Uncertainty Analysis
of the
Thunder Scientific Model 9500 Two-Pressure Humidity Generator

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1.0 Introduction

The generated humidity uncertainty analysis is described here, following the Guidelines of NIST and NCSL International [1, 6, 7], for a Model 9500 Humidity Generator that utilizes the NIST-developed and proven two-pressure humidity generation principle [2, 3]. The generation of humidity in a system of this type does not require direct measurements of the water vapor content of the gas. Instead, the generated humidity is derived from the measurements of saturation and chamber pressures and saturation and test chamber temperatures.

The measurement instrumentation used in both our in-house working standards and our manufactured devices is obtained from companies that have demonstrated either NIST traceability or traceability to other acceptable standards. In most cases, we use the specifications supplied by these manufacturers as the strting point for our uncertainty statements. Over time, comparison calibrations against a NIST traceable pressure gauge and NIST traceable standard resistance thermometer, as well as the results of an ongoing intercomparison program of both the individual components and of the outputs of generators as a system, have allowed the determination of the ranges of disagreement among the various temperatures and pressures that go into the final decision 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 provide overall uncertainty statements.

This document lists the various uncertainty sources, their magnitudes, and their origins over the operating range of the Model 9500 generator. Refer to the specifications section in the Model 9500 system manual [10] for the operating range and the HumiCalc with Uncertainty Reference Manual [11] for a complete description of the humidity equations used. This analysis is based on the test results from the Model 9500 Humidity Generator serial numbers 22030153 and 22030154.

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:

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

Where *y* is the humidity equation of interest, *x* is the input and *∂* is the partial derivative of the equation y for the input *x*. The partial derivative (often referred to as a sensitivity coefficient) represents the rate of change or instantaneous slope at a specific point for input *x* in the equation *y*. This partial derivative is key to humidity uncertainties, especially in a two-pressure humidity generation where the major uncertainty contributors are in terms of pressure and temperature and must be converted into terms of %RH, Dew Point, or Frost Point.

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. The following formula can express relative humidity in a two-pressure humidity generator:

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

Where the f functions are enhancement factors, e is the saturation vapor pressure, η_S is the % efficiency of saturation, T_C is the test chamber temperature, T_D is the Dew/Frost point temperature, and Pc is the chamber pressure. The following formulas can express the Dew/Frost point temperatures in a two-pressure humidity generator:

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

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

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 2 with equations 3 and 4, we can express Relative Humidity in terms of saturation and test chamber temperatures and saturation and chamber pressure only by the following formula:

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

By incorporating the relationship in equation 1 into an uncertainty equation of the form of equation 5, the total uncertainty in relative humidity is given by the expression:

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

Similarly, incorporating the relationship in equation 1 into an uncertainty equation of the form of equations 3 and 4, the uncertainties in dew point and frost point measurement are given by the expression:

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

and

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

3.0 Uncertainty Components

In the mathematical analysis of equations 6, 7, and 8, we analyze the uncertainties due to each component separately and then combine the uncertainties to obtain the total expanded uncertainty. We are concerned with four basic categories of uncertainty: pressure, temperature, the saturation vapor pressure/enhancement factor equations, and the percent efficiency of the saturator. Each of these categories may also have associated uncertainty components. In determining components of uncertainty, there are several things to consider, such as measurement accuracy or uncertainty, measurement resolution, uniformity, etc.

The identified significant uncertainty contributors and components for the Model 9500 humidity generator are listed below.

- Uncertainty contribution from pressure (P_S and P_c) which includes:
  - Measurement accuracy
    - Transducer accuracy [9]
      - Intrinsic performance of the instrument
      - Measurement uncertainty of the reference instrument
      - Long-term stability
      - Influence of ambient conditions
      - Drift
      - Temperature effects over the compensated range
  - Measurement resolution
  - Pressure control stability
- Uncertainty contribution from temperature (T_S and T_c), which includes:
  - Measurement accuracy
    - Reference standard
    - Module resolution
    - Module errors
    - Reproducibility
    - Repeatability
    - Self-Heating
  - Measurement resolution
  - Temperature control stability
  - Saturator temperature gradients (applies to saturation temperature (T_s) only)
  - Chamber uniformity (applies to test chamber temperature (T_c) only)
- Uncertainty contribution from equations, 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 9500 humidity generator uses two pressure transducers to measure the saturation pressure and another pressure transducer to measure the chamber pressure. Each pressure transducer contributes its own uncertainty to the overall system in this design and is addressed independently.

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 (using either P_C or P_S) multiplied by the uncertainty of the pressure component. The equation for this becomes:

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

$\mathrm{uRH}_{[\mathrm{component}]}$ = 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 (using either P_C or P_S) multiplied by the uncertainty of the pressure component. The equation for this becomes:

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

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

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

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

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

3.1.1 Pressure Accuracy Uncertainty Component

The Model 9500 humidity generator uses two pressure transducers to improve the accuracy of the saturation pressure measurement. When operating below a 45 psiA saturation pressure, the low range pressure transducer is used for measurement; when operating above a 45 psiA saturation pressure, the high range pressure transducer is used for measurement. The transducer manufacturer specifies the total uncertainty (k=2) to be 0.008% of the full scale. This total uncertainty includes the reference standard, linearity, drift, hysteresis, temperature effects over the calibrated range, and repeatability [9]. Taking a conservative approach that is based on a rectangular distribution of the manufacturer's total uncertainty, the uncertainty components of the saturation pressure accuracy are:

$$uP_{s[accuracy\ <45psiA]} = (45\ \text{psiA (full scale)} * 0.008\%) / \sqrt{3}$$

$$= (0.0036\ \text{psiA}) / \sqrt{3}\ \text{(DOF=infinite)}$$

$$uP_{s[accuracy\ >45psiA]} = (325\ \text{psiA (full scale)} * 0.008\%) / \sqrt{3}$$
$$= (0.026\ \text{psiA}) / \sqrt{3}\ \text{(DOF=infinite)}$$

resulting in

$$uP_{s[accuracy\ <45psiA]} = 0.0042\ \text{psiA}$$

$$uP_{s[accuracy\ >45psiA]} = 0.030\ \text{psiA}$$
(using a coverage factor, k=2, at an approximate level of confidence of 95%)

The Model 9500 humidity generator uses a single pressure transducer to measure the test chamber pressure. The transducer manufacturer specifies the total uncertainty (k=2) to be 0.008% of the full scale. This total uncertainty includes the reference standard, linearity, drift, hysteresis, temperature effects over the calibrated range, and repeatability [9]. Taking a conservative approach that is based on a rectangular distribution of the manufacturer's total uncertainty, the uncertainty components of the chamber pressure accuracy are:

$$uP_{c[accuracy]} = (23\ \text{psiA (full scale)} * 0.008\%) / \sqrt{3}$$
$$= (0.00184\ \text{psiA}) / \sqrt{3}\ \text{(DOF=infinite)}$$

resulting in

$$uP_{c[accuracy]} = 0.0021\ \text{psiA}$$
(using a coverage factor, k=2, at an approximate level of confidence of 95%)

Note: This analysis uses 14.7 psiA as the test chamber pressure reading for all calculations

3.1.2 Pressure Resolution Uncertainty Component

The Model 9500 humidity generator digitally communicates with the low and high-range saturation transducer and the test chamber pressure transducer. Based on a rectangular distribution of the half-interval of the resolution, the uncertainty component of pressure resolution is:

$uP_{s\,[resolution]}$ = 0.001 psiA / √12 (DOF=infinite)

$uP_{c\,[resolution]}$ = 0.001 psiA / √12 (DOF=infinite)

3.1.3 Pressure Control Stability Uncertainty Component

The Model 9500 humidity generating system incorporates a computer-controlled design for saturation and chamber pressure measurement and control. For the saturation pressure, the generator uses two pressure ranges, one pressure transducer (T3) for saturation pressures below 45 psiA and one pressure transducer (T4) for saturation pressures above 45 psiA. The chamber pressure uses a single pressure transducer (T2). The system utilizes three 1/4 turn ball valves for pressure control. Each ball valve is driven by an individual 4:1 reduction gear box to an intelligent hybrid stepper motor using Thunder Scientifics custom programming.

To quantify the uncertainty contributed by the saturation pressure control, the average standard deviation of the two saturation pressure transducers (T3 & T4) was determined from the 10-minute sample period of each "As Left" humidity profile point.

$uP_{s\,[stability\,<45psiA]}$ = 0.002 psiA (DOF=559)

$uP_{s\,[stability\,>45psiA]}$ = 0.004 psiA (DOF=559)

To quantify the uncertainty contributed by the chamber pressure control, the average standard deviation of the single chamber pressure transducers (T2) was determined from the 10-minute sample period of each "As Left" humidity profile point.

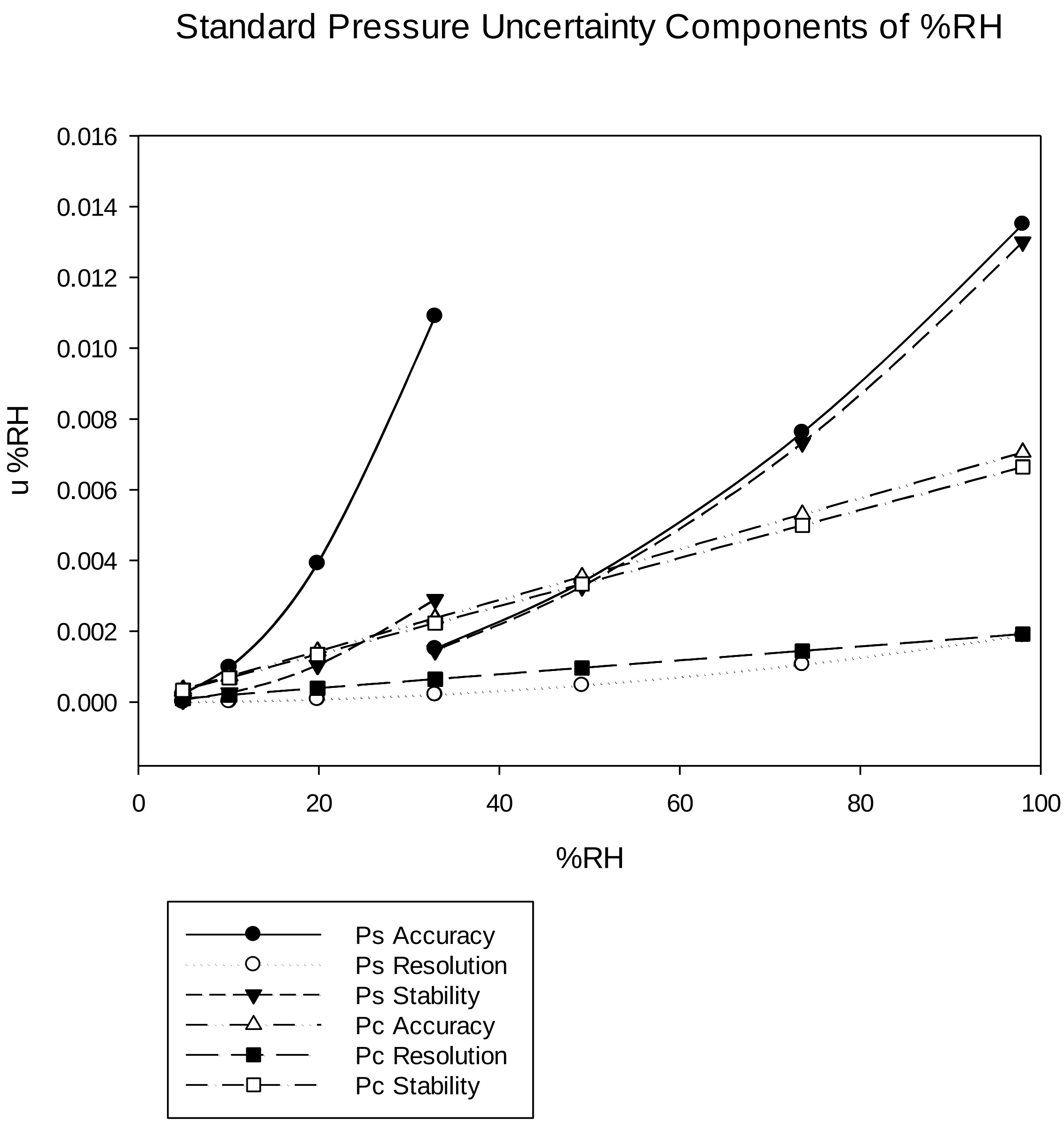
$uP_{c[stability]}$ = 0.001 psiA (DOF=559)

3.1.4 Pressure Uncertainty Contribution Summary

The standard %RH uncertainty components (*u%RH)* calculated using equation 9 from the associated individual pressure components are summarized in Table 1 and Figure 1.

Standard Pressure Uncertainty Components of %RH											
		Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA									
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
Saturation Temperature	**Description**	**15**	**20**	**30**	**45**	**45**	**75**	**150**	**316**	**Degrees of Freedom**	**Evaluation**
		98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.9%RH**	**10.1%RH**	**5.0%RH**		
0 °C	Ps Accuracy	0.013531	0.007611	0.003383	0.001503	0.010858	0.003908	0.000977	0.000220	Infinity	Type B
	Ps Resolution	0.001879	0.001057	0.000470	0.000209	0.000209	0.000075	0.000019	0.000004	Infinity	Type B
	Ps Stability	0.013021	0.007324	0.003255	0.001447	0.002893	0.001041	0.000260	0.000059	559	Type A
	Pc Accuracy	0.007058	0.005300	0.003542	0.002370	0.002370	0.001432	0.000729	0.000360	Infinity	Type B
	Pc Resolution	0.001918	0.001440	0.000962	0.000644	0.000644	0.000389	0.000198	0.000098	Infinity	Type B
	Pc Stability	0.006644	0.004989	0.003334	0.002231	0.002231	0.001348	0.000686	0.000339	559	Type A
	Combined	*0.021303*	*0.012951*	*0.006844*	*0.003924*	*0.011718*	*0.004515*	*0.001436*	*0.000553*	*~Infinity*	
		98.0%RH	**73.6%RH**	**49.1%RH**	**32.8%RH**	**32.8%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**		
35 °C	Ps Accuracy	0.013542	0.007618	0.003386	0.001505	0.010868	0.003912	0.000978	0.000220	Infinity	Type B
	Ps Resolution	0.001881	0.001058	0.000470	0.000209	0.000209	0.000075	0.000019	0.000004	Infinity	Type B
	Ps Stability	0.013031	0.007330	0.003258	0.001448	0.002896	0.001043	0.000261	0.000059	559	Type A
	Pc Accuracy	0.007063	0.005302	0.003541	0.002367	0.002367	0.001428	0.000724	0.000354	Infinity	Type B
	Pc Resolution	0.001919	0.001441	0.000962	0.000643	0.000643	0.000388	0.000197	0.000096	Infinity	Type B
	Pc Stability	0.006649	0.004991	0.003333	0.002228	0.002228	0.001344	0.000681	0.000333	559	Type A
	Combined	*0.021319*	*0.012961*	*0.006847*	*0.003923*	*0.011727*	*0.004516*	*0.001432*	*0.000545*	*~Infinity*	
		98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**		
70 °C	Ps Accuracy	0.013524	0.007615	0.003388	0.001507	0.010882	0.003919	0.000980	0.000221	Infinity	Type B
	Ps Resolution	0.001878	0.001058	0.000471	0.000209	0.000209	0.000075	0.000019	0.000004	Infinity	Type B
	Ps Stability	0.013014	0.007328	0.003260	0.001450	0.002900	0.001044	0.000261	0.000059	559	Type A
	Pc Accuracy	0.007054	0.005297	0.003538	0.002364	0.002364	0.001425	0.000720	0.000350	Infinity	Type B
	Pc Resolution	0.001917	0.001439	0.000961	0.000642	0.000642	0.000387	0.000196	0.000095	Infinity	Type B
	Pc Stability	0.006640	0.004986	0.003330	0.002226	0.002226	0.001341	0.000678	0.000329	559	Type A
	Combined	*0.021291*	*0.012953*	*0.006845*	*0.003921*	*0.011740*	*0.004521*	*0.001430*	*0.000541*	*~Infinity*	

Table 1



Standard Pressure Uncertainty Components of %RH
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
u %RH
0
20
40
60
80
100
%RH
Ps Accuracy
Ps Resolution
Ps Stability
Pc Accuracy
Pc Resolution
Pc Stability

Figure 1

The standard Dew Point Temperature uncertainty components (uT_D) calculated using equation 10 from the associated individual pressure components are summarized in Table 2 and Figure 2.

Standard Pressure Uncertainty Components of Dew Point Temperature (°C)											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**305**		
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-14.4 °C**	**-14.4 °C**	**-20.4 °C**	**-27.9 °C**	**-35.0 °C**		
0 °C	Ps Accuracy	0.001896	0.001376	0.000875	0.000557	0.004024	0.002275	0.001044	0.000462	Infinity	Type B
	Ps Resolution	0.000263	0.000191	0.000122	0.000077	0.000077	0.000044	0.000020	0.000009	Infinity	Type B
	Ps Stability	0.001824	0.001324	0.000842	0.000536	0.001072	0.000606	0.000278	0.000123	559	Type A
	Pc Accuracy	0.000989	0.000958	0.000916	0.000878	0.000878	0.000833	0.000779	0.000730	Infinity	Type B
	Pc Resolution	0.000269	0.000260	0.000249	0.000239	0.000239	0.000226	0.000212	0.000198	Infinity	Type B
	Pc Stability	0.000931	0.000901	0.000863	0.000826	0.000826	0.000784	0.000733	0.000687	559	Type A
	Combined	*0.002985*	*0.002341*	*0.001771*	*0.001454*	*0.004343*	*0.002628*	*0.001535*	*0.001128*	*~Infinity*	
		34.6 °C	**29.6 °C**	**22.7 °C**	**16.3 °C**	**16.3 °C**	**8.6 °C**	**-1.1 °C**	**-10.0 °C**		
35 °C	Ps Accuracy	0.002490	0.001797	0.001136	0.000718	0.005187	0.002913	0.001329	0.000588	Infinity	Type B
	Ps Resolution	0.000346	0.000250	0.000158	0.000100	0.000100	0.000056	0.000026	0.000011	Infinity	Type B
	Ps Stability	0.002396	0.001729	0.001093	0.000691	0.001382	0.000776	0.000354	0.000157	559	Type A
	Pc Accuracy	0.001299	0.001250	0.001187	0.001129	0.001129	0.001063	0.000983	0.000911	Infinity	Type B
	Pc Resolution	0.000353	0.000340	0.000323	0.000307	0.000307	0.000289	0.000267	0.000248	Infinity	Type B
	Pc Stability	0.001222	0.001177	0.001118	0.001063	0.001063	0.001000	0.000925	0.000858	559	Type A
	Combined	*0.003919*	*0.003057*	*0.002296*	*0.001872*	*0.005597*	*0.003362*	*0.001945*	*0.001414*	*~Infinity*	
		69.5 °C	**63.1 °C**	**54.4 °C**	**46.3 °C**	**46.3 °C**	**36.7 °C**	**24.8 °C**	**13.7 °C**		
70 °C	Ps Accuracy	0.003180	0.002282	0.001431	0.000899	0.006495	0.003622	0.001639	0.000723	Infinity	Type B
	Ps Resolution	0.000442	0.000317	0.000199	0.000125	0.000125	0.000070	0.000032	0.000014	Infinity	Type B
	Ps Stability	0.003060	0.002195	0.001377	0.000865	0.001731	0.000965	0.000437	0.000193	559	Type A
	Pc Accuracy	0.001659	0.001588	0.001496	0.001413	0.001413	0.001319	0.001206	0.001107	Infinity	Type B
	Pc Resolution	0.000451	0.000432	0.000407	0.000384	0.000384	0.000358	0.000328	0.000301	Infinity	Type B
	Pc Stability	0.001561	0.001495	0.001409	0.001330	0.001330	0.001241	0.001135	0.001042	559	Type A
	Combined	*0.005007*	*0.003882*	*0.002894*	*0.002343*	*0.007008*	*0.004179*	*0.002394*	*0.001721*	*~Infinity*	

Table 2

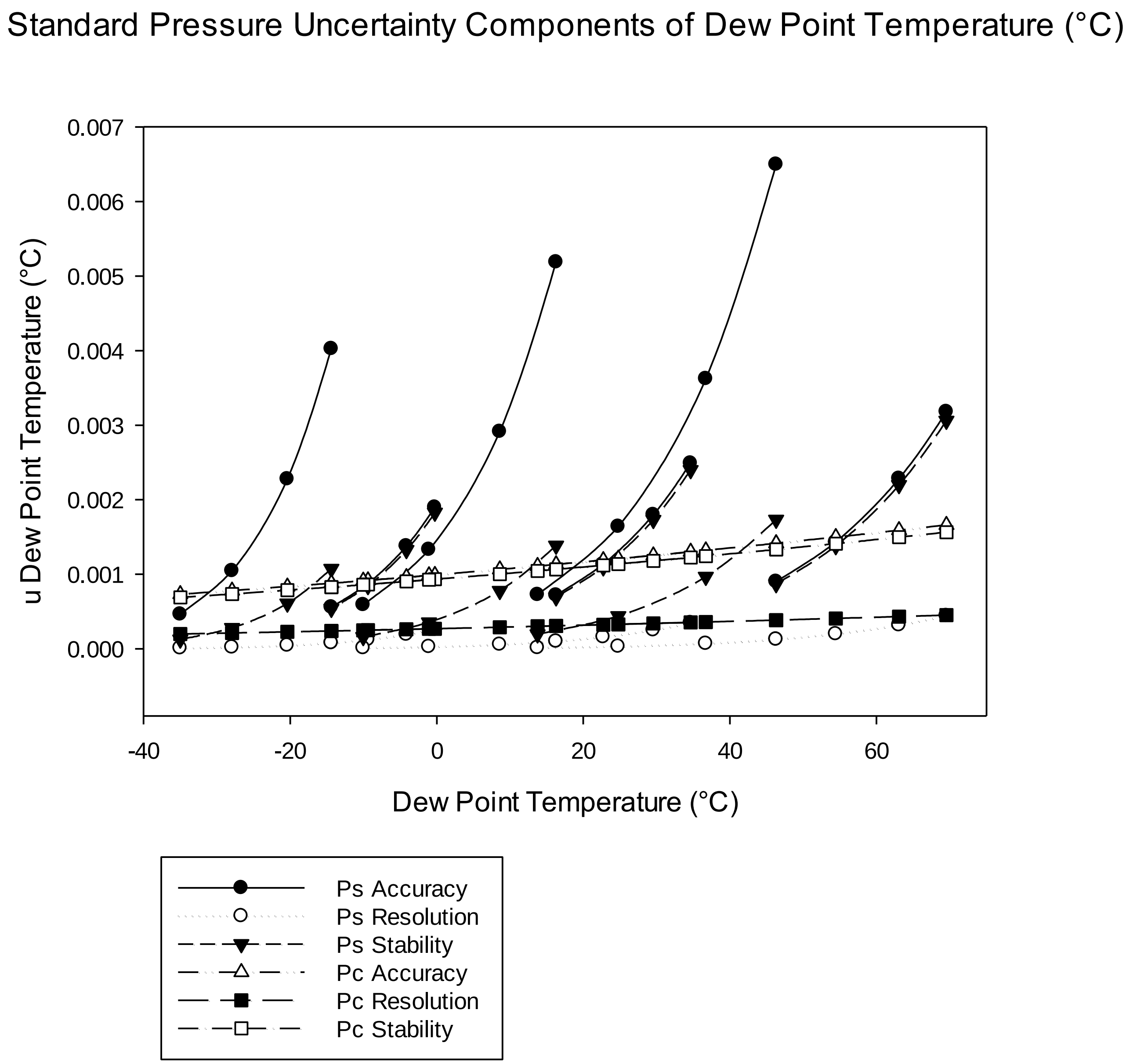

Standard Pressure Uncertainty Components of Dew Point Temperature (°C)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
u Dew Point Temperature (°C)
-40
-20
0
20
40
60
Dew Point Temperature (°C)
Ps Accuracy
Ps Resolution
Ps Stability
Pc Accuracy
Pc Resolution
Pc Stability

Figure 2

The standard Frost Point Temperature uncertainty components (uT_F) calculated using equation 11 from the associated individual pressure components are summarized in Table 3 and Figure 3.

Note: Any frost point value that is not possible is grayed out of the following table. No Frost Point temperature can be generated at a 70 °C saturation temperature; therefore, the temperature is not included in the table.

Standard Pressure Uncertainty Components of Frost Point Temperature (°C)											
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom	Evaluation
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA					
		15	20	30	45	45	75	150	308		
		-0.2 °C	-3.7 °C	-8.4 °C	-12.9 °C	-12.9 °C	-18.3 °C	-25.2 °C	-31.9 °C		
0 °C	Ps Accuracy	0.001673	0.001222	0.000785	0.000504	0.003636	0.002076	0.000964	0.000427	Infinity	Type B
	Ps Resolution	0.000232	0.000170	0.000109	0.000070	0.000070	0.000040	0.000019	0.000008	Infinity	Type B
	Ps Stability	0.001610	0.001176	0.000755	0.000484	0.000969	0.000553	0.000257	0.000114	559	Type A
	Pc Accuracy	0.000873	0.000851	0.000821	0.000793	0.000793	0.000760	0.000719	0.000681	Infinity	Type B
	Pc Resolution	0.000237	0.000231	0.000223	0.000216	0.000216	0.000207	0.000195	0.000185	Infinity	Type B
	Pc Stability	0.000822	0.000801	0.000773	0.000747	0.000747	0.000716	0.000677	0.000641	559	Type A
	Combined	*0.002634*	*0.002079*	*0.001587*	*0.001314*	*0.003924*	*0.002398*	*0.001418*	*0.001051*	*~Infinity*	
								-0.9 °C	-9.0 °C		
35 °C	Ps Accuracy							0.001174	0.000522	Infinity	Type B
	Ps Resolution							0.000023	0.000010	Infinity	Type B
	Ps Stability							0.000313	0.000139	559	Type A
	Pc Accuracy							0.000868	0.000817	Infinity	Type B
	Pc Resolution							0.000236	0.000222	Infinity	Type B
	Pc Stability							0.000817	0.000769	559	Type A
	Combined							*0.001719*	*0.001265*	*~Infinity*	

Table 3

Standard Pressure Uncertainty Components of Frost Point Temperature (°C)

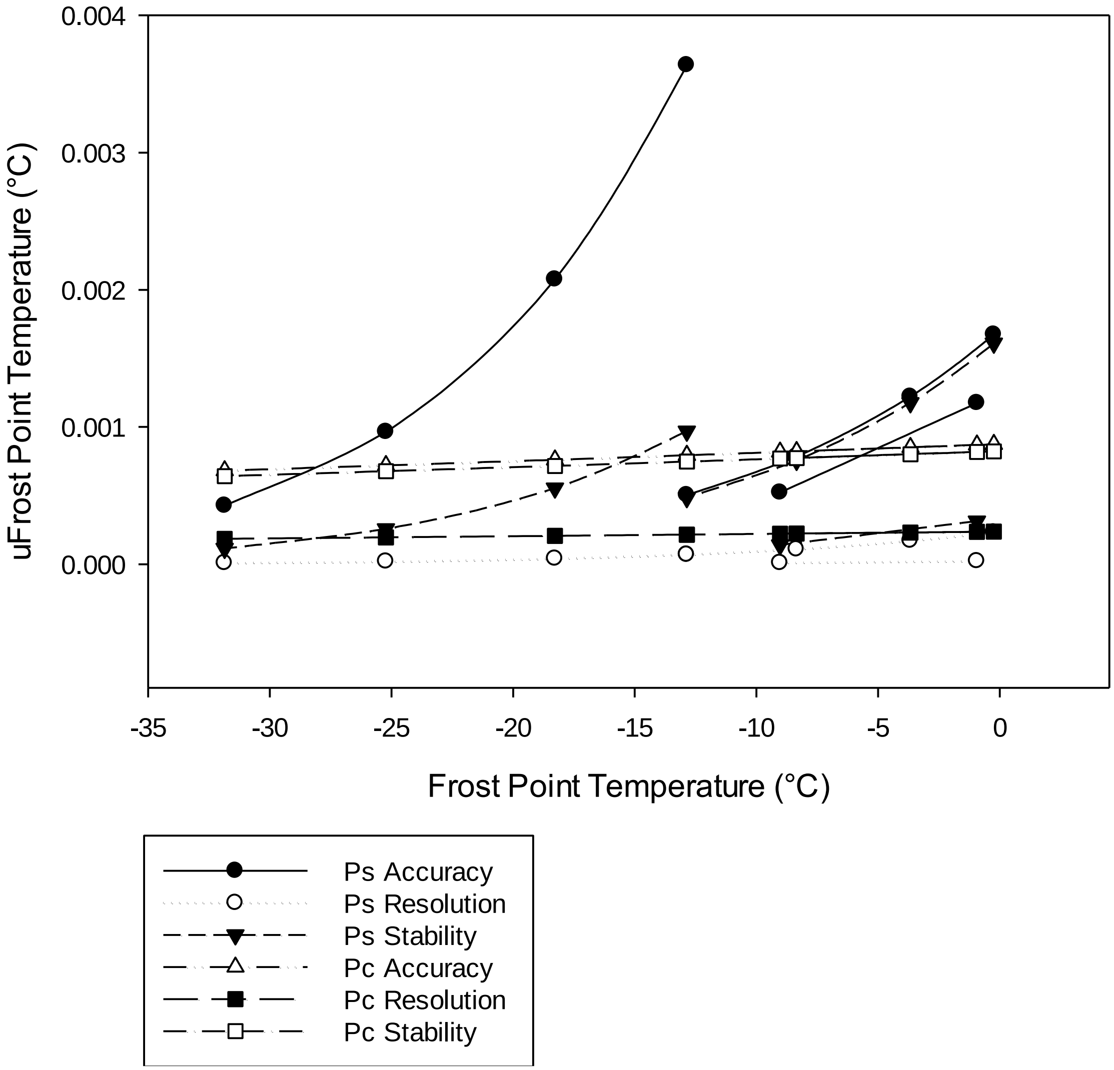


Figure 3

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 9500 humidity generator uses one temperature probe to measure the saturation temperature and another temperature probe to measure the test chamber temperature. In this design, each temperature probe contributes its own uncertainty to the overall system and is addressed independently of one another.

3.2.1 Temperature Probe Self-Heating

The 9500's temperature measurement circuitry applies a small current to each PRT to perform the resistance measurement of the platinum element. This small current can cause a slight self-heating of the probe, especially in probes that operate in an air environment. The chamber, saturation, and expansion valve temperature probes in the Model 9500 humidity generator operate in an air environment and can exhibit the most self-heating effects.

In the past, self-heating was measured using a test fixture comprised of stainless-steel tubing immersed in a liquid bath of constant temperature while at the same time exposing the probe surface to still air. For the Model 9500, the self-heating test was modified to use the actual probe locations in the generator since they are already located in still air (when in the shutdown state) surrounded by the large thermal mass of the bath fluid.

To quantify the self-heating uncertainty contributor, the generator was left powered off overnight with the bath at ambient room temperature. The generator was powered on, and the chamber, saturation, and expansion valve temperature probes were measured with the generator in the shutdown state (not generating with the probes in still air) over 30 minutes. During this time, each probe heated slightly before cooling back to equilibrium with the ambient conditions. Each probe's peak temperature was then compared to the starting temperature to determine a max self-heating uncertainty contributor for the probes. This temperature probe self-heating uncertainty is applied to both the saturation and chamber temperature as the "Self-Heating" subcomponent in Table 4.

$uT_{[\text{self-heating}]} = 0.097\ °C / \sqrt{3}$ (DOF=infinite)

It is worth noting that some self-heating is unavoidable as the probe is continuously operated with a slight current running through it. In general, this is accounted for during the temperature probe calibration meaning that this self-heating uncertainty contributor is most likely overestimated.

3.2.2 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:

$$\mathrm{uRH}_{[\text{component}]} = \frac{\partial}{\partial T_S}\left[\frac{e_S(T_S)\cdot f(T_S,P_S))}{e_S(T_C)\cdot f(T_C,P_C)}\cdot\frac{P_C}{P_S}\cdot\eta_S\right]\cdot \mathrm{u}T_{S[\text{component}]} \tag{12}$$

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

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

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:

$$\mathrm{uT}_{\mathrm{D[component]}} = \frac{\partial}{\partial T_S}\left[e_W(T_D)\cdot f(T_D,P_C) = f(T_S,P_S)\cdot e(T_S)\cdot \frac{P_C}{P_S} \right]\cdot \mathrm{uT}_{\mathrm{S\ [component]}} \tag{13}$$

$$\mathrm{uT}_{\mathrm{F[component]}} = \frac{\partial}{\partial T_S}\left[e_I(T_F)\cdot f(T_F,P_C) = f(T_S,P_S)\cdot e(T_S)\cdot \frac{P_C}{P_S} \right]\cdot \mathrm{uT}_{\mathrm{S\ [component]}} \tag{14}$$

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

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

$\mathrm{uT}_{\mathrm{S[component]}}$ = Saturation Temperature component uncertainty in terms of temperature.

3.2.2.1 Saturation Temperature Measurement Uncertainty Component

The temperature measurement accuracy of the Model 9500 humidity generator's saturation temperature probe encompasses seven separate subcomponents that are listed and combined in Table 4.

Model 9500 Temperature Components of Uncertainty					
Description	Uncertainty (±)	k=	Distribution	Degrees of Freedom	Evaluation
Standard - Fluke 1595A	0.0044	2	Normal	Infinity	Type B
NI-9216 Resolution	0.0000625849	1	Resolution	Infinity	Type B
NI-9216 Offset Error	0.00237	1	Rectangular	Infinity	Type B
NI-9216 Gain Error	0.00002765	1	Rectangular	Infinity	Type B
5622 Reproducibility	0.0003	1	Normal	104	Type A
5622 Repeatability	0.0018	1	Normal	104	Type A
Self-Heating	0.0097	1	Rectangular	545	Type A
				Combined Standard Uncertainty (±):	0.0064
				Effective Degrees of Freedom:	900
				Confidence:	95.45%
				k:	2.00
				Expanded Combined Uncertainty (±):	0.013

Table 4

Using the expanded result from table 4 and taking a conservative approach that is based on a rectangular distribution, the uncertainty component of saturation temperature accuracy is:

$$uT_{s[accuracy]} = 0.013\ °C / \sqrt{3}\ \text{(DOF=infinite)}$$

resulting in

$$uT_{s[accuracy]} = 0.015°C$$

(using a coverage factor, k=2, at an approximate level of confidence of 95%)

3.2.2.2 Saturation Temperature Resolution Uncertainty Component

The Model 9500 humidity generator digitally communicates with the module that measures the saturation temperature probe. Based on a rectangular distribution of the half-interval of the resolution, the uncertainty component of saturation temperature resolution is:

$$uT_{s\ [resolution]} = 0.001\ °C / \sqrt{12}\ \text{(DOF=infinite)}$$

3.2.2.3 Saturation Temperature Control Stability

The Model 9500 humidity generating system incorporates a computer-controlled temperature bath, utilizing distilled water as the heat transfer medium. The test chamber, saturators, heat exchanger, and connecting tubing are immersed in approximately 20 gallons of distilled water circulated at 50 gallons per minute by a magnetically coupled centrifugal pump. This temperature bath provides the temperature conditioning of these components, resulting in inherent temperature stability and stable humidity.

The temperature bath stability inherently impacts the saturation temperature stability. To quantify the uncertainty contributed by the system's overall temperature control stability, the average standard deviation of the saturation temperature probe (RTD2) was determined from the 10-minute sample period of each "As Left" humidity profile point.

$$uT_{s\ [stability]} = 0.001\ °C\ \text{(DOF=559)}$$

3.2.2.4 Saturator Temperature Gradients

Saturation of the airstream upstream of the expansion valve is accomplished in two single-pass tube-in-shell type heat exchangers. These assemblies are called saturators and are located within the fluid bath beneath the test chamber. The design of the saturators is that of a counter-flow design where the fluid medium flows in a direction opposite that of the saturated gas stream. Thermal gradients do exist within the saturator from inlet to outlet. Controlling the direction of this gradient is essential to proper saturation. The temperature of the fluid is measured and controlled at the point that it enters the saturator cavity, which is the exact point that the saturated gas stream exits the saturator due to the counter-flow design. The temperature is 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 ensures that the exiting gas has reached thermal equilibrium with the entering fluid and is, therefore, at fluid temperature.

A theoretical analysis study using computational fluid dynamics (CFD) was performed on a smaller Model 2900 saturator to quantify the thermal gradients and saturator efficiency. The Model 9500 uses two slightly larger saturators compared to the single saturator in Model 2900, but the overall design principles are the same. This similarity allowed the CFD data to be used to estimate the saturators' thermal gradient uncertainty component.

$$uT_{s\ [gradient]} = 0.005\ °C / \sqrt{3}\ \text{(DOF=infinite)}$$

The Model 9500's saturator design, combined with its computer-controlled temperature bath, is key to reducing the adverse effects that temperature gradients might otherwise cause. Furthermore, this design improves the ability of the saturator to fully saturate the gas stream with water vapor, thereby improving saturator efficiency.

3.2.3 Test Chamber Temperature Uncertainty Contribution

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

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

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

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

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

3.2.3.1 Test Chamber Temperature Measurement Uncertainty Component

The temperature measurement accuracy of the Model 9500 humidity generator's test chamber temperature probe encompasses the same seven subcomponents as those listed and combined in Table 4.

Using the expanded result from table 4 and taking a conservative approach that is based on a rectangular distribution, the uncertainty component of test chamber temperature accuracy is:

$\mathrm{uT}_{\mathrm{c}\ [\text{accuracy}]}$ = 0.013 °C / √3 (DOF=infinite)

resulting in

$\mathrm{uT}_{\mathrm{c}\ [\text{accuracy}]}$ = 0.015°C
(using a coverage factor, k=2, at an approximate level of confidence of 95%)

3.2.3.2 Test Chamber Temperature Resolution Uncertainty Component

The Model 9500 humidity generator digitally communicates with the module that measures the test chamber temperature probe. Based on a rectangular distribution of the half-interval of the resolution, the uncertainty component of test chamber temperature resolution is:

$\mathrm{uT}_{\mathrm{c}\ [\text{resolution}]}$ = 0.001 °C / √12 (DOF=infinite)

3.2.3.3 Test Chamber Temperature Uniformity Uncertainty Component

The 9500 operates by generating the %RH setpoint based on pressure and temperatures, including the test chamber temperature probe. This means the system automatically compensates for any temperature difference in the test chamber based on the actual test chamber temperature probe reading. In scenarios where the device under test is not bundled with the test chamber temperature probe or when there are multiple devices under test in the test chamber, temperature variations within the test chamber can contribute to the overall %RH uncertainty of the generator.

Using the expanded result from the "Model 9500 Chamber Temperature Uniformity Analysis" [12] that is based on a rectangular distribution, the uncertainty component of chamber temperature uniformity is:

$uT_{c[uniformity]}$ = 0.008 °C / √3 (DOF=infinite)

3.2.3.4 Test Chamber Temperature Control Stability

The test chamber temperature stability is a component of the overall test chamber temperature uniformity uncertainty component listed above. Therefore, it is not listed independently in this analysis. Refer to the "Model 9500 Chamber Temperature Uniformity Analysis" [12] temperature fluctuations subcomponents.

3.2.4 Temperature Uncertainty Contribution Summary

The standard %RH uncertainty components (u%RH) calculated using equations 12 and 15 from the previously shown individual temperature components are summarized in Tables 5a (continued into 5b) and Figure 4.

Standard Temperature Uncertainty Components of %RH											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**316**		
		98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.9%RH**	**10.1%RH**	**5.0%RH**		
0 °C	Ts Accuracy	0.053443	0.040124	0.026806	0.017927	0.017927	0.010824	0.005497	0.002706	Infinity	Type B
	Ts Resolution	0.002055	0.001543	0.001031	0.000689	0.000689	0.000416	0.000211	0.000104	Infinity	Type B
	Ts Stability	0.007120	0.005346	0.003571	0.002388	0.002388	0.001442	0.000732	0.000361	559	Type A
	Ts Gradients	0.020555	0.015432	0.010310	0.006895	0.006895	0.004163	0.002114	0.001041	Infinity	Type B
	Tc Accuracy	0.053442	0.040130	0.026817	0.017943	0.017943	0.010843	0.005520	0.002726	Infinity	Type B
	Tc Resolution	0.002055	0.001543	0.001031	0.000690	0.000690	0.000417	0.000212	0.000105	Infinity	Type B
	Tc Uniformity	0.032888	0.024695	0.016503	0.011042	0.011042	0.006673	0.003397	0.001678	Infinity	Type B
	Combined	*0.085296*	*0.064044*	*0.042793*	*0.028625*	*0.028625*	*0.017292*	*0.008793*	*0.004336*	*~Infinity*	

Table 5a

Standard Temperature Uncertainty Components of %RH ...continued											
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom	Evaluation
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA					
		15	20	30	45	45	75	150	316		
		98.0%RH	73.6%RH	49.1%RH	32.8%RH	32.8%RH	19.9%RH	10.0%RH	4.9%RH		
35 °C	Ts Accuracy	0.040715	0.030562	0.020408	0.013638	0.013638	0.008221	0.004159	0.002026	Infinity	Type B
	Ts Resolution	0.001566	0.001175	0.000785	0.000525	0.000525	0.000316	0.000160	0.000078	Infinity	Type B
	Ts Stability	0.005425	0.004072	0.002719	0.001817	0.001817	0.001095	0.000554	0.000270	559	Type A
	Ts Gradients	0.015660	0.011755	0.007849	0.005245	0.005245	0.003162	0.001600	0.000779	Infinity	Type B
	Tc Accuracy	0.040715	0.030565	0.020414	0.013646	0.013646	0.008232	0.004172	0.002040	Infinity	Type B
	Tc Resolution	0.001566	0.001176	0.000785	0.000525	0.000525	0.000317	0.000160	0.000078	Infinity	Type B
	Tc Uniformity	0.025056	0.018809	0.012562	0.008398	0.008398	0.005066	0.002567	0.001256	Infinity	Type B
	Combined	*0.064983*	*0.048781*	*0.032577*	*0.021774*	*0.021774*	*0.013131*	*0.006649*	*0.003246*	*~Infinity*	
		98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.8%RH	10.0%RH	4.9%RH		
70 °C	Ts Accuracy	0.031820	0.023911	0.015981	0.010683	0.010683	0.006438	0.003250	0.001574	Infinity	Type B
	Ts Resolution	0.001224	0.000920	0.000615	0.000411	0.000411	0.000248	0.000125	0.000061	Infinity	Type B
	Ts Stability	0.004239	0.003186	0.002129	0.001423	0.001423	0.000858	0.000433	0.000210	559	Type A
	Ts Gradients	0.012238	0.009197	0.006147	0.004109	0.004109	0.002476	0.001250	0.000606	Infinity	Type B
	Tc Accuracy	0.031818	0.023892	0.015959	0.010665	0.010665	0.006428	0.003249	0.001579	Infinity	Type B
	Tc Resolution	0.001224	0.000919	0.000614	0.000410	0.000410	0.000247	0.000125	0.000061	Infinity	Type B
	Tc Uniformity	0.019580	0.014703	0.009821	0.006563	0.006563	0.003956	0.001999	0.000972	Infinity	Type B
	Combined	*0.050784*	*0.038147*	*0.025487*	*0.017035*	*0.017035*	*0.010266*	*0.005186*	*0.002517*	*~Infinity*	

Table 5b

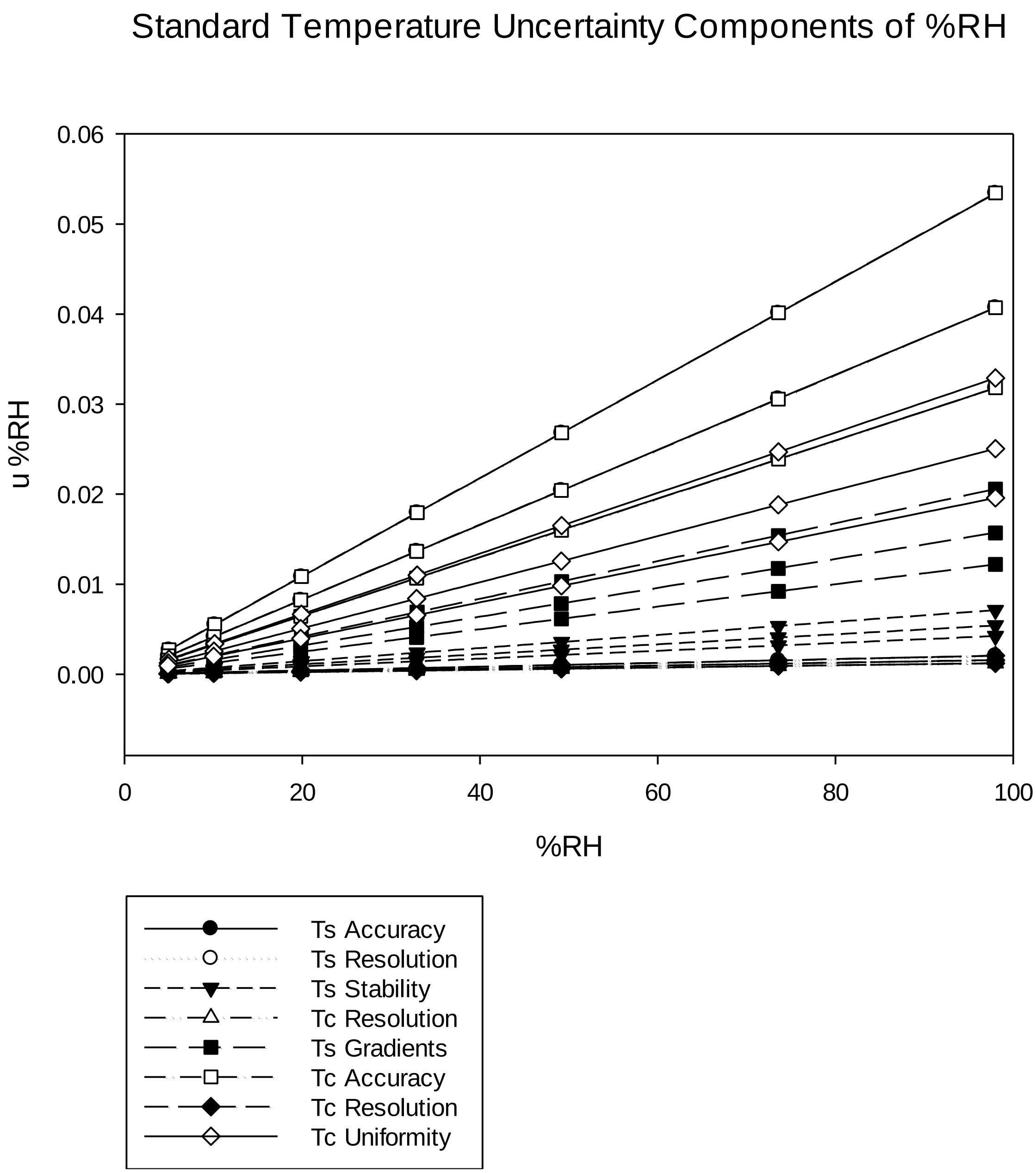

Standard Temperature Uncertainty Components of %RH
0.06
0.05
0.04
0.03
0.02
0.01
0.00
u %RH
0
20
40
60
80
100
%RH
Ts Accuracy
Ts Resolution
Ts Stability
Tc Resolution
Ts Gradients
Tc Accuracy
Tc Resolution
Tc Uniformity

Figure 4

The standard Dew Point Temperature uncertainty components (uTD) calculated using equation 13 from the previously shown individual temperature components are summarized in Tables 6a (continued into 6b) and Figure 5.

Standard Temperature Uncertainty Components of Dew Point Temperature (°C)											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**305**		
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-14.4 °C**	**-14.4 °C**	**-20.4 °C**	**-27.9 °C**	**-35.0 °C**		
0 °C	Ts Accuracy	0.007488	0.007251	0.006937	0.006644	0.006644	0.006302	0.005879	0.005486	Infinity	Type B
	Ts Resolution	0.000288	0.000279	0.000267	0.000256	0.000256	0.000242	0.000226	0.000211	Infinity	Type B
	Ts Stability	0.000998	0.000966	0.000924	0.000885	0.000885	0.000840	0.000783	0.000731	559	Type A
	Ts Gradients	0.002880	0.002789	0.002668	0.002555	0.002555	0.002424	0.002261	0.002110	Infinity	Type B
	Tc Accuracy									Infinity	Type B
	Tc Resolution									Infinity	Type B
	Tc Uniformity									Infinity	Type B
	Combined	*0.008090*	*0.007834*	*0.007495*	*0.007178*	*0.007178*	*0.006808*	*0.006351*	*0.005927*	*~Infinity*	
		34.6 °C	**29.6 °C**	**22.7 °C**	**16.3 °C**	**16.3 °C**	**8.6 °C**	**-1.1 °C**	**-10.0 °C**		
35 °C	Ts Accuracy	0.007485	0.007208	0.006844	0.006509	0.006509	0.006121	0.005651	0.005223	Infinity	Type B
	Ts Resolution	0.000288	0.000277	0.000263	0.000250	0.000250	0.000235	0.000217	0.000201	Infinity	Type B
	Ts Stability	0.000997	0.000960	0.000912	0.000867	0.000867	0.000816	0.000753	0.000696	559	Type A
	Ts Gradients	0.002879	0.002772	0.002632	0.002503	0.002503	0.002354	0.002173	0.002009	Infinity	Type B
	Tc Accuracy									Infinity	Type B
	Tc Resolution									Infinity	Type B
	Tc Uniformity									Infinity	Type B
	Combined	*0.008087*	*0.007788*	*0.007394*	*0.007032*	*0.007032*	*0.006613*	*0.006105*	*0.005642*	*~Infinity*	

Table 6a

Standard Temperature Uncertainty Components of Dew Point Temperature (°C) ...continued											
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom	Evaluation
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA					
		15	20	30	45	45	75	150	305		
		69.5 °C	63.1 °C	54.4 °C	46.3 °C	46.3 °C	36.7 °C	24.8 °C	13.7 °C		
70 °C	Ts Accuracy	0.007482	0.007164	0.006752	0.006377	0.006377	0.005949	0.005436	0.004976	Infinity	Type B
	Ts Resolution	0.000288	0.000276	0.000260	0.000245	0.000245	0.000229	0.000209	0.000191	Infinity	Type B
	Ts Stability	0.000997	0.000954	0.000900	0.000850	0.000850	0.000793	0.000724	0.000663	559	Type A
	Ts Gradients	0.002878	0.002755	0.002597	0.002453	0.002453	0.002288	0.002091	0.001914	Infinity	Type B
	Tc Accuracy									Infinity	Type B
	Tc Resolution									Infinity	Type B
	Tc Uniformity									Infinity	Type B
	Combined	*0.008083*	*0.007740*	*0.007295*	*0.006889*	*0.006889*	*0.006427*	*0.005872*	*0.005376*	*~Infinity*	

Table 6b

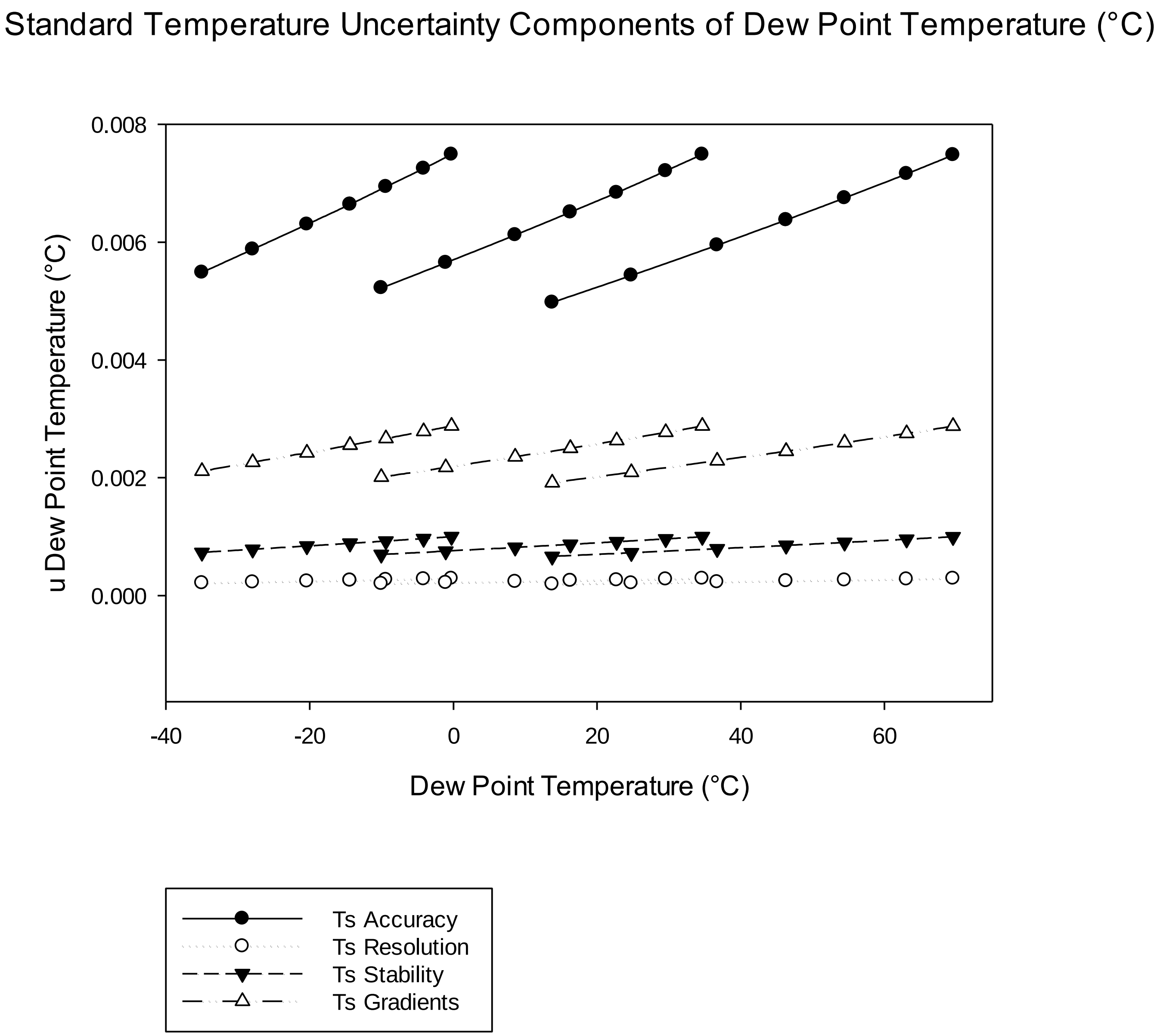

Standard Temperature Uncertainty Components of Dew Point Temperature (°C)
0.008
0.006
0.004
0.002
0.000
u Dew Point Temperature (°C)
-40
-20
0
20
40
60
Dew Point Temperature (°C)
Ts Accuracy
Ts Resolution
Ts Stability
Ts Gradients

Figure 5

The standard Frost Point temperature uncertainty components (uT_F) calculated using equation 14 from the associated individual temperature components previously shown are summarized in Table 7 and Figure 6.

Note: Any frost point value that is not possible is grayed out of the following table. No Frost Point temperature can be generated at a 70 °C saturation temperature; therefore, the temperature is not included in the table.

Standard Temperature Uncertainty Components of Frost Point Temperature (°C)											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**308**		
		-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-12.9 °C**	**-12.9 °C**	**-18.3 °C**	**-25.2 °C**	**-31.9 °C**		
0 °C	Ts Accuracy	0.006607	0.006442	0.006218	0.006004	0.006004	0.005750	0.005428	0.005118	Infinity	Type B
	Ts Resolution	0.000254	0.000248	0.000239	0.000231	0.000231	0.000221	0.000209	0.000197	Infinity	Type B
	Ts Stability	0.000880	0.000858	0.000828	0.000800	0.000800	0.000766	0.000723	0.000682	559	Type A
	Ts Gradients	0.002541	0.002478	0.002392	0.002309	0.002309	0.002211	0.002088	0.001968	Infinity	Type B
	Tc Accuracy									Infinity	Type B
	Tc Resolution									Infinity	Type B
	Tc Uniformity									Infinity	Type B
	Combined	*0.007138*	*0.006960*	*0.006718*	*0.006486*	*0.006486*	*0.006212*	*0.005865*	*0.005529*	*~Infinity*	
								-0.9 °C	**-9.0 °C**		
35 °C	Ts Accuracy							0.004994	0.004682	Infinity	Type B
	Ts Resolution							0.000192	0.000180	Infinity	Type B
	Ts Stability							0.000665	0.000624	559	Type A
	Ts Gradients							0.001921	0.001801	Infinity	Type B
	Tc Accuracy									Infinity	Type B
	Tc Resolution									Infinity	Type B
	Tc Uniformity									Infinity	Type B
	Combined							*0.005395*	*0.005058*	*~Infinity*	

Table 7

Standard Temperature Uncertainty Components of Frost Point Temperature (°C)

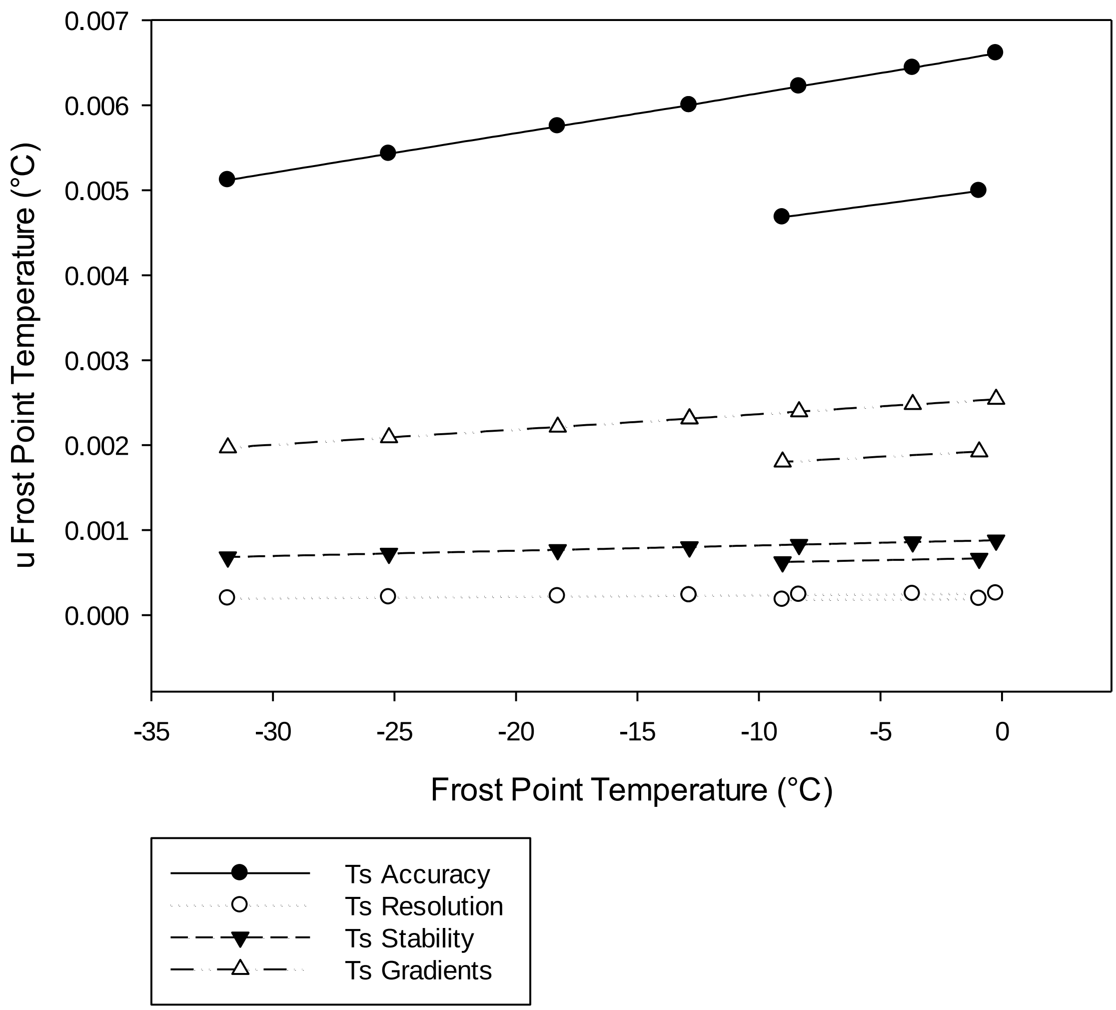


Figure 6

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 overall 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 Wexler's [4] saturation vapor pressure equation. Wexler [4] lists 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.

At higher saturation pressures, P_S, the enhancement factor equation uncertainty, becomes the predominant uncertainty component for both the Dew Point temperature and Frost Point temperature uncertainties. The Model 9500 can reduce this uncertainty contributor by using a lower saturation pressure to generate all but the lowest Dew/Frost Point temperature within its operating range. This is done by allowing the system to automatically pick the best bath temperature setpoint for the desired Dew/Frost Point setpoint or manually operating the bath temperature 2°C to 30 °C warmer than the desired Dew/Frost Point setpoint to prevent high saturation pressures. To achieve the best uncertainty, the summary section at the end of this document defines two uncertainty specifications based on the saturation pressure P_S range used to generate a particular Dew/Frost Point temperature.

3.3.3 Equation Uncertainty Contribution Summary

The standard %RH uncertainty components (u%RH) calculated using the associated equation uncertainty tables mentioned above are summarized in Table 8 and Figure 7.

Standard Equation Uncertainty Components of %RH											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**316**		
		98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.9%RH**	**10.1%RH**	**5.0%RH**		
0 °C	SVP@Ts	0.001562	0.001172	0.000781	0.000521	0.000521	0.000312	0.000156	0.000074	Infinity	Type B
	F@Ts,Ps	0.010136	0.010148	0.010172	0.010209	0.010209	0.010249	0.009967	0.010717	Infinity	Type B
	SVP@Tt	0.001563	0.001173	0.000784	0.000525	0.000525	0.000317	0.000161	0.000080	Infinity	Type B
	F@Tt,Pt	0.009933	0.007459	0.004985	0.003335	0.003335	0.002015	0.001026	0.000507	Infinity	Type B
	Combined	*0.014363*	*0.012703*	*0.011382*	*0.010765*	*0.010765*	*0.010454*	*0.010022*	*0.010730*	*Infinity*	
		98.0%RH	**73.6%RH**	**49.1%RH**	**32.8%RH**	**32.8%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**		
35 °C	SVP@Ts	0.008209	0.006157	0.004105	0.002737	0.002737	0.001642	0.000821	0.000389	Infinity	Type B
	F@Ts,Ps	0.007623	0.007783	0.007951	0.008075	0.008075	0.008214	0.008575	0.008936	Infinity	Type B
	SVP@Tt	0.008210	0.006163	0.004116	0.002752	0.002752	0.001660	0.000841	0.000411	Infinity	Type B
	F@Tt,Pt	0.007458	0.005599	0.003739	0.002500	0.002500	0.001508	0.000764	0.000374	Infinity	Type B
	Combined	*0.015765*	*0.012955*	*0.010535*	*0.009302*	*0.009302*	*0.008672*	*0.008688*	*0.008962*	*Infinity*	
		98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**		
70 °C	SVP@Ts	0.002050	0.001539	0.001027	0.000685	0.000685	0.000411	0.000206	0.000098	Infinity	Type B
	F@Ts,Ps	0.003652	0.004423	0.005200	0.005726	0.005726	0.006177	0.006745	0.007174	Infinity	Type B
	SVP@Tt	0.002050	0.001539	0.001028	0.000687	0.000687	0.000414	0.000209	0.000102	Infinity	Type B
	F@Tt,Pt	0.003518	0.002642	0.001765	0.001179	0.001179	0.000711	0.000359	0.000175	Infinity	Type B
	Combined	*0.005841*	*0.005593*	*0.005680*	*0.005926*	*0.005926*	*0.006245*	*0.006760*	*0.007178*	*Infinity*	

Table 8

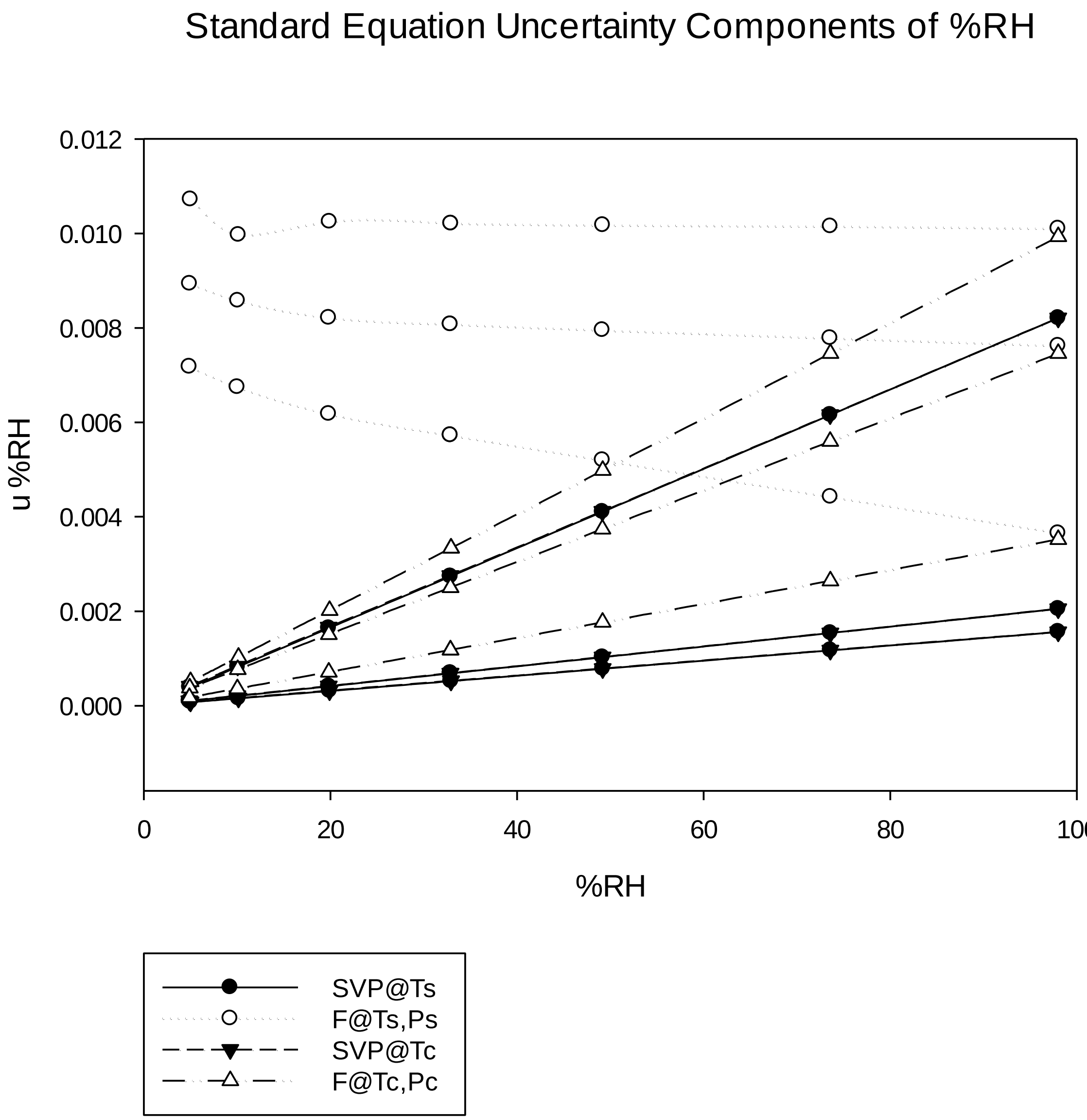

Standard Equation Uncertainty Components of %RH
0.012
0.010
0.008
0.006
0.004
0.002
0.000
u %RH
0
20
40
60
80
100
%RH
SVP@Ts
F@Ts,Ps
SVP@Tc
F@Tc,Pc

Figure 7

The standard Dew Point temperature uncertainty components (uT_D) calculated using the associated equation uncertainty tables mentioned above are summarized in Table 9 and Figure 8.

Standard Equation Uncertainty Components of Dew Point Temperature (°C)											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**305**		
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-14.4 °C**	**-14.4 °C**	**-20.4 °C**	**-27.9 °C**	**-35.0 °C**		
0 °C	SVP@Ts	0.000219	0.000212	0.000202	0.000193	0.000193	0.000182	0.000167	0.000150	Infinity	Type B
	F@Ts,Ps	0.001420	0.001834	0.002633	0.003784	0.003784	0.005967	0.010657	0.020996	Infinity	Type B
	SVP@Td	0.000219	0.000212	0.000203	0.000194	0.000194	0.000184	0.000172	0.000162	Infinity	Type B
	F@Td,Pt	0.001411	0.001630	0.001902	0.002130	0.002130	0.002349	0.002200	0.002572	Infinity	Type B
	Combined	*0.002026*	*0.002472*	*0.003260*	*0.004351*	*0.004351*	*0.006417*	*0.010885*	*0.021154*	*Infinity*	
		34.6 °C	**29.6 °C**	**22.7 °C**	**16.3 °C**	**16.3 °C**	**8.6 °C**	**-1.1 °C**	**-10.0 °C**		
35 °C	SVP@Ts	0.001509	0.001452	0.001377	0.001306	0.001306	0.001223	0.001115	0.001005	Infinity	Type B
	F@Ts,Ps	0.001401	0.001836	0.002667	0.003854	0.003854	0.006116	0.011650	0.022248	Infinity	Type B
	SVP@Td	0.001541	0.001905	0.001997	0.001429	0.001429	0.000820	0.000218	0.000202	Infinity	Type B
	F@Td,Pt	0.001338	0.000923	0.001439	0.001585	0.001585	0.001493	0.001457	0.001933	Infinity	Type B
	Combined	*0.002899*	*0.003156*	*0.003881*	*0.004595*	*0.004595*	*0.006466*	*0.011796*	*0.022355*	*Infinity*	
		69.5 °C	**63.1 °C**	**54.4 °C**	**46.3 °C**	**46.3 °C**	**36.7 °C**	**24.8 °C**	**13.7 °C**		
70 °C	SVP@Ts	0.000482	0.000461	0.000434	0.000409	0.000409	0.000380	0.000344	0.000309	Infinity	Type B
	F@Ts,Ps	0.000859	0.001325	0.002197	0.003418	0.003418	0.005708	0.011280	0.021881	Infinity	Type B
	SVP@Td	0.000485	0.000507	0.000739	0.000988	0.000988	0.001382	0.002186	0.001221	Infinity	Type B
	F@Td,Pt	0.000844	0.001025	0.001063	0.001365	0.001365	0.001550	0.001291	0.001554	Infinity	Type B
	Combined	*0.001385*	*0.001810*	*0.002587*	*0.003833*	*0.003833*	*0.006086*	*0.011568*	*0.021972*	*Infinity*	

Table 9

Standard Equation Uncertainty Components of Dew Point Temperature (°C)

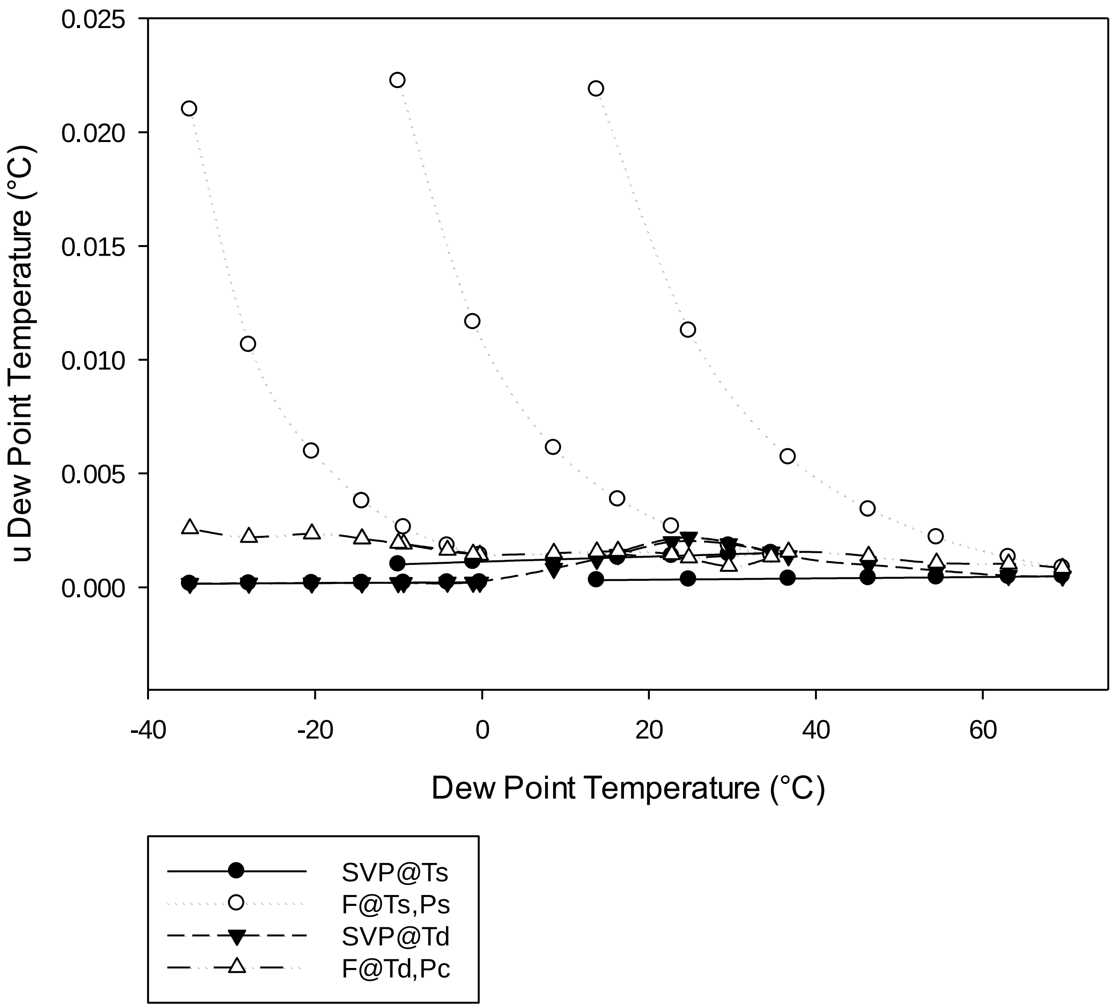


Figure 8

The standard Frost Point temperature uncertainty components (uT_F) calculated using the associated equation uncertainty tables mentioned above are summarized in Table 10 and Figure 9.

Note: Any frost point value that is not possible is grayed out of the following table. No Frost Point temperature can be generated at a 70 °C saturation temperature; therefore, the temperature is not included in the table.

Standard Equation Uncertainty Components of Frost Point Temperature (°C)

Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA — Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA				Degrees of Freedom	Evaluation
		15	20	30	45	45	75	150	308		
		-0.2 °C	-3.7 °C	-8.4 °C	-12.9 °C	-12.9 °C	-18.3 °C	-25.2 °C	-31.9 °C		
0 °C	SVP@Ts	0.000193	0.000188	0.000181	0.000174	0.000174	0.000166	0.000154	0.000140	Infinity	Type B
	F@Ts,Ps	0.001254	0.001629	0.002359	0.003419	0.003419	0.005444	0.009841	0.019772	Infinity	Type B
	SVP@Tf	0.000353	0.002536	0.005335	0.007569	0.007569	0.009865	0.012163	0.013942	Infinity	Type B
	F@Tf,Pt	0.001244	0.001420	0.001644	0.001839	0.001839	0.002052	0.002030	0.002102	Infinity	Type B
	Combined	*0.001811*	*0.003337*	*0.006063*	*0.008508*	*0.008508*	*0.011454*	*0.015777*	*0.024285*	*Infinity*	
								-0.9 °C	-9.0 °C		
35 °C	SVP@Ts							0.000986	0.000901	Infinity	Type B
	F@Ts,Ps							0.010297	0.020131	Infinity	Type B
	SVP@Tf							0.000804	0.005722	Infinity	Type B
	F@Tf,Pt							0.001280	0.001675	Infinity	Type B
	Combined							*0.010453*	*0.021014*	*Infinity*	

Table 10

Standard Equation Uncertainty Components of Frost Point Temperature (°C)

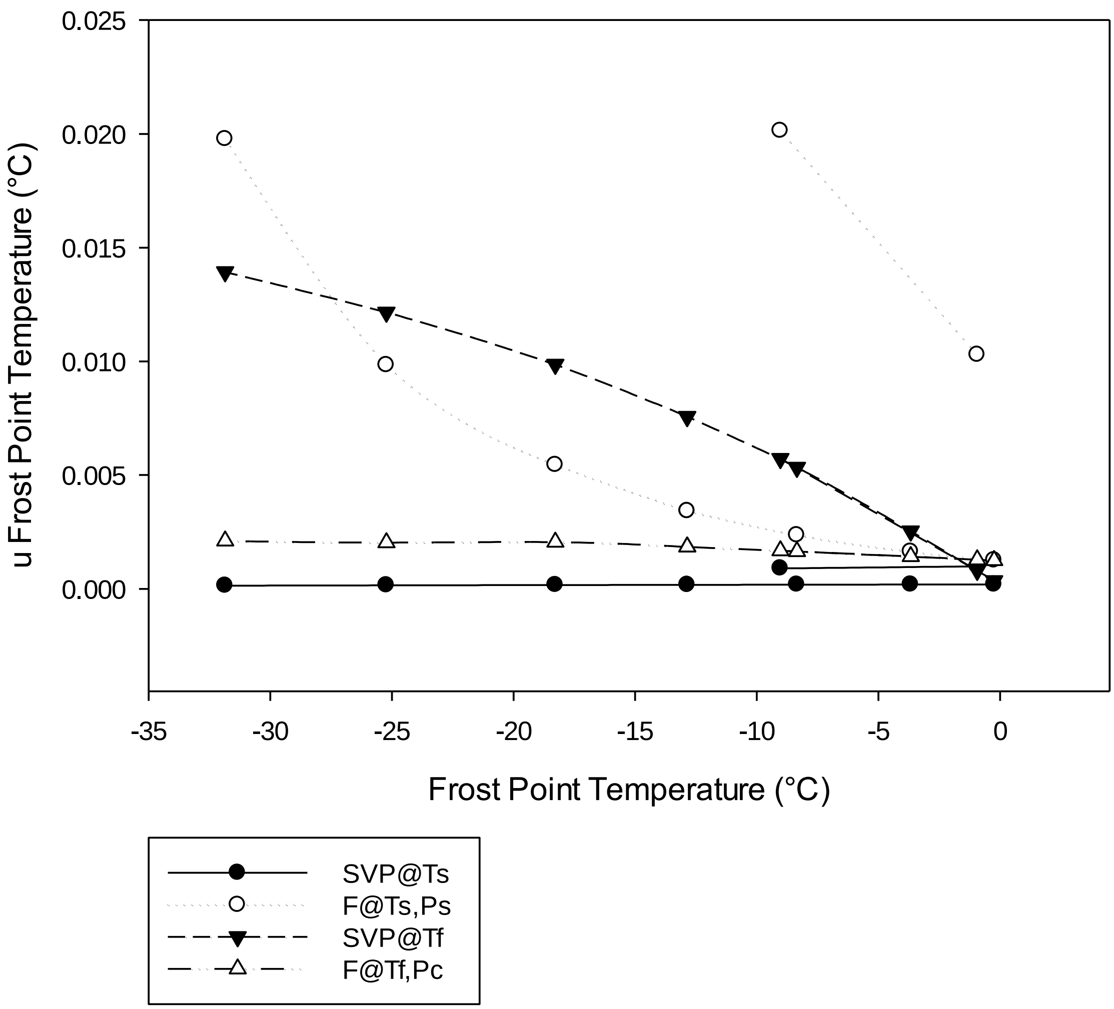


Figure 9

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 airstream from the Pre-Saturator, humidified to an absolute moisture content greater than saturation at fluid bath temperature, is made to flow through the two saturators on the shell side of the heat exchanger while temperature-controlled fluid flows through the tube side of the saturators in a direction opposite that of the airstream. As the pre-saturated air flows through the saturator, excess water vapor is condensed as the airstream establishes thermal equilibrium with the fluid, ensuring that the airstream is fully saturated at bath temperature.

Although this design helps assure near 100% saturation of the gas, there may still be small amounts of uncertainty caused by other contributors, such as contamination within air or water, which can impact the overall efficiency. Based on engineering research and development work on the Model 9500, the uncertainty component of % efficiency of saturation is determined to be:

$$\eta_S = 99.98\%$$

The standard %RH uncertainty components (u%RH) calculated using the above-associated % efficiency component are summarized in Table 11 and Figure 10.

Standard Saturator Efficiency Uncertainty Components of %RH											
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom	Evaluation
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA					
		15	20	30	45	45	75	150	316		
		98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.9%RH	10.1%RH	5.0%RH		
0 °C	η_S	0.019601	0.014719	0.009836	0.006581	0.006581	0.003977	0.002025	0.001000	Infinity	Type B
	Combined	*0.019601*	*0.014719*	*0.009836*	*0.006581*	*0.006581*	*0.003977*	*0.002025*	*0.001000*	*Infinity*	
		98.0%RH	73.6%RH	49.1%RH	32.8%RH	32.8%RH	19.8%RH	10.0%RH	4.9%RH		
35 °C	η_S	0.019601	0.014714	0.009828	0.006569	0.006569	0.003963	0.002008	0.000982	Infinity	Type B
	Combined	*0.019601*	*0.014714*	*0.009828*	*0.006569*	*0.006569*	*0.003963*	*0.002008*	*0.000982*	*Infinity*	
		98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.8%RH	10.0%RH	4.9%RH		
70 °C	η_S	0.019602	0.014719	0.009831	0.006570	0.006570	0.003960	0.002001	0.000973	Infinity	Type B
	Combined	*0.019602*	*0.014719*	*0.009831*	*0.006570*	*0.006570*	*0.003960*	*0.002001*	*0.000973*	*Infinity*	

Table 11

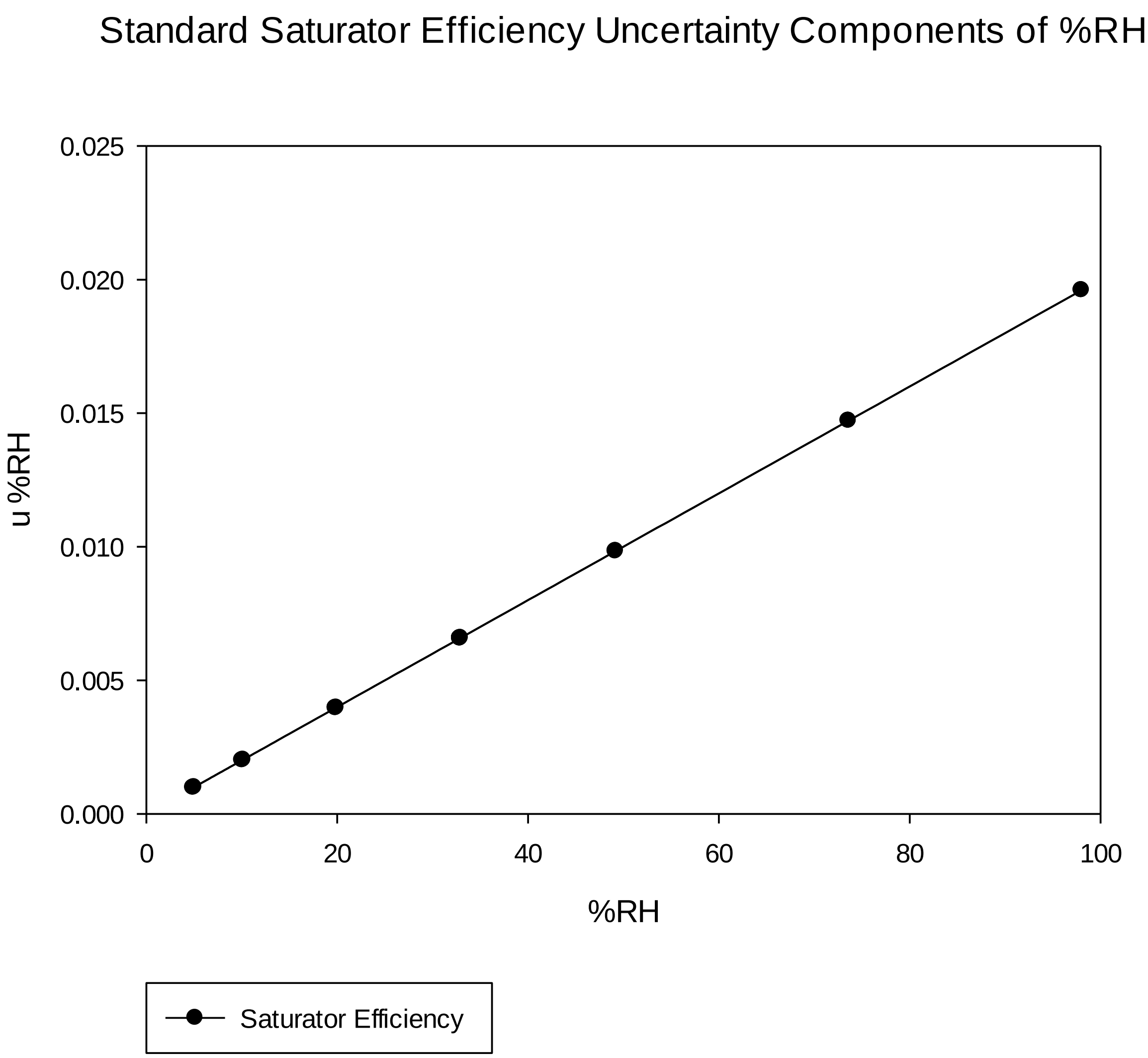

Standard Saturator Efficiency Uncertainty Components of %RH
0.025
0.020
0.015
0.010
0.005
0.000
u %RH
0
20
40
60
80
100
%RH
Saturator Efficiency

Figure 10

The standard Dew Point temperature uncertainty components (uTD) calculated using the above-associated % efficiency component are summarized in Table 12 and Figure 11.

Standard Saturator Efficiency Uncertainty Components of Dew Point Temperature (°C)											
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom	Evaluation
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA					
		15	20	30	45	45	75	150	305		
		-0.3 °C	-4.1 °C	-9.4 °C	-14.4 °C	-14.4 °C	-20.4 °C	-27.9 °C	-35.0 °C		
0 °C	η_S	0.002747	0.002660	0.002546	0.002439	0.002439	0.002315	0.002165	0.002029	Infinity	Type B
	Combined	*0.002747*	*0.002660*	*0.002546*	*0.002439*	*0.002439*	*0.002315*	*0.002165*	*0.002029*	*Infinity*	
		34.6 °C	29.6 °C	22.7 °C	16.3 °C	16.3 °C	8.6 °C	-1.1 °C	-10.0 °C		
35 °C	η_S	0.003604	0.003470	0.003296	0.003135	0.003135	0.002951	0.002729	0.002532	Infinity	Type B
	Combined	*0.003604*	*0.003470*	*0.003296*	*0.003135*	*0.003135*	*0.002951*	*0.002729*	*0.002532*	*Infinity*	
		69.5 °C	63.1 °C	54.4 °C	46.3 °C	46.3 °C	36.7 °C	24.8 °C	13.7 °C		
70 °C	η_S	0.004609	0.004410	0.004154	0.003922	0.003922	0.003659	0.003348	0.003074	Infinity	Type B
	Combined	*0.004609*	*0.004410*	*0.004154*	*0.003922*	*0.003922*	*0.003659*	*0.003348*	*0.003074*	*Infinity*	

Table 12

Standard Saturator Efficiency Uncertainty Components of Dew Point Temperature (°C)

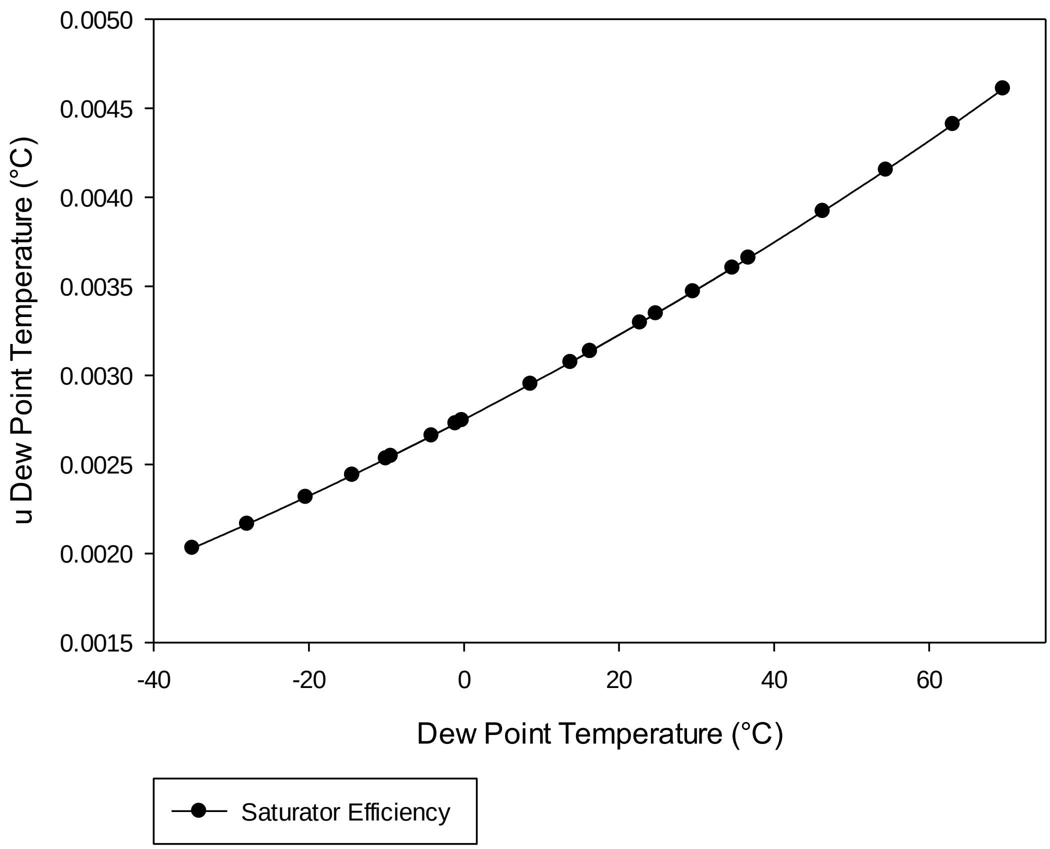


Figure 11

The standard Frost Point temperature uncertainty components (uT_F) calculated using the above-associated % efficiency component are summarized in Table 13 and Figure 12.

Note: Any frost point value that is not possible is grayed out of the following table. No Frost Point temperature can be generated at a 70 °C saturation temperature; therefore, the temperature is not included in the table.

Standard Saturator Efficiency Uncertainty Components of Frost Point Temperature (°C)											
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**	**Evaluation**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**					
		15	**20**	**30**	**45**	**45**	**75**	**150**	**308**		
		-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-12.9 °C**	**-12.9 °C**	**-18.3 °C**	**-25.2 °C**	**-31.9 °C**		
0 °C	η_S	0.002424	0.002363	0.002281	0.002204	0.002204	0.002113	0.001999	0.001893	Infinity	Type B
	Combined	*0.002424*	*0.002363*	*0.002281*	*0.002204*	*0.002204*	*0.002113*	*0.001999*	*0.001893*	*Infinity*	
								-0.9 °C	**-9.0 °C**		
35 °C	η_S							0.002412	0.002270	Infinity	Type B
	Combined							*0.002412*	*0.002270*	*Infinity*	

Table 13

Document: Model_9500_Uncertainty_Analysis_Rev3.2
Author: Michael Hamilton
Date: September 2022

Standard Saturator Efficiency Uncertainty Components of Frost Point Temperature (°C)

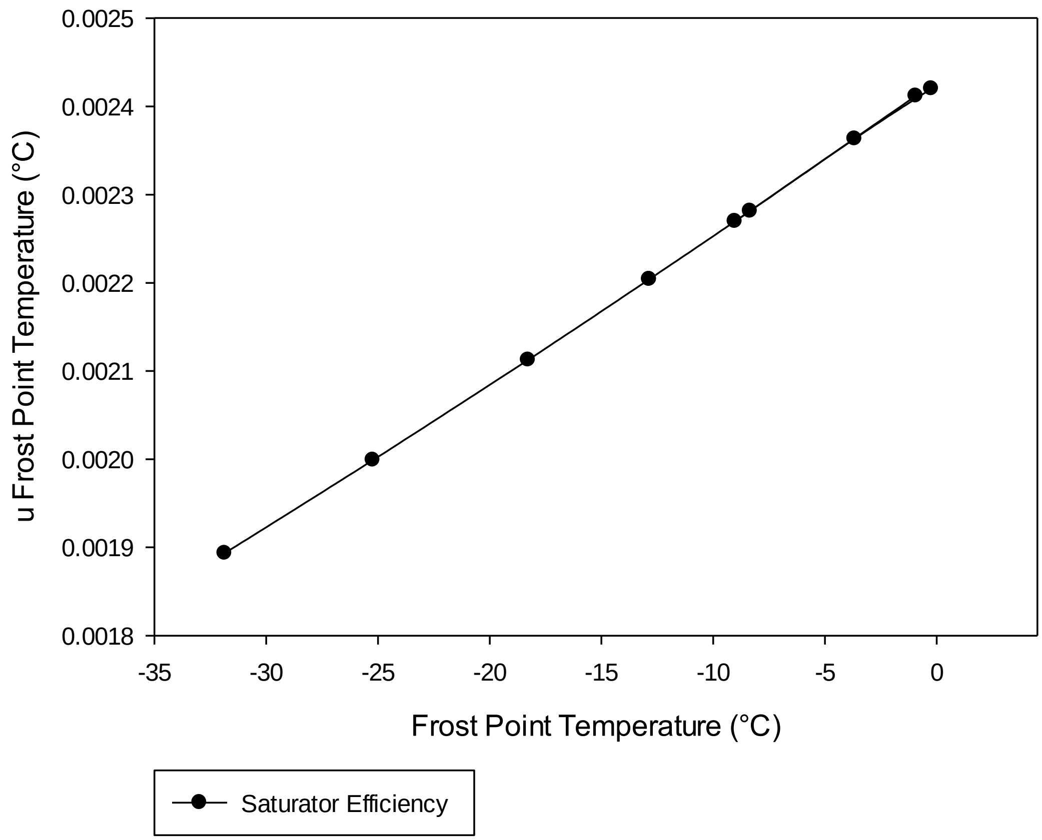


Figure 12

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 shown in the following formula:

$$U = k * u_c \tag{16}$$

Using equations 6 and 16, the combined individual standard uncertainty components for pressure, temperature, equation, and saturator efficiency, the total combined standard uncertainty (u), and the total combined expanded uncertainty (U) in terms of relative humidity %RH are summarized in Tables 14a (continued into 14b) and Figure 13.

Uncertainty Components of %RH										
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA				
		15	20	30	45	45	75	150	316	
		98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.9%RH	10.1%RH	5.0%RH	
0 °C	Pressure	0.021303	0.012951	0.006844	0.003924	0.011718	0.004515	0.001436	0.000553	~Infinity
	Temperature	0.085296	0.064044	0.042793	0.028625	0.028625	0.017292	0.008793	0.004336	~Infinity
	Equation	0.014363	0.012703	0.011382	0.010765	0.010765	0.010454	0.010022	0.010730	Infinity
	Saturator Efficiency	0.019601	0.014719	0.009836	0.006581	0.006581	0.003977	0.002025	0.001000	Infinity
	Combined	*0.091213*	*0.068172*	*0.045873*	*0.031528*	*0.033406*	*0.021083*	*0.013562*	*0.011629*	*~Infinity*
	Expanded (k=2)	*0.182425*	*0.136344*	*0.091747*	*0.063056*	*0.066811*	*0.042167*	*0.027125*	*0.023258*	
		98.0%RH	73.6%RH	49.1%RH	32.8%RH	32.8%RH	19.8%RH	10.0%RH	4.9%RH	
35 °C	Pressure	0.021319	0.012961	0.006847	0.003923	0.011727	0.004516	0.001432	0.000545	~Infinity
	Temperature	0.064983	0.048781	0.032577	0.021774	0.021774	0.013131	0.006649	0.003246	~Infinity
	Equation	0.015765	0.012955	0.010535	0.009302	0.009302	0.008672	0.008688	0.008962	Infinity
	Saturator Efficiency	0.019601	0.014714	0.009828	0.006569	0.006569	0.003963	0.002008	0.000982	Infinity
	Combined	*0.072870*	*0.054147*	*0.036273*	*0.024883*	*0.027227*	*0.016844*	*0.011215*	*0.009597*	*~Infinity*
	Expanded (k=2)	*0.145740*	*0.108294*	*0.072546*	*0.049766*	*0.054454*	*0.033688*	*0.022430*	*0.019194*	

Table 14a

Uncertainty Components of %RH ...continued										
Saturation Temperature	Description	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA								Degrees of Freedom
		Low Range, Ps < 45.0 psiA				High Range, Ps > 45.0 psiA				
		15	20	30	45	45	75	150	316	
		98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.8%RH	10.0%RH	4.9%RH	
70 °C	Pressure	0.021291	0.012953	0.006845	0.003921	0.011740	0.004521	0.001430	0.000541	~Infinity
	Temperature	0.050784	0.038147	0.025487	0.017035	0.017035	0.010266	0.005186	0.002517	~Infinity
	Equation	0.005841	0.005593	0.005680	0.005926	0.005926	0.006245	0.006760	0.007178	Infinity
	Saturator Efficiency	0.019602	0.014719	0.009831	0.006570	0.006570	0.003960	0.002001	0.000973	Infinity
	Combined	*0.058742*	*0.043254*	*0.028729*	*0.019592*	*0.022501*	*0.013436*	*0.008869*	*0.007687*	*~Infinity*
	Expanded (k=2)	*0.117484*	*0.086507*	*0.057459*	*0.039184*	*0.045002*	*0.026872*	*0.017737*	*0.015374*	

Table 14b

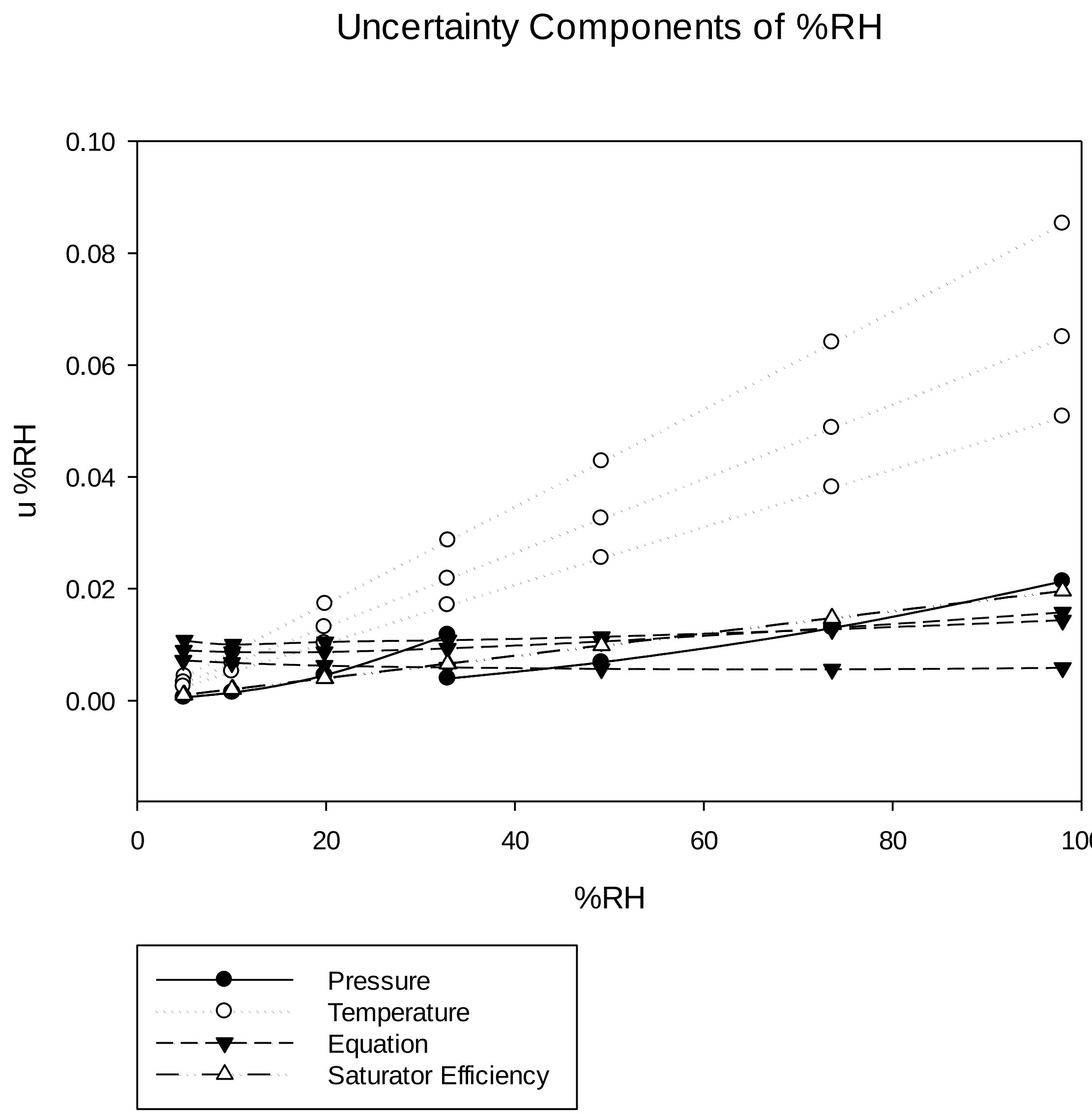

Uncertainty Components of %RH
0.10
0.08
0.06
0.04
0.02
0.00
u %RH
0
20
40
60
80
100
%RH
Pressure
Temperature
Equation
Saturator Efficiency

Figure 13

Using equations 7 and 16, the combined individual standard uncertainty components for pressure, temperature, equation, and saturator efficiency, the total combined standard uncertainty (u), and the total combined expanded uncertainty (U) in terms of dew point temperature Td (°C) are summarized in Table 15 and Figure 14.

Uncertainty Components of Dew Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**				
		15	**20**	**30**	**45**	**45**	**75**	**150**	**305**	
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-14.4 °C**	**-14.4 °C**	**-20.4 °C**	**-27.9 °C**	**-35.0 °C**	
0 °C	Pressure	0.002985	0.002341	0.001771	0.001454	0.004343	0.002628	0.001535	0.001128	~Infinity
	Temperature	0.008090	0.007834	0.007495	0.007178	0.007178	0.006808	0.006351	0.005927	~Infinity
	Equation	0.002026	0.002472	0.003260	0.004351	0.004351	0.006417	0.010885	0.021154	Infinity
	Saturator Efficiency	0.002747	0.002660	0.002546	0.002439	0.002439	0.002315	0.002165	0.002029	Infinity
	Combined	*0.009274*	*0.008946*	*0.008742*	*0.008861*	*0.009760*	*0.009990*	*0.012878*	*0.022091*	*~Infinity*
	Expanded (k=2)	*0.018548*	*0.017893*	*0.017483*	*0.017722*	*0.019520*	*0.019980*	*0.025756*	*0.044182*	
		34.6 °C	**29.6 °C**	**22.7 °C**	**16.3 °C**	**16.3 °C**	**8.6 °C**	**-1.1 °C**	**-10.0 °C**	
35 °C	Pressure	0.003919	0.003057	0.002296	0.001872	0.005597	0.003362	0.001945	0.001414	~Infinity
	Temperature	0.008087	0.007788	0.007394	0.007032	0.007032	0.006613	0.006105	0.005642	~Infinity
	Equation	0.002899	0.003156	0.003881	0.004595	0.004595	0.006466	0.011796	0.022355	Infinity
	Saturator Efficiency	0.003604	0.003470	0.003296	0.003135	0.003135	0.002951	0.002729	0.002532	Infinity
	Combined	*0.010107*	*0.009591*	*0.009267*	*0.009159*	*0.010570*	*0.010274*	*0.013698*	*0.023238*	*~Infinity*
	Expanded (k=2)	*0.020214*	*0.019183*	*0.018534*	*0.018319*	*0.021139*	*0.020548*	*0.027397*	*0.046476*	
		69.5 °C	**63.1 °C**	**54.4 °C**	**46.3 °C**	**46.3 °C**	**36.7 °C**	**24.8 °C**	**13.7 °C**	
70 °C	Pressure	0.005007	0.003882	0.002894	0.002343	0.007008	0.004179	0.002394	0.001721	~Infinity
	Temperature	0.008083	0.007740	0.007295	0.006889	0.006889	0.006427	0.005872	0.005376	~Infinity
	Equation	0.001385	0.001810	0.002587	0.003833	0.003833	0.006086	0.011568	0.021972	Infinity
	Saturator Efficiency	0.004609	0.004410	0.004154	0.003922	0.003922	0.003659	0.003348	0.003074	Infinity
	Combined	*0.010657*	*0.009884*	*0.009248*	*0.009112*	*0.011254*	*0.010450*	*0.013610*	*0.022893*	*~Infinity*
	Expanded (k=2)	*0.021314*	*0.019768*	*0.018496*	*0.018223*	*0.022508*	*0.020899*	*0.027220*	*0.045785*	

Table 15

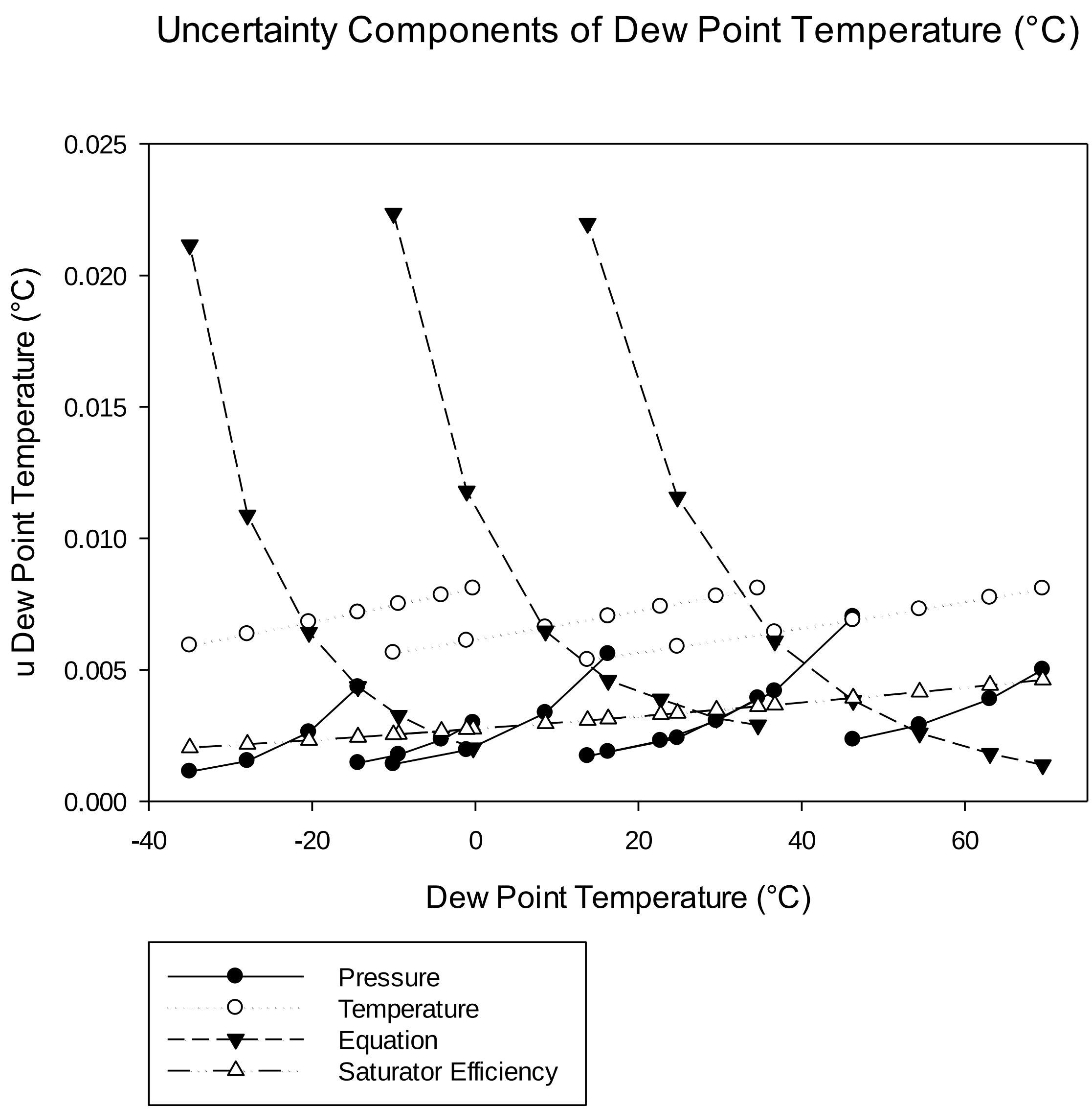

Uncertainty Components of Dew Point Temperature (°C)
0.025
0.020
0.015
0.010
0.005
0.000
u Dew Point Temperature (°C)
-40
-20
0
20
40
60
Dew Point Temperature (°C)
Pressure
Temperature
Equation
Saturator Efficiency

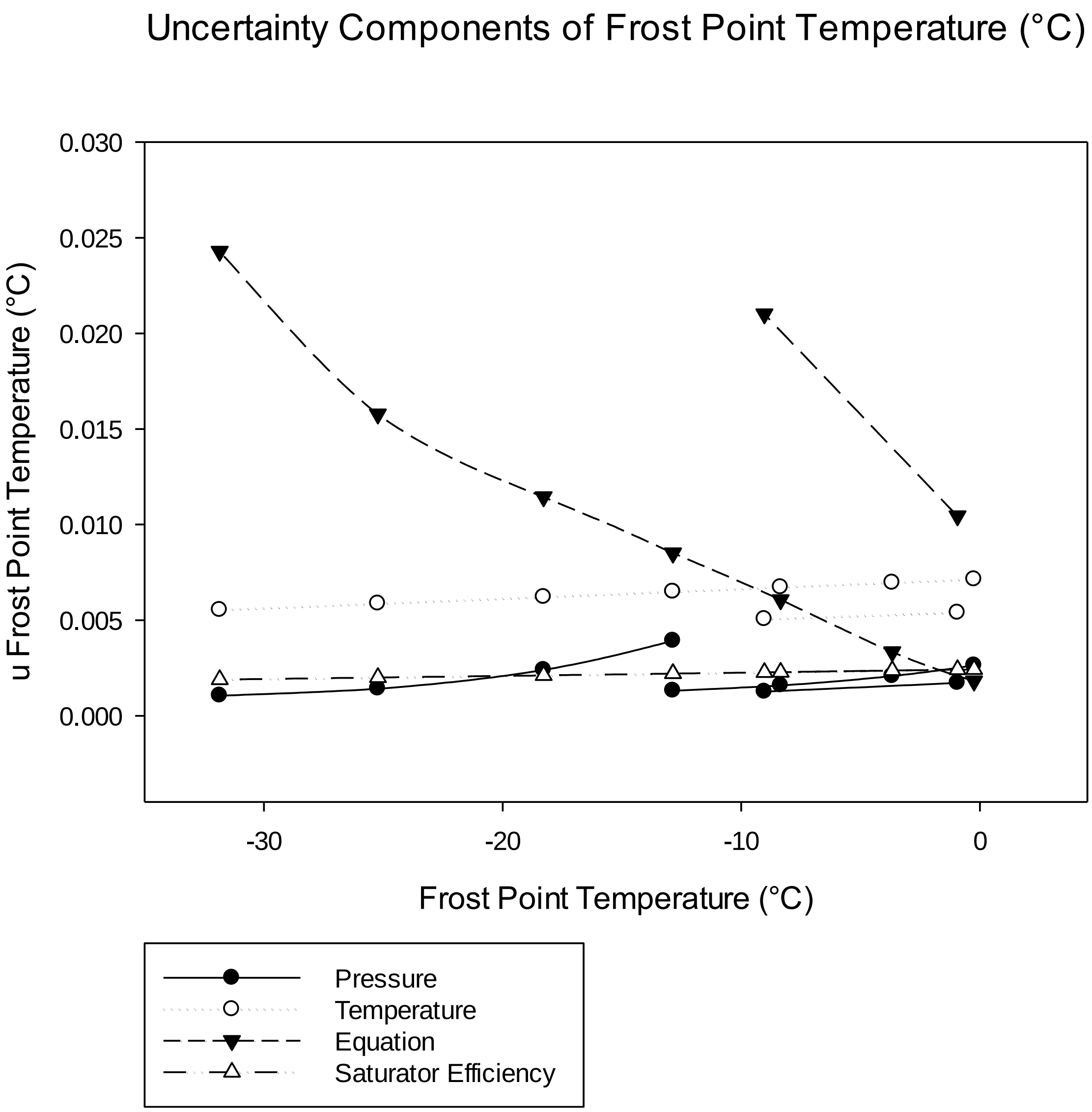
Figure 14

Using equations 8 and 16, the combined individual standard uncertainty components for pressure, temperature, equation, and saturator efficiency, the total combined standard uncertainty (u), and the total combined expanded uncertainty (U) in terms of Frost point temperature Tf (°C) are summarized in Table 16 and Figure 15.

Note: Any frost point value that is not possible is grayed out of the following table. No Frost Point temperature can be generated at a 70 °C saturation temperature; therefore, the temperature is not included in the table.

Uncertainty Components of Frost Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**				
		15	**20**	**30**	**45**	**45**	**75**	**150**	**308**	
		-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-12.9 °C**	**-12.9 °C**	**-18.3 °C**	**-25.2 °C**	**-31.9 °C**	
0 °C	Pressure	0.002634	0.002079	0.001587	0.001314	0.003924	0.002398	0.001418	0.001051	~Infinity
	Temperature	0.007138	0.006960	0.006718	0.006486	0.006486	0.006212	0.005865	0.005529	~Infinity
	Equation	0.001811	0.003337	0.006063	0.008508	0.008508	0.011454	0.015777	0.024285	Infinity
	Saturator Efficiency	0.002424	0.002363	0.002281	0.002204	0.002204	0.002113	0.001999	0.001893	Infinity
	Combined	*0.008189*	*0.008336*	*0.009466*	*0.011002*	*0.011607*	*0.013416*	*0.017010*	*0.025000*	*~Infinity*
	Expanded (k=2)	*0.016377*	*0.016671*	*0.018933*	*0.022004*	*0.023214*	*0.026833*	*0.034019*	*0.050000*	
								-0.9 °C	**-9.0 °C**	
35 °C	Pressure							0.001719	0.001265	~Infinity
	Temperature							0.005395	0.005058	~Infinity
	Equation							0.010453	0.021014	Infinity
	Saturator Efficiency							0.002412	0.002270	Infinity
	Combined							*0.012131*	*0.021770*	*~Infinity*
	Expanded (k=2)							*0.024262*	*0.043540*	

Table 16



Uncertainty Components of Frost Point Temperature (°C)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
u Frost Point Temperature (°C)
-30
-20
-10
0
Frost Point Temperature (°C)
Pressure
Temperature
Equation
Saturator Efficiency

Figure 15

5.0 Summary

To simplify the %RH uncertainty results, the following uncertainty specification statement using equation 17 is used to describe the overall %RH uncertainty for the Model 9500. Where R is the %RH reading.

$$0.17\% * R + 0.016 \tag{17}$$

(using a coverage factor, k=2, at an approximate level of confidence of 95%)

*Example 1: If the %RH reading is 50 %RH. The uncertainty would then be: 0.17% * 50 + 0.016 = 0.101*
*Example 2: If the %RH reading is 10 %RH. The uncertainty would then be: 0.17% * 10 + 0.016 = 0.033*

It is important to note that the Model 9500 ControLog software computes the real-time uncertainty using an internal HumiCalc with Uncertainty computation engine. This report used the same computation engine to calculate the listed %RH uncertainty values. It is encouraged to substitute the above specification with the real-time calculated value displayed and recorded by the software during regular generator operation.

A summary of the combined expanded uncertainties ($U_{\%RH}$) and uncertainty specification for %RH are shown in Table 17 and Figure 16.

Expanded Uncertainty of %RH								
Saturation Temperature	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**							
	15	**20**	**30**	**45**	**45**	**75**	**150**	**316**
	98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.9%RH**	**10.1%RH**	**5.0%RH**
0 °C	0.182	0.136	0.092	0.063	0.067	0.042	0.027	0.023
	98.0%RH	**73.6%RH**	**49.1%RH**	**32.8%RH**	**32.8%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**
35 °C	0.146	0.108	0.073	0.050	0.054	0.034	0.022	0.019
	98.0%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**
70 °C	0.117	0.087	0.057	0.039	0.045	0.027	0.018	0.015
%RH Specification	0.183	0.141	0.100	0.072	0.072	0.050	0.033	0.024

Table 17

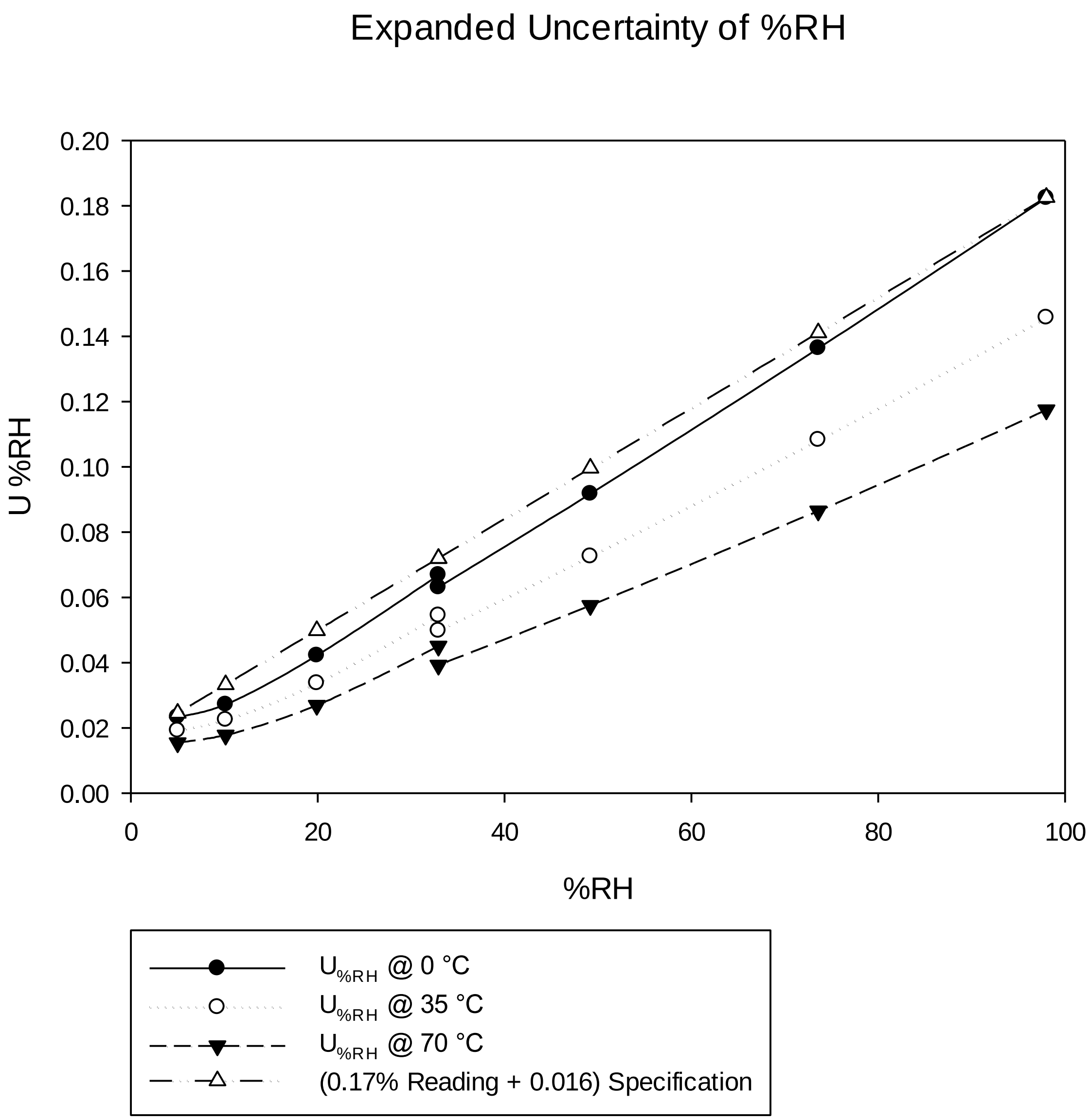
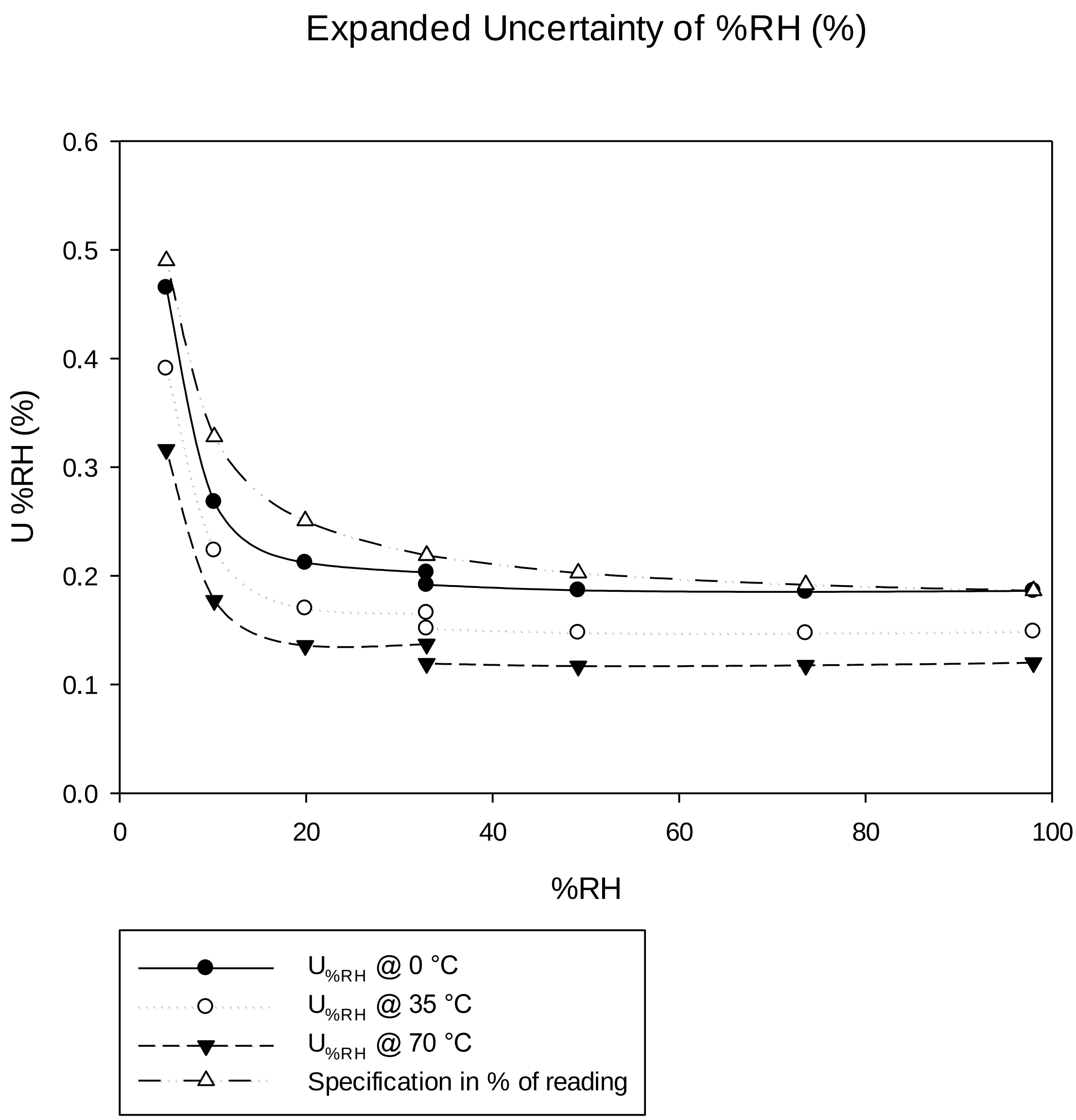

Expanded Uncertainty of %RH
U %RH
%RH
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0
20
40
60
80
100
U%RH @ 0 °C
U%RH @ 35 °C
U%RH @ 70 °C
(0.17% Reading + 0.016) Specification

Figure 16

While equation 17 is the best linear representation of the overall %RH uncertainty for the Model 9500, it can be challenging to understand, especially when comparing to another lab's capabilities. Table 18 and Figure 17 show the same combined expanded uncertainties ($U_{\%RH}$) data from equation 17 and Table 17 but in a nonlinear percent of reading (%) equivalent.

Expanded Uncertainty of %RH (%)								
Saturation Temperature	Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA							
	15	20	30	45	45	75	150	316
	98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.9%RH	10.1%RH	5.0%RH
0 °C	0.186%	0.185%	0.187%	0.192%	0.203%	0.212%	0.268%	0.465%
	98.0%RH	73.6%RH	49.1%RH	32.8%RH	32.8%RH	19.8%RH	10.0%RH	4.9%RH
35 °C	0.149%	0.147%	0.148%	0.152%	0.166%	0.170%	0.223%	0.391%
	98.0%RH	73.6%RH	49.2%RH	32.9%RH	32.9%RH	19.8%RH	10.0%RH	4.9%RH
70 °C	0.120%	0.118%	0.117%	0.119%	0.137%	0.136%	0.177%	0.316%
%RH (%) Specification	0.186%	0.192%	0.203%	0.219%	0.219%	0.250%	0.328%	0.490%

Table 18



Expanded Uncertainty of %RH (%)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
U %RH (%)
0
20
40
60
80
100
%RH
U%RH @ 0 °C
U%RH @ 35 °C
U%RH @ 70 °C
Specification in % of reading

Figure 17

To simplify the Dew Point Temperature uncertainty results, the following uncertainty specification statement is used to describe the Dew Point (°C) uncertainty (U_{Td}) for the Model 9500. To minimize the enhancement factor equation uncertainty component when operating at high saturation pressures, P_S, the Dew Point Temperature specification is split into two pressure ranges. One Dew Point Temperature uncertainty for when the saturation pressure is less than or equal to 140 psiA and another when the saturation pressure is more than 140 psiA.

0.03 °C (Ps <= 140 psiA)

0.05 °C (Ps > 140 psiA)

(using a coverage factor, k=2, at an approximate level of confidence of 95%)

It is important to note that the Model 9500 ControLog software computes the real-time uncertainty using an internal HumiCalc with Uncertainty computation engine. This report used the same computation engine to calculate the listed Dew Point (°C) uncertainty values. It is encouraged to substitute the above specification with the real-time calculated value displayed and recorded by the software during regular generator operation.

A summary of the combined expanded uncertainties and uncertainty specifications for Dew Point Temperature (°C) are shown in Table 19, Figures 18 & 19.

Expanded Uncertainty of Dew Point Temperature (°C)								
Saturation Temperature	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**							
	15	**20**	**30**	**45**	**45**	**75**	**150**	**305.3**
	-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-14.4 °C**	**-14.4 °C**	**-20.4 °C**	**-27.9 °C**	**-35.0 °C**
0 °C	0.019	0.018	0.017	0.018	0.020	0.020	0.026	0.044
	34.6 °C	**29.6 °C**	**22.7 °C**	**16.3 °C**	**16.3 °C**	**8.6 °C**	**-1.1 °C**	**-10.0 °C**
35 °C	0.020	0.019	0.019	0.018	0.021	0.021	0.027	0.046
	69.5 °C	**63.1 °C**	**54.4 °C**	**46.3 °C**	**46.3 °C**	**36.7 °C**	**24.8 °C**	**13.7 °C**
70 °C	0.021	0.020	0.018	0.018	0.023	0.021	0.027	0.046
Td Specification	0.030	0.030	0.030	0.030	0.030	0.030	0.050	0.050

Table 19

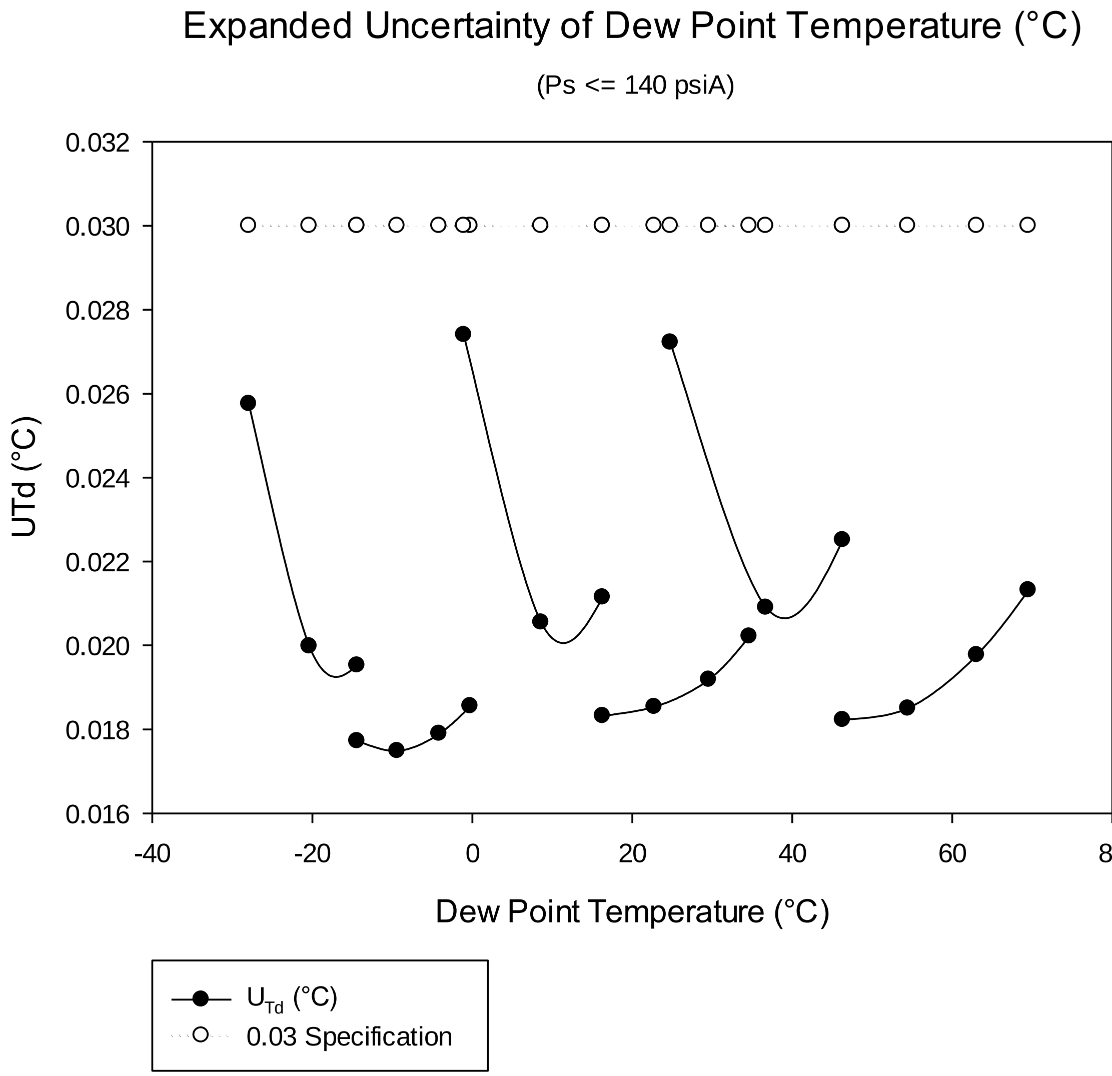

Expanded Uncertainty of Dew Point Temperature (°C)
(Ps <= 140 psiA)
0.032
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
UTd (°C)
-40
-20
0
20
40
60
80
Dew Point Temperature (°C)
U_Td (°C)
0.03 Specification

Figure 18

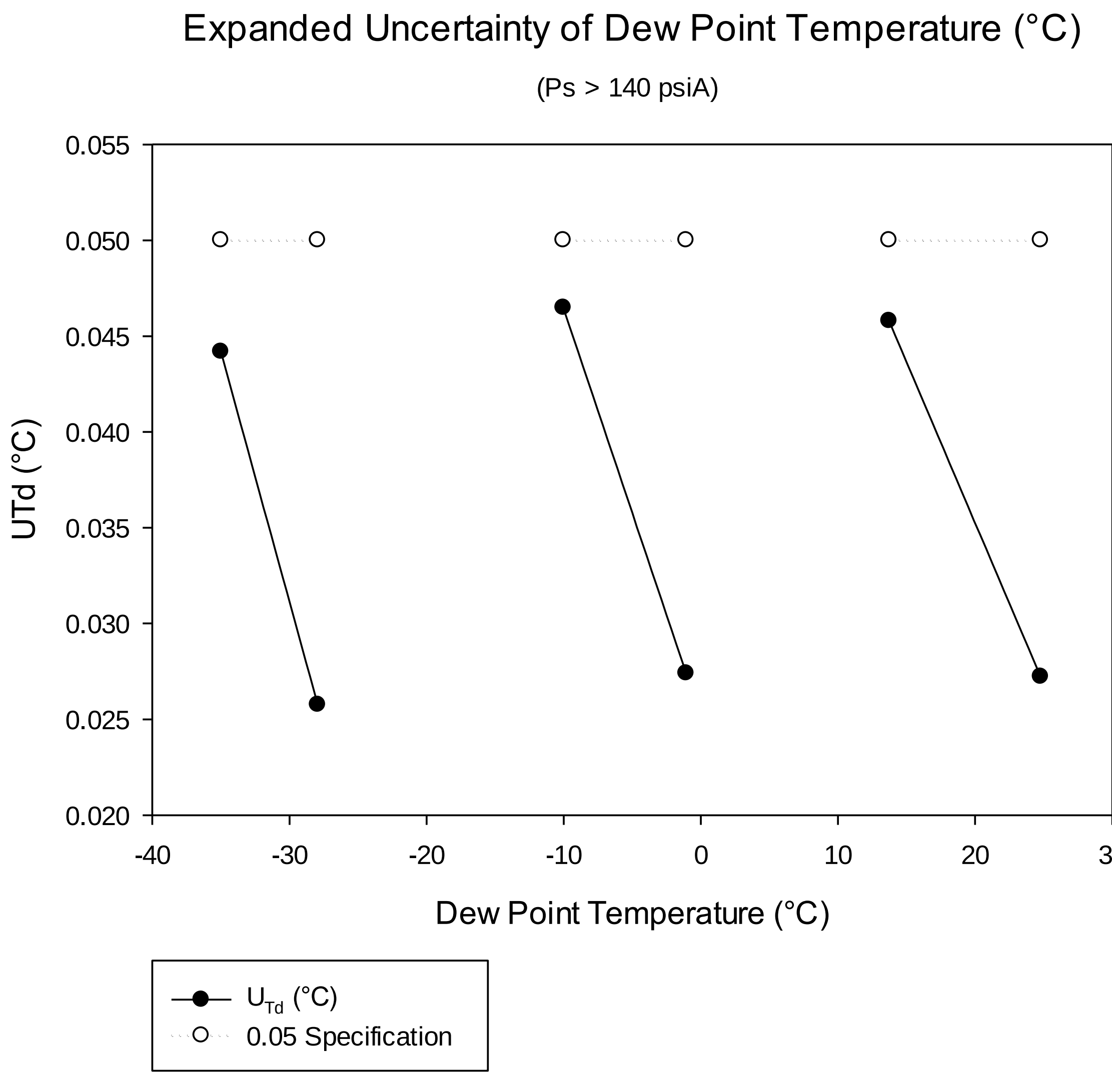

Expanded Uncertainty of Dew Point Temperature (°C)
(Ps > 140 psiA)
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
UTd (°C)
-40
-30
-20
-10
0
10
20
30
Dew Point Temperature (°C)
U_Td (°C)
0.05 Specification

Figure 19

To simplify the Frost Point Temperature uncertainty results, the following uncertainty specification statement is used to describe the Frost Point (°C) uncertainty (U_{Tf}) for the Model 9500. To minimize the enhancement factor equation uncertainty component when operating at high saturation pressures, P_S, the Frost Point Temperature specification is split into two pressure ranges. One Frost Point Temperature uncertainty for when the saturation pressure is less than or equal to 100 psiA and another when the saturation pressure is more than 100 psiA.

0.03 °C (Ps <= 100 psiA)

0.05 °C (Ps > 100 psiA)

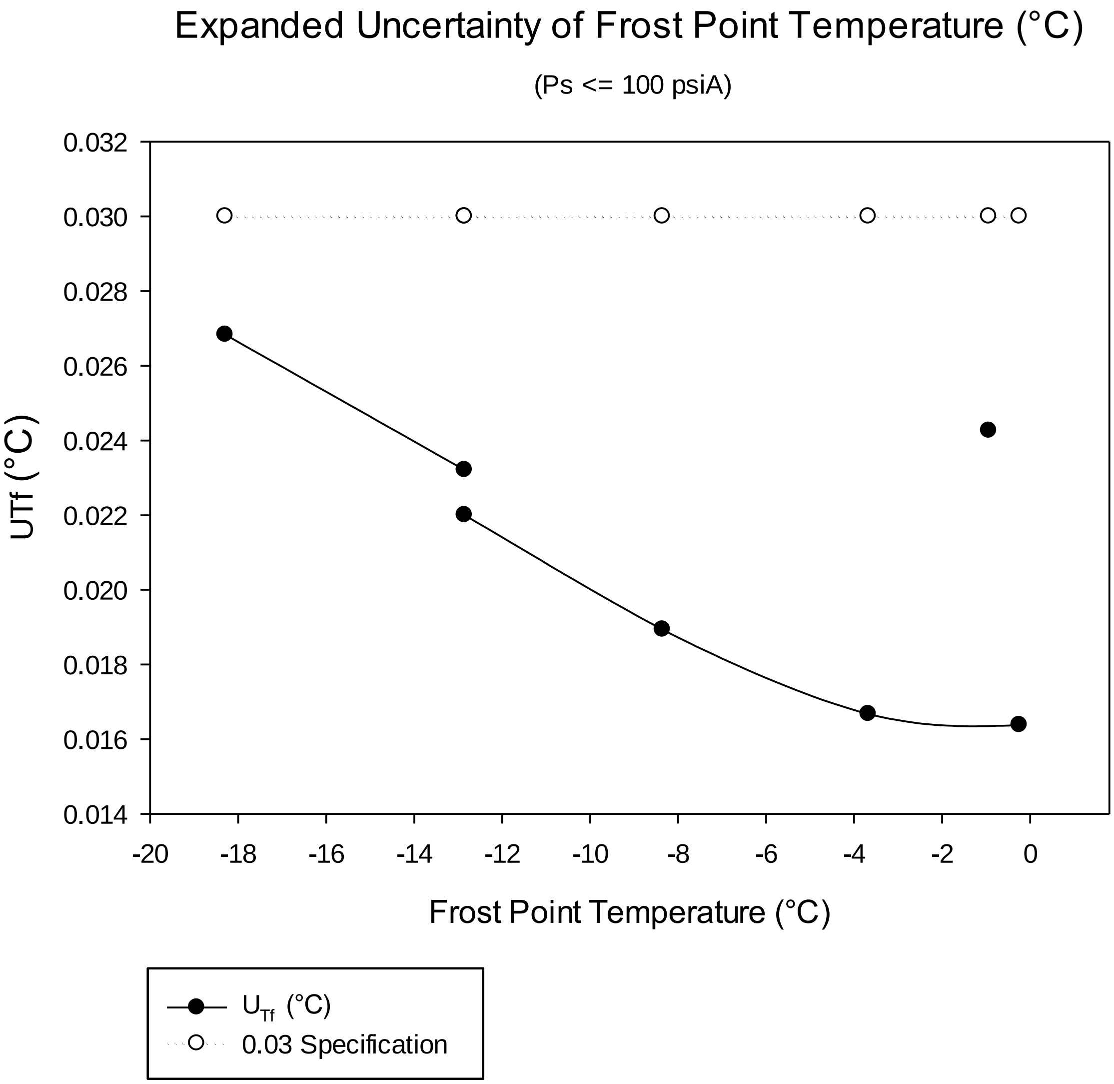
(using a coverage factor, k=2, at an approximate level of confidence of 95%)

It is important to note that the Model 9500 ControLog software computes the real-time uncertainty using an internal HumiCalc with Uncertainty computation engine. This report used the same computation engine to calculate the listed Frost Point (°C) uncertainty values. It is encouraged to substitute the above specification with the real-time calculated value displayed and recorded by the software during regular generator operation.

A summary of the combined expanded uncertainties and uncertainty specifications for Frost Point Temperature (°C) are shown in Table 20, Figures 20 & 21.

Expanded Uncertainty of Frost Point Temperature (°C)								
Saturation Temperature	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**							
	15	**20**	**30**	**45**	**45**	**75**	**150**	**308**
	-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-12.9 °C**	**-12.9 °C**	**-18.3 °C**	**-25.2 °C**	**-31.9 °C**
0 °C	0.016	0.017	0.019	0.022	0.023	0.027	0.034	0.050
							-0.9 °C	**-9.0 °C**
35 °C							0.024	0.044
Tf Specification	0.030	0.030	0.030	0.030	0.030	0.030	0.050	0.050

Table 20



Expanded Uncertainty of Frost Point Temperature (°C)
(Ps <= 100 psiA)
0.032
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
UTf (°C)
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
Frost Point Temperature (°C)
U_Tf (°C)
0.03 Specification

Figure 20

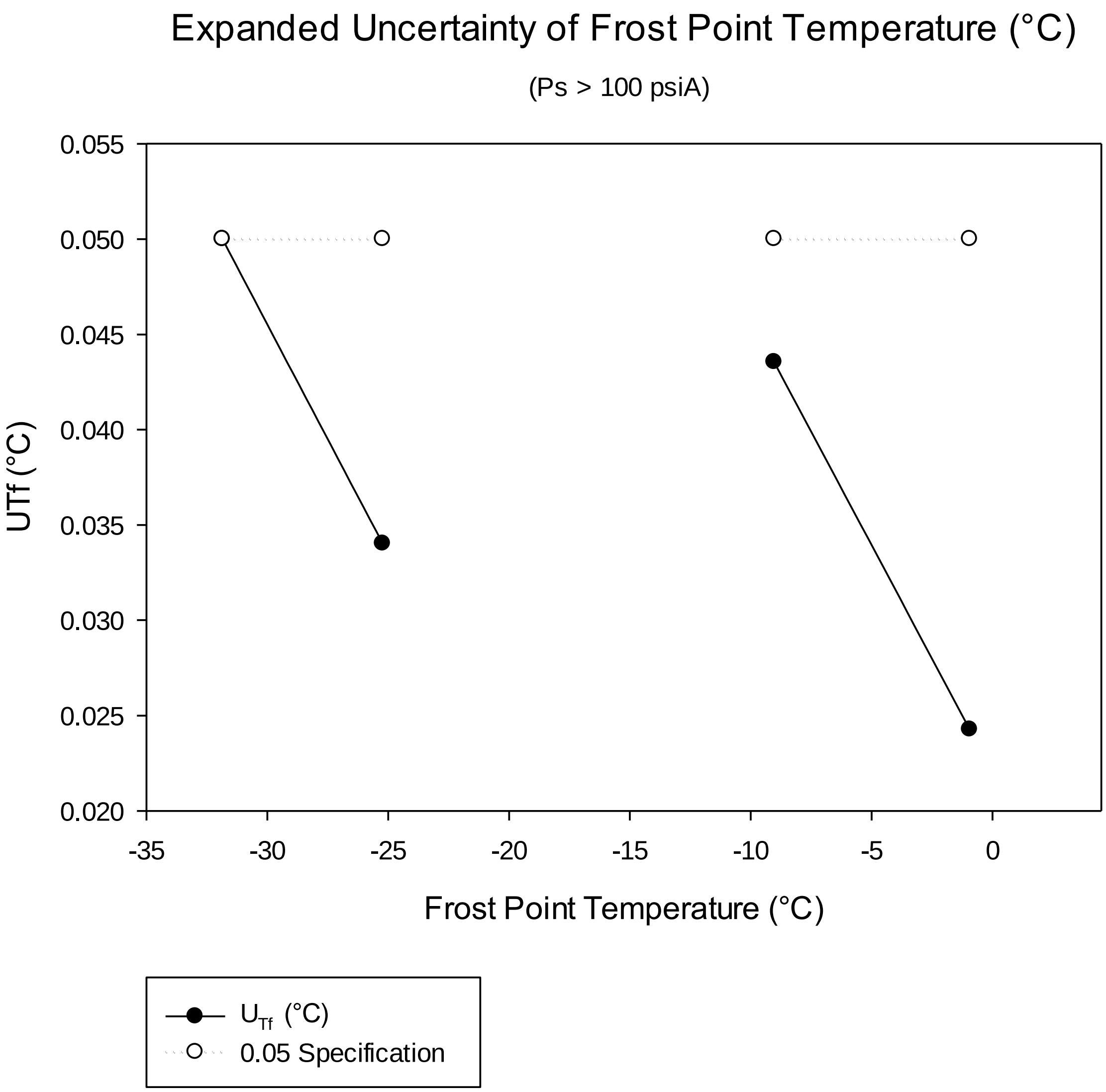

Expanded Uncertainty of Frost Point Temperature (°C)
(Ps > 100 psiA)
UTf (°C)
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
-35
-30
-25
-20
-15
-10
-5
0
Frost Point Temperature (°C)
U_Tf (°C)
0.05 Specification

Figure 21

Appendix A

The Model 9500 Humidity Generator can generate Dew Point Temperatures up to 70 °C, but because of the Model 9500's 2-Pressure design, the system always requires some pressure delta between the saturator and test chamber. Due to this pressure delta, the system must run the saturation temperature at 72 °C to generate a 70 °C Dew Point Temperature.

A summary of the combined expanded uncertainties ($U_{\%RH}$) and uncertainty specification for %RH when operating at 72°C are shown in Table 21 and Figures 22 & 23.

Uncertainty Components of %RH										
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**				
		16	**20**	**30**	**45**	**45**	**75**	**150**	**316**	
		91.8%RH	**73.6%RH**	**49.2%RH**	**32.9%RH**	**32.9%RH**	**19.8%RH**	**10.0%RH**	**4.9%RH**	
72 °C	Pressure	0.018936	0.012951	0.006845	0.003921	0.011741	0.004522	0.001430	0.000540	~Infinity
	Temperature	0.046911	0.037635	0.025149	0.016810	0.016810	0.010131	0.005117	0.002483	~Infinity
	Equation	0.005452	0.005300	0.005416	0.005694	0.005694	0.006042	0.006555	0.006993	Infinity
	Saturator Efficiency	0.018353	0.014720	0.009833	0.006571	0.006571	0.003961	0.002002	0.000972	Infinity
	Combined	*0.054091*	*0.042766*	*0.028378*	*0.019328*	*0.022272*	*0.013239*	*0.008673*	*0.007504*	*~Infinity*
	Expanded (k=2)	*0.108181*	*0.085532*	*0.056756*	*0.038655*	*0.044544*	*0.026478*	*0.017345*	*0.015007*	

%RH Specification	0.172	0.141	0.100	0.072	0.072	0.050	0.033	0.024
%RH (%) Specification	0.187%	0.192%	0.203%	0.219%	0.219%	0.251%	0.330%	0.499%

Table 21

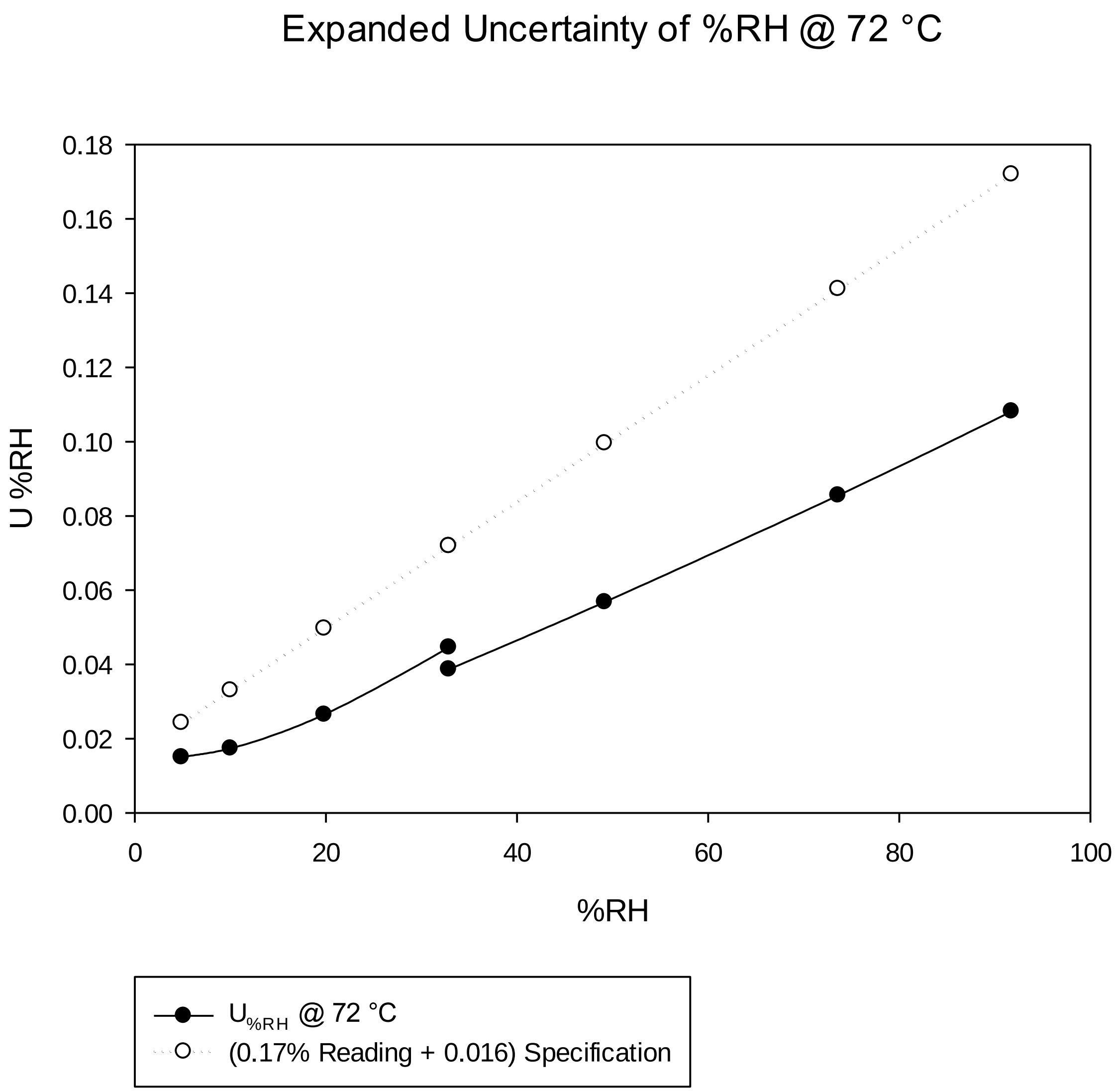

Expanded Uncertainty of %RH @ 72 °C
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
U %RH
0
20
40
60
80
100
%RH
U%RH @ 72 °C
(0.17% Reading + 0.016) Specification

Figure 22

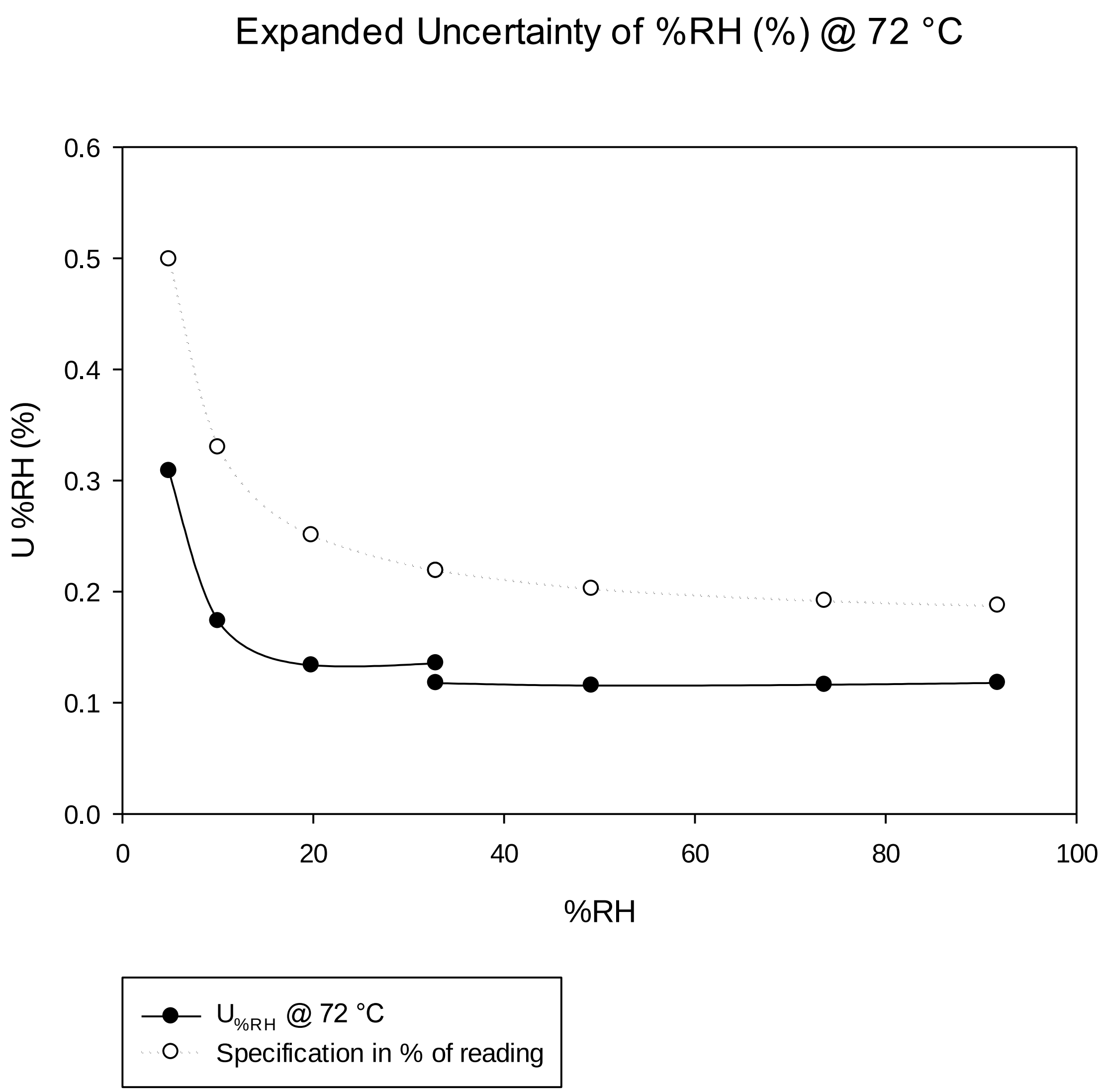

Expanded Uncertainty of %RH (%) @ 72 °C
0.6
0.5
0.4
0.3
0.2
0.1
0.0
U %RH (%)
0
20
40
60
80
100
%RH
U%RH @ 72 °C
Specification in % of reading

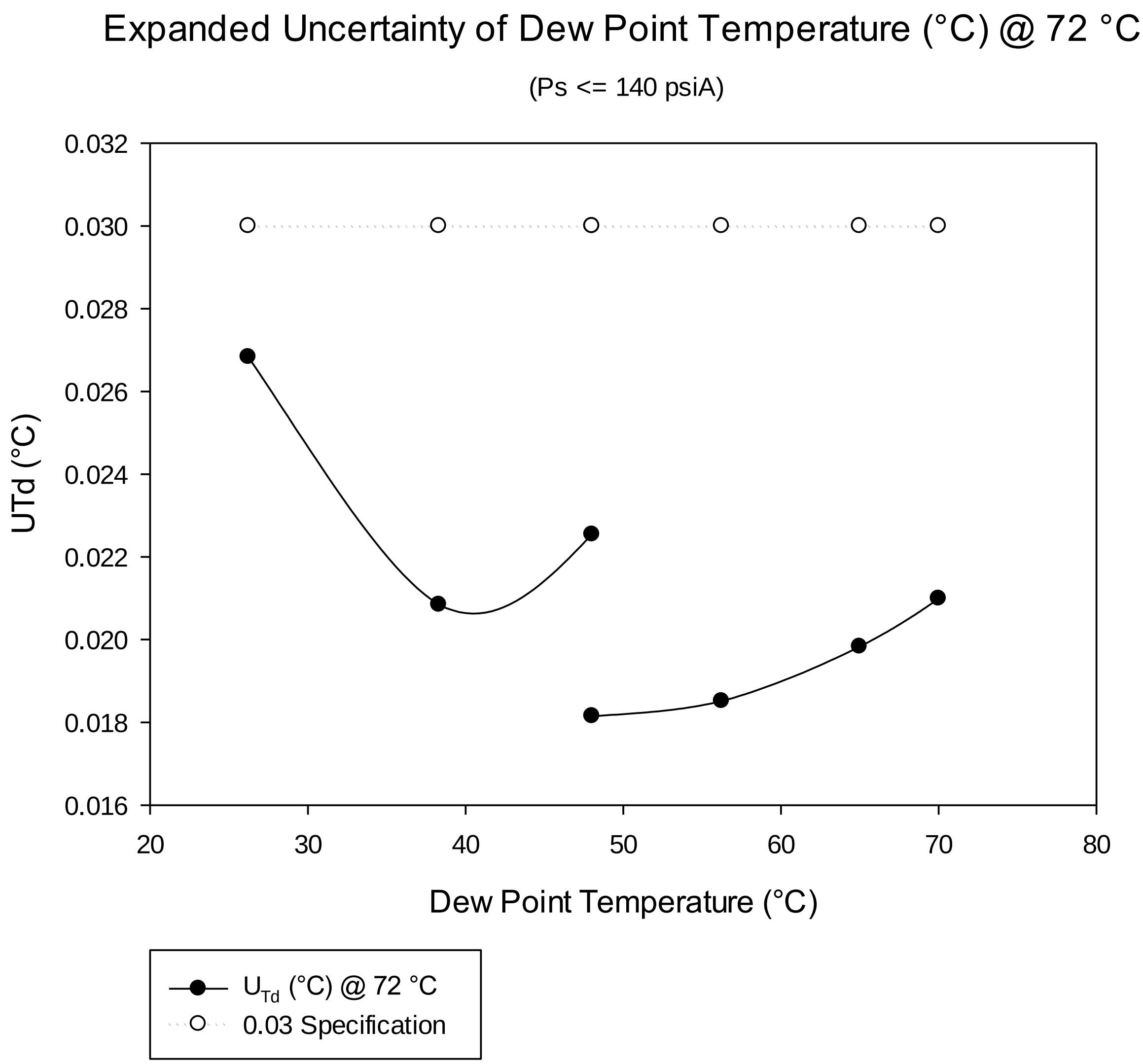
Figure 23

A summary of the combined expanded uncertainties and uncertainty specifications for Dew Point Temperature (°C) when operating at 72°C are shown in Table 22, Figures 24 & 25.

Uncertainty Components of Dew Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psiA), Chamber pressure = 14.7 psiA**								**Degrees of Freedom**
		Low Range, Ps < 45.0 psiA				**High Range, Ps > 45.0 psiA**				
		16	**20**	**30**	**45**	**45**	**75**	**150**	**316**	
		70.0 °C	**65.0 °C**	**56.2 °C**	**48.0 °C**	**48.0 °C**	**38.3 °C**	**26.2 °C**	**14.5 °C**	
72 °C	Pressure	0.004771	0.003932	0.002930	0.002371	0.007093	0.004228	0.002420	0.001721	~Infinity
	Temperature	0.008001	0.007737	0.007289	0.006881	0.006881	0.006416	0.005860	0.005340	~Infinity
	Equation	0.001406	0.001734	0.002507	0.003687	0.003687	0.005990	0.011329	0.022329	Infinity
	Saturator Efficiency	0.004624	0.004468	0.004206	0.003970	0.003970	0.003702	0.003384	0.003094	Infinity
	Combined	*0.010495*	*0.009914*	*0.009257*	*0.009073*	*0.011270*	*0.010422*	*0.013416*	*0.023229*	*~Infinity*
	Expanded (k=2)	*0.020990*	*0.019828*	*0.018513*	*0.018146*	*0.022540*	*0.020845*	*0.026832*	*0.046459*	

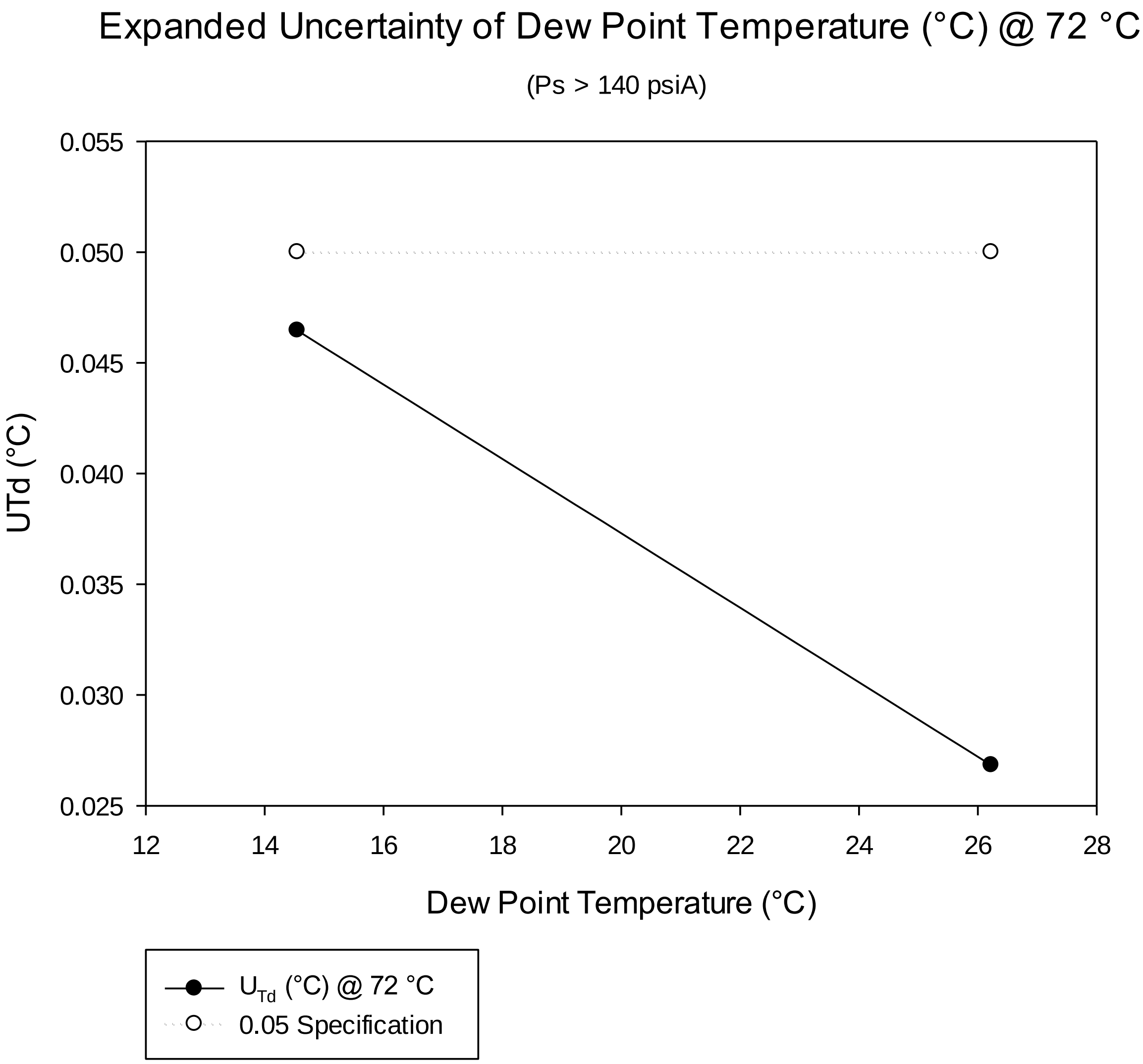
Td Specification	0.030	0.030	0.030	0.030	0.030	0.030	0.050	0.050

Table 22



Expanded Uncertainty of Dew Point Temperature (°C) @ 72 °C
(Ps <= 140 psiA)
0.032
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
UTd (°C)
20
30
40
50
60
70
80
Dew Point Temperature (°C)
U_{Td} (°C) @ 72 °C
0.03 Specification

Figure 24



Expanded Uncertainty of Dew Point Temperature (°C) @ 72 °C
(Ps > 140 psiA)
0.055
0.050
0.045
0.040
0.035
0.030
0.025
UTd (°C)
12
14
16
18
20
22
24
26
28
Dew Point Temperature (°C)
UTd (°C) @ 72 °C
0.05 Specification

Figure 25

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
2. Wexler, Arnold and Daniels, Raymond, *Pressure-Humidity Apparatus*, Journal of Research of the National Bureau of Standards, April 1952, Vol. 48, No. 4, 269-274.
3. Hasagawa, S. and Little, J.W., *The NBS Two-Pressure Humidity Generator, Mark 2*, Journal of Research of the National Bureau of Standards – A. Physics and Chemistry, January-February 1977, Vol. 81A, No. 1, 81-88
4. Wexler, Arnold, *Vapor Pressure Formulations 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, Equation 15.
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. Kuyatt, Chris, et al., *Determining and Reporting Measurement Uncertainties*, Recommended Practice RP-12, National Conference of Standards Laboratories, April 1995
7. NCSL International RISP-5, *Two-Pressure, Two-Temperature Humidity Generator*, Recommended Intrinsic/Derived Standards Practice, January 2002
8. A. Wexler and R.W. Hyland, "In Thermodynamic properties of dry air, moist air and water and SI psychrometric charts", 1983 ASHRAE (Project 216−RP), Table 20.
9. Precision pressure sensor Premium version Model CPT9000, Mensor, WIKA data sheet CT 25.12
10. Thunder Scientific Corporation, *9500 System Manual*, July 2022.
11. Thunder Scientific Corporation, *HumiCalc with Uncertainty Reference Manual*, July 2019.
12. Thunder Scientific Corporation, "Model 9500 Chamber Temperature Uniformity Analysis", July 2022