sugar solutions, temperatures, and among sweet cherry varieties, as well as for the interaction of sugar solution x temperature and variety x temperature (Table 4.15). As can be seen from Figure 4.14 and 4.15, the sugar solution x temperature response increased at a different rate (as the solution concentration increased) at 15.5°C than the rate of the fruit held at 4.4 and 26.6°C. This response was attributed to other factors not determined in this experiment.

As the percent of sugar solution increases from 0 to 30 percent, the puncture force resistance increases (Figures 4.14 and 4.15). The lowest puncture force for the soaking tests was at the lowest temperature and the highest puncture force was at the highest temperature. The sweet cherry varieties tested for puncture resistance, during a soak test in a sugar solution, indicate that the resistance increased with higher temperature and higher sugar solutions within the tested range.

Additional tests of the skin strength were made on sweet cherries treated with a chemical loosener (ethephon) and a firming agent (SADH). These tests were made to determine if the skin strength was significantly affected by these compounds. Puncture force readings at the middle of each fruit were made on the suture, opposite the suture and on both cheeks for twenty Schmidt cherries taken from each treatment.

TABLE 4.15.--Analysis of variance table for puncture of sweet cherries.

Source of Variance	Degrees of Freedom	F Statistic
Sugar solutions (0, 10, 20, 30%)	3	58.16**
Variety (Napoleon and Schmidt)	1	176.82**
Sugar solution x variety	3	0.40
Temperature (4.4, 15.5, & 26.6°C)	2	172.75**
Sugar solution x temperature	6	4.74**
Variety x temperature	2	7.29**
Sugar solution x variety x temperature	6	0.67
Remaining error	576	
Total	599	

Manufacture force in grams = 149.68 $\pm$ 32.36

Mean values for varieties: Napoleon = 137.85
Schmidt = 161.51

Mean values for solution concentrations:*

0% = 133.02
10% = 144.57
20% = 158.12
30% = 163.00

Mean values for temperature of solutions (C°):*

4.4° = 128.66
15.5° = 151.32
26.6° = 169.00

** α = 0.01

*All treatment means were significantly different at the α = 0.01 level as tested by Tukey's w-procedure.

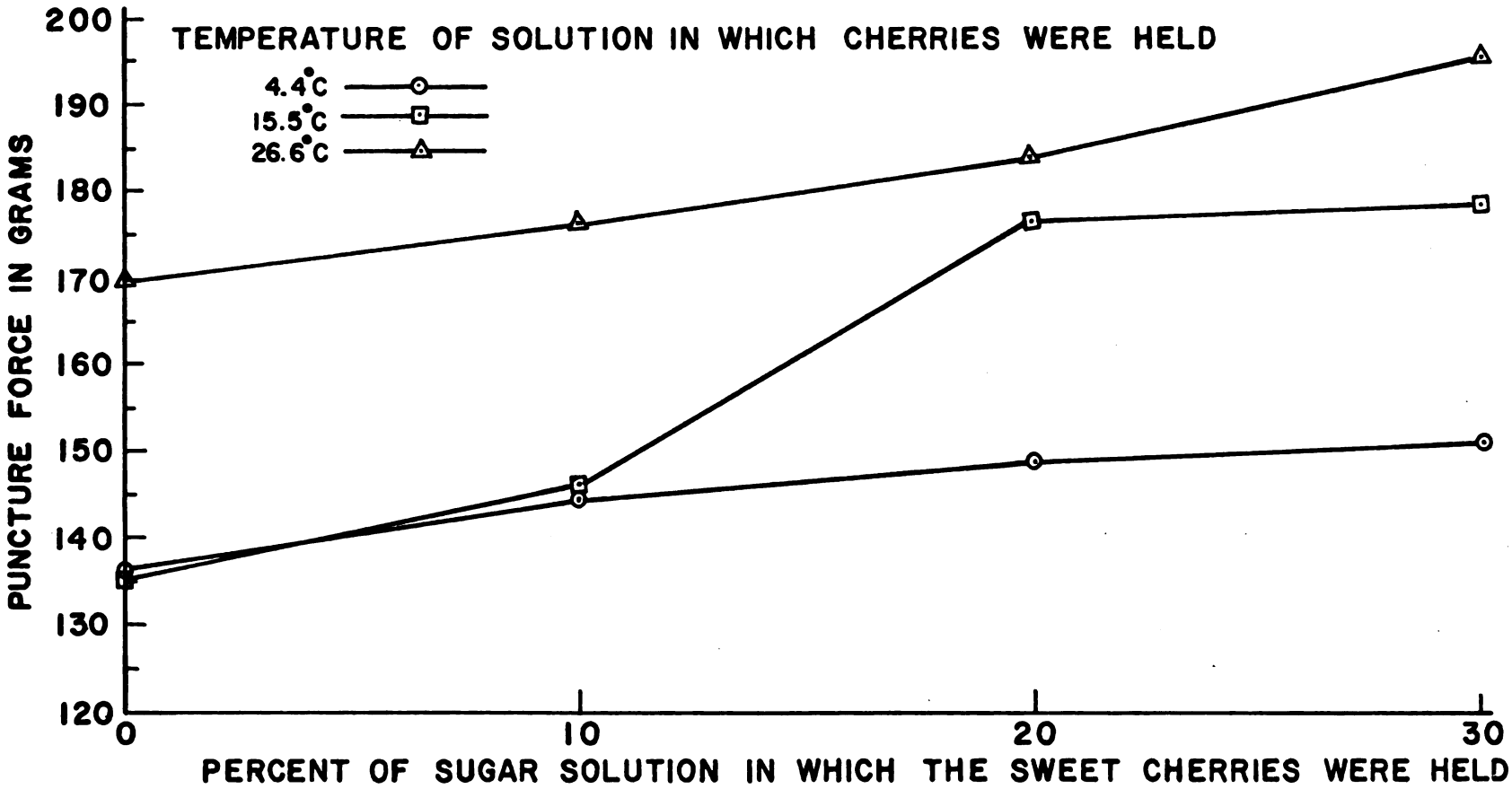


Figure 4.14.--Mean value for puncture force obtained from a 0.125 inch diameter probe after the Schmidt cherries were held for 24 hours in sugar solutions at different temperatures.

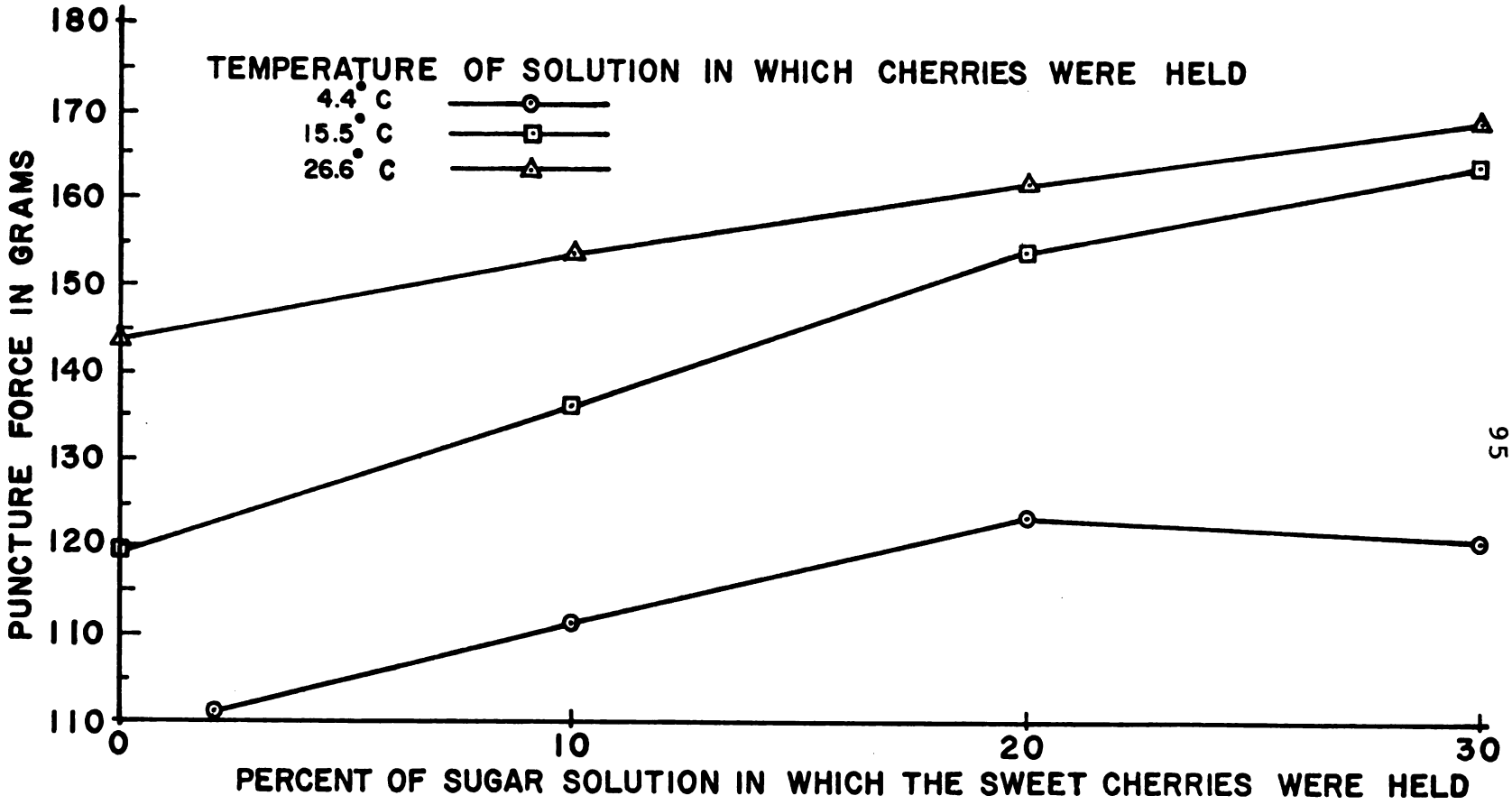


Figure 4.15.--Mean value for puncture force obtained from a 0.125 inch diameter probe after the Napoleon cherries were held for 24 hours in a sugar solution at different temperatures.

For ethephon treated fruit, there was no significant difference between the skin puncture force required for the various locations on the cherries. Similar results occurred for the non-treated fruit. Because of the decrease in incidence of split fruit treated by the ethephon soaking test, one would expect the skin strength to be increased by this treatment. This was not the case. Therefore, the decrease in fruit splitting for ethephon treated cherries must be caused by some mechanism other than soluble solid content and skin strength.

For the SADH treated fruit, the overall skin puncture force was below the values obtained for the non-treated cherries. The reduction in the average puncture strength for the SADH treated fruit may somewhat explain the increased percent of fruit that split during soaking.

The effect of time on puncture force for ethephon treated sweet cherries varied considerably for some unknown reason throughout the 24-hour period in respect to the ability of fruit to resist puncture (Table 4.16). The position on the fruit in respect to puncture and the cheek on which the puncture force occurred were not significant. Neither was there a significant interaction between the treatment and location of the puncture on the fruit.

TABLE 4.16.--Analysis of variance table for puncture force on fruit in two locations (1970)--cheek and opposite cheek.

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	2	9.27**
Location (cheek)	1	0.18
Ethephon x location	2	0.38
Time	6	13.53**
Ethephon x time	12	1.33
Ethephon x location x time	12	1.54
Remaining error	174	
Total	209	

Mean sweet cherry puncture force for different times.

	Time (hours)	Puncture Force (ounce)
7/15/1970	12:00 Noon	4.917
	4:00 PM	6.325
	8:00 PM	5.808
	12:00 Midnight	6.308
	4:00 AM	6.325
	8:00 AM	6.583
7/16/1970	12:00 Noon	5.825

Mean sweet cherry puncture force for different times listed for Tukey's w-procedure.

Time (hours)	Puncture Force (ounce)	α 0.01 , 0.05
8:00 AM	6.583	
4:00 AM	6.325	
4:00 PM	6.325	
12:00 Midnight	6.308	
12:00 Noon (final)	5.825	
8:00 PM	5.808	
12:00 Noon (start)	4.917	

**α = 0.01 Mean puncture force (1/16 inch probe) = 6.01 $\pm$ 1.02 oz.

Mean non-treated = 6.33 oz.*
Mean 250 ppm ethephon = 6.00 oz.
Mean 500 ppm ethephon = 5.72 oz.

*All treatment means were significantly different at the α = 0.01 level as tested by Tukey's w-procedure.

Tukey's w-procedure--Values connected by common line were not significant at the indicated levels.

Also, the treatment location and time interactions were not significant for this particular test. The mean puncture force value was greater for the non-treated fruit than either level of ethephon (Figure 4.16). The lowest value of puncture force was obtained from the highest level of ethephon treatment. This experiment was replicated during another season to determine if seasonal effects influence the fruit resistance to puncture force after being treated with different levels of ethephon. The 1971 test for puncture resistance of the sweet cherry skin resulted in the same order of significance that was obtained the previous season (Table 4.17). Both ethephon treatment and time of day had a significant effect on the puncture resistance of the fruit skin (Figure 4.17). Comparing the mean values of puncture resistance for the 1970 season, one finds the highest value was obtained for the non-treated fruit and the lowest value for the highest level of treated fruit. The 1971 season results were completely reversed from the previous year's mean puncture force values. Apparently, the effects of puncture values of the sweet cherry skin vary for season, as well as for treatment and time of day.

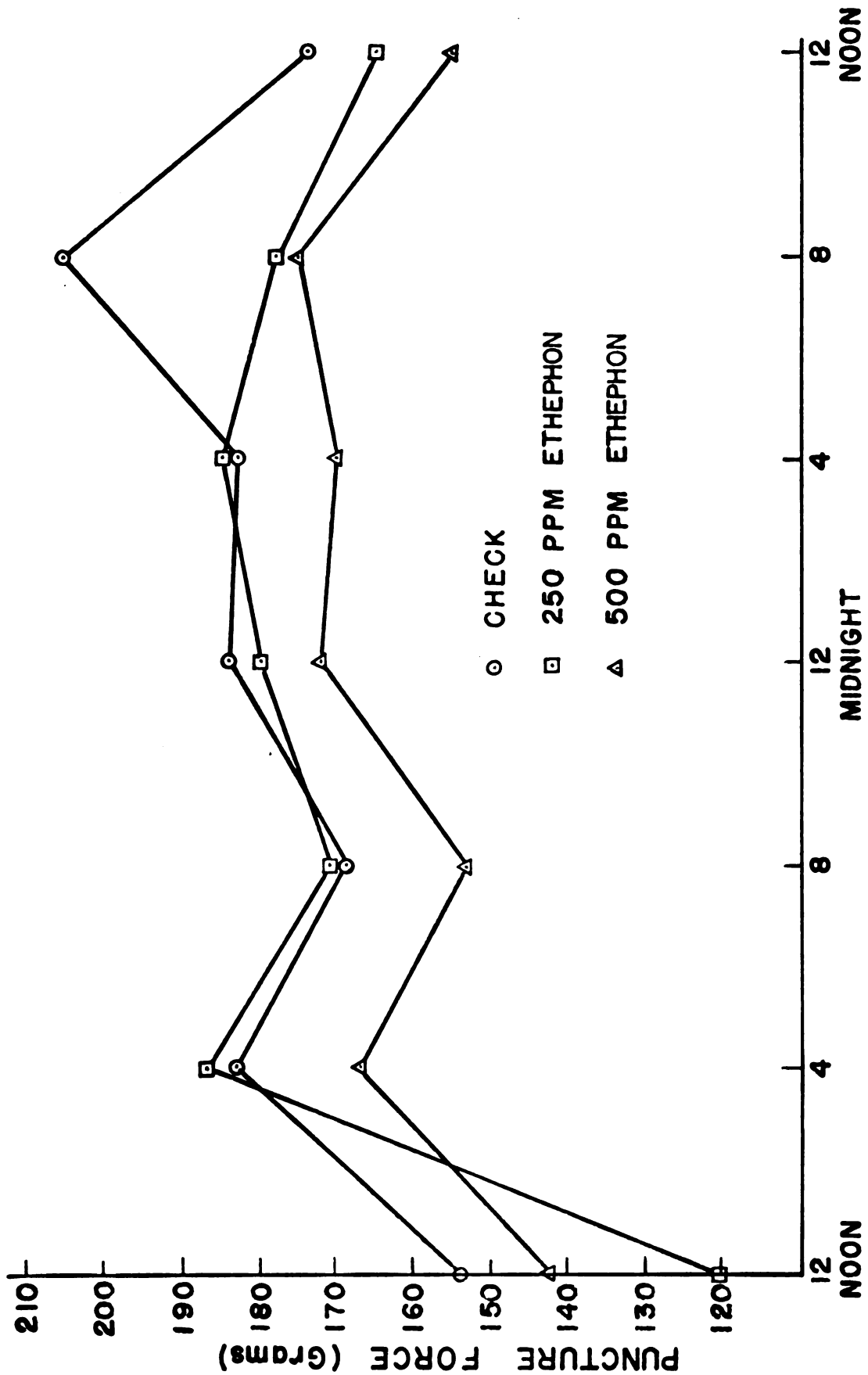


Figure 4.16.--The effect of time on puncture force for sweet cherries under the influence of ethephon for the 1971 season.

TABLE 4.17.--Analysis of variance table for puncture force on cheek of tomatoes (1971).

Source of Variance	Degrees of Freedom	F Statistic
Ethephon	1	4.09*
Replication	1	4.09*
Ethephon x replication	1	3.27
Time of day	6	5.70**
Ethephon x time	6	0.78
Ethephon x time x replication	6	0.84
Remaining error	118	
Total	139	

Mean sweet cherry puncture force for different times.

	Time (hours)	Puncture Force (ounce)
7/12/1971	3:00 PM	2.08
	7:00 PM	2.42
	11:00 PM	2.68
7/13/1971	3:00 AM	2.54
	7:00 AM	2.32
	11:00 AM	2.42
	3:00 PM	2.19

Mean sweet cherry puncture force for different times listed for Tukey's w-procedure.

Time (hours)	Puncture Force (ounce)	α 0.01 and 0.05
11:00 AM	2.68	
3:00 AM	2.54	
7:00 PM	2.42	
11:00 AM	2.42	
7:00 AM	2.32	
3:00 PM (final)	2.19	
3:00 PM (start)	2.08	

* $\alpha = 0.05$ Mean puncture force = 2.38 $\pm$ 0.42
** $\alpha = 0.01$ Mean puncture force of non-treated = 2.31
Mean puncture force of treated = 2.44

Tukey's w-procedure--Values connected by a common line were not significant at the indicated levels.

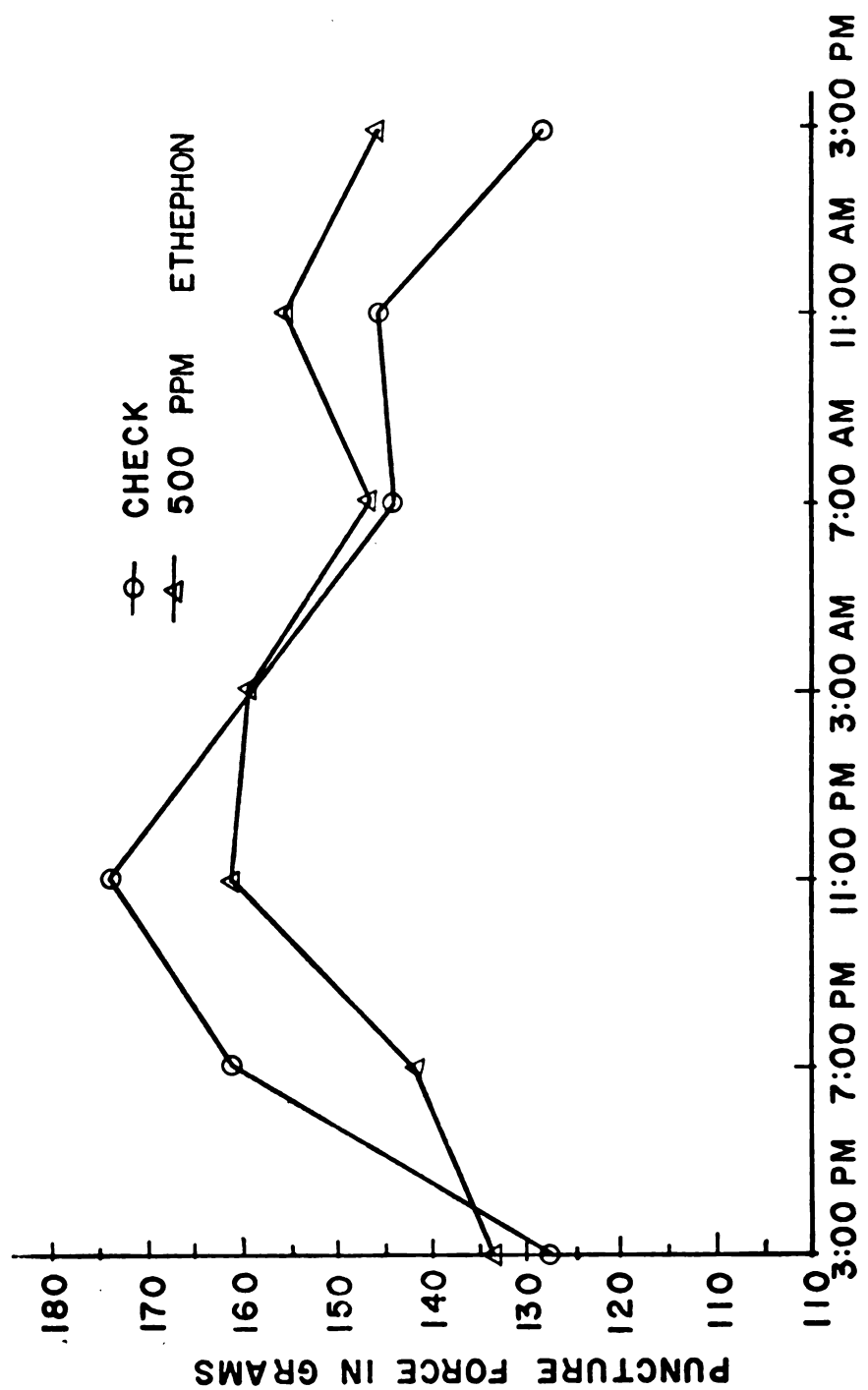


Figure 4.17.--The effects of time on puncture force for sweet cherries under the influence of ethephon for the 1971 season.

4.5 Puncture and Tensile Tests for Tomatoes

4.5.1 Procedure for Stress and Analysis

Tomato skins of two commercially grown varieties were isolated according to the method employed by Yamada, et al. (1965). Tensile samples were taken from the dehydrated skin and placed into the Instron Universal testing machine and loaded at 0.2 inches per minute until failure occurred. Two samples from each of the 10 fruit were from the cheek to cheek and stem to apex direction. Two additional tensile tests were made on tomato skin samples cut off the fruit by a stamp specimen cutter. These tests were to determine the effect of ethephon on the skin strength of tomato fruit. Twelve plots of each variety were sprayed with 0, 1000, and 3000 ppm of ethephon. Samples of four fruit each were taken from these plots every three days. Tensile force in two directions and two puncture force determinations were made at the same location on the fruit. A correlation between tensile and puncture force determinations was sought.

4.5.2 Discussion of Results

Puncture determinations were made on both Heinz 1350 and Campbell 1327 commercially grown tomato varieties with an 1/8-inch cylindrical probe at 0.5 inches per minute load rate. A total of nine punctures were selected,

consisting of one puncture on the apex end, four punctures in the middle of the fruit or cheek section, and four punctures on the stem end. Each of the four punctures were perpendicular to the preceding determination about the central axis (stem-apex) of the fruit. Correlation analysis of these 20 determinations on each variety held at three temperatures (4.4°, 15.5° and 26.6° centigrade) indicated that the Heinz variety 1350 had less correlation between puncture locations than did the Campbell 1327 variety. Thus, the Campbell variety 1327 has a more homogeneous skin than the Heinz 1350 variety.

A further analysis of this tomato puncture test indicated that temperature at which the fruit was held had a significant effect on the puncture resistance of the tomato skin (Table 4.18). The average value at which the fruit was held for 24-hours increased from 4.4° to 26.6° centigrade. The resistance to puncture on the fruit was the highest in the middle of the fruit or the cheek area, with a somewhat lower resistance obtained for the apex end and the lowest resistance at the stem end of the fruit (Table 4.18). This confirms Voisey's (1965) findings that more cracking occurs in the area of the lowest resistance to puncture of the skin. The interactions were not interpreted because the Campbell 1327 has been replaced by Campbell 28 as a variety grown for processing. Thus, the

TABLE 4.18.--Analysis of variance table for puncture force on an 1/8-inch diameter probe for tomato fruit held for 25 hours at the various temperatures.

Source of Variance	Degrees of Freedom	F Statistic
Variety (Campbell 1327 and Heinz 1350)	1	0.82
Temperature (4.4, 15.5 and 26.6°C)	2	13.73**
Variety x temperature	2	18.55**
Location (apex, cheek, and stem end)	2	10.95**
Variety x location	2	2.51
Variety x temperature x location	4	3.36
Remaining error	256	
Total	269	

Puncture Force	Pounds	Tukey's w-procedure $\alpha = 0.01$
Temperature		
4.4°	1.338	|
15.5°	1.274	
26.6°	1.169	
Locations		
Apex end	1.302	|
Middle of fruit	1.307	
Stem end	1.173	

Temperature	Heinz 1350	Campbell 1327
4.4°	1.421	1.256 |
26.6°	1.166 |	1.174 |
15.5°	1.159 |	1.399

* $\alpha = 0.05$
** $\alpha = 0.01$

Tukey's w-procedure--Values connected by a common line were not significant at the 0.01 level.

1971 analysis was done on Heinz 1350 and Campbell 28 varieties.

From the test results of the dehydrated skins, the tensile stress was calculated using an average value stated by Bukovac (1970a) for the fruit skin thickness as $t = 3.160 \times 10^{-4}$ inches. The average values obtained were the following:

Cheek to cheek direction

$\sigma = 2{,}965.0$ psi,

Cavity to apex

$\sigma = 2{,}901.0$ psi.

Thus, the tomato skin had a slightly larger stress value in the cheek-to-cheek direction. This may somewhat explain why tomatoes have more concentric than radial cracking.

The statistical analysis of the ethephon treated plots indicated that there was no significance ($\alpha = 0.05$) in the tensile stress for determinations, varieties (Heinz 1350 and Campbell 28), direction (cheek-to-cheek or cavity-to-apex) and time after treatment. Significance was not found among the puncture determinations for the various combinations. Assuming a skin thickness of $t = 3.160 \times 10^{-4}$ inches, Table 4.19 was developed. These values of skin stress recorded with hydrated skins were approximately 2.3 times greater than the value obtained from the dehydrated condition.

TABLE 4.19.--Values obtained for tensile and shear stress calculated by equation 25.

Variety	Tensile Stress in Two Directions, psi	
	Cheek-to-cheek	Stem-to-apex
Campbell 28	6,850 ± 1690	6,420 ± 2182
Heinz 1350	6,551 ± 1620	6,195 ± 1865
	Shear stress, psi (equation 25)	
Campbell 28	10,350 ± 1471	
Heinz 1350	9,650 ± 1540	

4.5.3 Prediction Equations for Tensile Force From Puncture Force Determinations of Tomato Skins

The tensile force determinations were very difficult and time-consuming to obtain. An attempt was made to determine if there was a relationship between puncture force and tensile force determinations. It was assumed that the puncture test determinations resulted in exact shearing occurring on the entire perimeter of the cylindrical probe. The shear value for puncture force could then be calculated by equation 25.

$$\tau = \frac{Fp}{\pi \times Dp \times t}, \qquad (25)$$

where: τ = Shear stress of skin

Fp = Puncture force, pounds,

Dp = Diameter of probe, inches,

t = Skin thickness, inches.

The resistance of the probe penetration into the fleshy epidermis of the tomato below the skin was found to be negligible (less than one percent of rupture force).

From equation 25, shear stress values were obtained and correlated with the corresponding tensile stress values obtained from the same skin locations. The values of the coefficients of linear regression equation were found to be highly significant ($\alpha = 0.01$). Using a cylindrical probe to rupture the skin, both varieties resulted in similar equations for computing the tensile stress:

Campbell 28

$$\sigma_t = 0.669\ \tau - 110.0,$$

Heinz 1350

$$\sigma_t = 0.416\ \tau + 2569.0.$$

CONCLUSIONS

The following conclusions can be drawn from this study:

5.1 General

1. Sufficient evidence was found in literature to describe a sweet cherry or tomato fruit as a pressure vessel filled with an arrangement of cubical or spherical shaped cells depending on the cell turgidity.

2. Mathematically it was shown that changes in the fruit model's cell shape (maintaining constant cell surface area during periods of low water potential) can be as great as 1.38 times the initial dimensions, resulting in an increased stress on the fruit skin that is a function of the cube of the fruit diameter.

5.2 Sweet Cherries

1. The highest incidence of sweet cherry cracking occurs on the fruit surface oriented away from the tree canopy, on the apex of the fruit, where mechanical damage has existed, and when the concentration of a soaking solution decreases.

2. Changes in the sweet cherry fruit diameter of the soaked sweet cherry fruit are a function of soluble

solid content, drop height for fruit, bruising when skin is ruptured, solution concentration, temperature, time and variety.

3. Ethephon treatment of sweet cherries has a significant effect and caused a decrease in puncture resistance, variability in the soluble solid content and a reduction in the diameter of the fruit.

4. Skin puncture resistance, diameter and water potential for sweet cherry samples taken from an orchard throughout a 24-hour period varied significantly. When sweet cherries were soaked in a sugar solution, the skin puncture resistance increased significantly with increases in temperature and increases in solution concentrations.

5.3 Tomatoes

1. Since puncture resistance is the highest in the cheek region of the fruit, the lowest resistance for puncture is at the stem end of the fruit, which was the area having the highest incidence of cracking. Puncture resistance decreased as the temperature of the fruit increased from 4.4°C to 26.6°C. It is evident that this method is reliable to determine crack resistance.

2. Tensile stress values for the tomato skin can be computed from puncture tests by using the circumference and rupture force to compute a shear stress which can be substituted in an empirical equation to compute tensile stress.

SUGGESTIONS FOR FURTHER STUDY

1. In developing a crack-resistant fruit variety, these three skin characteristics would contribute toward success:

    a. A highly elastic and puncture-resistant outer surface,

    b. A good moisture barrier in the skin to avoid excessive moisture flow from outside to the internal fruit cell complex, and

    c. A cell arrangement near the outer surface composed primarily of spherical cells.

2. Continuation of the search for dehydrating and anti-transpiration compounds that can be applied when periods of low water stress occur is definitely recommended.

3. Likewise, continuation of the search for chemicals (ethephon, etc.) that have a significant effect on the puncture resistance, soluble solid content and diameter of the fruit are suggested.

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APPENDIX

APPENDIX

CONVERSION FACTORS

1 Bar = 0.987 atmospheres

1 Bar = 1×10^6 dynes per centimeter

1 Bar = 1×10^6 ergs per centimeter

1 Inch = 2.540 centimeters

1 Pound = 4.448×10^5 dynes

1 Pound = 453.6 grams

1 Pound = 16 ounces

1 Pound per square inches = 0.06804 atmospheres

1 Pound per square inches = 6.895×10^4 dynes per square centimeter.