MODEL CR-3 HYGROMETER

OPERATING MANUAL

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MODEL CR-3 HYGROMETER OPERATING MANUAL

1. INTRODUCTION

The Model CR-3 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-3 is designed for use in the laboratory or for process control**. Never install the CR-3 in an aircraft application, as this will void the warranty.** The technology incorporated in the CR-3 is protected by domestic and foreign patents.

1.1 General Description

The CR-3 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 by means of a heater/control system. Optical detectors are used for sensing condensate on a mirror, and an ultra-stable thermistor imbedded in the mirror is used to determine mirror temperature -- the dew or frost point. Since operation of the CR-3 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 main unit consists of a sensor assembly, cryocooler and control/readout circuitry. The control/readout circuitry contains a microcontroller with flash memory that can be reprogrammed in the field. If this needs to be done, contact Buck Research Instruments, LLC for instructions.

The sensor assembly consists of a sample chamber with 1.33” and 2.75” CF flanges. The 1.33” flange can use either an o-ring or a nickel or copper gasket, while the 2.75” flange captures the mirror pedestal assembly. Both are replaceable if corrosion occurs due to exposure to corrosive gases. Please contact Buck Research Instruments, LLC for instructions about replacing the mirror assembly.

A separate display module displays dew/frost point temperature, pressure, balance and allows for manual control of the instrument, but is not required for operation.

The components of the CR-3 are:

- Main unit (Cryocooler unit and display)
- Cleaning kit
- Power cables
- Interface cable (1 ft)
- Operating manual

1.2 Specifications, Model CR-3 Cryocooled Hygrometer

Measurement range	
Dew/frost point temperature	-120^{o}C to +30^{o}C*
Moisture concentration	<1 ppbv to 3% at standard pressure
Frost point reading accuracy	$\pm$ 0.15^{o}C above -70 ^{o}C $\pm$ 0.25^{o}C below -70 ^{o}C
Response time	Less than 40 sec typical
Nominal operating range	
Ambient Temperature	-20 to +40^{o}C
Operating Pressure	0 – 150 psia (0 – 10 bar)
Flow rate of sample	0.2 - 3 liters/minute
Cryocooler type:	Kleemenko cycle, mixed refrigerant
Operating lifetime:	Approx. 100,000 hours
Output signals	Dew/frost point, pressure, mirror balance, 0-10V, 4-20mA and RS-232 (9600 baud 8-N-1) outputs
Construction	Aluminum (mounting hardware) 316L Stainless steel (sensor assembly)
Input voltage	110VAC 60 Hz (220VAC 50-60 Hz requires step-up transformer)
Power consumption (typical)	< 250 watts $\pm$ 10%
Approximate dimensions, inches and (cm)	
Main unit:	16” w x 15" d x 10" h (41 x 38 x 38 cm)
Approximate Weight (excluding cable and heat sink)	
Main unit:	50 lbs (23 kg)

* +30 ^{o}C assumes an ambient temperature above +30 ^{o}C

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

2. LOCATION OF PRINCIPLE COMPONENTS

2.1 Cryocooler Unit (Figure 1)

FRONT

1. **Watlow coldfinger temperature indicator**
2. **Refrigerator pressure gauge**
3. **Air intake. Clean every 3 months.**
4. **Air exhaust. DO NOT BLOCK.**
5. **Coldfinger Temp. Adjust.**

BACK

1. **Compressor Power Switch and Power Connector**
2. **J3 Interface Connector**
3. **Pressure Sensor**
4. **Inlet**
5. **Outlet**
6. **Optics block and viewing port**
7. **Cryo Sleeve evacuation port**

Fig. 1. Cryocooler unit

FRONT

1. WATLOW TEMPERATURE CONTROLLER. This sets the coldfinger temperature. **DO NOT SET BELOW -155° C.** Temperatures below this can cause the refrigerant to freeze and cause cryocooler failure. This is already set to the correct temperature **DO NOT ADJUST**.

2. PRESSURE GAUGE. Starts at 75psi when off. Goes up to 400 psi when instrument is turned on and will vary between 200 and 400 psi after coldfinger reaches temperature set on TEMPERATURE CONTROLLER.

3. CONDENSER AND AIR INTAKE. Internal fan cools condenser and compressor/ Keep air intake and exhaust port clear of obstruction or overheating will result. Clean air intake of dust as needed.

4. COLDFINGER TEMPERATURE ADJSUTMENT. If using the CR-3 on 50 Hz, you may need to adjust so that the cooler will cool to -155 ºC. The compressor may not cool as much on 50 Hz, and the pot is adjusted to not go below -156 ºC on 60 Hz power. It is important that the coldfinger does not cool below -156 ºC as compressor damage will result. To adjust the temperature, loosen the nut and adjust pot counter-clockwise using a screwdriver. Once properly adjusted, retighten nut.

BACK

1. COMPRESSOR POWER SWITCH AND POWER CONNECTOR. Turns on power to the cryocooler compressor. Connect power connector to the mating power connector on the display box using the included cable.

2. J3 INTERFACE CONNECTOR. This connector **must** be connected to the mating connector on the Display Box in order for the CR-3 to function.

3. PRESSURE SENSOR. Druck precision 0-10 bar sensor.

4. INLET. Do not overstress when attaching tubing. Use stainless steel tubing for measuring below -70 ºC.

5. OUTLET.

6. OPTICS BLOCK AND VIEWING PORT. Contains LED and detectors that measure mirror reflectivity. Also has viewing port for observing frost or dew formation on the mirror.

7. CRYO SLEEVE EVACUATION PORT. This dewar plug can be used to reevacuate cryo sleeve. Contact Buck Research Instruments, LLC for instructions if you think that this needs to be done.

2.2 Display (Figure 2)

FRONT

A. DEW/FROST POINT DISPLAY. This is the primary display. On the top line, H2O concentration is displayed once a dew point is reached. Mirror temperature is displayed as Mirror T = until Balance is within 200 counts of 0, then D/F Point = is displayed. On the next 2 lines, pressure and balance are displayed.

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 LED stays lit 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.

BACK

1. Main Power Connector and Switch
2. Main Fuse
3. Cryocooler Power Connector
4. Interface Cable Connector
5. Signal Out Connector (DATA OUT)
6. Serial Connector (RS-232 8-N-1 9600 BAUD)

Figure 2. Display module (front and back)

3. INSTALLATION AND OPERATION

3.1 Installation

1. Inspect the instrument for mechanical or other damage

2. Install the CR-3 in its permanent location.

3. WAIT AT LEAST 24 HOURS BEFORE TURNING THE UNIT ON THE FIRST TIME THAT IT IS UNPAKCED. FAILURE TO DO SO WILL VOID THE WARRANTY. THIS IS TO ENSURE THAT ALL THE COMPRESSOR OIL HAS SETTLED AND IT IS SAFE TO TURN ON THE COMPRESSOR.

4. Connect the inlet and outlet gas flow lines to the sensor assembly with dry gas (dew point of -40°C or less) flowing through the sensor. Make sure there is some flexibility in both inlet and outlet lines to avoid stress and possible damage to the CR-3. 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.

5. 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 7.3. This is especially important when operating the instrument in a humidity environment that is very different from that of the sampled air.

3.2 Power-up Procedure

1. Connect the cryo unit power and interface cables to the display.

2. Flip the main power switch to the ON position. The display will turn on and the main control board will initialize. Wait for the instrument to finish initializing and do a Balance Routine before continuing to setp 3. When the Balance Routine is finished, the display will show H2O Conc., Mirror T, Pressure and Balance on the display.

3. Flip the compressor power switch to the ON position. Monitor the coldfinger temperature on the front of the main unit. It should reach –155 within an hour with dry gas flowing through the sample chamber.

4. Then, wait for the instrument to stabilize at the operating point. The balance reading (BALANCE) should be within 200 counts of 0.

5. The instrument is now ready for use.

NOTE: It is always advisable to start measuring at relatively high humidity values (above -60^{o}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, heating the mirror up for a few seconds by pressing the HEAT button can speed up initial acquisition of frost. When the mirror is colder than the dew point of the gas, moisture condenses adjacent to the mirror surface where the temperature is below the dew point. When the mirror is heated, these surfaces are heated above the dew point and that moisture then recondenses on the mirror as long as the mirror stays below the dew point. This causes the balance number to head in a positive direction, speeding up acquisition time. Be careful, if you press the HEAT button for too long, you can burn the layer completely off and you will have to start over again. If you do this several times in a row, you can cut acquisition time from hours to minutes depending upon the dew point of the gas.

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

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.

The Display Module provides convenient displays for most parameters, as an alternative to the signal outputs available at J2 or RS-232 output on J4. Both dew/frost point (mirror temperature) indications are accurate to 0.1 ^{o}C. The Display Module should be connected only when the power is off. The Display Module can be disconnected at any time.

Normal operation is indicated by BAL reading within 200 counts of 0; 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 reading BAL to completely stabilize before taking a reading.

To avoid internal line condensation and resultant erroneous readings, do not allow the inlet lines to cool below the expected frost point temperature.

3.4 Power-down Procedure

1. If contamination is a likely hazard, shut off flow through the sensor to protect the mirror. Otherwise, flow dry gas through the sample chamber.

2. Flip the Compressor Switch to OFF. Wait 5-10 minutes. Press the BALANCE switch. This helps to heat the mirror so that does not stay cold for as long.

3. Turn the Main Power Switch to OFF.

The mirror will remain very 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, pin 7.
H2O CONC	ppbv, ppmv, PPTV, 0-10V (optional), pin 9.
BAL	Balance voltage, 0-10V, pin 3.

4.2 Data Reduction Equations

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

$$T_{df} = [-150 + 20 \times VDF]. \qquad (1)$$

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.

Pressure Correction: Dew/frost point temperature (or humidity in any other units) may be corrected for variations in chamber pressure as follows:

1. Convert dew/frost point reading to vapor pressure e.

2. Calculate corrected vapor pressure e_c, according to

$$e_c = e \times p_a/p_c, \qquad (3)$$

where p_a = ambient (static) pressure, and
p_c = chamber pressure.

3. Convert e_c back to dew/frost point temperature, or to other units as needed.

5. PRINCIPLES OF OPERATION

5.1 General

The CR-3 is a chilled-mirror, condensation-type hygrometer, consisting of the following principle components: a 316L stainless steel mirror with an attached stem, an associated temperature sensor and heating coil, an MMR Kleemenko 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 that 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-3 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 3 and the sensor assembly is diagrammed in Figure 4.

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.

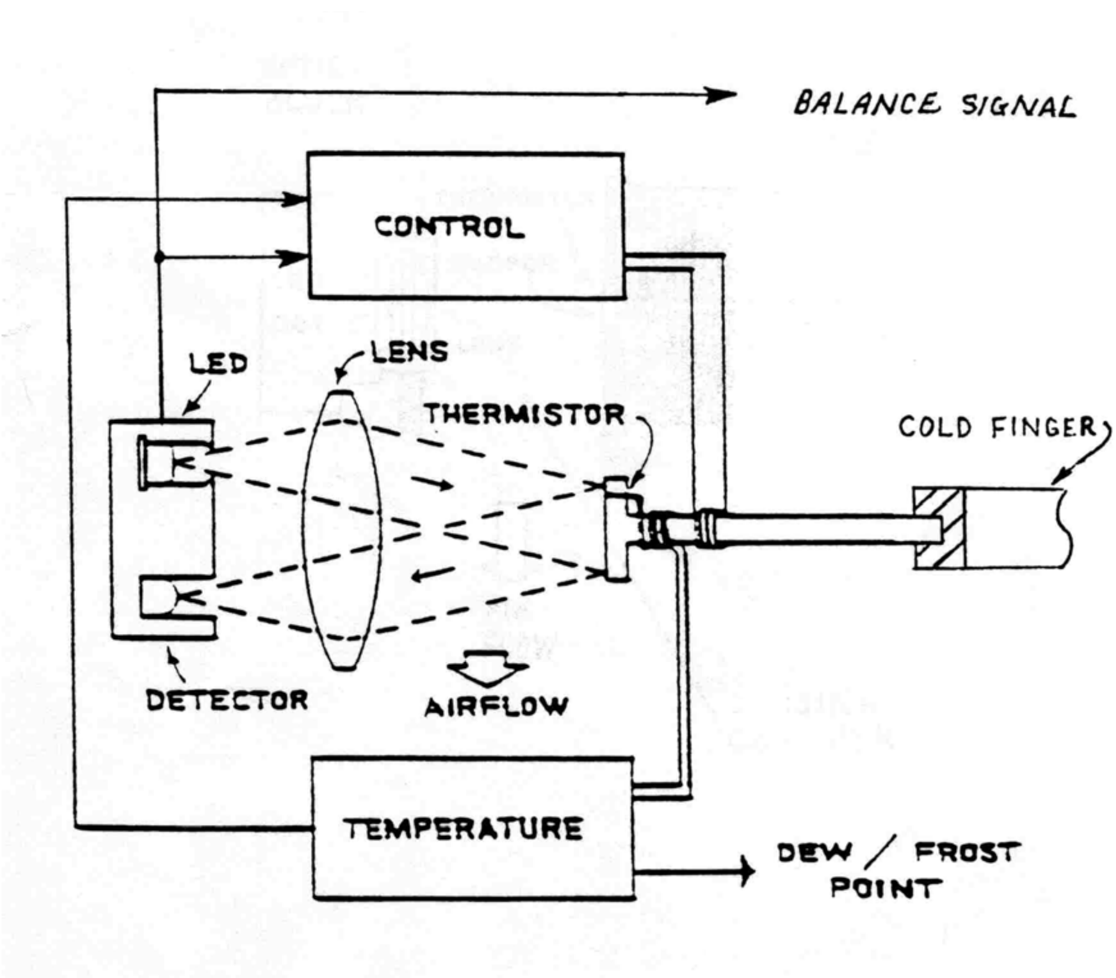

Fig. 3. Block diagram, CR-3 frost-point hygrometer

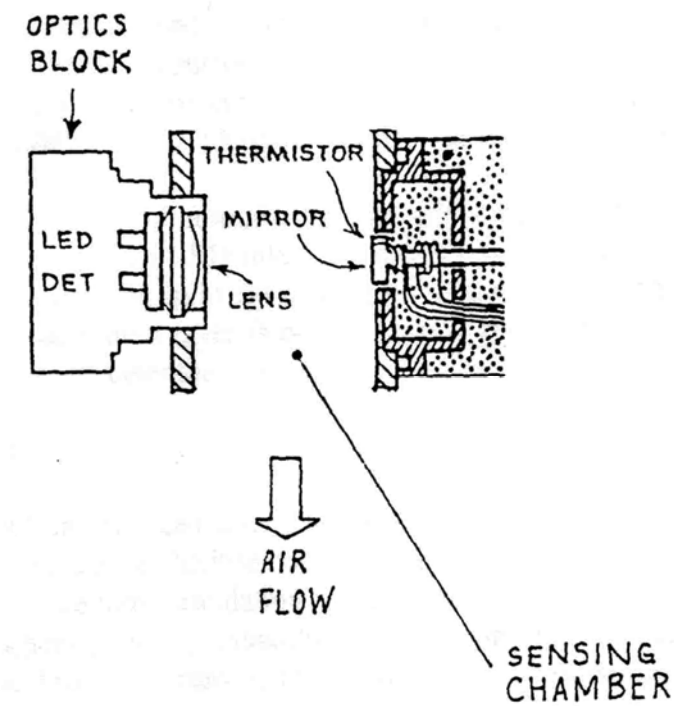

Fig. 4. Sensor assembly block diagram

The sampling system must be carefully sealed to prevent room air from contaminating the measurements. This is accomplished using nickel or copper gaskets with knife-edge seals. 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 sensor which are attached to the mirror. 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 sensor located at the tip of the stem monitors stem 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 80 % 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 mixed refrigerant 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 sleeve containing cryogenic insulation and backfilled with CO2.

5.2.5 Thermistor Readout

For obtaining the dew or frost point temperature from the temperature senor, three readouts are provided: VDF signal voltage, RS-232 output and a direct temperature indication on the display. Both are accurate within 0.1^{o} 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^{o}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)

3. Maintaining good insulation in the cryo sleeve (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.

2. See Appendix 4 for detailed procedure.

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 can be effective.)

   CAUTION: The mirror surface 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 air flow through the instrument.

2. Push COOL switch and hold, and observe mirror temperature. It should go to -125 ^{o}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, return the CR-3 to Buck Research Instruments, LLC. Do not disturb either the crocooler or the cryo sleeve, and do not open the cryo sleeve - doing so will void the warranty and possibly damage the assembly.

7.4 Troubleshooting Guide

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-3 will continue to function normally, but be prepared to clean mirror soon.

Oscillation of output:

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^{o}C, cavity resonance (interaction with contaminants in the chamber) may be occurring. Clean mirror with acetone followed by water.

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/m3
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 10^3 + 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 10^3 + r)	(r)
	= RH x f1(T)/100	(RH)
	= rho x Tk/216.7	(rho)
Mixing ratio (r), ppmw	= 622x10^3 x e/(P-e)	(e)
	= 622x10^3 x f1(DP)/[P - f1(DP)]	(DP)
	= 622x10^3 x RH x es/(100 x P - RH x es)	(RH)
	= 622x10^3 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/[(622x10^3 + 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: f1(DP) and f2(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:

$$f1(DP) = EF \times aw \times \exp [(bw - DP/dw) \times DP/(DP + cw)] \quad \text{(over water)}$$

$$= EF \times ai \times \exp [(bi - DP/di) \times DP/(DP + ci)] \quad \text{(over ice)}$$

DP vs. e or T vs. es:

$$f2(e) = dw/2 \times [bw - s - ((bw - s)^2 - 4\ cw \times s/dw)^{1/2}] \quad \text{(over water)}$$

$$= di/2 \times [bi - s - ((bi - s)^2 - 4\ ci \times s/di)^{1/2}] \quad \text{(over ice)}$$

where:

aw = 6.1121	ai = 6.1115
bw = 18.678	bi = 23.036
cw = 257.14	ci = 279.82
dw = 234.5	di = 333.7

$s = \ln (e/EF) - \ln (aw \text{ or } ai)$

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

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

where P is in kPa and T is in ^oC.

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 f1 and f2 for ice agree with an extrapolation of NBS values down to -120 deg C, within 0.5%.

APPENDIX 2: CONNECTOR PIN ASSIGNMENTS

J2 16-pin Signal connector

Pin	
1	N/C
2	N/C
3	Balance
4	Balance Return
5	N/C
6	N/C
7	VDF
8	VDF Return
9	H2O Conc.
10	H2O Conc. Return
11	Alarm 1
12	Alarm 2
13	Program jumper
14	Program jumper
15	Shield
16	Shield

J3 24-pin Display connector

Pin	
1	Heat Switch
2	Cool Switch
3	Common
4	Balance Switch
5	Service Mirror LED
6	Rebalance LED
7	Rebalance LED Return
8	Service Mirror LED Return
9	Shield
10	+5V
11	Common
12	Data
13-37	Not used

J4 RS-232 connector

9600 Baud, 8-N-1. Flow control - NONE. Use null modem cable with Female/Female ends.

APPENDIX 3: 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

NOTWITHSTANDING ANY OTHER PROVISION OF THIS CONTRACT, NO OTHER WARRANTIES WHETHER STATUTORY OR ARISING BY OPERATION OF LAW, EXPRESSED OR IMPLIED, INCLUDING BUT NOT LIMITED TO THOSE OF MERCHANTABILITY OR FITNESS FOR PARTICULAR PURPOSE, SHALL APPLY TO THE GOODS OR SERVICES PROVIDED HEREUNDER, OTHER THAN THE REPAIR AND REPLACEMENT WARRANTY ABOVE . SELLER SHALL IN NO EVENT BE LIABLE TO BUYER OR ANY THIRD PARTY FOR ANY DAMAGE, INJURY OR LOSS, INCLUDING LOSS OF USE OR ANY DIRECT OR INDIRECT INCEDENTAL OR CONSEQUENTIAL DAMAGES OF ANY KIND.

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Appendix 4. CR-3 Mirror Cleaning Procedure

Removal

Insert 3/32" ball driver through the 2 top holes of the optics cap to find the 4-40 socket head screws inside. Loosen those screws to remove the optics block. Using the 9/64" ball driver, completely remove all 6 socket head screws from the lens holder. Be careful when removing the last screw as there is a nickel gasket in between the lens holder and the top of the sample chamber. Also, the lens sticks out of the lens holder, so do not place the lens holder lens-side down. Always have the lens facing you when setting the lens holder down. You should be able to reuse the gasket about 10 times, and if you are lucky and do not touch it, the gasket will stay in place.

Cleaning the Mirror

Once you have access to the mirror, dip a cotton tipped applicator in acetone and clean the mirror gently. Use each applicator only once. After the mirror has been cleaned with acetone, wipe the mirror with a dry applicator. Then dip another applicator in water and wipe the mirror off again. Finally, wipe the mirror off with a dry applicator to complete the cleaning process.

Replacement

Now, put the lens holder back on the sample chamber.Use the index marks to get the correct alignment. Start middle 2 screws that are 180 degrees apart. Leave a ¼” gap for the gasket if the gasket has separated from the sample chamber. Next, insert the bottom 2 socket head screws to prevent the gasket from falling through. Drop the gasket into the ¼” gap making sure that it is in the correct position before tightening the screws any further. If the gasket is sitting too low a small metal strip or a metal ruler can be used to lift the gasket (or optional viton o-ring) back into place. Tighten the captive screws first, using the 9/64" ball driver. Alternate back and forth between both screws. Tighten the other 4 socket head screws making sure that there is no gap between the sample chamber and the lens holder. Do not use excessive force when tightening the screws. Do a leak check now. If there is a leak, alternate tightening the 6 screws by tightening the screw 180 degrees from the one just tightened, then move to the next screw and do the same thing. (If you number the screws 1-6 where 1 is on the top, go 1-4-2-5-3-6.) You may need to use a right-angle 9/64” hex key to get more torque if the ball driver will not tighten the screws any more.

Lastly, put the optics block and cap back on using the 5/64' ball driver. Insert the ball driver into the 2 holes on top of the optics cap to find the socket head screws in the optics block. Make sure that there is no gap between the optics block and the lens holder.

NEVER TILT THE CR-3 TO CLEAN THE MIRROR. IF THE CR-3 IS TILTED, YOU MUST WAIT 24 HOURS BEFORE APPLYING POWER OR THE COMPRESSOR WILL BE DAMAGED.

Figure 5. Complete unit with cables connected.

Addendum:

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 2/3rds
P increase the proportional gain coefficient by 50%
d decrease the derivative gain coefficient by 2/3rds
D increase the derivative gain coefficient by 50%
i decrease the integrator time constant coefficient by 2/3rds
I increase the integrator time constant coefficient by 50%

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 87%

R resets all coefficients and contrast to original values
B initiates a balance routine