023/CO2 BOWEN RATIO SYSTEM WITH CO2 FLUX
INSTRUCTION MANUAL

REVISION: 4/98

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023/CO2 BOWEN RATIO SYSTEM WITH CO2 FLUX
TABLE OF CONTENTS

PAGE

SECTION 1. SYSTEM OVERVIEW

SECTION 2. LI-6262 INSTALLATION

SECTION 3. STATION INSTALLATION

SECTION 4. SAMPLE 023/CO2 PROGRAM

SECTION 5. STATION OPERATION

SECTION 6. CALCULATING FLUXES USING SPLIT

APPENDIX

TABLES

FIGURES

SECTION 1. SYSTEM OVERVIEW

1.1 REVIEW OF THEORY

By analogy with molecular diffusion, the flux-gradient approach to vertical transport of an entity from or to a surface assumes steady diffusion of the entity along its mean vertical concentration gradient.

When working within a few meters of the surface, the water vapor flux density, sensible heat flux, and carbon dioxide flux density, E, H, and F_c may be expressed as:

$$E = k_v \frac{\partial \rho_v}{\partial z} \tag{1}$$

$$H = \rho C_p k_H \frac{\partial T}{\partial z} \tag{2}$$

$$F_c = k_c \frac{\partial \rho_c}{\partial z} \tag{3}$$

where ρ_v is vapor density, ρ is air density, ρ_c is carbon dioxide density, C_p is the specific heat of air, T is temperature, z is height, and k_v, k_H, and k_c are the eddy diffusivities for vapor, heat, and carbon dioxide respectively. Air density and the specific heat of air should account for the presence of water vapor. The eddy diffusivities are functions of height. The vapor and temperature gradients reflect temporal and spatial averages.

Applying the Universal Gas Law to Eq. (1), and using the latent heat of vaporization, λ, the latent heat flux density, L_e, can be written in terms of mole fraction of water vapor (w).

$$L_e = \lambda k_v \frac{PM_v}{TR} \frac{\partial w}{\partial z} \tag{4}$$

Here P is atmospheric pressure, R is the universal gas constant, and M_v is the molecular weight of water. Similarly, Eq. (3) can be written as:

$$F_c = k_c \frac{PM_c}{TR} \frac{\partial c}{\partial z} \tag{5}$$

where c is the mole fraction of carbon dioxide and M_c is the molecular weight of carbon dioxide.

In practice, finite concentration gradients are measured and an effective eddy diffusivity assumed over the vertical gradient:

$$L_e = \lambda k_v \frac{PM_v}{TR} \frac{(w_2 - w_1)}{(z_1 - z_2)} \tag{6}$$

$$H = \rho C_p k_H \frac{(T_2 - T_1)}{(z_1 - z_2)} \tag{7}$$

$$F_c = k_c \frac{PM_c}{TR} \frac{(c_2 - c_1)}{(z_1 - z_2)} \tag{8}$$

where the subscripts 1 and 2 refer to the upper and lower arms respectively.

In general, k_v and k_H are not known but under specific conditions are assumed equal. The ratio of H to L_e is then used to partition the available energy at the surface into sensible and latent heat flux. This technique was first proposed by Bowen (1926). The Bowen ratio, β, is obtained from Eq. (6) and Eq. (7),

$$\beta = \frac{H}{L_e} = \frac{C_p}{\lambda \varepsilon} \frac{(T_2 - T_1)}{(w_2 - w_1)} \tag{9}$$

where ε is the ratio of the molecular weight of water vapor to dry air. The surface energy budget is given by,

$$R_n - G = H + L_e, \tag{10}$$

where R_n is net radiation for the surface and G is the total soil heat flux. R_n and F_c are positive into the surface and G, H, and L_e are positive away from the surface. Substituting βL_e for H in Eq. (10) and solving for L_e yields:

$$L_e = \frac{R_n - G}{1 + \beta}. \tag{11}$$

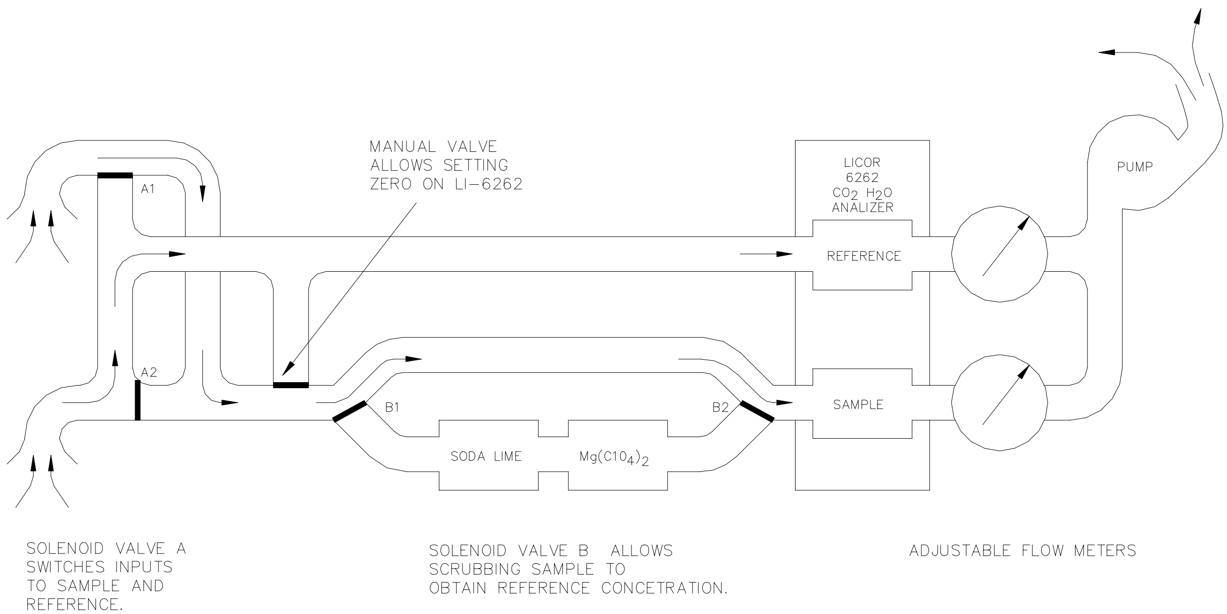


FIGURE 1.2-1 Vapor Measurement System

Sensible heat flux is found by substituting Eq. (11) into Eq. (10) and solving for H.

$$H = R_n - G - LE \qquad (12a)$$

$$H = R_n - G - \left[\frac{R_n - G}{1 + \beta} \right] \qquad (12b)$$

If the eddy diffusivity for carbon dioxide, k_c, is assumed equal to k_v (k_H), F_c can be found using Eq. (13) and (8).

$$k_c = \frac{(z_1 - z_2)}{(T_2 - T_1)} \frac{H}{\rho C_p} \qquad (13)$$

Measurements of R_n and G, and the gradients of w, T, and c are required to estimate latent and sensible heat, and carbon dioxide flux.

Atmospheric pressure is also a necessary variable, however, it seldom varies by more than a few percent. It may be calculated for the site, assuming a standard atmosphere, or obtained from a nearby station and correcting for any elevation difference.

The following equation can be used to estimate the site pressure if the elevation is known:

$$P = 101325 \left[1 - \frac{E}{44307.69231} \right]^{5.25328} \qquad (14)$$

where P is in kPa and the elevation, E, is in meters (Wallace and Hobbes, 1977).

Eq. (9) shows that the sensitivity of β is directly related to the measured gradients; a 1% error in a measurement results in a 1% error in β.

When the Bowen ratio approaches -1, the calculated fluxes approach infinity. Fortunately, this situation usually occurs during early morning and late evening when the flux changes direction and there is little available energy, R_n - G. In practice, when β is close to -1 (e.g., $-1.25 < \beta < -0.75$), L_e and H are assumed to be negligible and are not calculated. Ohmura (1982) describes an objective method for rejecting erroneous Bowen ratio data.

1.2 SYSTEM DESCRIPTION

1.2.1 WATER VAPOR AND CARBON DIOXIDE MEASUREMENTS

Carbon dioxide and water vapor concentrations are measured with a single Infrared Gas Analyzer (Model LI-6262, LI-COR Inc., Lincoln, NE) (IRGA), using a technique developed for multiple level gradient studies (Lemon, 1960). Air samples from two heights are routed to the IRGA (Figure 1.2-1). The IRGA continuously measures the gradient between the two levels.

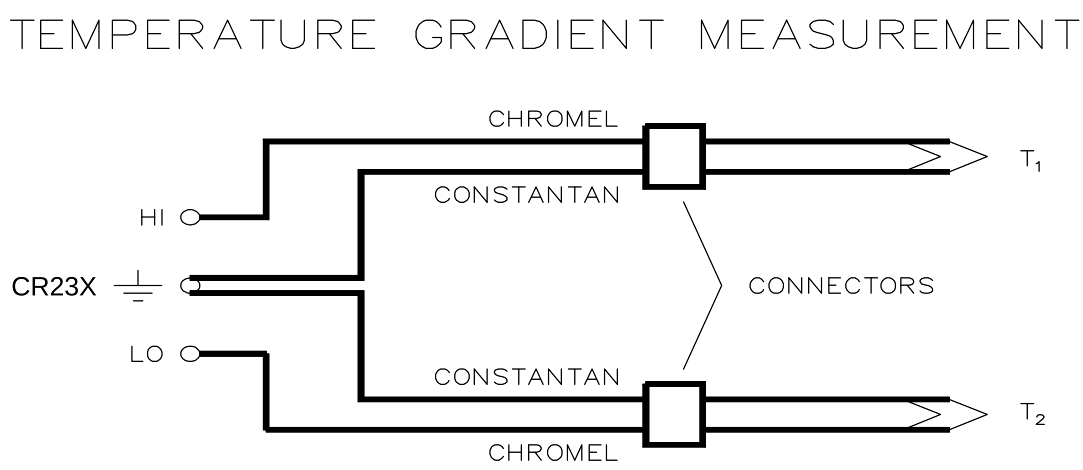


FIGURE 1.2-2. Thermocouple Configuration

Inverted Teflon filters (Gelman, ACRO50) with a 1 µm pore size prevent dust contamination of lines and IRGA. They also prevent liquid water from entering the system.

A single low power DC pump aspirates the system. Manually adjustable flow meters are used to adjust and match the flow rates. A flow rate of 0.4 liters/minute is recommended. A CR23X datalogger measures all sensors and controls the valves that switch air streams through the IRGA.

Every two minutes the air drawn through the IRGA is reversed with the first valve. Forty seconds is allowed for the pump to purge the IRGA. One minute and 20 seconds of measurements are made and averaged for each two minute cycle.

The carbon dioxide and water vapor gradients are measured every second. The average carbon dioxide and water vapor gradients are calculated every 20 minutes. At the top of every hour the sample cell in the IRGA is scrubbed of carbon dioxide and water vapor. The absolute concentration of carbon dioxide and water vapor is then measured by the IRGA.

1.2.2 AIR TEMPERATURE MEASUREMENT

The air temperature gradient is measured with fine wire chromel–constantan thermocouples. The thermocouples are wired into the datalogger such that the temperature gradient is measured differentially (Figure 1.2-2). The differential voltage is due to the difference in temperature between T_1 and T_2 and has no inherent sensor offset error. The datalogger resolution is 0.006°C with 0.1 µV rms noise.

The thermocouples are not aspirated. Calculations indicate that a 25 µm (0.001 in) diameter thermocouple experiences less than 0.2°C and 0.1°C heating at 0.1 m s^{-1} and 1 m s^{-1} wind speeds, respectively, under 1000 W m^{-2} solar radiation (Tanner, 1979). More importantly, error in the gradient measurement is due only to the difference in the radiative heating of the two thermocouple junctions. The physical symmetry of the thermocouple junction minimizes this error. Conversely, contamination of only one junction can cause large errors. A pair of 76 µm (0.003 in) thermocouples with two parallel junctions at each height are used to make the temperature gradient measurement

Applying temperature gradients to the thermocouple connectors was found to cause offsets. The connector mounts were designed with radiation shields and thermal conductors to minimize gradients.

1.2.3 NET RADIATION AND SOIL HEAT FLUX

Net radiation and soil heat flux are averaged over the same time period as the water vapor, temperature, and carbon dioxide gradient.

To measure soil heat flux, heat flux plates are buried in the soil at a depth of eight centimeters. The average temperature of the soil layer above the plate is measured using four parallel thermocouples. The heat flux at the surface is then calculated by adding the heat flux measured by the plate to the energy stored in the soil layer. The storage term is calculated by multiplying the change in soil temperature over the averaging period by the soil heat capacity.

1.2.4. POWER SUPPLY

The current requirements of the components of the 023/CO2 Bowen Ratio system are given in Table 1.2-1.

TABLE 1.2-1. Component Power Requirements

COMPONENT	CURRENT at 12 VDC
LI-6262	1000 mA
Pump	60 mA
CR23X	5 mA

Two large solar panels (60 watts or greater) and a 70 amp-hour battery are capable of providing a continuous current of 1.1 A, assuming 1000 Wm^{-2} of incoming solar radiation for 12 hours a day. The solar panels are required to keep a full charge on the battery. The voltage of the battery must be monitored by the station operator. Do not allow the battery voltage to fall below 11 VDC. If the battery voltage falls below 11 VDC, the IRGA will shut down. The station operator must then manually reset the IRGA by turning the power switch (on the front panel) off and then on. A datalogger control port is used to control power to the pump via relays.

SECTION 2. LI-6262 INSTALLATION

This section describes how the LI-6262 Infrared Gas Analyzer is integrated into the 023/CO2 enclosure.

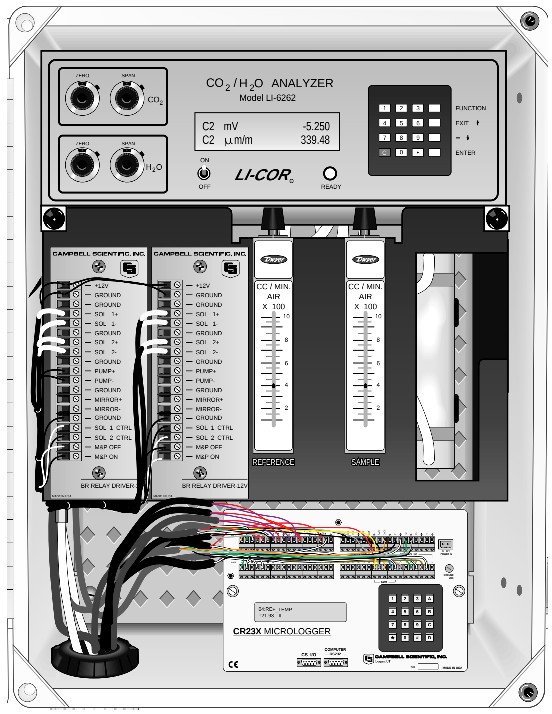


FIGURE 2-1. 023/CO2 Bowen Ratio System

2.1 ANALYZER PREPARATION

The LI-6262 has two inline Balston filters inside the analyzer, ahead of the reference and sample cells. These filters have high flow rates with low back pressure. However, they have a time constant of about a minute. To decrease the time constant of the analyzer, replace the Balston filters with tubing. The ACRO50 filters installed on the Bowen Ratio arms will provide sufficient filtration for the LI-6262. Section 7.5 of the LI-6262 manual provides more information on removing the Balston filters.

> **CAUTION:** Never operate the LI-6262 without adequate filtration ahead of the reference and sample cells.

2.2 INITIAL SETUP

The LI-6262 is mounted on top of the black bracket inside the 023/CO2 enclosure. It is held in place by two mounting rails that are attached to the bottom of the analyzer by four pan head screws (Figure 2.2-1). It may be necessary to relocate the rubber feet of the LI-6262 so they do not interfere with the black mounting bracket.

The 023/CO2 Bowen Ratio system requires that the LI-6262 operate in differential mode (see the LI-6262 manual for details). In this mode carbon dioxide and water vapor are scrubbed on the chopper input.

Prepare a soda lime and desiccant tube, as described in Section 7.4 of the LI-6262 manual. The bevaline tube that connects the soda lime and desiccant tube to the LI-6262 chopper must be replaced with longer tubes, to accommodate mounting the desiccant tube to the enclosure backplate. Attach the bottom hose (nearest the soda lime) to the FROM CHOPPER fitting and the top hose (nearest the perchlorate) to the TO CHOPPER fitting (Figure 2.2-2). Install the tube in the enclosure using the two clips mounted on the left side of the backplate.

Every hour the sample cell of the analyzer is scrubbed of carbon dioxide and water vapor with external soda lime and desiccant tubes. The absolute concentration of carbon dioxide and water vapor is then measured by the analyzer. The soda lime and desiccant tubes are plumbed in series and are integrated into the system with a pair of quick connect connectors.

Fill the tube with the female connector with soda lime and the tube with the male connector with magnesium perchlorate. Plumb the tubes as shown in Figure 2.2-3. The tubes are attached to the backplate with two pair of clips.

The analyzer's analog output is connected to the CR23X datalogger with the 023/CO2 signal cable. Table 2.2-1 describes the connections on the analyzer end of the signal cable. Table 3.3-1 (Section 3) describes the connections on the CR23X end of the cable.

TABLE 2.2-1. LI-6262 Analog Output Connections

COLOR	CONNECTION	CHANNEL
BLACK	SIG GND	8
GREEN	CO2 0.1 SEC	9
WHITE	H2O 0.1 SEC	11
RED	TEMP 5V	13
CLEAR	CHASSIS GND	16

After the analyzer is plumbed and wired into the 023/CO2 system and the mounting rails are fastened to the analyzer, slide the analyzer over the black bracket as shown in Figure 2.2-1. Line the push buttons with the holes on either side of the bracket and press firmly until the analyzer is seated on the bracket. Push the buttons in until a click is heard and LI-6262 is securely attached to the black bracket.

NOTE: The analyzer fits snugly within the fiberglass enclosure. The zero and span knobs will make contact with the inside of the enclosure lid. With time, four black rings will appear on the lid. The zero and span knobs are not exposed to any excessive stress when the lid is closed and latched.

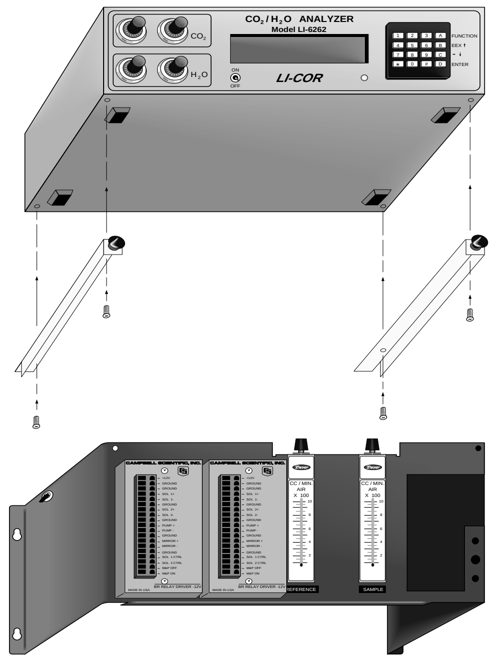


FIGURE 2.2-1. LI-6262 and Mounting Hardware

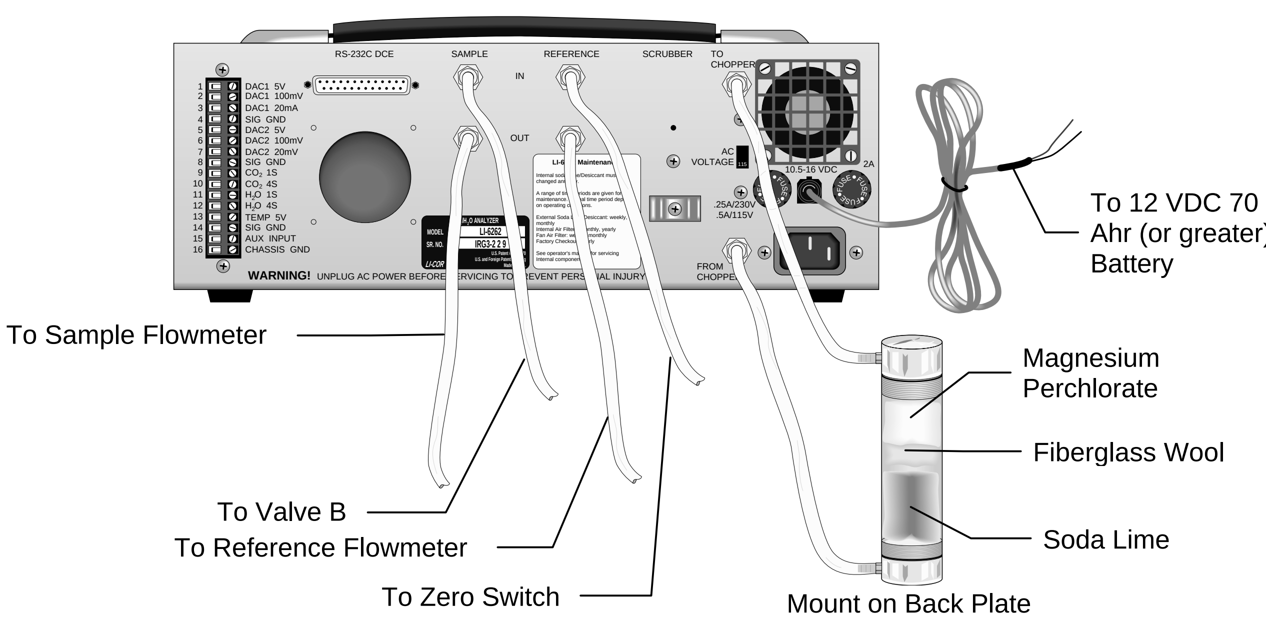


FIGURE 2.2-2. Plumbing Inputs

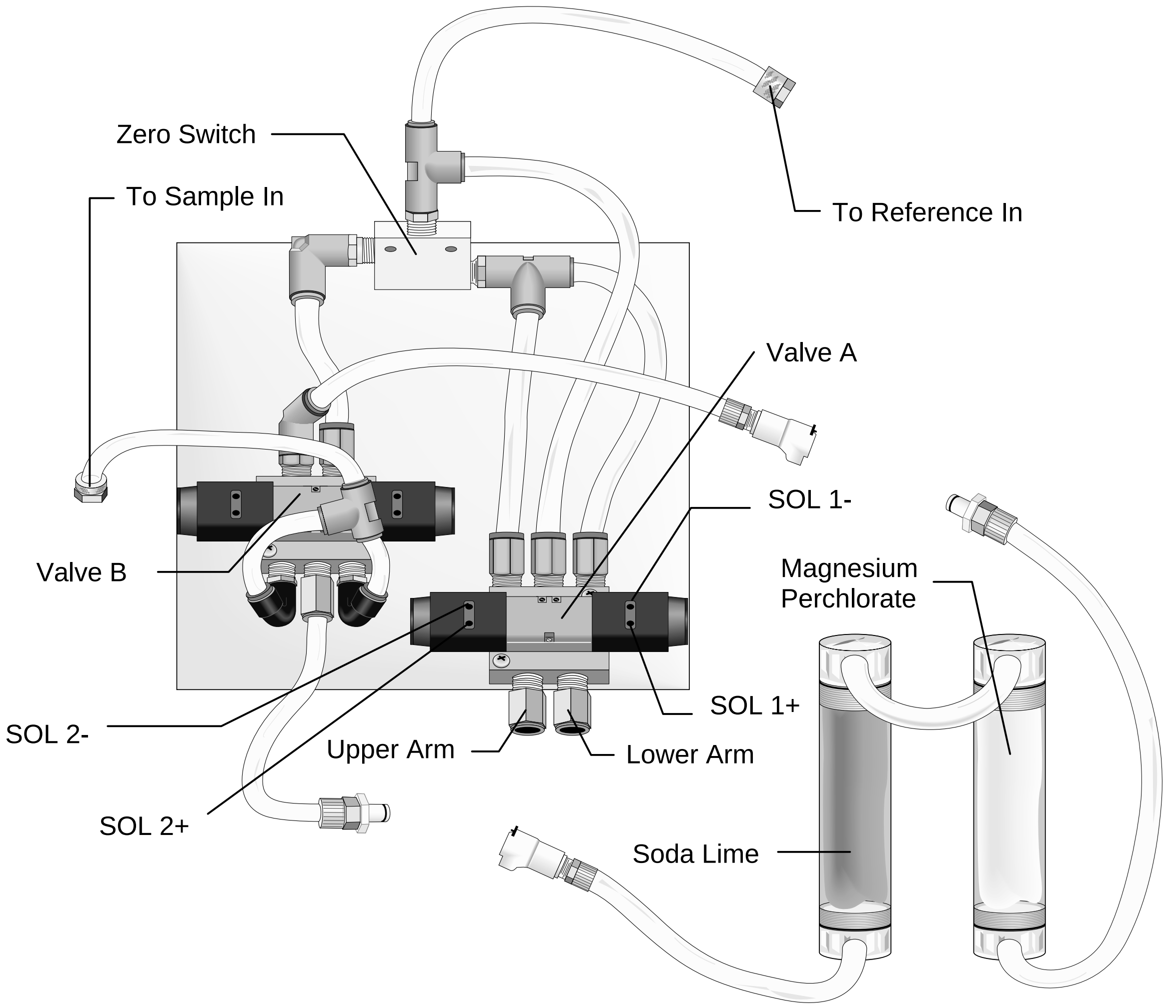


FIGURE 2.2-3. 023/CO2 Plumbing, Valves, and Soda Lime and Desiccant Tubes

SECTION 3. STATION INSTALLATION

Figure 3-1 shows the typical 023/CO2 system installed on a CM10 tripod. The 023/CO2 enclosure and mounting arms mount to the tripod mast (1 1/2 in. pipe) with U-bolts. The size of the tripod allows the heights of the arms to be adjusted from 0.5 to 3 meters. The mounting arms should be oriented due south to avoid partial shading of the thermocouples.

Two solar panels (60 watts or greater) are mounted on a separate tripod or A-frame (not provided by Campbell Scientific). The net radiometer is mounted on a separate stake (not provided by Campbell Scientific). It should be positioned so that it is never shaded by the tripod and mounting hardware, and such that the mounting hardware is not a significant portion of its field of view.

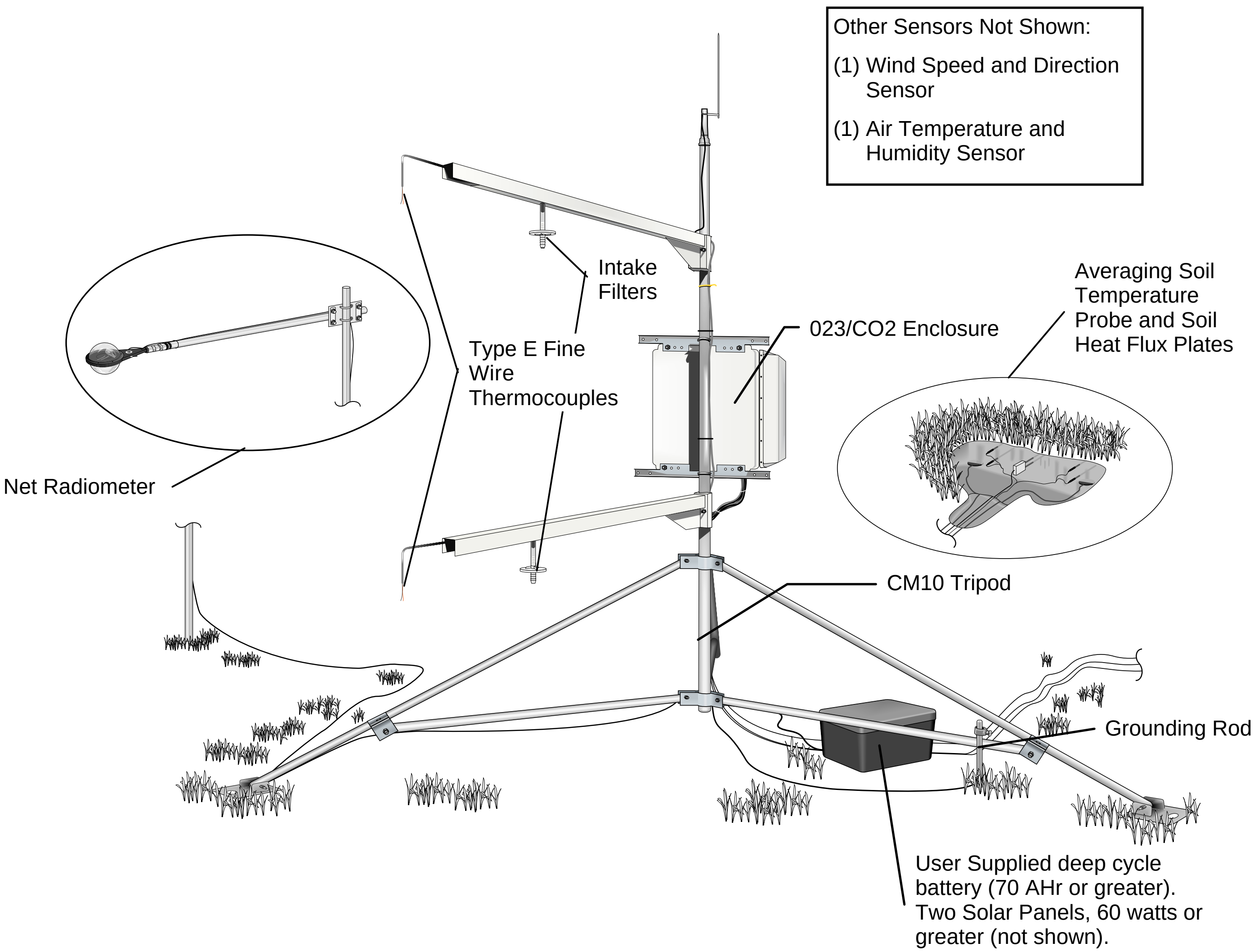


FIGURE 3-1. 023/CO2 Bowen Ratio System with CO_2 Flux

3.1 SENSOR HEIGHT AND SEPARATION

There are several factors which must be balanced against each other when determining the height at which to mount the support arms for the thermocouples and air intakes.

The differences in moisture, temperature, and carbon dioxide increase with height, thus the resolution of the gradient measurements improves with increased separation of the arms.

The upper mounting arm must be low enough that it is not sampling air that is coming from a different environment up wind. The air that the sensors see must be representative of the soil/vegetation that is being measured. As a rule of thumb, the surface being measured should extend a distance upwind that is **at least** 100 times the height of the sensors. The following references discuss fetch requirements in detail: Brutsaert (1982); Dyer and Pruitt (1962); Gash (1986); Schuepp, et al. (1990); and Shuttleworth (1992).

The lower mounting arm needs to be higher than the surrounding vegetation so that the air it is sampling is representative of the bulk crop surface, and not a smaller surface i.e. do not place the lower arms in between the rows of a row crop like sorghum.

The example SPLIT parameter file that calculates the surface fluxes assumes a 1.0 meter arm separation. If your station is installed with an arm separation other than 1.0 meter, measure and note the separation. Be sure to change the arm separation, DZ, in the SPLIT parameter file CALBRC.PAR.

3.2 SOIL THERMOCOUPLES AND HEAT FLUX PLATES

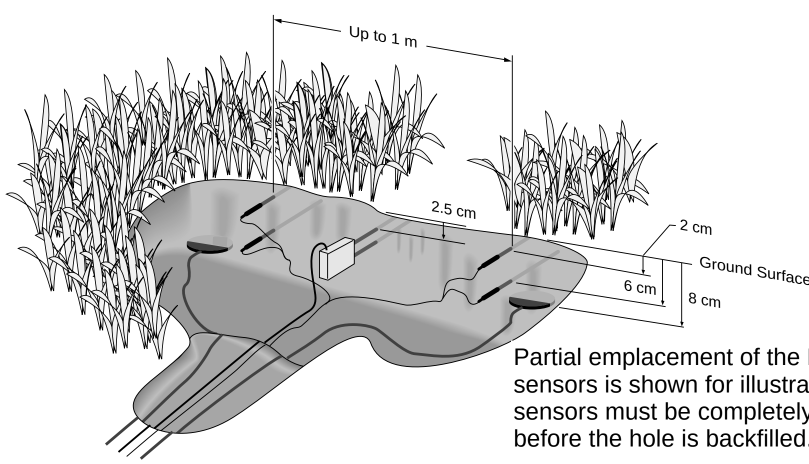
The soil thermocouples and heat flux plates are installed as shown in Figure 3.2-1. The TCAV parallels four thermocouples together to provide the average temperature, see Figure 3.2-2. It is constructed so that two thermocouples can be used to obtain the average temperature of the soil layer above one heat flux plate and the other two above the second plate. The thermocouple pairs may be up to two meters apart.

The location of the two heat flux plates and thermocouples should be chosen to be representative of the area under study. If the ground cover is extremely varied, it may be necessary to have additional sensors to provide a valid average.

Use a small shovel to make a vertical slice in the soil and excavate the soil to one side of the slice. Keep this soil intact so that it can be replaced with minimal disruption.

The sensors are installed in the undisturbed face of the hole. Measure the sensor depths from the top of the hole. Make a horizontal cut eight cm below the surface with a knife into the undisturbed face of the hole and insert the heat flux plate into the horizontal cut. Press the stainless steel tubes of the TCAVs above the plates as shown in Figure 3.2-1. When removing the thermocouples, grip the tubing, not the thermocouple wire.

Install the CS615 as shown in Figure 3.2-1. See the CS615 manual (Section 5) for detailed installation instructions.



Partial emplacement of the HFT3 and the TCAV sensors is shown for illustration purposes. All sensors must be completely inserted into the soil face before the hole is backfilled.

FIGURE 3.2-1. Placement of Thermocouples and Heat Flux Plates

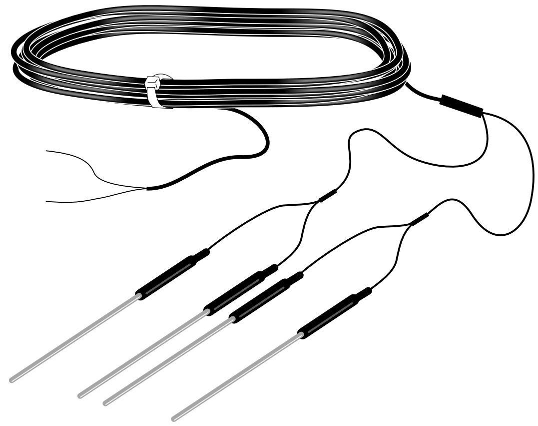


FIGURE 3.2-2. TCAV Spatial Averaging Thermocouple Probe

Never run the leads directly to the surface. Rather, bury the sensor leads a short distance back from the hole to minimized thermal conduction on the lead wires. Replace the excavated soil back into its original position after the TCAVs are installed.

Finally, wrap the thermocouple wire around the CR23X base at least twice before wiring them into the terminal strip. This will minimized thermal conduction into the terminal strip. After all the connections are made, replace the terminal strip cover.

3.3 WIRING

Table 3.3-1 lists the connections to the CR23X for the standard 023/CO2 system using the example program in Section 4. Because the air temperature measurements are so critical, the air temperature thermocouples are connected to channel 4 (the channel that is closest to the reference temperature thermistor). The input terminal strip cover for the CR23X must be installed once all connections have been made and verified (Section 13.4.1 of the CR23X manual).

Finally, wrap the thermocouple wire around the CR23X base at least twice before wiring them into the terminal strip. This will minimized thermal conduction into the terminal strip. After all the connections are made, replace the terminal strip cover.

3.4 BATTERY CONNECTIONS

Two terminal strip adapters for the battery posts (P/N 4386) are provided with the 023/CO2 (Figure 3.4-1). These terminal strips will mount to the wing nut battery posts on most deep cycle lead acid batteries.

The solar panels (60 watts or greater), BR relay driver, LI-6262, and CR23X each have separate power cables. Once the system is installed, these power cables are then connected to the external battery (red to positive, black to negative). The CR23X power cable is shipped in the 023/CO2 enclosure and must be connected to the +12V (red from power cable) and ground (black from power cable) terminals on the CR23X wiring panel.

Several deep cycle batteries can be connected in parallel, to provide power to the system during cloudy or overcast days.

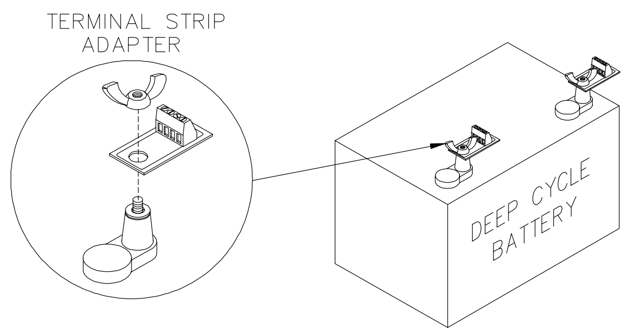


FIGURE 3.4-1. Terminal Strip Adapters for Connections to Battery

The LI-6262 can not be turned on and off with relays without a hardware modification to the power board (contact LI-COR for details). After the hardware modification has been made. A Crydom D1D07 (P/N 7321) can be used to power the LI-6262. The control side of the D1D07 can be operated by a BR relay driver. Do not power the LI-6262 through the BR relay driver, because there is a 0.8 V drop through it and the high current drain of the LI-6262 may create an offset in single ended measurements.

TABLE 3.3-1. CR23X/Sensor Connections for Example Program

CHANNEL	SENSOR	COLOR
1H	Q7.1	RED
1L	Q7.1	BLACK
≑	Q7.1	CLEAR
2H	CS615	GREEN
2L	WIND DIRECTION	RED
≑	CS615	BLACK/CLEAR
	WIND DIRECTION	WHITE/CLEAR
3H	TCAV	PURPLE
3L	TCAV	RED
≑	TCAV	CLEAR
4H	UPPER 0.003 TC - CHROMEL	PURPLE
4L	LOWER 0.003 TC - CHROMEL	PURPLE
≑	AIR TEMP TCs - CONSTANTAN	RED/RED
5H	HFT3 #1	BLACK
5L	HFT3 #1	WHITE
≑	HFT3 #1	CLEAR
6H	HFT3 #2	BLACK
6L	HFT3 #2	WHITE
≑	HFT3 #3	CLEAR
7H	LI-6262 (CO2 0.1 Second)	GREEN
7L	LI-6262 (Signal low)	BLACK
≑		
8H	LI-6262 (H2O 0.1 Second)	WHITE
8L	LI-6262 (Jumper to 6L)	BLACK
≑		
9H	LI-6262 (Analyzer Temperature)	RED
9L	LI-6262 (Jumper to 7L)	BLACK
≑	LI-6262 (Ground)	CLEAR
10H	HMP45C (Temperature)	YELLOW
10L	HMP45C	PURPLE
≑		CLEAR
11H	HMP45C (Relative Humidity)	BLUE
11L	JUMPER TO 10L	JUMPER TO 10L
≑		
P1	WIND SPEED	BLACK
GND	WIND SPEED	WHITE/CLEAR
EX2	WIND DIRECTION	BLACK
+12 V	CS615	RED
+12 V	HMP45C	RED
G	HMP45C	BLACK
+5 V	HMP45C	ORANGE
C1	PULSE FOR LOWER ARM TO REFERENCE	
	AND UPPER ARM TO SAMPLE	ORANGE w/ WHITE
C2	PULSE FOR UPPER ARM TO REFERENCE	
	AND LOWER ARM TO SAMPLE	BLUE w/ WHITE
C3	PULSE TO END SCRUB	WHITE w/ ORANGE
C4	PULSE TO SCRUB	WHITE w/ BLUE

C5	PULSE TO **TURN ON PUMP** (SET FLAG 5 AND 6; RESET FLAG 5)	GREEN w/ WHITE WHITE w/ GREEN
C6	PULSE TO **TURN OFF PUMP** (SET FLAG 5; RESET FLAG 6 AND 5)	BROWN w/ WHITE WHITE w/ BROWN
C7	CS615 (Control)	ORANGE
G	GROUND WIRE	CLEAR

SECTION 4. SAMPLE 023/CO2 PROGRAM

4.1 PROGRAM DETAILS

4.1.1 SCRUBBING THE SAMPLE CELL

The signal from the analyzer is proportional to the difference in concentration between the reference and sample cells. If the reference concentration, C_r, is known, the absolute concentration in the sample cell can be found using the relationship below,

$$C_S = f\left[\left(VG + V_r\right)\frac{P_o}{P}\right]\frac{T}{T_o} \qquad (15)$$

where the function f is a fifth order polynomial of the form

$$f(V) = AV + BV^2 + CV^3 + DV^4 + EV^5 \qquad (16)$$

with coefficients A, B, C, D, and E that are unique to each analyzer, C_S is the gas concentration in the sample cell, V is the analyzer output, V_r is the signal output from the analyzer if there was zero concentration in the reference cell and a known concentration, C_r, in the sample cell, T and T_o are the analyzer temperature and calibration temperature, P and P_o are the ambient and calibration (sea level) pressures, and G is given by:

$$G = \frac{K - V_r}{K} \qquad (17)$$

where K is a calibration constant.

Every hour the sample cell is scrubbed of carbon dioxide and water vapor. The absolute concentration of carbon dioxide and water vapor can then be calculated. Scrubbing the sample cell and leaving the reference cell at ambient avoids the zero offset shift that occurs when the concentration in the reference cell changes.

The equations presented in the LI-6262 manual are for the case when the concentration in the reference cell is known (scrubbed) and the concentration in sample cell is unknown. Since the 023/CO2 system scrubs the sample cell, the equations must be reformulated.

When the sample cell is scrubbed the concentration C_S in Eq. (13) is equal to zero and the following is true,

$$VG + V_r = 0 \qquad (18)$$

$$V_r = -VG. \qquad (19)$$

Substituting Eq. (17) into (15) and solving for G yields the relationship below.

$$G = \frac{K}{K - V} \qquad (20)$$

Now substitute Eq. (18) into (17).

$$V_r = -\frac{VK}{K - V} \qquad (21)$$

V_r is the signal the analyzer would output if the reference cell was scrubbed instead of the sample cell. The value found from Equation (21) is used in the fifth order polynomial to find the absolute concentration of carbon dioxide and water vapor. New values of V_r and G are calculated every hour and used in measuring the carbon dioxide and water vapor gradient.

The absolute concentration of water vapor and carbon dioxide are not corrected for T/To online. Thus, during a scrub, the absolute concentrations displayed by the LI-6262 will differ by a factor of T/To to those calculated by the CR23X.

4.1.2 COEFFICIENTS

The unique calibration coefficients for the LI-6262 must be entered in the CR23X program. The calibration temperature (Kelvins) and K coefficients are entered in Subroutine 1. The polynomial coefficients A (C1), B (C2), C (C3), D (C4), and E (C5) are entered in Subroutine 7.

The magnitude of the coefficients that can be entered into the polynomial instruction (Instruction 55) is 0.00001 to 99999. Since the coefficients are outside this range, they must be prescaled. The input to the polynomial is multiplied by 10^{-3} by the first instruction in Subroutine 7. The coefficients, as they are given by LI-COR, must be transformed in order to enter them into the program. To perform the carbon dioxide and water vapor coefficient transformation; multiply the A (C1) coefficient by 10^3, the B (C2) coefficient by 10^6, the C (C3) coefficient by 10^9, the D (C4) coefficient by 10^{12}, and the E (C5) coefficient by 10^{15}. Table 4.1-1 provides and example of how to transform typical LI-6262 water vapor coefficients.

TABLE 4.1-1. Example LI-6262 Carbon Dioxide Coefficients

Coefficient (LI-COR)	LI-6262	Multiply by	CR23X	Coefficient (CSI)
A	0.15053	10^3	150.53	C1
B	7.0875×10^{-6}	10^6	7.0875	C2
C	8.4794×10^{-9}	10^9	8.4794	C3
D	-1.1482×10^{-12}	10^{12}	-1.1482	C4
E	7.5212×10^{-17}	10^{15}	0.07512	C5

4.2 CR23X PROGRAM

A copy of the example program for the CR23X is available on the Campbell Scientific ftp site at ftp://ftp.campbellsci.com/pub/outgoing/files/br_co2.exe. Br_co2.exe is a self extracting file. At a DOS prompt, type in br_co2.exe and press the <enter> key. Use EDLOG to edit the example program. Table 4.2-2 lists the outputs from the example program.

TABLE 4.2-1. Example Datalogger Program

```
;{CR23X}
;
;c:\dl\co2\co2feb98.csi
;23 February 1998

;Example CR23X program for the 023/CO2 Bowen ratio system w/ CO2 Flux.

;Flag 1 -  When HIGH stops averaging during scrubbing or manual
;          control of flow valves. When LOW Subroutine 1 loads
;          constants.
;Flag 2 -  When HIGH the upper arm is routed into the sample input
;          and the lower arm into the reference, when LOW the
;          upper arm is routed into the reference and the lower
;          arm into the sample.
;Flag 3 -  When HIGH timing out for forty seconds after switching
;          upper and lower levels.
;Flag 4 -  Is set HIGH during automatic and manual scrub.
;Flag 5 -  When HIGH allows manual control of flow valves and turning
;          the pump on and off. Use Flag 2 to toggle the valve
;          and Flag 6 to operate the pump.
;Flag 6 -  When HIGH the pump is on, When LOW the pump is off.
;Flag 7 -  Used in Subroutine 7 to determine which polynomial to use.
;Flag 8 -  Set HIGH to perform a manual scrub.


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

;Make measurements.

01:  Internal Temperature (P17)
     1:    35      Loc [ refrnc    ]
```

```
02:   Thermocouple Temp (SE) (P13)
      1:      1      Reps
      2:     21      10 mV, 60 Hz Reject, Slow Range
      3:      8      In Chan
      4:      2      Type E (Chromel-Constantan)
      5:     35      Ref Temp Loc [ refrnc    ]
      6:     33      Loc [ lwr_TC    ]
      7:      1      Mult
      8:      0      Offset

03:   Thermocouple Temp (Diff) (P14)
      1:      1      Reps
      2:     21      10 mV, 60 Hz Reject, Slow Range
      3:      4      In Chan
      4:      2      Type E (Chromel-Constantan)
      5:     33      Ref Temp Loc [ lwr_TC    ]
      6:     32      Loc [ upr_TC    ]
      7:      1      Mult
      8:      0      Offset

04:   Z=X-Y (P35)
      1:     33      X Loc [ lwr_TC    ]
      2:     32      Y Loc [ upr_TC    ]
      3:     34      Z Loc [ del_TC    ]

05:   If Flag/Port (P91)
      1:     24      Do if Flag 4 is Low
      2:     30      Then Do

06:   Volt (Diff) (P2)
      1:      2      Reps
      2:     24      1000 mV, 60 Hz Reject, Slow Range
      3:      7      In Chan
      4:     10      Loc [ co2mV     ]
      5:      1      Mult
      6:      0      Offset

07:   If (X<=>F) (P89)
      1:     10      X Loc [ co2mV     ]
      2:      4      <
      3:   -500      F
      4:     30      Then Do

08:   Volt (Diff) (P2)
      1:      1      Reps
      2:     25      5000 mV, 60 Hz Reject, Fast Range
      3:      7      In Chan
      4:     10      Loc [ co2mV     ]
      5:      1      Mult
      6:      0      Offset

09:   End (P95)

;Compute CO2 and H2O gradient.
;
10:   Do (P86)
      1:      3      Call Subroutine 3              ;Analyzer Temperature
```

```
11:  Do (P86)
     1:   27       Set Flag 7 Low

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

13:  Z=X*Y (P36)
     1:   10--     X Loc [ co2mV     ]
     2:   26--     Y Loc [ G_co2     ]
     3:   41--     Z Loc [ co2mVinpt ]

14:  Z=X+Y (P33)
     1:   41--     X Loc [ co2mVinpt ]
     2:   24--     Y Loc [ Vr_co2_mV ]
     3:   41--     Z Loc [ co2mVinpt ]

15:  Do (P86)
     1:    7       Call Subroutine 7            ;Apply Polynomial

16:  Z=X-Y (P35)
     1:   28--     X Loc [ co2_uM    ]
     2:   21--     Y Loc [ co2ref_uM ]
     3:   30--     Z Loc [ del_co2   ]

17:  Z=X*Y (P36)
     1:   30--     X Loc [ del_co2   ]
     2:   18--     Y Loc [ Ta_To_co2 ]
     3:   30--     Z Loc [ del_co2   ]

18:  Do (P86)
     1:   17       Set Flag 7 High

19:  End (P95)

20:  Do (P86)
     1:    8       Call Subroutine 8            ;Move values and change sign

21:  Else (P94)

22:  Do (P86)
     1:    1       Call Subroutine 1            ;Scrub

23:  End (P95)

;If valves have just switched or the
;system is in manual control (Flag 5 High)
;set Flag 9 High.
;
24:  If Flag/Port (P91)
     1:   11       Do if Flag 1 is High
     2:   30       Then Do

25:  Do (P86)
     1:   19       Set Flag 9 High
```

```
26:   Else (P94)

27:   If Flag/Port (P91)
      1:      13        Do if Flag 3 is High
      2:      19        Set Flag 9 High

28:   End (P95)

;Generate gradient output array every twenty minutes.
;
29:   If time is (P92)
      1:       0        Minutes into a
      2:      20        Minute Interval
      3:      10        Set Output Flag High

30:   Set Active Storage Area (P80)
      1:       1        Final Storage
      2:      21        Array ID

31:   Real Time (P77)
      1:    1110        Year,Day,Hour/Minute

32:   Resolution (P78)
      1:       1        high resolution

33:   Average (P71)
      1:       5        Reps
      2:      36        Loc [ co2mVcorr ]

34:   Sample (P70)
      1:       7        Reps
      2:      21        Loc [ co2ref_uM ]

35:   Do (P86)
      1:      29        Set Flag 9 Low

36:   Average (P71)
      1:       3        Reps
      2:      33        Loc [ lwr_TC    ]

37:   Sample (P70)
      1:       2        Reps
      2:      62        Loc [ scb_Tao_C ]

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

39:   Do (P86)
      1:       2        Call Subroutine 2              ;Manual valve control

40:   Else (P94)
```

```
;Perform an automatic scrub at the top of
;the hour.
;
41:   If time is (P92)
      1:     0       Minutes into a
      2:    60       Minute Interval
      3:    14       Set Flag 4 High

42:   If Flag/Port (P91)
      1:    18       Do if Flag 8 is High
      2:    14       Set Flag 4 High

;Synchronize valve switching every four
;minutes.
;
43:   If time is (P92)
      1:     0       Minutes into a
      2:     4       Minute Interval
      3:    30       Then Do

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

45:   Do (P86)
      1:    42       Set Port 2 High

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

47:   Do (P86)
      1:    13       Set Flag 3 High

48:   Do (P86)
      1:     9       Call Subroutine 9          ;Set all ports LOW

49:   End (P95)

50:   If time is (P92)
      1:     2       Minutes into a
      2:     4       Minute Interval
      3:    30       Then Do

51:   Do (P86)
      1:    41       Set Port 1 High

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

53:   Do (P86)
      1:    13       Set Flag 3 High

54:   Do (P86)
      1:     9       Call Subroutine 9          ;Set all ports LOW

55:   End (P95)
```

```
56:   If time is (P92)
      1:     40--       Minutes (Seconds --) into a
      2:     60         Interval (same units as above)
      3:     23         Set Flag 3 Low

57:   End (P95)

58:   Serial Out (P96)
      1:     71         SM192/SM716/CSM1


*Table 2 Program
  01:                   10                          Execution Interval (seconds)

01:   Batt Voltage (P10)
      1:      9         Loc [ battry    ]

02:   Volt (Diff) (P2)
      1:      1         Reps
      2:     24         1000 mV, 60 Hz Reject, Slow Range
      3:     10         DIFF Channel
      4:      1         Loc [ HMP_T     ]
      5:       .1       Mult
      6:    -40         Offset

03:   Volt (Diff) (P2)
      1:      1         Reps
      2:     24         1000 mV, 60 Hz Reject, Slow Range
      3:     11         DIFF Channel
      4:      8         Loc [ rh_frac   ]
      5:       .001     Mult
      6:      0         Offset

04:   Saturation Vapor Pressure (P56)
      1:      1         Temperature Loc [ HMP_T     ]
      2:      2         Loc [ HMP_e     ]

05:   Z=X*Y (P36)
      1:      8         X Loc [ rh_frac   ]
      2:      2         Y Loc [ HMP_e     ]
      3:      2         Z Loc [ HMP_e     ]

06:   Z=X/Y (P38)
      1:      2         X Loc [ HMP_e     ]
      2:     23         Y Loc [ P_kPa     ]
      3:      3         Z Loc [ h2o_mM_M  ]

07:   Z=X*F (P37)
      1:      3         X Loc [ h2o_mM_M  ]
      2:   1000         F
      3:      3         Z Loc [ h2o_mM_M  ]
```

```
08:   Volt (Diff) (P2)
      1:      1       Reps
      2:     23       200 mV, 60 Hz Reject, Slow Range
      3:      1       DIFF Channel
      4:      4       Loc [ Rn      ]
      5:      1       Mult
      6:      0       Offset

09:   If (X<=>F) (P89)
      1:      4       X Loc [ Rn      ]
      2:      3       >=
      3:      0       F
      4:     30       Then Do

;Apply the positive calibration and
;wind speed corrections.
;
10:   Do (P86)
      1:      4       Call Subroutine 4

11:   Else (P94)

;Apply the negative calibration and
;wind speed corrections
;
12:   Do (P86)
      1:      5       Call Subroutine 5

13:   End (P95)

14:   Volt (Diff) (P2)
      1:      2       Reps
      2:     22       50 mV, 60 Hz Reject, Slow Range
      3:      5       DIFF Channel
      4:      5       Loc [ shf1    ]
      5:      1       Mult
      6:      0       Offset

;Enter the multiplier for soil heat flux
;number 1 (x.xxx1).
;
15:   Z=X*F (P37)
      1:      5       X Loc [ shf1    ]
      2:      1       F                          ;x.xxx1 <- unique value
      3:      5       Z Loc [ shf1    ]

;Enter the multiplier for soil heat flux
;number 2 (x.xxx2).
;
16:   Z=X*F (P37)
      1:      6       X Loc [ shf2    ]
      2:      1       F                          ;x.xxx2 <- unique value
      3:      6       Z Loc [ shf2    ]
```

```
17:    Thermocouple Temp (Diff) (P14)
       1:      1          Reps
       2:     21          10 mV, 60 Hz Reject, Slow Range
       3:      3          In Chan
       4:      2          Type E (Chromel-Constantan)
       5:     35          Ref Temp Loc [ refrnc    ]
       6:      7          Loc [ Ts        ]
       7:      1          Mult
       8:      0          Offset

;Turn on CS615 soil moisture probe every twenty minutes.
;
18:    If time is (P92)
       1:     10          Minutes into a
       2:     20          Minute Interval
       3:     30          Then Do

19:    Do (P86)
       1:     47          Set Port 7 High

;Measure CS615 soil moisture probe.  When the
;CS615 is off (Control Port 7 low), the values
;in CS615_ms and s_wtr will not change.
;
20:    Period Average (SE) (P27)
       1:      1          Reps
       2:      4          200 kHz Max Freq @ 500 mV Peak to Peak, Period Output
       3:      3          SE Channel
       4:     10          No. of Cycles
       5:      5          Timeout (units = 0.01 seconds)
       6:     64          Loc [ cs615_ms  ]
       7:        .001     Mult
       8:      0          Offset

;Turn the CS615 off.
;
21:    Do (P86)
       1:     57          Set Port 7 Low

;Apply the CS615 calibration for a soil
;with an electrical conductivity < 1.0 dS/m.
;See Section 9 of the CS615 manual for
;more information.
;
22:    Polynomial (P55)
       1:      1          Reps
       2:     64          X Loc [ cs615_ms  ]
       3:     67          F(X) Loc [ s_wtr     ]
       4:       -.187     C0
       5:        .037     C1
       6:        .335     C2
       7:      0          C3
       8:      0          C4
       9:      0          C5
```

```
23:   Z=X (P31)
      1:     64        X Loc [ cs615_ms  ]
      2:     68        Z Loc [ cs615_mso ]

24:   Z=X (P31)
      1:     67        X Loc [ s_wtr     ]
      2:     69        Z Loc [ s_wtr_o   ]

25:   End (P95)

26:   Pulse (P3)
      1:      1        Reps
      2:      1        Pulse Input Chan
      3:     21        Low Level AC, Output Hz
      4:     16        Loc [ wnd_spd   ]
      5:        .75    Mult
      6:        .2     Offset

27:   If (X<=>F) (P89)
      1:     16        X Loc [ wnd_spd   ]
      2:      1        =
      3:        .2     F
      4:     30        Then Do

28:   Z=F (P30)
      1:      0        F
      2:      0        Exponent of 10
      3:     16        Z Loc [ wnd_spd   ]

29:   End (P95)

30:   AC Half Bridge (P5)
      1:      1        Reps
      2:     25        5000 mV, 60 Hz Reject, Fast Range
      3:      4        In Chan
      4:      2        Excite all reps w/Exchan 2
      5:   5000        mV Excitation
      6:     17        Loc [ wnd_dir   ]
      7:    355        Mult
      8:      0        Offset

31:   If time is (P92)
      1:      0        Minutes into a
      2:     20        Minute Interval
      3:     10        Set Output Flag High

32:   Set Active Storage Area (P80)
      1:      3        Input Storage
      2:     13        Loc [ avg_Ts    ]

33:   Average (P71)
      1:      1        Reps
      2:      7        Loc [ Ts        ]

34:   If Flag/Port (P91)
      1:     10        Do if Output Flag is High (Flag 0)
      2:     30        Then Do
```

```
;Find the change in soil temperature.
;
35:   Z=X-Y (P35)
      1:      13          X Loc [ avg_Ts    ]
      2:      12          Y Loc [ prv_Ts    ]
      3:      14          Z Loc [ del_Ts    ]

36:   Z=X (P31)
      1:      13          X Loc [ avg_Ts    ]
      2:      12          Z Loc [ prv_Ts    ]

;Apply the temperature correction to
;the soil moisture measured by the CS615,
;if the soil temperature is in the range of
;10 degrees C to 30 degrees C. See Section
;4.3.4 of the CS615 manual for more information.
;
37:   If (X<=>F) (P89)
      1:      13          X Loc [ avg_Ts    ]
      2:       3          >=
      3:      10          F
      4:      30          Then Do

38:   If (X<=>F) (P89)
      1:      13          X Loc [ avg_Ts    ]
      2:       4          <
      3:      30          F
      4:      30          Then Do

39:   Z=X+F (P34)
      1:      13          X Loc [ avg_Ts    ]
      2:     -20          F
      3:      65          Z Loc [ D         ]

40:   Polynomial (P55)
      1:       1          Reps
      2:      69          X Loc [ s_wtr_o   ]
      3:      66          F(X) Loc [ E      ]
      4:         -.0346   C0
      5:       1.9        C1
      6:      -4.5        C2
      7:       0          C3
      8:       0          C4
      9:       0          C5

41:   Z=X*F (P37)
      1:      66          X Loc [ E         ]
      2:         .01      F
      3:      66          Z Loc [ E         ]

42:   Z=X*Y (P36)
      1:      65          X Loc [ D         ]
      2:      66          Y Loc [ E         ]
      3:      65          Z Loc [ D         ]
```

```
43:   Z=X-Y (P35)
      1:      69        X Loc [ s_wtr_o   ]
      2:      65        Y Loc [ D         ]
      3:      70        Z Loc [ s_wtr_o_T ]

44:   Else (P94)

;Do not apply temperature correction if the
;soil temperature is outside the range of
;10 degrees C to 30 degrees C.
;
45:   Z=X (P31)
      1:      69        X Loc [ s_wtr_o   ]
      2:      70        Z Loc [ s_wtr_o_T ]

46:   End (P95)

47:   Else (P94)

;Do not apply temperature correction if the
;soil temperature is outside the range of
;10 degrees C to 30 degrees C.
;
48:   Z=X (P31)
      1:      69        X Loc [ s_wtr_o   ]
      2:      70        Z Loc [ s_wtr_o_T ]

49:   End (P95)

50:   End (P95)

;Generate energy balance and meteorological
;output array every twenty minutes.
;
51:   If Flag/Port (P91)
      1:      10        Do if Output Flag is High (Flag 0)
      2:      10        Set Output Flag High

52:   Set Active Storage Area (P80)
      1:       1        Final Storage
      2:      22        Array ID

53:   Real Time (P77)
      1:    1110        Year,Day,Hour/Minute

54:   Resolution (P78)
      1:       1        High Resolution

55:   Average (P71)
      1:       6        Reps
      2:       1        Loc [ HMP_T     ]

56:   Sample (P70)
      1:       2        Reps
      2:      13        Loc [ avg_Ts    ]
```

```
57:  Sample (P70)
     1:      1      Reps
     2:      8      Loc [ rh_frac   ]

58:  Average (P71)
     1:      1      Reps
     2:      9      Loc [ battry    ]

59:  Wind Vector (P69)
     1:      1      Reps
     2:     60      Samples per Sub-Interval
     3:     00      S, qu, & s(qu) Polar
     4:     16      Wind Speed/East Loc [ wnd_spd   ]
     5:     17      Wind Direction/North Loc [ wnd_dir   ]

60:  Sample (P70)
     1:      3      Reps
     2:     68      Loc [ cs615_mso ]


*Table 3 Subroutines


;Scrub.

01:  Beginning of Subroutine (P85)
     1:      1      Subroutine 1

02:  If Flag/Port (P91)
     1:     21      Do if Flag 1 is Low
     2:     30      Then Do

;Enter the CO2 calibration
;temperature (Kelvin).
;
03:  Z=F (P30)
     1:      1      F                            ;To(CO2) <- unique value
     2:      0      Exponent of 10
     3:     54      Z Loc [ To_co2    ]

;Enter the H2O calibration
;temperature (Kelvin).
;
04:  Z=F (P30)
     1:      1      F                            ;To(H2O) <- unique value
     2:      0      Exponent of 10
     3:     55      Z Loc [ To_h2o    ]

;Enter the K coefficient for CO2.
;
05:  Z=F (P30)
     1:      1      F                            ;K(CO2) <- unique value
     2:      0      Exponent of 10
     3:     56      Z Loc [ K_co2     ]
```

```
;Enter the K coefficient for H2O.
;
06:   Z=F (P30)
      1:      1        F                               ;K(H2O) <- unique value
      2:      0        Exponent of 10
      3:     57        Z Loc [ K_h2o     ]

;Enter the local pressure in kPa.
;
07:   Z=F (P30)
      1:      1        F                               ;P(kPa) <- unique value
      2:      0        Exponent of 10
      3:     23        Z Loc [ P_kPa     ]

;Location 43 = Po/(P*1000)
;
08:   Z=F (P30)
      1:         .10132 F
      2:      0        Exponent of 10
      3:     43        Z Loc [ Po_P_1000 ]

09:   Z=X/Y (P38)
      1:     43        X Loc [ Po_P_1000 ]
      2:     23        Y Loc [ P_kPa     ]
      3:     43        Z Loc [ Po_P_1000 ]

10:   Do (P86)
      1:     11        Set Flag 1 High

;During first pass switch the upper arm
;into the reference cell, the lower arm
;into the sample cell, and set the
;scrub valve.
;
11:   Do (P86)
      1:     42        Set Port 2 High

12:   Do (P86)
      1:     44        Set Port 4 High

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

14:   Do (P86)
      1:      9        Call Subroutine 9               ;Set all ports LOW

15:   End (P95)

16:   Z=Z+1 (P32)
      1:     46        Z Loc [ scrub_ctr ]
```

```
17:   Volt (Diff) (P2)
      1:       2       Reps
      2:      25       5000 mV, 60 Hz Reject, Fast Range
      3:       7       In Chan
      4:      10       Loc [ co2mV     ]
      5:       1       Mult
      6:       0       Offset

18:   Do (P86)
      1:       3       Call Subroutine 3                ;Analyzer temperature

19:   If (X<=>F) (P89)
      1:      46       X Loc [ scrub_ctr ]
      2:       3       >=
      3:      50       F
      4:      10       Set Output Flag High

20:   Set Active Storage Area (P80)
      1:       3       Input Storage
      2:      10       Loc [ co2mV     ]

21:   If (X<=>F) (P89)
      1:      46       X Loc [ scrub_ctr ]
      2:       4       <
      3:      40       F
      4:      19       Set Flag 9 High

22:   Average (P71)
      1:       2       Reps
      2:      10       Loc [ co2mV     ]

23:   Do (P86)
      1:      27       Set Flag 7 Low

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

25:   Z=X-Y (P35)
      1:      56--     X Loc [ K_co2     ]
      2:      10--     Y Loc [ co2mV     ]
      3:      26--     Z Loc [ G_co2     ]

26:   Z=X/Y (P38)
      1:      56--     X Loc [ K_co2     ]
      2:      26--     Y Loc [ G_co2     ]
      3:      26--     Z Loc [ G_co2     ]

27:   Z=X*Y (P36)
      1:      26--     X Loc [ G_co2     ]
      2:      10--     Y Loc [ co2mV     ]
      3:      24--     Z Loc [ Vr_co2_mV ]

28:   Z=X*F (P37)
      1:      24--     X Loc [ Vr_co2_mV ]
      2:      -1       F
      3:      24--     Z Loc [ Vr_co2_mV ]
```

```
29:  Z=X (P31)
     1:    24--      X Loc [ Vr_co2_mV ]
     2:    41--      Z Loc [ co2mVinpt ]

30:  Do (P86)
     1:     7        Call Subroutine 7            ;Apply polynomial

31:  Z=X (P31)
     1:    28--      X Loc [ co2_uM    ]
     2:    21--      Z Loc [ co2ref_uM ]

32:  Z=X (P31)
     1:    18--      X Loc [ Ta_To_co2 ]
     2:    62--      Z Loc [ scb_Tao_C ]

33:  Do (P86)
     1:    17        Set Flag 7 High

34:  End (P95)

;During the autoscrub make one pass
;through the calculation.  During a
;manual scrub, pass through the
;calculation until Flag 8 is set Low.
;
35:  If Flag/Port (P91)
     1:    28        Do if Flag 8 is Low
     2:    30        Then Do

36:  If Flag/Port (P91)
     1:    10        Do if Output Flag is High (Flag 0)
     2:    30        Then Do

37:  Do (P86)
     1:    24        Set Flag 4 Low

38:  Z=F (P30)
     1:     0        F
     2:     0        Exponent of 10
     3:    46        Z Loc [ scrub_ctr ]

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

40:  Do (P86)
     1:     9        Call Subroutine 9            ;Set all ports LOW

41:  End (P95)

42:  End (P95)

43:  End (P95)

;Manual valve control.
```

```
44:  Beginning of Subroutine (P85)
     1:      2        Subroutine 2

45:  Do (P86)
     1:     11        Set Flag 1 High

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

47:  If Flag/Port (P91)
     1:     22        Do if Flag 2 is Low
     2:     42        Set Port 2 High

48:  If Flag/Port (P91)
     1:     16        Do if Flag 6 is High
     2:     45        Set Port 5 High

49:  If Flag/Port (P91)
     1:     26        Do if Flag 6 is Low
     2:     46        Set Port 6 High

50:  Do (P86)
     1:      9        Call Subroutine 9              ;Set all ports LOW

51:  End (P95)

;Analyzer temperature measurement.

52:  Beginning of Subroutine (P85)
     1:      3        Subroutine 3

53:  Volt (Diff) (P2)
     1:      1        Reps
     2:     25        5000 mV, 60 Hz Reject, Fast Range
     3:      9        In Chan
     4:     40        Loc [ T_Anlyzr  ]
     5:        .01221 Mult
     6:      0        Offset

54:  Z=X+F (P34)
     1:     40        X Loc [ T_Anlyzr  ]
     2:   273.15      F
     3:     53        Z Loc [ T_anlyr_K ]

55:  Z=X/Y (P38)
     1:     53        X Loc [ T_anlyr_K ]
     2:     54        Y Loc [ To_co2    ]
     3:     18        Z Loc [ Ta_To_co2 ]

56:  Z=X/Y (P38)
     1:     53        X Loc [ T_anlyr_K ]
     2:     55        Y Loc [ To_h2o    ]
     3:     19        Z Loc [ Ta_To_h2o ]

57:  End (P95)
```

```
;Positive calibration and wind speed
;corrections.

58:   Beginning of Subroutine (P85)
      1:      4       Subroutine 4

59:   Z=X*F (P37)
      1:     16       X Loc [ wnd_spd   ]
      2:       .2     F
      3:     60       Z Loc [ C         ]

60:   Z=X*F (P37)
      1:     60       X Loc [ C         ]
      2:       .066   F
      3:     58       Z Loc [ A         ]

61:   Z=X+F (P34)
      1:     60       X Loc [ C         ]
      2:       .066   F
      3:     59       Z Loc [ B         ]

62:   Z=X/Y (P38)
      1:     58       X Loc [ A         ]
      2:     59       Y Loc [ B         ]
      3:     61       Z Loc [ corr_fac  ]

63:   Z=Z+1 (P32)
      1:     61       Z Loc [ corr_fac  ]

;Enter the positive multiplier (p.ppp).
;
64:   Z=X*F (P37)
      1:      4       X Loc [ Rn        ]
      2:      1       F                              ;p.ppp <- unique value
      3:      4       Z Loc [ Rn        ]

65:   Z=X*Y (P36)
      1:      4       X Loc [ Rn        ]
      2:     61       Y Loc [ corr_fac  ]
      3:      4       Z Loc [ Rn        ]

66:   End (P95)

;Negative calibration and wind speed
;corrections.

67:   Beginning of Subroutine (P85)
      1:      5       Subroutine 5

68:   Z=X*F (P37)
      1:     16       X Loc [ wnd_spd   ]
      2:       .00174 F
      3:     58       Z Loc [ A         ]
```

```
69:   Z=X+F (P34)
      1:      58          X Loc [ A          ]
      2:        .99755    F
      3:      61          Z Loc [ corr_fac  ]

;Enter the negative multiplier (n.nnn).
;
70:   Z=X*F (P37)
      1:       4          X Loc [ Rn         ]
      2:       1          F                              ;n.nnn <- unique value
      3:       4          Z Loc [ Rn         ]

71:   Z=X*Y (P36)
      1:       4          X Loc [ Rn         ]
      2:      61          Y Loc [ corr_fac  ]
      3:       4          Z Loc [ Rn         ]

72:   End (P95)

;Apply the LI-COR 6262 coefficient to
;CO2 and H2O.

73:   Beginning of Subroutine (P85)
      1:       7          Subroutine 7

74:   Z=X*Y (P36)
      1:      41--        X Loc [ co2mVinpt ]
      2:      43          Y Loc [ Po_P_1000 ]
      3:      41--        Z Loc [ co2mVinpt ]

75:   If Flag/Port (P91)
      1:      27          Do if Flag 7 is Low
      2:      30          Then Do

;Enter the A (C1), B (C2), C (C3),
;D (C4), and E (C5) coefficients for
;CO2 (see Section 4.1.2).
;
76:   Polynomial (P55)
      1:       1          Reps
      2:      41          X Loc [ co2mVinpt ]
      3:      28          F(X) Loc [ co2_uM    ]
      4:       0          C0
      5:       1          C1                             ;A <- unique value
      6:       1          C2                             ;B <- unique value
      7:       1          C3                             ;C <- unique value
      8:       1          C4                             ;D <- unique value
      9:       1          C5                             ;E <- unique value

77:   Else (P94)
```

```
;Enter the A (C1), B (C2), C (C3),
;D (C4), and E (C5) coefficients for
;H2O (see Section 4.1.2).
;
78:   Polynomial (P55)
      1:     1        Reps
      2:    42        X Loc [ h2omVinpt ]
      3:    29        F(X) Loc [ h2o_mM    ]
      4:     0        C0
      5:     1        C1                          ;A <- unique value
      6:     1        C2                          ;B <- unique value
      7:     1        C3                          ;C <- unique value
      8:     1        C4                          ;D <- unique value
      9:     1        C5                          ;E <- unique value

79:   End (P95)

80:   End (P95)

;Correct the sign on the gradients.

81:   Beginning of Subroutine (P85)
      1:     8        Subroutine 8

82:   Z=X (P31)
      1:    30        X Loc [ del_co2   ]
      2:    38        Z Loc [ co2_corr  ]

83:   Z=X (P31)
      1:    31        X Loc [ del_h2o   ]
      2:    39        Z Loc [ h2o_corr  ]

84:   Z=X (P31)
      1:    10        X Loc [ co2mV     ]
      2:    36        Z Loc [ co2mVcorr ]

85:   Z=X (P31)
      1:    11        X Loc [ h2omV     ]
      2:    37        Z Loc [ h2omVcorr ]

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

87:   Beginning of Loop (P87)
      1:     0        Delay
      2:     4        Loop Count

88:   Z=X*F (P37)
      1:    36--      X Loc [ co2mVcorr ]
      2:    -1        F
      3:    36--      Z Loc [ co2mVcorr ]

89:   End (P95)

90:   Else (P94)
```

```
91:   End (P95)

92:   End (P95)

;Set all the control ports low,
;with a delay.

93:   Beginning of Subroutine (P85)
      1:      9        Subroutine 9

94:   Excitation with Delay (P22)
      1:      3        Ex Chan
      2:      0        Delay w/Ex (units = 0.01 sec)
      3:      2        Delay After Ex (units = 0.01 sec)
      4:      0        mV Excitation

95:   Set Port(s) (P20)
      1:   9900        C8..C5 = nc/nc/low/low
      2:   0000        C4..C1 = low/low/low/low

96:   End (P95)

End Program
```

TABLE 4.2-2. Output From Example 023/CO2 Bowen ratio System Program

01: 21 Array ID, 20 minute gradient data
02: Year
03: Day
04: hhmm
05: CO2mVcorr
06: H2OmVcorr
07: CO2 corr
08: H2O corr
09: T Anlyzr
10: CO2 ref uM
11: H2O ref mM
12: P kPa
13: Vr CO2 mV
14: Vr H2O mV
15: G CO2
16: G H2O
17: TC lower
18: del TC
19: RefTemp
20: Ta/To CO2 during SCRUB
21: Ta/To H2O during SCRUB

01: 22 Array ID, 20 minute energy balance and meteorological data
02: Year
03: Day
04: hhmm
05: T amb C
06: e amb kPA

07: H2O mM/M
08: Rn
09: SHF#1
10: SHF#2
11: avg Tsoil
12: del Tsoil
13: RH frac
14: Batt Volt
15: Wind Spd
16: Wind Dir
17: Std Wind Dir
18: CS615 mSec
19: Soil Water
20: Soil Water Corr. for Temp.

SECTION 5. STATION OPERATION

This section assumes that the operator has a fundamental understanding of the CR23X keyboard commands. Specifically, viewing input locations and setting flags. For information on keyboard operation, see the overview section of the CR23X manual.

5.1 PUMP

The pump is turned on by setting flag 5 and then flag 6 high. After the pump has started, set flag 5 low. To turn the pump off, set flag 5 high and flag 6 low. When the pump turns off, set flag 5 low.

> **NOTE**: When flag 5 is high no averaging takes place on the water vapor or carbon dioxide data. When flag 5 is set low averaging resumes on the next four minute cycle.

5.2 MANUAL VALVE CONTROL

Set flag 5 high to active manual valve control. Flag 2 is used to switch the inputs on the LI-6262. When flag 2 is high the upper arm is routed to the sample input and the lower arm to the reference input. The opposite is true when flag 2 is low. To exit manual valve control set flag 5 low.

> **NOTE:** When flag 5 is high no averaging takes place on the water vapor or carbon dioxide data. When flag 5 is set low averaging resumes on the next four minute cycle.

5.3 ZERO AND SPAN CALIBRATION

Before the zero and span calibration can be performed, the 023/CO2 system must go through at least one scrub cycle. An automatic scrub is performed at the top of the hour. A manual scrub is performed by setting flag 8 high and then low. The manual scrub takes one minute to complete.

5.3.1 ZERO

The zero valve, located on the left side of the black mounting bracket, is used to route the air stream from a single level into both the reference and sample inputs of the LI-6262. Flag 2 determines which level is being split. When flag 2 is high the air is from the lower arm. When flag 2 is low the air is from the upper arm. The air stream is split when the zero switch is in the forward position.

> **CAUTION:** Be sure to place the switch in the operate (backward) position after zero calibration of the LI-6262.

Set flag 5 high (disable averaging) and flag 2 low. Move the zero switch to the zero (forward) position. Display the carbon dioxide gradient on the CR23X (Input Location 30). Unlock the carbon dioxide zero potentiometer and adjust it until the gradient is close to zero. Lock the carbon dioxide zero potentiometer.

Display the water vapor gradient on the CR23X (Input Location 31). Unlock the water vapor zero potentiometer and adjust it until the gradient is close to zero. Lock the zero potentiometer and move the zero switch into the operate (backward) position. Set flag 5 low.

Wait four minutes or until flag 1 goes low before continuing to the span calibration. For more information on the zero calibration see Section 4.2 of the LI-6262 manual.

5.3.2 SPAN

Set flag 8 (Manual Scrub) high. After the valves latch, set flag 5 high and wait one minute for the carbon dioxide and water vapor to be scrubbed from the LI-6262 sample cell. Check the water vapor concentration in Input Location 3 (HMP45C) and make a mental note of that value. Display the absolute water vapor concentration measured by the IRGA on the CR23X (Input Location 29). Unlock the water vapor span potentiometer and adjust it until the absolute concentration is close to that of the HMP45C (Input Location 3). Note that the CR23X does not correct the absolute water vapor concentration for T/To. This correction is applied in the SPLIT parameter file RAWBRC.PAR.

Set flag 6 low (turn pump off). Plumb a carbon dioxide span gas, through a "T" connector, that is vented to the atmosphere, and an ACRO50 filter into the upper arm input on the first valve (see Figure 5.3-1). Open the span gas bottle so that there is a slight flow venting out through the "T" connector into the atmosphere. Set flag 6 high (turn pump on). Display the absolute carbon dioxide concentration on the CR23X (Input Location 28). Unlock the carbon dioxide span potentiometer and adjust it until the absolute concentration is close to the span gas concentration in µmol/mol. Note that the CR23X does not correct the absolute carbon dioxide concentration for T/To. This correction is applied in the SPLIT parameter file RAWBRC.PAR. Set flag 6 low (turn pump off). Plumb the upper arm back into the valve. Set flag 6 high (turn pump on).

Lock the span potentiometers and set flag 8 and 5 low. For more information on the span calibration see Section 4.2 of the LI-6262 manual.

> **NOTE**: There will be small zero offset with the water vapor span calibration, therefore, repeat the water vapor zero calibration.

> **CAUTION:** Do not leave flag 8 high (manual scrub mode) for prolonged periods of time. Doing so will shorten the useful life of the soda lime and magnesium perchlorate and result to contamination of the LI-6262 sample cell.

5.4 ROUTINE MAINTENANCE

Replace air intake filters*	1-2 weeks
Clean thermocouples	as needed
Clean Radiometer domes	as needed
Replace Soda Lime and Magnesium Perchlorate	as needed

* Gelman ACRO50 inline Teflon filters with a 1 µm pore size

To disable averaging while replacing filters and cleaning thermocouples set flag 5 high. Set flag 5 low when maintenance is complete. Averaging will resume on the next four minute cycle.

Before removing the filters, turn the pump off (see Section 5.1). Install the clean filters with the printed side down. Remove all debris from the fine wire thermocouples. A camel-hair brush and tweezers can be used to clean the thermocouples.

The thermocouples can also be dipped in a mild acid to dissolve spider webs. For example, muriatic acid (hydrochloric acid) is available in most hardware stores. Rinse the thermocouples thoroughly with distilled water after dipping.

For the meteorological sensors, follow the recommended maintenance in the operator's manual and the weather station installation manual.

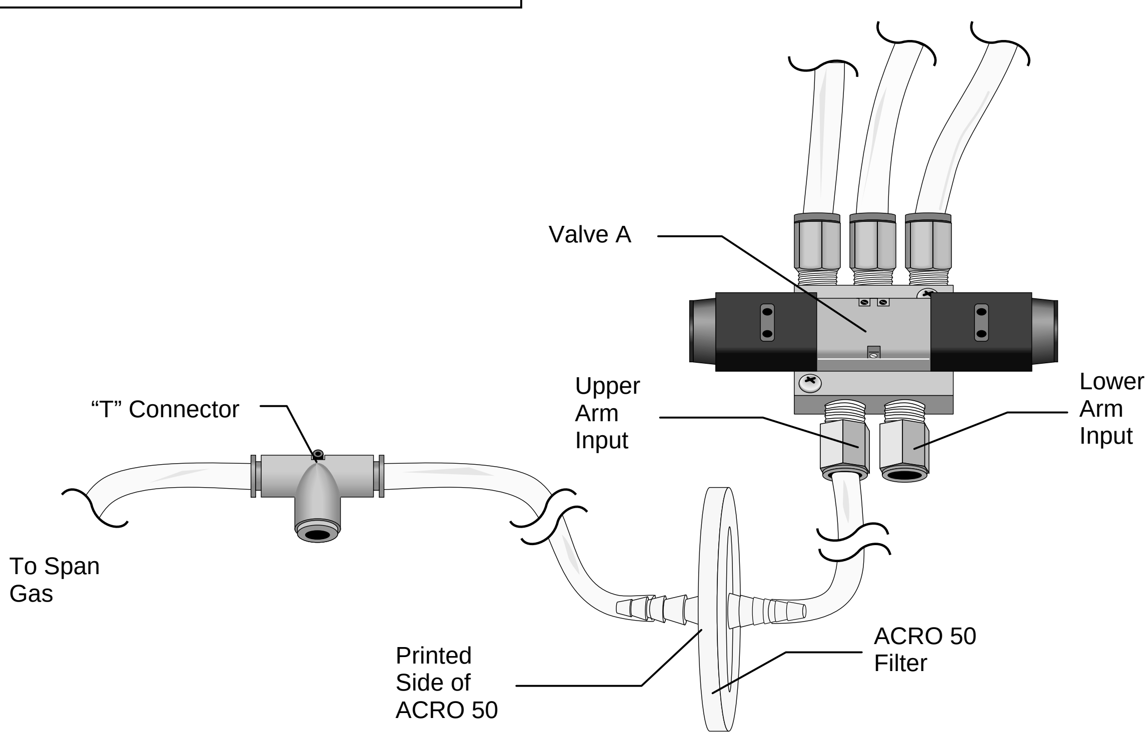


FIGURE 5.3-1. Assembly for Spanning the LI6262

SECTION 6. CALCULATING FLUXES USING SPLIT

SPLIT (PC208W software) can be used to calculate fluxes from the data produced by the 023/CO2 Bowen Ratio System with CO2 Flux. This section describes those calculations.

Two runs are required using SPLIT to compute the fluxes. The first run operates on the raw data files generated by the CR23X. The definitions of the points in this data set are given in Table 5. The output file from the first run (RAWBRC.PRN) is defined in the parameter file RAWBRC.PAR in Table 6. The fluxes and corrections are then calculated during the second run using SPLIT with the parameter file CALCBRC.PAR.

The example SPLIT parameter files are available on the Campbell Scientific ftp site, ftp://ftp.campbellsci.com/pub/outgoing/files/br_co2.exe. Br_co2.exe is a self extracting file. Type br_co2.exe at a DOS prompt and press the <Enter> key.

6.1 WEBB ET AL. CORRECTION

When carbon dioxide gradients are measured insitu using the mean gradient technique and are brought to a common analyzer temperature and pressure. It is necessary to account for carbon dioxide density changes caused by the simultaneous flux of heat and/or water vapor (Webb et al., 1980).

Start with Webb et al.'s Eq. (36)

$$F_c = k_c \frac{PT_i}{P_iT}\frac{\Delta\rho_{ci}}{\Delta z} + k_c \frac{PT_i}{P_iT}\frac{M_a\rho_{ci}}{M_v\rho_{ai}}\frac{\Delta\rho_{vi}}{\Delta z} \qquad (22)$$

where F_c is the flux density of carbon dioxide, P is the total atmospheric pressure, P_i is the pressure within the LI-6262, T is the ambient air temperature, T_i is the temperature within the LI-6262, ρ_{ci} is the density of carbon dioxide, ρ_{ai} is the density of dry air, and ρ_{vi} is the density of water vapor where the subscript i indicates that the densities are at the pressure and temperature of the LI-6262, k_c is the eddy diffusivity for carbon dioxide, M_a and M_v are the molecular weights of dry air and water vapor respectively, and z is height.

The first term on the right hand side is the carbon dioxide flux and the second term is the Webb et al. correction. The datalogger outputs the gradient of carbon dioxide and water vapor as a concentration and not a density. Thus, it would be convenient to write Eq. (22) in terms of a concentration.

Start with the ideal gas law

$$PV = nRT \qquad (23)$$

where V is the volume, n is the number of moles of the gasses in the volume, and R is the universal gas constant.

Let $N_a = n_a/V$, $N_v = n_v/V$, and $N_c = n_c/V$ where the subscripts a, v, and c are dry air, water vapor, and carbon dioxide and N is the number of moles per unit volume of dry air, water vapor, and carbon dioxide. The ideal gas law can now be written in the following form.

$$\frac{P}{T} = R\left(N_a + N_v + N_c\right) \qquad (24)$$

Note that $N_c << N_a$ and $N_c << N_v$. Thus, the partial pressure contribution of carbon dioxide can be absolved and Eq. (24) assumes the form below.

$$\frac{P_i}{T_i} = R\left(N_{ai} + N_{vi}\right) \qquad (25)$$

Substituting Eq. (25) into (22) yields the following.

$$F_c = \frac{k_c}{T}\frac{P}{R}\frac{\left[\Delta\rho_{ci}\big/\left(N_{ai}+N_{vi}\right)\right]}{\Delta z} + \frac{k_c}{T}\frac{P}{R}\frac{M_a}{M_v}\frac{\rho_{ci}}{\rho_{ai}}\frac{\left[\Delta\rho_{vi}\big/\left(N_{ai}+N_{vi}\right)\right]}{\Delta z} \qquad (26)$$

By definition $\rho_{ai} = N_{ai}\,M_{ai}$, $\rho_{vi} = N_{vi}\,M_{vi}$, $\rho_{ci} = N_{ci}\,M_{ci}$. It then follows that:

$$F_c = M_c\frac{k_c}{R}\frac{P}{T}\frac{\left[\Delta N_{ci}\big/\left(N_{ai}+N_{vi}\right)\right]}{\Delta z}$$

$$+M_c \frac{k_c}{T} \frac{P}{R} \frac{N_{ci}}{N_{ai}} \frac{\left[\Delta N_{vi}/N_{ai} + N_{vi}\right]}{\Delta z} \qquad (27)$$

is true and finally,

$$F_c = k_c \frac{PM_c}{TR} \frac{\Delta c}{\Delta z} + k_c \frac{PM_c}{TR} \frac{c}{1-w} \frac{\Delta w}{\Delta z}. \qquad (28)$$

The flux of carbon dioxide is now written in terms of a concentration gradient. Similarly, the flux of water vapor can be written as follows:

$$L_e = \lambda k_v \frac{PM_v}{TR} \frac{\Delta w}{\Delta z} + \lambda k_v \frac{PM_v}{TR} \frac{w}{1-w} \frac{\Delta w}{\Delta z}. \qquad (29)$$

6.2 SOIL HEAT FLUX AND STORAGE

The soil heat flux at the surface is calculated by adding the measured flux at a fixed depth, d, to the energy stored in the layer above the heat flux plates. The specific heat of the soil and the change in soil temperature, ΔT_s, over the output interval, t, are required to calculate the stored energy.

The heat capacity of the soil is calculated by adding the specific heat of the dry soil to that of the soil water. The values used for specific heat of dry soil and water are on a mass basis. The heat capacity of the moist is given by:

$$C_s = \rho_b \left(C_d + \theta_m C_w\right) = \rho_b C_d + \theta_v \rho_w C_w \qquad (30)$$

$$\theta_m = \frac{\rho_w}{\rho_b} \theta_v \qquad (31)$$

where C_S is the heat capacity of moist soil, ρ_b is bulk density, ρ_w is the density of water, C_d is the heat capacity of a dry mineral soil, θ_m is soil water content on a mass basis, θ_v is soil water content on a volume basis, and C_w is the heat capacity of water.

This calculation requires site specific inputs for bulk density, mass basis soil water content or volume basis soil water content, and the specific heat of the dry soil. Bulk density and mass basis soil water content can be found by sampling (Klute, 1986). The volumetric soil water content is measured by the CS615 water content reflectometer. The value used for the heat capacity of dry soil in the example SPLIT parameter file is a reasonable value for most mineral soils (Hanks and Ashcroft, 1980).

The storage term is then given by Eq. (32).

$$S = \frac{\Delta T_s C_s d}{t} \qquad (32)$$

6.3 COMBINING RAW DATA

First, the air temperature, and water vapor and carbon dioxide concentration gradients must combined into one file with net radiation, soil heat flux, and change in soil temperature. To do this use the SPLIT parameter file called RAWBRC.PAR. This parameter file assumes that the data files from the datalogger were saved on disk under the name BRC.DAT. It creates a file with the raw data necessary to calculate fluxes (RAWBRC.PRN).

Plot the data in RAWBRC.PRN, check the temperature, water vapor, and carbon dioxide gradients as well as the soil heat flux, soil temperature, delta soil temperature, and net radiation for anomalous readings. Check the wind speed and direction to determine if the fetch conditions are adequate.

Plot the battery voltage as well. A steady decrease in the battery voltage and then sudden increase could indicate the LI-6262 has shut down.

6.4 CALCULATING FLUXES

Once the necessary data is in one file, the fluxes can be calculated using the example SPLIT parameter file CALCBRC.PAR. The SPLIT parameter file CALCBRC.PAR assumes that the Bowen ratio arms are installed with a 1.0 meter separation (DZ=1.). If your arms are installed with different separation, change DZ accordingly. CALCBRC.PAR assumes that the volumetric soil water content was measured by a CS615. If the soil water content was determined by other means, the parameter file must be changed accordingly. The constants and parameters necessary for calculating the fluxes are listed in Table 6.4-1. All of the calculations in CALCBOW.PAR are explained in Sections 1, 6.1, and 6.2. Unit analysis for selected sections of CALCBRC.PAR is given in Table 6.4-2.

TABLE 6.4-1. Input Values for Flux Calculations

VAR	VALUE	UNITS	DESCRIPTION
	44.0	g mol^{-1}	Molecular weight of carbon dioxide
	8.314	$Jkg^{-1}mol^{-1}$	Universal gas constant
	0.622	—	Molecular weight of water divided by weight of air
B		—	Bowen Ratio
DB*	1200.0	kg/m^3	Soil bulk density **(must be measured for the site)**
CP		kJ/(kg K)	Specific heat of moist air
	1.005	kJ/(kg K)	Specific heat of dry air
	840.0	J/(kg K)	Specific heat of dry soil
	4190.0	J/(kg K)	Specific heat of water
DZ	1.0	m	Arm separation (z_1 - z_2)
	0.08**	m	Depth of soil heat flux plates
EW		kJ/kg	Latent heat of vaporization
	2450.0	kJ/kg	Latent heat of vaporization at 20^{o}C
F		W/m^2	Soil heat flux measured at 8 cm
FC		$mg/(m^2s)$	Carbon dioxide flux
G		W/m^2	Soil heat flux at surface (F+S)
H		W/m^2	Sensible heat flux
K		m^2/s	Eddy diffusivity for carbon dioxide (assumed to equal to the eddy diffusivity for heat and water vapor)
LE		W/m^2	Latent heat flux
8*		kPa	Atmospheric pressure
Q		kg-H_2O/kg-air	Specific humidity of air
RA		kg/m^3	Density of moist air
RD		kg/m^3	Density of dry air
15		W/m^2	Net radiation
RV		kg/m^3	Density of water vapor
S		W/m^2	Stored heat (calculated from soil heat capacity and the measured change in temperature)
	1200**	s	Output Interval
W		vol-H_2O/bulk vol-soil	Soil Water Content on a volume basis measured by the CS615
WPLC		$mg/(m^2s)$	Webb et al. correction for carbon dioxide flux
WPLV		W/m^2	Webb et al. correction for latent heat flux

* These values are unique for a site. Correct values must be entered for the site under study.
** These values may need to change if the program or installation differs from the example.

TABLE 6.4-2. Selected Code from CALCBRC.PAR with Unit Analysis

SPLIT Code Equation	Units
Q=(.622*13)/(8-(13*.378))	
$q = \frac{\varepsilon e}{P - e(1-\varepsilon)}$	$[\text{unit less}] = \frac{[\text{kPa}]}{[\text{kPa}]}$
CP=(1.+(.87*Q))*1.005	
$C_p = (1 + (0.87q))C_{pdry}$	$[\text{kJ K}^{-1}\text{ kg}^{-1}]$
RD=(8-13)*1000./(287.05*(12+273.15))	
$\rho_d = \frac{(P-e)1000}{R_d(T+273.15)}$	$[\text{kg m}^{-3}] = \frac{[\text{kPa}][1000\text{Pa/kPa}]}{[\text{J K}^{-1}\text{ kg}^{-1}][\text{K}]}$
RV=13*1000./(461.5*(12+273.15))	
$\rho_v = \frac{e1000}{R_v(T+273.15)}$	$[\text{kg m}^{-3}] = \frac{[\text{kPa}][1000\text{Pa/kPa}]}{[\text{J K}^{-1}\text{ kg}^{-1}][\text{K}]}$
EW=2500.5-2.359*12	
$\lambda = \lambda_o - 2.359T$	$[\text{kJ kg}^{-1}]$
B=CP*10*1000./(.622*EW*5)	
$\beta = \frac{C_p(T_2 - T_1)1000}{\varepsilon\lambda(w_2 - w_1)}$	$[\text{unit less}] = \frac{[\text{kJ K}^{-1}\text{kg}^{-1}][\text{K}][1000\text{ mmol/mol}]}{[\text{kJ kg}^{-1}][\text{mmol mol}^{-1}]}$
S=19*.08*(DB*840.+W*1000.*4190.)/1200.	
$S = \frac{\Delta T_s d\ (\rho_d C_d + \theta_v \rho_w C_w)}{t}$	$[\text{W m}^{-2}] = \frac{[\text{K}][\text{m}][\text{kg m}^{-3}][\text{J kg}^{-1}\text{K}^{-1}]}{[\text{s}]}$
K=DZ*H/(10*CP*1000.*RA)	
$k_c = \frac{(z_1 - z_2)H}{(T_2 - T_1)C_p 1000\rho_a}$	$[\text{m}^2\text{ s}^{-1}] = \frac{[\text{m}][\text{Wm}^{-2}]}{[\text{K}][\text{kJ kg}^{-1}\text{K}^{-1}][1000\text{ J/kJ}][\text{kg m}^{-3}]}$
FC=K*8*44.*4/((12+273.15)*8.314*DZ)	

$$F_c = \frac{k_c \; P \left(c_2 - c_1\right) M_c}{T \; R \left(z_1 - z_2\right)} \qquad \left[\text{mg m}^{-2}\text{s}^{-1}\right] = \frac{\left[\text{m}^2\text{s}^{-1}\right][\text{kPa}]\left[\mu\text{mol mol}^{-1}\right]\left[\text{g mol}^{-1}\right]}{[\text{K}]\left[\text{J K}^{-1}\text{mol}^{-1}\right][\text{m}]}$$

WPLV=LE*7/(1000.-7)

$$\text{WPLV} = \frac{L_e w}{1000 - w} \qquad \left[\text{W m}^{-2}\right] = \frac{\left[\text{Wm}^{-2}\right]\left[\text{mmol mol}^{-1}\right]}{\left([\text{1000mmol/mol}] - \left[\text{mmol mol}^{-1}\right]\right)}$$

WPLC=K*8*44.*6*5/((12+273.15)*8.314*DZ*(1000.-7))

$$\text{WPLC} = \frac{K_c \; P \; M_c \; c \left(w_2 - w_1\right)}{T \; R \left(z_1 - z_2\right) (1000 - w)} \qquad \left[\text{mg m}^{-2}\text{s}^{-1}\right] = \frac{\left[\text{m}^2\text{s}^{-1}\right][\text{kPa}]\left[\text{g mol}^{-1}\right]\left[\mu\text{mol mol}^{-1}\right]\left[\text{mmol mol}^{-1}\right]}{[\text{K}]\left[\text{J K}^{-1}\text{mol}^{-1}\right][\text{m}]\left(\left[\text{1000mmol/mol} - \text{mmol mol}^{-1}\right]\right)}$$

APPENDIX A. REFERENCES

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