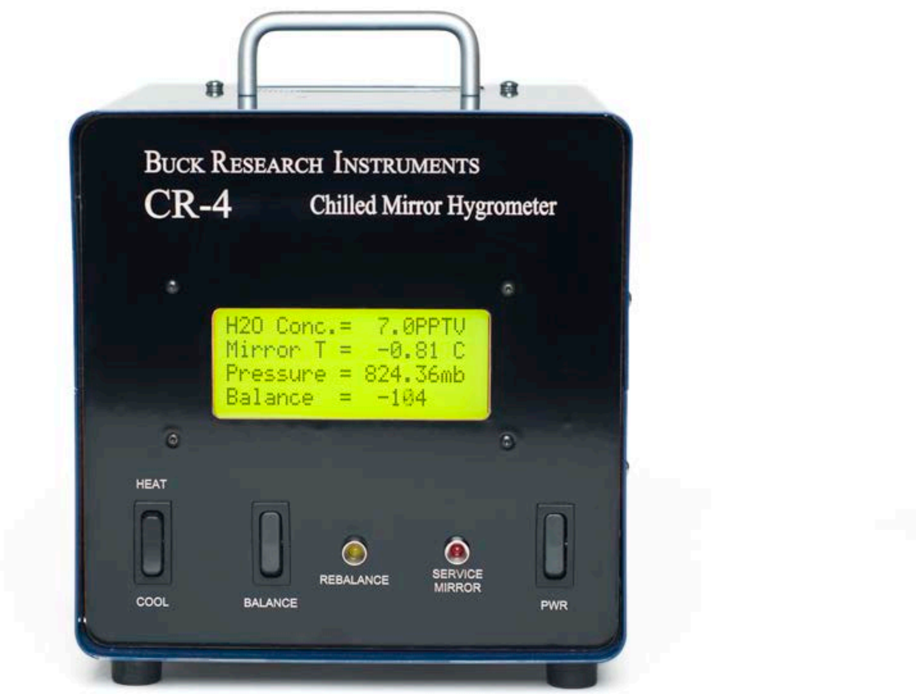
MODEL CR-4 HYGROMETER

OPERATING MANUAL



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MODEL CR-4 HYGROMETER OPERATING MANUAL

1. INTRODUCTION

The CR-4 is a chilled mirror hygrometer that uses a 3-stage thermoelectric cooler (TEC) to enable frost point measurements of as low as –60°C, under favorable ambient conditions. Depending upon configuration, it can measure dew points as high as +60°C and can display moisture concentration (ppmv or lbs/MMscf) with optional pressure sensor or %RH with optional ambient temperature sensor. The CR-4 is designed to measure in air and most non-corrosive gases at pressures ranging from near vacuum to up to 100 psia, or as high as 1000 psia with optional high pressure sample chamber.

1.1 General Description

The CR-4 is a chilled mirror, condensation type hygrometer. It achieves its high performance by heating and cooling a mirror, using a thermoelectric cooler (TEC), and holding the mirror at the dew or frost point by means of a servo control system. An IR LED and optical detectors are used for sensing condensate on a mirror, and an ultra-stable temperature sensor imbedded in the mirror is used to determine mirror temperature - the dew or frost point. Since operation of the CR-4 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. We do recommend having the unit sent in for validation

The CR-4 features an autobalancing function that automatically adjusts for mirror contamination. To keep a constant layer of dew or frost on the mirror, the reflectivity of the mirror must be measured when the mirror is completely cleared of condensation and when it is completely obscured by condensation. Once this is done, 20% of this span is calculated and set to be the control point. This is achieved by heating the mirror to a high enough temperature to remove condensation, then turning on and off the LED that shines on the mirror. If contamination ever gets to be enough that the control point cannot be achieved, another balance function will be initiated and the control point reset. Once the contamination becomes too great, an LED is illuminated to indicate that the mirror needs to be cleaned.

The CR-4 is microcontroller-based. The microcontroller uses flash memory that is field-programmable and updateable. If this is required, please contact Buck Research for instructions.

The components of the CR-4 are:

- Main unit containing sensor assembly and LCD display
- Power cable and 24 VDC brick power supply
- Data connector with pins and Null Modem cable
- Operating manual
- Cleaning Kit with spares

Optional parts:

- Membrane filter with spares
- Glycol filter with spares
- Pressure regulator and 0-5 lpm flowmeter

1.2 Specifications, Model CR-4 Chilled Mirror Hygrometer

Measurement range:	
Dew/frost point temperature:	-60°C to ambient[1]
Moisture concentration:	1 lb/MMscf (20 ppmv) to 3% at standard pressure
Dew/Frost point reading accuracy:	± 0.1°C
Response time (10 degree step):	Less than 20 sec typical[2]
Nominal operating range:	
Ambient Temperature:	-40 to +40°C
Relative Humidity:	0 to 100% RH, non-condensing
Flow rate of sample:	0.2 - 2 liters/minute
Max pressure rating:	150 psia
Thermoelectric cooler type:	3-stage cascade
Output signals:	Mirror temp, balance, concentration and pressure 0-10 V, 4-20 mA and RS-232
Construction	Aluminum and steel (case) 316L SS (sensor assembly)
Input voltage	100-240 VAC, 50-60 Hz (brick supply) 24-28 VDC (without brick supply)
Power consumption (typical)	< 45 watts
Dimensions, inches and (cm):	8" (20) w x 10.5" (26) d x 9" (22.5) h
Approximate Weight:	8.8 lbs (4 kg)

[1]Do not attempt to read dew points above ambient without heating sample lines and sample chamber. Please contact Buck Research Instruments, LLC if you plan to do this.

[2]Response time once initial frost layer acquired. See section 7 for ways to dramatically improve the speed of initial frost formation, which can otherwise take 15 to 30 minutes.

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

2. LOCATION OF PRINCIPAL COMPONENTS

2.1 Main Unit (Figure 1)

Front

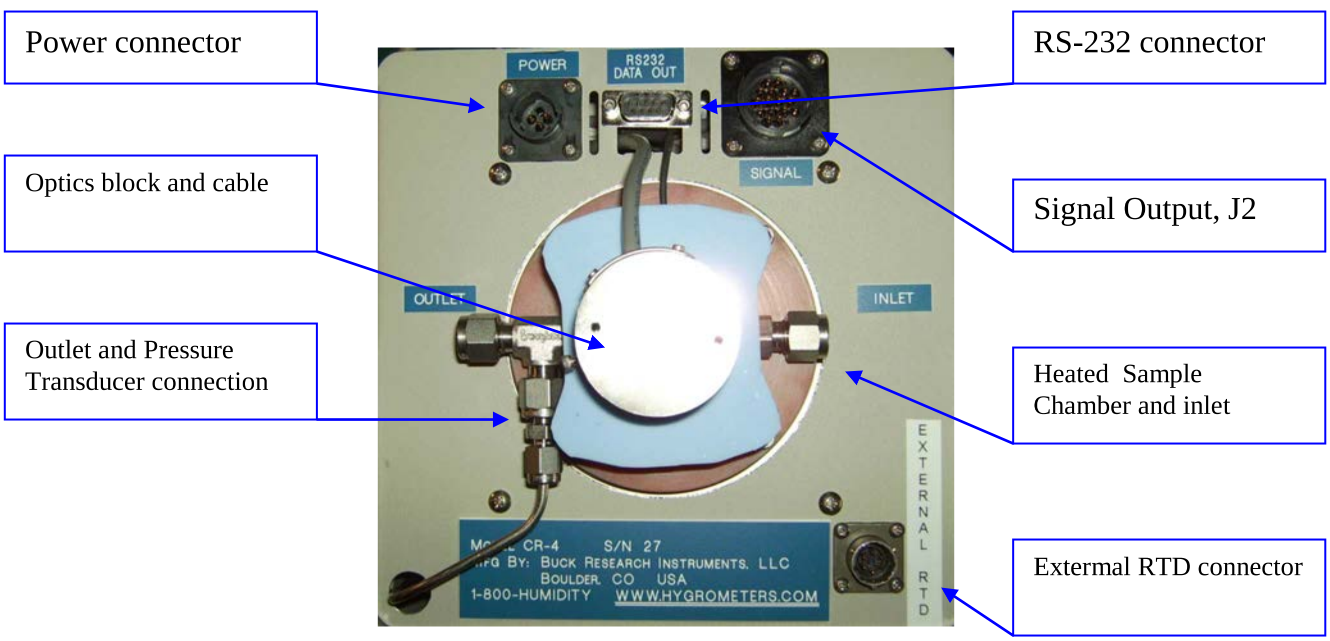

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Fig. 1. Main unit

A. BALANCE SWITCH (momentary). Depress for 5 seconds to initiate a balance cycle. This will heat the mirror up to +30° C to clear off condensation and rebalance the optics circuit.
B. HEAT/COOL SWITCH (momentary). Provides additional heat to partially clear the mirror of condensate, or full cooling to allow additional frost to collect on the mirror. Also used to speed initial layer formation. See section 3.2.
C. REBALANCE LED. Lights during balance cycle. Also stays lit after balance cycle if there is a small amount of contamination on the mirror.
D. DISPLAY. Backlit LCD display that displays moisture concentration (H2O Conc,), mirror temperature (Mirror T or D/F Point when dew or frost point acquired), pressure and balance (± 200 when dew/frost point acquired). For optional Ambient Temperature units display shows Ambient Temperature first, then mirror temperature, pressure and balance.
E. POWER SWITCH
F. SERVICE MIRROR LED. Flashes when there is too much contamination on mirror. Mirror must be cleaned to restore normal operation of instrument.
G. OUTLET AND PRESSURE TRANSDUCER. Connect sampling pump or vent here. 1/8" tubing goes to pressure transducer inside instrument.
H. OPTICS BLOCK AND CABLE. Contains LED and detector that looks at mirror through lens. Use 5/64 ball driver to access mirror here. See section on mirror cleaning.
I. POWER CONNECTOR. Connect included power supply to this connector.
J. RS-232. Connect to data acquisition system or PC running Hyperterminal .
K. INLET AND HEATED SAMPLE CHAMBER. Connect tubing to inlet. The chamber is heated to about 60 C. The blue silicone cover is there to insulate the chamber and to protect anyone who may touch the chamber.
L. EXTERNAL RTD CONNECTOR. For connecting optional RTD for measuring ambient temperature.
M. SIGNAL OUTPUT 0-10 V and 4-20 mA outputs for various signals. See section 4.

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-4. NOTE: do not over tighten Swagelok-type fittings. Over tightening can destroy their sealing ability. Adjust the flow rate of the gas so that it is less than 2 lpm (4 scf/h).

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. 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 external power supply to the power connector on the back of the instrument. Flip the power switch to the ON position.

2. After initialization of the electronics, a balance cycle will be initiated. The Rebalance LED will light and the display will show an increasing mirror temperature until +50° C is reached.

3. Then, wait for the instrument to stabilize at the operating point. The mirror temperature will decrease until the Balance value gets close to 0. Then the mirror temperature will increase until the Balance voltage stays between ± 200, at which point the display changes from Mirror T to D/F Point and H2O Conc. Will change from XXX.X to a value.

4. The instrument is now ready for use.

   NOTE: It is always advisable to start measuring at relatively high humidity values (above -20°C), to allow easy acquisition of condensation, and then go down in frost point temperature. If it is necessary to begin operating initially at very low frost points, acquisition of frost can be speeded up by use of the HEAT/COOL SWITCH and by spiking the pressure inside the sample chamber. To do this, stop flow through the sample chamber for no more than 1-2 seconds by putting a finger over the outlet of tubing connected to the outlet of the sample chamber, or closing a valve downstream of the outlet of the sample chamber. This will spike the pressure inside the chamber, causing a large amount of moisture to collect on the mirror. Watch the BALANCE value on the display. It will go positive. As soon as the value stops increasing depress the COOL switch and hold it. This will keep the frost layer on the mirror from being burned off and enable readings within 1 or 2 minutes instead of 10 to 20 minutes.

3.3 Operation

During operation, no special attention is required. If possible, keep flow in the range 0.5 - 2 liters/minute (0.25 – 4 scf/h).

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. WHEN MEASURING WATER CONCENTRATION IN NATURAL GAS, A GLYCOL-ABSORBING FILTER, SUCH AS AN A+ GLYSORB FILTER, MUST BE INSTALLED BEFORE THE INLET TO THE CR-4 OR ERRONEOUS READINGS WILL RESULT.

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 D/F point temperature 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.

2. Flip the Power Switch to OFF.

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

3.5 Battery Power (optional)

If supplied with optional 24V 9Ah NiMH batteries, which should allow for between 6 and 8 hours of continuous operation, note the following. When the power supply brick is connected to the back of the CR-4 and plugged in to AC power and the LED on it is lit, the batteries will be charging. The current to the batteries is limited to 1A during charging, which means that it will take at least 9 hours to charge them when fully depleted. If the batteries get within 10% of completely discharged, the unit will display “Low Battery” on the LCD display and the backlight and both LEDs will flash until the unit is turned off. Please turn off the unit and connect up the power supply brick. If you want, you can then turn the CR-4 back on and continue to use it while the batteries are charging. **It is strongly recommended that the power supply brick be disconnected from the back of the CR-4 when it is not being used for extended periods of time, as the battery pack continues to charge in this situation.** There is protection built in to limit the amount of charge below what is unsafe for NiMH batteries, but the battery pack will get warm and waste power in this situation. Also, if the brick is connected to the CR-4, but not connected to AC power, the batteries will also discharge slowly through the brick supply. You can see this because the LED on the brick will stay lit. That is why the brick needs to be disconnected at the CR-4 and not at the AC power input.

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 (optional)
BAL	Balance voltage, 0-10v and 4-20 mA
VAMB	Ambient temperature, 0-10v and 4-20 mA (optional)

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} (°C) = [-100 + 20 x VDF(v)]. (0-10V) (1)
T_{df} (°C) = [-100 + 8 x IDF(ma)]. (4-20 mA) (2)

VAMB: Chamber temperature is determined from VAMB by:

T_{amb} (°C) = [-100 + 20 x VAMB(v)]. (0-10V) (3)
T_{amb} (°C) = [-100 + 8 x IAMB(ma)]. (4-20 mA) (4)

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

Press = (Vpress – 1.6) * 1.5625 (0 – 10 bar sensor) (/10 for 1 bar sensor) (5)
Press = (Ipress – 4) / 1.6 (0 – 10 bar sensor) (/10 for 1 bar sensor) (6)

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-4 is a chilled-mirror, condensation-type hygrometer, consisting of the following principle components: a rhodium-plated copper mirror with an attached stem, an associated temperature sensor, a 3-stage thermoelectric cooler (TEC), an optical system to sense condensing frost or dew (mirror reflectance) and control circuitry for controlling mirror temperature via the TEC.

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-4 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 Instruments 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 chilled mirror hygrometer is given in Figure 2 and the sensor assembly is diagrammed in Figure 3.

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.

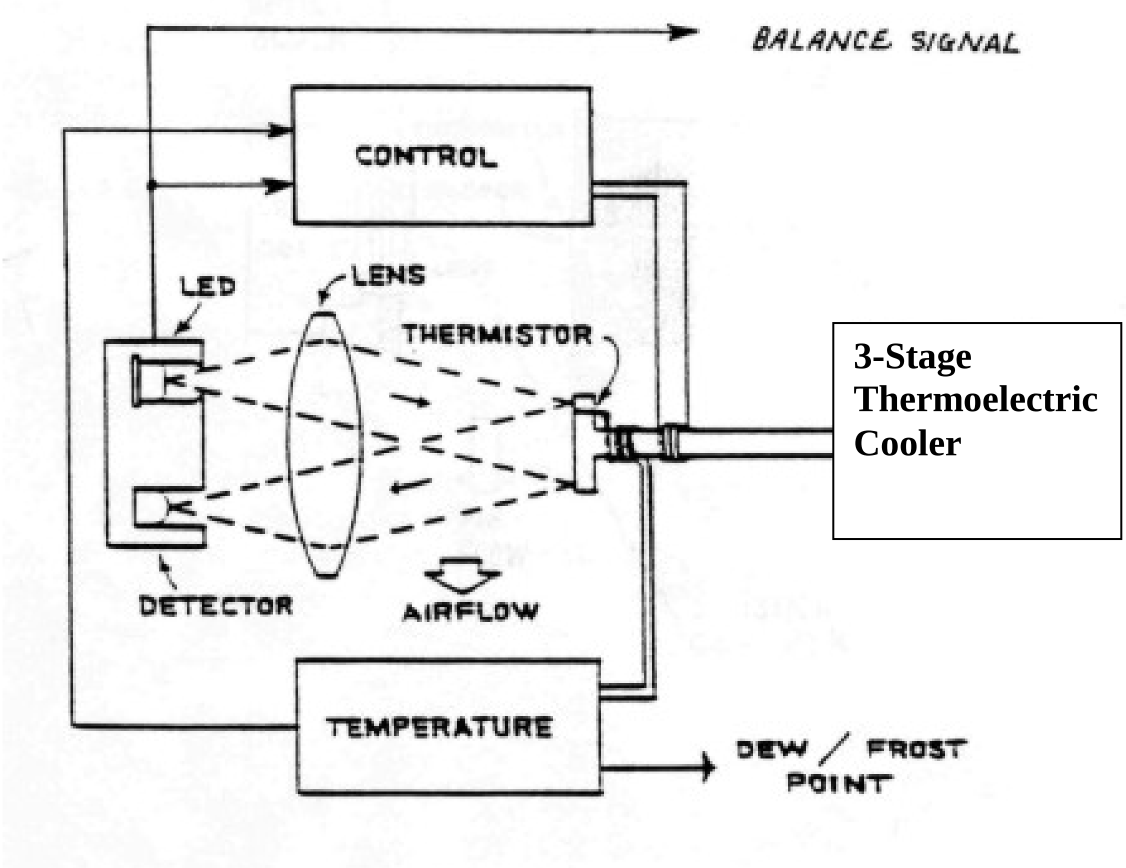

Fig. 2. Block diagram, CR-4 chilled mirror hygrometer

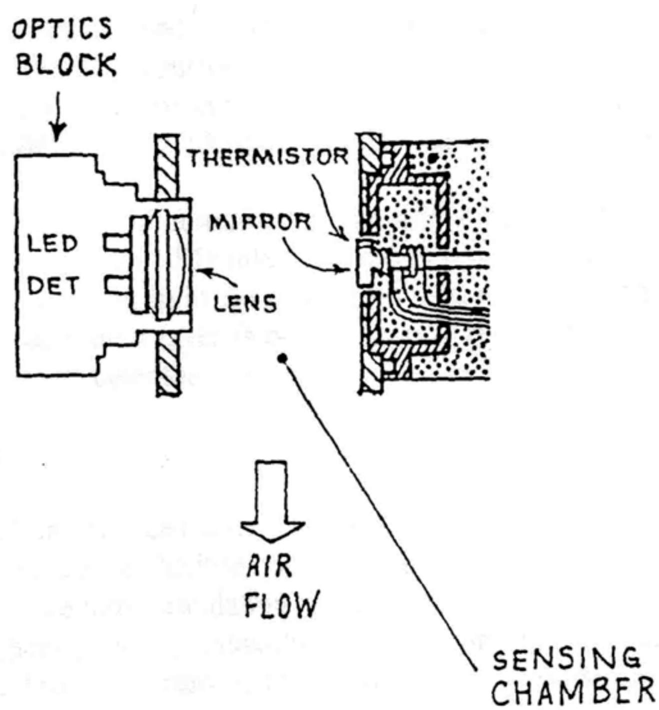

Fig. 3. Sensor assembly block diagram

The sampling system must be carefully sealed to prevent room air from contaminating the measurements.

5.2.2 Mirror Module

The mirror assembly consists of a mirror, a mirror support, a temperature sensor, a 3-stage TEC, a heat sink and a fan. A small, ultra-stable temperature sensor is installed in the mirror face to measure the dew/frost point temperature. Heating and cooling is provided by the 3-stage TEC, heat sink and fan.

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 photodiode pair and a light emitting diode (LED). One photodiode maintains constant LED intensity; the other photodiode 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 is thermally coupled to the 3-stage TEC by a thermally conductive coupling. In operation, heat is pumped away from the TEC by the heat sink and fan. Since the TEC 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 TEC are surrounded by ULTEM, which is also resistant to acetone.

5.2.5 Temperature 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. All are accurate within $\pm 0.1^{o}C$ 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°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)

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 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. <u>Never use alcohol</u> 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 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-4 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. There may be liquid water in the chamber.
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 sensing chamber with the CR-4 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/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	= (18.02/ M.W. of gas) x 10^6 x e/(P-e)	(e)
	= (18.02/ M.W. of gas) x 10^6 x f1(DP)/[P - f1(DP)]	(DP)
	= (18.02/ M.W. of gas) x 10^6x RH x es/(100 x P - RH x es)	(RH)
	= (18.02/ M.W. of gas) x 10^6 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 (M.W. of gas)/ 18.02
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:

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

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

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 millibars 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	Balance (0-10 V)
2	Balance Return
3	Balance (4-20 mA) Return
4	+24 VDC
5	Pressure (0-10 V)
6	Pressure Return
7	Pressure (4-20 mA) Return
8	+24 VDC
9	VDF (0-10V)
10	VDF Return
11	VDF (4-20 mA) Return
12	+24 VDC
13	VAMB or H2O Conc. (0-10V)
14	VAMB or H2O Conc. Return
15	VAMB or H2O Conc. (4-20 mA) Return
16	+24 VDC

J4 RS-232 connector

Pin	
2	Rx (Data In)
3	Tx (Data Out)
5	Gnd

Use Hyperterminal with settings: 9600 Baud, 8-N-1. Flow control set to NONE. Use null modem cable with Female/Female ends.(Included)

External RTD connector

Pin	
A	RTD Power
B	RTD Sense +
C	RTD Sense –
D	RTD Ground

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.

APPENDIX 4: INSTRUCTIONS FOR USING CR-4 WITH A SAMPLING PUMP.

1. You will need 2 pieces of tubing.
2. Connect one end of one piece of tubing to the outlet of the flowmeter and the other end to the sampling pump.
3. Connect one end of the other piece of tubing to the inlet (bottom) of the flowmeter and place a ¼” Swagelok ferrule on the other end of the tubing. Connect the Swagelok connector to the outlet of the CR-4. Outlet is the side where the pressure sensor connects, or the right side when looking at the front of the instrument.
4. Connect your piece of tubing to the inlet of the CR-4, tubing should be stainless steel or heated, depending upon the application. If you don’t have tubing, place the CR-4 in the path of the dry air after you complete step 8 below. Connect filter (if included) to other end of tubing.
5. Plug in power to the CR-4 using the included brick power supply.
6. Turn on CR-4. Once balancing is complete, record the pressure. This is ambient pressure.
7. Turn on pump. Use knob on flow meter to keep flow at 1lpm. Record the pressure again. There will be an offset of 5-10 mb between this reading and ambient pressure. Record this difference and remember to add this value to the reading on the display (and RS-232 output) to obtain ambient pressure. NOTE: Sensor pressure is what is relevant for doing conversions to mixing ratio and not ambient pressure.
8. Allow CR-4 to settle. At normal ambient temperatures, this should take no more than 1-2 minutes. At –30 to 40 C this can take about 10 minutes. This is dependent upon how long it takes to acquire a layer of frost on the mirror. One way to speed this up is to put your finger over the outlet of the sample pump for a second or two and then remove your finger from the outlet. Watch the balance signal. It will start to go positive. At the same time, the heater will start heating the mirror. If you push and hold the cool switch at the right time, usually when the balance starts to go back down from high positive numbers closer to 0, you will keep an adequate layer on the mirror and get a reading much quicker.

RS-232 output stream when LCD display is switched off (optional)

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 display is not switched off, HyperTerminal will display what is on the LCD display on the front panel of the CR-4. If the LCD display is turned off, you will see the following:

XXX.X,28.13,2,0,0,0,0,0, 27.50,03/17/03,16:43:30
XXX.X,27.72,0, 835.0,-8396,0,0, 28.00,03/17/03,16:43:31
1.4,-18.91,1, 835.0,153,155,0, 27.50,03/17/03,16:50:01

Mixing ratio, temp, status, pressure, balance, PWM, mirror, board_temp, date, time

Where
Mixing ratio: ppmv or parts per thousand by volume (PPTV). XXX.X = not on a dew point (status != 1)
temp : mirror temperature in degrees C
status : 0 = mirror temperature, 1 = dew/frost point, 2 = balance routine
pressure : pressure in mb
balance : within + or – 300 counts of zero indicates dew or frost point
PWM : 0 to 255, indicates how much power is applied to heater
Mirror : 0 = clean mirror, 1 = mirror contaminated, should be cleaned soon
Board_temp : temperature of main PCB
Date : date in months/days/years
Time : time in 24 hours: minutes : seconds

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 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 60%. 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)