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Thermal-Response Characteristics of Tobacco Leaf exposed to Microwave Radiation *

by

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SUMMARY

A microwave generator and a closed-circuit wind tunnel were used to study thermoregulatory responses of tobacco leaf. Heating and cooling curves at various wind velocities showed the maximum reduction of steady-state temperature occurred at 10 cm / s. Wind gusts of high intermittency were very effective in transferring heat from leaf tissue; gust interval and dynamic equilibrium leaf temperature were found to be linearly related. Thermal-time constant and half-cooling time of a tobacco leaf were determined as a function of wind velocity under the conditions of the Newtonian law of cooling. It was determined that transpirational cooling of tobacco leaf in total darkness could occur if leaf temperature was raised above 40 °C. This study confirmed that microwaves can be effectively used to study heat exchanges of flue-cured tobacco leaves *in vivo* under both continuous and fluctuating wind conditions.

ZUSAMMENFASSUNG

Die Thermoregulation des Tabakblattes wurde im Windkanal mit umlaufendem Luftstrom unter Verwendung eines Mikrowellengenerators untersucht. Die Erwärmungs- und Abkühlungskurven bei verschiedenen Windgeschwindigkeiten zeigten, daß der tiefste Wert der Gleichgewichtstemperatur bei 10 cm / s lag. Windstöße in größeren Abständen erwiesen sich als besonders wirksam bei der Wärmeableitung vom Blattgewebe, und zwischen den Windstoßintervallen und der dynamischen Gleichgewichtstemperatur des Blattes bestand ein linearer Zusammenhang. Die thermische Zeitkonstante und die Halbkühlzeit eines Tabakblattes wurden als Funktion der Windgeschwindigkeit nach dem Newtonschen Kältegesetz bestimmt. Dabei wurde festgestellt, daß bei einem Tabakblatt in völliger Dunkelheit Schwitzkühlung eintreten konnte, wenn die Blattemperatur höher als 40 °C war. Mit dieser Studie konnte gezeigt werden, daß Mikrowellen für eine *in vivo*—Untersuchung des Wärmeaustausches bei „flue-cured"-Tabakblättern bei gleichbleibender bzw. wechselnder Luftströmung gut geeignet sind.

RESUME

La thermorégulation de la feuille de tabac a été étudiée dans une soufflerie à circuit fermé, au moyen d'un générateur de micro-ondes. Les courbes d'échauffement et de refroidissement correspondant à différentes vitesses de l'air ont montré que la valeur la plus basse de la température d'équilibre était obtenue pour une vitesse de 10 cm / s. Les «rafales» à intervalles de longue durée se sont avérées particulièrement efficaces pour le transfert de la chaleur provenant du tissu foliaire; l'étude a montré en outre qu'il existait une relation linéaire entre

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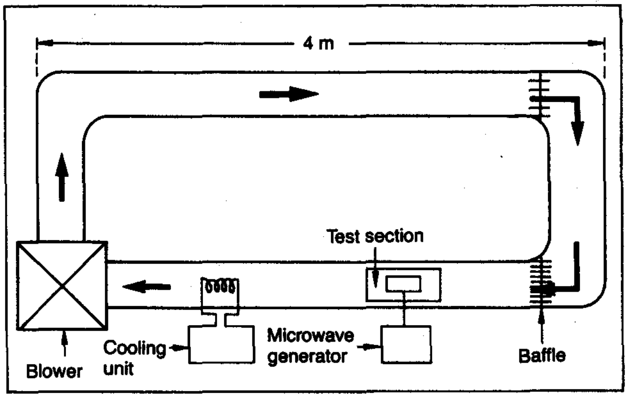
les intervalles séparant les rafales et la température d'équilibre dynamique de la feuille. La constante thermique de temps et la durée de semi-refroidissement d'une feuille de tabac ont été déterminées en fonction de la vitesse de l'air dans les conditions de la loi newtonienne de refroidissement. Il a été constaté qu'une feuille de tabac placée dans l'obscurité pouvait se refroidir par exsudation si sa température était supérieure à 40 °C. Ces travaux ont permis de montrer que les micro-ondes convenaient bien à l'étude *in vivo* des échanges de chaleur dans le cas des feuilles de tabac «flue-cured», que l'écoulement d'air soit constant ou variable.

Figure 1.
Schematic of the wind tunnel.



INTRODUCTION

Microwave radiation has been used to study the dynamic thermal response of plant foliage (1—5). A particular advantage of using this type of radiation is that the dielectric heating mechanism of microwaves allows energy absorption to occur in leaf tissue without directly altering its immediate physical environment. Other methods used to study the thermal response of foliage include alternately exposing plants to and shading them from solar radiation and infrared heat (6). Heating a plant with solar radiation or an infrared source causes a direct change in the thermal state of the surroundings of the foliage. The leaf then re-equilibrates in a thermally altered medium. Thus, the solar radiation - shading and infrared heating methods to study the thermal response of plants may give misleading results. Instances of energy transfer between leaves and thermally stable air are usually encountered during periods of radiation frosts and hot but calm weather.

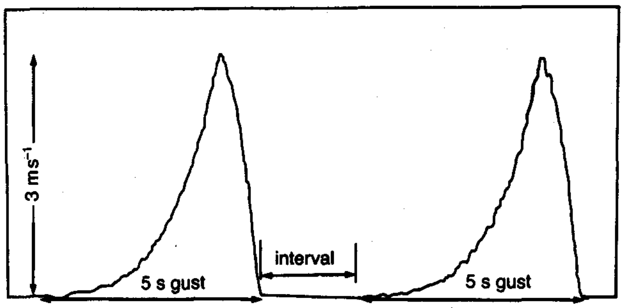
Another important advantage in using microwaves is that the energy budget of leaves can be studied *in vivo*. Previously, leaf simulating models, consisting of a network of electric heating elements, have been used to study heat transfer (7). Results from this approach, however, cannot be extrapolated to represent leaves attached to a plant.
The present study forms a part of an ongoing research project to determine the amount of energy required to protect plants from frosts that occur in the tobacco-growing region of Quebec, Canada. The objective of this paper, however, was to explore the suitability of microwave radiation as a tool to study thermoregulatory behaviour of tobacco leaf at relatively high temperatures and fluctuating winds.

MATERIALS AND METHODS

On 6th April 1987, seeds of Delgold tobacco (*Nicotiana tabacum* L.) were sown in greenhouse beds containing organic soil and the resulting seedlings grown according to provincial recommendations. On 1st June, seedlings were transplanted into 15 cm diameter plastic pots containing Pro-mix and were kept in a greenhouse for an additional two weeks. Plants were then transferred to a darkened closed-circuit wind tunnel (Figure 1) where experiments were conducted after the plants had attained thermal equilibrium.
Briefly, the wind tunnel consisted of a 4 m long galvanized iron air duct of 0.35 m × 0.35 m cross section, insulated with 2.5 cm thick Eccosorb CH 460 to absorb microwaves. This material was obtained from Microwave Instruments and Components*. Baffles were installed in the tunnel to produce laminar air flow in the test section and air was circulated by a centrifugal blower. The air-stream velocity was measured by a hot-wire anemometer. Gusts of wind were created by turning the blower on for 5 s and each individual gust attained a peak velocity. The wind velocity attained a steady state at the end of 5 s time intervals if the blower was not turned off. A recorder trace of the anemometer output was used to define a typical gust and its interval or intermittency (Figure 2); ambient and leaf temperatures were measured by 0.035 cm diameter copper-constantan thermocouples. Problems associated with tissue-temperature measurements in the presence of microwaves have been well demonstrated (8). To circumvent the difficulties in measuring temperature within a microwave field, the temperature sensor

* 6600 Bombardier, Montreal, Quebec, Canada.

Figure 2.
Wind gust and gust interval or intermittency.



was inserted into the midrib of the trial leaf perpendicular to the direction of incident microwaves to avoid coupling and local heating around the sensing element. The non-magnetic materials of the thermocouple combined with its small dimension (ratio of microwave wavelength to sensor diameter exceeded 500) were not expected to interfere with the absorption of microwaves by the leaf tissue. Leaf temperatures during heating were measured under this assumption. Microwaves were not present inside the wind tunnel when the cooling curves were obtained.

A single leaf was heated by a microwave transmitter* which was operated at 2,450 MHz frequency. The microwave applicator formed a part of the wind-tunnel wall so that energy could be delivered from a short distance without attenuation by the relatively dry air. Any radiation that was transmitted, reflected or missed the horizontally oriented leaf was absorbed by the Eccosorb lining of the walls. The power output of the microwave generator was kept constant at 75 W throughout these experiments.

* Model EMS Microtron 200, Raytheon Company, England.

RESULTS AND DISCUSSION

The temperature of the trial leaf exposed to microwave radiation increased rapidly and attained a thermodynamic steady state in 5 minutes in still air (Figure 3). As the air flow across the leaf was increased, the time required to reach steady state was reduced and the temperature decreased even though the incident radiation was kept constant. The results were reproducible. With an air-flow velocity as low as 10 cm / s, the steady-state temperature decreased by about 4 °C. Successive increases in wind velocity caused progressively smaller reduction in leaf temperature which is in agreement with reported results (9).

Wind gusts (peak and continuous velocities were equal) were found to be very effective in reducing leaf temperature (Figure 4). Gusts at 5 s intervals maintained the equilibrium leaf temperature at 32.2 °C which was 1.5 °C greater than for continuous wind. The amplitude of the leaf-temperature fluctuations decreased with the increase of gust intermittency. Previous studies of the effect of wind gusts on leaf temperature (peak velocity equal to the average continuous wind velocity) in

Figure 3.
Heating and cooling curves of a 143 cm² tobacco leaf at 47% relative humidity.
Air temperature = 23.8 °C. The numerals beside the curves represent wind speed in m/s.

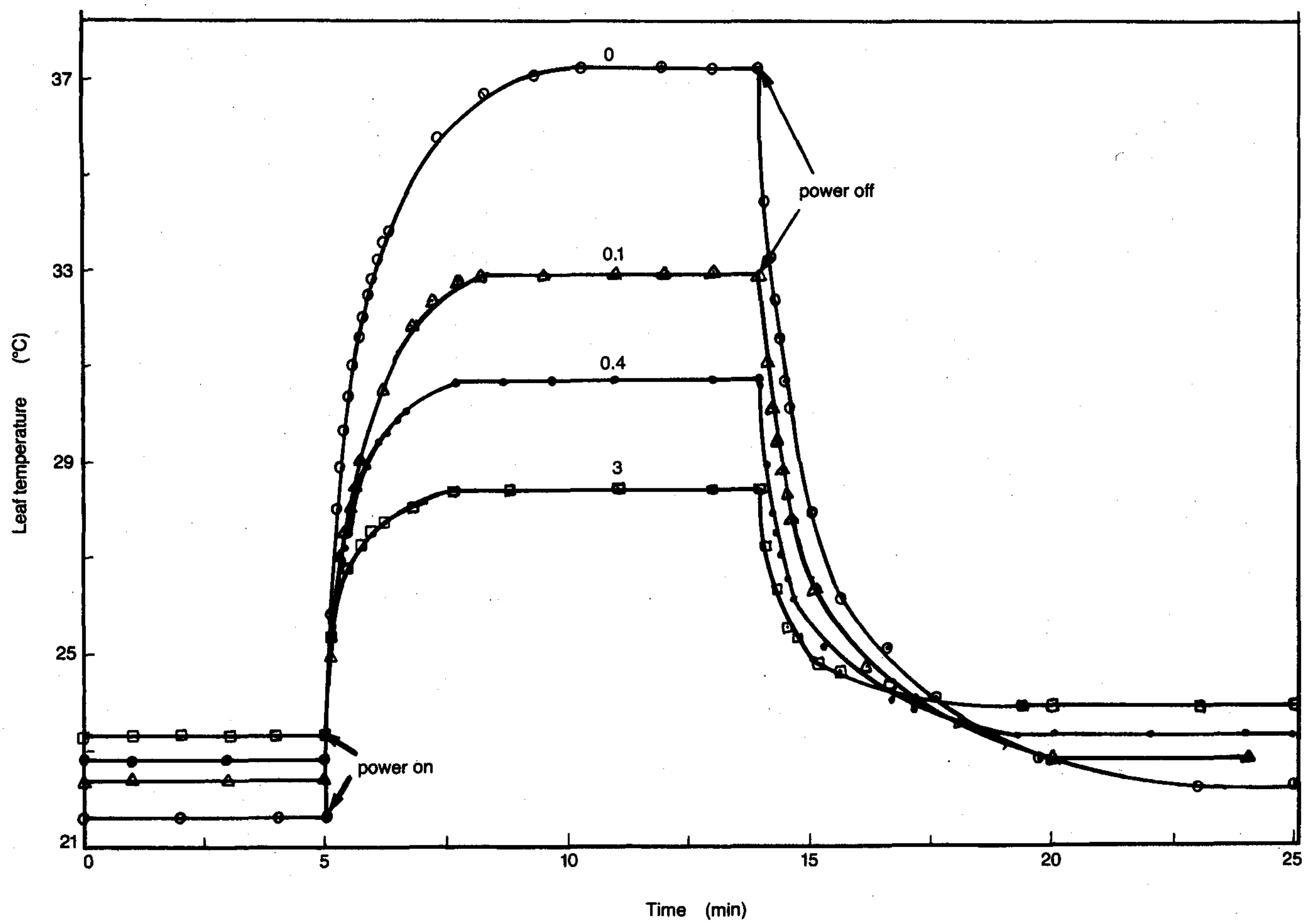


Figure 4.
Gust interval vs. time for a tobacco leaf under constant radiation.

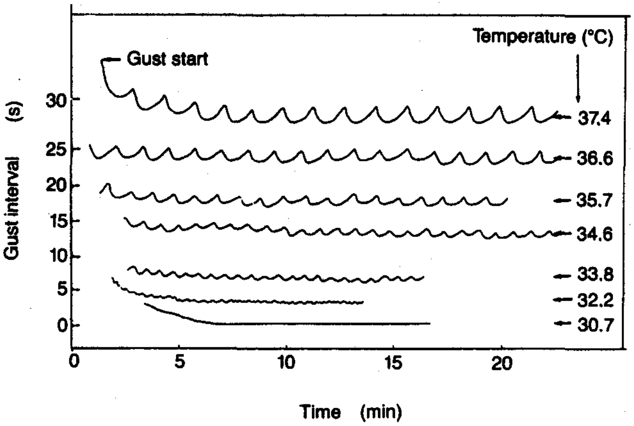


Figure 5.
Equilibrium leaf temperature vs. gust interval for a tobacco leaf.

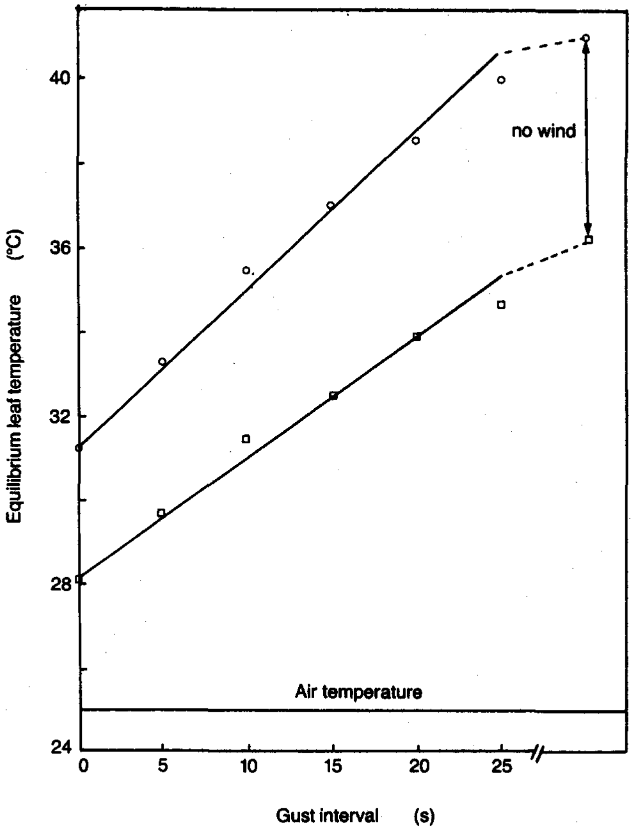
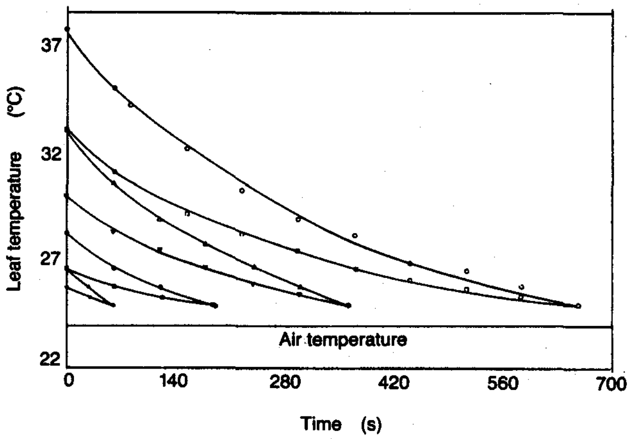


Figure 6.
Cooling curves of a tobacco leaf at two points on the midrib 3 cm apart. The numerals beside the curves represent wind speed in m/s.



which heat-flux plates were used to represent leaves, showed a 30% higher intermittent-heat transfer than the steady-state transfer (10). Moreover, heat-transfer coefficients under natural windy (gusty) conditions on metal disks were known to be 1.5 times greater than the predicted values (11). The results from these two latter studies would indicate that it is preferable to study the effect of wind gusts on leaf temperature *in vivo*. The relationship between the dynamic equilibrium leaf temperatures and gust intervals was observed to be linear (Figure 5). Equilibrium leaf temperature approached the natural convection value as a limit when the gust interval was longer than 25 s. Leaf irradiation by microwaves produced a non-isothermal surface which might be attributed to the lack of uniformity in the thickness of a tobacco leaf and to amorphous populations of the palisade and mesophyll cells. Also, the temperature rise in leaf tissue by dielectric heating depends on the amount of water present. It was observed that the leaf-temperature difference between two points on the midrib 5 cm apart was about 3 °C for continuous wind and about 5 °C for still air. Temperature increased towards the leaf base. A temperature gradient along the tobacco leaf existed as long as the radiation was held fixed. A similar temperature distribution was observed in a vine leaf exposed to solar radiation (12).

Isothermal states were achieved at various times after the microwave radiation was stopped. Under free convective conditions, the temperature gradient disappeared after 10 minutes whereas temperatures were equalized in 1 minute at 1.3 m / s wind velocity (Figure 6). These results raised the question of the validity of the lumped-capacitance method of studying the transient-heat transfer problem in tobacco leaf. This method has been used to determine heat-transfer coefficients of leaves (13). The lumped-capacitance method is a well-established and the simplest method used to solve transient-conduction problems in engineering (14). Biot number (Bi) determines the criterion for the condition under which the method may be used with reasonable accuracy. This dimensionless parameter can be defined as:

$$Bi = hL/k = (T_2 - T_1)/(T_1 - T_a) \quad , \qquad [1]$$

where T_2 and T_1 are the leaf temperatures at two points along the midrib. The ambient temperature is T_a, and $T_2 > T_1 > T_a$, L = characteristic length of the leaf, h = heat-transfer coefficient, and k = thermal conductivity of leaf material. If Bi $\ll$ 1, the resistance to conduction within the leaf is much lower than the resistance to convection across the aerodynamic boundary layer. The data from Figure 6 and equation 1 show that Bi < 0.45 which is higher than the value of Bi < 0.2 generally accepted for the lumped-capacitance method to be applicable without significant error (14). However, the method could still be used as a guide to estimate the cooling rate of tobacco leaves. The cooling rate is used to determine the time taken to reach a given temperature or the temperature that will be reached in a given time.

If the temperature gradient within the leaf is neglected and the leaf is taken as a spacewise isothermal surface, the Newtonian law of cooling allows the governing differential equation for heat transfer to be written as:

$$d(\Delta T)/\Delta T = -(hA/MS)\,dt \quad , \qquad [2]$$

where ΔT = excess temperature between leaf and air, M = leaf mass, S = specific heat of leaf tissue, A = leaf area, t = time. The experiments have been performed in darkness and therefore transpirational cooling can be neglected. Radiative-heat transfer is small due to the small temperature difference between the leaf and the walls of the wind tunnel.

The initial condition, t = 0, $\Delta T = \Delta T_0$, was used to derive the solution of equation 2 as:

$$\Delta T = \Delta T_0 \exp(-hA/MS)\,t \quad . \qquad [3]$$

Equation 3 indicates that the difference between leaf and air temperatures must decay exponentially to zero as t approaches infinity. This behaviour is shown in Figures 2 and 6. Semi-logarithmic plots of cooling curves showed the experimental points to fall on a straight line except at the two extremities. These nonlinearities were small enough to assume equation 3 to hold good for leaf cooling. The quantity (hA/MS) in equation 3 may be interpreted as a thermal-time constant. This time constant may be expressed as:

$$z = MS/hA = RC \quad , \qquad [4]$$

where R is the resistance and C the capacitance of an equivalent electrical circuit. The thermal behaviour of a leaf is analogous to the voltage decay that occurs when a capacitor is discharged through a resistor in an electrical RC circuit. R in equation 4 can be interpreted as resistance to convective heat transfer and C as the thermal lumped capacitance of the leaf. If the product RC is increased, a leaf will respond more slowly to changes in its thermal environment and the time required to reach thermal equilibrium will increase. The reciprocal of the thermal-time constant can be defined as leaf cooling rate:

$$\text{cooling rate} = hA/MS = \ln(\Delta T_0/\Delta T)/t \quad . \qquad [5]$$

Table 1.
Thermal-time constant and half-cooling time of a tobacco leaf.

Wind velocity (m/s)	Excess temperature (ΔT_0) (°C)	Thermal-time constant (s)	$t_{1/2}$ (s)
0	12.5	336	234
0.25	8.5	252	174
0.75	4.5	180	126
1.05	4.0	138	96
1.30	3.0	102	72

The cooling rate or the thermal-time constant for tobacco leaves was determined from the slopes of the linear portions of the cooling curves obtained by plotting temperature ratio ($\Delta T_0/\Delta T$) and time on the semi-logarithmic scale. The concept of half-cooling time is defined as the time required for the temperature difference between the tobacco leaf and its surroundings to become one half of the initial temperature difference under the conditions of the Newtonian cooling:

$$t_{1/2} = z \ln 2 \quad . \qquad [6]$$

One can estimate the half-cooling time by inspection of the temperature - time curve. However, computation of $t_{1/2}$ from equation 6 would be more accurate as it is based on the knowledge of the leaf thermal-time constant. The variation of the average thermal-time constant and $t_{1/2}$ values for three trials with wind velocity is shown in Table 1. The heat-transfer coefficient can be determined from equation 4 if the specific heat of tobacco is known. A guarded-plate method was developed to determine the specific heat of tobacco during the curing process (15).

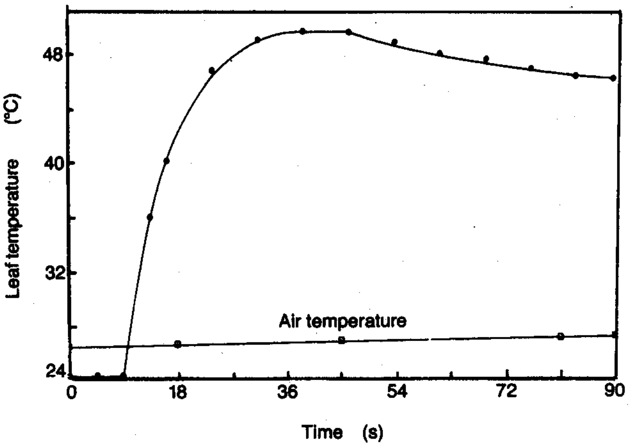
If the specific heat of the dry matter is S_d and that of water S_w, the specific heat S of the tobacco leaf of moisture content M (in percent) can be determined from:

$$S = (S_w - S_d)\,M/100 + S_d \quad . \qquad [7]$$

The specific heat of the dry matter in tobacco was found to vary between 1269 and 1415 J/kg °C (16), depending on the tobacco variety. The specific heat of water in tobacco may also vary with the variety.

Although heat loss due to transpiration was not taken into account, the experimental results showed that considerable cooling could occur if leaf temperature was raised in total darkness (Figure 7). There was no air flow to disturb the leaves mechanically. Stomatal opening and increased transpiration have been reported to occur at high temperatures (17, 18), which might explain the decreased leaf temperature under high radiation. The leaf became flaccid with time and it was evident that the water balance in the leaf was not being maintained: water absorption by the roots seemed to lag behind transpiration.

Figure 7.
Illustration of leaf cooling at an elevated temperature in darkness.



These experiments confirmed that microwaves can be effectively used to study thermoregulatory responses of tobacco leaf *in vivo*. This technique would seem to more accurately measure heat exchanges from leaves compared to the leaf simulation models previously used in such studies. It would appear that microwaves could also be used to study the effect of extreme heat or cold on tobacco leaves or to better understand the curing process of tobacco. Studies are in progress to determine energy budgets of tobacco leaves with microwaves under subfreezing conditions.

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