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LEAF TEMPERATURE MEASUREMENT I. THERMOCOUPLES*

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SUMMARY

A theoretical and experimental analysis of the systematic errors in the measurement of leaf temperature with thermocouples has been made. These errors are due to radiative heat exchange with the environment and to convective heat exchange with the ambient air. The magnitude of the error depends on the relevant temperature differences and on the resistance to heat transport between the object and the junction. The irreproducibility of this resistance causes the large variability in the measured temperatures. Measurement errors up to 7 °C or to 30 % of the temperature difference between object and environment are found with thermocouples of 0.1 mm diameter. The radiation and convection error can be minimized by a reduction of the wire diameter and a careful positioning of the junction against the leaf surface with a slight pressure permanently exerted on it.

1. INTRODUCTION

Investigating the development of sun and shade leaves of *Acer pseudoplatanus* L. and of *Populus euramericana* 'Robusta', the rate of photosynthesis has been measured under conditions of constant temperature and a high CO_2-content of the atmosphere.

With leaf-disks floating on water, the relationship between light intensity and photosynthesis showed a fair light saturation. With leaves in a small assimilation chamber, however, no light saturation could be obtained *(fig. 1)*.

A check on the gas analysis system did not disclose any errors. Further experiments ascertained that neither carbon dioxide nor light were limiting, so the attention was directed to the possible occurrence of systematic errors in the measurement of leaf temperatures (Pieters 1972), since temperature is a third parameter governing the rate of photosynthesis.

The leaf temperature was kept constant at different light-intensities by adjusting both the temperature of the walls of the assimilation chamber and that of the air circulating through it to keep the temperature reading at a fixed value. Leaf temperature was measured by thermocouples of various design.

It is well known that thermocouple measurements of surface temperature often give erroneous results when there is a considerable temperature difference between the surface and the ambient air (Green & Hunt 1962; Idle 1968;

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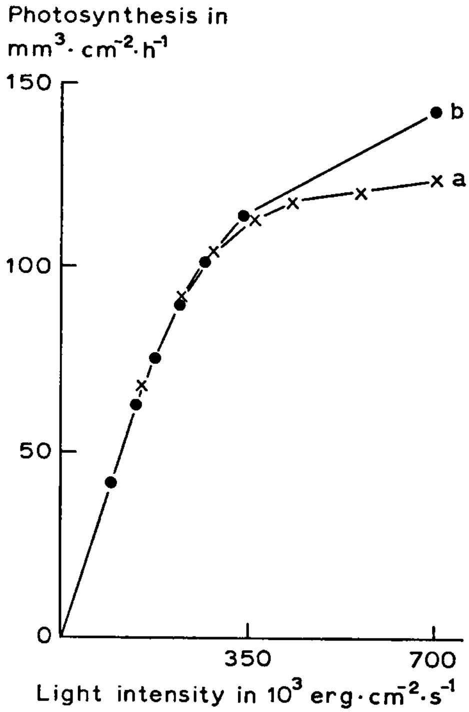

Fig. 1. Rate of photosynthesis of a poplar leaf versus irradiation.
a. leaf floating on water.
b. leaf in the assimilation chamber, temperature controled by thermocouples.

PERRIER 1968, 1971). Since this situation prevails here, a more detailed evaluation of the factors influencing the temperature reading has been made.

Thermocouple errors can be studied on the basis of a discussion of the heat balance of the junction. The junction temperature is governed by the net effect of a number of heat flows, viz.:

1. the conductive heat transfer between the object and the bead: this depends on the size of the contact surface and on the thermal conductivities (λ) on both sides;
2. the conductive heat transfer between the wires and the bead: this depends on the diameter and the material (λ) of the wires and on the difference between ambient and object temperature;
3. the convective heat transfer between the ambient air and the bead with the adjacent wires: this depends on the dimensions of the bead and the wires, on the temperature difference between the environment and the bead with wires, and on the velocity of the airstream (heat transfer increases with this velocity);
4. the radiative heat transfer from a source of short wave radiation (visible or near infrared) to the bead; this depends on the absorptiveness of the thermocouple material and on the irradiance;
5. the radiative heat transfer from the object and the surroundings to the bead and vice versa (net long-wave infrared radiation): this depends on the emissivity of the thermocouple material and on the temperature difference between

the thermocouple and its surroundings.

In some cases the net effect of these heat flows can be calculated on the basis of a simplified model (GREEN & HUNT 1962). Such a model fails in our system, as the most important quantity, the overall coefficient of heat transfer from the object to the bead, is highly uncertain. Calculation shows that its value differs by a factor of 10 for direct contact or an air space of 0.01 mm between object and bead. With this in mind it is evident that the reproducibility of the contact area (governed by contact pressure and the local geometry of the surface), when placing a thermocouple against a surface, is low and that the thermal resistance between leaf and bead can vary over an order of magnitude or more.

The other terms in the model contribute to the occurrence of errors in the reading of the thermocouple. In our system the walls of the assimilation chamber and the air circulating in it are colder than the leaf. The conductive, convective and long-wave radiative heat flows all tend to lower the junction temperature. The radiation-error from short-wave radiation has the opposite sign.

This situation being recognized, two ways were open, viz. skip the thermocouples and use an entirely different method of temperature measurement, or measure the thermocouple-errors and find a technique to avoid them.

A different method is offered by the infrared thermometers presently available. For their use one side of the assimilation chamber should be closed with a sheet of infrared transmitting polythene. These instruments have, however, their own difficulties when used for measurements with high accuracy of temperatures near that of the environment. A full discussion of findings with some of these instruments will be presented separately (SCHURER & PIETERS, in prep.). As a consequence of the problems encountered in the infrared techniques, an evaluation of the thermocouple errors has been explored as well.

To separate some of the effects involved, the experiments have been made with an opaque object having a good thermal conductivity and a reproducible surface. Since respiration and photosynthesis are not essential for the study of thermocouple errors, thin copper plate has been chosen as an artificial leaf in the assimilation chamber.

2. APPARATUS

2.1. Thermocouples

Thermocouples with two diameters have been used, viz. copper-constantan wires (Honeywell) of 0.1 mm and chromel-constantan wires of 0.025 mm. The copper-constantan couples were made by soldering the parallel ends, the chromel-constantan couples were bent to form a loop and spotwelded ((*fig. 2)*.

2.2. Infrared thermometers

Two different types of instruments were used, viz. a radio meter after STOUTJESDIJK (1966) and a thermal imaging camera, the Thermovision model 652 of

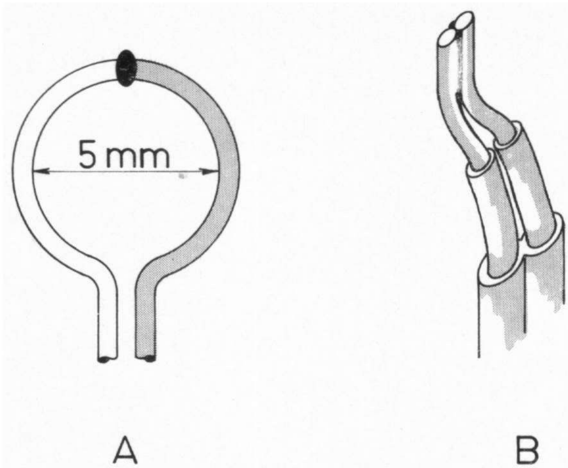

Fig. 2. Construction of thermocouples:
A. chromel constantan couple of 25 and 100 μm
B. copper constantan couple of 100 μm.

A.G.A., Sweden[1]. Both instruments are capable of resolving temperature differences of 0.2 K. The spatial resolution of the camera is about 1 mm^2 at its nearest focus; the viewing angle of the Stoutjesdijk radio meter is 36°.

2.3. Assimilation chamber

The assimilation chamber consists of an aluminium frame with double glass windows on both sides. The inside of the chamber measures 100 × 95 × 12 mm^3. One of the double windows can be taken off to give access to the interior of the chamber. The space between each pair of glass panes is part of a cooling circuit. In some experiments the removable part was replaced by a frame closed with a thin polyethylene sheet to permit infrared thermometry. The leaf is held in place in the middle of the assimilation chamber by a number of thin nylon wires. The petiole can be lead through a slot in the aluminium frame. Nine thermocouples can be put through nine holes. The air inlet and outlet consist of twenty short steel capillaries each distributed over the whole width of the chamber (*fig. 3*). The air stream was vertical and usually ascending. Of the gas flow circuit connected to the assimilation chamber only the recirculation circuit was used in the present experiments. The air flow through the chamber was usually 1 m^3/h, corresponding to a mean wind velocity of 0.24 m/s.

2.4. Artificial leaf

The artificial leaf was made of copper sheet. It measured 80 × 60 × 3 mm^3; front and back had been painted black with Parson's Optical Black Lacquer. Two thermocouples had been soldered onto the copper; five more couples had been inserted in 30 mm deep holes of 1 mm diameter drilled into the sides of the artificial leaf. The temperature indicated by these couples has been taken to be the true temperature of the leaf.

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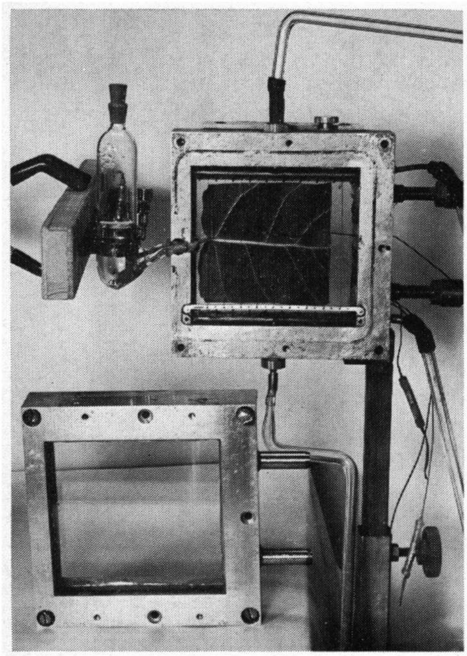

Fig. 3. Assimilation chamber with air flow system.

3. MEASUREMENTS

3.1. Preliminary work

Since the discussion of physiological measurements on leaves had disclosed the probability of systematic errors in the temperature measurements with thermocouples, it was thought useful to carry out some comparative tests on leaves with thermocouples and with the infrared camera.

In the first test a fresh and firm leaf was placed vertically and irradiated from one side. Temperature measurements with thermocouples indicated a difference of several K between the temperature of both sides, the irradiated side being the warmer. The infrared camera, however, disclosed a small effect of a few tenths of a kelvin only.

Calculation of the temperature difference between both sides of a 0.1 mm thick leaf through which a heat flux of 500 W/m^2 flows, gives a value of 0.08 K when the leaf is taken to consist entirely of water, and of 2 K when it is supposed to be completely filled with air. A more realistic model of a leaf 0.3 mm thick with 70% water and 30% air space yields a temperature difference over the leaf of 0.35 to 0.5 K, depending on the particular distribution of water and air. These values suggest that the large differences found with thermocouples are likely to be due to a radiation- and convection-error, rather than to a physiological phenomenon in the leaf, as e.g. different diffusion resistances for water vapour on both sides, as PALLAS et al. (1967) suggested.

In a second test the temperature distribution over the shade side of a leaf in the assimilation chamber was measured. The leaf was heated by illumination from one side and cooled by the air circulating through the chamber. With nine thermocouples pressed against the leaf at different places a temperature gradient in the direction of the air stream was found, the upper edge of the leaf being up to 6 K warmer than the lower edge. Apart from this gradient irregular local differences up to 2 K over a distance of 10 mm have been observed. The edges of the leaf to the left and the right were found to be cooler than the part in between at the same height. This effect has been ascribed to a better thermal exchange near the edges between the leaf and the ambient air by HOFMANN (1956) and by RASCHKE (1956).

The infrared camera produced a markedly different picture. No large local gradients were observed, the gradient in the direction of the air stream was present, but much smaller than suggested by the thermocouples. On a horizontal line over the leaf only small temperature differences were observed, attributable to the intensity distribution of the illumination; the veins were seen as slightly cooler when the leaf temperature was rising and warmer when the temperature was falling.

The temperatures measured with the infrared camera were higher in both tests than those measured with the thermocouples. The same was found for the difference between temperatures measured with the "Stoutjesdijk" radiometer and the thermocouples.

The outcome of these experiments pointed to radiative heating and convective cooling of the thermocouples. Radiative heating can be largely reduced by using small thermocouples. With wires 25 μm in diameter the radiation error in stagnant air does not exceed 0.1 K (SCHURER 1972) for an irradiation of 100 W/m^2 (shade side of the leaf). To investigate the effects of convective cooling alone further experiments were made with thermocouples on the shaded side of an opaque object, the artificial leaf.

3.2. Temperature distribution over the artificial leaf

The artificial leaf was placed in the assimilation chamber and heated by a radiation flux of about 700 W/m^2. The temperature distribution over the leaf as measured with the internal thermocouples is shown in *table 1.* The wind velocity varied from 0.24 m/s downward to 0.24 m/s upward. The figures in the table show a smooth temperature distribution with a gradient in the direction of the air stream.

3.3. Soldered thermocouples

Table 2 shows temperature values measured with both internal and soldered thermocouples. The obvious agreement proves that soldering provides so good a thermal contact as to make any convective or conductive heat losses negligible.

3.4. Leaf surface temperature with thermocouples

Nine thermocouples were placed in a regular pattern against the shaded side of

Table 1. Temperature distribution (in °C) over the artificial leaf (copper plate). Temperatures measured with internal thermocouples.
Irradiation 1000 W/m²; air temperature 12 °C.

Wind velocity in m/s:	0.24 up			0.24 down			0.12 up		
near upper edge		32.3	32.6		34.5	34.8		36.6	37.3
middle		31.5			36.9			35.9	
near lower edge	30.5	30.8		37.3	37.2		35.0	35.3	

Table 2. Temperature distribution (in °C) over artificial leaf (copper plate). Temperatures measured with internal and soldered thermocouples.
Irradiation 700 W/m²; air temperature 12 °C; wind velocity 0.24 m/s upward. Values with * soldered couples, other values internal couples.

near upper edge		29.0	29.2*
middle	28.2	28.0	28.9
near lower edge	27.3*	27.7	

the artificial leaf. *Table 3* summarizes some of the temperature distributions measured. The true temperature of the leaf was measured with the soldered thermocouples.

In darkness the situation is relatively simple. The leaf approximately takes the air temperature, and consequently the temperatures measured with both sets of thermocouples are virtually the same. Local differences are few and relatively small. When the leaf is illuminated its temperature rises considerably over that of the air, and an entirely different situation is found to develop.

Table 3. Temperature distribution (in °C) over artificial leaf (copper plate). Comparison of temperatures measured with 8 external thermocouples with those measured with soldered thermocouples.
Irradiation: 0 W/m²; air temperature: 12 °C; wind velocity 0.24 m/s.

expt. a,			expt. b,		
13.2		13.6	15.4		15.3
13.7	13.5	13.8	15.4	15.8	15.4
13.8	14.3	13.5	15.4	15.3	14.9
mean:	13.7		mean:	15.3	
mean temperature from soldered couples:					
	13.8			15.3	

Irradiation: 700 W/m²; air temperature: 12 °C; wind velocity 0.24 m/s.

expt. c,			expt. d,		
26.0		29.9	24.8		27.7
29.8	23.6	27.7	27.7	24.8	28.0
23.6	21.6	22.2	24.8	23.5	24.3
mean:	25.5		mean:	25.7	
mean temperature from soldered couples:					
	31.7			30.6	

All external thermocouples measure a temperature lower than that of the leaf, the mean difference between both values amounting to 5 or 6 K. The temperature distribution shows the same features as found with real leaves: large and irregular gradients. *Table 4* shows another feature, viz. the sometimes large variations found at one point on the leaf when the same situation is measured twice with the nine external thermocouples taken away and replaced between measurements. The differences between the values measured in the same positions in both experiments were three times less than 0.2 K, three times between 0.2 and 1.0 K, and three times between 2 and 5 K.

An approximately linear relationship between the difference of the temperature of the object and the temperature of the incoming air, and the thermocouple error, is to be expected for any given geometry, although the absolute

Table 4. Temperature distribution (in °C) over artificial leaf (copper plate). Same situation measured twice with thermocouples taken away and replaced between the measurements. Irradiation: 1000 W/m^2; air temperature: 12°C; wind velocity: 0.24 m/s.

1st measurement			2nd measurement		
26.6	28.5	29.0	27.1	28.4	29.1
30.8	26.3	29.1	29.8	31.3	27.0
24.3	25.4	25.5	27.5	25.1	25.6
mean:	27.3		mean:	27.9	
mean temperature from soldered couples:					
	34.1			34.0	

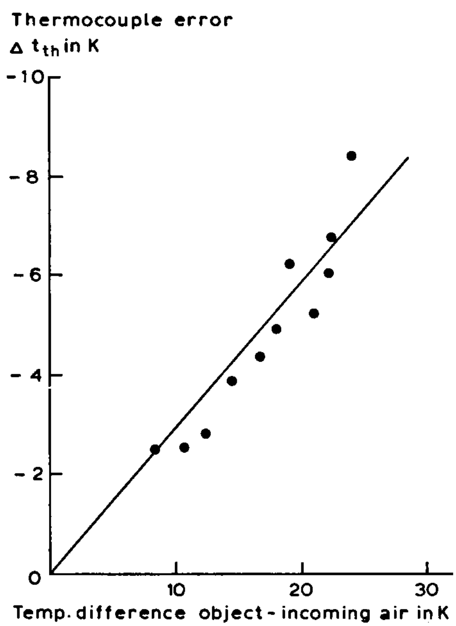

Fig. 4. Example of measured temperature errors for external thermocouples as a function of the temperature difference between object and incoming air. The actual errors will depend largely on the geometry of the couple and the experimental set-up. The different temperatures of the object result from different irradiations and wind velocities.

value of the error may vary largely for different geometries. An example of this relation is shown in *fig. 4*, where values obtained with a 0.1 mm thermocouple are presented.

3.5. Air velocity and direction of flow

Wind velocity is an important factor in the heat balance of the leaf. *Fig. 5* shows the temperatures of different parts of the artificial leaf for wind velocities between 0 and 0.24 m/s upward as well as downward. It was expected that reversion of the airstream should reverse the direction of the temperature gradient. In *table 1* data are given which are consistent with this expectation, but *fig. 5* shows a temperature maximum with the downward stream for the middle of the leaf. This difference is attributed to differences in the convection pattern in both cases. The mean temperature of the leaf depends on both speed and direction of the air stream; an upward stream is more effective in cooling the leaf, since natural and forced convection cooperate in this case.

In another experiment both the air temperature and the temperature of the artificial leaf were kept at a fixed value (differing 23 °C) by adjusting the cooling and heating power, while varying the wind velocity between 0 and 0.24 m/s (upward). *Fig. 6* shows the temperature differences measured between external and internal thermocouples (= thermocouple error) at different points of the leaf. In stagnant air the air temperature in the assimilation chamber rises to the leaf temperature. As soon as some ventilation exists, cooler air enters the chamber and a boundary layer with a thermal gradient develops.

The thermocouple error caused by this gradient for a constant temperature

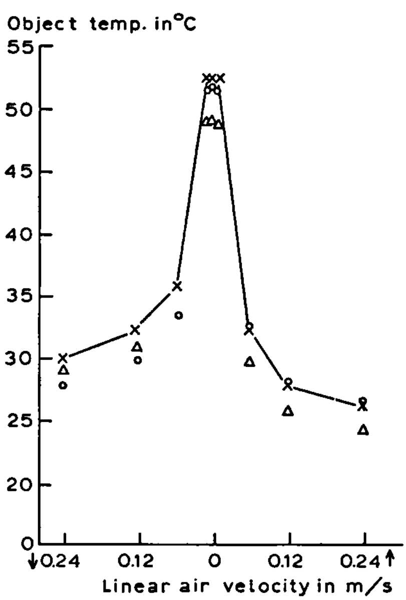

Fig. 5. Temperatures of the artificial leaf in the vertical assimilation chamber as a function of wind velocity. The direction of the airstream is indicated by the arrows. Irradiation ca. 700 W/m²; air temperature 10 °C. Upper part (o), middle part (×) and lower part (△) of the artificial leaf.

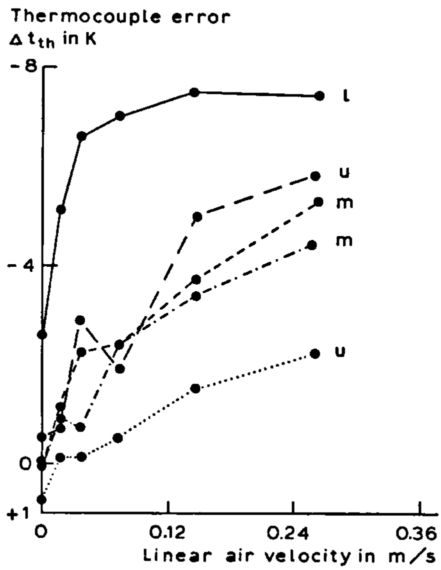

Fig. 6. Temperature difference between internal and external thermocouples as a function of wind velocity at constant temperature difference between object and incoming air of 23 K. u = upper part, m = middle part, l = lower part of the artificial leaf.

difference between object and incoming air is seen to increase with wind velocity. The convective heat losses cause errors of up to about 7 K or one third of the difference between object temperature and air temperature, in this case amounting to 23 K.

3.6. Dimensions and positioning of thermocouples

Generally speaking, it is to be expected that smaller thermocouples will give more accurate results. Most of the experiments described so far were performed with thermocouples with a wire diameter of 0.1 mm. The beads of some thermocouples were flattened to increase the contact area with the leaf. The results in *table 5* show that no improvement was observed.

To reduce the heat exchange with the air, thermocouples were placed on the leaf and covered with plastic paste. *Table 6* shows, that again no improvement occurs. This is attributed to a loss of thermal contact between the leaf and the thermocouples. A check on the contact is impeded by the opaque mass covering the thermocouple.

Anyhow, this method can not be used with real leaves, as it interferes with transpiration and therefore will disturb the local heat balance on the very spot of temperature measurement.

Table 5. Temperature distribution (in °C) over the artificial leaf as measured with flattened thermocouples. Conditions as in *table 4.*

31.1	27.8	22.3	mean: 27.3 °C
27.8	24.3	33.3	mean internal temperature: 35.8
24.5	27.5		

Table 6. Temperature distribution (in °C) over the artificial leaf (copper plate).
Thermocouples covered with plastic paste.
Same conditions as in last experiments of *table 3*.

29.0		26.5	mean: 26.4°C
28.3	25.8	25.9	mean internal temperature: 29.3°C
26.4	25.6	21.8	

Thermocouples of 0.025 mm wire are delicate, but with some care their use is not impossible. With some experience in handling these couples and by consistently checking the contact between the leaf and the bead with a magnifying glass, a good result can be obtained. *Table 7* shows some of the results.

Large errors occurred whenever the junction did not touch the leaf, even though some length of lead was pressed against it. It has been found advantageous to exert a slight pressure (a few grams) on the thermocouple to ensure a good and lasting contact between the junction and the leaf.

4. CONCLUSION

The results of the experiments reported here make it clear that the erratic temperature distribution measured with thermocouples on both a real leaf and a copper plate have a common cause, viz. the ill-defined overall coefficient of heat transfer from the object to the thermocouple junction. The temperature of an irradiated leaf is measured as too low, and non-existing temperature differences are measured between sun- and shade-side of the leaf because of the radiation- and convection-error of the thermocouple.

The radiation-error can be minimized by reducing the wire diameter, and by measuring on the shade side of the leaf whenever feasible. Then a radiation error of not more than 0.1 K is to be expected for a 0.025 mm thermocouple.

The effect of convective losses is also lower for thinner wires and a smaller

Table 7. Temperatures measured on the artificial leaf (copper plate) in the assimilation chamber with 0.025 mm thermocouples.
Irradiation: 700 W/m^2; air temperature: 10°C.

Internal °C	External °C	Difference °C	Wind velocity m/s	Remarks
10.0	10.0	0.0	0.3	dark
25.3	20.5	4.8	0.3	
30.8	25.4	5.4	0.3	experiments on
30.9	25.9	5.0	0.3	proper
30.3	28.3	2.0	0.3	positioning
53.1	51.9	1.2	0	
25.4	25.2	0.2	0.3	pressure of : applied
25.5	21.8	3.7	0.3	2g on couple : not applied

bead. The error can be made less than about 1 K by carefully positioning the couple with a slight force permanently exerted on it. The care in positioning implies a check on the direct contact of bead and object with a magnifying glass. Even so, deviations up to 5 K under the conditions described can occasionally occur. Though Seybold already made this observation as early as 1929, many theories have since been based on thermocouple measurements (GAASTRA 1959; PALLAS et al. 1967; SLATYER 1971).

Some reserve concerning the soundness of the base of these theories seems to be justified.

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