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SOIL AND PLANT WATER POTENTIALS
IN RELATION TO TOMATO FRUIT CRACKING

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DOROTA HAMAN BURGESS

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George E. Merva
Major professor

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SOIL AND PLANT WATER POTENTIALS

IN RELATION TO TOMATO FRUIT CRACKING

By

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ABSTRACT

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Body of Abstract

The objective of this investigation was to examine water potential of the ripe tomato fruit as a function of drastical change in water potential of the soil. A sudden increase of water potential of the soil was reflected in the water potential of the ripe fruit. However, the water potential change in the fruit appeared to be inversely proportional to the water potential change in the root zone. Aspects of tomato fruit cracking were also discussed.

Approved George E. Merva
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Approved Richard H. Hughes
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I. INTRODUCTION

The tomato plant, Lycopersicon esculentum L.(cv Michigan-Ohio Hybrid) nightshade family, which includes also potato, tobacco and many poisonous plants as well. The fruit of the tomato plant requires from 40 to 60 days to ripen from flowering. It takes about one week from mature green stage to fully ripe. The week from mature green to fully ripe is the time when cracking mostly occurs if conditions are favorable. Only in the very immature stage is there no cracking of tomato fruits.

It is known that the water status of the fruit is a direct cause of tomato fruit cracking. The water status can be modeled by the water potential of the fruit tissue. It is very likely that cracking is related to a rapid change of water potential in the fruit. However, there are many different factors which influence water potential and indirectly cause tomato cracking.

For example:

1. Water influence - irrigation, rain, dew, humidity
2. Temperature and radiation
3. Minerals applied to the soil and directly to the plant
4. Genetic and anatomical properties of the plant

A proper understanding of these influences can help control the water potential of the fruit, and, possibly prevent it from cracking.

The objective of this investigation was to find the relationship

between water potential of the soil and water potential of the mature, ripe tomato fruit, especially in the transient phases after saturation of very dry soil.

II. LITERATURE REVIEW

1. Cracking of tomato fruit - irrigation, rain, humidity, temperature and radiation.

The opinion of many is that rain and overhead irrigation can cause the most damage in tomato fruits (Frazier 1934, 1935, Brown & Price 1934, Reynard 1960).

Tomato fruit cracking is not supposed to be the major problem when a continuous supply of water is available provided it is not overhead irrigation, but furrow or trickle irrigation (Reynard 1960). Drip irrigation which allows for wetting the soil to the extent that the water potential approaches zero and maintains low water tension for a desired duration of time (Rudich, et. al. 1977), should decrease tomato cracking. Tomato cracking is also a minor problem in areas with very little or no rain during the picking season such as Hawaii (Frazier 1947).

It appears that rain or overhead irrigation causes a significant change in water status of the plant by changing soil moisture, humidity, and temperature, and allowing water to accumulate near the stem end, where it may be absorbed through the stem scar into the fruit.

Frazier (1947) found that a "water deficit of sufficient severity to affect the cell occurred as a result of daily fluctuation in the

evaporating power of the air, regardless of soil moisture content". This is understandable if one remembers that cracking is caused by the plant state, not by the soil water state. Plant water stress depends on relative rates of water absorption and water loss, not on the water absorption alone (Brix 1962). This means that it is mainly influenced by transpiration of the plant which occures mostly through the stomata in the leaves. Rain or overhead irrigation likely causes stomatal closure by change of environmental conditions (like temperature, humidity). Stomatal closure must be followed by serious changes in transpiration. Stomata closure is also the main cause for transpiration decline during development of water stress. Since stomata control only part of the total resistance, their closure will vary the magnitude of stomatal resistance relative to that of boundary layer (Hsiao 1973). Since sometimes very small amounts of water have to be absorbed by a fruit for cracking to occur (Frazier 1934), the small decrease in transpiration can be sufficient to cause damage.

Most authors assume that water cannot be absorbed through the skin of the fruit, since it is known that a tomato fruit does not have stomata. It was found that the fruit apparently does transpire because dew condensation was found after bagging the fruits (Sing and Young 1970). This could be due to the gases and vapor exchange through the cuticle (Schonherr and Bukovak 1973, Schonherr 1979) in the skin of the fruit.

Transpiration of the plant can also be influenced by many other factors. The main ones are atmospheric conditions, e.g., temperature, humidity, wind and radiation.

I.V. Inverson (1938) has related tomato fruit cracking to soil moisture. He indicates that with high soil moisture and high relative humidity, practically no tomato cracking occurs. It is known that hydroponic plants which have a continuous supply of water can crack severely (Herrera 1978). Hydroponic plants have a higher rate of transpiration than plants grown in soil. The root zone has a high moisture supply, but very often a deficit of water in a left tissue follows high transpiration (Ledovskii 1980). This means that the water potential inside the plant changes significantly which can result in tomato fruit cracking.

The temperature of the fruit, which is due mostly to radiation, appears to have significant effect on the tomato cracking. Fruits which are not protected by the foliage have the greatest daily range of temperatures. Such fruits are from 13 to 25°F (7 to 14°C) higher in temperature at noon than ones which are protected by leaves, and also slightly cooler at night because of radiation losses (MacGillvray 1934).

The temperature of the air itself can be critical for tomato fruit cracking. In Florida, fluctuation in temperature along with a drive of cold air (which frequently occurs in the southern part of the state) can cause severe cracking (Reynard 1934).

Frazier (1935) also checked the influence of pruning the plant on the cracking of tomato fruits. "Pruning and stacking increased the occurrence of cracking but further pruning of these plants by leaf removal reduced it, but not to the extent shown by unpruned, unstaked plants".

It was found that shading of whole plants with muslin decreased the severity of cracking (Frazier 1934), but covering the plants with a plastic tent (no movement of the air) enhanced cracking significantly (Sing and Young 1970). However, protection from radiation usually results in decrease in quality of the fruit. Shaded fruits are high in water content and low in total sugars and carbohydrates (Frazier 1934).

We know that carbohydrates is transported from the tomato plant leaf in two directions; upwards towards the apex, and downwards towards the root. The suggestion was that carbon flows upward via internal phloem and downward via external phloem (Bonnemain 1965).

The translocation of carbohydrates is not a process confined to dark periods. Some authors are of the opinion that translocation is favored by low temperature and that it limits the growth and flowering of fruit at temperatures above 18°C (Kristoffersen 1963). The widely held belief that a plant can fully compensate for a missing truss through yields on other trusses is not necessarily true (Slack, et. al. 1977). However, cracking was shown to be positively related to the numbers of fruits produced in clusters of six of more (Howlett and Kretchman 1968).

Sugars constitute 1.5-4.5% of the fresh weight in a ripe fruit. The sugar content increases through maturation and ripening. Shading or removal of the leaves decreases the level of sugars in ripe fruit. The sugars in a fruit reflect differences in the intensity and duration of light (Hobson and Davies 1970).

Maximum starch content can be found in 8 week old tomato fruits, shortly before they start to color. The starch disappeares rapidly during ripening of the fruits. We can assume that the starch content of the fruit is 0.1% (Hobson and Davies 1970), and only half of this breaks down into sugars during ripening.

The predominant acid in a ripe tomato is citric acid, with malic acid second in abundance (traces of few others exist). Maximum acidity (pH 4.1) coincides with an appearence of pink color. The level of acidity drops during ripening (pH 4.5) (Charles, et. al. 1978).

2. Minerals - their influence on tomato cracking.

Many experiments were done to check the influence of different chemicals on the tomato plant. The amount of cracking has been shown to increase with added nitrogen. An interesting interaction has been found with nitrogen and potassium; at lower potassium levels, cracking increased with added nitrogen and than decreased after a certain level of nitrogen had been reached. At higher potassium levels, cracking appeared uniformly in large amounts with added nitrogen (Howlett 1973).

There was a very close relationship between the potassium level of the fruit and acidity of the fruit. Any increase of potassium level of the fruit produced a corresponding increase in organic acids in order to maintain a constant pH.

The acidity of the tomato also increased with increasing levels of nitrogen and decreased with increasing levels of phosphates (Hobson and Davies 1970).

Application of potassium permanganate to the soil was found to increase biological activity of the tomato plants and to stimulate production of a more fiberous type of root system. This was largely due to the effect of magnesium, not to the chemical oxidation. The plant size was increased overall and there was a reduction in fruit cracking (Inverson 1938).

It was also found that an excess accumulation of Mg induces a physiological deficit of Ca in the tissue of the plants. The calcium deficit leads to an inhibition of nitrate assimilation (Suder et. al. 1977). It was found that a high calcium level decreased acidity when combined with high amounts of potassium.

The influence of Ca on the plant appeares to be the more important factor in tomato fruit cracking. Sodium and calcium ions change the permability of the outer membranes of the root tissue of the plants (Pridhod'ko 1970). Van Goor (1968) showed that the permability of the fruit tissue in Ca deficient tomato plants is higher then that for plants receiving normal Ca applications. However, by spraying only the leaves with radioactive ^{45}Ca, it was shown that Ca does not move from the leaves to the fruit (Bangerth 1973). Patterns of transport change with the development of the plant (Khan, et. al. 1967).

All tested ions which have a strong effect in preventing fruit cracking have also a strong precipitating or cross linking effect on pectins. It appears that Ca in the cell walls and especially in the middle lamella plays an important role in the cracking process (Bangerth 1973). Protopectin is highest in the ovary wall stem end tissue.

It would seen that the breakdown of protopectin, which accompanies maturity, may be the reason for cracking of ripe fruit (Frazier 1934). The percentage of cracked fruits is increased drastically by immersing the fruits in a solution, such as pure acids, which dissolves Ca from the cell wall (Bangerth 1973). It was also shown that the addition of Ca to the sprinkler system water reduced cracking and that Ca reduced it more than other divalent ions. Also overhead sprinkler with tap water caused less cracking than rain water. Application of calcium during the rainfall was suggested (Bangerth 1973).

3. Tomato fruit cracking - genetic and anatomical factors.

There are many reasons why the tomato has become a favorite subject for genetic studies. One is the plant's high rate of self pollination which leads to early expression of recessive mutation (Charles, et. al. 1978). Some authors (Frazier 1947, Thompson 1965, Reynard 1960, Armstrong, et. al. 1967) suggested the breeding of tomato varieties with increased resistance to fruit cracking. The chromosome maps for the tomato are among the best (Charles, et. al. 1978). Many genes governing crack resistance in tomato fruit are found in a number of different varieties and strains. Gene effects are usually considered to be multiplicative rather then additive (Reynard 1960). Apparently, two separate gene systems govern radial crack resistance and concentric crack resistance. Nhuchi and Honda (1959) induced concentric cracking by water uptake from the outside through

the corky spots, and radial cracking by expansion pressure of the fruit. It is known that determinate vine habit (sp) and (y) - clear skin genes are associated with radial crack resistance. Concentric crack resistance is associated with (fl) - flashy calyx and the number of fruits per plant. (Mi) - root knot resistance gives susceptibility to concentric cracking. Radial and concentric crack resistance are associated with (u) - uniform ripening and (d) - dwarf genes (reynard 1960). The positive association of crack resistance and flashy calyx indicates that the (fl) gene can be utilized as a morfological marker in the selection of crack resistance tomato varieties (Mel Chinh-Yu Chu, et. al. 1972). Thompson (1967) emphasize that certain types of crack resistance are conditioned by a large number of genetic factors, each having a relatively small individual effect. It was shown that resistance to cracking can be improved through recombination and selection of two unrelated lines (Thompson 1965).

Some anatomical differences between tomato fruits susceptible to cracking and tomato fruits resistant to cracking were found. For example, fruits showing resistance to concentric cracking possessed flattened epidermal cells. No consistent anatomical differences were linked to radial crack resistance (Cotner, et. al. 1969). There are also some differences in the cutinized layer between tomatoes resistant to cracking and tomatoes susceptible to cracking. Cracking resistance depends on skin strength and its ability to stretch; it does not depend on the thickness (Voisey 1970). The elastic modulus

of the tomato skin is a function of water potential (Murase and Merva 1977).

4. Water potential.

The energy status of water is called water potential and is composed of several components (Feddes, et. al. 1978)

$$\psi_{Tot} = \psi_p + \psi_s + \psi_g + \psi_\tau$$

where (Merva 1975):

ψ_s - osmotic potential

ψ_τ - matrix potential

ψ_g - gravitational potential

ψ_p - pressure potential

The potentials are defined relative to the potential or pure water at the same temperature and atmospheric pressure. Water potential can be expressed in dimensions of pressure (Pa-Pascal).

Under equilibrium conditions, using vapor pressure, the water potential can be expressed in terms of relative humidity:

$$\psi_\omega = RT \ln(e/e^\circ)/\overline{V}_w$$

where (Merva 1975):

R - ideal gas constant (82.05 cm^3 - atm/k°-mole)

T - absolute temperature (°K)

e - partial pressure of water vapor

e°- saturated partial pressure of water vapor

$\overline{V}_w$- partial molal volume of liquid water (cm^3/mole)

e/e°- relative humidity

The water potential can be measured using a Peltier psychrometer at a constant temperature and pressure. It can be done by measuring the vapor pressure over a freely evaporating surface of the sample (in this case, a piece of tissue). The equilibrium conditions necessary require 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).

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

$$\psi_\omega = \psi_s + \psi_p \qquad \text{(Merva 1975)}$$

where:

ψ_s - solute potential due to the sugars and minerals inside the cell

ψ_p - pressure potential due to the turgor pressure inside the cell

Water always moves from the points where it has a high energy status to points where it has a lower one (Feddes, et. al. 1978).

This is in agreement with Merva (1975) who pointed out that water movement in the plant occurs as a result of water potential gradient.

It has been found that the modulus of elasticity of tomato skin is a function of water potential (Murase and Merva 1977). It was concluded that cracking phenomena is possibly a skin failure of fruits due to stresses produced in fruit skin by changes in tissue water potential.

5. Plant water potential measurement

The need for accurate measurement of water potential of green plants was pointed out by Kramer (1963). The water potential is a key property of the plant influencing turgor, growth, transpiration, photosynthesis and respiration.

Miniature thermocouple psychrometers necessary for water potential measurement was developed by Spanner (1951) and Richards and Ogata (1958). Thermocouple psychrometers provide a measurement of water potential by sensing the relative humidity of their environment. They function as follows: The junction of the thermocouple is cooled by the passage of a Peltier current to a temperature below the dew point, causing water condensation on the junction. The cooling current is then discontinued and water from the junction is allowed to evaporate back into the surrounding atmosphere. This causes a temperature depression of the junction due to heat of vaporization. The magnitude of the depression depends on the relative humidity of the surrounding atmosphere, since, as indicated,

the water potential is a function of the relative humidity and absolute temperature (Merva 1975).

Murase and Horinkowa (1977)** developed a method of fruit water potential measurement using a left thermocouple transducer. The measurements technique requires removal of the cuticle. Since the cuticle is extremely thin, it is impossible to avoid excision of epidermal and parenchym cells. This however, does not affect the measurement of water potential since, after removal of cuticle, it is possible to measure the relative humidity in the intercellular spaces. Under equilibrium conditions, this gives the water potential of the fruit cells.

** Murase and Horinkova unpublished paper, Department of Agricultural Engineering, Michigan State University.

III. EXPERIMENTAL PROCEDURE

Tomato plants of the Michigan-Ohio Hybrid WR-7 were grown under greenhouse conditions in 9 inch clay pots using a greenhouse soil mix. The plants were fumigated with Orethene to control insect infestation. The flowers were pollinated by shaking flower clusters during warm, sunny days around noon. The plants were heavily watered (saturated) once or twice a day depending on the weather until the first fruit matured on each plant. After maturation of the first fruit, 100-200 ml. of water per day was added depending on the weather conditions and leaf water potential.

Leaf samples were taken using a paper punch. The discs were placed in the C-52 sample chamber, where the water potential of the sample was measured using the dew point method**. The thermocouples were cleaned before measurements using steam. Samples were taken before adding the water and one hour after adding the water. Sufficient water was added to maintain the water potential of the plant near -8 atmospheres. It was assumed that the water potential did not vary significantly throughout the plant. However, the plant is almost never in an equilibrium state (Herrera 1978). It was also pointed by Kozlowski (1964) that the water is often transported from old to the young tissues under conditions of internal water stress and it may cause a nonequilibrium state throughout the plant (Herrera 1978). When this is taken under consideration it can be

**WESCOR INC. - Instruction manual to HR-33 Dew Point Microvoltometer

only concluded that the tomato plants had limited supply of water during ripening and that water stress developed in the plant. Consequently, a single measurement of the water potential of any leaf probably does not describe the water status of the entire plant.

Following fruit ripening, the plants were transported to the laboratory at different times and placed in the Sherer environmental chamber in preparation for the experiment. Each plant was kept for 3 days at constant temperature, humidity and light before the experiment was started. The plants were not watered during this time. A ripe fruit that had no cracks was selected for the experiment. It was placed in a ring stand for support and the spot near the stem end where the thermocouple was to be placed was wiped with distilled water. An L-51 leaf psychrometer was removed from it's metal casing and fastened in a swivel damp. The small circular piece of epidermis was removed with a scalpel and forcepts to expose the intercellular spaces to the thermocouple psychrometer. Distilled water was used to clean the broken epidermal and parenchyma cells.

An L-51 thermocouple psychrometer was placed against the tomato, and exposed to the fleshy parenchyma where the epidermis was removed. A positive contact between tomato and the outside ring of the psychrometer was attempted to insure a good vapor seal. Petroleum jelly was placed around the outside edge of the left psychrometer to further prevent any vapor escape. Two L-51 leaf psychrometers were used for leaf water potential measurements, but the date thus obtained were not reliable since it was the end of the summer and the tomato plants were

quite old. Continuous exposure to light in the environmental chamber together with the very dry conditions caused the leaves to die rapidly and frequent changes of psychrometers from one left to another were necessary. To be representative, the measurement should have been taken from the same leaf since water moves from one leaf to the other depending on the age and position of the leaves and this may cause the nonequilibrium of the water potential throughout the plant (Kozlowski 1964). In the side of each pot two holes were drilled to allow for inertion of soil psychrometers; the first was 6 cm from the top and the second 13 cm from the top of the pot. The soil psychrometers were placed perpendicular to the wall where they appeared to work satisfactorily. However, after adding the water to the soil to the point of saturation, the water potential reading from the soil psychrometers remained far below zero indicating that they did not function properly. If leaf water potential is a good indication of the soil water potential, it can be assume that the soil water potential was about -1200 Pascals.

The soil was first dried to a powder and then saturated to the point where the water appeared in a pan below the pot. Since drainage occured it can be assumed that after adding water, the soil water potential approached zero. The purpose of the experiment was to observe the reaction of the ripe fruit to the saturation of the soil after a very dry period. The water potential of the fruit was measured by passing a Peltier current through the junction of the thermocouple, an HR-33T Microvoltometer was used. An automatic switching device

incorporating the HR-33T design** was used for the measurement. The output of each transducer was recorded sequentially on chart paper using a 10 mv VOM5 Chart Recorder.

**constructed by Murase 1977.

IV. RESULTS

The experiments were performed on 5 different tomato plants. All numerical data for the experiments are included in the appendix.

The results of the first experiment are presented graphically in figure 1. For the first 4600 minutes (during the dry period) the average water potential of the ripe fruit dropped down from about -300 kPa to -500 kPa. In the first experiment we have records of water potential for the leaf during the dry period. The average water potential for the leaf, which is an indication of the water status of the whole plant, was about -1800 kPa. Since the soil psychrometers did not equilibrate after adding the water to the soil we can only assume that the water potential of the saturated soil (4600 min) was close to zero. We therefore treat the water potential of the soil as a step function following addition of water. When the water was added (after 4600 min) to the soil, a sudden drop in the water potential of the fruit was observed. In this experiment possibility of the influence of the different temperature of the water added to the soil on equilibrium conditions was not taken under consideration. In all of the following experiments, the water temperature was brought up to the temperature of the environmental chamber before adding it to the soil. In the first experiment the drop in the water potential of the ripe tomato fruit down to -2500 kPa was probably due to some kind of nonequilibrium state when the cold water was added to the soil. After achieving an equilibrium state,

(440 min later), the records during the next 936 minutes showed that on the average the water potential of the tomato fruit dropped to -900 kPa.

The second experiment is presented graphically in figure 2. The water potential of the fruit during the dry time (first 1380 min) was on the average -450 kPa. After adding the water to the soil we observed a drop in the fruit water potential to -1300 kPa for about 420 minutes; than during the next 1800 minutes were recorded an average water potential of -1000 kPa. The last part of the recording shows much bigger fluctuations since a less precise scale was used in an attempt to measure the soil and fruit water potential simultaneously. However, the same problems with the psychrometers occured as in the first experiment so that a step function for the soil water potential had to be assumed.

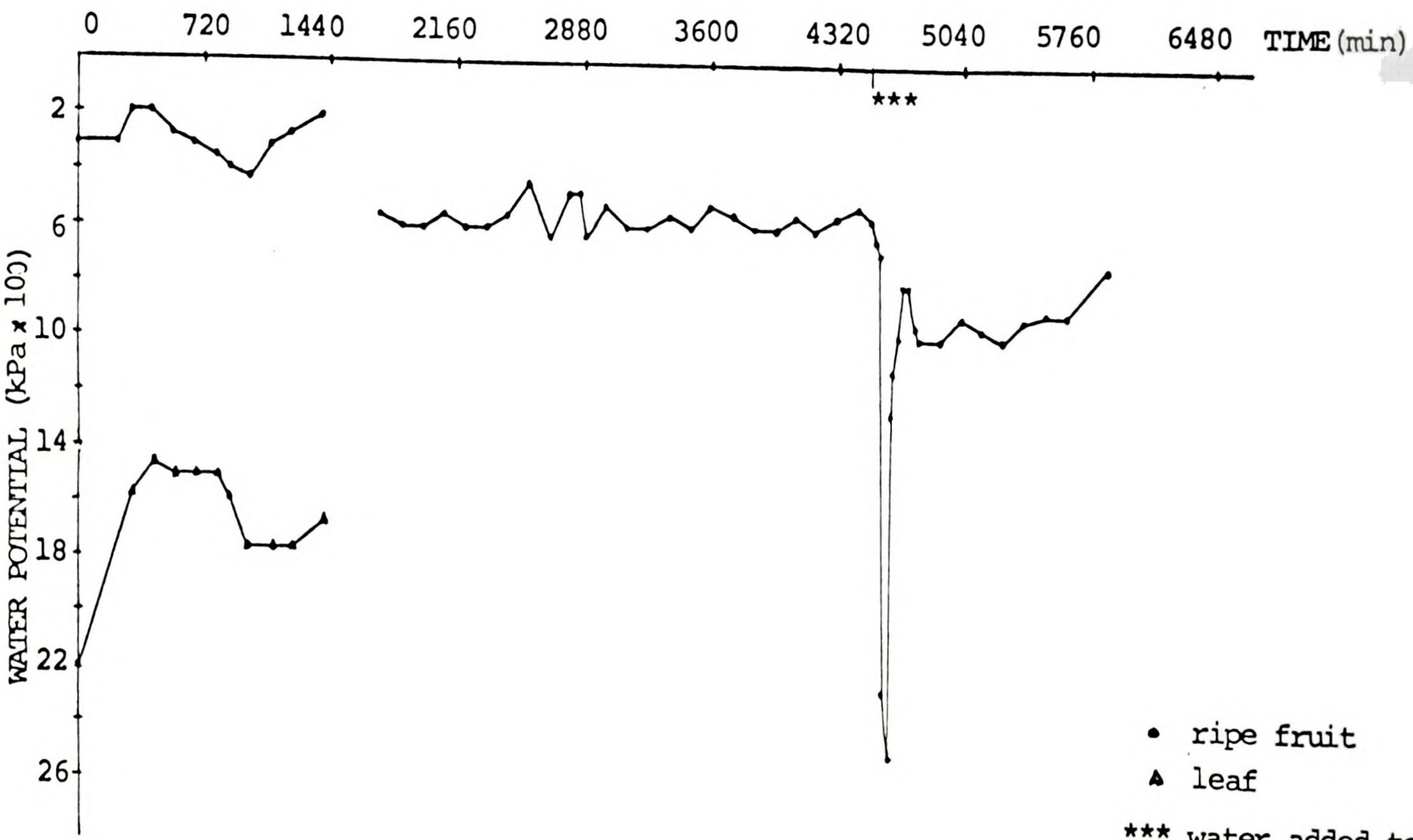
In the third experiment, two psychrometers (L-51) were placed on the same fruit in order to get more frequent recordings immediately after saturation of the soil. Each psychrometer had a twenty minutes equilibration time so the water potential of the fruit was recorded every ten minutes. The average water potential of the fruit during the dry period was -1100 kPa. For the first 180 minutes after saturation of the soil, the measurement were taken every ten minutes. However, except for big fluctuations in the observed values (from -400 kPa to -1700 kPa), the average value seemed to stay at about -1100 kPa. There can be a few reasons for this: the plant did not respond during the first three hours because of the physiological reasons,

anatomical reasons or the psychrometers were not given enough time to equilibrate (twenty minutes), so that the readings were not very precise. However, later on, when the reading was taken from only one psychrometer, with equilibration time 60 minutes, we can see an analogical drop in the water potential of the fruit as in the first and second experiments. For the last 1020 minutes, the water potential was on the average -1700 kPa.

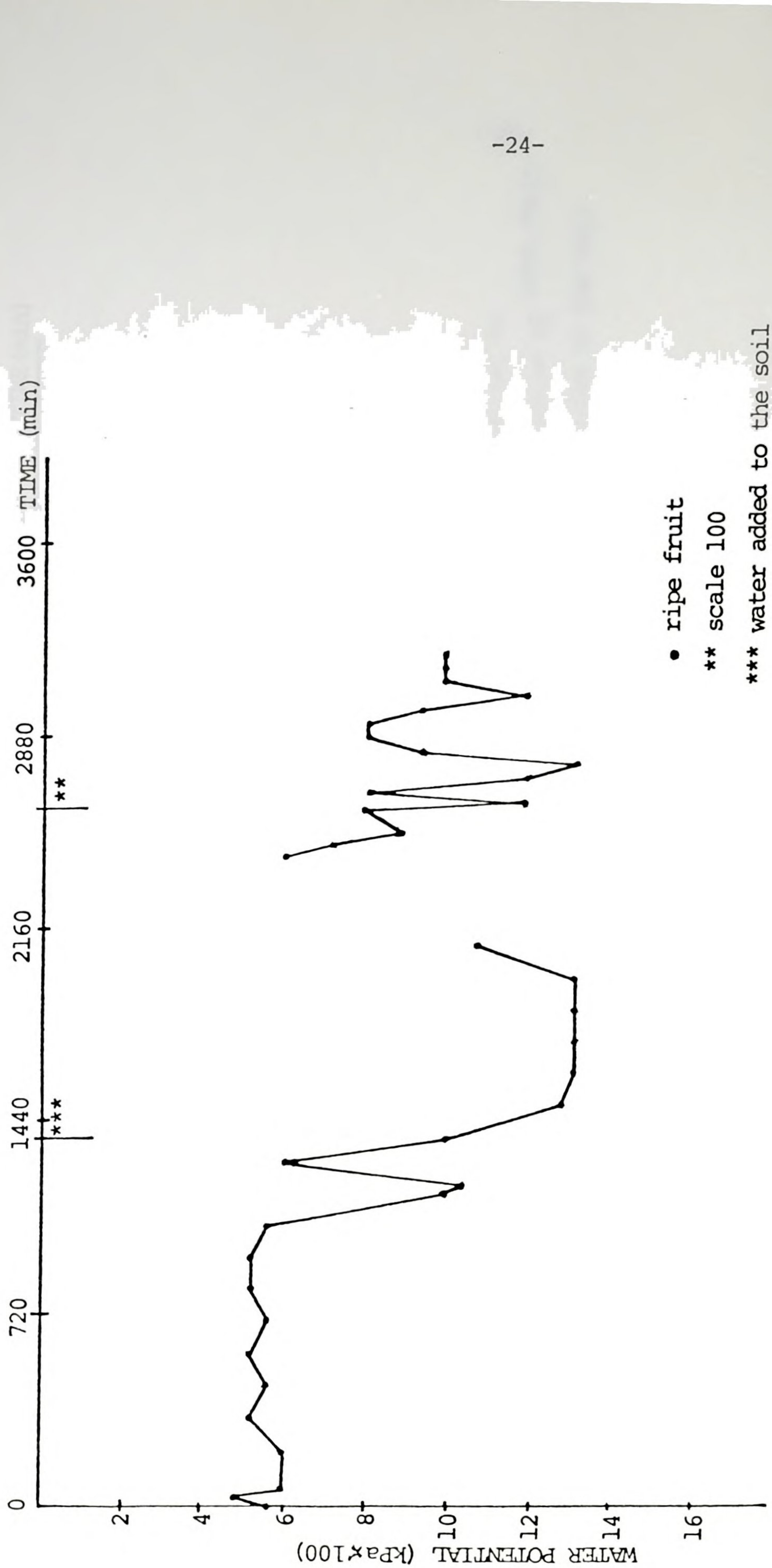
The fourth plant followed a similar pattern; the water potential of the ripe tomato fruit during the dry time was an average of -400 kPa. After adding the water to the soil, it dropped down to -600 kPa (average).

In the fifth experiment, two fruit psychrometers on two different fruits and one soil psychrometer were to record the data. From the beginning of the experiment, during the first 5070 minutes the water potential of the soil dropped down from -1850 kPa to -3000 kPa. Then water was added to one of the fruits by spraying the stem area with distilled water twice: the first time after 3330 minutes (from the beginning of the experiment) and later after 4080 minutes. The other fruit was left dry. The water potential of the first fruit dropped down and then came back to about same level as before adding the water. The water potential of the second fruit dropped slightly, especially spetially after adding the water the second time to the first fruit (50 kPa). It was observed that the water potential of both fruits fluctuated more about the average value than in the first 3330 minutes of the experiment. After 5070 minutes the water was added to the soil.

It can be assumed that the water potential of the soil was close to zero. After a few hours of equilibration, both fruits showed a drop in water potential. However, the fruit which had the water added to the stem showed smaller drop than the other one. The first fruit dropped from -600 kPa to -900 kPa after soil saturation. The second fruit dropped from -600 kPa to -700 kPa after adding the water to the first fruit and to -1100 kPa after saturation of the soil.



Experiment #1 - Water potential of the rape tomato fruit and the leaf in relation to the sudden change of water potential of the soil.

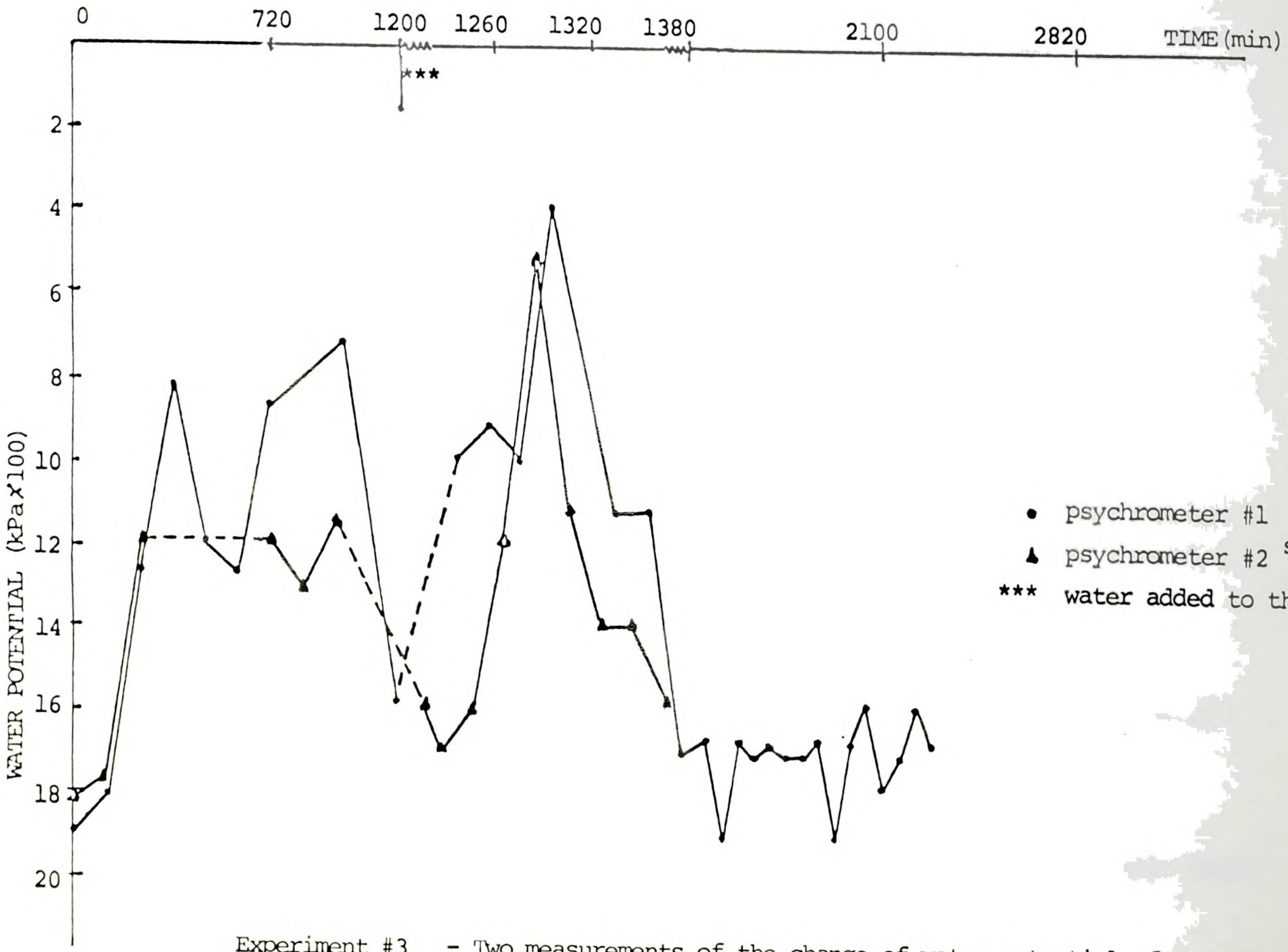


Experiment #2 - The response of the water potential of the ripe tomato fruit to the sudden change of water potential of the soil.

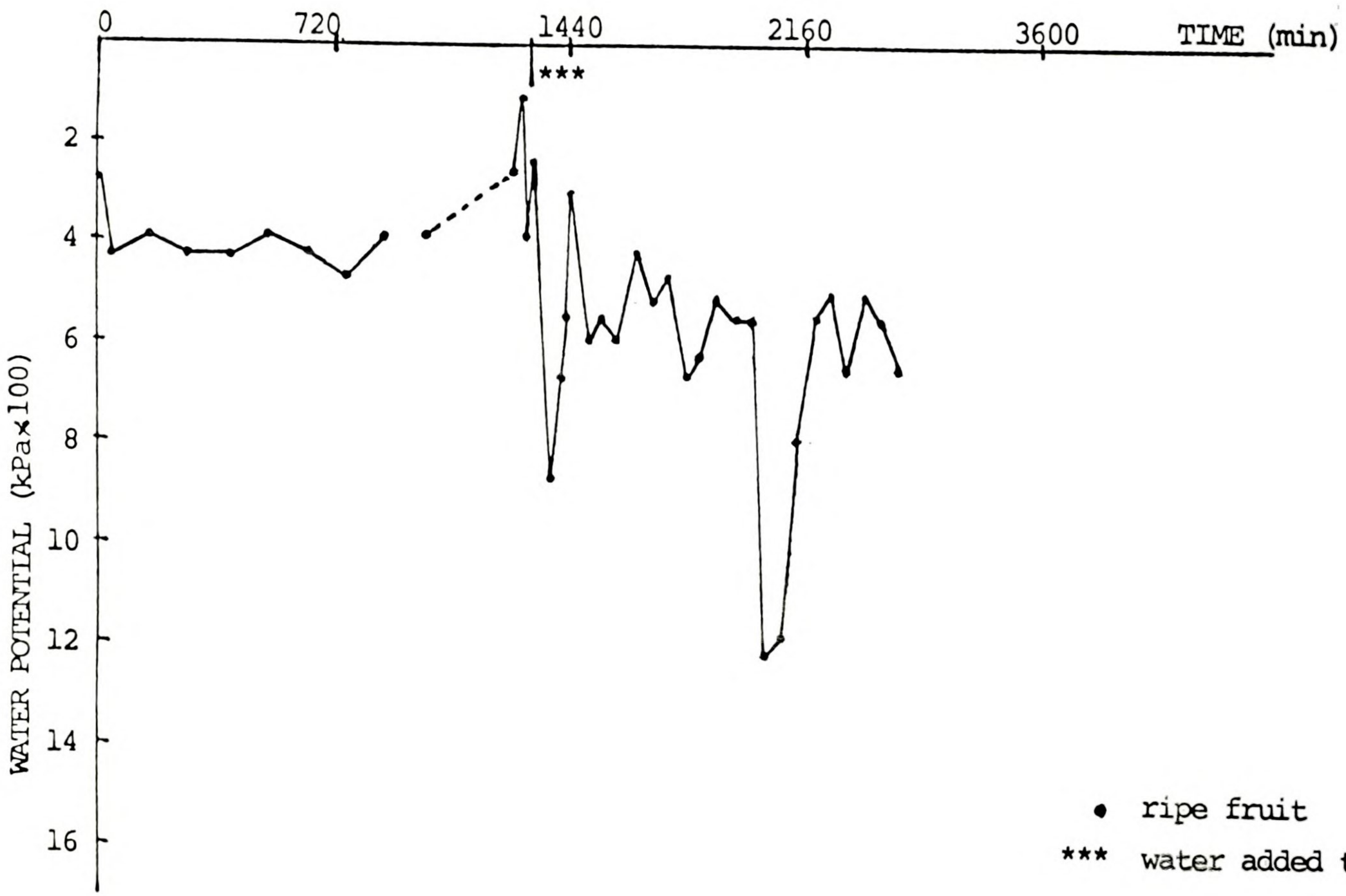
• ripe fruit

** scale 100

*** water added to the soil



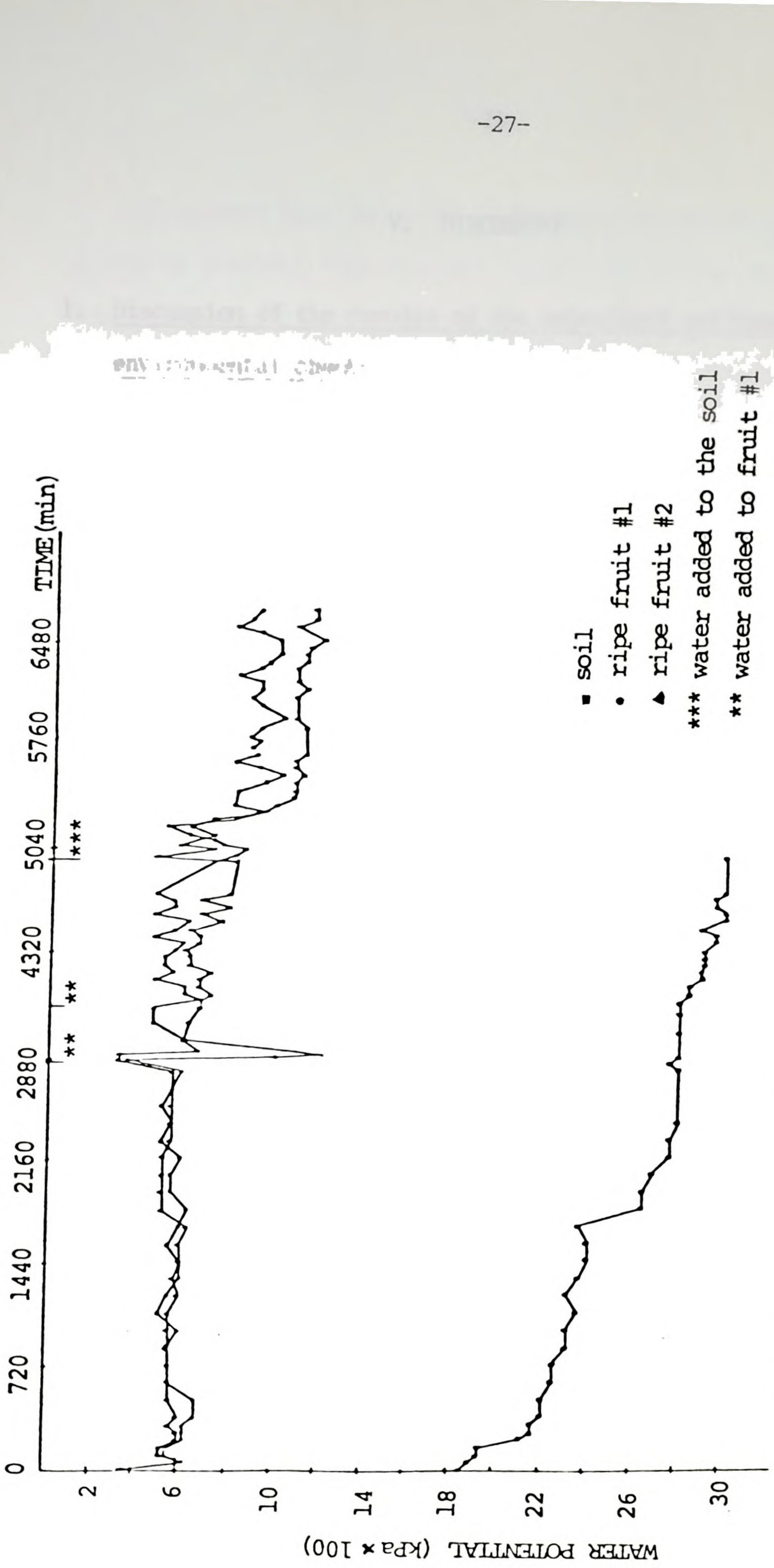
Experiment #3 - Two measurements of the change of water potential of the tomato fruit in relation to the sudden change of soil water potential.



• ripe fruit

*** water added to the soil

Experiment #4 - The response of the water potential of the ripe tomato fruit to the sudden change of water potential of the soil.



Experiment #5 - Water potential of two tomato fruits from the same plant in relation to the sudden change of soil water potential.

V. DISCUSSION

1. Discussion of the results of the experiment performed in the environmental chamber.

In each of the five experiments we observe a sudden drop in the water potential of the ripe tomato fruit after adding water to the soil. Water was added following the dry period during which the water potential of the leaves was -1200 to -1500 kPa in average. At the same time, the water potential of the ripe fruit did not drop below -600 to -900 in average (except for experiment #3), which suggests that the fruits did not experience a water stress. The difference in water potential between the leaves and a fruit in experiment #1, a phenomenon pointed out also by H. Herrera (1978) is probably due to water transfered through the phloem to the fruit from the leaves. It seems likely that, during the ripening process, water is mostly transported into the fruit through the phloem since xylem flow is mostly regulated by the potential differences due to the process of transpiration. Even in the white lupin, where the transpiration ratio of the fruit is 22.5 ml per gram of dry matter accumulated, phloem becomes predominant as a water donor once the seeds start to fill (Page, J.S. et. al. 1977). Since the loss in water vapor through the cuticle of tomato fruit is negligable if it is very likely that there is no flow in xylem into the tomato fruit and the water is supply only by the phloem.

It appears that the water is transported against the water potential gradient from the leaf (-1200 kPa) to the fruit (-6000 kPa). However, water transport is related to the sugar transport in the phloem. Ever since the classic demonstration by Mason and Maskell (1928), that sugar passes from mesophyll to vein against the concentration gradient, loading and unloading of the phloem has been recognized as an active process. If the loading of sugars into the phloem and unloading at the sink (fruit) are active processes the metabolic activity is responsible for the transfer (Esau, K. et. al. 1957). Since there is a solute concentration gradient between the fruit and the leaf, water transport through the xylem may cease (as ripening occurs), especially if the hypothesis about phloem transporting all the water to the fruit is correct. More investigation must be done on the mechanism of water transport throughout the plant and the role of the xylem and phloem in transporting the water into the tomato fruit.

The sudden drop in water potential of the fruit after adding the water to the soil, which was observed in all five experiments can also be related to the solute transfer throughout the plant. Plaut Z. et. a. (1965) observed a very strong temporary acceleration of transport of sugars as compared with fully irrigated controls when wilted bean plants were irrigated. This response seemed to be almost immediate, and occured well before the leaves recovered their turgidity as assessed by relative turgidity measurements.

Leonora Reinhold (1975) referring to Plaut's experiment suggesting that the veins were heavily loaded with sugars in the stressed leaves,

and that water passed rapidly straight from the xylem to the phloem on irrigation, thus, generating a stronger driving force in the stressed group than in the control group of plants. It is reasonable that the sudden drop of water potential of the tomato fruit after watering the plant can be connected with very strong temporary acceleration of the sugar transport in the plant, which may cause a sudden increase of solute concentration in the fruit followed by the water potential drop. The observation that the water potential drops and remain almost at the lower value agrees with the hypothesis of no flow through the xylem. A slightly increase of water potential can be observed in experiment #1 and #3 but it could be explained by different sugar concentration which would be present after more than 12 hours. If the water would be supplied by the xylem the increase of water potential of the fruit should be rapid, since the root zone was saturated and water was readily available to the xylem.

With respect to experiment #5, it can be noticed that the water added directly to the stem area did not cause the water potential to drop in the fruit to which the water was added. However, a slight drop of water potential of the other tomato fruit on the plant was noticed (the other tomato fruit was very close). The observed phenomena is to be expected if we assume that the water worked as a trigger for sugar transfer. The water potential of the first fruit did not change since there was distilled water available for equilibration. The water potential of the second fruit had to drop because of increase of the sugar concentration. After water was added to the soil, both fruits

showed a lower water potentials, but the first fruit dropped lower than the second. It appears that the same amount of sugar was transferred to the both fruits when the water was added to the soil, since the water potential difference between the fruits remained the same as it was after the water was added to the stem of the first fruit, but before water was added to the root environment. In the experiment #3, we can observe the drop of water potential of the fruit. However, it is probable that a systematic mistake occured during taking of the measurements, since the water potential observed was so slow. The sugar concentration of the fruit should be checked before and after watering. More investigations should be done on phloem and xylem transport.

2. Discussion of the observation connected with tomato fruit cracking.

No fruit cracked during the experiment even through the water potential of the root zone was changed very drastically. For example, in experiment #5, the soil water potential changed suddenly from -3000 kPa to a value near saturation (close to zero). At the same time, the temperature and humidity in the chamber was not subjected to any significant changes. This agrees with the situation discussed previously where the xylem is not supplying the water through the abcission layer and water acts as a trigger for the sugar flow in the phloem.

There is some indication that temprature and humidity changes may

be the cause of tomato cracking. The single case when tomato fruit cracked in the environmental chamber occured after the experiment was completed. In this case the environmental chamber was not operating. There was no light and no exchange of air. The temperature and humidity, therefore, increased significantly. Note, that during this period the soil of the plant was virtually saturated and during the few hours immediately following chamber shutdown the tomato fruit cracked.

The single other case of observed cracking happened when one of the plants was being exposed to cold weather, rain and wind (about 5-8°C lower than in the greenhouse) for about one minute before being returned quickly to the shelter of the greenhouse. It is obvious that the light cold shower could not change the root water potential in that short time period. It should be mentioned that the soil in the pot was quite dry (about -10,000, -20,000 kPa) when exposure occured. After the plant was returned to the temperature and humidity of the greenhouse, within 2-3 minutes all ripe tomatoes cracked. No cracking was observed on the green tomatoes.

From this two occurences, it seems that temperature and humidity changes around the plant are significant factors in tomato fruit cracking. As stated in the literature review, in Florida, fluctuation in temperature (up, down and back up) along with a drive of cold air, may cause severe cracking (Reynard 1960). If the xylem connection through the abscisson layer does not exist, the water could be transferred only through the phleom. It is known that the sudden exposure

to the cold temperatures lowers the rate of sugar transfer (Reinhold, 1975), but it is not known how cold temperature influence water transfer into the fruit. If the assumption about termination of the xylem flow into the fruit is correct, it seems more realistic that cracking is a thermodynamic problem.

In Michigan, cracking occures following rainfall or overhead irrigation. Overhead irrigation and rainfall change the temperature and humidity in the air surrounding the plant. Even small change of temperature at the surface of the tomato fruit can cause water condensation in the intercellular spaces where humidity is 0.996%. If free water is transfered into the surrounding cells, the water potential of the cells below the epidermal layer will increase. The cells will expand and cracking may result. Since, during the condensation of the water vapor, some heat is released (heat of vaporization), heat transfer through the tomato cells is quite complicated. At this time the nature of the phenomena is unknown.

The change of temperature and humidity of the boundary layer of the leaves and fruits changes also the rate of transpiration and assimilation of the plant. Since the water status of the plant depends on the relative rates of water absorption and water loss, sudden change of transpiration rate (water loss) may cause more significant changes in the water potential of the plant, that any change of the water status of the root zone. This change of water status in the plant may be responsible for tomato fruit cracking itself, or may trigger physiological phenomena responsible for cracking.

Accurate observations of the influence of short time temperature fluctuations on the water potential of the fruit would be very difficult if not impossible using the thermocouple psychrometer method. For proper precision measurement of the water potential, short term fluctuations of the temperature on the thermocouple itself should be less than $\pm$ 0.0005°C (H.H. Wiebe, et. al. 1971). More investigation should be done on equilibrium times for the measuring system. It may be necessary to develop a new method for the water potential measurement of the fruit during temperature change.

VI. CONCLUSIONS

It can be concluded that:

1. The increase of water potential of the soil after long dry period is not followed by the increase of water potential of the fruit.

2. The change of the water potential of the ripe tomato fruit is not directly proportional to the change of the water potential in the root zone.

3. There exists a difference in water potential between the fruit and the leaves under the water stress conditions.

VII. SUGGESTIONS

From the results of the above experiments it can be seen that the water uptake by the fruit after a dry period is a very complicated process. More research remains to be done on this subject. Certainly, the water uptake of tomato fruit at different stages of development (mature green, pink, red-ripe) should be investigated. At the same time the water potential of the leaves should be monitored, so it would be possible to investigate the water potential differences between the different parts of the plant. It would appear that an experiment in which a complete water balance check could be maintained would lead to useful results regarding fruit cracking, because it would enable one to more closely follow the partitioning of water throughout the plant.

Since, in the above experiments, the water potential of the leaf was much lower than the one of the fruit, it would be very interesting to investigate the source of the water in the fruit. Water furnished during the time when the fruit is ripe is probably supplied to the fruit via the phloem as was suggested during the discussion. It would be interesting to know the amount of water which comes from the other parts of the plant and the amount of water coming from the root zone. It would be valuable to check the hypothesis regarding termination of xylem transport into the fruit during ripening process. It seems to be rather important to know when xylem transport terminates (it if does) in order to control the water potential of the fruit by engineering means,

i.e., soil irrigation. In the above experiments, the water probably did not come from the root zone since the water potential of the fruit dropped after saturation of the soil. By checking the water content of the leaf and the loss due to transpiration, one could determine if the water supplied to the fruit comes from the leaves.

Kozlowski (1964) has stated that during drought, the water can flow from the old to the young leaves. It would be worthwhile to find out if such flow causes a water potential gradient throughout the plant, or, if the gradient is compensated for by growth of the young tissue.

It appears that the problem of tomato fruit cracking can be solved in the greenhouse by controlling temperature and humidity. Not using the overhead irrigation and keeping temperature and humidity from changing drastically can provide relatively constant evapotranspiration conditions. Since the water status of the plant depends mostly on the water loss through the transpiration process, one can expect that the water status of the plant in the above-mentioned conditions would be rather constant.

Future experiments should be conducted in the growth chamber and temperature, humidity, transpiration and CO_2 production (indication of stomata opening) should be constantly monitored. Water should be added to the soil in such a fashion that it does not influence evapo-transpiration conditions in the environmental chamber.

As it was mentioned in the discussion, tomato fruit cracking can be also a thermodynamic problem. In order to check that possibility,

several experiments need to be performed. Heat transfer through the epidermal layer, than through the parenchyma cells, and finally for the entire tomato fruit should be modeled. At the same time, water transfer from intercellular spaces into the cell and vice versa should be investigated.

The water potential changes inside of the fruit during changes of temperature have to be determinated and the water movement due to thermally created gradients of water potential should be investigated.

Another method for solving the problem of fruit cracking using engineering methods lies in the proper supply of Ca. Since Ca can penetrate the cuticular layer of the tomato fruit (Schonherr, et. al. 1973) and influence the middle lamella of the ripening fruit (Van Goor 1968), the effect of spraying with Ca just before ripening and during ripening should be throughly investigated. If the influence of Ca on the middle lamella is stronger than the effect of the change in the water potential, treatment of the fruit with CA should be considered as the engineering solution to fruit cracking. It was suggested by Van Goor (1968) that the influence of applying CA during rainfall in order to reduce cracking be investigated.

APPENDIX

Experiment 1			Experiment 2		Experiment 3		
Time (min)	LWP[1] (kPa)	RFWP[2] (kPa)	Time (min)	RFWP[2] (kPa)	Time (min)	RFWP[2] psychro-meter #1 (kPa)	RFWP[2] psychro-meter #2 (kPa)
0	-2200	-320	0	-550	0	-1900	-1800
245	-2100	-320	30	-470	120	-1800	-1800
322	-1600	-200	60	-590	240	-1300	-1200
442	-1500	-200	90	-590	360	-830	-
562	-1500	-210	210	-590	480	-1200	-
682	-1500	-320	330	-510	600	-1300	-
802	-1500	-560	450	-550	720	-1200	-
922	-1600	-400	570	-510	840	-870	-1200
1042	-1800	-430	690	-550	960	-	-1300
1162	-1800	-320	810	-510	990	-	-1100
1282	-1800	-280	930	-510	1110	-710	***
1402	-1700	-200	1050	-550	1190	-1600	-
1720	-	-560	1170	-1000	1215	-	-1600
1840	-	-600	1200	-1000	1225	-	-1700
1960	-	-600	1230	-	1235	-990	-
2080	-	-560	1240	-590	1245	-	-1600
2200	-	-600	1310	-1000	1255	-900	-
2320	-	-600	1430	-1300	1265	-	-1200
2440	-	-550	1550	-1300	1275	-990	-
2560	-	-430	1670	-1300	1285	-	-510
2680	-	-630	1790	-1300	1295	-400	-
2800	-	-470	1910	-1300	1305	-	-1100
2920	-	-470	2030	-1100	1315	-	-
2945	-	-630	2355	-590	1325	-	-1400
3060	-	-510	2405	-710	1335	-1100	-
3180	-	-600	2455	-870	1345	-	-1400
3300	-	-600	2505	-790**	1355	-1100	-
3420	-	-550	2555	-1200	1365	-	-1600
3540	-	-600	2605	-790	1375	-1700	-

1) L.W.P. - Leaf water potential
2) R.F.W.P. - Ripe fruit water potential
3) S.W.P. - Soil water potential

Experiment 1			Experiment 2		Experiment 3		
Time (min)	LWP[1] (kPa)	RFWP[2] (kPa)	Time (min)	RFWP[2] (kPa)	Time (min)	RFWP[2] psychrometer #1 (kPa)	RFWP[2] psychrometer #2 (kPa)
3660	-	-510	2655	-1200	1455	-1700	-
3780	-	-550	2705	-1300	1515	-1900	-
3900	-	-600	2755	-970	1575	-1700	-
4020	-	-600	2805	-790	1635	-1700	-
4140	-	-550	2855	-790	1695	-1600	-
4260	-	-600	2905	-920	1755	-1700	-
4380	-	-550	2955	-1184	1815	-1700	-
4495	-	-500	3005	-970	1875	-1700	-
4640	-	-550***	3055	-970	1935	-1900	-
4661	-	-630	3105	-970	1995	-1700	-
4675	-	-670			2055	-1600	-
4695	-	-2300			2115	-1800	-
4720	-	-2500			2175	-1700	-
4740	-	-1300			2240	-1600	-
4760	-	-1100			2300	-1700	-
4775	-	-1000					
4805	-	-790					
4835	-	-790					
4865	-	-950					
4895	-	-990					
5015	-	-990					
5135	-	-910					
5255	-	-950					
5375	-	-1000					
5495	-	-900					
5615	-	-870					
5735	-	-870					
5975	-	-710					

1) L.W.P. - Leaf waterpotential
2) R.F.W.P. - Ripe fruit water potential
3) S.W.P. - Soil water potential

Experiment 4		Experiment 5				
Time (min)	R.F.W.P.[2] (kPa)	Time (min)	R.F.W.P.[2] Fruit #1 (kPa)	R.F.W.P.[2] Fruit #2 (kPa)	S.W.P.[3] #1 (kPa)	S.W.P.[3] #2 (kPa)
0	-280	0	-580	-350	-830	-1900
40	-430	50	-590	-630	-790	-1900
160	-400	100	-550	-510	-870	-1900
280	-430	150	-550	-510	-870	-1900
400	-430	200	-630	-590	-1100	-2100
520	-400	250	-630	-590	-1100	-2100
640	-430	310	-630	-550	-1100	-2100
760	-470	370	-610	-590	-1100	-2200
880	-400	490	-610	-550	-1100	-2200
1000	-400	610	-550	-550	-1100	-2300
1275	-280	730	-550	-550	-1100	-2300
1300	-160	850	-550	-550	-1100	-2300
1310	-400***	970	-590	-550	-1200	-2300
1380	-870	1090	-510	-590	-1100	-2400
1410	-670	1210	-550	-550	-1100	-2300
1425	-550	1330	-590	-590	-1200	-2400
1435	-320	1450	-590	-590	-1200	-2400
1485	-590	1570	-560	-590	-1500	-2600
1535	-550	1690	-590	-510	-1200	-2400
1585	-590	1810	-630	-510	-1500	-2600
1635	-430	1930	-550	-510	-1500	-2600
1685	-510	2050	-550	-510	-1500	-2700
1735	-470	2170	-590	-550	-1500	-2700
1835	-670	2290	-510	-550	-1500	-2800
1885	-510	2410	-550	-550	-1500	-2800
1835	-553	2530	-510	-	-1540	-2800
1885	-510	2650	-	-550	-	-
1935	-550	2770	-590	-550	-1600	-2800
1985	-550	2840	-360	-320	-1600	-2800

1) L.W.P. - Leaf water potential
2) R.F.W.P. - Ripe fruit water potential
3) S.W.P. - Soil water potential

Experiment 4		Experiment 5				
Time (min)	R.F.W.P.[2] (kPa)	Time (min)	R.F.W.P.[2] Fruit #1 (kPa)	R.F.W.P.[2] Fruit #2 (kPa)	S.W.P.[3] #1 (kPa)	S.W.P.[3] #2 (kPa)
2035	-1200	2870	-1000	-390	-1600	-2800
2135	-790	2990	-590	-590	-1500	-2800
2185	-550	3110	-470	-630	-1500	-2800
2235	-510	3210	-470	-670	-1500	-2800
2285	-670	3260	-670	-670	-1500	-2800
2335	-510	3310	-590	-710	-1500	-2800
2385	-550	3360	-590	-670	-1500	-2900
2425	-670	3410	-470	-670	-1500	-2900
		3460	-550	-710	-1500	-2900
		3510	-510	-630	-1500	-2900
		3560	-510	-630	-1500	-2900
		3610	-550	-590	-1500	-3000
		3660	-590	-670	-1500	-3000
		3710	-470	-670	-1500	-2900
		3760	-550	-630	-1600	-3000
		3810	-630	-750	-1500	-3000
		3860	-470	-670	-1500	-3000
		3910	-550	-790	-1600	-3000
		3960	-550	-670	-1600	-3000
		4010	-470	-790	-1600	-3000
		4060	-	-	-1600	-3000
		4230	-710	-830	-1700	-3000
		4275	-830	-470	-	-
		4310	-810	-710	-	-
		4345	-750	-550	-	-
		4375	-710	-710	-	-
		4425	-630	-710	-	-
		4475	-510	-630	-	-
		4525	-790	-710	-	-

1) L.W.P. - Leaf water potential
2) R.F.W.P. - Ripe fruit water potential
3) S.W.P. - Soil water potential

Experiment 4		Experiment 5				
Time (min)	R.F.W.P.[2] (kPa)	Time (min)	R.F.W.P.[2] Fruit #1 (kPa)	R.F.W.P.[2] Fruit #2 (kPa)	S.W.P.[3] #1 (kPa)	S.W.P.[3] #2 (kPa)
		4575	-950	-910	-	-
		4625	-790	-980	-	-
		4675	-830	-1000	-	-
		4725	-830	-1000	-	-
		4775	-950	-1000	-	-
		4825	-1000	-1100	-	-
		4875	-900	-1100	-	-
		4925	-790	-1100	-	-
		4975	-990	-1100	-	-
		5025	-870	-1100	-	-
		5075	-900	-1100	-	-
		5125	-870	-1100	-	-
		5175	-900	-1100	-	-
		5225	-1000	-1100	-	-
		5275	-950	-1100	-	-
		5325	-900	-1100	-	-
		5375	-870	-1100	-	-
		5425	-900	-1100	-	-
		5475	-910	-1100	-	-
		5525	-830	-1100	-	-
		5575	-910	-1100	-	-
		5625	-950	-1100	-	-
		5675	-990	-1100	-	-
		5725	-990	-1200	-	-
		5775	-990	-1100	-	-
		5825	-910	-1100	-	-
		5875	-790	-1100	-	-
		5925	-870	-1100	-	-
		5975	-910	-1200	-	-

1) L.W.P. - Leaf water potential
2) R.F.W.P. - Ripe fruit water potential
3) S.W.P. - Soil water potential

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