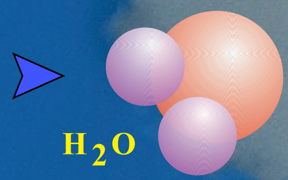
NVLAP
Laboratory Code 200582-0

Thunder Scientific Corporation



Precision Humidity Generation, Calibration and Measurement

THUNDER SCIENTIFIC CORPORATION
623 WYOMING BLVD. SE ⚡ ALBUQUERQUE, NEW MEXICO 87123-3198
800-872-7728 ⚡ TEL: (505) 265-8701 ⚡ FAX: (505) 266-6203
WWW.THUNDERSCIENTIFIC.COM

1966 45TH ANNIVERSARY 2011

Click here to visit Thunder's website.

www.thunderscientific.com

About Thunder

Humidity Calibration Equipment and Service...

Thunder Scientific is the leading manufacturer of NIST traceable humidity calibration equipment for humidity sensors, hygrothermographs and dewpoint hygrometers. Thunder Scientific can calibrate and certify, through the use of fundamentally based two-pressure and two-temperature humidity generator standards, originally established by NIST, virtually any type of humidity sensor or dewpoint measuring equipment over the frostpoint/dewpoint range of -95 °C to +65 °C. Utilizing the speed and reliability of today's computers, the humidity generation process has been automated, increasing overall accuracy and repeatability while reducing uncertainties due to human error or misinterpretation of data. Toward the goal of increased accuracy, the computer now controls all aspects of the humidity generation, freeing the operator from the burden of continuous and tedious humidity calculations and corrections. The staff at Thunder Scientific has experience with a wide variety of different humidity and dewpoint sensing probe configurations enabling a quick turn around for your instrument. It will be returned with a detailed Certificate of Calibration, which conforms to ISO/IEC17025:2005 and relevant requirements of ANSI/NCSL Z540-1-1994; Part 1. Thunder now offers NVLAP accredited calibrations, the National Voluntary Laboratory Accreditation Program has assigned a Laboratory Code of 200582-0 to Thunder. **See the NVLAP accreditation page.** A complete instrument calibration test procedure can be included upon request. Thunder Scientific's staff is always available for site audit or examination per your specific requirements. Please visit Thunders web-site at **www.thunderscientific.com** for new equipment news and information.

Calibration Laboratory

Manufacturing Plant

Contact Thunder:

Thunder Scientific Corporation
623 Wyoming Blvd. SE
Albuquerque, New Mexico 87123-3198

Toll Free: (800) 872-7728
Tel: (505) 265-8701
Fax: (505) 266-6203
Web: www.thunderscientific.com
E-mail: sales@thunderscientific.com

Click here to E-mail a Support Representative.

support@thunderscientific.com

Click here to E-mail a Sales Representative.

sales@thunderscientific.com

Humidity Generation and Calibration Equipment

THUNDER SCIENTIFIC CORPORATION The Humidity Source

GSA Schedule
Contract GS-24F-0053N

GSA Contract Information:

Thunder Scientific Corporation has a United States General Services contract available for Federal Agencies.

Thunder's contract information:

Contract Number:	GS-24F-0053N
Contractor:	Thunder Scientific Corporation
Address:	623 Wyoming Blvd. SE Albuquerque, NM 87123-3198
Phone:	(505) 265-8701
E-mail:	jeff@thunderscientific.com
Web Address:	http://www.thunderscientific.com
Expiration Date:	April 2, 2018
SINs:	602 32
Schedule Number:	66

The General Services Administration, (GSA Advantage) web site can be found at http://www.gsaadvantage.gov/.

Please contact, Thunder Scientific Corporation sales department if you have questions concerning our GSA Advantage products. You can reach us toll free at 800-872-7728 or via e-mail at sales@thunderscientific.com.

Thunder Humidity Generators

Model 1200
Mini Two-Pressure Humidity Generator

Model 2500
Mobile Two-Pressure Humidity Generator

Model 3900
Two-Pressure Two-Temperature Low Humidity Generator

Model 4500
Automated Low Humidity Generator

Model 9000
Automated Humidity Generator

Thunder Scientific Corporation

Humidity Generation,
Calibration and Measurement

Model 1200

Mini "Two-Pressure"
Humidity Generator

Model 1200

Mini “Two-Pressure” Humidity Generator

FEATURES

- **±0.5 % RH Uncertainty**[1]
- **Traceable to NIST**
- **Based on NIST Proven Two-Pressure Principle**
- **Generate: RH, DP, FP, PPM, Multipoint Profiles**
- **Computerized Internal Transducer Calibration**
- **Computes System Uncertainties in Real Time**
- **Automatically Applies Enhancement Factors**
- **No Refrigerants - Thermoelectric Cooling/Heating**
- **Only 4 square feet of floor space (20” x 30”)**
- **Touch-screen Control**
- **USB and Ethernet Interface**

DESCRIPTION

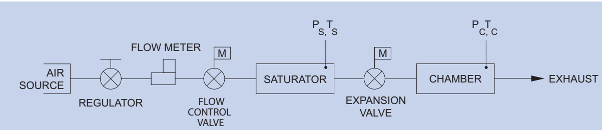
The **Model 1200** Mini Humidity Generator produces accurate humidity values using the fundamental, NIST proven, “two-pressure” principle. The **1200** will automatically supply relative humidity, dew point, frost point, and other calculated values for instrument calibration and evaluation as well as precision environmental testing. This system automatically generates multipoint profiles as well as manually entered humidity levels, while continuously storing and printing system data.

Virtually all functions of the **1200** humidity generator are computer controlled. All desired humidities, temperatures, and time intervals may be programmed. Visual indications of system status are displayed in real time on the computer screen. The automated features of the **1200** allow the generation of known humidity levels completely unattended. This frees the operating technician from the task of monitoring and adjusting.

PRINCIPLE OF OPERATION

The “two-pressure” humidity generation process involves saturating air or nitrogen with water vapor at a known temperature and pressure. The saturated high-pressure air flows from the saturator, through a pressure reducing valve, where the air is isothermally reduced to test pressure at test temperature.

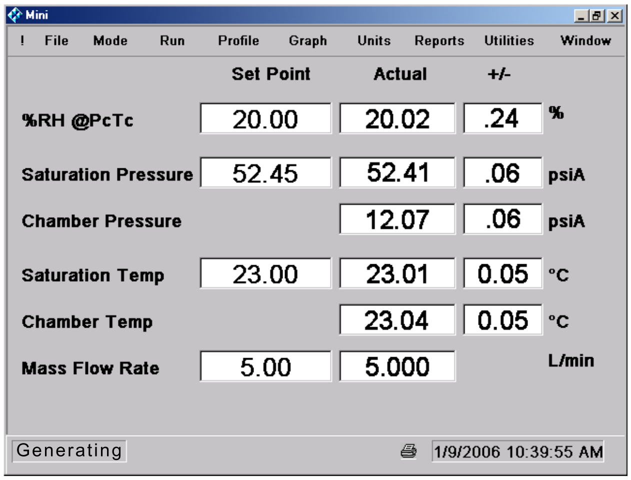
Humidity generation by the **1200** does not depend upon measuring the amount of water vapor in the air, but rather is dependent on the measurements of temperature and pressure alone. System precision is determined by temperature and pressure measurement accuracy, and on the constancy of the measurements throughout. When setpoint equilibration has been reached the indications of saturation temperature, saturation pressure, test temperature, and test pressure, are used in the determination of all hygrometric parameters.



Elemental Schematic of the 1**200** generator

COMPUTER/CONTROL SYSTEM

The Computer/Control System performs all control functions required for humidity generation, as well as displaying, printing, and storing system parameters in real time. The computer/controller is made up of several main components, each with individual yet cooperative functions. The Computer/Control System utilizes a Windows based computer system that is used to read transducers and temperature sensors; supply digital outputs for control of temperatures, pressures, and mass flow; and control relay outputs for control of system power, heaters, heat pump and circulation pump.



Embedded **1200 ControLog®** run screen.

Temperature Control: Ultra stable temperatures are attained through solid-state thermoelectric cooling and heating of a circulating fluid that jackets the test chamber and associated humidity generation components. Chamber and saturation temperatures are governed by this medium which is computer controlled at any value between 10 °C and 60 °C using PID (proportional-integral-derivative) algorithms.

Pressure And Flow Control: Pressure control and mass flow control are accomplished through computer actuation of electromechanical valve assemblies. Saturation pressure and mass flow are measured continuously and controlled using PID algorithms similar to those employed in temperature control.

Calibration: Proper calibration of the temperature sensors and pressure transducer ultimately determines the accuracy of the generator. The system employs an integral programmatic calibration scheme allowing the sensors and transducers to be calibrated while they are electrically connected to the humidity generator. Coefficients for each transducer are calculated by the computer and stored to memory.

TEST CHAMBER

The test chamber accommodates various solid-state sensors, data loggers, chilled mirror hygrometers, and material samples for environmental testing. The **1200** humidity generating system incorporates a 300 series stainless steel fluid jacketed test chamber, with internal dimensions of 6" x 6" x 6" (152 mm x 152 mm x 152 mm). Access is available through a 1.625" (41.3 mm) diameter port on the right side for probes, cables, sample tubes, etc.

APPLICATIONS FOR USE

Virtually any humidity and temperature may be generated within the operational limits of the generator. The output or recording of the device under test may then be compared with the generator's data for analysis.

Chilled Mirror Hygrometers: Install the actual chilled mirror head into the chamber or insert a sample tube through the test port and draw a sample through the chilled mirror head and you can: verify mirror temperature measurement accuracy (calibration) when the hygrometer is in thermal equilibrium with its environment; perform operational checks of the heat-pump and optical components before and after mirror cleaning and balancing; determine whether the hygrometer is controlling the mirror deposit in the liquid phase or ice phase when operating at dew and frost points below 0 °C; determine if the hygrometer is correctly calculating other humidity parameters; determine the hygrometer's repeatability, stability, and drift characteristics.

Humidity Sensors and Data Loggers: Insert your humidity probes through the chamber access port or install the data logger into the chamber and you can: determine humidity calibration accuracy and/or characterize humidity sensitivity by subjecting the humidity sensor to a variety of humidity levels; perform operational checks such as the sensing systems capability to correctly calculate and display other humidity parameters; determine the repeatability, stability, hysteresis, and drift characteristics of various humidity sensing systems.

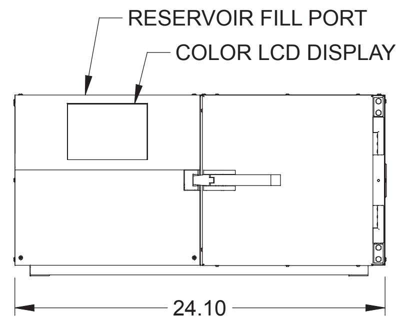
Environmental Testing: The **1200** can serve as a test bed for evaluation and R&D of humidity sensors, humidity sensing systems, and humidity sensitive products, e.g., polymers, composites, film, magnetic medium, pharmaceuticals, soil hydrology, consumables, electronics, optics, etc.

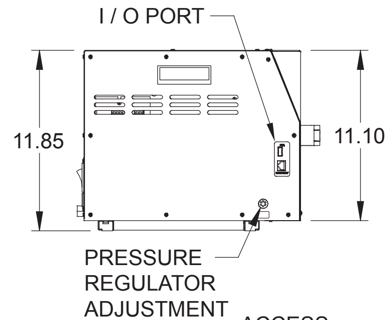
Model 1200

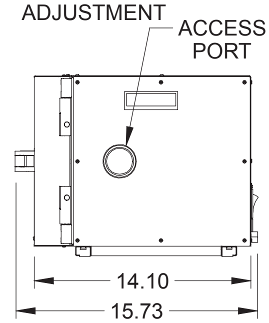
Mini "Two-Pressure" Humidity Generator

SPECIFICATIONS

Relative Humidity Range: 10 to 95%
Relative Humidity Resolution: 0.05%
Relative Humidity Uncertainty @ PcTc: [1] ±0.5%
Frost Point Temperature Range: –18 to 0 °C
Dew Point Temperature Range: –20 to 50 °C
Dew Point Accuracy: ±0.1 °C
Chamber Temperature Range: 10 to 60 °C
Chamber Temperature Measurement Resolution: 0.02 °C
Chamber Temperature Control Stability: ±0.04 °C
Chamber Temperature Uniformity: [2] 0.1 °C
Chamber Temperature Measurement Uncertainty: [1] ±0.05 °C
Chamber Temperature Cooling Rate: 4 Minutes Per °C Average
Chamber Temperature Heating Rate: 2 Minutes Per °C Average
Saturation Pressure Range: Ambient to 152 psiA
Saturation Pressure Uncertainty: [1] ±0.08% of FS psiA
Saturation Pressure Resolution: 0.02 psiA
Test Chamber Pressure Range: Ambient
Test Chamber Pressure Resolution: 0.02 psiA
Test Chamber Pressure Uncertainty: [1] ±0.08% of FS psiA
Gas Type: Air or Nitrogen
Gas Pressure Rating (MAWP): 175 psiG
Gas Flow Rate Range: 2 to 10 L/m
Gas Flow Rate Resolution: 0.01 L/m
Gas Flow Rate Uncertainty: [1] ±1.0 L/m
Test Chamber Dimensions: 6" x 6" x 6" (152 mm x 152 mm x 152 mm)
Access Port: 1.625" (41.3 mm) located on right side
Physical Dimensions: 24.10" W x 14.10" D x 11.85" H (61 cm x 35.8 cm x 30.1 cm)
Dry Weight (Generator Only): 56 lbs. (25.40 Kg)
Wet Weight (Generator Only): 65 lbs. (29.48 Kg)
Utility Cart Dimensions: 30.6" W x 20.0" D x 33.0" H (77.7 cm x 50.8 cm x 83.8 cm)
Utility Cart Weight: 84 lbs. (38.10Kg)





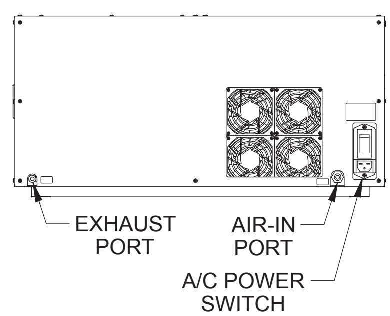


UTILITIES

Electrical Power: 100/240 V, ~6/3 A, 50/60 Hz
Gas Supply (External): 155-175 psiG @ 0.5 scfm

ENVIRONMENTAL

Operating Temperature: 15 to 30 °C
Storage Temperature: 0 to 50 °C
Humidity: 5 to 95% RH Non-condensing



[1] Represents an expanded uncertainty using a coverage factor, k=2, at an approximate level of confidence of 95%.
[2] When operated within ±10 °C of ambient temperature.

For More Information or to Place an Order Contact:

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Ordering: 800.872.7728 Tel: 505.265.8701 FAX: 505.266.6203
www.thunderscientific.com

THUNDER SCIENTIFIC CORPORATION
The Humidity Source

Model ACS-1200

Oil-less Compressed Air System

Humidity Calibration and Measurement Instruments

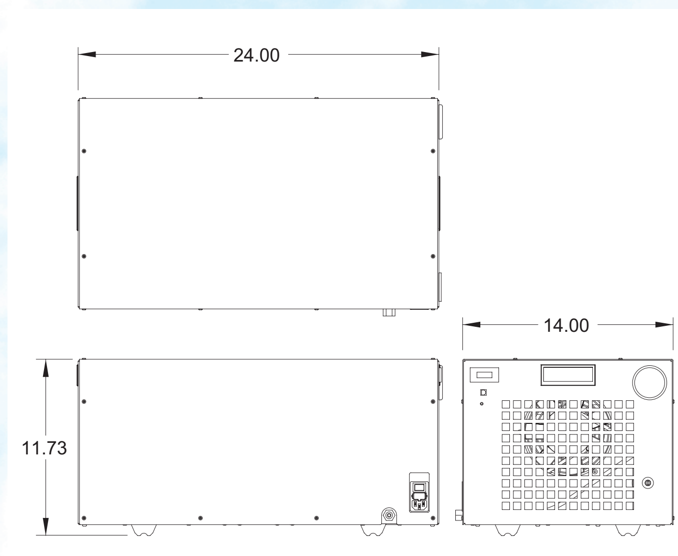
A Fully Enclosed Compressed Air Supply
with Dryer & Sound Muffling Cabinet

SPECIFICATIONS

The **ACS-1200** is an oil-less air compressor that can produce a pressure of 175 psi, at a maximum ambient air temperature of 30°C, continuously for up to 5,000 hours before a minor maintenance service kit is required.

VOLTAGE INPUT OPTIONS

The **ACS-1200** system is available in ether 100-115/220-240V 50/60Hz and 7.5/5A depending on your needs.



FEATURES

- **175 psiG Oil-Less Air Supply**
- **Dry Air To <-30 °C Ambient Pressure Dew Point**
- **Sound level <70 db**
- **Vibration Isolated Compressor**
- **Membrane Air Dryer**
- **10' Air Hose Extension**
- **On/Off Fuse Switch**
- **8' Removable AC Power Cord**
- **Indoor Use Only**
- **Dimensions L 24" x W 14" x H 11.73"**
- **Cabinet Weight Approximately 40 Lbs.**

DESCRIPTION

The **ACS-1200** is designed to be used as the air supply for a Model 1200 Humidity Generator. This is a fully enclosed compressed air supply incorporating a membrane style air dryer in a sound muffling cabinet. This system is ideal for in-lab use because of the low sound level at less than 70 decibels.

ORDERING INFORMATION

When ordering an **ACS-1200** air compressor system you will also receive a ten foot air hose extension and an eight foot removable AC power cord. If you already have a Model 1200 Humidity Generator and you only need to order the **ACS-1200**, specify this part number when ordering. If you need to order a compressor only, specify part number **GASTUNIV**.

Thunder Scientific Corporation

Humidity Generation,
Calibration and Measurement

Model 2500

Benchtop / Mobile "Two-Pressure" Humidity Generator

Model 2500 Benchtop / Mobile

"Two-Pressure" Humidity Generator

FEATURES

- **±0.5 %RH Uncertainty**[1]
- **Traceable to NIST**
- **Self Contained and Mobile**
- **Automated Control of User Setpoints**
- **2500 ControLog® Automation Software**
- **HumiCalc® with Uncertainty Software**
- **Computerized Internal Transducer Calibration**
- **Low Noise Air Compressor with Air Dryer**
- **RS-232C Serial Interface**

DESCRIPTION

The **Model 2500** Benchtop Humidity Generator is a self contained system capable of producing atmospheres of known humidities using the fundamental, NIST proven, "two-pressure" principle. This system is capable of continuously supplying accurately known humidity values for instrument calibration, evaluation, and verification, as well as for environmental testing.

Simply apply power and the **2500** will power-up ready to generate. Humidity setpoint values are input by the operator from the front panel keypad and are limited only by the range of the **2500** humidity generator.

Relative humidities are calculated from the measurements of pressure and temperature with the formula:

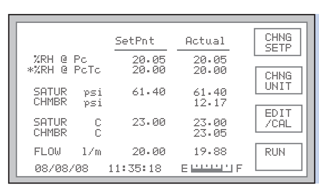
$$\%RH = \frac{f_s}{f_c} \cdot \frac{e_s}{e_c} \cdot \frac{P_c}{P_s} \cdot 100$$

To generate a known humidity, the computer controls the pressure ratio P_c/P_s utilizing the enhancement factor ratio f_s/f_c and the effective degree of saturation e_s/e_c. Humidity produced is solely dependent on the measurement of pressures and temperatures and does not rely on any other device (such as a dew point hygrometer, psychrometer, or humidity sensor) for the measurement of water vapor content. Precision humidity generation is determined by the accuracy of the pressure measurements and on the accuracy and uniformity of temperature throughout the generating system.

PRINCIPLE OF OPERATION

The **Model 2500** Benchtop Humidity Generator operates using an on board multifunction CPU in conjunction with other peripheral cards to perform calculation and control functions. The embedded computer control system allows the **2500** to generate known humidity levels unattended, freeing the operating technician from the task of system monitoring and adjustment. A computer and/or printer may be connected via the bidirectional RS-232C interface ports allowing remote setpoint control and continuous acquisition of system data.

Humidity and temperature setpoint values are input by the operator from the front panel keypad while visual indications of system status are displayed in real time on the liquid crystal display.

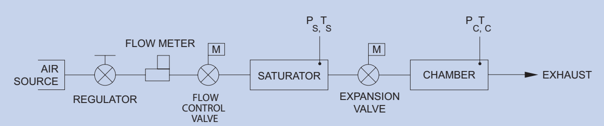


Control Display

All control and measurement parameters critical to the operation of the humidity generator are displayed on this screen. Each parameter in the left most column is identified with a brief title and corresponding units. The generator operates in a variety of user selectable pressure, temperature, and flow units. Some of these are °C, °F, psi, "Hg, Tor, mbar, kPa, l/m, l/h, cfm and cfh. Humidity is calculated and displayed in percent relative humidity (%RH). The asterisk in the left most column indicates the active humidity control parameter. The “SetPnt” column lists control setpoints and the “Actual” column lists all of the measured data and calculated parameters of the generator.

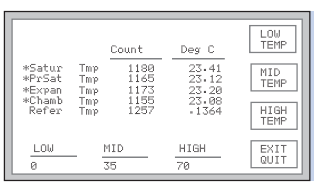
Temperature Control: The system utilizes a fluid jacketed test chamber for extremely stable temperature control. Temperature setpoint control is attained by controlling the temperature of the circulating fluid medium that jackets the test chamber and associated humidity generation components. Chamber and saturation temperatures are governed by this medium and are digitally controlled by the computer at any value between 0 °C and 70 °C using PID (proportional-integral-derivative) algorithms.

Pressure And Flow Control: Pressure control and mass flow control are accomplished through computer actuation of electromechanical valve assemblies. Pressure and flow are measured continuously and controlled using PID algorithms similar to those employed in temperature control.



Elemental Schematic of the **2500** generator

Calibration: The **2500** humidity generator employs an integral programmatic calibration scheme allowing the temperature and pressure transducers to be calibrated while they are electrically connected to the humidity generator.



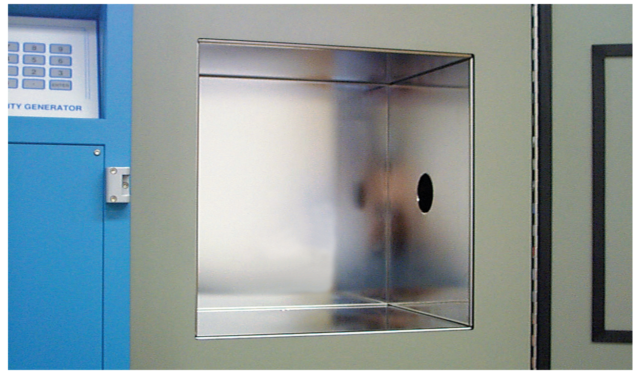
Calibration Display

Coefficients for each transducer are calculated by the computer and stored in the system’s nonvolatile memory until the next calibration is performed.

The liquid crystal display has many different user features, like the liquid level readout.

APPLICATIONS

The fluid jacketed test chamber can accommodate humidity sensors, hygrothermographs, chilled mirror hygrometers, and various material samples for environmental testing.



Virtually any humidity and temperature point may be generated, for any length of time, within the operational limits of the generator. The output of the device under test may then be compared with the generator’s printed data for analysis.

Humidity Sensors And Chart Recorders: Insert humidity probes through the two inch port in the side of the chamber or place hygrothermographs into the chamber and you can: determine humidity calibration accuracy and characterize humidity sensitivity by subjecting the sensing system to a variety of humidity levels; perform operational checks such as the sensing systems capability to correctly calculate and display other humidity parameters; determine the repeatability, stability, hysteresis, and drift characteristics of various humidity sensing systems.

Chilled Mirror Hygrometers: Install the actual chilled mirror head into the chamber or insert a sample tube through the test port and draw a sample through the chilled mirror head and you can: verify mirror temperature measurement accuracy (calibration) when the hygrometer is in thermal equilibrium with its environment; perform operational checks of the heat pump and optical components before and after mirror cleaning and balancing; determine whether the hygrometer is controlling the mirror deposit in the liquid phase or ice phase when operating at dew and frost points below 0°C; determine if the hygrometer is correctly calculating other humidity parameters; determine the hygrometer’s repeatability, stability, and drift characteristics.

Environmental Testing: The **2500** can serve as a test bed for evaluation and R&D of humidity sensors, humidity sensing systems, and humidity sensitive products, e.g., polymers, composites, film, magnetic medium, blood gas analysis, pharmaceuticals, soil hydrology, consumables, electronics, optics, etc. Depending on the temperature and humidity being generated, the **2500** may operate continuously from hours to months. With continuous generation of a nominal 50 %RH at 21°C, the reservoir will last about two weeks between refills.

Model 2500 Benchtop / Mobile
"Two-Pressure" Humidity Generator

SPECIFICATIONS

Relative Humidity Range: .... 10 to 95%
Relative Humidity Resolution: 0.02%
Relative Humidity Uncertainty @ $P_C T_C$: [1] .... ±0.5%
Chamber Temperature Range: .... 0 to 70 °C
Chamber Temperature Range: (Optional) .... -10 to +70 °C
Chamber Temperature Resolution: .... 0.02 °C
Chamber Temperature Uniformity: [2] .... ±0.1 °C
Chamber Temperature Uncertainty: [1] .... ±0.06 °C
Chamber Pressure Range: .... Ambient
Gas Flow Rate Range: .... 5 to 20 l/m
Gas Type: .... Air or Nitrogen
Gas Pressure Rating (MAWP): .... 175 psiG
Heating/Cooling Rate: .... 2.5 Minutes Per °C Average
Chamber Window: .... 6" x 6" (152 mm x 152 mm)
Physical Dimensions: .... Table A
Physical Dimensions With Cart: .... Table B
Chamber Dimensions: .... Table C
Access Port: .... Table D

UTILITIES

Electrical Power: .... 100/120 V~, 15 A, 50/60 Hz
(Optional) .... 200/240 V~, 8 A, 50/60 Hz
Air Compressor: .... 100/120 V~, 5 A, 50/60 Hz
(Optional) .... 200/240 V~, 2.5 A, 50/60 Hz
Air Supply (External): .... Clean Oil Free Instrument Air
.... @ 175 psiG & 20 slpm

ENVIRONMENTAL

Operating Temperature: .... 15 to 30 °C
Storage Temperature: .... 0 to 50 °C
Humidity: .... 5 to 95% RH Non-condensing

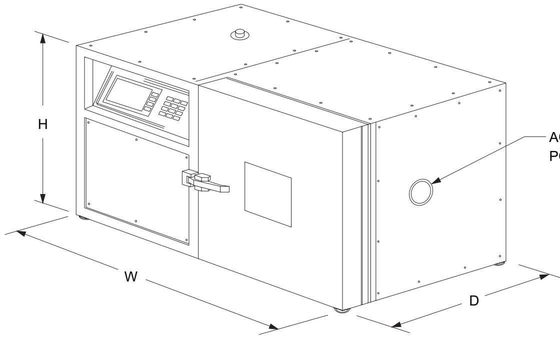


TABLE A
Physical Dimensions

Model	H	W	D
2500	19.00" (483 mm)	33.00" (838 mm)	20.00" (508 mm)
2500ST	22.00" (559 mm)	36.00" (914 mm)	23.00" (584 mm)

Not including feet, handle, or other protrusions.

TABLE B
Overall Dimensions With Cart

Model	H	W	D
2500	53.00" (1.35 m)	40.00" (1.02 m)	23.00" (584 mm)
2500ST	56.00" (1.42 m)	43.00" (1.09 mm)	26.00" (660 mm)

TABLE C
Chamber Dimensions

Model	H	W	D
2500	12.00" (305 mm)	12.00" (305 mm)	10.00" (254 mm)
2500ST	15.00" (381 mm)	15.00" (381 mm)	12.00" (305 mm)

TABLE D
Access Port Dimensions

Option	# Ports	Port Diameter	Location
Standard	1	1.9" (48 mm)	Right Side
-TPA	2	1.9" (48 mm)	Right Side
	1	1/4" Swagelok	Right Side
-MPD	6	1.1" (28 mm)	In Door
-QPW	4	1.1" (28 mm)	Window Door

Other custom options are available.

[1] Represents an expanded uncertainty using a coverage factor, k=2, at an approximate level of confidence of 95%.
[2] When operated at temperatures within 10 °C of room ambient temperature.

For More Information or to Place an Order Contact:

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Ordering: 800.872.7728 ⌿ Tel: 505.265.8701 ⌿ FAX: 505.266.6203
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CE

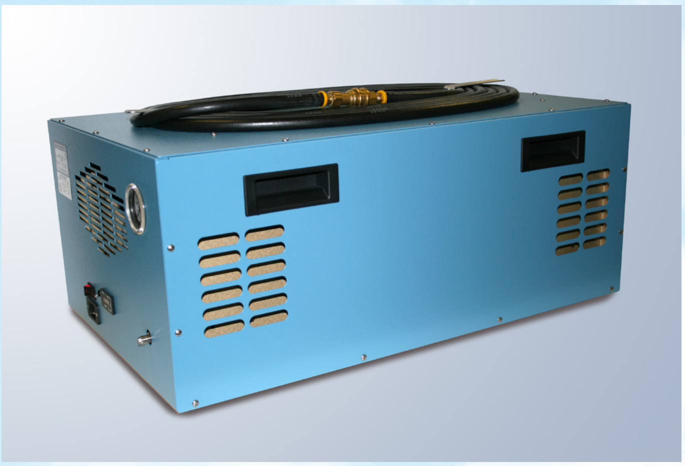
THUNDER SCIENTIFIC CORPORATION The Humidity Source

Model ACS2520

Oil-less Compressed Air System

A Fully Enclosed Compressed Air Supply
with Dryer & Sound Muffling Cabinet

Humidity Calibration and Measurement Instruments



DESCRIPTION

The ACS2520 is used with a Model 2500 and fits on the bottom shelf of the 2500 mobile cart. This is a fully enclosed compressed air supply with an air dryer and sound muffling cabinet. This system is ideal for in lab use because the sound level is less than 70 decibels. The Model ACS2520 has a hose hold down on top for ease of storage of the extension air hose.

SPECIFICATIONS

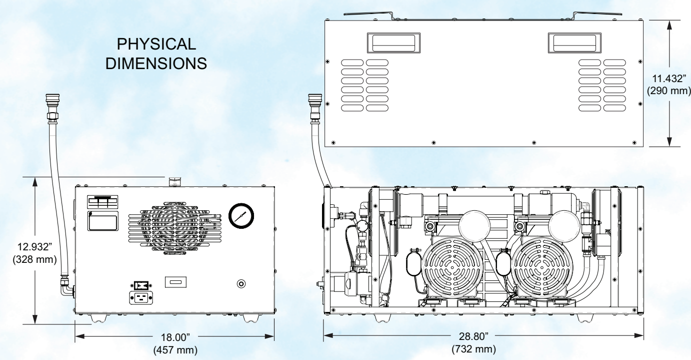
The ACS2520 has two 1/2 HP oil-less air supplies and can run with a continuous pressure of 175 psi at a maximum ambient air temperature of 40 °C. This system can run at a continuous duty of up to 15,000 hours before a minor maintenance service kit is required.

VOLTAGE INPUT OPTIONS

You can receive the ACS2520 system in ether 115V or 230V at 50/60Hz depending on your needs.

FEATURES

- **Two 175 psiG Oil-Less Air Supplies**
- **Dry Air To <-40 °C Ambient Pressure Dew Point**
- **Sound level <70 db**
- **Vibration Isolated Compressors**
- **Membrane Air Dryer**
- **Particulate-Filter**
- **Pressure Regulator and Air Gauge**
- **25’ Extension Air Hose**
- **On/Off Circuit Breaker Switch**
- **10’ Removable AC Power Cord**
- **Indoor Use Only**
- **Dimensions L 29” x W 18” x H 13”**
- **Cabinet Weight Approximately 100 Lbs.**



ORDERING INFORMATION

When ordering a new air compressor system, part number ACS2520, you will receive an extension air hose, a removable AC power cord and the enclosure with two air compressors. Here are the part numbers for ordering the ACS2520 air compressor system. Use this part number for the 115 volt system, ACS2520-115. If you need to order a high voltage air system, specify this part number, ACS2520-230 for the 230 volt system.

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Thunder Scientific Corporation

Humidity Generation,
Calibration and Measurement

Model 3900

"Two-Pressure Two-Temperature"
Low Humidity Generator

Model 3900

Low Humidity Generator

FEATURES

- **Traceable to NIST**
- **Two-Pressure Two-Temperature Principle**
- **Push Button (Keypad) Control**
- **Automated Control of User Setpoints**
- **Automatically Applies Enhancement Factors**
- **Computerized Internal Transducer Calibration**
- **RS-232C Serial Interface**
- **Only Nine Square Feet of Floor Space**
- **Timed/Formatted Output to Printer**
- **Battery Backed-up Real Time Clock**
- **Backlit Liquid Crystal Display**

DESCRIPTION

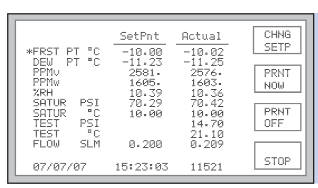
The **Model 3900** Low Humidity Generator is an extremely accurate means of producing known humidity values for calibrating and verifying humidity instrumentation. Based on the combined, NIST proven, fundamental "two-pressure" and "two-temperature" principles, this system will automatically supply a continuous humidified gas stream, within the frost/dew point range of -95.0 °C to 10.0 °C, for days or even weeks unattended.

Simply apply power to the system, and the **3900** will powerup ready to purge and/or generate. Humidity setpoint values are input by the operator from the front panel keypad and are limited only by the operational range of the **3900** humidity generator.

PRINCIPLE OF OPERATION

The "two-pressure two-temperature" generation process involves saturating a continuous stream of air or nitrogen with water vapor at a known temperature and pressure. The saturated high pressure air then passes through an expansion valve where it expands to a lower pressure. The **3900** generates a particular humidity by first selecting a suitable saturation temperature, T_s. It then determines the saturation pressure, P_s, required to establish the correct saturation vapor pressure. The precision of the system is determined by the accuracy of the temperature and pressure measurements and on the constancy of them throughout. When setpoint equilibration has been reached, the indication of saturation temperature, saturation pressure, test temperature, and test pressure may be used in the determination of all hygrometric parameters. Furthermore, because the humidity generated is based solely on the fundamental principles of temperature and pressure, no humidity sensing is used to measure or control the amount of water vapor produced by this system.

The **3900** operates using an on-board multifunction CPU in conjunction with other peripheral cards to perform calculation and control functions. The embedded computer control system allows the **3900** to generate known humidity levels completely unattended with visual indications of system status displayed in real time on the Liquid Crystal Display.



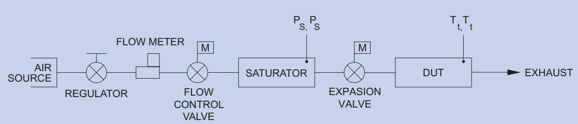
Control Display

This frees the operating technician from the task of system monitoring and adjustment. A computer and/or printer may be connected via the bi-directional RS-232C interface ports allowing remote setpoint control and continuous system data retrieval.

Temperature Control: Temperature setpoint control is attained by controlling the temperature of a circulating fluid medium that jackets the saturator of the generator. The saturation temperature is governed by the temperature of this medium, which is digitally controlled by the computer at any value between -80 °C and 12 °C through the use of PID (proportional-integral-derivative) algorithms.

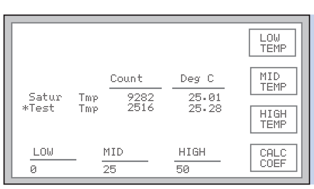
Pressure and Flow Control: Pressure control and mass flow rate control are accomplished through computer actuation of electromechanical valve assemblies. Saturation pressure and mass flow are measured continuously and controlled using PID algorithms similar to those employed in temperature control.

Two-Pressure Two-Temperature Generator: Regulated compressed air or nitrogen is directed through the saturator, which is a fluid encapsulated heat exchanger containing several planes of pure ice or water. The saturator is maintained at the required saturation temperature and saturation pressure. As the gas thermally equilibrates, it becomes saturated with water vapor. The saturation temperature (T_s) and saturation pressure (P_s) are measured at the point of final saturation. The saturation pressure is then reduced to test pressure (P_t) and the conditioned gas is admitted to the unit under test (UUT) at the desired humidity conditions. The final pressure (P_t) and temperature (T_t) of the gas is measured within or just after the UUT. The UUT is then exhausted to atmosphere or to a back pressure regulator to achieve pressure control.



Elemental Schematic of the **3900** generator

Calibration: Proper calibration of the temperature and pressure transducers ultimately determines the accuracy of the generator. This system employs an integral programmatic calibration scheme allowing the transducers to be calibrated while they are electrically connected to the humidity generator.



Calibration Display

This approach helps eliminate systemic errors that might be induced by removing the transducers from the generator. All calibration is performed mathematically by the computer so manual adjustments are not needed. Coefficients for each transducer are calculated by the computer and stored in the system's nonvolatile memory until the next calibration is performed.

The main panel has easy access to the keypad, function keys, and test temperature and test pressure connectors.

APPLICATIONS

Virtually any humidity may be generated, for any length of time, within the operational limits of the generator. The output of the unit under test may then be compared with the generator's printed data for analysis.

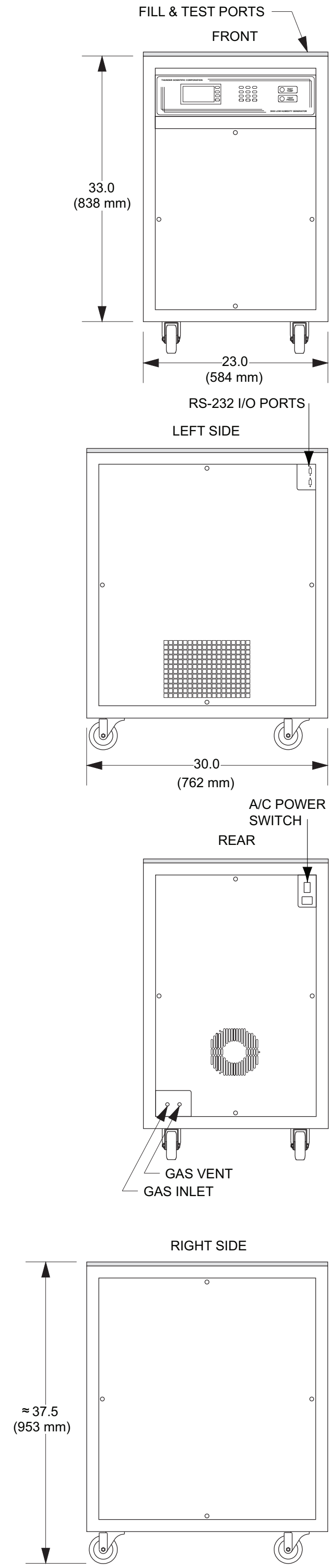
Chilled Mirror Hygrometers: Connect the generator output to your chilled mirror hygrometer and you can: verify mirror temperature measurement accuracy (calibration) when the hygrometer is in thermal equilibrium with its environment; perform operational checks of the heatpump and optical components, before and after mirror cleaning and balancing; determine whether the hygrometer is controlling the mirror deposit in the liquid phase or ice phase when operating at dew and frost points below 0 °C; determine if the hygrometer is correctly calculating other humidity parameters; determine hygrometer repeatability, stability, and drift characteristics.

Humidity Sensors and Electrolytic Hygrometers: Connect the generator output to your Electrolytic Hygrometer, sampling system, special fixtures, or sensors and you can: determine humidity calibration accuracy and/or characterize humidity sensitivity by subjecting the humidity sensor to a variety of humidity levels; perform operational checks such as the sensing systems capability to correctly calculate and display other humidity parameters; determine repeatability, stability, hysteresis, and drift characteristics of various humidity sensing systems.

Environmental Testing: The **3900** can serve as a test bed for evaluation and R&D of humidity sensors, humidity sensing systems, and humidity sensitive products, e.g., polymers, composites, film, magnetic medium, pharmaceuticals, soil hydrology, consumables, electronics, optics, etc.

Model 3900

Low Humidity Generator



SPECIFICATIONS

Frost Point Uncertainty: [1] .... (-70 to 10 °C) ±0.1 °C
.... (<-70 °C) ±0.2 °C
Frost Point / Dew Point Range: .... –95 to +10 °C
Frost Point Resolution: .... 0.01 °C
Parts Per Million Range: .... 0.05 to 12000 PPMv
Relative Humidity Range: .... 0.0002 to 50%
Saturation Pressure Range: .... Ambient to 300 psiA
Saturation Pressure Uncertainty (10-50 psiA): [1] .... ±0.05
Saturation Pressure Uncertainty (50-300 psiA): [1] .... ±0.30
Saturation Pressure Resolution (10-100 psiA): 0.01
Saturation Pressure Resolution (100-300 psiA): 0.1
Saturation Temperature Range: .... –80 to +15 °C
Saturation Temperature Uncertainty: [1] .... ±0.08 °C
Saturation Temperature Resolution: .... 0.01 °C
Saturation Temperature Heating/Cooling Rate: .... 2 Minutes Per °C Average
Gas Flow Rate Range: .... 0.1 to 5 slpm
Gas Flow Rate Resolution: .... 0.02 slpm
Gas Type: .... Air or Nitrogen
Gas Pressure Rating (MAWP): .... 350 psiG
Test Port: .... 1/4 Inch Swagelok® Tube Fitting
Physical Dimensions: .... 23” x 30” x 37.5” (584 mm x 762 mm x 953 mm)

UTILITIES

Electrical Power: .... 200/240 V~, 10 A, 50/60 Hz
Gas Supply (External): .... 350 psiG, 5 l/m, with ambient
.... pressure frost point <-80 °C
Floor Space: .... 9 ft^2 (0.6 m^2)

ENVIRONMENTAL

Operating Temperature: .... 15 to 30 °C
Storage Temperature: .... 0 to 50 °C
Humidity: .... 5 to 95% RH Non-condensing

[1] Represents an expanded uncertainty using a coverage factor, k=2, at an approximate level of confidence of 95%.

For More Information or to Place an Order Contact:

CE

Thunder Scientific
623 Wyoming Blvd. SE Albuquerque, New Mexico 87123-3198
Ordering: 800.872.7728 Tel: 505.265.8701 FAX: 505.266.6203
www.thunderscientific.com

0610-3900

Thunder Scientific
Corporation

Humidity Generation,
Calibration and Measurement

Model 4500

Automated Low Humidity Generator

Model 4500

Automated Low Humidity Generator

FEATURES

- **Traceable to NIST**
- **±0.1 °C Frost Point Uncertainty**[1]
- **Two-Pressure Two-Temperature Principle**
- **ControLog® Automation Software**
- **Computerized Internal Transducer Calibration**
- **Automatically Applies Enhancement Factors**
- **Computes System Uncertainties in Real Time**

DESCRIPTION

The **Model 4500** automated low humidity generating system is based on the fundamental, NIST proven, "two temperature" and "two pressure" principles. This system is capable of continuously supplying extremely accurate humidity values for instrument calibration and evaluation. When used within the specified frost/dew point range of -95 °C to 10 °C, this system will automatically generate multipoint profiles as well as manually entered setpoints for days or even weeks.

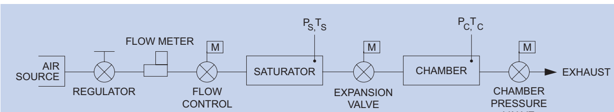
Virtually all functions of the **4500** humidity generator are controlled automatically. All desired humidities, temperatures, test pressures, and time intervals may be programmed. Visual indications of system status are displayed in real time on the computer monitor.

Simply apply power to the system, and the computer will load the controller with power-up and generation routines. A menu of options will appear, manual or automated control is selected, humidity and temperature setpoints are entered, or a profile is selected and generation begins. Humidity and temperature setpoints and profiles are limited only by the physical response time and range of the **4500** humidity generator.

Automated features of the **4500** allow the generator to perform humidity and temperature profiles completely unattended, while continuously recording and printing system data. This frees the operating technician from the task of system monitoring and adjustment. Upon completion of a profile, the system will adjust to a pre-selected humidity value and await a new instrument load or shutdown.

PRINCIPLE OF OPERATION

The "two-temperature two-pressure" humidity generation process involves saturating air or some other gas, such a nitrogen, with water vapor at a known temperature and pressure. The saturated high pressure gas flows from the saturator, through a pressure reducing valve where the gas pressure is reduced to test pressure, at the desired humidity and temperature conditions.



Elemental Schematic of the **4500** generator

Humidity generation by the **4500** does not depend upon measuring the amount of water vapor in the gas, but rather is dependent on the measurements of temperature and pressure alone. The precision of the system is determined by the accuracy of the temperature and pressure measurements and on the constancy of them throughout. When setpoint equilibration has been reached, the indication of saturation temperature, saturation pressure, test temperature, and test pressure may be used in the determination of all hygrometric parameters.

COMPUTER / CONTROL SYSTEM

The Computer/Control System performs all control functions required for humidity generation, as well as displaying, printing, and storing system parameters in real time. The computer/controller is made up of several main components, each with individual yet cooperative functions. The Computer/Control System utilizes a Windows based computer system that communicates with an HP3852A data acquisition/control system. The system consists of an integrating 5-1/2 digit volt/ohmmeter employing: multiplexed inputs to read transducers and PRT's; digital outputs for control of temperatures, pressures, and mass flow; and relay outputs for control of system power, heaters, compressors and circulation pumps.

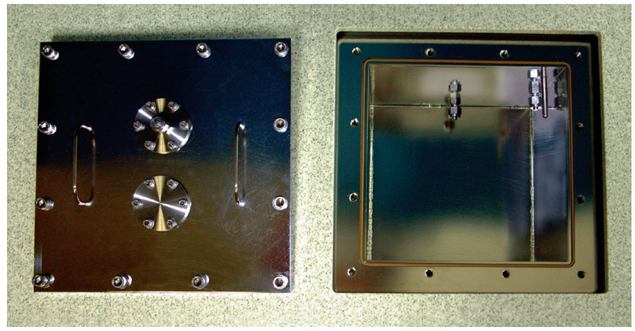
Temperature Control: Temperature setpoint control is attained by controlling the temperatures of the two independent circulating fluid mediums that jacket the saturator and test chamber of the generator. The saturation and chamber temperatures are governed by the temperature of the circulating fluids, which are digitally controlled by the computer through the use of PID (proportional-integral-derivative) algorithms. Each fluid medium is heated by time proportioning an immersion heater in the fluid circulation path. Cooling, while also time proportioned, is accomplished by injecting refrigerant into a heat exchanging evaporator located in the fluid circulation path. Using PID algorithms for temperature control allows the fluid temperature to be maintained at the desired saturation temperature with a stability to within approximately 0.02°C over the operating range.

Pressure and Flow Control: Pressure control and mass flow control are accomplished through computer actuation of electromechanical valve assemblies. Saturation pressure, chamber pressure, and mass flow are measured continuously and controlled using PID algorithms similar to those employed in temperature control.

Calibration: Proper calibration of the temperature and pressure transducers ultimately determines the accuracy of the generator. The **4500** employs an integral programmatic calibration scheme allowing the transducers to be calibrated while they are electrically connected to the humidity generator. Coefficients for each transducer are calculated by the computer and stored in memory.

TEST CHAMBER

The **Model 4500** low humidity generating system incorporates a test chamber that is surrounded by a fluid jacket on five sides. The fluid provides temperature conditioning, as well as thermal stability to the test space. Chamber temperature is tunable from -10 °C to 85 °C. Interior chamber dimensions are 8"x8"x8". Test chamber pressure range is ambient to 30 psiA. User access for sensors, cables, and tubing is available through two 1.25" diameter ports. Removal of the chamber cover allows a full eight inch by eight inch access to the test space.



APPLICATIONS

The test chamber can accommodate various solid state sensors, chilled mirror hygrometers, and various material samples for environmental testing. Virtually any humidity, test temperature, and test pressure, for any length of time, may be generated within the operational limits of the generator. The output or recording of the device under test may then be compared with the generator's printed data for analysis.

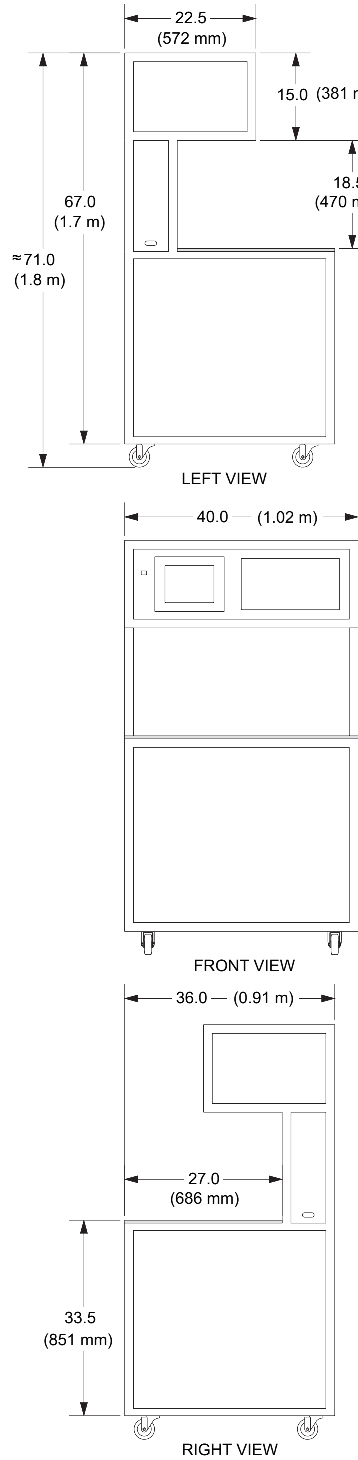
Humidity Sensors and Electrolytic Hygrometers: Insert your humidity probes through a test port in the chamber or connect the Electrolytic Hygrometer to a test port and you can: determine humidity calibration accuracy and/or characterize humidity sensitivity by subjecting the humidity sensor to a variety of humidity levels; perform operational checks such as the sensing systems capability to correctly calculate and display other humidity parameters; determine the repeatability, stability, hysteresis, and drift characteristics of various humidity sensing systems.

Chilled Mirror Hygrometers: Install the actual chilled mirror head into the chamber or connect a sample tube to the test port and feed a sample through the chilled mirror head and you can: verify mirror temperature measurement accuracy (calibration) when the hygrometer is in thermal equilibrium with its environment; perform operational checks of the heatpump and optical components before and after mirror cleaning and balancing; determine whether the hygrometer is controlling the mirror deposit in the liquid phase or ice phase when operating dew or frost points below 0 °C; determine if the hygrometer is correctly calculating other humidity parameters; determine hygrometer's repeatability, stability, and drift characteristics.

Environmental Testing: The **4500** can serve as a test bed for evaluation and R&D of humidity sensors, humidity sensing systems, and humidity sensitive products, e.g., polymers, composites, film, magnetic medium, pharmaceuticals, soil hydrology, consumables, electronics, optics, etc.

Model 4500

Automated Low Humidity Generator



SPECIFICATIONS

Frost Point Uncertainty: [1] .... (-80 to 10 °C) ±0.1 °C
.... (<-80 °C) ±0.2 °C
Frost Point / Dew Point Range: .... –95 to +10 °C
Frost Point Resolution: .... 0.001 °C
Parts Per Million Range: .... 0.04 to 12000 PPMv
Saturation Pressure Range: .... 15 to 300 psiA
Saturation Pressure Uncertainty (10-45 psiA): [1] .... ±0.0045
Saturation Pressure Uncertainty (30-300 psiA): [1] .... ±0.030
Saturation Pressure Resolution (10-45 psiA): 0.001
Saturation Pressure Resolution (30-300 psiA): 0.01
Saturation Temperature Range: .... –80 to +10 °C
Saturation Temperature Uncertainty: [1] .... ±0.05 °C
Saturation Temperature Resolution: .... 0.001 °C
Saturation Temperature Heating/Cooling Rate: .... 2 Minutes Per °C Average
Chamber Pressure Range: .... Ambient to 30 psiA
Chamber Pressure Uncertainty: [1] .... ±0.003 psiA
Chamber Pressure Resolution: .... 0.001 psiA
Chamber Temperature Range: .... -10 to 85 °C
Chamber Temperature Range: (Optional) [2] .... -80 to +20 °C
Chamber Temperature Uncertainty: [1] .... ±0.05 °C
Chamber Temperature Resolution: .... 0.001 °C
Chamber Fluid Heating/Cooling Rate: .... 2 Minutes Per °C Average
Chamber Dimensions: .... 8” x 8” x 8” (203 mm x 203 mm x 203 mm)
Generation Gas Flow Rate Range: .... 0.5 to 5 slpm
Physical Dimensions: .... 40” x 36” x 71” (1.02 m x 0.91 m x 1.8 m)

UTILITIES

Electrical Power: .... 220/240 V~, 15 A, 50/60 Hz
Gas Supply (External): .... 350 psiG, 5 l/m, with ambient
.... pressure frost point <-80 °C
Cooling Water: .... 1 gpm (4 l/m) Maximum @ 21 °C

ENVIRONMENTAL

Operating Temperature: .... 15 to 30 °C
Storage Temperature: .... 0 to 50 °C
Humidity: .... 5 to 95% RH Non-condensing

[1] Represents an expanded uncertainty using a coverage factor, k=2, at an approximate level of confidence of 95%.
[2] -LT, Low Temperature Option.

For More Information or to Place an Order Contact:

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Ordering: 800.872.7728 · Tel: 505.265.8701 · FAX: 505.266.6203
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Thunder Scientific Corporation

Humidity Generation,
Calibration and Measurement

Model 9000

Automated "Two-Pressure" Humidity Generator

Model 9000

Automated "Two-Pressure" Humidity Generator

FEATURES

- **Traceable to NIST**
- **±0.3% RH Uncertainty**[1]
- **High Flow Capability**
- **Based on NIST Proven "Two-Pressure" Principle**
- **Generate: RH, DP, FP, PPM, Multipoint Profiles**
- **Computerized Internal Transducer Calibration**
- **Computes System Uncertainties in Real Time**
- **Automatically Applies Enhancement Factors**
- **ControLog® Automation Software**

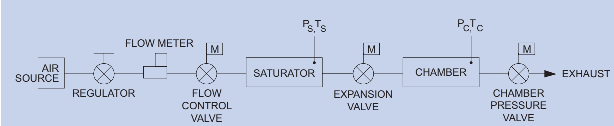
DESCRIPTION

The **Model 9000** Humidity Generator produces extremely accurate humidity values using the fundamental, NIST proven, "two-pressure" principle. The **9000** will automatically supply relative humidity, dew point, frost point, ppm, or other calculated values for instrument calibration and evaluation as well as precision environmental testing. This system will automatically generate multipoint profiles as well as manually entered humidity levels, while continuously storing and printing system data.

Virtually all functions of the **9000** humidity generator are computer controlled. All desired humidities, temperatures, test pressures, and time intervals may be programmed. Visual indications of system status are displayed in real time on the computer monitor. The automated features of the **9000** allow the generation of known humidity levels completely unattended for hours or even days. This frees the operating technician from the task of system monitoring and adjustment.

PRINCIPLE OF OPERATION

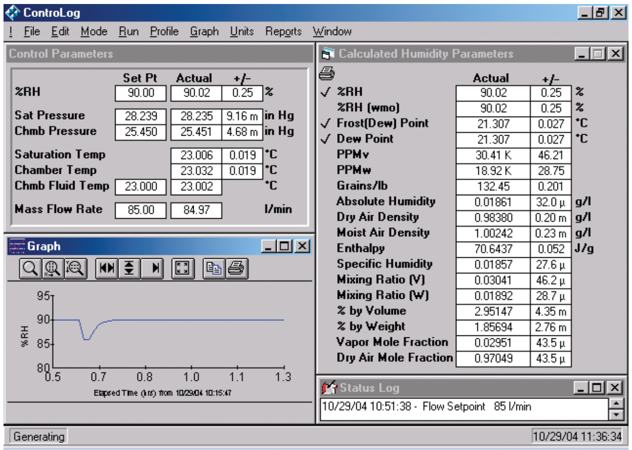
The "two-pressure" humidity generation process involves saturating air or nitrogen with water vapor at a known temperature and pressure. The saturated high pressure air flows from the saturator, through a pressure reducing valve, where the air is isothermally reduced to test pressure at test temperature. Humidity generation by the **9000** does not depend upon measuring the amount of water vapor in the air, but rather is dependent on the measurements of temperature and pressure alone. System precision is determined by temperature and pressure measurement accuracy, and on the constancy of the measurements throughout. When setpoint equilibration has been reached, the indication of saturation temperature, saturation pressure, test temperature, and test pressure, may be used in the determination of all hygrometric parameters.



Elemental Schematic of the **9000** generator

COMPUTER / CONTROL SYSTEM

The Computer/Control System performs all control functions required for humidity generation, as well as displaying, printing, and storing system parameters in real time. The computer/controller is made up of several main components, each with individual yet cooperative functions. The Computer/Control System utilizes a Windows based computer system that communicates with an HP3852A data acquisition/control system. The system consists of an integrating 5-1/2 digit volt/ohmmeter employing: multiplexed inputs to read transducers and PRT's; digital outputs for control of temperatures, pressures, and mass flow; relay outputs for control of system power, heaters, compressor and circulation pump.



9000 Controlog™ default startup screen.

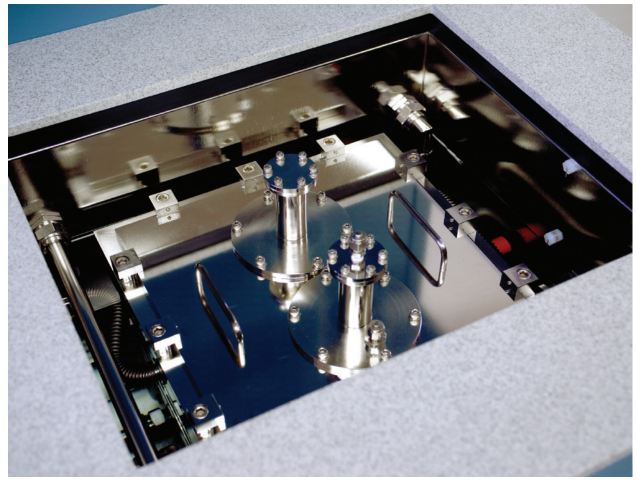
Temperature Controlled Bath: The **9000** humidity generating system incorporates a computer controlled temperature bath. Bath temperature is digitally controlled by the computer at any value between 0 °C and 70 °C using PID (proportional-integral-derivative) algorithms. The test chamber, saturators, heat exchangers, and connecting tubing are immersed in approximately 20 gallons of distilled water that is circulated at the rate of 50 gallons per minute by a magnetically coupled centrifugal pump. Fast fluid circulation provides the temperature conditioning of these components, resulting in long term bath stability and uniformity. This allows a very stable humidity to be generated.

Pressure And Flow Control: Pressure control and mass flow control are accomplished through computer actuation of electromechanical valve assemblies. Saturation pressure, chamber pressure, and mass flow are measured continuously and controlled using PID algorithms similar to those employed in temperature control.

Calibration: Proper calibration of the temperature and pressure transducers ultimately determines the accuracy of the generator. The **9000** employs an integral programmatic calibration scheme allowing the transducers to be calibrated while they are electrically connected to the humidity generator. Coefficients for each transducer are calculated by the computer and stored to memory.

TEST CHAMBER

The **9000** humidity generating system incorporates a completely immersed test chamber, with internal dimensions of 12" x 12" x 12". Test chamber pressure range is ambient to 20 PSIA. The main chamber cover is removable utilizing quick release hold downs. Removal of the chamber cover allows a full 12 inch by 12 inch access to the test space. Access is also available through two 3.65" diameter ports in the chamber cover or two 1.125" inside diameter port cover adapters.



APPLICATIONS FOR USE

The test chamber can accommodate various solid state sensors, chilled mirror hygrometers, psychrometers, hygrothermographs, and material samples for environmental testing. Virtually any humidity and temperature may be generated, for any length of time, within the operational limits of the generator. The output or recording of the device under test may then be compared with the generator's printed data for analysis.

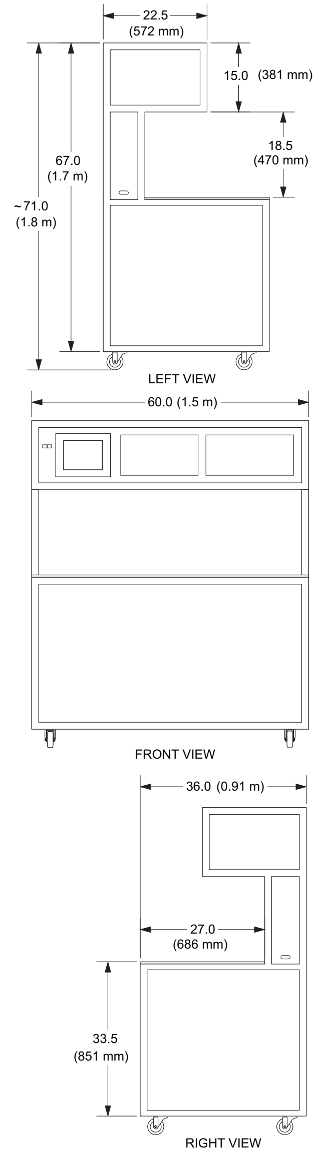
Chilled Mirror Hygrometers: Install the actual chilled mirror head into the chamber or insert a sample tube through the test port and draw a sample through the chilled mirror head and you can: verify mirror temperature measurement accuracy (calibration) when the hygrometer is in thermal equilibrium with its environment; perform operational checks of the heatpump and optical components before and after mirror cleaning and balancing; determine whether the hygrometer is controlling the mirror deposit in the liquid phase or ice phase when operating at dew and frost points below 0°C; determine if the hygrometer is correctly calculating other humidity parameters; determine hygrometer's repeatability, stability, and drift characteristics.

Humidity Sensors And Chart Recorders: Insert your humidity probes through a test port in the chamber or install the hygrothermograph into the chamber and you can: determine humidity calibration accuracy and/or characterize humidity sensitivity by subjecting the humidity sensor to a variety of humidity levels; perform operational checks such as the sensing systems capability to correctly calculate and display other humidity parameters; determine the repeatability, stability, hysteresis, and drift characteristics of various humidity sensing systems.

Environmental Testing: The **9000** can serve as a test bed for evaluation and R&D of humidity sensors, humidity sensing systems, and humidity sensitive products, e.g., polymers, composites, film, magnetic medium, pharmaceuticals, soil hydrology, consumables, electronics, optics, etc.

Model 9000

Automated "Two-Pressure" Humidity Generator



SPECIFICATIONS

Relative Humidity Range:	5 to 99%
Relative Humidity Resolution:	0.01%
Relative Humidity Uncertainty:[1,2]	±0.3%
Frost Point Temperature Range:	–32 to 0 °C
Dew Point Temperature Range:	–35 to 69.7 °C
Parts Per Million By Volume Range:	300 to 440000 PPMv
Bath Temperature Range:	0 to 70 °C
Bath Temperature Measurement Resolution:	0.005 °C
Bath Temperature Control Stability:	±0.02 °C
Bath Temperature Uniformity:	0.04 °C
Bath Temperature Measurement Uncertainty:[1]	±0.038 °C
Bath Temperature Heating/Cooling Rate:	1.5 Minutes Per °C Average
Gas Type:	Air or Nitrogen
Gas Pressure Rating (MAWP):	300 psiG
Gas Flow Rate Range:	5 to 150 slpm
Gas Flow Rate Resolution:	0.1 slpm
Gas Flow Rate Uncertainty:[1]	±3 slpm
Saturation Pressure - Low Range:	Ambient to 45 psiA
Saturation Pressure Uncertainty - Low Range:[1]	±0.0045 psiA
Saturation Pressure Resolution - Low Range:	0.001 psiA
Saturation Pressure - High Range:	45 to 300 psiA
Saturation Pressure Uncertainty - High Range:[1]	±0.03 psiA
Saturation Pressure Resolution - High Range:	0.01 psiA
Saturation To Chamber Temp Intercomparison Uncertainty:[1,3]	0.038 °C
Test Chamber Pressure Range:	Ambient to 20 psiA
Test Chamber Pressure Resolution:	0.001 psiA
Test Chamber Pressure Uncertainty:[1]	±0.0023 psiA
Test Chamber Dimensions:	12" x 12" x 12" (305 mm x 305 mm x 305 mm)
Physical Dimensions:	60" x 36" x 71" (1.5 m x 0.91 m x 1.8 m)

UTILITIES

Electrical Power:	200/230 V~, 20 A, 3 Ø, 50/60 Hz, 4 Wire
Gas Supply:	350 psiG @ 5 scfm
Cooling Water:	2 gpm (8 l/m) Maximum @ 21°C

ENVIRONMENTAL

Operating Temperature:	15 to 30 °C
Storage Temperature:	0 to 50 °C
Humidity:	5 to 95% RH Non-condensing

[1] Represents an expanded uncertainty using a coverage factor, k=2, at an approximate level of confidence of 95%.

[2] Allowing for necessary corrections of temperature and pressure over the relative humidity range of 5% to 95%, at fluid temperatures from 0 °C to 70 °C, at a mass flow rate of 20 to 100 slpm, while using air as the carrier gas.

[3] Saturation to Chamber Temperature Intercomparison Accuracy is defined as the maximum temperature difference existing between the saturation temperature and chamber temperature measurements when intercompared in a homogeneous medium.

For More Information or to Place an Order Contact:

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THUNDER SCIENTIFIC CORPORATION

NVLAP Lab Code 200582-0

ACCREDITED HUMIDITY CALIBRATION SERVICES PER ISO/IEC 17025:2005

Thunder Scientific maintains calibration systems capable of producing known humidity values using the combined fundamental “two-pressure” and “two-temperature” principle. These systems are capable of continuously supplying accurately known humidity, temperature, and pressure values for instrument calibration and special tests.

Humidity Parameter	Range	Uncertainty
Relative Humidity	0% to 99%	0.3% of reading
Dew / Frost Point	-90 to -70 °C	±0.2 °C
	-70 to -20 °C	±0.1 °C
	-20 to 70 °C	±0.05 °C
Volume ratio, V (ppm)	0.1 to 3.0 ppm	4.0% of value
	3.0 to 200 ppm	2.0% of value
	200 to 400000 ppm	0.1% of value

Humidity Generation and Calibration Equipment

THUNDER SCIENTIFIC CORPORATION

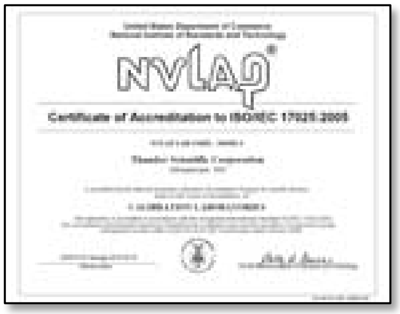
The Humidity Source

NVLAP®

NVLAP Lab Code 200582-0

Click here to view our Certificate of Accreditation (PDF: 27 KB).

Cert >



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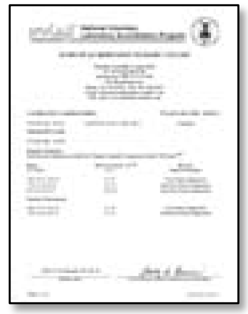

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Thunder Scientific Corporation is pleased to announce that for the effective dates July 01, 2012 through June 30, 2013, Thunder Scientifics' calibration laboratory received renewed accreditation (Laboratory Code 200582-0) from the National Voluntary Laboratory Accreditation Program (NVLAP), administered by the National Institute of Standards and Technology.

Thunder Scientific is now NVLAP Accredited for On-Site Calibrations

Thunder Scientific has added to its scope of accreditation, on-site calibration of all series 2500 humidity generators. Holding true to Thunder Scientifics' commitment to quality, all on-site calibrations are compliant to ISO/IEC 17025:2005 and ANSI/NCSL Z540-1-1994, Part 1 requirements.

Thunder's Calibration Laboratory field support staff will travel to your location with traceable standards for dew-point inter-comparison, pressure calibration and temperature calibration of your Model 2500 generator. Our field support staff will inspect and conduct all required maintenance on your humidity generator. Calibration reports include the NVLAP logo and laboratory code, "As Found" data, "As Left" data, and a concise statement of the method used.

Thunder's accredited on-site humidity uncertainties are the lowest commercially available. Our turn-around times are excellent and prices are very competitive.

NVLAP accreditation criteria are established in accordance with the U.S. Code of Federal Regulations (CFR, Title 15, Part 285), NVLAP Procedures and General Requirements, and encompass the requirements of ISO/IEC 17025. Accreditation is granted following successful completion of a process which includes submission of an application and payment of fees by the laboratory, an on-site assessment, resolution of any nonconformities identified during the on-site assessment, participation in proficiency testing, and technical evaluation. The accreditation is formalized through issuance of a Certificate of Accreditation and Scope of Accreditation and publicized by announcement in various government and private media.

NVLAP provides an unbiased third-party evaluation and recognition of performance, as well as expert technical guidance to upgrade laboratory performance. NVLAP accreditation signifies that a laboratory has demonstrated that it operates in accordance with NVLAP management and technical requirements pertaining to quality systems; personnel; accommodation and environment; test and calibration methods; equipment; measurement traceability; sampling; handling of test and calibration items; and test and calibration reports.

More information about the NVLAP program can be found at http://ts.nist.gov/standards/accreditation/.

Please contact: Thunder Scientific Corporation sales department if you have questions or would like to arrange for a NVLAP accredited calibration. You can reach us toll free at 800-872-7728 or via e-mail at sales@thunderscientific.com

United States Department of Commerce
National Institute of Standards and Technology

NVLAP®

Certificate of Accreditation to ISO/IEC 17025:2005

NVLAP LAB CODE: 200582-0

Thunder Scientific Corporation

Albuquerque, NM

is accredited by the National Voluntary Laboratory Accreditation Program for specific services, listed on the Scope of Accreditation, for:

CALIBRATION LABORATORIES

This laboratory is accredited in accordance with the recognized International Standard ISO/IEC 17025:2005. This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer to joint ISO-ILAC-IAF Communique dated January 2009).

DEPARTMENT OF COMMERCE · UNITED STATES OF AMERICA

2014-07-01 through 2015-06-30

Effective dates

For the National Institute of Standards and Technology

National Voluntary
Laboratory Accreditation Program

CALIBRATION LABORATORIES **NVLAP LAB CODE 200582-0**

SCOPE OF ACCREDITATION TO ISO/IEC 17025:2005

Thunder Scientific Corporation 623 Wyoming Blvd SE Albuquerque, NM 87123-3198 Mr. Jarred Crouse Phone: 505-265-8701 Fax: 505-266-6203 E-mail: jcrouse@thunderscientific.com URL: http://www.thunderscientific.com	**Parameter(s) of Accreditation** Thermodynamic This laboratory is compliant to ANSI/NCSL Z540-1-1994; Part 1. (NVLAP Code: 20/A01)

CALIBRATION AND MEASUREMENT CAPABILITIES (CMC) Notes 1,2

Measured Parameter or Device Calibrated	Range	Uncertainty (k=2) Note 3, 5	Remarks
THERMODYNAMIC			
HUMIDITY (20/T02)			
Humidity Generation Field calibrations available Note 4			
Relative Humidity	0 % RH to 99 % RH	0.3 %	Over a Dry Bulb temperature range of -10 °C to 70 °C
Frost Point Temperature	-90.0 °C to -70.0 °C	0.2 °C	
Dew/Frost Point Temperature	-70.0 °C to -20.0 °C -20.0 °C to 70.0 °C	0.1 °C 0.05 °C	
Humidity Measurement Frost Point Temperature	-90.0 °C to -70.0 °C	0.2 °C	
Dew/Frost Point Temperature	-70.0 °C to 70.0 °C	0.1 °C	
PRESSURE (20/T05)			
Pressure	0 psi to 600 psi	0.005 %	Ruska 2465 Piston Pressure Gage
RESISTANCE THERMOMETRY (20/T07)			
Platinum Resistance Thermometers	-80 °C to 85 °C	0.003 °C	Hart 1575/5680
END			

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CALIBRATION LABORATORIES **NVLAP LAB CODE 200582-0**

Notes
Note 1: A Calibration and Measurement Capability (CMC) is a description of the best result of a calibration or measurement (result with the smallest uncertainty of measurement) that is available to the laboratory's customers under normal conditions, when performing more or less routine calibrations of nearly ideal measurement standards or instruments. The CMC is described in the laboratory's scope of accreditation by: the measurement parameter/device being calibrated, the measurement range, the uncertainty associated with that range (see note 3), and remarks on additional parameters, if applicable.
Note 2: Calibration and Measurement Capabilities are traceable to the national measurement standards of the U.S. or to the national measurement standards of other countries and are thus traceable to the internationally accepted representation of the appropriate SI (Système International) unit.
Note 3: The uncertainty associated with a measurement in a CMC is an expanded uncertainty using a coverage factor, $k = 2$, with a level of confidence of approximately 95 %. Units for the measurand and its uncertainty are to match. Exceptions to this occur when marketplace practice employs mixed units, such as when the artifact to be measured is labeled in non-SI units and the uncertainty is given in SI units (Example: 5 lb weight with uncertainty given in mg).
Note 3a: The uncertainty of a specific calibration by the laboratory may be greater than the uncertainty in the CMC due to the condition and behavior of the customer's device and specific circumstances of the calibration. The uncertainties quoted do not include possible effects on the calibrated device of transportation, long term stability, or intended use.
Note 3b: As the CMC represents the best measurement results achievable under normal conditions, the accredited calibration laboratory shall not report smaller uncertainty of measurement than that given in a CMC for calibrations or measurements covered by that CMC.
Note 3c: As described in Note 1, CMCs cover calibrations and measurements that are available to the laboratory's customers under *normal conditions.* However, the laboratory may have the capability to offer special tests, employing special conditions, which yield calibration or measurement results with lower uncertainties. Such special tests are not covered by the CMCs and are outside the laboratory's scope of accreditation. In this case, NVLAP requirements for the labeling, on calibration reports, of results outside the laboratory's scope of accreditation apply. These requirements are set out in Annex A.1.h. of NIST Handbook 150, Procedures and General Requirements.
Note 4: Uncertainties associated with field service calibration may be greater as they incorporate on-site environmental contributions, transportation effects, or other factors that affect the measurements. Field service capability is only for Thunder Scientific 2500 series units.
Note 5: Values listed with percent (%) are percent of reading or generated value unless otherwise noted.
Note 6: NVLAP accreditation is the formal recognition of specific calibration capabilities. Neither NVLAP nor NIST guarantee the accuracy of individual calibrations made by accredited laboratories.
Note 7: See NIST Handbook 150 for further explanation of these notes.

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2500 ControLog®
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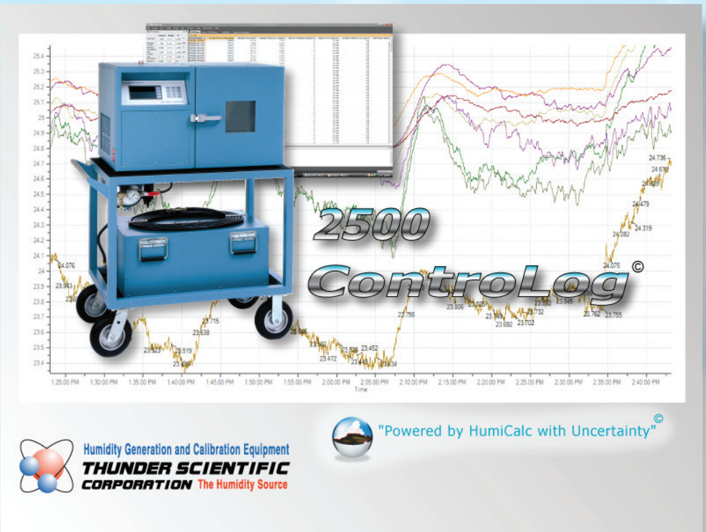
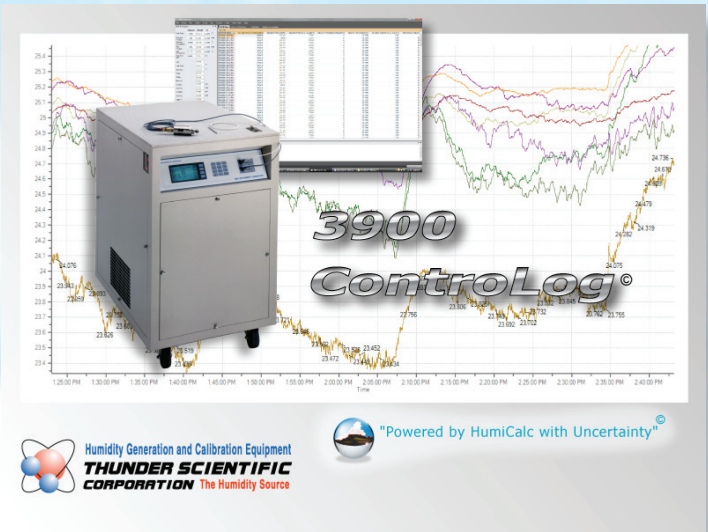


3900 ControLog®
Automation and Control Software



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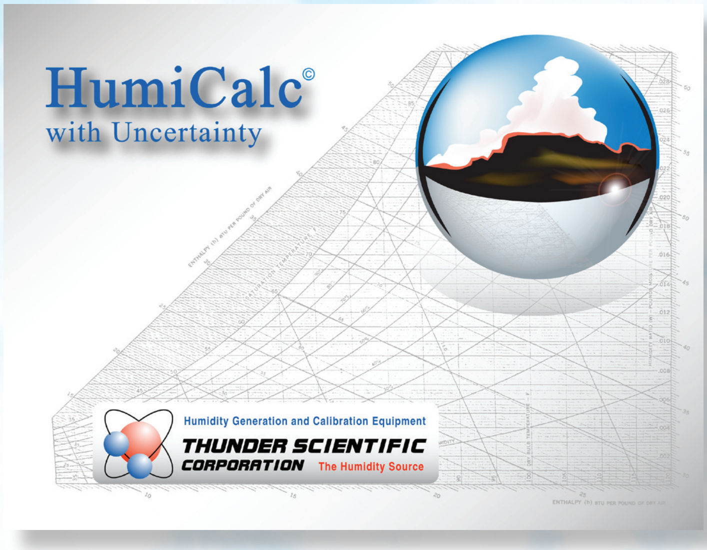
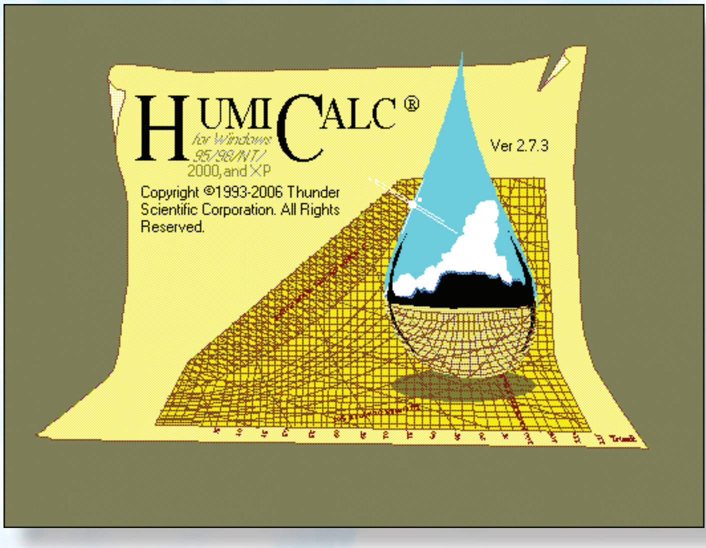


HumiCalc®
Humidity Conversion Software



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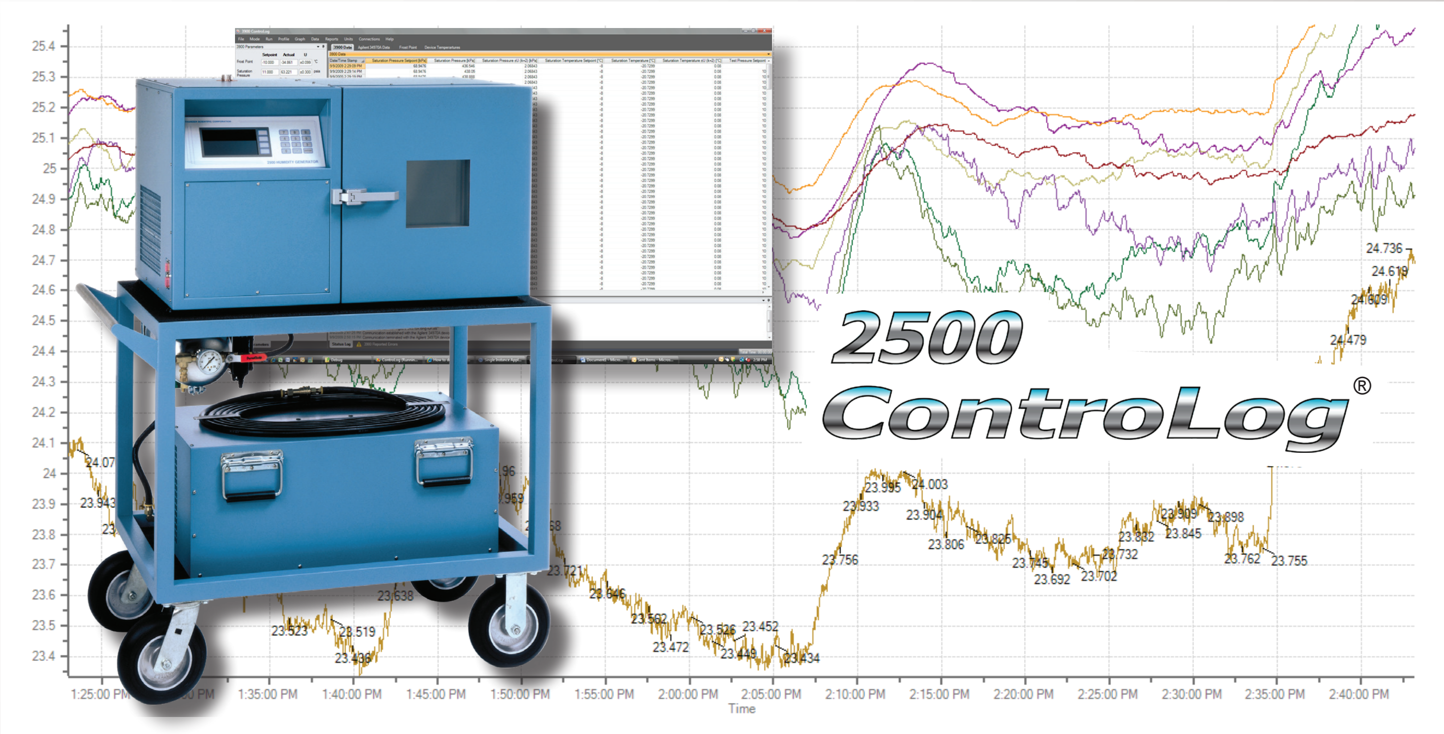
Automation Software for the Model 2500 Humidity Generator



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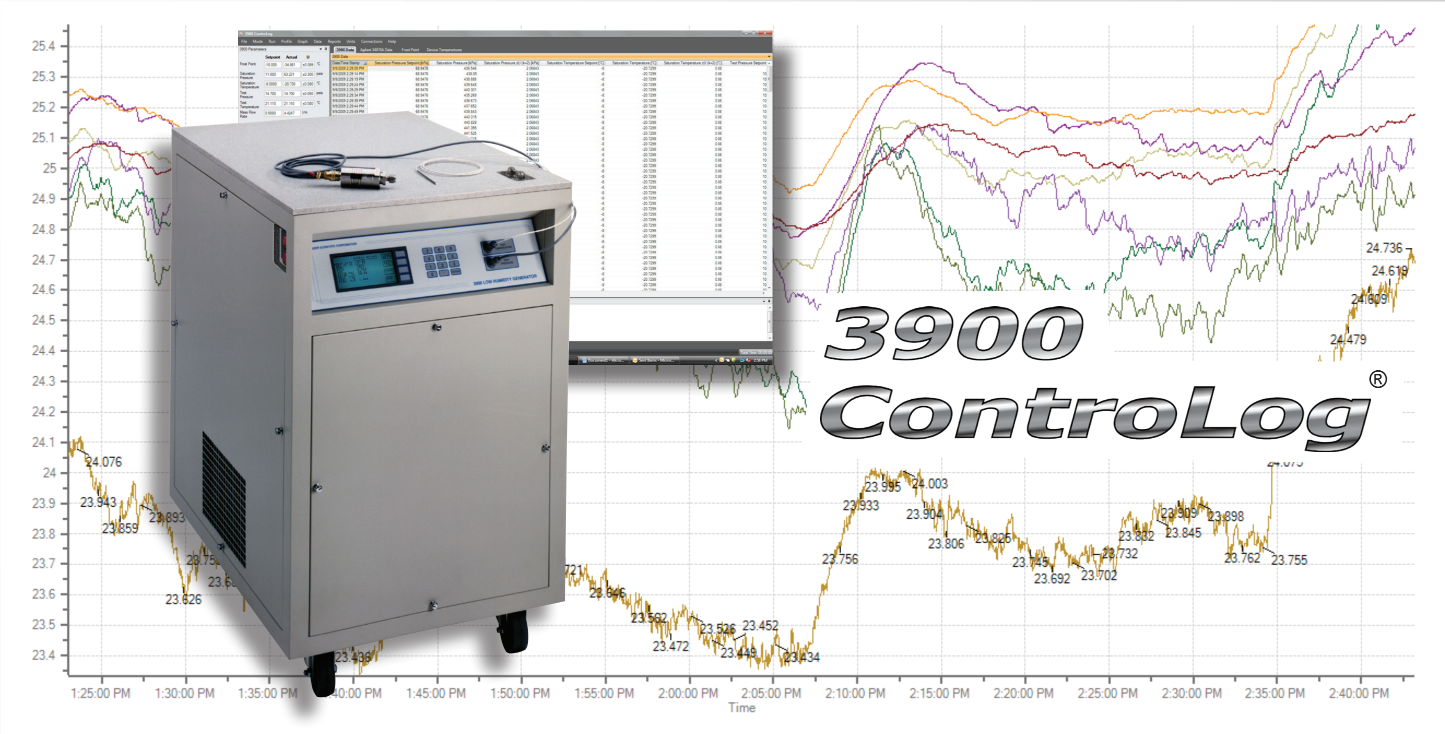
Automation Software for the Model 3900 Low Humidity Generator



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The Humidity Source

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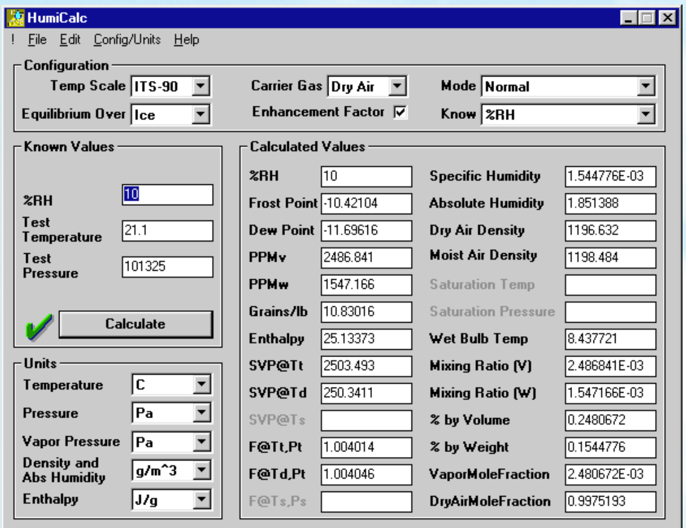
Humidity Conversion Software

The Ultimate in Complex Humidity Conversions
Made for Windows 98, NT, 2000 and XP.**

Humidity Calibration and Measurement Instruments



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- **Highly Accurate Formulas that Replace Charts and Tables**
- **Automatically Applies Enhancement Factors and Temperature/Pressure Corrections**
- **User Selectable Units of Temperature, Pressure, Vapor Pressure, Density, and Enthalpy**
- **Formatted Output to Disk**

DESCRIPTION

HumiCalc® software is the first of its kind to make simple work of complex humidity conversions. No more charts! No more tables! No more guess work! With its high accuracy formulas, **HumiCalc®** gives you the right answer every time. View data on screen or output to disk. With the multiple calculation feature, you can automatically convert an entire range of data, with selectable end points and step sizes. And you can even send the calculated data to a spreadsheet compatible datafile for import into your favorite spreadsheet or graphing program. A typical calculation requires only a temperature, a pressure, and one known humidity parameter. From this minimal input, **HumiCalc®** computes all the final humidity values for you.

CALCULATION RANGE

Relative Humidity:................................ ≈0.0001 to 100.00 %RH
Frost Point:... -99.99 to 0.01 °C
Dew Point:.. -50.00 to 100.0 °C
Temperature:... -99.99 to 200.0 °C*
Pressures:.. Near 0 to 5000 psia*

* Vapor Pressure and enhancement factor formulas for pressures greater than 1500 psia and temperatures greater than 100 °C are based on extrapolated data.

SPECIFICATIONS

HumiCalc® for Windows requires Microsoft Windows 98, NT, 2000 and XP.

OUTPUT OPTIONS

Input one known humidity parameter, temperature and pressure, then **HumiCalc®** computes all other humidity values including:

- %RH
- Specific Humidity
- Absolute Humidity
- Frost Point
- PPMw
- PPMv
- Enthalpy
- Mole Fraction of Dry Air
- Mole Fraction of Vapor
- Wet Bulb Temperature
- Moist Air Density
- Partial Dry Air Density
- Vapor Pressures
- Grains per Pound
- Mixing Ratio by Volume
- Mixing Ratio by Weight
- Percent by Volume
- Percent by Weight
- Enhancement Factors

ORDERING INFORMATION

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with *Uncertainty*

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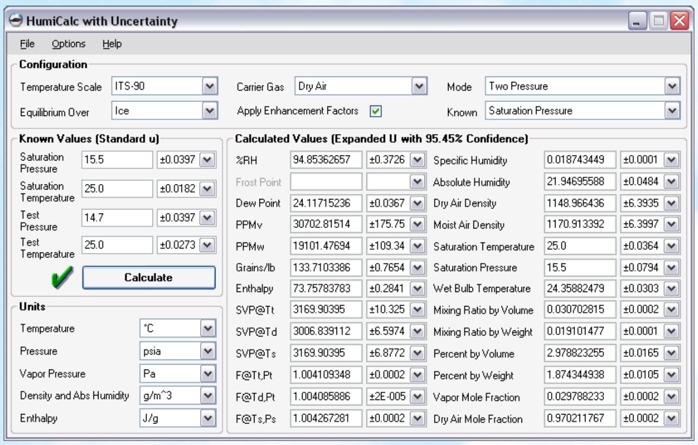
Made for Windows 2000, XP, Vista and 7.**



FEATURES

- **Highly Accurate Formulas that Replace Charts and Tables**
- **Automatically Applies Enhancement Factors and Temperature/Pressure Corrections**
- **User Selectable Units of Temperature, Pressure, Vapor Pressure, Density, and Enthalpy**
- **Now includes the ability to Calculate Uncertainty and As Found Error**

DESCRIPTION

HumiCalc® software is the first of its kind to make simple work of complex humidity conversions. No more charts! No more tables! No more guess work! With its high accuracy formulas, **HumiCalc®** gives you the right answer every time. The new **HumiCalc®** with Uncertainty expands on the original **HumiCalc®** with the ability to calculate complex humidity uncertainties with ease.

UNCERTAINTY FUNCTIONALITY

HumiCalc® with Uncertainty can make simple work of Uncertainty budgets by giving you a calculator that performs all your humidity uncertainty calculations automatically.

NEW FEATURES

Each known item now contains an uncertainty field that you can expand to enter individual uncertainty components.

Once the calculation is performed, the newly calculated values are displayed along with the expanded uncertainty values at the desired confidence level. Each calculated result can also be expanded to see the individual components that made up the final expanded uncertainty value.

SPECIFICATIONS

HumiCalc® with Uncertainty Minimum System Requirements

1GHz Intel® Pentium® or equivalent processor
256MB of RAM (512MB recommended for complex uncertainty scenarios)
Minimum 800 x 600 screen resolution
Microsoft® Windows® Vista; Windows XP Professional, or Home Edition with Service Pack 2; Microsoft Windows 2000 with Service Pack 4
Microsoft .NET Framework version 2.0
Adobe® Acrobat® Reader
Microsoft Internet Explorer® 6.0 through 8.0

VALIDATION PACKAGE

HumiCalc® with Uncertainty Validation is a series of documents used to confirm that the **HumiCalc®** with Uncertainty application complies with its requirements and specifications.

The validation contains around 1,800 pages of test cases composed of detailed mathematical calculations for the core conversion, derivative uncertainty and unit calculations.

This Validation Document can be purchased separately.

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Thunder Reference Library

System Analysis Documents

Humidity Definitions Document
Basic Humidity Definitions

Humidity Calibration Tutorial
NCSL Presentation

Solving Humidity Calibration Challenges
InToday's Metrology Lab
NCSL Paper

TS-90 Formulations
for Vapor Pressure, Frostpoint, Temperature,
Dewpoint Temperature and Enhancement Factors
in the Range -100º to +100 ºC

Table of Contents

Uncertainty Analysis
of the
Model 1200 Two-Pressure Humidity Generator

Uncertainty Analysis
of the
Thunder Scientific Model 1200 Two-Pressure Humidity Generator

1.0 Introduction

Described here is the generated humidity uncertainty analysis, following the Guidelines of NIST and NCSL International [1, 6, 7], for a Model 1200 Humidity Generator that utilizes the NIST developed and proven two-pressure humidity generation principle [2, 3]. Generation of humidity in a system of this type does not require direct measurements of the water vapor content of the gas. Rather, the generated humidity is derived from the measurements of saturation and chamber pressures, and saturation and chamber temperatures.

The measurement instrumentation used in both our in-house working standards and our manufactured devices are obtained from companies which have demonstrated either NIST traceability or traceability to other acceptable standards. In most cases we therefore use the specifications supplied by these manufacturers as the starting point for our uncertainty statements. Over time, check calibrations against a NIST traceable pressure gauge and NIST traceable standard resistance thermometer, as well as the results of an on-going intercomparison program of both the individual components and of the outputs of operating generators, have allowed the determination of the ranges of disagreement among the various temperatures and pressures that enter into the final determination of the output uncertainties. The average values of these disagreements represent the uncertainties from our in-house processes and things like instrument drift over time, and these are coupled with the uncertainties given by the various instrument manufacturers to give overall uncertainty statements.

This document lists the various uncertainty sources, their magnitudes, and their origins over the operating range of the Model 1200 generator.

2.0 Defining Equations

NIST Technical Note 1297[1] states that the uncertainty in a dependent variable, which depends only on uncorrelated input variables, is

$$u^2(y) = \sum_i u^2(x_i)\left(\frac{\partial y}{\partial x_i}\right)^2 \qquad (1)$$

Relative Humidity is defined as the amount of water vapor in a sample compared to the maximum amount possible at the given sample's temperature and pressure.

This can be expressed by the following formula

$$\%RH = \frac{e(T_D)\, f(T_D, P_C)}{e(T_C)\, f(T_C, P_C)} \cdot \eta_S \qquad (2)$$

Where the *f* functions are enhancement factors, *e* is the saturation vapor pressure, η_S is the % efficiency of saturation, T_C, T_D are the chamber and Dew/Frost point temperatures, and Pc is the chamber pressure.

The Dew/Frost point temperatures can be expressed by the following formulas

$$e_W(T_D)\cdot f(T_D,P_C)=f(T_S,P_S)\cdot e(T_S)\cdot\frac{P_C}{P_S} \qquad (3)$$

$$e_I(T_F)\cdot f(T_F,P_C)=f(T_S,P_S)\cdot e(T_S)\cdot\frac{P_C}{P_S} \qquad (4)$$

Where the *f* functions are enhancement factors, e_w is the saturation vapor pressure over water, e_I is the saturation vapor pressure over ice, T_D, T_F, T_S are the Dew point, Frost point and saturation temperatures, and Pc and Ps are the chamber and saturation pressures. Note that the actual Dew/Frost point temperature is defined implicitly and must be obtained through iterative solving.

Combining equation 1 with equations 3 and 4 we can express Relative Humidity in the terms of saturation and chamber temperatures and saturation and chamber pressure only by the following formula

$$\%RH=\frac{e(T_S)\,f(T_S,P_S)}{e(T_C)\,f(T_C,P_C)}\cdot\frac{P_C}{P_S}\cdot\eta_S \qquad (5)$$

By incorporating the relationship in equation 2 into an uncertainty equation of the form of equation 5, it can be shown that the total uncertainty in relative humidity is given by the expression

$$u^2(RH)=u^2(T_C)\left(\frac{\partial RH}{\partial T_C}\right)^2+u^2(T_S)\left(\frac{\partial RH}{\partial T_S}\right)^2+u^2(P_C)\left(\frac{\partial RH}{\partial P_C}\right)^2+u^2(P_S)\left(\frac{\partial RH}{\partial P_S}\right)^2+u^2(\eta_S)\left(\frac{\partial RH}{\partial \eta_S}\right)^2 \qquad (6)$$

Similarly incorporating the relationship in equation 2 into an uncertainty equation of the form of equation 3 and 4, the uncertainties in dew point and frost point measurement are

$$u^2(T_D)=u^2(T_S)\left(\frac{\partial T_D}{\partial T_S}\right)^2+u^2(P_C)\left(\frac{\partial T_D}{\partial P_C}\right)^2+u^2(P_S)\left(\frac{\partial T_D}{\partial P_S}\right)^2+u^2(\eta_S)\left(\frac{\partial T_D}{\partial \eta_S}\right)^2 \qquad (7)$$

and

$$u^2(T_F)=u^2(T_S)\left(\frac{\partial T_F}{\partial T_S}\right)^2+u^2(P_C)\left(\frac{\partial T_F}{\partial P_C}\right)^2+u^2(P_S)\left(\frac{\partial T_F}{\partial P_S}\right)^2+u^2(\eta_S)\left(\frac{\partial T_F}{\partial \eta_S}\right)^2 \qquad (8)$$

3 Uncertainty Components

In the mathematical analysis of equation 6, 7 and 8, we'll analyze the uncertainties due to each of the above components separately and then combine the uncertainties to obtain the total expanded uncertainty. We are therefore concerned with four basic categories of uncertainty, pressure, temperature, saturator efficiency and the equations themselves. Each of these categories may also have associated uncertainty components. In determining components of uncertainty, there are several things to consider, such as measurement uncertainty, measurement hysteresis, and measurement resolution.

Listed below are the identified major uncertainty contributors and their components for the Model 1200 humidity generator.

- Uncertainty contribution from pressure (P_s and P_c) which includes
  - Measurement uncertainty
  - Measurement resolution
  - Measurement hysteresis

- Uncertainty contribution from temperature (T_s and T_c), which includes
  - Measurement uncertainty
  - Measurement resolution
  - Self heating

- Uncertainty contribution from Equations (e(T) and f(T,P)), which includes
  - Saturation Vapor Pressure Equation (e(T))
  - Enhancement Factor Equation (f(T,P))

- Uncertainty contribution from percent efficiency of the saturator (η_S)

3.1 Pressure Uncertainty Contribution

The pressure terms, P_c or P_s, in a two-pressure humidity generator are major determining factors. The Model 1200 humidity generator uses one pressure transducer to measures the chamber pressure and the saturation pressure. Due to this design many pressure uncertainties are shared between the chamber and saturation pressure. Any uncertainty contributed by this single transducer will simultaneously affect both the chamber and saturation pressure readings.

The pressure uncertainty contribution in terms of relative humidity can be determined by the partial numeric differential of the RH equation with respect to pressure, multiplied by the uncertainty of the pressure component. The equation for this becomes

$$\mathrm{uRH}_{[\mathrm{component}]} = \frac{\partial}{\partial P}\left[\frac{e_S(T_S)\,f(T_S, P+(P_S-P_C))}{e_S(T_C)\,f(T_C,P)}\cdot\frac{P}{P+(P_S-P_C)}\cdot\eta_S\right]\cdot \mathrm{uP}_{[\mathrm{component}]} \qquad (9)$$

$\mathrm{uRH}_{[\mathrm{component}]}$ = Pressure component uncertainty in terms of percent relative humidity.

$\mathrm{uP}_{[\mathrm{component}]}$ = Pressure component uncertainty in terms of pressure.

The pressure uncertainty contribution in terms of dew or frost point temperature can be determined by the partial numeric differential of the iterative dew or frost point equation with respect to pressure, multiplied by the uncertainty of the pressure component. The equations for these become

$$\mathrm{uT}_{\mathrm{D[component]}} = \frac{\partial}{\partial P}\left[e_W(T_D)\cdot f(T_D,P) = f(T_S, P+(P_S-P_C))\cdot e(T_S))\cdot \frac{P}{P+(P_S-P_C)} \right]\cdot \mathrm{uP}_{\mathrm{[component]}} \tag{10}$$

$$\mathrm{uT}_{\mathrm{F[component]}} = \frac{\partial}{\partial P}\left[e_I(T_F)\cdot f(T_F,P) = f(T_S, P+(P_S-P_C))\cdot e(T_S))\cdot \frac{P}{P+(P_S-P_C)} \right]\cdot \mathrm{uP}_{\mathrm{[component]}} \tag{11}$$

$\mathrm{uT}_{\mathrm{D[component]}}$ = Pressure component uncertainty in terms of dew point temperature.

$\mathrm{uT}_{\mathrm{F[component]}}$ = Pressure component uncertainty in terms of frost point temperature.

$\mathrm{uP}_{\mathrm{[component]}}$ = Pressure component uncertainty in terms of pressure.

3.1.1 Pressure Measurement Uncertainty Component

Pressure Measurement uncertainty of Model 1200 humidity generator's pressure transducer is specified as 0.04% of the full scale. Based on a rectangular distribution, the uncertainty component of the pressure measurement is then

$\mathrm{uP}_{\mathrm{[measurement]}}$ = (155 psia (full scale) * 0.04%) / √3
= ±(0.062 psia) / √3 (DOF=infinite)

3.1.2 Pressure Resolution Uncertainty Component

The Model 1200 humidity generator uses an Analog to Digital device to translate the pressure transducer's voltage reading into a digital value. The Analog to Digital conversion process resolves over the range of the pressure transducer. Based on a rectangular distribution of the half-interval of resolution, the uncertainty component of pressure resolution is then

$\mathrm{uP}_{\mathrm{[resolution]}}$ = 155 psia (transducer range) / 2^15 * 0.5/√3
= ±0.00473022460938 psia / √12 (DOF=infinite)

3.1.3 Pressure Hysteresis Uncertainty Component

Since the Model 1200 humidity generator incorporates only one pressure transducer in a time-shared approach, the transducer is subject to some measurement hysteresis. For around 99.7% of the time, the transducer monitors the saturation pressure. For less than 0.3% of the time (once every 30 minutes for approximately 5 seconds), the transducer monitors the chamber pressure. By this criterion, it is only the chamber pressure, which is affected by hysteresis and therefore only applied to the chamber pressure component. To determine this uncertainty in terms of relative humidity we have to isolate only the chamber pressure component. This can be determined by the partial numeric differential of the RH equation with respect to only the chamber pressure, multiplied by the uncertainty of the chamber pressure component. The equation for this becomes.

$$\text{uRH}_{[\text{component}]} = \frac{\partial}{\partial P_C}\left[\frac{e_S(T_S)f(T_S,P_S)}{e_S(T_C)f(T_C,P_C)} \cdot \frac{P_C}{P_S} \cdot \eta_S\right] \cdot \text{uP}_{C\,[\text{component}]} \quad (12)$$

$\text{uRH}_{[\text{component}]}$ = Pressure component uncertainty in terms of relative humidity.

$\text{uP}_{C[\text{component}]}$ = Chamber Pressure component uncertainty in terms of pressure.

The pressure uncertainty contribution in terms of dew or frost point temperature can be determined by the partial numeric differential of the iterative dew or frost point equation with respect to chamber pressure, multiplied by the uncertainty of the chamber pressure component. The equations for these become

$$\text{uT}_{D[\text{component}]} = \frac{\partial}{\partial P_C}\left[e_W(T_D) \cdot f(T_D,P_C) = f(T_S,P_S) \cdot e(T_S)) \cdot \frac{P_C}{P_S}\right] \cdot \text{uP}_{C\,[\text{component}]} \quad (13)$$

$$\text{uT}_{F[\text{component}]} = \frac{\partial}{\partial P_C}\left[e_I(T_F) \cdot f(T_F,P_C) = f(T_S,P_S) \cdot e(T_S)) \cdot \frac{P_C}{P_S}\right] \cdot \text{uP}_{C\,[\text{component}]} \quad (14)$$

$\text{uT}_{D[\text{component}]}$ = Pressure component uncertainty in terms of dew point temperature.

$\text{uT}_{F[\text{component}]}$ = Pressure component uncertainty in terms of frost point temperature.

$\text{uP}_{[\text{component}]}$ = Pressure component uncertainty in terms of pressure.

The maximum amount of hysteresis specified for the Model 1200 humidity generator's pressure transducer is ±0.04% of the measured difference between the saturation and chamber pressures, with a rectangular distribution.

$\text{uP}_{C[\text{hysteresis}]}$ = ±{0.04% * (P_s-P_c) } psia / √3 (DOF=infinite)

3.1.3 Pressure Uncertainty Contribution Summary

The standard uncertainties, uRH, components calculated using equation 9 and 12 from the associated individual pressure components previously shown are summarized in the following table.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following table.

Standard Pressure Uncertainty Components of RH (±%)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
10 °C	Pc Hysteresis	0.00119	0.00611	0.01178	0.01464	0.01638	0.01875	0.02001	0.02139	Infinity	Type B
	P Measurement	0.01192	0.04748	0.06106	0.05692	0.05094	0.03888	0.03111	0.02217	Infinity	Type B
	P Resolution	0.00045	0.00181	0.00233	0.00217	0.00194	0.00148	0.00119	0.00085	Infinity	Type B
		94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
35 °C	Pc Hysteresis	0.00119	0.00611	0.01178	0.01463	0.01636	0.01872	0.01995	0.02129	Infinity	Type B
	P Measurement	0.01192	0.04747	0.06101	0.05685	0.05086	0.03879	0.03100	0.02205	Infinity	Type B
	P Resolution	0.00045	0.00181	0.00233	0.00217	0.00194	0.00148	0.00118	0.00084	Infinity	Type B
				49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
60 °C	Pc Hysteresis			0.01177	0.01463	0.01635	0.01869	0.01991	0.02121	Infinity	Type B
	P Measurement			0.06094	0.05678	0.05078	0.03871	0.03092	0.02196	Infinity	Type B
	P Resolution			0.00232	0.00217	0.00194	0.00148	0.00118	0.00084	Infinity	Type B

Table 1

The standard uncertainties, uT_D, components calculated using equation 10 and 13 from the associated individual pressure components previously shown are summarized in the following table.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following table.

Standard Pressure Uncertainty Components of Dew Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	9.2 °C Td	5.5 °C Td	-0.2 °C Td	-4.0 °C Td	-6.9 °C Td	-12.0 °C Td	-15.5 °C Td	-20.2 °C Td		
10 °C	Pc Hysteresis	0.00019	0.00119	0.00329	0.00527	0.00718	0.01174	0.01612	0.02455	Infinity	Type B
	P Measurement	0.00186	0.00928	0.01706	0.02049	0.02232	0.02435	0.02507	0.02545	Infinity	Type B
	P Resolution	0.00007	0.00035	0.00065	0.00078	0.00085	0.00093	0.00096	0.00097	Infinity	Type B
		34.0 °C Td	29.6 °C Td	22.7 °C Td	18.1 °C Td	14.6 °C Td	8.6 °C Td	4.5 °C Td	-1.1 °C Td		
35 °C	Pc Hysteresis	0.00022	0.00144	0.00395	0.00630	0.00856	0.01393	0.01906	0.02890	Infinity	Type B
	P Measurement	0.00225	0.01119	0.02046	0.02448	0.02659	0.02886	0.02962	0.02994	Infinity	Type B
	P Resolution	0.00009	0.00043	0.00078	0.00093	0.00101	0.00110	0.00113	0.00114	Infinity	Type B
				45.4 °C Td	40.0 °C Td	35.9 °C Td	28.8 °C Td	23.4 °C Td	17.5 °C Td		
60 °C	Pc Hysteresis			0.00467	0.00743	0.01006	0.01629	0.02222	0.03354	Infinity	Type B
	P Measurement			0.02419	0.02884	0.03124	0.03374	0.03452	0.03473	Infinity	Type B
	P Resolution			0.00092	0.00110	0.00119	0.00129	0.00132	0.00132	Infinity	Type B

Table 2

The standard uncertainties, uT_F, components calculated using equation 11 and 14 from the associated individual pressure components previously shown are summarized in the following table.

Note: Any frost point value that is theoretically not possible is grayed out of the following table.

Standard Pressure Uncertainty Components of Frost Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**			-0.1 °C Tf	-3.6 °C Tf	-6.2 °C Tf	-10.7 °C Tf	-13.8 °C Tf	-18.1 °C Tf		
10 °C	Pc Hysteresis			0.00290	0.00468	0.00641	0.01057	0.01460	0.02239	Infinity	Type B
	P Measurement			0.01505	0.01820	0.01992	0.02191	0.02269	0.02321	Infinity	Type B
	P Resolution			0.00057	0.00069	0.00076	0.00084	0.00087	0.00089	Infinity	Type B
									-0.9 °C Tf		
35 °C	Pc Hysteresis								0.02554	Infinity	Type B
	P Measurement								0.02646	Infinity	Type B
	P Resolution								0.00101	Infinity	Type B
60 °C	Pc Hysteresis									Infinity	Type B
	P Measurement									Infinity	Type B
	P Resolution									Infinity	Type B

Table 3

3.2 Temperature Uncertainty Contribution

The temperature terms, T_c or T_s, in a two-pressure humidity generator are another major contributor of uncertainty and are used mathematically to calculate saturation vapor pressures. The Model 1200 humidity generator uses two temperature probes to measures the chamber temperature and the saturation temperature. Due to this design each temperature probe contributes its own uncertainty to the over all system and will be addressed independent of one another.

3.2.1 Saturation Temperature Uncertainty Contribution

The saturation temperature uncertainty contribution in terms of relative humidity can be determined by the partial numeric differential of the RH equation with respect to saturation temperature, multiplied by the uncertainty of the saturation temperature component. The equation for this becomes

$$\mathrm{uRH}_{[\text{component}]} = \frac{\partial}{\partial T_S}\left[\frac{e_S(T_S)\,f(T_S,P_S))}{e_S(T_C)\,f(T_C,P_C)}\cdot\frac{P_C}{P_S}\cdot\eta_S\right]\cdot \mathrm{u}T_{S[\text{component}]} \qquad (15)$$

$\mathrm{uRH}_{[\text{component}]}$ = Sat Temperature component uncertainty in terms of percent relative humidity.

$\mathrm{uT}_{S[\text{component}]}$ = Sat Temperature component uncertainty in terms of pressure.

The saturation temperature uncertainty contribution in terms of dew or frost point temperature can be determined by the partial numeric differential of the iterative dew or frost point equation with respect to saturation temperature, multiplied by the uncertainty of the saturation temperature component. The equations for these become

$$\mathrm{uT}_{\mathrm{D[component]}} = \frac{\partial}{\partial T_S}\left[e_W(T_D)\cdot f(T_D,P_C) = f(T_S,P_S)\cdot e(T_S))\cdot \frac{P_C}{P_S} \right]\cdot \mathrm{uT}_{\mathrm{S\,[component]}} \qquad (16)$$

$$\mathrm{uT}_{\mathrm{F[component]}} = \frac{\partial}{\partial T_S}\left[e_I(T_F)\cdot f(T_F,P_C) = f(T_S,P_S)\cdot e(T_S))\cdot \frac{P_C}{P_S} \right]\cdot \mathrm{uT}_{\mathrm{S\,[component]}} \qquad (17)$$

$\mathrm{uT}_{\mathrm{D[component]}}$ = Pressure component uncertainty in terms of dew point temperature.

$\mathrm{uT}_{\mathrm{F[component]}}$ = Pressure component uncertainty in terms of frost point temperature

$\mathrm{uT}_{\mathrm{S[component]}}$ = Pressure component uncertainty in terms of pressure.

3.2.1.1 Saturation Temperature Measurement Uncertainty Component

Temperature measurement uncertainty of Model 1200 humidity generator's saturation temperature probe is specified as 0.05 °C. Based on a rectangular distribution, the uncertainty component of saturation temperature measurement is then

$\mathrm{uT}_{\mathrm{S[measurement]}}$ = ±0.05 °C / √3 (DOF=infinite)

3.2.1.2 Saturation Temperature Resolution Uncertainty Component

The Model 1200 humidity generator uses a computer module to translate the saturation temperature probe readings into digital values. The computer module has a specified resolution of 0.01°C. Based on a rectangular distribution of the half-interval of resolution, the uncertainty component of saturation temperature resolution is then

$\mathrm{uT}_{\mathrm{S\,[resolution]}}$ = 0.01°C * 0.5/√3
= ±0.01°C / √12 (DOF=infinite)

3.2.1.3 Saturation Temperature Self-Heating Uncertainty Component

The saturation temperature probe is installed in a thermo-well, affixed with heat sink compound, within the fluid jacket at the outlet of the Model 1200's saturator. This design is similar to a well-stirred fluid bath and since the probe is not in air, the effects of self-heating associated with its measurement are considered insignificant and will not be considered.

3.2.2 Chamber Temperature Uncertainty Contribution

The chamber temperature uncertainty contribution in terms of relative humidity can be determined by the partial numeric differential of the RH equation with respect to chamber temperature, multiplied by the uncertainty of the chamber temperature component. The equation for this becomes

$$\mathrm{uRH}_{[\mathrm{component}]} = \frac{\partial}{\partial T_C}\left[\frac{e_S(T_S)\,f(T_S,P_S))}{e_S(T_C)\,f(T_C,P_C)}\cdot\frac{P_C}{P_S}\cdot\eta_S\right]\cdot \mathrm{u}T_{C[\mathrm{component}]} \qquad (18)$$

$\mathrm{uRH}_{[\mathrm{component}]}$ = Chamber Temperature component uncertainty in terms of percent relative humidity.

$\mathrm{uT}_{C[\mathrm{component}]}$ = Chamber Temperature component uncertainty in terms of pressure.

Examining equations 3 and 4, dew and frost point equations, we see that the chamber temperature has no component and therefore no uncertainty contribution to the generated dew or frost point temperatures.

3.2.2.1 Chamber Temperature Measurement Uncertainty Component

Temperature measurement uncertainty of Model 1200 humidity generator's chamber temperature probe is specified as 0.05 °C. Based on a rectangular distribution, the uncertainty component of chamber temperature measurement is then

$\mathrm{uT}_{C[\mathrm{measurement}]}$ = ±0.05 °C / √3 (DOF=infinite)

3.2.2.2 Chamber Temperature Resolution Uncertainty Component

The Model 1200 humidity generator uses a 16 Bit computer module to translate the chamber temperature probe readings into digital values. The computer module has a specified resolution of 0.01°C. Based on a rectangular distribution of the half-interval of resolution, the uncertainty component of chamber temperature resolution is then

$\mathrm{uT}_{C\ [\mathrm{resolution}]}$ = 0.01°C * 0.5/√3
= ±0.01°C / √12 (DOF=infinite)

3.2.2.3 Chamber Temperature Self-Heating Uncertainty Component

Unlike the saturation temperature probe, the chamber temperature probe is used in air and there is the possibility of some self-heating associated with this measurement that must be considered. The self-heating, with temperature measurements in °C, is estimated to be 0.05% of reading. The equation for the chamber temperature uncertainty of self-heating is then

$\mathrm{uT}_{C\ [\mathrm{self\text{-}heating}]}$ = ± (0.05% * T_c) / √3 (DOF=infinite)

3.2.3 Temperature Uncertainty Contribution Summary

The standard uncertainties, uRH, components calculated using equation 15 and 18 from the associated individual temperature components previously shown are summarized in the following table.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following table.

Standard Temperature Uncertainty Components of RH (±%)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
10 °C	Ts Measurement	0.18350	0.14233	0.09507	0.07144	0.05726	0.03836	0.02891	0.01946	Infinity	Type B
	Tc Measurement	0.18350	0.14236	0.09511	0.07149	0.05732	0.03842	0.02897	0.01953	Infinity	Type B
	Tc Self Heating	0.01835	0.01424	0.00951	0.00715	0.00573	0.00384	0.00290	0.00195	Infinity	Type B
	Tc Resolution	0.03670	0.02847	0.01902	0.01430	0.01146	0.00768	0.00579	0.00391	Infinity	Type B
	Ts Resolution	0.01835	0.01423	0.00951	0.00714	0.00573	0.00384	0.00289	0.00195	Infinity	Type B
		94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
35 °C	Ts Measurement	0.15156	0.11755	0.07849	0.05896	0.04725	0.03162	0.02381	0.01600	Infinity	Type B
	Tc Measurement	0.15156	0.11756	0.07851	0.05899	0.04728	0.03166	0.02385	0.01605	Infinity	Type B
	Tc Self Heating	0.05305	0.04114	0.02748	0.02065	0.01655	0.01108	0.00835	0.00562	Infinity	Type B
	Tc Resolution	0.03031	0.02351	0.01570	0.01180	0.00946	0.00633	0.00477	0.00321	Infinity	Type B
	Ts Resolution	0.01516	0.01175	0.00785	0.00590	0.00472	0.00316	0.00238	0.00160	Infinity	Type B
				49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
60 °C	Ts Measurement			0.06574	0.04939	0.03957	0.02647	0.01992	0.01337	Infinity	Type B
	Tc Measurement			0.06571	0.04936	0.03955	0.02647	0.01993	0.01339	Infinity	Type B
	Tc Self Heating			0.03943	0.02962	0.02373	0.01588	0.01196	0.00803	Infinity	Type B
	Tc Resolution			0.01314	0.00987	0.00791	0.00529	0.00399	0.00268	Infinity	Type B
	Ts Resolution			0.00657	0.00494	0.00396	0.00265	0.00199	0.00134	Infinity	Type B

Table 4

The standard uncertainties, uT_D, components calculated using equation 16 from the associated individual temperature components previously shown are summarized in the following table.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following table.

Standard Temperature Uncertainty Components of Dew Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	9.2 °C Td	5.5 °C Td	-0.2 °C Td	-4.0 °C Td	-6.9 °C Td	-12.0 °C Td	-15.5 °C Td	-20.2 °C Td		
10 °C	Ts Measurement	0.02869	0.02784	0.02658	0.02574	0.02511	0.02404	0.02332	0.02236	Infinity	Type B
	Ts Resolution	0.00287	0.00278	0.00266	0.00257	0.00251	0.00240	0.00233	0.00224	Infinity	Type B
		34.0 °C Td	29.6 °C Td	22.7 °C Td	18.1 °C Td	14.6 °C Td	8.6 °C Td	4.5 °C Td	-1.1 °C Td		
35 °C	Ts Measurement	0.02867	0.02772	0.02632	0.02540	0.02471	0.02354	0.02277	0.02173	Infinity	Type B
	Ts Resolution	0.00287	0.00277	0.00263	0.00254	0.00247	0.00235	0.00228	0.00217	Infinity	Type B
				45.4 °C Td	40.0 °C Td	35.9 °C Td	28.8 °C Td	23.4 °C Td	17.5 °C Td		
60 °C	Ts Measurement			0.02607	0.02506	0.02433	0.02307	0.02223	0.02114	Infinity	Type B
	Ts Resolution			0.00261	0.00251	0.00243	0.00231	0.00222	0.00211	Infinity	Type B

Table 5

The standard uncertainties, uT_F, components calculated using equation 17 from the associated individual temperature components previously shown are summarized in the following table.

Note: Any frost point value that is theoretically not possible is grayed out of the following table.

Standard Temperature Uncertainty Components of Frost Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**			-0.1 °C Tf	-3.6 °C Tf	-6.2 °C Tf	-10.7 °C Tf	-13.8 °C Tf	-18.1 °C Tf		
10 °C	Ts Measurement			0.02345	0.02286	0.02241	0.02164	0.02111	0.02039	Infinity	Type B
	Ts Resolution			0.00235	0.00229	0.00224	0.00216	0.00211	0.00204	Infinity	Type B
									-0.9 °C Tf		
35 °C	Ts Measurement								0.01921	Infinity	Type B
	Ts Resolution								0.00192	Infinity	Type B
60 °C	Ts Measurement									Infinity	Type B
	Ts Resolution									Infinity	Type B

Table 6

3.3 Equation Uncertainty Contribution

The equations used to calculate the saturation vapor pressure at a given temperature and its enhancement factor at the same temperature and given pressure have published uncertainties as determined by the author or authors of the equations. These equations are used throughout the Relative Humidity, Dew point and Frost point equations and therefore contribute their own uncertainty to the over all system.

3.3.1 Saturation Vapor Pressure Equation Uncertainty Component

The saturation vapor pressure is the partial pressure of the water vapor at a given temperature with respect to ice or water. The saturation vapor pressure is dependent on temperature only and is computed with the Wexler's [4] saturation vapor pressure equation. Wexler [4] also list a table of uncertainties at various temperatures for his saturation vapor pressure equation. These uncertainty values are interpolated to determine the saturation vapor pressure equation uncertainty component for a given temperature.

3.3.2 Enhancement Factor Equation Uncertainty Component

Enhancement factors are slight correction factors used to account for the non-ideal behavior of water vapor when admixed with other gases. The enhancement factor is dependent on both temperature and pressure and is computed with Greenspan's [5] enhancement factor equation. Wexler and R.W. Hyland [8] list a table of uncertainties for various temperatures and pressures for the enhancement factor equation. These uncertainty values are interpolated to determine the enhancement factors equation uncertainty component for a given temperature and pressure.

3.3.3 Equation Uncertainty Contribution Summary

The standard uncertainties, uRH, components calculated using the associated equation uncertainty tables mentioned above are summarized in the following table.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following table.

Standard Equation Uncertainty Components of RH (±%)											
Saturation Temperature	**Description**	**Saturation Pressure Range (psia), Chamber pressure = 14.7 psia**								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
		94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
10 °C	SVP@Tt	0.00590	0.00457	0.00306	0.00230	0.00184	0.00123	0.00093	0.00063	Infinity	Type B
	SVP@Ts	0.00590	0.00457	0.00305	0.00228	0.00183	0.00122	0.00091	0.00061	Infinity	Type B
	F@Tt,Pt	0.00960	0.00745	0.00497	0.00374	0.00300	0.00201	0.00152	0.00102	Infinity	Type B
	F@Ts,Ps	0.01006	0.00980	0.00951	0.00938	0.00931	0.00921	0.00901	0.00889	Infinity	Type B
		94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
35 °C	SVP@Tt	0.00795	0.00616	0.00412	0.00309	0.00248	0.00166	0.00125	0.00084	Infinity	Type B
	SVP@Ts	0.00794	0.00616	0.00411	0.00308	0.00246	0.00164	0.00123	0.00082	Infinity	Type B
	F@Tt,Pt	0.00722	0.00560	0.00374	0.00281	0.00225	0.00151	0.00114	0.00076	Infinity	Type B
	F@Ts,Ps	0.00764	0.00778	0.00795	0.00804	0.00810	0.00821	0.00838	0.00857	Infinity	Type B
				49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
60 °C	SVP@Tt			0.00118	0.00088	0.00071	0.00047	0.00036	0.00024	Infinity	Type B
	SVP@Ts			0.00117	0.00088	0.00070	0.00047	0.00035	0.00023	Infinity	Type B
	F@Tt,Pt			0.00252	0.00189	0.00151	0.00101	0.00076	0.00051	Infinity	Type B
	F@Ts,Ps			0.00705	0.00752	0.00781	0.00819	0.00822	0.00827	Infinity	Type B

Table 7

The standard uncertainties, uT_D, components calculated using the associated equation uncertainty tables mentioned above are summarized in the following table.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following table.

Standard Equation Uncertainty Components of Dew Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	9.2 °C Td	5.5 °C Td	-0.2 °C Td	-4.0 °C Td	-6.9 °C Td	-12.0 °C Td	-15.5 °C Td	-20.2 °C Td		
10 °C	SVP@Ts	0.00092	0.00089	0.00085	0.00082	0.00080	0.00076	0.00074	0.00070	Infinity	Type B
	SVP@Td	0.00087	0.00060	0.00022	0.00021	0.00021	0.00020	0.00019	0.00018	Infinity	Type B
	F@Ts,Ps	0.00157	0.00192	0.00266	0.00338	0.00408	0.00577	0.00727	0.01021	Infinity	Type B
	F@Td,Pt	0.00150	0.00146	0.00140	0.00162	0.00178	0.00203	0.00218	0.00235	Infinity	Type B
		34.0 °C Td	29.6 °C Td	22.7 °C Td	18.1 °C Td	14.6 °C Td	8.6 °C Td	4.5 °C Td	-1.1 °C Td		
35 °C	SVP@Ts	0.00150	0.00145	0.00138	0.00133	0.00129	0.00122	0.00118	0.00112	Infinity	Type B
	SVP@Td	0.00158	0.00190	0.00200	0.00159	0.00129	0.00082	0.00052	0.00022	Infinity	Type B
	F@Ts,Ps	0.00145	0.00184	0.00267	0.00346	0.00424	0.00612	0.00801	0.01165	Infinity	Type B
	F@Td,Pt	0.00128	0.00092	0.00144	0.00161	0.00156	0.00149	0.00145	0.00146	Infinity	Type B
				45.4 °C Td	40.0 °C Td	35.9 °C Td	28.8 °C Td	23.4 °C Td	17.5 °C Td		
60 °C	SVP@Ts			0.00047	0.00045	0.00043	0.00041	0.00039	0.00037	Infinity	Type B
	SVP@Td			0.00101	0.00112	0.00145	0.00196	0.00211	0.00153	Infinity	Type B
	F@Ts,Ps			0.00280	0.00382	0.00480	0.00714	0.00917	0.01308	Infinity	Type B
	F@Td,Pt			0.00144	0.00189	0.00146	0.00099	0.00135	0.00160	Infinity	Type B

Table 8

The standard uncertainties, uT_F, components calculated using the associated equation uncertainty tables mentioned above are summarized in the following table.

Note: Any frost point value that is theoretically not possible is grayed out of the following table.

Standard Equation Uncertainty Components of Frost Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**			-0.1 °C Tf	-3.6 °C Tf	-6.2 °C Tf	-10.7 °C Tf	-13.8 °C Tf	-18.1 °C Tf		
10 °C	SVP@Ts			0.00075	0.00073	0.00072	0.00069	0.00067	0.00064	Infinity	Type B
	SVP@Td			0.00029	0.00247	0.00405	0.00660	0.00800	0.00978	Infinity	Type B
	F@Ts,Ps			0.00235	0.00300	0.00364	0.00519	0.00658	0.00931	Infinity	Type B
	F@Td,Pt			0.00124	0.00141	0.00154	0.00175	0.00188	0.00204	Infinity	Type B
									-0.9 °C Tf		
35 °C	SVP@Ts								0.00099	Infinity	Type B
	SVP@Td								0.00080	Infinity	Type B
	F@Ts,Ps								0.01030	Infinity	Type B
	F@Td,Pt								0.00128	Infinity	Type B
60 °C	SVP@Ts									Infinity	Type B
	SVP@Td									Infinity	Type B
	F@Ts,Ps									Infinity	Type B
	F@Td,Pt									Infinity	Type B

Table 9

3.4 Saturator Efficiency Uncertainty Contribution

All two-pressure humidity generators rely on the ability of the saturator to fully saturate the gas with water vapor as it passes from inlet to outlet. The Model 1200 humidity generator incorporates a pre-saturator device along with the saturator to assure the full saturation of the gas with water vapor. Why this design helps assure 100% saturation of the gas, there may still be small amounts of uncertainty with regards to saturator efficiency, but they are considered insignificant and will not be considered. This analysis assumes 100% saturator efficiency.

4.0 Combined Standard and Expanded Uncertainty

The combined standard uncertainty is obtained by the statistical combination of the individual standard uncertainty components of pressure, temperature, and equation in terms of relative humidity, dew point or frost point.

Utilizing a confidence level of 95.45% and a coverage factor k=2, the expanded uncertainty, U, is expressed by multiplying the combined standard uncertainty by the coverage factor as show in the following formula

$$U = k * u_c \quad (19)$$

Using equation 6 and 19, the following tables reflect the standard uncertainty components, uRH, the combined standard uncertainty, u_cRH, and the combined expanded uncertainty, URH, at various temperatures and pressures.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following tables.

Uncertainty Components of RH (±%)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
10 °C	Ts Measurement	0.18350	0.14233	0.09507	0.07144	0.05726	0.03836	0.02891	0.01946	Infinity	Type B
	Tc Measurement	0.18350	0.14236	0.09511	0.07149	0.05732	0.03842	0.02897	0.01953	Infinity	Type B
	Tc Resolution	0.03670	0.02847	0.01902	0.01430	0.01146	0.00768	0.00579	0.00391	Infinity	Type B
	Tc Self Heating	0.01835	0.01424	0.00951	0.00715	0.00573	0.00384	0.00290	0.00195	Infinity	Type B
	Ts Resolution	0.01835	0.01423	0.00951	0.00714	0.00573	0.00384	0.00289	0.00195	Infinity	Type B
	P Measurement	0.01192	0.04748	0.06106	0.05692	0.05094	0.03888	0.03111	0.02217	Infinity	Type B
	F@Ts,Ps	0.01006	0.00980	0.00951	0.00938	0.00931	0.00921	0.00901	0.00889	Infinity	Type B
	F@Tt,Pt	0.00960	0.00745	0.00497	0.00374	0.00300	0.00201	0.00152	0.00102	Infinity	Type B
	SVP@Tt	0.00590	0.00457	0.00306	0.00230	0.00184	0.00123	0.00093	0.00063	Infinity	Type B
	SVP@Ts	0.00590	0.00457	0.00305	0.00228	0.00183	0.00122	0.00091	0.00061	Infinity	Type B
	Pc Hysteresis	0.00119	0.00611	0.01178	0.01464	0.01638	0.01875	0.02001	0.02139	Infinity	Type B
	P Resolution	0.00045	0.00181	0.00233	0.00217	0.00194	0.00148	0.00119	0.00085	Infinity	Type B
Combined Standard Uncertainty		**0.26414**	**0.21031**	**0.15044**	**0.11871**	**0.09864**	**0.07067**	**0.05639**	**0.04258**	**Infinity**	
Expanded Uncertainty (k=2)		**0.52829**	**0.42061**	**0.30089**	**0.23742**	**0.19728**	**0.14133**	**0.11278**	**0.08517**		

Table 10

Uncertainty Components of RH (±%)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
35 °C	Ts Measurement	0.15156	0.11755	0.07849	0.05896	0.04725	0.03162	0.02381	0.01600	Infinity	Type B
	Tc Measurement	0.15156	0.11756	0.07851	0.05899	0.04728	0.03166	0.02385	0.01605	Infinity	Type B
	Tc Self Heating	0.05305	0.04114	0.02748	0.02065	0.01655	0.01108	0.00835	0.00562	Infinity	Type B
	Tc Resolution	0.03031	0.02351	0.01570	0.01180	0.00946	0.00633	0.00477	0.00321	Infinity	Type B
	Ts Resolution	0.01516	0.01175	0.00785	0.00590	0.00472	0.00316	0.00238	0.00160	Infinity	Type B
	P Measurement	0.01192	0.04747	0.06101	0.05685	0.05086	0.03879	0.03100	0.02205	Infinity	Type B
	SVP@Tt	0.00795	0.00616	0.00412	0.00309	0.00248	0.00166	0.00125	0.00084	Infinity	Type B
	SVP@Ts	0.00794	0.00616	0.00411	0.00308	0.00246	0.00164	0.00123	0.00082	Infinity	Type B
	F@Ts,Ps	0.00764	0.00778	0.00795	0.00804	0.00810	0.00821	0.00838	0.00857	Infinity	Type B
	F@Tt,Pt	0.00722	0.00560	0.00374	0.00281	0.00225	0.00151	0.00114	0.00076	Infinity	Type B
	Pc Hysteresis	0.00119	0.00611	0.01178	0.01463	0.01636	0.01872	0.01995	0.02129	Infinity	Type B
	P Resolution	0.00045	0.00181	0.00233	0.00217	0.00194	0.00148	0.00118	0.00084	Infinity	Type B
Combined Standard Uncertainty		**0.22424**	**0.18023**	**0.13178**	**0.10536**	**0.08829**	**0.06409**	**0.05166**	**0.03967**	**Infinity**	
Expanded Uncertainty (k=2)		**0.44848**	**0.36046**	**0.26357**	**0.21071**	**0.17657**	**0.12818**	**0.10333**	**0.07933**		

Table 11

Uncertainty Components of RH (±%)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**			49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH		
60 °C	Ts Measurement			0.06574	0.04939	0.03957	0.02647	0.01992	0.01337	Infinity	Type B
	Tc Measurement			0.06571	0.04936	0.03955	0.02647	0.01993	0.01339	Infinity	Type B
	Tc Self Heating			0.03943	0.02962	0.02373	0.01588	0.01196	0.00803	Infinity	Type B
	Tc Resolution			0.01314	0.00987	0.00791	0.00529	0.00399	0.00268	Infinity	Type B
	Ts Resolution			0.00657	0.00494	0.00396	0.00265	0.00199	0.00134	Infinity	Type B
	P Measurement			0.06094	0.05678	0.05078	0.03871	0.03092	0.02196	Infinity	Type B
	F@Ts,Ps			0.00705	0.00752	0.00781	0.00819	0.00822	0.00827	Infinity	Type B
	F@Tt,Pt			0.00252	0.00189	0.00151	0.00101	0.00076	0.00051	Infinity	Type B
	SVP@Tt			0.00118	0.00088	0.00071	0.00047	0.00036	0.00024	Infinity	Type B
	SVP@Ts			0.00117	0.00088	0.00070	0.00047	0.00035	0.00023	Infinity	Type B
	Pc Hysteresis			0.01177	0.01463	0.01635	0.01869	0.01991	0.02121	Infinity	Type B
	P Resolution			0.00232	0.00217	0.00194	0.00148	0.00118	0.00084	Infinity	Type B
Combined Standard Uncertainty				**0.11969**	**0.09684**	**0.08177**	**0.06006**	**0.04877**	**0.03786**	**Infinity**	
Expanded Uncertainty (k=2)				**0.23939**	**0.19369**	**0.16353**	**0.12012**	**0.09755**	**0.07571**		

Table 12

Using equation 7 and 19, the following tables reflect the standard uncertainty components, uT_D, the combined standard uncertainty, u_cT_D, and the combined expanded uncertainty, UT_D, at various temperatures and pressures.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit is grayed out of the following tables.

Uncertainty Components of Dew Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia									
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	9.2 °C Td	5.5 °C Td	-0.2 °C Td	-4.0 °C Td	-6.9 °C Td	-12.0 °C Td	-15.5 °C Td	-20.2 °C Td	**Degrees of Freedom**	**Evaluation**
10 °C	Ts Measurement	0.02869	0.02784	0.02658	0.02574	0.02511	0.02404	0.02332	0.02236	Infinity	Type B
	Ts Resolution	0.00287	0.00278	0.00266	0.00257	0.00251	0.00240	0.00233	0.00224	Infinity	Type B
	P Measurement	0.00186	0.00928	0.01706	0.02049	0.02232	0.02435	0.02507	0.02545	Infinity	Type B
	F@Ts,Ps	0.00157	0.00192	0.00266	0.00338	0.00408	0.00577	0.00727	0.01021	Infinity	Type B
	F@Td,Pt	0.00150	0.00146	0.00140	0.00162	0.00178	0.00203	0.00218	0.00235	Infinity	Type B
	SVP@Ts	0.00092	0.00089	0.00085	0.00082	0.00080	0.00076	0.00074	0.00070	Infinity	Type B
	SVP@Td	0.00087	0.00060	0.00022	0.00021	0.00021	0.00020	0.00019	0.00018	Infinity	Type B
	Pc Hysteresis	0.00019	0.00119	0.00329	0.00527	0.00718	0.01174	0.01612	0.02455	Infinity	Type B
	P Resolution	0.00007	0.00035	0.00065	0.00078	0.00085	0.00093	0.00096	0.00097	Infinity	Type B
Combined Standard Uncertainty		**0.02900**	**0.02963**	**0.03203**	**0.03365**	**0.03476**	**0.03678**	**0.03869**	**0.04320**	**Infinity**	
Expanded Uncertainty (k=2)		**0.05800**	**0.05925**	**0.06405**	**0.06729**	**0.06951**	**0.07357**	**0.07737**	**0.08641**		

Table 13

Uncertainty Components of Dew Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia									
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**	34.0 °C Td	29.6 °C Td	22.7 °C Td	18.1 °C Td	14.6 °C Td	8.6 °C Td	4.5 °C Td	-1.1 °C Td	**Degrees of Freedom**	**Evaluation**
35 °C	Ts Measurement	0.02867	0.02772	0.02632	0.02540	0.02471	0.02354	0.02277	0.02173	Infinity	Type B
	Ts Resolution	0.00287	0.00277	0.00263	0.00254	0.00247	0.00235	0.00228	0.00217	Infinity	Type B
	P Measurement	0.00225	0.01119	0.02046	0.02448	0.02659	0.02886	0.02962	0.02994	Infinity	Type B
	F@Ts,Ps	0.00158	0.00190	0.00200	0.00159	0.00129	0.00082	0.00052	0.00022	Infinity	Type B
	F@Td,Pt	0.00150	0.00145	0.00138	0.00133	0.00129	0.00122	0.00118	0.00112	Infinity	Type B
	SVP@Ts	0.00145	0.00184	0.00267	0.00346	0.00424	0.00612	0.00801	0.01165	Infinity	Type B
	SVP@Td	0.00128	0.00092	0.00144	0.00161	0.00156	0.00149	0.00145	0.00146	Infinity	Type B
	Pc Hysteresis	0.00022	0.00144	0.00395	0.00630	0.00856	0.01393	0.01906	0.02890	Infinity	Type B
	P Resolution	0.00009	0.00043	0.00078	0.00093	0.00101	0.00110	0.00113	0.00114	Infinity	Type B
Combined Standard Uncertainty		**0.02904**	**0.03023**	**0.03391**	**0.03620**	**0.03771**	**0.04037**	**0.04282**	**0.04847**	**Infinity**	
Expanded Uncertainty (k=2)		**0.05809**	**0.06046**	**0.06781**	**0.07239**	**0.07542**	**0.08075**	**0.08564**	**0.09693**		

Table 14

Uncertainty Components of Dew Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								Degrees of Freedom	Evaluation
		15.5	20.0	30.0	40.0	50.0	75.0	100.0	150.0		
Saturation Temperature	Description			45.4 °C Td	40.0 °C Td	35.9 °C Td	28.8 °C Td	23.4 °C Td	17.5 °C Td		
60 °C	Ts Measurement			0.02607	0.02506	0.02433	0.02307	0.02223	0.02114	Infinity	Type B
	Ts Resolution			0.00261	0.00251	0.00243	0.00231	0.00222	0.00211	Infinity	Type B
	P Measurement			0.02419	0.02884	0.03124	0.03374	0.03452	0.03473	Infinity	Type B
	F@Ts,Ps			0.00280	0.00382	0.00480	0.00714	0.00917	0.01308	Infinity	Type B
	F@Td,Pt			0.00144	0.00189	0.00146	0.00099	0.00135	0.00160	Infinity	Type B
	SVP@Ts			0.00101	0.00112	0.00145	0.00196	0.00211	0.00153	Infinity	Type B
	SVP@Td			0.00047	0.00045	0.00043	0.00041	0.00039	0.00037	Infinity	Type B
	Pc Hysteresis			0.00467	0.00743	0.01006	0.01629	0.02222	0.03354	Infinity	Type B
	P Resolution			0.00092	0.00110	0.00119	0.00129	0.00132	0.00132	Infinity	Type B
Combined Standard Uncertainty				**0.03613**	**0.03927**	**0.04127**	**0.04471**	**0.04772**	**0.05441**	**Infinity**	
Expanded Uncertainty (k=2)				**0.07226**	**0.07854**	**0.08255**	**0.08942**	**0.09544**	**0.10882**		

Table 15

Using equation 8 and 19, the following tables reflect the standard uncertainty components, uT_F, the combined standard uncertainty, u_cT_F, and the combined expanded uncertainty, UT_F, at various temperatures and pressures.

Note: Any frost point value that is theoretically not possible is grayed out of the following tables.

Uncertainty Components of Frost Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**			-0.1 °C Tf	-3.6 °C Tf	-6.2 °C Tf	-10.7 °C Tf	-13.8 °C Tf	-18.1 °C Tf		
10 °C	P Measurement			0.01505	0.01820	0.01992	0.02191	0.02269	0.02321	Infinity	Type B
	Pc Hysteresis			0.00290	0.00468	0.00641	0.01057	0.01460	0.02239	Infinity	Type B
	Ts Measurement			0.02345	0.02286	0.02241	0.02164	0.02111	0.02039	Infinity	Type B
	SVP@Td			0.00029	0.00247	0.00405	0.00660	0.00800	0.00978	Infinity	Type B
	F@Ts,Ps			0.00235	0.00300	0.00364	0.00519	0.00658	0.00931	Infinity	Type B
	F@Td,Pt			0.00124	0.00141	0.00154	0.00175	0.00188	0.00204	Infinity	Type B
	Ts Resolution			0.00235	0.00229	0.00224	0.00216	0.00211	0.00204	Infinity	Type B
	P Resolution			0.00057	0.00069	0.00076	0.00084	0.00087	0.00089	Infinity	Type B
	SVP@Ts			0.00075	0.00073	0.00072	0.00069	0.00067	0.00064	Infinity	Type B
Combined Standard Uncertainty				**0.02826**	**0.02998**	**0.03128**	**0.03376**	**0.03592**	**0.04060**	**Infinity**	
Expanded Uncertainty (k=2)				**0.05652**	**0.05997**	**0.06256**	**0.06751**	**0.07183**	**0.08119**		

Table 16

Uncertainty Components of Frost Point Temperature (±°C)											
		Saturation Pressure Range (psia), Chamber pressure = 14.7 psia								**Degrees of Freedom**	**Evaluation**
		15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**		
Saturation Temperature	**Description**								-0.9 °C Tf		
35 °C	P Measurement								0.02646	Infinity	Type B
	Pc Hysteresis								0.02554	Infinity	Type B
	Ts Measurement								0.01921	Infinity	Type B
	F@Ts,Ps								0.01030	Infinity	Type B
	Ts Resolution								0.00192	Infinity	Type B
	F@Td,Pt								0.00128	Infinity	Type B
	P Resolution								0.00101	Infinity	Type B
	SVP@Ts								0.00099	Infinity	Type B
	SVP@Td								0.00080	Infinity	Type B
Combined Standard Uncertainty									**0.04284**	**Infinity**	
Expanded Uncertainty (k=2)									**0.08568**		

Table 17

5.0 Summary

A summary of the final combined expanded uncertainty is summarized in the following tables.

Note: The Model 1200 humidity generator is limited to a maximum dew point temperature of 50°C. Any value calculated above this limit or that is theoretically not possible, is grayed out of the following tables.

Expanded %RH Uncertainty (k=2)								
	Saturation Pressure Range (psia), Chamber pressure = 14.7 psia							
	15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**
Saturation Temperature	94.9 %RH	73.6 %RH	49.1 %RH	36.9 %RH	29.6 %RH	19.9 %RH	14.9 %RH	10.0 %RH
10 °C	±0.528	±0.421	±0.301	±0.237	±0.197	±0.141	±0.113	±0.085
35 °C	±0.448	±0.360	±0.264	±0.211	±0.177	±0.128	±0.103	±0.079
60 °C			±0.239	±0.194	±0.164	±0.120	±0.098	±0.076

Table 18

Expanded Dew Point Temperature Uncertainty (k=2)								
	Saturation Pressure Range (psia), Chamber pressure = 14.7 psia							
	15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**
Saturation Temperature	9.2 °C Td	5.5 °C Td	-0.2 °C Td	-4.0 °C Td	-6.9 °C Td	-12.0 °C Td	-15.5 °C Td	-20.2 °C Td
10 °C	±0.058	±0.059	±0.064	±0.067	±0.070	±0.074	±0.077	±0.086
	34.0 °C Td	29.6 °C Td	22.7 °C Td	18.1 °C Td	14.6 °C Td	8.6 °C Td	4.5 °C Td	-1.1 °C Td
35 °C	±0.058	±0.060	±0.068	±0.072	±0.075	±0.081	±0.086	±0.097
			45.4 °C Td	40.0 °C Td	35.9 °C Td	28.8 °C Td	23.4 °C Td	17.5 °C Td
60 °C			±0.072	±0.079	±0.083	±0.089	±0.095	±0.109

Table 19

Expanded Frost Point Temperature Uncertainty (k=2)								
	Saturation Pressure Range (psia), Chamber pressure = 14.7 psia							
	15.5	**20.0**	**30.0**	**40.0**	**50.0**	**75.0**	**100.0**	**150.0**
Saturation Temperature			-0.1 °C Tf	-3.6 °C Tf	-6.2 °C Tf	-10.7 °C Tf	-13.8 °C Tf	-18.1 °C Tf
10 °C			±0.057	±0.060	±0.063	±0.068	±0.072	±0.081
								-0.9 °C Tf
35 °C								±0.086

Table 20

6.0 References

1. Taylor, Barry N. and Kuyatt, Chris E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition
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Chamber Temperature Uniformity Analysis of the Model 1200 Two-Pressure Humidity Generator

Chamber Temperature Uniformity Analysis
Of the
Thunder Scientific Model 1200 Two-Pressure Humidity Generator

1 Introduction

Described here is the Chamber Temperature Uniformity for a Model 1200 Humidity Generator. Chamber temperature uniformity has a direct influence on relative humidity gradients within the test chamber. In order to determine the chamber temperature uniformity, 10 thermometers of equivalent type and nominal resistance where calibrated together over the temperature range 10 to 60 °C. The 10 thermometers were then strategically placed at various locations within the test chamber, approximately 1/2 inch from each corner, one mounted rear center, and one mounted bottom center.

2 Defining Equations

The maximum measurement deviation from the mean will be determined by noting the maximum and minimum readings from the set of probes at the same point in time, then taking half the difference of these values.

$$\text{MaxDev} = \pm 0.5(\text{MaxReading-MinReading}) \qquad [1]$$

The uniformity will then be computed by RSS combination (root of the sum of the squares) of the maximum deviation, MaxDev, and the estimated thermometer uncertainty, u(T).

$$\text{uniformity}^2 = \text{MaxDev}^2 + u^2(T) \qquad [2]$$

3 Calibration of Thermometers

The 10 thermometers were calibrated at the same time, in the same bath, against the same reference thermometer. Although they were calibrated in a well-stirred fluid bath, yet used in air, self-heating is not considered a significant contributor since all probes are used in the same type of environment. All should be subjected to similar self-heating effects that tend to cancel one another when viewing differences between probes. The accuracy of the reference standard is also considered insignificant, since the desired value here is relative probe difference, not individual probe accuracy. The only concern in calibration of the thermometers is the relative accuracy of each with respect to the group. With this in mind, the uncertainty of the probes, u(T), with respect to each other after calibration is estimated to be

$$u(T) = \pm 0.025\ °C$$

3.1 Measurement of Chamber Temperatures

The following data was gathered during the uniformity analysis conducted on Sep 2, 2003, using a Model 1200, serial number 0308001. The generator was run at a fixed humidity of 50% RH, and was allowed to stabilize for a minimum of two hours at each temperature listed. Note that the maximum and minimum readings are indicated in bold type.

Probe	Location	10 °C nominal	25 °C ambient	60 °C nominal
1	Lower Left Rear	10.063	25.052	**59.983**
2	Lower Right Rear	10.056	25.056	60.000
3	Lower Left Front	10.059	25.052	59.998
4	Lower Right Front	10.047	25.043	59.992
5	Back Center	**10.046**	**25.035**	59.985
6	Upper Left Rear	10.057	25.050	59.994
7	Upper Right Rear	10.047	25.037	59.991
8	Upper Left Front	10.057	25.058	**60.010**
9	Upper Right Front	**10.068**	25.058	60.004
10	Bottom Center	10.067	**25.059**	60.008
Maximum Deviation (MaxDev)		±0.011	±0.012	±0.014

4. Chamber Temperature Uniformity

As per equation 2, the uniformity at each of the 3 temperatures is computed as

$$\text{Uniformity} = \text{sqrt}(0.011^2 + 0.025^2)$$

$$= \pm 0.027\ °C \text{ (at 10 °C)}$$
$$= \pm 0.028\ °C \text{ (at 25 °C)}$$
$$= \pm 0.029\ °C \text{ (at 60 °C)}$$

This is within the stated uniformity specification of ±0.10 °C.

5. Calculation of Percent Relative Humidity Gradients

The Relative Humidity Gradients (uniformity) within the test chamber caused by the temperature uniformity is calculated based on the 50%RH@Pc given the temperatures observed within the chamber in section 3.1. This is mathematically calculated assuming a uniform Dew Point within a chamber void of any heat-generating devices.

Note: When the 1200 generator is operated in %RH@PcTc mode the system will maintain the desired %RH value at the chamber temperature probe. Any %RH uniformity would then originate from the point of the chamber temperature probe.

Probe	Location	10 °C nominal	25 °C ambient	60 °C nominal
1	Lower Left Rear	49.789 %RH	49.845 %RH	**50.039 %RH**
2	Lower Right Rear	49.813 %RH	49.833 %RH	50.000 %RH
3	Lower Left Front	49.803 %RH	49.845 %RH	50.005 %RH
4	Lower Right Front	49.843 %RH	49.872 %RH	50.019 %RH
5	Back Center	**49.846 %RH**	**49.896 %RH**	50.035 %RH
6	Upper Left Rear	49.809 %RH	49.851 %RH	50.014 %RH
7	Upper Right Rear	49.843 %RH	49.890 %RH	50.021 %RH
8	Upper Left Front	49.809 %RH	49.827 %RH	**49.977 %RH**
9	Upper Right Front	**49.773 %RH**	49.827 %RH	49.991 %RH
10	Bottom Center	49.776 %RH	**49.824 %RH**	49.981 %RH
Maximum Deviation (MaxDev)		±0.037 %RH	±0.036 %RH	±0.031 %RH

5.1. Percent Relative Humidity Uncertainties Based on the Temperature Uncertainty

Calculating the percent relative humidity uncertainty at each temperature range based on the uncertainty of the temperature probes in section 3 we obtain the following:

uRH(T) = ±0.083 (at 10 °C)
uRH(T) = ±0.074 (at 25 °C)
uRH(T) = ±0.058 (at 60 °C)

6. Chamber Percent Relative Humidity Uniformity

As per equation 2, the uniformity at each of the 3 temperature ranges is computed as

$$\text{uniformity} = \text{sqrt}(0.037^2 + 0.083^2)$$

= ±0.091%RH (at 10 °C)
= ±0.082%RH (at 25 °C)
= ±0.066%RH (at 60 °C)

Relative Humidity Uncertainty Analysis of the Model 2500 Two-Pressure Humidity Generator

Uncertainty Analysis
of the
Thunder Scientific Model 2500 Two-Pressure Humidity Generator

Revision A
12/10/2006

1.0 Introduction

Described here is the Relative Humidity Uncertainty Analysis, following the Guidelines of NIST and NCSL International [1, 6, 7], for a Model 2500 Humidity Generator that utilizes the NIST developed and proven two-pressure humidity generation principle [2, 3]. Generation of humidity in a system of this type does not require direct measurements of the water vapor content of the gas. Rather, the generated humidity is derived from the measurements of saturation and chamber pressures, and saturation and chamber temperatures.

The measurement instrumentation used in both our in-house working standards and our manufactured devices are obtained from companies which have demonstrated either NIST traceability or traceability to other acceptable standards. In most cases we therefore use the specifications supplied by these manufacturers as the starting point for our uncertainty statements. Over time, check calibrations against a NIST traceable pressure gauge and NIST traceable standard resistance thermometer, as well as the results of an on-going intercomparison program of both the individual components and of the outputs of operating generators, have allowed the determination of the ranges of disagreement among the various temperatures and pressures that enter into the final determination of the output uncertainties. The average values of these disagreements represent the uncertainties from our in-house processes and things like instrument drift over time, and these are coupled with the uncertainties given by the various instrument manufacturers to give overall uncertainty statements.

This document lists the various uncertainty sources, their magnitudes, and their origins over the operating range of the 2500 generator. Calculations of uncertainties associated with specific generator outputs are done in detail.

2.0 Defining Equations

NIST Technical Note 1297[1] states that the uncertainty in a dependent variable, which depends only on uncorrelated input variables, is

$$u^2(y) = \sum_i u^2(x_i)\left(\frac{\partial y}{\partial x_i}\right)^2 \qquad (1)$$

Relative Humidity in a two-pressure humidity generator is determined from the measurements of temperature and pressure only and is expressed by the formula [3]

$$\%RH = \frac{e_S(T_S)\,f(T_S,P_S)}{e_S(T_C)\,f(T_C,P_C)} \cdot \frac{P_C}{P_S}\eta_S \qquad (2)$$

Whereas the dew point and frost point temperatures are defined implicitly by the following relations and must be obtained through iterative solutions.

$$e_W(T_D) = e_S(T_S) \cdot \frac{f(T_S, P_S)}{f(T_D, P_C)} \cdot \frac{P_C}{P_S} \cdot \eta_S \tag{3}$$

$$e_I(T_F) = e_S(T_S) \cdot \frac{f(T_S, P_S)}{f(T_F, P_C)} \cdot \frac{P_C}{P_S} \cdot \eta_S \tag{4}$$

Where the *f* functions are enhancement factors, e_S is the saturation vapor pressure, e_w is the saturation vapor pressure over water, e_I is the saturation vapor pressure over ice, η_S is the % efficiency of saturation, T_D, T_F, T_C, T_S are the dew point, frost point, chamber and saturation temperatures, and Pc and Ps are the chamber and saturation pressures.

By incorporating the relationship in equation 2 into an uncertainty equation of the form of equation 1, it can be shown that the total uncertainty in relative humidity is given by the expression

$$u^2(RH) = u^2(T_C)\left(\frac{\partial RH}{\partial T_C}\right)^2 + u^2(T_S)\left(\frac{\partial RH}{\partial T_S}\right)^2 + u^2(P_C)\left(\frac{\partial RH}{\partial P_C}\right)^2 + u^2(P_S)\left(\frac{\partial RH}{\partial P_S}\right)^2 + u^2(\eta_S)\left(\frac{\partial RH}{\partial \eta_S}\right)^2 \tag{5}$$

Similarly, the uncertainties in dew point and frost point measurement are

$$u^2(T_D) = u^2(T_S)\left(\frac{\partial T_D}{\partial T_S}\right)^2 + u^2(P_C)\left(\frac{\partial T_D}{\partial P_C}\right)^2 + u^2(P_S)\left(\frac{\partial T_D}{\partial P_S}\right)^2 + u^2(\eta_S)\left(\frac{\partial T_D}{\partial \eta_S}\right)^2 \tag{6}$$

and

$$u^2(T_F) = u^2(T_S)\left(\frac{\partial T_F}{\partial T_S}\right)^2 + u^2(P_C)\left(\frac{\partial T_F}{\partial P_C}\right)^2 + u^2(P_S)\left(\frac{\partial T_F}{\partial P_S}\right)^2 + u^2(\eta_S)\left(\frac{\partial T_F}{\partial \eta_S}\right)^2 \tag{7}$$

Clearly there are five inputs, which contribute uncertainty to the generation of relative humidity. These are the uncertainties in the two pressures, two temperatures, and the efficiency of saturation. There are four inputs, which contribute uncertainty to the generation of dew point and frost point. These are the uncertainties in the two pressures, saturation temperature, and the efficiency of saturation.

3.0 Uncertainty Components

In the mathematical analysis of equation 2, we'll analyze the uncertainties due to each of the above ratios separately, then combine the uncertainties to obtain the total expanded uncertainty. We are therefore concerned with four specific categories of uncertainty, each of which may have associated uncertainty components.

- uncertainty contribution from the pressure ratio term P_c/P_s, which includes
  - measurement uncertainty
  - measurement hysteresis

measurement resolution

- uncertainty contribution from the vapor pressure ratio term E_s/E_c, which includes
  - measurement uncertainty
  - saturation vs. chamber temperature intercomparison uncertainty
  - measurement resolution
  - chamber temperature self heating
  - chamber temperature uniformity
- uncertainty contribution from the enhancement factor ratio Fs/Fc
- uncertainty contribution from saturator efficiency

3.1 Uncertainty in the Pressure Ratio, Pc/Ps

The pressure ratio term, P_c/P_s, in a two-pressure humidity generator is the major %RH determining factor since both the E_s/E_c and F_s/F_c ratios are nearly equal to 1. Under those conditions, RH ≅ Pc/Ps * 100. To determine the affect a small change in pressure has on the computed RH, the difference can be taken between the RH computed with the pressure uncertainty included, and the RH computed without this uncertainty. This in effect is the partial numeric differential of RH with respect to pressure, computed at that pressure. The equation for this becomes

$$u(P) = \pm\{[(P_c \pm \partial P_c)/(P_s \pm \partial P_s) * F_s/F_c * E_s/E_c * 100] - RH\} \quad (8)$$

where u(P) is designated as the uncertainty in relative humidity due to pressure

∂P_c = delta-chamber-pressure measurement, for which we will use one standard deviation in chamber pressure measurement uncertainty.

∂P_s = delta-saturation-pressure measurement, for which we will use one standard deviation in saturation pressure measurement uncertainty.

This equation may be simplified by substituting F_s/F_c =1 and E_s/E_c =1, as those two ratios will be dealt with later. Also note, with these simplifying assumptions, that RH = P_c/P_s * 100. Since the focus here is on differences between the ideal and the delta-induced values, the simplifying assumptions remain valid for the remainder of this uncertainty analysis. In quantifying components, applying each of these substitutions results in

$$u(P) = \pm\{(P_c \pm \partial P_c)/(P_s \pm \partial P_s) - (P_c/P_s)\} * 100 \quad (9)$$

In the use of this formula, it may be necessary to apply values to only ∂P_c or ∂P_s while maintaining all others constant. Or it may be necessary to apply both simultaneously with careful application of sign. The method chosen in each instance depends upon the component of uncertainty being evaluated and related factors.

In determining components of uncertainty, there are several things to consider, such as measurement uncertainty, measurement hysteresis, and measurement resolution.

3.1.1 Measurement Uncertainty Components of Pressure

Measurement uncertainty components of pressure were analyzed from *as found* data of 10 separate Model 2500 humidity generators during their annual recalibrations. Each system was tested at no fewer than 3 points over the range of the individual pressure transducers, resulting in no fewer than 30 measurement results from which to compute statistical standard deviations.

For saturation pressures above 50 psia, one transducer measures the chamber pressure and a separate transducer measures the saturation pressure. In this mode of operation, the standard deviation from the desired mean values are:

Std dev = 0.039 psia for P<50 psia
Std dev = 0.089 psia for P>50 psia

The statistical standard deviations calculated from the calibration history also have an uncertainty component from the Mensor PCS400 pressure standard used during the calibration process. The uncertainty of the Mensor PCS400 pressure standard for the low and high-pressure ranges are as follows:

$$uP_{c[std]} = 0.007 \text{ psia}$$

$$uP_{s[std]} = 0.007 \text{ psia for } P<50 \text{ psia}$$
$$= 0.033 \text{ psia for } P>50 \text{ psia}$$

Therefore, the uncertainties in chamber and saturation pressure measurements, ∂P_c and ∂P_s, are

$$\partial P_c = \sqrt{((0.039)^2 + (0.007)^2)} = 0.040 \text{ psia}$$

$$\partial P_s = \sqrt{((0.039)^2 + (0.007)^2)} = 0.040 \text{ psia for } P<50 \text{ psia}$$
$$= \sqrt{((0.089)^2 + (0.033)^2)} = 0.095 \text{ psia for } P>50 \text{ psia}$$

3.1.1.1 Measurement Uncertainty due to Pressure when Ps>50 psia

Sample calculations of the pressure uncertainty contributions would go as follows. First assume conditions where the ambient (i.e., chamber) pressure is 14.7 psia. Since the chamber can operate only at ambient pressure, then the chamber pressure is P_c=14.7. The individual %RH uncertainty contributions due to the pressure ratio term under these conditions are then written and analyzed numerically for the high range saturation pressures as

$$\begin{aligned} u(P_c) &= \pm\{(P_c \pm \partial P_c)/(P_s) - (P_c/P_s)\} * 100 \\ &= \pm\{\pm\partial P_c/P_s\} * 100 \qquad (10) \\ &= \pm\{\pm 0.040/50\} * 100 \\ &= \pm 0.079 \text{ \%RH (at } P_s=50, \text{ \%RH} = Pc/Ps*100 = 29.40) \end{aligned}$$

$$\begin{aligned} u(P_s) &= \pm\{(P_c)/(P_s \pm \partial P_s) - (P_c/P_s)\} * 100 \qquad (11) \\ &= \pm\{(14.7)/(50 \pm 0.095) - (14.7/50)\} * 100 \\ &= \pm 0.056 \text{ \%RH (at Ps=50, \%RH =29.40)} \end{aligned}$$

where $u(P_c)$ is RH uncertainty due to uncertainty in chamber pressure P_c
$u(P_s)$ is RH uncertainty due to uncertainty in saturation pressure P_s

Note: In the above equations, only one value was varied at a time. Because of this and the fact that the values will be squared before further use, the sign of the result is of no concern.

Now, performing the same calculations at a saturation pressure of 100 psia results in

$$u(P_c) = \pm\{\pm 0.040/100\} * 100$$
$$= \pm 0.040 \text{ \%RH (at } P_s=100, \text{ \%RH}=14.70)$$

$$u(P_s) = \pm\{(14.7)/(100 \pm 0.095) - (14.7/100)\} * 100$$
$$= \pm 0.014 \text{ \%RH (at } P_s=100, \text{ \%RH}=14.70)$$

Performing the same calculations at a saturation pressure of 150 psia results in

$$u(P_c) = \pm 0.026 \text{ \%RH (at } P_s=150, \text{ \%RH}=9.80)$$

$$u(P_s) = \pm 0.006 \text{ \%RH (at } P_s=150, \text{ \%RH}=9.80)$$

Notice that as saturation pressure increases, %RH uncertainty decreases as expected.

3.1.1.2 Measurement Uncertainty due to Chamber Pressure when P_s<50 psia

For saturation pressures below 50 psia, a different measurement scheme is employed. Rather than using two separate transducers for measuring chamber and saturation pressures, only one transducer is used and it is time shared between the chamber and saturator. While this approach reduces RH uncertainty, it complicates the analysis somewhat. Any measurement deviation in this single transducer will simultaneously affect both the chamber and saturation pressure readings. So when accounting for this uncertainty, it should be applied equally to both the chamber and saturation pressures simultaneously, and both instances of it must contain the same sign and magnitude. Computing uncertainty due to chamber pressure uncertainty then becomes

$$u(P_c) = \pm\{(P_c + \partial P_c)/(P_s + \partial P_c) - (P_c/P_s)\} * 100 \qquad (12)$$

Computing uncertainty due to chamber pressure measurement at various saturation pressures between P_s=15.5 and 50 psia results in

$$u(P_c) = \pm\{(14.7 + 0.040)/(15.5 + 0.040) - (14.7/15.5)\} * 100$$
$$= \pm 0.013 \text{ \%RH (at } P_s=15.5, \text{ \%RH}=94.84)$$

$$u(P_c) = \pm\{(14.7 + 0.040)/(20 + 0.040) - (14.7/20)\} * 100$$
$$= \pm 0.052 \text{ \%RH (at } P_s=20, \text{ \%RH}=73.50)$$

$$u(P_c) = \pm\{(14.7 + 0.040)/(30 + 0.040) - (14.7/30)\} * 100$$
$$= \pm 0.067 \text{ \%RH (at } P_s=30, \text{ \%RH}=49.00)$$

$$u(P_c) = \pm\{(14.7 + 0.040)/(40 + 0.040) - (14.7/40)\} * 100$$
$$= \pm 0.062 \text{ \%RH (at } P_s=40, \text{ \%RH}=36.75)$$

$$u(P_c) = \pm\{(14.7 + 0.040)/(50 + 0.040) - (14.7/50)\} * 100$$
$$= \pm 0.056 \text{ \%RH (at } P_s=50, \text{ \%RH}=29.4)$$

3.1.1.3 Measurement Uncertainty due to Saturation Pressure with P_s<50

The final component of pressure measurement uncertainty to account for when dealing with saturation pressures below 50 psia is the uncertainty due to saturation pressure. The same transducer is used for both the saturation and chamber pressure measurements, and some uncertainty of this transducer has already been accounted for in the analysis due to chamber pressure measurement uncertainty. Double counting of the uncertainty component associated with the saturation pressure measurement can be avoided estimating its weighted value based on the value of the reading. For instance, at 50 psia the entire uncertainty of ±0.039 psia should apply, but at lower pressures, the uncertainty in measurement should drop proportionately. The uncertainty should therefore be accounted for as a function of reading rather than a straight sum. This scaled uncertainty in pressure measurement is then estimated by

$$\partial P_s = 0.040/50 * P_s$$
$$= 0.0008 * P_s \quad [\text{for } P_s<50 \text{ psia}]$$

The associated uncertainty formula will then be

$$u(P_s) = \pm\{(P_c)/(P_s \pm \partial P_s) - (P_c/P_s)\} * 100$$
$$= \pm\{(P_c)/(P_s \pm(0.0008*P_s)) - (P_c/P_s)\} * 100 \qquad (13)$$

Computing uncertainty due to saturation pressure measurement at various saturation pressures between P_s=15.5 and 50 psia (with Pc=14.7) results in

$u(P_s)$ = ±0.075 %RH (at Ps=15.5, %RH =94.84)
$u(P_s)$ = ±0.058 %RH (at Ps=20, %RH =73.50)
$u(P_s)$ = ±0.039 %RH (at Ps=30, %RH =49.00)
$u(P_s)$ = ±0.029 %RH (at Ps=40, %RH =36.75)
$u(P_s)$ = ±0.023 %RH (at Ps=50, %RH =29.40)

3.1.2 Uncertainty due to Pressure Hysteresis

When the low range pressure transducer is time shared as it is for saturation pressures below 50 psia, the transducer is also subject to some measurement hysteresis. For more than 98% of the time, the transducer monitors the saturation pressure (approximately 5 minutes). For less than 2% of the time (once every 5 minutes for approximately 5 seconds), the transducer monitors the chamber pressure. By this criteria, it is only the chamber pressure which is affected by hysteresis. Again the sign of the deviation is important since hysteresis will always tend to increase the apparent measured value of the chamber pressure. The equation for uncertainty due to hysteresis, u(H), is

$$u(H) = \pm\{(P_c+\text{Hysteresis})/(P_s) - (P_c/P_s)\}*100$$

The maximum amount of hysteresis is estimated as +0.1% of the measured difference between the saturation and chamber pressures, with a rectangular distribution. The full interval is believed to ride on only one side of the true value, rather than centered about its mean. Therefore, the full interval, rather than half interval, is used in the following computations

$$\text{Hysteresis} = \{0.1\% * (P_s-P_c)\}/\sqrt{3}$$
$$= 0.00058 * (P_s-P_c)$$

So the uncertainty component due to hysteresis is then computed as

$$u(H) = \pm\{(P_c + 0.00058*(P_s\text{-}P_c))/(P_s) - (P_c/P_s)\} * 100 \quad (14)$$
$$= \pm 0.058(1\text{-}P_c/P_s) \quad \text{or} \quad \pm 0.00058(100\text{-}RH)$$

Computing uncertainty due to hysteresis at various saturation pressures between P_s=15.5 and 50 psia (with P_c=14.7) results in

u(H) = ±0.003 %RH (at P_s=15.5, %RH=94.84)
u(H) = ±0.015 %RH (at P_s=20, %RH=73.50)
u(H) = ±0.030 %RH (at P_s=30, %RH=49.00)
u(H) = ±0.034 %RH (at P_s=40, %RH=36.75)
u(H) = ±0.041 %RH (at P_s=50, %RH=29.40)

3.1.3 Uncertainty in Pressure Measurement Resolution

The Analog to Digital conversion process resolves 1 part in 25000 over the range of each of the pressure transducers. Based on a rectangular distribution of the half-interval of resolution, the uncertainty component of pressure resolution is then

$$\text{resolution}_p = (\text{transducer range})/25000*0.5/\sqrt{3}$$
$$= 0.00058 \text{ psia for } P<50$$
$$= 0.00174 \text{ psia for } P>50$$

Since this uncertainty is specific to each and every individual measurement taken, it must be considered separately for both the chamber and saturation pressure measurements, regardless of which transducer is being utilized for the given operating conditions. The equations for uncertainty due to chamber pressure measurement resolution, $u(R_{Pc})$, and saturation pressure measurement resolution, $u(R_{Ps})$, are similar to equations 10 and 11 and are shown as

$$u(R_{Pc}) = \pm\{\text{resolution}_p/P_S\} * 100 \quad (15)$$

$$u(R_{Ps}) = \pm\{(P_c)/(P_S \pm \text{resolution}_p) - (P_c/P_s)\} * 100 \quad (16)$$

Computing the uncertainties due to pressure measurement resolution at chamber pressure of 14.7 psia, and over the saturation pressure range of 15.5 to 150 psia results in

$u(R_{Pc})$ = ±0.004 %RH (at P_s=15.5, %RH=94.84)
$u(R_{Pc})$ = ±0.003 %RH (at P_s=20, %RH=73.50)
$u(R_{Pc})$ = ±0.003 %RH (at P_s=30, %RH=49.00)
$u(R_{Pc})$ = ±0.001 %RH (at P_s=40, %RH=36.75)
$u(R_{Pc})$ = ±0.001 %RH (at P_s=50, %RH=29.40)
$u(R_{Pc})$ = ±0.001 %RH (at P_s=100, %RH=14.70)
$u(R_{Pc})$ = ±0.000 %RH (at P_s=150, %RH=9.80)

$u(R_{Ps})$ = ±0.004 %RH (at P_s=15.5, %RH=94.84) [low range]
$u(R_{Ps})$ = ±0.002 %RH (at P_s=20, %RH=73.50) [low range]
$u(R_{Ps})$ = ±0.001 %RH (at P_s=30, %RH=49.00) [low range]
$u(R_{Ps})$ = ±0.001 %RH (at P_s=40, %RH=36.75) [low range]

$u(R_{Ps})$ = ±0.000 %RH (at P_s=50, %RH=29.40) [low range]
$u(R_{Ps})$ = ±0.001 %RH (at P_s=50, %RH=29.40) [high range]
$u(R_{Ps})$ = ±0.000 %RH (at P_s=100, %RH=14.70) [high range]
$u(R_{Ps})$ = ±0.000 %RH (at P_s=150, %RH=9.80) [high range]

3.1.4 Summary of Uncertainty in the Pressure Ratio P_c/P_s

The standard uncertainty, $u_c(P_c/P_s)$, in the pressure ratio P_c/P_s is determined from the associated individual components previously shown.

$$u_c^2(P_c/P_s) = u^2(P_c) + u^2(P_s) + u^2(R_{Pc}) + u^2(R_{Ps}) + u^2(H) \quad (17)$$

It is summarized in the following table.

Table 1: Standard Uncertainty Components of RH due to Pressure Ratio Pc/Ps

Standard Uncertainty Components of RH due to pressure at Various Saturation Pressures										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
Source	**Type**	**Term**	**15.5**	**20**	**30**	**40**	**50**	**50**	**100**	**150**
measurement	A	$u(P_c)$	0.013	0.052	0.067	0.062	0.056	0.079	0.040	0.026
measurement	A	$u(P_s)$	0.075	0.058	0.039	0.029	0.023	0.056	0.014	0.006
resolution	B	$u(R_{Pc})$	0.004	0.003	0.001	0.001	0.001	0.001	0.001	0.000
resolution	B	$u(R_{Ps})$	0.004	0.005	0.001	0.001	0.000	0.001	0.000	0.000
hysteresis	B	$u(H)$	0.003	0.015	0.03	0.034	0.041			
combined		$u_c(P_c/P_s)$	0.076	0.080	0.083	0.076	0.073	0.097	0.042	0.027

3.2 Uncertainty in the Vapor Pressure Ratio, E_s/E_c

E_s and E_c are Saturation Vapor Pressures computed at the saturation temperature and chamber temperature respectively, using the equation of Wexler[4]. In a perfectly ideal two-pressure humidity generator, the saturation temperature and chamber temperature would be exactly the same, resulting in an ideal E_s/E_c ratio of 1.00 exactly. A calculated E_s/E_c ratio of 1.0 contributes nothing to the calculation of %RH. However, in a real system, some slight differences do exist between the saturation and chamber temperatures, providing the need for measurement of these temperatures.

The uncertainty in RH due to temperature can be determined in a manner similar to that of equation 8, with the underlying assumptions that F_s/F_c =1, and P_c/P_s *100 =RH. The formula for computing the contribution due to temperature is

$$u(T) = \pm\{P_c/P_s * (E_{[Ts \pm \partial Ts]})/(E_{[Tc \pm \partial Tc]}) * F_s/F_c\}*100 - RH$$
$$\pm \{(E_{[Ts \pm \partial Ts]})/(E_{[Tc \pm \partial Tc]}) - 1\} * RH \quad (18)$$

where $u(T)$ is designated as uncertainty in RH due to temperature
∂T_c = uncertainty in chamber temperature measurement
∂T_s = uncertainty in saturation temperature measurement

$E_{[Ts - \partial Ts]}$ = Saturation Vapor Pressure computed at the Saturation Temperature, T_s, when perturbed by the possible temperature uncertainty, ∂T_s

$E_{[Tc + \partial Tc]}$ = Saturation Vapor Pressure computed at the Saturation Temperature, T_c, when perturbed by the possible temperature uncertainty, ∂T_c.

The individual uncertainty components which must be examined are measurement uncertainty, uncertainty of vapor pressure equations, saturation vs. chamber temperature intercomparison uncertainty, measurement resolution, and self heating.

3.2.1 Measurement Uncertainty Components of Temperature

Since the temperatures are always nearly equal, and are computed as a ratio of the corresponding saturation vapor pressures, it can be easily seen that if there is no mismatch between the chamber and saturation temperatures, then the ratio becomes 1.0 exactly and there is no uncertainty contribution due to temperature. This could also be true even if the temperature measurement of the two probes was actually incorrect or in error, provided the relative difference between them was zero. So if both were in error, but indicated the same numeric value at the same equal temperature, then again there would be no uncertainty contribution. Therefore, the contribution of uncertainty to RH due to temperature measurement accuracy is considered insignificant.

The contribution of uncertainty to Dew Point due to temperature measurement accuracy is on the other hand not insignificant. Since chamber temperature has no role in the Dew Point equation only saturator temperature measurement accuracy has an affect. This affect will be covered in the Intercomparison Uncertainty section.

3.2.2 Uncertainty of Vapor Pressure Equations

The equations used for computation of vapor pressure are those of Wexler[4]. While there is uncertainty associated with the use of these equations, vapor pressures are always computed in ratio to one another with temperatures nearly equal to each another. Under these circumstances, the individual vapor pressure values, while they may be in error, cause no significant uncertainty when taken as a ratio. Therefore, the contribution due to uncertainty in the vapor pressure equations is considered insignificant.

3.2.3 Saturation vs. Chamber Temperature Intercomparison Uncertainty

While the actual measurement accuracy of the two temperature probes is of little concern, the ability of the chamber and saturation temperature probes to indicate the same measured value at the same temperature is important, and is termed the intercomparison uncertainty. Intercomparison uncertainty was analyzed from *as found* data of 11 separate Model 2500 humidity generators during their annual calibration. Each system was tested at no fewer than 3 points over the range of 0 to 70 °C, resulting in 47 intercomparison results (difference between the indicated saturation temperature and indicated chamber temperature) from which to compute statistical standard deviation. The standard deviation of the difference between the saturation and chamber temperatures over the stated temperature range is

$$\text{Std dev} = 0.00985\ °\text{C}$$

For Dew Point the saturation temperature measurement uncertainty was analyzed from the same *as found* data and was found to be slightly lower than the intercomparison standard deviation above. To aid in simplicity the larger intercomparison standard deviation is assumed and will be applied to the saturation temperature.

Since it is the difference between the temperature probes that is of concern, not the actual measurement accuracy, then the above number need only be applied to one of the temperatures while maintaining the other constant. In this case, the saturation temperature is chosen as the one to perturb, while maintaining the chamber temperature constant at the ideal value. The perturbation amount which represents the intercomparison uncertainty is simply the standard deviation, and is therefore

$$\partial T_s = 0.00985\ °C$$

The RH uncertainty due to temperature intercomparison, $u(T_i)$, is then written as

$$u(T_i) = \pm \{(E_{[Ts + 0.00985]})/(E_{[Tc]}) - 1\} * RH \tag{19}$$

and may now be computed at several different saturation (or system) temperatures.

$$\begin{aligned} u(T_i) &= \pm \{(E_{0 + 0.00985})/(E_0) - 1\} * RH \\ &= \pm \{611.6495 / 611.1533 - 1\} * RH \\ &= \pm 0.00081 * RH \text{ (at } T_s=T_c=0\ °C) \\ \\ &= \pm \{E_{35.00985}/E_{35} - 1\} * RH \\ &= \pm \{5629.514 / 5626.447 - 1\} * RH \\ &= \pm 0.00055 * RH \text{ (at } T_s=T_c=35\ °C) \\ \\ &= \pm \{E_{70.00985}/E_{70} - 1\} * RH \\ &= \pm \{31190.6 / 31177.31 - 1\} * RH \\ &= \pm 0.00043 * RH \text{ (at } T_s=T_c=70\ °C) \end{aligned}$$

3.2.4 Uncertainty in Temperature Measurement Resolution

The analog to digital conversion process, which transforms probe resistance into digital values resolves to 0.01 °C. Based on a rectangular distribution of the half-interval, the uncertainty component of temperature resolution is then

$$\begin{aligned} resolution_t &= 0.01 * 0.5/\sqrt{3} \\ &= 0.0029 \end{aligned}$$

Since this uncertainty is specific to each and every individual measurement taken, it must be considered separately for both the chamber and saturation temperature measurements. The equations for uncertainty due to chamber temperature resolution, $u(R_{Tc})$, and saturation temperature resolution, $u(R_{Ts})$, are given as

$$u(R_{Tc}) = \pm \{(E_{Ts}/E_{Tc+0.0029}) - 1\} * RH \tag{20}$$

$$u(R_{Ts}) = \pm \{(E_{Ts+0.0029}/E_{Tc}) - 1\} * RH \tag{21}$$

The uncertainty components due to temperature resolution can now be computed at several temperatures using the above equations.

$$\begin{aligned} u(R_{Tc}) &= \pm 0.00024 * RH \text{ (at } T_s=T_c=0\ °C) \\ u(R_{Tc}) &= \pm 0.00016 * RH \text{ (at } T_s=T_c=35\ °C) \end{aligned}$$

$u(R_{Tc})$ = ± 0.00013 * RH (at T_s=T_c=70 °C)

$u(R_{Ts})$ = ± 0.00024 * RH (at T_s=T_c=0 °C)
$u(R_{Ts})$ = ± 0.00016 * RH (at T_s=T_c=35 °C)
$u(R_{Ts})$ = ± 0.00013 * RH (at T_s=T_c=70 °C)

3.2.5 Uncertainty due to Self-Heating of Chamber Temperature Probe

The chamber temperature probe is generally calibrated and checked in a well-stirred fluid bath, but used in air. There is the possibility of some self-heating associated with this measurement then that must be considered. The self-heating, with temperature measurements in °C, is estimated to be 0.05% of reading. The equation for the temperature uncertainty of self-heating is then

Self-Heating = 0.05% * T_c /√3
= 0.00029 *T_c

The equation for RH uncertainty due to self heating of the chamber temperature probe is then expressed as

$$u(SH) = \pm \{(E_{Ts}/E_{1.00029*Tc}) - 1\} * RH \quad (22)$$

Again, computing this at several temperatures results in

$u(SH)$ = ± 0 (at T_s=T_c=0 °C)
$u(SH)$ = ± 0.00055 * RH (at T_s=T_c=35 °C)
$u(SH)$ = ± 0.00087 * RH (at T_s=T_c=70 °C)

3.2.6 Summary of Uncertainty in the Saturation Vapor Pressure Ratio E_s/E_c

The standard uncertainty of RH due to temperature, $u_c(E_s/E_c)$, in the saturation vapor pressure ratio E_s/E_c is determined form the individual components previously shown, and are combined using the equation

$$u_c^2(E_s/E_c) = u^2(T_i) + u^2(R_{Tc}) + u^2(R_{Ts}) + u^2(SH) \quad (23)$$

Table 2: Standard Uncertainty Components of RH due to Vapor Pressure Ratio Es/Ec

Standard Uncertainty Components of RH due to Temperature at Various Temperatures					
Source	**Type**	**Term**	**Temperature**		
			0 °C	**35 °C**	**70 °C**
Ts-Tc intercomparison	A	u(Ti)/RH	0.00081	0.00055	0.00043
Ts resolution	B	u(RTs)/RH	0.00024	0.00016	0.00013
Tc resolution	B	u(RTc)/RH	0.00024	0.00016	0.00013
self heating	B	u(SH)/RH	0.00000	0.00055	0.00087
combined		u(Es/Ec)/RH	0.00088	0.00081	0.00099

3.3 Uncertainty in the Enhancement Factor Ratio F_s/F_c

Enhancement factors are slight correction factors used to account for the non-ideal behavior of water vapor when admixed with other gases. The enhancement factor is dependent on both temperature and pressure and is computed with the equation of Greenspan[5]. In determining the uncertainty due to the enhancement factor ratio, the individual uncertainty components that must be evaluated are measurement uncertainty due to temperature and pressure, and uncertainty of the enhancement factor equations.

3.3.1 Measurement Uncertainty due to Temperature and Pressure

The enhancement factor ratio, F_s/F_c, varies insignificantly with small perturbations in temperature and pressure. Uncertainties calculated from the ratio of F_s/F_c are at least an order of magnitude less than the uncertainties computed from the terms P_c/P_s and E_s/E_c. Therefore, measurement uncertainty due to temperature and pressure is considered negligible for this evaluation.

3.3.2 Uncertainty of the Enhancement Factor Equation

The computational uncertainty of the enhancement factor ratio causes a corresponding uncertainty in computed RH of ±0.007% at 10%RH, reducing linearly toward an RH uncertainty of 0 at 100%. An equation to define this systematic uncertainty in RH due to the enhancement factor equation is written as

$$\text{EqDiff} = \pm[0.00008(100-\text{RH})] \tag{24}$$

Since this is determined to be a known, systematic, uncorrected error, the uncertainty in RH due to the enhancement factor equation, $u(F_{eq})$, is then

$$u(F_{eq}) = 0.00008(100-\text{RH}) \tag{25}$$

3.3.3 Summary of Uncertainty in the Enhancement Factor Ratio

The standard uncertainty, $u_c(F_s/F_c)$, in the enhancement factor ratio is dominated by the uncertainty of the enhancement factor equation, and is therefore given as

$$u_c(F_s/F_c) = 0.00008(100-\text{RH}) \tag{26}$$

Table 3: Standard Uncertainty Components of RH due to Enhancement Factor

Standard Uncertainty Components of RH due to Enhancement Factor										
Source	**Type**	**Term**	Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	**20**	**30**	**40**	**50**	**50**	**100**	**150**
			94.84 %RH	73.50 %RH	49.00 %RH	36.75 %RH	29.40 %RH	29.40 %RH	14.70 %RH	9.80 %RH
equation	B	$u(F_{eq})$	0.0004	0.0021	0.0041	0.0051	0.0054	0.0056	0.0068	0.0074
combined		$u_c(F_s/F_c)$	0.0004	0.0021	0.0041	0.0051	0.0054	0.0056	0.0068	0.0074

3.4 Uncertainty due to Saturator Efficiency

All two pressure humidity generators rely on the ability of the saturator to fully saturate the gas with water vapor as it passes from inlet to outlet. This analysis assumes 100% saturator efficiency.

4.0 Combined Standard Uncertainty

The combined standard uncertainty, $u_c(RH)$, is obtained by statistical combination of the standard uncertainty components of pressure ratio, vapor pressure ratio, enhancement factor ratio, and saturator efficiency. The combined uncertainty formula is then the sum of the variances

$$u_c^2(RH) = u_c^2(P_c/P_s) + u_c^2(E_s/E_c) + u_c^2(F_s/F_c) \quad (27)$$

The following tables reflect the standard uncertainty components and the combined standard uncertainty at various temperatures and pressures.

Table 4: Combined Standard Uncertainty Components of RH at 0 °C

Combined Standard Uncertainty of RH due to Standard Uncertainty Components at 0 °C										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	20	30	40	50	50	100	150
Source	Type	Term	94.84 %RH	73.50 %RH	49.00 %RH	36.75 %RH	29.40 %RH	29.40 %RH	14.70 %RH	9.80 %RH
pressure ratio	A,B	$u_c(P_c/P_s)$	0.076	0.080	0.083	0.076	0.073	0.097	0.042	0.027
vapor pressure ratio	A,B	$u_c(E_s/E_c)$	0.083	0.065	0.043	0.032	0.026	0.026	0.013	0.009
enhancement factor ratio	B	$u_c(F_s/F_c)$	0.0004	0.0021	0.0041	0.0051	0.0054	0.0056	0.0068	0.0074
combined		$u_c(RH)$	0.113	0.103	0.094	0.083	0.078	0.101	0.044	0.029

Table 5: Combined Standard Uncertainty Components of RH at 35 °C

Combined Standard Uncertainty of RH due to Standard Uncertainty Components at 35 °C										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	20	30	40	50	50	100	150
Source	Type	Term	94.84 %RH	73.50 %RH	49.00 %RH	36.75 %RH	29.40 %RH	29.40 %RH	14.70 %RH	9.80 %RH
pressure ratio	A,B	$u_c(P_c/P_s)$	0.076	0.080	0.083	0.076	0.073	0.097	0.042	0.027
vapor pressure ratio	A,B	$u_c(E_s/E_c)$	0.077	0.060	0.040	0.030	0.024	0.024	0.012	0.008
enhancement factor ratio	B	$u_c(F_s/F_c)$	0.0004	0.0021	0.0041	0.0051	0.0054	0.0056	0.0068	0.0074
combined		$u_c(RH)$	0.108	0.100	0.092	0.082	0.077	0.100	0.044	0.029

Table 6: Combined Standard Uncertainty Components of RH at 70 °C

Combined Standard Uncertainty of RH due to Standard Uncertainty Components at 70 °C										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	20	30	40	50	50	100	150
Source	Type	Term	94.84 %RH	73.50 %RH	49.00 %RH	36.75 %RH	29.40 %RH	29.40 %RH	14.70 %RH	9.80 %RH
pressure ratio	A,B	$u_c(P_c/P_s)$	0.076	0.080	0.083	0.076	0.073	0.097	0.042	0.027
vapor pressure ratio	A,B	$u_c(E_s/E_c)$	0.094	0.073	0.049	0.036	0.029	0.029	0.015	0.010
enhancement factor ratio	B	$u_c(F_s/F_c)$	0.0004	0.0021	0.0041	0.0051	0.0054	0.0056	0.0068	0.0074
combined		$u_c(RH)$	0.121	0.108	0.096	0.084	0.079	0.101	0.045	0.030

4.1 Combined Standard Dew Point Uncertainty

Given any %RH, saturation temperature, saturation pressure and chamber pressure a corresponding dew point can be derived. The following tables show the combined Dew Point uncertainty at various saturation temperatures and dew points, using the RH values and uncertainties from the previous sections.

Table 7: Combined Standard Uncertainty Components of Dew Point at 0 °C

Combined Standard Uncertainty of Dew Point due to Standard Uncertainty Components at 0 °C										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	20	30	40	50	50	100	150
Source	Type	Term	-0.64 °C DP	-3.69 °C DP	-8.40 °C DP	-11.64 °C DP	-14.10 °C DP	-14.10 °C DP	-23.82 °C DP	-25.29 °C DP
pressure ratio	A,B	$u_c(P_c/P_s)$	0.011	0.015	0.022	0.026	0.030	0.040	0.032	0.030
vapor pressure	A,B	$u_c(E_s)$	0.012	0.011	0.011	0.011	0.011	0.011	0.010	0.010
enhancement factor ratio	B	$u_c(F_s/F_d)$	0.000	0.000	0.002	0.002	0.002	0.002	0.005	0.008
combined		$u_c(DP)$	0.016	0.019	0.024	0.028	0.031	0.041	0.034	0.033

Table 8: Combined Standard Uncertainty Components of Dew Point at 35 °C

Combined Standard Uncertainty of Dew Point due to Standard Uncertainty Components at 35 °C										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	20	30	40	50	50	100	150
Source	Type	Term	34.05 °C DP	29.55 °C DP	22.69 °C DP	18.04 °C DP	14.54 °C DP	14.54 °C DP	4.25 °C DP	-1.40 °C DP
pressure ratio	A,B	$u_c(P_c/P_s)$	0.015	0.019	0.028	0.033	0.039	0.051	0.041	0.038
vapor pressure	A,B	$u_c(E_s)$	0.015	0.014	0.014	0.013	0.012	0.012	0.012	0.011
enhancement factor ratio	B	$u_c(F_s/F_d)$	0.000	0.001	0.002	0.002	0.002	0.003	0.006	0.010
combined		$u_c(DP)$	0.021	0.024	0.031	0.036	0.041	0.053	0.043	0.040

Table 9: Combined Standard Uncertainty Components of Dew Point at 70 °C

Combined Standard Uncertainty of Dew Point due to Standard Uncertainty Components at 70 °C										
			Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
			15.5	20	30	40	50	50	100	150
Source	Type	Term	68.78 °C DP	63.05 °C DP	54.36 °C DP	48.51 °C DP	44.13 °C DP	44.13 °C DP	31.35 °C DP	24.40 °C DP
pressure ratio	A,B	$u_c(P_c/P_s)$	0.018	0.024	0.035	0.041	0.048	0.063	0.051	0.046
vapor pressure	A,B	$u_c(E_s)$	0.023	0.022	0.020	0.019	0.019	0.019	0.018	0.017
enhancement factor ratio	B	$u_c(F_s/F_d)$	0.000	0.001	0.002	0.003	0.003	0.003	0.008	0.013
combined		$u_c(DP)$	0.029	0.033	0.041	0.046	0.052	0.066	0.054	0.051

5.0 Expanded Uncertainty

Utilizing a coverage factor k=2, the expanded uncertainty, U, is expressed in the following table at various temperatures and humidities, using the formula

$$U = k * u_c(RH) \tag{28}$$

All values expressed for expanded uncertainty, U, are %Relative Humidity (%RH).

Table 10: Expanded Uncertainty of RH

Expanded Uncertainty of RH with coverage factor k=2								
	Low Range Pressure, Ps<50					High Range Pressure, Ps>50		
	15.5	20	30	40	50	50	100	150
Saturation Temperature	94.84 %RH	73.50 %RH	49.00 %RH	36.75 %RH	29.40 %RH	29.40 %RH	14.70 %RH	9.80 %RH
0 °C	±0.23	±0.21	±0.19	±0.17	±0.16	±0.20	±0.09	±0.06
35 °C	±0.22	±0.20	±0.18	±0.16	±0.15	±0.20	±0.09	±0.06
70 °C	±0.24	±0.22	±0.19	±0.17	±0.16	±0.20	±0.09	±0.06

5.1 Expanded Dew Point Uncertainty

Utilizing a coverage factor k=2, the expanded uncertainty, U, is expressed in the following table at various temperatures and dew points, using the formula

$$U = k * u_c(DP) \tag{29}$$

All values expressed for expanded uncertainty, U, are Dew Point (°C).

Table 11: Expanded Uncertainty of Dew Point

Expanded Uncertainty of DP/FP °C with coverage factor k=2								
	Low Range Pressure, Ps≤45					High Range Pressure, Ps≥45		
	15.5	20	30	40	50	50	100	150
Saturation Temperature	-0.64 °C DP	-3.69 °C DP	-8.40 °C DP	-11.64 °C DP	-14.10 °C DP	-14.10 °C DP	-23.82 °C DP	-25.29 °C DP
0 °C	±0.03	±0.04	±0.05	±0.06	±0.06	±0.08	±0.07	±0.07
	34.05 °C DP	29.55 °C DP	22.69 °C DP	18.04 °C DP	14.54 °C DP	14.54 °C DP	4.25 °C DP	-1.40 °C DP
35 °C	±0.04	±0.05	±0.06	±0.07	±0.08	±0.11	±0.09	±0.08
	68.78 °C DP	63.05 °C DP	54.36 °C DP	48.51 °C DP	44.13 °C DP	44.13 °C DP	31.35 °C DP	24.40 °C DP
70 °C	±0.06	±0.07	±0.08	±0.09	±0.10	±0.13	±0.11	±0.10

6.0 References

1. Taylor, Barry N. and Kuyatt, Chris E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition

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Chamber Temperature Uncertainty Analysis of the Model 2500 Two-Pressure Humidity Generator

Chamber Temperature Uncertainty Analysis of the Thunder Scientific Model 2500 Two-Pressure Humidity Generator

Bob Hardy, Thunder Scientific Corporation,Albuquerque, NM, USA

1 Introduction

Described here is the Chamber Temperature Uncertainty Analysis, following NIST Guideline 1297[1], for a Model 2500 Humidity Generator. The chamber temperature is measured with a 10k ohm thermistor, calibrated in-circuit against a reference thermometer in a well stirred fluid bath.

2 Defining Equation

The actual equation used to convert resistance of the thermistor to temperature is considered insignificant to this analysis since the thermistor is calibrated in the system, as a system to align the thermistor's indicated temperature readings with the reference thermometer. The exact equations and mathematics used to achieve this alignment are not considered in this analysis.

3 Uncertainty Components

In the mathematical analysis of chamber temperature, there are several factors to consider. Those factors include measurement uncertainty, measurement resolution, self heating, and uncertainty of the reference standard.

3.1 Measurement Uncertainty

For computation of chamber temperature uncertainty due to measurement uncertainty, analysis was performed on ***as found*** data of 10 separate Model 2500 humidity generators during their annual recalibrations. This data is from customer owned units, returned to Thunder Scientific for calibration, each with one year or more of service since the previous calibration***. This analysis typifies expected uncertainty after one year of in field use***.

Each chamber temperature was tested against a reference thermometer at 3 points over the range of 0 to 70°C, resulting in 30 points from which to compute statistical standard deviation. The standard deviation of the difference between the reference standard and chamber temperatures over the stated temperature range is

$$\text{Std dev} = 0.018°\text{C}$$

The uncertainty in chamber temperature due to measurement, u(M), is then the standard deviation of the repeated measurements just stated.

$$u(M) = 0.018°\text{C}$$

3.2 Uncertainty in Temperature Measurement Resolution

The analog to digital conversion process which transforms probe resistance into digital values resolves to 0.01°C. Based on a rectangular distribution of the half-interval, the uncertainty component of temperature resolution is then

$$u(R) = 0.01 * 0.5/\sqrt{3}$$
$$= 0.0029$$

3.3 Uncertainty due to Self Heating of Chamber Temperature Probe

The chamber temperature probe is generally calibrated and checked in a well stirred fluid bath, but used in air. There is the possibility of some self heating associated with this measurement then that must be considered. The self heating, with temperature measurements in °C, is estimated to be +0.05% of reading. Based on rectangular distribution of the interval, the equation for the temperature uncertainty of self heating, u(SH), is then

$$
\begin{aligned}
u(SH) &= 0.05\% * T_c / \sqrt{3} \\
&= 0.00029 * T_c
\end{aligned}
$$

3.4 Uncertainty of the Temperature Reference Standard

The reference thermometer has a manufacturer stated accuracy of ±0.01°C. Assuming rectangular distribution of the half interval, the uncertainty of the temperature reference standard, $u(T_{ref})$, is then

$$
\begin{aligned}
u(T_{ref}) &= 0.01/\sqrt{3} \\
&= 0.006°C
\end{aligned}
$$

4 Combined Standard Uncertainty of Chamber Temperature

The standard uncertainty components and the resulting combined standard uncertainty of chamber temperature, $u_c(T_c)$, are listed in the following table. The combined uncertainty was computed as the square root of the sum of the variances with the equation

$$u_c^2(T_c) = u^2(M) + u^2(R) + u^2(SH) + u^2(T_{ref})$$

Standard Uncertainty Components of Chamber Temperature

Source	**Type**	**Term**	**Temperature**		
			0	**35**	**70**
Measurement	A	u(M)	0.018		
Resolution	B	u(R)	0.003		
Self Heating	B	u(SH)	0.000	0.010	0.020
Reference	B	$u(T_{ref})$	0.006		
combined		$u_c(T_c)$	.019	.022	.028

5. Expanded Uncertainty

Utilizing a coverage factor k=2, the expanded uncertainty, U, is listed in the following table at various temperatures using the following formula.

$$U = k * u_c(T_c)$$

Expanded Uncertainty of Chamber Temperature with Coverage Factor k=2					
Source	**Term**	**Time Interval**	**Temperature**		
			0	**35**	**70**
Chamber Temperature	U	One Year	±0.038°C	±0.044°C	±0.056°C

Note that the expanded uncertainties shown represent expected uncertainties after one year of use.

References:

1. Taylor, Barry N. and Kuyatt, Chris E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition
2. Kuyatt, Chris, et al., *Determining and Reporting Measurement Uncertainties*, Recommended Practice RP-12, National Conference of Standards Laboratories, April 1995

Chamber Temperature Uniformity Analysis of the Model 2500 Two-Pressure Humidity Generator

Chamber Temperature Uniformity Analysis
Of the
Thunder Scientific Model 2500 Two-Pressure Humidity Generator

1 Introduction

Described here is the Chamber Temperature Uniformity for a Model 2500 Humidity Generator. Chamber temperature uniformity has a direct influence on relative humidity gradients within the test chamber. In order to determine the chamber temperature uniformity, 10 thermometers of equivalent type and nominal resistance where calibrated together over the temperature range 15 to 35 °C. The thermometers were then strategically placed at various locations within the test chamber, approximately 1 to 2 inches from each corner (8 probes total), and 2 inches left and right of center (2 probes total).

2 Defining Equations

The maximum measurement deviation from the mean will be determined by noting the maximum and minimum readings from the set of probes at the same point in time, then taking half the difference of these values.

$$\text{MaxDev} = \pm 0.5(\text{MaxReading} - \text{MinReading}) \qquad [1]$$

The uniformity will then be computed by RSS combination (root of the sum of the squares) of the maximum deviation, MaxDev, and the estimated thermometer uncertainty, u(T).

$$\text{uniformity}^2 = \text{MaxDev}^2 + u^2(T) \qquad [2]$$

3 Calibration of Thermometers

The 10 thermometers were calibrated at the same time, in the same bath, against the same reference thermometer. Although they were calibrated in a well stirred fluid bath, yet used in air, self heating is not considered a significant contributor since all probes are used in the same type of environment. All should be subjected to similar self heating effects which tend to cancel one another when viewing differences between probes. The accuracy of the reference standard is also considered insignificant, since the desired value here is relative probe difference, not individual probe accuracy. The only concern in calibration of the thermometers is the relative accuracy of each with respect to the group. With this in mind, the uncertainty of the probes, u(T), with respect to each other after calibration is estimated to be

$$u(T) = \pm 0.025\ °C$$

3.1 Measurement of Chamber Temperatures

The following data was gathered during the uniformity analysis conducted on 4 Dec 1997, using a Model 2500, serial number 9711116. The generator was run at a fixed humidity of 50% RH, and was allowed to stabilize for a minimum of one hour at each temperature listed. Note that the maximum and minimum readings are indicated in bold type.

Probe	Location	15 °C nominal	25 °C ambient	35 °C nominal
1	Lower Left Front	15.169	24.937	34.856
2	Lower Right Front	15.215	24.906	34.812
3	Lower Left Rear	**15.333**	**24.938**	**34.710**
4	Lower Right Rear	15.225	24.916	34.787
5	Upper Left Front	**15.150**	24.935	**34.868**
6	Upper Right Front	15.164	24.897	34.853
7	Upper Left Rear	15.163	24.935	34.850
8	Upper Right Rear	15.156	24.914	34.852
9	Left Center	15.171	24.917	34.847
10	Right Center	15.169	**24.894**	34.829
Maximum Deviation (MaxDev)		±0.0915	±0.022	±0.079

4. Chamber Temperature Uniformity

As per equation 2, the uniformity at each of the 3 temperatures is computed as

$$\text{uniformity} = \text{sqr}(\ 0.0915^2 + 0.025^2)$$

= ±0.095°C (at 15 °C)
= ±0.033°C (at 25 °C)
= ±0.083°C (at 35 °C)

This is within the stated accuracy specification of ±0.10 °C when the chamber is operated within ±10 °C of ambient temperature.

5. Calculation of Percent Relative Humidity Gradients

The Relative Humidity Gradients (uniformity) within the test chamber caused by the temperature uniformity is calculated based on the 50%RH@Pc given the temperatures observed within the chamber in section 3.1. This is mathematically calculated assuming a uniform Dew Point within a chamber void of any heat-generating devices.

Note: When the 2500 generator is operated in %RH@PcTc mode the system will maintain the desired %RH value at the chamber temperature probe. Any %RH uniformity would then originate from the point of the chamber temperature probe.

Probe	***Location***	***15 °C nominal***	***25 °C ambient***	***35 °C nominal***
1	Lower Left Front	49.459 %RH	50.188 %RH	50.400 %RH
2	Lower Right Front	49.313 %RH	50.281 %RH	50.523 %RH
3	Lower Left Rear	**48.940 %RH**	**50.185 %RH**	**50.810 %RH**
4	Lower Right Rear	49.281 %RH	50.251 %RH	50.594 %RH
5	Upper Left Front	**49.520 %RH**	50.194 %RH	**50.367 %RH**
6	Upper Right Front	49.475 %RH	50.308 %RH	50.409 %RH
7	Upper Left Rear	49.478 %RH	50.194 %RH	50.417 %RH
8	Upper Right Rear	49.500 %RH	50.257 %RH	50.412 %RH
9	Left Center	49.453 %RH	50.248 %RH	50.426 %RH
10	Right Center	49.459 %RH	**50.317 %RH**	50.476 %RH
Maximum Deviation (MaxDev)		±0.290 %RH	±0.066 %RH	±0.222 %RH

5.1. Percent Relative Humidity Uncertainties Based on the Temperature Uncertainty

Calculating the percent relative humidity uncertainty at each temperature range based on the uncertainty of the temperature probes in section 3 we obtain the following:

uRH(T) = ±0.079 (at 15 °C)
uRH(T) = ±0.075 (at 25 °C)
uRH(T) = ±0.069 (at 35 °C)

6. Chamber Percent Relative Humidity Uniformity

As per equation 2, the uniformity at each of the 3 temperature ranges is computed as

$$\text{uniformity} = \text{sqr}(0.290^2 + 0.079^2)$$

= ±0.300%RH (at 15 °C)
= ±0.100%RH (at 25 °C)
= ±0.232%RH (at 35 °C)

Frost/Dew Point Uncertainty Analysis of the Model 3900 Low Humidity Generator

Dew/Frost Point Uncertainty Analysis of the Model 3900 Two-Temperature, Two-Pressure Low Humidity Generator

Revision A
December 7, 2006

1 Introduction

Described here is the Dew Point and Frost Point Uncertainty Analysis, following NIST Guideline 1297[1], for a Model 3900 Humidity Generator, manufactured by Thunder Scientific Corporation, that combines the NIST developed and proven two-temperature and two-pressure humidity generation principles.[2,3] Generating gas of a known dew point or frost point temperature in a system of this type does not require direct measurements of the water vapor content of the gas. Rather, the generated dew point and/or frost point temperature is derived from the measurements of saturation temperature, saturation pressure, and the pressure at the point of use, commonly referred to as either test pressure or chamber pressure. For the purposes of this analysis, the terms 'test pressure' and 'chamber pressure' are synonymous with each other.

2 Defining Equations

2.1 Common Equations

The following equations of Hardy[7] for saturation vapor pressure, enhancement factor, and temperature (from saturation vapor pressure) are common and fundamental to most humidity calculations presented here.

2.1.1 Saturation Vapor Pressure over Water, *e*

Saturation vapor pressure over *water* at a given ITS-90 temperature is defined by the formula [7]

$$e = \exp\left(\sum_{i=0}^{6} g_i T^{i-2} + g_7 \ln T\right) \qquad (1)$$

where e is the saturation vapor pressure, in Pascals, over liquid water in the pure phase,
T is the temperature in Kelvin,
and $g_0 = -2.8365744 \cdot 10^3$
$g_1 = -6.028076559 \cdot 10^3$
$g_2 = 1.954263612 \cdot 10^1$
$g_3 = -2.737830188 \cdot 10^{-2}$
$g_4 = 1.6261698 \cdot 10^{-5}$
$g_5 = 7.0229056 \cdot 10^{-10}$
$g_6 = -1.8680009 \cdot 10^{-13}$
$g_7 = 2.7150305$

2.1.2 Saturation Vapor Pressure over Ice, *e*

Saturation vapor pressure over *ice* at a given temperature is defined by the formula [7]

$$e = \exp\left(\sum_{i=0}^{4} k_i T^{i-1} + k_5 \ln T\right) \qquad (2)$$

where e is the saturation vapor pressure, in Pascals, over ice in the pure phase
T is the temperature in Kelvin
and $k_0 = -5.8666426 \cdot 10^{3}$
$k_1 = 2.232870244 \cdot 10^{1}$
$k_2 = 1.39387003 \cdot 10^{-2}$
$k_3 = -3.4262402 \cdot 10^{-5}$
$k_4 = 2.7040955 \cdot 10^{-8}$
$k_5 = 6.7063522 \cdot 10^{-1}$

2.1.3 Enhancement Factors

The 'effective' saturation vapor pressure over water or ice in the presence of other gases differs from the ideal saturation vapor pressures given in equations 1 and 2. The effective saturation vapor pressure is related to the ideal by

$$\acute{e} = e \cdot f \qquad (3)$$

where $\acute{e}$ is the 'effective' saturation vapor pressure
e is the ideal saturation vapor pressure (as given in equation 1 or 2)
and f is the enhancement factor.

The enhancement factor, for an air-water vapor mixture, is determined at a given temperature and pressure from the formula [7]

$$f = \exp\left[\alpha\left(1 - \frac{e}{P}\right) + \beta\left(\frac{P}{e} - 1\right)\right] \qquad (4)$$

with $$\alpha = \sum_{i=0}^{3} a_i T^{i} \qquad (5)$$

and $$\beta = \exp\left(\sum_{i=0}^{3} b_i T^{i}\right) \qquad (6)$$

where f is the enhancement factor
e is the ideal saturation vapor pressure (as given in equation 1 or 2)
P is pressure in the same units as e
T is temperature in Kelvin
and a_I, b_I depend on temperature range and are given as

for water

223.15 to 273.15 K (-50 to 0 °C)	273.15 to 373.15 K (0 to 100 °C)
$a_0 = -5.5898101 \cdot 10^{-2}$	$a_0 = -1.6302041 \cdot 10^{-1}$
$a_1 = 6.7140389 \cdot 10^{-4}$	$a_1 = 1.8071570 \cdot 10^{-3}$
$a_2 = -2.7492721 \cdot 10^{-6}$	$a_2 = -6.7703064 \cdot 10^{-6}$
$a_3 = 3.8268958 \cdot 10^{-9}$	$a_3 = 8.5813609 \cdot 10^{-9}$
$b_0 = -8.1985393 \cdot 10^{1}$	$b_0 = -5.9890467 \cdot 10^{1}$
$b_1 = 5.8230823 \cdot 10^{-1}$	$b_1 = 3.4378043 \cdot 10^{-1}$

$b_2 = -1.6340527 \cdot 10^{-3}$ $b_2 = -7.7326396 \cdot 10^{-4}$
$b_3 = 1.6725084 \cdot 10^{-6}$ $b_3 = 6.3405286 \cdot 10^{-7}$

for ice

173.15 to 223.15 K (-100 to -50 °C)	223.15 to 273.15 K (-50 to 0 °C)
$a_0 = -7.4712663 \cdot 10^{-2}$	$a_0 = -7.1044201 \cdot 10^{-2}$
$a_1 = 9.5972907 \cdot 10^{-4}$	$a_1 = 8.6786223 \cdot 10^{-4}$
$a_2 = -4.1935419 \cdot 10^{-6}$	$a_2 = -3.5912529 \cdot 10^{-6}$
$a_3 = 6.2038841 \cdot 10^{-9}$	$a_3 = 5.0194210 \cdot 10^{-9}$
$b_0 = -1.0385289 \cdot 10^{2}$	$b_0 = -8.2308868 \cdot 10^{1}$
$b_1 = 8.5753626 \cdot 10^{-1}$	$b_1 = 5.6519110 \cdot 10^{-1}$
$b_2 = -2.8578612 \cdot 10^{-3}$	$b_2 = -1.5304505 \cdot 10^{-3}$
$b_3 = 3.5499292 \cdot 10^{-6}$	$b_3 = 1.5395086 \cdot 10^{-6}$

2.1.4 Temperature from Saturation Vapor Pressure

Equations 1 and 2 are easily solved for saturation vapor pressure over water or ice for a given saturation temperature. However, if vapor pressure is known while temperature is the unknown desired quantity, the solution immediately becomes complicated and must be solved by iteration. For ease of computation, the following inverse equation is provided. This equation is generally used to find the dew point or frost point temperature when the vapor pressure of a gas has been determined. When vapor pressure is known, use the water coefficients to obtain dew point, and use the ice coefficients to obtain frost point.

$$T = \frac{\sum_{i=0}^{3} c_i (\ln e)^i}{\sum_{i=0}^{3} d_i (\ln e)^i} \tag{7}$$

where T is the temperature in Kelvin
and e is the saturation vapor pressure in Pascals

with coefficients

for water	for ice
$c_0 = 2.0798233 \cdot 10^{2}$	$c_0 = 2.1257969 \cdot 10^{2}$
$c_1 = -2.0156028 \cdot 10^{1}$	$c_1 = -1.0264612 \cdot 10^{1}$
$c_2 = 4.6778925 \cdot 10^{-1}$	$c_2 = 1.4354796 \cdot 10^{-1}$
$c_3 = -9.2288067 \cdot 10^{-6}$	$c_3 = 0$
$d_0 = 1$	$d_0 = 1$
$d_1 = -1.3319669 \cdot 10^{-1}$	$d_1 = -8.2871619 \cdot 10^{-2}$
$d_2 = 5.6577518 \cdot 10^{-3}$	$d_2 = 2.3540411 \cdot 10^{-3}$
$d_3 = -7.5172865 \cdot 10^{-5}$	$d_3 = -2.4363951 \cdot 10^{-5}$

2.2 Dew Point and Frost Point Determination

2.2.1 Definitions of Terms

T_s *Saturation Temperature*. The temperature at which the gas is fully saturated with water vapor, and is most often made by a direct measurement of the temperature of the saturator itself. T_s is in Kelvin, t_s is in °C.

T_c *Chamber Temperature*. The temperature of the gas in the test chamber, or in the device under test, at the location of the humidity sensor. T_c is in Kelvin, t_c is in °C.

T_d *Dew Point Temperature*. The temperature to which a gas must be cooled in order to just begin condensing in the form of liquid dew. While contrary to common sense, liquid dew can form in a meta-stable state at temperatures below freezing (called super-cooled dew). Thus, dew point temperatures below 0 °C are quite common and reproducible. While dew point and frost point exhibit identical vapor pressures, dew point and frost point temperatures are not the same, except at 0.01 °C which is the triple point of water. T_d is in Kelvin, t_d is in °C.

T_f *Frost Point Temperature*. The temperature to which a gas must be cooled in order to just begin condensing in the form of frost or ice. Frost point only exists at temperatures below freezing (t_f <= 0.01 °C). While frost point and dew point exhibit identical vapor pressures, frost point and dew point temperatures are not the same, except at 0.01 °C which is the triple point of water. T_f is in Kelvin, t_f is in °C.

P_s *Saturator Pressure*. (As it applies to the humidity generators described in this document, *Saturation Pressure* is synonymous with *Saturator Pressure*.) The total pressure in the saturator, measured at the *final point of saturation* (generally the saturator outlet). This is an absolute (not gauge) measurement. P_s is in Pascals.

P_c *Chamber Pressure*. The total pressure as measured in the test chamber, or at the device under test, at the location of the humidity sensor. This is also referred to throughout this document as Test Pressure. This is an absolute (not gauge) measurement. P_c is in Pascals.

e_s *Saturation Vapor Pressure at the Saturation Temperature*. The partial pressure of the water vapor in the saturator, as determined by measurement of the saturation temperature. Regardless of the total pressure of the saturator, e_s is dependent on saturation temperature only and further assumes that full saturation is actually being achieved. For temperatures above freezing, e_s is computed as *Saturation Vapor pressure over Water*. For temperatures below freezing, e_s is generally computed as *Saturation Vapor Pressure over Ice*. e_s is expressed in Pascals.

e_c *Saturation Vapor Pressure at the Chamber Temperature*. The maximum possible partial pressure of water vapor that could exist in the test chamber, if the gas were fully saturated with water vapor at the chamber temperature. Regardless of the total pressure of the chamber, e_c is dependent on chamber temperature only. For temperatures above freezing, e_c is computed as *Saturation Vapor pressure over Water*. For temperatures below freezing, e_c is generally computed as *Saturation Vapor Pressure over Ice*. However, when using e_c in the computation of %RH, but only when doing so in accordance with the World Meteorogical Organization (WMO) adopted quidelines, e_c is to be computed with respect to water for all temperature conditions, even those below freezing. e_c is expressed in Pascals.

e_d *Saturation Vapor Pressure at the Dew/Frost Point Temperature (also known as Dew Point Vapor Pressure, Frost Point Vapor Pressure, and partial water vapor pressure).* The partial pressure of the water vapor at the dew point temperature and computed with respect to liquid water, or at the frost point temperature and computed with respect to ice. Where frost point exists (at all temperatures below freezing), dew point vapor pressure calculated a the dew point temperature with repect to liquid water and frost point vapor pressure calculated at the frost point temperature with respect to ice are always equal and synonymous terms. e_d is expressed in Pascals.

f_s *Enhancement Factor at Saturation Temperature and Saturation Pressure*. The enhancement factor corrects for the slight non-ideal behavior of water vapor when admixed with other gases. The *effective* saturation vapor pressure that results under saturation at any given temperature and pressure condition is determined by computing the product of the saturation vapor pressure and the enhancement factor.

f_c *Enhancement Factor at Chamber Temperature and Chamber Pressure*. The enhancement factor corrects for the slight non-ideal behavior of water vapor when admixed with other gases. The *effective* saturation vapor pressure that results under saturation at any given temperature and pressure condition is determined by computing the product of the saturation vapor pressure and the enhancement factor.

f_d *Enhancement Factor at Dew/Frost Point Temperature and Chamber Pressure*. The enhancement factor corrects for the slight non-ideal behavior of water vapor when admixed with other gases. The *effective* dew/frost point vapor pressure that results under saturation at any given temperature and pressure condition is determined by computing the product of the dew/frost point vapor pressure and the enhancement factor.

2.2.2 Dew Point Temperature, T_d

Dew point temperature is the temperature to which a gas must be cooled in order to just begin condensing water vapor in the form of dew. Dew point temperature in this system is obtained with the following iterative steps.

A. The vapor pressure e_s at the saturation temperature is calculated with equation 1 or equation 2. To get e_s from this equation, the saturation temperature T_s is used for T. When $T_s > 0$, equation 1 is used. When $T_s < 0$, specific knowledge of the state of the water (whether liquid or ice) is needed. While it is possible for the water in a saturator to remain liquid for a short time when below 0 °C, liquid water in a saturator operating below 0 °C will eventually freeze into a state of ice. (A saturator that has been operating at or below –5 °C for more than an hour is most often expected to be operating in a state of ice.) Once frozen into ice, the water remains in that state as long as the saturation temperature remains below 0 °C. When the saturator is operating in a state of ice, equation 2 is required.

B. The enhancement factor f_s at the saturation temperature and saturation pressure is calculated using equation 4. To get f_s from this equation, calculations are performed using $e = e_s$, $P = P_s$, and $T = T_s$. Equation 4 must be used with the correct coefficients (relative to the correct temperature range for water or ice) based upon saturation temperature T_s and specific knowledge of the state of the water in the saturator.

C. An educated guess is made at the dew/frost point enhancement factor, f_d. Setting $f_d = 1$ is a suitable first guess.

D. The dew/frost point vapor pressure e_d of the gas is computed with the two-pressure, two-temperature relationship

$$e_d = e_s \cdot \frac{f_s}{f_d} \cdot \frac{P_c}{P_s} \tag{8}$$

E. Dew point temperature T_d is calculated from dew/frost point vapor pressure e_d using equation 7 and the coefficients for water. To get T_d from this equation, calculations are performed using $e = e_d$.

F. The dew/frost point enhancement factor f_d is calculated using equation 4 and the coefficients for water of the appropriate range (based on the value of T_d). To get f_d from this equation, calculations are performed using $e = e_d$, $P = P_c$, and $T = T_d$.

G. The dew point temperature, T_d, converges to the proper value by iterating steps D through F several times as necessary.

2.2.3 Frost Point Temperature, T_f

Frost point temperature is the temperature to which a gas must be cooled in order to just begin condensing water vapor in the form of frost or ice. Frost point only exists at temperatures below freezing.

Note that generating a frost point does not require ice in the saturator, nor does generating a dew point temperature require liquid water in the saturator. While the state of the saturator is required for proper application of the equations and their calculations, the generator is ultimately controlling at some specified vapor pressure. Dew point temperature and frost point temperature share the same vapor pressure and enhancement factor, but have different numeric values of temperature. All vapor pressures that correspond to a dew point temperature at or below 0.01 °C also have a corresponding frost point temperature. At a dew point temperature of 0.01 °C, frost point temperature is equal to dew point temperature. For all values below that, the two diverge from each other with dew point temperature always lower in value than the corresponding frost point temperature. Dew point temperature and frost point temperature, while different from each other in numeric value, are equally valid methods of expressing the same vapor pressure.

Frost point is obtained with the following iterative steps.

A. The vapor pressure e_s at the saturation temperature is calculated with equation 1 or equation 2. To get e_s from this equation, the saturation temperature T_s is used for T. When $T_s > 0$, equation 1 is used. When $T_s < 0$, specific knowledge of the state of the water (whether liquid or ice) is needed. While it is possible for the water in a saturator to remain liquid for a short time when below 0 °C, liquid water in a saturator operating below 0 °C will eventually freeze into a state of ice. (A saturator that has been operating at or below –5 °C for more than an hour is most often expected to be operating in a state of ice.) Once frozen into ice, the water remains in that state as long as the saturation temperature remains below 0 °C. When the saturator is operating in a state of ice, equation 2 is required.

B. The enhancement factor f_s at the saturation temperature and saturation pressure is calculated using equation 4. To get f_s from this equation, calculations are performed using $e = e_s$, $P = P_s$, and $T = T_s$. Equation 4 must be used with the correct coefficients (relative to the correct temperature range for water or ice) based upon saturation temperature T_s and specific knowledge of the state of the water in the saturator.

C. An educated guess is made at the dew/frost point enhancement factor, f_d. Setting $f_d = 1$ is a suitable first guess.

D. The dew/frost point vapor pressure e_d of the gas is using equation 8.

E. Frost point temperature T_f is calculated from dew/frost point vapor pressure e_d using equation 7 and the coefficients for ice. To get T_f from this equation, calculations are performed using $e = e_d$.

F. The dew/frost point enhancement factor f_d is calculated using equation 4 and the coefficients for ice of the appropriate range (based on the value of T_f). To get f_d from this equation, calculations are performed using $e = e_d$, $P = P_c$, and $T = T_f$.

G. The frost point temperature, T_f, converges to the proper value by iterating steps D through F several times as necessary.

3 Uncertainty

To analyze the overall expanded uncertainty in generated dew point and/or frost point temperature, the uncertainties associated with temperatures and pressures must be determined, along with other possible sources of uncertainty. These individual components of uncertainty must then be statistically combined to form the Combined Uncertainty. The Expanded Uncertainty is then determined by multiplying the Combined Uncertainty by a suitable coverage factor, k, based on the desired confidence level.

Due to the complexity associated with the computations, and the iterative requirement to reach a final solution, algebraic methods involving partial derivatives of the underlying equations prove difficult. Rather, a more straightforward approach will be taken that utilizes a table of sensitivity coefficients at various temperature and pressure combinations. The table will identify the sensitivity of generated dew and frost point temperature to uncertainty in the saturation temperature, saturation pressure, and test pressure. Construction of the sensitivity tables will then allow straight forward determination of the uncertainty in dew and frost point temperature due to:

- uncertainty in saturation pressure which includes
  - measurement uncertainty
  - measurement hysteresis
  - measurement resolution
- uncertainty in test pressure which includes
  - measurement uncertainty
  - measurement hysteresis
  - measurement resolution
- uncertainty in saturation temperature which includes
  - measurement uncertainty
  - measurement hysteresis
  - measurement resolution
- uncertainty contribution from saturator efficiency
- uncertainty in vapor pressure
- uncertainty in enhancement factors
- uncertainty contribution due to adsorption, desorption, and permeation

3.1 Creation of Sensitivity Coefficients at Various Saturation Temperatures and Pressures

Due to the complexity in developing algebraic solutions, a numerical approach is taken to determine these values. The calculation steps of sections 2.2.2 and 2.2.3 along with equations 1 through 8 are programmed into a computer that determines dew point and frost point temperatures using variable inputs of saturation temperature T_s, saturation pressure P_s, and test pressure P_c. A sensitivity coefficient is determined by calculating dew/frost point temperature at nominal values of saturation temperature, saturation pressure, and chamber pressure. Next, one of these three input values is altered slightly and a new calculation performed. The difference of the dew/frost point results divided by the deviation of the input value is used as the sensitivity coefficient for that temperature, pressure combination.

Table 1. Dew Point & Frost Point Sensitivity Coefficients

Humidity Generator Conditions			Frost Point Sensitivity Coefficients			Dew Point Sensitivity Coefficients		
Nominal FP [°C]	Ts [°C]	Ps [kPa]	ΔFP/ΔTs [°C/°C]	ΔFP/ΔPs [°C/kPa]	ΔFP/ΔPc [°C/kPa]	ΔDP/ΔTs [°C/°C]	ΔDP/ΔPs [°C/kPa]	ΔDP/ΔPc [°C/kPa]
-95	-80	1668.93	0.844	0.003				
	-79.05	2000	0.833	0.001	0.051			
-90	-80	597.029	0.897	0.009				
	-75	1414.74	0.849	0.003				
	-73.04	2000	0.830	0.001	0.054			
-80	-80	101.325	1.000	0.060				
	-72.37	344.74	0.925	0.017				
	-70	498.099	0.903	0.012				
	-60.91	2000	0.821	0.002	0.060			
-70	-70	101.325	1.000	0.066				
	-61.54	344.74	0.921	0.019				
	-60	427.266	0.908	0.015				
	-50	1667.27	0.824	0.004				
	-48.66	2000	0.811	0.003	0.066			
-60	-60	101.325	1.000	0.073				
	-50.66	344.74	0.917	0.021				
	-50	374.63	0.912	0.019				
	-40	1277.76	0.832	0.005				
	-36.28	2000	0.804	0.003	0.073			
-50	-50	101.325	1.000	0.080				
	-40	334.27	0.916	0.024				
	-39.73	344.74	0.913	0.023				
	-30	1020.07	0.839	0.008				
	-23.76	2000	0.795	0.003	0.080			
-40	-40	101.325	1.000	0.087		1.057	0.092	
	-30	302.6	0.919	0.029		0.971	0.031	
	-28.76	344.74	0.910	0.025		0.961	0.027	
	-20	839.95	0.846	0.010		0.894	0.011	
	-11.1	2000	0.786	0.004	0.087	0.830	0.004	0.092
-30	-30	101.325	1.000	0.095		1.075	0.102	
	-20	277.21	0.922	0.034		0.990	0.037	
	-17.73	344.74	0.905	0.027		0.972	0.030	
	-10	708.82	0.852	0.013		0.914	0.014	
	0	1723.92	0.787	0.005		0.845	0.006	
	1.96	2000	0.682	0.004	0.095	0.732	0.005	0.102
-20	-20	101.325	1.000	0.103		1.092	0.113	
	-10	256.5	0.924	0.040		1.010	0.044	
	-6.66	344.74	0.901	0.030		0.984	0.033	
	0	610.31	0.857	0.017		0.936	0.018	
	10	1248.98	0.696	0.008		0.760	0.009	
	16.91	2000	0.657	0.005	0.103	0.718	0.005	0.112
-10	-10	101.325	1.000	0.111		1.111	0.124	
	0	239.37	0.927	0.047		1.031	0.052	
	5.08	344.74	0.785	0.032		0.873	0.036	
	10	484.44	0.755	0.023		0.839	0.026	
	17	770.59	0.714	0.014	0.111	0.793	0.016	0.124
0	0	101.325				1.000	0.136	
	10	204.24				0.922	0.067	
	17	323.42				0.873	0.042	0.136
10	10	101.325				1.000	0.148	
	17	160.19				0.946	0.094	0.148

Notice that in the table of sensitivity coefficients, nominal frost and dew point values are shown with a variety of saturation temperature and pressure combinations. For each specific frost point or dew point temperature listed, an attempt was made to include the maximum possible saturation pressure, minimum saturation pressure, and a pressure equal to the switch-over point between the high and low range saturation pressure transducer. In addition, the lowest and highest possible saturation temperature was also listed. For all of the above calculations, a common test pressure (standard atmospheric pressure) is assumed.

3.2 Uncertainty Contribution from Pressure

Determining the uncertainty in generated output based on saturation pressure and test pressure requires knowledge of uncertainty in the pressure measurement, pressure hysteresis, and measurement resolution of the saturator and test pressure transducers.

3.2.1 Pressure Measurement

This system utilizes three absolute pressure transducers. One is used for the test pressure measurement. While it has a full scale of 0 to 345 kPa absolute, it is generally used only for the barometric pressure range. For the purposes of this analysis, standard barometric pressure of 101.325 kPa is assumed. The other two pressure transducers are of different ranges and are used for the measurement of saturation pressure. For low saturation pressures (those below 345 kPa), the low range transducer is used. For higher saturation pressure, where the uncertainty in saturation pressure is of a lesser concern, a higher range transducer is used.

Pressure measurement uncertainty was analyzed from the data collected during annual calibration of the pressure transducers. During calibration, each transducer was tested at no fewer than 3 points over its specific range using a total system calibration approach. With this approach, the transducers remain electrically connected to the system allowing the pressure transducer, the measuring electronics, and the displayed data to be calibrated as a complete system rather than as individual components. Data gathered during the calibration is system rather than component data. The combined data from several years of calibration history were used in the computation of statistical standard deviations. For each of the pressure transducers (which includes the measurement electronics and display), the standard deviation, σ_P, from the desired mean values were determined to be:

σ_P = 0.069 kPa (0.01 psia) for $P<345$ kPa (<50 psia)
σ_P = 0.276 kPa (0.04 psia) for $P>345$ kPa (>50 psia)

Using normal distribution, the pressure uncertainties normalized to one sigma are equivalent to the standard deviation values given above for each of the transducers.

$$uP_{c[meas]} = 0.069 \text{ kPa (0.01 psia)}$$

$$uP_{s[meas]} = 0.069 \text{ kPa (0.01 psia) for } P<345 \text{ kPa (<50 psia)}$$
$$= 0.276 \text{ kPa (0.04 psia) for } P>345 \text{ kPa (>50 psia)}$$

The statistical standard deviations calculated from the calibration history also have an uncertainty component from the Mensor PCS400 pressure standard used during the calibration process. The uncertainty of the Mensor PCS400 pressure standard for the low and high-pressure ranges are as follows:

$$uP_{c[std]} = 0.046 \text{ kPa}$$

$$uP_{s[std]} = 0.046 \text{ kPa for } P<345 \text{ kPa (<50 psia)}$$
$$= 0.228 \text{ kPa for } P>345 \text{ kPa (>50 psia)}$$

3.2.2 Pressure Hysteresis

The system most often operates for hours, days, or weeks on end at one saturation pressure. When a change in saturation pressure is made, the new condition is again maintained for hours, days, or weeks.

The test pressure transducer generally monitors changes only in the barometric pressure. Since both the saturator and test pressure measurements result in very slow moving, nearly steady state conditions, hysteresis in pressure measurement is nearly imperceptible. However, the affect of any hysteresis must still be considered in the overall analysis. Based on triangular distribution, hysteresis in pressure measurement normalized to one sigma, is estimated to be

$$uP_{c[hyst]} = 0.035/\sqrt{6}\ \text{kPa}\ (0.005/\sqrt{6}\ \text{psia})$$
$$= 0.014\ \text{kPa}\ (0.002\ \text{psia})$$

$$uP_{s[hyst]} = 0.035/\sqrt{6}\ \text{kPa}\ (0.005/\sqrt{6}\ \text{psia})\ \text{for}\ P<345\ \text{kPa}\ (50\ \text{psia})$$
$$= 0.014\ \text{kPa}\ (0.002\ \text{psia})\ \text{for}\ P<345\ \text{kPa}\ (50\ \text{psia})$$

$$= 0.172/\sqrt{6}\ \text{kPa}\ (0.025/\sqrt{6}\ \text{psia})\ \text{for}\ P>345\ \text{kPa}\ (50\ \text{psia})$$
$$= 0.070\ \text{kPa}\ (0.010\ \text{psia})\ \text{for}\ P>345\ \text{kPa}\ (50\ \text{psia})$$

3.2.3 Pressure Resolution

The analog to digital conversion process resolves 1 part in 25000 over the range of each of the pressure transducers. The resolution is then computed as

$$resolution_p = (TransducerRange)/25000$$

The resolution for each of the transducers is then

$$resolution_{pc} = 345\ \text{kPa} / 25000$$
$$= 0.014\ \text{kPa}\ (0.002\ \text{psia})$$

$$resolution_{ps} = 345\ \text{kPa} / 25000$$
$$= 0.014\ \text{kPa for P<345 kPa (0.002 psia for P<50 psia)}$$

$$= 2068\ \text{kPa} / 25000$$
$$= 0.083\ \text{kPa for P>345 kPa (0.012 psia for P>50 psia)}$$

Based on a rectangular distribution of the half-interval of resolution, the uncertainty of pressure due to resolution normalized to one sigma is computed by multiplying the resolution by 0.5/√3. The uncertainty of pressure due to resolution is then

$$uP_{[res]} = resolution_p * 0.5/\sqrt{3}$$

$$uP_{c[res]} = 0.004\ \text{kPa}\ (0.0006\ \text{psia})$$

$$uP_{s[res]} = 0.004\ \text{kPa for}\ P<345\ \text{kPa}\ \ (0.0006\ \text{psia for}\ P<50\ \text{psia})$$
$$= 0.024\ \text{kPa for}\ P>345\ \text{kPa}\ \ (0.0035\ \text{psia for}\ P>50\ \text{psia})$$

3.2.4 Summary of Pressure Uncertainties

Pressure uncertainties of various types may be combined statistically using the following

$$(uP)^2 = (uP_{[meas]})^2 + (uP_{[std]})^2 + (uP_{[hyst]})^2 + (uP_{[res]})^2 \ldots$$

Uncertainty data in tables 2 through 4 are combined in that manner.

Table 2. Test Pressure Uncertainty, uP_c

Source	Type	Uncertainty [kPa]
$uP_{c[meas]}$	A	0.069
$uP_{c[std]}$	B	0.046
$uP_{c[hyst]}$	B	0.014
$uP_{c[res]}$	A	0.004
uP_c		0.084

Table 3. Saturation Pressure Uncertainty, uP_s (for P_s<345 kPa)

Source	Type	Uncertainty [kPa]
$uP_{s[meas]}$	A	0.069
$uP_{s[std]}$	B	0.046
$uP_{s[hyst]}$	B	0.014
$uP_{s[res]}$	A	0.004
uP_s (P_s < 345 kPa)		0.084

Table 4. Saturation Pressure Uncertainty, uP_s (for P_s>345 kPa)

Source	Type	Uncertainty [kPa]
$uP_{s[meas]}$	A	0.276
$uP_{s[std]}$	B	0.228
$uP_{s[hyst]}$	B	0.070
$uP_{s[res]}$	A	0.024
uP_s (P_s > 345 kPa)		0.366

3.3 Uncertainty Contribution from Temperature

Determining the uncertainty in generated output based on saturation temperature requires knowledge of uncertainty in the measurement, the resolution, and the self-heating of the saturation thermometer.

Saturation temperature is measured by a 1k ohm thermistor to measure the saturation temperature range of –80 to +17 °C. Temperature measurement uncertainty was analyzed from the data collected during annual calibration of the saturator temperature probe. During calibration, the saturation thermometer was tested at no fewer than 3 points over its measurement range using a total system calibration approach. With this approach, the thermometer remains electrically connected to the system allowing the temperature probe, the measuring electronics, and the displayed data to be calibrated as a complete system rather than as individual components. Data gathered during the calibration is system rather than component data. The combined data from several years of calibration history were used in the computation of statistical standard deviations. The standard deviation of the saturation thermometer system, σ_T, from the desired mean values were determined to be:

$$\sigma_{T\ [meas]} = 0.04\ °C$$

Using normal distribution, the temperature measurement uncertainty normalized to one sigma is equivalent to the standard deviation value given above for the saturation thermometer.

$$uT_{s[meas]} = 0.04\ °C$$

The statistical standard deviations calculated from the calibration history also have an uncertainty component from the Hart 1560 Black Stack & 5626 PRT temperature standard used during the calibration process. The uncertainty of the Hart 1560 Black Stack & 5626 PRT temperature standard is as follows:

$$uT_{s[std]} = 0.006\ °C$$

3.3.1 Temperature Resolution

The analog to digital conversion process which transforms the saturation thermometer resistance into digital values resolves to 0.002 °C. Based on a rectangular distribution of the half-interval, the uncertainty component of saturation temperature resolution is then

$$uT_{s[res]} = 0.01 * 0.5/\sqrt{3}$$
$$= 0.003$$

3.3.3 Self Heating

The saturation temperature probe is generally calibrated and checked in a well-stirred fluid bath. In use, it is also immersed directly within a pumped fluid surrounding the saturator. Since the conditions of calibration and use are very similar, both immersed within moving fluid, the self heating is considered almost negligible. However, an estimate of uncertainty will be applied.

$$uT_{s[self\ heating]} = 0.005\ °C$$

3.3.4 Thermal Lag

The saturator is of a stacked plate design, constructed completely of stainless steel, sealed and immersed in a pumped fluid medium. Direction of the fluid flow is counter to that of the saturator gas stream.
The temperature of the pumped fluid medium is controlled to the desired saturation temperature and measured by the saturation temperature probe. Given adequate time, the saturator outlet is assumed to come into thermal equilibrium with the average temperature of the pumped fluid medium. However, during times of temperature transition, the saturator plates will lag the temperature of the fluid by up to several degrees. No attempt will be made here to predict the uncertainty associated with thermal lag. However it will be assumed that adequate time is allowed for the saturator to regain thermal equilibrium with the pump fluid medium prior to relying on the data from the generator. Lag times of 30 minutes to 1 hour are not considered uncommon. When approaching the final value, the rate of change is very slow and become difficult to detect on the instrument under test. Therefore, an estimate of uncertainty will be applied.

$$uT_{s[thermal\ lag]} = 0.01\ °C$$

3.3.5 Thermal Gradients

Design of the saturator is that of a counter-flow design where the fluid medium flows in a direction opposite that of the gas stream being saturated. Thermal gradients do exist within the saturator from inlet to outlet. Controlling the direction of this gradient is important to proper saturation. The temperature of the fluid is measured and controlled at the point it enters the saturator cavity, which is the same point that the saturated gas stream exits the saturator due to the counter flow design. The temperature will be slightly higher at the fluid exit point, which is also the gas entry point. Provided the saturator is of sufficient thermal capacity and effective path length, complete thermal transfer between the gas flowing in one direction and the fluid flowing in the opposite direction will ensure that the exiting gas has reached thermal equilibrium with the entering fluid and is therefore at fluid temperature. An estimate of uncertainty will be applied.

$$uT_{s[gradient]} = 0.005\ °C$$

[It is believed that the design of the saturator reduces any negative affects that a temperature gradient might otherwise cause if uncontrolled or improperly directed. Furthermore, it is believed that this design actually improves the ability of the saturator to fully saturate the gas stream with water vapor, thereby improving saturator efficiency.]

3.3.6 Temperature Control Stability

Temperature stability relates to the ability of the temperature control system to maintain a constant temperature in the pumped fluid medium, and ultimately in the saturator itself. The saturator temperature control system maintains the saturation temperature fluid at the setpoint with a standard deviation of 0.02 °C. Using normal distribution, the uncertainty in temperature relating to control stability normalized to one sigma is equivalent to the standard deviation. It is given therefore as

$$uT_{s[stability]} = 0.02\ °C$$

3.3.7 Summary of Temperature Uncertainties

Temperature uncertainties of various types may be combined statistically using the following

$$(uT)^2 = (uT_{[meas]})^2 + (uT_{[resolution]})^2 + (uT_{[std]})^2 \ldots$$

Uncertainty data in table 5 is combined in that manner.

Table 5. Saturation Temperature Uncertainty, uT

Source	Type	Uncertainty [°C]
$uT_{s[meas]}$	A	0.040
$uT_{s[res]}$	A	0.003
$uT_{s[std]}$	B	0.006
$uT_{s[self\ heating]}$	B	0.005
$uT_{s[thermal\ lag]}$	B	0.010
$uT_{s[gradients]}$	B	0.005
$uT_{s[control\ stability]}$	B	0.020
uT_{s}		0.047

3.4 Saturation Efficiency,

All two-pressure two-temperature humidity generators of single pass design rely on the ability of the saturator to fully saturate the gas with water vapor as it passes from inlet to outlet. Based on the counter flow design of the saturator (fully discussed in *Thermal Gradients*), it is assumed for all practical purposes that the saturator efficiency is 100%. Even given that assumption, small differences in saturation within the system can lead to uncertainty in the generated dew and frost point temperatures. This uncertainty is very small and very difficult to isolate or even measure outright, making it difficult to accurately quantify its value. Because of this, an instrument comparison was used to help identify this uncertainty. The premise of the instrument comparison was a RH Systems 373 chilled mirror. Data gathered during instrument comparison tests from several years of calibration history resulted in uncertainty of +/ - 0.0175 °C in the dew or frost point value. When normalized to one sigma, and assuming a triangular distribution, the affect of uncertainty in the small differences in saturation can be expressed as

$$uSE = 0.017\ °C/\sqrt{6}$$
$$= 0.007\ °C$$

3.5 Vapor Pressure

Vapor pressure equations are given in equations 1 and 2 for water and ice respectively. There are uncertainties assigned to the experimental data used as a basis for those equations. When calculating dew or frost point temperature from the humidity generator, the vapor pressure equations are only used as a means to transform data from saturation temperature to vapor pressure, then from vapor pressure back to dew or frost point temperature. Since the vapor pressure equations are used simply as bi-directional transfer functions, and round-trip transformation is always made, uncertainty in the data used to create these functions is of little significance, especially when the saturation temperature and dew or frost temperature are nearly equal. Under that circumstance, the dew and frost point vapor pressure is nearly equal to the saturation vapor pressure. However, when the ratio of saturation temperature to dew or frost temperature is high, the dew and frost point vapor pressure is lower than the saturation vapor pressure (likewise, the dew or frost point temperature is lower than the saturation temperature). This results in the possibility that the transformation function in one direction (temperature to saturation vapor pressure) occurs on a different portion of the function's curve than the inverse transformation (vapor pressure to dew or frost point temperature). Due to slight variations of the original experimental data, the quality of fit of the function to the data, and other factors, some allowance must be made for uncertainty associated with use of the vapor pressure equations. Uncertainty in the vapor pressure data is estimated to be within 0.5% of value. When the transfer functions are used to fully convert saturation vapor pressure into dew or frost point temperature, the resulting uncertainty due to vapor pressure is not expected to exceed +/- 0.007 °C in the dew or frost point value. When normalized to one sigma, and assuming a triangular distribution, the affect of uncertainty in vapor pressure can be estimated as

$$uVp = 0.007\ °C/\sqrt{6}$$
$$= 0.003\ °C$$

3.6 Enhancement Factor

Enhancement factors are slight correction factors used to account for the non-ideal behavior of water vapor when admixed with other gases. The enhancement factor is dependent on both temperature and pressure and is given in equation 4. In use, the enhancement factor is applied as a multiplier to the vapor pressure resulting in the 'effective vapor pressure'. For analytical purposes the enhancement factor can be considered in a manner similar to the vapor pressure for determining the affect of uncertainty in the enhancement factor data and formula. In the case of enhancement factor the pressure differences between saturator and test pressure results in the possibility that the transformation function in one direction occurs on a different portion of the function's curve than the inverse transformation. The uncertainty in the enhancement factor is estimated to be within 1.3% of value. When the transfer functions are used to fully convert saturation temperature and saturation pressure into dew or frost point at test pressure, the resulting uncertainty due to enhancement factor is not expected to exceed +/ - 0.018 °C in the dew or frost point value. When normalized to one sigma, and assuming a triangular distribution, the affect of uncertainty in enhancement factor can be expressed as

$$uEF = 0.018\ °C/\sqrt{6}$$
$$= 0.006\ °C$$

3.7 Permeation, Adsorption and Desorption

Permeation, adsorption and desorption refers to a continuous influx from or outgas to the humidity of the surrounding environment (such as the air within the laboratory) through small leaks or semi-permeable surfaces through the walls, fittings, valves, and dead spaces within the system. Although somewhat difficult to accurately quantify, instrument comparison has shown that these permeation affects start to become noticeable at frost point temperatures below approximately –60 °C with the greatest negative impact at the lowest frost point values. In the case of this generator, permeation affects are due to permeation of water vapor from the high ambient room conditions, through the tubing, fittings, or valves, into the dry gas stream output of the generator. Permeation tends to increase the frost point temperature of the generated gas stream. It is estimated that permeation tends to increase the concentration of water vapor in the gas stream independent of saturation temperature, saturation pressure, and test pressure. However the affect of this permeation is most noticeable when running at the lowest frost points (where the concentration of water vapor in the gas is also very low), and at low flow rates. By increasing the flow rate of the generated gas, while assuming a constant permeation rate, the affect of that permeation is minimized. Like wise, if the gas being generated is of higher concentration (i.e., warmer frost point), then the affect of added water vapor from permeation is reduced. While the nominal frost point value being generated may be very low, it is recommended that the highest flow rate possible be used for the low frost point conditions to minimize the affect of permeation. This analysis assumes that the generator is run at the highest possible flow rate. Even with the high flow rate, permeations impacts the generation of low frost point values. This permeation uncertainty is again very small and very difficult to isolate and measure outright, making it difficult to accurately quantify. Because of this, the same instrument comparison described in section 3.4 was also used to identify the uncertainty caused by permeation. Permeation leads more to an uncorrected bias than to a random variation in output, resulting in an offset during the instrument comparison tests. The follow table shows the estimated permeation uncertainty bias deduced by the instrument comparison data.

Table 6. Permeation, absorption and desorption uncertainty bias, u_{bias}

Nominal [°C]	bias [°C FP]
-95	0.14
-90	0.1
-80	0.05
-70	0.02
-60	0.003
-50	0

Because permeation leads more to an uncorrected bias than to a random variation in output it will be treated slightly different in the analysis. Uncertainty associated with uncorrected bias will be algebraically added to the expanded uncertainty rather than statistically included in combined uncertainty.

4. Combined Standard Uncertainty

The combined standard uncertainty, u_c, is obtained by statistical combination of the individual uncertainty components of pressure, temperature, and others, each multiplied by their associated sensitivity coefficients. Statistical combination is performed in accordance with the following:

$$u_c^2 = u_{c1}^2 + u_{c2}^2 + \ldots + u_{cn}^2$$

where $u_{c1}, u_{c2}, \ldots u_{cn}$ are individual components of uncertainty each multiplied by their respective sensitivity coefficients

The following tables reflect the standard uncertainty components and the combined standard uncertainty at various frost and dew point temperatures at a variety of saturation pressures and temperatures.

Table 7. Combined Uncertainty at 10 °C Dew Point

Combined Uncertainty at 10°C Dew Point						
			Ts =	10.00	*Ts* =	17.00
			Ps =	101.33	*Ps* =	160.19
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.148	**0.012**	0.148	**0.012**
Sat Pressure <345	uP_s	0.084	0.148	**0.012**	0.094	**0.008**
Sat Pressure >345		0.366				
Sat Temp	uT_s	0.047	1.000	**0.047**	0.946	**0.044**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.051**		**0.048**

Table 8. Combined Uncertainty at 0 °C Dew Point

Combined Uncertainty at 0°C Dew Point								
			Ts =	0.00	*Ts* =	10.00	*Ts* =	17.00
			Ps =	101.33	*Ps* =	204.24	*Ps* =	323.42
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.136	**0.011**	0.136	**0.011**	0.136	**0.011**
Sat Pressure <345	uP_s	0.084	0.136	**0.011**	0.067	**0.006**	0.042	**0.004**
Sat Pressure >345		0.366						
Sat Temp	uT_s	0.047	1.000	**0.047**	0.922	**0.043**	0.873	**0.041**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.051**		**0.046**		**0.044**

Table 9. Combined Uncertainty at -10 °C Frost Point

Combined Uncertainty at -10°C Frost Point

Source	Name	Assigned Uncertainty	*Ts =* -10.00		*Ts =* 0.00		*Ts =* 5.08		*Ts =* 5.08		*Ts =* 10.00		*Ts =* 17.00	
			Ps = 101.33		*Ps =* 239.37		*Ps =* 344.74		*Ps =* 344.74		*Ps =* 484.44		*Ps =* 770.59	
			Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.111	**0.009**	0.111	**0.009**	0.111	**0.009**	0.111	**0.009**	0.111	**0.009**	0.111	**0.009**
Sat Pressure <345	uP_s	0.084	0.111	**0.009**	0.047	**0.004**	0.032	**0.003**						
Sat Pressure >345		0.366							0.032	**0.012**	0.023	**0.008**	0.014	**0.005**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.927	**0.043**	0.785	**0.037**	0.785	**0.037**	0.755	**0.035**	0.714	**0.033**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.050**		**0.046**		**0.039**		**0.041**		**0.039**		**0.036**

Table 10. Combined Uncertainty at -20 °C Frost Point

Combined Uncertainty at -20°C Frost Point

Source	Name	Assigned Uncertainty	*Ts =* -20.00		*Ts =* -10.00		*Ts =* -6.66		*Ts =* -6.66		*Ts =* 0.00		*Ts =* 10.00		*Ts =* 16.91	
			Ps = 101.33		*Ps =* 256.50		*Ps =* 344.74		*Ps =* 344.74		*Ps =* 610.31		*Ps =* 1249.0		*Ps =* 2000.0	
			Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.103	**0.009**	0.103	**0.009**	0.103	**0.009**	0.103	**0.009**	0.103	**0.009**	0.103	**0.009**	0.103	**0.009**
Sat Pressure <345	uP_s	0.084	0.103	**0.009**	0.040	**0.003**	0.030	**0.003**								
Sat Pressure >345		0.366							0.030	**0.011**	0.017	**0.006**	0.008	**0.003**	0.005	**0.002**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.924	**0.043**	0.901	**0.042**	0.901	**0.042**	0.857	**0.040**	0.696	**0.033**	0.657	**0.031**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.049**		**0.045**		**0.044**		**0.046**		**0.043**		**0.035**		**0.034**

Table 11. Combined Uncertainty at -30 °C Frost Point

Combined Uncertainty at -30°C Frost Point																
			Ts =	-30.00	*Ts* =	-20.00	*Ts* =	-17.73	*Ts* =	-17.73	*Ts* =	-10.00	*Ts* =	0.00	*Ts* =	1.96
			Ps =	101.33	*Ps* =	277.21	*Ps* =	344.74	*Ps* =	344.74	*Ps* =	708.82	*Ps* =	1723.9	*Ps* =	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.095	**0.008**	0.095	**0.008**	0.095	**0.008**	0.095	**0.008**	0.095	**0.008**	0.095	**0.008**	0.095	**0.008**
Sat Pressure <345	uP_s	0.084	0.095	**0.008**	0.034	**0.003**	0.027	**0.002**								
Sat Pressure >345		0.366							0.027	**0.010**	0.013	**0.005**	0.005	**0.002**	0.004	**0.002**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.922	**0.043**	0.905	**0.042**	0.905	**0.042**	0.852	**0.040**	0.787	**0.037**	0.682	**0.032**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.049**		**0.045**		**0.044**		**0.045**		**0.042**		**0.039**		**0.034**

Table 12. Combined Uncertainty at -40 °C Frost Point

Combined Uncertainty at -40°C Frost Point														
			Ts =	-40.00	*Ts* =	-30.00	*Ts* =	-28.76	*Ts* =	-28.76	*Ts* =	-20.00	*Ts* =	-11.10
			Ps =	101.33	*Ps* =	302.60	*Ps* =	344.74	*Ps* =	344.74	*Ps* =	839.95	*Ps* =	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.087	**0.007**	0.087	**0.007**	0.087	**0.007**	0.087	**0.007**	0.087	**0.007**	0.087	**0.007**
Sat Pressure <345	uP_s	0.084	0.087	**0.007**	0.029	**0.002**	0.025	**0.002**						
Sat Pressure >345		0.366							0.025	**0.009**	0.010	**0.004**	0.004	**0.001**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.919	**0.043**	0.910	**0.043**	0.910	**0.043**	0.846	**0.040**	0.786	**0.037**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.049**		**0.045**		**0.044**		**0.045**		**0.042**		**0.039**

Table 13. Combined Uncertainty at -50 °C Frost Point

Combined Uncertainty at -50°C Frost Point														
			Ts =	-50.00	*Ts =*	-40.00	*Ts =*	-39.73	*Ts =*	-39.73	*Ts =*	-30.00	*Ts =*	-23.76
			Ps =	101.33	*Ps =*	334.27	*Ps =*	344.74	*Ps =*	344.74	*Ps =*	1020.1	*Ps =*	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.080	**0.007**	0.080	**0.007**	0.080	**0.007**	0.080	**0.007**	0.080	**0.007**	0.080	**0.007**
Sat Pressure <345	uP_s	0.084	0.080	**0.007**	0.024	**0.002**	0.023	**0.002**						
Sat Pressure >345		0.366							0.023	**0.008**	0.008	**0.003**	0.003	**0.001**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.916	**0.043**	0.913	**0.043**	0.913	**0.043**	0.839	**0.039**	0.795	**0.037**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.049**		**0.045**		**0.044**		**0.045**		**0.041**		**0.039**

Table 14. Combined Uncertainty at -60 °C Frost Point

Combined Uncertainty at -60°C Frost Point														
			Ts =	-60.00	*Ts =*	-50.66	*Ts =*	-50.66	*Ts =*	-50.00	*Ts =*	-40.00	*Ts =*	-36.28
			Ps =	101.33	*Ps =*	344.74	*Ps =*	344.74	*Ps =*	374.63	*Ps =*	1277.8	*Ps =*	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.073	**0.006**	0.073	**0.006**	0.073	**0.006**	0.073	**0.006**	0.073	**0.006**	0.073	**0.006**
Sat Pressure <345	uP_s	0.084	0.073	**0.006**	0.021	**0.002**								
Sat Pressure >345		0.366					0.021	**0.008**	0.019	**0.007**	0.005	**0.002**	0.003	**0.001**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.917	**0.043**	0.917	**0.043**	0.912	**0.043**	0.832	**0.039**	0.804	**0.038**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.049**		**0.045**		**0.045**		**0.045**		**0.041**		**0.039**

Table 15. Combined Uncertainty at -70 °C Frost Point

Combined Uncertainty at -70°C Frost Point														
			Ts =	-70.00	*Ts =*	-61.54	*Ts =*	-61.54	*Ts =*	-60.00	*Ts =*	-50.00	*Ts =*	-48.66
			Ps =	101.33	*Ps =*	344.74	*Ps =*	344.74	*Ps =*	427.27	*Ps =*	1667.3	*Ps =*	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.066	**0.006**	0.066	**0.006**	0.066	**0.006**	0.066	**0.006**	0.066	**0.006**	0.066	**0.006**
Sat Pressure <345	uP_s	0.084	0.066	**0.006**	0.019	**0.002**								
Sat Pressure >345		0.366					0.019	**0.007**	0.015	**0.006**	0.004	**0.001**	0.003	**0.001**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.921	**0.043**	0.921	**0.043**	0.908	**0.043**	0.824	**0.039**	0.811	**0.038**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.049**		**0.045**		**0.045**		**0.044**		**0.040**		**0.040**

Table 16. Combined Uncertainty at -80 °C Frost Point

Combined Uncertainty at -80°C Frost Point												
			Ts =	-80.00	*Ts =*	-72.37	*Ts =*	-72.37	*Ts =*	-70.00	*Ts =*	-60.91
			Ps =	101.33	*Ps =*	344.74	*Ps =*	344.74	*Ps =*	498.10	*Ps =*	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.060	**0.005**	0.060	**0.005**	0.060	**0.005**	0.060	**0.005**	0.060	**0.005**
Sat Pressure <345	uP_s	0.084	0.060	**0.005**	0.017	**0.001**						
Sat Pressure >345		0.366					0.017	**0.006**	0.012	**0.004**	0.002	**0.001**
Sat Temp	uT_s	0.047	1.000	**0.047**	0.925	**0.043**	0.925	**0.043**	0.903	**0.042**	0.821	**0.038**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.048**		**0.045**		**0.045**		**0.044**		**0.040**

Table 17. Combined Uncertainty at -90 °C Frost Point

Combined Uncertainty at -90°C Frost Point								
			Ts =	-80.00	*Ts =*	-75.00	*Ts =*	-73.04
			Ps =	597.03	*Ps =*	1414.7	*Ps =*	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.054	**0.005**	0.054	**0.005**	0.054	**0.005**
Sat Pressure <345	uP_s	0.084						
Sat Pressure >345		0.366	0.009	**0.003**	0.003	**0.001**	0.001	**0.000**
Sat Temp	uT_s	0.047	0.897	**0.042**	0.849	**0.040**	0.830	**0.039**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.044**		**0.041**		**0.040**

Table 18. Combined Uncertainty at -95 °C Frost Point

Combined Uncertainty at -95°C Frost Point						
			Ts =	-80.00	*Ts =*	-79.05
			Ps =	1668.9	*Ps =*	2000.0
Source	Name	Assigned Uncertainty	Sens Coef	Std Uncert	Sens Coef	Std Uncert
Test Pressure	uP_c	0.084	0.051	**0.004**	0.051	**0.004**
Sat Pressure <345	uP_s	0.084				
Sat Pressure >345		0.366	0.003	**0.001**	0.001	**0.000**
Sat Temp	uT_s	0.047	0.844	**0.040**	0.833	**0.039**
Vapor Pressure	uVp	0.003	1.000	**0.003**	1.000	**0.003**
Enhancement Factor	uEF	0.006	1.000	**0.006**	1.000	**0.006**
Saturation Efficiency	uSE	0.007	1.000	**0.007**	1.000	**0.007**
combined	u_c			**0.041**		**0.040**

5 Expanded Uncertainty

Utilizing a coverage factor k=2, the expanded uncertainty, U, is computed using the formula

$$U = (k * u_c) + \text{bias}$$

Where k = the coverage factor (2 for 95% confidence level)

u_c = uncertainties at specific saturation temperatures and saturation pressures. u_c is obtained from the tables listed in section 4.

bias = any uncorrected bias associated with the nominal frost point or at a specific saturation temperature and saturation pressure. Values of bias are obtained from the table in section 3.7

Like the combined uncertainties listed in the tables of section 4, there are two separate calculations of expanded uncertainty at the saturation pressure of 344.74 kPa for many of the nominal frost point values. This saturation pressure is at the switch point between use of the low-pressure transducer and use of the high-pressure transducer. At this saturation pressure, either transducer may be in use. If the low range transducer is in use, the associated expanded uncertainty is lower. If the high range transducer has switched in, then the expanded uncertainty will be larger in value. There is a step change (or more precisely, a discontinuity) in the associated expanded uncertainty at this possible pressure switching point.

The expanded uncertainty values are listed in table 19. Expanded uncertainty values are shown in °C frost point (°C dew point for nominal generated values above 0 °C).

Table 19. Expanded Uncertainty (k=2)

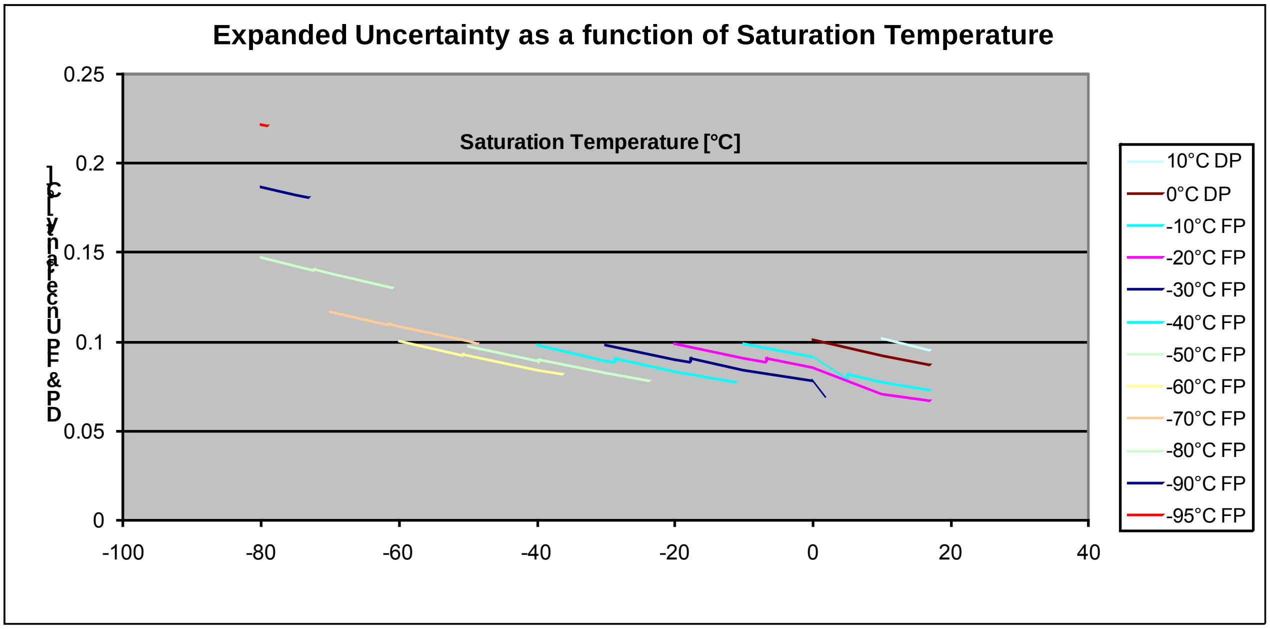
Nominal FP [°C]	Ts [°C]	Ps [kPa]	U
-95	-80	1668.93	*0.22195841*
	-79.05	2000	0.22098739
-90	-80	597.029	*0.18710805*
	-75	1414.74	0.18250425
	-73.04	2000	0.18074429
-80	-80	101.325	0.14735384
	-72.37	344.74	0.1400313
	-72.37	344.74	*0.14086376*
	-70	498.099	0.13839375
	-60.91	2000	0.13058154
-70	-70	101.325	0.1170872
	-61.54	344.74	0.10933371
	-61.54	344.74	*0.11036138*
	-60	427.266	0.1087497
	-50	1667.27	0.10050131
	-48.66	2000	0.09937391
-60	-60	101.325	0.10035821
	-50.66	344.74	0.09213931
	-50.66	344.74	*0.09337108*
	-50	374.63	0.09270654
	-40	1277.76	0.08448185
	-36.28	2000	0.08185657
-50	-50	101.325	0.09766832
	-40	334.27	0.08916669
	-39.73	344.74	0.08897108
	-39.73	344.74	*0.09046345*
	-30	1020.07	0.08240079
	-23.76	2000	0.07826117
-40	-40	101.325	0.09802079
	-30	302.6	0.08970781
	-28.76	344.74	0.08883015
	-28.76	344.74	*0.0906215*
	-20	839.95	0.08332251
	-11.1	2000	0.07767192
-30	-30	101.325	0.09842438
	-20	277.21	0.0902515
	-17.73	344.74	0.08869417
	-17.73	344.74	*0.0908113*
	-10	708.82	0.08429512
	0	1723.92	0.07809934
	1.96	2000	0.06886193
-20	-20	101.325	0.09887788
	-10	256.5	0.09079135
	-6.66	344.74	0.08860088
	-6.66	344.74	*0.09110239*
	0	610.31	0.08535581
	10	1248.98	0.07051384
	16.91	2000	0.06704467
-10	-10	101.325	0.09939101
	0	239.37	0.09139796
	5.08	344.74	0.07863997
	5.08	344.74	*0.08190908*
	10	484.44	0.07758465
	17	770.59	0.07292033
0	0	101.325	*0.10109039*
	10	204.24	0.09226586
	17	323.42	0.08747145
10	10	101.325	*0.10202521*
	17	160.19	0.09550903

Notes:

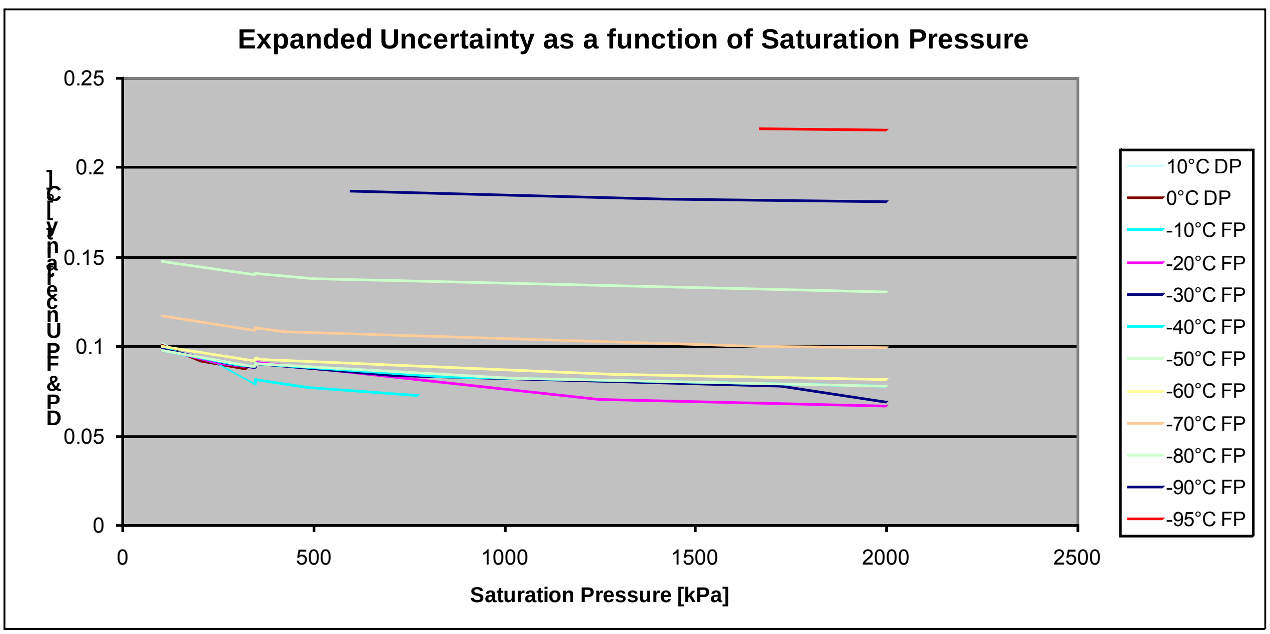
1. 10 °C nominal frost point listed above is actually 10 °C dew point. Expanded uncertainties at this nominal dew point are also listed in °C dew point.

2. Largest uncertainty at each nominal frost/dew point is indicated above in italic print.

Graph 1: The following graph indicates the expanded uncertainties at various saturation pressures. Each nominal frost/dew point value is shown separately.



Graph 2: The following graph indicates the expanded uncertainties at various saturation temperatures. Each nominal frost/dew point value is shown separately.

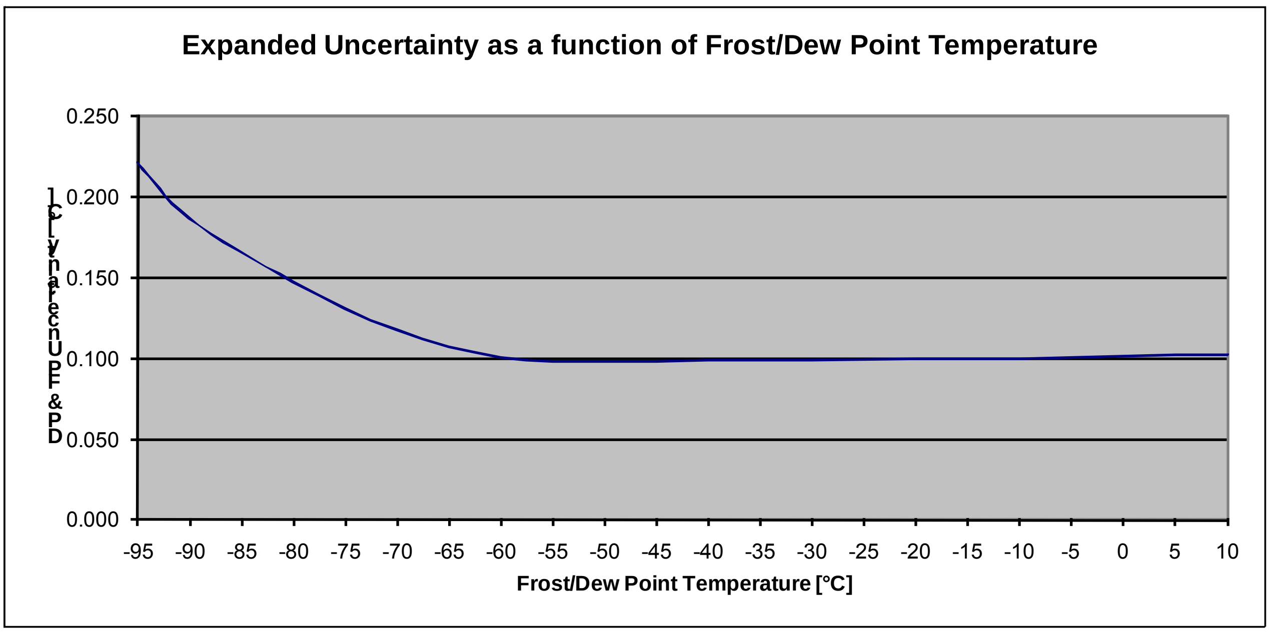


Note that at each frost/dew point value, there is only small variation in the uncertainty at the various saturation temperature and saturation pressure combinations. In order to obtain uncertainty as a direct function of frost/dew point temperature, independent of the saturation temperature and pressure combinations, the maximum uncertainty value at each nominal frost/dew point value is chosen. The result of using the maximum value of expanded uncertainty at each nominal frost/dew point is illustrated in the following table.

Table 20. Maximum Expanded Uncertainty (k=2)

Nominal FP [°C]	U
-95	0.222
-90	0.187
-80	0.147
-70	0.117
-60	0.100
-50	0.098
-40	0.098
-30	0.098
-20	0.099
-10	0.099
0	0.101
10	0.102

Graph 3: This graph, from the above table, depicts the maximum uncertainty at each of the nominal frost/dew point temperatures.



6 Summary

Expanded uncertainty of the low humidity generator in terms of dew point and frost point is relatively constant between +10 and about –75 °C, varying only gradually over that entire range. For values below approximately –75 °C, the affect of permeation tends to dominate the uncertainty.

It is also worth noting that the uncertainty at any given frost or dew point temperature is relatively constant regardless of the specific combinations of saturation temperature and saturation pressure. This allows the system to adequately generate frost or dew point temperatures without much regard for the specific saturation temperature-pressure combination chosen.

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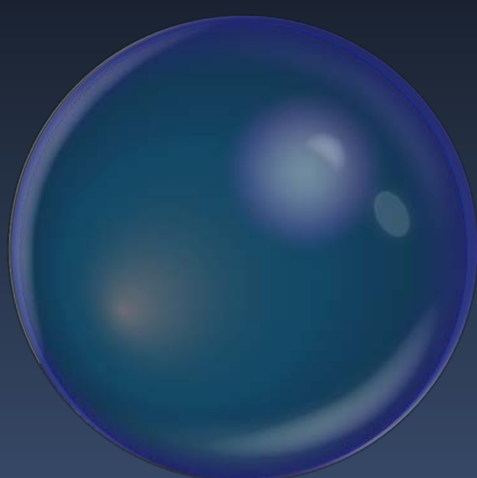
Basic Humidity Definitions



Basic Humidity Definitions

Speaker/Author
Bill Swartz
Thunder Scientific Corp
623 Wyoming SE
Albuquerque, NM 87123
phone: 505-265-8701
fax: 505-266-6203
e-mail: bill@thunderscientific.com

Abstract

This Workshop presents a tutorial on the different measures of humidity and their relationships to each other. Air, or moist air as it is called, consists of water vapor and the remaining dry air. The tutorial starts with the conceptually simplest measures of humidity involving masses and volumes of water vapor, dry air, and moist air. Although simple conceptually, these measures are impractical to implement. After introducing the Ideal Gas Law, saturation vapor pressure and enhancement factors are presented. Then other measures of humidity are introduced involving the moles of the components of moist air. Finally, the NIST two-temperature two-pressure humidity generator is discussed.

Mixing Ratio by Weight

From Wexler[1], in a given sample of moist air, the Mixing Ratio by Weight is

$$\frac{\text{mass of water vapor}}{\text{mass of dry air}}$$

The Mixing Ratio by Weight of a moist air sample does not change when either temperature or pressure changes. The Mixing Ratio by Weight is related to the Mixing Ratio by Volume through the Molecular Weights of water vapor and dry air.

$$\text{mixing ratio by weight} = \frac{\text{Mv}}{\text{Ma}} \times \text{mixing ratio by volume}$$

Specific Humidity

From Wexler[1], in a given sample of moist air, the Specific Humidity is

$$\frac{\text{mass of water vapor}}{\text{total mass of moist air}}$$

The Specific Humidity of a moist air sample does not change when either temperature or pressure changes. In terms of Partial Pressures and Molecular Weights,

$$\begin{aligned}
&\text{specific humidity} \\
&= \frac{\text{mass of water vapor}}{\text{mass of water vapor} + \text{mass of dry air}} \\
&= \frac{\text{Mv} \times \text{moles of water vapor}}{\text{Mv} \times \text{moles of water vapor} + \text{Ma} \times \text{moles of dry air}} \\
&= \frac{\text{Mv} \times \text{partial pressure of water vapor}}{\text{Mv} \times \text{partial pressure of water vapor} + \text{Ma} \times \text{partial pressure of dry air}} \\
&= \frac{\text{Mv} \times \text{e}}{\text{Mv} \times \text{e} + \text{Ma} \times (\text{P} - \text{e})}
\end{aligned}$$

Percent by Weight

From Wexler[(1)], the Percent by Weight of a given sample of moist air is the Specific Humidity expressed as a percent,

$$\frac{\text{mass of water vapor}}{\text{total mass of moist air}} \times 100$$

The Percent by Weight of a moist air sample does not change when either temperature or pressure changes. The Percent by Weight is related to the Percent by Volume through the Molecular Weights of water vapor and dry air.

$$\frac{1}{\text{percent by weight}} - 1 = \frac{\text{Ma}}{\text{Mv}}\left(\frac{1}{\text{percent by volume}} - 1\right)$$

Parts per Million by Weight

The Parts per Million by Weight of a given sample of moist air is the Mixing Ratio by Weight expressed in parts per million,

$$\frac{\text{mass of water vapor}}{\text{mass of dry air}} \times 10^6$$

The Parts per Million by Weight of a moist air sample does not change when either temperature or pressure changes. The Parts per Million by Weight is related to the Parts per Million by Volume through the Molecular Weights of water vapor and dry air.

$$\text{parts per million by weight} = \frac{\text{Mv}}{\text{Ma}} \times \text{parts per million by volume}$$

Grains per Pound

In a given sample of moist air, the Grains per Pound is

$$\begin{aligned} \text{grains/lb} &= \frac{\text{grains of water vapor}}{\text{lb of moist air}} \\ &= \frac{\text{lb of water vapor}}{\text{lb of moist air}} \times 7000 \frac{\text{grains}}{\text{lb}} \end{aligned}$$

The Grains per Pound of a moist air sample does not change when either temperature or pressure changes. With the usual identification of weight and mass,

$$\text{grains/lb} = \text{specific humidity} \times 7000$$

Absolute Humidity, Vapor Concentration, Water Vapor Density

From Wexler[(1)], Absolute Humidity, Vapor Concentration, and Water Vapor Density are all the same. In a moist air sample, they all equal

$$\frac{\text{mass of water vapor}}{\text{volume of sample}}$$

Using the Ideal Gas Law, the Molecular Weight of water vapor, and Partial Pressures,

$$\text{absolute humidity} = \frac{\text{Mv} \times \text{e}}{\text{R} \times \text{T}}$$

where

Mv = molecular weight of water vapor

e = partial pressure of water vapor

R = Universal Gas Constant

T = Temperature in Kelvin

Dry Air Density

In a given sample of moist air, the Dry Air Density is

$$\frac{\text{mass of dry air}}{\text{volume of sample}}$$

Using the Ideal Gas Law, the Molecular Weight of dry air, and Partial Pressures,

$$\text{dry air density} = \frac{Ma(P - e)}{R \times T}$$

where

Ma = molecular weight of dry air

P = total pressure of sample

e = partial pressure of water vapor

R = Universal Gas Constant

T = Temperature in Kelvin

Moist Air Density

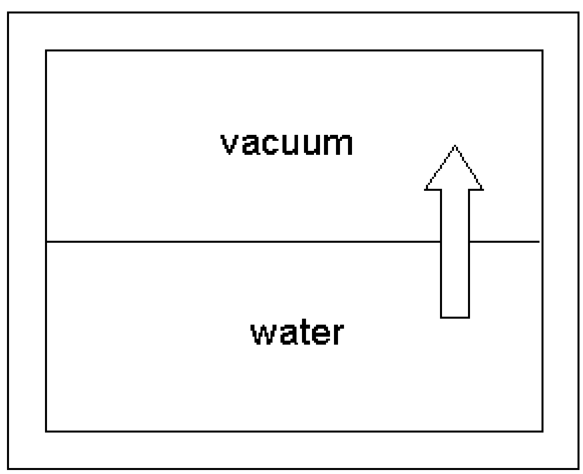
In a given sample of moist air, the Moist Air Density is

$$\frac{\text{mass of moist air}}{\text{volume of sample}}$$

Moist Air Density is the sum of Dry Air Density and Absolute Humidity.

$$\text{absolute humidity} + \text{dry air density} = \text{moist air density}$$

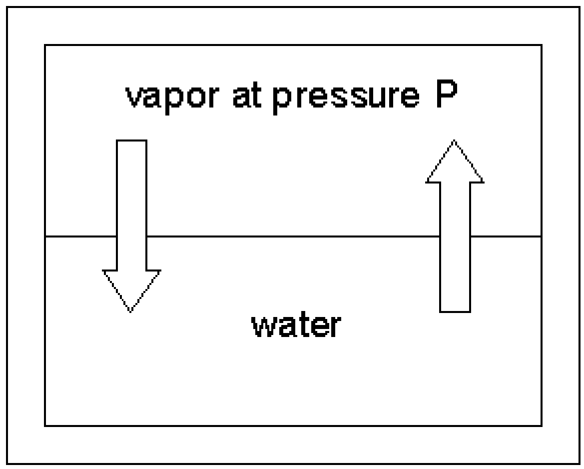
Saturation Vapor Pressure



chamber at temperature T

Saturation Vapor Pressure is a function of temperature. Sonntag[(2)] is one source of approximating formulas. The function can best be described by a lab setup. Imagine a chamber whose temperature T can be controlled. The chamber is partially filled with water. Initially, the remaining space is a vacuum. The pressure P of the space over the water can be measured. At a fixed temperature, water molecules will leave the water and enter the space above at a fixed rate.

As water molecules accumulate over the liquid water, the pressure there will increase, and molecules will re-enter the liquid at an increasing rate. Finally, water molecules will be entering and leaving the liquid at the same rate, giving equilibrium and a constant pressure P over the water.



chamber at temperature T

The equilibrium pressure P is the Saturation Vapor Pressure at temperature T.

$$e_S(T) = P$$

At temperatures above freezing, equilibrium is achieved over water. At temperatures below freezing, equilibrium can be achieved either over water or over ice. This gives two functions,

$$e_{WS}(T) \quad \text{and} \quad e_{IS}(T)$$

The two functions agree for values of T above freezing. They differ for values of T below freezing.

Mole

A Mole is like a dozen or a gross, only much larger. From Wexler[1],

$$1 \text{ mole} = 6.023 \times 10^{26}$$

Molecular Weight

The Molecular Weight of a substance is the weight in grams of a mole of that substance. From Wexler[(1)],

$$\begin{aligned}\text{water vapor:} &\quad \text{Mv} = 18.02 \text{ gm/mole}\\ \text{dry air:} &\quad \text{Ma} = 28.9645 \text{ gm/mole}\end{aligned}$$

Mole Fraction

From Wexler[(1)], the Mole Fraction of a component gas present in a mixture of gases is

$$\frac{\text{moles of component gas}}{\text{total moles of mixture}}$$

From Dalton's Law,

$$\text{mole fraction} = \frac{\text{partial pressure of component gas}}{\text{total pressure of mixture}}$$

Universal Gas Constant

The Universal Gas Constant is denoted R. From Wexler[(1)],

$$R = 8.31432 \frac{\text{Joules}}{\text{mole} \times \text{Kelvin}}$$

Ideal Gas Law

The Ideal Gas Law relates the pressure, volume, moles, and temperature of a sample of ideal gas.

$$\begin{aligned}&P \times V = n \times R \times T\\ &\text{where}\\ &\quad P = \text{pressure (Pascals)}\\ &\quad V = \text{volume}\left(m^3\right)\\ &\quad n = \text{moles}\\ &\quad R = \text{Universal Gas Constant}\left(\frac{\text{Joules}}{\text{mole} \times \text{Kelvin}}\right)\\ &\quad T = \text{temperature (Kelvin)}\end{aligned}$$

Dalton's Law

Dalton's Law states that the Ideal Gas Law applies to mixtures of ideal gases. Two ideal gases, n1 moles of the first gas and n2 moles of the second, both at the same temperature, must each individually satisfy the Ideal Gas Law.

$$P_1 \times V_1 = n_1 \times R \times T$$
$$P_2 \times V_2 = n_2 \times R \times T$$

If the two gases are combined to form a mixture of n moles, again at the same temperature, then

$$P \times V = n \times R \times T$$
$$n = n_1 + n_2$$

Since temperatures are all the same, the Mole Fraction of the first gas in the mixture must satisfy

$$\text{mole fraction} = \frac{n_1}{n} = \frac{P_1 \times V_1}{P \times V}$$

If, in addition to the temperatures, all three pressures are the same, then

$$\text{mole fraction} = \frac{n_1}{n} = \frac{V_1}{V}$$

If, in addition to the temperatures, all three volumes are the same, then

$$\text{mole fraction} = \frac{n_1}{n} = \frac{P_1}{P}$$

Similarly for the Mole Fraction of the second gas. Dalton's Law also applies to mixtures of more than two gases.

Partial Pressures

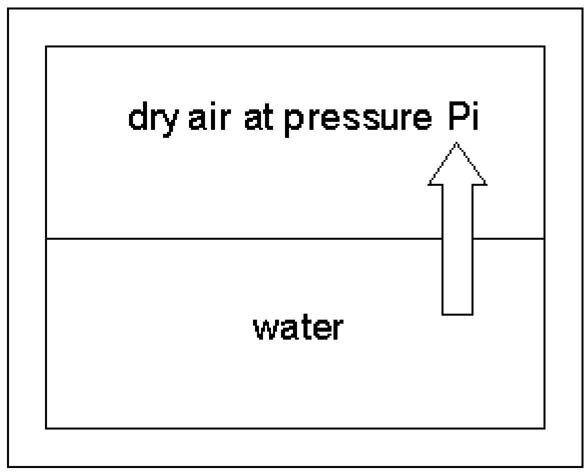
The pressure P of a mixture of gases is the sum of the Partial Pressures of the component gases.

$$P = P_1 + P_2 + P_3 + \cdots$$

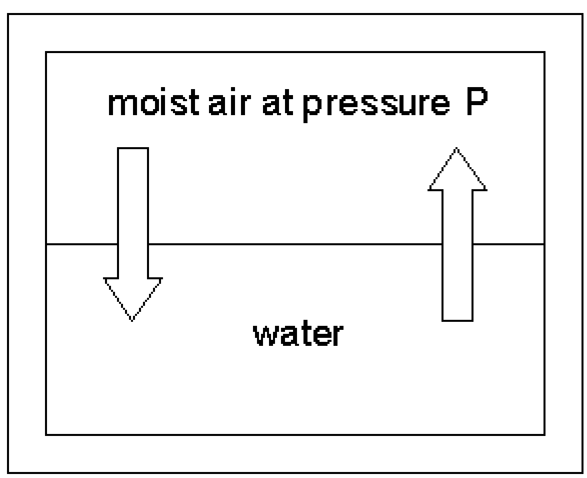
Where Pi, the Partial Pressure of the ith component gas, is the pressure that would be measured if the volume were occupied by only the ith component gas. This is a consequence Dalton's Law. In a sample of moist air, the total pressure is denoted P, and the Partial Pressure of the water vapor present is denoted e. Then the Partial Pressure of the dry air in the sample must be (P-e).

Enhanced Saturation Vapor Pressure

Enhanced Saturation Vapor Pressure, or Saturation Vapor Pressure of Moist Air, is a function of both pressure and temperature. Like Saturation Vapor Pressure, it can best be described by a lab setup. Imagine a chamber whose temperature T and pressure can be controlled. The chamber is partially filled with water. The pressure of the space over the water can be measured. Initially, the remaining space is filled with dry air at initial pressure Pi. At a fixed temperature, water molecules will leave the water and enter the dry air above at a fixed rate.



chamber at temperature T



chamber at temperature T

As water molecules accumulate over the liquid water, the pressure there will increase, and molecules will re-enter the liquid at an increasing rate. Finally, water molecules will be entering and leaving the liquid at the same rate, giving equilibrium and a constant final pressure P over the water.

The Enhanced Saturation Vapor Pressure (Saturation Vapor Pressure of Moist Air) at temperature T and pressure P is the Partial Pressure due to the water vapor in the moist air.

$$e'_s(T,P) = P - P_i$$

At temperatures above freezing, equilibrium is achieved over water. At temperatures below freezing, equilibrium can be achieved either over water or over ice. This gives two functions, as with Saturation Vapor Pressure,

$$e'_{ws}(T,P) \quad \text{and} \quad e'_{is}(T,P)$$

The two functions agree for values of T above freezing. They differ for values of T below freezing.

Enhancement Factor

The Enhancement Factor at temperature T and pressure P is the ratio of the Enhanced Saturation Vapor Pressure to the Saturation Vapor Pressure. One source of approximating formulas is Greenspan[3].

$$f(T,P) = \frac{e'_s(T,P)}{e_s(T)}$$

or

$$f(T,P) \times e_s(T) = e'_s(T,P)$$

As with Enhanced Saturation Vapor Pressure and Saturation Vapor Pressure, there are really two functions, one for equilibrium over water, the other for equilibrium over ice.

$$f_w(T,P) \quad \text{and} \quad f_i(T,P)$$

Dew Point

The Dew Point of a moist air sample is the temperature to which the sample must be cooled to reach saturation with respect to liquid water. Using the Enhanced Saturation Vapor Pressure function, given

$$P = \text{total pressure of moist air sample}$$
$$e = \text{partial pressure of water vapor in the sample}$$

solve

$$e = e'_{ws}\left(T_d, P\right)$$

for

$$T_d = \text{dew point temperature}$$

The Enhanced Saturation Vapor Pressure at the Dew Point temperature and pressure P is the same as the Partial Pressure of the water vapor in the moist air sample at the current temperature T and the same pressure P.

Frost Point

The Frost Point of a moist air sample is the temperature to which the sample must be cooled to reach saturation with respect to ice. Using the Enhanced Saturation Vapor Pressure function,

given

$$P = \text{total pressure of moist air sample}$$
$$e = \text{partial pressure of water vapor in the sample}$$

solve

$$e = e'_{is}\left(T_f, P\right)$$

for

$$T_f = \text{frost point temperature}$$

The Enhanced Saturation Vapor Pressure at the Frost Point temperature and pressure P is the same as the Partial Pressure of the water vapor in the moist air sample at the current temperature T and the same pressure P.

Mixing Ratio by Volume

The Mixing Ratio by Volume of a moist air sample is really the Mixing Ratio by Moles.

$$\begin{aligned}
&\text{mixing ratio by volume} \\
&\quad = \frac{\text{moles of water vapor}}{\text{moles of dry air}} \\
&\quad = \frac{\text{partial pressure of water vapor}}{\text{partial pressure of dry air}} \\
&\quad = \frac{e}{P - e}
\end{aligned}$$

Here P is the pressure of the moist air sample and e is the Partial Pressure of the water vapor present in the sample. The Mixing Ratio by Volume of a moist air sample does not change when either temperature or pressure changes. The Mixing Ratio by Volume is related to the Mixing Ratio by Weight through the Molecular Weights of water vapor and dry air.

$$\text{mixing ratio by weight} = \frac{Mv}{Ma} \times \text{mixing ratio by volume}$$

Dry Air Mole Fraction

The Dry Air Mole Fraction Wexler[1] in a moist air sample is

$$\begin{aligned}
&\text{dry air mole fraction} \\
&= \frac{\text{moles of dry air}}{\text{moles of moist air}} \\
&= \frac{\text{partial pressure of dry air}}{\text{total pressure of moist air}} \\
&= \frac{P - e}{P}
\end{aligned}$$

Here P is the pressure of the moist air sample and e is the Partial Pressure of the water vapor present in the sample. The Dry Air Mole Fraction of a moist air sample does not change when either temperature or pressure changes. Dry Air Mole Fraction and Vapor Mole Fraction are related by

$$\text{dry air mole fraction} + \text{vapor mole fraction} = 1$$

Vapor Mole Fraction

The Vapor Mole Fraction Wexler[1] in a moist air sample is

$$\begin{aligned}
&\text{vapor mole fraction} \\
&= \frac{\text{moles of water vapor}}{\text{moles of moist air}} \\
&= \frac{\text{partial pressure of water vapor}}{\text{total pressure of moist air}} \\
&= \frac{e}{P}
\end{aligned}$$

Here P is the pressure of the moist air sample and e is the Partial Pressure of the water vapor present in the sample. The Vapor Mole Fraction of a moist air sample does not change when either temperature or pressure changes. Vapor Mole Fraction and Dry Air Mole Fraction are related by

$$\text{dry air mole fraction} + \text{vapor mole fraction} = 1$$

Percent by Volume

Percent by Volume Wexler[1] is really Percent by Moles. It is the Vapor Mole Fraction expressed as a percent. In a moist air sample,

$$\begin{aligned}
&\text{percent by volume} \\
&= \frac{\text{moles of water vapor}}{\text{moles of moist air}} \times 100 \\
&= \frac{\text{partial pressure of water vapor}}{\text{total pressure of moist air}} \times 100 \\
&= \frac{e}{P} \times 100 \\
&= \text{vapor mole fraction} \times 100
\end{aligned}$$

Here P is the pressure of the moist air sample and e is the Partial Pressure of the water vapor present in the sample. The Percent by Volume of a moist air sample does not change when either temperature or pressure changes. The Percent by Volume is related to the Percent by Weight through the Molecular Weights of water vapor and dry air.

$$\text{percent by volume} = \frac{Mv}{Ma} \times \text{percent by weight}$$

Parts Per Million by Volume

Parts Per Million by Volume is really Parts Per Million by Moles. It is the Mixing Ratio by Volume expressed in parts per million. In a moist air sample,

$$\begin{aligned}
&\text{parts per million by volume} \\
&= \frac{\text{moles of water vapor}}{\text{moles of dry air}} \times 10^6 \\
&= \frac{\text{partial pressure of water vapor}}{\text{partial pressure of dry air}} \times 10^6 \\
&= \frac{e}{P - e} \times 10^6 \\
&= \text{mixing ratio by volume} \times 10^6
\end{aligned}$$

Here P is the pressure of the moist air sample and e is the Partial Pressure of the water vapor present in the sample. The Parts Per Million by Volume of a moist air sample does not change when either temperature or pressure changes. The Parts per Million by Volume is related to the Parts per Million by Weight through the Molecular Weights of water vapor and dry air.

$$\text{parts per million by volume} = \frac{\text{Ma}}{\text{Mv}} \times \text{parts per million by weight}$$

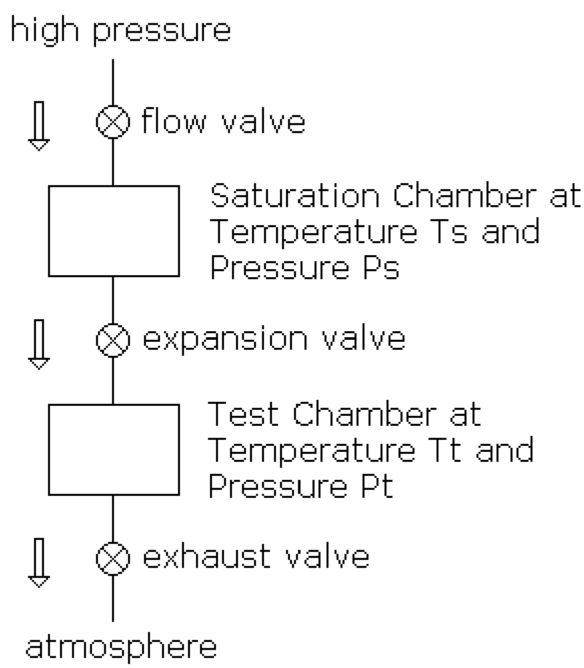
Relative Humidity

Relative Humidity is the ratio of the amount of water vapor in a sample to the maximum amount possible at the same temperature and pressure. It is expressed as a percent. In a sample of moist air at pressure P and temperature T, using the Enhanced Saturation Vapor Pressure,

$$\begin{aligned}&\text{relative humidity}\\ &= \frac{\text{partial pressure of water vapor}}{\{\text{enhanced saturation vapor pressure}} \times 100\\ &= \frac{e}{e_s'(T,P)} \times 100\end{aligned}$$

Two-Pressure/Two-Temperature Humidity Generator

A Two-Pressure/Two-Temperature Humidity Generator has a chamber, the Test Chamber, in which the humidity can be set to a predetermined value.



The pressures and temperatures in both chambers can be controlled. If the valve is not present at the Test Chamber exhaust, then Test Pressure is atmospheric pressure. If the apparatus is such that both temperatures are always the same, it is called a Two-Pressure Generator. If the apparatus is such that both pressures are always the same, it is called a Two-Temperature

Generator. The air in the Saturation Chamber is saturated. That is, Partial Pressure of the water vapor in the Saturation Chamber is

$$e'_s(Ts, Ps)$$

The same moist air flows through both chambers, so the Vapor Mole Fractions must be the same.

$$\frac{e'_s(Ts, Ps)}{Ps} = \frac{e}{Pt}$$

Where e is the Partial Pressure of the water vapor in the Test Chamber. If it is desired to achieve a specified Relative Humidity in the Test Chamber at a given test temperature and pressure, then the saturation temperature and pressure can be adjusted accordingly. Using the equation for Relative Humidity to get rid of the variable e gives

$$e'_s(Ts, Ps) \times \frac{Pt}{Ps} = \frac{\%RH}{100} \times e'_s(Tt, Pt)$$

For a desired Relative Humidity, test temperature, and test pressure, suitable values of saturation pressure and temperature must be found to satisfy this equation.

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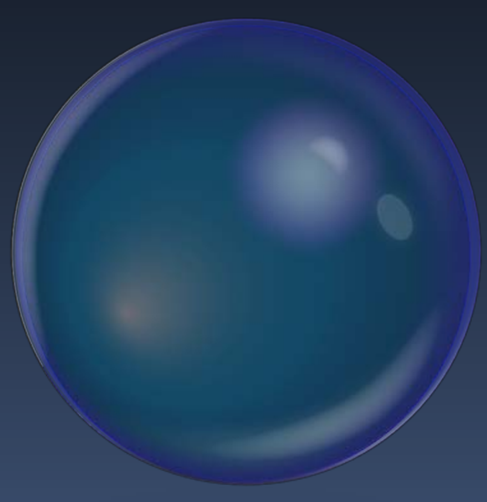
Sonntag, D. "Important New Values of the Physical Constants of 1986, Vapour Pressure Formulations based on the ITS-90, and Psychrometer Formulae", Z. Meteorol., 1990, 40, pages 340-344.

Greenspan, L. "Functional Equations for the Enhancement Factors for CO2-Free Moist Air", Journal of Research of the National Bureau of Standards - A. Physics and Chemistry, Vol. 80A, No. 1, January - February 1976; page 41, equation 3; page 42, equations 5 and 6, Table 1.

Solving Humidity Calibration Challenges In Today's Metrology Lab

- NCSL Paper



Solving Humidity Calibration Challenges in Today's Metrology Lab

Author/Speaker: Jeff Bennewitz
Thunder Scientific Corporation
623 Wyoming Blvd. SE
Albuquerque, NM 87123 U.S.A.
Email: jeff@thunderscientific.com
Phone: (505) 265-8701; FAX: (505) 266-6203

Introduction/Abstract

Two-pressure humidity calibration technology has long been the recognized standard for on site instrumentation calibration, test and verification. The goal of this paper is to provide a tool to help you as a metrologist take advantage of the benefits of this technology so you will be able to apply the information to your daily laboratory applications. This paper will cover the operation and benefits of modern two-pressure humidity calibration systems, explain how you calibrate them, provide some sample applications and a brief history of the technology.

The Importance of Reliable Humidity Calibration in Your Lab

Whatever your industry, your end product is only as good as the calibration it has received. Therefore, the equipment used to calibrate or test the limits of your end product must be first, a reliable, proven technology and, second, be presented in equipment that is easy to use and also easy to validate for optimum operation parameters; preferably at your laboratory, in-house.

Whether you are calibrating transducers, tools for silicon wafer production, controlling comfort levels in HVAC systems or are involved with the tight humidity management required in manufacturing moisture sensitive products such as film, semiconductors, and pharmaceuticals, you are stepping up your demand for increased reliability and accuracy in humidity measurements. Today, calibration systems are required to both obtain and maintain a 4:1 accuracy ratio. To accomplish this, humidity and dew point hygrometers must be calibrated against a source of humidity at a stable test temperature.

The most accurate and reliable method of continuous humidity generation in use today for the range of ~5-98% RH is based on the "two-pressure" principle originally developed by the National Institute of Standards and Technology (NIST). The two-pressure principle is used in the most accurate on-site calibration and verification systems. These are mobile and self-contained, with an integral humidity generator that is capable of simulating a wide range of temperature/humidity values with sufficient accuracy and consistency to maintain strict 4:1 calibration ratios. In a 10-year track record, this has been the only system of its kind that can meet tight tolerance requirements. It is still the primary standard of choice for humidity calibration.

Understanding How the Two-Pressure RH Generator Operates

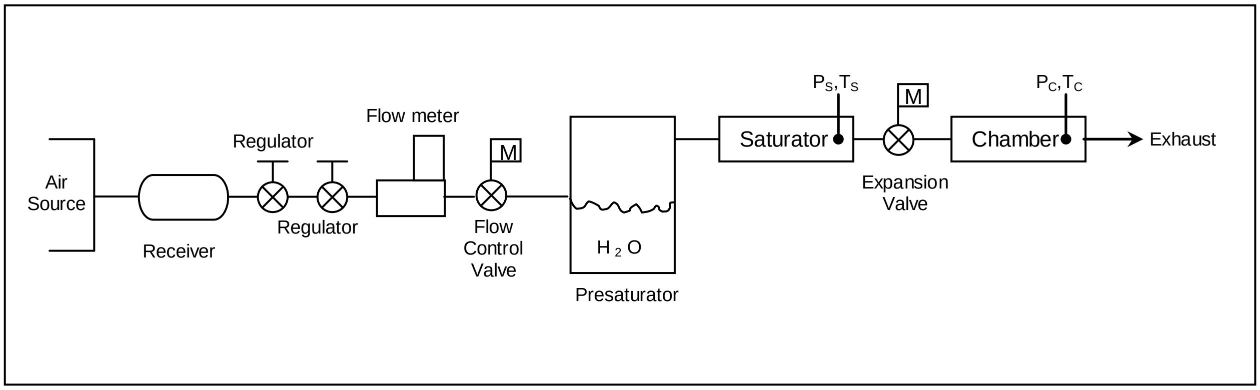


Figure 1. Operational flow schematic.

The best way to describe operation is by dissecting the actual operational technology of an established system. We will use the Model 2500 two-pressure humidity generator for this purpose. Model 2500 is a portable, self-contained, two-pressure humidity generator that uses compressed air of up to 175 psia (1207) kPa) provided by either a portable oil-free air compressor or other equal source and directed to a receiver. The air then passes through dual regulators, achieving regulated pressure of ~ 150 psia (1034 kPa) and is directed to a flow control valve. Although the humidity does not depend on flow rate, the flow control valve is adjusted to set an airflow rate of 2-20 slpm through the system. The flow rate is monitored by a flowmeter installed directly upstream of the flow control valve. Then the gas flows to a presaturator.

The presaturator is a vertical cylinder partially filled with water that is maintained at a temperature ~ 10-20 °C above the desired final saturation temperature. Air entering the presaturator first flows through a coil of tubing immersed in the water, a configuration that forms a heat exchanger. As the air passes through the immersed tubing, it is warmed to “at or near” the presaturator temperature. Air exiting the tubing is deflected downward onto the water surface in a manner that causes circular airflow within the presaturator. While passing through the presaturator, the gas continues to warm to the presaturator temperature and becomes saturated with water vapor to nearly 100% RH.

Next, the gas flows to the saturator, which is a fluid-encapsulated heat exchanger maintained at the desired final saturation temperature. As the nearly 100% RH gas travels through the saturator, it begins to cool, forcing it to the dew point or 100% saturation condition. The gas continues to cool to the desired saturation temperature, causing moisture in excess of 100% to condense out. Forcing condensation ensures 100% humidified gas. The saturation pressure P_S and the saturation temperature T_S of the gas are measured at the point of final saturation before the gas stream exits the saturator.

The gas then enters the expansion valve, where it is expanded to a lower pressure, which is the test chamber pressure P_C. Because adiabatically expanding gas naturally cools, the valve is heated to keep the gas above dew point while it expands to the lower pressure. If the gas or the valve were allowed to cool to or below the dew point, condensation could occur at the valve and alter the humidity content of the gas. The cooling effects of expansion, while mostly counteracted by the heated valve, are fully compensated by flowing the gas through a small post-expansion heat exchanger. This allows it to reestablish thermal equilibrium with the fluid surrounding the chamber and saturator before it enters the test chamber. The final pressure P_C and temperature T_C of the gas are measured within the test chamber. The test chamber exhausts to atmospheric or ambient pressure and so is very near ambient pressure.

A computer/controller embedded in the system controls the entire humidity generation process: temperatures, pressures, and system flow rate. It also handles keypad input, parameter measurements and calculations, data display, and external I/Os to link to peripherals such as additional computers or printers.

Temperature Control: Every humidity generating process requires precise temperature control (setpoint) and good temperature stability. These are ensured by digital computer control of the temperature of a circulating water/glycol mix that jackets the saturator and test chamber areas of the generator. The saturation and chamber temperatures are governed by the temperature of this medium. The computer will keep this at any value from 0 to 70° through the use of PID (proportional – integral – derivative) algorithms.

The PID algorithm compares the measured temperature to the desired setpoint temperature to calculate the temperature difference (proportional); the current rate at which the temperature is changing (derivative); and the accumulation of the temperature difference over time (integral). Each calculation is effectively multiplied by an associated weighing factor, and the three are then added together to provide a numerical value. This value, termed the PID output, represents the percentage of the total available heating or cooling capacity required at a given time. The value is recalculated approximately once each second and is used to time-proportion heating and cooling devices. In short, the PID output determines how long to apply power to a specific heating element or how long to open a refrigeration or coolant solenoid during each one – second interval.

The fluid medium is heated by time-proportioning an immersion heater in the fluid circulation path. Cooling, while also time-proportioned, is accomplished by injecting a high-pressure liquid refrigerant (R-134) from a closed compressor system into a heat-exchanging evaporator in the fluid circulation path. Using PID algorithms for temperature control allows the fluid temperature to be maintained at the desired saturation temperature with a stability to within ~ 0.02 °C over the operating range.

The presaturator temperature is similarly controlled by time proportioning. Heating is done by applying power to an immersion heater and is bucked merely by the ambient temperature of the incoming air.

Pressure Control: A computer controlled electromechanical valve assembly controls the pressure control of the saturator. Saturator pressure is measured at ~1 sps and is used as data in PID algorithms similar to those employed in temperature control. The algorithms determine the required valve position.

Conventional two-pressure generators incorporate three separate pressure transducers: one for chamber pressure, one for lower saturator pressures and one for higher saturator pressures. The problem with this approach is that at low saturator pressures, a dual-drift effect (offset drift between the chamber and low-pressure saturator transducer) can cause significant errors in the calculated RH.

The generator discussed here solves this problem by using only two transducers: one low-range for chamber and lower saturator pressures, and one high-range transducer for higher saturator pressures. The low- range transducer is time-shared between the chamber and the saturator when it is operating at lower pressures. Time-sharing of the low-range transducer eliminates the dual drift often seen when using separate chamber and low-range saturator pressure transducers.

Validating Your Calibration System

It goes without saying that the system you use to calibrate and test your product must, itself, be in prime parameters. The easier it is to validate for optimum operation and calibrate to strict specifications, if necessary, the more value is added to the equipment. If a system must be sent outside for recalibration or a specialist must be brought in, it adds to your cost of ownership.

The ability to validate and recalibrate laboratory equipment in-house should be high on any metrologist's priority list. It is not cost effective to have equipment in your lab that you can't calibrate yourself.

Simple Calibration

Since proper calibration of the temperature and pressure transducers ultimately determines the accuracy of a two-pressure humidity generator, a good portable system employs an integral programmatic calibration scheme. Rather than removing transducers from the system and sending them to a laboratory for calibration, you just take the entire system to your lab or bring the appropriate pressure and temperature standards to the system. You calibrate the transducers while they're electrically connected to the humidity generator. This "in the system, as a system" approach helps eliminate systemic errors that might be induced by other calibration methods. Because all calibration is performed mathematically by the computer, manual adjustments are not needed.

Calibration is performed on each transducer by the computer solution of the coefficients ZERO, SPAN, and LIN to this simple quadratic formula:

$$Y = LIN \bullet X^2 + SPAN \bullet X + ZERO \quad (2)$$

Where:

X = raw count (or output) of the A/D converter while measuring the transducer.

Y = desired value (the standard or reference transducer reading) for the transducer being measured.

The coefficients ZERO, SPAN and LIN are found by applying three separate, distinct, and stable references to each transducer and then solving the resulting mathematical system of three equations with three unknowns. Since all the measurements and calculations are performed automatically by the embedded computer, you only need to provide the three known stable references: one near the low end, one near the center, and one near the upper end of each transducer's intended range.

For a low-end temperature calibration point, you take the temperature bath to a low point, ensure stability, and then enter the value indicated by a standard or reference thermometer. Repeat this procedure at two additional points: near the middle and upper ends of the temperature range.

When the three reference points have been applied, the new coefficients for each probe are displayed. The coefficients for each transducer are stored in the system's nonvolatile memory until the next calibration is performed.

You should run intercomparison validations on a regular basis. These tests must compare your equipment against a chilled-mirror hygrometer, psychrometer or other known consistent humidity-measuring device. Use a variety of humidity values and temperatures for this validation, and keep current control charts on all the results to ensure they are within the estimated uncertainty. Make sure this includes both normal trends and abnormalities because this is the most accurate record you will have to indicate if temperature probes or pressure transducers start to drift from their required calibration. Drifts will also warn you of other operational faults, including water or heating problems in the presaturator or saturator. Water contamination, leaks in the gas path and numerous other issues will also show up clearly if you have a basic tracking schedule established to easily pinpoint whenever points or out-of-spec drifts occur. This should be part of your overall preventative statistical process control (SPC) to catch abnormalities before they can cause problems.

Field Trials and Test Data

A relative humidity uncertainty analysis[2] was conducted on the Model 2500 portable, self-contained, two-pressure humidity generator used for data in this presentation, following NIST Guideline 1297. The relative humidity in a two-pressure humidity generator of this type is determined from the measurements of temperature and pressure only using the following formula:

$RH = P_c / P_s * E_s / E_c * F_s / F_c * 100$ where P_c = Chamber Pressure,

P_s = Saturation Pressure,

E_s = Saturation Vapor Pressure at Saturation Temperature,

E_c = Saturation Vapor Pressure at Chamber Temperature,

F_s = Enhancement Factor at Saturation Temperature and Pressure,

F_c = Enhancement Factor at Chamber Temperature and Pressure,

100 = nominal saturator efficiency.

The study was concerned with analysis of the above ratios separately and then combined, within four specific categories of uncertainty: contribution from the pressure ratio term P_c / P_s contribution from the vapor pressure ratio term E_s / E_c; contribution from the enhancement factor ratio F_s / F_c, and contribution from saturator efficiency.

This analysis was conducted to validate the accuracy of performance using temperature and pressure uncertainty calculations. These uncertainty calculations of the Model 2500 two-pressure humidity generator served to establish that the system is within the manufacturer's stated specification and that traceability can be established with NIST. Full analytical details of the study are available on the Thunder Scientific Corporation website.[3]

Application Examples

Portable two-pressure humidity generation calibration equipment is in heavy use in pharmaceutical, aerospace and semiconductor applications. It's also the number one system used by sensor manufacturers. US Air Force, US Army and US Navy metrology or "PMEL" laboratories use this type of equipment for humidity calibration standards. The technology is also found in regular use in pharmaceutical production, semiconductor clean room monitoring sensors, medical laboratories and in HVAC environmental controls. The range of applications is extremely wide. The following are only a few examples:

Chart Recorders: A test chamber can typically accommodate two standard size hygrothermographs. Temperature/humidity data can be run at virtually any points desired and for any length of time. Charts can then be compared with the printer output for analysis and adjustment. Once adjusted, either the same points or others may be run again for verification. Onsite calibration eliminates rough handling and exposure of the recorder to undesirable temperature/humidity extremes. In addition, because temperature is variable (even while maintaining constant RH), temperature sensitivity is easily determined.

Chilled Mirror Hygrometers: A humidity computer can be used to determine either the saturation pressure or RH necessary to generate a specific dew or frost point. First, the generator is run to allow most of the gas to exhaust to ambient through the chamber vent. A small sample is drawn through the side port of the chamber, next through the chilled mirror head, and then through an adjustable valve or flowmeter. Because the chamber naturally operates at a very small positive pressure, flow rates of ~ 1 slpm through the chilled mirror head are easily obtainable. Flow rate through the head may also be adjusted by partially restricting the chamber exhaust.

The entire head can also placed in the chamber with the head exhausting to ambient. The slight positive chamber pressure forces a small flow of gas through the head. Again, a flowmeter should be used downstream, with flow adjustments made either with a valve or by partial restriction of normal chamber exhaust.

Environmental Testing: A portable two-pressure humidity calibrator can serve as a test bed for evaluation and R&D of humidity and/or temperature-sensitive products such as; plastics, composites, film, tobacco, blood gas analysis, pharmaceuticals, soil hydrology, consumables, electronics, and optics. Depending on the temperature and humidity being generated, the system may operate continuously from hours to months; the only limiting factor is typically the 1-gallon capacity of the internal distilled water reservoir used by the presaturator to humidify the air stream. With continuous generation of a nominal 50% RH at 21 °C, the reservoir will last about two weeks between refills. When generating dry cold gas, e.g., 10% RH at 0 °C, continuous operation is possible for more than nine months.

Portable two-pressure humidity generation calibration equipment is also a valuable tool in humidity sensor research and development, hygrometer calibration, certification, and humidity sensor original calibration certification. This technology is also critical in special long-term environmental exposure tests for weather related calibration of atmospheric and land-based humidity sensor instrument packages and for large volume humidity sensor calibration production.

History of Two-Pressure Humidity Calibration

Older methods of on-site verification were accomplished by either using a portable transfer instrument or conducting full laboratory calibration. But, using a portable transfer instrument that is first calibrated in the laboratory and then moved to the site for comparison only provides a best ratio of comparison around 1:1. Although more accurate, full laboratory calibration using humidity-generating equipment requires removing the instrument to be calibrated from its installation, transporting it to the lab and then replacing it after it is fully calibrated, which can cause a wide range of measurement errors.

Over the years, the National Bureau of Standards (now the National Institute of Standards and Technology – NIST) worked to solve these problems by developing a two-pressure humidity calibration technology that would eventually become the commercial device seen today in most labs worldwide. The origin of the commercial device in use today was a device developed in 1948 by E.R. Weaver and R. Riley at the National Bureau of Standards that utilized pressure rather than water vapor for the generation and control of humidity.

The Riley-Weaver two-pressure device utilized air or some other gas saturated with water vapor at a high pressure and then expanded to a lower pressure while kept at a constant temperature. The resulting relative humidity of the gas was the ratio of the lower pressure to the higher pressure.

That method was improved upon by A. Wexler and R.D. Daniels, also at NBS, in 1951 with the addition of temperature control. Using temperature control enabled Wexler and Daniels to saturate a gas with water vapor at a given temperature and then raise the temperature to a higher value, allowing the measurement of temperature and pressure to be used to determine the relative humidity.

The combined two-pressure, two-temperature humidity generators in commercial production today allow independent control of temperature and pressure. This device has been identified by NCSL International as an intrinsic/derived standard since the value of relative humidity is a mathematical relationship based on pressure and temperature.

The basic principle for the NIST Mark 2 humidity generator involves saturating a continuous stream of air or some other gas with water vapor at a given pressure and temperature. The saturated gas then flows through an expansion valve where it is expanded to a lower pressure. The resulting RH of the gas is then determined by the formula:

$$\%RH = \frac{f_W(P_S,T_S)}{f_W(P_C,T_C)} \bullet \frac{e_W(T_S)}{e_W(T_C)} \bullet \frac{P_C}{P_S} \bullet 100 \quad (1)$$

where:
f_W = enhancement factor
e_W = saturation vapor pressure
P_S = saturation pressure
P_C = chamber pressure
T_S = saturation temperature
T_C = chamber temperature

The RH generated by the two-pressure principle only depends on the pressure and temperature of saturation and on the temperature after expansion. When these factors are measured and controlled it permits precise control of the generated humidity. Also, because the humidity generated is based solely on the fundamental principles of temperature and pressure, no humidity sensors are needed to measure it.

NCSL International has published a Recommended Practice for Intrinsic/Derived Standards (RISP-5) on the two-pressure, two-temperature humidity generator.[1]

Conclusion
Increasingly stringent testing and calibration will be needed to meet the requirements of new technologies being developed for a wide range of instrumentation and devices — some yet unknown. As a metrologist, you must always stay one step ahead of these requirements for your specific industry. Today, you can be assured that at least in the area of humidity calibration and testing, the technology will allow you to keep pace with your accelerating industry requirements.

Two-pressure humidity generation technology is proven and traceable to NIST standards and the portable equipment integrating the technology has been designed to meet the strict requirements of all laboratory humidity calibration applications. Better yet, this equipment can be easily validated and recalibrated in your lab without calling in your original outside vendor. When calibration is done, you can be satisfied that your system will meet our toughest specification, just as it did when it was first delivered it to your lab.

This translates into ultimate reliability: the capability of modern portable two-pressure humidity generator/calibration systems to provide the highest standard for all laboratory calibrations on a continuing basis.

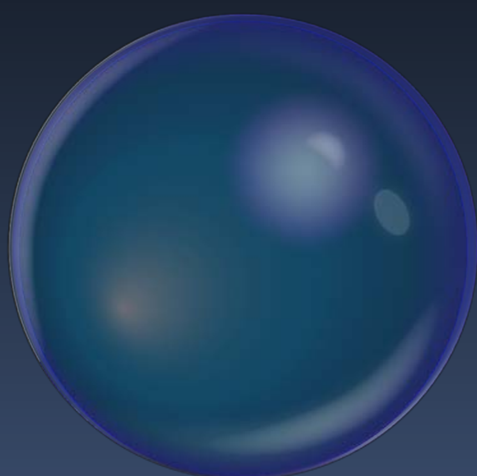
1 - RISP-5 is available from NCSL International, 1800 30th Street, Suite 305B, Boulder, CO 80301-1026, tel 303-440-3339, fax 303-440-3384. A full list of NCSLI Recommended Practices and other metrology training information is available at www.ncslinternational.org.

2 - Relative Humidity Uncertainty analysis of the Thunder Scientific Model 2500 Two-Pressure Humidity Generator, by Bob Hardy, Thunder Scientific Corporation, Albuquerque, NM, USA.

3 – Thunder Scientific Corporation website www.thunderscientific.com

ITS-90 Formulations

- For Vapor Pressure, Frostpoint, Temperature, Dewpoint, Temperature and Enhancement factors in the Range -100º to +100 ºC



ITS-90 FORMULATIONS FOR VAPOR PRESSURE, FROSTPOINT TEMPERATURE, DEWPOINT TEMPERATURE, AND ENHANCEMENT FACTORS IN THE RANGE –100 TO +100 C

Bob Hardy

Thunder Scientific Corporation, Albuquerque, NM, USA

Abstract: With the change in the temperature scale of ITS-90, new temperature dependent equations were required which predict saturation vapor pressure over water and ice, enhancement factor over water and ice, frostpoint temperature, and dewpoint temperature. Internationally recognized formulas based on the previous temperature scale, viewed as self-consistent data sets for vapor pressures and enhancement factors, were chosen as initial defining equations. These formulas, coupled with those defining the temperature difference between the two scales, were used to compute new data sets consistent with the temperature scale of ITS-90. These new data sets were then fitted to equations of the original form, yielding new ITS-90 compatible coefficients to the familiar vapor pressure and enhancement factor equations. In addition, the resulting vapor pressure equations were used to produce a set of inverse approximating equations to yield frostpoint and dewpoint temperatures when the vapor pressure is known. The resulting coefficients, equations, and the conversion methods that produced them are presented.

Keywords: ITS-90, saturation vapor pressure, enhancement factor, frostpoint, dewpoint

1 INTRODUCTION

Prior to establishment of the temperature scale of ITS-90, humidity related quantities were generally computed with respect to the IPTS-68 temperature scale, and continue to be in many cases even well after the adoption of ITS-90. With a maximum deviation between IPTS-68 and ITS-90 of only 26 mK over the range of –100 to +100°C, continued use of IPTS-68 equations does seem to have merit. For instance, when computing percent relative humidity (%RH), it is computed from a ratio of vapor pressures within relatively close proximity to one another. So the end results, when computed on one temperature scale versus the other, are of negligible difference. However, when the use of these ratios is not involved, and as humidity generation and measurement techniques become inherently more precise, the need arises for humidity parameters to be more closely matched to the new temperature scale.

While others have generated equations for vapor pressures and enhancements factors on ITS-90, the intent here is not to contradict or negate these prior works. Rather, the purpose is to augment those works with the addition of a consistent set of equations of the exact same form as the IPTS-68 originals, with equivalent useable ranges and comparable accuracies to their IPTS-68 counterparts. This process involved converting a series of ITS-90 temperatures to their IPTS-68 equivalents, computing vapor pressures and enhancement factors using existing IPTS-68 equations, then pairing the results with the original ITS-90 temperatures. The paired data was curve fit to equations of the IPTS-68 form to generate the corresponding ITS-90 coefficients. In addition to determining these new coefficients, new formulas used to predict frostpoint and dewpoint from vapor pressure were also generated.

2 TEMPERATURE CONVERSION BETWEEN ITS-90 AND IPTS-68

The defining equation chosen for conversion of temperatures between the ITS-90 and IPTS-68 scales was that of Rusby[1] . Depicted here as equation 1, it covers the range of –189 to +630°C, with a stated accuracy of approximately ±1.5 mK below 0°C and ±1 mK above 0°C.

$$t_{90} - t_{68} = \sum_{i=1}^{8} b_i (t_{90} / 630)^i \tag{1}$$

where t_{90} is temperature in °C on the ITS-90 scale
and t_{68} is temperature in °C on the IPTS-68 scale

with coefficients

b_1 = -0.148759
b_2 = -0.267408
b_3 = 1.080760
b_4 = 1.269056
b_5 = -4.089591
b_6 = -1.871251
b_7 = 7.438081
b_8 = -3.536296

3 SATURATION VAPOR PRESSURE

While there have been several vapor pressure equations written over the years on the IPTS-68 temperature scale, those of Wexler[2,3] have gained the largest international acceptance. In fact, many of the other equations written have been limited range simplifications based on the data from Wexler’s formulations. With the assumption that the Wexler equations are considered to be self-consistent data sets on the IPTS-68 temperature scale, his equations were chosen as the basis for conversion to ITS-90.

3.1 Saturation Vapor Pressure over Water

Wexler’s[2] equation 15 (shown here as equation 2) was utilized as the defining formula for saturation vapor pressure over water in the range of 0 to 100°C. Coupled with equation 1 above, 301 independent values of ITS-90 vapor pressures were computed from -100 to +200°C at 1 degree intervals. The data was then curve fit to Wexler’s formula to generate new coefficients consistent with the ITS-90 scale. Since it is a common practice to extrapolate Wexler’s formula beyond his intended limits of 0 to 100°C, note that extrapolation was also used in the generation of this new data set. The ITS-90 formulation will therefore exhibit comparable results when used in the extrapolated regions below 0 and above 100°C. Wexler’s original formulation and coefficients, along with the new coefficients computed for ITS-90 are

$$\ln e_s = \sum_{i=0}^{6} g_i T^{i-2} + g_7 \ln T \tag{2}$$

where e_s is the saturation vapor pressure, in Pa, over water in the pure phase
and T is the temperature in Kelvin

with Wexler's coefficients

$g_0 = -2.9912729\text{x}10^3$	
$g_1 = -6.0170128\text{x}10^3$	
$g_2 = 1.887643854\text{x}10^1$	
$g_3 = -2.8354721\text{x}10^{-2}$	
$g_4 = 1.7838301\text{x}10^{-5}$	
$g_5 = -8.4150417\text{x}10^{-10}$	
$g_6 = 4.4412543\text{x}10^{-13}$	
$g_7 = 2.858487$	

and for the new ITS-90 scale

$g_0 = -2.8365744\text{x}10^3$	
$g_1 = -6.028076559\text{x}10^3$	
$g_2 = 1.954263612\text{x}10^1$	
$g_3 = -2.737830188\text{x}10^{-2}$	
$g_4 = 1.6261698\text{x}10^{-5}$	
$g_5 = 7.0229056\text{x}10^{-10}$	
$g_6 = -1.8680009\text{x}10^{-13}$	
$g_7 = 2.7150305$	

Curve fit of the above equation with ITS-90 coefficients was performed using equal weighting of each of the data points. However, when rounding the coefficients to the resolution shown, slight graphical adjustment of g_2 and g_3 was required to constrain the vapor pressure at the triple point of water to 611.657 Pa while maintaining minimal error across the range. The maximum deviation of vapor pressures between Wexler's formulation (with proper adjustment of temperature to IPTS-68), and the ITS-90 formulation presented here, is within 0.05 ppm from –100 to 100°C. Since this is more than 2 orders of magnitude below Wexler's stated experimental uncertainties, his estimates of uncertainty remain applicable to this ITS-90 formulation.

3.2 Saturation Vapor Pressure over Ice

Wexler's[3] equation 54 (shown below as equation 3) was used as the defining formula for saturation vapor pressure over ice in the range of –100 to 0°C. Coupled with equation 1 given previously, 151 values of ITS-90 vapor pressures were computed from –149.99 to +0.01°C at 1 degree intervals. The data was then curve fit to Wexler's equation to generate new coefficients consistent with the ITS-90 scale. Wexler's original formulation and coefficients, along with the new coefficients computed for ITS-90 are

$$\ln e_s = \sum_{i=0}^{4} k_i T^{i-1} + k_5 \ln T \qquad (3)$$

where e_s is the saturation vapor pressure, in Pa, over ice in the pure phase
and T is the temperature in Kelvin

with Wexler's coefficients

$k_0 = -5.8653696\text{x}10^3$	
$k_1 = 2.224103300\text{x}10^1$	
$k_2 = 1.3749042\text{x}10^{-2}$	
$k_3 = -3.4031775\text{x}10^{-5}$	
$k_4 = 2.6967687\text{x}10^{-8}$	
$k_5 = 6.918651\text{x}10^{-1}$	

and for the new ITS-90 scale

$k_0 = -5.8666426\text{x}10^3$	
$k_1 = 2.232870244\text{x}10^1$	
$k_2 = 1.39387003\text{x}10^{-2}$	
$k_3 = -3.4262402\text{x}10^{-5}$	
$k_4 = 2.7040955\text{x}10^{-8}$	
$k_5 = 6.7063522\text{x}10^{-1}$	

Curve fit of this equation with ITS-90 coefficients was constrained at the triple point of water by proportional over-weighting of that data point. After rounding of coefficients to the resolution shown, some slight graphical adjustment of k_1 through k_3 was required to obtain a flat error trend, while maintaining the vapor pressure relative to the triple point of water at 611.657 Pa. The maximum deviation of vapor pressures between Wexler's formulation (with proper adjustment of temperature to IPTS-68), and the ITS-90 formulation presented here, is within 0.3 ppm from –100 to 0.01°C. Since this is several orders of magnitude below

Wexler's originally stated estimates of uncertainty, his estimates remain applicable to this ITS-90 formulation.

4 DEWPOINT AND FROSTPOINT FORMULAS

Equations 2 and 3 are easily solved for vapor pressures at any given temperature, namely the dewpoint and frostpoint temperatures. However, if vapor pressure is known with temperature as the unknown desired quantity, the solution immediately becomes complicated and must be solved by iteration. For ease of computation, inverse equations have been developed to yield temperature at a given vapor pressure.

4.1 Dewpoint Formula

Equation 2 with ITS-90 coefficients was used to create a table of 201 data points from –100 to 100°C, at 1 degree intervals. The data was equally weighted and fit to equation 4. Agreement between this dewpoint formula and equation 2 with ITS-90 coefficients is better than 0.3 mK over the range of –100 to 100°C.

$$T_d = \frac{\sum_{i=0}^{3} c_i (\ln e_s)^i}{\sum_{i=0}^{3} d_i (\ln e_s)^i} \tag{4}$$

where T_d is dewpoint temperature in Kelvin
and e_s is the saturation vapor pressure in Pa

with coefficients
c_0 = 2.0798233x10^{2}
c_1 = -2.0156028x10^{1}
c_2 = 4.6778925x10^{-1}
c_3 = -9.2288067x10^{-6}
d_0 = 1
d_1 = -1.3319669x10^{-1}
d_2 = 5.6577518x10^{-3}
d_3 = -7.5172865x10^{-5}

4.2 Frostpoint Formula

Equation 3 with ITS-90 coefficients was used to create a table of 161 data points from –150 to 10°C, at 1 degree intervals. The data was equally weighted and fit to equation 5. Agreement between this dewpoint formula and equation 3 with ITS-90 coefficients is better than 0.1 mK over the range of –150 to 0.01°C.

$$T_f = \frac{\sum_{i=0}^{2} c_i (\ln e_s)^i}{\sum_{i=0}^{3} d_i (\ln e_s)^i} \tag{5}$$

where T_f is frostpoint temperature in Kelvin
and e_s is the saturation vapor pressure in Pa

with coefficients
c_0 = 2.1257969x10^{2}
c_1 = -1.0264612x10^{1}
c_2 = 1.4354796x10^{-1}
d_0 = 1
d_1 = -8.2871619x10^{-2}
d_2 = 2.3540411x10^{-3}
d_3 = -2.4363951x10^{-5}

5 ENHANCEMENT FACTORS

The effective saturation vapor pressure over water or ice in the presence of other gases differs from the ideal saturation vapor pressures given in equations 2 and 3. The effective saturation vapor pressure is related to the ideal by

$$e_s^{'} = e_s f \qquad (6)$$

where $e_s^{'}$ is the 'effective' saturation vapor pressure
e_s is the ideal saturation vapor pressure (as given in equation 2 or 3)
and f is the enhancement factor.

Hyland[4] gave numeric values and an extensive equation for prediction of the enhancement factor at various temperature and pressure conditions. Greenspan[5] utilized the data and equations of Hyland to fit the enhancement factor to a more simplified equation, the form of which is due to Goff and Gratch[6] given as

$$f = \exp\left[a\left(1-\frac{e_s}{P}\right)+b\left(\frac{P}{e_s}-1\right)\right] \qquad (7)$$

with $$a = \sum_{i=0}^{3} A_i t^i \qquad (8)$$

and $$\ln b = \sum_{i=0}^{3} B_i t^i \qquad (9)$$

where f is the enhancement factor
e_s is the ideal saturation vapor pressure (as given in equation 2 or 3)
P is pressure in the same units as e_s
t is temperature in °C
and A_i, B_i depend on temperature range and are given in the following sections.

5.1 Enhancement Factors for Water, -50 to 100°C

Greenspan used two equations to obtain enhancement factors for water. One applies for temperatures between –50 and 0°C, while the other is used from 0 to 100°C. Equations 8 and 9 with the appropriate IPTS-68 coefficients for the temperature range, coupled with equation 1, were used to generate *a* and *b* data sets for each of the ranges at 1 degree increments. The original coefficients, along with those for ITS-90 in °C and K, are listed below.

For Water –50 to 0°C

IPTS-68 [°C]	ITS-90 [°C]	ITS-90 [K]
$A_0 = 3.62183 \times 10^{-4}$	$A_0 = 3.62183 \times 10^{-4}$	$A_0 = -5.5898101 \times 10^{-2}$
$A_1 = 2.60553 \times 10^{-5}$	$A_1 = 2.6061244 \times 10^{-5}$	$A_1 = 6.7140389 \times 10^{-4}$
$A_2 = 3.86501 \times 10^{-7}$	$A_2 = 3.8667770 \times 10^{-7}$	$A_2 = -2.7492721 \times 10^{-6}$
$A_3 = 3.82449 \times 10^{-9}$	$A_3 = 3.8268958 \times 10^{-9}$	$A_3 = 3.8268958 \times 10^{-9}$
$B_0 = -1.07604 \times 10^{1}$	$B_0 = -1.07604 \times 10^{1}$	$B_0 = -8.1985393 \times 10^{1}$
$B_1 = 6.39725 \times 10^{-2}$	$B_1 = 6.3987441 \times 10^{-2}$	$B_1 = 5.8230823 \times 10^{-1}$
$B_2 = -2.63416 \times 10^{-4}$	$B_2 = -2.6351566 \times 10^{-4}$	$B_2 = -1.6340527 \times 10^{-3}$
$B_3 = 1.67254 \times 10^{-6}$	$B_3 = 1.6725084 \times 10^{-6}$	$B_3 = 1.6725084 \times 10^{-6}$

For Water 0 to 100°C

IPTS-68 [°C]	ITS-90 [°C]	ITS-90 [K]
$A_0 = 3.53624 \times 10^{-4}$	$A_0 = 3.53624 \times 10^{-4}$	$A_0 = -1.6302041 \times 10^{-1}$
$A_1 = 2.93228 \times 10^{-5}$	$A_1 = 2.9328363 \times 10^{-5}$	$A_1 = 1.8071570 \times 10^{-3}$
$A_2 = 2.61474 \times 10^{-7}$	$A_2 = 2.6168979 \times 10^{-7}$	$A_2 = -6.7703064 \times 10^{-6}$
$A_3 = 8.57538 \times 10^{-9}$	$A_3 = 8.5813609 \times 10^{-9}$	$A_3 = 8.5813609 \times 10^{-9}$
$B_0 = -1.07588 \times 10^{1}$	$B_0 = -1.07588 \times 10^{1}$	$B_0 = -5.9890467 \times 10^{1}$
$B_1 = 6.32529 \times 10^{-2}$	$B_1 = 6.3268134 \times 10^{-2}$	$B_1 = 3.4378043 \times 10^{-1}$
$B_2 = -2.53591 \times 10^{-4}$	$B_2 = -2.5368934 \times 10^{-4}$	$B_2 = -7.7326396 \times 10^{-4}$
$B_3 = 6.33784 \times 10^{-7}$	$B_3 = 6.3405286 \times 10^{-7}$	$B_3 = 6.3405286 \times 10^{-7}$

5.2 Enhancement Factors for Ice, -100 to 0°C

To obtain enhancement factors for ice in the range of –100 to 0°C, Greenspan provided 3 equations. One was for the temperature range –100 to –50°C, one was for the temperature range –50 to 0°C, and the final one was somewhat less accurate than the other two but covers the entire range of –100 to 0°C. Again, equations 8 and 9, coupled with equation 1 and the appropriate IPTS-68 coefficients, were used to generate three sets of ITS-90 data for *a* and *b* at 1 degree intervals. The original coefficients, along with those for ITS-90 in °C and K, are listed below.

For Ice –100 to 0°C

IPTS-68 [°C]	ITS-90 [°C]	ITS-90 [K]
$A_0 = 3.64449 \times 10^{-4}$	$A_0 = 3.64449 \times 10^{-4}$	$A_0 = -6.0190570 \times 10^{-2}$
$A_1 = 2.93631 \times 10^{-5}$	$A_1 = 2.9367585 \times 10^{-5}$	$A_1 = 7.3984060 \times 10^{-4}$
$A_2 = 4.88635 \times 10^{-7}$	$A_2 = 4.8874766 \times 10^{-7}$	$A_2 = -3.0897838 \times 10^{-6}$
$A_3 = 4.36543 \times 10^{-9}$	$A_3 = 4.3669918 \times 10^{-9}$	$A_3 = 4.3669918 \times 10^{-9}$
$B_0 = -1.07271 \times 10^{1}$	$B_0 = -1.07271 \times 10^{1}$	$B_0 = -9.4868712 \times 10^{1}$
$B_1 = 7.61989 \times 10^{-2}$	$B_1 = 7.6215115 \times 10^{-2}$	$B_1 = 7.2392075 \times 10^{-1}$
$B_2 = -1.74771 \times 10^{-4}$	$B_2 = -1.7490155 \times 10^{-4}$	$B_2 = -2.1963437 \times 10^{-3}$
$B_3 = 2.46721 \times 10^{-6}$	$B_3 = 2.4668279 \times 10^{-6}$	$B_3 = 2.4668279 \times 10^{-6}$

For Ice –100 to –50°C

IPTS-68 [°C]	ITS-90 [°C]	ITS-90 [K]
A_0 = 9.88896x10^{-4}	A_0 = 9.8830022x10^{-4}	A_0 = -7.4712663x10^{-2}
A_1 = 5.74491x10^{-5}	A_1 = 5.7429701x10^{-5}	A_1 = 9.5972907x10^{-4}
A_2 = 8.90422x10^{-7}	A_2 = 8.9023096x10^{-7}	A_2 = -4.1935419x10^{-6}
A_3 = 6.20355x10^{-9}	A_3 = 6.2038841x10^{-9}	A_3 = 6.2038841x10^{-9}
B_0 = -1.04148x10^{1}	B_0 = -1.0415113x10^{1}	B_0 = -1.0385289x10^{2}
B_1 = 9.11735x10^{-2}	B_1 = 9.1177156x10^{-2}	B_1 = 8.5783626x10^{-1}
B_2 = 5.14117x10^{-5}	B_2 = 5.1128274x10^{-5}	B_2 = -2.8578612x10^{-3}
B_3 = 3.55087x10^{-6}	B_3 = 3.5499292x10^{-6}	B_3 = 3.5499292x10^{-6}

For Ice –50 to 0°C

IPTS-68 [°C]	ITS-90 [°C]	ITS-90 [K]
A_0 = 3.61345x10^{-4}	A_0 = 3.61345x10^{-4}	A_0 = -7.1044201x10^{-2}
A_1 = 2.94650x10^{-5}	A_1 = 2.9471685x10^{-5}	A_1 = 8.6786223x10^{-4}
A_2 = 5.21676x10^{-7}	A_2 = 5.2191167x10^{-7}	A_2 = -3.5912529x10^{-6}
A_3 = 5.01622x10^{-9}	A_3 = 5.0194210x10^{-9}	A_3 = 5.0194210x10^{-9}
B_0 = -1.07401x10^{1}	B_0 = -1.07401x10^{1}	B_0 = -8.2308868x10^{1}
B_1 = 7.36812x10^{-2}	B_1 = 7.3698447x10^{-2}	B_1 = 5.6519110x10^{-1}
B_2 = -2.68806x10^{-4}	B_2 = -2.6890021x10^{-4}	B_2 = -1.5304505x10^{-3}
B_3 = 1.53964x10^{-6}	B_3 = 1.5395086x10^{-6}	B_3 = 1.5395086x10^{-6}

5.2 Notes Regarding Enhancement Factors

Since the temperature dependency of enhancement factors is very small, little error would be induced by the use of IPTS-68 enhancement factor formulas with ITS-90 temperatures while at low to moderate pressures. However at high pressure, near 2 MPa, the error of this approach is negligible near 0°C, but approaches errors of 15 ppm at –50 and +100°C, and exceeds 50 ppm at –100°C. Although somewhat more significant, these induced errors are still generally more than an order of magnitude lower than Hyland's original uncertainty estimates. Use of the ITS-90 equations can reduce this systematically induced computation error more than 2 orders of magnitude to within 0.2 ppm over the range –100 to –50°C, 0.05 ppm over the range -50 to 0°C, and within 0.1 ppm over the range 0 to 100°C. Since the use of the ITS-90 formulations prevent any significant additional contribution to the overall computational error, Hyland's original estimates of uncertainty remain valid.

As an additional note, it is also important to understand that the IPTS-68 enhancement factor formulas of Greenspan where derived using Wexler's vapor pressure equation for water prior to his 1976 revision, and Goff's saturation vapor pressure equation for ice based on the temperature scale of 1948. While these IPTS-68 enhancement factor equations apparently remained valid without change up to 1990, even though there were newer equations for the vapor pressures of both water and ice, no attempt was made here to account for these apparent previous discrepancies. The equations presented here for ITS-90 are done so solely in an effort to prevent further degradation of the enhancement formulas from 1990 forward. The goal attempted and accomplished was only that an IPTS-68 enhancement factor computed from an IPTS-68 temperature would yield the same numeric value as an ITS-90 enhancement factor computed from an ITS-90 temperature, when the two temperatures are of the same hotness.

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1 Preston-Thomas, H. et al., *Supplementary Information for the International Temperature Scale of 1990*, Bureau International Des Poids Et Mesures (BIPM), December 1990, 1-28

2 Wexler, A., *Vapor Pressure Formulation for Water in Range 0 to 100°C. A Revision*, Journal of Research of the National Bureau of Standards – A. Physics and Chemistry, September – December 1976, Vol. 80A, Nos. 5 and 6, 775-785

3 Wexler, A., *Vapor Pressure Formulation for Ice*, Journal of Research of the National Bureau of Standards – A. Physics and Chemistry, January – February 1977, Vol. 81A, No. 1, 5-19

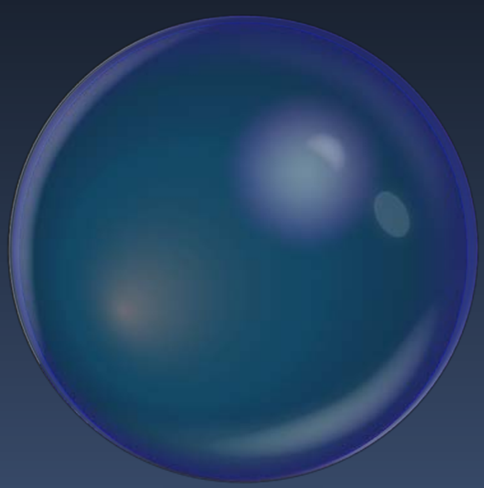
4 Hyland, R.W., *A correlation for the second interaction virial coefficients and enhancement factors for CO_2-free moist air from –50 to +90°C*, Journal of Research of the National Bureau of Standards – A. Physics and Chemistry, July-August 1975, Vol. 79A, No. 4, 551-560.

5 Greenspan, L., *Functional Equations for the Enhancement Factors for CO_2-Free Moist Air*, Journal of Research of the National Bureau of Standards – A. Physics and Chemistry, January-February 1976, Vol. 80A, No. 1, 41-44.

6 Goff, J. A., *Standardization of Thermodynamic Properties of Moist Air*, Heating, Piping, and Air Conditioning, 1949, Vol. 21, 118.

Humidity Calibration Tutorial

- NCSL Presentation



Humidity Generation and Calibration Equipment
THUNDER SCIENTIFIC CORPORATION The Humidity Source

NVLAP Lab Code 200582-0

Humidity Calibration Tutorial

Jeff Bennewitz
Co Presenter Mike Hamilton

Thunder Scientific Corporation
623 Wyoming Blvd. SE
Albuquerque, NM 87123-3198

Phone: 505-265-8701
1-800-872-7728

Web: www.thunderscientific.com

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Speaker: Jeff Bennewitz

HUMIDITY CALIBRATION

For many hygrometers, the need for recalibration depends on the accuracy required, the sensors stability, and the conditions to which the sensor is subjected. Hygrometers should be calibrated regularly by exposure to an atmosphere maintained at a known humidity and temperature, or by comparison with a transfer standard hygrometer. Complete calibration usually requires observation of a series of temperatures and humidities. Methods for producing known humidities include saturated salt solutions, mechanical systems such as the divided flow, two-pressure two-temperature and the two-pressure humidity generator. All these systems rely on precise methods of temperature and pressure control within a controlled environment to produce a known humidity, usually with accuracies of 0.5 to 1.0%. The operating range of the precision generator is typically 5% to 95% RH.

Definitions

- **Humidity**
  - The presence of water vapor in a gas. The word "humidity" is sometimes used to express relative humidity only. Humidity refers to all expressions related to water vapor.
- **Relative Humidity**
  - Describes the ability of air to moisten or dry materials and compares the actual amount of water vapor present with the maximum amount of water vapor the air could hold at that temperature. Example, saturated air at 50 °F (saturated means 100% relative humidity) would be quite dry if heated to 100 °F (less than 19% relative humidity).
- **Hygrometer**
  - An instrument for measuring humidity.
- **Hygrometry**
  - The subject of humidity measurement.

Humidity Instrument Calibration

- **Section 1**
  - Hygrometer Calibration
- **Section 2**
  - Humidity and Temperature Chart Recorder Calibration
- **Section 3**
  - Humidity and Temperature Data Logger Calibration
- **Section 4**
  - Calibration Set-Up
- **Section 5**
  - Chilled Mirror Hygrometer Calibration
- **Section 6**
  - High Dew Point Hygrometer Calibration
- **Section 7**
  - Calibration Divided Flow Humidity Generator

Thunder Calibration Procedure

Humidity Calibration using the Model 2500 Two-Pressure Humidity Generator

Hygrometer Calibration

Figure 1.1

A typical hand held hygrometer with humidity and temperature probe EdgeTech Model 650.

Typical accuracy for this hygrometer is specified at ±1.0 % RH.

The calibration of the hand held hygrometer as described and illustrated will be a simple 3 point calibration at 20, 50, & 80% RH at a test temperature of 23 °C.

It is always a good idea to review the operations manual for the instrument you will be calibrating.

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For this calibration use the manifold accessory in the test chamber of the 2500. The manifold will thread into the chamber inlet port with a ¼ inch NPT male thread. It is not necessary to seal or tighten the manifold tight.

The manifold accessory will reduce the calibration test time.

Bundle the RH/Temp probe and the chamber temp sensor from the 2500 together in the manifold as illustrated. It is important that the RH/Temp probe from the hygrometer is positioned with the 2500 chamber temp sensor.

See figure 1.2 on next slide.

Figure 1.2

Position the RH/Temp probe into the manifold fixture with the 2500 chamber temperature sensor. Close the 2500 chamber door.

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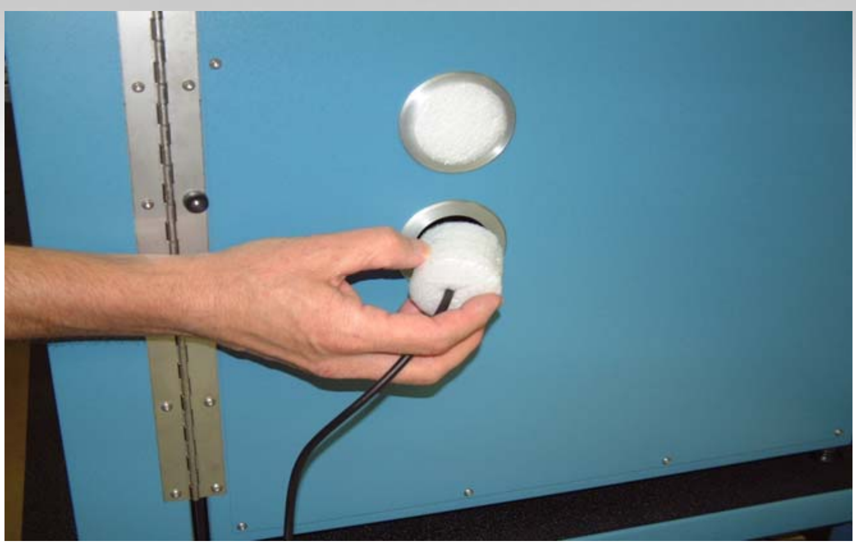

Figure 1.3

Seal the access port with the white foam plug, the foam plug can be drilled or cut for the probe cable.

Figure 1.4

Change the set point on the 2500 control screen to 20% RH at PC/TC, change the chamber temperature set point to 23 °C.

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Figure 1.5

Press RUN to start the 2500 and begin the calibration. As a rule of thumb we will allow the 2500 system and hand held hygrometer to warm up for 60 minutes before taking our first test point. The test point interval will be 30 minutes after the initial warm up.

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Figure 1.6

Thunder metrologists use a calibration worksheet to record data from the 2500 and the device under test. Ambient test conditions in the lab are noted and dated on the work sheet. Data collected from the 2500 will include the headings as listed in this example.

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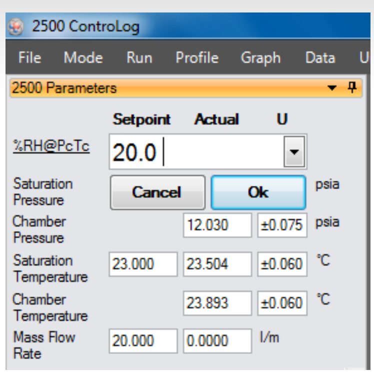

Figure 1.7

ControLog® Automation software can be used in place of the manual set points as described in the previous section. Click on the %RH Set point field of the Control Parameters window using the keyboard enter a set point of 20 then click OK.

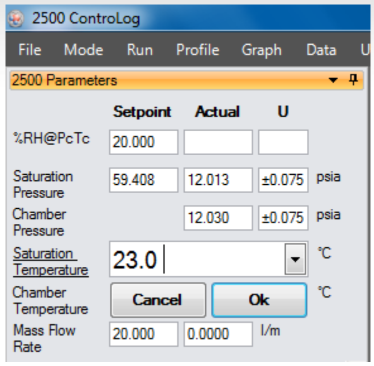

Figure 1.8

Click on the Saturation Temp Set point field of the Control Parameters window, using the keyboard enter a set point of 23 for a chamber temperature of 23 °C and then click OK.

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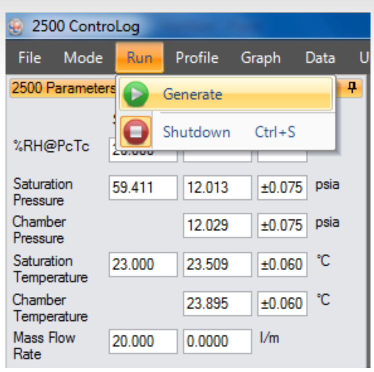

Figure 1.9

Select Generate from the Run menu and click. When Generate mode begins, all fields on the Control Parameters window and the Calculated Humidity Values window begin to update, and the Status Log shows the time that the Generate Mode was started.

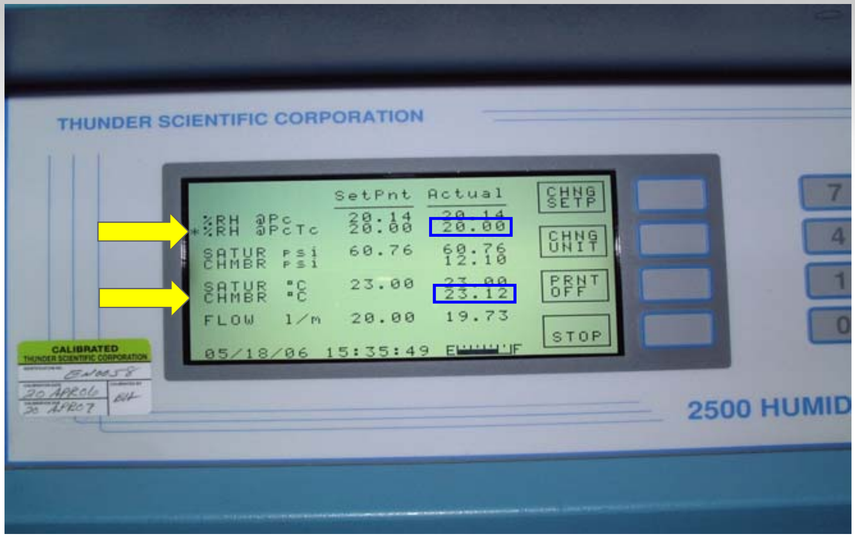

Figure 1.10

After 60 minutes we are ready to take a test point at 20% RH at 23 °C. Record the readings from the 2500 and hand held hygrometer. Allow extra time if the DUT is still stabilizing at the test point.

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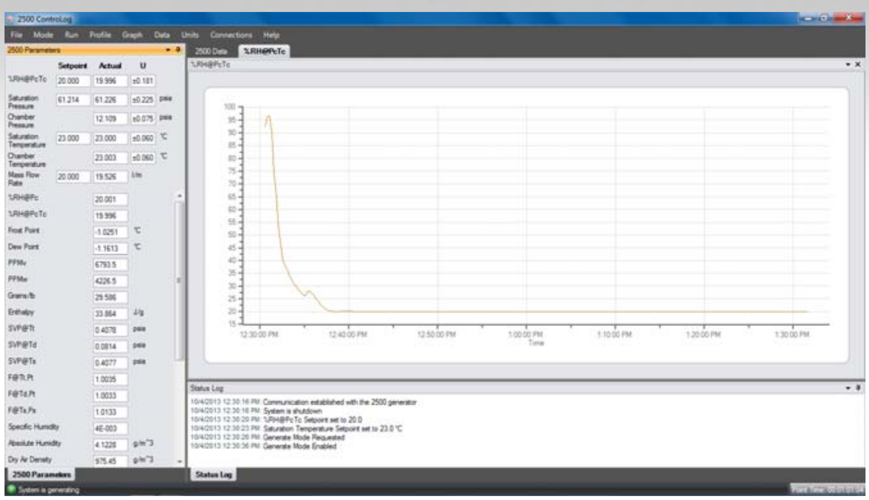

Figure 1.11

ControLog® Automation screen in the graph mode shows a stable set point at 20% RH and 23 °C chamber temperature.

Figure 1.12

The displayed output values from the hand held hygrometer should be recorded for %RH and Temperature.

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Figure 1.13

Change the set point on the 2500 to 50% RH at 23 °C, allow 30 minutes for the system to stabilize at the new calibration point.

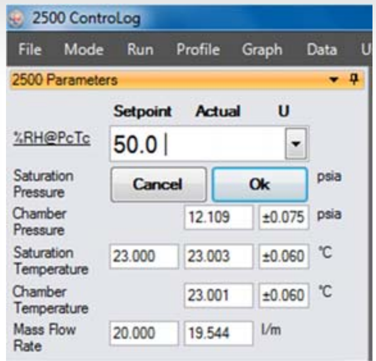

Figure 1.14

Click on the %RH Set point field of the Control Parameters window, using the keyboard enter a set point of 50 then click OK, allow 30 minutes for the system to stabilize at the new calibration point.

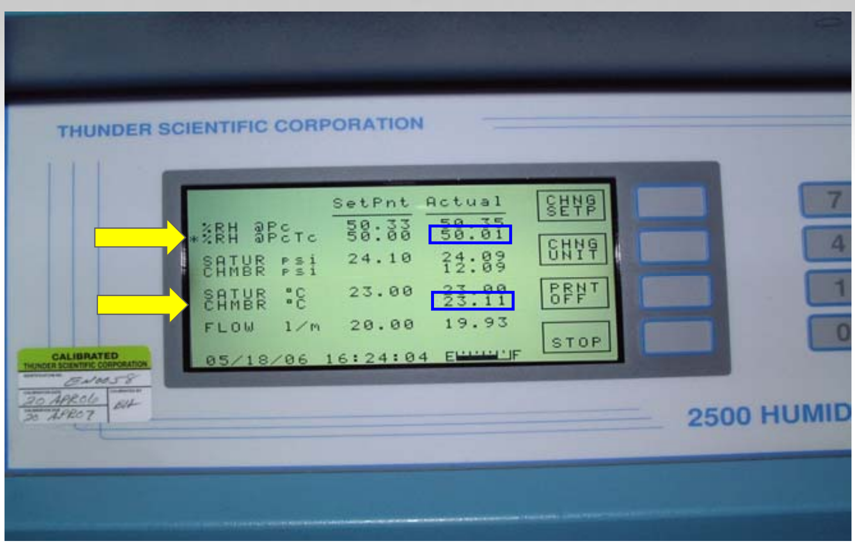

Figure 1.15

After 30 minutes we are ready to take a test point at 50% RH at 23 °C. Record the readings from the 2500 and hand held hygrometer. Allow extra time if the DUT is still stabilizing at the test point.

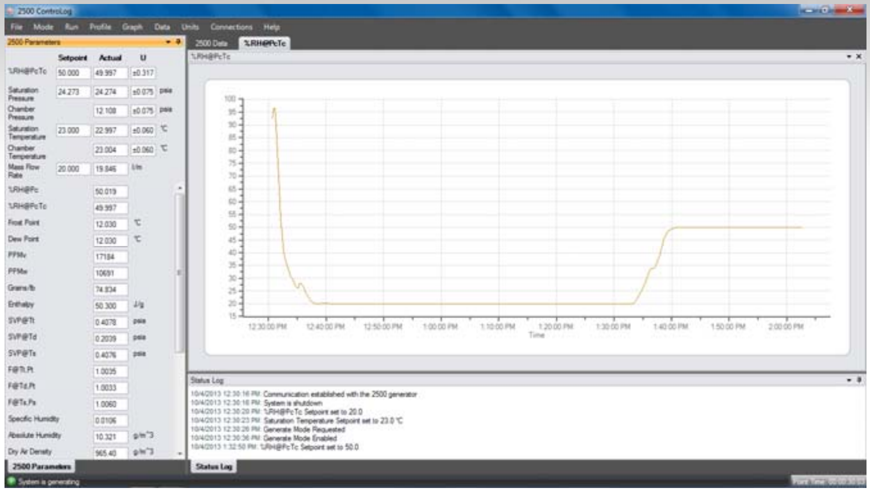

Figure 1.16

ControLog® Automation screen in the graph mode shows a stable set point at 50% RH and 23 °C chamber temperature.

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Figure 1.17

The displayed output values from the hand held hygrometer should be recorded for %RH and Temperature, allow extra time if the DUT is still stabilizing.

Figure 1.18

Change the set point on the 2500 to 80% RH at 23 °C, allow 30 minutes for the system to stabilize at the new calibration point.

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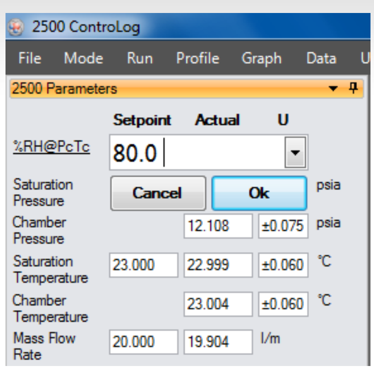

Figure 1.19

Click on the %RH Set point field of the Control Parameters window, using the keyboard enter a set point of 80 then click OK, allow 30 minutes for the system to stabilize at the new calibration point.

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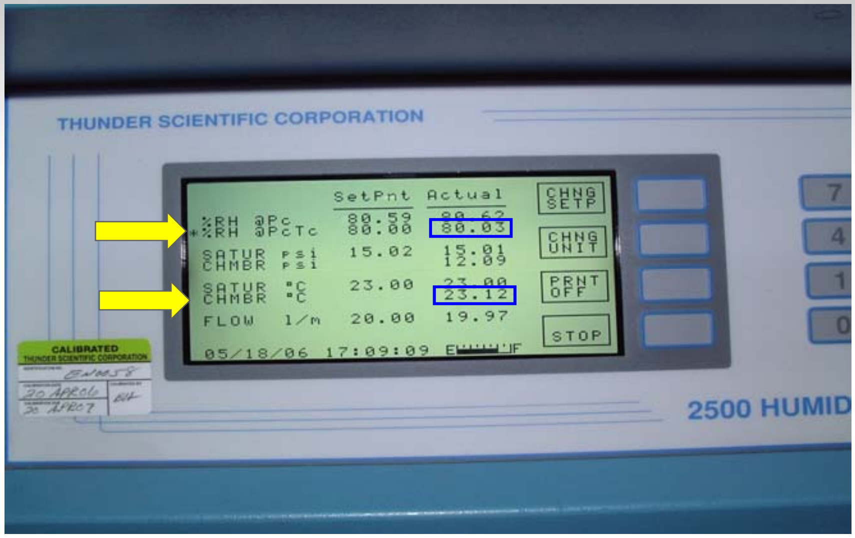

Figure 1.20

After 30 minutes we are ready to take a test point at 80% RH at 23 °C. Record the readings from the 2500 and hand held hygrometer. Allow extra time if the DUT is still stabilizing at the test point.

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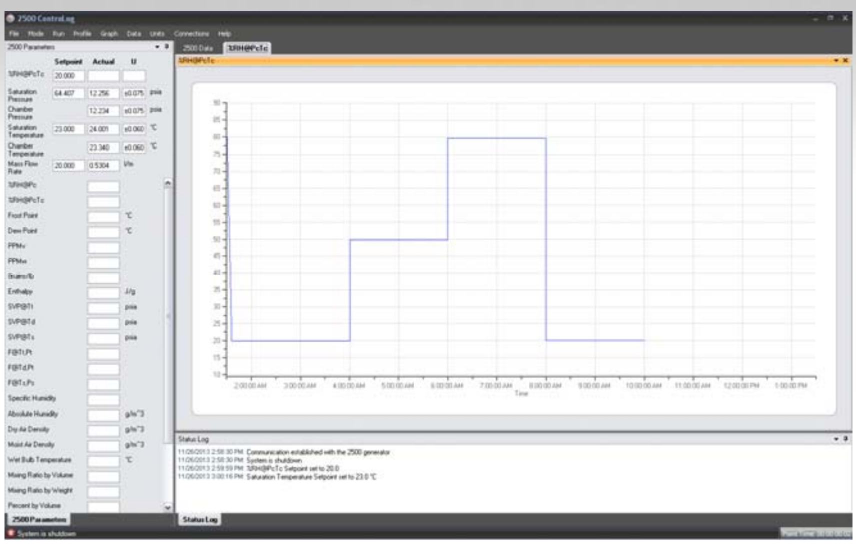

Figure 1.21

ControLog® Automation screen in the graph mode shows a stable set point at 80% RH and 23 °C chamber temperature.

Figure 1.22

Record the final test point from the DUT display for %RH and Temperature.

Press Stop on the 2500 keyboard or, Select Shutdown from the Run menu, once the 2500 generator is shut down the system will prompt you to save the system data, which was acquired during this calibration.

The initial as found calibration is complete. The filter element or screen that protects the humidity sensor element should be cleaned and inspected as per the manufacturers recommendation before calibration adjustment and testing the as left calibration of the hand held hygrometer.

The as left calibration should be performed at the same test temperature of 23 °C using the same 3 test points beginning at 20% RH, test point interval will be 30 minutes.

Questions?

Comments?

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Chart Recorder Calibration

Figure 2.1

Calibration article (DUT) Humidity and temperature chart recorder, adjustable chart speed from 24 hour, 7 day or 30 day chart.

Before calibration install a fresh 24 hour chart if available, select 24 hour chart speed.

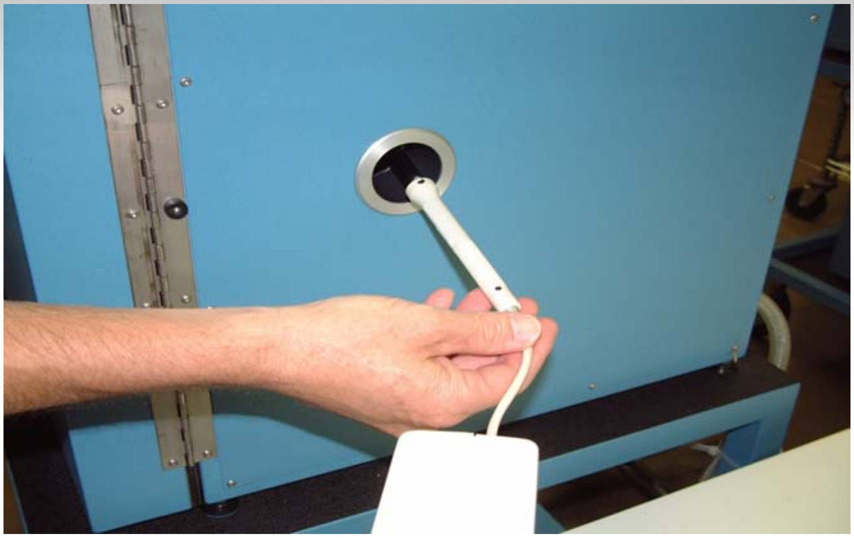

Figure 2.2

Connect the RH/Temp probe to an extension cable if available to allow access to the test chamber. Seal the opening with the white foam access plug. Connect power supply to the chart recorder.

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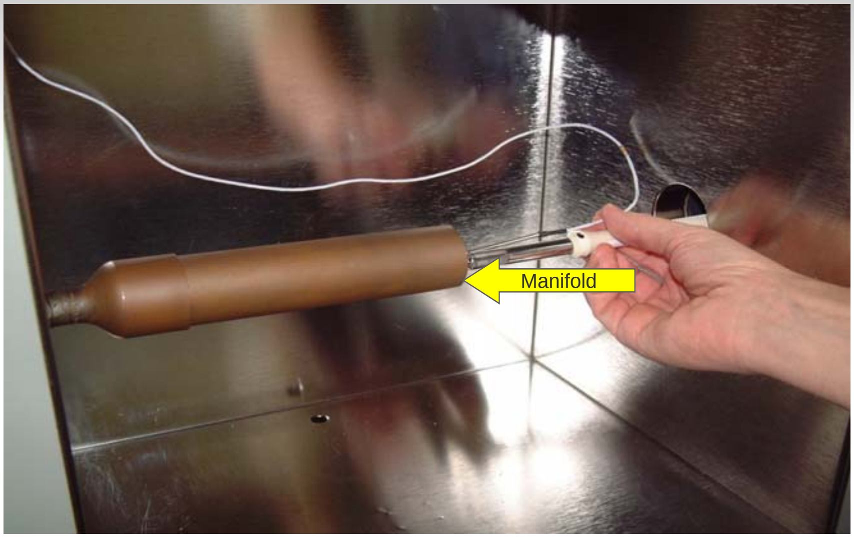

Figure 2.3

Position the RH/Temp probe into the manifold fixture with the 2500 chamber temperature sensor. Close the 2500 chamber door.

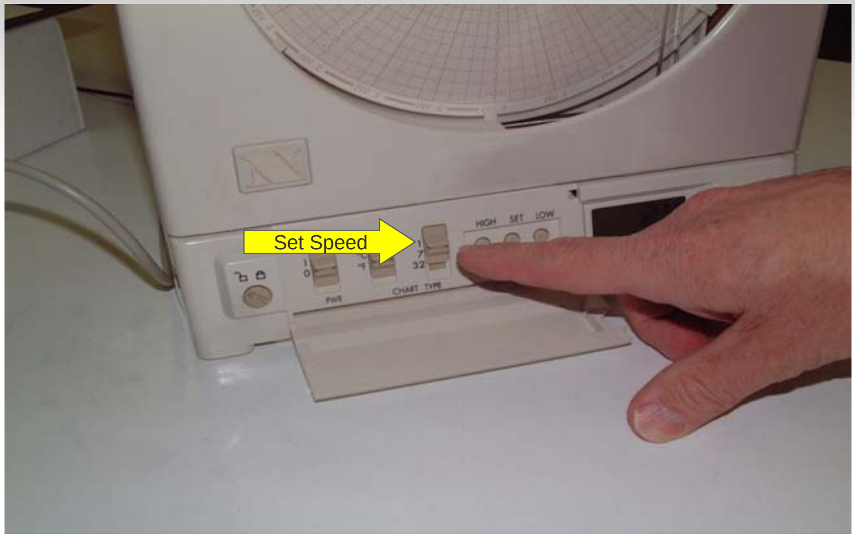

Figure 2.4

Adjust the chart recorder chart speed to 1 day or 24 hour chart speed if adjustable. Apply power to the chart recorder.

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Figure 2.5

Review the ControLog® Manual if you are not familiar with this software.
Open ControLog® software; under the Profile menu select New Profile.

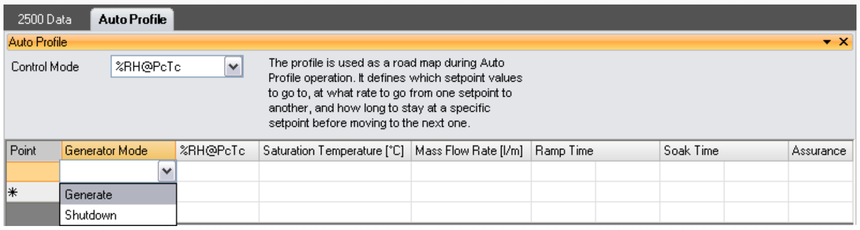

Figure 2.6

Click once on the cell of any value needing a change. It is usually best to start at the upper leftmost cell. For this automatic profile calibration we will use 20.0% RH as the first test point.

- The test points selected will be 20%, 50% & 80% returning to 20% RH, the test temperature has been entered as 23.0 °C, a flow rate of 20 SLPM, you should always run the 2500 at the maximum flow rate of 20 SLPM for best uniformity of the test chamber. The ramp time entered is 0; we want the 2500 to reach the set point as fast as possible. The soak time for the test point will be 2 hours or 120 minutes. This time can be reduced based on the response time of the DUT. We have selected NO for the assured soak conditions; the 2500 will stabilize as close as possible to the test point as selected.

See figure 2.7 on next slide.

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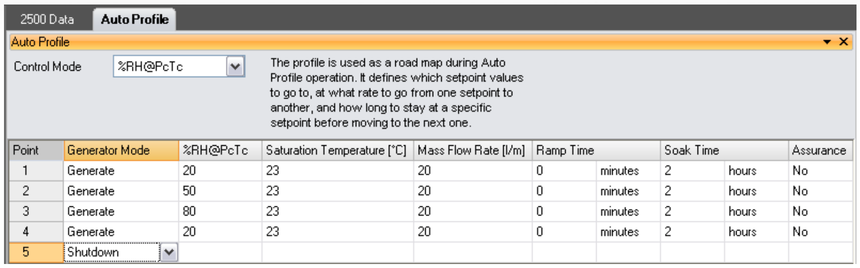

Point	Generator Mode	%RH@PcTc	Saturation Temperature [°C]	Mass Flow Rate [l/m]	Ramp Time		Soak Time		Assurance
1	Generate	20	23	20	0	minutes	2	hours	No
2	Generate	50	23	20	0	minutes	2	hours	No
3	Generate	80	23	20	0	minutes	2	hours	No
4	Generate	20	23	20	0	minutes	2	hours	No
5	Shutdown								

Figure 2.7

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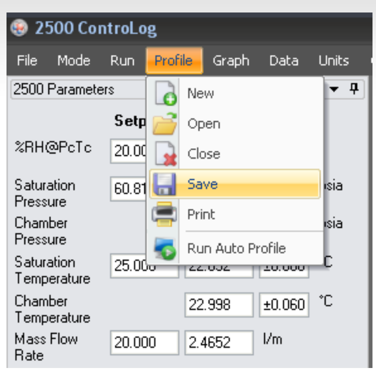

Figure 2.8

Select Save Profile under the Profile menu. The profile as designed can be reused or revised for similar auto profile calibrations.

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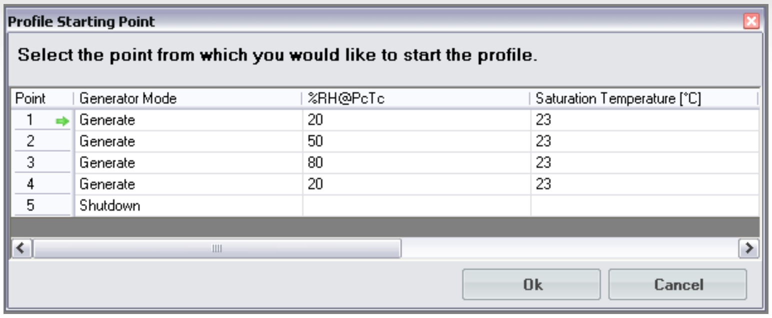

Profile Starting Point

Select the point from which you would like to start the profile.

Point	Generator Mode	%RH@PcTc	Saturation Temperature [°C]
1	Generate	20	23
2	Generate	50	23
3	Generate	80	23
4	Generate	20	23
5	Shutdown		

Ok Cancel

Figure 2.9

Select Run Auto Profile under the Profile menu from the tool bar, the Auto Profile insert will be displayed with an arrow indicating the first test point, click OK the 2500 will start at 20.0% RH at a test temperature of 23 °C.

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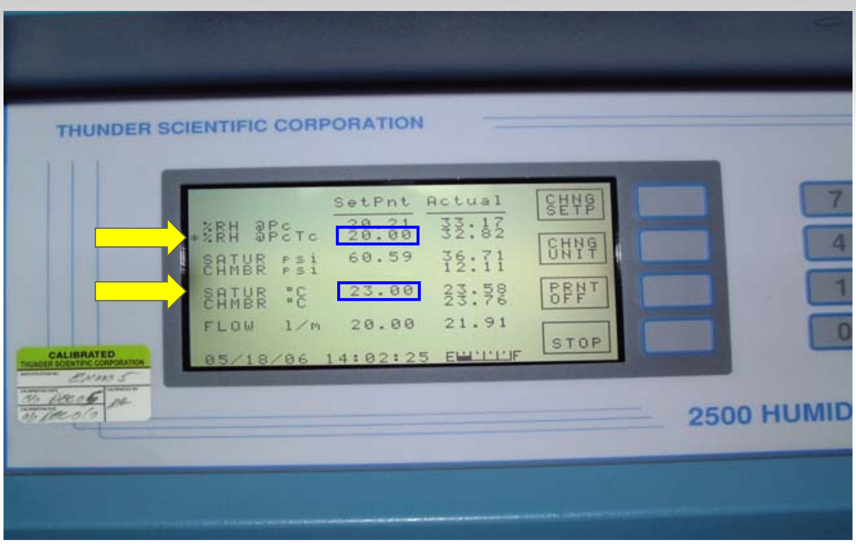

Figure 2.10

The 2500 run screen will display the set points as programmed from ControLog® Auto Profile.

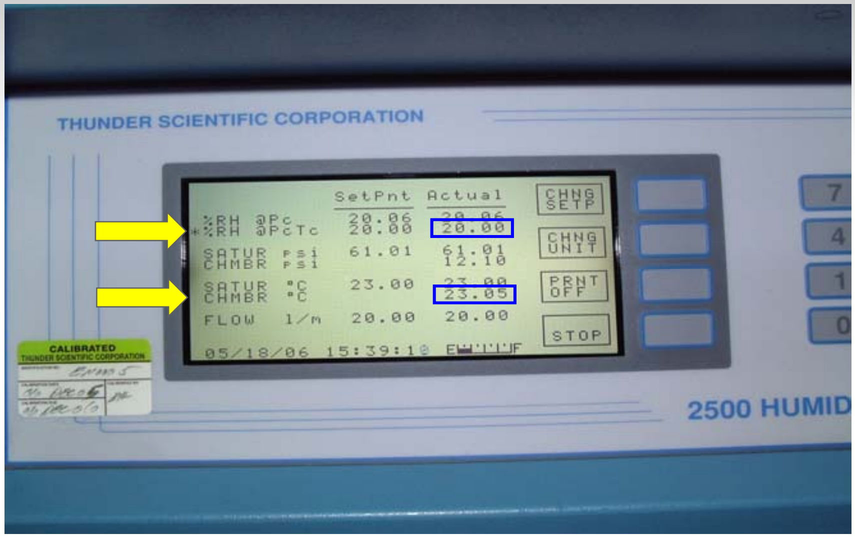

Figure 2.11

The 2500 display screen after 90 minutes displays a stable reading at 20% RH at the test temperature of 23 °C.

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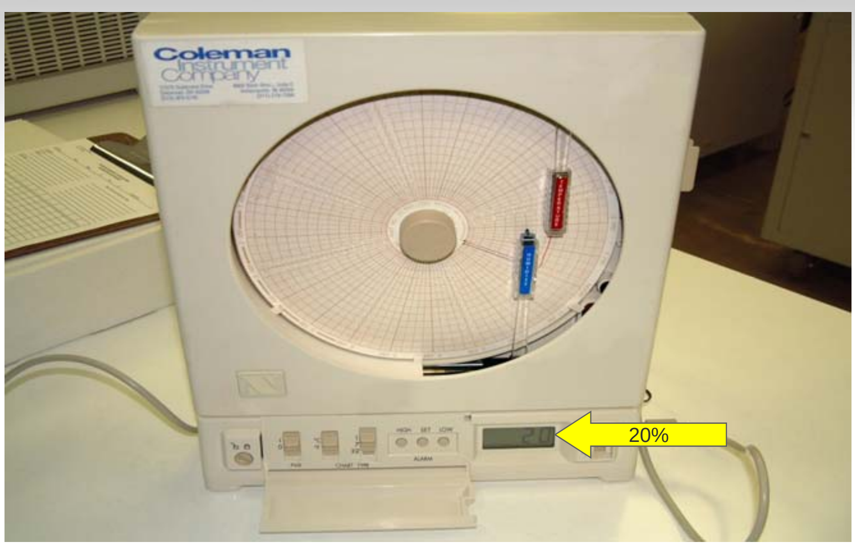

Figure 2.12

The DUT RH/Temp recorder is shown with a displayed output of 20 at 20.0% RH, you should monitor the calibration to be sure the displayed output agrees with the trace on the chart record.

Figure 2.13

The DUT RH/Temp recorder is shown with the displayed output for temperature at test temp of 23 °C.

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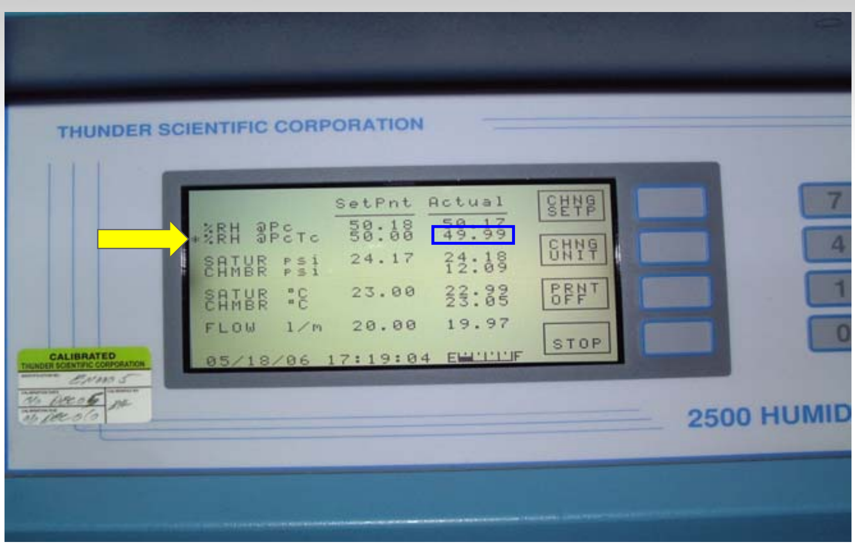

Figure 2.14

The 2500 display screen is shown with the set point change to 50% RH after 2 hours.

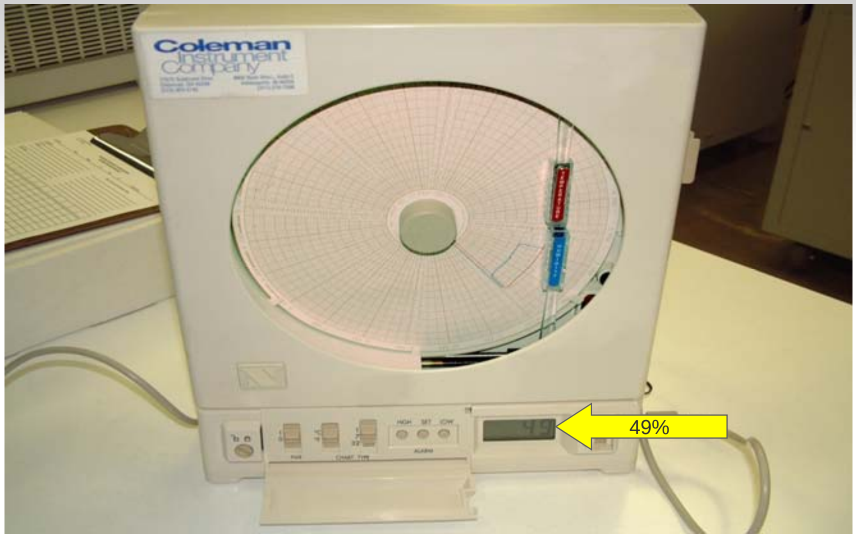

Figure 2.15

The DUT RH/Temp recorder is shown with the displayed output of 49% at the 50.0 %RH set point.

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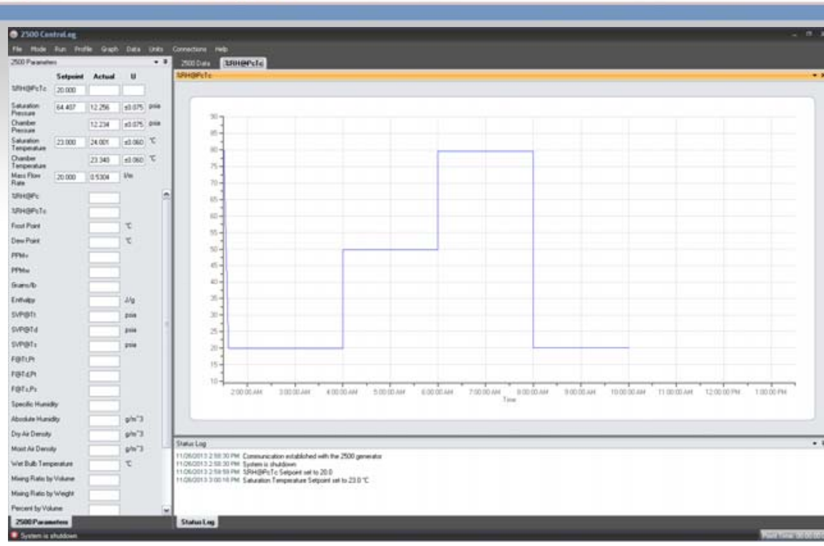

Figure 2.16

After 8 hours of Auto profile calibration the ControLog® graph displays the 4 point profile from 20% RH to 80% RH with a final point at 20% RH. The ControLog graph confirms the stability and time duration of the Auto profile. The file should be saved with appropriate serial number or file name for the RH/Temp recorder.

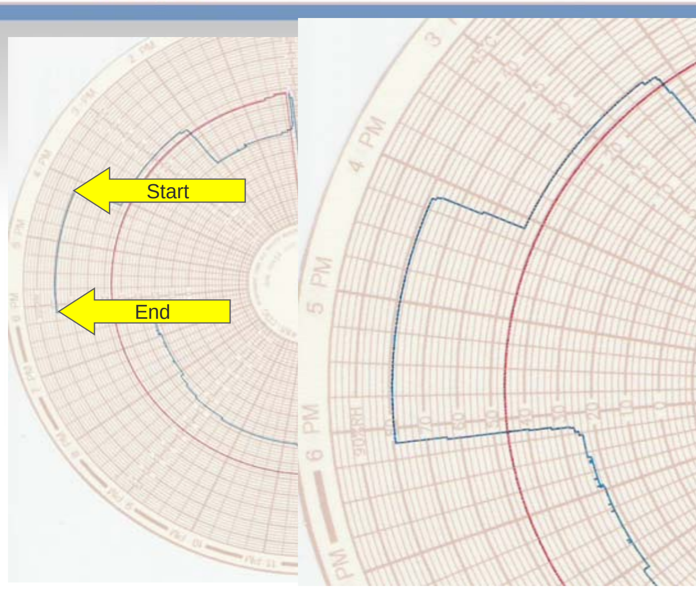

Figure 2.17

The RH/Temp chart record can be compared to the 2500 ControLog data for error and test stability, the calibration as performed on this instrument was within the manufacturers tolerance. The chart record as prepared should be scanned or photographed for file history on this instrument.

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Questions?

Comments?

Humidity & Temperature Data Logger Calibration Using ControLog Automation Software

Figure 3.1

Calibration article (DUT) Humidity and Temperature Data Logger positioned in the chamber using the shelf accessory. Locate the 2500 chamber temperature sensor with the RH/Temp loggers. Close the 2500 chamber door.

Figure 3.2

Open ControLog® software; under the Profile menu select Open Profile.

The profile test points will be 40% & 60% RH, the test temperature has been entered as 23.0 °C, a flow rate of 20 SLPM, you should always run the 2500 at the maximum flow rate of 20 SLPM for best uniformity of the test chamber. The ramp time entered is 0; we want the 2500 to reach the set point as fast as possible. The soak time for each test point will be 8 hours. This time can be reduced based on the response time of the DUT. We have selected NO for the assured soak conditions; the 2500 will stabilize as close as possible to the test point as selected.

See figure 3.3 on next slide.

Humidity Generation and Calibration Equipment
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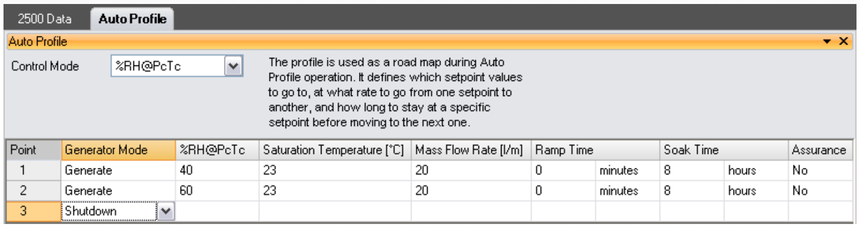
2500 Data | Auto Profile

Auto Profile

Control Mode: %RH@PcTc

The profile is used as a road map during Auto Profile operation. It defines which setpoint values to go to, at what rate to go from one setpoint to another, and how long to stay at a specific setpoint before moving to the next one.

Point	Generator Mode	%RH@PcTc	Saturation Temperature [°C]	Mass Flow Rate [l/m]	Ramp Time		Soak Time		Assurance
1	Generate	40	23	20	0	minutes	8	hours	No
2	Generate	60	23	20	0	minutes	8	hours	No
3	Shutdown								

Figure 3.3

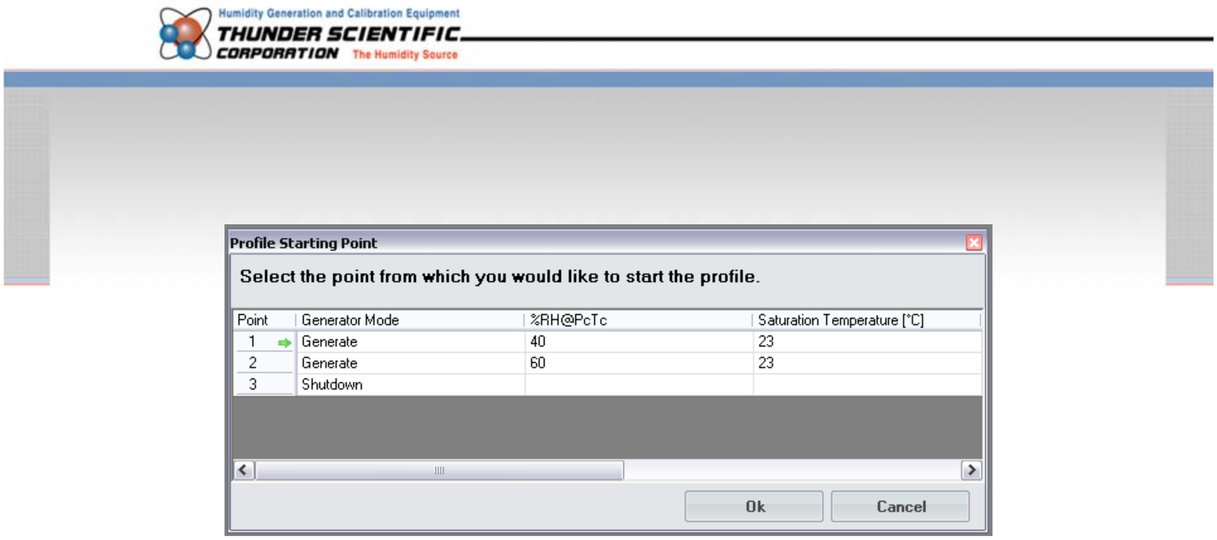

Figure 3.4

Select Run Auto Profile under the Profile menu from the tool bar, the Auto Profile insert will be displayed with an arrow indicating the first set point.

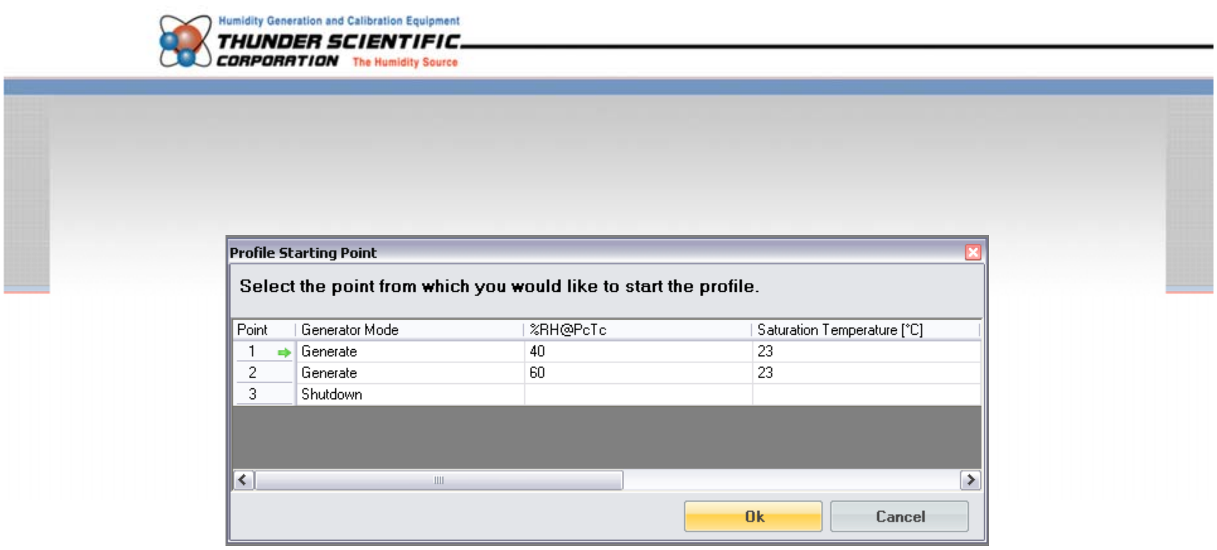

Figure 3.5

Click OK the 2500 will start at the first test point of 40.0% RH at a test temperature of 23 °C.

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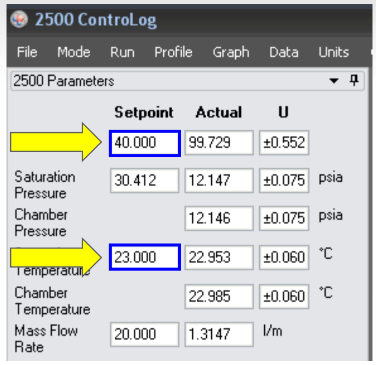

Figure 3.6

Note the set point of 40.0% RH at a test temperature of 23 °C.

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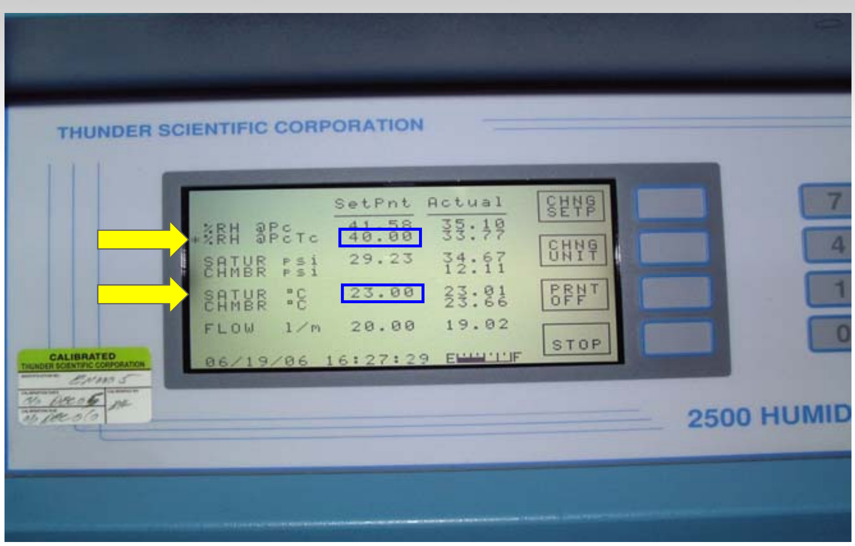

Figure 3.7

The 2500 run screen will display the set points as programmed from ControLog® Auto Profile.

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After 16 hours of Auto profile calibration the ControLog® graph displays the 2 point profile from 40% RH to 60% RH. The ControLog graph confirms the stability and time duration of the Auto profile. The file should be saved with appropriate serial number or file name for the RH/Temp loggers.

See figure 3.8 on next slide.

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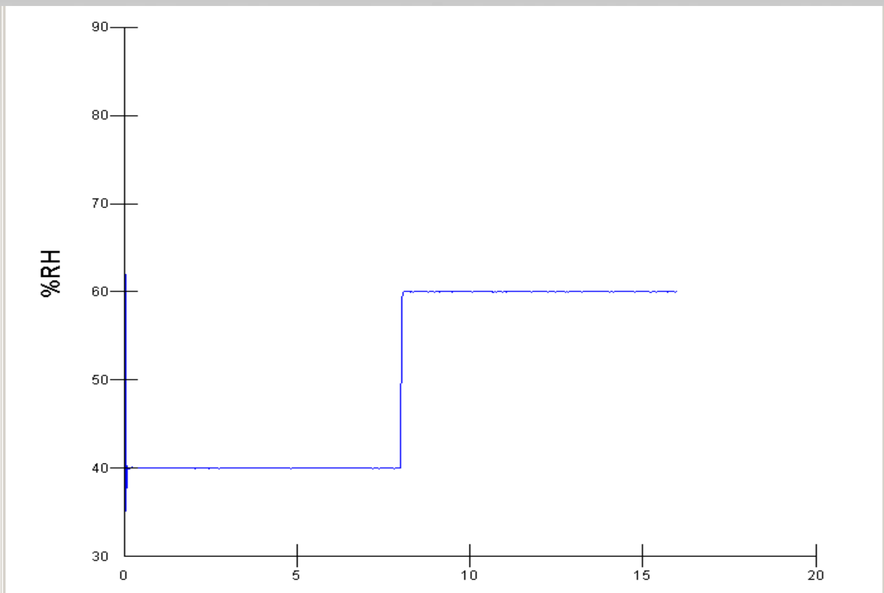

Figure 3.8

Figure 3.9 shows the data collected from the Veriteq data logger program.

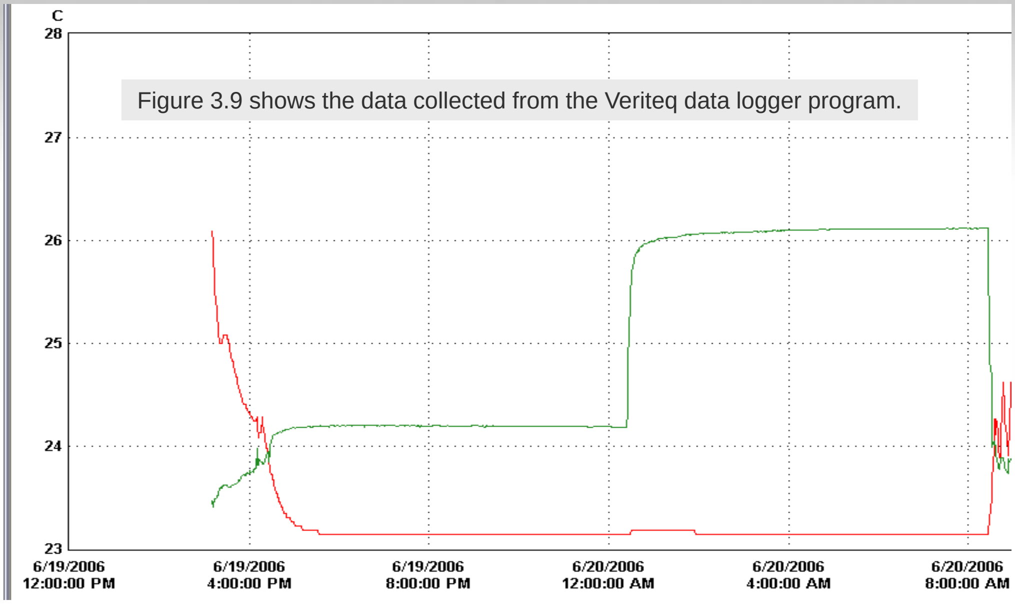

Figure 3.9

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Questions?

Comments?

Calibration Set-Up RH/Temp Transmitters

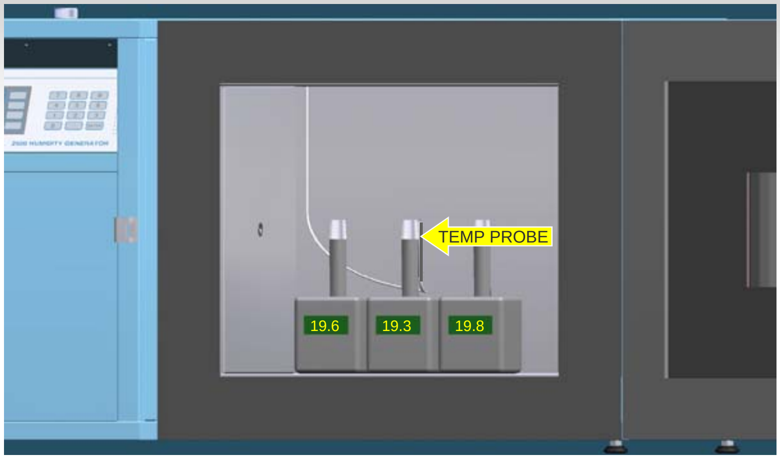

Figure 4.1

- Multiple sensors in the test chamber will sometimes exhibit self heating due to the imbedded electronics in the transmitter housing. It is important to locate the chamber temp probe as close to the RH/Temp probe as possible. Observe inter-comparison of temperature output between sensors.

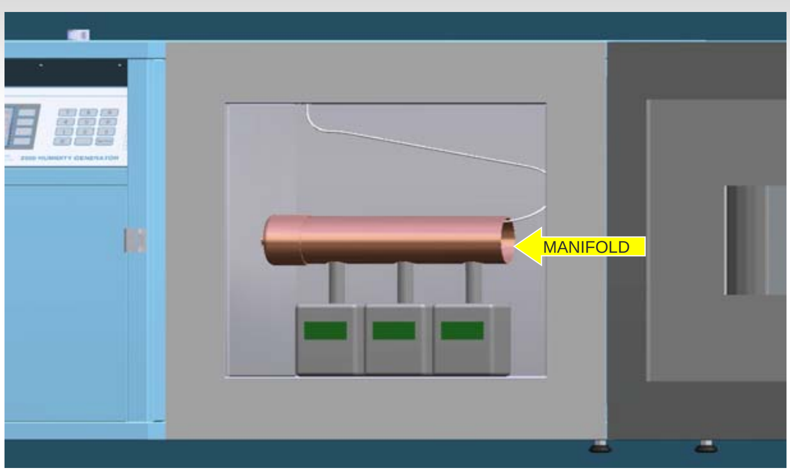

Figure 4.2

- A manifold fixture is a simple solution to duct the in coming humidity test value over the probes during calibration. The manifold solution will improve temperature uniformity between probes. Locate the chamber temperature probe inside the manifold during calibration.

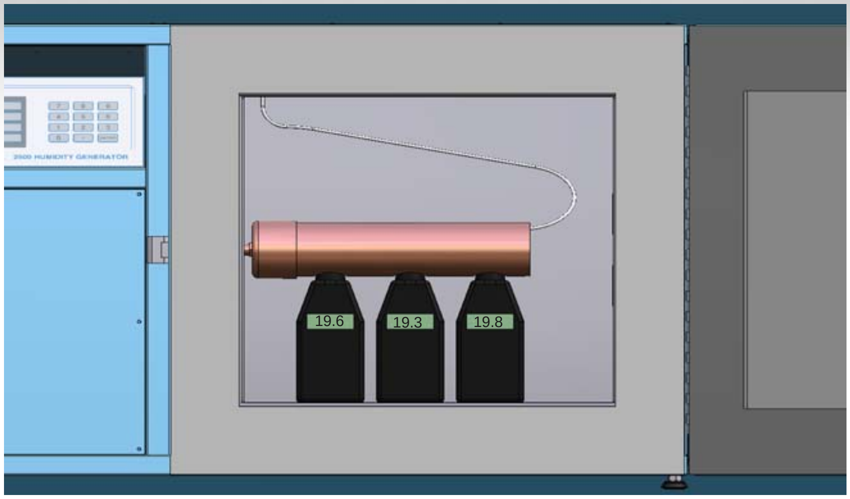

Figure 4.3

- A similar manifold fixture can be used for calibration of small hand-held devices where the humidity value is displayed on the device. It is possible to open the door for brief periods for adjustment of the device during calibration.

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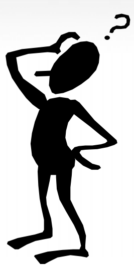

Questions?

Comments?

What is Dew Point?

A dew-point hygrometer utilizes a temperature-controlled, highly polished observable surface. In the instrument's simplest form, crushed ice is slowly added to a liquid in a thin-walled silver container such as a mint julep cup. An accurate mercury bulb thermometer is used to constantly stir the liquid in the cup. When the first sign of condensation (dew) is observed on the outside of the cup, the temperature of the liquid in the cup is read as the dew-point temperature. This method requires that the temperature of the outside surface of the silver cup and the temperature of the liquid in the cup be essentially the same. In actual practice, the temperature of the liquid in the cup will be slightly lower than the outside surface temperature of the cup.

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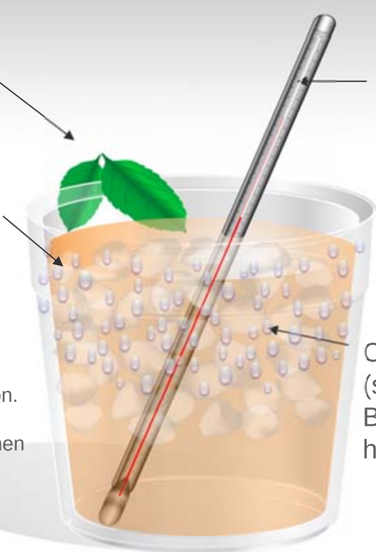
What is Dew Point?

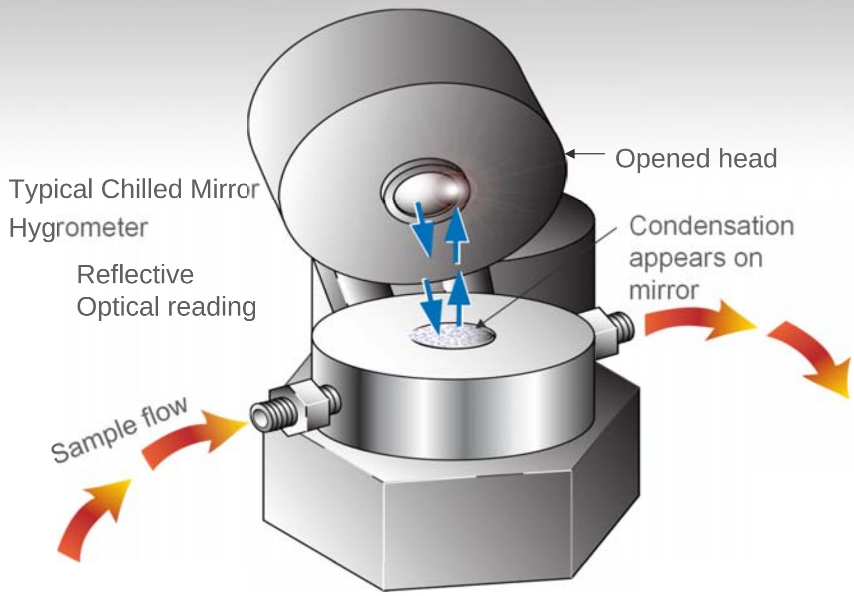


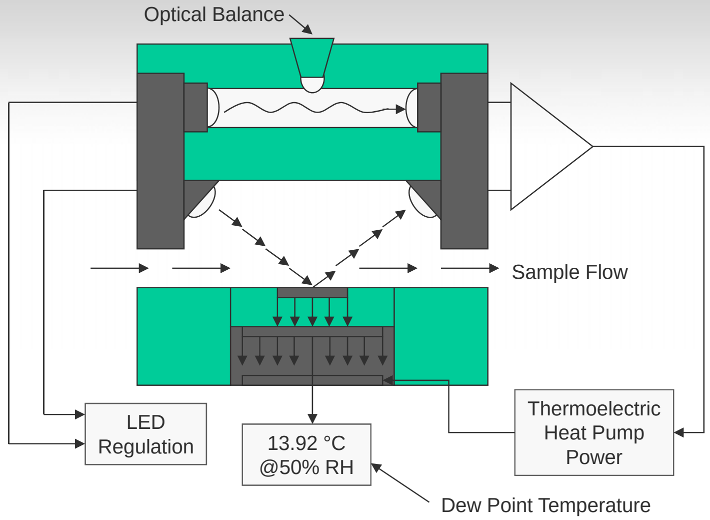
Instructions

1. Slowly add ice, stir and observe temperature and evidence of condensation.
2. Dew-point is thermometer reading when fog or condensation first appears.
3. Dispose of contents of cup in compliance with all regulations.

Chilled Mirror Hygrometer Calibration

In its most fundamental form, dew point is detected by cooling a reflective condensation surface (mirror) until water begins to condense, and by detecting condensed fine water droplets optically with an electro-optic detection system. The signal is fed into an electronic feed back control system to control the mirror temperature, which maintains a certain thickness of dew at all times.





Schematic of conventional chilled mirror sensor.

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Dew Point Mirror & Hygro M4

Figure 5.1

A typical dew point hygrometer with air temp sensor (AT) Series Hygro M4 is a general purpose optical condensation hygrometer used for industrial and laboratory applications.

Optical condensation hygrometry is a precise technique for determining the water vapor content in gases by measuring dew or frost temperatures. Optical condensation hygrometry works on the chilled-mirror principle. A metallic mirror surface is cooled until it reaches a temperature at which condensation begins to form on it. The dew layer is optically detected and the mirror is held at that temperature. The mirror temperature, measured with a platinum resistance thermometer is an accurate indicator of the dew or frost point.

Typical accuracy for this hygrometer is specified at ±0.2 °C DP.

The calibration of the dew point hygrometer as described and illustrated, will be a 3 point sample calibration at 20, 50, & 80% RH at a test temperature of 25 °C.

Dew point values will be calculated using HumiCalc® Humidity Conversion software.

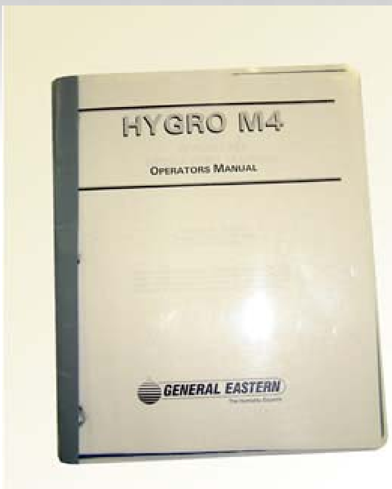

Figure 5.2

It's always a good idea to review the operations manual for the instrument you will be calibrating.

Figure 5.3

You will need a sample air pump as illustrated. The air pump is used for drawing a sample from the Model 2500 test chamber and flowing this sample over the dew point mirror. It is important to have adequate flow rate over the dew point mirror. A flow rate of less than 1 L/m is specified by the manufacturer. To much flow over the mirror will cause instability and accuracy problems.

Please refer to Fig. 5.42 & 5.44 for an alternate method of providing metered flow over the dew point mirror.

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Figure 5.4

Install the manifold accessory in the test chamber of the 2500. The manifold will thread into the chamber inlet port with a ¼ inch NPT male thread. It's not necessary to seal or tighten the manifold tight.

The manifold accessory will reduce the calibration test time.

Figure 5.5

Remove the 2500 foam access port plug and guide the air temp probe and sample tube into the test chamber. The tubing used for the inlet and outlet from the sample air pump should be a clean ¼ inch Teflon tube. It is not a good idea to use rubber or plastic tubing such as PVC because of the hygroscopic nature of the material.

Figure 5.6

Bundle the sample tube, air temp probe and the chamber temp sensor from the 2500 together in the manifold as illustrated. It is important that the air temp probe from the hygrometer is positioned with the 2500 chamber temp sensor.

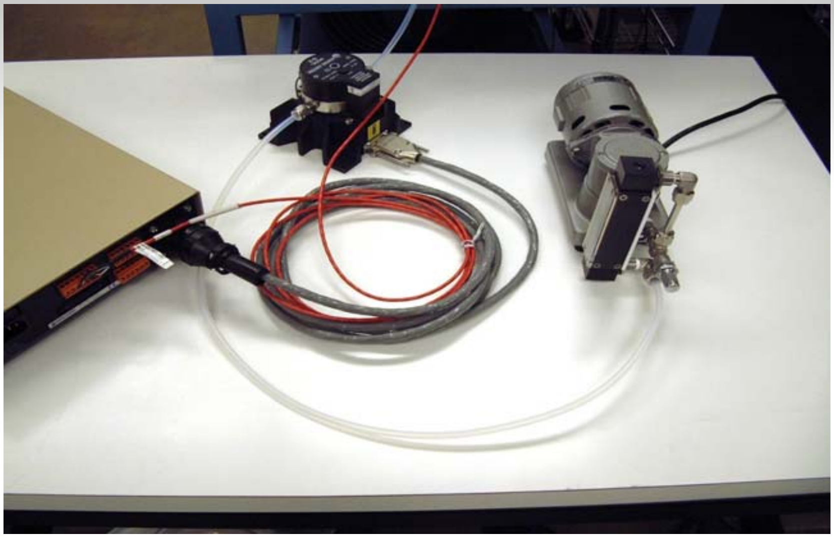

Figure 5.7

The sample tube from the 2500 test chamber is connected to one side of the dew point mirror using ¼" Swagelok fitting. The outlet of the dew point mirror is connected to the air sample pump. You will note the outlet of the pump has been fitted with a flow meter.

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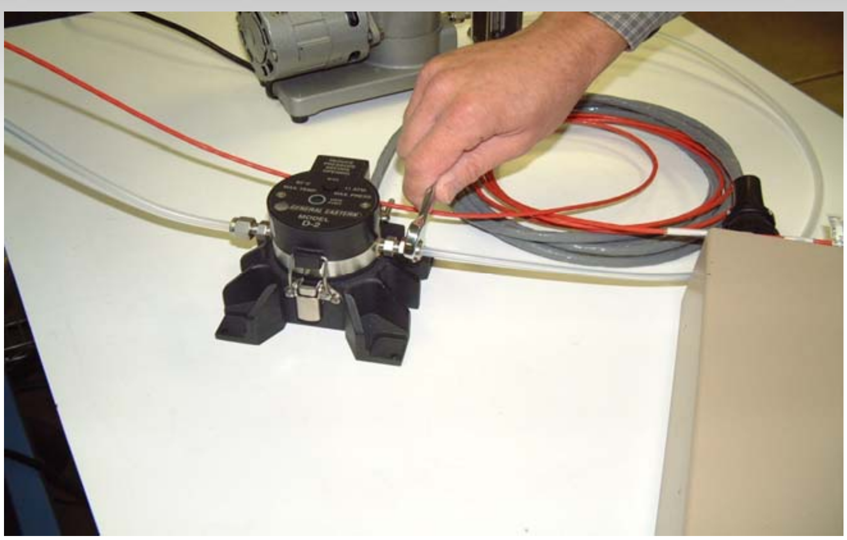

Figure 5.8

Tighten the fittings as shown.

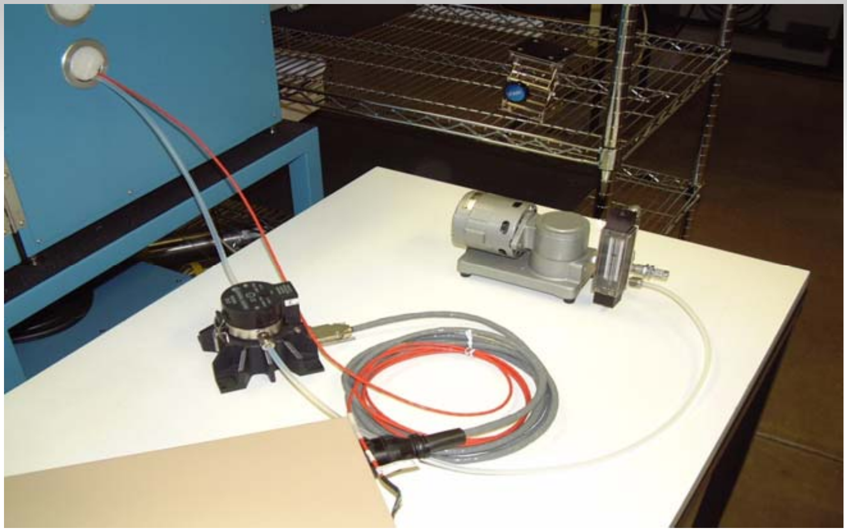

Figure 5.9

The sample tube and air pump as illustrated are ready for calibration.

Connect the dew point mirror and air temp probe to the connections on the display.

Apply AC power to the sample air pump and dew point hygrometer.

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Figure 5.10

The flow meter connected to the outlet of the sample air pump is adjusted for a value less than 1 L/m. It is important to have adequate flow rate over the dew point mirror. A flow rate of less than 1 L/m is specified by the manufacturer. To much flow over the mirror will cause instability and accuracy problems.

Figure 5.11

Apply AC power to the Model 2500 and air compressor accessory.

Change the set point on the 2500 control screen to 20% RH at PC/TC, change the chamber temperature set point to 25 °C.

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Calculate Dewpoint

- Using HumiCalc® we will calculate the dew point for a humidity set point of 20% RH.
- In the Normal mode select %RH as the known value, input the chamber test temperature of 25 °C, input the test pressure as displayed on the 2500 screen Chamber PSI.
- The calculated dew point for 20% RH as displayed in the example is 0.54230 DP.

See figure 5.12 on next slide.

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HumiCalc
@ 20% RH

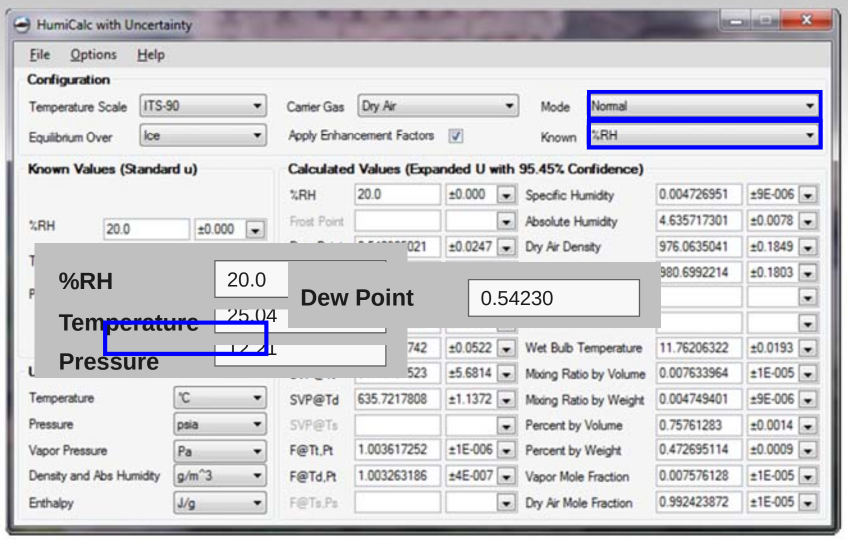

Figure 5.12

Humidity Generation and Calibration Equipment
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Figure 5.13

Press RUN to start the 2500 and begin the calibration. If you are using ControLog® Automation software click Run and select Generate. As a rule of thumb we will allow the 2500 system and dew point hygrometer to warm up for 60 minutes before taking our first test point. The test point interval will be 30 minutes after the initial warm up.

Figure 5.14

Thunder metrologists use a calibration worksheet to record data from the 2500 and the device under test. Ambient test conditions in the lab are noted and dated on the work sheet. Data collected from the 2500 will include the headings as listed in this example.

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Figure 5.15

After 60 minutes we are ready to take a test point at 20% RH at 25 °C. Record the readings from the 2500 and dew point hygrometer.

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The displayed output values from the hygrometer are illustrated in sequence Figs. 5.16 - 5.20.

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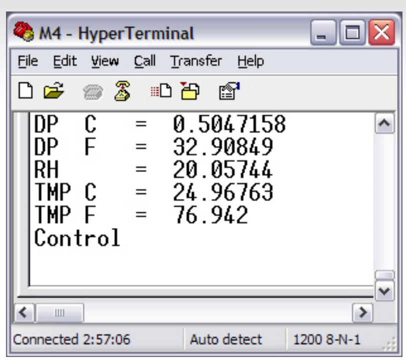

Figure 5.21

In addition to the manual readings the serial output from the hygrometer has been recorded using a terminal program on a PC laptop. The displayed values offer higher resolution and permanent record for the 20% RH test point.

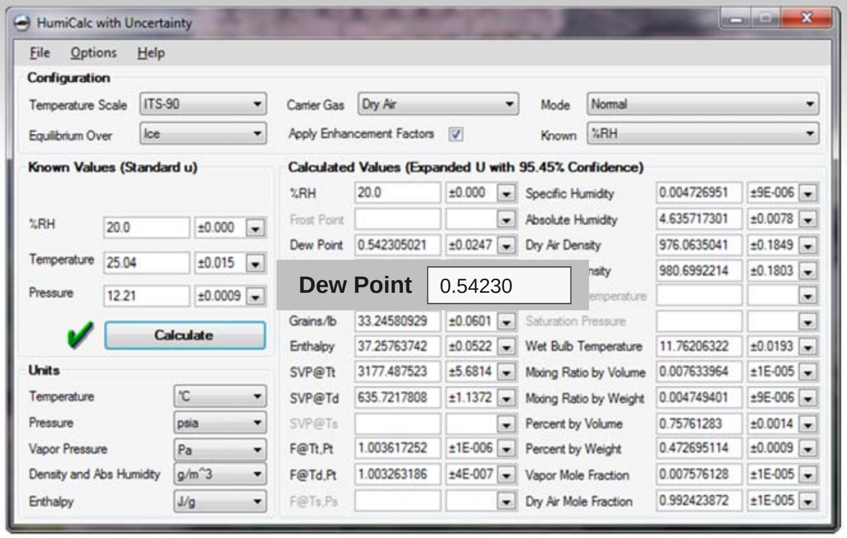

Figure 5.22

Using HumiCalc® the dew point value has been calculated at the 20% RH test point using the measured values from the 2500.

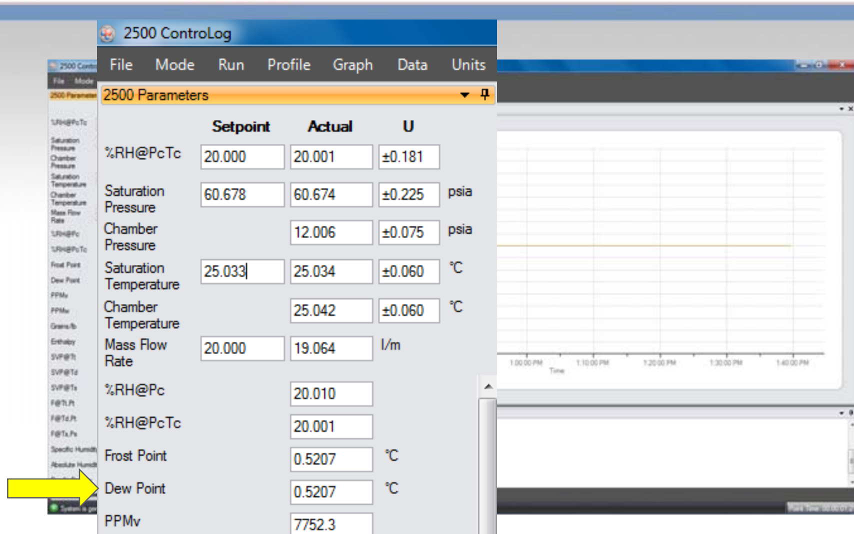

Figure 5.23

- The display screen from ControLog® Automation software is shown in Fig. 5.23, note the dew point value is displayed in the calculated humidity parameters. Using ControLog® in conjunction with the serial output from the hygrometer will save time recording and storing calibration data.

Figure 5.24

Change the set point on the 2500 to 50% RH at 25 °C. When using ControLog® click on the humidity set point and input the new set point of 50% RH. The set point stabilization time will be 30 minutes. Record the readings from the 2500 and dew point hygrometer at 50% RH.

Humidity Generation and Calibration Equipment
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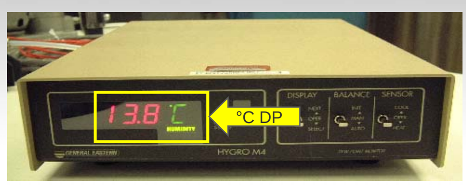

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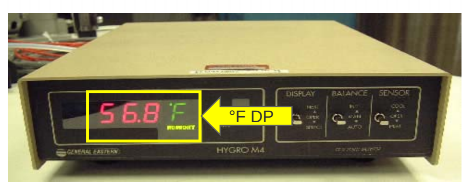

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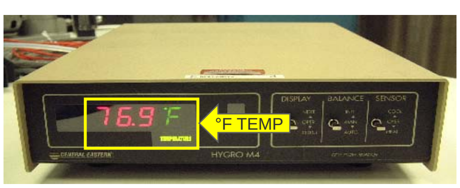

The displayed output values from the hygrometer are illustrated in sequence Figs. 5.25 - 5.29.

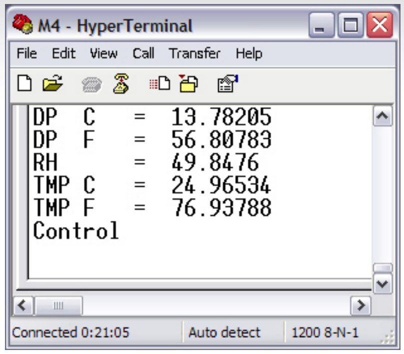

Figure 5.30

In addition to the manual readings the serial output from the hygrometer has been recorded using a terminal program on a PC laptop. The displayed values offer higher resolution and permanent record for the 50% RH test point.

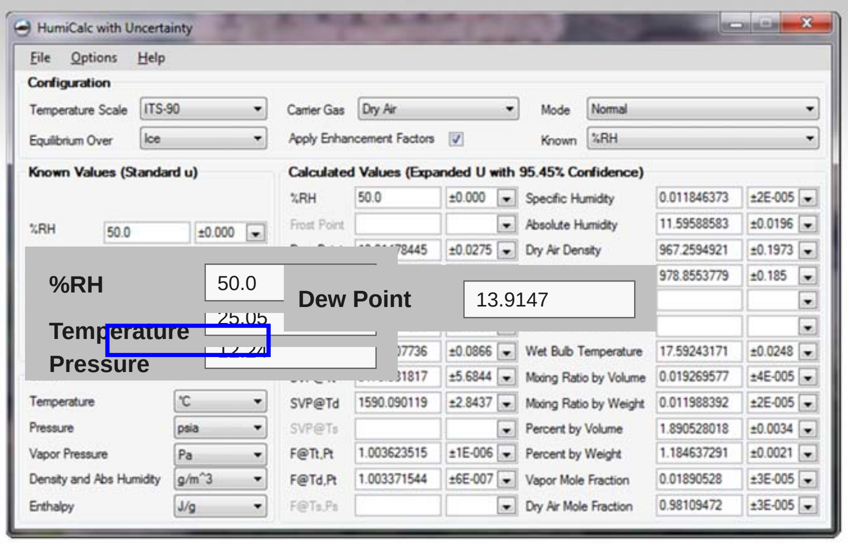

Figure 5.31

Using HumiCalc® the dew point value has been calculated at the 50% RH test point using the measured values from the 2500.

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The Humidity Source

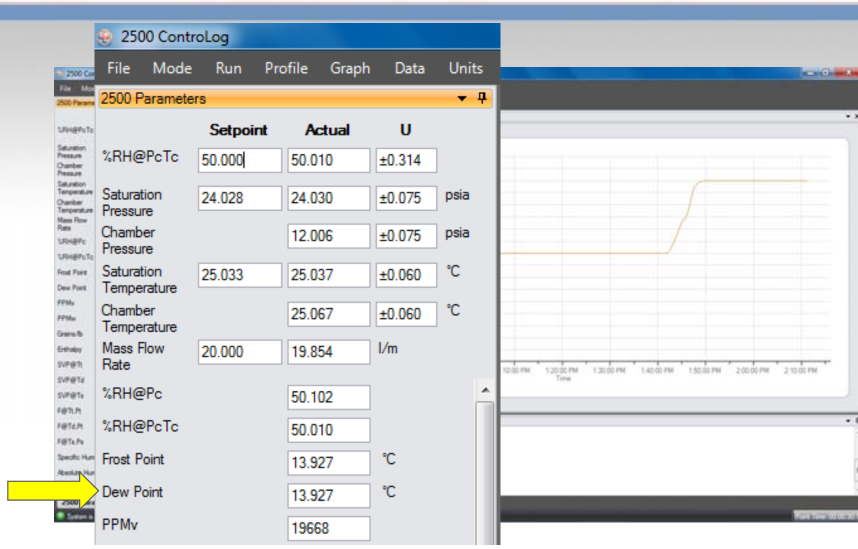

Figure 5.32

- The display screen from ControLog® Automation software is shown in Fig. 5.32 note the dew point value is displayed in the calculated humidity parameters.

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The Humidity Source

Figure 5.33

Change the set point on the 2500 to 80% RH at 25 °C. When using ControLog® click on the humidity set point and input the new set point of 80% RH. The set point stabilization time will be 30 minutes.

Record the readings from the 2500 and dew point hygrometer at 80% RH.

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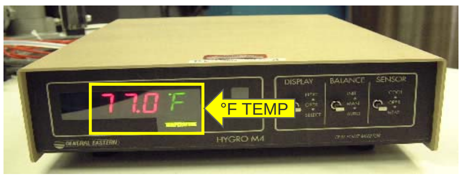

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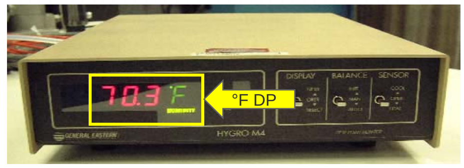

The displayed output values from the hygrometer are illustrated in sequence Figs. 5.34 - 5.38.

Humidity Generation and Calibration Equipment
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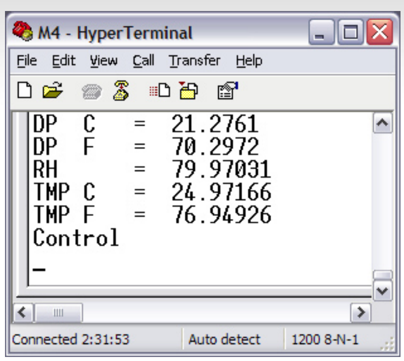

Figure 5.39

In addition to the manual readings the serial output from the hygrometer has been recorded using a terminal program on a PC laptop. The displayed values offer higher resolution and permanent record for the 80% RH test point.

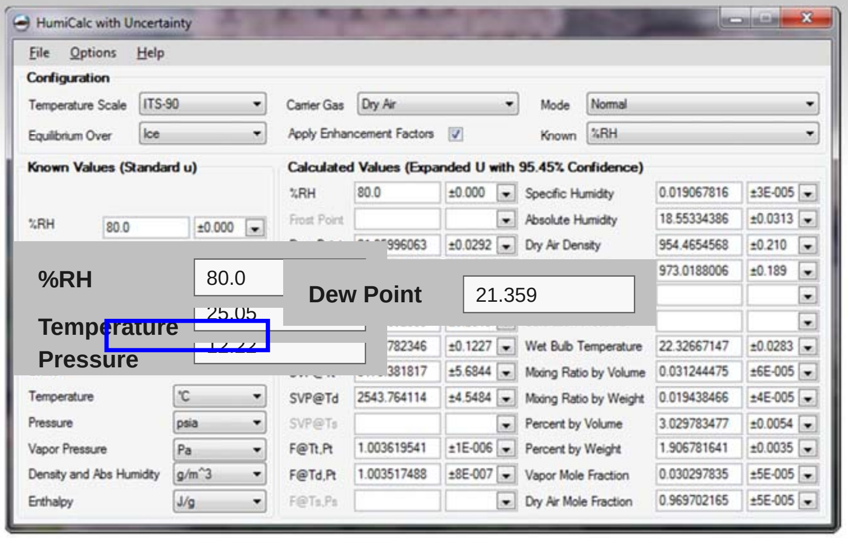

Figure 5.40

Using HumiCalc® the dew point value has been calculated at the 80% RH test point using the measured values from the 2500.

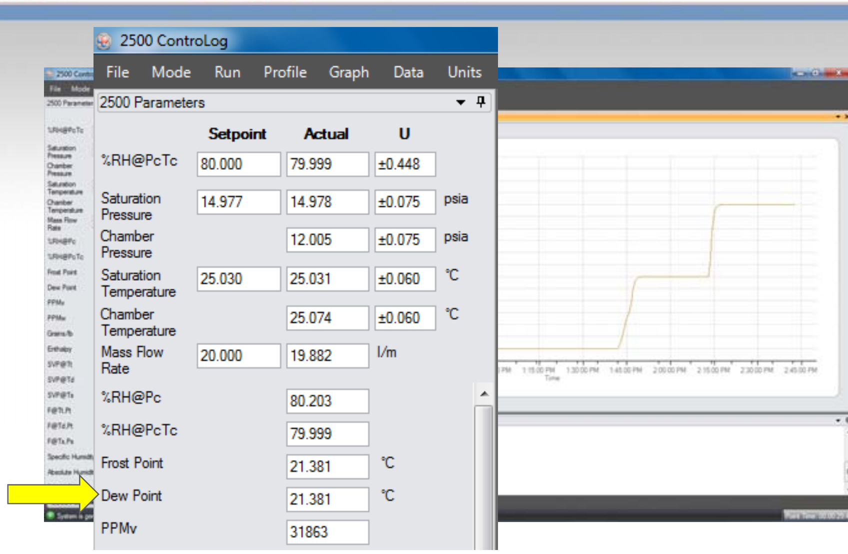

Figure 5.41

- The display screen from ControLog® Automation software is shown in Fig. 5.41 note the dew point value is displayed in the calculated humidity parameters.

- The initial as found calibration is complete. The dew point mirror should be cleaned and inspected as per the manufacturers recommendation before testing the as left calibration of the dew point hygrometer.
- The as left calibration will be performed using the same test points beginning at 20% RH, test point interval will be 30 minutes.

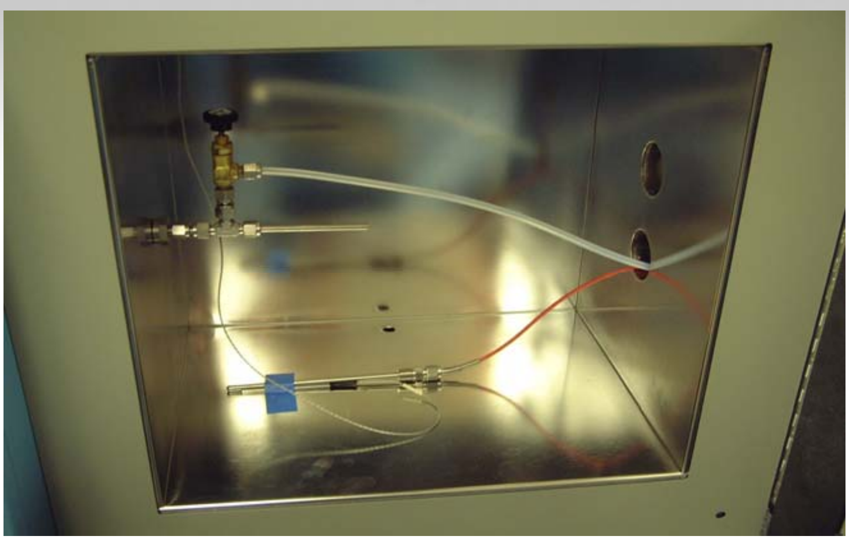

Figure 5.42

An alternate test setup when the air sample pump is not available is shown in the following illustrations.

See the next three figures.

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- A tee fitting with needle adjustment valve has been assembled and threaded into the 2500 chamber inlet port. The inlet of the tee fitting is open to the test chamber. The sample tube is connected to the needle valve at one end, the other end is connected to the dew point mirror. The 2500 chamber temp sensor and hygrometer temp probe have been taped to the bottom of the test chamber.

See figure 5.43 on next page.

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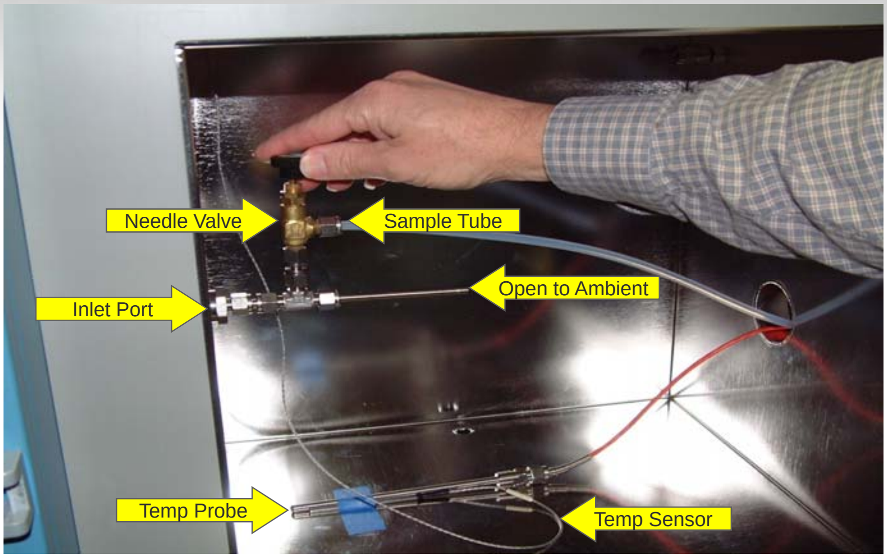

Figure 5.43

Figure 5.44

The outlet from the mirror is shown connected to the flow meter. It will be necessary to run the 2500 at the first test point and adjust the needle valve for proper flow rate through the dew point mirror as shown in Fig. 5.43 Wait 5 minutes for the 2500 to stabilize at the set point before attempting the flow rate adjustment.

Humidity Generation and Calibration Equipment
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Questions?

Comments?

High Dew Point Calibration

Calibration at dew points above ambient temperatures…

Figure 6.1

Humidity Generation and Calibration Equipment
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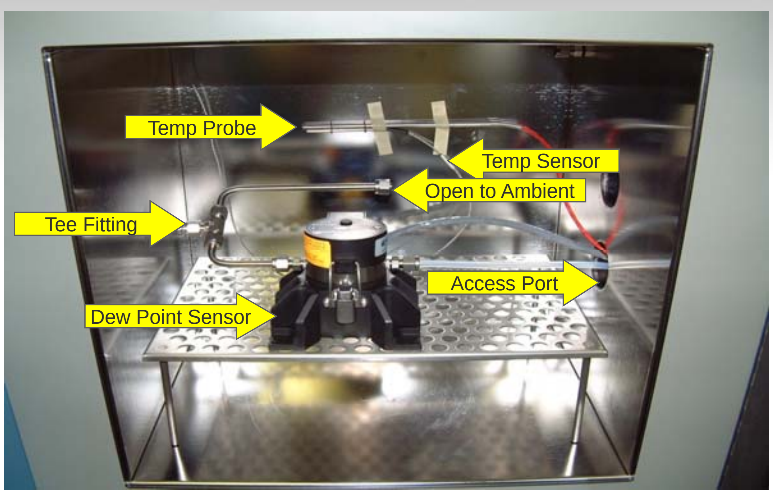

Figure 6.2

Install the dew point sensor in the test chamber as shown in Fig. 6.2 in this example a shelf is used to position the dew point sensor in-line with the access port.

The temperature probe from the test instrument DUT will be taped to the back wall of the test chamber with the 2500 chamber temperature sensor.

- A tee fitting is installed at the chamber inlet for connection to the dew point sensor; note an open tube on the opposite end of the tee fitting is used to direct the additional flow into the test chamber. The outlet of the dew point sensor is connected to clean ¼" Teflon tubing, the sample line should be sloped downward from the dew point sensor to prevent condensation in the tubing from draining back to the dew point sensor.

Refer back to figure 6.2

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Figure 6.3

The outlet tubing is connected to an adjustable valve and flow meter. Change the 2500 flow rate to 10 L/m, adjust the valve to a flow rate of 1 L/m at the flow meter.

Figure 6.4

Note the flow meter will be removed during the calibration due to the potential condensation at the outlet tube.

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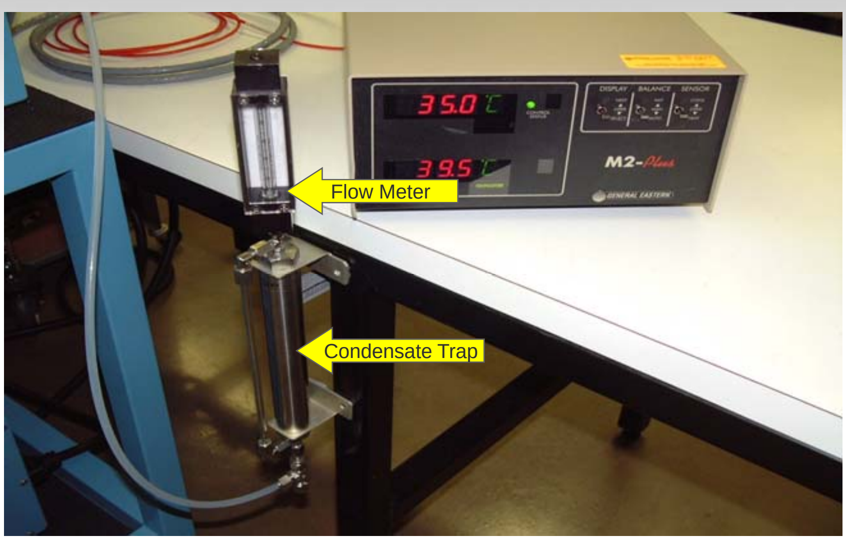


Figure 6.5

A condensate trap can be used to collect condensing moisture before the flow meter as shown in Fig. 6.5

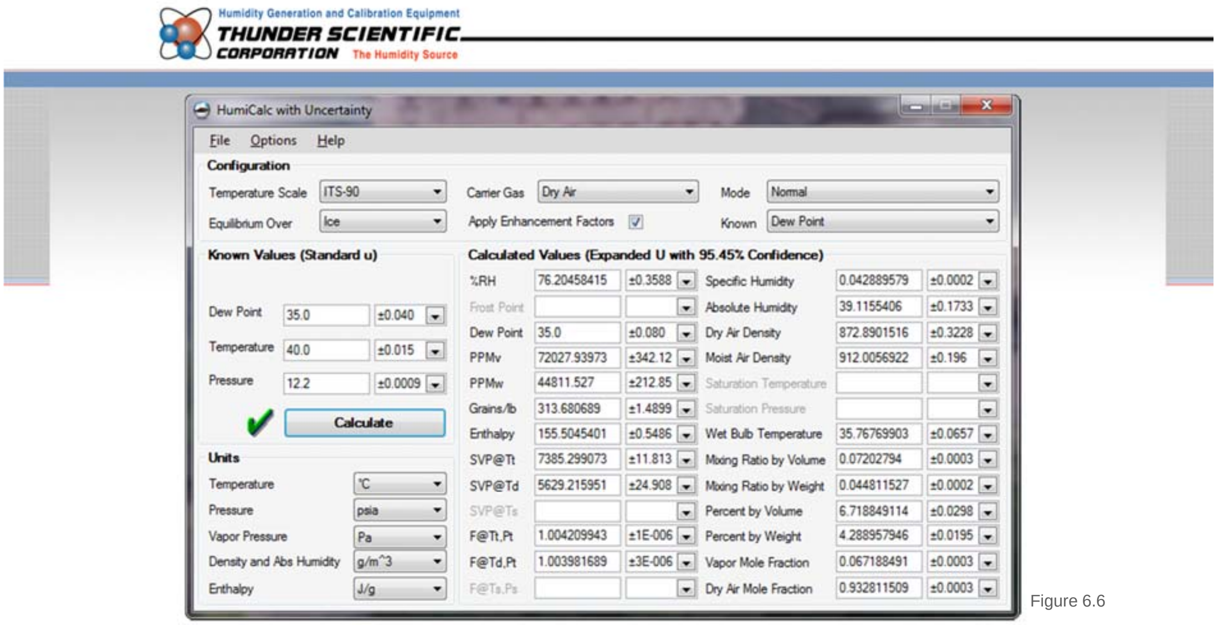
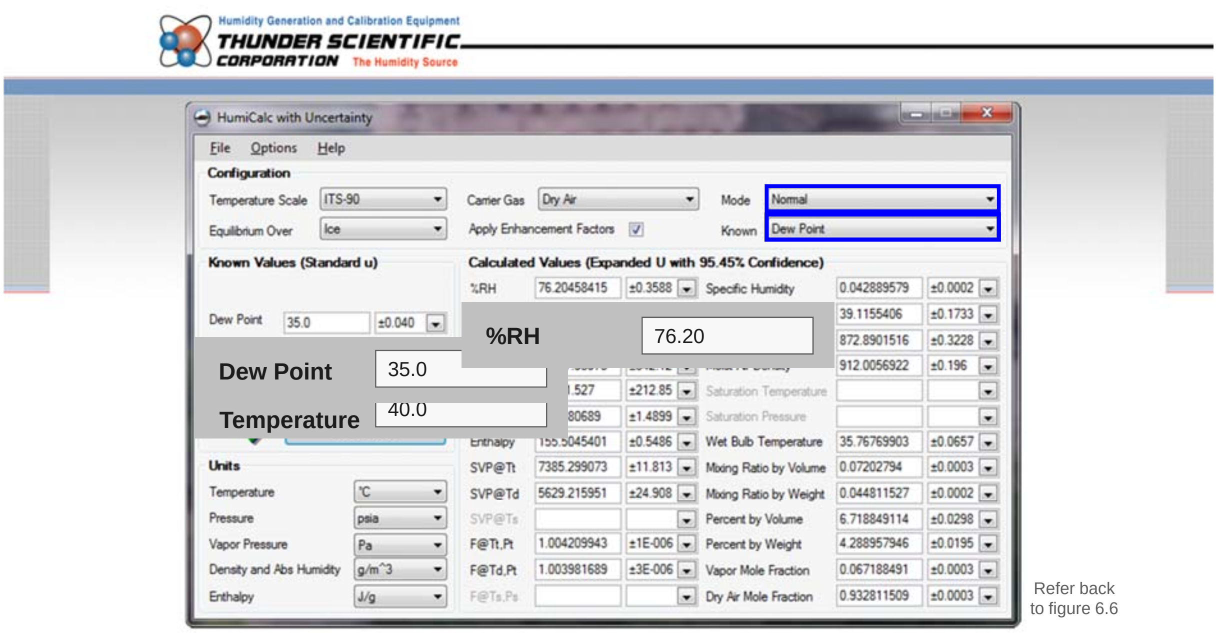


Figure 6.6

The target test point for this calibration is +35 °C dew point, to accomplish this elevated dew point it will be necessary to operate the test chamber at a test temperature of 40 °C.

Using HumiCalc® we can calculate the humidity set point at 40 °C test temperature to achieve the desired dew point. Please view HumiCalc® example screen Fig. 6.6.



Refer back to figure 6.6

Select Normal Mode, the known value will be Dew Point DP, the test temperature needs to be higher than the known dew point DP, enter 40 °C test temp, enter 35 °C for the known dew point DP value. The %RH calculated is 76.20% RH.

Begin the Calibration Test

- You should begin the calibration test at a lower %RH set point until the test chamber temperature is within 2 degrees of the desired set point of 40 °C, as an example start the test at 20% RH until the test chamber actual displays 38 °C, change the humidity set point to 76.20% RH and allow the 2500 to stabilize for a minimum of 30 minutes. Wait for the DUT dew point indication to stabilize before recording the calibration point.

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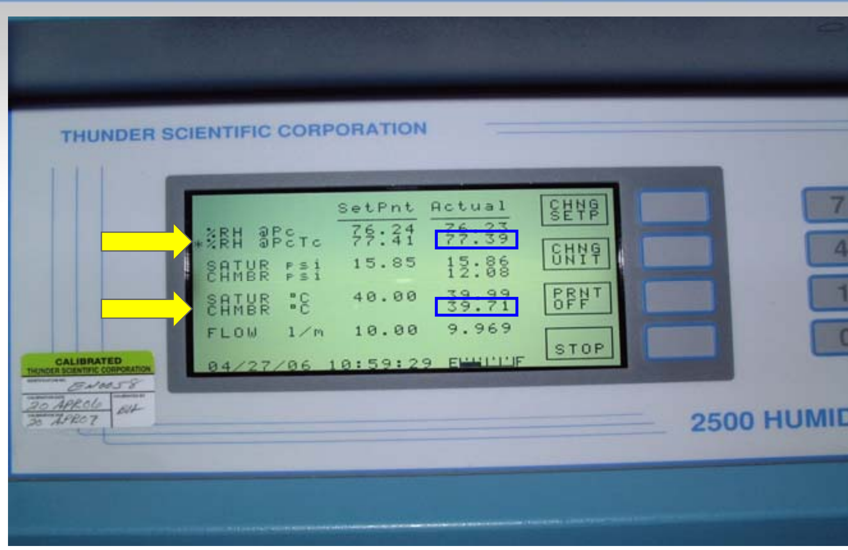

Figure 6.7

Input actual humidity, chamber temperature and chamber pressure, press calculate, HumiCalc® will display the generated dew point as shown in Fig. 6.7. A normal test time duration of 2 hours will be required to complete this test.

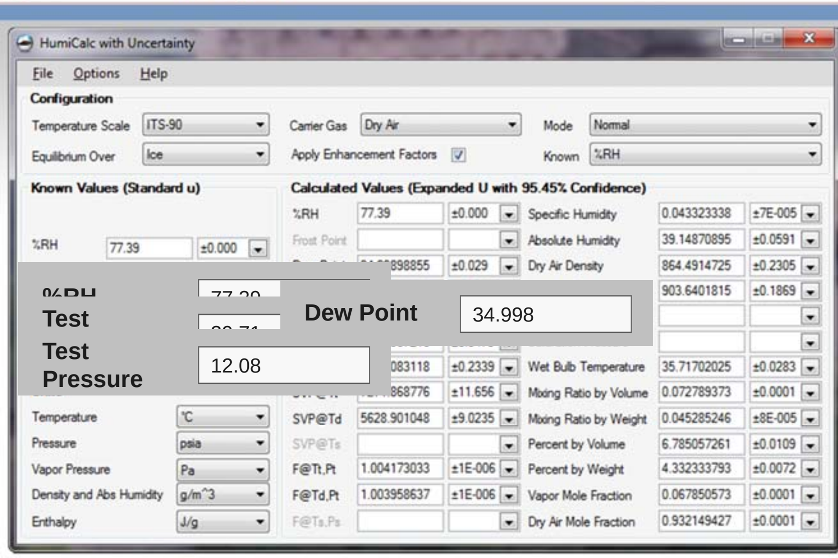

Figure 6.8

Using HumiCalc® calculate the actual generated dew point using the values displayed on the 2500 screen Fig. 6.8.

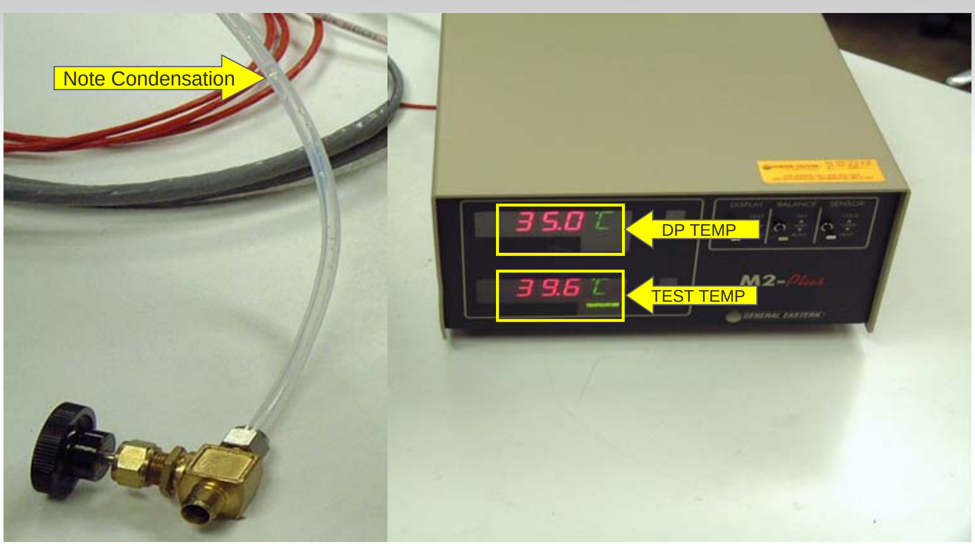

Figure 6.9

DUT display at a humidity set point of 77.39 calculated dew point 34.998, test temperature of 39.71.

- Using ControLog® Automation software under Mode in the menu tool bar select Dew Point, change the test temperature to 40 °C; change the dew point set point to 35 °C.
- Select Generate under the Run menu and begin the calibration test. You should begin the calibration test at a lower dew point until the test chamber temperature is within 2 degrees of the desired set point of 40 °C, as an example start the test at 20 °C dew point until the test chamber actual displays 38 °C, change the dew point set point to 35 °C dew point and allow an additional 30 minutes for stabilization.
- A normal test time duration of 2 hours will be required to complete this test.

Humidity Generation and Calibration Equipment
THUNDER SCIENTIFIC CORPORATION The Humidity Source

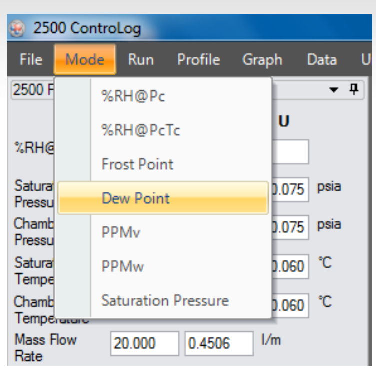

Figure 6.10

Humidity Generation and Calibration Equipment
THUNDER SCIENTIFIC CORPORATION The Humidity Source

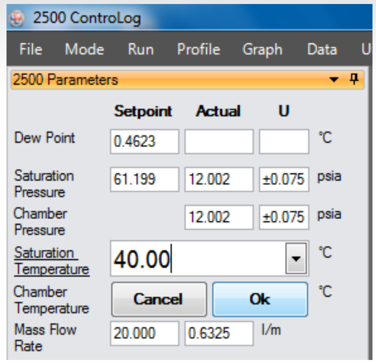

Figure 6.11

Humidity Generation and Calibration Equipment
THUNDER SCIENTIFIC CORPORATION The Humidity Source

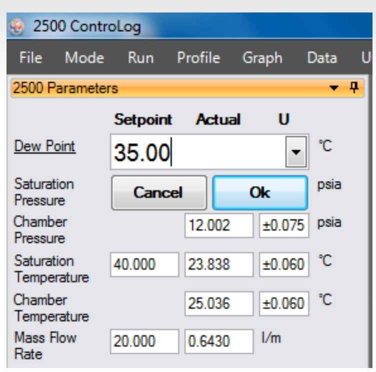

Figure 6.12

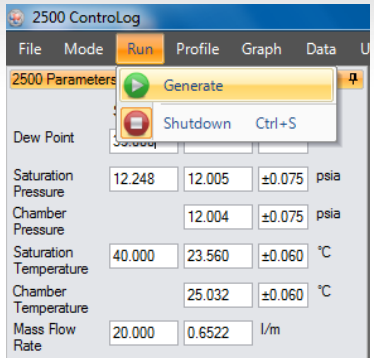

Figure 6.13

Humidity Generation and Calibration Equipment
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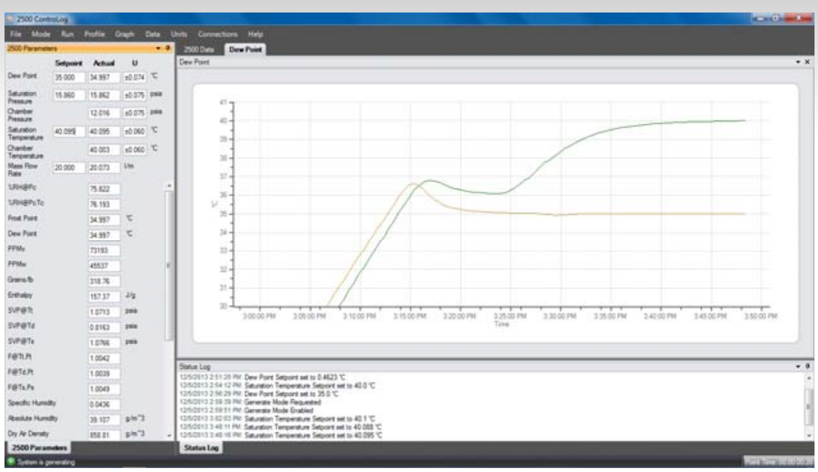


Figure 6.14

Using ControLog® Automation Software, view Fig. 6.14.

Questions?

Comments?

Calibration Divided Flow Humidity Generator

Figure 7.1

- As found calibration using a precision dew point standard with an accuracy of ±0.1 °C DP.
- Dew point hygrometer sample tube installed in the humidity generator test chamber.
- Additional temperature measurement for as found temperature comparison.
- Record as found calibration at humidity test points from 10% RH to +90% RH.

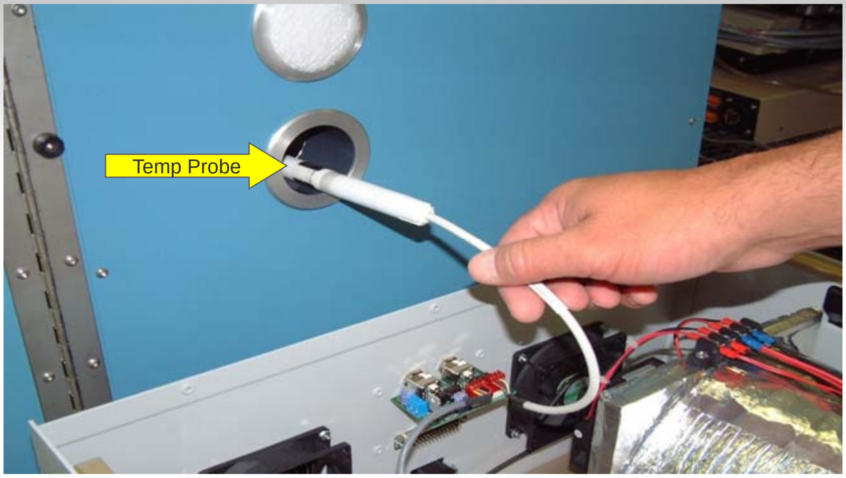


Figure 7.2

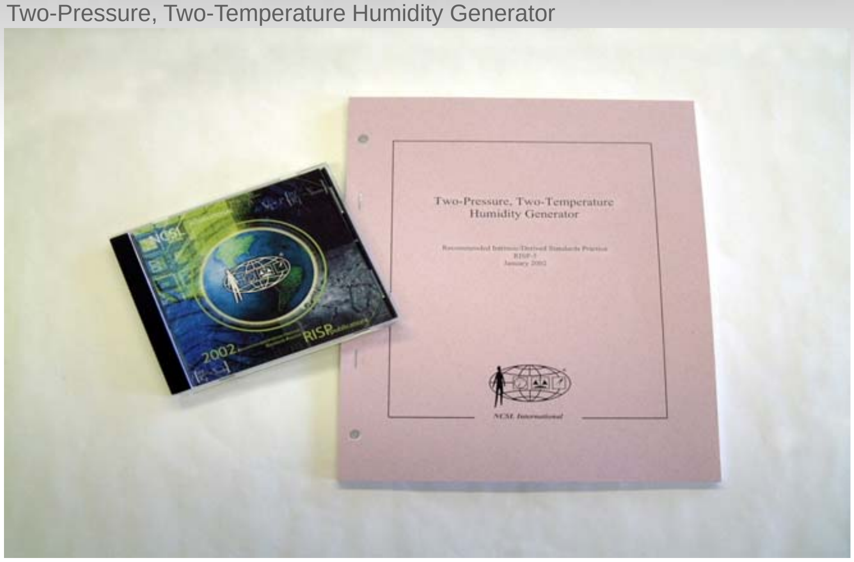
- Calibrate the embedded RH/Temp probe in the Model 2500 humidity generator Calibrate as per the manufacturers test points and procedure.
- Retest the Divided Flow Humidity Generator as left calibration after calibration adjustment of the embedded RH/Temp control sensor.

Questions?

Comments?

NCSL – RISP – 5

Two-Pressure, Two-Temperature Humidity Generator



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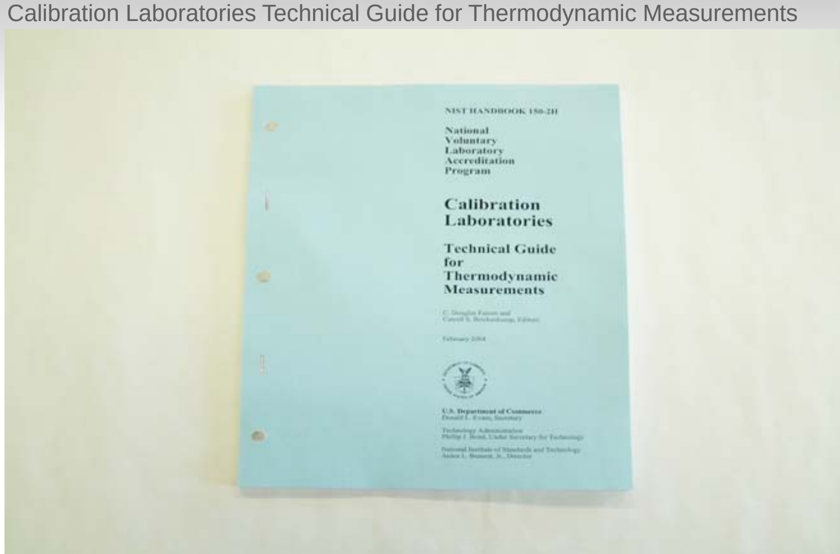
NIST – Handbook 150-2H

Calibration Laboratories Technical Guide for Thermodynamic Measurements



ASTM D 4230-02
Standard Test Method of Measuring Humidity with Cooled-Surface Condensation (Dew-Point) Hygrometer

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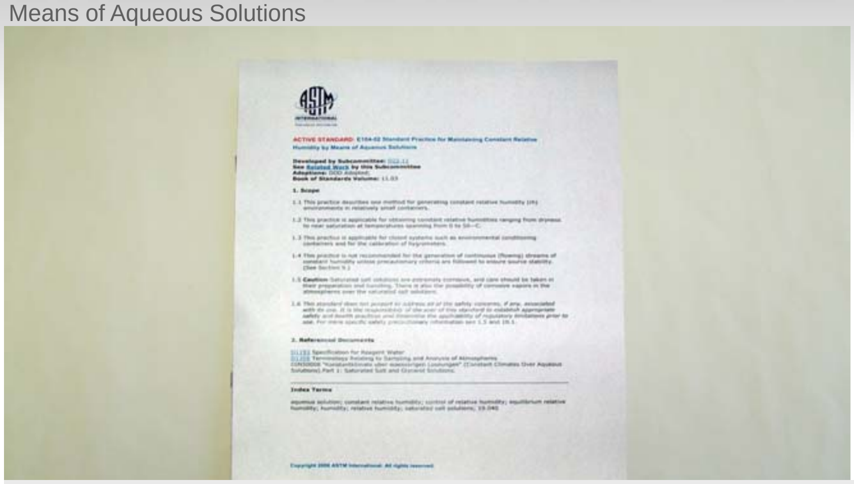
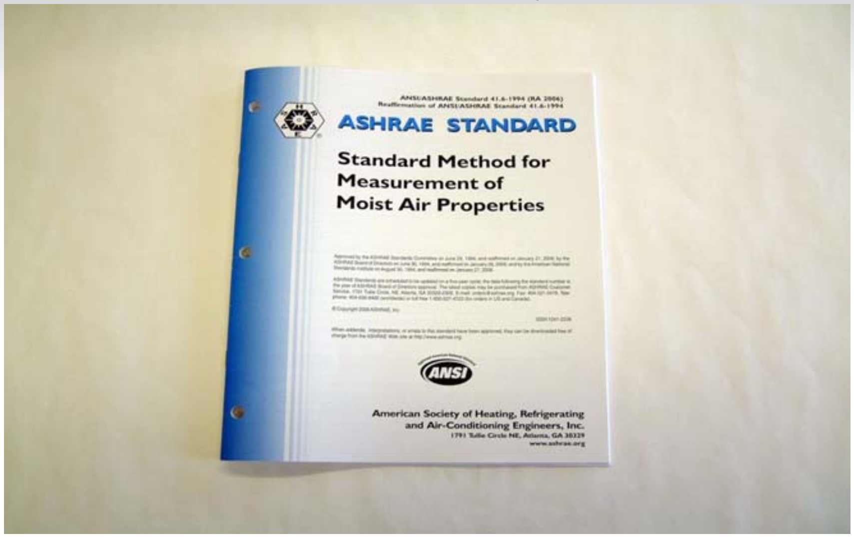
ASTM E104-02
Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions



Caution-Saturated salt solutions are extremely corrosive, and care should be taken in their preparation and handling. There is also the possibility of corrosive vapors in the atmospheres over the saturated salt solutions.

ASHRAE Standard – Spc.41.6-1994R
Standard Method for Measurement of Moist Air Properties



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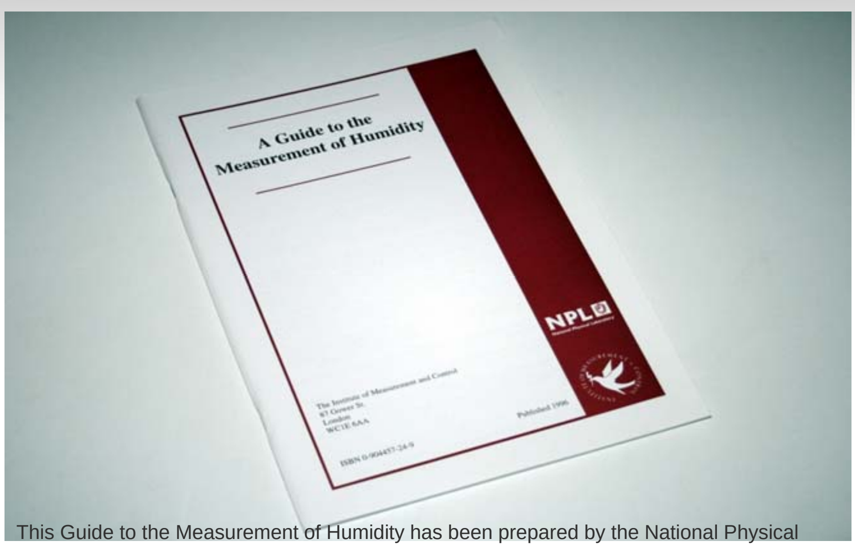
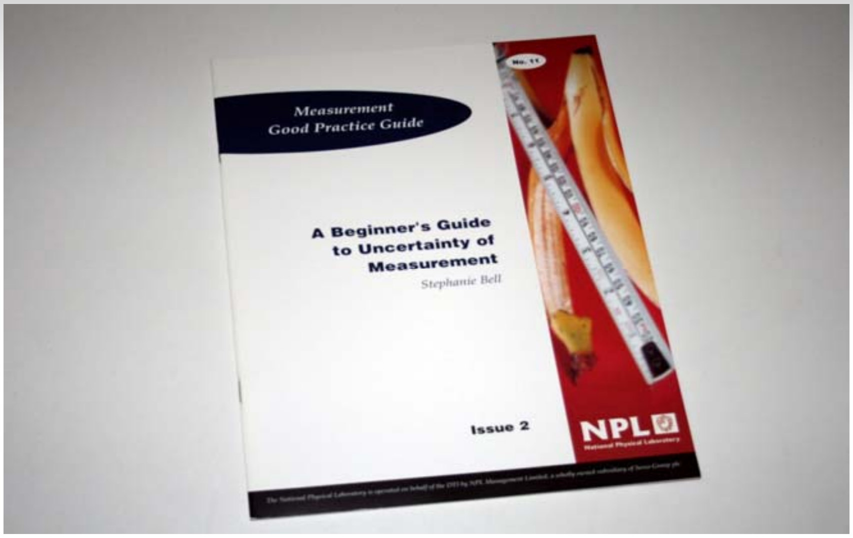
A Guide to the Measurement of Humidity



This Guide to the Measurement of Humidity has been prepared by the National Physical Laboratory and the Institute of Measurement & Control, supported by the National Measurement System Policy Unit of the Department of Trade and Industry.

A Beginner's Guide to Uncertainty of Measurement



The aim of this Beginner's Guide is to introduce the subject of measurement uncertainty.

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Principles for Calibration Point Selection

This technical paper will give you a basic understanding of Calibration Point Selection.

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HUMICALC CONVERSION EXAMPLES

This section provides you with a few examples relating to the different features and configurations of HumiCalc. By following along, you will become familiar with how to use these features and configurations. The examples shown here do not constitute a comprehensive list of humidity computations, but may be used as guidelines in solving similar or related humidity problems.

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CONVERTING %RH TO A NEW PRESSURE AND TEMPERATURE

- Convert 50.0 %RH measured at 25.0 °C and 12.5 psia, to the resulting Relative Humidity at 50.0 °C and 14.7 psia.

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- This type of operation requires a two-step process. First, we will convert %RH at one pressure and temperature to PPMv. We will then convert this PPMv to a %RH at a new pressure and temperature. PPMv is used as the intermediary variable to effectively hold the mixing ratio of the gas, since once determined; it will not vary with changes in pressure and/or temperature.

- RH-to-RH conversions of this type should always be done through PPMv or another temperature and pressure insensitive variable.

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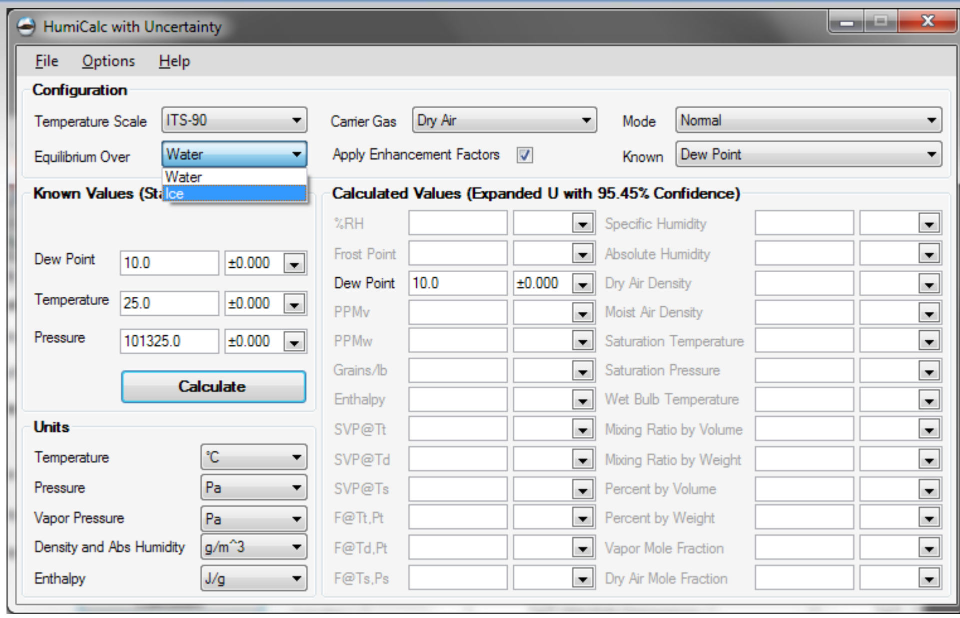

Set the Equilibrium to Ice

Humidity Generation and Calibration Equipment
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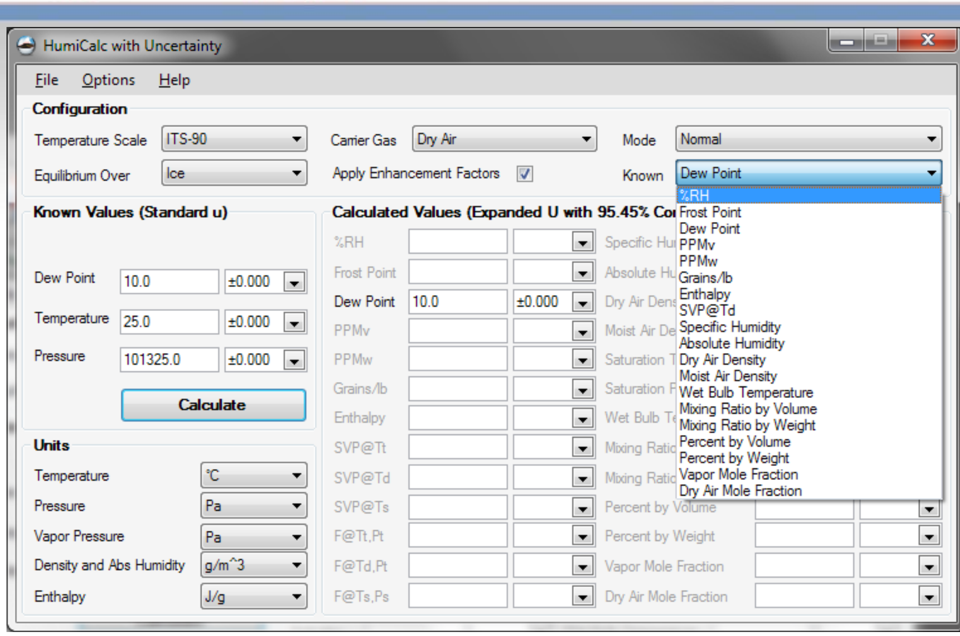
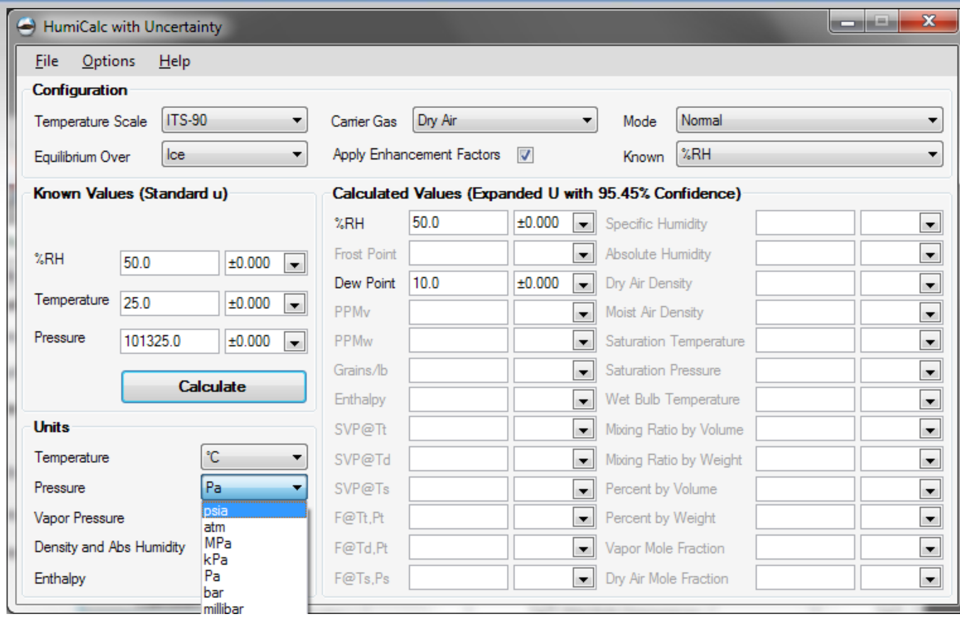
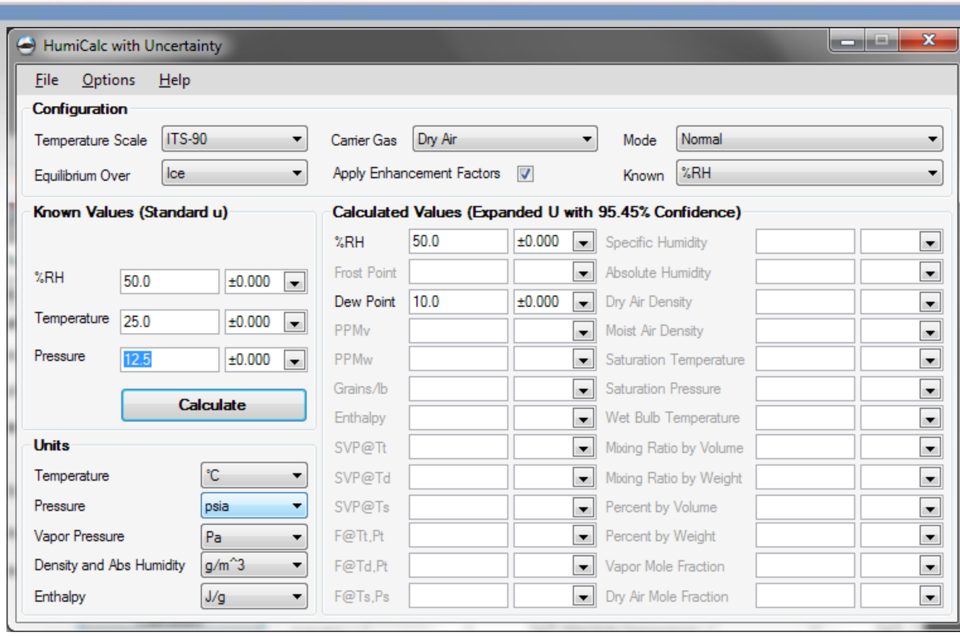


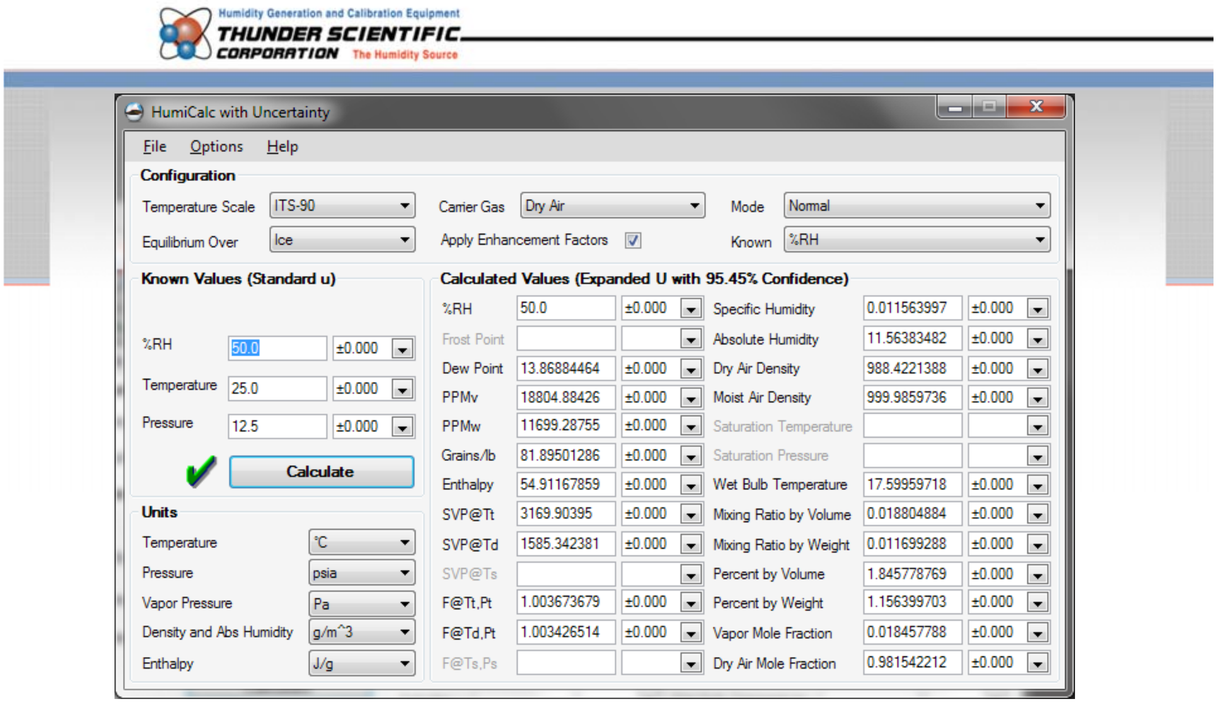
Set the Known to %RH



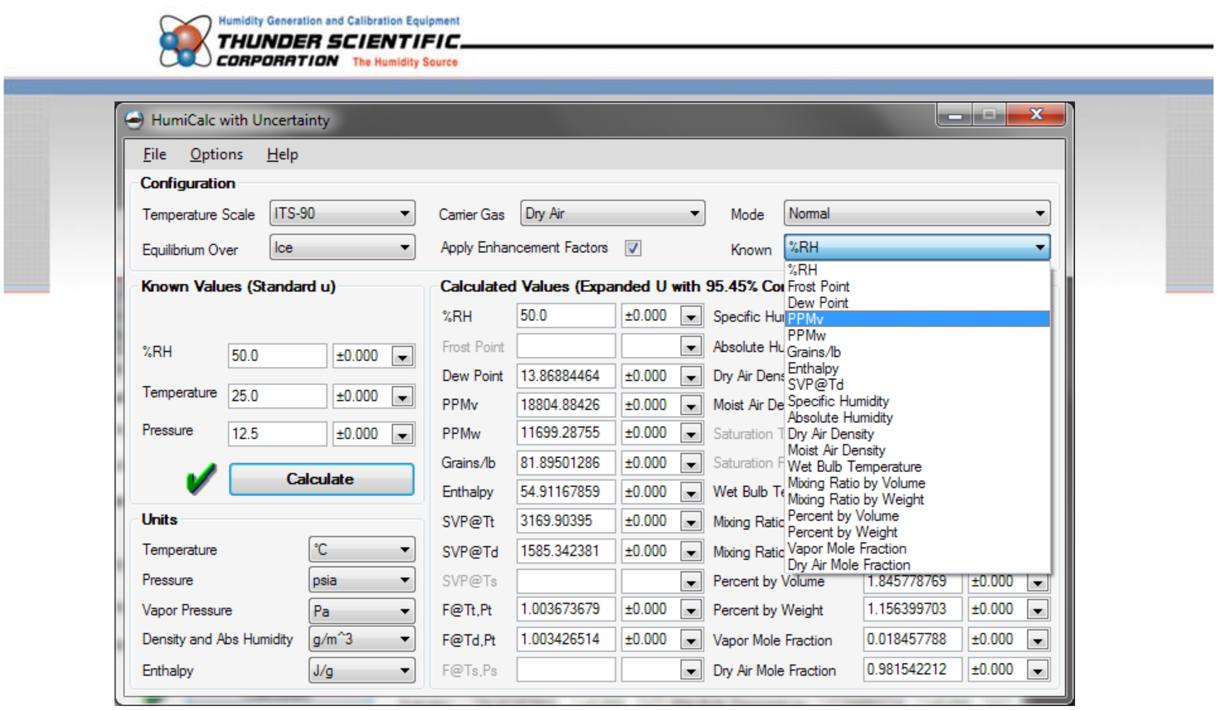
Set the Pressure Units to psia



Enter the Known Values



Click the Calculate button



Change the Configuration to have the known set to PPMv.

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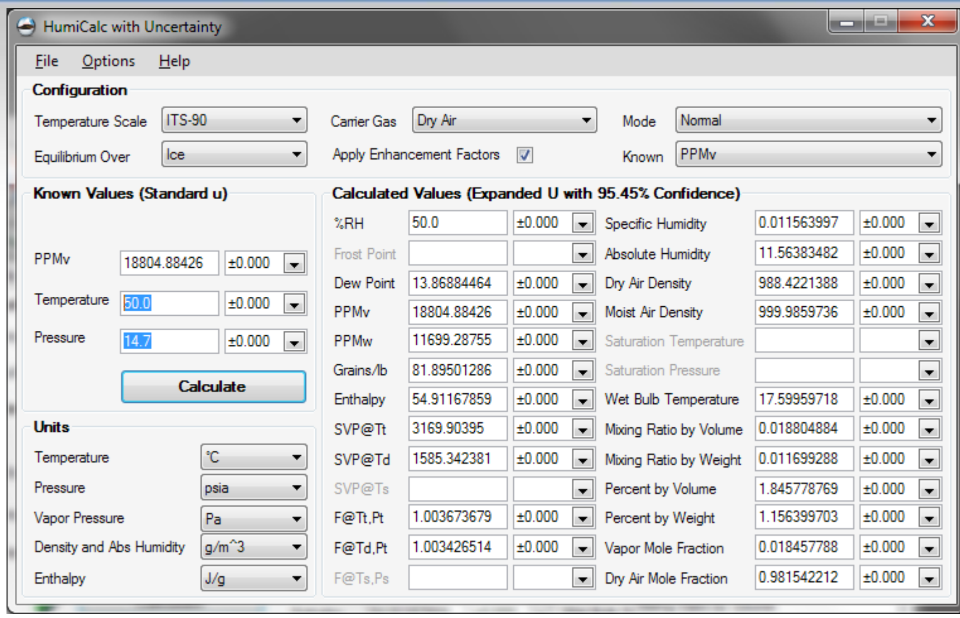

Enter the new Temperature and Pressure values but leave the PPMv

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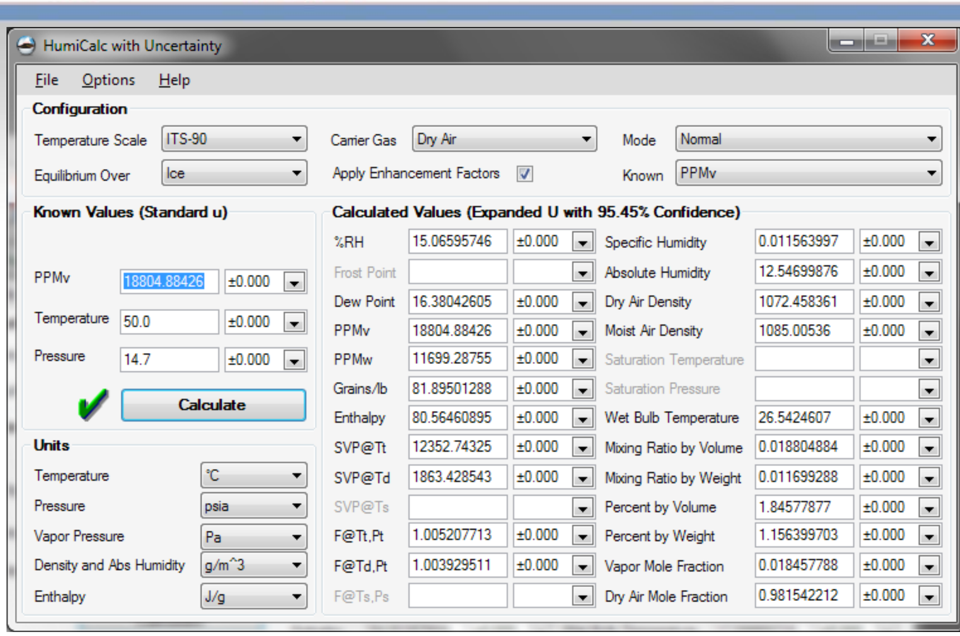
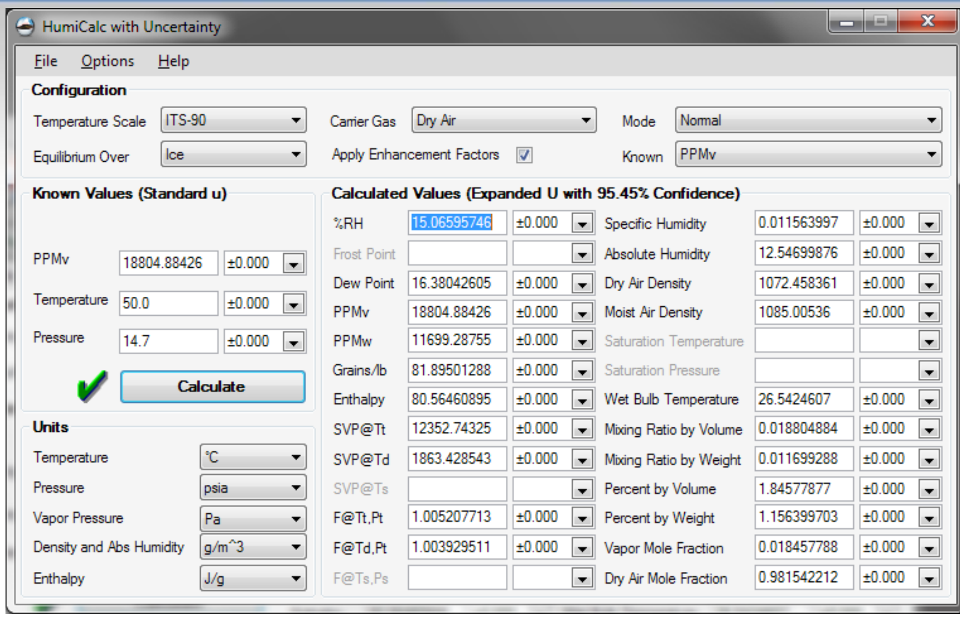


Click the Calculate button



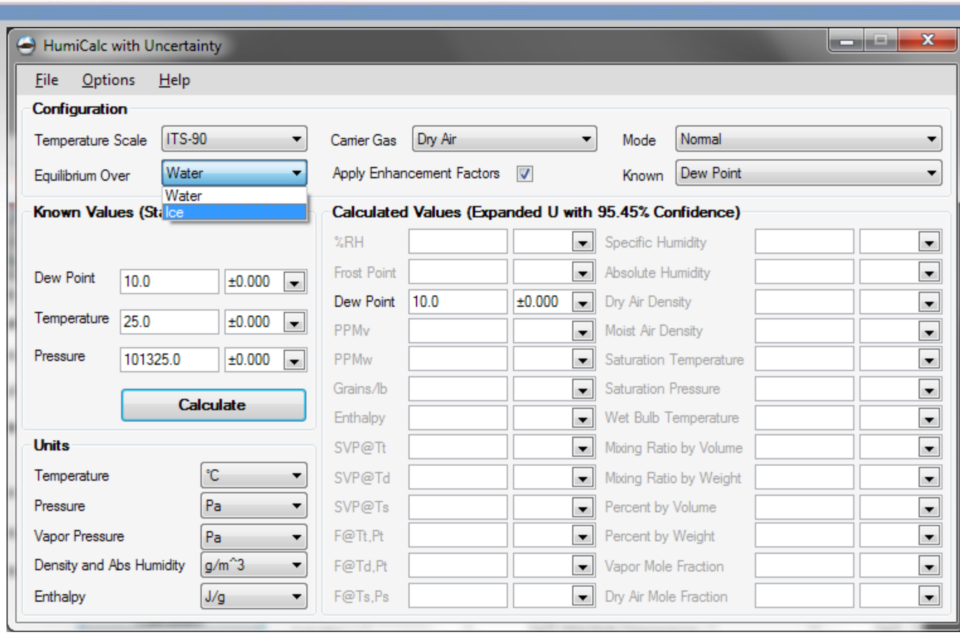
Look at the calculated value for new %RH

Questions?

Comments?

Dewpoint Control in a Two Pressure Generator

- Determine the Saturation Pressure needed in order to generate air with a Dew Point of 5.0 °C in the chamber of a Two Pressure Humidity Generator.
- Also determine the corresponding %RH.
- For this example we will use a Saturation Temperature of 21.15 °C, a Test Pressure of 15.0 psia and a Test Temperature of 21.11 °C.



Set the Equilibrium to Ice

Humidity Generation and Calibration Equipment
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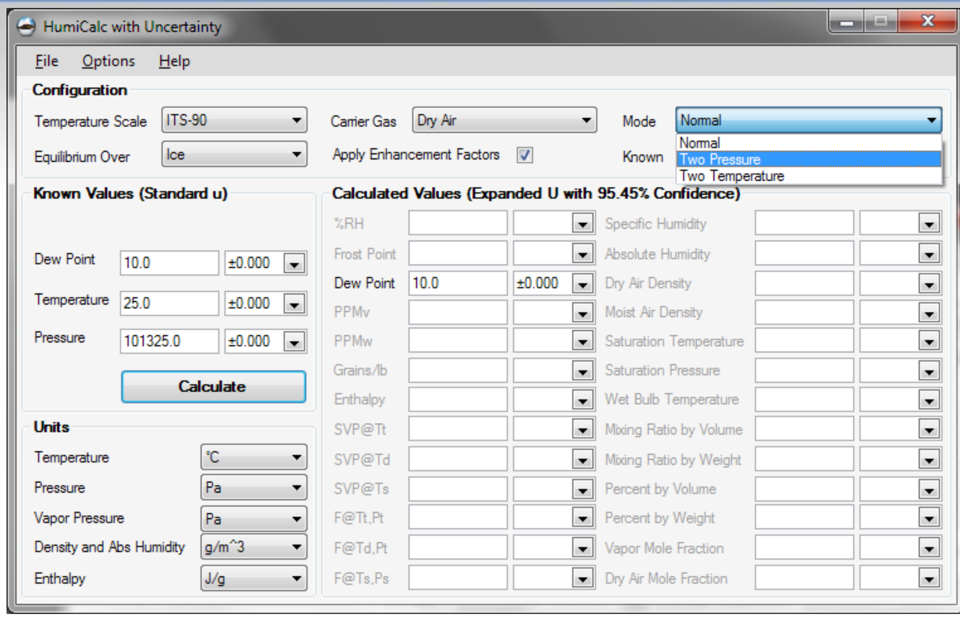

Set the Mode to Two Pressure

Humidity Generation and Calibration Equipment
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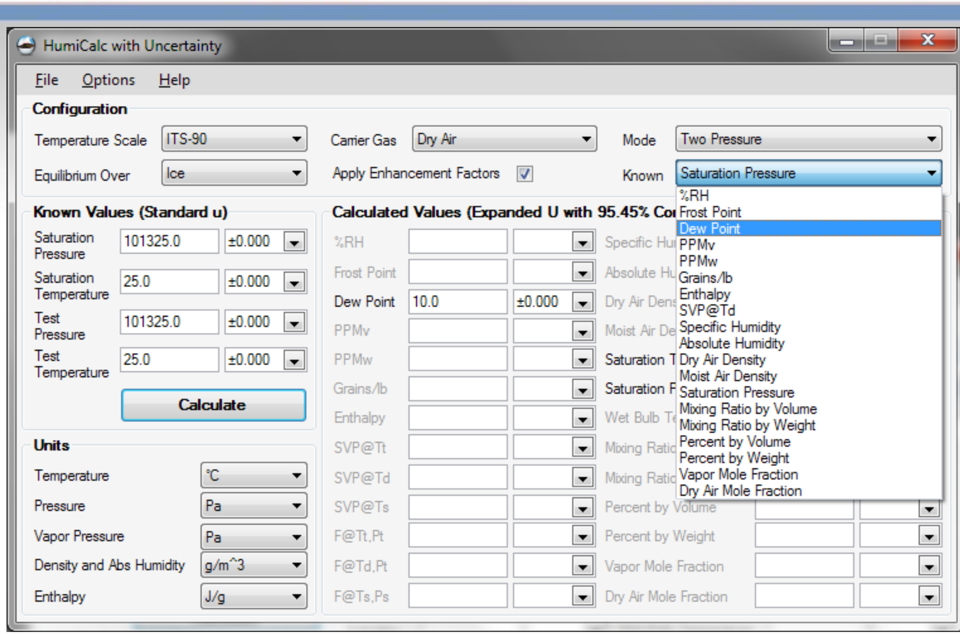
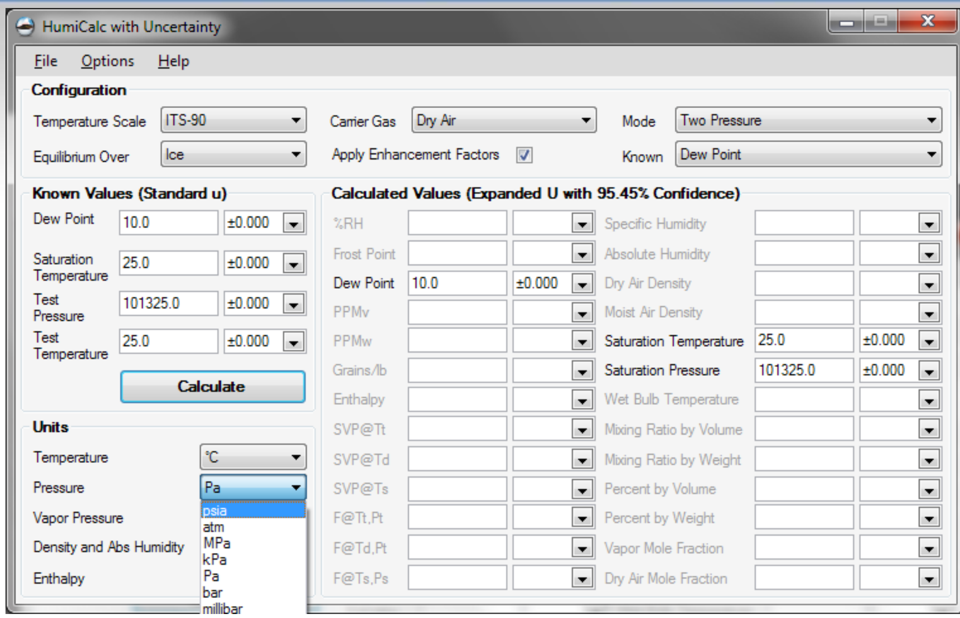
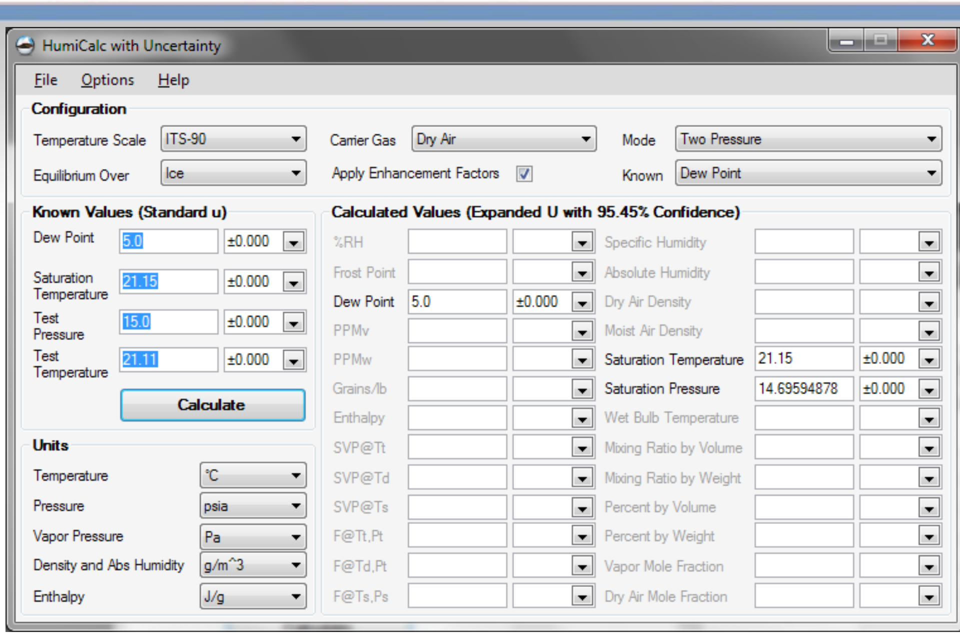


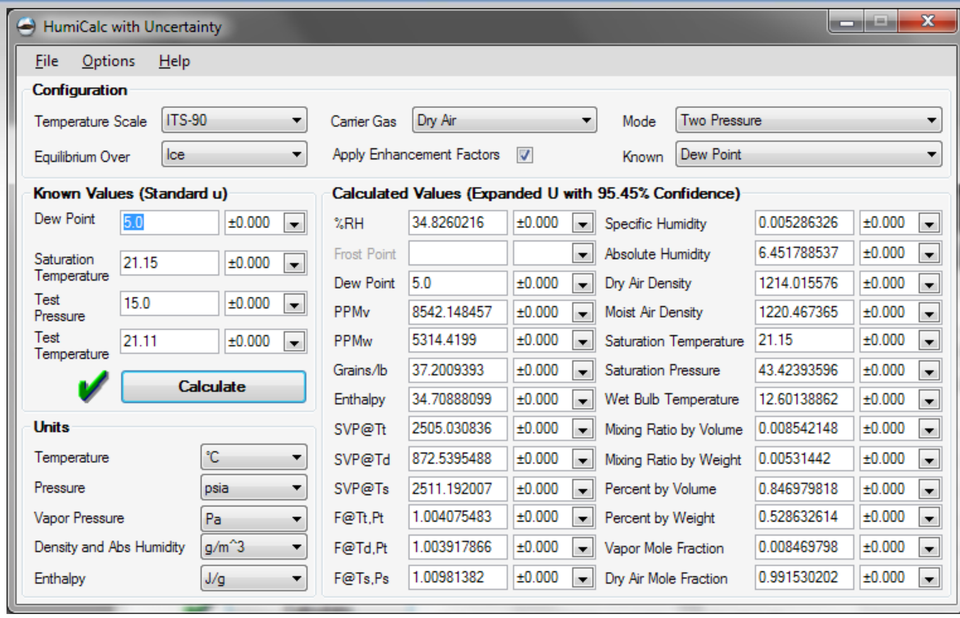
Set the Known to Dew Point



Set the Pressure Units to psia

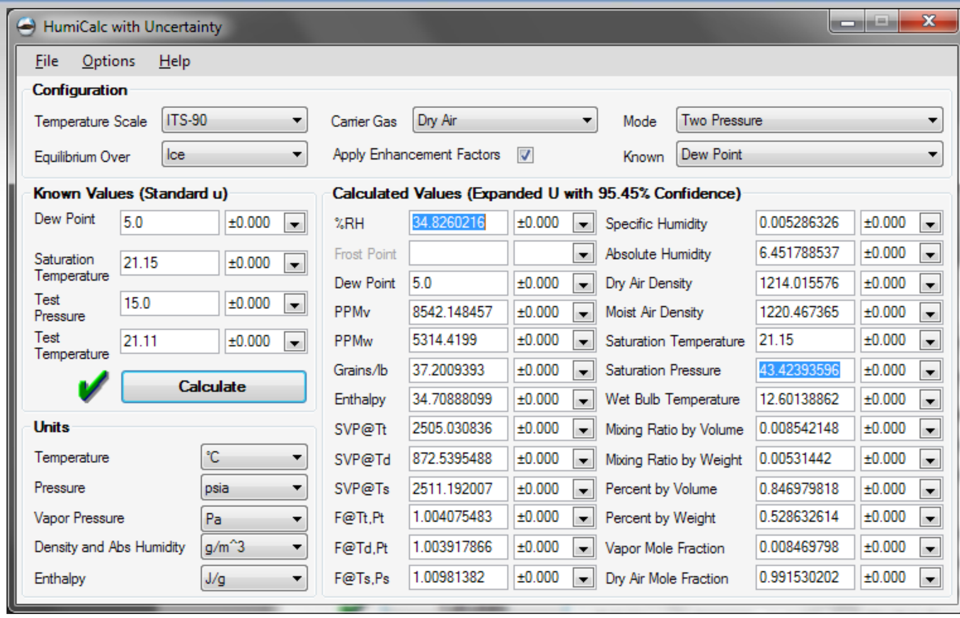


Enter the Known Values



Click the Calculate button

- Look at the calculated values for the Saturation Pressure and %RH. These are the %RH or Saturator Pressure setpoints needed to generate a 5.0 °C Dew Point.



Look at calculated Saturator Pressure and %RH

Questions?

Comments?

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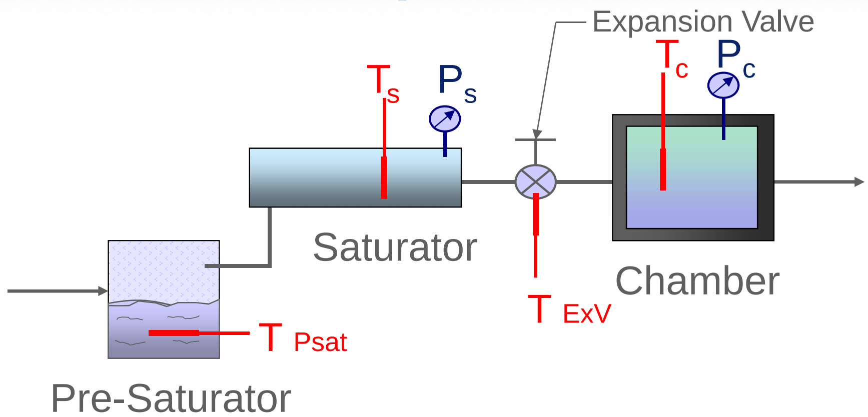
Two-Pressure Humidity Generator Operation



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Pre-Saturation Temperature Probe

The air stream of a two-pressure generator must be 100% saturated with water vapor at test temperature on the high-pressure (saturator) side of the expansion valve. This is accomplished by first passing the air stream through a "pre-saturator". The pre-saturator is a vertical pressure vessel presenting a water surface to the incoming air stream and is maintained constant at a temperature 15 to 20 °C warmer than the desired system (chamber) temperature. The pre-saturator temperature probe is used in the control of the pre-saturator heaters, which when activated, are used to control this 15 to 20 °C temperature offset.

Expansion Valve Temperature Probe

The expansion valve temperature probe is used in the control of the expansion valve heaters, which when activated, are used to warm the expansion valve body, offsetting the cooling effects due to gas expansion. This expansion valve temperature is always maintained above the saturation temperature.

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Saturation and Chamber Temperature and Pressure

Saturation and Chamber Temperatures and Pressures are the major determining factors of error with a Two-Pressure humidity generator.

Flow Meter

The flow rate has no influence on the computed value of the generated humidity, but flow rate errors may have an affect on the devices you are calibrating with the your Two-Pressure Humidity Generator.

How it all comes together

Relative Humidity in a two-pressure humidity generator is determined from the measurements of temperature and pressure only and is expressed by the following formula:

$$\%RH = \frac{e_S(T_S)f(T_S,P_S)}{e_S(T_C)f(T_C,P_C)} \cdot \frac{P_C}{P_S}\eta_S$$

Where the *f* functions are enhancement factors, *eS* is the saturation vapor pressure, *hS* is the % efficiency of saturation, *Tc and Ts* are the chamber and saturation temperatures, and Pc and Ps are the chamber and saturation pressures.

Questions?

Comments?

DETERMINING %RH IN A TWO PRESSURE GENERATOR

- When using a Two Pressure generator, you are calibrating a unit that displaces enough heat to raise the chamber temperature by 1.4 °C above the fluid bath and saturator temperatures. What is the %RH in the chamber at this elevated chamber temperature?

- Also, assuming that you know the internal temperature of the unit, which is generating this heat load, what is the relative humidity within the unit under test at its temperature?

- First we will find the %RH at the chamber temperature.
- Then, since HumiCalc will already be configured correctly, we can recalculate the %RH at the temperature of the heat-loading unit under test.
- For this example we will use a Saturation Pressure of 64.75 psia, a Saturation Temperature of 21.1 °C, a Test Pressure of 15.0 psia and a Test Temperature of 22.5 °C.

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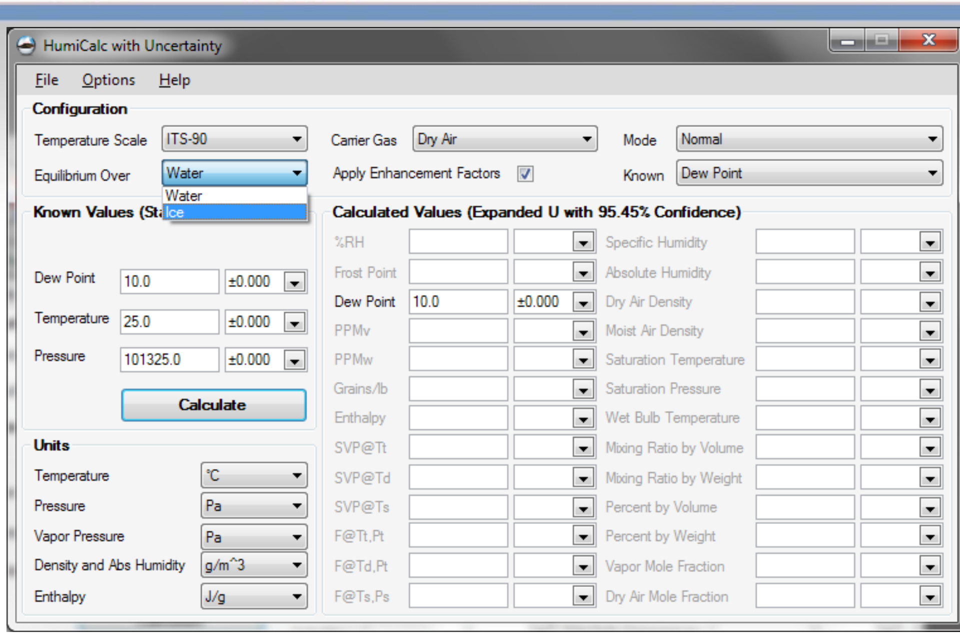
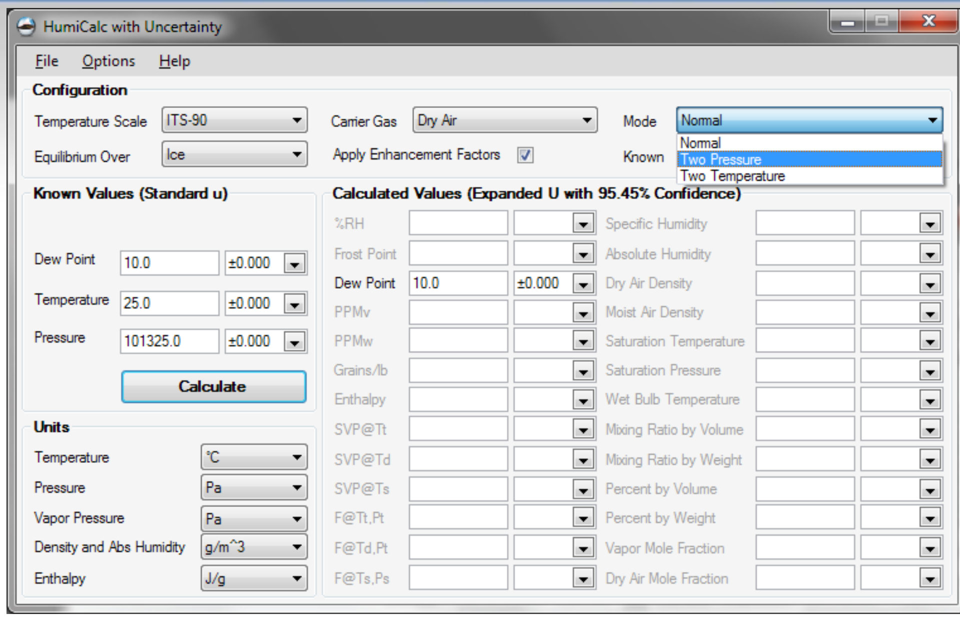
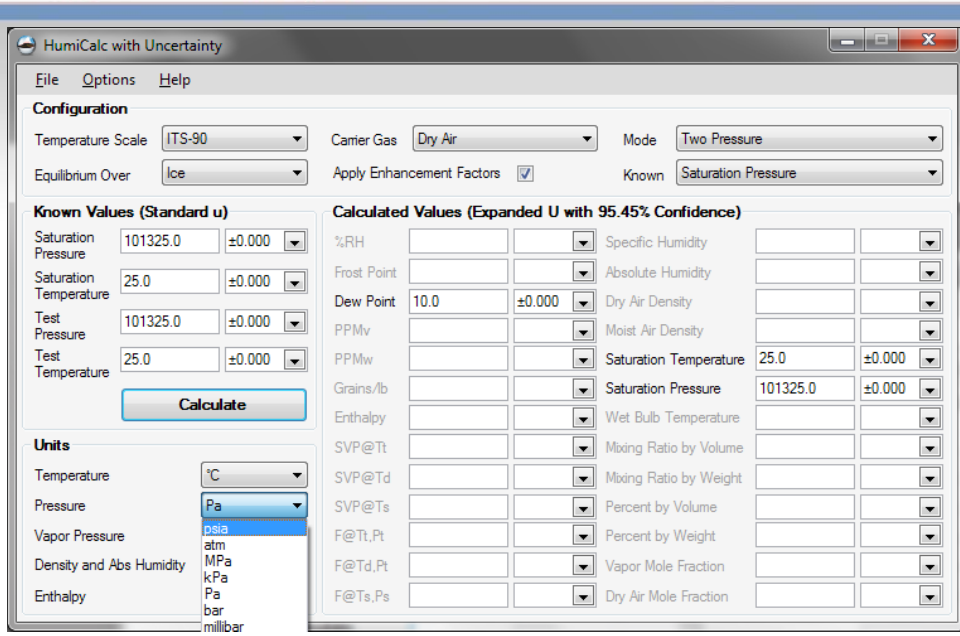


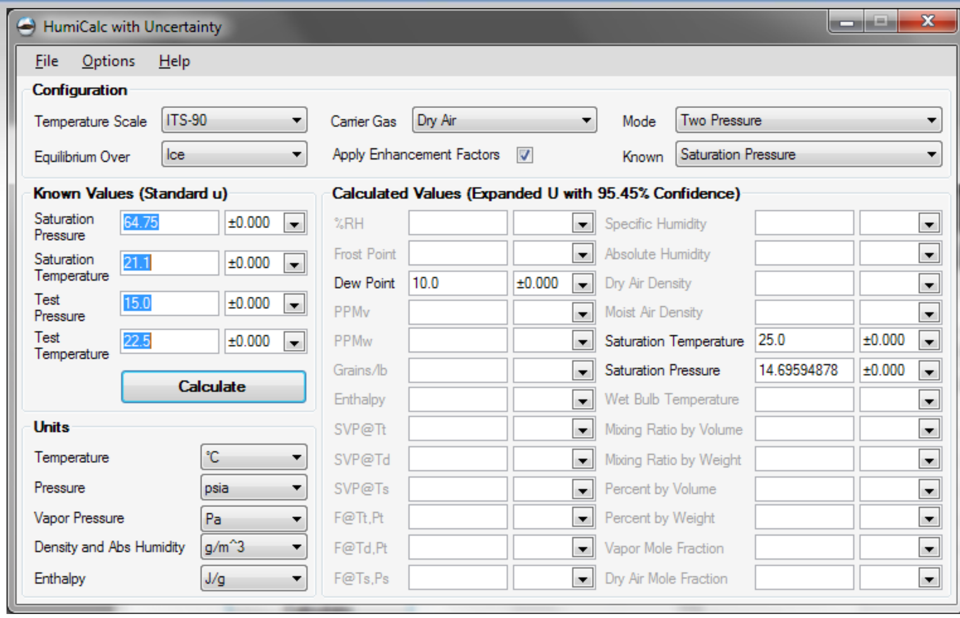
Set the Equilibrium to Ice



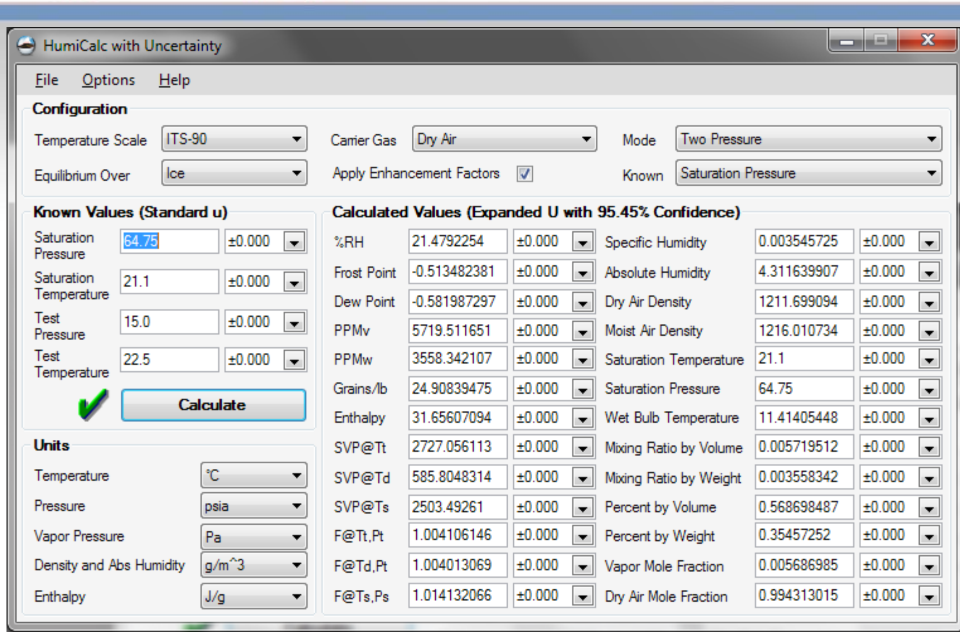
Set the Mode to Two Pressure



Set the Pressure Units to psia



Enter the Known Values



Click the Calculate button

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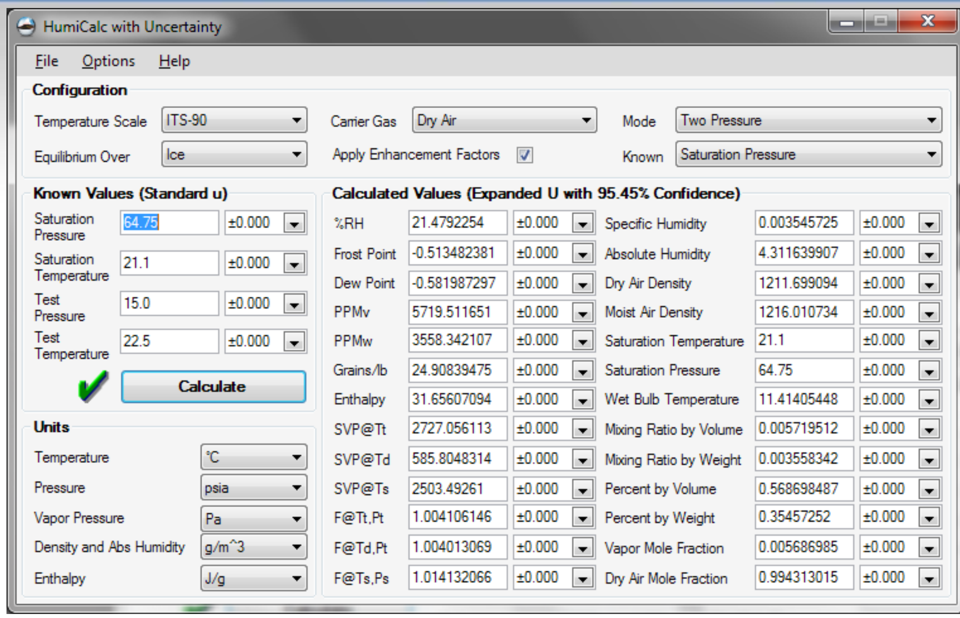

Look at the calculated value for %RH at the chamber temperature

Humidity Generation and Calibration Equipment
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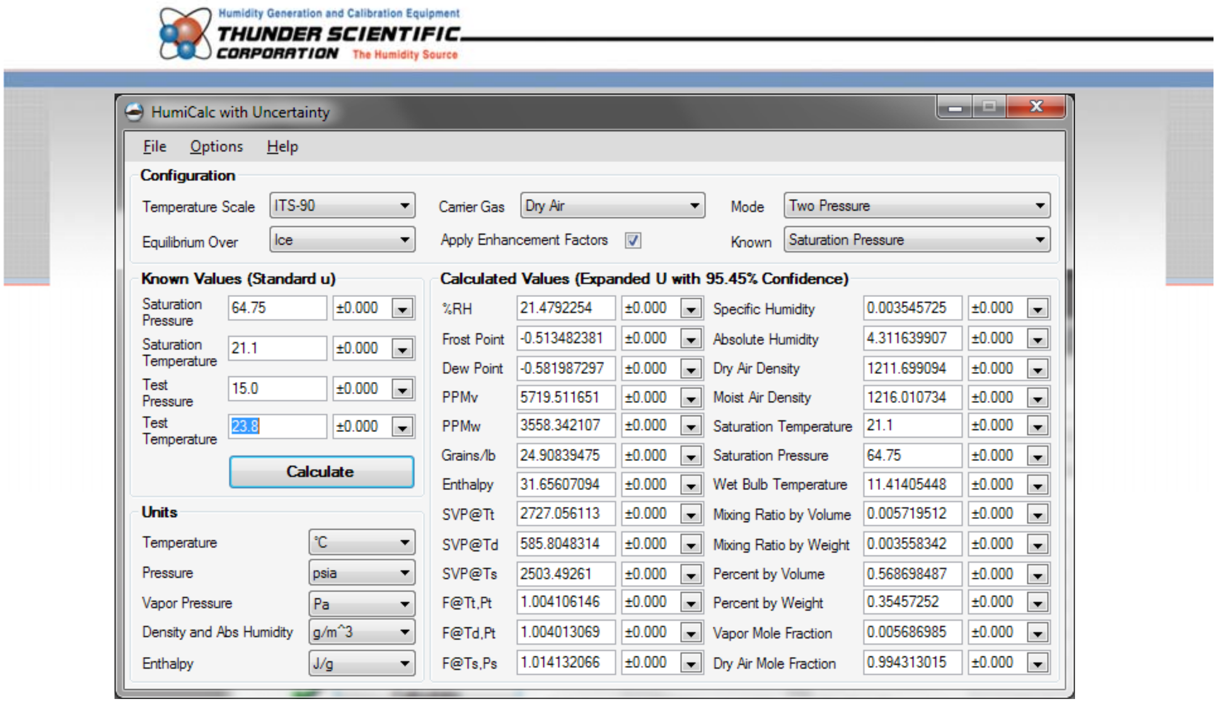
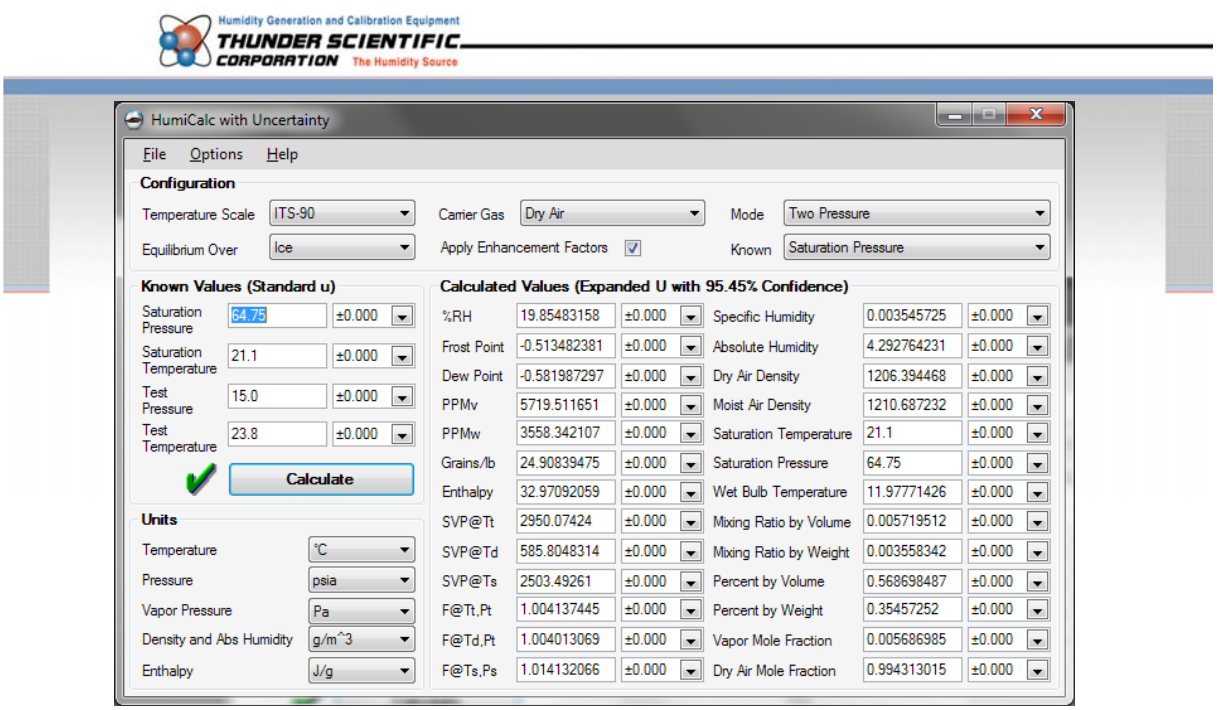
- Change the Test Temperature Known Value to the temperature inside the unit under test
- 22.5 °C + 1.4 °C = 23.8 °C.

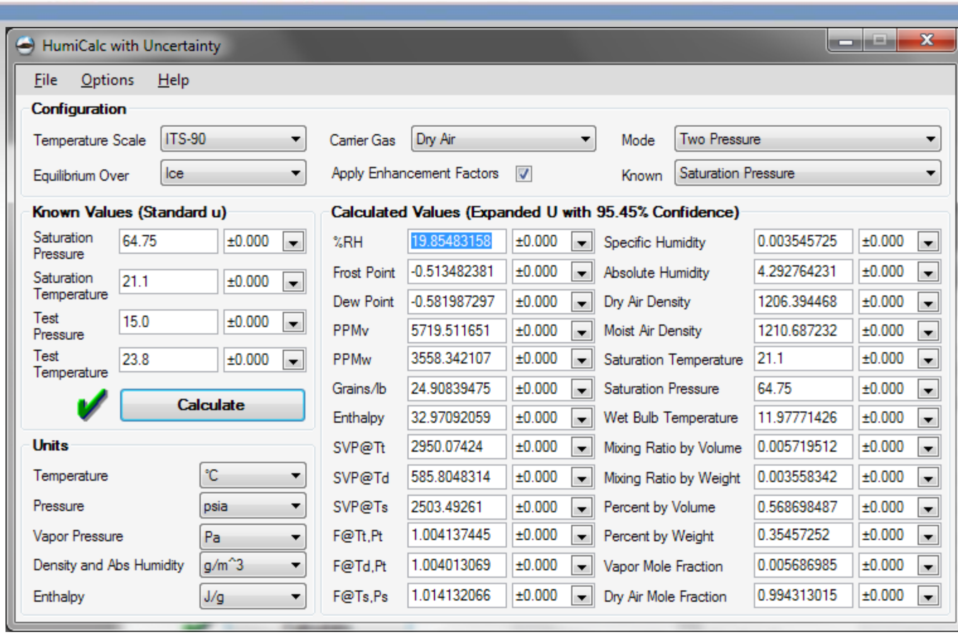


Enter the Known temperature value for inside the unit under test



Click the Calculate button

- Look at the calculated value for %RH at the temperature measured inside the unit under test.



Look at the calculated value for %RH based on the unit under test

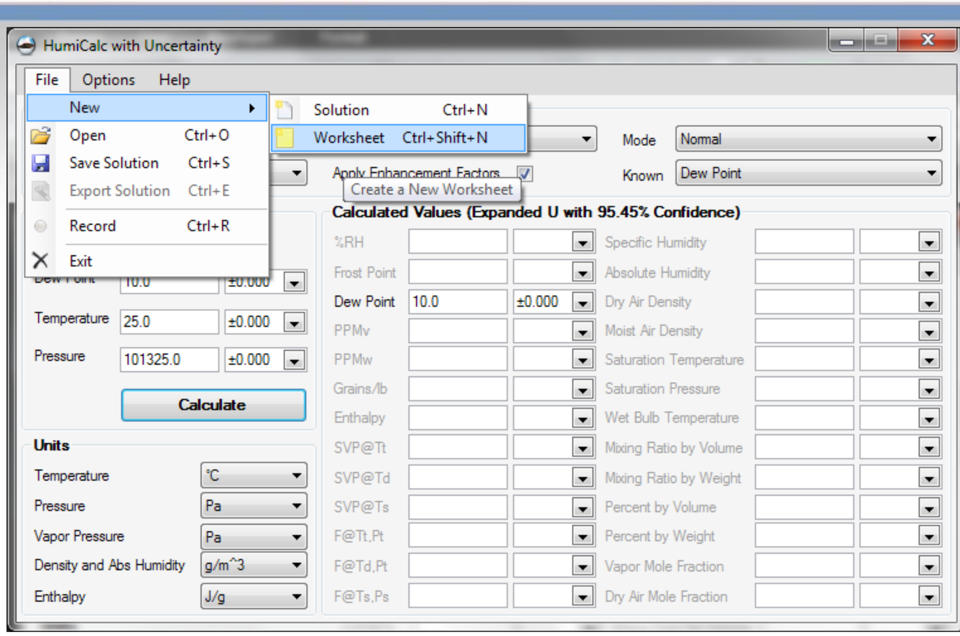
Questions?

Comments?

HUMICALC WORKSHEET EXAMPLE

This section deals with HumiCalc's ability to perform simple "law of propagation of uncertainty" type calculations. These calculations can be performed using HumiCalc worksheets. Worksheets are great for any uncertainty calculation that is of the same unit even non humidity related uncertainty problems.

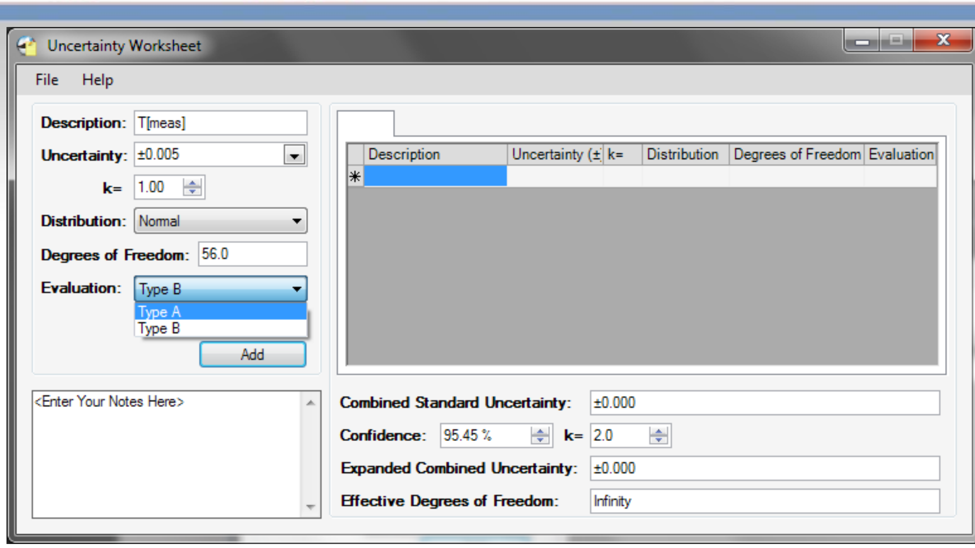
- Using a HumiCalc worksheet, determine the expanded combined uncertainty at a 99.73% confidence given the following three uncertainty components:
  - Temperature measurement uncertainty statically determined from 57 points to be 0.005.
  - Temperature measurement hysteresis specified by the manufacture to be 0.001 with a rectangular type distribution.
  - Temperature measurement resolution of 0.01.



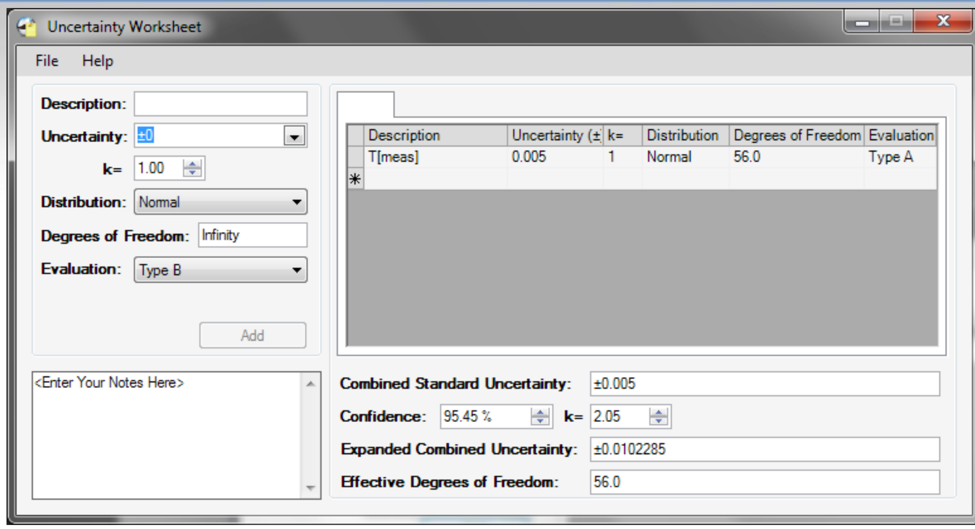
Open a new worksheet

- Start by entering the first individual uncertainty component.

- The first component will have a k=1 since the problem did not specify a k value. We will assume a normal distribution because this is a statically determined value and we will set the degrees of freedom to the number of sample points minus one (57-1=56). Since this was a statically determined value we will set it to be a Type A evaluation.

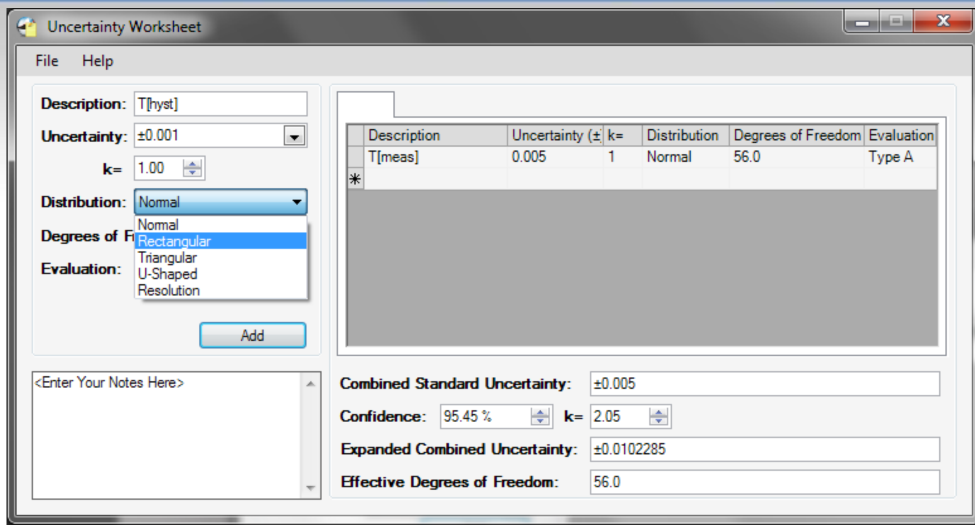


Enter the first uncertainty component

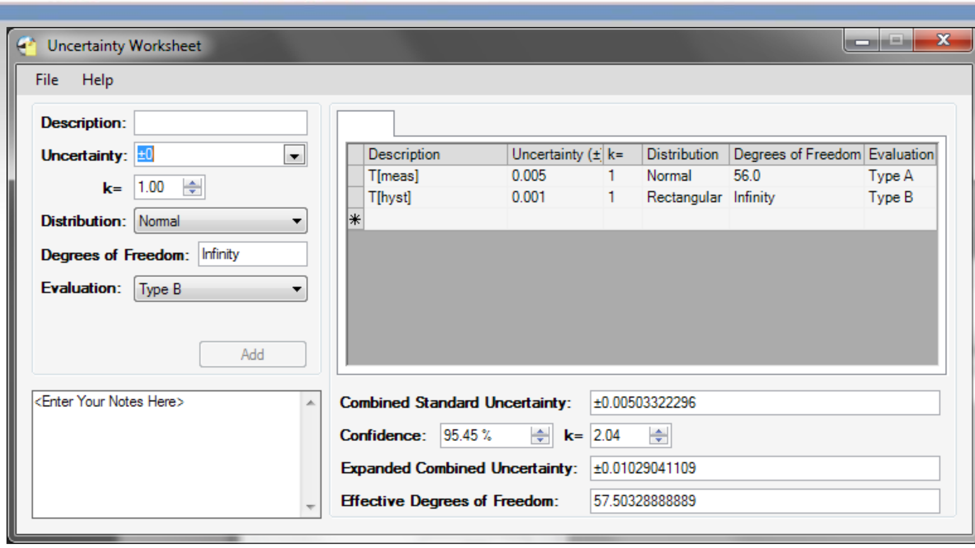


Once the information for the component has been entered, press the Add button to add the component to the worksheet.

- Next add the information for the second individual uncertainty component.
- The second component has a rectangular distribution and is a Type B evaluation since it is based on a manufacturer's specification.



Enter the second uncertainty component



Press the Add button to add the new component. Notice that HumiCalc automatically updates the Combined Standard and Expanded Uncertainty as each component is added.

- Last, enter the final individual uncertainty component values.
- The last component has a resolution type distribution and is again a Type B evaluation.

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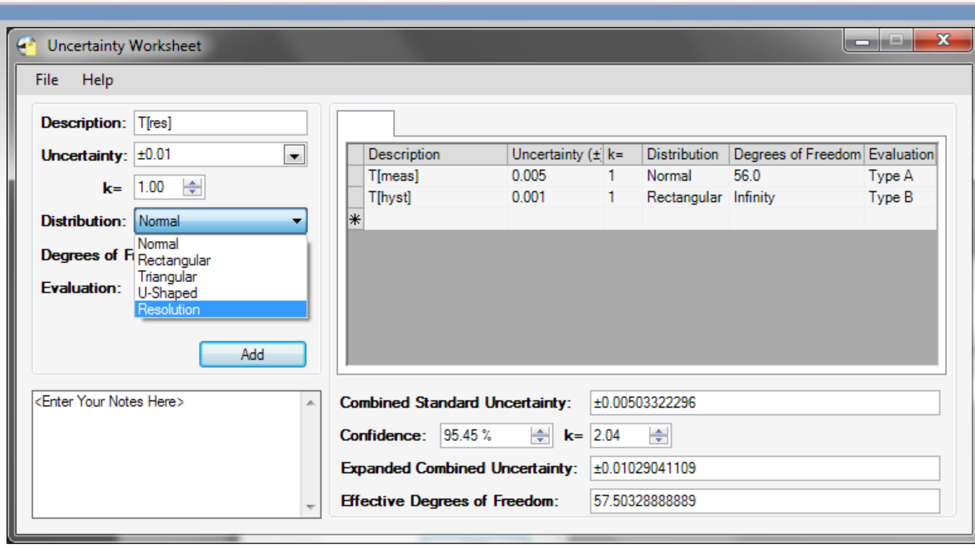
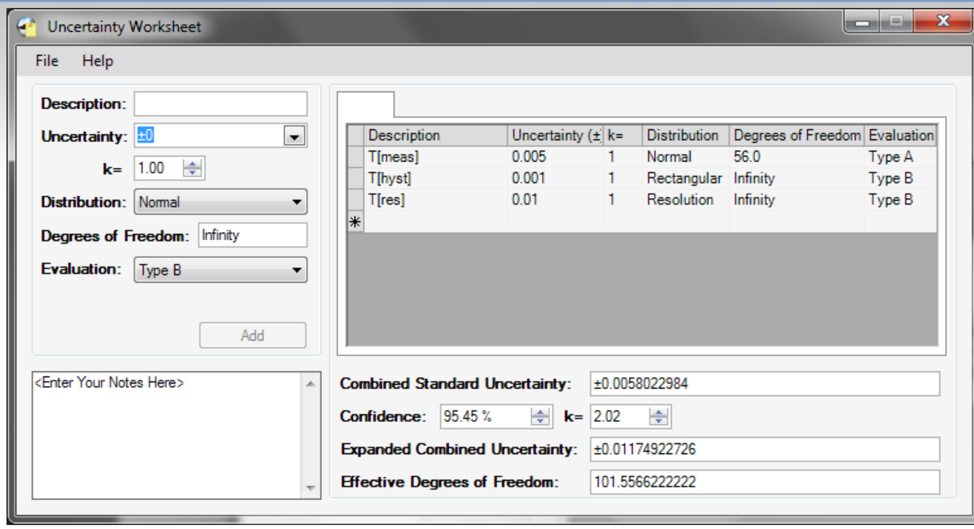


Enter the third and last uncertainty component



Add the component

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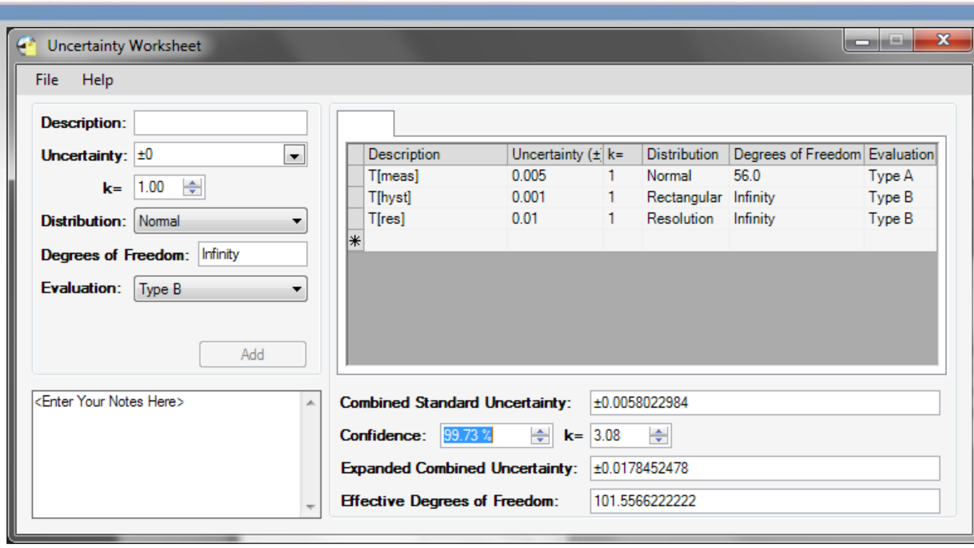

Now select the desired confidence level of 99.73%. Notice how HumiCalc automatically recalculates the correct k factor for the given confidence and effective degrees of freedom.

Humidity Generation and Calibration Equipment
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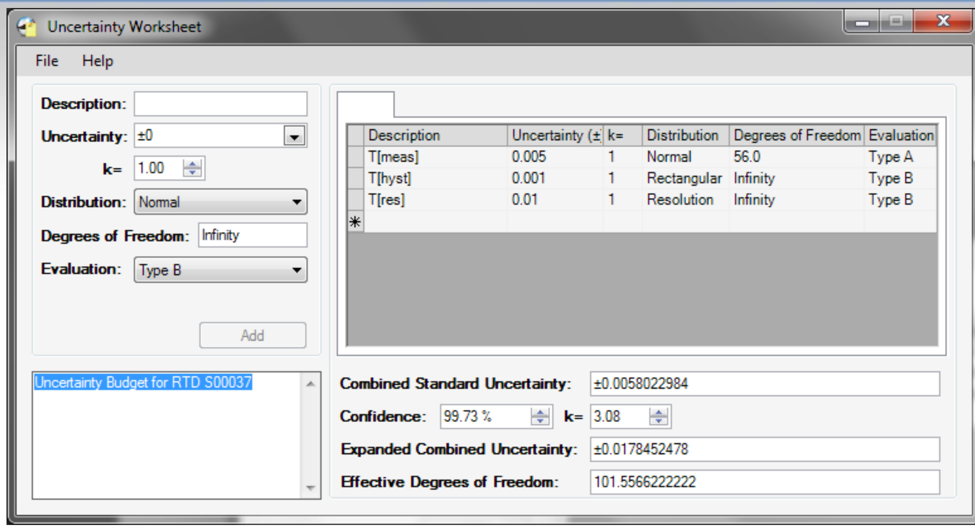

Worksheets also allow the user to record notes on the worksheet that are stored along with the entries when the worksheet is saved.

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Questions?

Comments?

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Uncertainty and Error

In this section we will analyze the uncertainty of performing calibrations using a Two-Pressure Humidity Generator. We will also discuss how to translate the "As Found" error discovered during a calibration of a Two-Pressure Humidity Generator directly into terms of humidity error.

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Definitions

Error is the difference between the measured value and the 'true value' of the item being measured. Whenever possible we try to correct for any known errors; for example, by applying corrections from the calibration process.

Uncertainty is a quantification of the doubt about the measurement result. The uncertainty in a stated measurement is the interval of confidence around the measured value such that the measured value is certain not to lie outside this stated interval.

UUT or unit under test. This is the device being calibrated.

Hand Held Hygrometer Percent Relative Humidity Uncertainty Example

Uncertainty Components

In this example will we calculate the percent relative humidity (%RH) uncertainty for a hand held hygrometer from the simple 3 point calibration shown earlier in presentation. The uncertainty calculation will be based on the following three individual uncertainty components.

1. The standard deviation of a series of measurements taken from the UUT during calibration (repeatability).
2. The display resolution of the UUT.
3. The uncertainty of the humidity reference or standard.

		Referenc/Standard	UUT		Referenc/Standard	UUT		Referenc/Standard
DATE	TIME	%RH Reading	%RH Reading		°C Reading	°C Reading		psia Reading
May 21 2008	11:25 AM	20.00	20.2		23.12	23.2		12.10
May 21 2008	11:30 AM	20.00	20.4		23.12	23.2		12.10
May 21 2008	11:35 AM	20.00	20.3		23.12	23.2		12.10
May 21 2008	11:40 AM	20.00	20.2		23.12	23.2		12.10
May 21 2008	11:45 AM	20.00	20.2		23.12	23.2		12.10
May 21 2008	11:50 AM	20.00	20.2		23.12	23.2		12.10
			Std Dev	0.0837				
May 21 2008	12:20 PM	50.01	50.5		23.11	23.2		12.09
May 21 2008	12:25 PM	50.01	50.5		23.11	23.2		12.09
May 21 2008	12:30 PM	50.01	50.6		23.11	23.2		12.09
May 21 2008	12:35 PM	50.01	50.4		23.11	23.2		12.09
May 21 2008	12:40 PM	50.01	50.4		23.11	23.2		12.09
May 21 2008	12:45 PM	50.01	50.5		23.11	23.2		12.09
			Std Dev	0.0753				
May 21 2008	1:15 PM	80.03	80.2		23.12	23.2		12.09
May 21 2008	1:20 PM	80.03	80.3		23.12	23.2		12.09
May 21 2008	1:25 PM	80.03	80.2		23.12	23.2		12.09
May 21 2008	1:30 PM	80.03	80.2		23.12	23.2		12.09
May 21 2008	1:35 PM	80.03	80.4		23.12	23.2		12.09
May 21 2008	1:40 PM	80.03	80.2		23.12	23.2		12.09
			Std Dev	0.0837				

First we calculate the Standard Deviation of the UUT from the data recorded during the first point of calibration.

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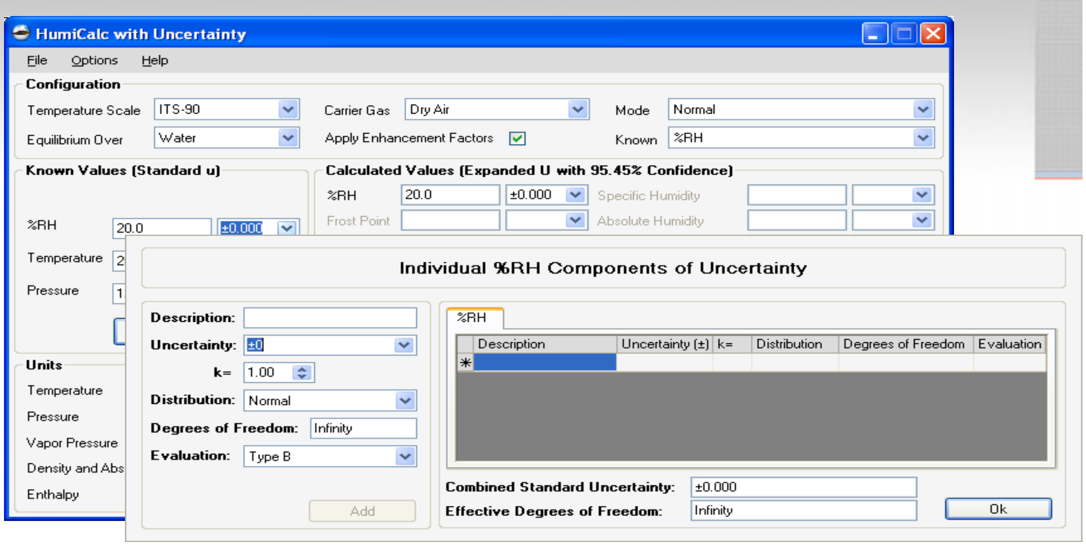
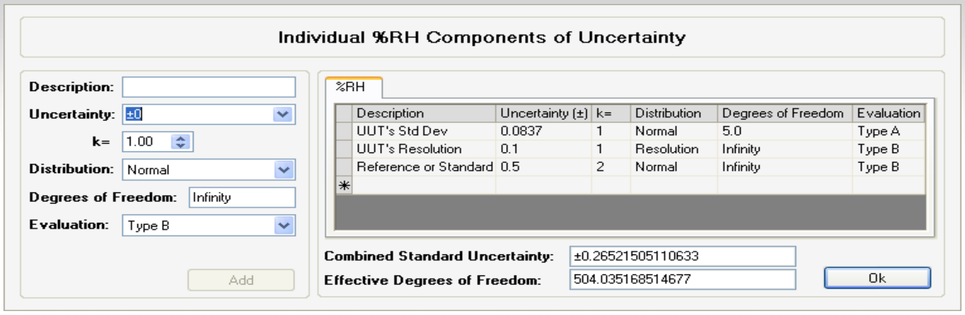
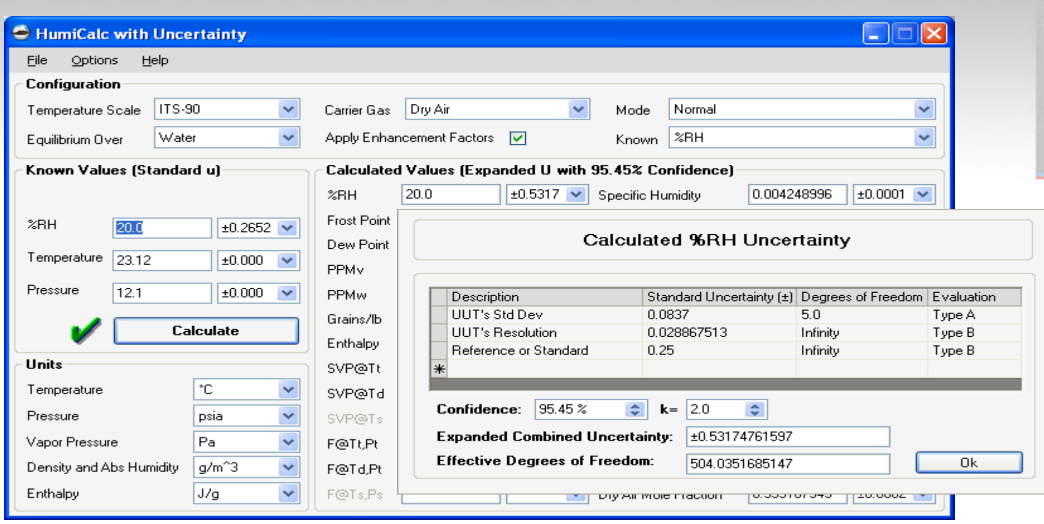


Next we enter the three individual %RH components of uncertainty into HumiCalc with Uncertainty



Starting with the calculated UUT Standard Deviation. Note that we enter the Degrees of Freedom based on the number of samples used in the calculation of the Standard Deviation minus one (6-1=5). Then we enter the UUT's resolution with a "resolution type distribution" and the uncertainty of the Reference or Standard used.



Now we can calculate and see the expanded combined uncertainty for the first point of the calibration at the desired 95.45% confidence level.

Questions?

Comments?

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Chilled Mirror Percent Relative Humidity Uncertainty Example

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Uncertainties of Varying Types

This example is a good illustration of the uncertainty challenges often encountered in the humidity industry. Components are calibrated that are of different types than the desired humidity uncertainty. In the previous uncertainty example all components were of the same type as the desired output. This makes the uncertainty calculation nothing but a simple Root-Sum-Squares of the components. In this example we will show how we can combine two temperature uncertainties to derive a %RH uncertainty using fundamental humidity equations.

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Relative Humidity Equation

Relative Humidity can be calculated based the ratio of the enhanced saturation vapor pressure at the Dew Point Temperature (Td) with respect to the enhanced saturation vapor pressure at the Test Temperature (Tc) as illustrated by the following equation.

$$\%RH = \frac{e(T_d) \cdot f(T_d, P_c)}{e(T_c) \cdot f(T_c, P_c)} \cdot 100$$

Vapor Pressure Equation

The saturation vapor pressure can be determine at a specific temperature and then enhanced based on the same temperature and a pressure as described in the following equations.

$$\ln e = \sum_{i=0}^{3} k_i T^{i-1} + k_4 \cdot \ln T$$

$$f(T,P) = \exp\left[a\left(1 - \frac{e(T)}{P}\right) + b\left(\frac{P}{e(T)} - 1\right)\right]$$

$$a = \sum_{i=0}^{3} (A_i \cdot T^i)$$

$$\ln b = \sum_{i=0}^{3} (B_i \cdot T^i)$$

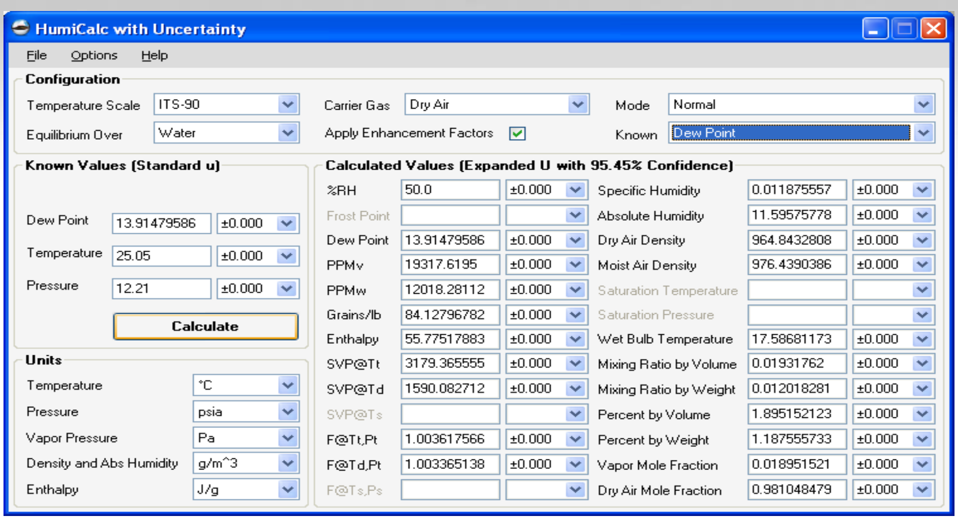
Combining Terms

To combine the individual components we need to find the sensitivity coefficients for each input using a partial derivative of the previously shown %RH equation. The partial derivative represents the rate of change or instantaneous slope at a specific point for a single input of an equation. The instantaneous slope determines the sensitivity of the equation's output for a given change in an equation's input. Given this we can multiply each sensitivity coefficient by the known uncertainty and combined it using the Root-Sum-Squares method.

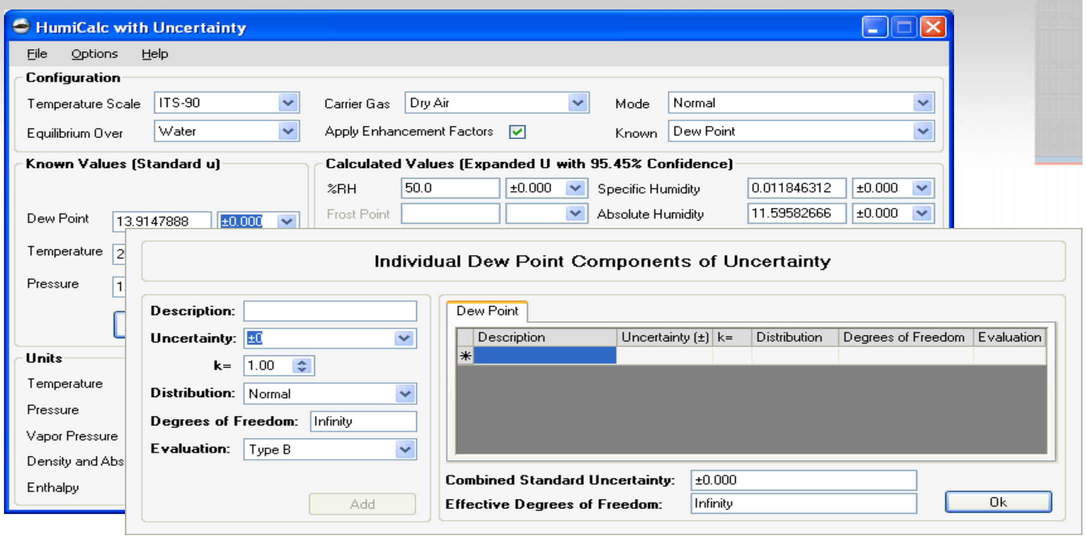
$$u_c = \sqrt{\left(\frac{d}{dT_d}\%RH \cdot u(T_d)\right)^2 + \left(\frac{d}{dT_t}\%RH \cdot u(T_t)\right)^2 + \left(\frac{d}{dP_c}\%RH \cdot u(P_c)\right)^2}$$

	Referenc/Standard		UUT		Referenc/Standard	UUT		Referenc/Standard
TIME	%RH Reading	Dew Point Reading °C	Dew Point Reading °C		°C Reading	°C Reading		psia Reading
10:25 AM	20.00	0.542	0.5		25.04	25.0		12.21
10:30 AM	20.00	0.542	0.6		25.04	24.9		12.21
10:35 AM	20.00	0.542	0.6		25.04	25.0		12.21
10:40 AM	20.00	0.542	0.5		25.04	25.0		12.21
10:45 AM	20.00	0.542	0.5		25.04	25.0		12.21
10:50 AM	20.00	0.542	0.6		25.04	25.0		12.21
			Std Dev	0.0548		Std Dev	0.0408	
10:25 AM	50.00	13.915	13.8		25.05	25.0		12.21
10:30 AM	50.00	13.915	13.7		25.05	25.0		12.21
10:35 AM	50.00	13.915	13.7		25.05	25.0		12.21
10:40 AM	50.00	13.915	13.8		25.05	25.0		12.21
10:45 AM	50.00	13.915	13.9		25.05	24.9		12.21
10:50 AM	50.00	13.915	13.7		25.05	24.9		12.21
			Std Dev	0.0816		Std Dev	0.0516	
10:25 AM	80.00	21.360	21.3		25.05	25.0		12.22
10:30 AM	80.00	21.360	21.3		25.05	24.9		12.22
10:35 AM	80.00	21.360	21.2		25.05	25.0		12.22
10:40 AM	80.00	21.360	21.2		25.05	25.0		12.22
10:45 AM	80.00	21.360	21.3		25.05	25.1		12.22
10:50 AM	80.00	21.360	21.3		25.05	25.1		12.22
			Std Dev	0.0516		Std Dev	0.0753	

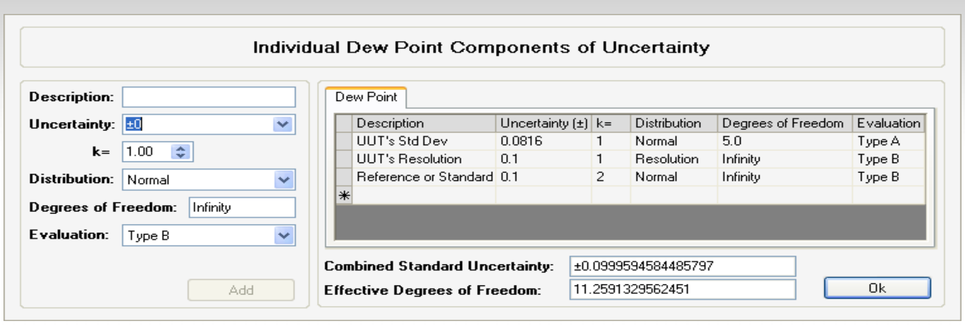
We begin by calculating the Standard Deviation of the UUT from the Dew Point data recorded during the calibration. We will only show the calculation of the second point to save time.



We will use HumiCalc with Uncertainty to perform the complex derivative calculations. We will start by first calculating the Dew Point Temperature based on the %RH value being generated.



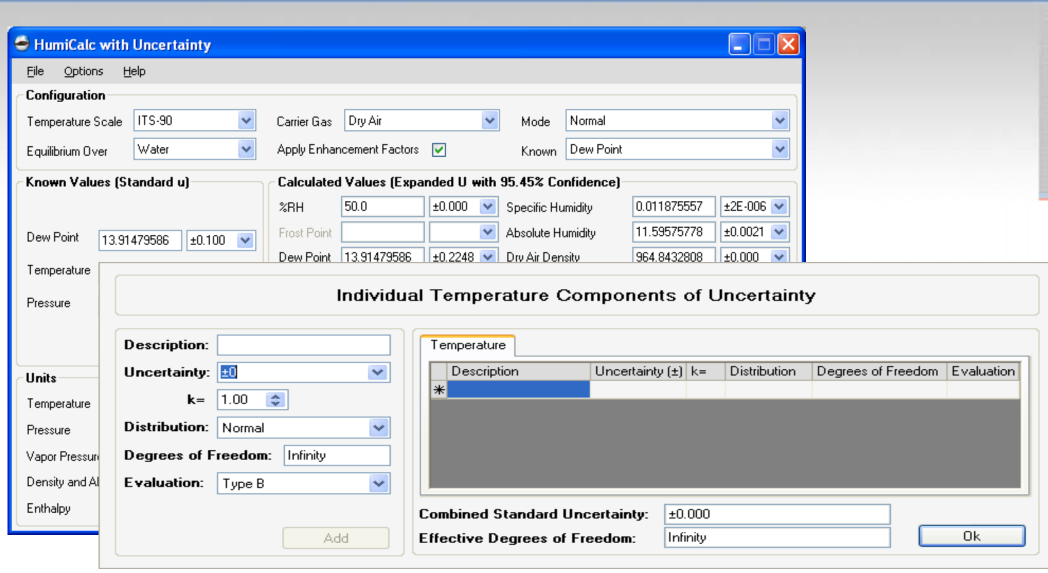
Next we enter the three individual Dew Point components of uncertainty into HumiCalc with Uncertainty



Starting with the calculate UUT Standard Deviation. Note that we again enter the Degrees of Freedom based on the number of samples used in the calculation of the Standard Deviation minus one (6-1=5). Then we enter the UUT's resolution with a "resolution type distribution" and the uncertainty of the Reference or Standard used.

	Referenc/Standard		UUT		Referenc/Standard	UUT		Referenc/Standard
TIME	%RH Reading	Dew Point Reading °C	Dew Point Reading °C		°C Reading	°C Reading		psia Reading
10:25 AM	20.00	0.542	0.5		25.04	25.0		12.21
10:30 AM	20.00	0.542	0.6		25.04	24.9		12.21
10:35 AM	20.00	0.542	0.6		25.04	25.0		12.21
10:40 AM	20.00	0.542	0.5		25.04	25.0		12.21
10:45 AM	20.00	0.542	0.5		25.04	25.0		12.21
10:50 AM	20.00	0.542	0.6		25.04	25.0		12.21
			Std Dev	0.0548		Std Dev	0.0408	
10:25 AM	50.00	13.915	13.8		25.05	25.0		12.21
10:30 AM	50.00	13.915	13.7		25.05	25.0		12.21
10:35 AM	50.00	13.915	13.7		25.05	25.0		12.21
10:40 AM	50.00	13.915	13.8		25.05	25.0		12.21
10:45 AM	50.00	13.915	13.9		25.05	24.9		12.21
10:50 AM	50.00	13.915	13.7		25.05	24.9		12.21
			Std Dev	0.0816		Std Dev	0.0516	
10:25 AM	80.00	21.360	21.3		25.05	25.0		12.22
10:30 AM	80.00	21.360	21.3		25.05	24.9		12.22
10:35 AM	80.00	21.360	21.2		25.05	25.0		12.22
10:40 AM	80.00	21.360	21.2		25.05	25.0		12.22
10:45 AM	80.00	21.360	21.3		25.05	25.1		12.22
10:50 AM	80.00	21.360	21.3		25.05	25.1		12.22
			Std Dev	0.0516		Std Dev	0.0753	

Next we calculate the Standard Deviation of the UUT from the Temperature data recorded during the calibration.



Now we enter the three individual Temperature components of uncertainty into HumiCalc with Uncertainty

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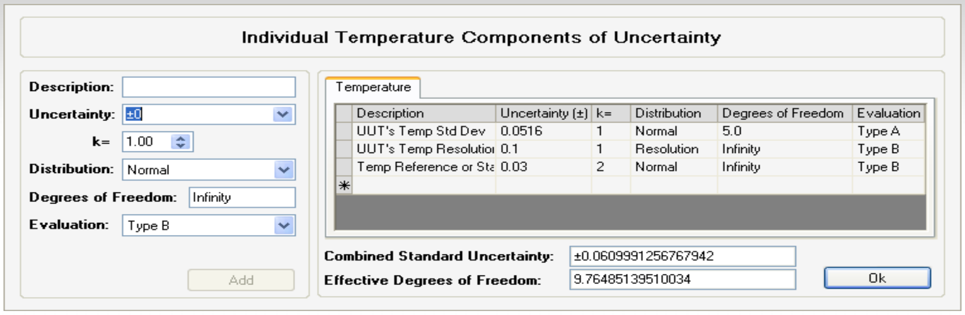

Again, starting with the calculated Temperature UUT Standard Deviation. Then we enter the UUT's Temperature resolution with a "resolution type distribution" and the uncertainty of the Temperature Reference or Standard used.

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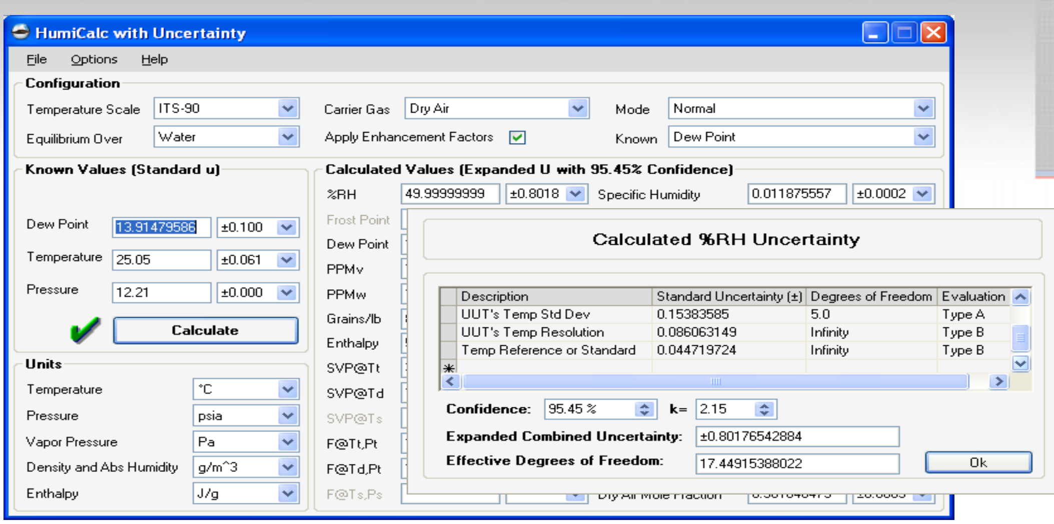

Last we have HumiCalc with Uncertainty perform the partial derivative calculations based on the inputs to produce a final expanded combined %RH uncertainty at the desired 95.45% confidence level.

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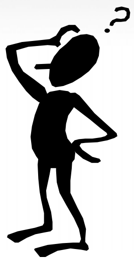

Questions?

Comments?

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As Found Calibration Data for a "Two-Pressure" Humidity Generator

How to Translate the As Found Error Discovered During a Calibration Directly into Terms of Generated Humidity Error.

"NOTE - The difference between error and uncertainty should always be borne in mind. For example, the result of a measurement after correction can unknowably be very close to the unknown value of the measurand, and thus have negligible error, even though it may have a large uncertainty" (NIST Technical Note 1297)

As Received Data:

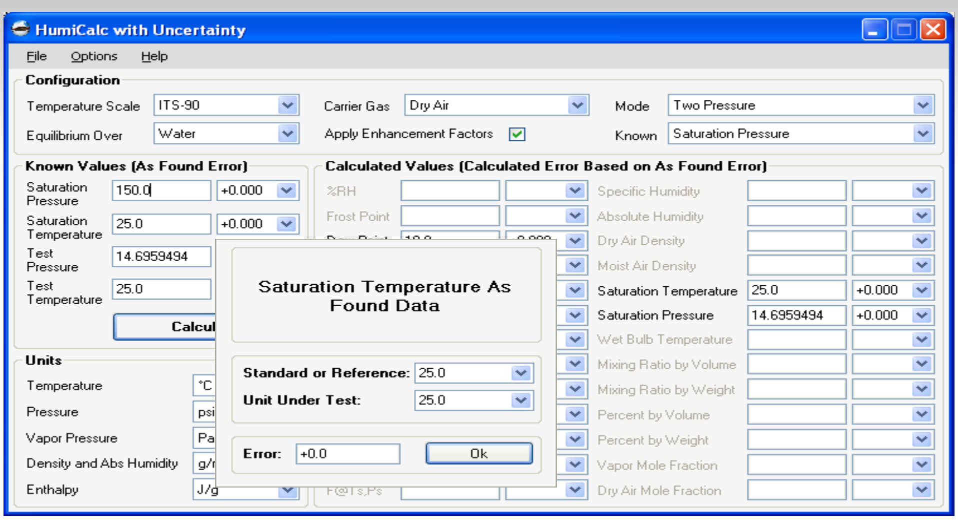
	Actual	Saturator	Error	Chamber	Error	Presat	Error	Exp Valve	Error	U
	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
	------	------	------	------	------	------	------	------	------	------
	70.000	69.99	-0.010	70.01	0.010	70.00	0.000	70.00	0.000	0.13
	35.000	34.90	-0.100	35.09	0.090	35.00	0.000	35.02	0.020	0.13
	0.000	0.020	0.020	0.030	0.030	0.000	0.000	0.000	0.000	0.13

Adjustments: Calibration coefficients were calculated and saved to memory.

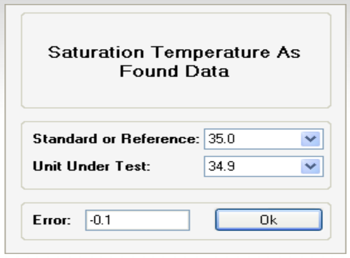
Manufacturer's specifications: ± 0.06 °C.

As Left: Within Tolerance: YES
Limited Range: NONE

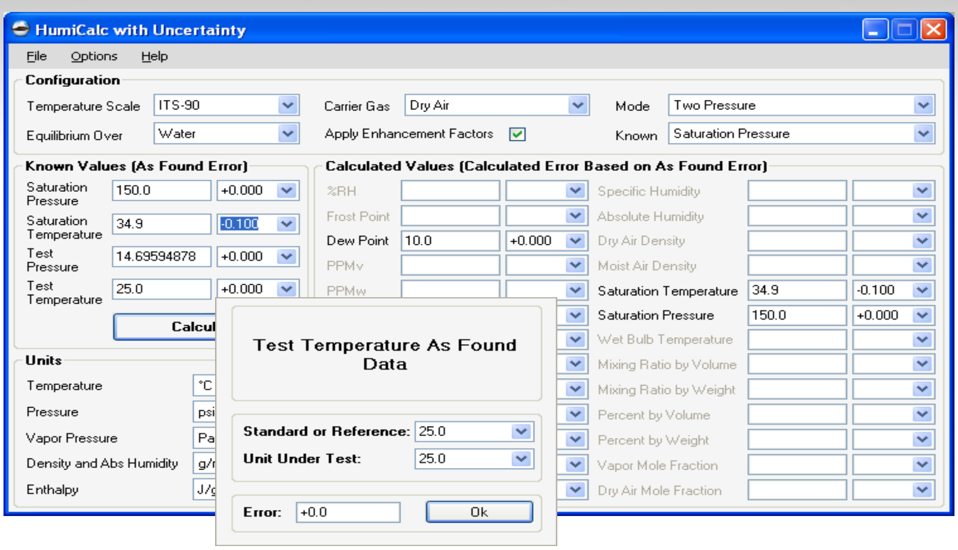
In this example we have two out of tolerance temperature probes at the 35° calibration point. We want to calculate how these temperature out of tolerances affected the generated %RH humidity.



We will use HumiCalc with Uncertainty's "As Found" Error mode to calculation the corresponding %RH error.



Start by entering the Saturation Temperature Probe's "As Found" values from the calibration report. We enter the reading of the Standard or Reference and the reading of the UUT.



Next, select the Test/Chamber Temperature.

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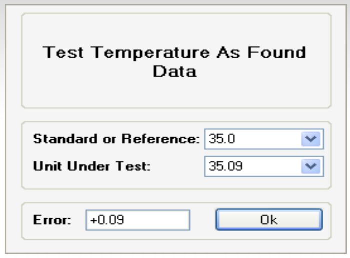

Enter the Test/Chamber Temperature Probe's "As Found" values from the calibration report.

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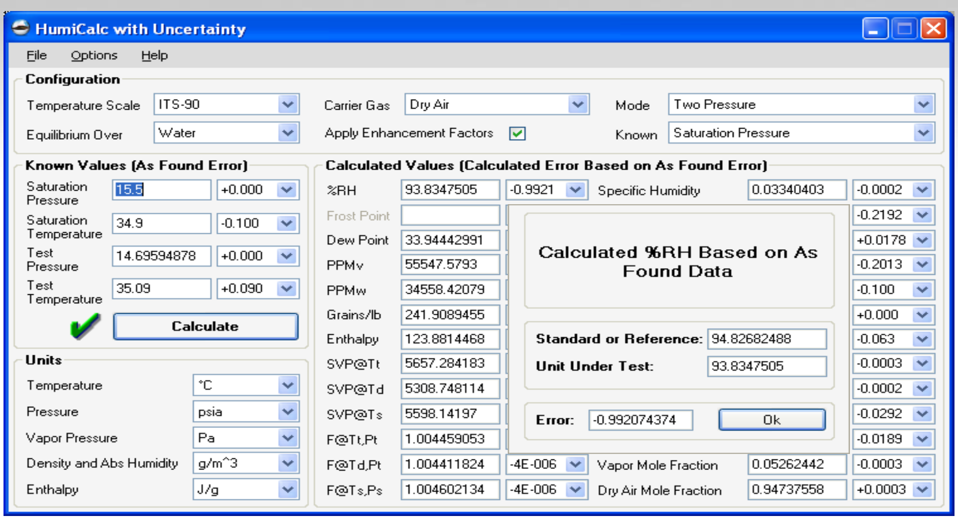

After Calculating we can see %RH "As Found" error caused by the out of tolerance temperature probes. We can also vary the Saturation Pressure and see the effects at various %RH levels.

Questions?

Comments?