Measurements of Sap Flow
by the Heat-Pulse Method.

An Instruction Manual for the HPV system

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Summary

Heat-pulse techniques can be used to measure sap flow in plant stems with minimal disruption to the sap stream (Swanson and Whitfield, 1981; Cohen et al., 1981; Green and Clothier, 1988). The measurements are reliable, use inexpensive technology, provide a good time resolution of sap flow, and they are well-suited to automatic data collection and storage. Sequential or simultaneous measurements on numerous trees are possible, permitting the estimation of transpiration from whole stands of trees.

The HPV system described here is based on the 'compensation' Heat-Pulse method (Swanson and Whitfield, 1981) and comprises a set of probes and associated electronics connected to a data logger (model CR10, Campbell Scientific Inc., Utah, USA). Included with the system is a set of computer programs to CAPTURE and ANALYZE the heat-pulse measurements, which are recorded automatically by the data logger. The purpose of this document is to describe how to successfully install and operate the HPV system.

Contents

1. Background and Theory

1.1 The Origin of Heat-pulse

Heat-pulse methods date back some 60 years to the work of Huber (1932) who first conceived the idea of using heat as a tracer of sap flow. In his early experiments on tropical liana, Huber found such high rates of sap flow that when heat was applied for one to two seconds it was still recognizable as a pulse at the junctions of a thermocouple sensor some 30 cm downstream from the heater. The time for the first appearance of heat at the sensor was assumed to be the same as the time taken for the sap to move this distance. However in later work, at slower sap speeds, Huber recognized the importance of distinguishing between the effect of convection by the moving sap and the transport of heat by thermal conduction. To separate these two effects, Huber and Schmidt (1937) developed an early version of the 'compensation' heat-pulse method in which one sensor was downstream and the other sensor was upstream of the heater. The time of peak warming of the upstream sensor compared to the downstream one, was used to 'compensate' for the effects of thermal conduction. In both cases the sensor and the heater were external to or just under the bark on the surface of the sapwood and it was assumed that the speed of the sap was identical with that of the heat pulse.

1.2 Idealized Heat-pulse Theory

Later work by Marshall (1958) developed a theoretical foundation for the heat-pulse technique and showed that Huber's assumptions were not well founded. From a theoretical viewpoint, Marshall showed that the speed of sap is not the same as that of the heat pulse. Rather, the heat pulse velocity is equal to the weighted average of the velocity of the moving sap and the stationary woody matrix, the weighting factor being determined largely by the physical properties of the woody matrix. Marshall (1958) also proposed a new probe arrangement. He advocated the use of a line heater and temperature probe to be inserted radially into the plant stem, with the temperature being measured at a point far enough below the surface of the stem to avoid the unknown losses of heat which had previously reduced the usefulness of Huber's method. Marshall's (1958) work was based on an analytical solution to the idealized heat flow equation. He used this theory to calculate the temperature rise at any point in the sapwood following the application of an instantaneous line source of heat. Thus, Marshall's contribution was an important first step in establishing a sound theoretical basis for the heat-pulse method.

Swanson (1962) was one of the first to utilize Marshall's analytical solutions, by applying them to the analysis of the 'compensation' heat pulse method in which two temperature sensors are placed asymmetrically either side of a line heater source (Fig. 1). Swanson showed that if the temperature rise following the release of a pulse of heat is measured at distances X_u [m] upstream and X_d [m] downstream from the heater, then the heat-pulse velocity can be calculated from

$$V = \left(\frac{X_d + X_u}{2\, t_z} \right) \tag{1}$$

where t_z [s] is the time delay for the temperatures at points X_d and X_u to become equal. In effect, Eq. (1) implies that following the application of an instantaneous heat-pulse, the centre of the heat-pulse is convected downstream, from the heater, to reach the point mid-way between the two temperature sensor after a t_z. Equation (1) is particularly well suited to data logging since it only requires electronics to detect a null temperature difference and an accurate timer to measure t_z. The t_z's are the only data that need to be recorded, since the distances X_u and X_d remain constant. We refer to this estimate of V [m s^{-1}] as the 'raw' heat-pulse velocity.

1.3 Wound Corrections to the Heat-Pulse Velocity

The calculation of V from Eq (1) is based on Marshall's (1958) idealized theory and assumes the heat-pulse probes have no effect on the measured heat flow. In reality, convection of the heat pulse is perturbed by the presence of the heater and temperature

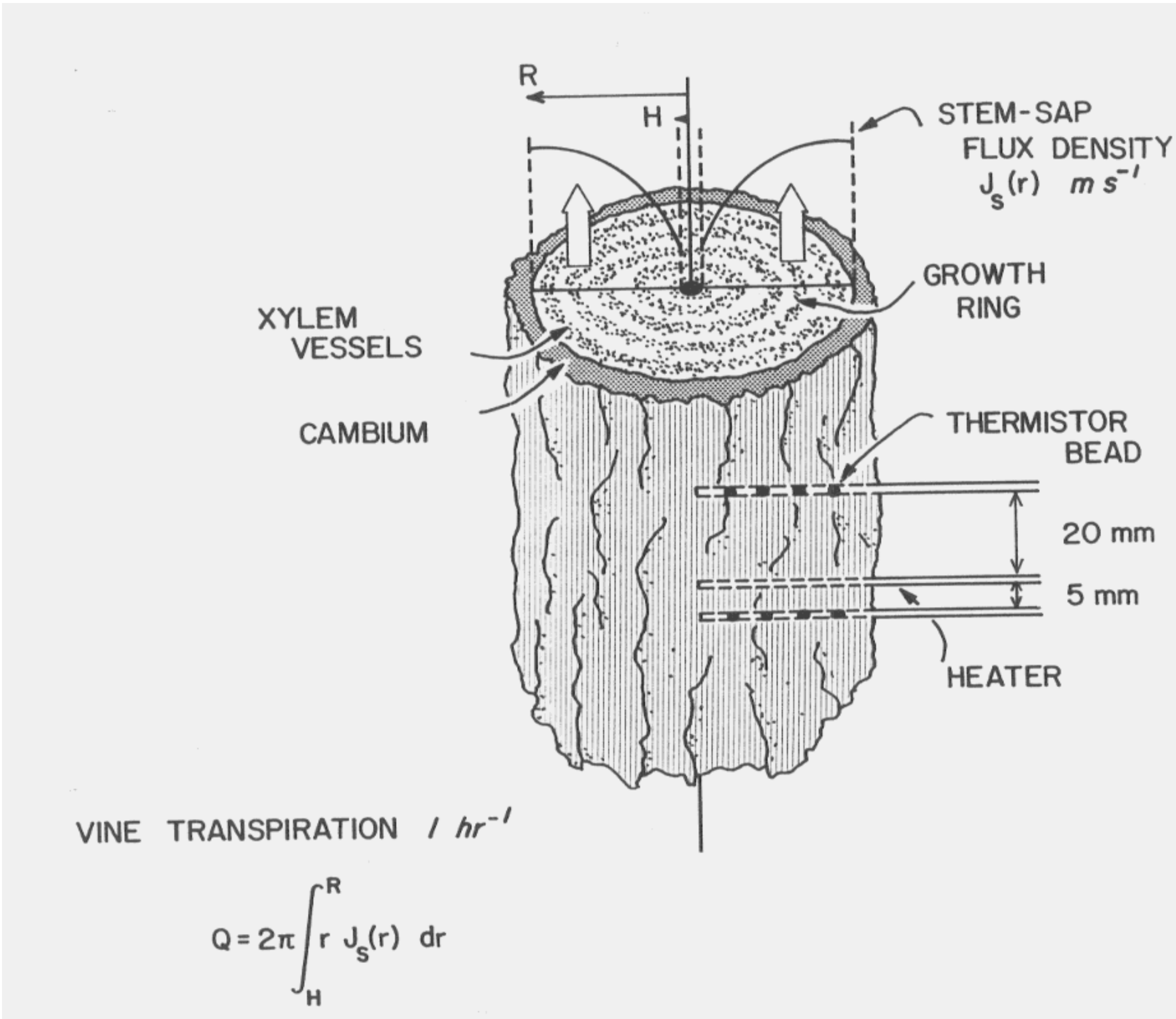


Figure 1. *Arrangement of sensors within a plant stem for the compensation heat-pulse method.*

probes, and by the disruption of xylem tissue associated with their placement. These perturbations produce a systematic underestimation in the measured heat-pulse velocity (Cohen et al., 1981; Green and Clothier, 1988). Consequently, the heat-pulse velocity must be corrected for the probe-induced effects of wounding. This correction can be done empirically (e.g. Cohen et al., 1981), or it can be based on sound physical principals, using an equation of the form:

$$V_c = a + bV + cV^2 \qquad (2)$$

where V_c [m s^{-1}] is the corrected heat-pulse velocity and V is the raw heat-pulse velocity given by Eq. (1). The correction coefficients a, b, and c have been derived by Swanson and Whitfield (1981) from numerical solutions of Marshall's (1958) equations, for various wound sizes. The full range of correction factors are listed in Table 1. These correction factors can also be seen in the ANALYSIS program, HPV-2000.FOR, which is described later. The use of Eq. (2) puts the heat-pulse method on a sound theoretical basis, and uses physical principals rather than an empirical calibration to obtain the best estimate of the heat-pulse velocity.

Wound width (mm)	a	b	c
0.0	0.000	1.000	0.000
1.6	0.393	1.356	0.036
2.0	0.807	1.203	0.058
2.4	1.184	1.072	0.087
2.8	1.524	0.964	0.124
3.2	1.826	0.879	0.169
3.6	2.090	0.818	0.221

Table 1. *Wound corrections for Eq. (2)(From Swanson and Whitfield, 1981)*

At this point, we note that *a priori* the wound size is not known, although we might expect it to be a little larger than the size of the drill hole. This is because of additional damage which results from mechanical disruption of vessels at the edges of the drill hole. Anatomical investigations by Barrett et al. (1995) indicated the total wound width is likely to extend about 0.3 mm either side of the drill hole. Thus, a wound correction of $(1.8 + 2\times 0.3)$ mm seems appropriate for a drill hole of 1.8 mm (as used here). We have used this wound width to successfully validate the heat-pulse method in apple, but found a larger wound correction of some 3.2 mm was required for kiwifruit vines to bring the heat-pulse measurement into line with actual flow rates (Green and Clothier, 1988). Kiwifruit have very large xylem vessels and a substantial interstitial area of woody matrix which affects the thermal homogeneity of the sapwood and, therefore, affects the transmission and measurement of heat-pulse in kiwifruit. Our results (Green and Clothier, 1988) and the results of Barrett et al. (1995) show the importance of validating the heat-pulse method in order to determine the appropriate wound factor. Such a validation is useful, and sometimes necessary, in order to reach a good level of competence and confidence in using the heat-pulse method.

We also issue a practical warning: if due care is not taken to align the centers of the drill holes with the longitudinal direction of the sap flow, then the actual wound width could well be higher than expected. In practice, we believe the 2.4 mm wound correction to be the lower limit appropriate for probes of 1.8 mm diameter. We also stress the importance of **being careful** when placing sensors in the tree stem since the calculations of total sap flow are very sensitive to the wound factor.

A final point on the wound corrections: if the probes are left in place for an extended period, e.g. many months, then the initial wounding may be expected to increase. This is because of increased blockage due to tylose formation in the vessels close to the probes, which may occur as the tree reacts to further isolate the ‘wound’. An increased wound reaction could reduce the sensitivity of the sap flow measurements. However, we have never experienced a significant decrease in the heat-pulse sensitivity over time, in either apple or kiwifruit, and so we have been able to use the same set of probes for periods of up to 3 months. In other species this may not be the case and then some reasoned assessment, or independent measure of transpiration, should be made to determine just how long the probes remain useful.

1.4 Converting Heat-Pulse Velocity to Sapflow

Once the corrected heat-pulse velocity, V_c, has been determined, the next step is to relate it to the actual sap flow. Marshall's (1958) analysis showed that if the sap and woody matrix are considered to form a homogeneous medium, then the sap flux density, J [m s^{-1}], can be calculated from

$$J = P\,(0.33 + M)\,V_c \qquad (3)$$

where P [kg m^{-3}] is the wood density (oven dry weight of wood/green volume) and M is the moisture content ((wet weight - oven dry weight)/oven dry weight) of sapwood. The density and moisture content of the sapwood are both physical properties of the woody matrix, and they can be determined easily from trunk cores. The factor 0.33 in Eq (3) is the specific heat of dry wood, which is assumed to be constant. In our analysis, we use an alternative expression for J, which was developed by Edwards and Warrick (1984) by considering the sapwood to comprise 3 phases of gas, solid and liquid with appropriate physical and thermal properties. The working equation is given by

$$J = (\,0.505\,F_M + F_L\,)\,V_c \qquad (4)$$

where F_M and F_L are the volume fractions of wood and water, respectively. The factor 0.505 is related to the thermal properties of the woody matrix, and is assumed to be constant within and between species.

1.5. Measuring the Volume fractions, F_M and F_L

Volume fractions F_M and F_L implicit in Eq. (4) are determined from the Archimede's principle, in the following manner. Firstly, a core sample is taken and its fresh weight, M_F [kg], is determined. This weight is equal to the mass of water and the mass of dry wood, since the mass of air is negligible. The core sample is then immediately submerged in a beaker of water which has been placed on an accurate mass balance. The balance reading will indicate an immediate increase in mass, which equals the displacement of water, D_T [kg]. The total volume, V_T [m^3], of the sample is then equal to ρ_L times D_T, where the density of water, ρ_L, is assumed to be 1000 kg m^3. The core sample is then oven-dried to determine the mass of dry wood, M_D [kg]. The difference between the fresh weight and the dry weight, (M_F-M_D) is equal to the mass of water, M_L [kg], contained in the fresh core sample. Thus, the volume fraction of water is $F_L = M_L/(\rho_L V_T)$. Similarly, the volume fraction of wood $F_M = M_D/(\rho_M V_T)$ where the density of dry wood, ρ_M equals 1530 kg m^3.

1.6. Estimating Volumetric Sapflow

Equation (4) provides an estimate of the values of J at any point in the conducting sapwood. It is widely recognized that sap flux density is not uniform throughout the sapwood, but rather peaks at a depth of 10 - 20 mm in from the cambium. Consequently, sampling at several depths in the sapwood is necessary to characterize the sapflow velocity profile (Cohen et al., 1981; Edwards and Warrick, 1984; Green and Clothier, 1988). A volumetric measure of total sap flux can be obtained by the integration of these point estimates over the sapwood conducting area. The most common approach is to fit a least-squares polynomial to the depthwise estimates of sap flux density, and then to integrate the fitted function over the sapwood cross section. This is the approach that we favour. An alternative, simpler integration method, as presented by Hatton et al. (1990), is based on a weighted average approach. According to Hatton et al. this simpler approach is a more robust estimator of the volume flux when the velocity profiles exhibit large curvature.

In the ANALYSIS program described later we use the most common approach to calculate volume sap flow. Since our probes measure J at four radial depths, we fit a second-order regression of the form

$$J(r) = \alpha r^2 + \beta r + \gamma \quad (5)$$

in order to get the expression for the velocity profile as a function of stem radius, r [m]. This curve is then integrated over the sapwood cross-section to calculate the volume sap flux, Q, as

$$Q = \int_{H}^{R} 2\pi r \; J(r) \; dr \qquad (6)$$

for a stem of cambium radius R [m] and heartwood radius H [m].The stem parameter H needs to be determined from an analysis of trunk cores taken at the end of the experiment while R can be derived from the stem circumference and an allowance for the depth of the bark.

2. Instrumentation

The HPV system described here is based on the 'compensation' Heat-Pulse method (Marshall, 1958; Swanson and Whitfield, 1981) and comprises a set of probes and associated electronics connected to a data logger (model CR10, CR21X or CR23X, Campbell Scientific Inc., Utah, USA). Each set of probes comprises a linear heater and two temperature sensors which are installed radially into the tree stem, as shown in Fig. 1. The heater probe is made from a length of 19 swg stainless steel tube, containing a central nichrome resistance wire (5 Ω m^{-1}) which is insulated inside a fine Teflon tube. The temperature sensors each comprise four copper-constantan thermo-couple junctions (42 swg) and are made from a length of Teflon tubing (18 swg) which is filled with epoxy resin. The electronics consists of a heater controller and a set of linear instrumentation amplifiers which have a gain of about 5000. The simple heat-pulse controllers do not have any amplifiers.

A data logger (Campbell Scientific Inc., Logan, Utah) is used to activate the heater, for 0.5 to 1 s, in order to introduce a heat-pulse tracer into the moving sap stream. A pair of temperature sensors are used to monitor subsequent changes in stem temperature which occur as the heat-pulse is propagated through the sapwood, both by conduction through the wood and sap matrix and by convection with the moving sap streams. Typically, output signals from the HPV unit should lie between ± 40 mV for the 1°C difference in temperature difference between the two sensors. The data logger is programmed to interpret the temperature signals and to record the subsequent ‘cross-over’ times which are used in Eq. (1) to calculate the raw heat-pulse velocity at a single point (depth) in the conducting sapwood. A laptop PC is later used to retrieve the t_z data from the logger and to calculate total sap flow in the tree stem, as described by Eqs. (4) - (6).

3. Connecting up the logger *and* getting it going.

This section refers to installation and operation of the the HPV units. **T**he wiring and operation of the simple heat-pulse controller (no amplifiers) is described in Appendix B.

3.1 Assembling the necessary hardware.

The following is a list of hardware needed to run the HPV unit.

3.1.1. You will need 2 sets of:

.. heat pulse probes (white ones with grey connectors)
.. heat pulse cables (white ones with silver connectors)
and 1 set of:
.. heat pulse unit with power lead
.. suite of heat pulse programs to capture and analyze the heat-pulse data

The above items are supplied with your installation.

3.1.2. You will also need:

.. Campbell Datalogger (CR10X, CR21X or CR23X)
.. external 12V (>70 AHr) battery
.. Laptop with SC32 interface and Campbell Software (PC208W)

These items are not supplied with your installation.

3.2. Connecting the HPV unit to the data logger:

There are two leads which must to be connected to the HPV unit - a signal lead and a power lead. The pin-out of these leads is listed below.

Signal lead: This lead has 7 coloured wires which must be connected as follows:

orange	=	1H or 3H or 5H	(analog input)
orange/white	=	1L or 3L or 5L	"
blue	=	2H or 4H or 6H	"
blue/white	=	2L or 4L or 6L	"
green	=	AG	(analog ground)
green/white	=	C1 or C2 or C3	(control line)
white	=	AG or GND	(cable shield)

Power lead: This lead has 2 coloured wires which must be connected as follows:

black = GRND
red = +12V

IMPORTANT: The black and red wires go to the POWER on the heat-pulse unit. A separate battery should be used for the logger. ALWAYS connect the red wire first, to avoid shorting out the logger. Also, be careful that you don't plug the wrong cable into the heat-pulse unit, since this may short-out the HPV unit or the logger (It hasn't happened yet, but that's little consolation for when it does!!!). As a precaution, there is a diode inside the heat-pulse unit to protect it against reverse-polarity.

VERY IMPORTANT: If the same battery powers the logger and the heat-pulse unit then <u>do not</u> connect the green wire of the signal lead to AG. This would cause a ground loop and might affect the results...

4. Installing the heat-pulse probes.

This section gives advice on how to install the heat-pulse probes into a plant stem. Note: It is good practice to test the operation of the logger and the probes, and to test all the wiring connections before inserting the probes into the plant stem. Although the HPV unit is designed to be operated automatically, the software does allow for a manual test of the system, as described later in the next section.

4.1. Checking if probes are OK

The pin-out for the connector on the temperature probes (the 9-pin D-plug) is:

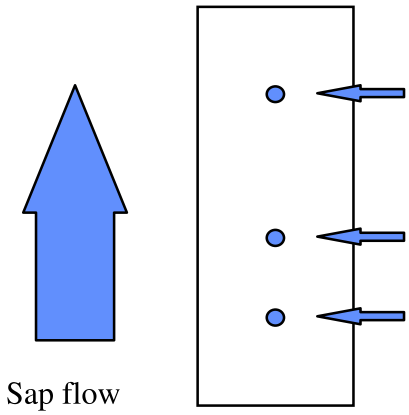
1&6 =	channel 1 (outer-most sensor, closest to the cambium)
2&7 =	channel 2
3&8 =	channel 3
4&9 =	channel 4 (inner-most sensor, closest to the stem centre)

Each temperature sensors should be electrically isolated. A quick 'beep-test' of the temperature sensors using a multi-meter should confirm each thermocouple is connected, and isolated from the others. The temperature probes should have a resistance of about 19 ohms. The heater probe normally has a resistance of about 0.4-0.6 ohms. If the heater is faulty then this resistance will exceed this value.

4.2. Procedure for installing probes.

4.2.1. Locate a fairly straight piece of stem, fairly free of bumps and knots. Measure the stem circumference, C, to the nearest mm.

4.2.2. Attach the drilling jig as shown below. Use thick sticky-tape for the stem, or use a special jig for roots and small branches.



4.2.3. Carefully drill the holes using a high-speed, electric drill.

- Don't drill too far at once (say more than 20mm) because this can 'over-bore' the hole. Make sure the hole is about 20 mm deeper than the longest probe.
- Remove the jig and 'plug' the holes with Vaseline.
- Take a 'cork bore' around the two outer holes so you can measure the bark depth, D (mm), *e.g.* with a set of calipers.

insert:

- Dip each probe in Vaseline, and then insert it CAREFULLY into the appropriate hole. The probe marked with the red dot goes closest to the heater. Insert the heater last.
- Tape the probes CAREFULLY to the tree stem, but don't bend them to far!!
- Check each probe to make sure its OK (see 4.1)

IF its OK THEN
- connect it to the logger.

ELSE
- get some new probes
- goto insert

ENDIF

4.3. Testing if everything is working.

Make sure the HPV system is properly connected (see 3.2 above)
Make sure the logger is properly programmed (see 5 below)
Fire a test pulse (see 5 below)

IF it seems to be OK THEN
go for a beer

```
ELSE
  swear a lot
  blame someone else (but not me)
  goto deep_shit
ENDIF
```

Note1: if you cant find deep_shit, then your not in it.
Note2: There is no deep_shit. I expect that every thing will work
Note3: Murphy's Law suggests there will be some other problem to find.

5. Installing the data-logger software

The following program is to be run on a Campbell data logger. The logger software is located in one of the three sub-directories on the disk provided with the installation.

5.1. Files in A:\LOGGER

C10-HP*.STN	C21-HP*.STN
C10-HP*.DLD	C21-HP*.DLD
C10-HP*.CSI	C21-HP*.CSI

This sub-directory contains the above CAPTURE programs designed to measure the outputs generated by the HPV unit, and to calculate and store the t_Z values associated with each set of the probes. The program is rather basic (in keeping with our philosophy). It is intended to be run on a Campbell logger (CR10, CR21X or CR23X). A CR10 will measure up to three sets of probes and a CR21X will measure up to four sets of probes, a CR23X will measure up to 6 sets of probes. The whild-card '*' in the file name implies the number of probes that will be measured.

Note: A single logger can up to 6 sets of probes. It is a simple matter to extend the total number of probes by using a Campbell AM25T solid state multiplexer, to switch the output from many more probes. This requires a slightly modified version of the CAPTURE program to include use of the multiplexer and to allocate the extra channels on the logger. If the USER wishes to consider either of these modifications then examples of the necessary programs can be supplied, via email, at a later date. Details are in Appendix A.

In what follows, we assume the USER is familiar with the various functions of the CR10 data logger, and the Campbell programs included with the PC208 software (GraphTerm and EDLOG).

The following files have been supplied in the sub-directory A:\LOGGER of the installation disk:

CR10-HP3.STN is the Station file required to communicate with the logger.
CR10-HP3.DLD is a file to be 'downloaded' to the logger, via the GT program.
CR10-HP3.CSI is a file created by the program editor, EDLOG.

The program CR10-HP3.DLD should be downloaded to the logger using the GT program (see Campbell PC208 manual for instructions on how to do this).

5.3. Down-loading programs to the logger

There are two ways to enter the CAPTURE program into the data logger - via the key pad or by using the PC208 software as supplied by Campbell Sci. The latter is the preferred option since GT can also be used to download program, and retrieve data, in the usual manner.

NOTE. to get the logger-prompt '>' via GT, enter 2718H at the '*' prompt. You can now talk to the logger via the PC, or exit GT and talk to the logger via the keypad. Special 'modes' for the logger are *1, *5, *6, and *7, as explained below. Remember, CTRL_ gets you back to the options menu. !!!!!

5.4. Review of the logger modes

For a full description of the logger modes, the USER should consult a Campbell data-logger manual. The following is some basic information that may help you to interpret the logger functions.

***1 mode** is used to enter and/or alter a program (Table-1) that resides in the memory of the logger. Enter '*1 X A' to view instruction no. x in Table 1.

***5 mode** is used to set the clock. !!! Most important to do this before the heat-pulse program is run. Expect the following responses:

Enter '*5 A YY A DOY A HRMIN A' to set the year, day-of-year and current time in hours and minutes.

Note: PC208 can also be used to download the PC time to the logger (the preferred option).

***6 mode** is used to view and set the 'flags' as well as the input value

***7 mode** is used to examine output memory. Enter *7 to see memory pointer to the next location in output memory (say 740). Enter *7 X to see data stored at location X (say 740).

5.5. Retrieving data from the logger

Use the program PC208 to retrieve all the ‘uncollected’ data from the data logger.

5.6. Operation of the logger program - C10-HP3.DLD

Here we describe a number of program changes and system tests that you may want to do. We also describe some ' normal' program behaviour that may be expected during the course of a measurement period. Note: After you have finished playing with the logger, ALWAYS press *0 to recompile any changes, or to continue by leaving the logger in the ' LOG1' mode.

5.6.1. To change the interval between heat pulses (alter Inst-1)

enter *1 1 A A A x A *0 where x = interval in minutes
The default time is 30 minutes

5.6.2. To fire a test heat-pulse

enter *6 A D 1 (the lights should go on, and the program will run)
enter *6 A D 6 for an early exit of program
enter *0 to continue

5.6.3. To check if the system is working properly (generally a good idea!)

fire a test heat pulse (see 5.6.2)
check the initial voltages (+/- 20 mV is OK, -9999 is stuffed)
i.e. enter *6 x A where x = 41..56
check the present voltages (+/- 100 mV is OK, -9999 is stuffed)
i.e. enter *6 x A where x = 21..36
enter *0 to continue

Note. Readings are in mV so anything in the range +/- 200 is OK.

5.6.4. To examine t_z data (stored in locations 1..16)

enter *6 x A where x is the location.
loc. 1 = tz1-1 (outer) .... loc. 4 = tz1-4 (inner)
loc. 5 = tz2-1 (outer) .... loc. 8 = tz2-4 (inner)
loc. 9 = tz3-1 (outer) .... loc.12 = tz3-4 (inner)
loc. 13 = tz4-1 (outer) .... loc.16 = tz4-4 (inner)
enter *0 to continue

5.6.5. To find out the total running-time since the heat-pulse was fired (loc. 99)

enter *6 99 A
enter *0 to continue

5.6.6. To change the duration of the heat pulse (alter Inst-44)

enter *1 44 A A A x A *0 where x is duration in s
default value is 2.0 s (this is also the maximum time)

5.6.7. To change the delay between firing a heat pulse and testing for a 'cross-over'. This may be necessary for really fast flows (alter Inst-49)

enter *1 49 A A A x A *0 where x is delay in multiples of 0.1s
default value is 15 s, i.e. x=150

5.6.8. To change the maximum time for a t_z calculation (alter Inst-14)
enter *1 14 A A A x A where x is max time in multiples of 0.1s
default value if 500 s, i.e. x=500, but 300s might be OK

5.7. Listing of the logger program - C10-HP3.CSI

This section gives a listing of the CAPTURE program designed to measure the outputs generated by the HPV unit, and to calculate and store the t_z's associated with each set of the probes. The program is rather basic (in keeping with our philosophy). It is located in the subdirectory A:\LOGGER on the installation disk provided. This programme was compiled using the latest version of EDLOG. As a result, the program may not install and run properly if the old version of EDLOG and GT is used. However, if any problems do occur then it is a simple matter to enter the following program by hand, via the keypad, and subsequently retrieve it back using the GT (or TERM) program.

Note: For the program to run, the USER needs to enter the *A mode and reset the number of final output locations to 100.

;{CR10}
*Table 1 Program
 01: 0.2500   Execution Interval (seconds)

1: If time is (P92)	**Flag 1** is used to activate automatic sampling
1: 0 Minutes (Seconds --) into a	once every 30 mins.
2: **30 Interval (same units as above)**	Change as required
3: 11 Set Flag 1 High	
2: If Flag/Port (P91)	**Flag 5** is set when t_z is calculated
1: 15 Do if Flag 5 is High	
2: 30 Then Do	
3: Timer (P26)	store current time in loc (99)

1: 99 Loc [_________]	
4: Volts (SE) (P1)	Measure current temp. signal and store in loc (21..32)
1: **12** **Reps**	**Change as required**
2: 14 ñ 250 mV Fast Range	
3: 1 SE Channel	
4: 21 Loc [_________]	Monitor loc (21..32) to observe temperature trace
5: 1 Mult	
6: 0 Offset	
5: Beginning of Loop (P87)	Check for cross-over times
1: 0 Delay	
2: **12** **Loop Count**	**Change as required**
6: IF (X<=>F) (P89)	
1: 1 -- X Loc [_________]	tz's are stored in loc (1..12)
2: 1 =	
3: 0 F	
4: 30 Then Do	
7: IF (X<=>Y) (P88)	test for a temperature 'cross over'
1: 41 -- X Loc [_________]	initial temperature signal in loc (41..52)
2: 3 >=	
3: 21 -- Y Loc [_________]	current temperature signal in loc (21..32)
4: 30 Then Do	
8: Z=X (P31)	If crossed over then
1: 99 X Loc [_________]	store tz in loc (1..12)
2: 1 -- Z Loc [_________]	
9: Z=Z+1 (P32)	inc a 'tz' counter
1: 90 Z Loc [_________]	
10: End (P95)	
11: End (P95)	
12: End (P95)	
13: IF (X<=>F) (P89)	If all 12 channels have crossed over then
1: 90 X Loc [_________]	set Flag 6
2: 3 >=	
3: **12** **F**	**Change as required**
4: 16 Set Flag 6 High	
14: IF (X<=>F) (P89)	If more than 500 s have elapsed then
1: 99 X Loc [_________]	set flag 6
2: 3 >=	
3: **500** **F**	**Change as required**
4: 16 Set Flag 6 High	
15: End (P95)	
16: If Flag/Port (P91)	If Flag 6 is set then
1: 16 Do if Flag 6 is High	output all the data

2: 30 Then Do

17: Do (P86)
1: 10 Set Output Flag High

18: Sample (P70) 1: 2 Reps 2: 91 Loc [_________]	Ouput the date and time
19: Sample (P70) 1: **12** **Reps** 2: 1 Loc [_________]	Output the 12 tz values **Change as required**

20: Do (P86)
1: 26 Set Flag 6 Low

21: Do (P86)
1: 25 Set Flag 5 Low

22: End (P95)

23: If Flag/Port (P91) 1: 11 Do if Flag 1 is High 2: 30 Then Do	If Flag 1 is set then Initialise and reset arrays
24: Time (P18) 1: 2 Hours into current year (maximum 8748) 2: 8784 Mod/By 3: 91 Loc [_________]	Store Day of Year in loc (91)

25: Z=X*F (P37)
1: 91 X Loc [_________]
2: .04167 F
3: 91 Z Loc [_________]

26: Z=INT(X) (P45)
1: 91 X Loc [_________]
2: 91 Z Loc [_________]

27: Z=Z+1 (P32)
1: 91 Z Loc [_________]

28: Time (P18) 1: 2 Hours into current year (maximum 8748) 2: 24 Mod/By 3: 92 Loc [_________]	Store time (hrmin) in loc (92)

29: Z=X*F (P37)
1: 92 X Loc [_________]
2: 100 F
3: 92 Z Loc [_________]

30: Time (P18)
1: 1 Minutes into current day (maximum 1440)

2: 60 Mod/By
3: 93 Loc [_________]

31: Z=X+Y (P33)
1: 92 X Loc [_________]
2: 93 Y Loc [_________]
3: 92 Z Loc [_________]

32: Beginning of Loop (P87) — Reset all storage arrays
1: 0 Delay
2: 90 Loop Count

33: Z=F (P30)
1: 0 F
2: 0 Exponent of 10
3: 1 -- Z Loc [_________]

34: End (P95)

35: Volts (SE) (P1) — Measure initial temp signal and store in loc (41..52)
1: **12** **Reps** — **Change as required**
2: 4 ñ 250 mV Slow Range
3: 1 SE Channel
4: 41 Loc [_________] — Monitor loc (41..52) to observe initial temp signal
5: 1 Mult
6: 0 Offset

36: Timer (P26) — Reset timer
1: 0 Loc [_________]

37: Do (P86)
1: 21 Set Flag 1 Low

38: Do (P86)
1: 12 Set Flag 2 High

39: End (P95)

40: If Flag/Port (P91) — Flag 2 is used to initiate the heat-pulse
1: 12 Do if Flag 2 is High
2: 30 Then Do

41: Set Port(s) (P20)
1: 0 C8..C5 = 0/0/0/0
2: 111 C4..C1 = 0/high/high/high

42: Beginning of Loop (P87)
1: 1 Delay
2: 0 Loop Count

43: Timer (P26)
1: 99 Loc [_________]

44: IF (X<=>F) (P89) — Fire a 2 s heat pulse
1: 99 X Loc [_________]

```
 2: 3       >=
 3: 2       F                                    Change as required
 4: 31      Exit Loop if True

45:  End (P95)

46:  Set Port(s) (P20)
 1: 0       C8..C5 = 0/0/0/0
 2: 0       C4..C1 = 0/0/0/0

47:  Beginning of Loop (P87)
 1: 1       Delay
 2: 0       Loop Count

48:  Timer (P26)
 1: 99      Loc [ _________ ]

49:  IF (X<=>F) (P89)                            Wait 15 s before sampling for cross overs
 1: 99      X Loc [ _________ ]
 2: 3       >=
 3: 15      F                                    Change as required
 4: 15      Set Flag 5 High

50:  If Flag/Port (P91)
 1: 15      Do if Flag 5 is High
 2: 31      Exit Loop if True

51:  End (P95)

52:  Do (P86)
 1: 22      Set Flag 2 Low

53:  End (P95)

54:  Batt Voltage (P10)                          Store battery voltage in loc (98)
 1: 98      Loc [ _________ ]

End Program
```

5.8. Operation of the logger program - C21-HP4.DLD

Here we describe the HPV program for a CR21X logger and the normal tests that you may want to do. We also describe some 'normal' program behaviour that may be expected during the course of a measurement period. Note: After you have finished playing with the logger, ALWAYS press *0 to recompile any changes, or to continue by leaving the logger in the 'LOG1' mode.

5.8.1. To change the interval between heat pulses (alter Inst-1)

enter *1 1 A A A x A *0 where x = interval in minutes

The default time is 30 minutes

5.8.2. To fire a test heat-pulse

enter *6 A D 1 (the lights should go on, and the program will run)
enter *6 A D 6 for an early exit of program
enter *0 to continue

5.8.3. To check if the system is working properly (generally a good idea!)

fire a test heat pulse (see 5.8.2)
check the initial voltages (+/- 20 mV is OK, -9999 is stuffed)
i.e. enter *6 x A where x = 41..56
check the present voltages (+/- 100 mV is OK, -9999 is stuffed)
i.e. enter *6 x A where x = 21..36
enter *0 to continue

Note. Readings are in mV so anything in the range +/- 200 is OK.

5.8.4. To examine t_z data (stored in locations 1..16)

enter *6 x A where x is the location.
loc. 1 = tz1-1 (outer) .... loc. 4 = tz1-4 (inner)
loc. 5 = tz2-1 (outer) .... loc. 8 = tz2-4 (inner)
loc. 9 = tz3-1 (outer) .... loc.12 = tz3-4 (inner)
loc. 13 = tz4-1 (outer) .... loc.16 = tz4-4 (inner)
enter *0 to continue

5.8.5. To find out the total running-time since the heat-pulse was fired (loc. 99)

enter *6 99 A
enter *0 to continue

5.8.6. To change the duration of the heat pulse (alter Inst-48)

enter *1 48 A A A x A *0 where x is duration in s
default value is 2.0 s (this is also the maximum time)

5.8.7. To change the delay between firing a heat pulse and testing for a 'cross-over'. This may be necessary for really fast flows (alter Inst-56)

enter *1 56 A A A x A *0 where x is delay in multiples of 0.1s
default value is 15 s, i.e. x=150

5.8.8. To change the maximum time for a t_z calculation (alter Inst-15)

enter *1 15 A A A x A where x is max time in multiples of 0.1s
default value if 500 s, i.e. x=500, but 300s might be OK

5.9. Listing of the logger program - C21-HP4.CSI

This section gives a listing of the CAPTURE program designed to measure the outputs generated by the HPV unit, and to calculate and store the t_z's associated with each set of the probes. Note: For the program to run on a CR21X, the USER needs to enter the *A mode and reset the number of final output locations to 100. The programme is similar to C10-HP3.CSI, except for minor changes caused by instructions P20 and P30 which are described in the Campbell data logger manual. Locations where the USER can make changes are written in bold type.

;{21X}
*Table 1 Program
01: 0.2000 Execution Interval (seconds)

1: If time is (P92)
1: 0 Minutes into a
2: 30 Minute Interval
3: 11 Set Flag 1 High

2: If Flag/Port (P91)
1: 15 Do if Flag 5 is High
2: 30 Then Do

3: Timer (P26)
1: 99 Loc [_________]

4: Volts (SE) (P1)
1: 16 Reps
2: 4 ñ 500 mV Slow Range
3: 1 SE Channel
4: 21 Loc [_________]
5: 1 Mult
6: 0 Offset

5: Beginning of Loop (P87)
1: 0 Delay
2: 16 Loop Count

6: IF (X<=>F) (P89)
1: 1 -- X Loc [_________]
2: 1 =
3: 0 F
4: 30 Then Do

7: IF (X<=>Y) (P88)
1: 41 -- X Loc [_________]
2: 3 >=
3: 21 -- Y Loc [_________]
4: 30 Then Do

8: Z=X (P31)
1: 99 X Loc [_________]
2: 1 -- Z Loc [_________]

9: Z=X*F (P37)
1: 1 -- X Loc [_________]
2: 0.1 F
3: 1 -- Z Loc [_________]

10: Z=Z+1 (P32)
1: 90 Z Loc [_________]

11: End (P95)

12: End (P95)

13: End (P95)

14: IF (X<=>F) (P89)
1: 90 X Loc [_________]
2: 3 >=
3: 16 F
4: 16 Set Flag 6 High

15: IF (X<=>F) (P89)
1: 99 X Loc [_________]
2: 3 >=
3: 5000 F
4: 16 Set Flag 6 High

16: End (P95)

17: If Flag/Port (P91)
1: 16 Do if Flag 6 is High
2: 30 Then Do

18: Do (P86)
1: 10 Set Output Flag High

19: Sample (P70)
1: 2 Reps
2: 91 Loc [_________]

20: Sample (P70)
1: 16 Reps
2: 1 Loc [_________]

21: Do (P86)
1: 26 Set Flag 6 Low

22: Do (P86)
1: 25 Set Flag 5 Low

23: End (P95)

24: If Flag/Port (P91)
1: 11 Do if Flag 1 is High
2: 30 Then Do

25: Time (P18)
1: 2 Hours into current year (max 8748)
2: 8784 Mod/By
3: 91 Loc [_________]

26: Z=X*F (P37)
1: 91 X Loc [_________]
2: .04167 F
3: 91 Z Loc [_________]

27: Z=INT(X) (P45)
1: 91 X Loc [_________]
2: 91 Z Loc [_________]

28: Z=Z+1 (P32)
1: 91 Z Loc [_________]

29: Time (P18)
1: 2 Hours into current year (maximum
8748)
2: 24 Mod/By
3: 92 Loc [_________]

30: Z=X*F (P37)
1: 92 X Loc [_________]
2: 100 F
3: 92 Z Loc [_________]

31: Time (P18)
1: 1 Minutes into current day (max 1440)
2: 60 Mod/By
3: 93 Loc [_________]

32: Z=X+Y (P33)
1: 92 X Loc [_________]
2: 93 Y Loc [_________]
3: 92 Z Loc [_________]

33: Beginning of Loop (P87)
1: 0 Delay
2: 90 Loop Count

34: Z=F (P30)
1: 0 F
2: 1 -- Z Loc [_________]

35: End (P95)

36: Volts (SE) (P1)
1: 16 Reps
2: 4 ñ 500 mV Slow Range
3: 1 SE Channel
4: 41 Loc [_________]
5: 1 Mult
6: 0 Offset

37: Timer (P26)
1: 0 Loc [_________]

38: Do (P86)
1: 21 Set Flag 1 Low

39: Do (P86)
1: 12 Set Flag 2 High

40: End (P95)

41: If Flag/Port (P91)
1: 12 Do if Flag 2 is High
2: 30 Then Do

42: Set Port (P20)
1: 1 Set High
2: 1 Port Number

43: Set Port (P20)
1: 1 Set High
2: 2 Port Number

44: Set Port (P20)
1: 1 Set High

2: 3 Port Number

45: Set Port (P20)
1: 1 Set High
2: 4 Port Number

46: Beginning of Loop (P87)
1: 1 Delay
2: 0 Loop Count

47: Timer (P26)
1: 99 Loc [_________]

48: IF (X<=>F) (P89)
1: 99 X Loc [_________]
2: 3 >=
3: 20 F
4: 31 Exit Loop if True

49: End (P95)

50: Set Port (P20)
1: 0 Set Low
2: 1 Port Number

51: Set Port (P20)
1: 0 Set Low
2: 2 Port Number

52: Set Port (P20)
1: 0 Set Low
2: 3 Port Number

53: Set Port (P20)
1: 0 Set Low
2: 4 Port Number

54: Beginning of Loop (P87)
1: 1 Delay
2: 0 Loop Count

55: Timer (P26)
1: 99 Loc [_________]

56: IF (X<=>F) (P89)
1: 99 X Loc [_________]
2: 3 >=
3: 150 F
4: 15 Set Flag 5 High

57: If Flag/Port (P91)
1: 15 Do if Flag 5 is High
2: 31 Exit Loop if True

58: End (P95)

59: Do (P86)
1: 22 Set Flag 2 Low

60: End (P95)

61: Batt Voltage (P10)
1: 98 Loc [_________]

*Table 2 Program
01: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

End Program

6. Running the ANALYSIS software ... (still under review)

This section describes the software used to analyze the tz data collected by the data loggers. The analysis software is located in one of the four sub-directories on the disk provided with the installation.

6.1. Files in A:\FORT

HPV-2000.FOR
HPV-2000.EXE
HPSAMPLE.DAT
HPHEADER.DAT

This subdirectory contains the FORTRAN programs required to analyze the heat-pulse data (HPV-2000.FOR and HPV-2000). This program has been compiled using Digital-Visual FORTRAN Version 5.1, and should run on any PC under Windows 3.1 or higher. The program HPV-2000.EXE can be copied to any sub-directory on a laptop or a PC. But in order to run HPV-2000, the program and the data (e.g. hpsample.dat) should reside in the same directory.

6.2. Setting up the input file

The file HPHEADER.DAT is an example of the first few lines which must be at the top of each data file. Because HPV-2000 uses a FORMATTED-read of the input data, it is important to include a header-file at the top of the t_z data, in exactly the same format as shown below. The header-file sets up the independent parameters involved in the sapflow calculations, e.g. sapwood radius, heartwood radius, the volume fractions of wood and water, etc. If you are familiar with FORTRAN then you can examine the source code (HPV-2000.FOR) to find the formatted read statement.

The process to set up the input data is as follows:
Step - 1.
Each data file should have the following 10+2*n* lines at the top of the data files (see e.g. HPHEADER.DAT as supplied on disk), where *n* is the number of probes being read. The example below is for *n*=3 sets of probes and *nsensors=4* is the no. of sensors in each probe.

```
nprobes:       3
nsensors:      4      4      4
wound_width:   2.40   2.40   2.40
Swanson fac:   1
v-frac wood:   0.36
v-frac wat :   0.54
sapwood_rad:   6.21   6.00   6.00
hrtwood_rad:   0.00   0.00
```

```
prob_depth1:   0.50   1.20   2.20   3.50
prob_space1:   1.00   1.00   1.00   1.00
prob_depth2:   0.50   1.20   2.20   3.50
prob_space2:   1.00   1.00   1.00   1.00
prob_depth3:   0.50   1.20   2.20   3.50
prob_space3:   1.00   1.00   1.00   1.00
Tmin,Tmax  :    185.    192.
Emax values:   5.00   5.00    5.00
```

The next example is the header-file required to analyze *n*=2 sets of probes:

```
nprobes:       2
nsensors:      4     4
wound_width:    2.40  2.40
Swanson fac:    1
v-frac wood:    0.36
v-frac wat :    0.54
sapwood_rad:    6.21    6.00
hrtwood_rad:   0.00   0.00
prob_depth1:   0.50   1.20   2.20   3.50
prob_space1:   1.00   1.00   1.00   1.00
prob_depth2:   0.50   1.20   2.20   3.50
prob_space2:   1.00   1.00   1.00   1.00
Tmin,Tmax  :    185.    192.
Emax values:   5.00   5.00
```

In the two examples given above, the program is expecting to analyze data beginning on day of year 185 (*Tmin*) through until day of year 192 (*Tmax*). The program will also plot the volume flow rates for each set of probes, assuming the maximum flow, *Emax*, equals 5.0 L h^{-1}. Swanson's correction factors (Table 1) are used if the parameter equals 1 (an integer). Otherwise, inputting a zero-value means the correction factors of Green and Clothier (1988) will be used. For wide probe spacings we recommend the Green and Clothier factors be used. Otherwise Swanson's factors are used for narrow spacings.

The USER can modify the input data (e.g. to change probe spacings, probe depths, sapwood radii, etc). But, be careful to keep them in the same ' format(a16,4f8.2)' , otherwise the program will probably generate an error.

<u>Step - 2.</u>

Next, add the t_z data collected from the logger. This data should look something like:

```
103,100,1200,120.5,135.6,180.2,268.2,195.6,140.2,78.2,30.4
103,100,1215,120.5,135.6,180.2,268.2,195.6,140.2,78.2,30.4
103,100,1230,120.5,135.6,180.2,268.2,195.6,140.2,78.2,30.4
103,100,1245,120.5,135.6,180.2,268.2,195.6,140.2,78.2,30.4
```

Note. The output from the logger is in the following format:

```
opid,day,hrmin,tz1_1,tz1_2,tz1_3,tz1_4,tz2_1,tz2_2,tz2_3,tz2_4
```

where

opid	=	output identifier (103 ⇒ output from table 1, line 3)
day	=	current day of year
hrmin	=	time when heat-pulse was fired
tz1_*	=	t_z times for probe 1 (*=1 is the outside depth)
tz2_*	=	t_z times for probe 2 (*=1 is the outside depth)

Step - 3

Just keep appending new data to the bottom of the old input file

6.3. Examining the output file

The analysis programme outputs three calculations of total sap flow, depending on how the volume sap flux, Q, is determined. In theory, this is given by the integral

$$Q = \int_H^R 2\pi r \ J(r) \ dr \tag{7}$$

for a stem of cambium radius R [m] and heartwood radius H [m]. In practice, this integral can be obtained by three different ways, where the operator <> will be used to represent the least-squares fit to the profile data.

Method 1: Fit the velocity profile and store the data in FILENAME.VEL.

$$Q = 2\pi \int_H^R r \left\langle \ J(r) \ \right\rangle dr \tag{7a}$$

Method 2: Fit the flux profile and store the data in FILENAME.FLX.

$$Q = 2\pi \int_H^R \left\langle \ r \ J(r) \ \right\rangle dr \tag{7b}$$

Method 3: Calculate a weighted sum of velocity, V_i, times an associated sapwood area, A_i and store the data in FILENAME.SUM (see Hatton, 1990 and analysis programme for details of A_i's).

$$Q = \sum_i A_i \ V_i \tag{7c}$$

For well-behaved velocity profiles (i.e. small curvature at large radii) all three methods yield similar results, but for profiles where the curvature near the cambium method 3 is recommended (Hatton et al, 1990).

6.4. Listing of the ANALYSIS program

The following is a listing of the FORTRAN program HPV-2000.FOR used to analyze the tz-data collected by the HPV data logger. The analysis procedure follows that outlined in the Background Section of this document. This is a fairly big program – only because it includes routines for graphical output to the screen.

```
c============================================================
c ... Program HPV2000.FOR to convert tz data to correct sap
c ... velocities using numerical simulation results for a
c ... given wound width and probe spacings of (-0.5,0,1.0)
C ...........................................................
C
C ...   ------ LAST modified AUG, 2000, S.R. Green  ------
C
c============================================================
        USE DFLIB
        IMPLICIT NONE
c  include files for MS Fortran graphics
        CHARACTER*50 CTITLE, ans
        REAL*8 NXPIX, NYPIX
        REAL*8 X1(101), Y1(101), X2(101), Y2(101)
        REAL*8 X1MIN, X1MAX, Y1MIN, Y1MAX
        INTEGER IX4, IY4, CWIN/0/
        LOGICAL STATUS, END_CALC
        TYPE (RCCOORD)      CURPOS
        TYPE (WINDOWCONFIG) WINC
        TYPE (QWINFO)          QWIN

      REAL TZ(4,4), HPV(4), PD(4,4), PS(4,4)
      REAL TMIN, TMAX, EMIN, F0, F1, F2, BEGYR
        REAL R1P, R1M, R2M, R3M, R4M, A3, A4
        INTEGER IDAY, ITOD, IJ
        REAL WC1(5,7), WC2(5,7)
      REAL R(4), SV(4), SF(4)
      REAL SVIJ(16),T(100), Y(100)
      REAL SAPFLOWV(4,100), SAPFLOWF(4,100), SAPFLOWS(4,100)
        REAL SWR(4), HWR(4), WW(4), EMAX(4)
        REAL VFWOOD, VFWAT, TOD
      REAL A0, A1, A2, FLUXVEL, FLUXFLX, FLUXV(4), FLUXF(4)
      REAL ID, MI, PI, TWOPI
        REAL CHANID,DAY,HRMIN, HR, MIN
      INTEGER NHPV, N, I, ICORR, IW(4), J, NCOL(4), NTC(4), NC
      CHARACTER*40 FILNAM
        CHARACTER*4 STR
      LOGICAL SWANCOR
      INTEGER*2 DUMMY2, FGD
      INTEGER*4 DUMMY4, BGD

        COMMON WINC
        COMMON QWIN

C-------------------------------------------------------------
c ... Set the wound corrections of Swanson and Whitfield (1983)
C-------------------------------------------------------------
         DATA WC1/   0, 0,  1,      0,    0.0,
     *    16,  0.393,    1.356,   0.036,   0.0,
     *    20,  0.807,    1.203,   0.058,   0.0,
     *    24,  1.184,    1.072,   0.087,   0.0,
     *    28,  1.524,    0.964,   0.124,   0.0,
```

```
     *    32,  1.826,    0.879,   0.169,   0.0,
     *    36,  2.090,    0.818,   0.221,   0.0 /

C--------------------------------------------------------------
c ... Set the wound corrections of Green and Clothier (1988)
C--------------------------------------------------------------
        DATA WC2/   0, 0,  1,      0,    0.0,
     *    16,  -0.171,    1.299,  0.0194,   -0.000093,
     *    20,  -0.159,    1.318,  0.0270,   -0.000140,
     *    24,  -0.135,    1.326,  0.0367,   -0.000194,
     *    28,  -0.143,    1.306,  0.0488,   -0.000267,
     *    32,  -0.067,    1.355,  0.0571,   -0.000203,
     *    36,  -0.013,    1.379,  0.0670,   -0.000105/
       PI=3.14159
      TWOPI=2.*PI

C-------------------------------------------------------------
c ... Set the graphics mode
C-------------------------------------------------------------
       CTITLE(1:40) = '       HEAT-PULSE analysis program     '
       CALL GRAPHICSMODE(CTITLE)
1      CALL CLEARSCREEN($GCLEARSCREEN)
       CALL SETTEXTPOSITION(5,1,CURPOS)
       NXPIX = WINC.NUMXPIXELS  !-20
       NYPIX = WINC.NUMYPIXELS  !- 100

       NCOL(1)=4
       NCOL(2)=10
       NCOL(3)=1
       NCOL(4)=15
       BEGYR = -9999

C-------------------------------------------------------------
C ... Open input/output files
C-------------------------------------------------------------
       WRITE(*,'(a\)') 'Enter the Input filename (.dat):   '
       READ(*,'(A)') FILNAM
       CALL NCSTRING(FILNAM,NC)
       OPEN(UNIT=30, FILE=FILNAM(1:NC)//'.DAT', STATUS='UNKNOWN')
      OPEN(UNIT=31, FILE=FILNAM(1:NC)//'.VEL', STATUS='UNKNOWN')
      OPEN(UNIT=32, FILE=FILNAM(1:NC)//'.FLX', STATUS='UNKNOWN')
      OPEN(UNIT=33, FILE=FILNAM(1:NC)//'.SUM', STATUS='UNKNOWN')

C-------------------------------------------------------------
c ... Read input data
C-------------------------------------------------------------
       WRITE(*,*)
       WRITE(*,*) 'Enter the number of heat pulse probes (1..4)'
       READ(30,1099) ANS, NHPV
1099  FORMAT(A16,4I8)
       WRITE(*,1099) ANS, NHPV
       WRITE(*,*)
       WRITE(*,*) 'Enter the number of sensors in each probe'
       READ(30,1099) ANS, (NTC(J), J=1,NHPV)
       WRITE(*,*) 'Enter the wound width from 1.6 to 3.6 (mm)'
       READ(30,1098) ANS, (WW(I), I=1,NHPV)
1098  FORMAT(A16,4F8.2)
       WRITE(*,1098) ANS, (WW(I), I=1,NHPV)
      SWANCOR = .FALSE.
      READ(30,1099) ANS, ICORR
      IF(ICORR.GT.(0.0)) THEN
        WRITE(*,*) 'Use Swansons corrections:  YES'
        SWANCOR=.TRUE.
      ELSE
        WRITE(*,*) 'Use Swansons corrections:  NO'
        SWANCOR=.FALSE.
      ENDIF
       WRITE(*,*)

       DO 12 J=1,NHPV
         IF(WW(J).EQ.(0.0)) IW(J) = 1
         IF(WW(J).GE.(1.6)) IW(J) = INT((WW(J)-1.6)/0.4+2.5)
         IF(IW(J).GT.7)     IW(J) = 7
12    CONTINUE

C-------------------------------------------------------------
```

```
c ... vfwood = volume fraction of wood  = 0.34
c ... vfwat  = volume fraction of water = 0.56
C-------------------------------------------------------------
       WRITE(*,*) 'Enter the volume fraction of wood '
       READ(30,1098) ANS,VFWOOD
       WRITE(*,*) 'Enter the volume fraction of water '
       READ(30,1098) ANS,VFWAT

C-------------------------------------------------------------
c ... mean sap wood radius in cm
C-------------------------------------------------------------
       WRITE(*,*) 'Enter the sap-wood radius of each stem/root [cm] '
       READ(30,1098) ANS, (SWR(J), J=1,NHPV)
       WRITE(*,1098) ANS, (SWR(J), J=1,NHPV)
       WRITE(*,*) 'Enter the heartwood radius of each stem/root [cm] '
       READ(30,1098) ANS, (HWR(J), J=1,NHPV)
       WRITE(*,1098) ANS, (HWR(J), J=1,NHPV)
       WRITE(*,*)

C-------------------------------------------------------------
c ... read in the probe depths
C-------------------------------------------------------------
       WRITE(*,*) 'Enter the thermistor depths of each probe [cm] '
       DO 30 J=1,NHPV
         READ(30,1098) ANS, (PD(I,J),I=1,NTC(J))
         WRITE(*,1098) ANS, (PD(I,J),I=1,NTC(J))
         READ(30,1098) ANS, (PS(I,J),I=1,NTC(J))
         WRITE(*,1098) ANS, (PS(I,J),I=1,NTC(J))
         DO 30 I=1,NTC(J)
30      PD(I,J) = ABS(SWR(J)-PD(I,J))
       WRITE(*,*)

C--------------------------------------------------------------
c ... read plot range
C--------------------------------------------------------------
       WRITE(*,*) 'Enter DOY range: Tmin, Tmax'
       READ(30,1098) ANS, TMIN,TMAX
       WRITE(*,1098) ANS, TMIN,TMAX
       WRITE(*,*) 'Enter SAPFLOW range: Emin, Emax'
       READ(30,1098) ANS, (EMAX(I), I=1,NHPV)
       WRITE(*,1098) ANS, (EMAX(I), I=1,NHPV)
       EMIN = 0.0

      CALL SETTEXTPOSITION(33 ,35,CURPOS)
       WRITE(*,*) '*****  Click <MOUSE> to END *****'
       CALL MOUSECLICK(IX4,IY4)
       CALL CLEARSCREEN($GCLEARSCREEN)

       STATUS = SETCOLOR(8)
       STATUS = RECTANGLE($GFILLINTERIOR,0,0,NXPIX,NYPIX)
       STATUS = SETCOLOR(2)

c-------------------------------------------------------------
c ... main Loop
c-------------------------------------------------------------
      IDAY=0
100   READ(30,*,END=1000) CHANID,DAY,HRMIN,
     *          ((TZ(I,J),I=1,NTC(J)),J=1,NHPV)
       IF(BEGYR.LT.0) THEN
         TMIN = DAY
         BEGYR = 9999
       ENDIF
       IF(HRMIN.LT.5) THEN
         IDAY=IDAY+1
          DO 120 J=1, NHPV
            DO 110 I=1,ITOD
            X1(I) = T(I)
                Y1(I) = SAPFLOWV(J,I)
110       CONTINUE
          X1MIN = TMIN  !T(1)
          X1MAX = TMIN+5.  !T(ITOD)
          Y1MIN = EMIN
          Y1MAX = EMAX(1)
          CALL NEWONEPLOT(X1,Y1,ITOD,'Day of Year', ''
     &,'Water_Use_[L/h]','', X1MIN,X1MAX,Y1MIN,Y1MAX,.TRUE.,.FALSE.,8+J)
120      CONTINUE
```

```
          ITOD = 1
          IF(IDAY.GT.5) THEN
            IDAY = 1
            TMIN = TMIN+5
            TMAX = TMAX+5
            CALL SETTEXTPOSITION(33 ,35,CURPOS)
            WRITE(*,*) '*****  Click <MOUSE> to CONTINUE  *****'
            CALL MOUSECLICK(IX4,IY4)
            CALL CLEARSCREEN($GCLEARSCREEN)
            STATUS = SETCOLOR(8)
            STATUS = RECTANGLE($GFILLINTERIOR,0,0,NXPIX,NYPIX)
            STATUS = SETCOLOR(2)
          ENDIF
        ELSE
          ITOD = ITOD+1
        ENDIF

C-------------------------------------------------------------
c ... convert hrmin to time of day
C-------------------------------------------------------------
        HR = INT(HRMIN/100)
        MIN = HRMIN - 100*HR
        TOD = DAY + (HR+MIN/60)/24
        T(ITOD) = TOD

C-------------------------------------------------------------
c ... For each set of probes find the corrected SV profile,
C ... then compute flux using three different methods
C-------------------------------------------------------------
        DO 300 J=1,NHPV
          DO 200 I=1,NTC(J)
            IF( TZ(I,J).gt.(0.0) ) THEN
              HPV(I) = PS(I,J)/(2.*TZ(I,J))*3600.
            ELSE
              HPV(I) = 0.0
            ENDIF

C-------------------------------------------------------------
c ... compute the corrected SV
C-------------------------------------------------------------
            IJ=(J-1)*NTC(J)+I
            IF(SWANCOR) THEN
              SV(I) =(WC1(5,IW(j))*HPV(I)*HPV(I)*HPV(I)
     *              + WC1(4,IW(j))*HPV(I)*HPV(I)
     *              + WC1(3,IW(j))*HPV(I)
     *              + WC1(2,IW(j)))*(0.505*VFWOOD + VFWAT)
            ELSE
              SV(I) =(WC2(5,IW(j))*HPV(I)*HPV(I)*HPV(I)
     *              + WC2(4,IW(j))*HPV(I)*HPV(I)
     *              + WC2(3,IW(j))*HPV(I)
     *              + WC2(2,IW(j)))*(0.505*VFWOOD + VFWAT)
            ENDIF
            R(I) = PD(I,J)
            SVIJ(IJ) = SV(I)
            SF(I) = SV(I)*R(I)
200      CONTINUE
        N = NTC(J)
        CALL REGRESS(N, R, SV, A0, A1, A2)
       CALL REGRESS(N, R, SF, F0, F1, F2)

C-------------------------------------------------------------
c ... compute total flow, making sure that it remains positive !!!
C-------------------------------------------------------------
        FLUXV(J) = 0.0
        FLUXF(J) = 0.0
        ID = HWR(J)-0.01
        DO WHILE(ID.LT.SWR(J))
          ID = ID + 0.01
          MI = ID + 0.005
          FLUXVEL = TWOPI*MI*(A0 + A1*MI + A2*MI*MI)*0.01
          IF(FLUXVEL.GT.(0.0)) FLUXV(J) = FLUXV(J) + FLUXVEL
          FLUXFLX = TWOPI*(F0 + F1*MI + F2*MI*MI)*0.01
          IF(FLUXFLX.GT.(0.0)) FLUXF(J) = FLUXF(J) + FLUXFLX
        END DO
        FLUXV(J) = FLUXV(J)/1000
        FLUXF(J) = FLUXF(J)/1000
```

```
        SAPFLOWV(J,ITOD) = FLUXV(J)
        SAPFLOWF(J,ITOD) = FLUXF(J)
c        GOTO 299
C-------------------------------------------------------------
C ... compute sum of sap velocity times relative sapwood area
C-------------------------------------------------------------
       R1P = SWR(J)
       R1M = (R(1)+R(2))/2.
       R2M = (R(2)+R(3))/2.
       R3M = (R(3)+R(4))/2.
        R4M = HWR(J)
       A1=(R1P*R1P-R1M*R1M)*PI
       A2=(R1M*R1M-R2M*R2M)*PI
       A3=(R2M*R2M-R3M*R3M)*PI
        A4=(R3M*R3M-R4M*R4M)*PI
        SAPFLOWS(J,ITOD) = A1*SV(1)+A2*SV(2)+A3*SV(3)
        SAPFLOWS(J,ITOD) = (SAPFLOWS(J,ITOD)+A4*SV(4))/1000.
299     CONTINUE

C-------------------------------------------------------------
c ... print out the results
C-------------------------------------------------------------
300     CONTINUE
301     CONTINUE
       WRITE(31,995) T(ITOD), (SAPFLOWV(J,ITOD) , J=1,NHPV)
C     *    ,(SAPFLOWV(1,ITOD)+SAPFLOWV(2,ITOD))/2.
        WRITE(32,995) T(ITOD), (SAPFLOWF(J,ITOD) , J=1,NHPV)
C     *    ,(SAPFLOWF(1,ITOD)+SAPFLOWF(2,ITOD))/2.
        WRITE(33,995) T(ITOD), (SAPFLOWS(J,ITOD) , J=1,NHPV)
C     *    ,(SAPFLOWS(1,ITOD)+SAPFLOWS(2,ITOD))/2.
       GOTO 100
1000    CONTINUE
999     FORMAT(2A40)
996     FORMAT(5x,'Time [d] = ',F8.3,'     Sap flow [L/h] = ',8F8.3
     *   ,6X,1H.)
995     FORMAT(1X,F8.3,8F8.3)

C-------------------------------------------------------------
       CALL SETTEXTPOSITION(33 ,35,CURPOS)
       WRITE(*,*) '*****  Click <MOUSE> to END *****'
       CALL MOUSECLICK(IX4,IY4)
       CALL CLEARSCREEN($GCLEARSCREEN)
C-------------------------------------------------------------
       STOP
       END

c=============================================================
       SUBROUTINE REGRESS(N, X, Y, A0, A1, A2)
C ... fit a parabola through the SFD data using N data points
C      of the form ... y = A0 + A1.x + A2.x^2
c=============================================================
       IMPLICIT NONE
       REAL X(4), Y(4), A0, A1, A2
       REAL SX, SY, SX2, SXY, SX2Y, SX3, SX4
       REAL SSX2, D
       INTEGER N, I

        IF(N.GT.2) THEN
       SX = 0
       SY = 0
       SX2 = 0
       SXY = 0
       SX3 = 0
       SX2Y = 0
       SX4 = 0
       DO 100 I=1,N
       SX = SX + X(I)
       SY = SY + Y(I)
       SXY = SXY + X(I)*Y(I)
       SX2 = SX2 + X(I)*X(I)
       SX2Y= SX2Y+ X(I)*X(I)*Y(I)
       SX3 = SX3 + X(I)**3
       SX4 = SX4 + X(I)**4
100     CONTINUE
       SSX2= SX2
       SX4 = SX4 - SX2*SX2/N
```

```
       SX3 = SX3 - SX*SX2/N
       SXY = SXY - SX*SY/N
       SX2Y= SX2Y- SX2*SY/N
       SX2 = SX2 - SX*SX/N
       D   = SX2*SX4 - SX3**2
       A1  = (SX4*SXY - SX3*SX2Y)/D
       A2  = (SX2*SX2Y - SX3*SXY)/D
       A0 = SY/N - A1*SX/N - A2*SSX2/N

        ELSE
          A0 = (Y(1)+Y(2))/2.
          A1=0.0
          A2=0.0
        ENDIF


       RETURN
       END

!==========================================================
       SUBROUTINE GRAPHICSMODE(CTITLE)
!==========================================================
       USE DFLIB
       IMPLICIT NONE
       TYPE (WINDOWCONFIG) WINC
       TYPE (QWINFO)          QW

       INTEGER RETI2, CWIN/0/
       LOGICAL STATUS, RESULT
       CHARACTER*50 CTITLE
       COMMON WINC
       COMMON QW

!-------------------------------------------
! ... set up the size of the frame window
!-------------------------------------------
       WINC.NUMXPIXELS  = -1
       WINC.NUMYPIXELS  = -1
       WINC.NUMTEXTCOLS = -1
       WINC.NUMTEXTROWS = -1
       WINC.NUMCOLORS   = -1
       WINC.TITLE       = CTITLE
       STATUS = SETWINDOWCONFIG(WINC)
       IF(.NOT.STATUS) STATUS = SETWINDOWCONFIG(WINC)
       STATUS = FOCUSQQ(CWIN)

!-----------------------------------------
! ... set the frame window to maximum
!-----------------------------------------
       QW.TYPE = QWIN$MAX
       RETI2 = SETWSIZEQQ(QWIN$FRAMEWINDOW, QW)
       RETI2 = SETWSIZEQQ(CWIN, QW)

       RETURN
       END SUBROUTINE GRAPHICSMODE

!=========================================================
        SUBROUTINE NCSTRING(STRING, NCHAR)
!=========================================================
        CHARACTER*40 STRING
        INTEGER NCHAR, I
        I = 2
        DO WHILE(STRING(I:I).NE.'')
          I=I+1
        END DO
        NCHAR = I-1
        END

!==========================================================
        SUBROUTINE INLINE(NUNIT, NLINE, OP)
c ... read nlines from file nunit write to screen in OP is true
!==========================================================
        IMPLICIT NONE
        INTEGER I,NLINE,NUNIT
        CHARACTER*80 LINE
        LOGICAL OP
```

```
        DO 10 I=1,NLINE
          READ(NUNIT,99) LINE
          IF(OP) WRITE(   *,99) LINE
10       CONTINUE
99      FORMAT(A75)
        RETURN
        END SUBROUTINE INLINE

!===========================================================
       SUBROUTINE NEWONEPLOT(X1,Y1,NUM1,XTITLE, XUNIT, YTITLE, YUNIT
     & ,GX1MIN, GX1MAX, GY1MIN, GY1MAX, Y1LABEL, Y2LABEL ,LCOL)
!===========================================================
       USE DFLIB
       IMPLICIT NONE
       TYPE (WINDOWCONFIG) WINC
       TYPE (QWINFO)          QW
       INTEGER NUM1, NTICKX1, NTICKY1
       INTEGER I, J,NXPIX, NYPIX, NC1, NC2
       INTEGER IX,IY, ix4,iy4, LCOL
       INTEGER STATUS
       REAL*8 X1(NUM1), Y1(NUM1)
       REAL*8 XX(NUM1), YY(NUM1)
       REAL*8 X1MIN, X1MAX, X1RANGE, Y1MIN, Y1MAX, Y1RANGE
       REAL*8 GX1MIN, GX1MAX, GY1MIN, GY1MAX
       REAL*8 X1SCALE, DTICKX1, DUMMYSCALE
       REAL*8 Y1SCALE, DTICKY1
       REAL*8 XP,YP, NEWX1MAX
       CHARACTER*40 XTITLE, XUNIT, NEWXUNIT, XTITLEUNIT
       CHARACTER*40 YTITLE, YUNIT, NEWYUNIT, YTITLEUNIT, GTITLE
       LOGICAL INVERT, LOGPLOT, SCALE, TALL, Y1LABEL, Y2LABEL

       COMMON WINC
       COMMON QW

       NXPIX = WINC.NUMXPIXELS  !-20
       NYPIX = WINC.NUMYPIXELS  !-100
       X1MIN = GX1MIN
       X1MAX = GX1MAX
       Y1MIN = GY1MIN
       Y1MAX = GY1MAX
       DO 10 I=1,NUM1
         XX(I) = (X1(I)-X1MIN)/(X1MAX-X1MIN)
         YY(I) = (Y1(I)-Y1MIN)/(Y1MAX-Y1MIN)
10     CONTINUE

       CALL AXISSET(X1MIN, X1MAX, X1SCALE, NTICKX1, DTICKX1)       ! SOMETHING WRONG HERE
??
       CALL AXISSET(Y1MIN, Y1MAX, Y1SCALE, NTICKY1, DTICKY1)

!      X1RANGE = (X1MAX-X1MIN)*X1SCALE
!      Y1RANGE = (Y1MAX-Y1MIN)*Y1SCALE

       CALL NCSTRING(XTITLE,NC1)
       CALL NCSTRING( XUNIT,NC2)
       XTITLEUNIT = XTITLE(1:NC1)//XUNIT(1:NC2)
       if(x1scale.gt.1.0) xtitleunit = xtitle(1:11)//']'
       CALL NCSTRING(YTITLE,NC1)
       CALL NCSTRING( YUNIT,NC2)
       YTITLEUNIT = YTITLE(1:NC1)//YUNIT(1:NC2)

       CALL SETVIEWPORT(0,0,NXPIX/1.0, NYPIX)
       ! FOR GRAPH1
       STATUS = SETWINDOW(.TRUE.,-0.25D0,-0.50D0,1.25D0,1.15D0)

       CALL TITLEAXIS(0.5D0,-0.15D0,XTITLEUNIT,1.4D0,1.4D0,NXPIX/1
     &   ,NYPIX,TALL,1)
       ! XAXIS TITLE
       CALL PLOTXTICK(X1MIN, X1MAX, X1SCALE, NTICKX1,15, TALL
     & ,1.4D0,1.4D0,NXPIX/1, NYPIX,.FALSE.)

       IF(Y1LABEL) THEN
         CALL TITLEAXIS(-0.20D0,0.5D0,YTITLEUNIT,1.4D0,1.4D0,NXPIX/1
     &   ,NYPIX,TALL,2)
       ! YAXIS TITLE
         CALL PLOTYTICK(0.0D0,Y1MIN, Y1MAX, Y1SCALE, NTICKY1,15, TALL
     & ,1.4D0,1.4D0,NXPIX/1, NYPIX)
```

```
      ENDIF

      IF(Y2LABEL) THEN
        CALL TITLEAXIS(1.15D0,0.5D0,YTITLEUNIT,1.4D0,1.4D0,NXPIX/1
     &    ,NYPIX,TALL,2)
       ! YAXIS TITLE
        CALL PLOTYTICK(1.0D0,Y1MIN, Y1MAX, Y1SCALE, NTICKY1,15, TALL
     & ,1.4D0,1.4D0,NXPIX/1, NYPIX)
      ENDIF

      STATUS = SETCOLOR(7)
      STATUS = RECTANGLE_W($GBORDER, 0.0D0,0.0D0,1.0D0,1.0D0)

      CALL PLOTLINE(XX,YY,NUM1,LCOL)

      RETURN
      END SUBROUTINE NEWONEPLOT

!==========================================================
      SUBROUTINE TITLEAXIS(WXP, WYP, AXTITLE, XW,YH
     & ,NXPIX, NYPIX,TALL ,NAXIS)
!==========================================================
      USE DFLIB
      IMPLICIT NONE
      REAL*8 WXP, WYP, DWXP, DWYP, XW, YH
      CHARACTER*30 AXTITLE
      INTEGER I, CHEI, CWID, NCBEG, NCEND, TLEN, NAXIS
      INTEGER STATUS, NXPIX, NYPIX
      LOGICAL TALL
      TYPE (WXYCOORD)     WXY
      TYPE (FONTINFO)     FONT

! ... set the font
      STATUS = INITIALIZEFONTS()
      I = SETFONT("T'COURIER NEW'H30W15")
      CWID = FONT.PIXWIDTH
      CHEI = FONT.PIXHEIGHT
      STATUS = SETCOLOR(INT2(0))

! ... trim the string for leading blanks
      NCBEG = 1
      DO WHILE(AXTITLE(NCBEG:NCBEG) .EQ.'')
        NCBEG = NCBEG+1
      END DO
      NCEND = NCBEG + LEN_TRIM(AXTITLE(NCBEG:))-1
      TLEN = GETGTEXTEXTENT(AXTITLE(NCBEG:NCEND))

! ... add an offset for the text
      IF(NAXIS.EQ.1) THEN
        DWYP = 0.0
        DWXP = -((REAL(TLEN)/2.)/REAL(NXPIX)*XW)
      ELSE IF(NAXIS.EQ.2) THEN
        DWYP = -((REAL(TLEN)/2.)/REAL(NYPIX)*YH)
        DWXP = 0.0
      ELSE
        DWYP = 0.0
        DWXP = -(REAL(TLEN/2.)/REAL(NXPIX)*XW)
      ENDIF

      CALL MOVETO_W(WXP+DWXP,WYP+DWYP,WXY)
      IF(NAXIS.EQ.2) THEN
        CALL SETGTEXTROTATION(900)
      ELSE
        CALL SETGTEXTROTATION(0)
      ENDIF
      CALL OUTGTEXT( AXTITLE(NCBEG:NCEND))

      RETURN
      END SUBROUTINE TITLEAXIS

C==========================================================
      SUBROUTINE PLOTLINE(XX,YY,NUM,LCOL)
C==========================================================
      USE DFLIB
      IMPLICIT NONE
      INTEGER I, NUM, LCOL, BGCOL
```

```
      REAL*8 XX(NUM), YY(NUM)
      LOGICAL STATUS
      TYPE (WXYCOORD)       WXY

      STATUS = SETCOLOR(LCOL)
      CALL MOVETO_W(XX(1), YY(1), WXY)
      DO 10 I=2,NUM
        STATUS = LINETO_W(XX(I), YY(I) )
10    CONTINUE

      RETURN
      END SUBROUTINE PLOTLINE

C===========================================================
      SUBROUTINE PLOTXTICK(LOWX, HIGHX, XSCALE, NTICK, NCOL,
     &                 TALL, XW,YH, NXPIX,NYPIX, LOGPLOT)
C===========================================================
      USE DFLIB
      IMPLICIT NONE
      TYPE (WXYCOORD)              WXY
      REAL*8 LOWX, HIGHX, XSCALE, XRANGE, XTICK, DXTICK
      REAL*8 LOWY, HIGHY, YSCALE, YRANGE, YTICK, DYTICK
      REAL*8 XW,YH, XLABEL
      REAL*8 TICKLEN /0.025/
      INTEGER I, NTICK, NCOL, NXPIX, NYPIX
      LOGICAL RESULT, STATUS, TALL, LOGPLOT

! plot the xticks
      STATUS = SETCOLOR(NCOL)
      IF(TALL) TICKLEN = 0.015
      DXTICK = 1.0D0/REAL(NTICK)
      DO 10 I=0,NTICK
        XTICK = REAL(I)*DXTICK
        YTICK = 0.0D0
        XLABEL = LOWX + XTICK*(HIGHX-LOWX)
        CALL MOVETO_W(XTICK, YTICK, WXY)
        RESULT = LINETO_W(XTICK, YTICK - TICKLEN)
        CALL NUMAXIS(XTICK,YTICK-2.0*TICKLEN,XLABEL, XW,YH,NXPIX, NYPIX
     &  ,1, LOGPLOT)
      !!!!!  LOG PLOT ON XAXIS
        XTICK = REAL(I)*DXTICK
        YTICK = 1.0D0
        CALL MOVETO_W(XTICK, YTICK, WXY)
        RESULT = LINETO_W(XTICK, YTICK + TICKLEN)
10    CONTINUE

      RETURN
      END SUBROUTINE PLOTXTICK

C===========================================================
      SUBROUTINE PLOTYTICK(XLOC,LOWY, HIGHY, YSCALE, NTICK, NCOL,
     &                         TALL, XW,YH,NXPIX, NYPIX  )!,Y1TICK,Y2TICK)
C===========================================================
      USE DFLIB
      IMPLICIT NONE
      TYPE (WXYCOORD)              WXY
      REAL*8 LOWX, HIGHX, XSCALE, XRANGE, XTICK, DXTICK
      REAL*8 LOWY, HIGHY, YSCALE, YRANGE, YTICK, DYTICK
      REAL*8 TICKLEN /0.01/
      REAL*8 XW,YH, YLABEL, XLOC
      INTEGER I, NTICK, NCOL,NXPIX, NYPIX
      LOGICAL RESULT, STATUS, TALL !, Y1TICK, Y2TICK

! plot the xticks
      STATUS = SETCOLOR(NCOL)
      IF(TALL) TICKLEN = 0.020
      DYTICK = 1.0D0/REAL(NTICK)
      DO 10 I=0,NTICK
        YTICK = REAL(I)*DYTICK
        XTICK = XLOC
        YLABEL = LOWY + YTICK*(HIGHY-LOWY)
        CALL MOVETO_W(XTICK, YTICK, WXY)
        RESULT = LINETO_W(XTICK-TICKLEN, YTICK )
        IF(XLOC.LT.0.5D0) THEN
          CALL NUMAXIS(XTICK-0.05,YTICK,YLABEL, XW,YH,NXPIX
     &  , NYPIX,2, .FALSE.)        !!!! NO LOG PLOT ON YAXIS
```

```
          ELSE
            CALL NUMAXIS(XTICK+0.1,YTICK,YLABEL, XW,YH,NXPIX
     &    , NYPIX,2, .FALSE.)          !!!! NO LOG PLOT ON YAXIS
          ENDIF
10      CONTINUE

        RETURN
        END SUBROUTINE PLOTYTICK

!=========================================================
        SUBROUTINE NUMAXIS(WXP,WYP,VALUE,XW,YH,NXPIX,NYPIX,NAXIS, LOGPLOT)
! THE MAJOR TICKS
!=========================================================
        USE DFLIB
        IMPLICIT NONE

        REAL*8 WXP, DWXP, WYP, DWYP, VALUE, XW,YH
        INTEGER NXPIX, NYPIX, CHEI, CWID
        INTEGER I, STATUS, NPOINTS/1/, NAXIS, TLEN
        INTEGER NCBEG, NCEND, NC1,NC2,NC3
        CHARACTER*16 TEMPSTR, FMS, LOGSTR
        LOGICAL LOGPLOT

        TYPE (XYCOORD)  XY
        TYPE (WXYCOORD) WXY
        TYPE (WINDOWCONFIG) WINC
        TYPE (FONTINFO) FONT

        COMMON WINC

! ... get the font information
        STATUS = INITIALIZEFONTS()
        I = SETFONT("T'COURIER NEW'H20W10")
        I = GETFONTINFO(FONT)
        CWID  = FONT.PIXWIDTH
        CHEI  = FONT.PIXHEIGHT

! ... get the tick value
        WRITE(FMS,'(A5,I2,A1)') '(F10.',NPOINTS,')'
        WRITE(TEMPSTR,FMS) VALUE

! ... trim the string for leading blanks
        NCBEG = 1
        DO WHILE(TEMPSTR(NCBEG:NCBEG) .EQ.'')
          NCBEG = NCBEG+1
        END DO
        NCEND = NCBEG + LEN_TRIM(TEMPSTR(NCBEG:))-1

! ... add in the exponent for a log scale
        IF(LOGPLOT) THEN
          LOGSTR = '1E'//TEMPSTR(NCBEG:NCEND)
          CALL NCSTRING(LOGSTR,NC1)
          TEMPSTR(1:NC1) = LOGSTR(1:NC1)
          NCBEG = 1
          NCEND = NC1
        ENDIF

        TLEN = GETGTEXTEXTENT(TEMPSTR(NCBEG:NCEND))
! ... add an offset for the text (to centre it on the ticks)
        IF(NAXIS.EQ.1) THEN
          DWYP = 0.0
          DWXP = -((REAL(TLEN)/2.)/REAL(NXPIX)*XW)
        ELSE
          DWYP =  ((REAL(CHEI)/2.)/REAL(NYPIX)*YH)
          DWXP = -((REAL(TLEN)   )/REAL(NXPIX)*XW)
        ENDIF

        CALL MOVETO_W(WXP+DWXP,WYP+DWYP,WXY)
        CALL SETGTEXTROTATION(0)
        CALL OUTGTEXT( TEMPSTR(NCBEG:NCEND))

        RETURN
        END SUBROUTINE NUMAXIS

C=========================================================
      SUBROUTINE AXISSET(LOW, HIGH, RSCALE, NTICKS, DTICKS)
```

```
C============================================================
        IMPLICIT NONE
        REAL*8 HIGH, LOW, RANGE, DLHI, DLLO, DTICKS
        REAL*8 RPOW, RSCALE, RMAG, TEMP, TINY/1E-20/
          INTEGER NTICKS, HELPSCALE

! ... find the range and magnitude and rescale if necessary
        RPOW = 0.0D0
          RANGE = HIGH - LOW
          IF(LOW .EQ.0.0D0) LOW  = TINY
          IF(HIGH.EQ.0.0D0) HIGH = 2.0d0*LOW
        IF(RANGE.EQ. 0.0D0) THEN   ! THE LINE IS VERTICAL
          HIGH = HIGH + 0.5
          LOW = LOW - 0.5
        ENDIF
        DLHI = DLOG10(ABS(HIGH))
        DLLO = DLOG10(ABS(LOW))
        DO WHILE(DLHI.LT.0.0D0 .AND. DLLO.LT.0.0D0)
          DLHI = DLHI + 3.0D0
          DLLO = DLLO + 3.0D0
          RPOW = RPOW + 3.0D0
        END DO
        HIGH = HIGH*10**RPOW
        LOW  = LOW*10**RPOW
        RSCALE = 10**-RPOW
        RANGE = HIGH-LOW
        RMAG  = 10**INT(DLOG10(RANGE))  ! 10S, 100S, 1000S FOR EG.

!  ... determine the lhs axis value
        TEMP  = LOW/RMAG                ! CALCULATE LOW (FOR AXIS)
        LOW   = INT(TEMP)
        IF(ABS(TEMP-LOW).GE.1.0E-12 .AND. TEMP.LT.0) THEN
          LOW = LOW - 1
        ENDIF
        LOW = LOW*RMAG

! ... determine the rhs axis value
        TEMP = HIGH/RMAG                ! CALCULATE HIGH (FOR AXIS)
        HIGH = INT(TEMP)
        IF(ABS(TEMP-HIGH).GE.1E-12 .AND. TEMP.GT.0) THEN
          HIGH = HIGH + 1
        ENDIF
        HIGH = HIGH*RMAG

! ... determine the number of axis ticks
        HELPSCALE = (HIGH-LOW)/RMAG
        IF(HELPSCALE.GT.5) THEN
          NTICKS = 5 !HELPSCALE
        ELSE
          SELECT CASE (HELPSCALE)
            CASE(5)
              NTICKS = 5
            CASE(4)
              NTICKS = 4
            CASE(3)
              NTICKS = 3
            CASE(2)
              NTICKS = 4
            CASE(1)
              NTICKS = 5
          END SELECT
        ENDIF
        DTICKS = (HIGH-LOW)/NTICKS
          RANGE  = HIGH-LOW
          IF(RANGE.GE.1000) THEN
            HIGH = HIGH*1.0D-3
            LOW  =  LOW*1.0D-3
            RSCALE = RSCALE*1.0D3
          ENDIF

       END SUBROUTINE AXISSET

!============================================================
       SUBROUTINE RANGESET(X, NX, XMIN, XMAX)
!============================================================
       IMPLICIT NONE
```

```
      INTEGER I, NX
      REAL*8 X(NX), XMIN, XMAX
      XMIN =  1.0D10
      XMAX = -1.0D10
      DO 10 I=1,NX
        IF(X(I).LE.XMIN) XMIN = X(I)
        IF(X(I).GE.XMAX) XMAX = X(I)
10    CONTINUE

      RETURN
      END SUBROUTINE RANGESET

!===========================================================
      SUBROUTINE MOUSECLICK(X,Y)
!===========================================================
      USE DFLIB
      IMPLICIT NONE
      INTEGER*4 MOUSEEVENT, KEYSTATE, X, Y, RESULT
        MOUSEEVENT = MOUSE$RBUTTONDOWN .OR. MOUSE$LBUTTONDOWN
        RESULT = WAITONMOUSEEVENT(MOUSEEVENT, KEYSTATE, X, Y)
!       WRITE(5,*) 'MOUSE AT ', X, Y
      RETURN
      END SUBROUTINE MOUSECLICK

!===========================================================
      SUBROUTINE MOUSETOEXIT(UNIT,MOUSEEVENT,KEYSTATE
     & ,MOUSEXPOS,MOUSEYPOS)
!===========================================================
        USE DFLIB
        INTEGER UNIT,MOUSEEVENT, KEYSTATE,MOUSEXPOS, MOUSEYPOS
        LOGICAL MOUSEEXIT
        COMMON /MOUSE/ MOUSEEXIT
        MOUSEEXIT = .TRUE.       ! ONLY EXECUTED IF MOUSE LBUTTON IS PRESSED
        RETURN
      END SUBROUTINE MOUSETOEXIT
```

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Appendix A – use of an AM25T multiplexer:

Listing of logger programme to connect 3 heat-pulse units to a single CR10 data logger. Note: One AM25T could be used to measure up to 6 heat-pulse units, but this requires a small modification to the programme described below. Please email the author for details.

CR10:	AM25T
+12	+12
G	G
C3	CLK
C2	RES
no connection	EX
AG	AG
1H	HI
1L	LO
	(1H, 1L, 2H, 2L) Output from box-1, probe 1
	(3H, 3L, 4H, 4L) Output from box-1, probe 2
	(5H, 5L, 6H, 6L) Output from box-2, probe 1
	(7H, 7L, 8H, 8L) Output from box-2, probe 2
	and so on ...

```
*Table 1 Program
  01: 0.25      Execution Interval (seconds)

1:  If time is (P92)            ; Flag 1 is automatic sampling
 1: 0000     Minutes (Seconds --) into a  ; once every 30 minutes
 2: 30       Interval (same units as above)     ;Change as required
 3: 11       Set Flag 1 High

2:  If Flag/Port (P91)          ; Flag 5 is set when tz is calculated
 1: 15       Do if Flag 5 is High
 2: 30       Then Do

3:  Timer (P26)
 1: 99       Loc [ __________ ]

4:  Do (P86)                    ; Activate AM25T
 1: 42       Set Port 2 High    ; Connect Port 2 (C2) to Reset on AM25T

5:  Beginning of Loop (P87)    ; Measure inputs on 2*N boxes
 1: 0000     Delay
 2: 12       Loop Count         ; (2* N boxes) Change as required

6:  Step Loop Index (P90)
 1: 2        Step

7:  Do (P86)                   ; Connect Port 3 (C3) to Clock on AM25T
 1: 43       Set Port 3 High

8:  Do (P86)
 1: 53       Set Port 3 Low

9:  Do (P86)
 1: 43       Set Port 3 High

10:  Do (P86)
```

```
 1: 53       Set Port 3 Low

11:  Volt (SE) (P1)
 1: 2        Reps
 2: 15       2500 mV Fast Range
 3: 1        SE Channel
 4: 31    -- Loc [ _________ ]
 5: 1.0      Mult
 6: 0.0      Offset

12:  Z=X-Y (P35)                      Calculate temperature difference
 1: 31    -- X Loc [ _________ ]
 2: 61    -- Y Loc [ _________ ]
 3: 31    -- Z Loc [ _________ ]    and store in loc (31..54)

13:  End (P95)

14:  Do (P86)                               De-activate AM25T
 1: 52       Set Port 2 Low

15:  Beginning of Loop (P87)          ; Check each input for a cross-over
 1: 0        Delay
 2: 24       Loop Count                     8*N boxes

16:  If (X<=>F) (P89)
 1: 1     -- X Loc [ _________ ]
 2: 1        =
 3: 0.0      F
 4: 30       Then Do

17:  If (X<=>F) (P89)                       If a cross-over has occurred
 1: 31    -- X Loc [ _________ ]
 2: 4        <
 3: 0.0      F
 4: 30       Then Do

18:  Z=X (P31)                              Store tz in loc (1..24)
 1: 99       X Loc [ _________ ]
 2: 1     -- Z Loc [ _________ ]

19:  Z=Z+1 (P32)                            Increment the 'tz' counter
 1: 90       Z Loc [ _________ ]

20:  End (P95)

21:  End (P95)

22:  End (P95)

23:  If (X<=>F) (P89)          ; If all 24 channels have crossed over
 1: 90       X Loc [ _________ ] ; then set flag 6 (to exit loop)
 2: 3        >=
 3: 24       F
 4: 16       Set Flag 6 High

24:  If (X<=>F) (P89)          ; if time > 300 s
 1: 99       X Loc [ _________ ]  ; then set flag 6 (to exit loop)
 2: 3        >=
 3: 300      F
 4: 16       Set Flag 6 High
```

```
25:  End (P95)

26:  If Flag/Port (P91)       ; Flag 6 is used to generate output
 1: 16       Do if Flag 6 is High
 2: 30       Then Do

27:  Do (P86)
 1: 10       Set Output Flag High

28:  Sample (P70)                       Output the date and time
 1: 2        Reps
 2: 91       Loc [ __________ ]

29:  Sample (P70)                       Output the 24 tz values
 1: 24       Reps                             change as required
 2: 1        Loc [ __________ ]

30:  Do (P86)
 1: 26       Set Flag 6 Low

31:  Do (P86)
 1: 25       Set Flag 5 Low

32:  End (P95)

33:  If Flag/Port (P91)       ; Flag 1 begins the heat-pulse routine
 1: 11       Do if Flag 1 is High
 2: 30       Then Do

34:  Time (P18)
 1: 2        Hours into current year (maximum 8784)
 2: 8784     Mod/By
 3: 91       Loc [ __________ ]

35:  Z=X*F (P37)
 1: 91       X Loc [ __________ ]
 2: .04167   F
 3: 91       Z Loc [ __________ ]

36:  Z=INT(X) (P45)
 1: 91       X Loc [ __________ ]
 2: 91       Z Loc [ __________ ]

37:  Z=Z+1 (P32)              ; Store the current day number (loc 91)
 1: 91       Z Loc [ __________ ]

38:  Time (P18)
 1: 2        Hours into current year (maximum 8784)
 2: 24       Mod/By
 3: 92       Loc [ __________ ]

39:  Z=X*F (P37)
 1: 92       X Loc [ __________ ]
 2: 100      F
 3: 92       Z Loc [ __________ ]

40:  Time (P18)
 1: 1        Minutes into current day (maximum 1440)
 2: 60       Mod/By
 3: 93       Loc [ __________ ]
```

```
41:  Z=X+Y (P33)               ; Store the time (hrmin)  (loc 92)
 1: 92       X Loc [ __________ ]
 2: 93       Y Loc [ __________ ]
 3: 92       Z Loc [ __________ ]

42:  Beginning of Loop (P87)
 1: 0        Delay
 2: 90       Loop Count

43:  Z=F (P30)                 ; Reset all storage arrays
 1: 0        F
 2: 0        Exponent of 10
 3: 1     -- Z Loc [ __________ ]

44:  End (P95)

45:  Do (P86)                  ; measure initial voltage using AM25T
 1: 42       Set Port 2 High   ; Port 2 is connected reset of AM25T

46:  Beginning of Loop (P87)
 1: 0        Delay
 2: 12       Loop Count        ; for 4* N boxes

47:  Step Loop Index (P90)
 1: 2        Step

48:  Do (P86)                  ; Port 3 (C3) connects to clock of AM25T
 1: 43       Set Port 3 High

49:  Do (P86)
 1: 53       Set Port 3 Low

50:  Do (P86)
 1: 43       Set Port 3 High

51:  Do (P86)
 1: 53       Set Port 3 Low

52:  Volt (SE) (P1)            ; Store initial voltage in Loc (61..84)
 1: 2        Reps
 2: 15       2500 mV Fast Range
 3: 1        SE Channel
 4: 61    -- Loc [ __________ ]
 5: 1.0      Mult
 6: 0.0      Offset

53:  End (P95)

54:  Do (P86)
 1: 52       Set Port 2 Low

55:  Timer (P26)
 1: 0        Reset Timer

56:  Do (P86)
 1: 21       Set Flag 1 Low

57:  Do (P86)
 1: 12       Set Flag 2 High

58:  End (P95)
```

```
59:  If Flag/Port (P91)
 1: 12       Do if Flag 2 is High
 2: 30       Then Do

60:  Set Port(s) (P20)        ; Port 1 (C1) is the heater control line
 1: 0        C8..C5 = low/low/low/low
 2: 1        C4..C1 = low/low/low/high

61:  Beginning of Loop (P87)
 1: 1        Delay
 2: 0        Loop Count

62:  Timer (P26)
 1: 99       Loc [ _________ ]

63:  If (X<=>F) (P89)         ; Fire the heater for 1 s
 1: 99       X Loc [ _________ ]
 2: 3        >=
 3: 1        F                            Change as required
 4: 31       Exit Loop if True

64:  End (P95)

65:  Set Port(s) (P20)
 1: 0        C8..C5 = low/low/low/low
 2: 0        C4..C1 = low/low/low/low

66:  Beginning of Loop (P87)
 1: 1        Delay
 2: 0        Loop Count

67:  Timer (P26)
 1: 99       Loc [ _________ ]

68:  If (X<=>F) (P89)         ; Wait 15 s for heat-pulse to arrive
 1: 99       X Loc [ _________ ]
 2: 3        >=
 3: 15       F                ; Change as required
 4: 15       Set Flag 5 High

69:  If Flag/Port (P91)
 1: 15       Do if Flag 5 is High
 2: 31       Exit Loop if True

70:  End (P95)

71:  Do (P86)
 1: 22       Set Flag 2 Low

72:  End (P95)

73:  Batt Voltage (P10)       ; Store battery voltage in Loc 98
 1: 98       Loc [ _________ ]
```

Appendix B - use of simple heat-pulse controller (no amplifiers)

The heat-pulse controller and probes can be operated with most Campbell data loggers. The wiring is to be connected as described below:

CR10/21X/23	Controller	
+12	Grey (external 12V battery)	
G	Grey/Black	
C1	Blue	of controller #1
AG	Blue/white	"
C2	Blue	of controller #2
AG	Blue/white	"
	Probe 1	
(1H, 1L)	Orange, Orange/white	
(2H, 2L)	Blue, Blue/white	
AG	Green[1]	
AG	Shield	
	Probe 2	
(3H, 3L)	Orange, Orange/white	
(4H, 4L)	Blue, Blue/white	
AG	Green[1]	
AG	Shield	

[1] **VERY IMPORTANT:** If the same battery powers the logger and the heat-pulse unit then do not connect the green wire of the signal lead to AG. This would cause a ground loop and might affect the results...

Listing of a CR10 logger programme to connect

```
;{CR10}
*Table 1 Program
  01: 0.2500    Execution Interval (seconds)

1:  If time is (P92)                ! set for 15 min intervals
 1: 0        Minutes (Seconds --) into a
 2: 15       Interval (same units as above) ! change as required
 3: 11       Set Flag 1 High

2:  If Flag/Port (P91)
 1: 15       Do if Flag 5 is High
 2: 30       Then Do

3:  Timer (P26)                     ! stores the time since heat-pulse
 1: 99       Loc [ __________ ]

4:  Thermocouple Temp (SE) (P13)    ! loc 21..28 = temperature signals
 1: 8        Reps
 2: 1        2.5 mV Slow Range
 3: 1        SE Channel
```

```
 4: 1        Type T (Copper-Constantan)
 5: 100      Ref Temp (Deg. C) Loc [ _________ ]
 6: 21       Loc [ _________ ]
 7: 1        Mult
 8: 0        Offset

5:  Beginning of Loop (P87)
 1: 0        Delay
 2: 8        Loop Count

6:  If (X<=>F) (P89)           ! loc 1..8 = Tz cross-over times
 1: 1     -- X Loc [ _________ ]
 2: 1        =
 3: 0        F
 4: 30       Then Do

7:  If (X<=>Y) (P88)
 1: 41    -- X Loc [ _________ ] ! loc 41..48 = original temperature
 2: 3        >=
 3: 21    -- Y Loc [ _________ ] ! loc 21..28 = temperatures now
 4: 30       Then Do

8:  Z=X (P31)
 1: 99       X Loc [ _________ ]
 2: 1     -- Z Loc [ _________ ]  ! loc 1..8 = final Tz time

9:  Z=Z+1 (P32)
 1: 90       Z Loc [ _________ ]

10:  End (P95)

11:  End (P95)

12:  End (P95)

13:  If (X<=>F) (P89)
 1: 90       X Loc [ _________ ]  ! loc 90 = number of Tz recorded
 2: 3        >=
 3: 8        F
 4: 16       Set Flag 6 High

14:  If (X<=>F) (P89)
 1: 99       X Loc [ _________ ]
 2: 3        >=
 3: 500      F                    ! time (s) for last measurement
 4: 16       Set Flag 6 High

15:  End (P95)

16:  If Flag/Port (P91)
 1: 16       Do if Flag 6 is High
 2: 30       Then Do

17:  Do (P86)
 1: 10       Set Output Flag High

18:  Sample (P70)              ! output the  day and decimal hour
 1: 2        Reps
 2: 91       Loc [ _________ ]
```

```
19:  Sample (P70)             ! output the cross-over times
 1: 8        Reps
 2: 1        Loc [ _________ ]

20:  Do (P86)
 1: 26       Set Flag 6 Low

21:  Do (P86)
 1: 25       Set Flag 5 Low

22:  End (P95)

23:  If Flag/Port (P91)
 1: 11       Do if Flag 1 is High
 2: 30       Then Do

24:  Time (P18)
 1: 2        Hours into current year (maximum 8784)
 2: 8784     Mod/By
 3: 91       Loc [ _________ ]      ! store day of year

25:  Z=X*F (P37)
 1: 91       X Loc [ _________ ]
 2: .04167   F
 3: 91       Z Loc [ _________ ]

26:  Z=INT(X) (P45)
 1: 91       X Loc [ _________ ]
 2: 91       Z Loc [ _________ ]

27:  Z=Z+1 (P32)
 1: 91       Z Loc [ _________ ]

28:  Time (P18)
 1: 2        Hours into current year (maximum 8784)
 2: 24       Mod/By
 3: 92       Loc [ _________ ]

29:  Z=X*F (P37)                     ! store the hour
 1: 92       X Loc [ _________ ]
 2: 100      F
 3: 92       Z Loc [ _________ ]

30:  Time (P18)
 1: 1        Minutes into current day (maximum 1440)
 2: 60       Mod/By
 3: 93       Loc [ _________ ]

31:  Z=X+Y (P33)              ! store the decimal hour
 1: 92       X Loc [ _________ ]
 2: 93       Y Loc [ _________ ]
 3: 92       Z Loc [ _________ ]

32:  Beginning of Loop (P87)
 1: 0        Delay
 2: 90       Loop Count

33:  Z=F (P30)                ! reset all storage
 1: 0        F
 2: 0        Exponent of 10
 3: 1     -- Z Loc [ _________ ]
```

```
34:  End (P95)

35:  Thermocouple Temp (SE) (P13)   ! measure initial temp difference
 1: 8        Reps
 2: 1        2.5 mV Slow Range
 3: 1        SE Channel
 4: 1        Type T (Copper-Constantan)
 5: 100      Ref Temp (Deg. C) Loc [ _________ ]
 6: 41       Loc [ _________ ]  ! loc 41..48 = initial temp difference
 7: 1        Mult
 8: 0        Offset

36:  Timer (P26)
 1: 0        Reset Timer

37:  Do (P86)
 1: 21       Set Flag 1 Low

38:  Do (P86)
 1: 12       Set Flag 2 High

39:  End (P95)

40:  If Flag/Port (P91)             ! fire the heat pulse
 1: 12       Do if Flag 2 is High
 2: 30       Then Do

41:  Set Port(s) (P20)
 1: 0        C8..C5 = low/low/low/low
 2: 11       C4..C1 = low/low/high/high

42:  Beginning of Loop (P87)
 1: 1        Delay
 2: 0        Loop Count

43:  Timer (P26)
 1: 99       Loc [ _________ ]

44:  If (X<=>F) (P89)               ! fire heater for just 0.75 s
 1: 99       X Loc [ _________ ]
 2: 3        >=
 3: .75      F                 ! change as required
 4: 31       Exit Loop if True

45:  End (P95)

46:  Set Port(s) (P20)
 1: 0        C8..C5 = low/low/low/low
 2: 0        C4..C1 = low/low/low/low

47:  Beginning of Loop (P87)
 1: 1        Delay
 2: 0        Loop Count

48:  Timer (P26)
 1: 99       Loc [ _________ ]
```

```
49:  If (X<=>F) (P89)         ! wait 10 s before making a Tz measure
 1: 99       X Loc [ __________ ]
 2: 3        >=
 3: 10       F                 ! change as required
 4: 15       Set Flag 5 High

50:  If Flag/Port (P91)
 1: 15       Do if Flag 5 is High
 2: 31       Exit Loop if True

51:  End (P95)

52:  Do (P86)
 1: 22       Set Flag 2 Low

53:  End (P95)

54:  Batt Voltage (P10)       ! store battery voltage in loc 98
 1: 98       Loc [ __________ ]

*Table 2 Program
  01: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

*Table 2 Program
 02: 0.0000   Execution Interval (seconds)

*Table 3 Subroutines

End Program