Uncertainty Analysis
of the
Thunder Scientific Model 3920 Low Humidity Generator

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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 3920 Low Humidity Generation System 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 test pressures, and saturation temperature.

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 use the specifications supplied by these manufacturers as the starting 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 on-going 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 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 3920 Low Humidity Generator (refer to the specifications section in the Model 3920 System Manual for exact operating range).

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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

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

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

$$e_W(T_D)\cdot f(T_D, P_T) = f(T_S, P_S)\cdot e(T_S)\cdot \frac{P_T}{P_S}\cdot \eta_S \quad (2)$$

$$e_I(T_F)\cdot f(T_F, P_T) = f(T_S, P_S)\cdot e(T_S)\cdot \frac{P_T}{P_S}\cdot \eta_S \quad (3)$$

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. P_S and P_T are the saturation and test pressures. η_S is the % efficiency of saturation. Note that the actual Dew/Frost point temperature is defined implicitly and must be obtained through iterative solving.

By incorporating the relationship in equation 1 into an uncertainty equation of the form of equation 2 and 3, the uncertainties in dew point and frost point measurement are given by the expression:

$$u^2(T_D) = u^2(T_S)\left(\frac{\partial T_D}{\partial T_S}\right)^2 + u^2(P_S)\left(\frac{\partial T_D}{\partial P_S}\right)^2 + u^2(P_T)\left(\frac{\partial T_D}{\partial P_T}\right)^2 + u^2(\eta_S)\left(\frac{\partial T_D}{\partial \eta_S}\right)^2 \quad (4)$$

and

$$u^2(T_F) = u^2(T_S)\left(\frac{\partial T_F}{\partial T_S}\right)^2 + u^2(P_S)\left(\frac{\partial T_F}{\partial P_S}\right)^2 + u^2(P_T)\left(\frac{\partial T_F}{\partial P_T}\right)^2 + u^2(\eta_S)\left(\frac{\partial T_F}{\partial \eta_S}\right)^2 \quad (5)$$

3.0 Uncertainty Components

In the mathematical analysis of equation 4 and 5, we will analyze the uncertainties due to each component separately and then combine the uncertainties to obtain the total expanded uncertainty. We are concerned with five basic categories of uncertainty; pressure, temperature, the saturation vapor pressure/enhancement factor equations, percent efficiency of the saturator and permeation/absorption. 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.

Listed below are the identified major uncertainty contributors and their components for the Model 3920 Low Humidity Generator.

- Uncertainty contribution from pressure (P_S and P_T) which includes
  - Measurement accuracy
    - Reference standard
    - Linearity
    - Drift
    - Hysteresis
    - Temperature effects over the calibrated range
    - Repeatability
  - Measurement resolution

- Uncertainty contribution from temperature (T_S), which includes
  - Measurement accuracy
    - Reference standard
    - Measurement resolution
    - Module error
    - Hysteresis
    - Self-Heating
    - Control Stability (Repeatability)
  - Thermal Lag
  - Thermal Gradients

- 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)

- Uncertainty contribution from Permeation and Absorption

3.1 Pressure Uncertainty Contribution

The pressure terms, P_S or P_T, in a two-pressure humidity generator are major determining factors. The Model 3920 Low Humidity Generator uses one pressure transducer to measure the saturation pressure and another pressure transducer to measure the test pressure. In this design, each pressure transducer contributes its own uncertainty to the overall system and will be addressed independent of one another.

3.1.1 Saturation Pressure Uncertainty Contribution

The saturation 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 equation for this becomes:

$$\mathrm{uT}_{\mathrm{D[component]}} = \frac{\partial}{\partial P_S}\left[e_W(T_D)\cdot f(T_D,P_T) = f(T_S,P_S)\cdot e(T_S)\cdot \frac{P_T}{P_S}\cdot \eta_S \right]\cdot \mathrm{uP}_{\mathrm{S[component]}} \quad (6)$$

$$\mathrm{uT}_{\mathrm{F[component]}} = \frac{\partial}{\partial P_S}\left[e_I(T_F)\cdot f(T_F,P_T) = f(T_S,P_S)\cdot e(T_S)\cdot \frac{P_T}{P_S}\cdot \eta_S \right]\cdot \mathrm{uP}_{\mathrm{S[component]}} \quad (7)$$

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

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

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

3.1.1.1 Saturation Pressure Accuracy Uncertainty Component

Pressure measurement accuracy of Model 3920 Low Humidity Generator's saturation pressure transducer is specified by the manufacturer as 0.02% of the full scale. This total manufacturer uncertainty (k=2) includes reference standard, linearity, drift, hysteresis, temperature effects over the calibrated range and repeatability. Taking a conservative approach that is based on a rectangular distribution, the uncertainty component of the saturation pressure accuracy is then:

$\mathrm{uP}_{\mathrm{s[accuracy]}}$ = (250 psia (full scale) * 0.02%) / √3
= (0.050 psia) / √3 (DOF=infinite)

3.1.1.2 Saturation Pressure Resolution Uncertainty Component

The Model 3920 Low Humidity Generator digitally communicates with the saturation pressure transducer. Based on a rectangular distribution of the half-interval of resolution, the uncertainty component of pressure resolution is then:

$\mathrm{uP}_{\mathrm{s\,[resolution]}}$ = 0.000001 psia / √12 (DOF=infinite)

3.1.2 Test Pressure Uncertainty Contribution

The test 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 equation for this becomes:

$$\mathrm{uT}_{\mathrm{D[component]}} = \frac{\partial}{\partial P_T}\left[e_W(T_D)\cdot f(T_D,P_T) = f(T_S,P_S)\cdot e(T_S)\cdot \frac{P_T}{P_S}\cdot \eta_S \right]\cdot \mathrm{uP}_{\mathrm{T[component]}} \tag{8}$$

$$\mathrm{uT}_{\mathrm{F[component]}} = \frac{\partial}{\partial P_T}\left[e_I(T_F)\cdot f(T_F,P_T) = f(T_S,P_S)\cdot e(T_S)\cdot \frac{P_T}{P_S}\cdot \eta_S \right]\cdot \mathrm{uP}_{\mathrm{T[component]}} \tag{9}$$

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

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

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

Note: This analysis will use standard pressure (14.7 psia) as the test pressure reading for all calculations

3.1.2.1 Test Pressure Accuracy Uncertainty Component

Pressure measurement accuracy of Model 3920 Low Humidity Generator's test pressure transducer is specified by the manufacturer as 0.02% of full scale. This total manufacturer uncertainty (k=2) includes reference standard, linearity, drift, hysteresis, temperature effects over the calibrated range and repeatability. Taking a conservative approach that is based on a rectangular distribution, the uncertainty component of the test pressure accuracy is then:

$\mathrm{uP}_{\mathrm{T[accuracy]}}$ = (50.0 psia (full scale) * 0.02%) / √3
= (0.010 psia) / √3 (DOF=infinite)

3.1.2.2 Test Pressure Resolution Uncertainty Component

The Model 3920 Low Humidity Generator digitally communicates with the test pressure transducer. Based on a rectangular distribution of the half-interval of resolution, the uncertainty component of pressure resolution is then:

$\mathrm{uP}_{\mathrm{T\,[resolution]}}$ = 0.000001 psia / √12 (DOF=infinite)

3.1.3 Pressure Uncertainty Contribution Summary

The standard Dew Point Temperature uncertainties, uT_D, components calculated using equation 6 and 8 with the associated individual pressure components, are summarized in Table 1 and Figure 1.

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

Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom	Evaluation
		15	20	30	50	100	175	250		
		11.7 °C	7.4 °C	1.7 °C	-5.2 °C	-13.9 °C	-20.3 °C	-24.2 °C		
12 °C	Ps Accuracy	0.029012	0.02101	0.01334	0.00753	0.00346	0.001838	0.001223	Infinity	Type B
12 °C	Ps Resolution	2.9E-07	2.1E-07	1.33E-07	7.53E-08	3.46E-08	1.84E-08	1.22E-08	Infinity	Type B
12 °C	Pt Accuracy	0.005921	0.005723	0.005461	0.005159	0.004792	0.004529	0.004376	Infinity	Type B
12 °C	Pt Resolution	2.96E-07	2.86E-07	2.73E-07	2.58E-07	2.4E-07	2.26E-07	2.19E-07	Infinity	Type B
	Combined	*0.029610*	*0.021776*	*0.014415*	*0.009128*	*0.005911*	*0.004888*	*0.004543*	*Infinity*	
		-0.3 °C	-4.1 °C	-9.4 °C	-15.7 °C	-23.6 °C	-29.5 °C	-33.1 °C		
0 °C	Ps Accuracy	0.026332	0.019103	0.012157	0.00688	0.003169	0.001685	0.00112	Infinity	Type B
0 °C	Ps Resolution	2.63E-07	1.91E-07	1.22E-07	6.88E-08	3.17E-08	1.68E-08	1.12E-08	Infinity	Type B
0 °C	Pt Accuracy	0.005375	0.005205	0.00498	0.004719	0.0044	0.004171	0.004037	Infinity	Type B
0 °C	Pt Resolution	2.69E-07	2.6E-07	2.49E-07	2.36E-07	2.2E-07	2.09E-07	2.02E-07	Infinity	Type B
	Combined	*0.026875*	*0.019800*	*0.013138*	*0.008342*	*0.005423*	*0.004498*	*0.004190*	*Infinity*	
		-22.5 °C	-25.7 °C	-30.0 °C	-35.3 °C	-41.9 °C	-46.9 °C	-49.9 °C		
-20 °C	Ps Accuracy	0.021774	0.015848	0.010128	0.005757	0.002664	0.001418	0.000942	Infinity	Type B
-20 °C	Ps Resolution	2.18E-07	1.58E-07	1.01E-07	5.76E-08	2.66E-08	1.42E-08	9.42E-09	Infinity	Type B
-20 °C	Pt Accuracy	0.004444	0.004318	0.004151	0.003956	0.003715	0.003541	0.003438	Infinity	Type B
-20 °C	Pt Resolution	2.22E-07	2.16E-07	2.08E-07	1.98E-07	1.86E-07	1.77E-07	1.72E-07	Infinity	Type B
	Combined	*0.022223*	*0.016426*	*0.010946*	*0.006985*	*0.004572*	*0.003814*	*0.003565*	*Infinity*	
		-43.9 °C	-46.6 °C							
-40 °C	Ps Accuracy	0.017858	0.013035						Infinity	Type B
-40 °C	Ps Resolution	1.79E-07	1.3E-07						Infinity	Type B
-40 °C	Pt Accuracy	0.003645	0.003553						Infinity	Type B
-40 °C	Pt Resolution	1.82E-07	1.78E-07						Infinity	Type B
	Combined	*0.018226*	*0.013511*						*Infinity*	

Table 1

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

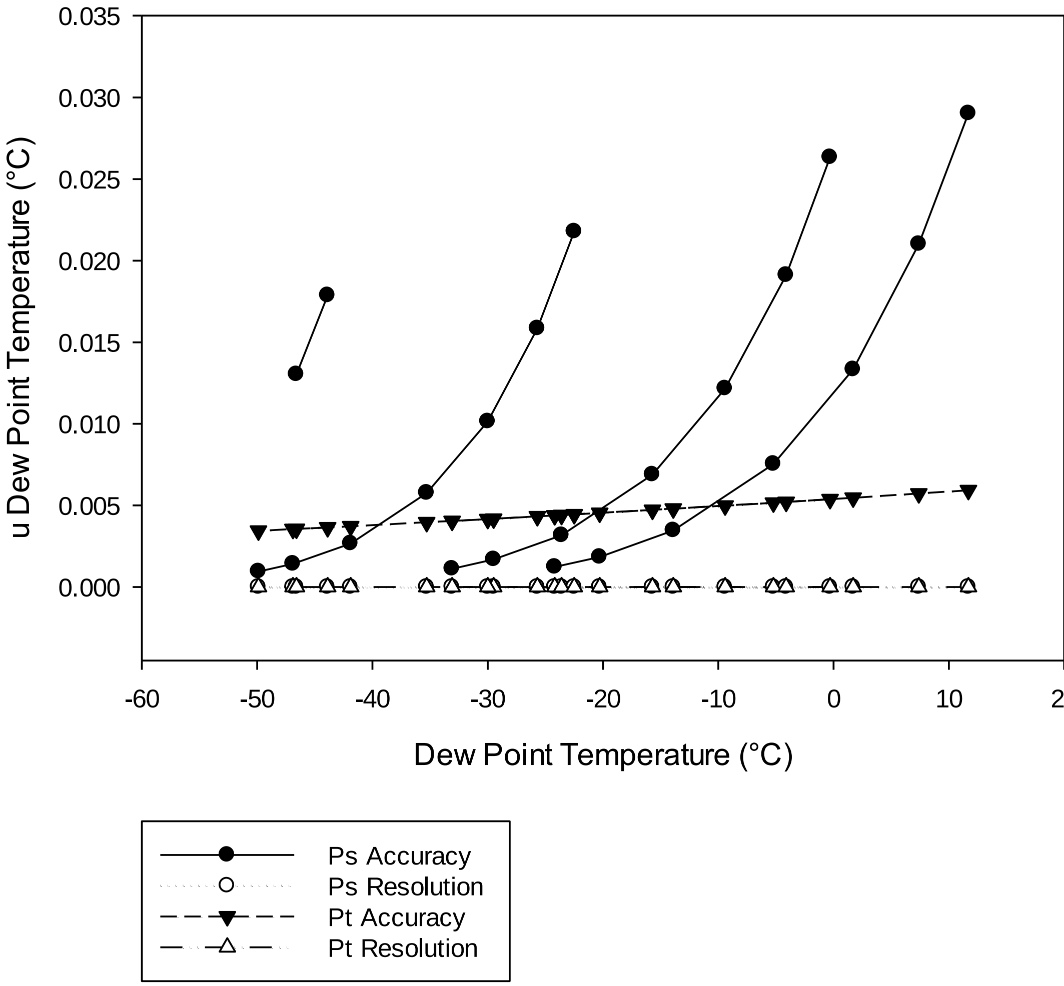


Figure 1

The standard Frost Point Temperature uncertainties, uT_F, components calculated using equation 7 and 9 with the associated individual pressure components, are summarized in Table 2 and Figure 2.

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

Standard Pressure Uncertainty Components of Frost Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**							**Degrees of Freedom**	**Evaluation**
		15	**20**	**30**	**50**	**100**	**175**	**250**		
					-4.6 °C	**-12.4 °C**	**-18.3 °C**	**-21.8 °C**		
12 °C	Ps Accuracy				0.006702	0.003124	0.001677	0.001122	Infinity	Type B
	Ps Resolution				6.7E-08	3.12E-08	1.68E-08	1.12E-08	Infinity	Type B
	Pt Accuracy				0.004591	0.004327	0.004132	0.004017	Infinity	Type B
	Pt Resolution				2.3E-07	2.16E-07	2.07E-07	2.01E-07	Infinity	Type B
	Combined				*0.008123*	*0.005337*	*0.004460*	*0.004171*	*Infinity*	
		-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-14.0 °C**	**-21.2 °C**	**-26.7 °C**	**-30.0 °C**		
0 °C	Ps Accuracy	0.023241	0.016972	0.010896	0.006229	0.002906	0.00156	0.001042	Infinity	Type B
	Ps Resolution	2.32E-07	1.7E-07	1.09E-07	6.23E-08	2.91E-08	1.56E-08	1.04E-08	Infinity	Type B
	Pt Accuracy	0.004743	0.004624	0.004463	0.004273	0.004036	0.003861	0.003758	Infinity	Type B
	Pt Resolution	2.37E-07	2.31E-07	2.23E-07	2.14E-07	2.02E-07	1.93E-07	1.88E-07	Infinity	Type B
	Combined	*0.023720*	*0.017590*	*0.011774*	*0.007554*	*0.004973*	*0.004164*	*0.003900*	*Infinity*	
		-20.2 °C	**-23.2 °C**	**-27.2 °C**	**-32.0 °C**	**-38.3 °C**	**-43.0 °C**	**-45.9 °C**		
-20 °C	Ps Accuracy	0.019934	0.014583	0.009383	0.005377	0.002513	0.001348	0.000899	Infinity	Type B
	Ps Resolution	1.99E-07	1.46E-07	9.38E-08	5.38E-08	2.51E-08	1.35E-08	8.99E-09	Infinity	Type B
	Pt Accuracy	0.004069	0.003974	0.003846	0.003694	0.003504	0.003364	0.003281	Infinity	Type B
	Pt Resolution	2.03E-07	1.99E-07	1.92E-07	1.85E-07	1.75E-07	1.68E-07	1.64E-07	Infinity	Type B
	Combined	*0.020345*	*0.015114*	*0.010141*	*0.006524*	*0.004312*	*0.003624*	*0.003402*	*Infinity*	
		-40.2 °C	**-42.7 °C**	**-46.1 °C**	**-50.2 °C**	**-55.6 °C**	**-59.6 °C**	**-62.0 °C**		
-40 °C	Ps Accuracy	0.016894	0.012379	0.007981	0.004583	0.002144	0.001147	0.000763	Infinity	Type B
	Ps Resolution	1.69E-07	1.24E-07	7.98E-08	4.58E-08	2.14E-08	1.15E-08	7.63E-09	Infinity	Type B
	Pt Accuracy	0.003448	0.003374	0.003275	0.003156	0.003007	0.002896	0.002831	Infinity	Type B
	Pt Resolution	1.72E-07	1.69E-07	1.64E-07	1.58E-07	1.5E-07	1.45E-07	1.42E-07	Infinity	Type B
	Combined	*0.017243*	*0.012831*	*0.008627*	*0.005564*	*0.003693*	*0.003115*	*0.002932*	*Infinity*	

		-60.1 °C	-62.2 °C	-65.1 °C	-68.6 °C	-73.1 °C	-76.4 °C	-78.4 °C		
-60 °C	Ps Accuracy	0.014116	0.010358	0.00669	0.003847	0.001799	0.000959	0.000634	Infinity	Type B
	Ps Resolution	1.41E-07	1.04E-07	6.69E-08	3.85E-08	1.8E-08	9.59E-09	6.34E-09	Infinity	Type B
	Pt Accuracy	0.002881	0.002825	0.002749	0.002657	0.002543	0.002458	0.002407	Infinity	Type B
	Pt Resolution	1.44E-07	1.41E-07	1.37E-07	1.33E-07	1.27E-07	1.23E-07	1.2E-07	Infinity	Type B
	Combined	*0.014407*	*0.010737*	*0.007233*	*0.004676*	*0.003114*	*0.002638*	*0.002489*	*Infinity*	
		-80.1 °C	**-81.8 °C**	**-84.2 °C**	**-87.1 °C**	**-90.7 °C**	**-93.5 °C**	**-95.1 °C**		
-80 °C	Ps Accuracy	0.011592	0.008517	0.005508	0.003169	0.001478	0.000782	0.000511	Infinity	Type B
	Ps Resolution	1.16E-07	8.52E-08	5.51E-08	3.17E-08	1.48E-08	7.82E-09	5.11E-09	Infinity	Type B
	Pt Accuracy	0.002366	0.002324	0.002267	0.002199	0.002113	0.00205	0.002012	Infinity	Type B
	Pt Resolution	1.18E-07	1.16E-07	1.13E-07	1.1E-07	1.06E-07	1.02E-07	1.01E-07	Infinity	Type B
	Combined	*0.011831*	*0.008828*	*0.005957*	*0.003857*	*0.002579*	*0.002194*	*0.002076*	*Infinity*	

Table 2

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

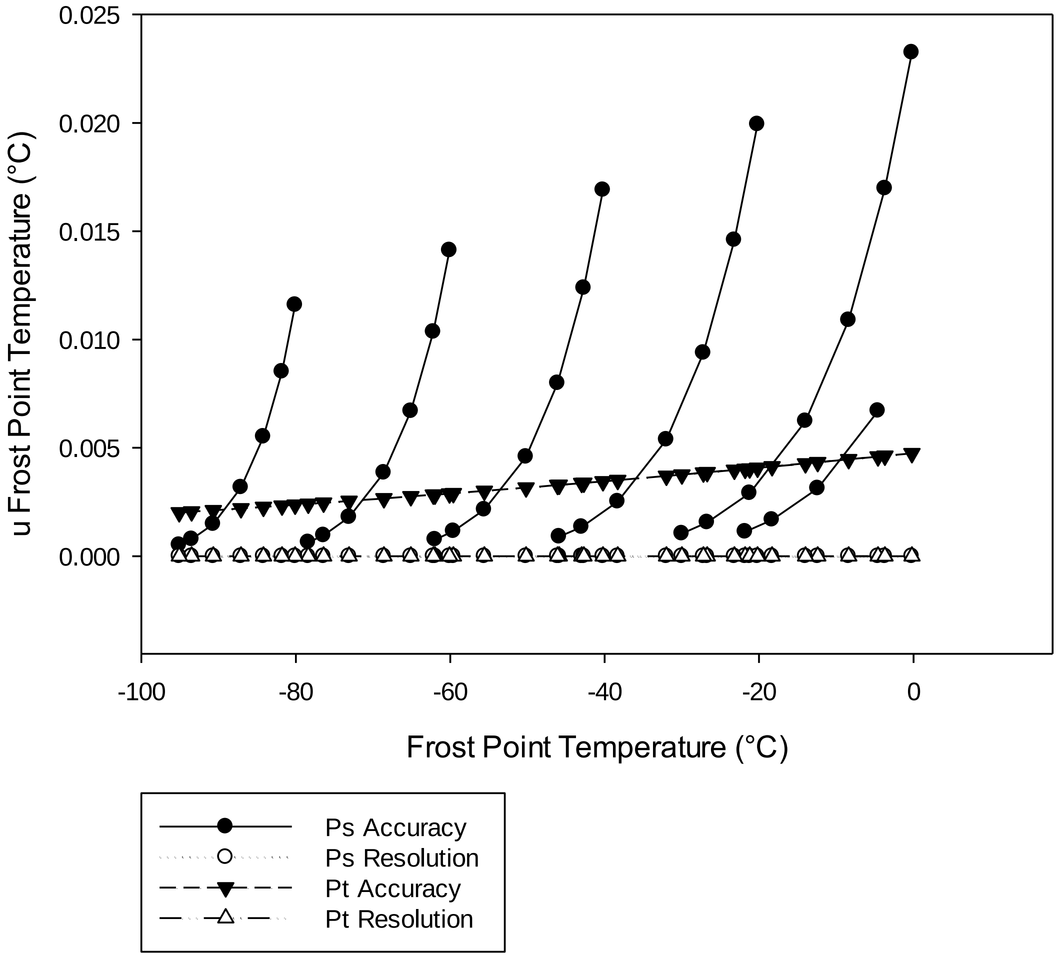


Figure 2

3.2 Temperature Uncertainty Contribution

The temperature term, T_S, in a two-pressure humidity generator is another major contributor of uncertainty and is used mathematically to calculate saturation vapor pressures. The Model 3920 Low Humidity Generator uses one temperature probe to measure the saturation temperature.

3.2.1 Saturation Temperature Uncertainty Contribution

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:

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

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

$\mathrm{uT}_{\mathrm{D[component]}}$ = 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.

3.2.1.1 Saturation Temperature Measurement Uncertainty Component

Temperature measurement accuracy of Model 3920 Low Humidity Generator's saturation temperature probe encompasses seven separate components that are listed and combined in Table 3.

Model 3920 Manufacture Specification Temperature Components of Uncertainty					
Description	Uncertainty (±)	k=	Distribution	Degrees of Freedom	Evaluation
Standard - 1560 Black Stack	2.0000E-02	2	Normal	Infinity	Type B
NI-9216 Resolution	6.2585E-05	1	Resolution	Infinity	Type B
NI-9216 Offset Error	2.3700E-03	1	Rectangular	Infinity	Type B
NI-9216 Gain Error	2.7650E-05	1	Rectangular	Infinity	Type B
5622 Repeatability	7.0000E-03	1	Rectangular	Infinity	Type B
5622 Self Heating	3.0000E-03	1	Rectangular	Infinity	Type A
Fluid Control Stability	8.0000E-03	1	Normal	Infinity	Type B
				Combined Standard Uncertainty (±):	0.0136
				Effective Degrees of Freedom:	Infinity
				Confidence:	95.45%
				k:	2
				Expanded Combined Uncertainty (±):	0.0272

Table 3

Using the expanded result from table 3 and taking a conservative approach that is based on a rectangular distribution, the uncertainty component of saturation temperature accuracy is then:

$$uT_{s[accuracy]} = 0.027\ °C / \sqrt{3}\ (DOF=infinite)$$

resulting in:

$$uT_{s[accuracy]} = 0.031\ °C$$

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

3.2.1.2 Thermal Lag Uncertainty Component

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 pumped 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 becomes difficult to detect on the instrument under test. Therefore, an estimate of uncertainty will be applied.

$$uT_{s[\text{thermal lag}]} = 0.01\ ^\circ\text{C} / \sqrt{3} \text{ (DOF=infinite)}$$

3.2.1.3 Thermal Gradients Uncertainty Component

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.

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

It is believed that the design of the saturator reduces any negative effects 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.

3.2.2 Temperature Uncertainty Contribution Summary

The standard uncertainties, uT_D, components calculated using equation 10 with the associated individual temperature components previously shown, are summarized in Table 4 and Figure 3.

Standard Temperature Uncertainty Components of Dew Point Temperature (°C)										
Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom	Evaluation
		15	20	30	50	100	175	250		
		11.7 °C	7.4 °C	1.7 °C	-5.2 °C	-13.9 °C	-20.3 °C	-24.2 °C		
12 °C	Ts Accuracy	0.015551	0.01503	0.014342	0.013544	0.012567	0.011855	0.011431	Infinity	Type B
	Ts Thermal Lag	0.00576	0.005567	0.005312	0.005016	0.004654	0.004391	0.004234	Infinity	Type B
	Ts Thermal Gradients	0.00288	0.002783	0.002656	0.002508	0.002327	0.002195	0.002117	Infinity	Type B
	Combined	*0.016831*	*0.016268*	*0.015523*	*0.014659*	*0.013602*	*0.012831*	*0.012373*	*Infinity*	
		-0.3 °C	-4.1 °C	-9.4 °C	-15.7 °C	-23.6 °C	-29.5 °C	-33.1 °C		
0 °C	Ts Accuracy	0.016605	0.016065	0.01536	0.014544	0.013538	0.0128	0.01236	Infinity	Type B
	Ts Thermal Lag	0.00615	0.00595	0.005689	0.005387	0.005014	0.004741	0.004578	Infinity	Type B
	Ts Thermal Gradients	0.003075	0.002975	0.002845	0.002693	0.002507	0.00237	0.002289	Infinity	Type B
	Combined	*0.017973*	*0.017388*	*0.016625*	*0.015741*	*0.014652*	*0.013854*	*0.013378*	*Infinity*	
		-22.5 °C	-25.7 °C	-30.0 °C	-35.3 °C	-41.9 °C	-46.9 °C	-49.9 °C		
-20 °C	Ts Accuracy	0.016999	0.016518	0.015877	0.015123	0.014187	0.013495	0.013079	Infinity	Type B
	Ts Thermal Lag	0.006296	0.006118	0.00588	0.005601	0.005255	0.004998	0.004844	Infinity	Type B
	Ts Thermal Gradients	0.003148	0.003059	0.00294	0.002801	0.002627	0.002499	0.002422	Infinity	Type B
	Combined	*0.018399*	*0.017878*	*0.017184*	*0.016368*	*0.015356*	*0.014606*	*0.014156*	*Infinity*	
		-43.9 °C	-46.6 °C							
-40 °C	Ts Accuracy	0.016453	0.016039						Infinity	Type B
	Ts Thermal Lag	0.006094	0.00594						Infinity	Type B
	Ts Thermal Gradients	0.003047	0.00297						Infinity	Type B
	Combined	*0.017808*	*0.017360*						*Infinity*	

Table 4

Document: Model_3920_Uncertainty_Analysis (Rev1)
Author: Michael Hamilton
Date: November 2019

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

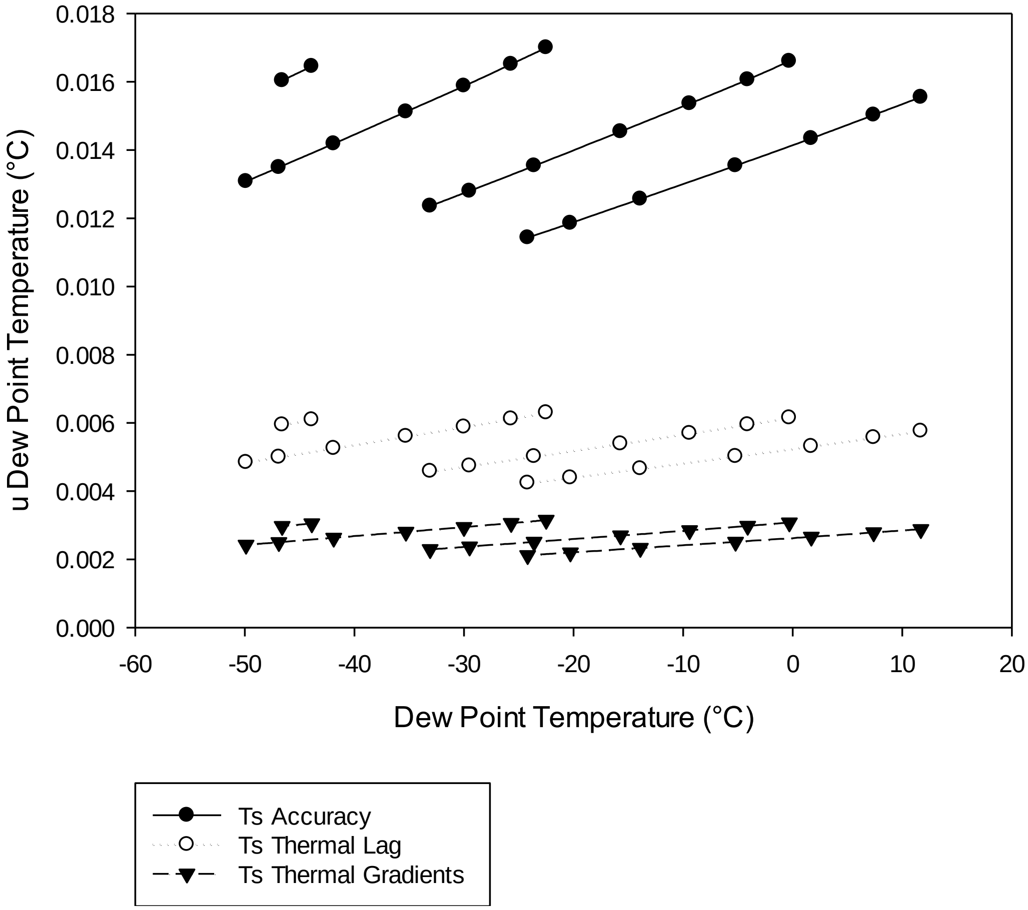


Figure 3

The standard uncertainties, uT_F, components calculated using equation 11 from the associated individual temperature components previously shown, are summarized in Table 5 and Figure 4.

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

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

Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom	Evaluation
		15	20	30	50	100	175	250		
					-4.6 °C	-12.4 °C	-18.3 °C	-21.8 °C		
12 °C	Ts Accuracy				0.012053	0.011346	0.010816	0.010494	Infinity	Type B
	Ts Thermal Lag				0.004464	0.004202	0.004006	0.003887	Infinity	Type B
	Ts Thermal Gradients				0.002232	0.002101	0.002003	0.001943	Infinity	Type B
	Combined				*0.013046*	*0.012281*	*0.011707*	*0.011359*	*Infinity*	
		-0.2 °C	-3.7 °C	-8.4 °C	-14.0 °C	-21.2 °C	-26.7 °C	-30.0 °C		
0 °C	Ts Accuracy	0.014664	0.014272	0.013768	0.013171	0.012419	0.011853	0.011507	Infinity	Type B
	Ts Thermal Lag	0.005431	0.005286	0.005099	0.004878	0.0046	0.00439	0.004262	Infinity	Type B
	Ts Thermal Gradients	0.002716	0.002643	0.00255	0.002439	0.0023	0.002195	0.002131	Infinity	Type B
	Combined	*0.015872*	*0.015447*	*0.014901*	*0.014255*	*0.013442*	*0.012829*	*0.012454*	*Infinity*	
		-20.2 °C	-23.2 °C	-27.2 °C	-32.0 °C	-38.3 °C	-43.0 °C	-45.9 °C		
-20 °C	Ts Accuracy	0.015562	0.015199	0.014709	0.014124	0.013382	0.012822	0.01248	Infinity	Type B
	Ts Thermal Lag	0.005764	0.005629	0.005448	0.005231	0.004956	0.004749	0.004622	Infinity	Type B
	Ts Thermal Gradients	0.002882	0.002815	0.002724	0.002616	0.002478	0.002374	0.002311	Infinity	Type B
	Combined	*0.016844*	*0.016451*	*0.015920*	*0.015287*	*0.014484*	*0.013878*	*0.013507*	*Infinity*	
		-40.2 °C	-42.7 °C	-46.1 °C	-50.2 °C	-55.6 °C	-59.6 °C	-62.0 °C		
-40 °C	Ts Accuracy	0.015565	0.015231	0.014779	0.014237	0.013546	0.013019	0.012696	Infinity	Type B
	Ts Thermal Lag	0.005765	0.005641	0.005474	0.005273	0.005017	0.004822	0.004702	Infinity	Type B
	Ts Thermal Gradients	0.002882	0.002821	0.002737	0.002636	0.002508	0.002411	0.002351	Infinity	Type B
	Combined	*0.016846*	*0.016485*	*0.015996*	*0.015409*	*0.014661*	*0.014091*	*0.013741*	*Infinity*	
		-0.2 °C	-3.7 °C	-8.4 °C	-14.0 °C	-21.2 °C	-26.7 °C	-30.0 °C		
-60 °C	Ts Accuracy	0.015567	0.015262	0.014848	0.014349	0.013707	0.013214	0.012909	Infinity	Type B
	Ts Thermal Lag	0.005765	0.005653	0.005499	0.005314	0.005077	0.004894	0.004781	Infinity	Type B
	Ts Thermal Gradients	0.002883	0.002826	0.00275	0.002657	0.002538	0.002447	0.00239	Infinity	Type B
	Combined	*0.016849*	*0.016519*	*0.016071*	*0.015530*	*0.014836*	*0.014302*	*0.013971*	*Infinity*	

		-80.1 °C	-81.8 °C	-84.2 °C	-87.1 °C	-90.7 °C	-93.5 °C	-95.1 °C		
-80 °C	Ts Accuracy	0.015569	0.015293	0.014916	0.014459	0.013868	0.013409	0.013123	Infinity	Type B
	Ts Thermal Lag	0.005766	0.005664	0.005524	0.005355	0.005136	0.004966	0.00486	Infinity	Type B
	Ts Thermal Gradients	0.002883	0.002832	0.002762	0.002678	0.002568	0.002483	0.00243	Infinity	Type B
	Combined	*0.016851*	*0.016552*	*0.016144*	*0.015650*	*0.015010*	*0.014513*	*0.014203*	*Infinity*	

Table 5

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

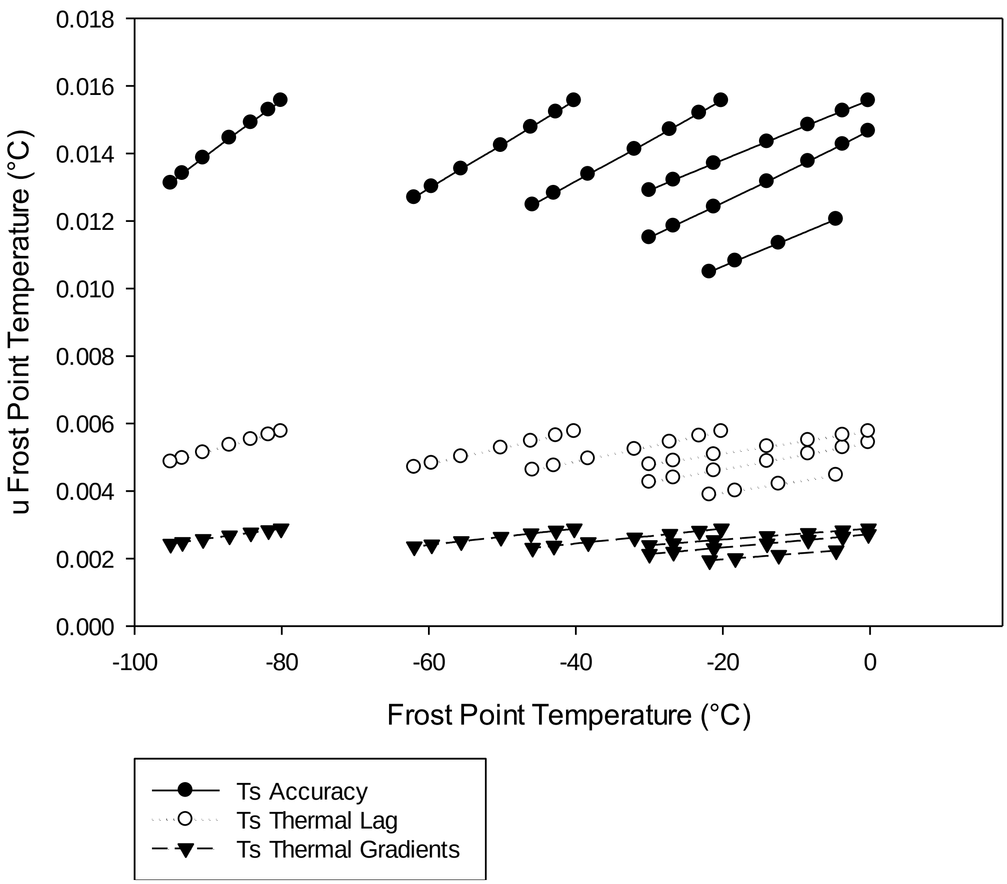


Figure 4

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 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 the Wexler's [4] saturation vapor pressure equation. Wexler [4] also 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.

3.3.3 Equation Uncertainty Contribution Summary

The standard uncertainties, uT_D, components calculated using the associated equation uncertainty tables mentioned above are summarized in Table 6 and Figure 5.

Standard Equation Uncertainty Components of Dew Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**							**Degrees of Freedom**	**Evaluation**
		15	**20**	**30**	**50**	**100**	**175**	**250**		
		11.7 °C	**7.4 °C**	**1.7 °C**	**-5.2 °C**	**-13.9 °C**	**-20.3 °C**	**-24.2 °C**		
12 °C	SVP@Ts	0.00108	0.00104	0.00099	0.00093	0.00086	0.0008	0.00076	Infinity	Type B
	F@Ts,Ps	0.00156	0.00193	0.00266	0.00406	0.00725	0.01179	0.01639	Infinity	Type B
	SVP@Tf	0.00106	0.00074	0.00033	0.00021	0.0002	0.00018	0.00018	Infinity	Type B
	F@Tf,Pt	0.00153	0.00148	0.00141	0.00169	0.00211	0.00235	0.00227	Infinity	Type B
	Combined	*0.002655*	*0.002749*	*0.003191*	*0.004501*	*0.007599*	*0.012051*	*0.016560*	*Infinity*	
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-15.7 °C**	**-23.6 °C**	**-29.5 °C**	**-33.1 °C**		
0 °C	SVP@Ts	0.00022	0.00021	0.0002	0.00019	0.00018	0.00016	0.00016	Infinity	Type B
	F@Ts,Ps	0.00142	0.00183	0.00263	0.00416	0.00755	0.01237	0.01738	Infinity	Type B
	SVP@Tf	0.00022	0.00021	0.0002	0.00019	0.00018	0.00017	0.00016	Infinity	Type B
	F@Tf,Pt	0.00141	0.00163	0.0019	0.00218	0.00228	0.00217	0.00242	Infinity	Type B
	Combined	*0.002026*	*0.002472*	*0.003260*	*0.004705*	*0.007888*	*0.012559*	*0.017550*	*Infinity*	
		-22.5 °C	**-25.7 °C**	**-30.0 °C**	**-35.3 °C**	**-41.9 °C**	**-46.9 °C**	**-49.9 °C**		
-20 °C	SVP@Ts	0.0115	0.01116	0.01069	0.01013	0.00938	0.00874	0.00829	Infinity	Type B
	F@Ts,Ps	0.00236	0.0031	0.00453	0.00729	0.01359	0.02273	0.03215	Infinity	Type B
	SVP@Tf	0.00018	0.00018	0.00017	0.00016	0.00015	0.00014	0.00014	Infinity	Type B
	F@Tf,Pt	0.00231	0.00224	0.00216	0.00259	0.00289	0.00276	0.00268	Infinity	Type B
	Combined	*0.011960*	*0.011794*	*0.011817*	*0.012748*	*0.016760*	*0.024503*	*0.033308*	*Infinity*	
		-43.9 °C	**-46.6 °C**							
-40 °C	SVP@Ts	0.01653	0.01608						Infinity	Type B
	F@Ts,Ps	0.00288	0.00363						Infinity	Type B
	SVP@Tf	0.00015	0.00014						Infinity	Type B
	F@Tf,Pt	0.00283	0.00277						Infinity	Type B
	Combined	*0.017015*	*0.016721*						*Infinity*	

Table 6

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

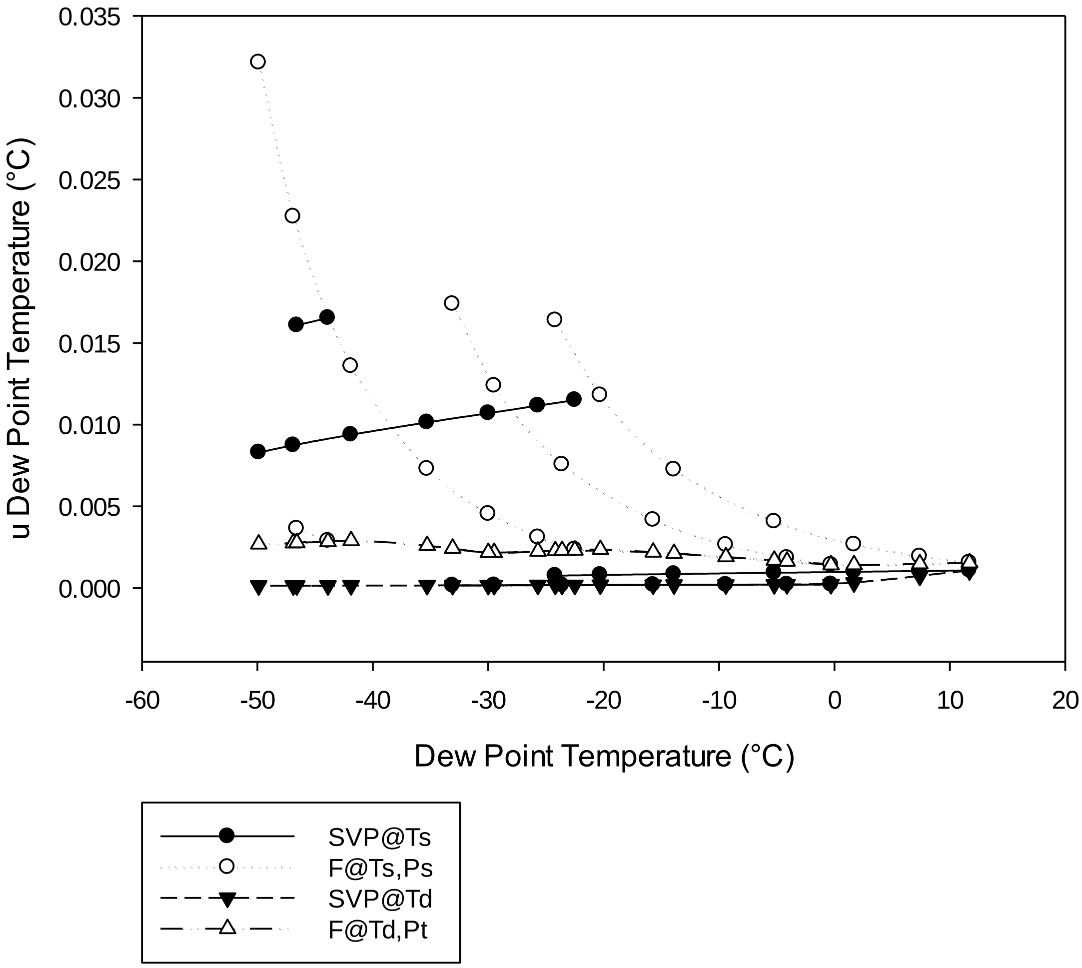


Figure 5

The standard uncertainties, uT_F, components calculated using the associated equation uncertainty tables mentioned above are summarized in Table 7 and Figure 6.

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

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

Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom	Evaluation
		15	20	30	50	100	175	250		
					-4.6 °C	-12.4 °C	-18.3 °C	-21.8 °C		
12 °C	SVP@Ts				0.00083	0.00078	0.00073	0.0007	Infinity	Type B
	F@Ts,Ps				0.00361	0.00654	0.01076	0.01504	Infinity	Type B
	SVP@Tf				0.00311	0.00736	0.00985	0.01112	Infinity	Type B
	F@Tf,Pt				0.00147	0.00182	0.00205	0.00209	Infinity	Type B
	Combined				*0.005057*	*0.010041*	*0.014748*	*0.018834*	*Infinity*	
		-0.2 °C	-3.7 °C	-8.4 °C	-14.0 °C	-21.2 °C	-26.7 °C	-30.0 °C		
0 °C	SVP@Ts	0.00019	0.00019	0.00018	0.00017	0.00016	0.00015	0.00014	Infinity	Type B
	F@Ts,Ps	0.00125	0.00163	0.00236	0.00377	0.00692	0.01145	0.01618	Infinity	Type B
	SVP@Tf	0.00035	0.00254	0.00533	0.00807	0.01094	0.01259	0.0135	Infinity	Type B
	F@Tf,Pt	0.00124	0.00142	0.00164	0.00189	0.00209	0.00201	0.00196	Infinity	Type B
	Combined	*0.001811*	*0.003337*	*0.006063*	*0.009104*	*0.013113*	*0.017134*	*0.021160*	*Infinity*	
		-20.2 °C	-23.2 °C	-27.2 °C	-32.0 °C	-38.3 °C	-43.0 °C	-45.9 °C		
-20 °C	SVP@Ts	0.01052	0.01026	0.00991	0.00946	0.00884	0.0083	0.00791	Infinity	Type B
	F@Ts,Ps	0.00216	0.00285	0.0042	0.00681	0.01282	0.02159	0.03068	Infinity	Type B
	SVP@Tf	0.01061	0.01154	0.01272	0.01398	0.01533	0.01623	0.01672	Infinity	Type B
	F@Tf,Pt	0.00211	0.00206	0.002	0.00212	0.00257	0.00262	0.00255	Infinity	Type B
	Combined	*0.015246*	*0.015840*	*0.016785*	*0.018327*	*0.022001*	*0.028377*	*0.035911*	*Infinity*	
		-40.2 °C	-42.7 °C	-46.1 °C	-50.2 °C	-55.6 °C	-59.6 °C	-62.0 °C		
-40 °C	SVP@Ts	0.01563	0.01527	0.01477	0.01414	0.01323	0.01239	0.01176	Infinity	Type B
	F@Ts,Ps	0.00273	0.00345	0.00487	0.00762	0.01434	0.02455	0.03502	Infinity	Type B
	SVP@Tf	0.01569	0.01616	0.01675	0.0174	0.01823	0.01876	0.01913	Infinity	Type B
	F@Tf,Pt	0.00268	0.00262	0.00255	0.00247	0.00256	0.00262	0.00265	Infinity	Type B
	Combined	*0.022480*	*0.022657*	*0.023003*	*0.023807*	*0.026823*	*0.033390*	*0.041685*	*Infinity*	

		-60.1 °C	-62.2 °C	-65.1 °C	-68.6 °C	-73.1 °C	-76.4 °C	-78.4 °C		
-60 °C	SVP@Ts	0.01878	0.01838	0.01781	0.01706	0.01596	0.01488	0.01405	Infinity	Type B
	F@Ts,Ps	0.00267	0.0035	0.0051	0.00822	0.01599	0.02792	0.04014	Infinity	Type B
	SVP@Tf	0.01884	0.01916	0.01957	0.02	0.02063	0.02108	0.02132	Infinity	Type B
	F@Tf,Pt	0.00263	0.00265	0.00268	0.00272	0.00285	0.00297	0.00303	Infinity	Type B
	Combined	*0.026865*	*0.026911*	*0.027078*	*0.027683*	*0.030726*	*0.038137*	*0.047673*	*Infinity*	
		-80.1 °C	-81.8 °C	-84.2 °C	-87.1 °C	-90.7 °C	-93.5 °C	-95.1 °C		
-80 °C	SVP@Ts	0.02146	0.02102	0.02039	0.01955	0.01824	0.01688	0.01578	Infinity	Type B
	F@Ts,Ps	0.00314	0.00406	0.00587	0.0094	0.01809	0.03174	0.04634	Infinity	Type B
	SVP@Tf	0.0215	0.02162	0.02178	0.02193	0.02223	0.02288	0.02323	Infinity	Type B
	F@Tf,Pt	0.00308	0.00308	0.00308	0.00307	0.00307	0.00313	0.00316	Infinity	Type B
	Combined	*0.030687*	*0.030584*	*0.030561*	*0.030997*	*0.034105*	*0.042727*	*0.054273*	*Infinity*	

Table 1

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

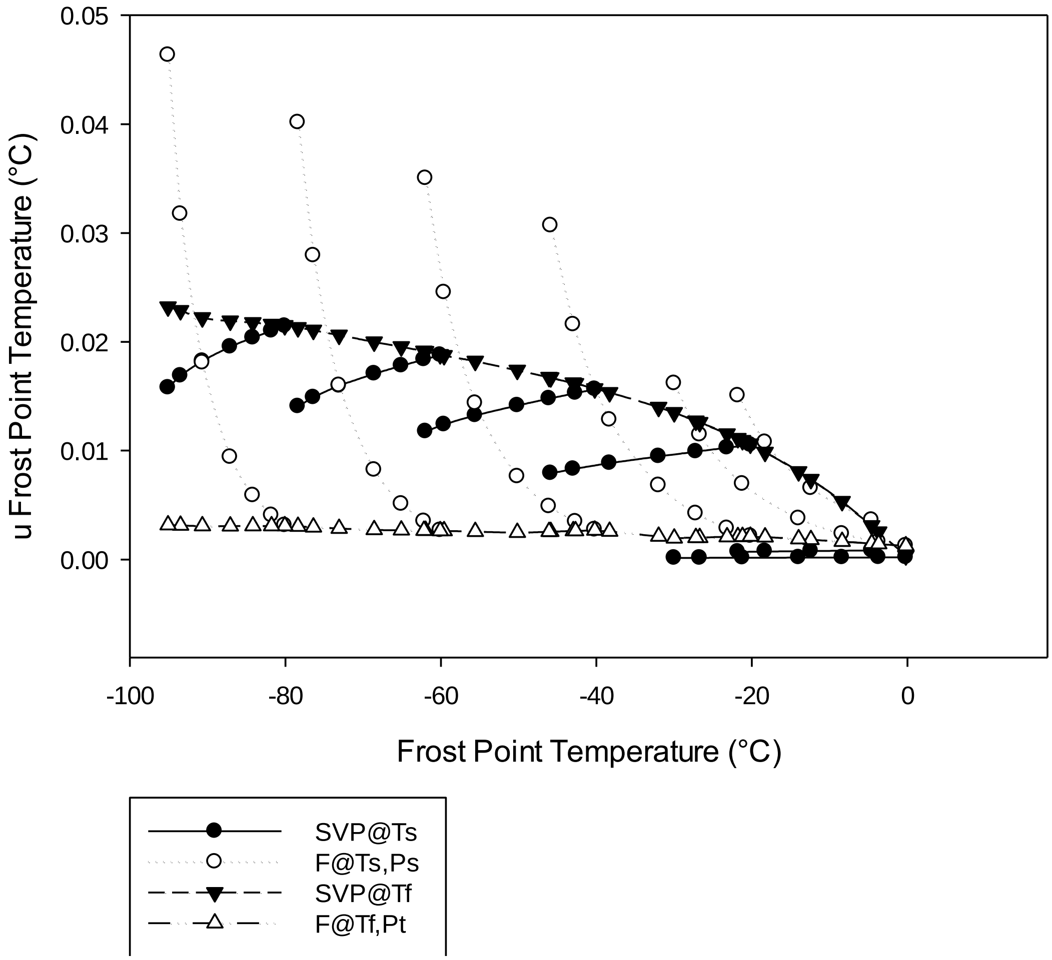


Figure 6

3.4 Saturator Efficiency Uncertainty Contribution

All two-pressure 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.

Based on engineering research and development work on the Model 3920, the uncertainty component of % efficiency of saturation is determined to be:

$$\eta_S = 99.95\%$$

The standard uncertainties, uT_D, components calculated using the above associated % efficiency component, are summarized in Table 8 and Figure 7.

Standard Saturator Efficiency Uncertainty Components of Dew Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**							**Degrees of Freedom**	**Evaluation**
		15	**20**	**30**	**50**	**100**	**175**	**250**		
		11.7 °C	**7.4 °C**	**1.7 °C**	**-5.2 °C**	**-13.9 °C**	**-20.3 °C**	**-24.2 °C**		
12 °C	η_S	0.007562	0.007310	0.006977	0.006592	0.006125	0.005790	0.005595	Infinity	Type B
	Combined	*0.007562*	*0.007310*	*0.006977*	*0.006592*	*0.006125*	*0.005790*	*0.005595*	*Infinity*	
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-15.7 °C**	**-23.6 °C**	**-29.5 °C**	**-33.1 °C**		
0 °C	η_S	0.006866	0.006650	0.006364	0.006032	0.005626	0.005335	0.005164	Infinity	Type B
	Combined	*0.006866*	*0.006650*	*0.006364*	*0.006032*	*0.005626*	*0.005335*	*0.005164*	*Infinity*	
		-22.5 °C	**-25.7 °C**	**-30.0 °C**	**-35.3 °C**	**-41.9 °C**	**-46.9 °C**	**-49.9 °C**		
-20 °C	η_S	0.005682	0.005522	0.005309	0.005060	0.004754	0.004532	0.004402	Infinity	Type B
	Combined	*0.005682*	*0.005522*	*0.005309*	*0.005060*	*0.004754*	*0.004532*	*0.004402*	*Infinity*	
		-43.9 °C	**-46.6 °C**							
-40 °C	η_S	0.004665	0.004548						Infinity	Type B
	Combined	*0.004665*	*0.004548*						*Infinity*	

Table 8

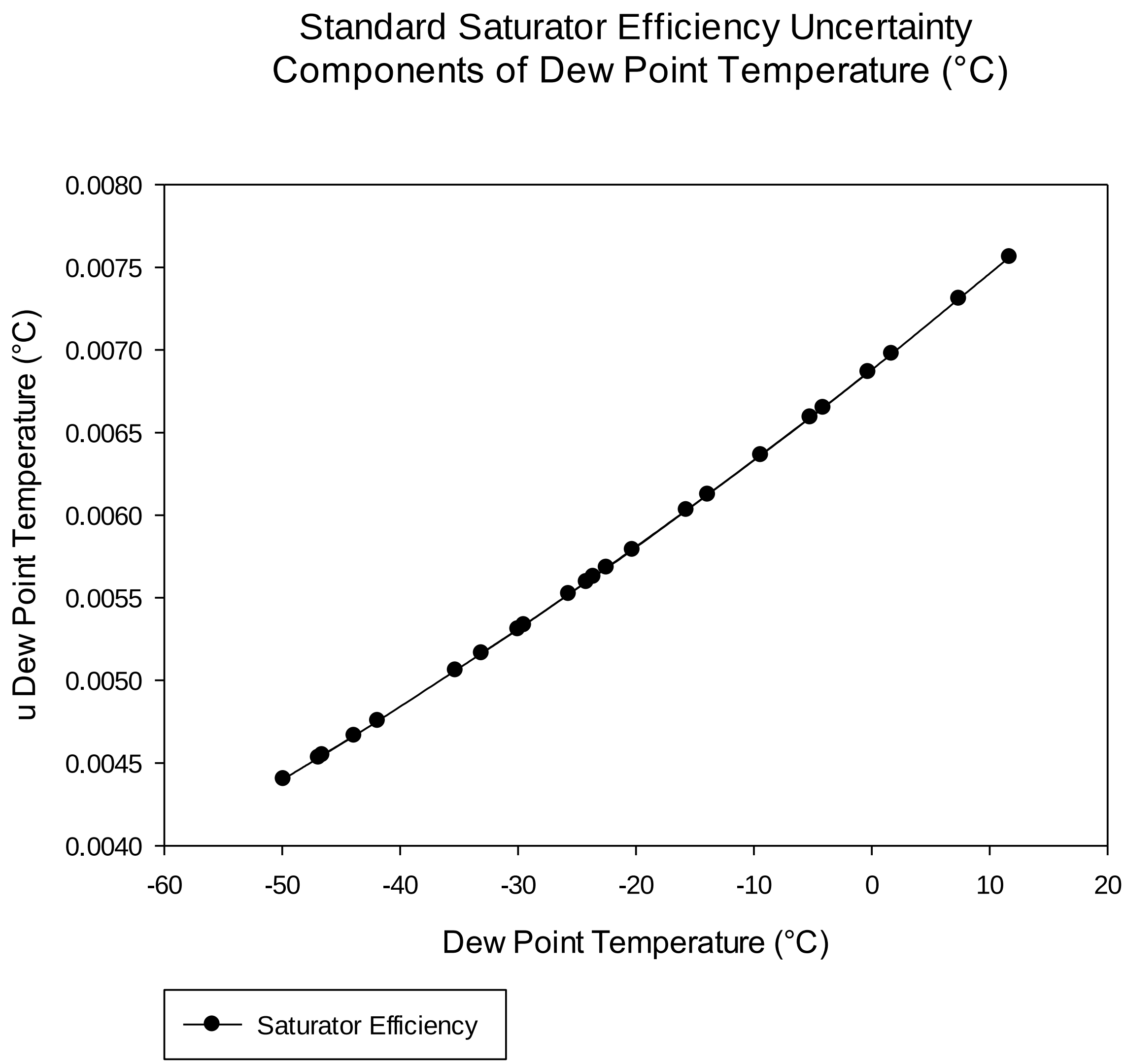

Standard Saturator Efficiency Uncertainty
Components of Dew Point Temperature (°C)
0.0080
0.0075
0.0070
0.0065
0.0060
0.0055
0.0050
0.0045
0.0040
u Dew Point Temperature (°C)
-60
-50
-40
-30
-20
-10
0
10
20
Dew Point Temperature (°C)
Saturator Efficiency

Figure 7

The standard uncertainties, uT_F, components calculated using the above associated % efficiency component, are summarized in Table 9 and Figure 8.

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

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

Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom	Evaluation
		15	20	30	50	100	175	250		
					-4.6 °C	-12.4 °C	-18.3 °C	-21.8 °C		
12 °C	η_S				0.005867	0.005530	0.005283	0.005137	Infinity	Type B
	Combined				*0.005867*	*0.005530*	*0.005283*	*0.005137*	*Infinity*	
		-0.2 °C	-3.7 °C	-8.4 °C	-14.0 °C	-21.2 °C	-26.7 °C	-30.0 °C		
0 °C	η_S	0.006060	0.005908	0.005703	0.005462	0.005160	0.004938	0.004807	Infinity	Type B
	Combined	*0.006060*	*0.005908*	*0.005703*	*0.005462*	*0.005160*	*0.004938*	*0.004807*	*Infinity*	
		-20.2 °C	-23.2 °C	-27.2 °C	-32.0 °C	-38.3 °C	-43.0 °C	-45.9 °C		
-20 °C	η_S	0.005202	0.005081	0.004919	0.004726	0.004485	0.004306	0.004201	Infinity	Type B
	Combined	*0.005202*	*0.005081*	*0.004919*	*0.004726*	*0.004485*	*0.004306*	*0.004201*	*Infinity*	
		-40.2 °C	-42.7 °C	-46.1 °C	-50.2 °C	-55.6 °C	-59.6 °C	-62.0 °C		
-40 °C	η_S	0.004413	0.004319	0.004192	0.004041	0.003852	0.003711	0.003628	Infinity	Type B
	Combined	*0.004413*	*0.004319*	*0.004192*	*0.004041*	*0.003852*	*0.003711*	*0.003628*	*Infinity*	
		-60.1 °C	-62.2 °C	-65.1 °C	-68.6 °C	-73.1 °C	-76.4 °C	-78.4 °C		
-60 °C	η_S	0.003692	0.003621	0.003524	0.003408	0.003262	0.003154	0.003091	Infinity	Type B
	Combined	*0.003692*	*0.003621*	*0.003524*	*0.003408*	*0.003262*	*0.003154*	*0.003091*	*Infinity*	
		-80.1 °C	-81.8 °C	-84.2 °C	-87.1 °C	-90.7 °C	-93.5 °C	-95.1 °C		
-80 °C	η_S	0.003038	0.002985	0.002913	0.002826	0.002717	0.002636	0.002589	Infinity	Type B
	Combined	*0.003038*	*0.002985*	*0.002913*	*0.002826*	*0.002717*	*0.002636*	*0.002589*	*Infinity*	

Table 9

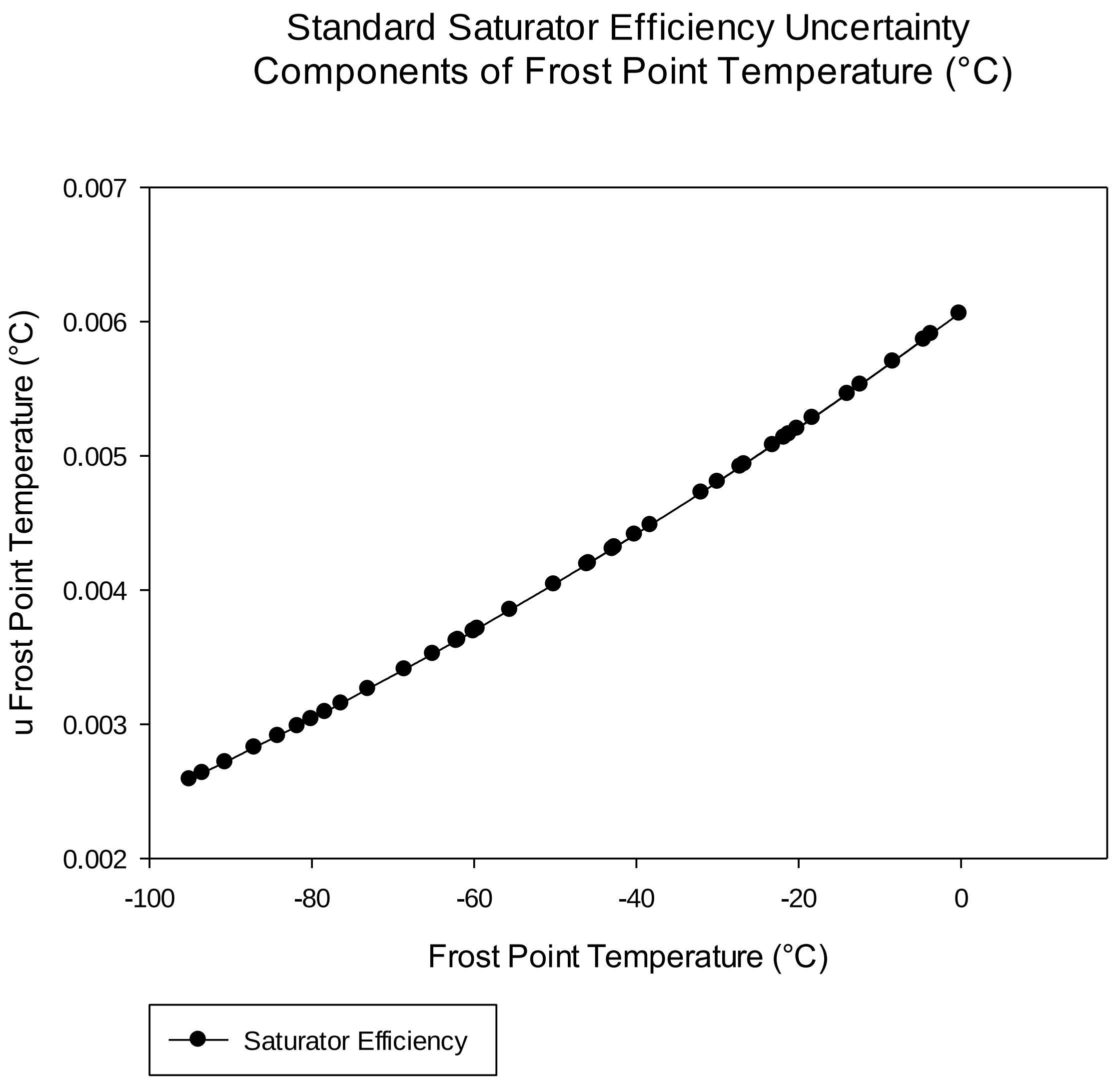

Standard Saturator Efficiency Uncertainty
Components of Frost Point Temperature (°C)
0.007
0.006
0.005
0.004
0.003
0.002
u Frost Point Temperature (°C)
-100
-80
-60
-40
-20
0
Frost Point Temperature (°C)
Saturator Efficiency

Figure 8

3.5 Permeation and Adsorption Uncertainty Contribution

Permeation and adsorption refer 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 below -90 °C. 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. To help reduce and even eliminate the effects of permeation and adsorption the system was designed using metal faced sealed fittings, orbital welded electro-polished tubing and ultra-high purity (UHP) diaphragm valves. This design optimizes flow paths to minimize pressure drops, minimizes internal surface area and eliminates dead spaces. By increasing the flow rate of the generated gas, while assuming a constant permeation rate, the effect of that permeation can also be minimized. Likewise, if the gas being generated is of higher concentration (i.e., warmer frost point), then the effect 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 effect of permeation. This analysis assumes that the generator is run at the highest possible flow rate. Even with the high flow rate, permeations impact the generation of low frost point values. This permeation uncertainty is again very small and very difficult to isolate and measure outright but can be best defined as a parts per million by volume (PPM_V) uncertainty component in terms of Dew and Frost point.

The Dew/Frost point temperatures can be expressed in relation to parts per million by volume (PPM_V) by the following formula:

$$e(T_D)\cdot f(T_D,P_T)=\frac{\left[\dfrac{PPM_V}{10^6}\cdot P_T\right]}{\left[1+\dfrac{PPM_V}{10^6}\right]} \tag{12}$$

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

$$\mathrm{uT}_{\mathrm{D[component]}}=\frac{\partial}{\partial PPM_V}\left[e_W(T_D)\cdot f(T_D,P_T)=\frac{\left[\dfrac{PPM_V}{10^6}\cdot P_T\right]}{\left[1+\dfrac{PPM_V}{10^6}\right]}\right]\cdot \mathrm{uPPM}_{\mathrm{V\ [component]}} \tag{13}$$

$$\mathrm{uT}_{F[\mathrm{component}]} = \frac{\partial}{\partial PPM_V}\left[e_W(T_D)\cdot f(T_D,P_T) = \frac{\left[\frac{PPM_V}{10^6}\cdot P_T\right]}{\left[1+\frac{PPM_V}{10^6}\right]}\right]\cdot \mathrm{uPPM}_{V\,[\mathrm{component}]} \qquad (14)$$

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

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

$\mathrm{uPPM}_{V[\mathrm{component}]}$ = PPM_V component uncertainty.

Based on engineering research and development work on the Model 3920, the uncertainty component of permeation and absorption is determined to be one part per billion (ppb) and based on a rectangular distribution, the uncertainty component of permeation and absorption is then:

$\mathrm{uPPM}_{V[\mathrm{permeation}]}$ = 0.001 PPM_V / √3 (DOF=infinite)

The standard uncertainties, uT_D, components calculated using the above associated permeation and absorption as a PPM_V component using equations 13 and 14, are summarized in Table 10 and Figure 9.

Standard Permeation and Adsorption Uncertainty Components of Dew Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**							**Degrees of Freedom**	**Evaluation**
		15	**20**	**30**	**50**	**100**	**175**	**250**		
		11.7 °C	**7.4 °C**	**1.7 °C**	**-5.2 °C**	**-13.9 °C**	**-20.3 °C**	**-24.2 °C**		
12 °C	Permeation and Adsorption	0.000002	0.000002	0.000001	0.000002	0.000003	0.000006	0.000008	Infinity	Type B
	Combined	*0.000002*	*0.000002*	*0.000001*	*0.000002*	*0.000003*	*0.000006*	*0.000008*	*Infinity*	
		-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-15.7 °C**	**-23.6 °C**	**-29.5 °C**	**-33.1 °C**		
0 °C	Permeation and Adsorption	0.000001	0.000002	0.000002	0.000004	0.000007	0.000012	0.000016	Infinity	Type B
	Combined	*0.000001*	*0.000002*	*0.000002*	*0.000004*	*0.000007*	*0.000012*	*0.000016*	*Infinity*	
		-22.5 °C	**-25.7 °C**	**-30.0 °C**	**-35.3 °C**	**-41.9 °C**	**-46.9 °C**	**-49.9 °C**		
-20 °C	Permeation and Adsorption	0.000007	0.000008	0.000012	0.000019	0.000036	0.000058	0.000079	Infinity	Type B
	Combined	*0.000007*	*0.000008*	*0.000012*	*0.000019*	*0.000036*	*0.000058*	*0.000079*	*Infinity*	
		-43.9 °C	**-46.6 °C**							
-40 °C	Permeation and Adsorption	0.000043	0.000056						Infinity	Type B
	Combined	*0.000043*	*0.000056*						*Infinity*	

Table 10

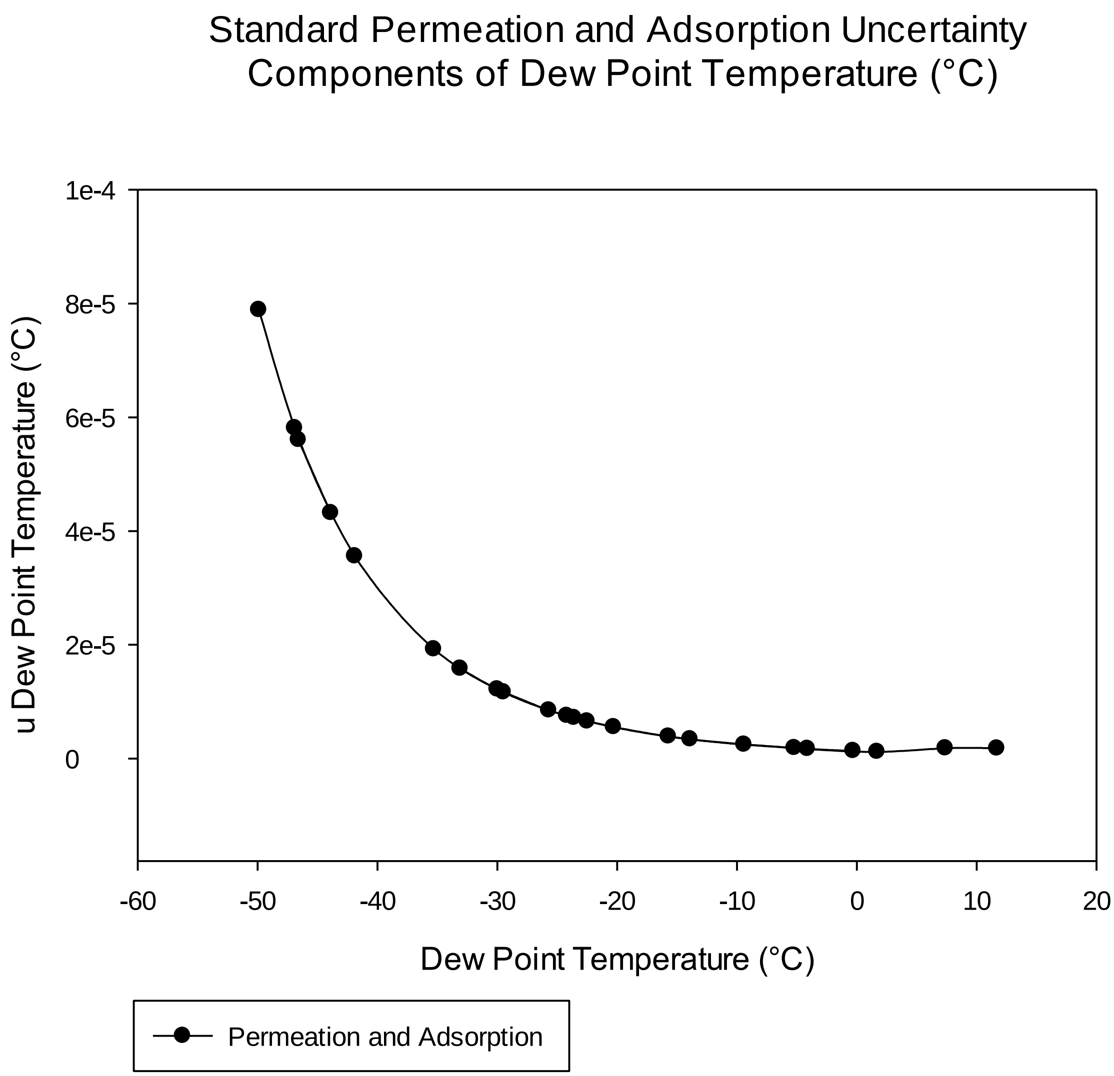


Figure 9

The standard uncertainties, uT_F, components calculated using the above associated permeation and absorption component, are summarized in Table 11 and Figure 10.

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

Standard Permeation and Adsorption Uncertainty Components of Frost Point Temperature (°C)										
Saturation Temperature	**Description**	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**							**Degrees of Freedom**	**Evaluation**
		15	**20**	**30**	**50**	**100**	**175**	**250**		
					-4.6 °C	**-12.4 °C**	**-18.3 °C**	**-21.8 °C**		
12 °C	Permeation and Adsorption				0.000002	0.000003	0.000005	0.000007	Infinity	Type B
	Combined				*0.000002*	*0.000003*	*0.000005*	*0.000007*	*Infinity*	
		-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-14.0 °C**	**-21.2 °C**	**-26.7 °C**	**-30.0 °C**		
0 °C	Permeation and Adsorption	0.000001	0.000002	0.000002	0.000004	0.000007	0.000011	0.000015	Infinity	Type B
	Combined	*0.000001*	*0.000002*	*0.000002*	*0.000004*	*0.000007*	*0.000011*	*0.000015*	*Infinity*	
		-20.2 °C	**-23.2 °C**	**-27.2 °C**	**-32.0 °C**	**-38.3 °C**	**-43.0 °C**	**-45.9 °C**		
-20 °C	Permeation and Adsorption	0.000006	0.000008	0.000011	0.000018	0.000034	0.000055	0.000075	Infinity	Type B
	Combined	*0.000006*	*0.000008*	*0.000011*	*0.000018*	*0.000034*	*0.000055*	*0.000075*	*Infinity*	
		-40.2 °C	**-42.7 °C**	**-46.1 °C**	**-50.2 °C**	**-55.6 °C**	**-59.6 °C**	**-62.0 °C**		
-40 °C	Permeation and Adsorption	0.000041	0.000053	0.000077	0.000123	0.000231	0.000378	0.000514	Infinity	Type B
	Combined	*0.000041*	*0.000053*	*0.000077*	*0.000123*	*0.000231*	*0.000378*	*0.000514*	*Infinity*	
		-60.1 °C	**-62.2 °C**	**-65.1 °C**	**-68.6 °C**	**-73.1 °C**	**-76.4 °C**	**-78.4 °C**		
-60 °C	Permeation and Adsorption	0.000406	0.000529	0.000769	0.001228	0.002299	0.003762	0.005091	Infinity	Type B
	Combined	*0.000406*	*0.000529*	*0.000769*	*0.001228*	*0.002299*	*0.003762*	*0.005091*	*Infinity*	
		-80.1 °C	**-81.8 °C**	**-84.2 °C**	**-87.1 °C**	**-90.7 °C**	**-93.5 °C**	**-95.1 °C**		
-80 °C	Permeation and Adsorption	0.006583	0.008600	0.012515	0.020005	0.037367	0.060758	0.081626	Infinity	Type B
	Combined	*0.006583*	*0.008600*	*0.012515*	*0.020005*	*0.037367*	*0.060758*	*0.081626*	*Infinity*	

Table 11

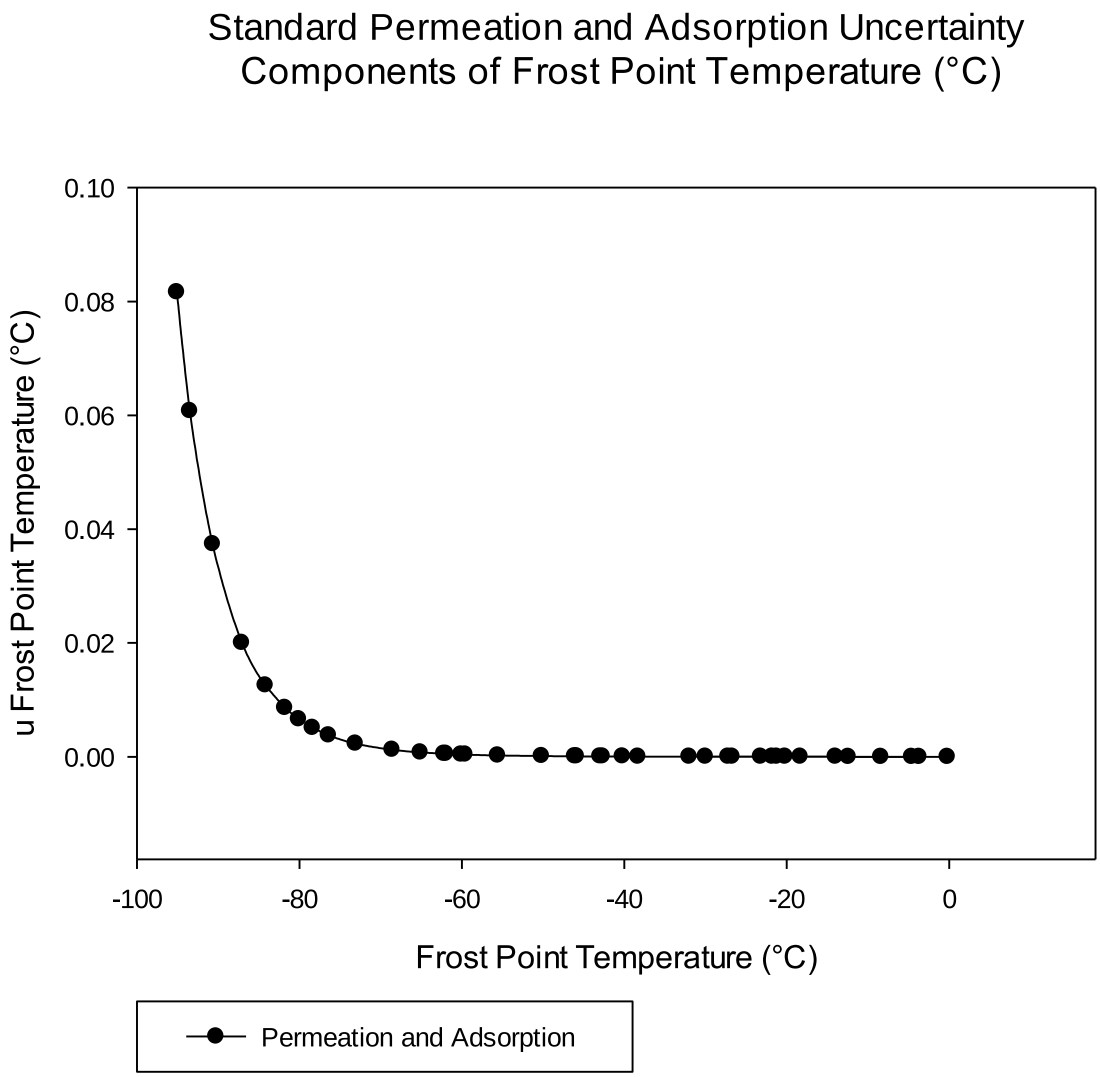

Standard Permeation and Adsorption Uncertainty
Components of Frost Point Temperature (°C)
u Frost Point Temperature (°C)
0.10
0.08
0.06
0.04
0.02
0.00
-100
-80
-60
-40
-20
0
Frost Point Temperature (°C)
Permeation and Adsorption

Figure 10

3.6 Combined Standard and Expanded Uncertainty

The combined standard uncertainty is obtained by the statistical combination of the individual standard uncertainty components of pressure, temperature, equation, saturator efficiency, permeation and absorption in terms of 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:

$$U = k * u_c \tag{15}$$

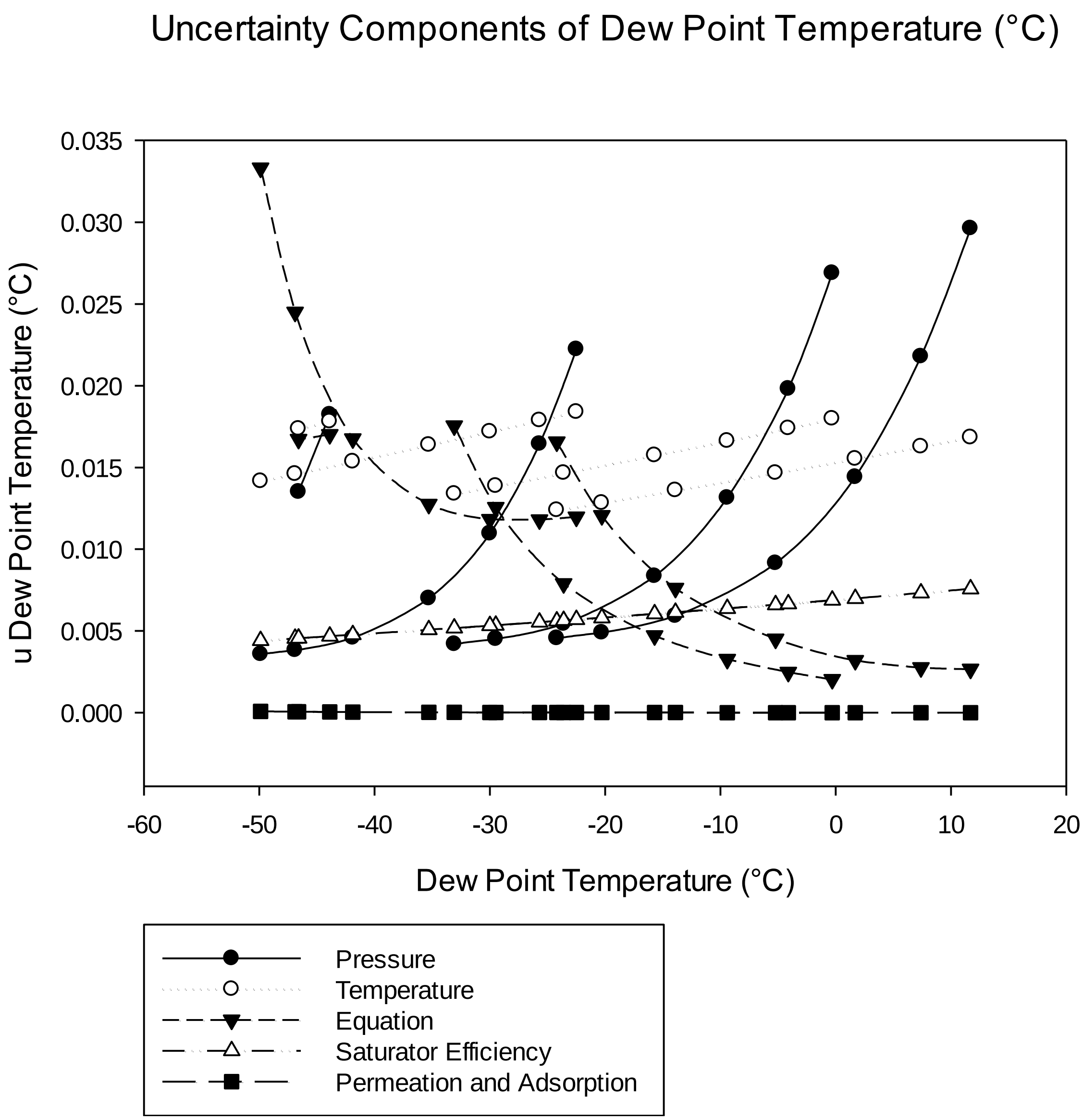
Using equation 4 and 15, the combined individual standard uncertainty components for pressure, temperature, equation, saturator efficiency, permeation and absorption, the total combined standard uncertainty (u) and the total combined expanded uncertainty (U) in terms of dew point temperature T_D (°C) are summarized in Table 12 and Figure 11.

Uncertainty Components of Dew Point Temperature (°C)

Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom
		15	20	30	50	100	175	250	
		11.7 °C	7.4 °C	1.7 °C	-5.2 °C	-13.9 °C	-20.3 °C	-24.2 °C	
12 °C	Pressure	0.029610	0.021776	0.014415	0.009128	0.005911	0.004888	0.004543	Infinity
	Temperature	0.016831	0.016268	0.015523	0.014659	0.013602	0.012831	0.012373	Infinity
	Equation	0.002655	0.002749	0.003191	0.004501	0.007599	0.012051	0.016560	Infinity
	Saturator Efficiency	0.007562	0.007310	0.006977	0.006592	0.006125	0.005790	0.005595	Infinity
	Permeation and Adsorption	0.000002	0.000002	0.000001	0.000002	0.000003	0.000006	0.000008	Infinity
	Combined	*0.034990*	*0.028281*	*0.022530*	*0.019024*	*0.017754*	*0.019165*	*0.021892*	*Infinity*
	Expanded (k=2)	*0.069979*	*0.056562*	*0.045060*	*0.038048*	*0.035508*	*0.038330*	*0.043785*	
		-0.3 °C	-4.1 °C	-9.4 °C	-15.7 °C	-23.6 °C	-29.5 °C	-33.1 °C	
0 °C	Pressure	0.026875	0.019800	0.013138	0.008342	0.005423	0.004498	0.004190	Infinity
	Temperature	0.017973	0.017388	0.016625	0.015741	0.014652	0.013854	0.013378	Infinity
	Equation	0.002026	0.002472	0.003260	0.004705	0.007888	0.012559	0.017550	Infinity
	Saturator Efficiency	0.006866	0.006650	0.006364	0.006032	0.005626	0.005335	0.005164	Infinity
	Permeation and Adsorption	0.000001	0.000002	0.000002	0.000004	0.000007	0.000012	0.000016	Infinity
	Combined	*0.033114*	*0.027289*	*0.022364*	*0.019388*	*0.018384*	*0.019959*	*0.023048*	*Infinity*
	Expanded (k=2)	*0.066227*	*0.054578*	*0.044727*	*0.038776*	*0.036768*	*0.039918*	*0.046095*	

		-22.5 °C	-25.7 °C	-30.0 °C	-35.3 °C	-41.9 °C	-46.9 °C	-49.9 °C	
-20 °C	Pressure	0.022223	0.016426	0.010946	0.006985	0.004572	0.003814	0.003565	Infinity
	Temperature	0.018399	0.017878	0.017184	0.016368	0.015356	0.014606	0.014156	Infinity
	Equation	0.011960	0.011794	0.011817	0.012748	0.016760	0.024503	0.033308	Infinity
	Saturator Efficiency	0.005682	0.005522	0.005309	0.005060	0.004754	0.004532	0.004402	Infinity
	Permeation and Adsorption	0.000007	0.000008	0.000012	0.000019	0.000036	0.000058	0.000079	Infinity
	Combined	*0.031744*	*0.027551*	*0.024144*	*0.022469*	*0.023669*	*0.029135*	*0.036632*	*Infinity*
	Expanded (k=2)	*0.063489*	*0.055101*	*0.048287*	*0.044938*	*0.047337*	*0.058270*	*0.073264*	
		-43.9 °C	-46.6 °C						
-40 °C	Pressure	0.018226	0.013511						Infinity
	Temperature	0.017808	0.017360						Infinity
	Equation	0.017015	0.016721						Infinity
	Saturator Efficiency	0.004665	0.004548						Infinity
	Permeation and Adsorption	0.000043	0.000056						Infinity
	Combined	*0.030993*	*0.028003*						*Infinity*
	Expanded (k=2)	*0.061986*	*0.056006*						

Table 12



Uncertainty Components of Dew Point Temperature (°C)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
u Dew Point Temperature (°C)
-60
-50
-40
-30
-20
-10
0
10
20
Dew Point Temperature (°C)
Pressure
Temperature
Equation
Saturator Efficiency
Permeation and Adsorption

Figure 11

Using equation 5 and 15, the combined individual standard uncertainty components for pressure, temperature, equation, saturator efficiency, permeation and absorption, the total combined standard uncertainty (u) and the total combined expanded uncertainty (U) in terms of frost point temperature T_F (°C) are summarized in Table 13 and Figure 12.

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

Uncertainty Components of Frost Point Temperature (°C)									
Saturation Temperature	Description	Saturation Pressure Range (psia), Test pressure = 14.7 psia							Degrees of Freedom
		15	20	30	50	100	175	250	
					-4.6 °C	-12.4 °C	-18.3 °C	-21.8 °C	
12 °C	Pressure				0.008123	0.005337	0.004460	0.004171	Infinity
	Temperature				0.013046	0.012281	0.011707	0.011359	Infinity
	Equation				0.005057	0.010041	0.014748	0.018834	Infinity
	Saturator Efficiency				0.005867	0.005530	0.005283	0.005137	Infinity
	Permeation and Adsorption				0.000002	0.000003	0.000005	0.000007	Infinity
	Combined				*0.017210*	*0.017627*	*0.020058*	*0.022968*	*Infinity*
	Expanded (k=2)				*0.034420*	*0.035254*	*0.040117*	*0.045936*	
		-0.2 °C	-3.7 °C	-8.4 °C	-14.0 °C	-21.2 °C	-26.7 °C	-30.0 °C	
0 °C	Pressure	0.023720	0.017590	0.011774	0.007554	0.004973	0.004164	0.003900	Infinity
	Temperature	0.015872	0.015447	0.014901	0.014255	0.013442	0.012829	0.012454	Infinity
	Equation	0.001811	0.003337	0.006063	0.009104	0.013113	0.017134	0.021160	Infinity
	Saturator Efficiency	0.006060	0.005908	0.005703	0.005462	0.005160	0.004938	0.004807	Infinity
	Permeation and Adsorption	0.000001	0.000002	0.000002	0.000004	0.000007	0.000011	0.000015	Infinity
	Combined	*0.029233*	*0.024374*	*0.020736*	*0.019313*	*0.020099*	*0.022358*	*0.025321*	*Infinity*
	Expanded (k=2)	*0.058466*	*0.048747*	*0.041471*	*0.038625*	*0.040198*	*0.044716*	*0.050642*	
		-20.2 °C	-23.2 °C	-27.2 °C	-32.0 °C	-38.3 °C	-43.0 °C	-45.9 °C	
-20 °C	Pressure	0.020345	0.015114	0.010141	0.006524	0.004312	0.003624	0.003402	Infinity
	Temperature	0.016844	0.016451	0.015920	0.015287	0.014484	0.013878	0.013507	Infinity

	Equation	0.015246	0.015840	0.016785	0.018327	0.022001	0.028377	0.035911	Infinity
	Saturator Efficiency	0.005202	0.005081	0.004919	0.004726	0.004485	0.004306	0.004201	Infinity
	Permeation and Adsorption	0.000006	0.000008	0.000011	0.000018	0.000034	0.000055	0.000075	Infinity
	Combined	*0.030938*	*0.027853*	*0.025733*	*0.025189*	*0.027065*	*0.032086*	*0.038746*	*Infinity*
	Expanded (k=2)	*0.061876*	*0.055706*	*0.051466*	*0.050377*	*0.054131*	*0.064172*	*0.077492*	
		-40.2 °C	**-42.7 °C**	**-46.1 °C**	**-50.2 °C**	**-55.6 °C**	**-59.6 °C**	**-62.0 °C**	
-40 °C	Pressure	0.017243	0.012831	0.008627	0.005564	0.003693	0.003115	0.002932	Infinity
	Temperature	0.016846	0.016485	0.015996	0.015409	0.014661	0.014091	0.013741	Infinity
	Equation	0.022480	0.022657	0.023003	0.023807	0.026823	0.033390	0.041685	Infinity
	Saturator Efficiency	0.004413	0.004319	0.004192	0.004041	0.003852	0.003711	0.003628	Infinity
	Permeation and Adsorption	0.000041	0.000053	0.000077	0.000123	0.000231	0.000378	0.000514	Infinity
	Combined	*0.033256*	*0.031119*	*0.029614*	*0.029181*	*0.031031*	*0.036566*	*0.044142*	*Infinity*
	Expanded (k=2)	*0.066512*	*0.062238*	*0.059229*	*0.058361*	*0.062062*	*0.073132*	*0.088283*	
		-60.1 °C	**-62.2 °C**	**-65.1 °C**	**-68.6 °C**	**-73.1 °C**	**-76.4 °C**	**-78.4 °C**	
-60 °C	Pressure	0.014407	0.010737	0.007233	0.004676	0.003114	0.002638	0.002489	Infinity
	Temperature	0.016849	0.016519	0.016071	0.015530	0.014836	0.014302	0.013971	Infinity
	Equation	0.026865	0.026911	0.027078	0.027683	0.030726	0.038137	0.047673	Infinity
	Saturator Efficiency	0.003692	0.003621	0.003524	0.003408	0.003262	0.003154	0.003091	Infinity
	Permeation and Adsorption	0.000406	0.000529	0.000769	0.001228	0.002299	0.003762	0.005091	Infinity
	Combined	*0.035028*	*0.033552*	*0.032509*	*0.032288*	*0.034493*	*0.041110*	*0.050095*	*Infinity*
	Expanded (k=2)	*0.070055*	*0.067104*	*0.065017*	*0.064577*	*0.068986*	*0.082220*	*0.100191*	
		-80.1 °C	**-81.8 °C**	**-84.2 °C**	**-87.1 °C**	**-90.7 °C**	**-93.5 °C**	**-95.1 °C**	
-80 °C	Pressure	0.011831	0.008828	0.005957	0.003857	0.002579	0.002194	0.002076	Infinity
	Temperature	0.016851	0.016552	0.016144	0.015650	0.015010	0.014513	0.014203	Infinity
	Equation	0.030687	0.030584	0.030561	0.030997	0.034105	0.042727	0.054273	Infinity
	Saturator Efficiency	0.003038	0.002985	0.002913	0.002826	0.002717	0.002636	0.002589	Infinity

	Permeation and Adsorption	0.006583	0.008600	0.012515	0.020005	0.037367	0.060758	0.081626	Infinity
	Combined	*0.037659*	*0.037015*	*0.037352*	*0.040358*	*0.052903*	*0.075760*	*0.099102*	*Infinity*
	Expanded (k=2)	*0.075318*	*0.074031*	*0.074704*	*0.080717*	*0.105806*	*0.151519*	*0.198203*	

Table 13

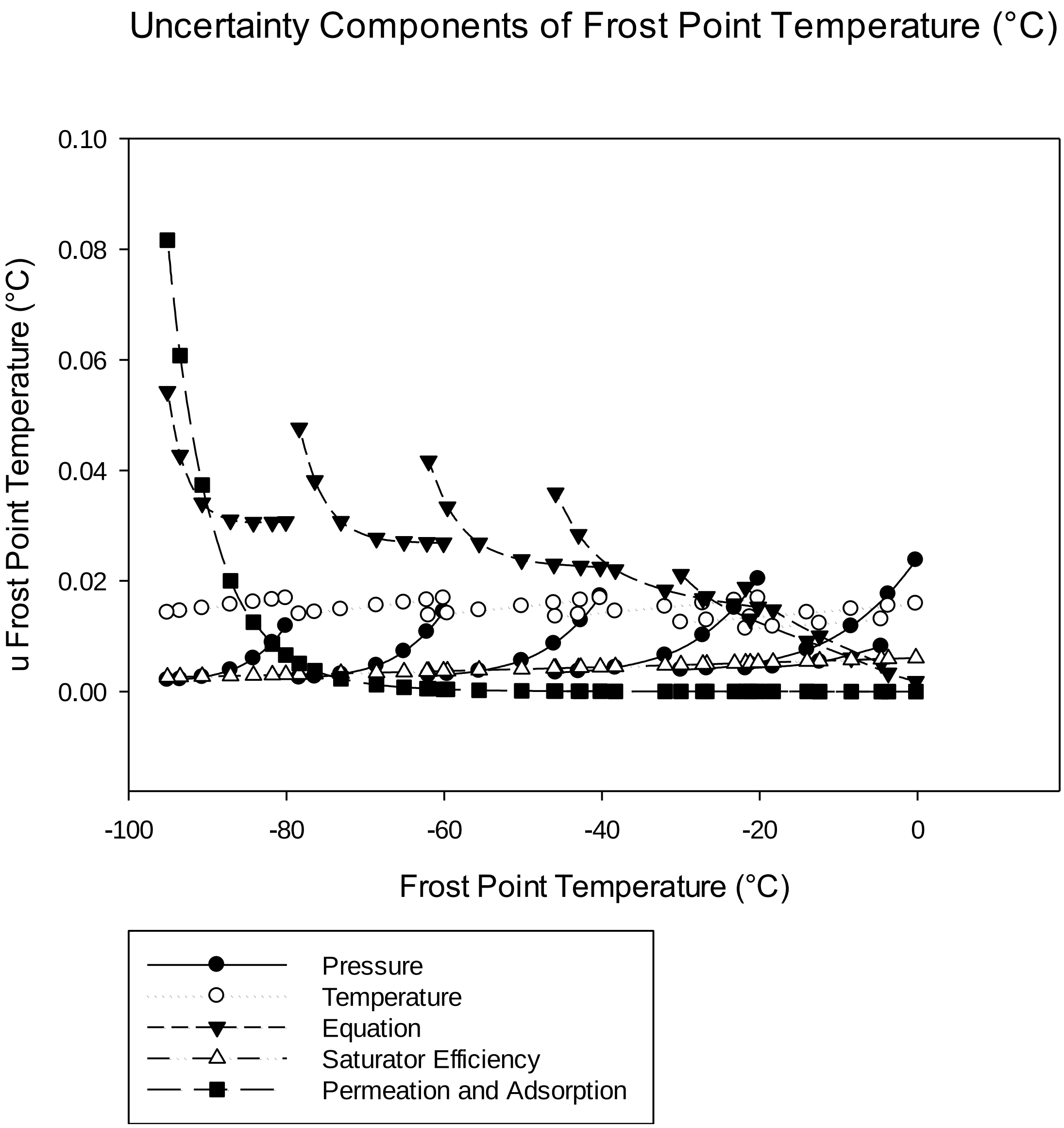


Figure 12

4.0 Summary

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 3920 over the range of -50 °C to 10 °C. Where R is the reading and |R| is the absolute value of the reading.

0.01% |R| + 0.07 °C

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

*Example: If the dew Point reading is 10 °C. The uncertainty would then be: 0.01% *10 + 0.07 °C = 0.071*

A summary of the combined expanded uncertainty and uncertainty specification for Dew Point Temperature (°C) are shown in Table 14 and Figure 13.

Expanded Uncertainty Components of Dew Point Temperature (°C)							
Saturation Temperature	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**						
	15	**20**	**30**	**50**	**100**	**175**	**250**
	11.7 °C	**7.4 °C**	**1.7 °C**	**-5.2 °C**	**-13.9 °C**	**-20.3 °C**	**-24.2 °C**
12 °C	0.069979	0.056562	0.045060	0.038048	0.035508	0.038330	0.043785
	-0.3 °C	**-4.1 °C**	**-9.4 °C**	**-15.7 °C**	**-23.6 °C**	**-29.5 °C**	**-33.1 °C**
0 °C	0.066227	0.054578	0.044727	0.038776	0.036768	0.039918	0.046095
	-22.5 °C	**-25.7 °C**	**-30.0 °C**	**-35.3 °C**	**-41.9 °C**	**-46.9 °C**	**-49.9 °C**
-20 °C	0.063489	0.055101	0.048287	0.044938	0.047337	0.058270	0.073264
	-43.9 °C	**-46.6 °C**					
-40 °C	0.061986	0.056006					
	11.7 °C	**7.4 °C**	**-9.4 °C**	**-15.7 °C**	**-23.6 °C**	**-46.9 °C**	**-49.9 °C**
Specification: 0.01% |R| + 0.07 °C	0.071170	0.070740	0.070940	0.071570	0.072360	0.074690	0.074990

Table 14

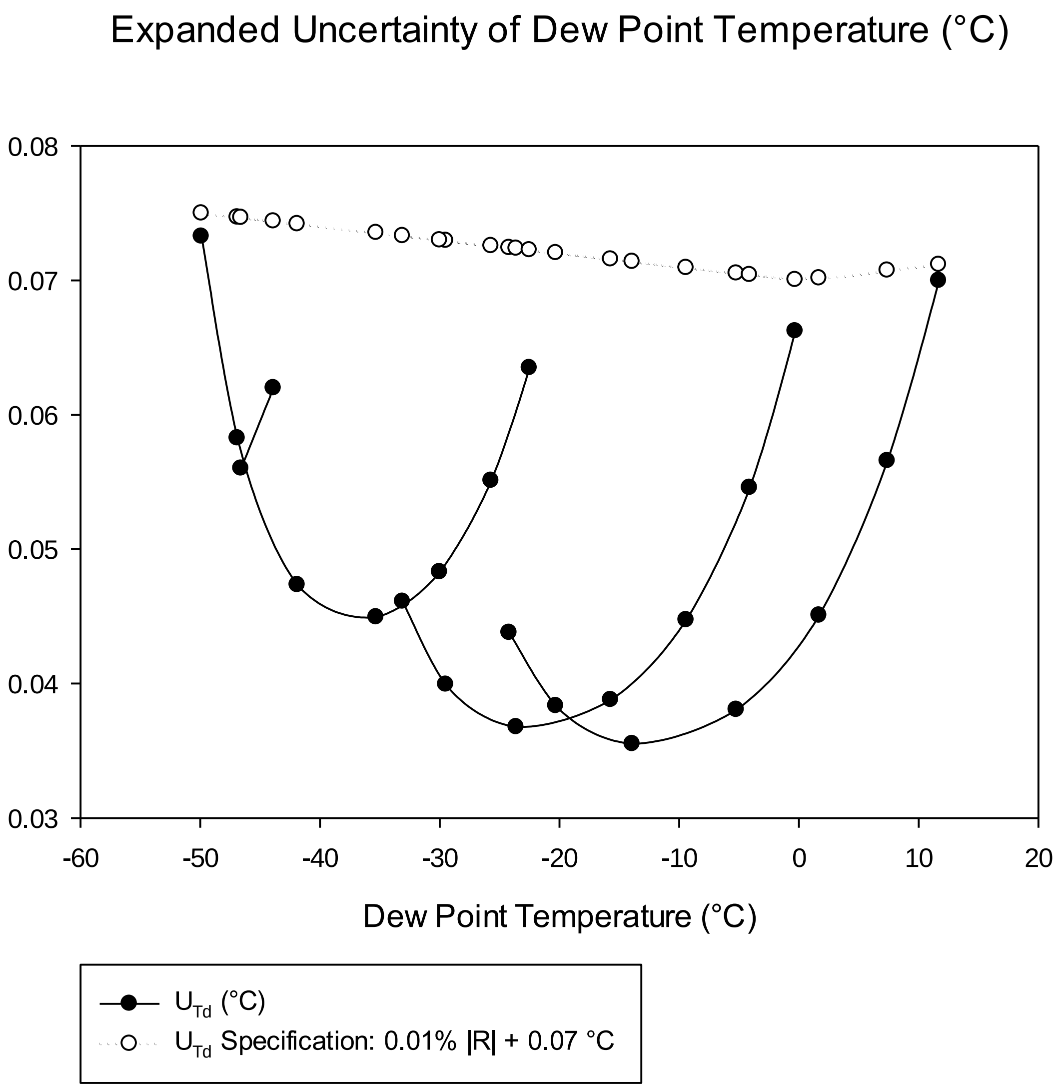

Expanded Uncertainty of Dew Point Temperature (°C)
0.08
0.07
0.06
0.05
0.04
0.03
-60
-50
-40
-30
-20
-10
0
10
20
Dew Point Temperature (°C)
U_Td (°C)
U_Td Specification: 0.01% |R| + 0.07 °C

Figure 13

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 3920 for Frost Point Temperatures greater or equal to -90 °C. Where R is the reading and |R| is the absolute value of the reading.

0.05% |R| + 0.07 °C

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

*Example: If the frost Point reading is -60 °C, the uncertainty would then be: 0.05% *60 + 0.07 °C = 0.1*

For Frost Point Temperatures less than -90 °C, the following uncertainty specification statement is used to describe the Frost Point (°C) uncertainty (U_{TF}) for the Model 3920. Where R is the reading and |R| is the absolute value of the reading.

2% |R| - 1.7 °C

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

*Example: If the frost Point reading is -95 °C, the uncertainty would then be: 2% *95 - 1.7 °C = 0.2*

A summary of the combined expanded uncertainty and uncertainty specifications for Frost Point Temperature (°C) are shown in Table 15 and Figure 14.

Expanded Uncertainty Components of Frost Point Temperature (°C)							
Saturation Temperature	**Saturation Pressure Range (psia), Test pressure = 14.7 psia**						
	15	**20**	**30**	**50**	**100**	**175**	**250**
				-4.6 °C	**-12.4 °C**	**-18.3 °C**	**-21.8 °C**
12 °C				0.034420	0.035254	0.040117	0.045936
	-0.2 °C	**-3.7 °C**	**-8.4 °C**	**-14.0 °C**	**-21.2 °C**	**-26.7 °C**	**-30.0 °C**
0 °C	0.058466	0.048747	0.041471	0.038625	0.040198	0.044716	0.050642
	-20.2 °C	**-23.2 °C**	**-27.2 °C**	**-32.0 °C**	**-38.3 °C**	**-43.0 °C**	**-45.9 °C**
-20 °C	0.061876	0.055706	0.051466	0.050377	0.054131	0.064172	0.077492
	-40.2 °C	**-42.7 °C**	**-46.1 °C**	**-50.2 °C**	**-55.6 °C**	**-59.6 °C**	**-62.0 °C**
-40 °C	0.066512	0.062238	0.059229	0.058361	0.062062	0.073132	0.088283
	-60.1 °C	**-62.2 °C**	**-65.1 °C**	**-68.6 °C**	**-73.1 °C**	**-76.4 °C**	**-78.4 °C**
-60 °C	0.070055	0.067104	0.065017	0.064577	0.068986	0.082220	0.100191
	-80.1 °C	**-81.8 °C**	**-84.2 °C**	**-87.1 °C**	**-90.7 °C**	**-93.5 °C**	**-95.1 °C**
-80 °C	0.075318	0.074031	0.074704	0.080717	0.105806	0.151519	0.198203

	-0.2 °C	-3.7 °C	-8.4 °C	-32.0 °C	-55.6 °C	-76.4 °C	-78.4 °C
Specification >= -90 °C: 0.05% |R| + 0.07 °C	0.070100	0.071850	0.074200	0.086000	0.097800	0.108200	0.109200
					-90.7 °C	-93.5 °C	-95.1 °C
Specification < -90 °C: 2% |R| - 1.7 °C					0.114000	0.170000	0.202000

Table 15

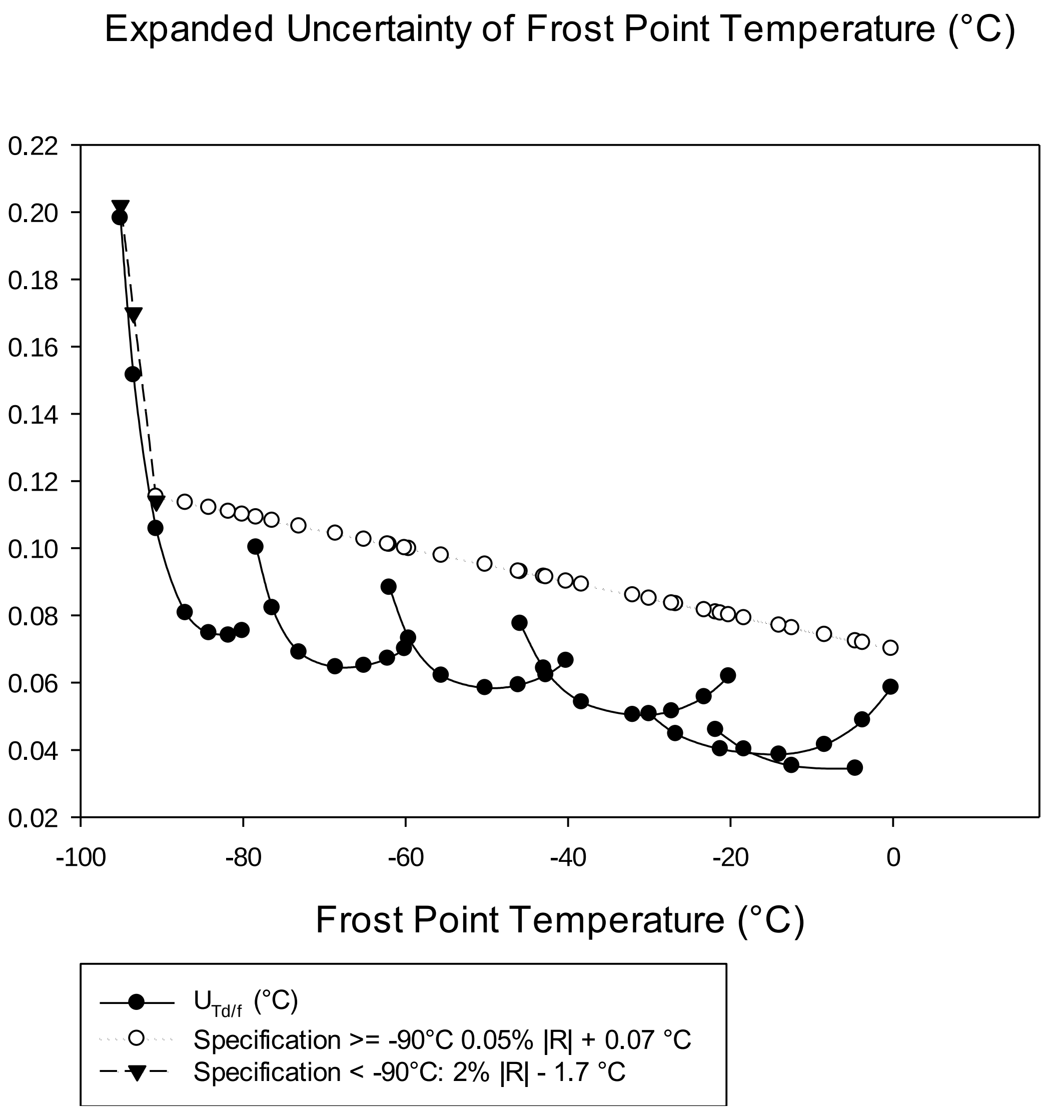


Figure 14

5.0 References

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