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GUIDANCE ON INSTRUMENTATION FOR CALIBRATION LABORATORIES INCLUDING RICs

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FOREWORD

Users of meteorological observations have increasing needs for high quality meteorological and hydrological data. The traceability of these data to the International System of Units (SI) standards is needed to ensure their quality and to meet the users' requirements.

Regional Instrument Centres, as well as NMHSs calibration laboratories are essential in ensuring data quality by providing calibration of the standards and traceability to SI. CIMO-XIV recognized that RICs needed guidance on how to build calibration laboratories and purchase calibration equipment to strengthen their capabilities. Therefore CIMO-XIV requested the Expert Team on Regional Instruments Centres (RICs), Quality Management Systems and Commercial Initiatives to develop a recommended set of calibration equipment suited for developing countries.

This IOM Report, prepared by a member of the Expert Team, Mr Drago Groselj provides a concise overview of various techniques for calibration. The main surface-based observing parameters are overviewed: temperature, humidity and pressure. This report describes primary, secondary, working and traveling reference standards. Their performance characteristics are briefly reviewed and their application in the calibration processes is described. An assessment of their advantages and limitations is also provided.

The information contained in this publication will assist specialists from RICs, as well as from NMHSs, in the modernization of present calibration systems by providing help in the selection of modern calibration equipment.

I wish to express my sincere gratitude and that of CIMO to the author of this report, D. Groselj (Slovenia), for elaborating this document.

I am confident that a number of WMO Members will find this report very useful and will help them improving and setting up their calibration facilities. In turn, this will benefit a much larger community, as it will contribute to the improvement of meteorological measurement quality.

John Nash

(Dr. J. Nash)

President Commission
for Instruments and Methods of Observation

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1. Introduction

For meteorological purposes temperature is measured for a number of media. The most common variable that is measured is air temperature (at various heights). Other variables are ground, soil, grass minimum and seawater temperature. Measurement of atmospheric humidity and air pressure, and often also its continuous recording, is an important requirement of most areas of meteorological activity.

According to the International Vocabulary of Basic and General Terms in Metrology [1]:

- **traceability** is the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties,
- **calibration** is the sets of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument and the corresponding known value of a measurand. The result of a calibration permits the estimation of the uncertainty of indication of the measuring instrument.

Calibration laboratory is an important subject in a quality assurance system in terms of periodical calibrations of field measuring instruments. Each calibration laboratory should establish and maintain its traceability to the national or international level. Recognition and analysis of uncertainty sources is most important subject in calibration procedure development and uncertainty evaluation.

A calibration certificate does not guarantee satisfactory performance under actual operating conditions, but it is an important starting point, and it tells a lot about the quality of a sensor. The calibration certificate should at least cover the full operating range of the instrument.

The field measurements are required for input to numerical weather forecast models, for agriculture, hydrology or climatology. Requirements on these measurements are described in the WMO Guide to Meteorological Instruments and Methods of Observations (WMO-No.8, CIMO Guide) [2].

This paper will try to present measurement instruments and measurement methods recommended for use in NHMS calibration laboratory (including RICs) in the filed of temperature, relative humidity and air pressure calibration.

2. Temperature

2.1. The International temperature scale ITS-90

The International Temperature Scale of 1990 (ITS-90) is an equipment calibration standard for making measurements on the Kelvin and Celsius temperature scales. ITS–90 is an approximation of the thermodynamic temperature scale that facilitates the comparability and compatibility of temperature measurements internationally. ITS–90 offers defined calibration points ranging from 0.65K to approximately 1358K (−272.5°C to 1085°C) and is subdivided into multiple temperature ranges which can sometimes overlap. ITS-90 is designed to represent the thermodynamic (absolute) temperature scale (referencing absolute zero) as closely as possible throughout its range. Many different thermometer designs are required to cover the entire range. These include helium vapour pressure thermometers, helium gas thermometers, standard platinum resistance thermometers (known as SPRTs, PRTs or Platium RTDs) and monochromatic radiation thermometers.

Although “International Temperature Scale of 1990” has the word “scale” in its title, this can be misleading. ITS–90 is not a scale; it is an equipment calibration standard. Temperatures measured with equipment calibrated per ITS–90 may be expressed using any temperature scale such as commonly Celsius and Kelvin (Fahrenheit).

Thermometers calibrated per ITS–90 use complex mathematical formulas to interpolate between its defined points. ITS–90 specifies rigorous control over variables to ensure reproducibility from lab to lab. ITS–90 also draws a distinction between “freezing” and “melting” points. The distinction depends on whether heat is going into (melting) or out of (freezing) the sample when the measurement is made. Only gallium is measured while melting, all the other metals are measured while the samples are freezing.

A practical effect of ITS–90 is the triple points and the freezing/melting points of its thirteen chemical elements are precisely known for all temperature measurements calibrated per ITS-90 since these thirteen values are fixed by its definition.

At the most basic level, a thermometer is a device with a measurable output that changes with temperature in a reproducible manner. If we can explicitly write an equation of state for a thermometer without introducing any unknown, temperature-dependent quantities, then we call that thermometer a primary thermometer. These include the gas thermometer, acoustic thermometer, noise thermometer, and total radiation thermometer. A secondary thermometer has an output that must be calibrated against defined fixed temperature points. For example, a platinum resistance temperature detector (RTD) is based on the change in resistance of a platinum wire with temperature.

Since primary thermometers are impractical (due to size, speed, and expense), secondary thermometers are used for most applications. The common practice is to use secondary thermometers and calibrate them to an internationally recognized temperature scale based on primary thermometers and fixed points.

The International Temperature Scale of 1990 defines temperature with:

- defining fixed points of temperature.
- interpolating thermometer and interpolating equations, a sensor with an output depending on temperature.

2.1.1. Defined fixed points

Although the Kelvin and Celsius scales are defined using absolute zero (0 K) and the triple point of water (273.16K), it is impractical to use this definition at temperatures that are very different from the triple point of water. Accordingly, ITS–90 uses numerous defined points, all of which are based on various thermodynamic equilibrium states of fourteen pure chemical elements and one compound (water). The following table shows different fixed points that define the ITS 90:

No	**Temperature**		**Material**	**Phase transition**
	T_{90} [K]	**t_{90} [°C]**		
1	3 to 5	-270.15 to -268.154	He	V
2	13.8033	-259.3467	e-H_2	T
3	~17	~-256.15	e-H_2 (or He)	V (or P)
4	~20.3	~-252.85	e-H_2(or He)	V (or P)
5	24.5561	-248.5939	Ne	T
6	54.3584	-218.7916	O_2	T
7	**83.8058**	**-189.3442**	**Ar**	**T**
8	**234.3156**	**-38.8344**	**Hg**	**T**
9	**273.16**	**0.01**	**H_2O**	**T**
10	**302.9146**	**29.7646**	**Ga**	**M**
11	**429.7485**	**156.5985**	**In**	**F**
12	505.078	231.928	Sn	F
13	629.677	419.527	Zn	F
14	933.473	660.323	Al	F
15	1234.93	961.78	Ag	F
16	1337.33	1064.18	Au	F
17	1357.77	1084.62	Cu	F

e-H2: according to molecular composition
V: saturated vapour pressure
T: triple point between fluid, vapour and gas
G: thermometer with gas
F,M: freezing or melting point

Table 1: The defining fixed points

Most of the defined points are based on a phase transition; specifically the melting/freezing point of a pure chemical element. However, the deepest cryogenic points are based exclusively on the vapour pressure/temperature relationship of helium and its isotopes whereas the remainder of its cold points (those less than room temperature) are based on triple points. The fixed points used for meteorological purpose are highlighted in blue colour.

Figure 1: Triple point of water cell ready to use and fixed point cells (Météo-France) gallium, mercury and water

2.1.2. Interpolating instrument and equations

International temperature scale ITS-90 defines three types of interpolating instruments:

1. Interpolating constant volume gas thermometer - ICVGT in temperature range from 3 K to 24.5561 K,
2. Standard platinum resistance thermometer - SPRT in temperature interval from 13.8033 K to 1234.94 K,
3. Radiation thermometer for temperature above silver freezing point (1234.94 K).

Meteorological range is between the triple point of mercury and the freezing point of indium. Between the triple point of hydrogen (13,8033K) and the freezing point of silver (961.78 °C) temperature, T_{90}, is defined with a platinum resistance thermometer calibrated against specific fixed points and using the interpolation functions.

Temperatures are determined in terms of the ratio of resistance $R(T_{90})$ at temperature T_{90} and the resistance R(273.16K) at the triple point of water:

$$W(T_{90}) = \frac{R(T_{90})}{R(273.16K)}$$

The characteristic of the area is the useage of two reference and two inverse functions:

- Temperature range from 273.15 K to 1234.94 K:

Reference function	Inverse reference function
$W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \cdot \left[\frac{T_{90} - 754.15}{481}\right]^i$	$T_{90} - 273.15 = D_0 + \sum_{i=1}^{9} D_i \cdot \left[\frac{W_r(T_{90}) - 2.64}{1.64}\right]^i$

- Temperature range from 13.8033 K to 273.16 K:

Reference function	Inverse reference function
$\ln\left[W_r(T_{90})\right] = A_0 + \sum_{i=1}^{12} A_i \cdot \left[\frac{\ln\left(\frac{T_{90}}{273.16}\right) + 1.5}{1.5}\right]^i$	$\frac{T_{90}}{273.16} = B_0 + \sum_{i=1}^{15} B_i \cdot \left[\frac{\left(W_r(T_{90})\right)^{\frac{1}{6}} - 0.65}{0.35}\right]^i$

Numeric values of reference function coefficients (A_i) and inverse reference function (D_i) are available in literature. Deviation function is a deviation of reference function $W_r(T_{90})$ and ratio $W(T_{90})$:

$$\Delta W(T_{90}) = W(T_{90}) - W_r(T_{90})$$

Where:

$W(T_{90})$ - resistance ratio at given temperature,

$W_r(T_{90})$ - reference function at given temperature,

$\Delta W(T_{90})$ - deviation function of ratio $W(T_{90})$ interpolating instrument.

The forms of deviation function differ according to different temperature range and used fixed points. In the temperature range from 13.8033 K to 1234.94 K three forms of deviation function are defined:

- from 13.8033 K to 273.16 K:

$$\Delta W(T_{90}) = a \cdot \left[W(T_{90}) - 1\right] + b \cdot \left[W(T_{90}) - 1\right]^2 + \sum_{i=1}^{5} c_i \cdot \left[\ln(W(T_{90})) - 1\right]^{i+n}$$

- from 83.8058 K to 273.16 K:

$$\Delta W(T_{90}) = a \cdot \left[W(T_{90}) - 1\right] + b \cdot \left[W(T_{90}) - 1\right] \cdot \ln\left(W(T_{90})\right)$$

- from 273.15 K to 1234.94 K:

$$\Delta W(T_{90}) = a \cdot \left[W(T_{90}) - 1\right] + b \cdot \left[W(T_{90}) - 1\right]^2 + c \cdot \left[W(T_{90}) - 1\right]^3 + d \cdot \left[W(T_{90}) - W(660.323°C)\right]^2$$

Values of coefficients a, b, c, c_i, d depends on temperature range and fixed point used in calibration.

2.2. Platinum Resistance Thermometer (PRT)

A platinum resistance thermometer (PRT) is a thermometer constructed from a high purity platinum element (wire-wound coil or thin film) placed in a tube of metal or glass and sealed with an inert atmosphere and/or mineral insulator. Two, three, or four leads are connected to the element and are used to provide for the measurement of the electrical resistance of the element. Some of these characteristics are:

- Wide temperature Range (–260°C to 1000°C)
- Electrical resistance is typically between 0Ω and 400Ω and depends on temperature
- Excitation current is typically 1mA
- Stable over time
- Stable over temperature

- Shallow slope (i.e. 0.4Ω/°C for a 100Ω PRT)
- Relatively easy to measure
- Relatively easy to calibrate
- Commercially available in many configurations

PRTs are suitable for use over a wide temperature range. No single instrument will be suitable for use over the entire range shown above. In calibration, the electrical resistance is measured at several temperature points and fitted to a mathematical expression. The number of calibration points depends on the range and accuracy desired but, because the temperature response of platinum is relatively linear and very well known, fewer calibration points are required for a given range compared to other sensor types. Also, because of the shallow slope, the readout used for the resistance measurement need not have a large range. PRTs, like any probe, have immersion requirements which vary from configuration to configuration. Often, the required immersion is not stated or specified. Since PRTs are used in so many different applications, we are presented with a large variety of shapes, sizes, and types.

2.2.1. Standard Platinum Resistance Thermometers

Standard Platinum Resistance Thermometers (SPRT) are the most accurate and stable instruments available for this purpose. They are generally available in 0.25, 2.5, 25, and 100Ω versions with either borosilicate glass, fused silica glass (quartz), stainless steel, or INCONEL sheath materials. The different resistance values and different sheath materials are intended for different temperature ranges. A typical quartz sheathed 25Ω SPRT will have a temperature range of –200°C to 660°C and with a high quality calibration will have calibration uncertainties from 0.001°C to 0.010°C. Additionally, since these instruments are actually part of the definition of the ITS-90, they are standardized. That is, there are minimum requirements for the purity of the platinum wire and the type of construction used. This results in less confusion as to the suitability of the instrument for a particular application and almost guaranteed good performance if calibrated and used correctly. These instruments are highly stable and accurate, but they are expensive and extremely delicate.

Figure 2: Standard platinum resistance thermometer

2.2.2. Industrial Platinum Resistance Thermometers (IPRTs)

When accuracy requirements are less severe, PRTs can be used successfully. PRTs are available in many configurations, however PRTs which are suitable for use as calibration standards are generally available as 100Ω stainless steel sheathed probes. Historically, they have been limited to a temperature range of –200°C to 420°C but a new type has been introduced which has extended the upper limit to 1000°C. Calibration uncertainties range from 0.010°C to 0.025°C. These instruments are not as accurate as SPRTs but they are generally more rugged and easier to work with. Not all designs perform to the level required for use as a reference. Be careful in the selection of a PRT to ensure that the type selected is appropriate for use as a calibration reference over the range of interest and with the required accuracy.

Figure 3: Industrial platinum resistance thermometer

Comparison between characteristics of SPRT and IPRT is shown in following table.

SPRT	IPRT
Capable of very high accuracy	Capable of moderate to high accuracy
Capable of large temperature range	Capable of large temperature range
Extremely stable	Very stable
Standardized	Not standardized
Relatively expensive to purchase	Relatively inexpensive to purchase
Relatively expensive to calibrate	Relatively inexpensive to calibrate
Extremely delicate	Less delicate

Table 2: Comparison of SPRT and IPRT properties

Usually, SPRTs are calibrated at fixed points, but due to high cost and time needed for calibration of fixed points, it can be reasonable to calibrate them by comparison at highest level. The calibration by comparison is widely used to calibrate measuring instruments in many secondary laboratories. Calibration procedures are based on transfer standards, which are usually calibrated in a primary laboratory, thus providing traceability to (inter)national standards through a process of dissemination of a unit with an associated uncertainty. In order to make optimal use, SPRTs are usually calibrated in fixed points but laboratory can also decide to calibrate SPRT by comparison with an uncertainty which can be sufficiently low. This technique is common for IPRT references also. The calibration in this case is a technique when you associate a value of the temperature, as measured with a ITS-90 calibrated reference SPRT thermometer, with the resistance value of the SPRT under test, inside a stable and homogeneous thermostatic bath. The relationship between the resistance of the platinum resistance thermometer under calibration and temperature measured with a reference thermometer is described with an interpolation equation. This equation is determined using the least-square method on the data acquired during the comparison. The Callendar-van Duesen (CVD) equation is generally accepted as interpolation equation for industrial platinum resistance thermometer, rather than for SPRTs (defined in the standard EN 60751):

$$R(t) = R_{(0°C)} \cdot (1 + A \cdot t + B \cdot t^2 + C \cdot (t - 100) \cdot t^3)$$

where

C = 0 for t > 0°C.

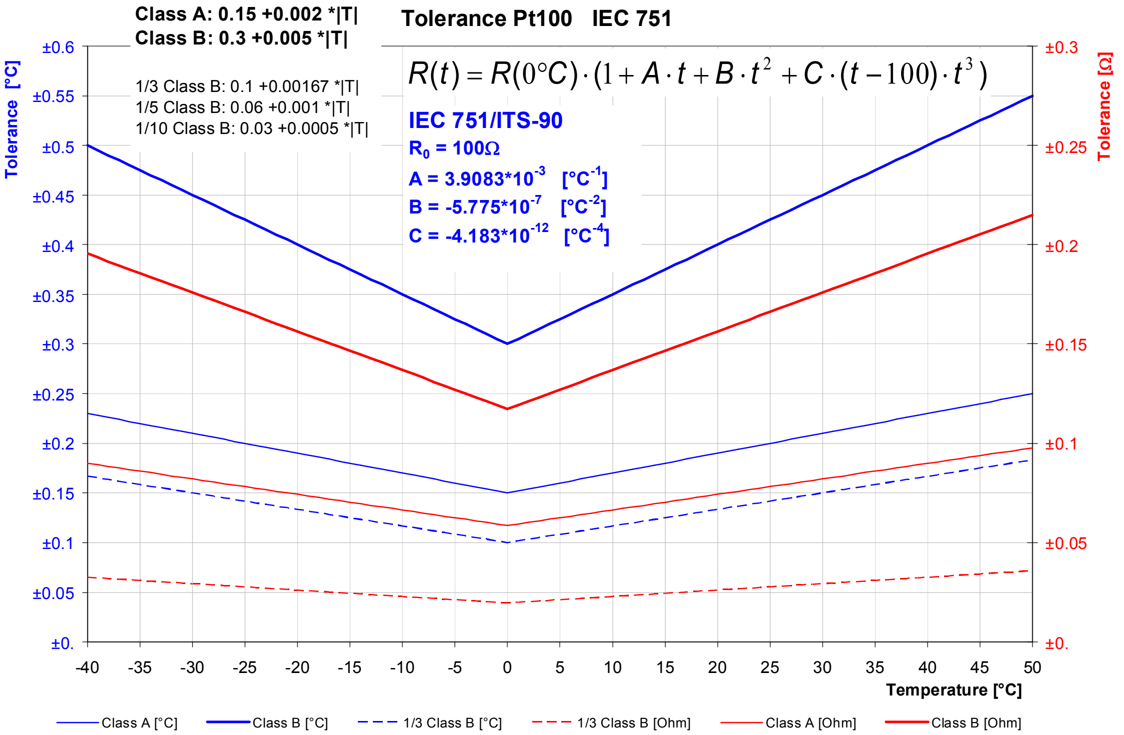

Figure 4: Chart of EN 60751

2.2.3. Liquid-in-glass thermometer

A liquid-in-glass thermometer (abbreviated by LiG) is widely used due to its accuracy for the temperature range -200°C to 600°C. Compared to other thermometers, it is simple and no other equipment beyond the human eye is required. The LiG thermometer is one of the earliest thermometers. The first thermometer appeared around 1650 and was a development from the thermoscope. The liquid used was spirit from wine. By 1714, thermometers with mercury were found to give a more linear scale than spirits. By 1742, a centigrade scale using 100 steps from the point of boiling water to the melting point of water was suggested by Anders Celsius.

In the LiG thermometer the thermally sensitive element is a liquid contained in a graduated glass envelope. The principle used to measure temperature is that of the apparent thermal expansion of the liquid. It is the difference between the volumetric reversible thermal expansion of the liquid and its glass container that makes it possible to measure temperature.

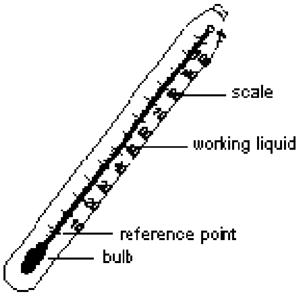

Figure 5: Liquid-in-glass thermometer

The liquid-in-glass thermometer comprises:

- a **bulb**, a reservoir in which the working liquid can expand or contract in volume
- a **stem**, a glass tube containing a tiny capillary connected to the bulb and enlarged at the bottom into a bulb that is partially filled with a working liquid. The tube's bore is extremely small - less than 0.5 millimetre in diameter
- a **temperature scale** is fixed or engraved on the stem supporting the capillary tube to indicate the range and the value of the temperature. It is the case for the precision thermometers whereas for the low accurate thermometers such as industrial thermometer, the scale is printed on a separate card and then protected from the environment. The liquid-in-glass thermometers is usually calibrated against a standard thermometer and at the melting point of water
- a **reference point**, a calibration point, the most common being the ice point

The accuracy of measurement depends mainly on the extent of immersion of the thermometer into the medium - not just the bulb but also the stem. There are three types of immersion, as shown in the following figure: total, partial and complete immersion, depending on the level of contact between the medium and the sensor.

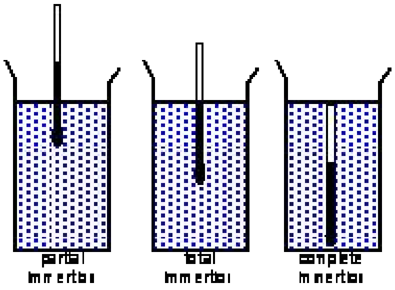

Figure 6: Immersion depth of LiG

An error can be produced when the thermometer is not immersed to the same extent as it was when it was originally calibrated. An 'emergent stem correction' may be necessary when it is not possible to immerse the thermometer sufficiently deeply.

The response of the thermometer depends on the bulb volume, bulb thickness, total weight and type of thermometer. To reduce the response time, the bulb should be small and the bulb wall thin. The sensitivity depends on the reversible thermal expansion of the liquid compared to the glass. The greater the fluid expansion, the more sensitive the thermometer is. The resolution and uncertainty of readings table are presented in the following table:

Scale division [mm]	Resolution	Expanded uncertainty
$d < 0.5$	Δ	$0.6 \cdot \Delta$
$0.5 < d < 2$	$0.5 \cdot \Delta$	$0.3 \cdot \Delta$
$2 \leq d < 5$	$0.25 \cdot \Delta$	$0.2 \cdot \Delta$

Δ … scale division [°C]

Table 3: Resolution and uncertainty of LiG thermometers

Mercury was the liquid the most often used because of its good reaction time, repeatability, linear coefficient of expansion and large temperature range. But it is poisonous and so other working liquids are used. Common organic liquids are toluene, ethyl alcohol, pentane; their expansion is high but not linear and they are limited at high temperature. They need to be dyed, the most common colours being red, blue and green. The following table gives for each liquid the useable temperature range.

Working liquid	**Temperature range (°C)**
Mercury	-38 to 650
Toluene	-90 to 100
Ethyl alcohol	-110 to 100
Pentane	-200 to 20

Table 4: Choice of organic liquids

Advantage	**Disadvantage**
no power source required	limited to applications where manual reading is acceptable
repeatable	have a limited useable temperature range
easy to use & cheap	cannot be digitised or automated

Table 5: Pro/contra for LiG

During calibration the thermometer must be correctly immersed in the calibration bath to ensure accurate measurements and to avoid a systematic error linked to the height of the emergent column above the surface of the bath. For precise work, the measurement can be performed with a microscope attached to the thermometer.

2.3. Travelling standards for temperature

Travelling temperature standard is typically used for on-site thermometer checks. Many different sensor types (platinum resistance thermometers, thermistors…) and manufacturers are available on the market. Summarized metrological characteristics for travelling temperature standard instruments are:

- Temperature range from –80°C to 80°C.
- accuracy in the range of 0.05°C,
- resistance to temperature conversion,

- good long term stability,
- good repeatability,
- small hysteresis,
- easy to measure,
- handheld instrument,
- battery powered.

Travelling temperature standards must be checked or calibrated against reference standard before and after on-site measurements to ensure metrological properties. Travelling standards must be handled with care to avoid generation of mechanical stress.

Figure 7: Examples of travelling standards for temperature

2.4. Calibration equipment

Comparison calibration is performed by measurement of the resistance of the instrument under calibration while it is exposed to a temperature. Fundamentally, four instruments are required as follows:

1. Reference standard
2. Data acquisition for the reference standard
3. Data acquisition for the instrument under calibration
4. Temperature source

2.4.1. Data acquisition

When calibrating PRTs against a reference PRT or SPRT, the technical requirements for the readout are the same for the instruments under calibration and the reference. If a switching system is available, one readout device can usually be used for both. If the readout is designed for temperature calibration (not just temperature measurement) and has variable settings (current, timing, etc.), then certainly it can be used for both. If the readout is not designed for temperature calibration and/or a switching system is not available, then two or more readouts will probably be required. Before selecting a readout, review the information presented in the readouts section with regard to current settings, timing, multiplexing, etc. Best results will be obtained with readouts designed specifically for thermometer calibration. There are two important points to consider with regard to PRT and SPRT:

- Ensure that the readout has a resistance range appropriate for the reference probe and instruments under calibration for which it is intended. Over the range of –80°C to 80°C, a 25Ω SPRT will vary in resistance from approximately 17Ω to 32Ω, a 100Ω PRT from approximately 68Ω to 130Ω. Many modern thermometer readouts are designed to cover this span on a single range. Changing ranges can cause discontinuities in the math fit (the equations are intended to fit platinum, not multimeter range offsets or gain errors).

- Ensure that the readout is using the proper source current. Too much source current will result in excessive self-heating and incorrect calibration. If the readout is a multimeter which requires range changes as mentioned above, the source current will change with the range, meaning different current values for measurements at different temperatures. This will result in inconsistent self-heating and additional calibration errors. A way to estimate self-heating is to perform calibrations at two different currents, typically 1mA and √2 mA.
-

2.4.2. Temperature Source

The most common temperature sources in meteorological applications for PRT calibration are calibration baths for waterproof instruments and climatic chambers for non-waterproof instruments.

Figure 8: Liquid baths

Figure 9: Climatic chamber

A calibration bath/chamber cannot be considered as completely stable in time and homogeneous all over its volume, especially when temperature calibrations by comparison are performed at the best level of uncertainty. This represents a major contribution to the total uncertainty of a calibration procedure. In order to decrease this uncertainty contribution equalizing blocks can be used in calibration baths. The dimension of the block depends on the bath dimension.

- Homogeneity: A gradient is observed as a change of a temperature reading of a thermometer according to a change of its position inside a calibration bath. Basic gradients that can be observed are vertical and horizontal gradient. Because a lot of calibration baths have either a cylindrical shape or equalizing blocks inside it is sometimes more appropriate to define axial and a radial gradient. Uncertainty contribution of an axial gradient is determined as maximum temperature difference between two different positions in axial direction of an equalizing block. The radial gradient is a maximum temperature difference between two different positions in a radial direction.
- Stability: important characteristic of a bath is also short-term stability of a medium temperature. It strongly depends on type of regulation and flow of medium inside the bath. Since the calibration measurements are taken within short time interval, the short-time stability is relevant. For the time stability of a bath, temperature deviations of a reference thermometer are observed.

2.5. Typical set-up for liquid-in-glass thermometer calibration

Pt 100 resistance thermometer or reference liquid-in-glass thermometer is used as the working temperature standard in the calibration laboratory. Stable temperature medium is a liquid bath with a working range from -40°C to 50°C. Data acquisition is performed via multimeter and GPIB interface or RS232 interface in the personal computer data base. Ambient temperature and relative humidity is monitored during calibration in one place and its influence appropriately evaluated. Reference Pt 100 four-wired is connected to the multimeter. For the correction purpose, the thermistor is connected in the immediate vicinity of the temperature bath, on the level of liquid-in-glass thermometers. The instrument of ambient temperature is fixed close to the measuring equipment where such influence is effective. Ambient temperature directly influences expanded measurement uncertainty of measuring devices through the contribution of multimeter. A corresponding chart is presented in figure below.

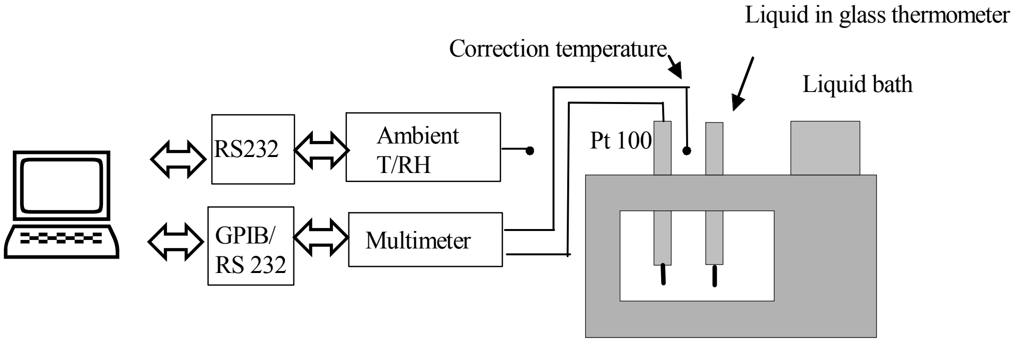

Figure 10: LiG calibration with platinum resistance thermometer as a reference

Working standard and instruments under calibration are placed in the area concerned of the medium where the criteria of bath temperature stability are defined.

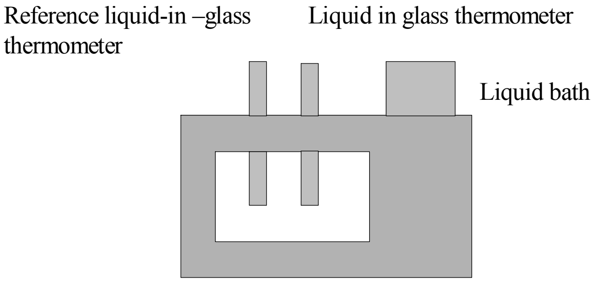

Figure 11: LiG calibration with reference LiG thermometer

2.6. Typical set-up for resistance thermometer calibration

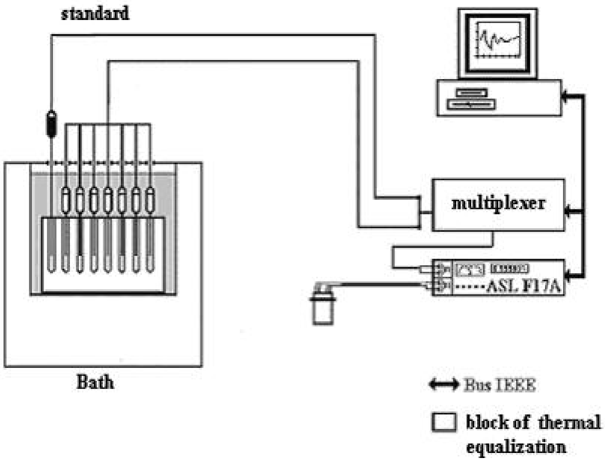

Figure 12: PRT calibration with platinum resistance thermometer as a reference

For routine calibrations of 4-wires resistance thermometers, a bath with a block of thermal equalization is commonly used. The calibration is made by comparing to the standard from -40°C to 40 °C. At a level of temperature, 100 measurements every 5 seconds are made with a bridge and multiplexer. The common measurement current is 1 mA.

The common error sources of a PRT are:

- *Insulation Resistance:* Error caused by the inability to measure the actual resistance of element. Current leaks into or out of the circuit through the sheath, between the element leads, or the elements.
- *Stability:* Ability to maintain R vs T over time as a result of thermal exposure.
- *Repeatability:* Ability to maintain R vs T under the same conditions after experiencing thermal cycling throughout a specified temperature range.
- *Hysteresis:* Change in the characteristics of the materials from which the RTD is built due to exposures to varying temperatures.
- *Stem Conduction:* Error that results from the PRT sheath conducting heat into or out of the process.

- *Lead Wire:* Errors that occur because a 4 wire or 3 wire measurement is not used, this is greatly increased by higher gauge wire.

  - 2 wire connection adds lead resistance in series with PRT element.

  - 3 wire connection relies on all 3 leads having equal resistance.
- *Self Heating:* Error produced by the heating of the PRT element due to the power applied.

2.7. Typical set-up for thermograph calibration

Pt 100 resistance thermometer is used as a working temperature standard in the calibration laboratory. A climatic chamber is used as a stable air medium, with working range from -20°C to 40°C. Data acquisition of working standard is performed via multimeter and GPIB or RS232 interface to the personal computer database.

Ambient temperature directly influence expanded measurement uncertainty of measuring devices, through the contribution of multimeter. If temperature is outside the interval, the contribution of uncertainty should be evaluated and taken into account. Thermograph is placed in climatic chamber. Several thermographs can be calibrated at the same time. A corresponding chart is presented in picture below.

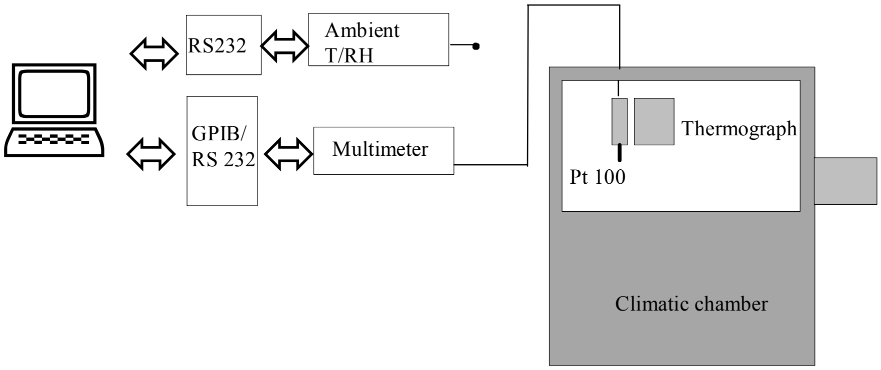

Figure 13: Thermograph calibration with platinum resistance thermometer as a reference

3. Humidity

The most fundamental standard that is used by national calibration laboratories is the gravimetric hygrometer. Using this method, a certain amount of dry gas is weighed and compared with the weight of the test gas in the same volume. From this, the amount of water is determined, and vapour pressure calculated. The method can provide the most accurate measurements possible, but the system is cumbersome, expensive, and time consuming to use.

Some national laboratories (such as the National Institute for Standards and Technology (NIST) in the U.S., the National Physics Laboratory (NPL) in the UK, and the National Research Laboratory of Metrology (NRLM) in Japan) have access to gravimetric hygrometers. However, these laboratories use the system only to calibrate other, slightly less accurate, standards that are easier and faster to use for day-to-day calibrations, such as the two-pressure humidity generator, a precision chilled mirror hygrometer, or a carefully designed psychrometer.

Many commercial humidity measurement instruments are supplied with a calibration report that shows the unit's accuracy at the time of manufacture or shipment from the factory. Traceability means that the instrument has been calibrated against a primary or transfer standard. The calibrations are conducted under controlled laboratory conditions and in most cases do not reflect the way the instrument will perform in the field.

With regard to humidity measurements, it's commonly accepted that a standard is a system or device that either can produce a gas stream of known humidity by reference to fundamental base units (e.g., temperature, mass, and pressure) or is an instrument that can measure humidity in a gas in a fundamental way, using similar base units. There are established standards for humidity in many countries, operating on various principles, such as gravimetric systems and two-pressure generators. Some of these national standards and the approximate ranges they are capable of covering are shown in following table.

Type	Class	Range	Typical Measurement Accuracy
Gravimetric	Primary	-50°C ÷ 100°C	0.1°C dew point
Chilled mirror hygrometer	Fundamental (transfer)	-90°C ÷ 90°C dew point	0.2°C dew point
Electrolytic hygrometer	Fundamental	1 to 2000 ppmv	5% of reading ppmv
Psychrometer	Fundamental	5% ÷ 95% RH 0 °C ÷ 100°C ambient	2% RH
Impedance hygrometer	Secondary	-100°C to 30°C dew point	2°C-4°C RH
Polymer RH sensor	Secondary	5% -95% RH 0°C -100°C ambient	2%-5% RH

Table 6: Hygrometer instrument classification

Standards used to calibrate humidity instruments fall into three classifications: primary standards, transfer standards and secondary devices.

3.1. Primary standards

These systems rely on fundamental principles and base units of measurement. A **gravimetric hygrometer** is such a device. This method is very accurate but difficult and laborious to use. A gravimetric hygrometer is expensive to build, and at low humidity levels, the device can require many hours of operation to obtain a large enough sample. It is not a practical system for day-to-day use. At a lower level and at somewhat lower accuracies, two-pressure generators, two-temperature generators, and some other systems are customarily used as primary standards.

3.2. Transfer standards

Instruments in this category operate on fundamental principles and can provide good, stable, and repeatable results, but if they are not properly used, the instruments can give incorrect results. Examples of commonly used instruments are chilled mirror hygrometer or psychrometer.

3.2.1. Chilled Mirror Hygrometer

Optical dew point hygrometers are often used as reference standards for calibration. A mirrored surface in contact with the gas stream to be monitored is cooled until condensation forms. The temperature at which condensation is formed is known as the dew point or frost point of the gas, and this temperature directly relates to the saturation water vapour pressure of the sample. From these data, any hygrometric equivalent parameter can be calculated, provided that other information (e.g., gas temperature and pressure) are also known.

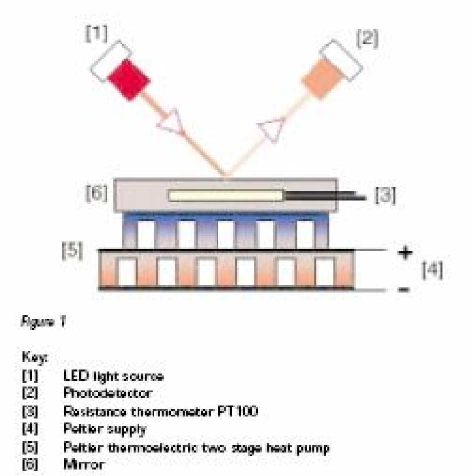

Figure 14: Measurement principle of dew point mirror hygrometer

Contaminants on the mirror of a chilled mirror hygrometer will affect its performance, so most automatic chilled mirror hygrometers will have a scheme to compensate for contaminants. When discussing contaminants, it is essential to distinguish between soluble and non-soluble ones:

Non-soluble Contaminant Compensation – Non-soluble contaminants (organics) affect the light reflective characteristics of the mirror and so compensation is required. This is done by establishing a periodic balance cycle in which the hygrometer heats the mirror above the dew/frost point until it is dry, looks at the reflectivity of the mirror as compared to a clean, dry mirror, and then adjusts the bias of the solid-state optics to compensate for the contamination. This works for quite a long time until, finally, the optics can no longer be compensated and the mirror must be cleaned. Most automatic, continuously controlling chilled mirror hygrometers employ some version of this compensation scheme.

Soluble Contaminant Compensation – Soluble contaminants (usually in the form of salts) do not change the reflectivity of the mirror. These salts dissolve in the water layer on the surface of the mirror and cause the vapour pressure to be lowered. This results in an excess build-up of water on the mirror surface at the true dew point. The hygrometer servo loop raises the mirror temperature to evaporate some of the excess water. This phenomenon is called the Raoult Effect, and can result in an error of several degrees. The contamination compensation schemes for non-soluble contaminants are ineffective in dealing with this type of contamination.

A conventional chilled mirror hygrometer grows water droplets on its mirror for dew points above 0°C, and ice crystals on its mirror for dew points below 0°C. Therefore, we speak of frost points below 0°C. At exactly 0°C, dew point and frost point are equal – they correspond to the same absolute concentration of water vapour.

Since liquid water can exist in a **super cooled** state below 0°C, it is possible to have a dew point below 0°C which differs from the frost point for the same gas sample. As you get further and further below 0°C, the discrepancy between the two values increases. While super cooled water may exist on the mirror temporarily, in the steady state it will all be converted to ice. Once it is converted to ice, it cannot revert to the super cooled liquid state. The conversion to ice will occur proportionally faster as the temperature becomes lower.

Advantage	Disadvantage
Uncertainty around 0.2°C	Expensive
Can provide precise measurement	Contamination can cause incorrect readings
Good long term performance	Dew points below 0°C require careful interpretation
Wide measurement range	Can be slow in response

Table 7: Pro/contra for dew point mirror hygrometer

Practical recommendations for daily operations with condensation hygrometers:

- Filter the air supply to the device to avoid contamination of the mirror with dust, droplets or mist.
- The mirror should be regularly cleaned with deionised or distilled water. Alcohol can be used to remove oil based contaminants.
- Use a cotton bud to clear the mirror. Drops should pull away cleanly – drops that continue to adhere are a sign of mirror contamination.
- The mirror should be cleaned daily or at least weekly.
- When using the device a viewing microscope should be employed to confirm the existence of a dew or a frost point.
- These devices cannot be calibrated in terms of temperature alone – they must be calibrated as a unit for humidity.

Equation defines the relationship between relative humidity, dew point temperature and air stream temperature:

$$\eta = 100 \cdot \frac{p_s(t_d)}{p_s(t_a)}$$

where:

$p_S(t_d)$ - saturation vapour pressure at dew point temperature t_d [Pa],

$p_S(t_a)$ - saturation vapour pressure at air temperature t_a [Pa],

t_d – dew/frost point temperature t_d [°C],

t_a – air temperature t_a [°C].

In literature are may expressions of saturated vapour pressure available but worldwide accepted Hardey formulae based on International temperature scale ITS-90:

$$p_{sv}(T) = e^{\left(\sum_{i=0}^{6} g_i \cdot T^{-2} + g_7 \cdot \ln(T)\right)} \quad \text{in the range } 0°\text{C} \div 100°\text{C}$$

$$p_{sl}(T) = e^{\left(\sum_{i=0}^{4} k_i \cdot T^{i-1} + k_5 \cdot \ln(T)\right)} \quad \text{in the range } -100°\text{C} \div 0.01°\text{C}$$

where:

$p_{Sv}(T)$ - saturation vapour pressure at temperature T over water [Pa],

$p_{Sl}(T)$ - vapour pressure at temperature T over ice [Pa],

g_i, k_i - constants available in literature.

Relative uncertainties of interpolating equations are $u_{p_{Sv}(T)} = 0.005\%$ and $u_{p_{Sl}(T)} = 0.5\%$.

The effective saturation vapour pressure over water or ice in the presence of other gases differs from the ideal saturation vapour pressures given in the equation above. The effective saturation vapour pressure is related to the ideal by

$$p_S'(T_i) = p_S(T_i) \cdot f(P)$$

where:

$p_S'(T_i)$ - 'effective' saturation vapour pressure at temperature T,

$p_S(T_i)$ - ideal saturation vapour pressure at temperature T,

$f(P)$ - enhancement factor.

Enhancement factors were initially introduced in 1949 (Goff). Now-a-days is worldwide accepted formulation:

$$f(P) = e^{\left[\alpha \cdot \left(1 - \frac{p_S(T_i)}{P}\right) + \beta \cdot \left(\frac{P}{p_S(T_i)}\right)\right]}$$

where:

P – atmospheric pressure [Pa].

With α and β:

$$\alpha = \sum_{i=0}^{3} A_i \cdot t^i \qquad \ln(\beta) = \sum_{i=0}^{3} B_i \cdot t^i$$

Coefficients A_i in B_i are defined in the literature. Implication of coefficients defines relative humidity as:

$$\eta = 100 \cdot \frac{p_s(t_d) \cdot f(t_d, P)}{p_s(t_a) \cdot f(t_a, P)}$$

Traceability scheme is shown in the following picture:

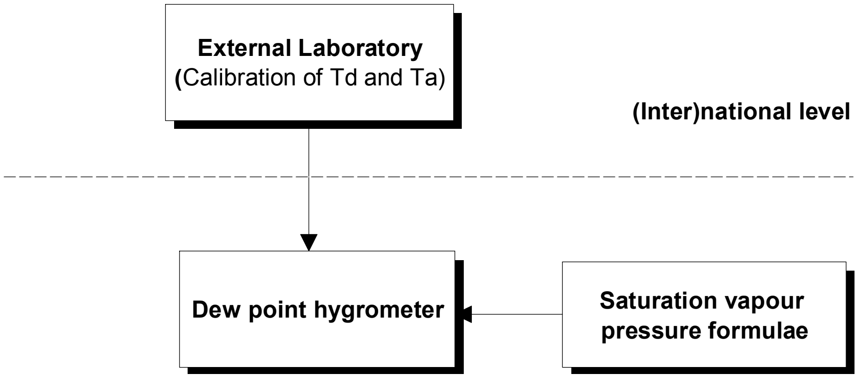

Figure 15: Traceability chart of dew point mirror hygrometer

3.2.2. Psychrometer

In a dry/wet bulb psychrometer, pure water is evaporated from a wick surrounding a temperature probe placed in the gas stream that passes over the wick at a proper velocity. The evaporation lowers the wet bulb's temperature. Under ideal conditions, the wet bulb's temperature is directly related to the relative humidity of the gas at the prevailing gas temperature, which is measured with the dry bulb thermometer. If all measurement parameters are known, the temperature difference (depression) is related fundamentally to the heat of evaporation of water. Hence, an absolute determination of the water vapour pressure of the gas can be made.

This technique was widely used in the past but is now considered to be the least desirable because of the large number of variables that can affect measurement results and must be controlled. The psychrometer also requires skilled operators to make accurate measurements.

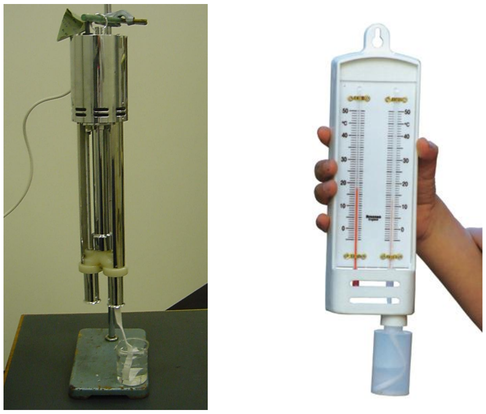

Figure 16: Examples of psychrometer

Advantage	Disadvantage
Simple, cheap, reliable and robust.	Some skill is required to use and maintain the instrument.
Can have good stability	A large air sample is required for measurement.
Wide range of humidity	The sample will be humidified by the wet sock.
Tolerate high temperatures and condensation.	Results have to be calculated from tables or software.
	Wick can become contaminated.
	Measurement is complicated below 10oC (dew or ice point).
	Whirling types are prone to serious errors.

Table 8: Psychrometer pro/contra

Particulates can also reduce the evaporation rate of a psychrometer wet wick, and they will clog an electrolytic cell.

Inorganic salts can affect the accuracy of psychrometers by modifying the saturation vapour pressure of liquid water on the surface of each type of device. Most salts are hygroscopic, and when they are deposited in the porous structure of an impedance or RH device, the salts can modify the device's characteristics Salts deposited on an electrolytic cell can change the coulomb metric relationship and cause damage to the cell.

Although **organic compounds** tend not to have a direct interference with water vapour, the compounds can condense on a mirror surface at a higher temperature than water or can evaporate from a psychrometer wick, causing additional evaporative cooling. It is possible for organics to damage secondary sensors if glues or epoxies are used in their manufacture. To eradicate or at least minimize these problems, conditions should be evaluated and steps taken to properly remove all or most contaminants from the gas stream by a suitable filtration method.

3.2.3. Electrolytic Hygrometer

This instrument operates on the principles of Faraday's laws of electrolysis to determine the amount of moisture in a gas stream. The water vapour in the gas stream is passed through the instrument's measurement cell, which electrolyzes the water molecules into their component parts (H2 and O2). The current consumed in this process is directly related to the amount of water electrolyzed. Provided the cell converts all the water in the gas stream into its component parts, the measurement of current represents an absolute measure of the moisture content.

3.3. Secondary devices

These devices are non-fundamental and must be calibrated against a transfer standard or other fundamental system. To obtain accurate data from them, you must recalibrate the device frequently. An example of a secondary humidity analyzer is an impedance hygrometer. These ceramic-aluminium oxide, and silicon oxide based sensors rely on a change in electrical properties (capacitance, resistance, or impedance) of a porous layer. The change in electrical properties is processed by simple electronics to give an output calibrated in a suitable hygrometric unit. Properly manufactured, calibrated, and operated, these devices can provide good on-line service for many years. However, calibration is required on a regular basis, and adjustments are often needed. In most applications, the accuracy of these devices is modest and much lower than that provided by transfer standard-type instruments.

3.3.1. Capacitive hygrometer

Capacitive hygrometers are another example of secondary humidity analyzers and are similar in principle to impedance hygrometer sensors. Capacitive hygrometers are constructed from polymer material with a hygroscopic dielectric and are designed to provide an electrical response corresponding to relative humidity. In recent years, significant improvements have been made, and these devices can now provide excellent low-cost service, particularly in normal ambient conditions.

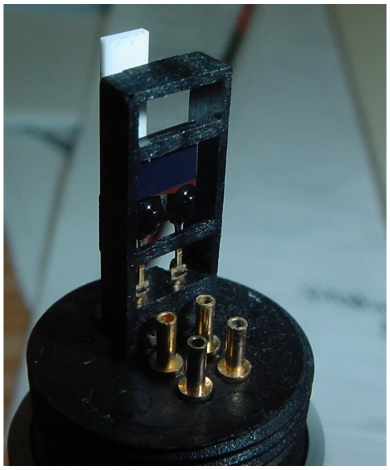

Figure 17: Example of capacitive hygrometer

Properties of capacitive hygrometers:
- They can achieve uncertainties of around 2 – 3% RH.
- They may suffer calibration shifts after experiencing high temperatures (> 40°C) or high humidity.
- May suffer drift and hysteresis.
- Can be damaged by aggressive chemicals.
- Capacitive sensors can usually tolerate condensation.
- Resistive sensors can be damaged by condensation.

In real-time applications of humidity measurement instruments, specifications of a manufacturer and calibration data of a standards laboratory lose some, and often much, of their significance. Operation of instrumentation under less-than-ideal conditions introduces variables likely to affect even the most reliable and accurate systems in some way. These variables include temperature, electronics and contaminants:

- **Temperature effects:** Most hygrometers are calibrated at a fixed ambient temperature. This may vary from manufacturer to manufacturer, but the temperature is usually around 20°C ±1°C. Variations from the ambient temperature can easily affect measurement results and accuracy. Sensor temperature coefficients in impedance-type sensors, like the capacitors and resistors they are derived from, exhibit temperature dependency. Many systems compensate for this either by using electronic compensation or by controlling the sensor temperature to negate the effect. Temperature coefficients of 0.1 to 0.2 are not uncommon, even in compensated systems, and result from non-uniformity of sensors and electronic components used in the compensation systems.
- **Electronics:** Modern electronic instrumentation is usually temperature insensitive over a normal ambient temperature range. Large temperature swings in exposed locations can cause performance errors in many electronic components. Instrument suppliers usually report the temperature range over which electronic performance is unaffected, and if these limits are adhered to, the temperature effects can be ignored. If the operating temperature exceeds these limits, you can expect errors and sometimes failure.
- **Contaminants.** Humidity measurement instruments are susceptible to errors caused by contamination.

3.4. Travelling standards for relative humidity

Travelling standards for relative humidity are typically used for on-site relative humidity checks. Many different measurement principles (dew-point, capacitve…) and manufacturers are available on the market. Summarized metrological characteristics for travelling relative humidity standard instruments are:

- Wide temperature range (typically from -10°C to 60°C),
- output in measured quantity (RH),
- accuracy in the range from 1% to 2%,
- good temperature stability,
- good repeatability,
- small hysteresis,
- easy to measure,
- handheld instrument,
- battery powered.

Travelling temperature standards must be checked or calibrated against reference standard before and after on-site measurements to ensure metrological properties.

Figure 18: Examples of travelling humidity standard

3.5. *Methods of calibration*

Calibration of instruments used in the field can be carried out at any level, from a full evaluation against a transfer standard to a one-point check against an assumed humidity level. Calibration against a standard represents the highest level of calibration. The national standard used may be the gravimetric train or an easier-to-use method, such as a two-temperature or two-pressure system.

3.5.1. Humidity Generators

Two-pressure humidity generation process involves saturating air with water vapour at a known temperature and pressure. The saturated high-pressure air flows from the saturator, through a pressure reducing valve, where the air is isothermally reduced to test pressure at the test temperature. System uncertainty is dependent on the accurate measurement of temperature and pressure and the stability of these measurements. The claimed uncertainty of commercially available systems is approximately 0.5 % RH. They offer good stability and reproducibility. These systems have a wide range of dew points from -20°C to +50°C.

Several manufacturers also offer two temperature – two pressure humidity generators which extend the range of operation over that obtained from a two pressure system. The cost of these systems is considerably more and their uncertainty similar to that of two pressure systems.

Figure 19: Example of Two Pressure Humidity Generator (left) and split stream system.

Alternatively, split stream humidity generators combine two air streams, one fully saturated while the other is 'dry'. Control of the ratio of the two streams determines the RH of the combined stream. Split stream systems can produce very low dew points (down to -100 °C DP) limited only by the dew point of the dry air stream. They possess good stability and reproducibility. Since flow rate is rarely a traceable measurement, the determination of dew point or RH is usually made with an associated dew point hygrometer. Typically, the uncertainty of these combined systems is 1% RH at ambient.

These systems can produce a range of low RH suitable for the assessment of hygrometers.

3.5.2. Climatic Chambers

Climatic chambers are divided into two types, those that control the humidity of a parcel of air by controlling the temperature of a body of water within the chamber separately from that of the chamber air temperature, and those that mix two streams of air, one saturated and one dry into the chamber. In the former, the temperature of the water body sets the dew point whilst the air temperature sets the ambient temperature. These systems have a limited range of humidity due the limited temperature range of liquid water at atmospheric pressure. Typically, 20%RH ÷ 90%RH at 20 °C measurement range is applied. There are known problems with temporal and spatial stability with environmental chambers. The chambers are also slow to change dew points and have long settling times, of the order of ½ an hour.

For systems employing a dry and saturated stream the range of RH is greater and the change in RH is faster. Typically, the measurement of chamber RH is made with an aspirated wet/dry bulb pair incorporated into the chamber. Uncertainty can be reduced by placing a dew point hygrometer in the chamber, or extracting air from the chamber for analysis by a dew point hygrometer.

Figure 20: Climatic chamber (left), split stream chamber (right)

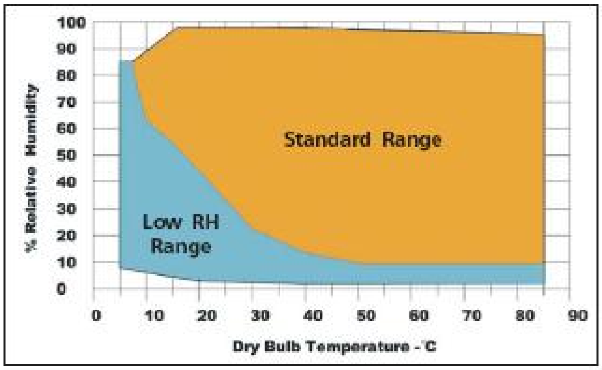

Figure 21: Typical RH versus temperature range for a climatic chamber

It can be seen in figure above that climatic chambers are suitable for producing surface level RH and are unsuited for evaluating instruments etc. Typical uncertainties for these systems are 2% RH when a dew point mirror device is incorporated.

3.5.3. Salt solutions generator

Several NMHS employ saturated salt solutions to calibrate RH probes. The dry salt is spread about 3 mm deep in a shallow tray that occupies most of the bottom of an airtight box. Water is added to moisten the salt. The instrument is then laid on a grid supported above the tray. Electronic sensors can be inserted through a hole in the box which is made reasonably airtight with a split rubber bung. A wide range of salt solutions are available. Their time to stabilize is poor and the solutions degrade with time.

Salt/Temperature °C	**5.0**	**10.0**	**15.0**	**20.0**	**25.0**
Lithium chloride	11.3	11.3	11.3	11.3	11.3
Magnesium chloride	33.6	33.5	33.3	33.1	32.8
Potassium carbonate	43.1	43.1	43.1	43.2	43.2
Sodium bromide	63.5	62.2	60.7	59.1	57.6
Sodium chloride	75.7	75.7	75.6	75.7	75.3
Potassium chloride	87.7	86.8	85.9	85.1	84.3
Potassium sulphate	98.5	98.2	97.9	97.6	97.3

Table 9: Nominal RH produced by various salt solutions at various temperatures

Due to the static air parcel above the salt solution the humidity must be monitored with an impedance type humidity probe. This increases the uncertainty of the calibration. These systems are cheap, but salt consumables must be changed regularly to maintain low uncertainties and therefore costs can be high. Typical uncertainties for these systems are 3% RH for fresh salt solutions.

Figure 22: The salt solution system

Considerable misunderstandings can exist when defining the accuracy of humidity sensors. Each manufacturer has its own way of measuring and specifying accuracy, and the user is often left confused. Although most manufacturers are not deliberately misstating accuracy claims, competition forces them to specify accuracy of their instruments in the most favorable way, sometimes only over a narrow range, at a fixed temperature, or under ideal laboratory conditions.

Sensors have different levels of sensitivity to contaminants, and such contamination effects vary depending on the type of sensor used and on the type of contaminant to which the sensor is exposed. Unfortunately, manufacturers generally have limited information on how their sensors perform when exposed to various contaminants, and most often, you are the one who must find this out in field tests.

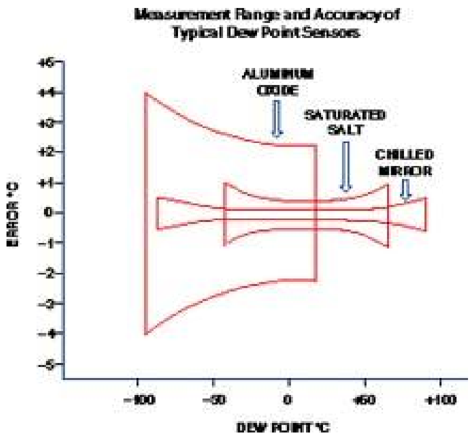

Figure 23: Attainable accuracies are different for different measurement methods

The saturated salt sensor, though having a narrower operating range, offers a better accuracy. The chilled mirror sensor is better than other dew point sensors in terms of accuracy. Generally accuracies deteriorate in the lower and higher ranges. A lower accuracy does not make the sensor inferior because it is often offset by features not available in other sensors. The user must determine which sensor is best for the application.

There are numerous sensors and measurement methods in use for measuring humidity, each having unique advantages and limitations. Theoretically attainable accuracies and operating ranges vary widely. The graph shown represents an attempt to display this for all sensors and measurement methods in terms of uncertainty vs. mixing ratio and dew/frost point in the range from -70ºC to 50ºC.

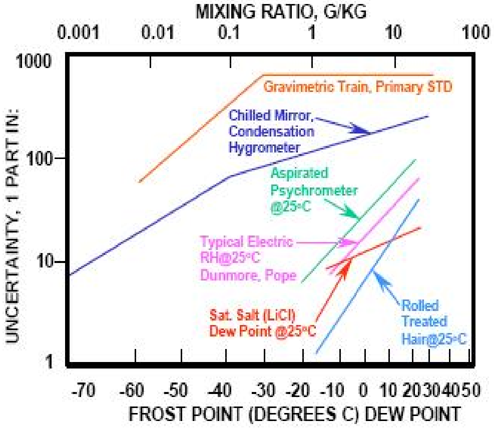

Figure 24: Approximate uncertainties of various humidity measuring techniques.

Recommendations:

1. The target uncertainty for the generation and measurement of humidity within a calibration laboratory should be 2 % RH or 0.3°C in dew point.
2. RICs should have a humidity generator or chamber capable of generating air streams or parcels of air within the range 5 % RH at 15°C to 90 % at 40°C. The streams or parcels should be stable to within ± 0.2% RH per minute.

3. If the source of humidity is not a first principles device, then measurement of the humidity should be with a dew point hygrometer with a 95 % uncertainty of 0.2°C or better.
4. Calibration of field humidity probes should be done with a view to maintaining a low overall uncertainty. The whole of measurement cycle, including inspection frequency, must be considered and appropriate levels of calibration uncertainty applied.

4. Pressure

The important decision to make is to determine what type of standard is appropriate for the calibration laboratory. The most important consideration in selecting a reference instrument is traceability. In pressure terms, traceability is defined as the ability to trace the calibration of a given measurement either directly or indirectly to standards of mass and length. The top choice is between primary and secondary laboratory standards.

A primary pressure standard is a pressure measuring instrument, which can reduce pressure measurements into measurements of mass, length and temperature and gravity. Examples are pressure balances or dead weight testers and primary mercury barometers. A secondary standard is an instrument which must be calibrated to relate the output directly to pressure. Both standards have advantages and disadvantages.

4.1. Primary Pressure Standards

The basic principle of the pressure balance consists of a vertical piston freely rotating within a cylinder. The two elements of good quality define a surface called 'effective area'. The pressure to be measured is applied of the piston, creating an upward vertical force. This force is equilibrated by the gravitational downward force due to masses submitted to the local gravity and placed on the top of the piston.

The primary mercury barometer must operate in high vacuum above mercury column, contain highly-pure mercury at constant temperature and be located in pollution safe environment.

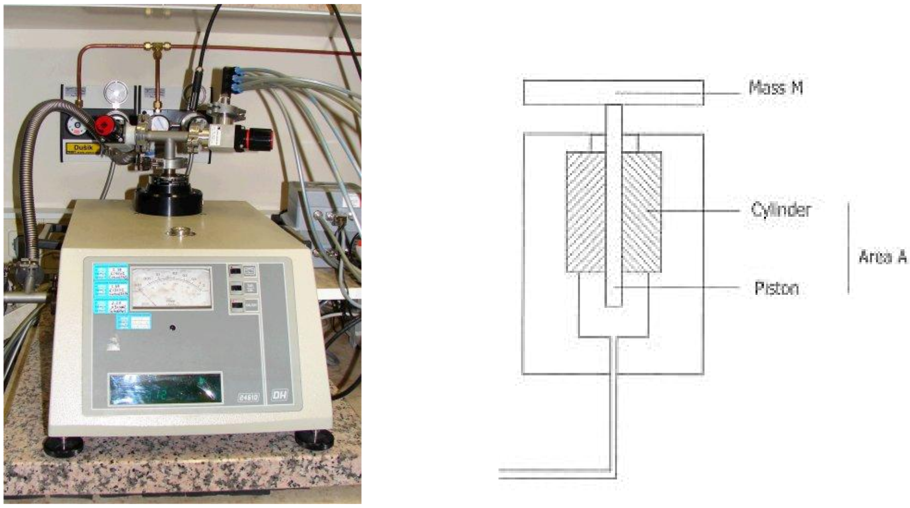

Figure 25: Example of primary pressure standard

The applied pressure can be calculated according to the formulae:

$$p = (1 - L \cdot p) \cdot k_n \cdot \frac{g_l}{g_n} \cdot \frac{N}{N_K} \cdot \frac{\rho_m - \rho_a}{\rho_m - 1{,}2} \left[1 - (\alpha_p + \alpha_c) \cdot (t - 20) \right] + \mu + \rho_a \cdot g_l \cdot h$$

Par.	**Description**	**Value**
L	Pressure distortion coefficient of the piston cylinder assembly	<0.000 Pa^{-1}
p	Pressure measured	[Pa]
k_n	Conversion coefficient of the piston cylinder given in the calibration certificate.	20.00270 kPa·kg^{-1}
g_l	Local gravity – measured	9,80615880 m·s^{-2}
g_n	Normal gravity	9.80665 m·s^{-2}
N	Readout on the dynamometer DPG	[dig]
N_k	Nominal coefficient of the dynamometer	100 000 dig/kg
ρ_m	Mass density – stainless steel AISI 304 L	7920 kg·m^{-3}
ρ_a	Air density during calibration of the dynamometer.	[kg.m^{-3}]
1.2	Normal air density	1.2 kg.m^{-3}
α_p	Thermal expansion coefficient of the piston	0.45.10^{-5} °C^{-1}
α_c	Thermal expansion coefficient of the cylinder	0.45.10^{-5} °C^{-1}
t	Temperature of the piston cylinder assembly	[°C^{-1}]
μ	Residual pressure	[Pa]

Air density has an influence on buoyancy on masses during a calibration and control of the dynamometer. It is calculated according to formula below:

$$\rho_a = \frac{p}{R_z \cdot T} - \frac{(M_z - M_v) \cdot f \cdot e_{so} \cdot e^{\left(\frac{h_i}{R_v} \cdot (1/T_0 - 1/T)\right)}}{R \cdot T}$$

Par.	**Description**	**Value**
R_z	Specific gas constant for the air	287.04 Jkg^{-1}K^{-1}
R_v	Specific gas constant for the vapour	461.5 Jkg^{-1}K^{-1}
R	General gas constant	8.314 472 Jmolar^{-1}K^{-1}
h_i	Specific evaporation heat (water-vapour)	2.50 MJkg^{-1}
F	Relative humidity of the air	
e_{so}	Partial pressure of the vapour at T_0 (T 20 ± 10)	
M_z	Molar mass of the air	28.964420 kg·kmolar^{-1}
M_v	Molar mass of the vapour	18.0153 kg·kmolar^{-1}
T	Temperature	[K]
T_0		273.15°K

Advantage	Disadvantage
Pressure balances are traceable to measurements of mass and length and therefore more directly to national standards.	Measurements must be corrected for temperature, local gravity and air buoyancy which can increase probability for errors as the corrections are applied.
They have good long term stability	Time consuming operation for day-to-day routine work.
High accuracy, high reproducibility, reliable and stable instrument.	Mercury barometers potentially represent a health and environmental hazard.

4.2. Secondary Pressure Standards

Secondary pressure standards may be secondary electronic barometers with good long term stability. With recent development of high quality electronic barometers measuring uncertainty was reduced to few Pascals level. Advantages of silicon diaphragm barometers are: very small size, insensitive to orientation, motion, and shock (portable), no gravity correction required and users are not exposed to toxic materials.

Figure 26: Example of secondary pressure standard

Advantage	Disadvantage
Faster and easier to use.	Pressure measurements cannot be reduced to measurements of mass, length or temperature.
Easy to adapt to automatic operation.	Higher measurement uncertainty.
Generally less expensive.	

Primary and secondary standard calibration devices are typically used and maintained by the calibration laboratory within an organization. With primary or secondary pressure standards laboratory can then directly calibrate working standards, calibrate travelling standards or calibrate field measuring instruments.

4.3. Travelling standards for air pressure

Travelling pressure standard is typically used for on-site calibration of barometers. Due to mercury barometer transportation problems it is more convenient to use an electronic barometer as a travelling standard. Travelling standards must be checked against reference standard before and after on-site measurements to ensure metrological properties. Once calibrated, it should on no account be opened or adjusted in any fashion until after the final on-site comparison. A reliable travelling standard barometer must retain its correction during transit to within 0.1 hPa. A travelling standard barometer needs to be carried in a high-quality, cushioned travelling case to protect it during transit.

Figure 27: Example of travelling pressure standard

4.3.1. Specifications of mercury barometers

Before the beginning of a tour, a mercury travelling standard should be examined carefully and checked to ensure that the mercury in the tube and cistern is clean, that there are no bubbles in the tube, and that the vacuum above the mercury in the tube is good. Every care should be taken in handling, packing and transporting travelling standards so that there is the least possible cause for any change, however slight, in their index correction. Quick, jerky movements which might cause air bubbles from the tube cistern to rise in the tube should be avoided. Mercury travelling standards should be carried in a suitably cushioned leather or metal case, with the cistern end always higher than the tube. Barometers should be calibrated over a wide pressure and temperature range, covering all possible values likely to be encountered.

4.3.2. Specifications of electronic barometers

The barometer must have a history of reliability with low drift corrections, as determined by several comparisons with a standard barometer both over a period of one year or more and over the maximum pressure range in which the barometer must be expected to operate. Electronic barometers with multiple pressure transducers under independent microprocessor control are preferred. The temperature compensation mechanism for the barometer must be proven to be accurate. The method for taking measurements from the pressure transducer must be contact-free and the barometer itself sufficiently robust to withstand the type of shock that may be encountered during transportation.

4.4. Calibration systems

When establishing pressure calibration laboratory several options regarding pressure standards must be discussed. There are different levels of pressure standards and traceability issues available to be implemented in calibration laboratory:

4.4.1. Using primary standards

Traceability must be maintained through periodic recalibrations to base SI units with smallest uncertainty level. Reference standards are then used for dissemination of value or, in some cases, calibration of instruments on smallest uncertainty level. Highly pure medium (nitrogen) for pressure generation combined with a pressure regulator generates calibration points in working standard comparison calibration. Working standards are then used for filed measuring instruments on a daily bases. Main components of each calibration system are:

- **Reference**: reference is the essential to obtain traceability of the calibration. Depending on the targeting uncertainty laboratory wish to achieve primary or secondary standards are used. In the case of barometric pressure primary standards are based on piston/cylinder assembly while secondary standards are electronic devices based on quartz sensor.
- **Medium**: barometric pressure media should be a clean gas. Purity is important for all types of instruments. In the case of mercury barometer dirtiness can directly dissolve in mercury and therefore deteriorate its properties. In the case of electronic barometers dirtiness deposits on the membrane covering a sensor. Any deposit changes elasticity of the membrane. In the case of piston/cylinder based instrument dirt deteriorates performance in two ways. It changes active surface of piston. Impurities can also fill the gap between piston and cylinder which is very small (few µm). Friction causes an additional force which is transferred to dynamometer. Electronic sensors can be sensitive to the kind of the gas. In such case clean air should be applied instead of nitrogen which is the most inexpensive choice.
- **Pressure supply**: changing and stabilization of pressure is as much important as other components. Changing can be either automatic or manual. Automatic regulators should be supplied with high and low pressure. The high one should be higher than maximum calibrating point and the low one should be lower than the lowest calibrating point. The regulator then actuates valves to achieve desired pressure. Speed of regulation mainly depends on the overall volume of setup. Bigger volume means slower regulation. On the other hand stability of pressure is better when the volume is bigger. High pressure is usually obtained from a cylinder of pure nitrogen. Low pressure is obtained with a pump capable to evacuate air below the pressure desired. Manual regulation is usually performed by appropriate manual pump capable to supply overpressure and under pressure. In this case media is usually air. In any case special care should be taken to protect system of temperature fluctuations which is immediately reflected in pressure. Therefore any touching of the tubing should be avoided during calibration.
- **Instrument under calibration**: all notes mentioned for the rest of the system are valid for the instrument under calibration too. Some instruments under calibration, especially older ones, don't have any appropriate connector for the tubing. In such case they should be calibrated in barometric chamber.

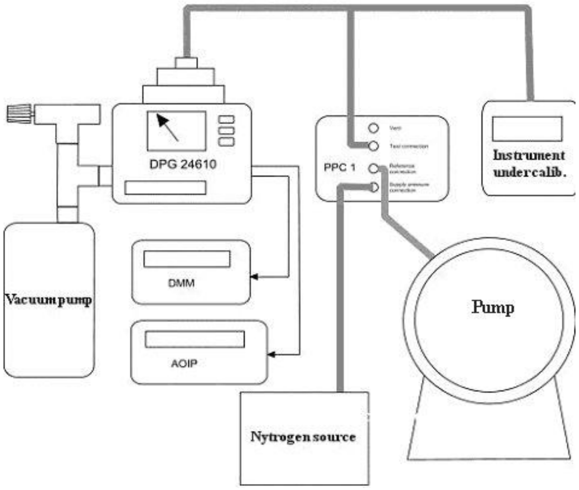

Figure 28: Calibration system using primary pressure standard

4.4.2. Using secondary standards

A secondary standard must be traceable directly through pressure calibrations to the national or international level. The measuring system must also include similar pressure medium like in previous case. Secondary standards can be used for working standards calibration purposes or field measuring instruments calibrations.

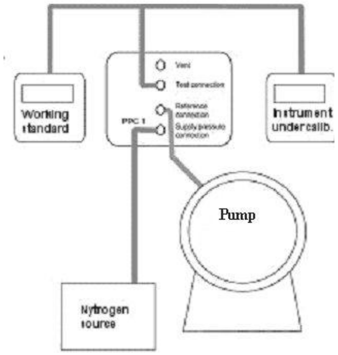

Figure 29: Calibration system using secondary pressure standard

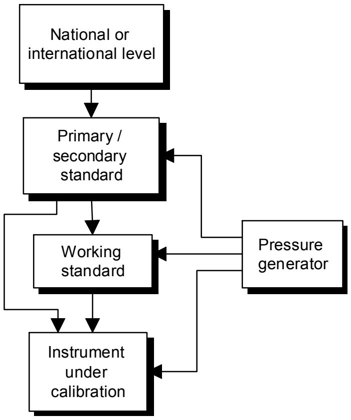

Figure 30: Traceability scheme using primary or secondary standards

4.4.3. Using working standards

A working standard must be traceable directly pressure calibrations to the national or international level. Barometric chamber (or other pressure generator) can be used for comparison calibrations of instruments.

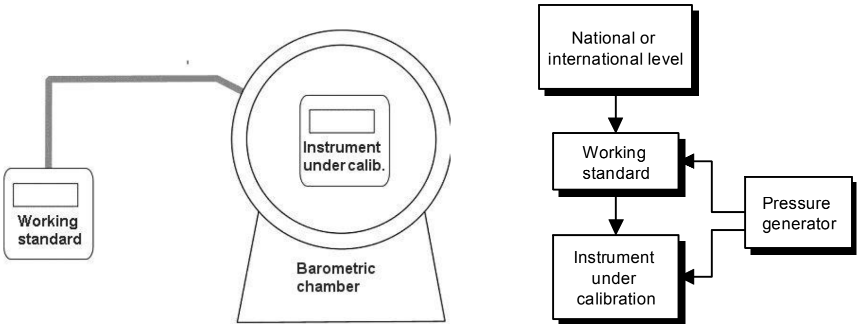

Figure 31: Calibration system and traceability scheme using working standard

Financial investments in calibration equipment increases when uncertainty approaches beneath 10 Pascal level. From financial perspective is very important to recognize different approaches to establish and maintain traceable of pressure calibrations especially in developing countries.

5. Conclusion

This review of recommended devices for metrology laboratory has been prepared to explain nowadays possibilities in terms of temperature, relative humidity and air pressure instruments calibration. Certainly, not all types of laboratory standards are included in this work, but it presents a base for further research. Any other available instruments, standards or medium generators not presented here can be also acceptable for laboratory use if they meet requirement.

The list of items required to undertake calibrations generally includes:

- suitable laboratory environment: the environment should normally be equipped with controlled ambient temperature and (if necessary humidity),
- reference standard: which must be traceable to (inter)national reference with all corrections applied,
- data acquisition: for much calibration work, measurements can be made adequately by eye and recorded by hand. In many situations, however, some degree of automation is possible. Much pressure measuring instrumentation provides electrical outputs, which can easily be connected to a computer for automatic or semi-automatic data logging,
- results calculation: essential is that the correct calculation is performed,
- calibration procedure: calibration procedure must be known by operator which should be documented,
- trained staff: both theoretical and practical training are needed for operator and staff management.

The work in a laboratory with implemented ‘good laboratory practice’ or accreditation should be based on following principles:

- Consistent respect for nationally and internationally valid standards, recommendations of the World Meteorological Organization (WMO), provisions of international conventions and protocols.
- Quality assurance and consistent observance of the accepted internal rules, regulations and documents which make part of the system.
- Ongoing development of methods and procedures for acquiring quality measurement data in accordance with the accepted programme.
- Constant concern of all employees in terms of quality services.
- Permanent education of the staff in individual specialized fields.
- Obligatory regular notification of employees regarding changes to the quality assurance system and of problems which have emerged, with the aim of immediately rectifying such problems.
- Fulfillment of requirements for acquiring and maintaining the accreditation of the calibration laboratory.
- Precise definition of responsibilities and authorizations in implementing quality assurance procedures.

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