

Basic Hygrometry Principles

Reference Guide



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1. Introduction

This reference guide contains general information about moisture monitoring techniques. System contaminants, moisture probe maintenance, process applications and other considerations for ensuring accurate moisture measurements are discussed. The following specific topics are covered:

- Moisture Monitor Hints
- Contaminants
- Aluminum Oxide Probe Maintenance
- Corrosive Gases and Liquids
- Calculations and Useful Formulas in Gas Applications
- Liquid Applications
- Solids Applications

2. Moisture Monitor Hints

Panametrics hygrometers, using aluminum oxide moisture probes, have been designed to reliably measure the moisture content of both gases and liquids. The measured dew point will be the real dew point of the system at the measurement location and at the time of measurement. However, no moisture sensor can determine the origin of the measured moisture content. In addition to the moisture content of the fluid being analyzed, the water vapor pressure at the measurement location may include components from sources such as: moisture from the inner walls of the piping; external moisture through leaks in the piping system; and trapped moisture from fittings, valves, filters, etc. Although these sources may cause the measured dew point to be higher than expected, it is the actual dew point of the system at the time of measurement.

The aluminum oxide sensors used with Panametrics hygrometers may be mounted either in-situ or in an external sample system. In-situ measurements are occasionally used in vacuum applications. While in-situ measurements reduce the overall system cost and may provide improved transport time, in-situ installations expose the sensor to contamination from the process. Thus, installation of the moisture probe in a sample system is generally recommended to control sample pressure, sample temperature and sample flow rate. In addition, the sample system can filter contaminants and facilitate removal of the sensor for maintenance and calibration. In short, sample systems allow a representative sample of the process gas to be exposed to the sensor for optimum performance.

Whether the sensor is installed in-situ or in a remote sampling system, the accuracy and speed of measurement depend on the piping system and the dynamics of the fluid flow. Response times and measurement values will be affected by the degree of equilibrium reached within the system. Factors such as gas pressure, flow rate, materials of construction, length and diameter of piping, initial moisture level and final moisture level will greatly influence the measured moisture levels and the response times.

Assuming that all secondary sources of moisture have been eliminated and the sample system has been allowed to come to equilibrium, then the measured dew point will equal the actual dew point of the process fluid.

Some of the most frequently encountered problems associated with moisture monitoring sample systems include:

- the moisture content value changes as the total gas pressure changes
- the measurement response time is very slow
- the dew point changes as the fluid temperature changes
- the dew point changes as the fluid flow rate changes.

Panametrics hygrometers measure only water vapor pressure. In addition, the instrument has a very rapid response time and it is not affected by changes in fluid flow rate. If any of the above situations occur, then they are almost always caused by a defect in the sample system, or by a problem with the overall process system in general. The moisture sensor itself cannot lead to such problems.

2.1 Pressure

Panometrics hygrometers can accurately measure dew points under pressure conditions ranging from vacuums as low as a few microns of mercury up to pressures of 5000 psig. The calibration data supplied with the moisture probe is directly applicable over this entire pressure range, without correction.

Note: *Although the moisture probe calibration data is supplied as meter reading vs. dew point, it is important to remember that the moisture probe responds only to water vapor pressure.*

When a gas is compressed, the partial pressures of all the gaseous components are proportionally increased. Conversely, when a gas expands, the partial pressures of the gaseous components are proportionally decreased. Therefore, increasing the pressure on a closed aqueous system will increase the vapor pressure of the water, and hence, increase the dew point. This is not just a mathematical artifact. The dew point of a gas with 1,000 ppm_v of water at 200 psig is 13°C, which is considerably higher than the dew point of a gas with 1,000 ppm_v of water at 1 atm, which is -20°C. Gaseous water vapor will actually condense to form liquid water at a higher temperature at the 200 psig pressure than at the 1 atm pressure. Thus, if the moisture probe is exposed to pressure changes, the measured dew point will be altered by the changed vapor pressure of the water.

It is generally advantageous to operate the hygrometer at the highest possible pressure, especially at very low moisture concentrations. This minimizes wall effects and results in higher dew point readings, and reduces the time necessary for an equilibrium dewpoint.

2.2 Response Time

The response time of the Panometrics standard M Series Aluminum Oxide Moisture Probe is very rapid. Thus, the observed response time to moisture changes is, in general, limited by the response time of the system as a whole. Water vapor is absorbed tenaciously by many materials, and a large, complex processing system can take several days to

“dry down” from atmospheric moisture levels to dew points of less than -60°C. Even simple systems consisting of a few feet of stainless steel tubing and a small chamber can take an hour or more to dry down from dew points of +5°C to -70°C. The rate at which the system reaches equilibrium will depend on flow rate, temperature, materials of construction, initial moisture content, final moisture content and system pressure. Generally speaking, an increase in flow rate and/or temperature will decrease the response time of the system.

To minimize any adverse affects on response time, the preferred materials of construction for moisture monitoring sample systems are stainless steel, PTFE and glass. Materials to be avoided include rubber elastomers and related compounds.

2.3 Temperature

For best results, it is recommended that the ambient temperature be at least 10°C higher than the measured dew point, up to a maximum of 70°C. Because an ambient temperature increase may cause water vapor to be desorbed from the walls of the sample system or process piping, it is possible to observe a diurnal change in moisture concentration for a system exposed to varying ambient conditions. In the heat of the day, the system walls will be warmed by the ambient air and an off-gassing of moisture into the process fluid, with a corresponding increase in measured moisture content, will occur. The converse will happen during the cooler evening hours.

2.4 Flow Rate

Panometrics hygrometers are unaffected by the fluid flow rate. The moisture probe is not a mass sensor but responds only to water vapor pressure. The moisture probe will operate accurately under both static and dynamic fluid flow conditions. In fact, the specified maximum fluid linear velocities (see *Table 1* and *Table 2*) for the aluminum oxide moisture probe indicate a mechanical stability limitation rather than a sensitivity to the fluid flow rate.

If the measured dew point of a system changes with the fluid flow rate, then it can be assumed that off-gassing or a leak in the sample system is causing the variation. If secondary moisture is entering the process fluid (either from an ambient air leak or the release of previously absorbed moisture from the sample system walls or process piping), an increase in the flow rate of the process fluid will dilute the secondary moisture source. As a result, the vapor pressure will be lowered and a lower dew point will be measured.

Note: *Refer to the Specifications section of the Hygrometer User’s Manual or Datasheet for the maximum allowable flow rate for your instrument.*

Table 1: Maximum Gas Flow Rates

Note: Based on the physical characteristics of air at a temperature of 77°F and a pressure of 1 atm, the following flow rates will produce the maximum allowable gas stream linear velocity of 10,000 cm/sec in the corresponding pipe sizes.

Inside Pipe Diameter (in.)	Gas Flow Rate (cfm)
0.25	7
0.50	27
0.75	60
1.0	107
2.0	429
3.0	966
4.0	1,718
5.0	2,684
6.0	3,865
7.0	5,261
8.0	6,871
9.0	8,697
10.0	10,737
11.0	12,991
12.0	15,461

Table 2: Maximum Liquid Flow Rates

Note: Based on the physical characteristics of benzene at a temperature of 77°F, the following flow rates will produce the maximum allowable fluid linear velocity of 10 cm/sec in the corresponding pipe sizes.

Inside Pipe Diameter (in.)	Flow Rate	
	(gal/hr)	(l/hr)
0.25	3	11
0.50	12	46
0.75	27	103
1.0	48	182
2.0	193	730
3.0	434	1,642
4.0	771	2,919
5.0	1,205	4,561
6.0	1,735	6,567
7.0	2,361	8,939
8.0	3,084	11,675
9.0	3,903	14,776
10.0	4,819	18,243
11.0	5,831	22,074
12.0	6,939	26,269

3. Contaminants

Industrial gases and liquids often contain fine particulate matter. Particulates of the following types are commonly found in such process fluids:

- carbon particles
- salts
- rust particles
- polymerized substances
- organic liquid droplets
- dust particles
- molecular sieve particles
- alumina dust

For convenience, the above particulates have been divided into three broad categories. Refer to the appropriate section that follows for a discussion of their affect on the Panametrics moisture probe.

3.1 Non-Conductive Particulates

Note: *Molecular sieve particles, organic liquid droplets and oil droplets are typical of this category.*

In general, the performance of the moisture probe will not be seriously hindered by the condensation of non-conductive, non-corrosive liquids. However, a slower response to moisture changes will probably be observed, because the contaminating liquid barrier will decrease the rate of transport of the water vapor to the sensor and reduce its response time.

Particulate matter with a high density and/or a high flow rate may cause abrasion or pitting of the sensor surface. This can drastically alter the calibration of the moisture probe and, in extreme cases, cause moisture probe failure. A stainless steel shield is supplied with the moisture probe to minimize this effect, but in severe cases, it is advisable to install a PTFE or stainless steel filter in the fluid stream. Also, a good sample system can mitigate the effects of particulate matter.

On rare occasions, non-conductive particulate material may become lodged under the contact arm of the sensor, creating an open circuit. If this condition is suspected, refer to “Aluminum Oxide Probe Maintenance” on page 5 and “Cleaning the Moisture Probe” on page 5, for the recommended cleaning procedure.

3.2 Conductive Particulates

Note: *Metallic particles, carbon particles, alcohols and other conductive liquid droplets are typical of this category.*

Since the hygrometer reading is inversely proportional to the impedance of the sensor, a decrease in sensor impedance will cause an increase in the meter reading. Thus, trapped conductive particles across the sensor leads or on the sensor surface, which will decrease the sensor impedance, will cause an erroneously high dew point reading. The most common particulates of this type are carbon (from furnaces), iron scale (from pipe walls), alcohols (used as water scavengers) and glycol droplets (from glycol-based dehydrators).

If the system contains conductive particulates, it is advisable to install an appropriate filter to minimize these effects. In addition, cleaning and recalibration of the moisture probe is recommended.

3.3 Corrosive Particulates

Note: *Sodium chloride and sodium hydroxide particulates are typical of this category.*

Since the active sensor element is constructed of aluminum, any material that corrodes aluminum will deleteriously affect the operation of the moisture probe. Furthermore, a combination of this type of particulate with water will cause pitting or severe corrosion of the sensor element. In such instances, the sensor cannot be cleaned or repaired and the probe must be replaced.

Obviously, the standard moisture probe cannot be used in such applications unless the complete removal of such particulates by adequate filtration is assured. Please contact Panametrics to review your application requirements.

4. Aluminum Oxide Probe Maintenance

As part of a routine preventive maintenance program, the moisture probe should be removed and returned to the factory for recalibration once a year. Between these calibrations, if the aluminum oxide moisture probe becomes contaminated with an electrically conductive liquid, the moisture measurements will be erroneously high. In such a situation, the probe should be removed from the sample system and cleaned as described in “Cleaning the Moisture Probe” on page 5.



WARNING! The probe cleaning procedure should be performed only by a qualified technician or chemist.

IMPORTANT: Moisture probes must be handled carefully and cannot be cleaned in any fluid which will attack its components. Panametrics recommends using hexane or toluene, as outlined in the cleaning procedure on the next page. Also, the sensor’s aluminum sheet is very fragile and can be easily bent or distorted. Do not permit anything to touch it!



WARNING! Make sure you reinstall the moisture probe before restarting the system.

4.1 Cleaning the Moisture Probe

To clean the moisture probe, the following items are required:

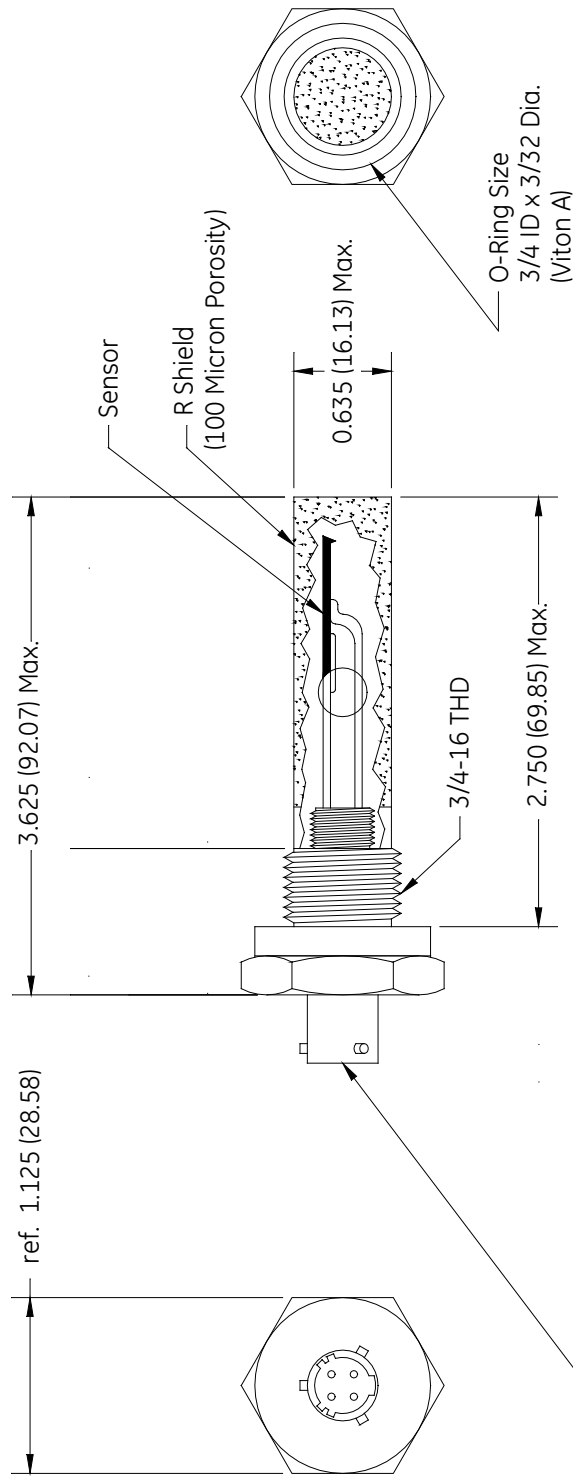
- approximately 600 ml of reagent grade hexane or toluene, divided into two batches of 300 ml each
- approximately 300 ml of distilled (NOI deionized) water
- three glass (NOI metal) containers to hold the above liquids

To clean the aluminum oxide moisture probe, complete the following steps:

1. Record the dew point of the ambient air.

IMPORTANT: To avoid damaging the sensor during the following steps, do not allow the sensor to contact the walls or the bottom of the containers.

2. Carefully remove the protective shield covering the sensor without touching the exposed sensor (see *Figure 1* on page 6).
3. Soak the sensor in one of the containers of hexane or toluene for 10 minutes.
4. Remove the sensor from the hexane or toluene and soak it in the container of distilled water for 10 minutes.
5. Remove the sensor from the distilled water and soak it in the second container of (clean) hexane or toluene for 10 minutes.
6. Remove the sensor from the hexane or toluene and place it sensor- side-up in an oven set at $50^{\circ}\text{C} \pm 2^{\circ}\text{C}$ ($122^{\circ}\text{F} \pm 3.6^{\circ}\text{F}$) for 24 hours.
7. Repeat Steps 3-6 to clean the protective shield. To ensure the removal of any contaminants that may have become embedded in the porous walls of the shield, swirl the shield in the solvents during the soaking procedure.
8. Without touching the exposed sensor, carefully reinstall the protective shield over the sensor.
9. Connect the probe cable to the cleaned probe and measure the dew point of the same ambient air recorded in Step 1.
10. If the probe is determined to be in proper calibration ($\pm 2^{\circ}\text{C}/\pm 3.6^{\circ}\text{F}$), it has been successfully cleaned and may be reinstalled in the sample cell. If the probe is not in proper calibration, proceed to Step 11.
11. Repeat Steps 1-10 using soaking time intervals of 5 times the previous cleaning sequence, until two consecutive cleanings produce identical probe responses to the ambient dew point.



Dimensions are in inches (millimeters).

Figure 1: Panametrics M Series Moisture Probe

5. Corrosive Gases And Liquids

Note: This category typically includes some acids and halogens.

Panametrics aluminum oxide moisture probes have been designed to minimize the effect of corrosive gases and liquids. The moisture content of gases containing corrosives, such as H₂S, SO₂, cyanide containing gases, acetic acid vapors, etc. may be measured directly, depending on the concentration level of corrosives. Please contact Panametrics for assistance.

IMPORTANT: Since the active sensor is aluminum, any fluid which corrodes aluminum will affect the sensor's performance.

By observing the following precautions, the moisture probe may be used successfully and reliably. Please consult Panametrics for assistance with your particular application.

1. Generally, the moisture content of the corrosive fluid must be 10 ppm_v or less at 1 atmosphere, or the concentration of the corrosive fluid must be 10 ppm_v or less at 1 atmosphere. However, the exact level that can be used depends on the application.
2. The moisture sensor should be installed in the sample system. The sample system must be pre-dried with a dry inert gas, such as nitrogen or argon, prior to introduction of the fluid stream. Any adsorbed atmospheric moisture on the sensor will react with the corrosive fluid to cause pitting or corrosion of the sensor.
3. The sample system and moisture sensor must be purged with a dry inert gas, such as nitrogen or argon, prior to removal of the moisture probe. Any adsorbed corrosive fluid on the sensor will react with ambient moisture to cause pitting or corrosion of the sensor.
4. Operate the sample system at the lowest possible gas pressure, to reduce the partial pressure of the corrosive contaminant.
5. At the onset of a high moisture upset, the moisture probe must be switched from process gas to a dry, inert purge gas, such as nitrogen. The moisture probe should remain in the purge gas until the process upset is corrected.
6. Prior to removing the moisture sensor from the sample system, the system must be purged with a dry, inert gas, such as nitrogen.

Using the precautions listed above, the moisture probe may be used to successfully measure the moisture content in gases containing hydrochloric acid, sulfur dioxide, chlorine and bromine. Please consult Panametrics for application assistance and recommendations for a proper sample system design.

6. Calculations and Useful Formulas in Gas Applications

A knowledge of the dew point, pressure, and temperature of a system enables one to calculate all other moisture measurement parameters. The most important fact to recognize is that *for a particular dew point there is one and only one equivalent vapor pressure.*

IMPORTANT: The calibration of Panametrics aluminum oxide moisture probes is based on the vapor pressure of liquid water above 0°C and frost below 0°C. Panametrics moisture probes are never calibrated with supercooled water.

Caution is advised when comparing dew points measured with a Panametrics aluminum oxide hygrometer to those measured with a Panametrics chilled mirror hygrometer, since such mirror-type hygrometers may provide the dew points of supercooled water.

As stated above, the dew/frost point of a system defines a unique partial pressure of water vapor in the gas. *Table 3 on page 11*, which lists water vapor pressure as a function of dew point, can be used to find either the saturation water vapor pressure at a known temperature or the water vapor pressure at a specified dew point. In addition, all definitions involving *humidity* can then be expressed in terms of the water vapor pressure.

6.1 Nomenclature

The following symbols and units are used in the equations that are presented in the next few sections:

- RH = relative humidity
- T_K = temperature ($^{\circ}\text{K} = ^{\circ}\text{C} + 273$)
- T_R = temperature ($^{\circ}\text{R} = ^{\circ}\text{F} + 460$)
- ppm_v = parts per million by volume
- ppm_w = parts per million by weight
- M_w = molecular weight of water (18)
- M_T = molecular weight of carrier gas
- P_S = saturation vapor pressure of water at the prevailing temperature (mm of Hg)
- P_W = water vapor pressure at the measured dew point (mm of Hg)
- P_T = total system pressure (mm of Hg)

6.2 Parts per Million by Volume

The water concentration in an ideal gas system, in parts per million by volume, is proportional to the ratio of the water vapor partial pressure to the total system pressure:

$$\text{ppm}_v = \frac{P_W}{P_T} \times 10^6 \quad (1)$$

In a closed system, increasing the total pressure of the gas will proportionally increase the partial pressures of the various components. The relationship between dew point, total pressure and ppm_v is provided in nomographic form in *Figure 2 on page 9*.

Note: The nomograph shown in *Figure 2 on page 9* is applicable only to gases. Do not apply it to liquids.

To compute the moisture content for any ideal gas at a given pressure, refer to *Figure 2 on page 9*. Using a straightedge, connect the dew point (as measured with the Panametrics Hygrometer) with the known system pressure. Read the moisture content in ppm_v where the straightedge crosses the moisture content scale.

Typical Problems

1. Find the water content in a nitrogen gas stream, if a dew point of -20°C is measured and the pressure is 60 psig.

Solution: In *Figure 2 on page 9*, connect 60 psig on the Pressure scale with -20°C on the Dew/Frost Point scale. Read **200 ppm_v** on the Moisture Content scale.

2. Find the expected dew/frost point for a helium gas stream having a measured moisture content of 1000 ppm_v and a system pressure of 0.52 atm.

Solution: In *Figure 2 on page 9*, connect 1000 ppm_v on the Moisture Content scale with 0.52 atm on the Pressure scale. Read the expected frost point of **-27°C** on the Dew/Frost Point scale.

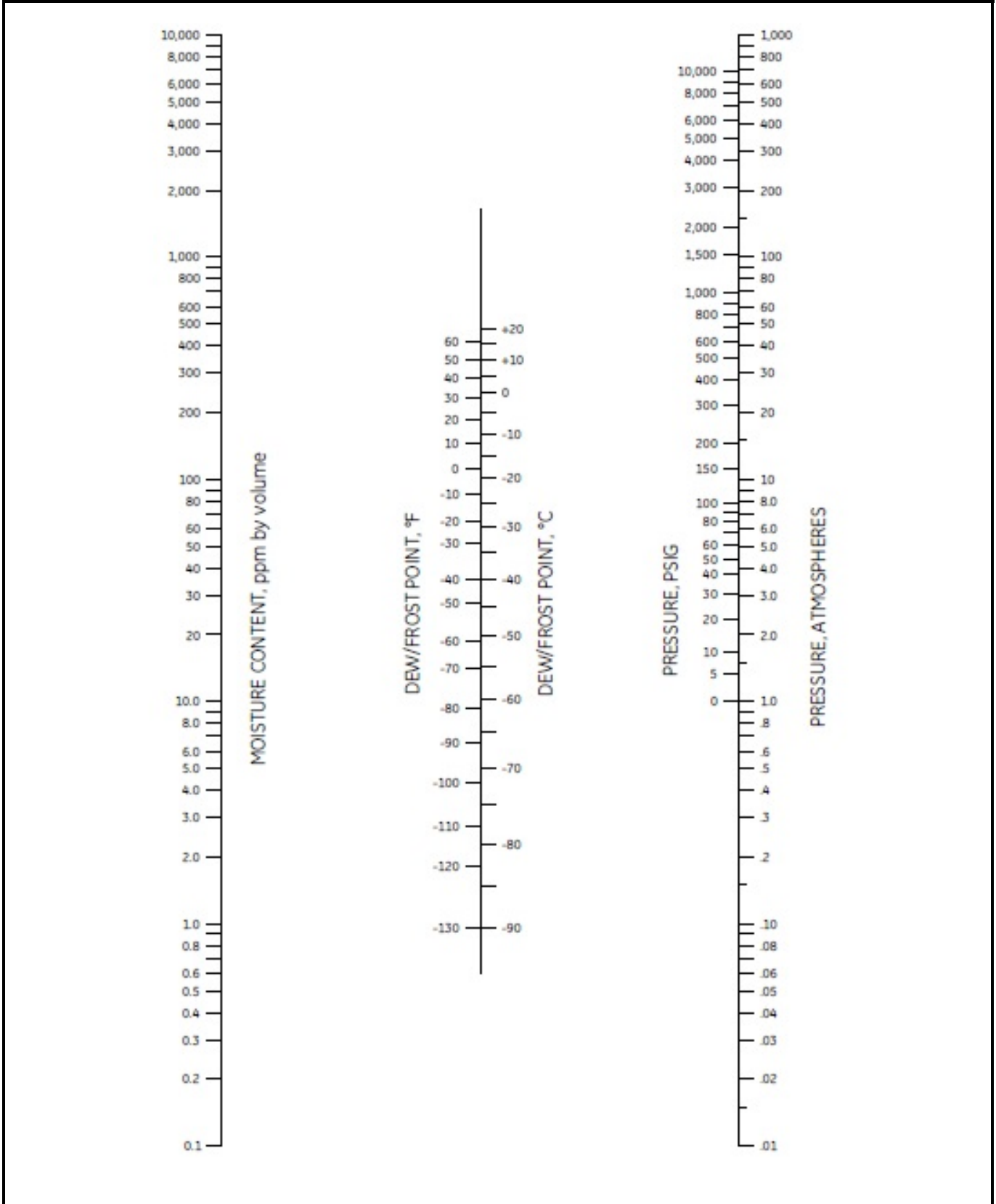


Figure 2: Moisture Content Nomograph for Gases

6.3 Parts per Million by Weight

The water concentration in the gas phase of a system, in parts per million by weight, can be calculated directly from the ppm_v and the ratio of the molecular weight of water to that of the carrier gas as follows:

$$\text{ppm}_w = \text{ppm}_v \times \frac{M_W}{M_T} \quad (2)$$

6.4 Relative Humidity

Relative humidity is defined as the ratio of the actual water vapor pressure to the saturation water vapor pressure at the prevailing ambient temperature, expressed as a percentage.

$$\text{RH} = \frac{P_W}{P_S} \times 100 \quad (3)$$

Typical Problems

Find the relative humidity in a system, if the measured dew point is 0°C and the ambient temperature is $+20^\circ\text{C}$.

Solution: From Table 3 on page 11, the water vapor pressure at a dew point of 0°C is 4.579 mm of Hg and the saturation water vapor pressure at an ambient temperature of $+20^\circ\text{C}$ is 17.535 mm of Hg. Therefore, the relative humidity of the system is $100 \times 4.579/17.535 = 26.1\%$.

6.5 Weight of Water per Unit Volume of Carrier Gas

Three units of measure are commonly used in the gas industry to express the weight of water per unit volume of carrier gas. They all represent a vapor density and are derivable from the vapor pressure of water and the Perfect Gas Laws. Referenced to a temperature of 60°F and a pressure of 14.7 psia, the following equations may be used to calculate these units:

$$\frac{\text{mg of water}}{\text{liter of gas}} = 289 \times \frac{P_W}{T_K} \quad (4)$$

$$\frac{\text{lb of water}}{\text{ft}^3 \text{ of gas}} = 0.0324 \times \frac{P_W}{T_R} \quad (5)$$

$$\frac{\text{lb of water}}{\text{MMSCF of gas}} = \frac{\text{ppm}_v}{21.1} = \frac{10^6 \times P_W}{21.1 \times P_T} \quad (6)$$

Note: MMSCF is an abbreviation for a "million standard cubic feet" of carrier gas.

6.6 Weight of Water per Unit Weight of Carrier Gas

Occasionally, the moisture content of a gas is expressed in terms of the weight of water per unit weight of carrier gas. In such a case, the unit of measure defined by the following equation is the most commonly used:

$$\frac{\text{grains of water}}{\text{lb of gas}} = 7000 \times \frac{M_W \times P_W}{M_T \times P_T} \quad (7)$$

For ambient air at 1 atm of pressure, the above equation reduces to the following:

$$\frac{\text{grains of water}}{\text{lb of gas}} = 5.72 \times P_W \quad (8)$$

Table 3: Vapor Pressure of Water

Note: If the dew/frost point is known, the table will yield the partial water vapor pressure (P_W) in mm of Hg. If the ambient or actual gas temperature is known, the table will yield the saturated water vapor pressure (P_S) in mm of Hg.

Water Vapor Pressure Over Ice

Temp. (°C)	0	2	4	6	8
-90	0.000070	0.000048	0.000033	0.000022	0.000015
-80	0.000400	0.000290	0.000200	0.000140	0.000100
-70	0.001940	0.001430	0.001050	0.000770	0.000560
-60	0.008080	0.006140	0.004640	0.003490	0.002610
-50	0.029550	0.023000	0.017800	0.013800	0.010600
-40	0.096600	0.076800	0.060900	0.048100	0.037800
-30	0.285900	0.231800	0.187300	0.150700	0.120900
Temp. (°C)	0.0	0.2	0.4	0.6	0.8
-29	0.317	0.311	0.304	0.298	0.292
-28	0.351	0.344	0.337	0.330	0.324
-27	0.389	0.381	0.374	0.366	0.359
-26	0.430	0.422	0.414	0.405	0.397
-25	0.476	0.467	0.457	0.448	0.439
-24	0.526	0.515	0.505	0.495	0.486
-23	0.580	0.569	0.558	0.547	0.536
-22	0.640	0.627	0.615	0.603	0.592
-21	0.705	0.691	0.678	0.665	0.652
-20	0.776	0.761	0.747	0.733	0.719
-19	0.854	0.838	0.822	0.806	0.791
-18	0.939	0.921	0.904	0.887	0.870
-17	1.031	1.012	0.993	0.975	0.956
-16	1.132	1.111	1.091	1.070	1.051
-15	1.241	1.219	1.196	1.175	1.153
-14	1.361	1.336	1.312	1.288	1.264
-13	1.490	1.464	1.437	1.411	1.386
-12	1.632	1.602	1.574	1.546	1.518
-11	1.785	1.753	1.722	1.691	1.661
-10	1.950	1.916	1.883	1.849	1.817
-9	2.131	2.093	2.057	2.021	1.985
-8	2.326	2.285	2.246	2.207	2.168
-7	2.537	2.493	2.450	2.408	2.367
-6	2.765	2.718	2.672	2.626	2.581
-5	3.013	2.962	2.912	2.862	2.813
-4	3.280	3.225	3.171	3.117	3.065
-3	3.568	3.509	3.451	3.393	3.336
-2	3.880	3.816	3.753	3.691	3.630
-1	4.217	4.147	4.079	4.012	3.946

Table 3: Vapor Pressure of Water

0	4.579	4.504	4.431	4.359	4.287
Aqueous Vapor Pressure Over Water					
Temp. (°C)	0.0	0.2	0.4	0.6	0.8
0	4.579	4.647	4.715	4.785	4.855
1	4.926	4.998	5.070	5.144	5.219
2	5.294	5.370	5.447	5.525	5.605
3	5.685	5.766	5.848	5.931	6.015
4	6.101	6.187	6.274	6.363	6.453
5	6.543	6.635	6.728	6.822	6.917
6	7.013	7.111	7.209	7.309	7.411
7	7.513	7.617	7.722	7.828	7.936
8	8.045	8.155	8.267	8.380	8.494
9	8.609	8.727	8.845	8.965	9.086
10	9.209	9.333	9.458	9.585	9.714
11	9.844	9.976	10.109	10.244	10.380
12	10.518	10.658	10.799	10.941	11.085
13	11.231	11.379	11.528	11.680	11.833
14	11.987	12.144	12.302	12.462	12.624
15	12.788	12.953	13.121	13.290	13.461
16	13.634	13.809	13.987	14.166	14.347
17	14.530	14.715	14.903	15.092	15.284
18	15.477	15.673	15.871	16.071	16.272
19	16.477	16.685	16.894	17.105	17.319
20	17.535	17.753	17.974	18.197	18.422
21	18.650	18.880	19.113	19.349	19.587
22	19.827	20.070	20.316	20.565	20.815
23	21.068	21.324	21.583	21.845	22.110
24	22.377	22.648	22.922	23.198	23.476
25	23.756	24.039	24.326	24.617	24.912
26	25.209	25.509	25.812	26.117	26.426
27	26.739	27.055	27.374	27.696	28.021
28	28.349	28.680	29.015	29.354	29.697
29	30.043	30.392	30.745	31.102	31.461
30	31.824	32.191	32.561	32.934	33.312
31	33.695	34.082	34.471	34.864	35.261
32	35.663	36.068	36.477	36.891	37.308
33	37.729	38.155	38.584	39.018	39.457
34	39.898	40.344	40.796	41.251	41.710
35	42.175	42.644	43.117	43.595	44.078
36	44.563	45.054	45.549	46.050	46.556
37	47.067	47.582	48.102	48.627	49.157
38	49.692	50.231	50.774	51.323	51.879

Table 3: Vapor Pressure of Water

Aqueous Vapor Pressure Over Water (cont.)					
Temp. (°C)	0.0	0.2	0.4	0.6	0.8
39	52.442	53.009	53.580	54.156	54.737
40	55.324	55.910	56.510	57.110	57.720
41	58.340	58.960	59.580	60.220	60.860
42	61.500	62.140	62.800	63.460	64.120
43	64.800	65.480	66.160	66.860	67.560
44	68.260	68.970	69.690	70.410	71.140
45	71.880	72.620	73.360	74.120	74.880
46	75.650	76.430	77.210	78.000	78.800
47	79.600	80.410	81.230	82.050	82.870
48	83.710	84.560	85.420	86.280	87.140
49	88.020	88.900	89.790	90.690	91.590
50	92.51	93.50	94.40	95.30	96.30
51	97.20	98.20	99.10	100.10	101.10
52	102.09	103.10	104.10	105.10	106.20
53	107.20	108.20	109.30	110.40	111.40
54	112.51	113.60	114.70	115.80	116.90
55	118.04	119.10	120.30	121.50	122.60
56	123.80	125.00	126.20	127.40	128.60
57	129.82	131.00	132.30	133.50	134.70
58	136.08	137.30	138.50	139.90	141.20
59	142.60	143.90	145.20	146.60	148.00
60	149.38	150.70	152.10	153.50	155.00
61	156.43	157.80	159.30	160.80	162.30
62	163.77	165.20	166.80	168.30	169.80
63	171.38	172.90	174.50	176.10	177.70
64	179.31	180.90	182.50	184.20	185.80
65	187.54	189.20	190.90	192.60	194.30
66	196.09	197.80	199.50	201.30	203.10
67	204.96	206.80	208.60	210.50	212.30
68	214.17	216.00	218.00	219.90	221.80
69	223.73	225.70	227.70	229.70	231.70
70	233.70	235.70	237.70	239.70	241.80
71	243.90	246.00	248.20	250.30	252.40
72	254.60	256.80	259.00	261.20	263.40
73	265.70	268.00	270.20	272.60	274.80
74	277.20	279.40	281.80	284.20	286.60
75	289.10	291.50	294.00	296.40	298.80
76	301.40	303.80	306.40	308.90	311.40
77	314.10	316.60	319.20	322.00	324.60
78	327.30	330.00	332.80	335.60	338.20

Table 3: Vapor Pressure of Water

Aqueous Vapor Pressure Over Water (cont.)					
Temp. (°C)	0.0	0.2	0.4	0.6	0.8
79	341.00	343.80	346.60	349.40	352.20
80	355.10	358.00	361.00	363.80	366.80
81	369.70	372.60	375.60	378.80	381.80
82	384.90	388.00	391.20	394.40	397.40
83	400.60	403.80	407.00	410.20	413.60
84	416.80	420.20	423.60	426.80	430.20
85	433.60	437.00	440.40	444.00	447.50
86	450.90	454.40	458.00	461.60	465.20
87	468.70	472.40	476.00	479.80	483.40
88	487.10	491.00	494.70	498.50	502.20
89	506.10	510.00	513.90	517.80	521.80
90	525.76	529.77	533.80	537.86	541.95
91	546.05	550.18	554.35	558.53	562.75
92	566.99	571.26	575.55	579.87	584.22
93	588.60	593.00	597.43	601.89	606.38
94	610.90	615.44	620.01	624.61	629.24
95	633.90	638.59	643.30	648.05	652.82
96	657.62	662.45	667.31	672.20	677.12
97	682.07	687.04	692.05	697.10	702.17
98	707.27	712.40	717.56	722.75	727.98
99	733.24	738.53	743.85	749.20	754.58
100	760.00	765.45	770.93	776.44	782.00
101	787.57	793.18	798.82	804.50	810.21

6.7 Comparison of ppm_v Calculations

There are three basic methods for determining the moisture content of a gas in ppm_v:

- the calculations described in this reference guide
- calculations performed with a slide-rule device that is available from Panametrics
- values determined from tabulated vapor pressures

For comparison purposes, examples of all three procedures are listed in *Table 4* below.

Table 4: Comparative ppm_v Values

Dew Point (°C)	Pressure (psig)	Calculation Method		
		Slide-Rule	This Guide	Tabulated
-80	0	0.5	0.55	0.526
	100	0.065	N.A.	0.0675
	800	0.009	N.A.	0.0095
	1500	0.005	N.A.	0.0051
-50	0	37	40	38.88
	100	4.8	5.2	4.98
	800	0.65	0.8	0.7016
	1500	0.36	0.35	0.3773
+20	0	N.A.	20,000	23,072.36
	100	3000	3000	2956.9
	800	420	400	416.3105
	1500	220	200	223.9

7. Liquid Applications

7.1 Theory of Operation

The direct measurement of water vapor pressure in organic liquids is accomplished easily and effectively with Panametrics aluminum oxide moisture probes. Since the moisture probe pore openings are small in relation to the size of most organic molecules, admission into the sensor cavity is limited to much smaller molecules, such as water. Thus, the surface of the aluminum oxide sensor, which acts as a semi-permeable membrane, permits the measurement of water vapor pressure in organic liquids just as easily as it does in gaseous media.

In fact, under equilibrium conditions, an accurate sensor electrical output will be registered whether the sensor is directly immersed in the organic liquid or it is placed in the gas space above the liquid surface. As with gases, the electrical output of the aluminum oxide probe is a function of the measured water vapor pressure.

7.2 Moisture Content Measurement in Organic Liquids

When using the aluminum oxide sensor in non-polar liquids having water concentrations $\leq 1\%$ by weight, *Henry's Law* is generally applicable.

Henry's Law Type Analysis

Henry's Law states that, at constant temperature, *the mass of a gas dissolved in a given volume of liquid is proportional to the partial pressure of the gas in the system*. Stated in terms pertinent to this discussion, it can be said that the ppm_w of water in hydrocarbon liquids is equal to the partial pressure of water vapor in the system times a constant which is specific to the fluid and its temperature.

As discussed above, a Panametrics aluminum oxide probe can be directly immersed in a hydrocarbon liquid to measure the equivalent dew point. Since the dew point is functionally related to the vapor pressure of the water, a determination of the dew point will allow one to calculate the ppm_w of water in the liquid by a Henry's Law type analysis. A specific example of such an analysis is shown below.

For liquids in which a Henry's Law type analysis is applicable, the parts per million by weight of water in the organic liquid is equal to the partial pressure of water vapor times a constant:

$$\text{ppm}_w = K \times P_w \quad (9)$$

where, "K" is the Henry's Law constant in the appropriate units, and the other variables are as defined in "Nomenclature" on page 8.

Also, the value of "K" is determined from the known water saturation concentration of the organic liquid at the measurement temperature:

$$K = \frac{\text{Saturation ppm}_w}{P_s} \quad (10)$$

As the temperature of the liquid varies, its saturation concentration and the saturation vapor pressure will also vary. Thus, it is important to know the temperature of the liquid at the moisture sensor for an accurate determination of PPM_w . For a mixture of organic liquids, an average saturation value can be calculated from the weight fractions and saturation values of the pure components as follows:

$$\text{Ave. } C_s = \sum_{i=1}^n X_i (C_s)_i \quad (11)$$

where, X_i is the weight fraction of the i^{th} component, $(C_s)_i$ is the saturation concentration (ppm_w) of the i^{th} component, and n is the total number of components.

In conclusion, the Henry's Law constant (K) is a constant of proportionality between the saturation concentration (C_s) and the saturation vapor pressure (P_s) of water, at the measurement temperature. In the *General Case*, the Henry's Law constant varies with the measurement temperature, but there is a *Special Case* in which the Henry's Law

constant does not vary appreciably with the measurement temperature. This special case applies to saturated, straight-chain hydrocarbons such as pentane, hexane, heptane, etc.

General Case

Determination of Moisture Content in PPM_w if C_s is Known:

The nomograph for liquids in *Figure 3 on page 18* can be used to determine the moisture content in an organic liquid, if the following values are known:

- the temperature of the liquid at the time of measurement
- the saturation water concentration at the measurement temperature
- the dew point, as measured with the Panametrics hygrometer

Complete the following steps to determine the moisture content from the nomograph:

1. Using a straightedge on the two scales on the right of *Figure 3 on page 18*, connect the known saturation concentration (ppm_w) with the measurement temperature ($^{\circ}\text{C}$).
2. Read the Henry's Law constant (K) on the center scale.
3. Using a straightedge, connect the above K value with the dew/frost point, as measured with the Panametrics hygrometer.
4. Read the moisture content (ppm_w) where the straight edge crosses the moisture content scale.

Determination of K and C_s

If the values of K and C_s are not known, the Panametrics hygrometer can be used to determine these values. In fact, only one of the values is required to determine ppm_w from the nomograph in *Figure 3 on page 18*. To perform such an analysis, proceed as follows:

1. Obtain a sample of the test solution with a known water content; or perform a *Karl Fischer* titration on a sample of the test stream to determine the ppm_w of water.

Note: *The Karl Fischer analysis involves titrating the test sample against a special Karl Fischer reagent until an endpoint is reached.*

2. Measure the dew point of the known sample with the Panametrics hygrometer.
3. Measure the temperature ($^{\circ}\text{C}$) of the sample.
4. Using a straightedge, connect the moisture content (ppm_w) with the measured dew point, and read the K value on the center scale.
5. Using a straightedge, connect the above K value with the measured temperature ($^{\circ}\text{C}$) of the sample, and read the saturation concentration (ppm_w).

IMPORTANT: Since the values of K and C_s vary with temperature, the hygrometer measurement and the test sample analysis must be done at the same temperature. If the moisture probe temperature is expected to vary, the test should be performed at more than one temperature.

Determination of moisture content if the Henry's Law constant (K) is known:

1. In the nomograph for liquids in *Figure 3 on page 18*, use a straightedge, connect the known K value on the center scale with the dew/frost point, as measured with the Panametrics hygrometer.
2. Read moisture content (ppm_w) where the straightedge crosses the scale on the left.

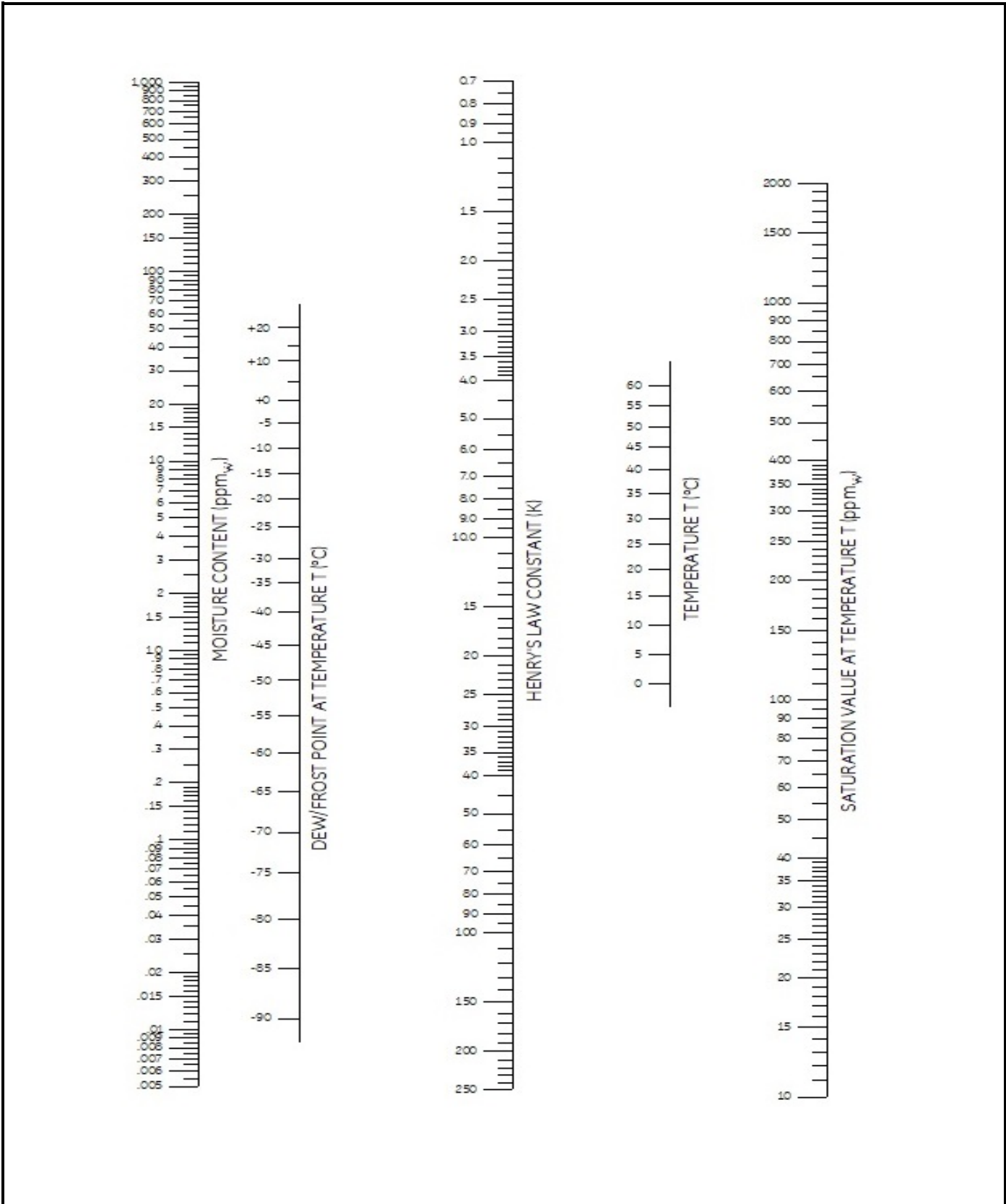


Figure 3: Moisture Content Nomograph for Liquids

Typical Problems

1. Find the moisture content in benzene, at an ambient temperature of 30°C, if a dew point of 0°C is measured with the Panametrics hygrometer.
 - a. From the literature, it is found that C_S for benzene at a temperature of 30°C is **870 ppm_w**.
 - b. Using a straightedge on *Figure 3 on page 18*, connect the 870 ppm_w saturation concentration with the 30°C ambient temperature and read the Henry's Law Constant of **27.4** on the center scale.
 - c. Using the straightedge, connect the above K value of 27.4 with the measured dew point of 0°C, and read the correct moisture content of **125 ppm_w** where the straightedge crosses the moisture content scale.
2. Find the moisture content in heptane, at an ambient temperature of 50°C, if a dew point of 3°C is measured with the Panametrics hygrometer.
 - a. From the literature, it is found that C_S for heptane at a temperature of 50°C is **480 ppm_w**.
 - b. Using a straightedge on *Figure 3 on page 18*, connect the 480 ppm_w saturation concentration with the 50°C ambient temperature and read the Henry's Law Constant of **5.2** on the center scale.
 - c. Using the straightedge, connect the above K value of 5.2 with the measured dew point of 3°C, and read the correct moisture content of **29 ppm_w** where the straightedge crosses the moisture content scale.
3. Find the moisture content in hexane, at an ambient temperature of 10°C, if a dew point of 0°C is measured with the Panametrics hygrometer.
 - a. From the literature, it is found that C_S for hexane at a temperature of 20°C is **101 ppm_w**.
 - b. Using a straightedge on *Figure 3 on page 18*, connect the 101 ppm_w saturation concentration with the 20°C ambient temperature and read the Henry's Law Constant of **5.75** on the center scale.
 - c. Using the straightedge, connect the above K value of 5.75 with the measured dew point of 0°C, and read the correct moisture content of **26 ppm_w** where the straightedge crosses the moisture content scale.

Note: *If the saturation concentration at the desired ambient temperature cannot be found for a straight-chain hydrocarbon, the value at any other temperature may be used, because K is nearly constant over a large temperature range.*

7.3 Additional Notes for Liquid Applications

In addition to the topics already discussed, the following general application notes pertain to the use of Panametrics moisture probes in liquid applications:

1. All Panametrics aluminum oxide moisture probes can be used in either gas phase or liquid phase applications.
2. The calibration data supplied with Panametrics moisture probes is applicable to both liquid phase (for those liquids in which a Henry's Law analysis is applicable) and gas phase applications.
3. As indicated in *Table 2 on page 3*, the linear velocity of the liquid is limited to a maximum of 10 cm/sec.
4. Possible probe malfunctions and their remedies are discussed in previous sections of this reference guide.

8. Solids Applications

Panametrics offers a line of humidity analyzers capable of measuring the moisture content in certain solid materials. Please contact Panametrics for more information.

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