This is to certify that the

thesis entitled

TOMATO FRUIT CRACKING
IN RELATION TO WATER POTENTIAL CHANGE

presented by

Hope Estelle Herrera

has been accepted towards fulfillment
of the requirements for

M.S. degree in Agr. Eng.

George E. Merva

Major professor
George E. Merva

Date November 2, 1978

TOMATO FRUIT CRACKING
IN RELATION TO WATER POTENTIAL CHANGE

By

Hope Estelle Herrera

A THESIS

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

MASTER OF SCIENCE

Department of Agricultural Engineering

1978

ABSTRACT

TOMATO FRUIT CRACKING
IN RELATION TO WATER POTENTIAL CHANGE

By

Hope Estelle Herrera

Cracking of tomato fruits is a major concern to tomato producers, resulting in severe losses for processing and fresh market production.

Horticulturalists have attempted to breed tomato varieties that are resistant to cracking, however, the problem still exists.

The objectives of this investigation were to; show that a change in fruit water potential is one of the factors causing fruit cracking, develop a suitable method for measuring fruit water potential and relate the fruit water potential with that of the plant and its surroundings.

An abrupt change in water potential at the root zone was reflected by a change in water potential throughout the plant which was accompanied by fruit cracking. A satisfactory method for measuring the fruit water potential was also developed. However, the effect of ambient temperature and humidity conditions on these measurements does warrent further investigation.

Approved _____
Major Professor

Approved _____
Department Chairperson

To Salvador

ACKNOWLEDGMENTS

The author wishes to thank Dr. George E. Merva for whose guidance this project was developed. A special thanks to Dr. Haruhiko Murase for his technical guidance in the measurement of water potential.

Thanks to Dr. Hugh C. Price (Horticulture) and Dr. Larry J. Segerlind for serving on the guidance committee, and Dr. S. Honma for his cooperation in running the greenhouse experiment.

A final thank you to my fellow graduate students, family and friends who made this project a success.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Cracking of mature fruits is one of the most serious problems of tomato production in the United States (Hepler, 1961). This physiological disorder can cause significant economic losses to growers of tomatoes for both fresh market and processing. Cracking may be erratic in its occurrence because of unpredictable weather conditions (Frazier, 1934). It may be serious one year and not another, or it may occur only at certain times during the season depending on the weather conditions. As a result, tomato production has shifted from the eastern states to the western area (USDA, 1977) primarily because of the longer growing season, higher yields and a predictable supply of water through the use of irrigation.

Tomato production in the United States was over 5 million tons during 1977 (Michigan Agr. Statistics, 1978). Michigan was sixth in the production of tomatoes for processing, producing 63,500 tons (0.8% of the US total), and seventh in the production of tomatoes for fresh market, producing 39 million pounds (2% of the US total), resulting in a total cash value of 13 million dollars for Michigan alone in 1977 (Michigan Agr. Statistics, 1978).

Results with fresh market tomatoes in Illinois demonstrate the potential importance of cracking. The amount of fruit not salable due to fruit cracks ranged from 2 to 55 percent of the total yield for a season (Hepler, 1961).

Cracking of fruits to be used for processing results in a lower

overall grade and a lower dollar value of the crop. The lower grade and price can be attributed to reduced quality of fruits due to the presence of mold and fruit fly eggs and larvae in the cracked areas (Porter, 1960).

The importance of cracking has become more significant with the utilization of mechanical harvesters. Mechanical harvesters have a tendancy to enlarge the cracks and mix soil with the fruit which is then transported to the processing plant. With the introduction of varieties of concentrated maturity for machine harvesting of processed tomatoes, a whole season could be lost if cracking conditions were optimum prior to harvesting.

Horticulturalists have attempted to produce tomato varieties that have a high level of crack resistance (Reynard, 1951; Thompson, 1965; and Armstrong and Thompson, 1967), but the problem still exists. Partially effective means of controlling fruit rupture include harvest of mature fruit as soon as possible (Brown and Price, 1934, Frazier, 1934, and O'Brien, et al.,1978), maintenance of constant, plentiful soil moisture supply (Niiuchi, et al.,1959), avoidance of heavy irrigation just prior to harvest (Frazier, 1934), a good fertility program (Howlett and Kretchman, 1969), and selection of varieties resistant to cracking (Hepler, 1961).

By controlling the above parameters, one is affectively controlling the water potential of the plant-soil-atmosphere continuum. A limiting factor in controlling the water potential of this continuum is the lack of a more suitable and convenient means of measuring this relationship.

The objectives of this investigation were to: develop a suitable

method[1] for measuring fruit water potential; use hydroponics to allow for rapid change in water potential at the root zone; relate the fruit water potential with that of the leaves, roots and the atmosphere; and show that a change in water potential of the fruit is one of the factors which causes cracking of the fruit epidermis.

---

[1] Murase (1978) presented a method of fruit water potential measurements using a leaf thermocouple transducer.

2. LITERATURE REVIEW

2.1 Cracking of tomatoes

Tomato fruits generally crack radially or concentrically. Radial cracks have been found to be more common, particularly under greenhouse conditions (Frazier, 1934), and have caused the most serious losses (Reynard, 1951). They occur on the stem end of the fruit and radiate from the stem scar. They generally occur over the interlocular walls of the fruit (Hepler, 1961), and are induced by internal expansion pressure of the fruit (Niiuchi, et al., 1959). Concentric cracks occur as arcs or circles on the stem end or shoulder of the fruit. They are not connected to the stem scar and are induced by water uptake through the corky spots on the fruit (Niiuchi, et al., 1959).

Changing the soil moisture from low to high moisture induced more cracks than that from medium to high moisture (Niiuchi, et al., 1959; Frazier, 1934; Brown and Price, 1934). Low evaporation during night hours (Frazier and Bowers, 1947) and reduction in transpiration (Singh and Young, 1970) may increase cell turgidity resulting in increased cracking.

Rain may produce cracking in tomatoes within a few hours (Frazier, 1934). The water is absorbed through the corky layer of the stem end, or may be taken in through small corky areas of the skin. Frazier found that perceptible increases in cracking following very light showers indicates that appreciable absorption of external water by the fruit

is not necessary for cracking to occur, but that the mere decrease in transpiration of water from the fruit [sic] is apparently sufficient to cause expansion and subsequent rupture. He concluded that traces of water on fruit surfaces, particularly about the stem, are also probably a factor under these specific conditions.

The degree of cracking increases with the stage of ripeness at which the fruit is picked, beginning a few days before reaching the pink stage and extending through the red ripe stage of development (Brown and Price, 1934; Frazier, 1934; Frazier and Bowers, 1938,1947). Only in the very immature stages are all of the fruits entirely free from cracks (Brown and Price, 1934).

Shading was found to be beneficial in reducing the severity of cracking (Brown and Price, 1934; Niiuchi, et al., 1959; Frazier, 1934). Fruits from shaded vines are high in water content, low in freezing point depression, low in total sugars, free reducing substances and total carbohydrates (Frazier, 1934). Frazier also stated that fruits low in water content are the ones most susceptible to severe cracking when conditions become favorable. Bagging the fruits with polyethylene bags or covering the plants with a plastic tent enhanced cracking probably by increasing the temperature and humidity under cover. This reduction in transpiration may increase cell turgidity which may contribute to tomato fruit cracking (Singh and Young, 1970).

Cracking was more prevalent on fruits from pruned, staked plants, as compared to those not pruned and not staked (Frazier, 1934,1935; Frazier and Bowers, 1947). Frazier and Bowers (1947) also concluded that not only was the foliage and shading of the fruit important in this case, but the restricted root system of pruned plants, with its

effect on internal water relations, must be considered. Removal of leaves from the pruned plants resulted in a decided decrease in cracking, as compared with pruned, non-defoliated plants (Frazier, 1935). Frazier (1936) found that the variability in cracking data on tomatoes was extremely high. His results showed wide differences in the degree of cracking of fruit from adjacent vines of the same variety of fruits of the same physiological age on a given vine and even of fruits on a given cluster.

There is general agreement that absorption and distribution of water in a tomato fruit is one of the major factors related to crack resistance (Mel Chih-Yu Chu and Thompson, 1972). Cotner, et al.(1969) found that fruits resistant to cracking have a more extensive vascular system.

Several methods have been developed to measure the crack resistance of various varieties: Frazier (1934) used a common corn pressure tester to measure the resistance of a tomato to puncture. Further skin puncture studies by Johannessen (1949), showed that the stem end of the ripe fruit was significantly less resistant to puncture then was the middle of the fruit and that resistance to puncture at the middle was significantly less than at the blossom end of the fruit. The texture of the flesh supporting the skin may influence the results of the puncture test (Voisey, et al., 1964, 1970). Cracking resistance does not appear to be governed by skin thickness, but by stress relaxation properties (Voisey and Lyall, 1964), skin strength and its ability to stretch (Voisey, et al., 1970) are the contributing factors to crack resistance.

Armstrong and Thompson (1967, 1969) used the Illinois vacuum-

immersion technique, developed by Hepler (1961) to measure crack susceptibility. They found that higher resistance to cracking could be obtained by imposing heavy selection pressure in prior generations. These results were in agreement with preliminary results by Thompson (1965) which demonstrated that it is possible to select lines with higher levels of crack resistance than that found in either of the resistant parents.

2.2 Cracking of other Fruits

Sweet cherries were found to crack during rain as a result of sudden enlargement of the fruit. Water was absorpted directly through the skin while the cherry was wet (Verner, 1939). The absorption of water through the skin of the fruit is affected by; the osmotic concentration [sic] of the fruit juice, turgor of the fruit, temperature of the water, and by skin permeability (Verner and Blodgett, 1931).

Stomate degeneration was found to be the major cause of prune cracking. Degeneration occured about two weeks prior to harvest primarily between the hours of 4:00 and 7:00 am when the fruit contained the most water and was largest in size (Newton, 1972).

Pronounced fluctuations in soil-moisture content showed no relationship to either the occurrence or the severity of cracking in Stayman Winesap apples. However, under normal orchard conditions, the occurrence of cracking was always found to be associated with very low evaporation rates (Verner, 1935). The tendency toward marked restriction of growth in the hypodermal layer late in the growing season while the fleshy portions of the fruit may be enlarging at a normal or an excessive rate was found to be a possible cause of cracking in

apples (Verner, 1938).

2.3 Hydroponics

The basic principle of water culture is that the plant roots develop and grow in a liquid medium which contains all the necessary nutrient minerals (Ellis and Swaney, 1947). Ellis and Swaney pointed out that in water culture, because it is essentially a non-buffered system, more exact control of the nutrient solution is often necessary, particularly the acidity, phosphate, and iron relations. The importance of sufficient oxygen in the immediate proximity of the roots to sustain proper plant growth was also noted.

Darkness in the root zone, aeration, circulation and temperature of the solution are several of the physical aspects of the nutrient solution that must be handled correctly to promote proper plant growth (Ellis and Swaney, 1947). Ellis and Swaney's recommendations to control these physical aspects follow: Roots must be kept in the dark to prevent growth of various green algae which will interfere with the proper growth of the crop. These green algae compete for nutrients, reduce the solution acidity, and make the culture slimy and adorous. The maintenance of a 5 to 7 cm air space between the liquid surface and the crown of the plant or the bottom of the tray is somewhat effective in supplying some oxygen to the roots. However, forced aeration is definitely needed to secure the best results in water culture. Circulation of the nutrient solution provides better distribution of the nutrient ions and better aeration. The nutrient solution should not become warmer than the daytime air temperature and preferably not over 32 to 38^{o}C.

The nutrient solution must provide the necessary inorganic elements required for plant growth; nitrogen, potassium, calcium, magnesium, sulfur, phosphorus, iron, manganese, boron, copper, and zinc. These elements must be supplied in a readily available form, thus complete solubility of the essential ions in water is a prerequisite for an inorganic nutrient solution (Ellis and Swaney, 1947). As the solute concentration of a nutrient solution increases, the availability of water to the plant roots decreases. Ellis and Swaney (1947) stated that it is entirely possible to stop the growth of the plant with a solution of high solute concentration or even kill the plant. Storm (1978) pointed out that it is sometimes necessary to rinse the roots with clear water to remove the ion buildup that accumulates on the roots from the solution.

2.4 Tomato Growth under Hydroponic Culture

Tomato plants are usually trained to a single stem by removing sideshoots at least weekly (Wittwer and Honma, 1969). The plants are occasionally supported by stakes, but usually by twine. One end of the twine is tied with a small non-slip loop to the base of the plant while the other is attached to a support 2 to 2½ meters above the plant row (Wittwer and Honma, 1969). Wittwer and Honma reported that, recently, plastic plant clips have been used as an alternative to the usual non-slip loop.

Pollination of greenhouse tomatoes is required in order for flowers to set fruit (Wittwer and Honma, 1969; Purdue University, 1974). Pollen is shed most abundantly on bright sunny days, if cloudy days persist for 2 or more days, the temperature of the green house must

be raised to remove the dampness from the pollen so that it will be more apt to fall free from the male portion of the flower to the female portion at the time of pollination (Purdue University, 1974).

Disease can be controlled by the use of pesticides, and an environmental control system maintaining three basic components: heating, ventilation and circulation of the atmosphere in the greenhouse.

2.5 Water Potential

Water potential is a measure of the free (potential) energy per mole of water in a system compared with the free energy of pure free water at the same temperature and pressure. It can be expressed in the units of pressure (atm), and is usually negative if the free energy is lower than that of pure free water at the same temperature and pressure (Van Haveren and Brown, 1972).

The water potential is the sum of a number of component forces acting on the water in a system that result from the presence of solutes, hydrostatic pressure, gravity and matric surfaces (Van Haveren and Brown, 1972; Merva, 1975). Thus, the total water potential as applied to the soil-plant-atmosphere continuum is often given as:

$$\Psi_w = \Psi_s + \Psi_p + \Psi_g + \Psi_t \qquad (1)$$

where $\Psi_s, \Psi_p, \Psi_g, \Psi_t$ are, respectively, the solute, pressure, gravitational, and matrix components (Van Haveren and Brown, 1972; Merva, 1975).

Under equilibrium conditions, using vapor pressure, the water potential is modeled by the expression:

$$\Psi_w = RT \ln(e/e^o) \; / \; \overline{V}_w \qquad (2)$$

(Merva, 1975) where; R = Ideal gas constant (82.05 cm^3-atm/^oK-mole)

T = Absolute temperature (^oK)

e = Partial pressure of water vapor

e^o = Saturated partial pressure of water vapor

$\bar{V}_w$ = Partial molal volume of liquid water(cm^3/mole)

e/e^o = Relative humidity

The Peltier psychrometer can be used to infer the water potential from the equilibrium vapor pressure (Eq. 2) at a constant temperature and pressure. This is accomplished by suspending the psychrometer over a freely evaporating surface of the tissue and is used to measure the vapor pressure that is in equilibrium with that system. This requires that the psychrometer either be sealed in a vapor tight chamber with the sample, or that it be placed in intimate contact with the system for in-situ measurements (Van Haveren and Brown, 1972).

Merva (1975) has shown that a relationship between temperature of a vapor T and the vapor pressure e^o exists and has the form;

$$e^o = \exp(a - b/T) \qquad (3)$$

where a and b for practical purposes can be considered constant. Merva (1975) concluded that if the temperature of the plant part fluctuates then the water potential as measured by the thermocouple psychrometer will vary.

Merva (1975) showed from equation 2, using Raoult's law, that the water potential of a solution is due to the solute concentration of that solution.

$$\Psi_w(\text{solution}) = \Psi_S = -RTC_S \qquad (4)$$

Where C_S is the number of moles of solute per volume of solution. For

pure water C_s is equal to zero, therefore the water potential of pure water is zero (atm). Thus any solution has a water potential less than that of pure water.

The water potential of the plant cell can be modeled by:

$$\Psi_w \text{ (plant cell)} = \Psi_s + \Psi_p \qquad (5)$$

(Merva, 1975) where; Ψ_s = Solute potential due to the sugars and minerals contained in the cell.

Ψ_p = Pressure potential due to the hydrostatic (turgor) pressure inside the cell.

The water potential of the atmosphere can be calculated using equation 2, page 10. At 27°C, the water potential would range from -817 atm. at 55% relative humidity to -305 atm. at 80% relative humidity.

In hydroponic culture, there is a water potential gradient from the rizosphere through the plant and to the atmosphere. Merva (1975) pointed out that water movement in vegetative tissue occurs as a result of this water potential gradient.

2.6 Plant Water Potential

Water potential of tissue has been shown to influence the mechanical properties of vegetative materials: Dal Fabbro, et al. (1978) reported that water potential of vegetative tissue influences the failure strain level significantly. Murase, et al. (1978) reported that the apparent Young's modulus of potatoes is dependent on the water potential. De Baerdemaeker, et al. (1978) found that water potential affects the tensile and compressive failure stresses of apple and potato tissue. Murase and Merva (1977a) developed constitutive equations for vegetative media. Murase (1977) reported that the stress

state of tomato epidermis is affected by cell water potential. Murase and Merva (1977b) found that the elastic modulus of tomato skin is a function of water potential. They concluded that the cracking phenomena is possibly a skin failure of fruits due to excessive stresses produced in fruit skin by changes primarily in tissue water potential.

2.7 Leaf Water Potential Measurement

Plant water stress depends on the relative rates of water absorption and water loss, not on the rate of water absorption alone (Kramer, 1959). Brix(1962) explained that it is possible for plants growing in relatively dry soil to be subjected to low water stress during periods of low transpiration, while plants in soil at field capacity may be subjected to high water stress during periods of rapid transpiration.

Kramer (1963) stressed the need for accurate measurements of water potential in plants, and pointed out that plant water potential is a key property affecting many other properties such as turgor, growth, stomatal aperture, transpiration, photosynthesis, and respiration. The development of miniature thermocouple psychrometers by Spanner (1951) and Richards and Ogata (1958) has facilitated this measurement (Brix, 1962; Ehlig, 1962; Barrs, 1965a, b; Boyer, 1967, 1968).

Water potential thermocouple psychrometers determine the energy status of water, by measuring the equilibrium vapor pressure (Van Haveren and Brown, 1972). The Peltier psychrometer, developed by Spanner (1951), is cooled by passing a peltier current through the thermocouple junction resulting in condensation of water vapor on

the junction (Van Haveren and Brown, 1972). This minute amount of moisture that collects on the thermocouple junction allows the junction to be used as an exceedingly fine 'wet-bulb' thermometer (Spanner, 1951). Boyer (1968) pointed out that determination with this equipment required the transfer of small amounts of water vapor between the leaf tissue and the thermocouple. However, he indicated that the resulting changes in water content of the tissue are negligibly small so that water uptake from the instrument has no influence on the measurement. Boyer used the Peltier psychrometer to measure the water potentials of intact leaves. He found that recovery from water deficits occured in two phases; first with the elimination of water deficits, and second with cell enlargements which were characterized by a steady rate of water uptake and a relatively constant leaf water potential.

The wet-loop psychrometer developed by Richards and Ogata (1958) is wetted by physically placing a drop of water in a small silver ring at the junction of the thermocouple (Van Haveren and Brown, 1972). Rawlins (1964) suggested that, in the case of the wet-loop psychrometer, the psychrometer may alter the potential within the equilibration chamber. Rawlins (1964) reported an error of at least 60 percent in the determination of the water potential of pepper leaves when he used the Richards and Ogata psychrometer. He indicated that water will distill continuously from the wet junction to the leaf, provided it is not fully turgid. Barrs (1965b) reported that if the leaf were to offer a significant resistance to water-vapor diffusion, the vapor pressure at the leaf surface would become significantly greater than that within the leaf. This would increase the psychrometer reading and

result in an overestimation of the water potential of the leaf (Barrs, 1965b). Ehlig (1962) described techniques which could be used to increase the accuracy of measuring the energy status of excised plant leaves with the Richards and Ogata psychrometer.

Barrs (1965a) concluded that the Spanner psychrometer has advantages over the Richards and Ogata instrument in the determination of leaf water potential. He reported that the Spanner psychrometer can be used to take into account the departure of chamber temperature from bath temperature caused by metabolic activity, whereas a single Richards psychrometer cannot. Barrs (1964, 1965a) measured temperature rises within the chamber when living tissue was present. Leaf permeability was not sufficiently low so as to affect determination of leaf water potential when either the Spanner or the Richards and Ogata psychrometer was used (Barrs, 1965b). He also found good agreement between the two instruments, provided corrections for respiration effects were applied.

2.8 Fruit Water Potential Measurement

Murase and Horinkova (1977) developed a method of fruit water potential measurement using a leaf thermocouple transducer. To utilize the vapor phase measuring system it was required to remove the cuticle. Since cuticle is extremely thin, it is impossible to avoid excision of epidermal and parenchyma cells, however, this does not affect the measured water potential (Murase and Horinkova, 1977).

3. EXPERIMENTAL PROCEDURE

3.1 Hydroponic Set Up

Tomato plants of the Vendor variety were received from the Marsh Greenhouse located in Rockwood, Michigan. They were initially rooted in vermiculite, thus requiring that the roots be rinsed before transplanting to the hydroponic solution.

Plastic kitchen dishpans were used to contain the solution for each individual plant. A wooden frame was constructed to fit the top of each dishpan. The frame supported a 15 mm mesh woven from fish line to form a support surface. A 4 cm layer of excelsior was used on top of the mesh to hold the plants in place and support the root system. Six to nine liters of solution were maintained at all times in each pan, providing a solution depth of 10 to 15 cm. Oxygen was supplied to the roots by forcing compressed air through small holes in tygon tubing which was submerged in the solution, while an air space of 5 to 10 cm was maintained between the solution and the excelsior to supply the additional oxygen required for root metabolism (See figure 1).

Black plastic was used to cover the dishpans and the excelsior to exclude light from the roots and to prevent algae growth on the roots.

3.2 Nutrient Solution

The nutrient solution consisted of 1 M (molar) stock solutions of the major elements, an iron solution and a micronutrient solution as follows:

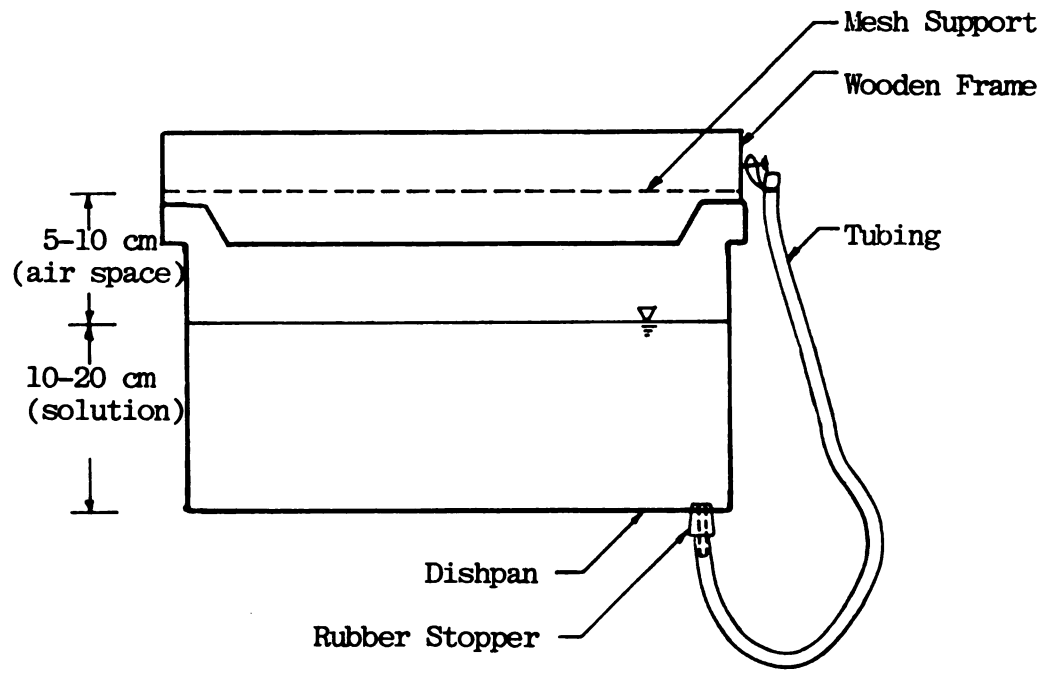

Figure 1. Hydroponic Setup

Major Elements (USDA, 1972)

#1	potassium dihydrogen phosphate	KH_2PO_4	131.1 g/l
#2	potassium nitrate	KNO_3	101.1 g/l
#3	calcium nitrate	$Ca(NO_3)$	236.2 g/l
#4	magnesium sulfate	$MgSO_4$	246.5 g/l

Iron Solution (USDA, 1972)

#5	iron chelates (10,000 ppm)	10.0 g/l

Micronutrients (Total to make 1 liter stock solution, each dissolved in the order listed to prevent precipitates.) (Hoagland and Arnon, 1950)

#6	a. boric acid	H_3BO_3	2.86 g/l
	b. manganese cloride	$MnCl_24H_2O$	1.81 g/l
	c. zinc sulfate	$ZnSO_47H_2O$	0.22 g/l
	d. cupric sulfate	$CuSO_45H_2O$	0.08 g/l
	e. molybdic acid	$H_2MoO_4H_2O$	0.02 g/l

Forty liters of nutrient solution were then prepared from the stock solutions by adding the following amounts to 39.4 liters of deionized water:

Stock Solution	ml
#1	40
#2	200
#3	200
#4	80
#5	40
#6	40

The reaction of the solution was adjusted to a pH of 6 to 6.5 by adding 0.1 N H_2SO_4.

It was necessary to change the solution every week during the first six weeks to provide the appropriate balance of nutrients for plant growth. After the initial growth period, it was necessary to change the solution every 3 to 4 days because of the increased rate of water uptake by the plant due to higher ambient temperatures, increasing day length and the greater amount of leaf surface area for transpiration to take place.

In order to change the solution on the roots without disturbing the plants, a 2.5cm hole, as shown in figure 1, was made in the bottom of each dishpan and fitted with a cork and rubber tubing. The tubing was fastened to the side of the wooden frame until the solution was to be emptied. The tubing was then lowered, allowing the solution to drain completely. The tubing was again fastened to the frame and the dishpans were refilled. The roots were rinsed with tap water every week to remove the ion accumulation on the root surfaces. The rinse water was allowed to remain for 24 hours and was then replaced by nutrient solution.

3.3 Plant Care

The plants were fumigated every 7 to 10 days with Orthene to control insect infestation. Supplemental lighting was applied between the hours of 6:00 am and 9:00 pm using a timing device and flourescent lights. The flowers were pollinated using an electrical vibrator on each flower cluster every other day during warm sunny weather between 10:00 am and 3:00 pm.

The plants were pruned weekly to a single stem and trained upward using plastic clips and twine, one end of which was fastened to a plastic clip at the base of the plant, while the other end was tied to an over-

hanging frame.

3.4 Plant Preparation and Treatment

Following fruit maturation and ripening, the plants for experiments 1, 2 and 3 were fastened to a support stand and transported to the laboratory at different times for testing. In each case, the nutrient solution remained in contact with the roots until the experiments were entirely set up. The first experiment was conducted at room temperature on a laboratory table. The nutrient solution was initially drained and the roots were allowed to remain in contact with the air for 3,315 minutes (55 hours and 15 minutes) at which time the roots were covered with distilled water. (It should be noted that the fruit in experiment 1 were initially cracked). The second and third experiments were carried out in a Sherer environmental chamber (model CEL 25-7HL)[1], which was used solely as an insulated box. In experiment 2, the cracked fruits were initially picked and the nutrient solution was allowed to remain on the roots until a time of 460 minutes when the solution was drained and replaced with distilled water. At the time of 806 minutes, the distilled water was drained and the roots remained in contact with the air until a time of 1,880 minutes when the roots were again covered with distilled water. In experiment 3, initially the cracked fruits were picked, the nutrient solution was drained, the roots were rinsed with distilled water and allowed to be in contact with the air, at a time of 1,170 minutes the roots were covered with distilled water.

---

1) Sherer-Gillett Co., Marshall, Michigan.

In experiment 4, the plants were grown hydroponically using a trough system[1]. When using the trough system, an extremely severe buildup of ions on the root surfaces develops, causing a salt incrustation, thus requiring that the roots be rinsed weekly with an acid solution to allow for further nutrient uptake. At a time of 800 minutes the nutrient solution was replaced with an acid solution until a time of 2,050 minutes when the nutrient solution was again replaced.

3.5 Water Potential Measurements

3.5.1 Preparation of the Fruit for Water Potential Measurements

An in-situ fruit that had no initial cracks was selected. It was held stable using a clamp and a ring stand (see Fig. 2). The location where the thermocouple transducer was to be placed was wiped clean using distilled water and paper tissues. An L-51 leaf psychrometer[2] was removed from its metal casing and fastened in a swivel clamp (see Fig. 2). The thermocouple cavity was then positioned against the tomato to maintain a smooth contact between the tomato surface and the outer ring (see Fig. 3) of the psychrometer. A slight pressure was created between the psychrometer and the fruit by attaching a rubber band on the clamp stem as shown in Fig. 2. The pressure assured good contact for a vapor seal, and at the same time created a slight impression of the thermocouple cavity on the fruit enabling removal of the circular piece of epidermis just below the thermocouple. A pivoting clamp was used to facilitate rotating the L-51 psychrometer away from the fruit allowing removal of

---

1) Experimental hydroponic system (Honma, Dept. of Horticulture, Michigan State University, 1978).
2) Wescor, Inc. Logan, Utah.

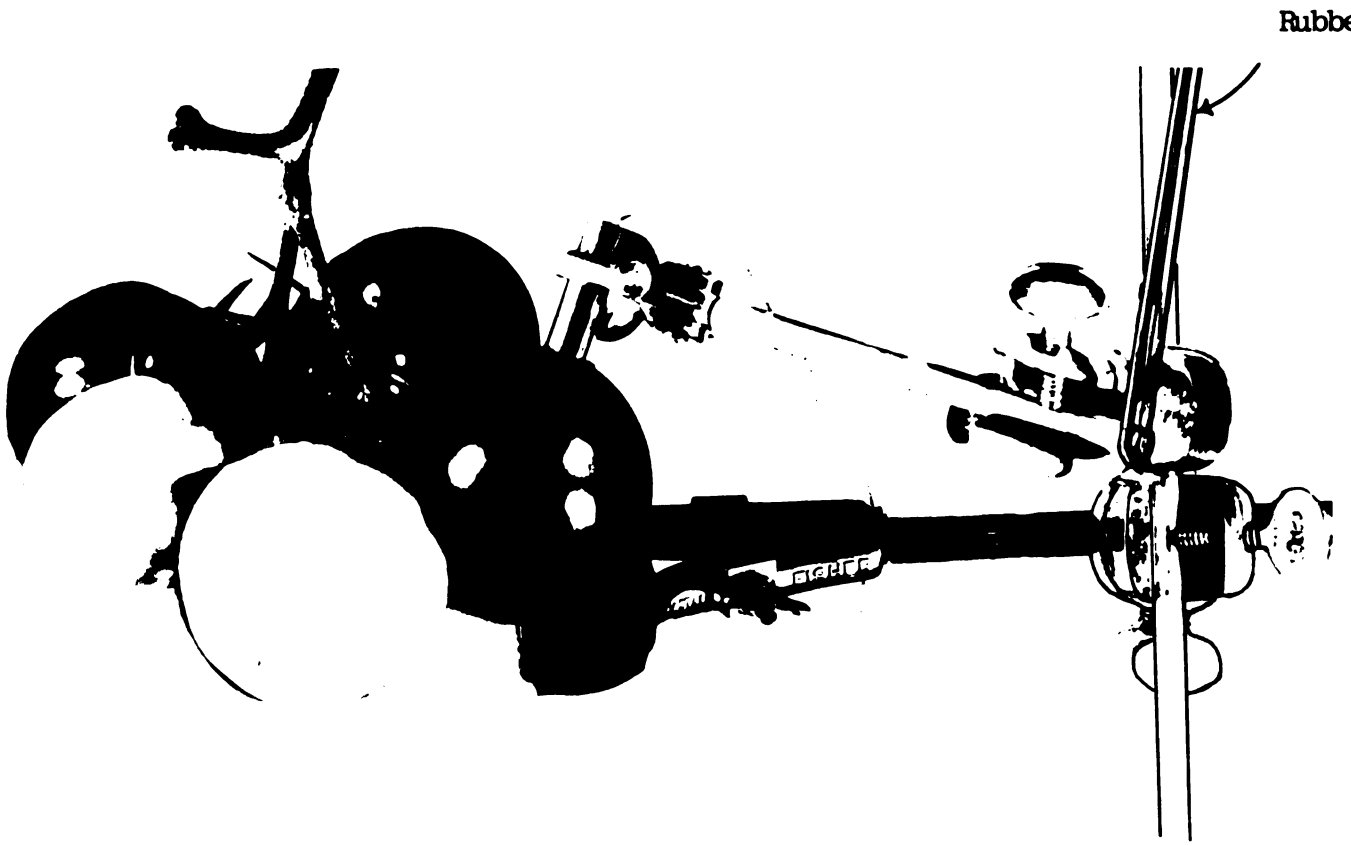

Figure 2. Preparation of Fruit (Scale ½:1)

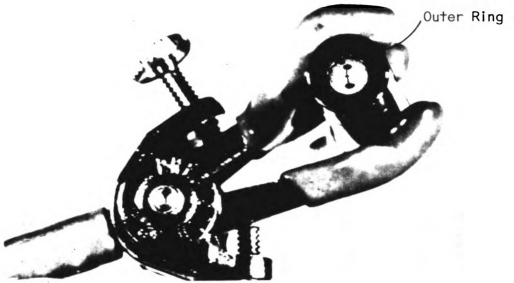

Figure 3. Thermocouple Psychrometer (Scale 2:1)

the epidermis where the indentation was formed. A scalpel and tweezers were used for this procedure. The area was then rinsed using a syringe filled with distilled water and blotted dry with a paper tissue to remove any solutes from within broken cells. A thin film of petroleum jelly was placed on the outer ring of the leaf psychrometer to provide the necessary vapor seal between the thermocouple cavity and the tomato. A ring of petroleum jelly was also placed around the outside edge of the leaf psychrometer where it made contact with the fruit to assure a complete vapor seal of the thermocouple cavity.

3.5.2 Preparation of the Leaf for Water Potential Measurements

A young in-situ leaf was chosen, washed with distilled water and wiped dry with paper tissue. The aluminum block of the leaf psychrometer (see Fig. 4), was clamped in a position that would allow insertion of the leaf chosen into the slot of the block. The cutin was then removed from a small area of the leaf using an ink eraser and light gentle strokes.[1] Care was taken to remove only the cutin without breaking the leaf cells. A thin film of petroleum jelly was then placed on the outer ring (see Fig. 3) of the psychrometer as above to provide the necessary seal. The leaf was then placed in the slot of the aluminum block (with the treated area directly beneath the thermocouple). The psychrometer was then placed in the block, pressed firmly against the leaf and secured by a hand screw located on the side of the aluminum block (see Fig. 4).

3.5.3 Measurement System

---

1) Techique developed by Merva, G. E. (1977).

Figure 4. Preparation of Leaf (Scale ½:1)

The junction of the thermocouple psychrometers were cooled by passing a Peltier current through the junction for 10 seconds, thus causing water vapor to condense on it. An HR-33T Microvoltmeter[1] was used in all of the experiments to supply the Peltier current. By switching the control unit to dewpoint, the current was reduced until equilibration of the thermocouple was reached. The difference in temperature between the sensing junction and the reference junction results in an emf output from the psychrometer which is immediately detected as a microvoltage deflection from zero on the microvoltmeter. When this reading stablizes it is assumed that the dewpoint in the chamber has been reached.

In the first experiment, the water potential measurements of the leaf, red fruit and green fruit were taken by manually switching the functions on the HR-33T Microvoltmeter and reading the microvolt output. In subsequent tests, an automatic switching and recording device incorporating the HR-33T function was used to automate the measurements.[2] The output of each reading was recorded sequentially on chart paper utilizing a 10 mv VOM5 Chart Recorder.[3]

---

1) Wescor, Inc. Logan, Utah.
2) Designed and constructed by H. Murase, 1977.
3) Bausch and Lomb, Rochester, New York.

4. RESULTS AND DISCUSSION

The results of experiment 1 are presented graphically in figure 5, and the data from which figure 5 was prepared are in the appendix, page 38. The following results should be noted in figure 5. A considerable fluctuation in ambient temperature between the limits of 26.5 to 29°C occured. Since, in this experiment, no attempt was made to insulate the plant from the ambient temperature changes, it is reasonable to assume that similar (although perhaps not so great) fluctuation occured in the plant. This fluctuation in the temperature of the plant may have been to extreme for the sensitivity of the instruments used.

In the range of temperatures and water potentials in which the measurements were made, a change in relative humidity e/e^{o} of 0.0001 will cause a significant change in the measured water potential. An increasing ambient temperature can be expected to lower the relative humidity and, accordingly, the measured water potential. Figure 5 verifies this phenomenon in that as ambient temperature rises, both leaf and fruit water potential decrease.

It is indicated by figure 5 that the plant parts are never in complete equilibrium, i.e., water potential gradients apparently exist between leaf and fruit since, at no time, are the readings consistantly identical. The wide temperature impressed fluctuations in water potential make accurate interpretation difficult. It should also be noted that in the case of the leaf water potential measurements, the aluminum

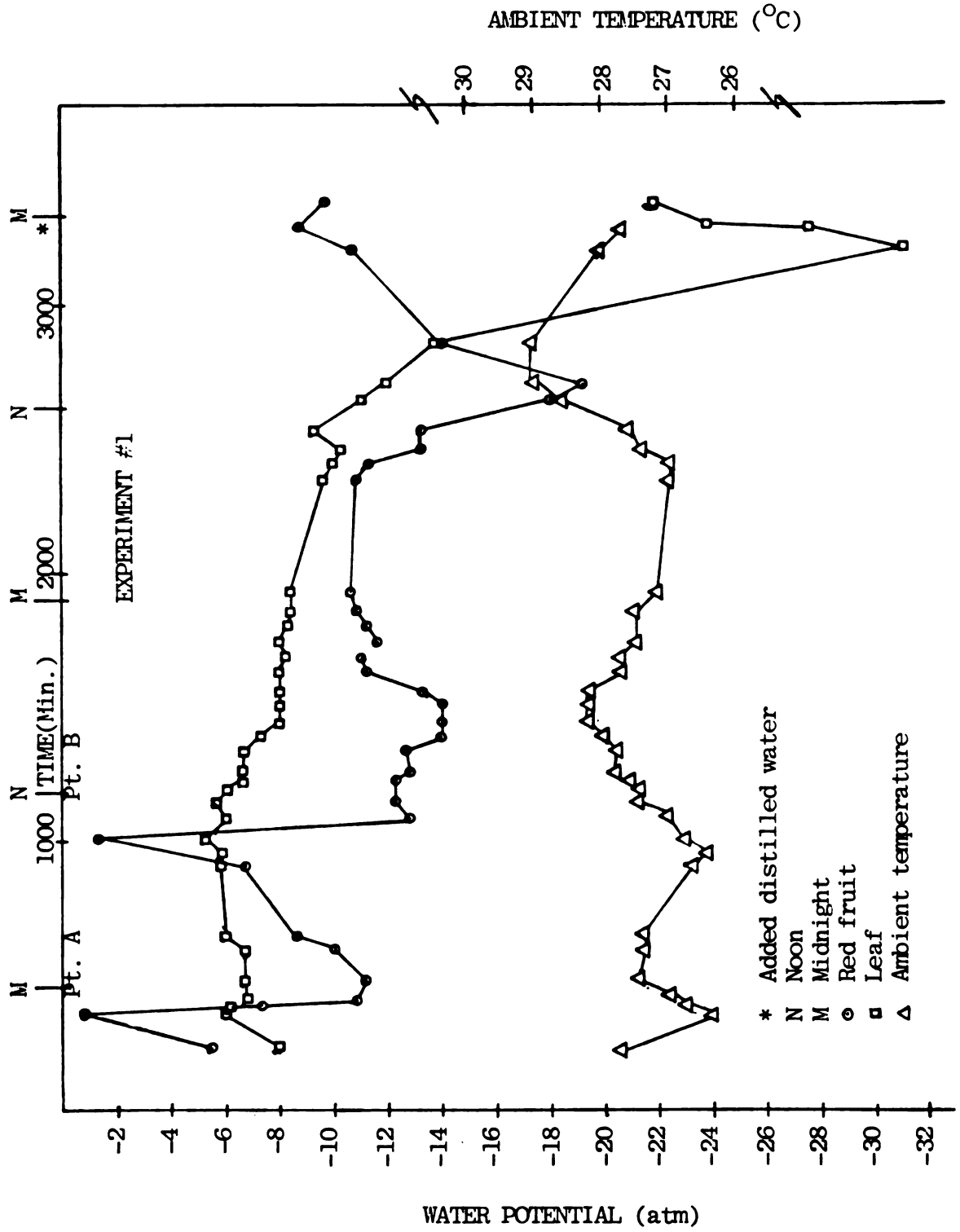

Figure 5. The response of the leaves and fruit water potential of the Vendor variety as a function of time. (The water potential at the root zone was changed with time by initially draining the nutrient solution, thus allowing the roots to remain in contact with the air, and then adding distilled water).

block acts as a heat sink. However, the thermocouple chamber that measures the fruit water potential may be affected by ambient temperature fluctuations since the aluminum block cannot be used. This could explain the sudden increase in fruit water potential with the decreasing temperature at points A and B in figure 5. Other than these two points, the water potential gradient was from the leaf to the fruit until 2,860 minutes, (Point A), when the gradient suddenly reversed from the fruit to the leaf. This reversal followed a period of "drying", as can be seen by the general trend of decreasing water potential of both the fruit and the leaf.

For the period between 480 minutes and 600 minutes, the temperature was relatively constant at 27.5°C and the direction of the water potential gradient in the plant was from the leaf to the fruit with the water potential in the fruit gradually increasing while a very small change (relatively speaking) occurred in the leaf water potential.

The results of experiment 2 are presented graphically in figure 6, and the data from which figure 6 was prepared are in the appendix, page 40. The following results should be noted. Temperature fluctuation was gradual and remained between the limits of 22.3 and 25.7°C. A water potential gradient from the fruit to the leaf was initially monitored while the original nutrient solution was in contact with the root zone. When the nutrient solution was changed to distilled water, the fruit and leaf water potential increased. It should be noted that the green fruit recovered (water potential increased) more than the red fruit, however the water potential gradient remained from the fruit

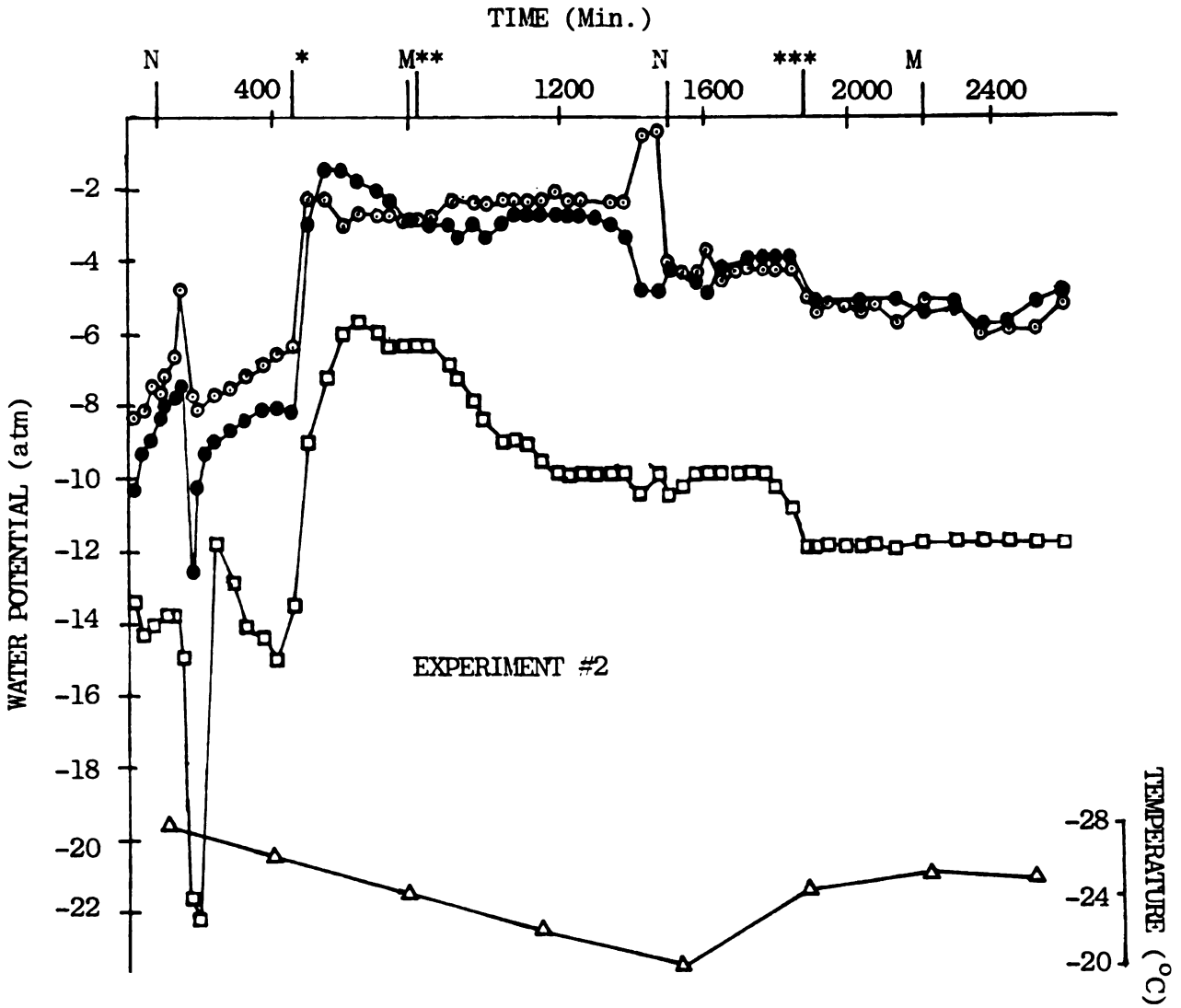

Figure 6. The response of the leaf and fruit water potential of the Vendor variety as a function of time under controlled temperature. (The water potential at the root zone was changed with time.)

to the leaf rather than from leaf to fruit as in figure 5, experiment 1.

After the distilled water was drained from the roots, the trend of the fruit and leaf water potential continued to decrease until the distilled water was replaced, at which time the water potential remained relatively constant. It is questionable as to why the leaf and fruit water potential did not increase upon replacement of the distilled water. At 1,450 minutes the green and red fruits followed opposite paths. The reason for this phenomena is unknown. It should be pointed out, however, that the accuracy of the measurements is probably very good since the fruit water potential measurements follow each other extremely well.

Experiment 2 was the only experiment in which the water potential gradient remained from the fruit to the leaf throughout the entire experiment. No explanation can be offered for this phenomena at this time.

The results of experiment 3 are presented graphically in figure 7, and the data from which figure 7 was prepared are in the appendix, page 44. A complete temperature history is not available, however for the temperatures measured, the range was from 23 to 25°C.

It is indicated by figure 7 that the plant parts are never in complete equilibrium, in fact, the water potential gradient between the leaf and the fruit is never consistently in one direction, but cycles back and forth throughout the experiment. This could possibly suggest that the plant may need to be conditioned before measurements are made because of the effect of diurnal cycling.

It can be seen in figure 7, point A, that a large rapid change in water potential of the fruit and leaf preceeded the cracking of the ripe fruit. In a 2½ hour time span, the leaf water potential dropped from -16.2 to -22.5 atm. (a change of -6.3 atm.), while the red fruit increased from -16.2 to -4.5 atm. (a change of 11.7 atm.) and the green fruit increased from -9.3 to -2.1 atm. (a change of 7.2 atm.).

It was also observed in figure 7 that the fruit cracked before the distilled water was replaced on the roots, and that the water available at the roots at the time was depleted. Therefore the fruits only source of water was from the leaves. This appears to be the source because when the fruit water potential increased, the leaf water potential decreased. It is also possible that a biochemical or physiological change in the fruit and/or leaves at this time was responsible for this phenomena. After adding distilled water to the roots, the leaf and green fruit water potential gradually rose.

The results of experiment 4 are presented graphically in figure 8, and the data from which figure 8 was prepared are in the appendix, page 45. It was required to make the water potential measurements under greenhouse conditions. Unfortunately, ambient temperatures and humidity fluctuated widely in the greenhouse and made it difficult, if not impossible, to monitor the water potential accurately. It should be noted, however, that the fruit water potential increased with increasing ambient relative humidity. The graph of fruit water potential and the graph of ambient relative humidity apparently follow the same trends.

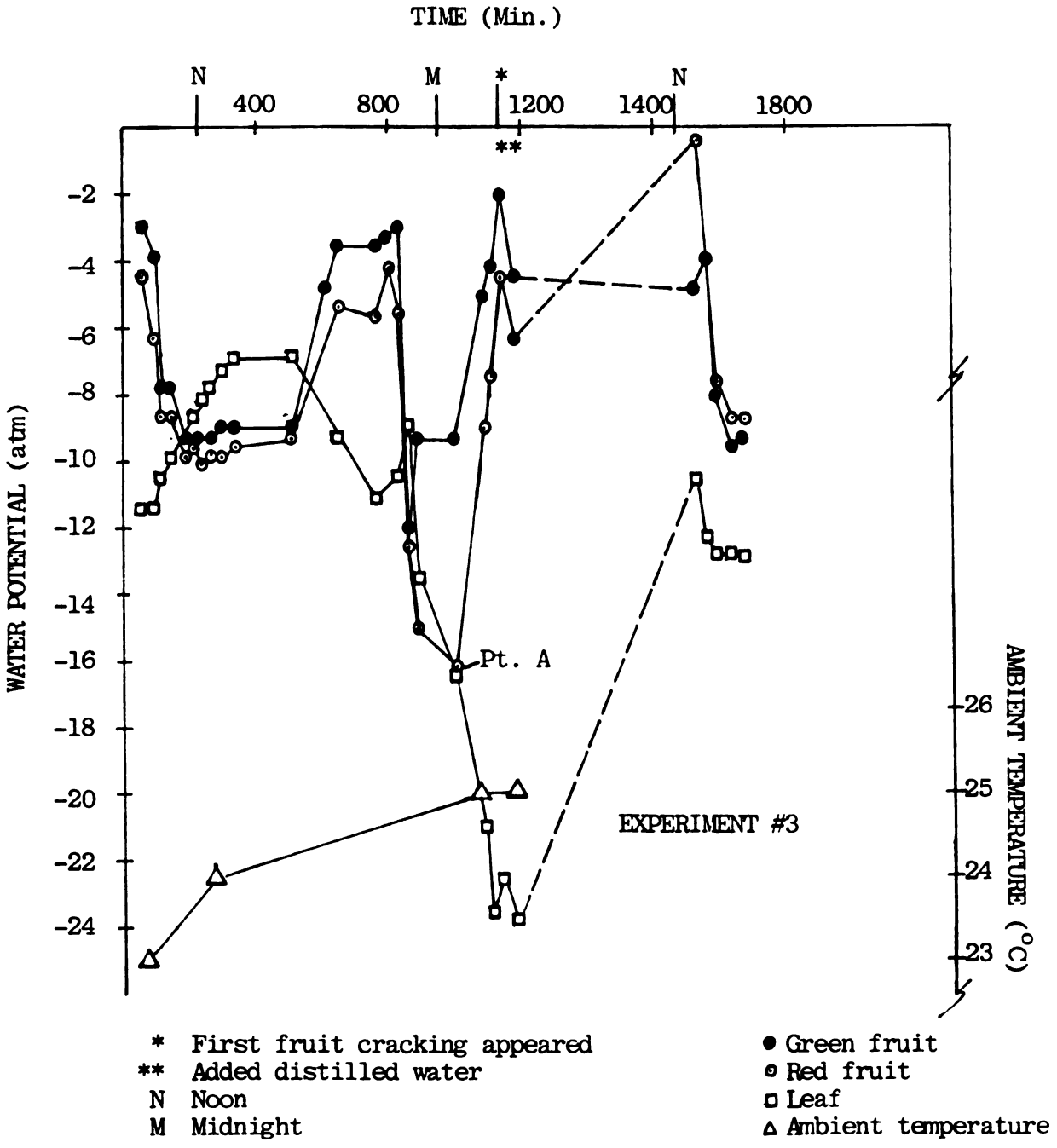

Figure 7. The response of the leaf and fruit water potential of the Vendor variety as a function of time under controlled temperature. The water potential at the root zone was changed with time by initially draining the nutrient solution, thus allowing the roots to remain in contact with air, and then adding distilled water.

It can be seen from figure 8, that during the cooler hours of the night when the ambient temperature and the humidity fluctuations were reduced, the water potential of the fruit increased substantially, and replacement of the nutrient solution, the fruit water potential decreased slightly each day. This confirms the observed ion buildup that accumulates each day.

After rinsing of the roots severe cracking was observed on several occasions. This investigator feels that more frequent rinsing could reduce the ion buildup, decreasing the magnitude of water potential change at the roots upon rinsing and resulting in fewer cracked tomatoes. The possibility of using a rinsing solution with a water potential closer to that of the nutrient solution to reduce the change in water potential at the root zone and perhaps decrease the occurance of cracking should also be considered.

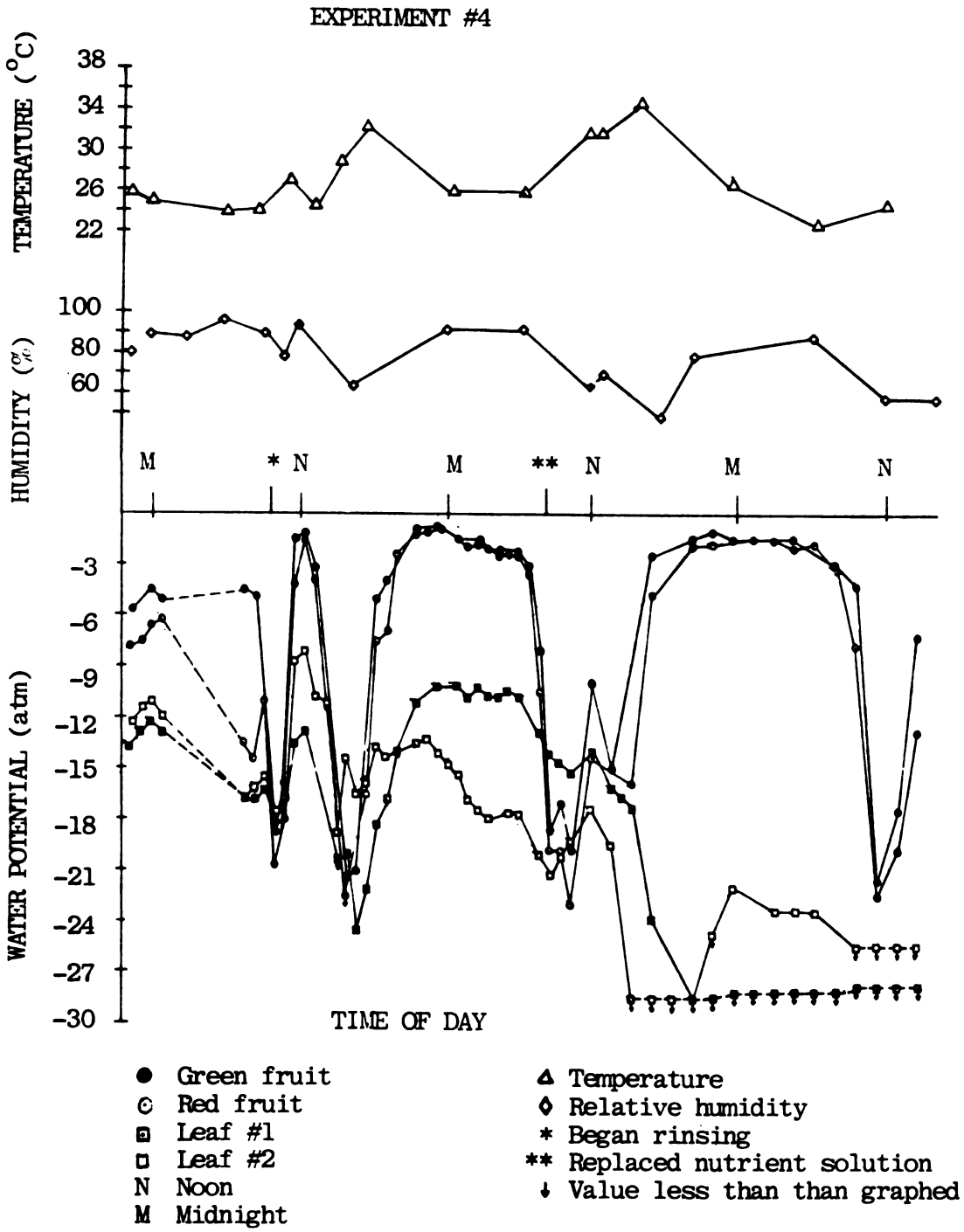

Figure 8. The response of the leaf and fruit water potential of the Tropic variety as a function of time. The measurements were made in the greenhouse on plants grown using the hydroponic trough system.

5. CONCLUSIONS

It was concluded that:

1. A change in water potential at the root zone is one of the factors causing fruit cracking.
2. The method used for measuring fruit water potential was satisfactory.
3. A rapid increase in fruit water potential causes fruit cracking.
4. Simultaneous measurement of water potential of fruit and leaves is possible.
5. An abrupt change in water potential of a plant at the rizoshpere is reflected by changes in water potential throughout the plant.

6. RECOMMENDATIONS FOR FUTURE STUDIES

1. The phenomena that causes the fruit water potential to increase when the leaf water potential decreases at the time of plant water stress should be investigated.
2. The possibility of reducing cracking when using the hydroponic trough system by modifying the rinsing procedure should be studied.
3. The reliability of water potential measurements under varying ambient temperature and humidity conditions should be established.
4. The greenhouse experiment (experiment 4) should be repeated with high, medium and low crack susceptible plants to gain further insight into the phenomenon of ion buildup and fruit cracking.

APPENDIX

Experiment #1
Data for May 27 - May 30, 1978

TIME (Min.)	ROOM TEMPERATURE (°C)	FRUIT WATER POTENTIAL (atm)	LEAF WATER POTENTIAL (atm)
240 (8:20 pm)	27.8	-5.6	-8.0
360	26.4	-0.7	-6.0
380	26.8	-7.3	-6.1
420	27.0	-10.7	-6.7
480 (12:20 am)	27.5	-11.2	-6.7
600	27.4	-10.0	-6.7
651	27.4	-8.7	-6.0
915	26.7	-6.7	-5.9
960	26.5	—	-5.9
1020	26.8	-1.3	-5.3
1090	27.1	-12.8	-6.0
1150	27.5	-12.3	-5.6
1200 (12:20 pm)	27.5	-12.3	-6.1
1230	27.6	-12.3	-6.7
1260	27.8	-12.8	-6.7
1330	27.8	-12.7	-6.7
1390	28.0	-14.0	-7.3
1450	28.2	-14.0	-8.0
1510	28.2	-14.0	-8.0
1570	28.2	-13.3	-8.0
1630	27.7	-11.2	-8.0
1690	27.7	-11.1	-8.3
1750	27.5	-11.6	-8.0
1810	—	-11.2	-8.3
1870	27.5	-10.9	-8.4
1930 (12:30 am)	27.2	-10.7	-8.4
2350	27.0	-10.9	-9.7
2410	27.0	-11.3	-10.0
2470	27.4	-13.3	-10.2
2530	27.6	-13.3	-9.3
2650 (12:30 pm)	28.6	-18.1	-11.1
2710	29.0	-19.3	-12.0
2860	29.0	-14.0	-14.0
3220	28.0	-10.7	-29.6
3290	27.7	-8.7	-31.3

Experiment #1 (Cont.)
Data for May 27 - May 30, 1978

TIME (Min.)	ROOM TEMPERATURE (°C)	FRUIT WATER POTENTIAL (atm)	LEAF WATER POTENTIAL (atm)
3305	--	-	-28.0
3315	--	-10.0	-24.0
3367 (12:27 am)	--	-9.7	-22.0

The solution was drained on May 27 at 4:20 pm, the room temperature was 28.2 °C, and the water potential of the solution was -2.0 atm. The experiment was run on a lab table at room temperature. The tomatoes were initially cracked.

Experiment #2
Data for June 3 and 4, 1978

TIME (Min.)	GREEN FRUIT WATER POTENTIAL (atm)	RED FRUIT WATER POTENTIAL (atm)	LEAF WATER POTENTIAL (atm)
20 (11:25 am)	-10.2	-8.4	-15.3
42	-9.3	-8.1	-14.4
64	-9.0	-7.5	-14.1
86	-8.4	-7.6	-13.8
108	-8.1	-7.2	-13.8
130	-7.8	-6.6	-13.8
152	-7.5	-4.8	-15.0
174	-12.6	-7.8	-21.6
196	-10.2	-8.1	-22.2
218	-9.3	-6.3	-10.2
240	-9.0	-7.8	-11.7
284	-8.7	-7.5	-12.9
328	-8.4	-7.2	-14.1
372	-8.1	-6.9	-14.4
416	-8.1	-6.6	-15.0
460 (6:45 pm)	-8.1	-6.3	-13.5@
504	-3.0	-2.4	-9.0
548	-1.5	-2.4	-7.2
592	-1.5	-3.0	-6.0
636	-1.8	-2.7	-5.7
680	-2.1	-2.7	-6.0
724	-2.4	-2.7	-6.3
768	-2.7	-2.7	-6.3
806 (12:24 am)	-3.0	-2.7	-6.3@@
844	-3.0	-2.7	-6.3
882	-3.0	-2.4	-6.9
920	-3.3	-2.4	-7.2
958	-3.0	-2.4	-7.8
996	-3.3	-2.4	-8.4
1034	-3.0	-2.4	-9.0

@ Changed solution to distilled water.

@@ Drained distilled water.

Experiment #2 (Cont.)
Data for June 3 and 4, 1978

TIME (Min.)	GREEN FRUIT WATER POTENTIAL (atm)	RED FRUIT WATER POTENTIAL (atm)	LEAF WATER POTENTIAL (atm)
1072	-2.7	-2.4	-9.0
1110	-2.7	-2.4	-9.3
1148	-2.7	-2.4	-9.6
1186	-2.7	-2.1	-9.9
1224	-2.7	-2.4	-9.9
1262	-2.7	-2.4	-9.9
1300	-2.7	-2.7	-9.9
1338	-3.0	-2.4	-9.9
1376	-3.3	-2.4	-9.9
1424	-4.8	-0.5	-10.5
1462	-4.8	-0.3	-9.9
1500 (12:05 pm)	-4.2	-4.2	-10.5
1538	-4.5	-4.5	-10.2
1576	-4.5	-4.5	-9.9
1614	-4.8	-3.6	-9.9
1652	-4.2	-4.5	-9.9
1690	-4.2	-4.2	-9.9
1728	-3.9	-4.2	-9.9
1766	-3.9	-4.2	-9.9
1804	-3.9	-4.2	-10.2
1842	-3.9	-4.2	-10.8
1880 (6:25 pm)	-5.1	-5.1	-12.0@@@
1918	-5.1	-5.4	-12.0
1956	-5.1	-5.1	-12.0
1994	-5.1	-5.1	-12.0
2032	-5.1	-5.4	-12.0
2070	-5.1	-5.1	-12.0
2146	-5.1	-5.7	-12.0
2222 (12:07 am)	-5.4	-5.1	-11.7
2298	-5.4	-5.4	-11.7

@@@ Added distilled water.

Experiment #2 (Cont.)
Data for June 3 and 4, 1978

TIME (Min.)	GREEN FRUIT WATER POTENTIAL (atm)	RED FRUIT WATER POTENTIAL (atm)	LEAF WATER POTENTIAL (atm)
2374	-5.7	-6.0	-11.7
2450	-5.7	-5.7	-11.7
2526	-5.1	-5.7	-11.7
2602 (6:27 am)	-4.8	-5.1	-11.7

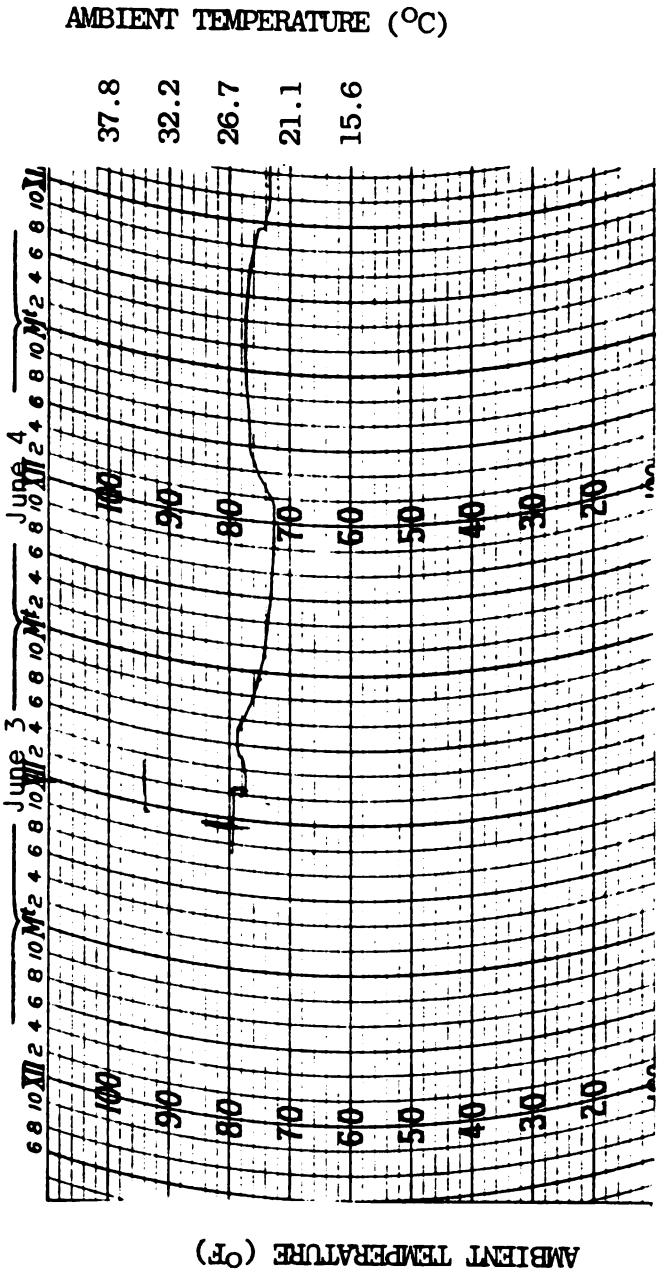

FIGURE 9. Temperature reading for June 3 and 4

Experiment #3
Date for June 5 and 6, 1978

TIME (Min.)	GREEN FRUIT WATER POTENTIAL (atm)	RED FRUIT WATER POTENTIAL (atm)	LEAF WATER POTENTIAL (atm)
60 (9:15 am)	-3.0	-4.5	-11.4
90	-3.9	-6.3	-11.4
120	-7.8	-8.7	-10.5
150	-7.8	-8.7	-9.9
180	-9.3	-9.9	-9.0
210 (11:45 am)	-9.3	-9.6	-8.7
240	-9.3	-10.2	-8.1
270	-9.3	-9.9	-7.8
300	-9.0	-9.9	-7.2
330	-9.0	-9.6	-6.9
510	-9.0	-9.3	-6.9
615	-4.8	--	--
650	-3.6	-5.4	-9.3
760	-3.6	-5.7	-11.1
-	-3.3	-4.2	--
-	-3.0	-5.7	-10.5
865	-12.0	-12.6	-9.0
895 (11:10 pm)	-9.3	-15.0	-13.5
-	-9.3	-16.2	-16.2
1075	-5.1	-9.0	-21.0
1110	-4.2	-7.5	-21.6
1135 (3:10 am)	-2.1	-4.5	-22.5*
1170 (3:45 am)	-4.5	-6.3	-23.7**
1725 (1:00 pm)	-4.8	-0.3	-10.5
1760	-3.9	-4.8	-12.3
1795	-8.1	-7.8	-12.9
1830	-9.6	-8.7	-12.9
1865 (3:20 pm)	-9.3	-8.7	-12.9

* First fruit cracking appeared.

** Added distilled water.

Experiment #4
Data for June 25-28, 1978 (Honma's hydroponic tomatoes)

TIME (Min.)	FRUIT WATER POTENTIAL (atm)		LEAF WATER POTENTIAL (atm)	
	RED	GREEN	LEAF #1	LEAF #2
40 (9:55 pm)	-7.8	-5.7	-13.8	-12.3
90	-7.5	-5.4	-12.9	-11.4
140	-6.6	-4.5	-12.3	-11.1
190	-6.3	-5.1	-12.9	-12.0
600 (7:15 am)	-13.5	-4.5	-16.8	-16.8
650	-14.4	-4.8	-16.8	-16.2
700	-11.1	-8.7	-16.2	-15.6
750	-20.7	-18.9	-18.3	-17.7
800	-18.0	-15.9	-17.1	-16.8@
850	-4.2	-1.5	-13.5	-8.7
900 (12:15 pm)	-1.5	-1.2	-12.9	-8.1
950	-3.9	-3.3	-15.3	-10.8
1000	-12.3	-11.1	-17.7	-11.1
1050	*-17.4	*-18.3	*-20.4	-18.9
1100	*-22.5	-21.6	-20.1	-14.4
1150	--	-21.0	-24.6	-16.5
1200	-16.5	-12.6	-22.2	-15.9
1250	-7.5	-5.1	-18.3	-13.8
1300	-6.9	-3.9	-16.8	-14.4
1350	-2.4	--	-13.8	-14.1
1450	-1.1	-0.9	-11.1	-13.7
1500	-1.1	-0.9	-10.5	-13.2
1550	-0.9	-1.1	-10.2	-14.1
1600	-1.2	-1.2	-10.2	-14.7
1650	-1.5	-1.4	-10.2	-15.3
1700 (1:35 am)	-2.0	-2.0	-10.8	-16.8
1750	-1.8	-1.8	-10.2	-17.4
1800	-2.1	-2.1	-10.8	-18.0
1850	-2.4	-2.1	-10.8	-18.0
1900	-2.4	-2.3	-10.5	-17.7

@ Rinsed with acid and water solution to remove ion buildup.

* Less than value given, graph went off scale.

Experiment #4 (Cont.)
Data for June 25-28, 1978

TIME (Min.)	FRUIT WATER POTENTIAL (atm)		LEAF WATER POTENTIAL (atm)	
	RED	GREEN	LEAF #1	LEAF #2
1950	-2.4	-2.3	-10.8	-17.7
2000	-3.6	-3.0	-11.7	-19.2
2050	-10.5	-8.1	-12.9	-20.1@@
2100	-20.4	-18.6	-14.1	-21.3
2150	-20.4	-17.1	-14.7	-20.1
2200	-23.1	-19.8	-15.3	-19.5
2300	-14.4	-9.9	-14.1	-17.4
2400 (1:15 pm)	--	-15.0	-16.2	-19.5
2500	-15.9	-11.1	-17.4	*-28.5
2600	-4.8	-2.4	-24.0	*-28.5
2700	--	--	-	*-28.5
2800	-1.8	-1.4	*-28.5	*-28.5
2900	-1.8	-1.1	*-28.5	-24.9
3000	-1.5	-1.5	*-27.0	-21.9
3100 (12:55 am)	-1.5	-1.5	*-27.0	-22.5
3200	-1.5	-1.5	*-27.0	-23.4
3300	-2.0	-1.5	*-27.0	-23.4
3400	-1.8	-2.0	*-27.0	-23.4
3500	-3.0	-3.0	*-27.0	-24.6
3600	-7.8	-4.2	*-25.5	*-25.5
3700	-22.5	-21.6	*-25.5	*-25.5
3800 (12:35 pm)	-20.4	-17.4	*-25.5	*-25.5
3900	-12.9	-7.2	*-25.5	*-25.5

* Less than value given, pen went off of graph.

@@ Replaced acid solution with nutrient solution.

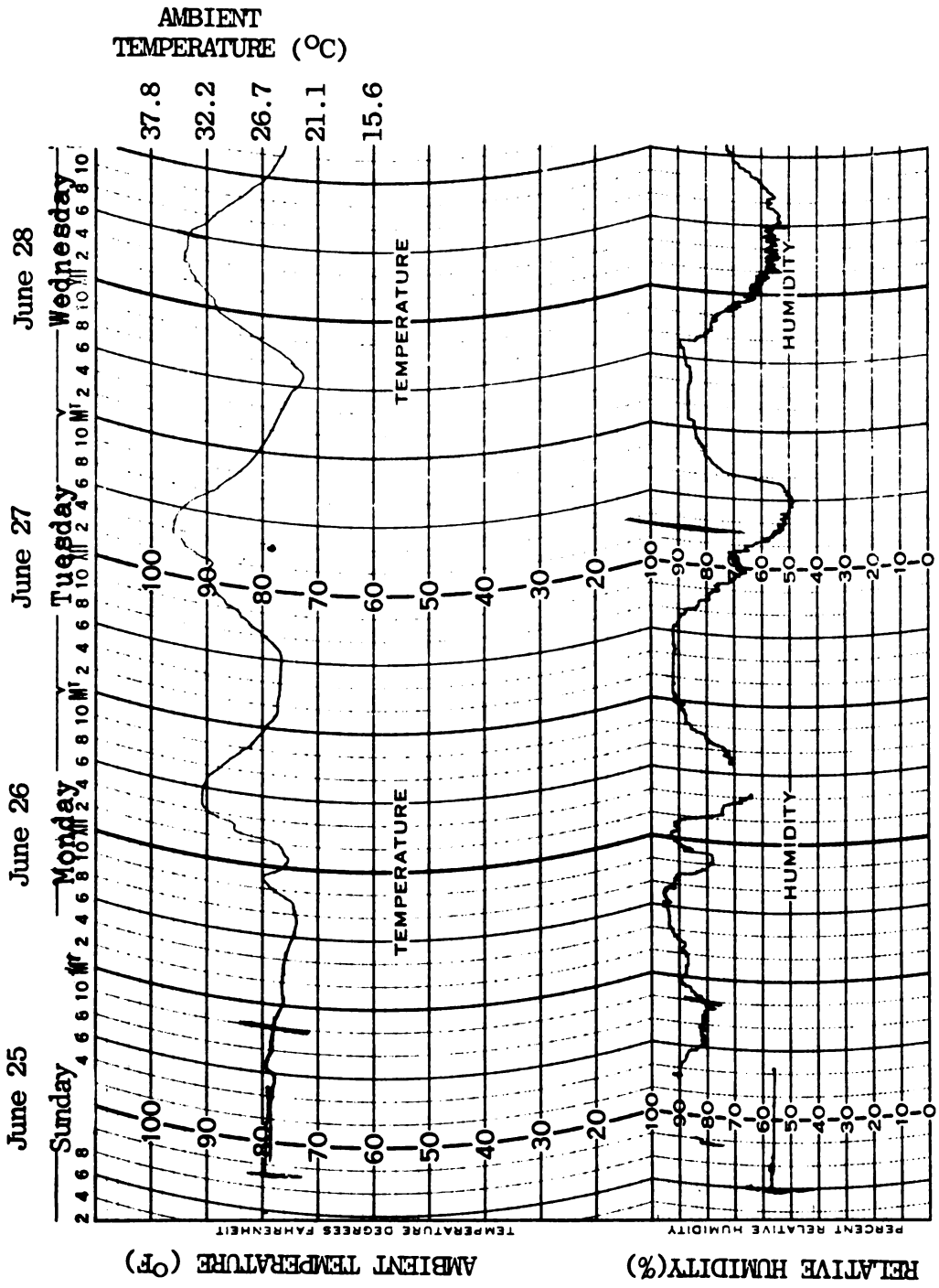

Figure 10. Temperature and humidity measurements for June 25-28.

REFERENCES

REFERENCES

Armstrong, R. J. and A. E. Thompson. 1967. A diallel analysis of tomato fruit cracking. Proc. Am. Soc. Hort. Sci. 91: 505-513.

Armstrong, R. J. and A. E. Thompson. 1969. A rapid and accurate system for scoring tomato fruit cracking. Hort. Sci. Vol. 4(4), pp 288-290.

Barrs, H. D. 1964. Heat of respiration as a possible source of error in the estimation by psychrometric methods of water potential in plant tissue. Nature. 203(4950): 1136-7.

Barrs, H. D. 1965a. Comparison of water potentials in leaves as measured by two types of thermocouple psychrometer. Aust. J. Biol. Sci. 18: 36-52.

Barrs, H. D. 1965b. Psychrometric measurement of leaf water potential: lack of error attributable to leaf permeability. Science. 149: 63-65.

Boyer, J. S. 1967. Leaf water potentials measured with a pressure chamber. Plant Physiol. 42: 133-37.

Boyer, J. S. 1968. Relationship of water potential to growth of leaves. Plant Physiol. 48: 1056-62.

Brix, H. 1962. The effect of water stress on the rates of photosynthesis and respiration in tomato plants and loblolly pine seedlings. Physiol. Plant. 15: 10-20.

Brown, H. D. and C. V. Price. 1934. Effect of irrigation, degree of maturity, and shading upon the yield and degree of cracking of tomatoes. Proc. Am. Soc. Hort. Sci. 32: 524-28.

Cotner, S. D., E. E. Burns, and P. W. Leeper. 1969. Pericarp anatomy of crack-resistant and susceptible tomato fruits. Jour. Am. Soc. Hort. Sci. 94: 136-37.

Dal Fabbro, I., H. Murase, G. E. Merva and L. J. Segerlind. 1978. Study on strain failure of vegetative material from consideration of water potential effect. Unpublished paper, Dept. of Agr. Eng. MSU, E. Lansing, Michigan.

De Baerdemaeker, J. G., L. J. Segerlind, H. Murase and G. E. Merva. 1978. Water potential effect on tensile and compressive failure stresses of apple and potato tissue. ASAE Paper No. 78-3057.

Ehlig, C. F. 1962. Measurement of energy status of water in plants with a thermocouple psychrometer. Plant Physiol. 37: 288-90.

Ellis, C. and M. W. Swaney. 1947. Soilless Growth of Plants. Second Edition, Revised and Enlarged by T. Eastwood. Reinhold Pub. Corp. New York, New York.

Frazier, W. A. 1934. A study of some factors associated with the occurrence of cracks in the tomato fruit. Proc. Am. Soc. Hort. Sci. 32: 519-523.

Frazier, W. A. 1935. Further studies on the occurrence of cracks in tomato fruits. Amer. Soc. Hort. Sci. 33: 536-541.

Frazier, W. A. 1936. Type and severity of fruit cracking in tomato varieties. Proc. Am. Soc. Hort. Sci. 34: 536.

Frazier, W. A. and J. L. Bowers. 1938. Varietal, climatic and age influences on daily cracking indices of tomato fruits. Proc. Am. Soc. Hort. Sci. 36: 746.

Frazier, W. A. and J. L. Bowers. 1947. A final report on studies of tomato fruit cracking in Maryland. Proc. Am. Soc. Hort. Sci. 49: 241-55.

Hepler, R. 1961. The measurement and inheritance of resistance to fruit cracking in the tomato. University of Illinois, Unpublished, Ph. D. Thesis.

Hoagland, D. R. and D. I. Arnon. 1950. The Water-Culture Method for Growing Plants without Soil. California Agr. Exp. Sta. pp 1-31.

Honma, S. 1978. Prof., Dept. of Horticulture. MSU, E. Lansing, Michigan. Personal communication.

Howlett, F. S. and D. W. Kretchman. 1969. Relation of nitrogen and potassium applications and leaf composition to fruit cracking--Spring 1968 tomato crop. Ohio Agr. Res. Dev. Center Res. Sum. 34: 17.

Johannessen, G. A. 1949. Skin puncture studies on red-ripe tomatoes. Proc. Am. Soc. Hort. Sci. 54: 272-76.

Kramer, P. J. 1959. The role of water in the physiology of plants. Advances in Agronomy XI: p. 51. Acad. Press Inc. N. Y.

Kramer, P. J. 1963. Water stress and plant growth. Agron. Jour. 55: 31-35.

Mel Chih-Yu Chu and A. E. Thompson. 1972. Morphology and genetics of fleshy calyx and their relation to crack resistance in tomatoes. Jour. Am. Soc. Hort. Sci. 97(2): 197-203.

Merva, G. E. 1975. Physioengineering Principles. The AVI Publishing Co., Inc. Westport, Connecticut.

Michigan Agricultural Statistics. 1978. Michigan Crop Reporting Service. Published by State of Michigan.

Murase, H. 1976. Stress variation in tomato skin due to epidermis water potential change. Unpublished paper, Dept. of Agri. Eng., MSU, E. Lansing, Michigan.

Murase, H. 1977. Theory of constitutive relations for vegetative materials as a porous viscoelastic medium. Unpublished paper, Dept. of Agr. Eng., MSU, E. Lansing, Michigan.

Murase, H. and G. E. Merva. 1977a. Constitutive Equation for vegetative media, ASAE Paper No. 77-5513, St. Joseph, Michigan.

Murase, H. and G. E. Merva. 1977b. Elastic modulus of tomato epidermis as affected by water potential. ASAE paper No. 77-3030. St. Joseph, Michigan.

Murase, H. and V. Horinkova. 1977. Indicial response of tomato fruit water potential to soil water potential change. Unpublished paper, Dept. of Agr. Eng., MSU, E. Lansing, Michigan.

Murase, H. and V. Horinkova. 1978. Steam cleaning of thermocouple psychrometry equipment. Unpublished paper, Dept. of Agr. Eng., MSU, E. Lansing, Michigan. Submitted to ASAE for publication.

Murase, H., G. E. Merva and L. J. Segerlind. 1978. Variation of the Young's modulus of vegetative tissue as a function of water potential. Unpublished paper, Dept. of Agr. Eng., MSU, E. Lansing, Michigan.

Newton, K. 1972. University of Southern California prune doctors probe 'cracking' cause and cures. The Daily Democrat. Tues., May 23, 1972. p 14.

Niiuchi, K., F. Honda and S. Ota. 1959. Studies on cracking in tomato fruits. I. Mechanism of fruit cracking. pp 287-293.

O'Brien, M., R. B. Fridley and L. L. Claypool. 1978. Food losses in harvest and handling systems for fruits and vegetables. ASAE Trans. 21(2): 386-390.

Porter, D. R. 1960. Quality criteria and their evaluation in a breeding program for processing type tomatoes. Proc. Plant Sci. Seminar, Campbell Soup Co. p 137-150.

Purdue University. 1974. Nutriculture Systems: Growing Plants without Soil. Dept. of Horticulture, Agr. Exp. Sta. Bul. No. 44. West Lafayette, Indiana. pp 1-20.

Rawlins, S. L. 1964. Systematic error in leaf water potential measurements with a thermocouple psychrometer. Science, 146: 644-46.

Reynard, G. B. 1951. Inherited resistance to radial cracks in tomato fruits. Proc. Am. Soc. Hort. Sci. 58: 231-44.

Richards, L. A. and G. Ogata. 1958. Thermocouple for vapor pressure measurement in biological and soil systems at high humidity. Sci. 128: 1089-90.

Singh, K. and J. O. Young. 1970. Effect of an antitranspirant and bagging the fruits or covering the plants on tomato fruit cracking. JNKVV Res. Jour. 4: 43-45.

Spanner, D. C. 1951. The peltier effect and its use in the measurement of suction pressure. Jour. Exp. Bot. 2: 145-68.

Storm, G. 1978. Technician, Dept. of Horticulture, Michigan State University, E. Lansing, Michigan. Personal communication.

Thompson, A. E. 1965. Breeding tomato varieties with increased resistance to fruit cracking. Ill. Res. 7(2): 12-13.

USDA, 1977, Agricultural Statistics. Pub. by United States Dept. of Agr.

USDA Agricultural Research Service. 1972. Growing Plants without Soil for Experimental Use. Miscellaneous Publication No. 1251. pp 1-17.

Van Haveren, B. P. and R. W. Brown. 1972. The properties and behavior of water in the soil-plant-atmosphere continuum. Psychrometry in Water Relations Research. Proc. of the Sym. on Thermocouple Psychrometers. Utah State Univ. pp 1-28.

Verner, L. 1935. A physiological study of cracking in Stayman Winesap apples. Jour. Agr. Res. 51(3): 191-222.

Verner, L. 1938. Histology of apple tissue in relation to cracking. Jour. Agr. Res. 57(11): 813-24.

Verner, Leif. 1939. The nature of cracking in sweet cherries and possible solutions of this problem. Wash. St. Hort. Asso. Proc. 35th annual meet. pp 54-57.

Verner, L. and E. C. Blodgett. 1931. Physiological studies of sweet cherries. Idaho Agr. Exp. Sta. Bul. No. 184. pp 1-15.

Voisey, P. W. and L. H. Lyall. 1964. Methods of determining the strength of tomato skins in relation to fruit cracking. Am. Soc. Hort. Sci. 86: 597-609.

Voisey, P. W., L.H. Lyall and M. Klock. 1970. Tomato skin strength -- Its measurement and relation to cracking. Jour. Am. Soc. Hort. Sci. 95(4): 485-88.

Wittwer, S. H. and S. Honma. 1969. Greenhouse Tomatoes, Guidelines for Successful Production. MSU Press, E. Lansing, Michigan.