

BUCK RESEARCH INSTRUMENTS L.L.C.

MODEL CR-2 HYGROMETER

OPERATING MANUAL



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MODEL CR-2 HYGROMETER OPERATING MANUAL

1. INTRODUCTION

The Model CR-2 Cryocooled Hygrometer is a high performance instrument, capable of fast, accurate measurements over an extremely wide humidity range. Because these performance capabilities have not previously been available in a single instrument, the CR-1, CR-2 and CR-3 family represents a significant advance in the state of the art.

The CR-2 is designed for use with research aircraft. **When using in the lab, make certain to provide adequate cooling for the instrument by reinstalling the heat sink and fan, if they were removed for aircraft installation.** The technology incorporated in the CR-2 is protected by domestic and foreign patents.

1.1 General Description

The CR-2 is a chilled mirror, condensation type hygrometer. Its high performance is achieved by cryogenically cooling a mirror, using a closed cycle cryocooler, and holding it at the frost point temperature by means of a heater/control system. Optical detectors are used for sensing condensate on a mirror, and an ultra-stable platinum RTD imbedded in the mirror is used to determine mirror temperature -- the dew or frost point. Since operation of the CR-2 is based on a fundamental property of water vapor (dew/frost point), it is intrinsically capable of long-term accuracy and stability, without the need for periodic recalibration.

The instrument's main unit consists of a sensor assembly, cryocooler, cryocooler drive circuitry, and control/readout circuitry. A separate display module displays operational and output voltages, and allows manual control of the instrument, but is not required for operation.

The components of the CR-2 are:

- Main unit containing sensor assembly
- Display module
- Display cable (9 ft)
- Service kit, containing:
 - tools, spare parts, power connector, signal output connector, and supplies.
- Operating manual

1.2 Specifications, Model CR-2 Cryocooled Hygrometer

Measurement range

Dew/frost point temperature -100°C to +30°C (reads beyond with reduced accuracy)

Accuracy $\pm 0.1^\circ\text{C}$

Response time Less than 40 sec from -100 to -40°C (frost)
Less than 1 sec from -40 C to +30°C (dew)

Nominal operating range

Electronics:

Temperature -40 to +40°C

Pressure 100 to 2000 mb (2 to 30 psia)

Sample gas:

Temperature -80 to +40°C

Pressure 1 to 2000 mb (.02 to 30 psia)

Flow rate of sample 0.2 - 3 liters/minute

Cryocooler type: Stirling cycle, helium

Operating lifetime: Approx. 10,000 hours

Output signals Dew/frost point, pressure, mirror balance,
Coldfinger temperature

Output format: RS-232 and 0-10 VDC

Construction Aluminum (mounting hardware)
316L Stainless steel (sensor assembly)

Input voltage 28 VDC, optional - 110 VAC 60-400 Hz

Power consumption (maximum) < 50 watts

Approximate dimensions, inches and (cm)

Main unit: 10" (25 cm) w x 10.75" (27 cm) d x 3.75" (9.5 cm) h

Display module: 8" (20 cm) w x 8" (20 cm) d x 5" (13 cm) h

Rack mounting optional

Approximate Weight (excluding cable and heat sink)

Main unit: 7 lbs (3.2 kg) (heat sink adds 3 lbs (1.4 kg))

Display module: 3.25 lbs (1.5 kg)

Note: These are approximate specifications. Exact performance will vary depending on installation and operating environment.

2. LOCATION OF PRINCIPLE COMPONENTS

2.1 Main Unit (Figure 1)

- A. Signal connector J2.
- B. Display connector J3.
- C. Power, J1 and RS-232 connector J4
- D. Sensor assembly. Consists of mirror module, sensing chamber, and optics module. Outlet on right
- E. Base plate.
- F. Heat sink and fan assembly. (Can be removed for aircraft installation).
- G. Lab legs. (Remove for aircraft installation).

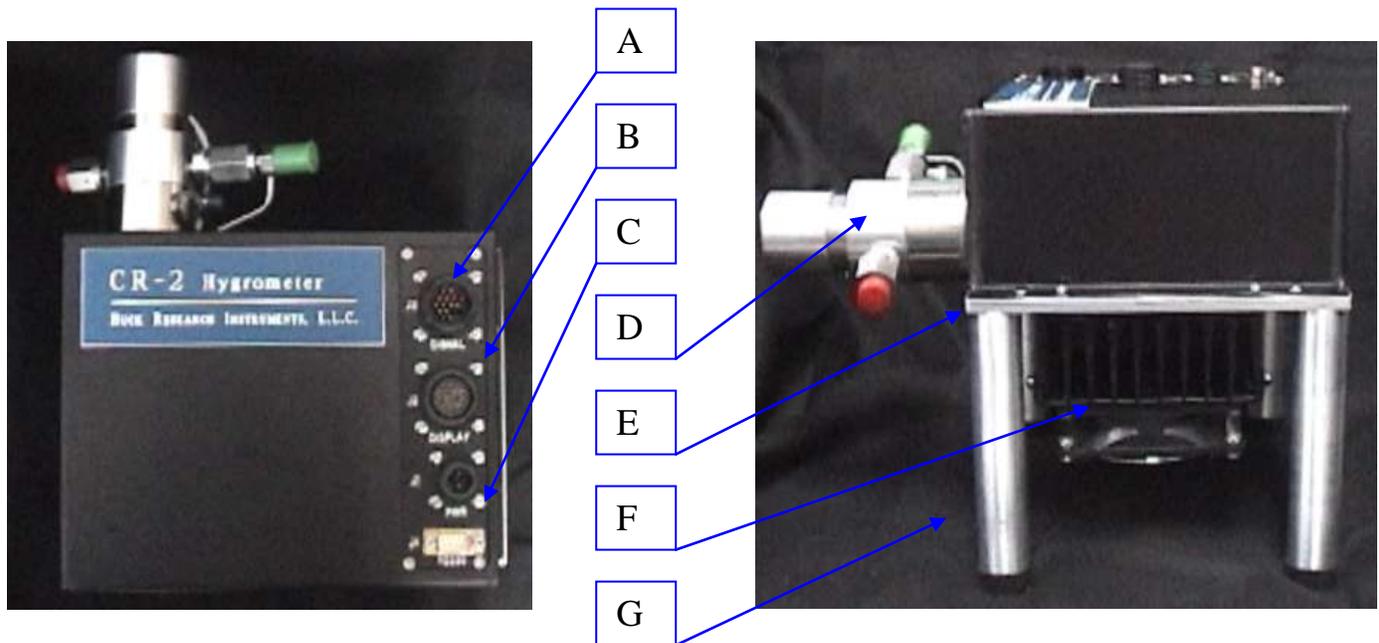


Fig. 1. Main unit

2.2 Display Module (Figure 2)

- A. DISPLAY. Backlit LCD display that displays H₂O concentration, mirror temperature (Mirror T or D/F Point when dew or frost point acquired), pressure (in millibar) and balance (± 200 when dew/frost point acquired). Displays internal main PCB temperature when HEAT/COOL switch depressed.
- B. HEAT-AUTO-COOL (momentary). Provides additional heat to partially clear the mirror of condensate, or full cooling to allow additional frost to collect on the mirror. Normal operation is AUTO.
- C. BALANCE (momentary). If held down for 5 seconds, initiates a balance routine.
- D. REBALANCE LED. Lights when a balance routine is performed. If it stays light after balance finishes, this indicates that mirror is becoming contaminated and will need to be cleaned soon.
- E. SERVICE MIRROR LED. This LED flashes to indicate that mirror is too contaminated for proper operation and needs to be cleaned.
- F. RUN-INTERRUPT. Turns off power to only the cryocooler.



Figure 2. Display module

3. INSTALLATION AND OPERATION

3.1 Installation

1. Inspect the instrument for mechanical or other damage.
2. Connect the inlet and outlet gas flow lines to the sensor assembly. Make sure there is some flexibility in both inlet and outlet lines to avoid stress and possible damage to the CR-2. NOTE: do not overtighten Swage or VCR type fittings. Overtightening can destroy their sealing ability. Make sure each VCR connection has one (but no more than one) metal gasket installed.
3. Initially and as often thereafter as necessary, check that all electrical and mechanical connections are secure. It may be advisable to test for leaks using one of the methods in Section 7.5. This is especially important when operating the instrument in a humidity environment that is very different from that of the sampled air.

3.2 Initial Power-up Procedure

1. Temporarily connect the display module to J3 of the main unit, using the cable supplied. Make sure that the RUN-INTERRUPT switch is in INTERRUPT position.
2. Apply power to J1. The display should show some diagnostic screens, then initiate a balance routine. When the balance routine is finished, flip the RUN-INTERRUPT switch to the RUN position. Monitor the coldfinger temperature by depressing the COOL Switch and reading the temperature on the second line of the LCD display. (If you do not have a pressure sensor, then coldfinger temperature is automatically displayed on line 2 of the LCD display.) With the COOL switch depressed continuously, or alternatively flowing very dry gas (-70°C or drier) through the sample chamber, the cold finger temperature should read at least -100°C after 10 minutes.
3. Then, with the HEAT-AUTO-COOL switch in AUTO position, wait for the instrument to stabilize at the operating point. The balance display should be within 200 counts of 0 and the Mirror T = on the display should change to D/F Point =.
4. The instrument is now ready for use.

NOTE: It is always advisable to start measuring at relatively high humidity values (above -40°C), to allow easy acquisition of condensation, then go down in frost point temperature.

If it is necessary to begin operating at very low frost points, initial acquisition of frost can be speeded up by spiking the pressure inside the sample chamber by quickly closing and opening a valve downstream of the outlet of the sample chamber. This will cause the dew point of the gas inside the chamber to dramatically increase above the

mirror temperature, causing moisture to condense quickly on the mirror. This can cause the balance reading to go from negative to positive very quickly, which will cause the servo to heat the mirror. If you regulate the mirror temperature by judiciously depressing and holding the cool button, you can keep the layer on the mirror from being burned off and decrease frost acquisition time from many hours to 1-2 minutes.

3.3 Operation

During operation, no special attention is required except for an occasional check of operating voltages to assure proper function. If possible, keep flow in the range 0.5 - 3 liters/minute. At very high dew/frost point temperatures, higher flow may be allowed.

Keep the sample line inlet protected from contamination. This is best achieved by keeping the sample line closed when not connected to the desired sample gas. To avoid internal line condensation and resultant erroneous readings, do not allow the inlet lines to cool below the expected frost point temperature.

The Display Module provides convenient displays for most parameters, as an alternative to the signal outputs available at J2. Both dew/frost point (mirror temperature) indications are accurate to 0.1 °C (see Appendix 3). The Display Module should be connected only when the power is off.

Normal operation is indicated by BAL settling to the range ± 200 ; however, at lower frost points, loss of equilibrium can result in only a small departure from its previous balance point. When making a large downward change in humidity, it is better to make several intermediate steps rather than one large step, to avoid losing the condensation layer on the mirror. At low frost point values, always allow time for the moisture levels in the lines and sensing chamber to equilibrate, and for the balance voltage BAL to completely stabilize before taking a reading.

Due to higher physical gain at high dew points, some oscillation is likely to occur at dew points above 0 °C, with amplitudes of a fraction of a degree. It is rather rapid and can easily be filtered out during data processing. Also, it is possible that the oscillations put the balance voltage outside the range where the display will switch to D/F Point from Mirror T. This is normal and you will still be getting dew/frost points when the mirror temperature looks stable, even though the display shows Mirror T.

3.4 Power-down Procedure

1. If contamination is a likely hazard, shut off flow through the sensor to protect the mirror.
2. Switch the RUN/INTERRUPT switch to INTERRUPT. Disconnect power.

The mirror will remain cold for several minutes. To avoid excessive condensation in the sensing chamber, allow the instrument to reach room temperature before opening inlet or outlet lines.

4. SIGNAL PROCESSING

4.1 Data Signals

The following analog signals are available at signal connector J2, and vary over the following ranges:

VDF	Mirror temperature (Dew/frost point), 0-10v and 4-20 mA
PRES	Chamber pressure, 0-10v and 4-20 mA
H2O CONC	lb/MMscf or ppmv, 0-10v and 4-20 mA
BAL	Balance voltage, 0-10v and 4-20 mA

The 4-20 mA outputs sink current. Connect up +24 VDC to the 4-20 mA returns, either using the pins on the connector or from your data acquisition system. The current flowing into the 4-20 mA returns corresponds with the equations below.

4.2 Data Reduction Equations

VDF: Dew/frost point temperature is determined from VDF by:

$$T_{df} (\text{°C}) = [-150 + 20 \times \text{VDF}(\text{v})]. \quad (0-10\text{V}) \quad (1)$$

$$T_{df} (\text{°C}) = [-150 + 8 \times \text{IDF}(\text{ma})]. \quad (4-20 \text{ mA}) \quad (2)$$

PRESSURE: Chamber pressure is calculated from the Vpress signal voltage by:

$$\text{Press} = (\text{Vpress} - 1.6) * 156.25 \quad \text{mbar} \quad (3)$$

$$\text{Press} = ((\text{Ipress} - 4) / 1.6) * 100 \quad \text{mbar} \quad (4)$$

BALANCE: When balanced, BAL = 5V or 12.5 mA.

H2O CONC: 2- 4 V = 0-1000 ppbv, 4-6 = 0-1000 ppmv, 6-8 V = 0-1000 PPTV.

Conversion to Other Humidity Units To convert dew/frost point readings to other humidity units, refer to Appendix 1.

5. PRINCIPLES OF OPERATION

5.1 General

The CR-2 is a chilled-mirror, condensation-type hygrometer, consisting of the following principle components: a gold plated copper mirror with an attached stem, an associated temperature sensor and heating coil, a Stirling-cycle cryocooler, an optical system to sense condensing frost or dew (mirror reflectance), and control circuitry for controlling mirror temperature via the heating coil.

Operation is based on maintaining equilibrium vapor pressure over a water or ice surface on the mirror. Above the equilibrium temperature, mass transport is away from the surface, and below the equilibrium temperature it is onto the surface. When the surface is just at the dew/frost point temperature, the mass of condensate on the surface remains constant.

As is the case with conventional cooled dew-point devices, the mirror, optics and electrical circuit make up a thermo-optical servo system which operates to maintain a constant layer of condensate. When condensate is thus equilibrated, mirror temperature is then at the dew/frost point, which is sensed by the imbedded temperature sensor. Since the dew/frost point temperature is a fundamental measure of humidity, the CR-2 is intrinsically capable of long term accuracy and stability.

The development of this hygrometer follows the original work of H.J. Mastenbrook at NRL. His work was adapted by the NOAA Geophysical Monitoring for Climatic Change (GMCC) program for balloon-borne stratospheric water vapor measurements. Buck Research has extensively redesigned and reconfigured the instrument for a broader range of measurements and applications, incorporating proprietary new technical innovations in the process.

5.2 Technical details

A block diagram of the cryocooled hygrometer is given in Figure 4 and the sensor assembly is diagrammed in Figure 5.

5.2.1 Sampling system

The gas to be measured (sample gas) is brought to the sensing chamber through an inlet system and allowed to flow across the mirror surface in the sensor chamber. At the exit of the sensor chamber, the sample gas flows by a pressure gauge and is then returned to the original gas stream or exhausted as desired.

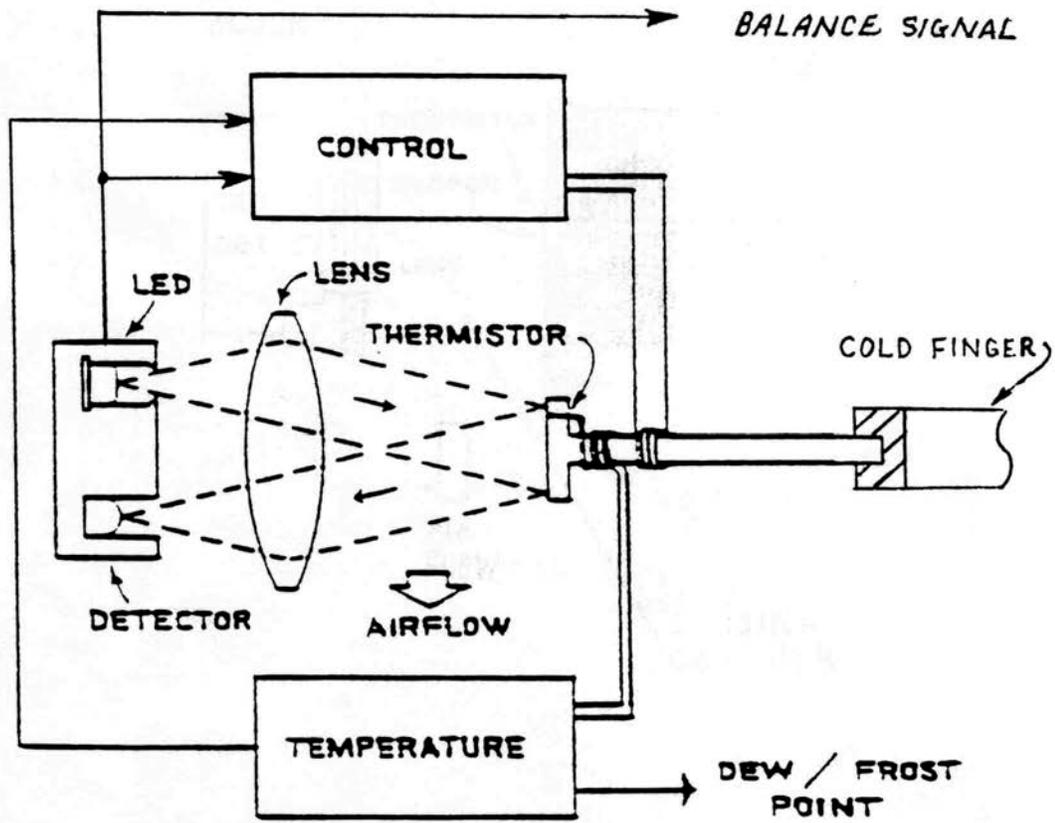


Fig. 3. Block diagram, CR-2 frost-point hygrometer

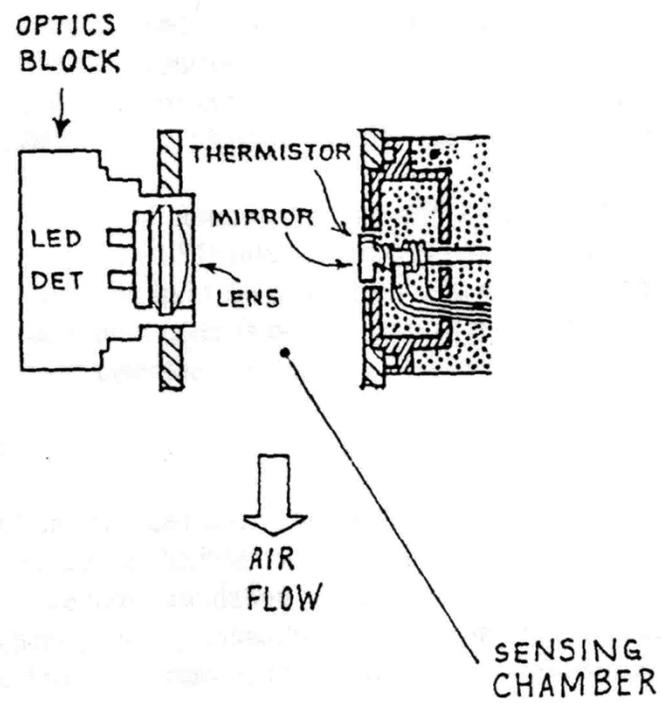


Fig. 4. Sensor assembly block diagram

The sampling system must be carefully sealed to prevent room air from contaminating the measurements. Stainless steel materials must be used throughout the inlet portion to minimize outgassing during low humidity sampling.

5.2.2 Mirror Module

The mirror assembly consists of a mirror, a mirror support and the thermistor, heater, and cryodiode, which are attached to the mirror stem. A small ultra-stable thermistor is installed in the mirror face to measure the dew/frost point temperature. Heating is provided by a resistive heater coil wound around the mirror stem. A diode located at the bottom of the stem monitors the cryocooler coldfinger temperature, which is controlled by its own control circuit.

5.2.3 Optics Module

The mirror surface is maintained continuously and automatically at the frost-point temperature by an electro-optical control system. This system measures the quantity of light specularly reflected from the mirror condensate and maintains a constant reflectance at the mirror surface, thus providing the condensate equilibrium for the frost-point temperature.

The optics module consists of a phototransistor pair and a light emitting diode (LED). One phototransistor maintains constant LED intensity; the other phototransistor provides a current output that is proportional to the light reflected from the mirror. The bias circuit is set so that when the proper condensation layer is on the mirror, about 85 - 92% of the light emitted by the LED is received at the detector.

5.2.4 Cooling System

The mirror stem is thermally coupled to the cold finger by a thermally conductive flexible coupling. In operation, heat is pumped away from the cold finger by the helium circulating from the cryocooler compressor. Since the cryocooler has limited heat-pumping capability, the coupling must be very efficient and well insulated from external heat. Therefore, to improve thermal isolation, the mirror stem and cold finger are enclosed in a sleeve containing cryogenic insulation and back-filled with CO₂.

5.2.5 Thermistor Readout

For obtaining the dew or frost point temperature from the temperature sensor, three readouts are provided: VDF signal voltage, RS-232 output and a direct temperature indication on the display. Both are accurate within 0.1 °C throughout the measurement range.

6. MEASUREMENT LIMITATIONS

Under field operations, measurement errors can arise from a number of causes. Any deviation of the mirror temperature from the frost-point temperature will of course cause error.

Perhaps the most common error source is from outside air leaking into the hygrometer sampling system. Therefore, it is important that the instrument be leak tested periodically, and with each relocation of the instrument, especially if components of the instrument have been exchanged or serviced.

Long exposure of the sampling system to high humidities, or condensation of water (which occurs if cold surfaces are exposed to ambient air which has a higher dew point than the temperature of the surfaces) causes temporarily high readings until the walls have completely outgassed. The lines may take a very long time to dry enough to allow accurate readings when measuring frost points below -50°C . Any hygroscopic material in the lines or chamber, such as dust, further lengthens this time. It is therefore advised to keep the lines clean and dry.

Calibration of the mirror temperature sensor and associated electronics is required to accurately determine dew/frost point temperature. Buck Research Instruments has done this. Once calibrated, the temperature sensor has been found to exhibit no measurable drift, even after years of use. Low drift components are used throughout the temperature sensing circuit to ensure long-term accuracy. However, recertification and recalibration is recommended yearly to ensure proper operation.

Errors can arise from failure to correct for differences between chamber pressure and ambient values. This is only important if you are measuring ambient dew/frost point and not H₂O concentration.

The system must be allowed to fully equilibrate before accurate readings can be obtained. When measuring very low frost points, equilibration can take much longer.

Within twenty degrees below freezing, the existence of supercooled water on the mirror can cause the temperature to read low, as the instrument is measuring dew point. Eventually the dew will turn to frost. To speed this up, press the COOL switch and allow the mirror to cool 5-10 degrees below the dew point reading, then release COOL switch. This will convert the dew to frost, as long as the mirror temperature does not go above 0°C after COOL switch is released

Contamination of the mirror by salt or other electrolytes can vary the relationship between vapor pressure and dew/frost point (Raoult error). Other chemical contamination may cause similar error. This is particularly relevant when measuring in natural gas, as glycols contained within it can condense out on the mirror. This is why a glycol-absorbing filter must be used when measuring natural gas.

7. MAINTENANCE AND TROUBLESHOOTING

The following maintenance items should receive attention as required:

1. Cleaning of sample lines, depending on use (Sect. 7.1).
2. Mirror check and cleaning (Sect. 7.2).
3. Leak checking (Sect. 7.3)
4. Cryocooler and cryo sleeve check (Sect. 7.4)

7.1 Sample line Cleaning

To keep sample lines clean, thus improving response at very low humidities, wash with water or acetone and blow dry with a mild pressure from a dry air or nitrogen source. It may be desirable to heat the lines for a few moments to drive off residual water.

7.2 Mirror cleaning

The mirror should be cleaned when the Check Mirror LED is flashing.

1. Make certain mirror is at or near the room temperature and power has been shut off. There are 2 holes in the flat part of the optics block. Insert 5/64" hex ball driver into holes and loosen each screw. The screws will remain captive inside. Once screws are loose, remove optics block. It will be held by the cable coming out of it, which is not removable. The mirror is now exposed and can be cleaned.
2. Moisten a soft cotton swab with mirror cleaning fluid (acetone) and gently wipe the swab over the mirror surface. Immediately dry the surface with fresh cotton swab. Inspection with flashlight may be helpful.
3. If necessary, repeat process. If contamination persists, clean again with acetone, followed by water, using a small amount. Never use alcohol in the sensing chamber, as this affects the hygroscopic properties of the mirror surface for some period of time. (In the absence of acetone, distilled water alone or used after acetone or MEK can be effective.)

CAUTION: The mirror surface has a coating that scratches easily. However, moderate scratching does not prevent normal operation. Use only soft flexible cotton swabs to clean the mirror. Apply minimal pressure

4. Turn instrument power on and wait and see if Service Mirror LED and Rebalance LEDs

turn off. If either or both LEDs stay lit, try cleaning the mirror again. Make sure the mirror is completely dry before turning power on.

5. If the Service Mirror LED cannot be turned off by cleaning the mirror, remove the optics block and clean the lens and entire sample chamber.

7.3 Leak Testing

The introduction of even small amounts of room air into the sampling system will cause errors in low frost point readings. Therefore, it is desirable that leak testing be performed on the instrument package and sampling system after initial assembly, and after any maintenance activity that involves disassembly of the instrument or interconnecting tubing.

Method 1. Connect a vacuum pump and vacuum gauge to the sampling system inlet port, and close or cap the outlet port (or vice versa). Evacuate down to the minimum attainable pressure. A reading of 100 microns Hg or less indicates the system is adequately sealed.

To locate a leak, place a few drops of alcohol on each tubing connection and watch the vacuum gauge pressure reading. If the reading abruptly increases, there is a leak. Allow some time for the vacuum readings to recover after each upscale deflection before proceeding to the next connection.

Method 2. If the vacuum pumping system is unable to evacuate the inlet plumbing to a level that will produce an on-scale reading on the vacuum gauge, disconnect the vacuum pump from the gas inlet port and replace it with a low pressure air supply with a needle valve for regulation. Slowly pressurize the gas inlet tubing, being careful to limit the pressure applied to no more than two atmospheres. Dampen the inlet tubing connections with soap solution or other leak detection solution, and watch for air bubbles forming at each connection. The presence of any air bubbles indicates a leak at the connection. Repair any connections found leaking and recheck for leaks. When no more bubbles can be found, disconnect the low pressure air supply and reconnect the vacuum pumping system. Repeat the preceding vacuum leak testing procedure.

CAUTION: Overpressure within the above limits will not damage the pressure sensor. However, slight calibration adjustments may be necessary after any overpressure. Overpressure limit: 100% of span.

Method 3. Plug one end of the sensing chamber. Attach an ordinary pump with a shutoff valve to the other end. Lower the pressure as much as possible. Close the shutoff valve and monitor pressure inside the sensing chamber to determine leak rate. With proper sealing, the pressure change rate should be less than 0.2 % of pressure differential per minute. Leaks can then be located by overpressuring the instrument as in Method 2.

7.4 Cryocooler and Cryo Sleeve Check

To check whether adequate insulation exists in the cryo sleeve, it is best to check minimum mirror temperature capability as follows, using the display module:

1. Stop sample airflow through the instrument.
2. Push COOL switch and hold, and observe mirror temperature. It should go below -95 °C. If not, the instrument is still operational, but it is beginning to lose significant insulating ability.
3. If the cryocooler or cryo sleeve must be serviced, contact Buck Research Instruments, LLC. Do not disturb either the croocooler or the cryo sleeve, and do not open the cryo sleeve without instructions from Buck Research Instruments, LLC - doing so will void the warranty and possibly damage the assembly.

7.5 Troubleshooting Guide

Display shows H2O Conc. = XXX.X :

1. This is normal. A concentration will not display until a dew or frost point is reached.

Display shows Mirror needs cleaning. Service Mirror LED blinking:

1. Mirror needs cleaning. Clean mirror
2. Optics cable is disconnected. Reconnect optics cable.

Rebalance LED stays lit after balance cycle finishes:

1. Mirror starting to get contaminated. CR-2 will continue to function normally, but be prepared to clean mirror soon.

Oscillation of output (some oscillation at dew point above 0 °C is normal):

1. Reduce sample flow until oscillation stops, then gradually increase flow again.
2. Turn instrument off, allow to warm up, and clean mirror.
3. If oscillation is slow (10-20 sec period) and most pronounced in the region -30 to -50°C, cavity resonance (interaction with contaminants in the chamber) may be occurring. Clean sensing chamber with the CR-2 cleaning fluid supplied.

APPENDIX 1: HUMIDITY CONVERSION EQUATIONS

(Revised 7/96)

Computer-efficient algorithms for converting among several humidity units, as used in HCON, are given here. They utilize vapor pressure formulations developed by A. Buck (1981).

DP	= dew or frost point in deg C
e	= vapor pressure in millibars
es	= saturation vapor pressure in millibars
P	= pressure in millibars
r	= mixing ratio by weight in ppm
RH	= relative humidity in percent
rho	= absolute humidity in g/m ³
rhos	= absolute humidity at saturation
T	= temperature in deg C
Tk	= absolute temperature in K

Saturation vapor pressure (es) = f1(T) = e/RH

Dew/frost point (DP) = f2(e) (e)
 = f2[r x P/(622 x 10³ + r)] (r)
 = f2(RH x f1(T)/100) (RH)
 = f2(rho x Tk/216.7) (rho)

Vapor pressure (e) = f1(DP) (DP)
 = r x P/(622 x 10³ + r) (r)
 = RH x f1(T)/100 (RH)
 = rho x Tk/216.7 (rho)

Mixing ratio (r), ppmw = 622x10³ x e/(P-e) (e)
 = 622x10³ x f1(DP)/[P - f1(DP)] (DP)
 = 622x10³ x RH x es/(100 x P - RH x es) (RH)
 = 622x10³ x rho x Tk/(216.7 x P - rho x Tk) (rho)

Relative humidity (RH) = 100 x f1(DP)/f1(T) (DP)
 = 100 x e/es (e)
 = 100 x r x P/[(622x10³ + r) x es] (r)
 = 100 x rho x Tk/(216.7 x es) (rho)

Absolute humidity (rho)= 216.7 x f1(DP)/Tk (DP)
 = 216.7 x e/Tk (e)
 = 0.2167 x r x P/[(622 + .001 x r) x Tk] (r)
 = 216.7 x RH x es/(100 x Tk) (RH)

mixing ratio by volume (ppmv) = mixing ratio by weight (ppmw) x 1.6077

grains/lb = r x 0.007

Precipitable cm per km = rho/10

NOTE 1: $f_1(DP)$ and $f_2(e)$ are variations on vapor pressure formulations found in Buck, A: J Appl Met 20, pp 1527-1532 (1981). They are given by:

e vs. DP or es vs. T:

$$\begin{aligned} f_1(DP) &= EF \times a_w \times \exp [(b_w - DP/d_w) \times DP / (DP + c_w)] \quad (\text{over water}) \\ &= EF \times a_i \times \exp [(b_i - DP/d_i) \times DP / (DP + c_i)] \quad (\text{over ice}) \end{aligned}$$

DP vs. e or T vs. es:

$$\begin{aligned} f_2(e) &= d_w/2 \times [b_w - s - ((b_w - s)^2 - 4 c_w \times s/d_w)^{1/2}] \quad (\text{over water}) \\ &= d_i/2 \times [b_i - s - ((b_i - s)^2 - 4 c_i \times s/d_i)^{1/2}] \quad (\text{over ice}) \end{aligned}$$

where:

$a_w = 6.1121$	$a_i = 6.1115$
$b_w = 18.678$	$b_i = 23.036$
$c_w = 257.14$	$c_i = 279.82$
$d_w = 234.5$	$d_i = 333.7$

$$s = \ln(e/EF) - \ln(a_w \text{ or } a_i)$$

$$EF_w = 1 + 10^{-4} [7.2 + P (0.0320 + 5.9 \times 10^{-6} T^2)],$$

$$EF_i = 1 + 10^{-4} [2.2 + P (0.0383 + 6.4 \times 10^{-6} T^2)],$$

where P is in millibars and T is in °C.

NOTE 2: RH is defined here using es with respect to ice below freezing. However, RH is also frequently defined using es with respect to water, even below freezing.

NOTE 3: These conversions are intended for use with moist air rather than pure water vapor. They therefore include EF, the enhancement factor, which corrects for the slight departure of the behavior of water in air from that of a pure gas.

NOTE 4: The definitions f_1 and f_2 for ice agree with an extrapolation of NBS values down to -120 deg C, within 0.5%.

APPENDIX 2: CONNECTOR PIN ASSIGNMENTS

J2 SIGNAL CONNECTOR PIN OUT

Pin	
1	Balance (0-10 V)
2	Balance Return
3	Balance (4-20 mA) (DC Power)
4	Balance (4-20 mA) Return (for self-powered loops)
5	Pressure (0-10 V)
6	Pressure Return
7	Pressure (4-20 mA)
8	Pressure (4-20 mA) Return
9	VDF (0-10 V)
10	VDF Return
11	VDF (4-20 mA)
12	VDF (4-20 mA) Return
13	H2O CONC (0-10 V)
14	H2O CONC Return
15	H2O CONC (4-20 mA)
16	H2O CONC (4-20 mA) Return

J1 POWER CONNECTOR PIN OUT

2	+28 VDC
3	+28 VDC Return (GND)
4	Chassis GND

J4 RS-232 CONNECTOR

9600 Baud, 8-N-1. Requires Female to Female null modem cable.

WARRANTY

Manufacturer warrants that the items delivered shall be free from defects (latent and patent) in material and workmanship for a period of one year after acceptance of the specific goods by Buyer. The Buyer's sole and exclusive remedy under this warranty shall be limited to repair or replacement. Defective goods must be returned to the Manufacturer promptly after the discovery of any defect within the above referenced one-year period. Transportation expenses to return unit to Manufacturer shall be borne by the Buyer. Return shipping to Buyer shall be borne by Manufacturer for valid warranty claims. This warranty shall become inapplicable in instances where the items have been misused or otherwise subjected to negligence by the Buyer

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RS-232 output stream

Connect RS-232 output using null modem cable to computer that has HyperTerminal. Set HyperTerminal for 9600-8-N-1 with flow control set to none. If the LCD display not connected and the “key” is installed in the display connector, you will see the following:

```
4088.58,-5.14,1,975.18,-11.6, 3,203,0, 16.50,2008.03.16,14:42:12
```

Mixing ratio (ppmv),mirror temperature,status flag,pressure,coldfinger temperature,balance,PWM,mirror flag,Board_temp,date,time

Where:

Mixing ratio given in ppmv. Calculated when there is a dew point (status flag = 1)

Mirror temperature is the mirror temperature.

Status flag is 0 when not controlling on a dew point, 1 when on a dew point and 2 during a balance cycle.

Pressure in mb.

Coldfinger temperature given by diode on tip of coldfinger. Should be lower than the mirror temp, but can be higher when cooling because it has slower response than the mirror temp sensor.

Balance indicates if the servo is controlling. Negative number means mirror too warm and needs to cool. Positive number means mirror too cold and needs to heat.

PWM: -255 to 255, indicates how much power is applied to TEC. – is cooling and + is heating.

Mirror flag: 0 = clean mirror, 1 = mirror contaminated, should be cleaned soon

Board_temp: temperature of main PCB

Date: date in years.months.days

Time: time in 24 hours: minutes : seconds

Manual key stroke input to RS-232

- c decrease the contrast of the LCD display by 2%
- C increase the contrast of the LCD display by 2%
- p decrease the proportional gain coefficient by 10%
- P increase the proportional gain coefficient by 10%
- d decrease the derivative gain coefficient by 10%
- D increase the derivative gain coefficient by 10%
- i decrease the integrator time constant coefficient by 10%
- I increase the integrator time constant coefficient by 10%

Each repeated key press is progressive. For example, 5 C presses will increase the contrast by 10%. 5 p presses will decrease the gain by about 40%

- R resets all coefficients and contrast to original values
- B initiates a balance routine
- G polled output of RS-232 data when LCD display switch is OFF (optional)
- F Forces frost below 0°C by cooling the mirror below -40°C

