Technical Manual for the

Porometer

type AP4

Version 4

Delta-T Devices

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Contents

Porometry and Stomata

Porometry is the study of gaseous mass transfer through stomata.

When leaves transpire, water evaporates from cell walls and escapes to the atmosphere by diffusing into substomatal cavities, through stomatal pores, and finally through the leaf boundary layer into the free atmosphere. During photosynthesis, molecules of carbon dioxide follow the same diffusion path in the opposite direction.

A rigorous treatment of a model of diffusion through pores should allow for the interaction of diffusing gases and for the difference in dry air pressure across pores needed to balance the difference in water vapour pressure. There is a class of problems in which these complications cannot be ignored (such as in the precise estimate of intercellular CO2 concentration) but for many practical purposes the elementary treatment which follows is adequate.

It will therefore be assumed that for a leaf lamina, the resistance of stomatal pores for a particular gas depends only on their geometry, size and spacing whereas the resistance offered by the boundary layer depends on leaf dimensions and windspeed.

Meidner and Mansfield (1968) tabulated stomatal populations and dimensions for 27 species including crop plants, deciduous trees and evergreens. The leaves of many species have between 100 and 200 stomata per mm^2 distributed on both the upper and lower epidermis (amphistomatous leaf) or on the lower surface only (hypostomatous leaf). The length of the pore is commonly between 10 and 30 µm and the area occupied by a complete stoma, including the guard cell responsible for opening and shutting the pore, ranges from 25 x 17 µm in *Medicago sativa* to 72 x 42 µm in *Phyllitis scalopendrium.*

Because stomata tend to be smaller in leaves where they are more numerous, the fraction of the leaf surface occupied by pores does not vary much between species and is about 1% on average for a pore width of 6 µm. There is a much greater variation in the geometry of pores: the stomata of grasses are usually long, narrow, and aligned in rows parallel to the midrib whereas the elliptical stomata of sugar beet *(Beta vulgaris)* and broad bean *(Vicia faba)* are randomly oriented but uniformly dispersed over the epidermis.

The network of resistances in the diagram opposite is an electrical analogue for the diffusion of water vapour between the intercellular spaces and the external air. The calculation of boundary layer resistance is discussed in Monteith (1980).

Values of 0.3 to 1 $s.cm^{-1}$ are expected for small leaves in a light wind. Many mesophytes have minimum stomatal resistances in the range 1 to 2 $s.cm^{-1}$ but values as small as

0.5 $s.cm^{-1}$ and as large as 4.8 $s.cm^{-1}$ have been reported for *Beta vulgaris* and *Phaseolus vulgaris* respectively.

Xerophytes have larger minimum resistances up to 30 s. cm^{-1}. Cuticular resistances range from 20 to 60 $s.cm^{-1}$ in mesophytes and from 40 to 400 $s.cm^{-1}$ in xerophytes. In both types of plant, the resistance of the cuticle is usually so much larger than the stomatal resistance that its role in water vapour and CO2 transfer can generally be ignored.

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RESISTANCE AND CONDUCTANCE UNITS

RESISTANCE: r is defined by the relation

$E = \delta\phi/r$ ………………………………………………………………………… (1)

where

E is the flux density of water vapour,

$\delta\phi$ is the concentration difference across the resistance r.

CONDUCTANCE: c is defined as the reciprocal of resistance

$C = 1/r$ ……………………………………………………………………… (2)

UNITS

Consistent units yielding "velocity" dimensions for r and c are:

E	ϕ	r	c
$g.\ m^{-2}.s^{-1}$ $mol.m^{-2}s^{-1}$	$g.m^{-3}$ $mol.m^{-3}$	s.m-1	m.s-1

By expressing concentration in dimensionless units of mol of water vapour per mol of air (mol mol^{-1}, effectively equivalent to the volume fraction vpm), the units for r become m^2 s mol^{-1} ("mol" units):

E	ϕ	r	c
$mol.m^{-2}s^{-1}$	$mol.mol^{-1}$	$m^2s.mol^{-1}$	$mol.m^{-2}s^{-1}$

CONVERSION FROM VELOCITY TO MOL UNITS OF RESISTANCE

$r' = r\ .V_o\ (T/To)\ (Po/P)$ ………………………………………………………………… (3)

where

r' is in $m^2s.mo1^{-1}$

r is in $s.m^{-1}$

V_o is in $m^3\ mol^{-1}$, the molar volume of air at T_o and P_o
= $22.7 \times 10^{-3}\ m^3\ mol^{-1}$ at 273°K and 1000 hPa (mbar)
T is in °K

For r = 0.1 $s.mm^{-1}$ (= 1 $s.cm^{-1}$)

r' = 2.44 $m^2s.mol^{-1}$ at 293°K

PRESSURE AND TEMPERATURE DEPENDENCE

Fick's law of diffusion is $E = D\, \delta\phi/\delta x$ .... (4)

Where: E is the mass flow rate,

D is the diffusion coefficient of water vapour, and
$\delta\phi/\delta x$ the concentration gradient.

Comparison with equation (1), shows that r varies inversely with D.
D depends on the absolute temperature and pressure as follows :

$D = D_o (T/T_0)^{1.75} (P_o/P)$ .... (5)

where D_o is the diffusion coefficient at reference values of T_o and P_o.
See also *Resistance dependence on diffusion coefficient* on page 37.

CONCLUSIONS

A. Resistance and conductance values expressed in velocity units are temperature and pressure dependent, by approximately 0.6% K^{-1} and 0.1% hPa^{-1}.

From (3) and (5), it can be seen that pressure effect is eliminated and the temperature effect is reduced to $(T/T_o)^{0.75}$ when mol units are used.

B. Resistance and conductance values expressed in mol units are independent of pressure but are weakly dependent on temperature, by approximately 0.25% K^{-1}.

You may take readings with the AP4 in any of the following units:

Resistance: $s.cm^{-1}$, $s.m^{-1}$, $m^2\, s.mol^{-1}$
Conductance: $cm.s^{-1}$, $mm.\ s^{-1}$, $mmol.m^{-2}\, s^{-1}$

($0.1\ s.mm^{-1} = 1.0\ s.cm^{-1} = 100\ s.m^{-1}$ etc.)

The values are referred to the actual cup temperature of the reading, and the pressure setting that you entered at the start of the measurement session.

If you wish to compare values in different units, remember that

a) conductance is the reciprocal of resistance
b) velocity units can be converted to mol units by (3) above

If you wish to compare readings in the same units, but taken at different temperatures and pressures, use equation (6) on page 36 for velocity units, and equation (3) above to convert to mol units.

Acknowledgements

The above arguments closely follow Chapter 10: Porometry, by Dr K.J.Parkinson in Instrumentation for environmental physiology (Eds B.Marshall & F.I.Woodward, Publ. Cambridge University Press, 1985).

Barometric Pressure

A STANDARDISED PRESSURE SETTING

This applies to "velocity" units, which are pressure dependent.

If you wish to standardise the readings to a preferred value (or if you do not know what the pressure is):

- Set the pressure to the preferred value (e.g. 1000 hPa)
- Calibrate, and then take leaf readings.

The readings will automatically be standardised to the set pressure value provided that the pressure does not change in between the calibration and taking the readings.

This is because the calibration plate and leaf resistance values move in unison.

Standardised readings have the advantage of being more immediately comparable, but you will have no record of the actual pressure at which the readings were made.

AN INCORRECT PRESSURE SETTING

Provided that the pressure does not change in between the calibration and taking the readings, the resistance values will not be in error, they will merely be referenced to the set pressure value.

(The stored set pressure value will of course be incorrect though).

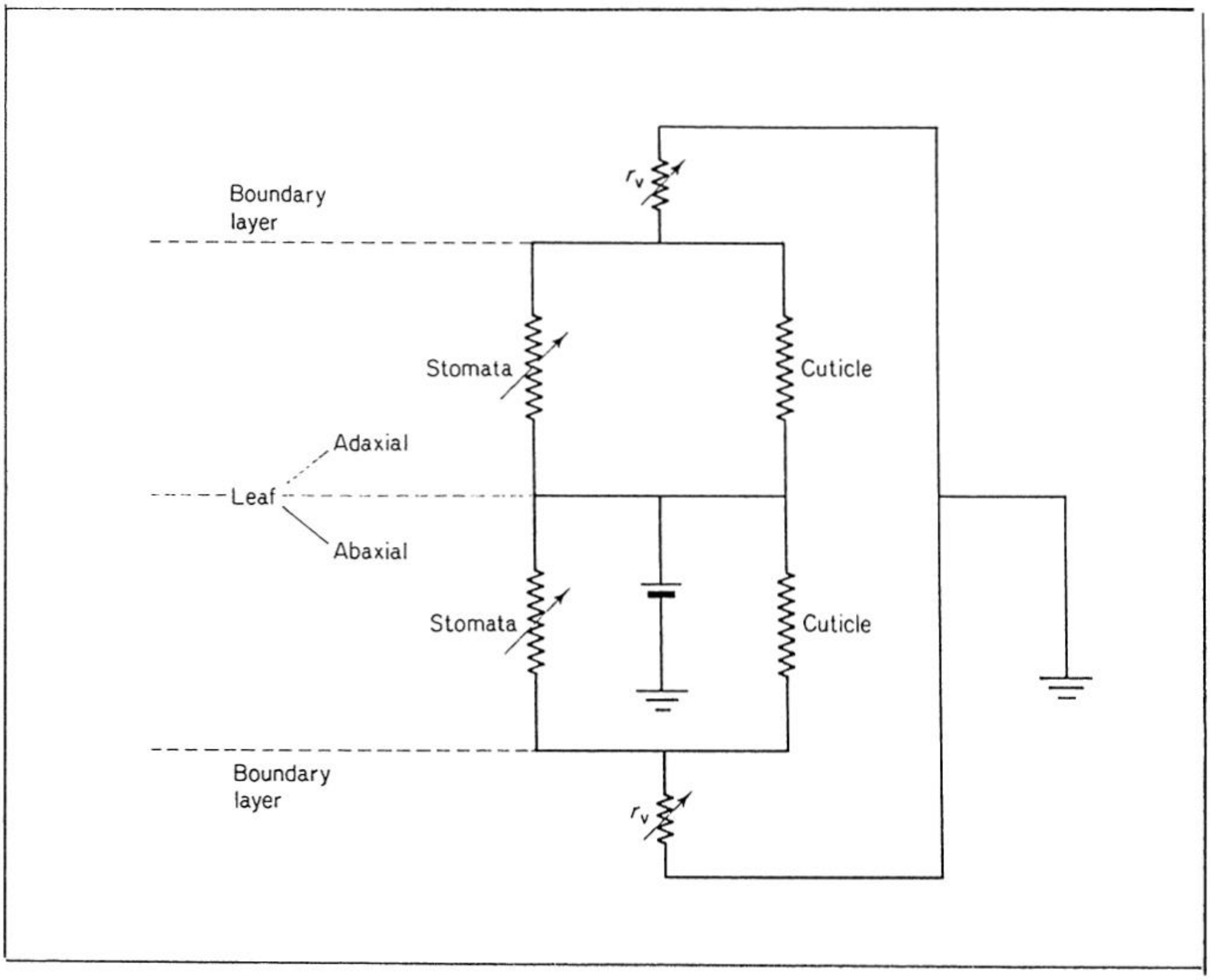
FAILURE TO RECALIBRATE WHEN THE PRESSURE CHANGES

The resistance values will be in error by an amount proportional to the change.

Barometric pressure at sea level may swing between extremes of 960 -1040 hPa, but changes of more than a few hPa in a day are unusual. This is unlikely to lead to significant errors and you may choose to ignore it.

Larger changes in pressure can occur with changes in altitude

(about 1 hPa per 10 m or 30 ft).
If you move to a new site at a different elevation you may need to recalibrate.



Equivalent electrical circuit for the loss of water vapour from a leaf by diffusion through the stomata and cuticle of the upper and lower epidermis.

(Reproduced with permission from Principles of Environmental Physics by J Monteith, published by Edward Arnold)

Spares, Consumables and Accessories

SPARES KIT: Type PSK2

Lid ribbon cable	
Pump Assembly:	Interpet AP2
Air inlet airline	
Air outlet airline	
Case hinge x 2	
Lid gasket 3	mm ERC x 700 mm
Nuts, bolts and rivets	
Charger board cable	
Qwerty board cable	
RS232 25 (male) to 9 (female) pin cable	
Container tube, (not including desiccant)	
Cup insert x 2	white polypropylene
Cup seal x 2	grey silicone rubber
Cup gasket	white silicone rubber
Cup RH sensor	
Cup thermistor	
Head flexible connector	
Head Go button	
Leaf pressure pad and thermistor	
Head cable assembly	
Charge socket	
Calibration plate	white polypropylene
Pouch for calibration plate	
User manual	

CONSUMABLES KIT: Type PCK1

Calibration Pads	Packet of 100
Silica gel crystal	500 g
Tape	
Cup seal	
Cup insert	
Silica gel container tube	
Screws x 2	M4 x 8mm nylon

OTHER OPTIONAL ACCESSORIES

PBR1	Barometer wristwatch.
PSH1	Spare sensor head.
PSB2	Spare AP4 re-chargeable battery[1]
PAD	Paper pads for AP4
AP4-CHG	Charger for AP4 battery
AP4-CP	Spare AP4 calibration plate

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[1] The PSB2 battery is not compatible with AP4 Porometers supplied before 2004, unless a chassis modification has been made. This affects chassis serial numbers lower than AP4-69-01. If you require a replacement battery or a spare battery for one of these earlier Porometers, please contact Delta-T

How to Service

BATTERY

Recharge
Care
Storage
Replacement

BATTERY RECHARGING

The AP4 contains an 8 Volt, 2.5 Ah sealed lead acid battery.
It takes about 14 hours to recharge. It has plenty of capacity for normal use:

Typical current consumptions are:

SLEEP (clock & data memory retention) = 20 mA
ON (normal use, not pumping) = 50 mA
PUMP (depending on pump rate) = 50 to 500 mA

Thus a normal average current is about 100 mA, depending on pump usage.
The 2.5 Ah battery should last for over 20 hours of this use.
New batteries have a lower capacity that builds up over the first few charge/discharge cycles.

When the remaining battery capacity falls to 15%, the AP4 display shows a warning that the battery is getting low. At 10% the AP4 shows a warning, "SHUTTING DOWN" and switches itself off to ensure data memory retention for at least another 2 weeks.

The sleep consumption, when the AP4 is switched off, is negligible and will normally be exceeded by the battery's self-leakage. The self-leakage is very temperature dependent, as can be seen from the maximum storage time graph, which shows the time for a fully charged battery to discharge through self-leakage.

BATTERY CARE

The lead acid battery should give many years of useful life, provided it is never deeply discharged:

ALWAYS PROMPTLY RECHARGE THE BATTERY WHEN IT'S RUN DOWN:

Connect the AP4 charger the CHARGE socket. The CHARGE indication LED should light.

The Porometer's battery life % indication on the first screen should rapidly increase. While charging, the % charge indication over-reads. A low battery takes about 16 hours to recharge.

It can be left on charge for several days without harm. The Porometer can be used as normal during charging.

Since the Porometer contains its own battery charge regulator, any 12 to 15 Volt DC supply can be used as a charger, including laboratory power supplies and 12V car batteries, connected by a 2.1mm co-axial "power" plug with the INNER POSITIVE.

A rising battery life % indication confirms that the battery is actually charging.

If the battery is deeply discharged, recharge it at soon as possible. When an AP4 with a flat battery is turned on it may display the warning, "SHUTTING DOWN" and then switch off.

An AP4 with a completely flat battery won't even turn on. When deeply discharged it may take a long time, even days, before it starts to accept charge, and then it may have reduced capacity.

The stored readings and the time/date may have been lost.

Re-set the time and date, if necessary, using <SET>.

STORAGE

THE BATTERY MUST BE CHARGED BEFORE AND PERIODICALLY DURING STORAGE,

to prevent deep discharge due to gradual self-leakage.

Recharge all batteries at least once a year.

For storage temperatures above 20˚C, recharge more frequently. See "Maximum Storage Time” graph, which shows the time for complete self-discharge of a fully charged battery.

We recommend recharging at least twice as frequently as indicated by this graph.

Any spare batteries should be rotated & recharged at these rates.

See CASE AND CHASSIS: How to Undo it - page 14

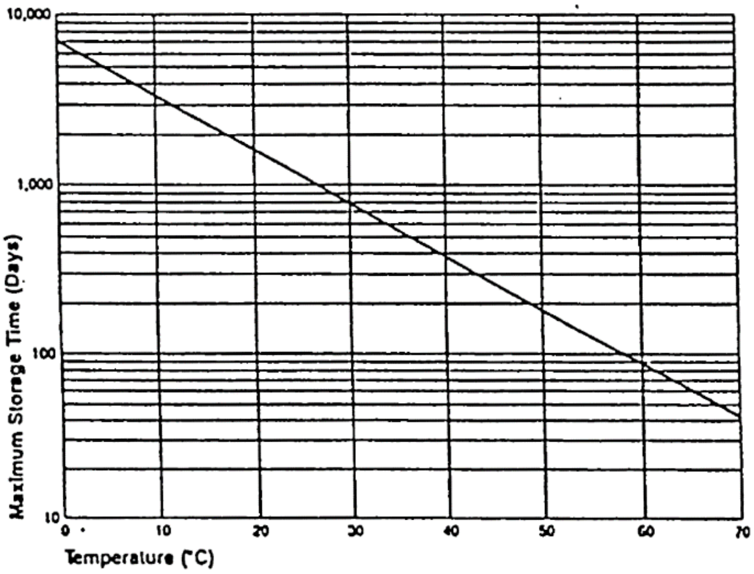
A fully charged battery has an open circuit voltage of about 8.7 V, falling to 7.9 V when discharged.

WARNING:

Do not short circuit the battery.

When connected to the AP4, the battery is protected by a self-resetting thermal fuse on the main circuit board.

If the battery is somehow accidentally shorted directly, there is a risk of fire or explosion .

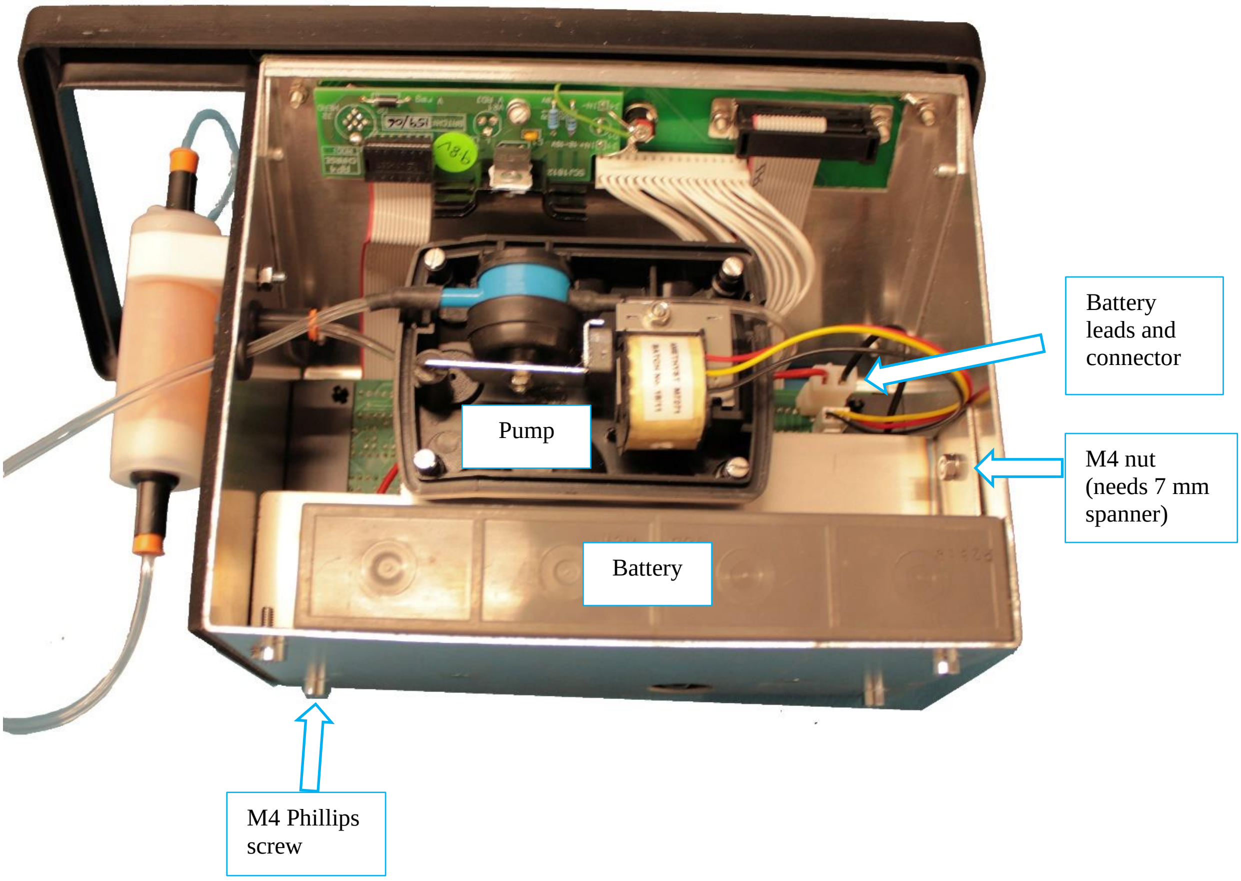


Graph showing the time it takes a battery to self discharge

BATTERY CHANGING

- Remove the chassis from the case as described on page 14 in CASE AND CHASSIS: How to Undo it.
- Disconnect the battery connector.
- Loosen the nut and screw that secures the battery clamp,
- Lift the clamp up enough to clear the battery,
- Carefully slide the battery with its wires and connector clear.

When fitting the new battery simply reverse the procedure but pay special attention not to trap the wires under the battery clamp. Feed them through first.



CASE AND CHASSIS: How to Undo it

REMOVE THE BAG FIRST

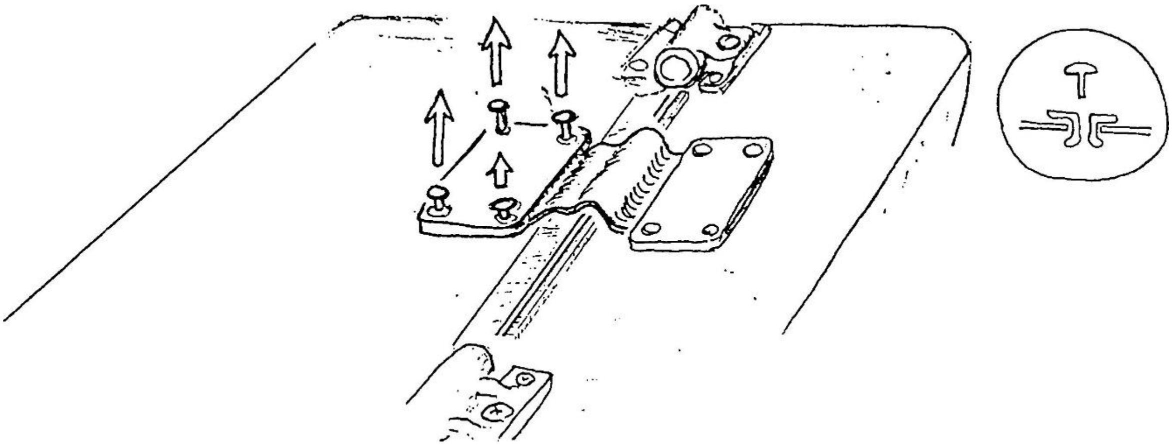
Unzip the bag completely around the lid section.

Slide fingers between lid and bag to unhook the velcro from inside, then pull the bag clear of the lid.

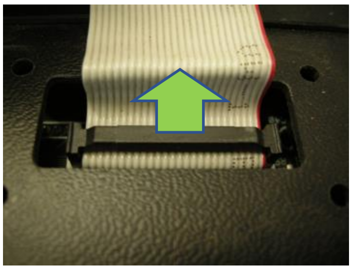
Unhook velcro from case section in the same manner and slide the bag from the case assembly.

TO OPEN THE CASE

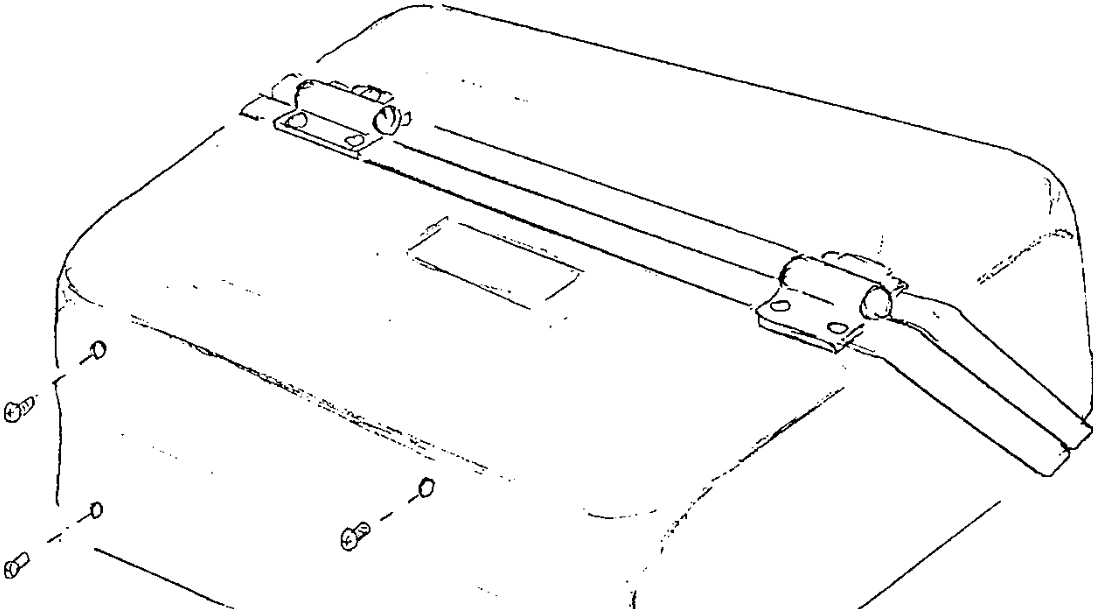
Lay the case on its front and using a steel rule or finger nails remove the four black rivets that hold the cover plate to the back of the case.



Remove the cover plate, grip the ribbon cable as close as possible to its connector and pull it clear from the case.



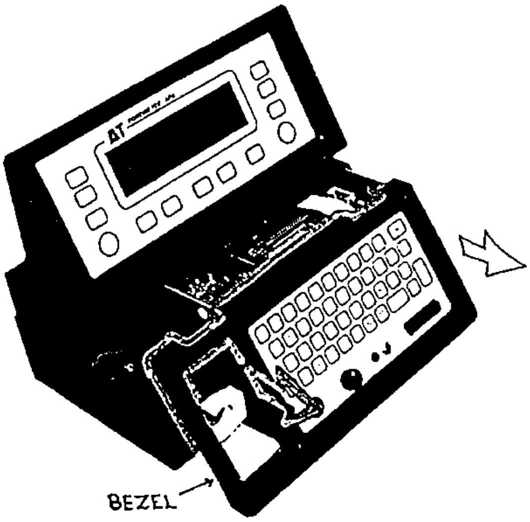
From the base of the case assembly remove the four screws that secure the chassis to the inside of the case.



Disconnect the head assembly and remove it from the side pocket. Unclip the desiccant assembly from its white clip and disconnect the outlet pipe. Remove the desiccant assembly from the side pocket.

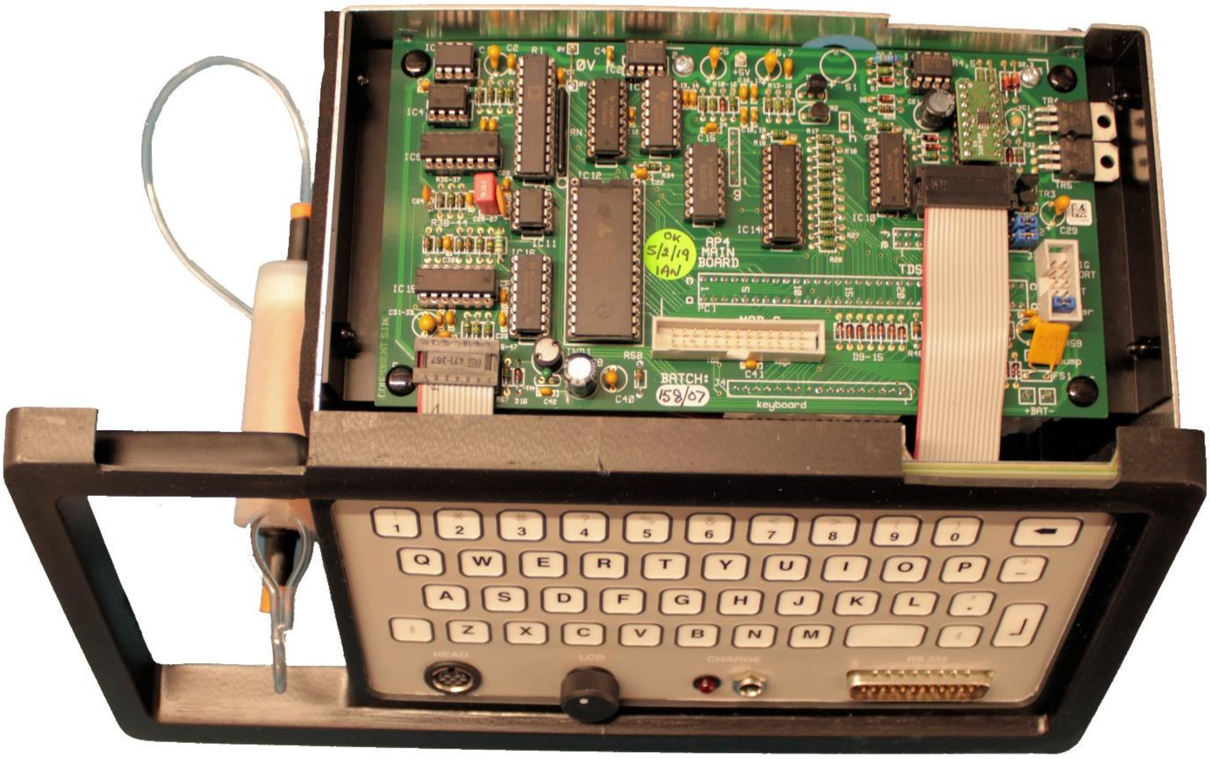
Seal the ends of the desiccant assembly. This helps minimise the exposure to air. Use the blank bung and the bung the head assembly.

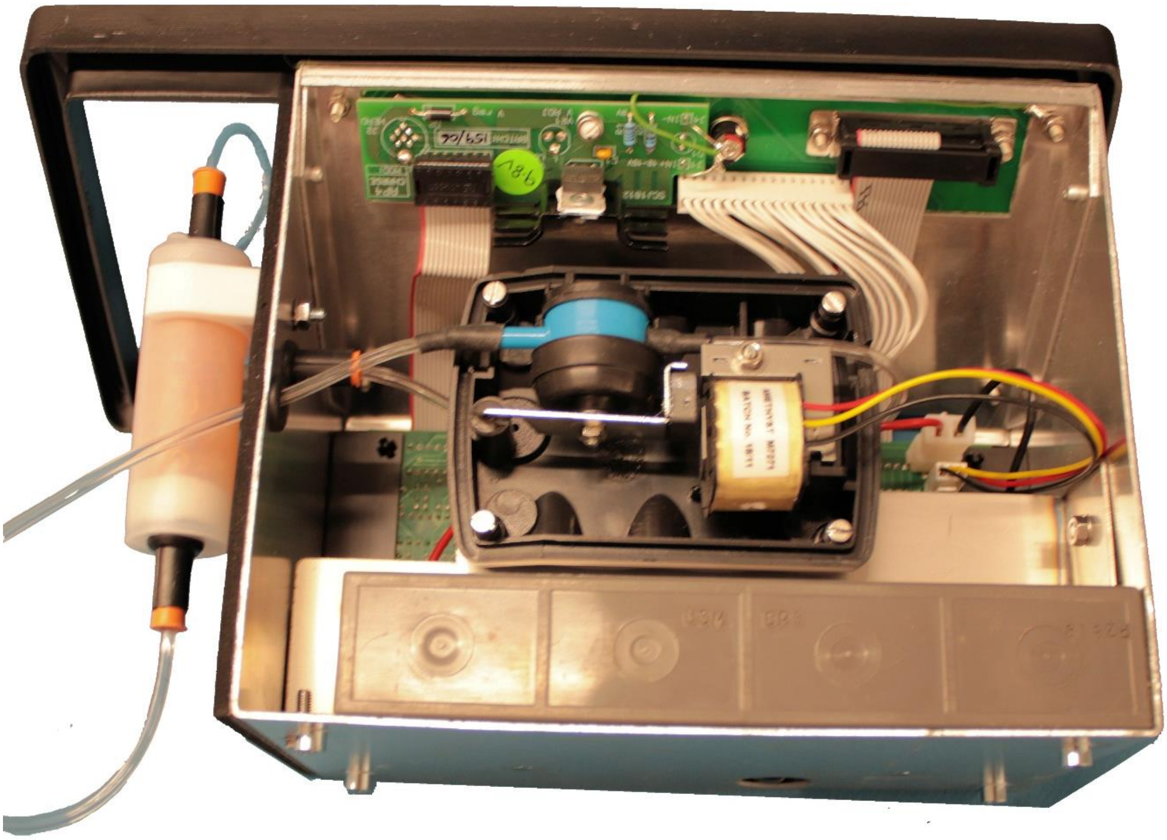
With one hand on the plastic clip inside the side pocket and the other on the bezel at the other end gently ease the chassis assembly from the case. Note that excessive force should not be applied to the bezel in an effort to remove the chassis from the case.



Once the chassis has been removed, the desiccant assembly can be clipped back into place and the pump outlet pipe attached. Keep the top sealed with the blank bung to minimise exposure to air.

CHASSIS LAYOUT





CUP: HOW TO CHANGE IT

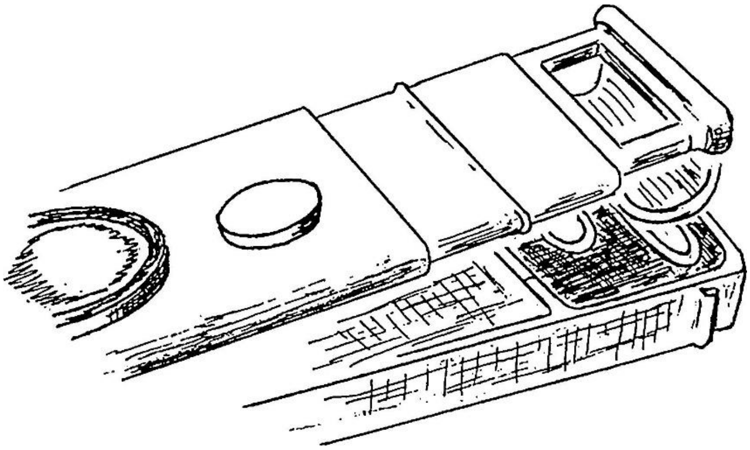
Two alternative cup shapes are provided in the head of the AP4.

A long, narrow slot, 2.5 x 17.5 mm, and a circular, 6 mm diameter aperture are both provided. Heads are shipped from the factory with the slot installed.

The active cup is the one at the end of the head. You can see it through the sliding window

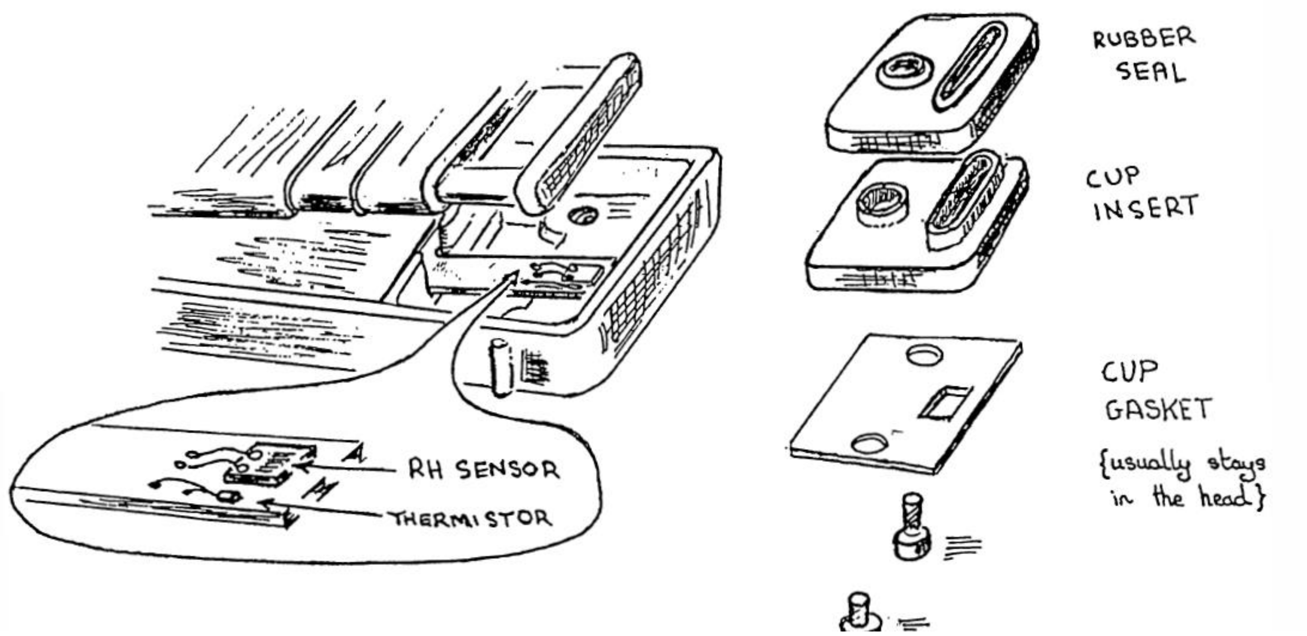
The calibration plate is designed for use with either cup.

POROMETER HEAD WITH SLOTTED CUP INSTALLED



POROMETER HEAD DISASSEMBLED

Showing rubber seal and cup insert



CHANGING THE CUP

Disassemble the two halves of the head unit, see HEAD: HOW TO DISASSEMBLE on page 21.
Unscrew the two large plastic screws readily visible on the outside of the head.
Gently tease out the rubber seal and cup insert.

WARNING

Take care not to touch, or shock the fragile RH sensor

Do not use organic solvents on or near the RH sensor

You can now rotate and replace cup insert and seal.

Do up the screws until you just feel some resistance, and then tighten up one more quarter turn.

WARNING

Avoid overtightening the screws. They are stronger than the plastic of the insert and may strip out the thread.

Change the cup type in the Calibration Settings.

DESICCANT: HOW TO CHANGE IT

The self- indicating silica-gel desiccant crystals change colour when wet. Typically (in 2020) they are orange when dry and green when wet. The colour, and colour change from dry to wet, can both vary depending on the type of desiccant. To be sure about your desiccant, wet a grain of it and make a note of the colour change

Unclip the desiccant container and remove it from the white plastic spring clip in the pocket to the left of the QWERTY keyboard.

Unplug the translucent air lines.

Open the hinged container. It opens at one end.

Either replace the desiccant with fresh self-indicating silica gel crystals or reconstitute the crystals - see below.

Reassemble.

RECONSTITUTION OF CRYSTALS

Note added 2020

WARNING

When the AP4 was first released in 1991 it was normal to reheat the desiccant to dry it.

Please note that this now is **not now recommended** as it damages the desiccant

If you are caught out in a remote location without fresh desiccant, then the following procedure temporary solution may help: -

Spread out the crystals in a heatproof dish or tray

Heat gently in an oven at 93°C (200°F) for 4 to 8 hours until the dry colour returns.

WARNING : Overheating crystals can reduce their capacity

FIRMWARE: HOW THE CHECK THE VERSION

This section has been drastically altered since 1991.

Replacing the EPROM used to be the way to upgrade the firmware, but we got rid of the EPROM and its associated printed circuit board (PCB) many years ago.

It was replaced by a microprocessor on a different PCB.
So there is no EPROM on recent AP4s

To find out what firmware you have installed

Press **SHIFT** + **OFF**
The Version is displayed on the bottom right of the screen.

EPROM version 2.28

If EPROM version 2.28 is displayed following SHIFT + OFF, then you do actually have an EPROM.
It should work fine, but if returned to Delta T we will offer to replace it with the latest microprocessor version (for an additional cost)

EPROM version 2.51 or 2.6

If either of these "EPROM" versions is displayed (following SHIFT + OFF), then you actually have a microprocessor on the daughter board PCB, and not the EPROM.
Version 2.6 is the latest version of the firmware at the time of writing, and includes a slightly more reliable pump controller on it.

We apologise for any confusion caused by calling all of these "EPROM" versions.

HEAD: HOW TO DISASSEMBLE

The AP4 head circuit board contains surface mount components and is not suitable for field repairs.
See Warranty, Service and Technical Support on page 52 of the AP4 user Manual

Reconfigure the head if you replace it.
See also
LIGHT SENSOR: CALIBRATION on page 23
THERMISTOR: CALIBRATION on page 26.

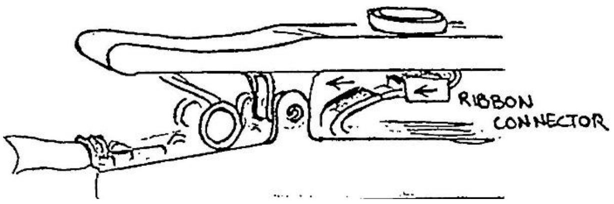
The two halves of the head can be separated for changing or cleaning the cup seal, cup insert and gasket.

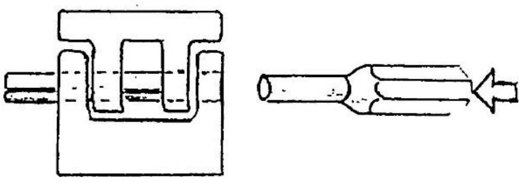
- Inspect the spring to see how it is located
- Push out the hinge pin .
- Unplug the ribbon cable.
- Remove the spring.

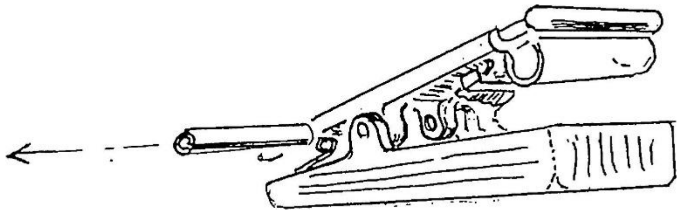
Observe the light sensor calibration factor written on the inside of the light half.

You can now change the cup if you wish – page 17
To reassemble

- Replace the spring.
- Reconnect the ribbon cable.
- Replace the hinge pin.



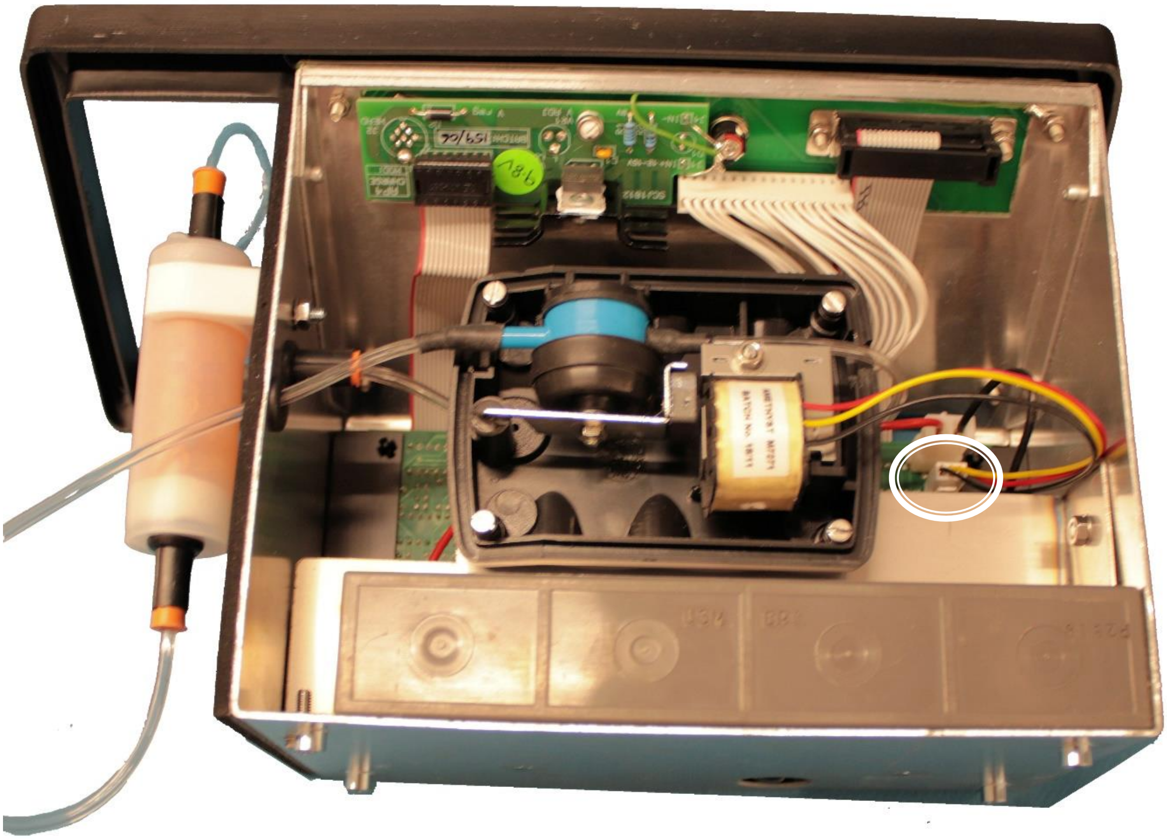




PUMP: HOW TO CHANGE IT

Remove the chassis - see page 14

Disconnect the pump connector (with red and yellow leads) from the back of the main circuit board and disconnect the pump inlet and outlet pipes.



Unscrew the pump mounting bracket and remove the pump and bracket.

Unscrew the four screws to remove the pump from its bracket.

When fitting the new pump simply reverse the procedure.

It may help to moisten the pump inlet and outlets before pushing on the flexible airline tubing.

LIGHT SENSOR: CALIBRATION

The AP4 sensor head has an unfiltered GaAsP photodiode with a spectral response approximately like the ideal photo-synthetically active (PAR) response.

Its sensitivity, as measured at Delta-T, is labelled inside the sensor head, as a sensitivity factor where about 0.5 is typical. This sensitivity should be stable.

It is easy to reprogram the AP4 with a different sensitivity factor should you change sensor heads or need to re-calibrate the light sensor.

- Clean the light sensor's translucent plastic cover with a damp cloth.
- Select the "CONFIGURE AP4 HEAD" screen by pressing the <SHIFT> and <OFF> keys together.
- Use the <+> & <-> keys to either: -

  Set the sensor's sensitivity factor to that marked on the inside of head, (typically about 0.7)

  or bring the displayed light intensity up to a known level. This will require the use of a calibrated source or a second, calibrated sensor.
- Press “GO” to confirm settings

RH SENSOR: CALIBRATION

- Introduction
- Setting the low RH indication
- Setting the high RH indication
- Repeat

See also CLEANING THE SENSOR HEAD on page 45 of the AP4 User Manual

Recalibration may be necessary if the RH sensor has been exposed to smoke, acid or solvent vapours or debris.

There are 2 trimmer potentiometers in the sensor head which you use for adjusting the output for low and high RH. See page 25. These have received a protective coat of silicon rubber glue.

SETTING THE LOW RH INDICATION

Select READ from the main menu to display the RH. Apply a known low RH to the sensor and adjust VR2 (via the hole in the side of the sensor head, furthest from the cup) to give the correct indicated RH.

Applying a known RH is not easy. Allow plenty of time for equilibration, since so many surfaces absorb & release water.

Some methods are: -

a) Blow dry, bottled gas onto the sensor. (You may need to separate the two halves of the sensor head by pushing out the hinge pin)

OR

b) Leave the opened sensor head in a sealed polythene bag with plenty of fresh desiccant for several hours.

SETTING THE HIGH RH INDICATION

Apply a known high RH to the sensor and adjust VR1 (via the hole nearest to the cup) to give the correct indicated RH.

The RH should preferably be in the 70-80% range to give a high output, avoiding >80% RH, where the sensor output is less linear.

Blow air onto the sensor from a humidity generator, eg; using hydrated ferrous sulphate. Take care to avoid or compensate for temperature differences between the RH source and the porometer's RH sensor.

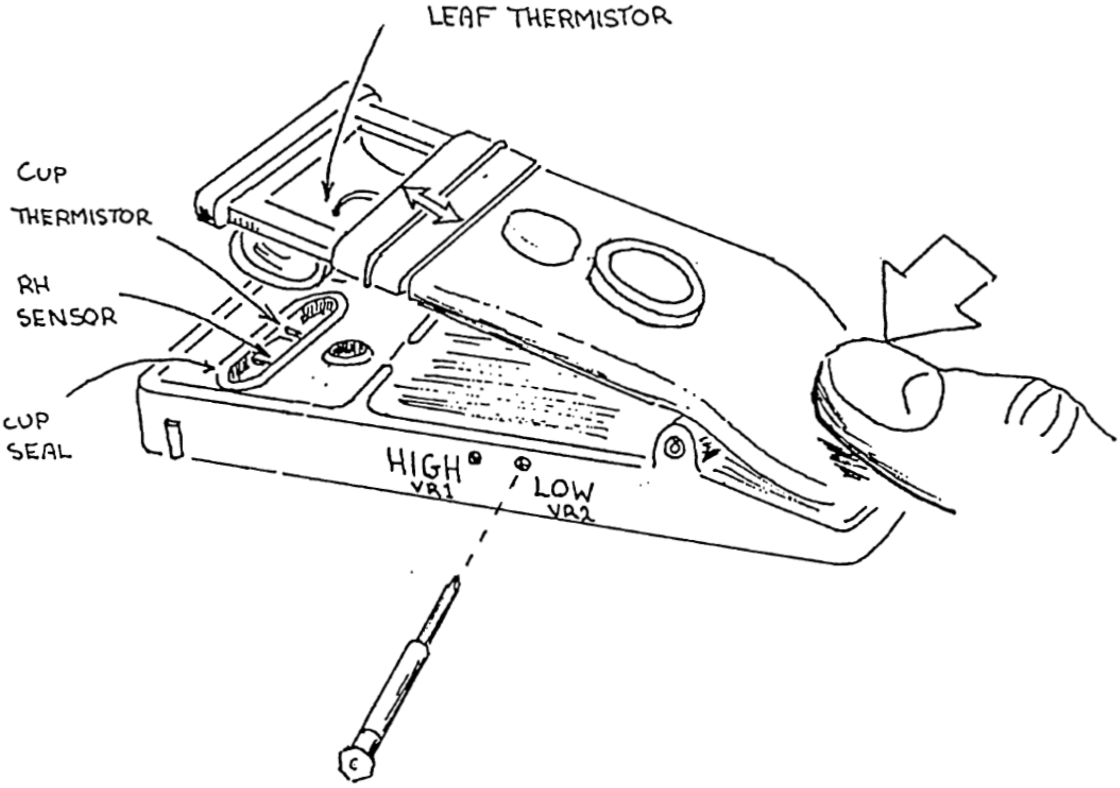
OR

Leave the opened sensor head in a humidity-controlled chamber.

REPEAT

Repeat setting the low and high RH until the two known set points can be read to within 0.5%

At Delta-T we find two iterations are usually sufficient.
More iterations will be required the further the low RH is away from 0%



THERMISTOR: CALIBRATION

The Cup and Leaf thermistors should have a resistance of 100 kΩ (±0.47%) at 25˚C.
They should maintain their accuracy, unless physically damaged.

To optimise the Cup-Leaf temperature difference accuracy, a zero reading is stored when the temperatures are equal. Subsequent readings are referred to this zero reading. Re-zeroing is necessary if you change the sensor head or if the temperature difference reading is not zero after good temperature equilibration.

To zero the temperature difference reading, select the "Configure AP4 Head" screen by pressing SHIFT and OFF keys together. On this screen is displayed the raw Cup and Leaf temperature readings, uncorrected for any systematic offset errors in the electronics.

Allow the head temperature to stabilise by placing it (with no plate or leaf) in the AP4 compartment, away from direct sunlight or sources of heat. When the displayed δT is stable, press GO.

This zero offset reading is automatically subtracted from all readings before they are displayed on all other screens (or recorded to memory).

If the displayed δT (on the SHIFT OFF screen) is more than ±0.5˚C, and the temperature has stabilised, then there may be a fault in one of the thermistors.

If the Cup temperature reading is obviously wrong, check that the sensor head connector is properly plugged into the main case and check the continuity of connection between the thermistor and the main circuit board. If these are OK, the cup or leaf thermistor may need replacing. See section 10.3 for how to expose the thermistor. If one of its leads is un-soldered, its resistance can be checked. It should be 100 kΩ (±0.47%) at 25°C, falling with rising temperature. If the resistance is not correct, replace the thermistor, taking care not to over-heat it during soldering.

Similarly, if the temperature difference reading cannot be zeroed and the Cup temperature reading is OK, check the leaf thermistor's connection to the main PCB. Its resistance can be checked after disconnecting the two sensor head halves. A replacement is supplied in the spares kit, already mounted in the silicone rubber leaf pad.

WARNING

IF YOU HAVE SELECTED THIS SCREEN TO CHANGE THE LIGHT SENSOR CALIBRATION FACTOR, OR JUST TO HAVE A LOOK ROUND, OR INSPECT THE SET SCREEN, AND YOU DO NOT WISH TO CHANGE THE CURRENT TEMPERATURE OFFSET, THEN LEAVE USING EXIT INSTEAD OF GO.

SOFTWARE CHANGES: HOW TO RESET

HARD RESET

Warning: This reboots the firmware **and you lose all data.**

Press Help, then press the Shift key (⇧) and C

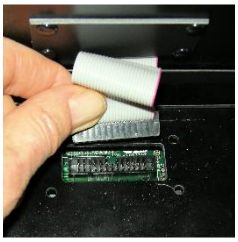
The display should return to the "Main Menu" screen and normal operation resume.

SOFT RESET

With Soft Reset you do not lose any stored readings.

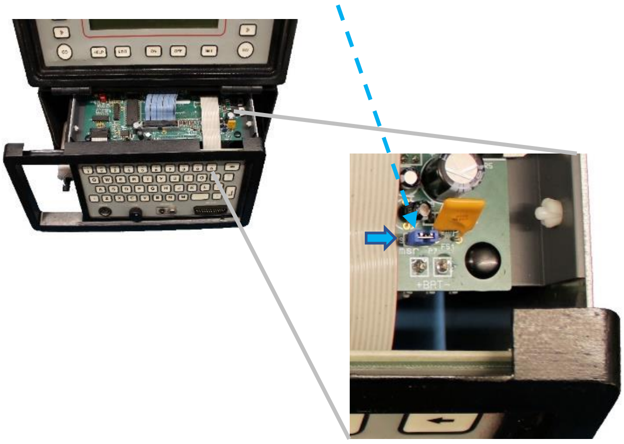
The display should return to the "Main Menu" screen and normal operation resume.

- Partially open the case. Remove the ribbon cable cover plate.
  (See CASE AND CHASSIS: How to Undo it on page 14)
- Unplug the ribbon cable at the back of the case



- Remove the 4 screws on the base of the case and start to slide the chassis assembly out of the case.
- Reconnect the ribbon cable at the front

- Remove the blue jumper plug for about 3 seconds, and then put it back on.
  This will do the soft reset.



- Re-connect the ribbon cable through the hole at the back of the case
- Re-assemble the case.

TROUBLE SHOOTING

SYMPTOMS		CHECK / DO:	REFER TO
DEAD	No display	Battery voltage, connection	Page 11
STUCK	Keys have no effect	Reset the CPU	Page 27
STUCK ON	Can't turn off	Reset the CPU	Page 27
BATTERY PROBLEMS	Short life Can't re-charge	High current consumption Old or abused battery Keep trying. Replace battery	Page 11
POOR READINGS	RH	Re-calibrate	Page 24
	Cup temperature	Check Cup thermistor	Page 26
	Temp difference	Re-zero temp difference	Page 26
		Check Leaf thermistor	Page 26
	PAR	Clean light sensor surface	Page 23
		Set Light Factor	Page 23
	Conductance or Resistance	Reading procedure Calibration procedure	AP4 User Manual
		Check cup seal	Page 17
		Change to other cup size	Page 17
	Data or notes lost	Low battery	Page 11
DATA LOSS	Can't communicate	Connections	See “Output
OUTPUT PROBLEMS	Can't communicate Can't lower RH	Parameters Handshaking	See “Output to Computer” page 36 of the AP4 User Manual
PUMP PROBLEMS		Renew desiccant	
		Blocked air pipe	
		Low battery	Page 11
		Change pump	Page 22

How it Works

Contents

WHAT HAPPENS IN THE HEAD

HOW THE RESULTS ARE CALCULATED

- Introduction
- Monteith equation gives resistance from transit time
- Wood's equation describes cup absorption
- Diffusion coefficient depends on pressure and temperature
- Saturated vapour pressure gradient depends on cup-leaf temperature difference
- Transit time depends on speed of RH sensor
- Calibration Algorithm Flowchart
- Measurement Algorithm Flowchart

WHAT HAPPENS IN THE HEAD

The small cup containing a relative humidity sensor is clamped to a leaf. Water vapour emitted by the leaf causes the relative humidity (RH) within the cup to rise. The instrument times how long it takes the RH to rise by a small increment, of 2.3% RH.

The leaf stomatal resistance is then automatically calculated, using the algorithms described in the next section.

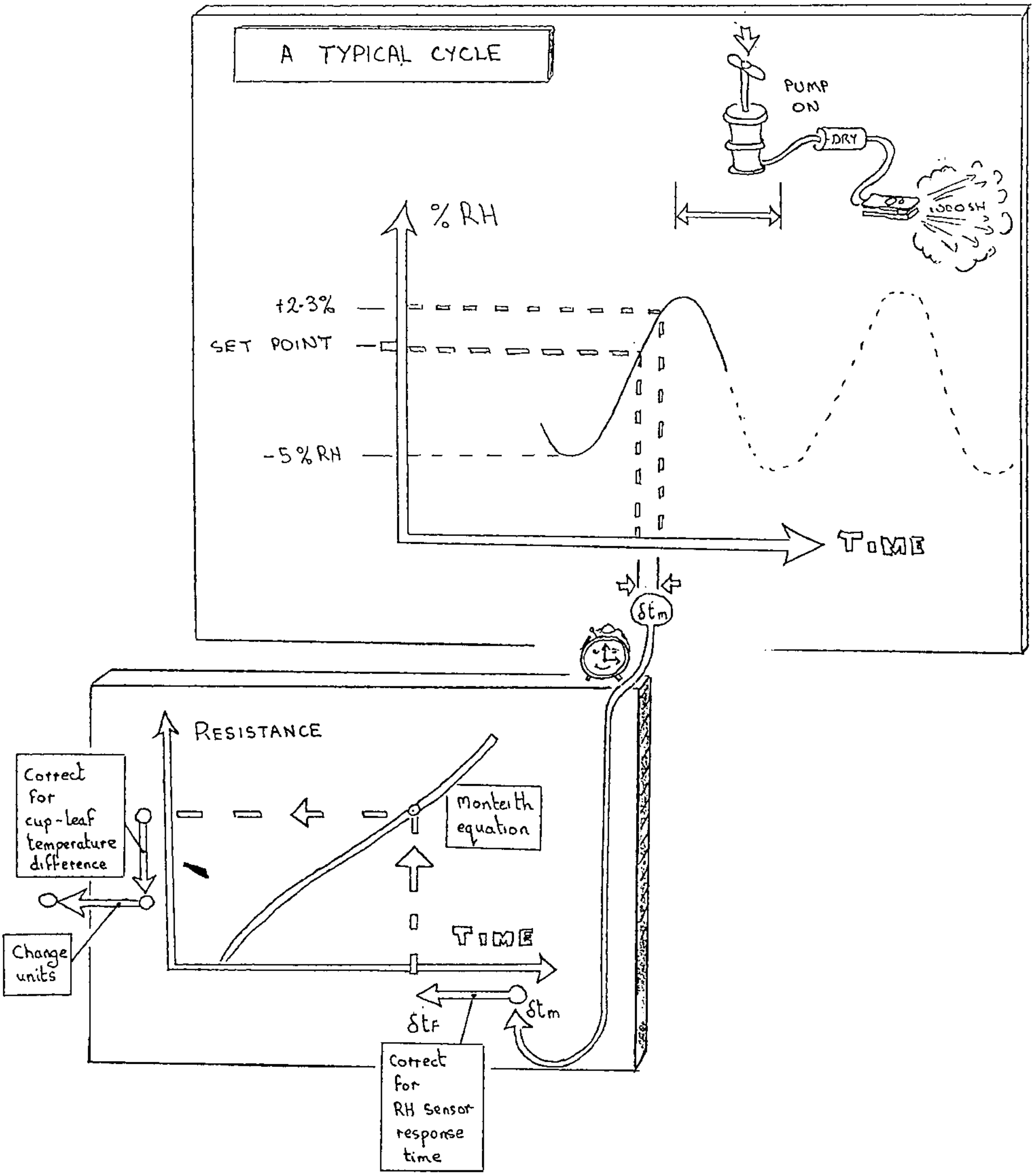
The instrument is calibrated using a calibration plate with precise holes of known dimensions from which the resistance has been directly calculated by finite element analysis.

The transit time is found to depend slightly on the RH history within the cup. So it is necessary to repeat the readings using a consistent cycle of humidification and desiccation until the conditions in the cup have stabilised. This usually takes about 3 or 4 cycles.

The cycle is produced by a pump, which blows dry air into the cup after each timing measurement. It takes the RH down about 5% RH below the set level. To minimise errors the instrument is cycled around ambient RH.

See also Appendix A : Design of the AP4

A TYPICAL CYCLE



HOW RESULTS ARE CALCULATED

Introduction

The AP4 is similar to our previous porometers in that it uses a calibration plate with 6 sets of pores of known resistance and conductance.

In the past the calibration plate was used to create a graph from which the user could look up the resistance corresponding to a measured transit time. When there was a shift in temperature the operator was encouraged to either recalibrate or apply several corrections. With hindsight these corrections now appear to have been too simple. It was also apparent that frequent recalibration in the field, with its laborious manual redrawing of graphs, was tedious and time consuming. Our main brief for the design of the AP4 was to circumvent this with the use of a microprocessor. We have gone beyond this - the porometer contains a theoretical model of its own behaviour, based on the gas diffusion laws. It is now able to compensate quite well for any temperature shifts and is quick and easy to recalibrate.

This has been made possible as a result of the work of Monteith, Campbell and Potter (1988) and Wood (unpublished and summarised here in Appendix A and B).

Monteith *et al* applied gas diffusion theory to derive an equation for resistance in terms of the transit time. Their theoretical model took account of the finite response time of the humidity sensor, the absorption of water vapour by the cup walls and sensor, and the difference between the leaf and cup temperatures. They found that the theory described quite well the sensitivity and the temperature coefficients of the Delta-T Mark 3 cycling porometer.

Wood made substantial additional contributions to the theory of cycling porometry. He extended the Monteith theory so that it can be implemented in the AP4. He also modelled the dynamic behaviour of the porometer cup, using two-dimensional finite element analysis. This improved our understanding of the dynamic behaviour of the vapour pressure gradient which drives the water vapour across the cup, and has given us a physical insight into the shape of the resistance versus transit-time graph. He also refined the calculation of calibration plate values using three-dimensional finite element analysis.

Wood extended the Monteith theory by investigating and characterising the temperature dependence of the absorption of water vapour in the cup, and also the behaviour of the RH sensor. He integrated these, and other temperature dependent variables, with the Monteith equation. The resulting set of algorithms can be used to accurately measure resistance over an extended range, well away from the calibration temperature.

Wood's method still requires the use of the calibration plate. With earlier cycling porometers the calibration plate was used to manually construct a graph of transit time versus resistance. The resistance of an unknown leaf was then manually read off. Now the calibration plate is used to characterise the water absorption by each individual cup, which is then substituted in the Monteith equation to automatically calculate the resistance.

Readings are now valid for modest excursions away from the ambient temperature existing at calibration. These corrections maintain the accuracy of readings to within ±20% for temperature variations of +10°C and -5°C away from calibration.

This means you do not have to recalibrate so often as with earlier porometers.

Cycling porometry has been well established as an experimentally validated technique for many years, and our instruments have a good reputation in the international scientific community. The development of the AP4 represents a profound improvement in the theoretical credibility of cycling porometry and the use of calibration plates, as an alternative to the steady state method.

The next section describes the equations used in the theoretical model of the porometer: -

- Monteith *et al* equations for resistance as a function of transit time.
- Wood's equations for cup absorption.
- Temperature and pressure dependence of the diffusion coefficient of water vapour, and its effect on resistance.
- Temperature dependence of saturated vapour pressure.
- Vapour pressure gradient dependence on cup-leaf temperature difference.
- RH and transit time dependence of the RH sensor response time.

It is followed by flow diagrams showing the order in which the various equations are used when calibrating and when reading.

See also: Appendix B - Test Results, which experimentally validate these algorithms

The Monteith *et al* Equation for Transit Time

If the time constant associated with the RH sensor is ignored, then the dynamic behaviour of the cup can be modelled as follows:-

$$\delta t = \left\{\frac{\delta\phi}{(1-\phi)}\left(\frac{4(L+L')^2}{\pi^2 D}\right) + r(L+L')\right\} \qquad \text{...} \qquad (1)$$

where δt = transit time

D = diffusion coefficient of water vapour in air

r = resistance of the leaf

L = cup length

L' = a notional extra cup length to account for the moisture absorption by the cup

φ = relative humidity

δφ = the small increase in relative humidity in time δt

The Monteith *et al* Equation for Resistance

We can reorganise the above equation to express the resistance r in terms of the transit time δt.

$$r_{\text{leaf}} = \frac{\delta t\ (1-\phi)}{(L=L')\delta\phi} - \frac{4\ (L+L')}{\pi^2\ D} \qquad \text{...} \qquad (2)$$

where

L is known - 7mm

φ is set - the RH set point about which the porometer cycles 60 is set at 2.3%RH

D is known, see below for an equation

δt is measured directly by the AP4

The only unknown is the term L', which represents the amount of water vapour absorbed directly by the cup walls (expressed as an extra cup length).

We determine this, the wall absorption, by calibrating each porometer head with the calibration plate, and then doing a least-squares fit, as described below.

A Minor Refinement to the Monteith Equations

The above two equations contain the factor:-

$$\frac{\delta\phi}{(1-\phi)} = \frac{0.023}{(1-\phi)}$$

This factor is in fact an approximation, and a better value is given by replacing

$$\frac{\delta\phi}{(1-\phi)} \text{ by } ln\frac{(1-\phi)}{(1-\phi-\delta\phi)} \qquad \text{...} \qquad (3)$$

where In denotes logarithm to the base e

Wood’s Equation for Cup Absorption

At Delta-T John Wood has experimentally determined what variables affect Monteith's cup length parameter L' associated with water absorption within the cup. A summary of these experiments, validating the algorithms, is given in Appendix B.

Wood also investigated the performance of a dynamic model of a cup using a 2-dimensional finite element analysis. This gave useful and complementary insights into the effects of slow sensor time constants on the curvature of the resistance versus transit time curve. It also helped in the redesign of the cup, and is summarised in Appendix A.

These investigations showed that L' depends both on the cup temperature and the transit time as follows:-

$L' = b(0) \bullet \exp(-0.009\ T_{cup}) \bullet (\delta t_f)^{b(1)} \bullet \exp\{b(2)[1n(\delta t_f)]^2\}$ ....(4)

where T_{cup} = cup temperature (°C)
δt_f = corrected transit time - see below

and where b(0), b(1) and b(2) are constants characteristic of each head. They are determined at calibration time as follows.

Wood's equation is used both when calibrating and when taking a reading.

When calibrating, L' is calculated for all 6 plate positions from the corrected transit times δt_f by rearranging Monteith's equation for L'.

The resistance values used are the theoretical (true) plate resistances calculated for the known physical dimensions of the calibration plate pores, at the known cup temperature with compensation for the measured cup-leaf temperature difference δT.

The AP4 then determines the constants b(0), b(1) and b(2) using least squares best fit on a log-log version of equation (4).

When taking a measurement Wood's equation is used to predict the cup absorption L' for a measured transit time and cup temperature. This is substituted in Monteith's equation (2) to obtain a resistance. This resistance is then corrected to that for an isothermal cup (δT=0).

Finally the resistance is converted to the units required by the user.

Temperature and Pressure Correction for the Diffusion Coefficient of Water Vapour in Air: -

The diffusion coefficient of water vapour in air varies with temperature as follows :

T °C	0	5	10	15	20	25	30	35	40	45	50
D cm^2s^{-1}	0.212	0.220	0.227	0.234	0.242	0.249	0.257	0.264	0.272	0.280	0.287

(reference Campbell 1977)

The temperature and pressure dependence can be written: -

$$D = Do \left(\frac{T+273}{To+273}\right)^{1.75} \frac{Po}{P} \quad \text{.... (Parkinson, 1985) ...} \qquad (5)$$

where

Do is the diffusion coefficient at temperature To and pressure Po and

D is the value at T and P

Over the range -5 to + 55°C the following linear approximation is adequate and is used in the AP4 :

$$D = (0.212 + 0.0015\,T) \times \frac{1000}{P} \quad \text{..} (6)$$

where T is in °C and P is in hPa (or mbar).

We use equation (6) within the AP4. On page 6, with regards to the conversion from velocity to mol units of resistance, we refer to equation (5).

Resistance Dependence on Diffusion Coefficient

From Fick's law Flux = D x concentration gradient

one can derive the following relationship by integrating with respect to distance

$$Flux = \frac{concentration\ difference}{resistance}$$

In other words the resistance is inversely proportional to the the diffusion coefficient D integrated over the whole volume of the chamber.

This is explained in a number of standard textbooks on environmental physics, see for instance Monteith & Unsworth (1990)

The resistance of the calibration plate is calculated at 20°C at an atmospheric pressure of 1000 hPa (mbar) from the known geometry of the pores.

The resistance at other temperatures is given by :-

$$r(T) = \frac{\mathrm{r(20°C)\ .\ D((20°C)}}{\mathrm{D(T)}}$$

Combining this with equation (6)

$$R(T_{cup}) = \frac{\mathrm{r(20°C)} \times 0.242 \times \mathrm{P}}{\left(0.212+0.0015\ \mathrm{T_{cup}}\right) \times 1000} \quad \text{...} \quad (7)$$

where T_{cup} is in °C

P is atmospheric pressure (in hPa or mbar)

and r(T) is the cup resistance at temperature T in velocity units.

This equation can be used to convert measured resistance values to other temperatures and pressures.

The porometer always gives you the answer at the cup temperature and set atmospheric pressure.

See also: RESISTANCE AND CONDUCTANCE UNITS on page 6.

Saturated Vapour Pressure Dependence on Temperature

In calculating resistance, it is assumed that the water vapour in the leaf, or calibration plate, is at the saturated vapour pressure. As pointed out by Monteith, and as reproduced in the section on poorometry and stomata, page 5 onwards, this assumption is valid for many practical purposes.

Tables of water vapour pressure as a function of temperature are available elsewhere (List RJ 1971 Smithsonian Meteorological Tables, 6th ed. Washington DC, Smithsonian Institution Press.)

The porometer uses the following approximation, from Campbell (1977)

$$SVP(T) = 10.26 \exp [52.57 - 6790/(273+T) - 5.03 \ln(273+T)] \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

where

T is in °C

and SVP is in hPa (or mbar)

Vapour Pressure Gradient Corrections due to Cup-Leaf Temperature Difference

The vapour pressure gradient is the appropriate driving force to use when the leaf, or plate, and the cup are not at the same temperature.

That is $\text{Flux } E = (P_1 - P_2)/r \times C$

where $P_1 - P_2$ is the vapour pressure difference,

the resistance $r = r_{cup} + r_{leaf}$

and C is a constant of proportionality.

P_1 is taken as the saturated vapour pressure of water vapour in air at T_{leaf}.

Also $P_2 = \phi \times SVP(T_{cup})$

where ϕ is the relative humidity in the porometer cup.

So the flow by diffusion of water vapour into the cup depends on the vapour pressure difference divided by the resistance.

If the leaf is cooler than the cup, the porometer will record the same transit time as from as another leaf of higher resistance at the same temperature as the cup.

We can therefore set up the following simultaneous equations:

$$E/C = \frac{(SVP(T_{leaf}) - \phi \times SVP(T_{cup}))}{(r_{leaf,\delta T\neq 0} + r_{cup})}$$

and

$$E/C = \frac{(SVP(T_{cup}) - \phi \times SVP(T_{cup}))}{(r_{leaf,\delta T\neq 0} + r_{cup})}$$

These can be rearranged and solved together to convert between measured resistances and what the resistance would be if $\delta T = 0$.

Measured resistances are always adjusted and quoted to be that which would be measured at isothermal conditions.

Case 1 : Using Calibration Plate, i.e. Resistance Known.

When calibrating, we know the resistance of the calibration plate for δT = 0.
The resistance the porometer detects for any given δT can be found by rearranging the above equations to give :

$$r_{plate,\delta T\neq 0} = (r_{ref} + r_{cup)} \left(\frac{SVP(T_{cup}) - \phi\times SVP(T_{cup})}{SVP(T_{plate}) - \phi\times SVP(T_{cup})}\right) - \ r_{cup} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

where:-

r_{ref} = known (i.e. theoretical or “true”) reference calibration plate resistance at cup temperature assuming no temperature garadienttemperature

r_{ref} = resistance of the porometer cup

Case 2 : Measuring a leaf, i.e. Resistance unknown

If the porometer is measuring a particular unknown resistance, at a measured δT, then the resistance it would measure assuming no temperature gradient is given by

$$r_{corrected} = (r_{measured} + r_{cup)} \left(\frac{SVP(T_{leaf}) - \phi\times SVP(T_{cup})}{SVP(T_{cup}) - \phi\times SVP(T_{cup})}\right) - \ r_{cup} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Note: Historically we have called this the δT correction

Cup Resistance

In both cases above the cup resistance is given by

$$r_{cup} \quad = \quad \frac{4\ (L + L\prime)}{\pi^2 . D(T)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

This is derived in Monteith *et al,* (1988)

Correction for the RH Sensor Time Constant (T)

The response time τ_s of the RH sensor is finite and is temperature dependent.

τ_s = 2.5 exp(-0.0723 T)
where T is in 'C

We have determined an equation which corrects the transit time for the finite response time of the RH sensor:-

$$\delta T_f \quad = \quad \delta T_m \quad \left\{1 - \frac{\left(1.5\times\left(1-\phi^2\right)\right)}{\left(\left(1-\phi-0.023\right)^2\right)} \ \exp - \left\{\left(\frac{\delta T}{(155\times\tau_s)}\right)^{0.7}\right\}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where

δT_f = corrected transit time that would be seen by a perfectly fast sensor
Δtm = measured transit time
τ_s = RH sensor time constant at temperature T
ϕ = RH cycling level - the "Set RH" point
0.023 = RH rise over which the transit is timed.

This equation was derived semi-empirically assuming that the relative humidity during a cycle is driven 5% below the RH set point, and there is no overshoot in the drying down portion of the cycle. Further explanation is given below.

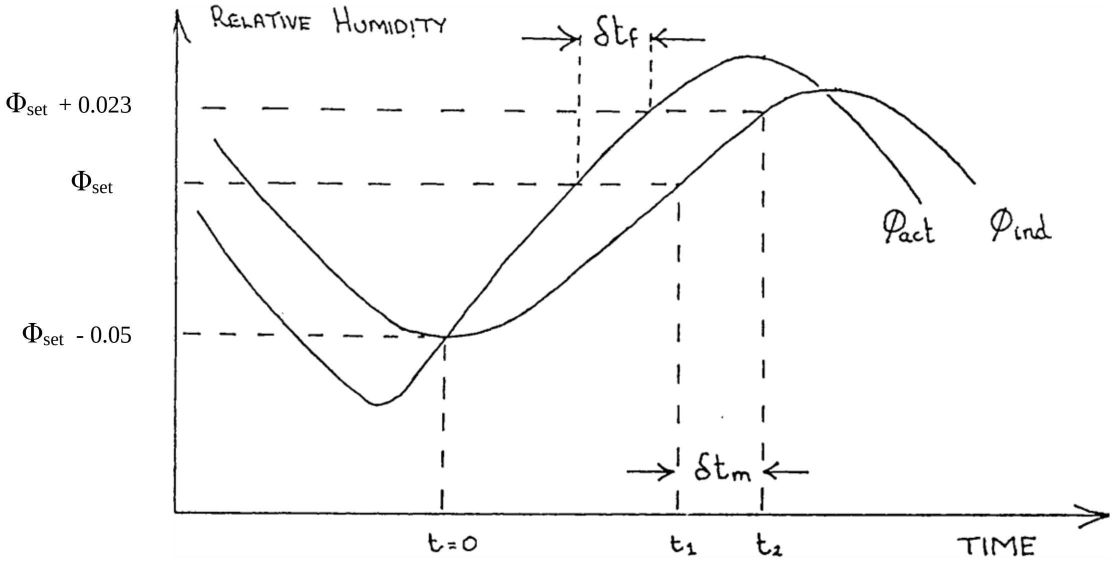
We find that this equation works well over the range of conditions we encounter in practice.

The sensor response time can account for up to half the actual transit time in some conditions.

Derivation of RH Sensor Time Constant Corrections

Schematic graph showing the true and measured RH in the cup.

The difference between the two curves is due to the finite response time of the RH sensor.



Definitions

Φ_{ind} = RH indicated by sensor
Φ_{act} = Actual RH at the sensor
δt_a = Transit time measured by sensor (from RH set point Φ_{set} to Φ_{set} + 2.3%)
δt_f = Corrected transit time that would be seen by a perfectly fast sensor
τ_S = Time constant of RH sensor
τ = Time constant of RH rise in the cup
T = Time

Assume that the indicated minimum RH is controlled to Φ_{set}-0.05, and that t = 0 when Φ_{ind} is a minimum.

Also that the actual RH in the cup follows an exponential curve.

then $\Phi_{act} = 1 - A \exp(-t/\tau)$

Setting t = 0 when $\Phi = \Phi_{set} - 0.05$
it can be shown that $A = 1 - (\Phi_{set} - 0.05)$

Similarly, setting $t = t_a$ when $\Phi = \Phi_{set}$
and $t = t_b$ when $\Phi = \Phi_{set} + 0.023$
and defining $\delta t_f = t_a - t_b$

then it can be shown that $\delta t_f = \tau . \ln(RH_{factor})$ ……………………… (13)

$$\text{where } RH_{factor} = \frac{(1-\Phi_{set})}{(1-(\Phi_{set}+0.023))}$$

φ_{ind} is described by the differential equation :

$$\frac{d\phi_{ind}}{dt} = \frac{(\phi_{act} - \phi_{ind})}{\tau_S} = \frac{\left(1 - A.\exp\left(-\frac{t}{\tau}\right) - \phi_{ind}\right)}{\tau_S}$$

This gives $$\phi_{ind} = 1 - \left[\frac{\tau.A.\exp\left(-\frac{t}{\tau}\right)}{(\tau - \tau_S)} - \frac{\tau_S.A.\exp\left(-\frac{t}{\tau_S}\right)}{(\tau - \tau_S)}\right]$$

Thus

At t = t_1 $$\left(\frac{1 - \phi_{ind}}{A}\right) = \left(\frac{\tau.\exp\left(-\frac{t_1}{\tau}\right)}{(\tau - \tau_S)}\right) - \left(\frac{\tau_S.\exp\left(-\frac{t_1}{\tau_S}\right)}{(\tau - \tau_S)}\right) \quad .... \quad (14)$$

At t = t_2 $$\left(\frac{1 - \phi_{set}}{A}\right) = \left(\frac{\tau.\exp\left(-\frac{t_2}{\tau}\right)}{(\tau - \tau_S)}\right) - \left(\frac{\tau_S.\exp\left(-\frac{t_2}{\tau_S}\right)}{(\tau - \tau_S)}\right) \quad ...... \quad (15)$$

Let us define $\delta t_m = t_2 - t_1$

Equations 14 and 15 were solved iteratively (using the Newton Raphson method) for - t_1 and t_2 for values of τ, τ_s, ϕ_{set} covering the range of AP4 operating conditions, and δt_m (t_2-t_1) compared with δt_f.

An empirical relationship was then found which predicted δt_f. from δt_m with errors less than ±10 ms over the whole range.

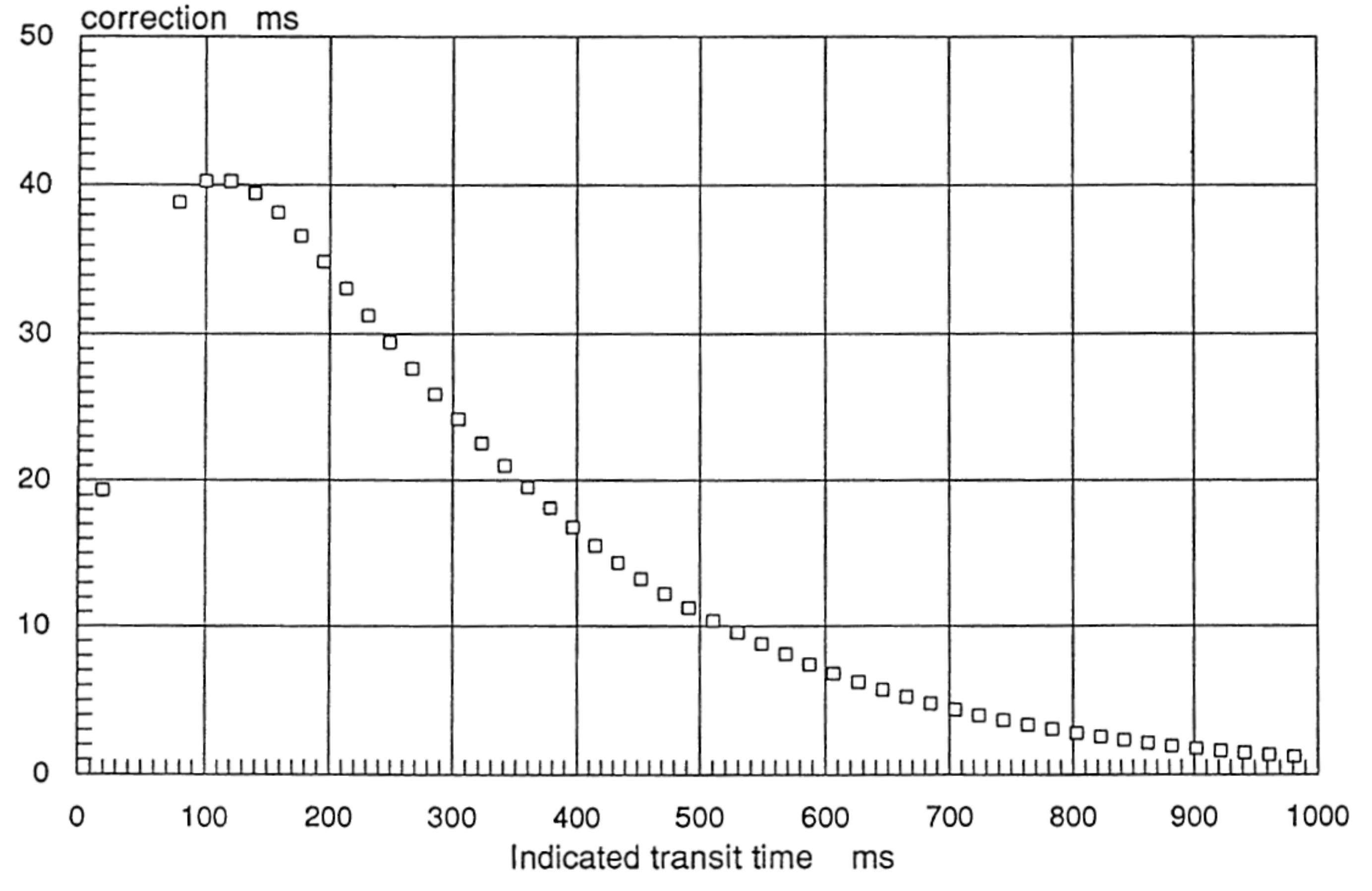
This is the RH sensor time constant correction - equation (12) :-

$$\delta T_f = \delta T_m \left\{1 - \frac{\left(1.5 \times (1 - \phi^2)\right)}{((1 - \phi - 0.023)^2)} \exp - \left\{\left(\frac{\delta T}{(155 \times \tau_S)}\right)^{0.7}\right\}\right\}$$

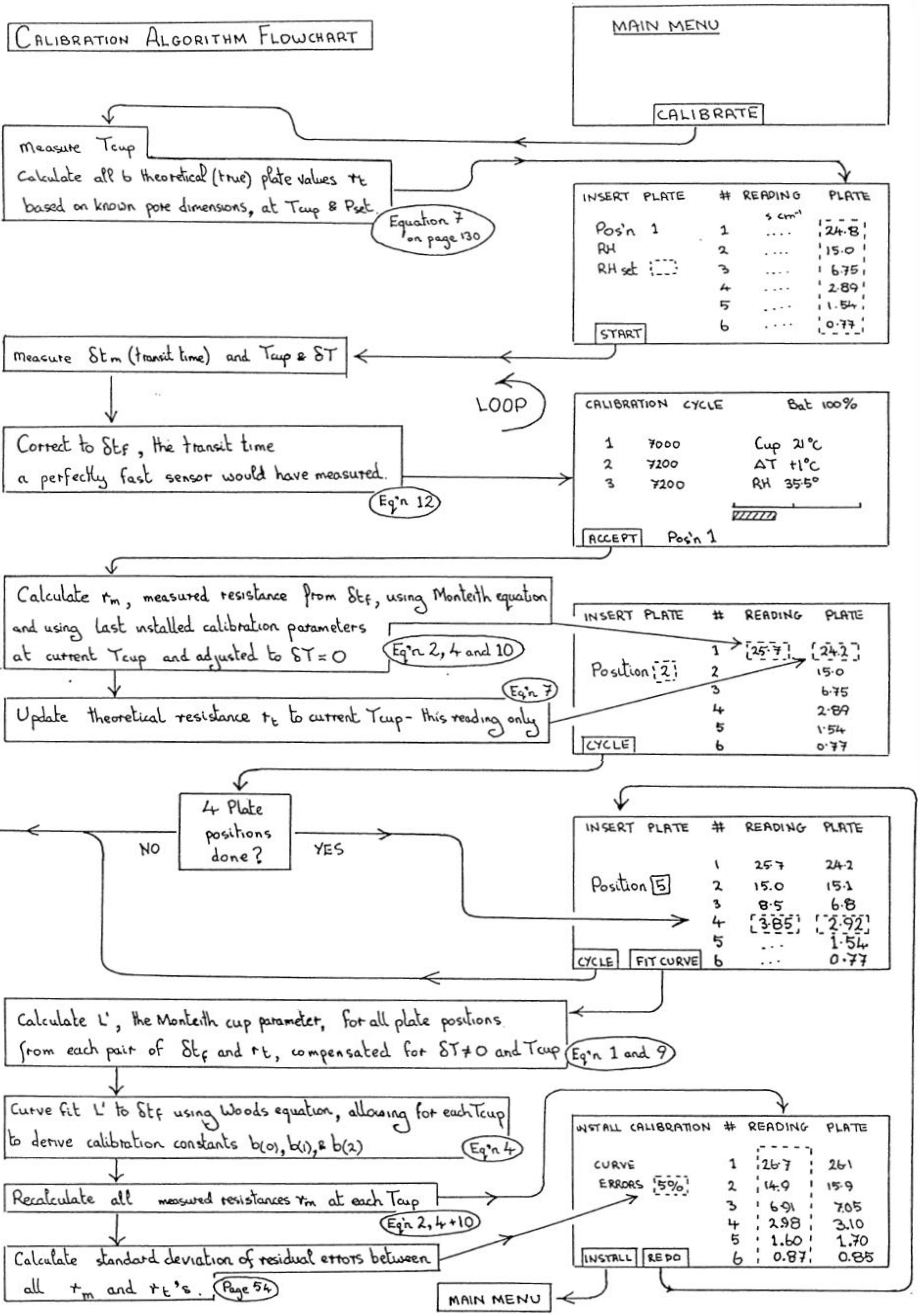
A graph of the correction for ϕset = 0.5 ; τ_s = 0.4 s (at 25°C) is given below.

Graph of a typical transit time correction

This graph obtained at 50 %RH and 25° C



Calibration Algorithm Flowchart



CALIBRATION ALGORITHM FLOWCHART

Measure Tcup

Calculate all 6 theoretical (true) plate values r_t based on known pore dimensions, at Tcup & Pset. (Equation 7 on page 130)

Measure δt_m (transit time) and Tcup & δT

Correct to δt_f, the transit time a perfectly fast sensor would have measured. (Eq'n 12)

Calculate r_m, measured resistance from δt_f, using Monteith equation and using last installed calibration parameters at current Tcup and adjusted to $\delta T = 0$ (Eq'n 2, 4 and 10)

Update theoretical resistance r_t to current Tcup - this reading only (Eq'n 7)

4 Plate positions done? NO / YES

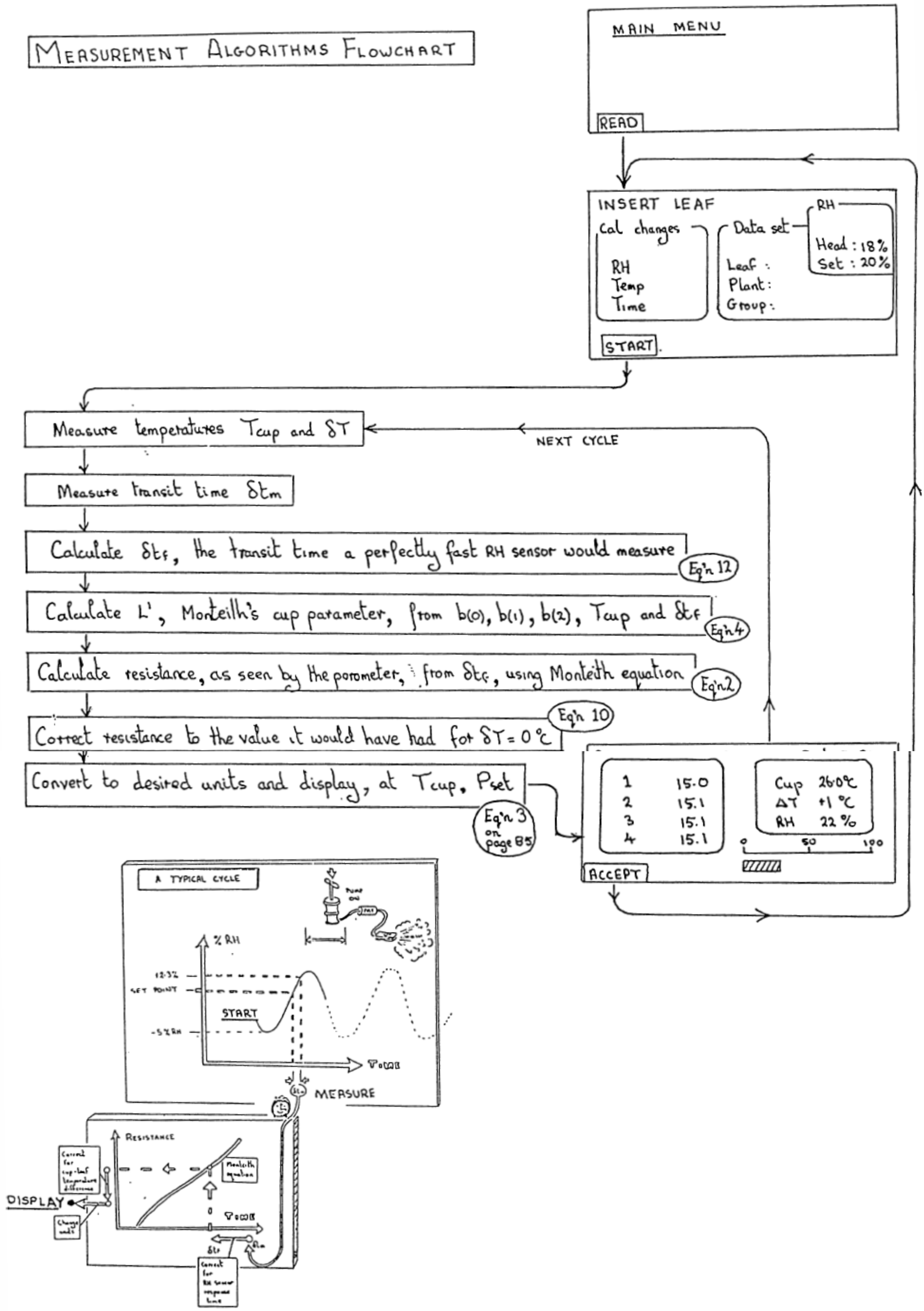
Calculate L', the Monteith cup parameter, for all plate positions from each pair of δt_f and r_t, compensated for $\delta T \neq 0$ and Tcup (Eq'n 1 and 9)

Curve fit L' to δt_f using Woods equation, allowing for each Tcup to derive calibration constants b(0), b(1), & b(2) (Eq'n 4)

Recalculate all measured resistances r_m at each Tcup (Eq'n 2, 4 + 10)

Calculate standard deviation of residual errors between all r_m and r_t's. (Page 54)

Measurement Algorithm Flowchart



Appendix A: Design of the AP4

This section describes the insights produced as a result of modelling the dynamic behaviour of the earlier, AP3, cup by using 2-dimensional finite element analysis.

It also describes how the calculation of the calibration plate values were refined using 3-dimensional finite element analysis.

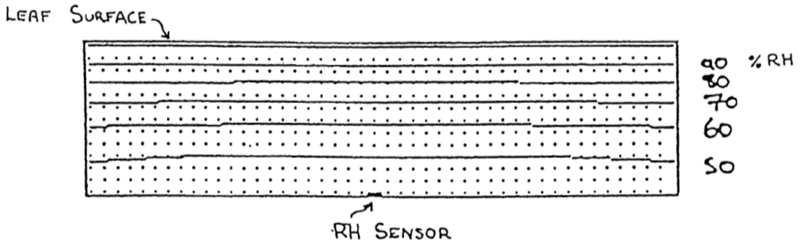
MODELLING OF CUP PERFORMANCE

A computer model of the Mk 3 porometer cup was created, using the method of finite element analysis. It incorporated a 2-dimensional representation of the head geometry, variations in leaf resistance, dry air flow, and sensor response time. The model calculated the RH throughout the cycle at every point on a 0.5 mm grid on a section through the cup.

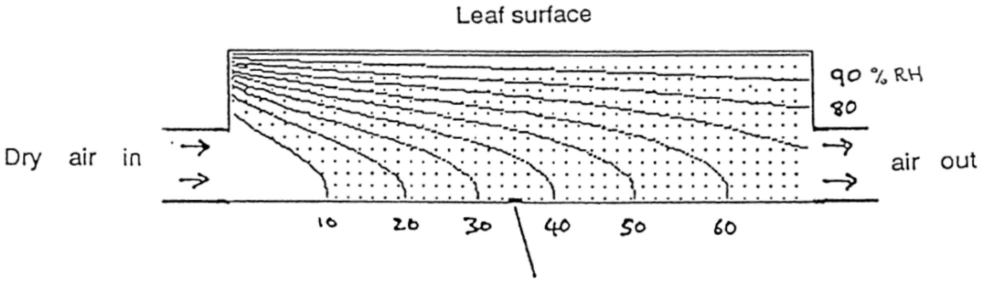
In this earlier design the dry air was fed in from the side.

A typical set of RH contour maps at different times through the cycle, is shown opposite.

Plots of RH Contours on a Section though Cup

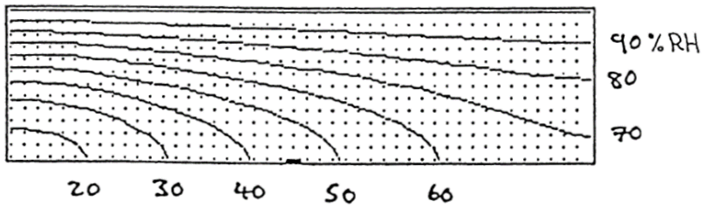


"Ideal" cup



AP3 cup

Start of humidification cycle



AP3 cup

End of humidification

The calibration curves produced by the finite element analysis of the cup model are shown opposite. (These assume the resistance value is known perfectly, and should not be confused with the theory and calculation of resistance values given below).

Points of Interest

- There is a significant gradient along the cup due to the direction of the drying airflow.
- This accounts for some of the bend in the calibration curve.
- The finite response time of the sensor also contributes to the bend in the curve.
- The Monteith *et al* theory gives the same linear curve as the model with an "ideal cup" ie starting from a uniform RH of 0% throughout and with an RH sensor with zero response time.
- A real cup is significantly slower than the model. This appears to be due to the effects of water absorption on the surface within the cup, which was not included in the finite element analysis model.
- The Monteith *et al* theory can be applied to the discrepancy to calculate the mass of water absorbed by the walls of the cup.
  It turns out to be a few micrograms.

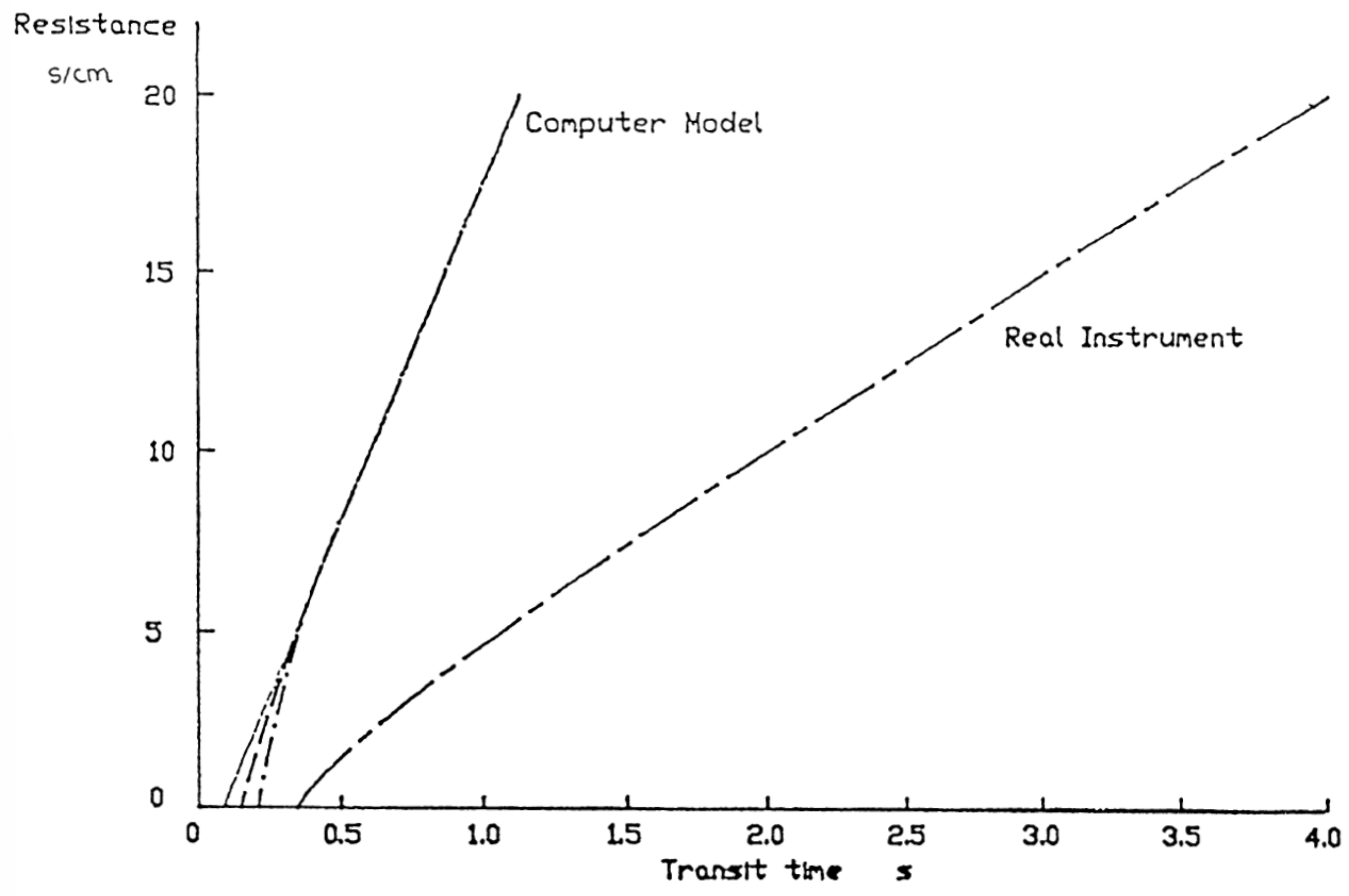
Consequences

The AP4 cup has been designed to introduce the drying air in the opposite direction to the RH gradient, rather than perpendicular to it. This produces more uniform cup conditions, reduces the extremes of RH across the cup, and hence reduces the possibility of leaf stress.

Resistance versus Transit Time Results

Key

———	Prediction from the Monteith et al equation and also the model results assuming an "ideal" case when the sensor response time is zero and the cup starts at 0% RH everywhere. This is a straight line.
– – – –	Predicted by the model cup with: air flushing vertically, and RH sensor with finite response time.
–·–·–	Air flushing horizontally and RH sensor with finite response time.
—·—	Test data from a Delta-T AP3 porometer



Calibration curves

MODELLING CALIBRATION PLATE PERFORMANCE

An advantage of the cycling porometer is that it does not rely on the absolute accuracy of its RH sensor. Readings are derived from a comparison with a calibration plate. Regular calibration gives confidence in the repeatability of measurements. However, the accuracy depends on how accurately we know the value of the calibration plate (amongst other things).

We use a perforated polypropylene plate, backed with a moist filter paper to provide this standard. The resistance of the pore groups is calculated from their known dimensions. In the past we have used a formula by Brown and Escombe (1900). This is based upon the assumption of a single pore above an infinite plane. More recently an alternative calculation has been proposed by Chapman and Parker (1981) based upon diffusion through concentric cylinders of different diameter, see opposite.

Neither of these exactly match the geometry of the actual calibration plate and cup combination, which consists of a row of pores diffusing into a rectangular slot. We have therefore modelled the calibration plate using finite element analysis. A commercial finite element analysis program was used (LUSAS, Finite Element Analysis Ltd, London). This ran on a DEC VAX computer at the Department of Engineering at Cambridge College of Arts and Technology.

A typical RH contour map is shown over the page.

Results

Plate Position	Resistance (s cm^{-1})			Values used in AP4
	B & E	C & P	F.E.A.	
1	26.4	25.8	27.3	27.3
2	16.3	15.6	16.5	16.5
3	7.5	7.0	7.4	7.4
4	3.4	2.9	3.1	3.1
5	2.0	1.5	1.6	1.6
6	1.4	0.7	0.8	0.8

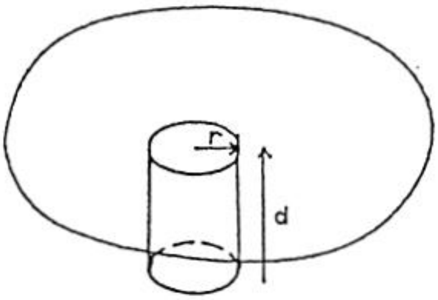
When performed on cylindrically symmetric sections the finite element analysis agreed to within 1% with the Chapman-Parker results. But the FEA results were about 6% higher using the non-symmetric geometry of the actual cup. We attribute this discrepancy to the non-ideal assumption of symmetry required by the Chapman-Parker theory. Therefore in the AP4 we use the finite element analysis results.

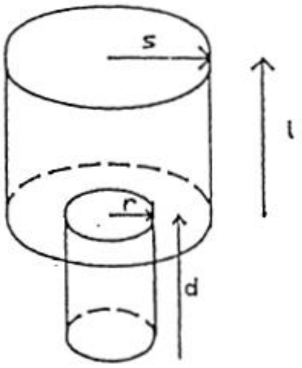
The Brown & Escombe values show significant errors at low resistances..

Calibration Plate Models

Brown & Escombe model

$$R \ = \ \frac{(d + \ \pi.d/4))}{\pi.r^2 \, D}$$





Chapman & Parker model

$$R \ = \ \frac{(d + \ R_d.\pi\, r^2/s))}{\pi.r^2 \, D}$$

Where

R_d : is taken from a table and depends on the ratio of r to s

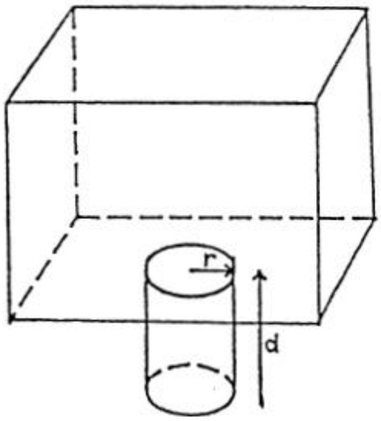
D : is the diffusion resistance

R : is independent of l if l > s

A part of the Delta-T calibration plate

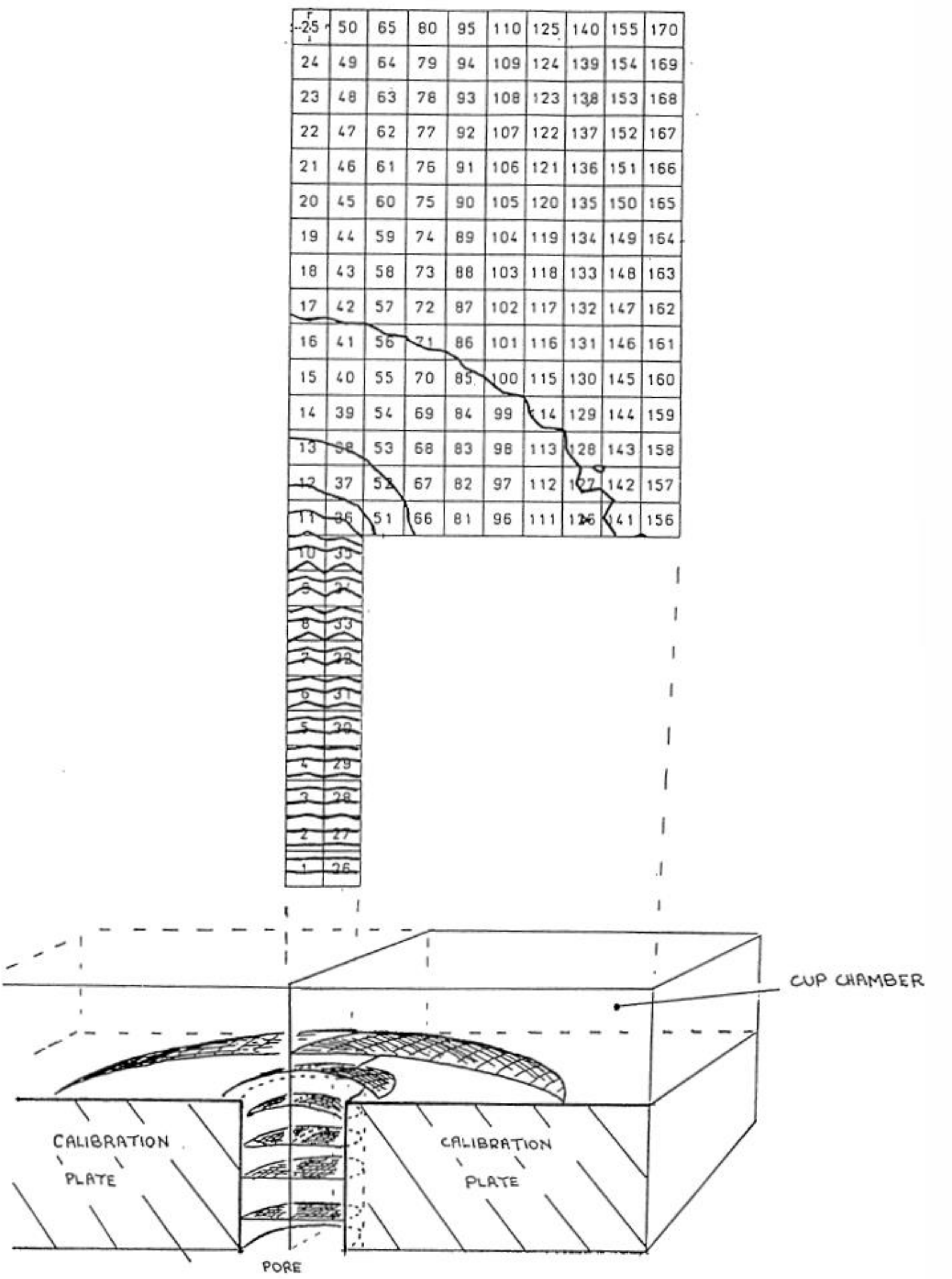
and cup geometry used in the

Fineite Element Analysis



Typical RH Contour Map

Showing the Finite Element Analysis cells and typical predicted RH contours used in calculating the calibration plate resistences.



Appendix B: Test results

There are two parts to this :

- Independent test comparison of version 1 of the AP4, that is, without temperature correction, with our previous model the Mark 3 porometer.
- Experimental basis for the AP4 version 2 temperature correction algorithms.

COMPARISON WITH DELTA-T MARK 3 POROMETER

Version 1 of the AP4 used an automatic calibration curve fitting process, similar to the manual one required for the Mark 3. It did not automatically correct for temperature changes occurring between calibration and reading. Dr Black's report can be taken to confirm that the raw data produced by the AP4 is close to that produced by our previous porometer.

Comparison tests were performed at ICRISAT, India, by Dr C. Black in controlled temperature greenhouses using well-watered pot-grown groundnut (TMV2) and pidgeonpea (#4251) plants. These were respectively 6-8 and 3-4 weeks old when used. Measurements were made throughout the day between about 0900 and 1800 h IST under a range of weather conditions to obtain as wide a range of stomatal conductances as possible. The air temperature during the measurement ranged between 28.5 and 32.5°C, but was typically 30 to 31˚C. The ambient relative humidity was 70-85% and PAR fluence rate ranged between 100-1300 µmol $m^{-2}s^{-1}$. Measurements were generally made on the younger mature leaves, beginning with the youngest leaf which would fit the porometer, but in pidgeonpea some measurements were made on older leaves.

Consecutive measurements were alternated between using the Mark 3 and AP4 first, to avoid introducing any systematic bias. A wide range of conductances was obtained, though the majority were below 1.25 cm s^{-1}. The correlation between the two instruments was good, with most points falling within 10% (dashed lines) of the 1:1 relation (solid line).

There is no evidence that either instrument consistently over-or underestimated conductance. It is not unexpected that there should be some scatter in the relation for several reasons.

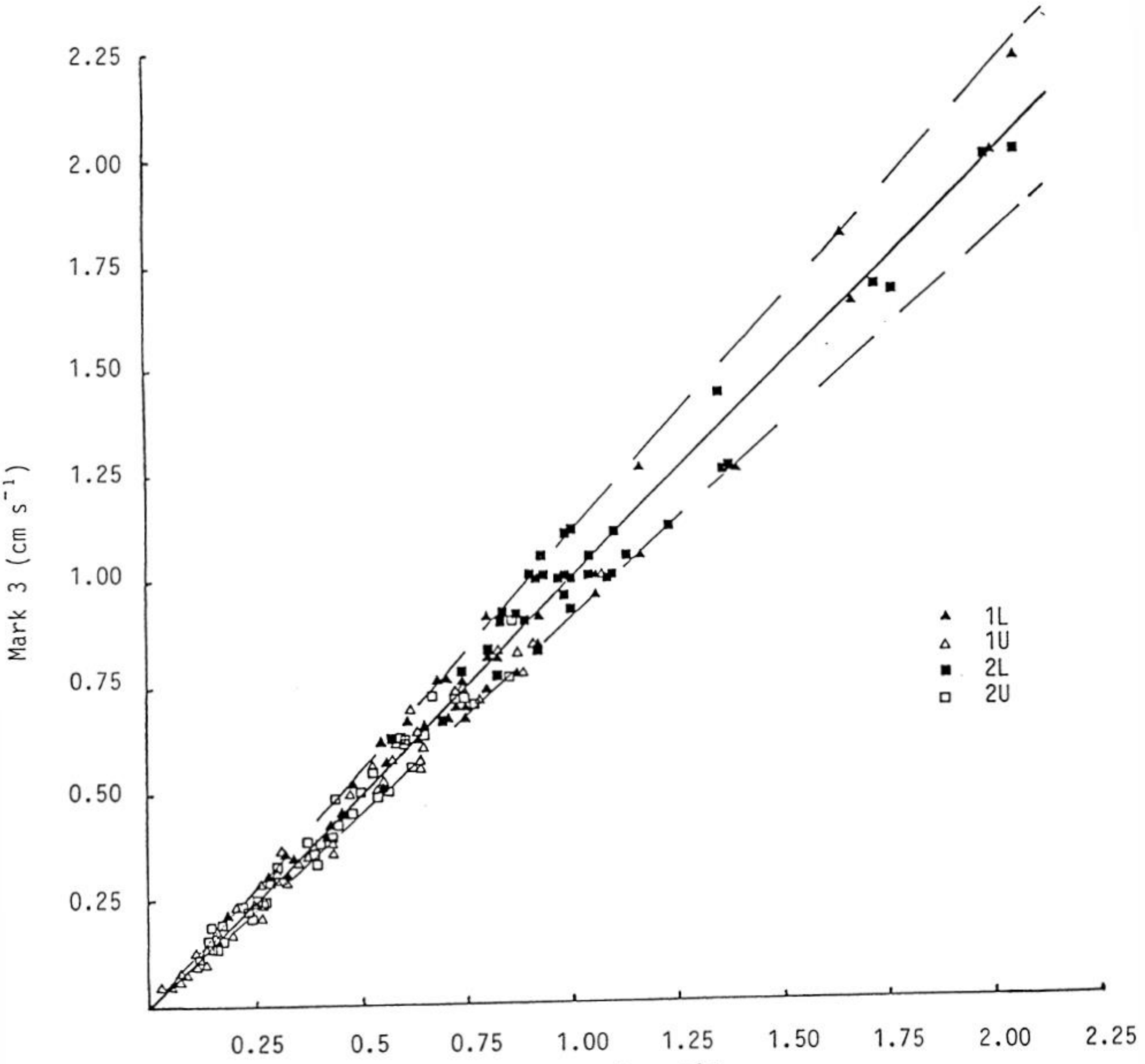
Firstly, it is difficult to position both sensor heads at exactly the same location, particularly since the Mark 3 samples a larger area (23 x 2.5 mm) than the AP4 (17.5 x 2.5 mm). Furthermore, the values recorded by the second porometer to be used may have been influenced by the preceding measurement with the other instrument, particularly at low conductances where cycling times are longer.

AP4 vs AP3 Inter-comparison Test Results

This figure shows the relation between stomatal conductance for the same leaflets of ground nut measured using the Delta-T Mark 3 and the AP4 (version 1) porometer with the slotted cup.

KEY

1L, 1U, 2L and 2U refer respectively to the lower and upper surfaces of leaf 1 & 2, the first and second mature leaves numbered from the stem apex.
The dashed lines represent 10% deviations from an ideal 1:1 relationship (solid line).



(Reproduced with the kind permission of the Director, ICRISAT, Hyderabad, India, and of the author Dr C Black, 1990)

EXPERIMENTAL BASIS FOR THE AP4 ALGORITHMS

- Introduction
- Method
- Results and discussion :
  - Dependence of L' on transit time ot.
  - Dependence of L' on temperature.
  - Validation of cup temperature algorithms.
  - Validation of cup-leaf temperature difference correction.
- Conclusion

Introduction

The AP4 version-2 temperature correction algorithms were developed and validated in Microsoft QuickBasic on a personal computer. This was interfaced, on-line, to receive data from a modified AP4 with its head in an environmental chamber. Once validated these algorithms were then rewritten in FORTH and implemented on the AP4 EPROM. This was retested against the same QuickBasic algorithms in a similar fashion.

First, Wood's equations for L', the cup parameter, and δt_f, the corrected transit time , were refined and developed along with the rest of the algorithms outlined in HOW RESULTS ARE CALCULATED, page 32 onwards, for calibrating and taking readings.

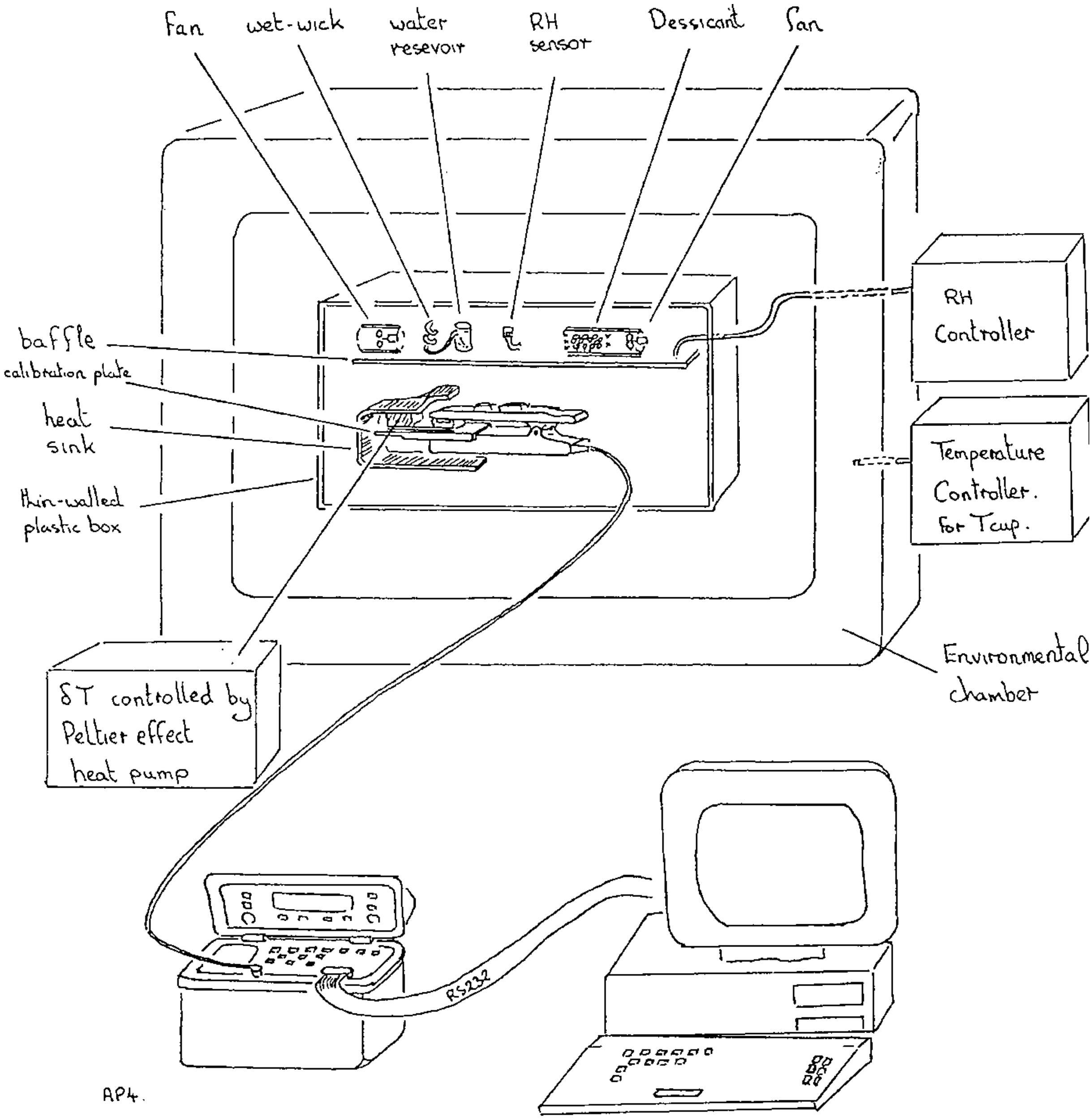
Porometer head cups were exercised through a representative range of RH, cup temperature and leaf-cup temperature differences to validate the algorithms.

The errors in the measured resistances were inspected to determine over what range accuracy was maintained to within 20%.

This range is quoted in the performance specification for the accuracy of the temperature correction, as follows:-

If the calibration is done carefully, then the ambient temperature can shift by +10 or -5°C, and the cup-leaf difference by ±2.5°C from that existing at calibration, and yet the reading will remain accurate to ±20%

Equipment for Testing the AP4 Algorithms



AP4.
Version 1.
modified to continuously
send all data to PC

PC computer logging AP4 output
running Quickbasic software
emulation of AP4 version2

Method

The development and validation of the algorithms was made using the apparatus shown in the diagram. The AP4 head was mounted inside an RH-controlled chamber which itself was inside a temperature-controlled cabinet.

The cup-leaf temperature difference was controlled by a Peltier-effect heat pump. A plate thermally connected to one side of the heat pump was inserted in the head, behind the calibration. plate -between it and the leaf temperature thermistor. The heat sink connected to the other side of the heat pump completely surrounded the AP4 head.

The RH was adjusted by fans blowing air either over a wet wick, or through a tube of desiccant. The controller was a modified AP3 porometer chassis, connected to both fans and a Vaisala HM1815 RH sensor.

The ambient temperature was regulated by an Austell Hearson Dutaform type BM commercial environmental chamber with a West 2050 programmable controller.

The EPROM of the AP4 was modified to send all the data, from every RH cycle, to an on-line Elonex 2086 computer. This included the transit time, cup temperature, and cup-leaf temperature difference. It also sent the resistance as calculated using the Mark 3 porometer-type calibration process implemented in version 1 of the AP4.

This resistance was measured by interpolating from a calibration curve fitted by the method of least squares to the set of six pairs of transit time and resistance obtained during calibration. No other corrections were used. The readings were output through the serial port at every cycle to the on-line computer.

The porometer was calibrated at every combination of 20, 50 and 70 %RH and 10, 25 and 40˚C. After each calibration the cup-leaf temperature difference, δT, and the ambient temperature T_{cup} were independently varied, over ±2.5°C for δT, and ±20˚C for T_{cup}.

The rate of change of temperature was limited by the West controller to 0.2°C per minute, so that each temperature cycle lasted some 6 hours.

At each cycle all the raw data, and the uncorrected resistance was sent to the computer, where the corrected (AP4-derived) resistance was calculated. Every 5 minutes the current readings were logged to disc. A representative sample of such a data set, analysed graphically using Supercalc5, is presented in the following graphs.

Results and Discussion

Dependence of L' on transit time : δt

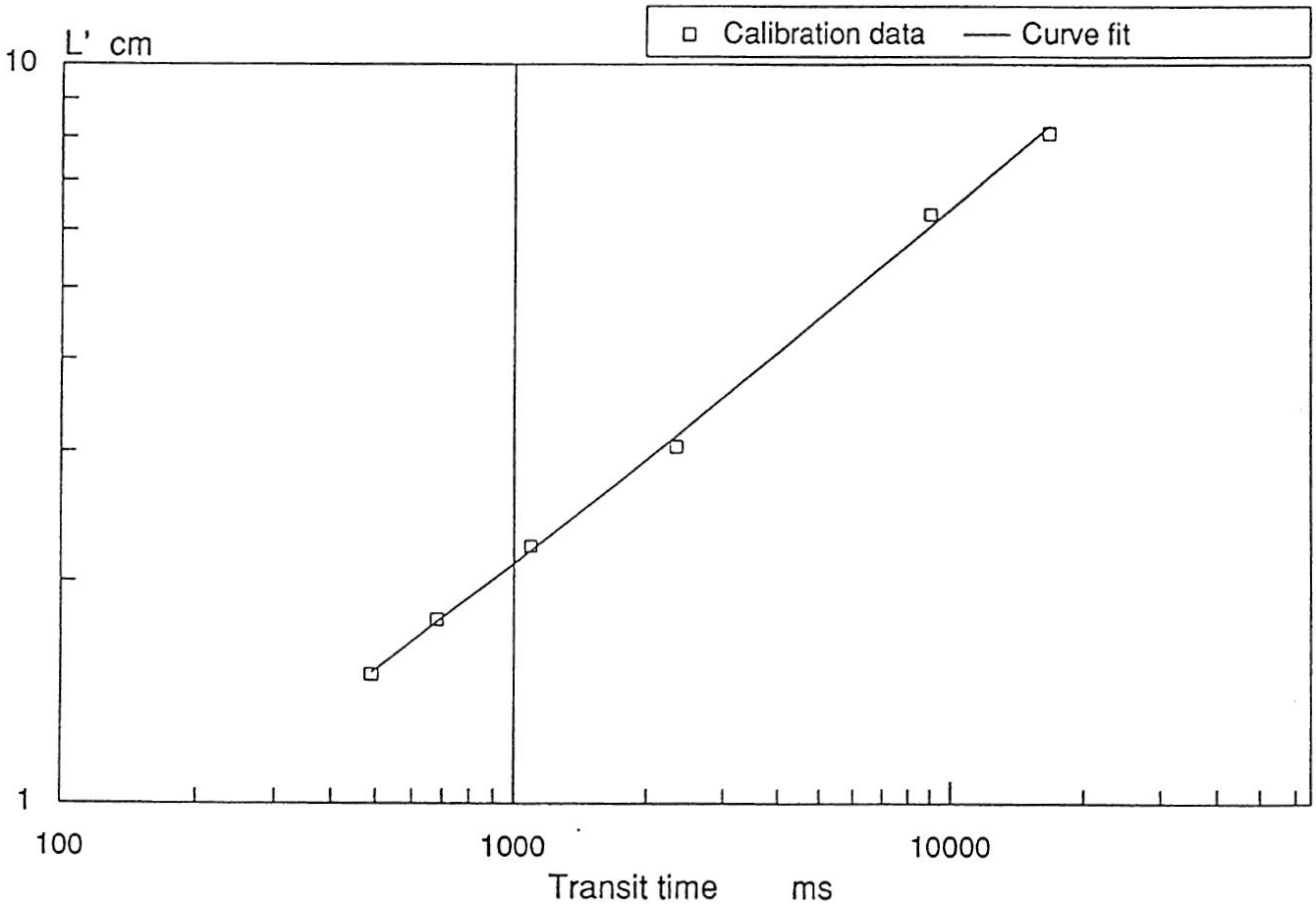
L' is the cup length parameter used in Monteith's equations relating transit time to resistance. These are reproduced as equations (1) and (2) on page 34. The parameter L' is associated with water absorption by the cup walls and RH sensor.

In calibration, the six pairs of transit times and known resistances are used to calculate the corresponding six values for L'.

Graph 1 shows these 6 values plotted against δt for a typical set of data. Plotted on log-log axes, they are close to a straight line, so they can be characterised by a quadratic curve. The calibration routine therefore fits a quadratic curve to these points (on the log-log graph). This graph is then used to calculate an appropriate value of L' when taking a reading. The curve typically has a slope near 0.5, and an intercept on the L' axis which depends on the calibration temperature. This relationship forms the basis for the transit time dependent part of the equation for L'. (See equation (4) on page 35)

Cup Absorption

Dependence on transit time Calibrated at 5O°RH /0 24.5°C



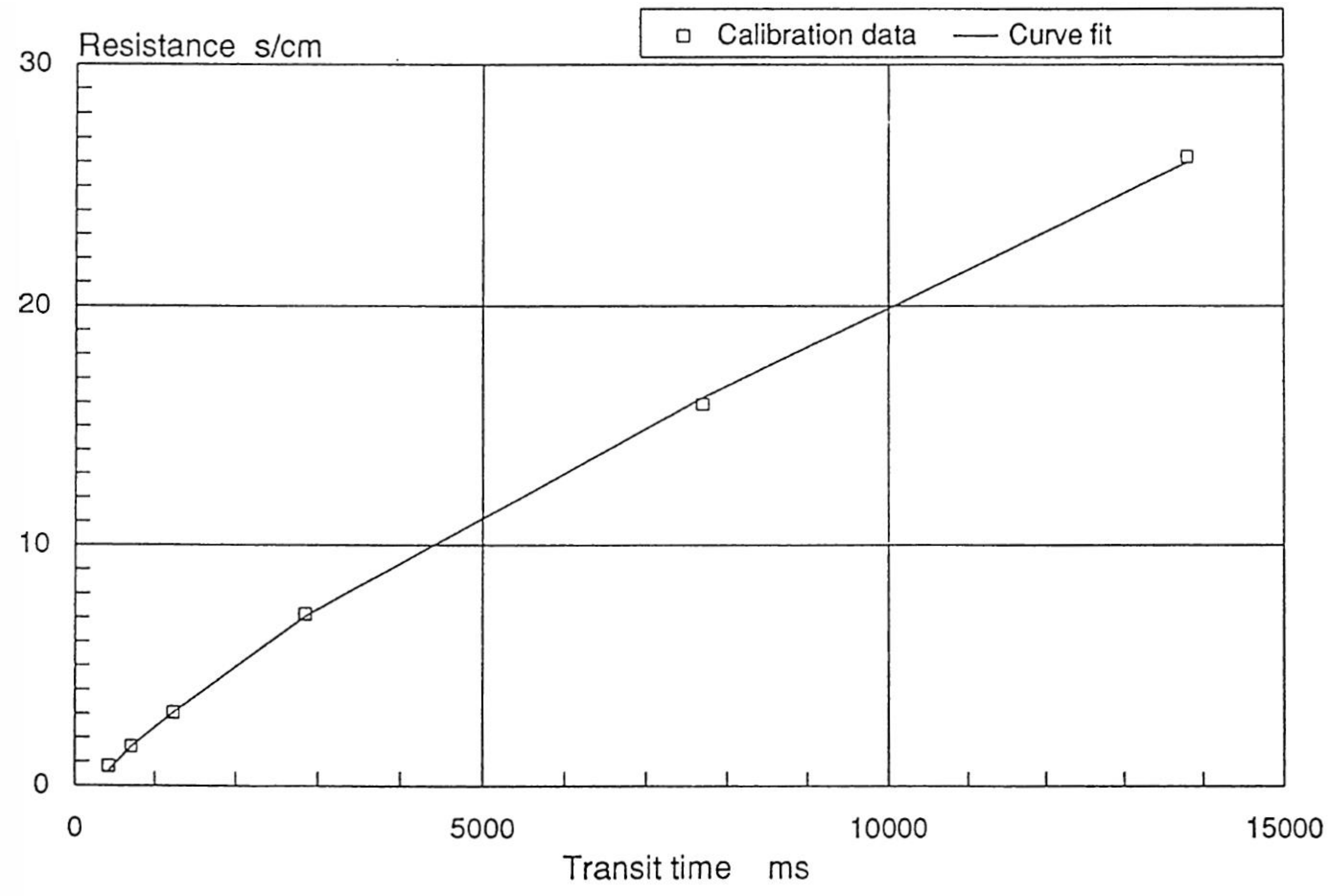
Graph 1

Graph 2 below shows the calibration data points interpreted using the AP4 calibration algorithms, plotted in the style of the Mark 3 calibration curve. This graph is included to reassure those familiar with the Mark 3 Porometer. We include it here because you can think of Graph 1 as being the calibration curve in the AP4, of L' vs δt. Whereas the earlier models, the Mark 3 and version 1 of the AP4, used graph 2 as the calibration curve.

Calibration Curve

AP3 style

Calibrated at RH 50% 26.1 °C



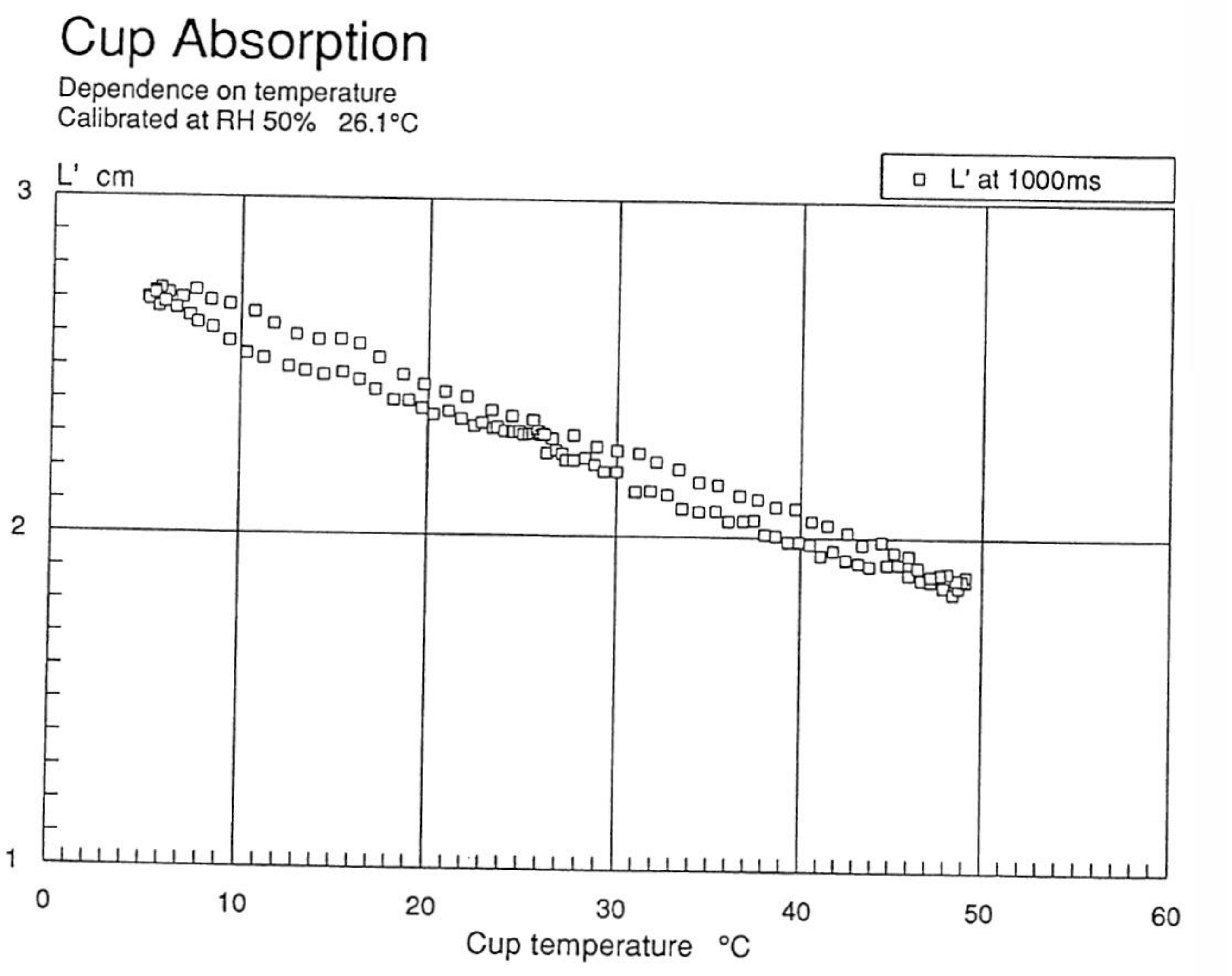
Graph 2

Dependence of L' on temperature

Graph 3 shows the temperature dependent part of L'. A porometer was calibrated, and then left measuring a particular known resistance, ie the calibration plate. The relative humidity of the air around the head was kept constant, while the ambient temperature was varied, and the porometer reading logged. From these readings and the known value of the resistance, L' was calculated for each reading.

These values were normalised using the calibration curve (graph 1) to the equivalent constant value of ot (1000ms). The results show the temperature dependent part of L'for a typical set of data.

This gives the temperature dependent part of equation 4 on page 35



Graph 3

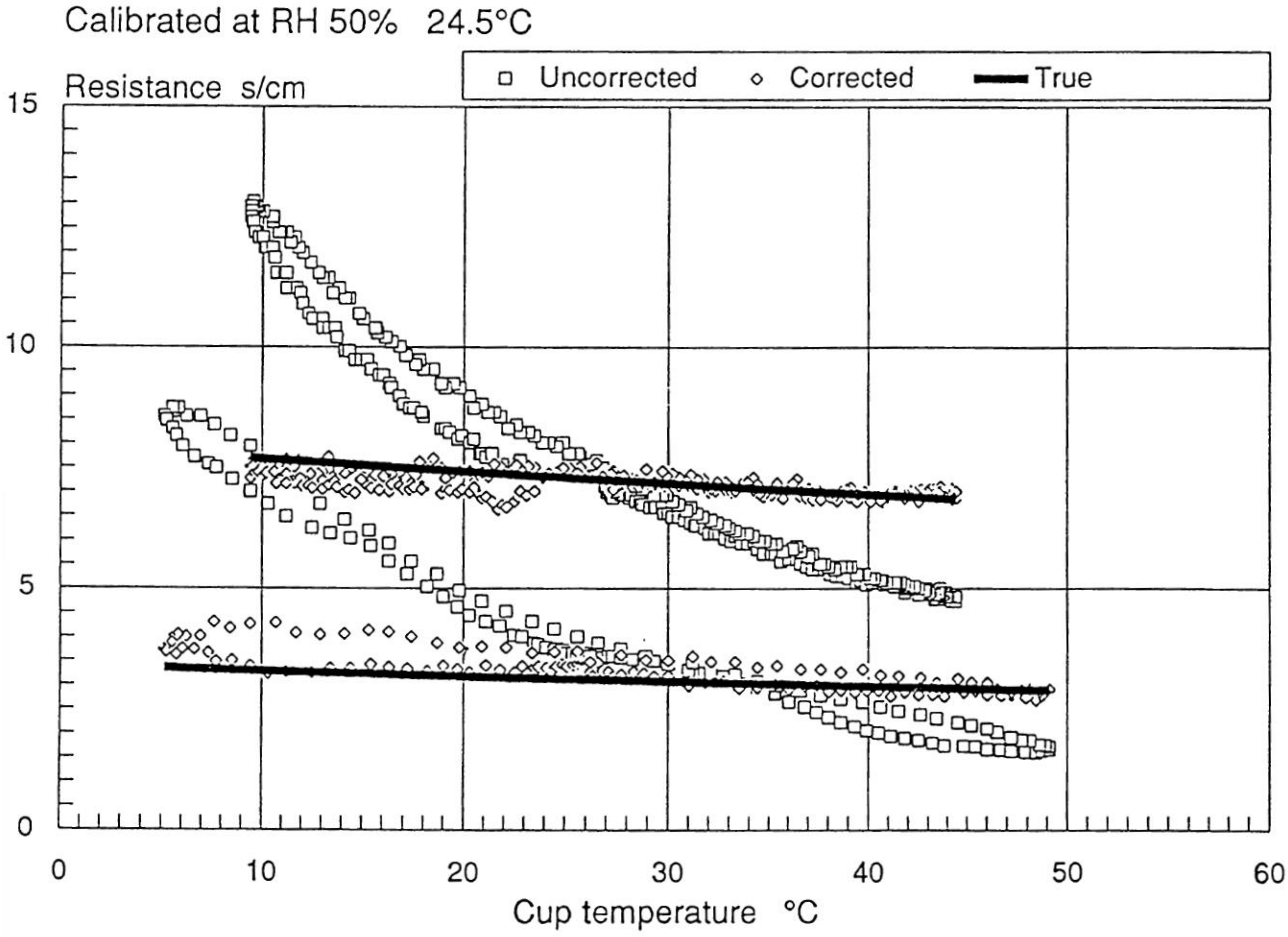
Validation of the cup temperature correction algorithms

Graph 4 compares the resistance measured using the Mark 3 algorithm, which has no temperature correction, with the AP4 version 2 algorithms, which do. Two known resistances are shown, corresponding to two calibration plate positions. The corrected resistances, ie as measured by the AP4 version 2 algorithm, can be seen to fit quite well with the theoretical curve based on the known (theoretical) resistance. These ideal curves are not horizontal because of the temperature dependence of the diffusion coefficient of water vapour in air. They obey equation 7 on page 37.

The extent to which these readings match the known plate values is a measure of the success of the algorithm in its ability to correct for deviations from the cup temperature existing at calibration. Whilst only two plate positions are shown here, for one particular set of conditions, we find it to be true for the rest of the combinations of parameters which we have so far explored.

A more rigorous statistical analysis of the success of these algorithms has not been applied. But the ability of the algorithms to correct for deviations away from those conditions existing at calibration is much better than we originally expected, and far superior to those previously available for the Mark 3 version.

Cup Temperature Correction



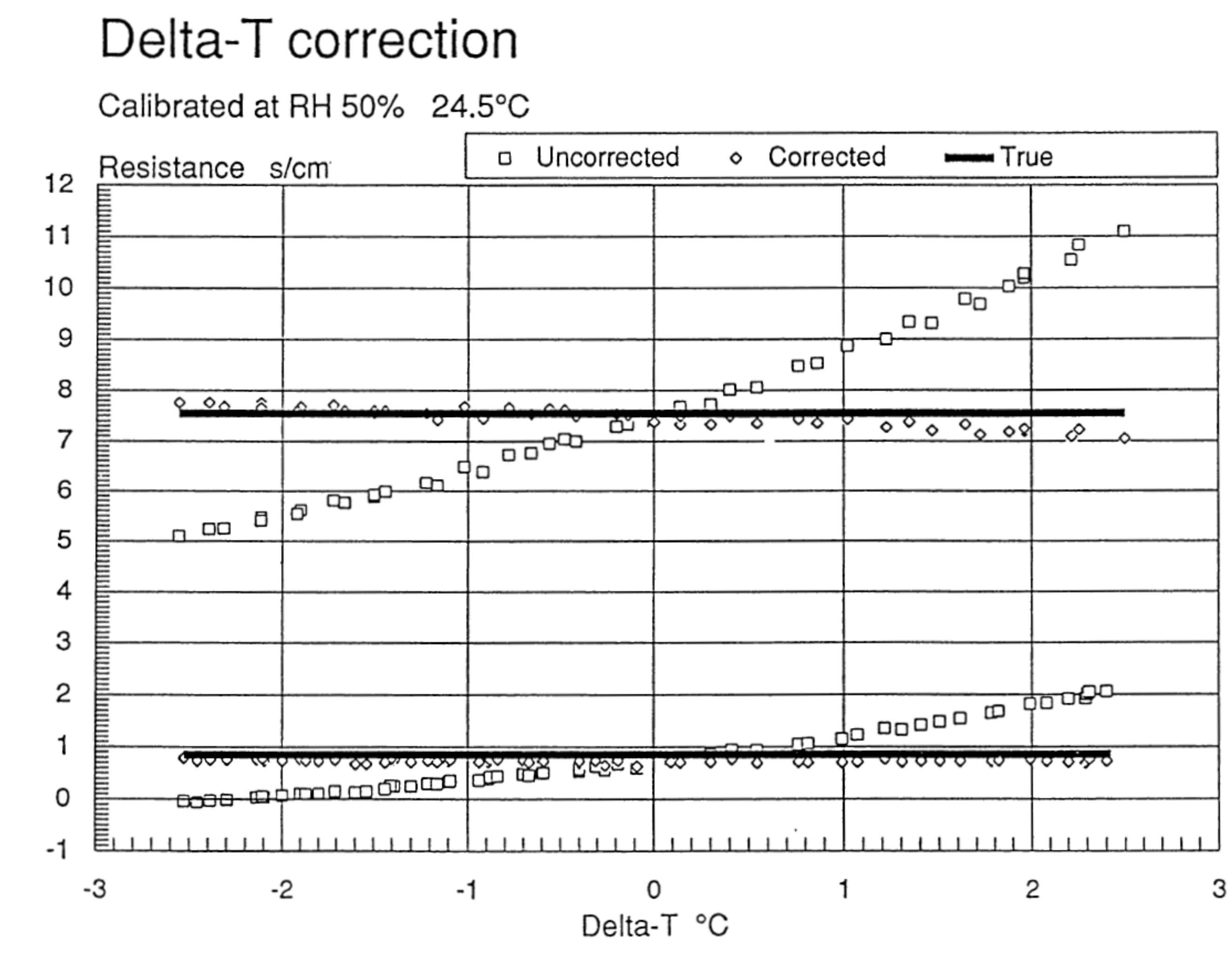
Graph 4

Validation of the cup-leaf temperature difference correction

Graph 5 shows how the corrected and uncorrected measured resistances vary with δT. In this experiment the ambient RH and temperature were kept constant, and the temperature of the calibration plate varied relative to that of the cup using a Peltier-effect heat pump.

In this graph the ideal correction is drawn as a horizontal straight line for both resistances.

Again, whilst we do not present a statistical analysis, inspection shows that the correction is very good.



Graph 4

Conclusion

Over the whole range of calibration conditions investigated, the measured reading was within ±20% of the theoretical (true) resistance over the range +10 to -5°C for cup temperature and ±2.5°C for cup-leaf temperature difference away from the conditions existing at calibration.

It is important to realise that this accuracy will be compromised by poor calibration. It may well be better than this using a careful calibration.

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