National Institute of Standards

المعهـــد القومــــي للمعايــــرة

Lecture on Pressure Calibration
For "Arab Industrial Development, Standardization & Mining Organization"
المنظمة العربية للتنمية الصناعية والتقييس والتعدين

19/12/2024

By

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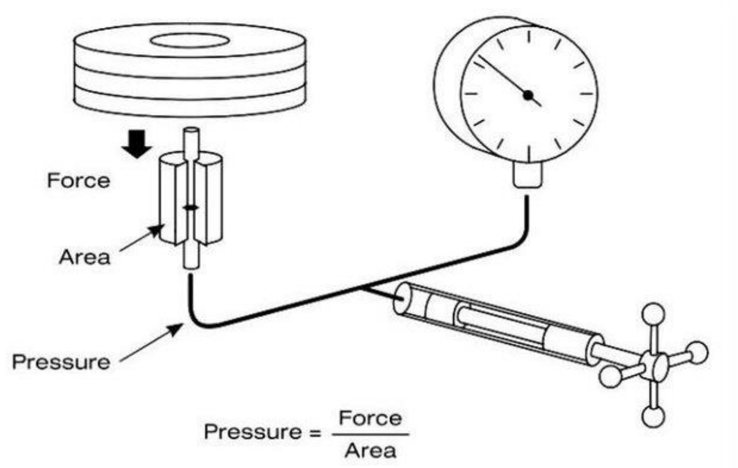
١ ـ التعرف بالنظام الدولى لوحدة قياس الضغط الحالي والمستقبلي

1- The current Definition of SI of pressure measurement units

Pressure is the amount of force applied perpendicular to the surface of an object per unit area and the for it is p (or P).

The SI unit for pressure is the pascal (Pa), equal to one newton per square metre (N/m^2, or $kg·m^{-1}·s^{-2}$).
Pascal is a so-called coherent derived unit in the SI with a special name and symbol.



2- The new Definition of SI of pressure measurement units

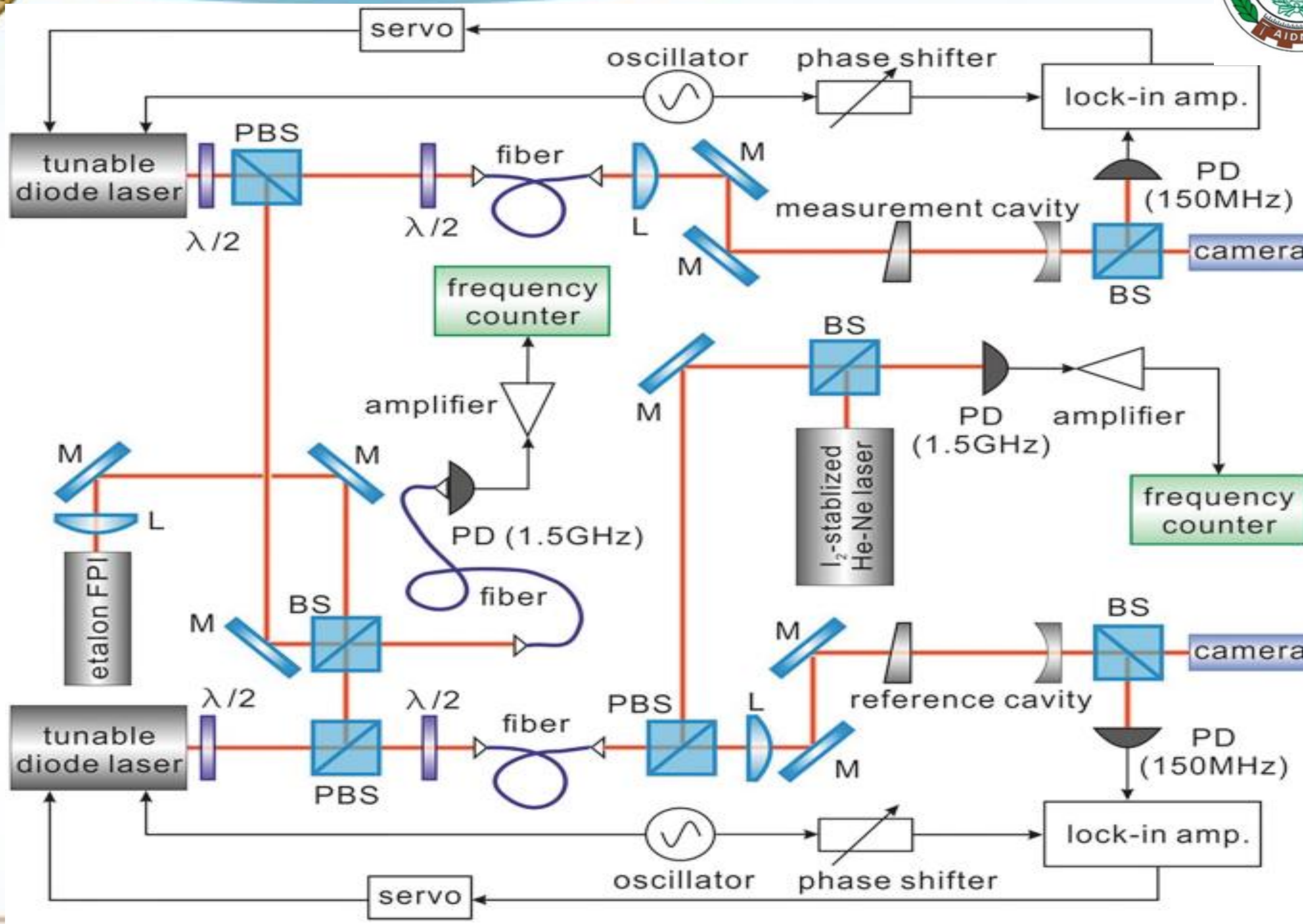
- After the redefinition of the International System of Units (SI),
- pascal, the SI unit of pressure, can be calculated more accurately because, according to ideal gas law, the pressure depends on temperature, gas number density, and few fundamental constants like Boltzmann's constant, the universal gas constant, and Avogadro's number.

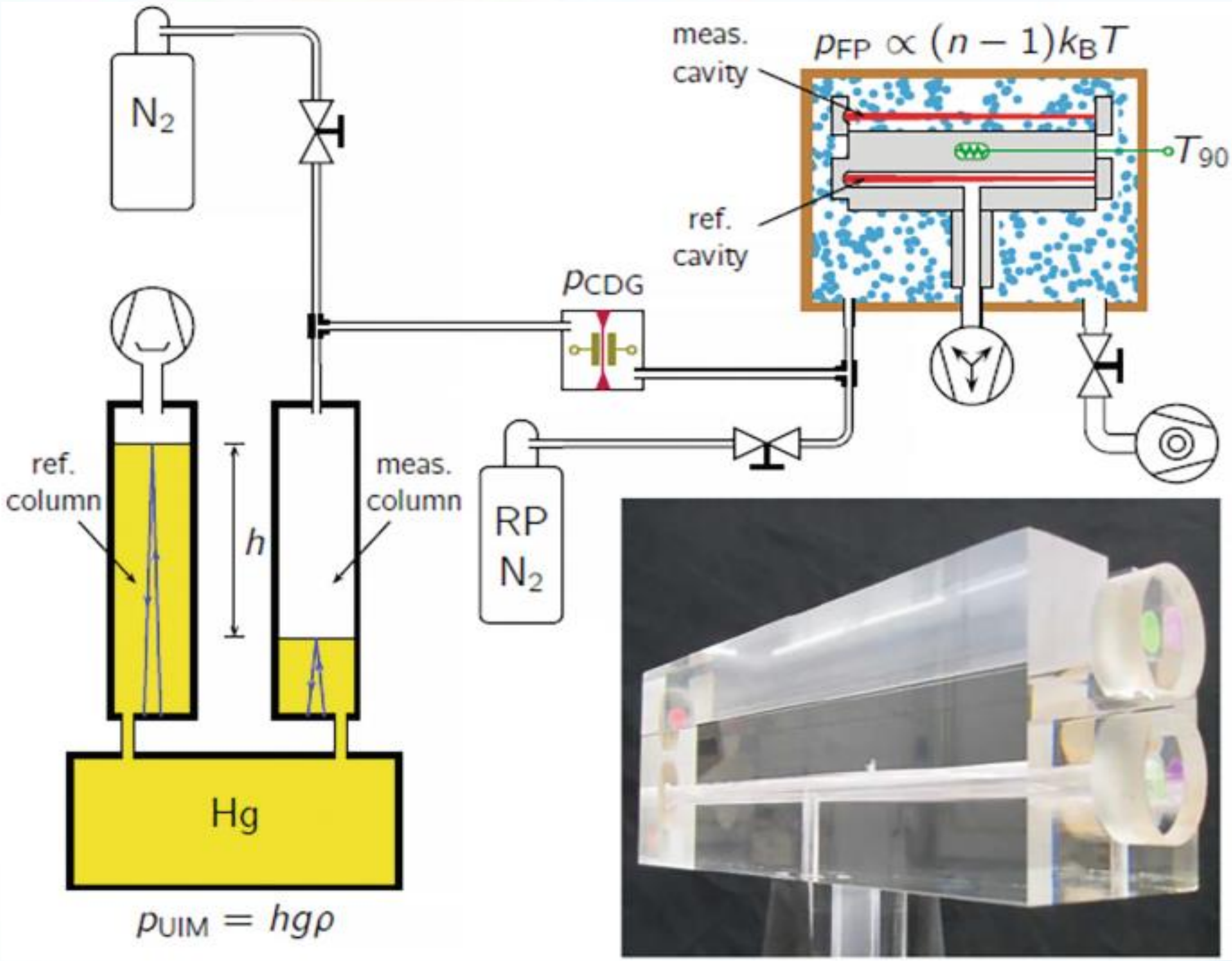
$p \propto (n-1)k_B T$ $\quad$ $p = \rho_N k_B T$ $\quad$ $\rho_N = N/V$

$N = \nu N_A$

$$P = k_B T \left(\rho_N + B_\rho \rho_N{}^2 + C_\rho \rho_N{}^3 + - - - - - -\right)$$

- the precise measurement of pascal depends majorly on gas number density, which can be computed using optical techniques. Quantum calculations involve calculating pressure using optical methods, also known as the quantum realization of pascal.


servo
oscillator
phase shifter
lock-in amp.
tunable diode laser
PBS
λ/2
fiber
L
M
measurement cavity
PD (150MHz)
camera
BS
frequency counter
amplifier
PD (1.5GHz)
I2-stablized He-Ne laser
etalon FPI
fiber
reference cavity
camera
PD (150MHz)
tunable diode laser
lock-in amp.
oscillator
phase shifter
servo


N2
meas.
cavity
$p_{FP} \propto (n-1)k_B T$
T_{90}
ref.
cavity
p_{CDG}
ref.
column
h
meas.
column
RP
N2
Hg
$p_{UIM} = hg\rho$

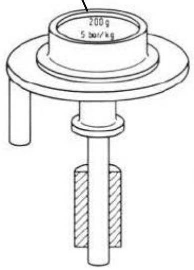
نظم الامامية فى مترولوجيا الضغوط

Primary systems in pressure metrology

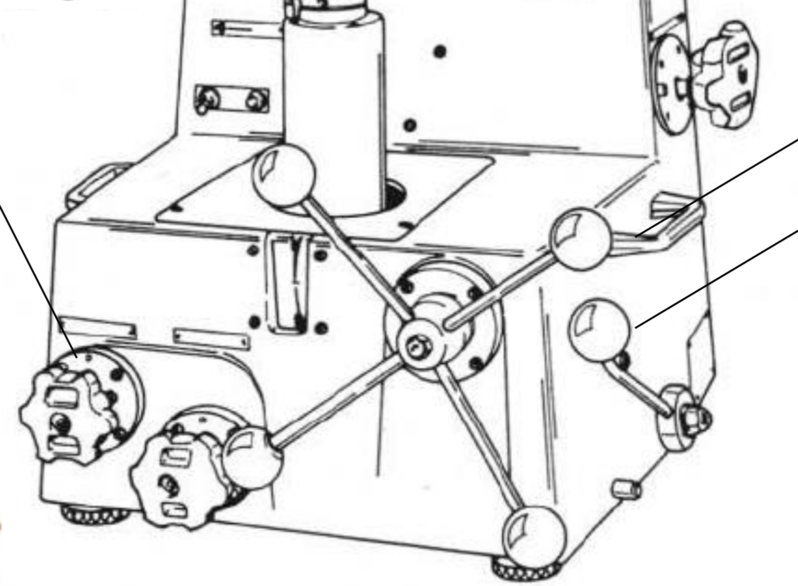
2-1 Pressure Balance

2-2 Liquid Manometer

Piston-Cylinder

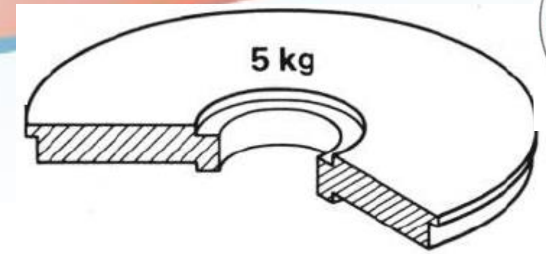


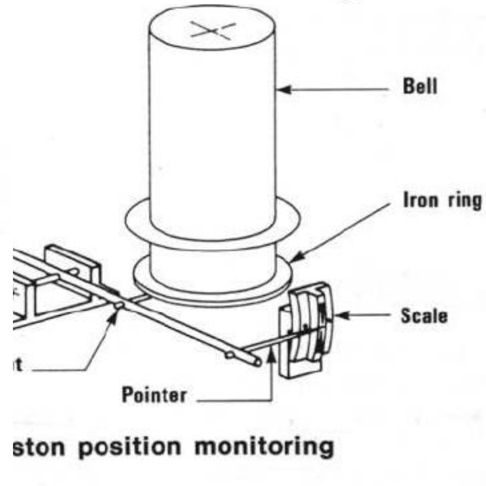
Isolation Valve



System Pump

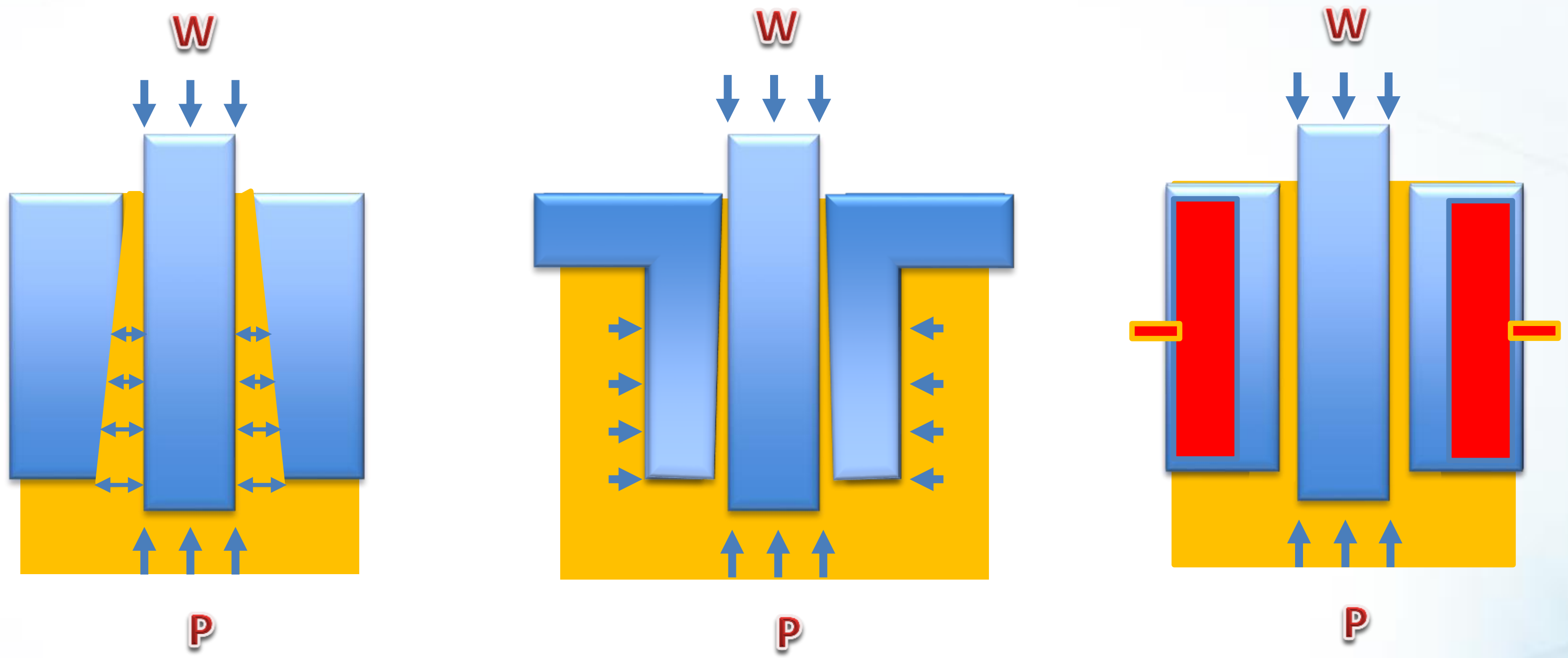
Primary Pump





Design Of PCA

There are basically three designs of PCA



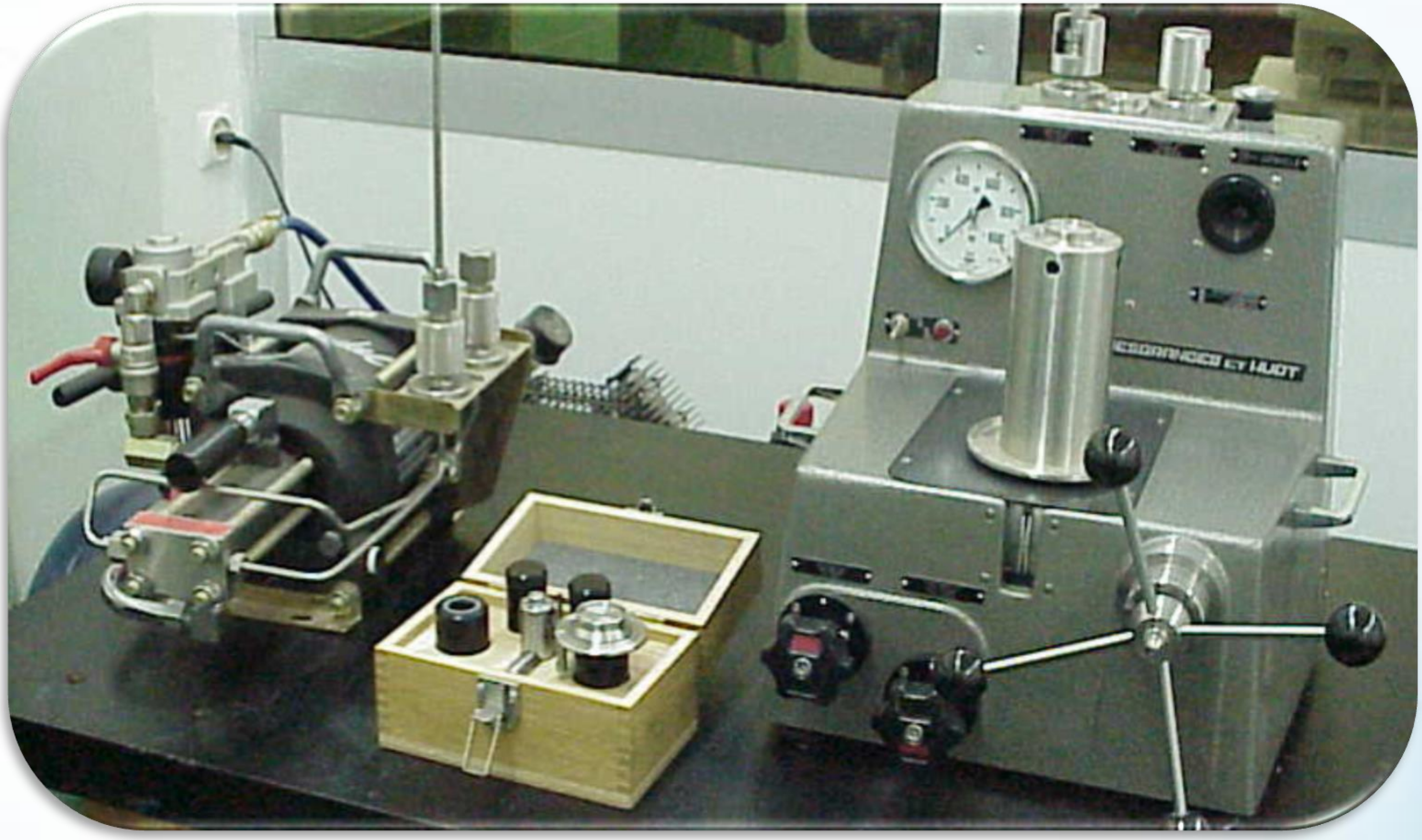
Simple piston-cylinder assembly

Re-entrant piston-cylinder assembly

Controlled-clearance piston-cylinder assembly

Absolute pressure up to 2 MPa.

Gas Pressure Balance for gauge pressure up to 40 MPa



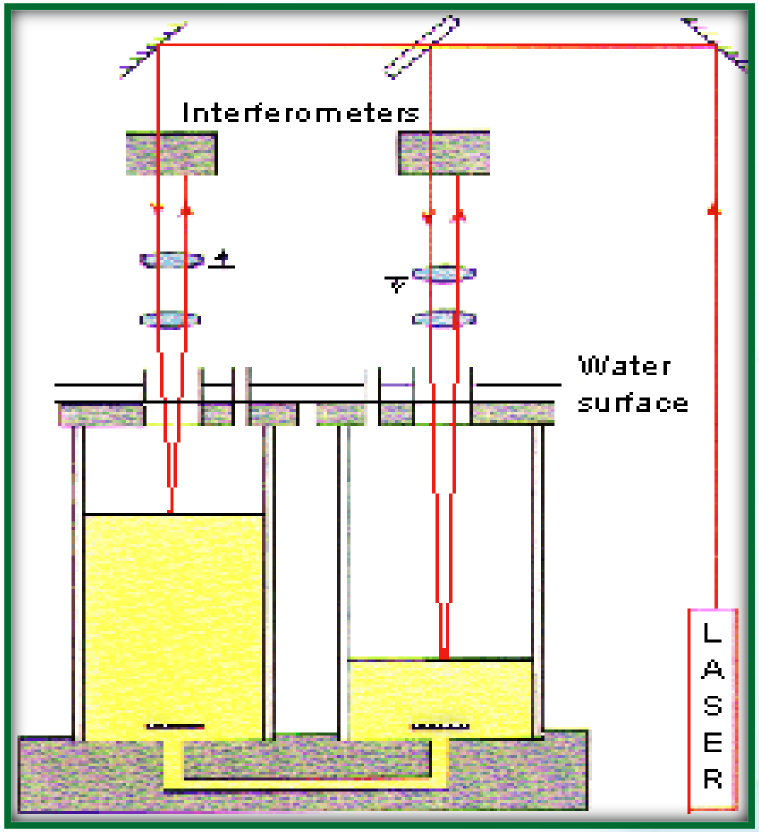
Oil Pressure Balance for gauge pressure up to 500 MPa

2-2 Liquid Manometer

Laser Interferometer Manometers
White-Light Interferometer Manometers
Ultrasonic Manometers

Important factors in using liquid manometers

- High thermal expansion coefficient of the mercury
- Vapor pressure of the used liquids
- Limited range
- Sensitive to speed of changing pressure
- Hazard
- Large volume
- Sensitive to contaminations

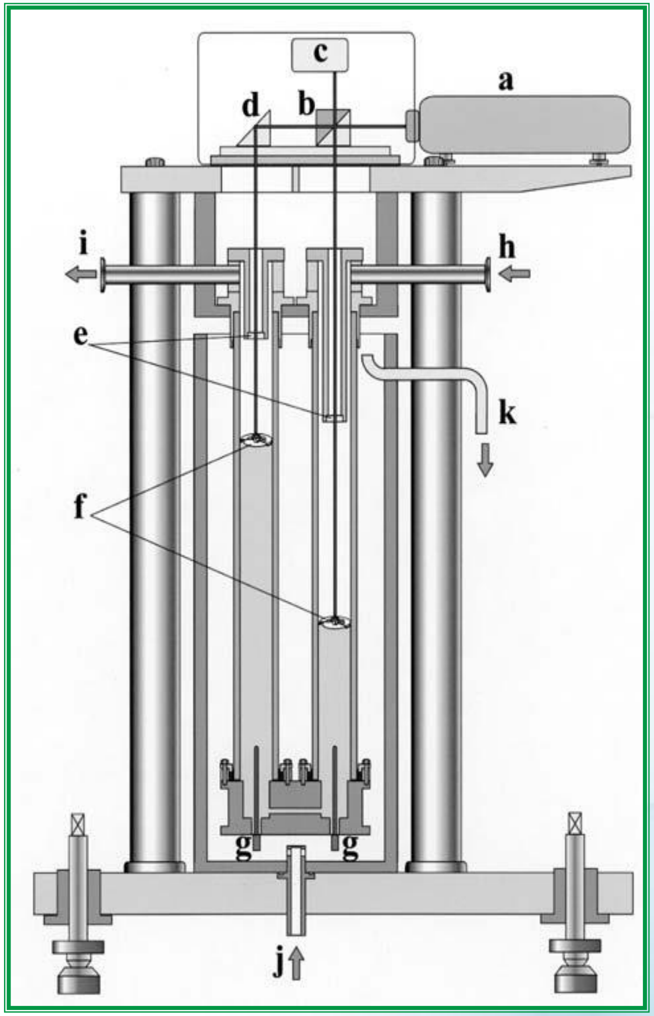


Mercury manometers (IMGC)

HG1 1986
HG3 1994
HG5 1999
HG6 2005 / CENAM – Mexico

- Thicker plates for the laser head
- Stainless steel made support columns
- Automatic valves control
- Automatic temperature data acquisition and control
- Stainless steel connection instead of Teflon between glass tubes
- Improved design of retroreflector floats

New operating program

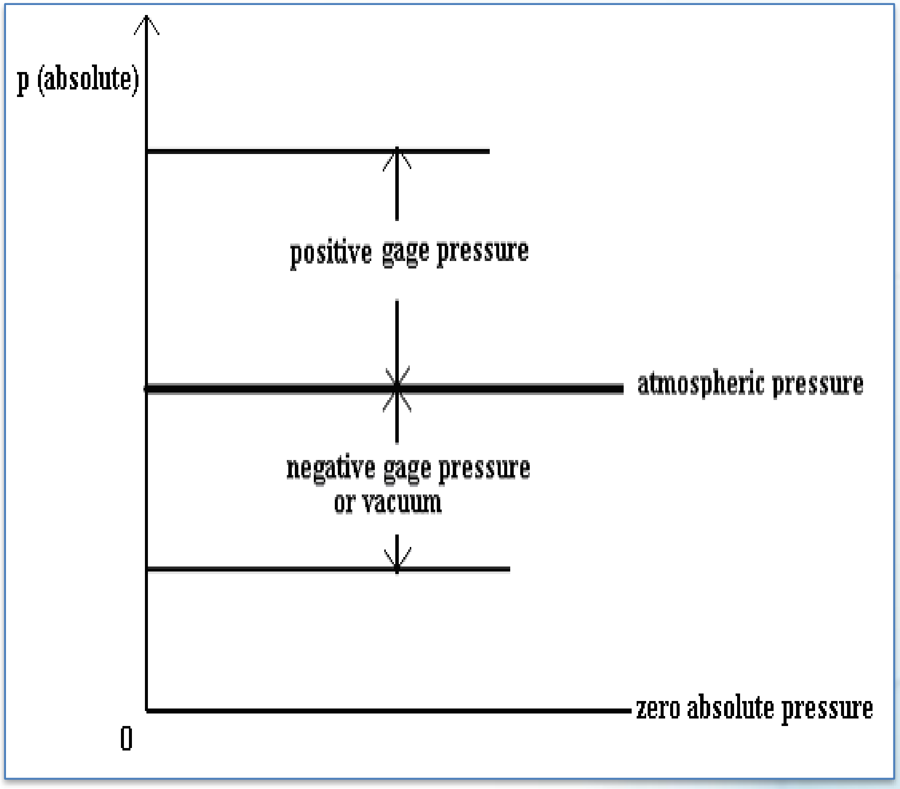


Types of Pressures ٣- أنواع الضغوط

1- The absolute pressure is usually positive.

2- The Gauge pressure may be positive or negative (vacuum)

3- The vacuum is usually smaller than the local atmospheric pressure.



- The pressure measurement devices for fluid are usually measure pressure in three different forms:

- absolute pressure,
- vacuum or
- Gauge pressure.

- Absolute pressure is the absolute value of the force per unit area exerted on the containing wall by a fluid.

- Gauge pressure is the positive difference between the absolute pressure and the local atmospheric pressure.

- Vacuum is the negative difference between the local atmospheric pressure and the absolute pressure.

- The units, psi and atm, often carry a trailing "a" or "g" to indicate that the pressure is absolute or gauge pressure. Thus, by psig, we me gauge pressure in psi and by psia, we me absolute pressure in psi. So is the meaning of atma or atmg if nothing is noted otherwise.

٤ـ تعيين الضغط من المعادلات الأساسيه

Determine pressure from basic equations

Mass

Local Acc. of Gravity

Air Density

Mass Density

Distortion due to jacket pressure

$$p_m = \frac{\sum_i m_i g\left(1 - \frac{\rho_{air}}{\rho_{mi}}\right) + \gamma C}{A_{op}(1+\lambda p_m)\left[1+(\alpha_p+\alpha_c)(T-T_R)\right]\left[1+d(p_z-p_j)\right]} + (\rho_f-\rho_a)gh$$

Jacket pressure

Effective area at zero pressure

Pressure distortion cof.

Thermal expansion cof.

Piston Cylinder Temp

Pressure minimize distortion

Pressure Balance

A pressure balance is essentially made up of:

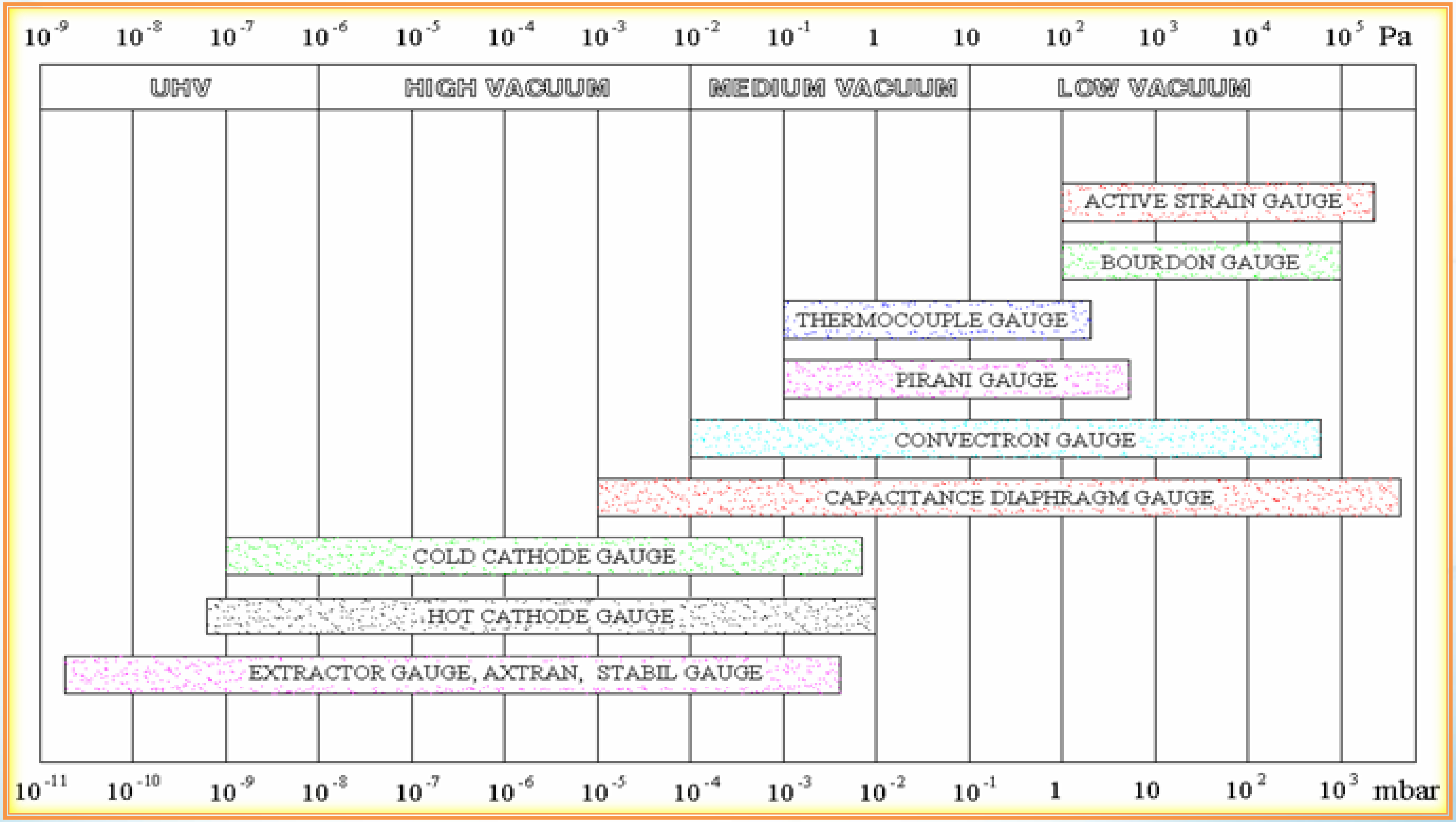
- Piston-and-cylinder assembly (PCA)
  - Materials; high compressive strength under elastic conditions.
  - Having a very small linear thermal expansion coefficient.
  - Diameter and roundness constancy inside ±100 nm.
  - The clearance between the piston and cylinder diameters must be small (typically from 0.2 to 1 μm) and uniform along all the engagement length of the piston in the cylinder
  - The piston must float freely along the engagement length of the cylinder without friction or metal-to-metal contact between the two parts.
  - The piston must be in permanent rotation in order to reduce possible piston-cylinder friction
- System for the application of a known vertical load on the piston
- Auxiliary instruments

٥- أنواع أجهزة قياس الضغط

Types of pressure measuring devices

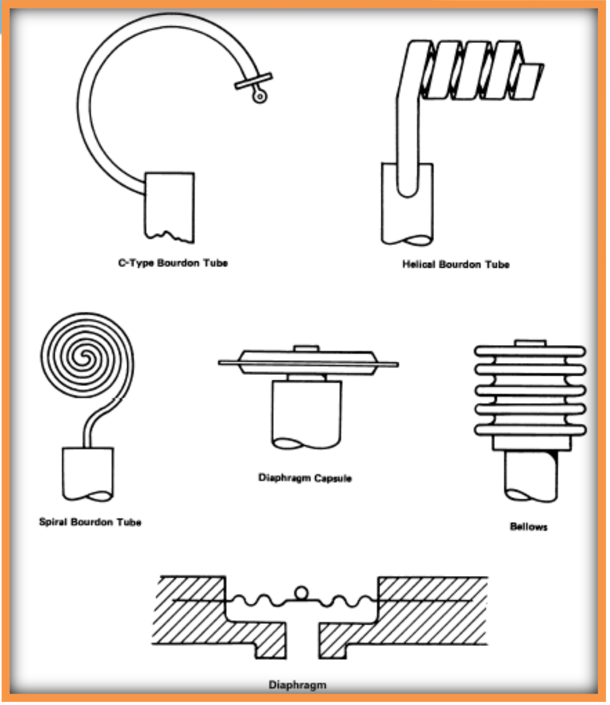
- **Pressure Measurement Principles**
  - **Direct**
    - Mechanical Deformation
      - Diaphragm
        - Capacitance Manometer
        - Piezo-resistive Strain gauge
        - Inductive
        - Frequency Tension
        - Schaffer
      - Bourdon Tube
        - Simple
        - Spiral
        - Helical
        - Eccentric Tube
      - Bellows/ Capsule
        - Anerooid Barometer
      - Pizo-electric
        - Quartz Crystal
      - Resistance
        - Manganin
    - Pressure Balance
      - Gas
      - Hydraulic
    - Liquid Column
      - Mercury Barometers
      - Water Manometers
      - Other Liquid
  - **Indirect**
    - Ionization
      - Hot Cathode
        - Bayard-Alpert
        - Triode
      - Cold Cathode
        - Penning
        - Inverted Magnetron
    - Thermal Conductivity
      - Pirani
      - Thermocoup le
    - Viscosity
      - Spinning rotor Gauge

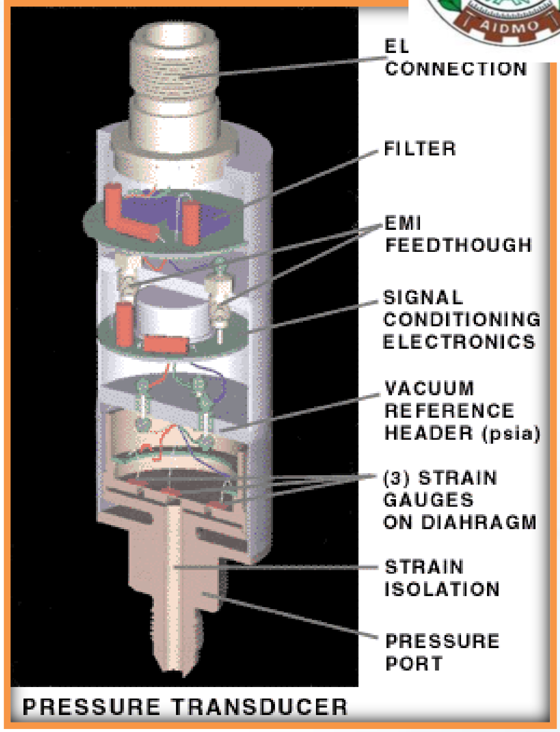
Pressure ranges of vacuum gauge products

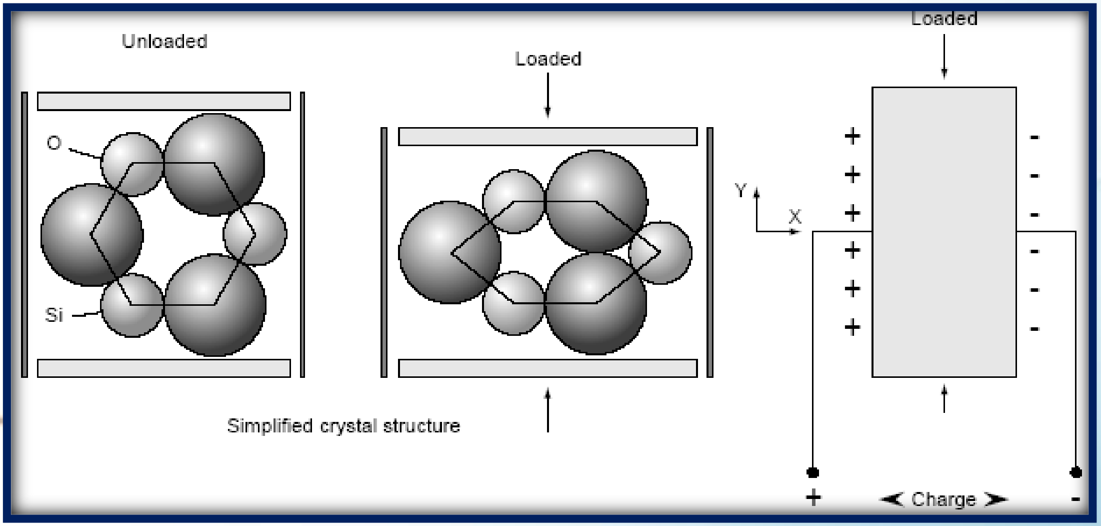


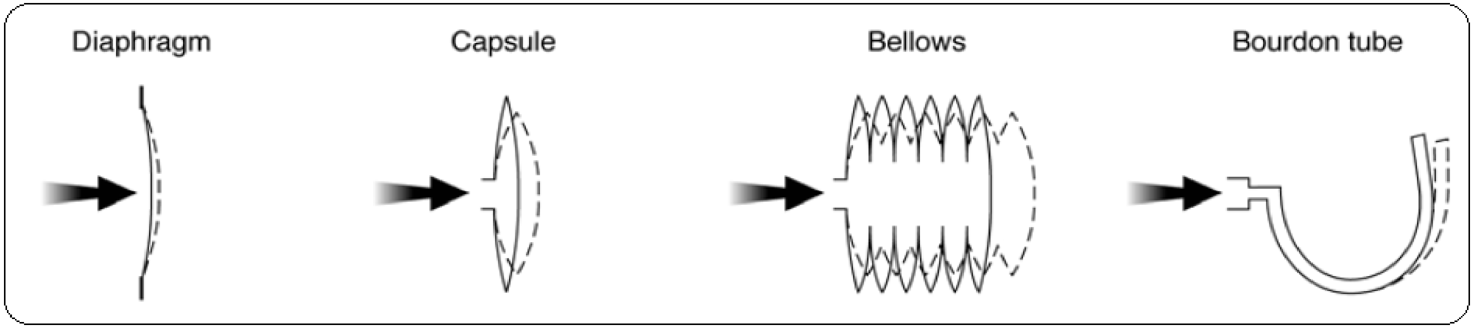
Direct measurements

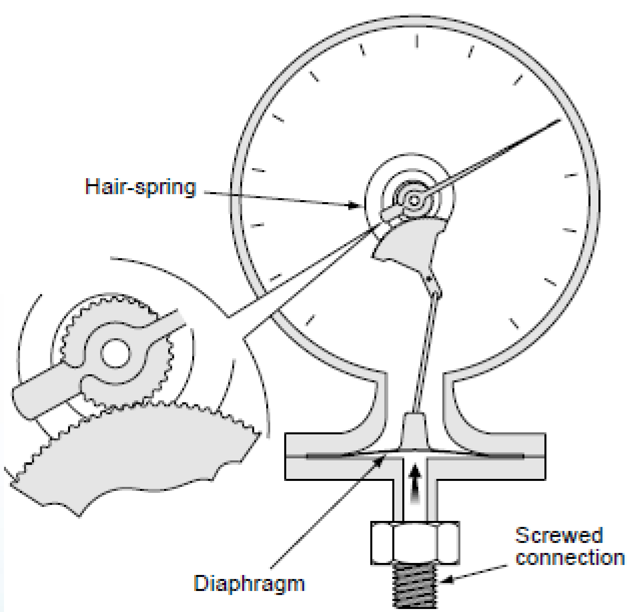
- ➢Diaphragms
- ➢Capsules
- ➢Bellows
- ➢Bourdon tubes
- ➢Cylinders
- ➢Mechanical display
- ➢Capacitive techniques
- ➢Linear variable differential transformers (LVDTs)
- ➢Strain gauges
- ➢Vibrating structures
- ➢Direct resonant pressure sensors
- ➢Pizo-electro devices

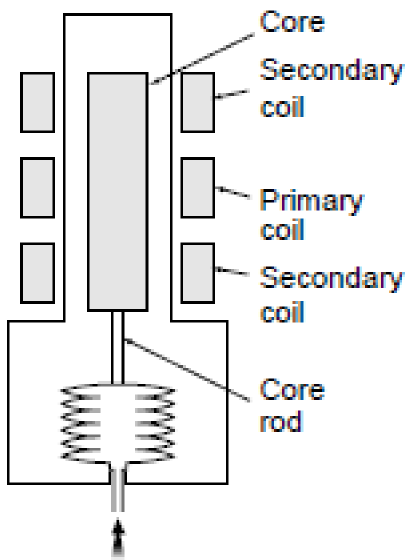


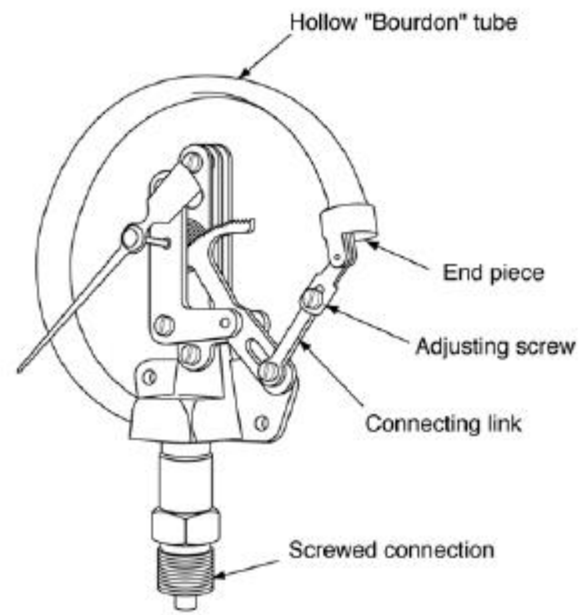




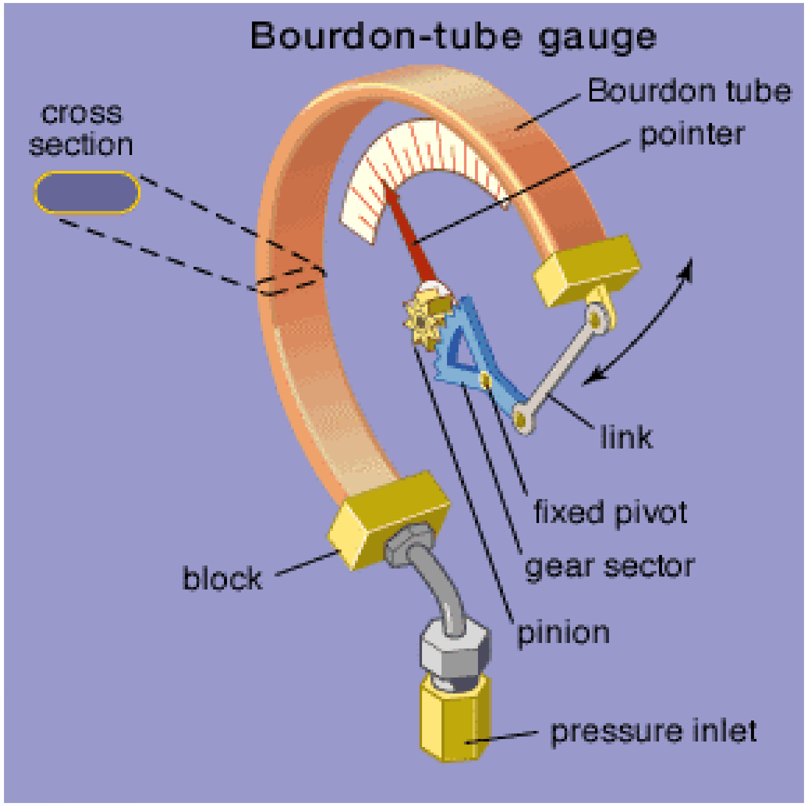

Diaphragm
Capsule
Bellows
Bourdon tube


Hair-spring
Diaphragm
Screwed connection


Core
Secondary coil
Primary coil
Secondary coil
Core rod


Hollow "Bourdon" tube
End piece
Adjusting screw
Connecting link
Screwed connection

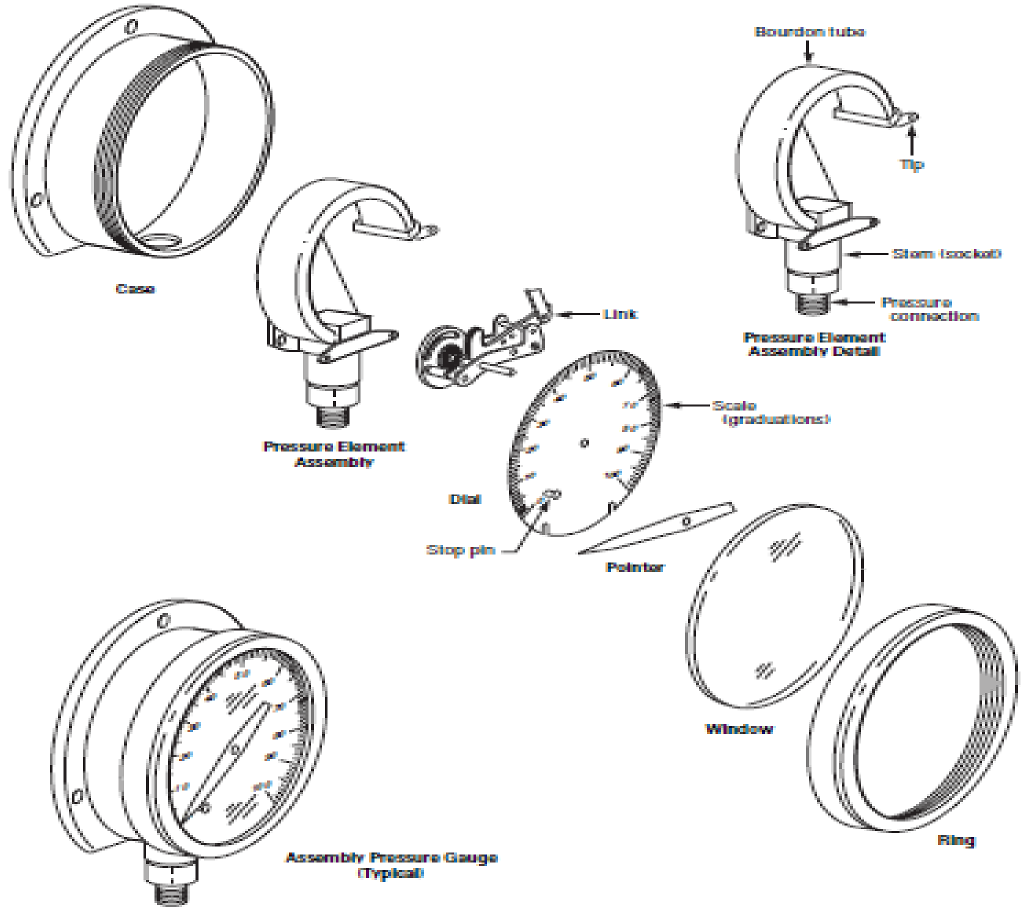
Bourdon tube pressure gauges



Electrical pressure gauges

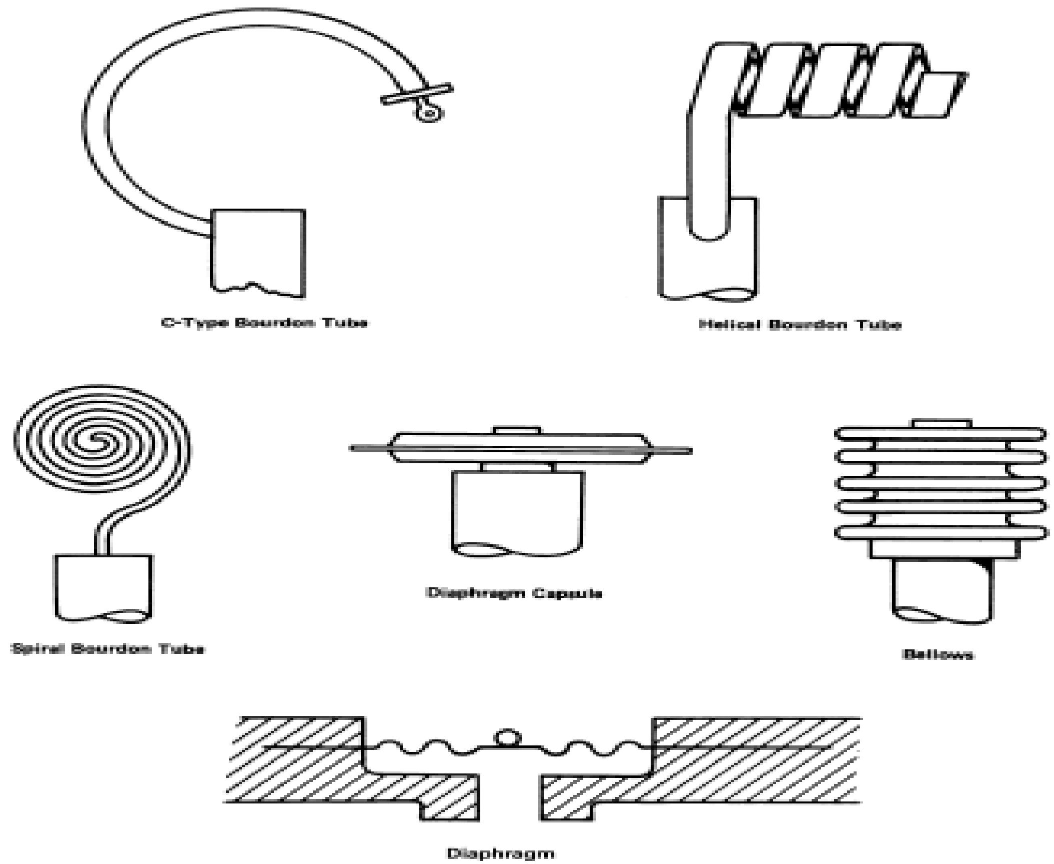
Pressure Transmitters with electrical output

Differential pressure



GENERAL NOTE: The above diagrams are schematic and not intended to show design details.

Fig. 2 Pressure Gauge Components (C-Type Bourdon Illustrated)

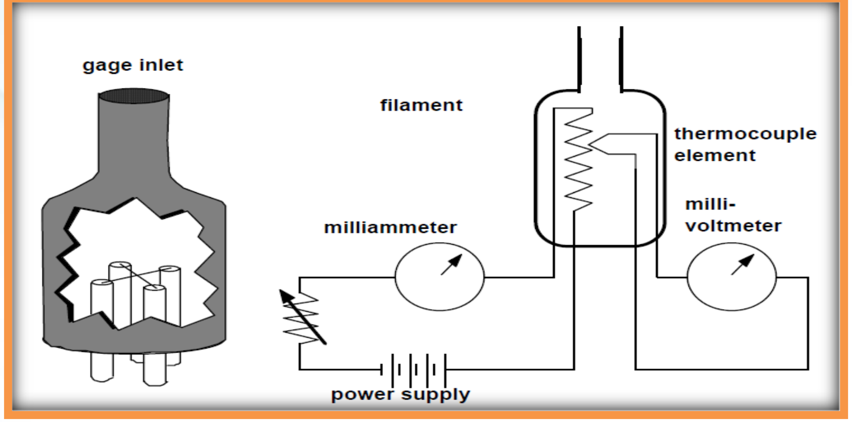


i. NOTE: The above diagrams of various types of elastic elements used in pressure gauges are schematic and not
d to show design detail.

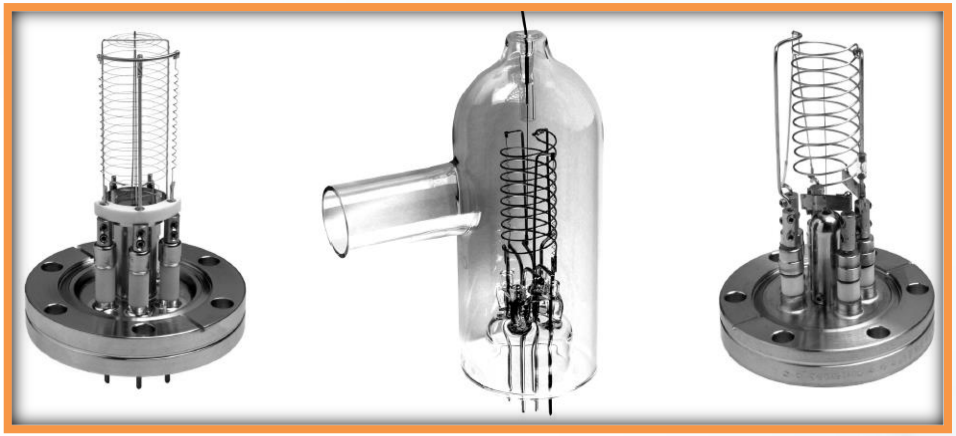
Fig. 3 Elastic Elements

Indirect

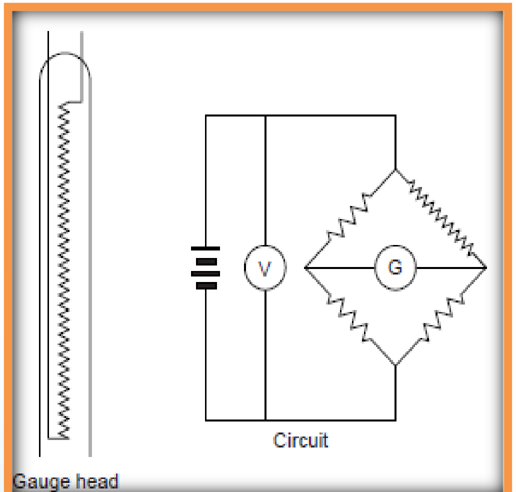
Pressure Measurement Techniques



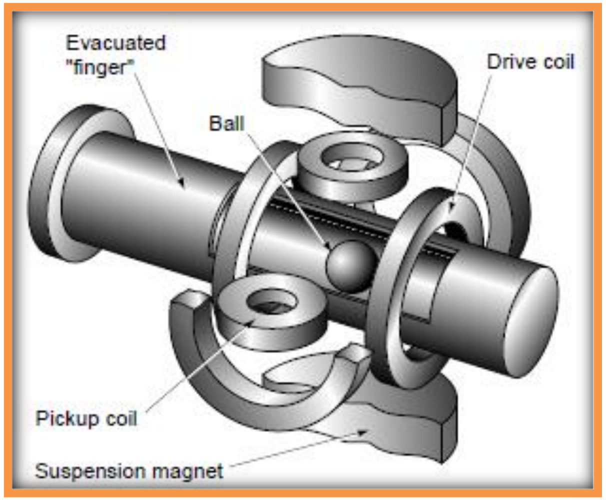
Thermocouple



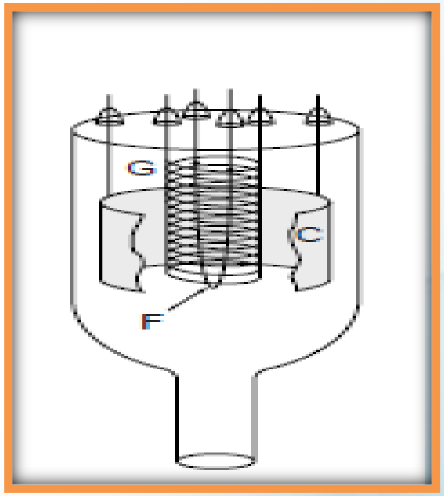
Bayard-Alpert gauges



Pirani Gauge



Spinning rotor gauge



Triode gauge

Guideline

DKD –R 6-1

Calibration of Pressure Gauges

➢ Deutscher Kalibrierdienst (DKD)

- The DKD comprises calibration laboratories in industrial enterprises, research institutes, technical authorities, inspection and testing institutes. They are accredited and supervised by the DKD.

- The DKD calibration certificates issued by these laboratories prove traceability to national standards as required in the ISO 9000 family and ISO/IEC 17025.

- It serves as a metrological basis for the inspection of measuring and test equipment within the framework of quality assurance measures.

➢ Purpose and scope of application

This Guideline serves to establish minimum requirements for the calibration method and the estimate of the measurement uncertainty in the calibration of pressure gauges.

It applies to Bourdon tube pressure gauges, electrical pressure gauges and pressure transmitters with electrical output for absolute pressure, differential pressure and overpressure with negative and positive values.

➢ Reference and working standards

The calibration takes place by direct comparison of the measurement values for the calibration item with those of the reference or working standard which has been directly or indirectly traced back to a national standard.

The reference standards such as pressure balances and liquid-level manometers. They are calibrated at the PTB at regular intervals and a calibration certificate is issued for them stating the expanded uncertainty under reference conditions.

The working standards documented in the quality manual of the DKD laboratory are calibrated in an accredited laboratory and a calibration certificate is issued for them stating the expanded uncertainty under reference conditions.

Recommendation:

The measurement uncertainty which is attributed to the measurement values of the reference or working standard should not exceed 1/3 of the uncertainty aimed, which will probably be attributed to the measurement values of the calibration item.

➢ Calibration item

Type	Standard	Calibration item	Auxiliary measuring devices
(1) **Burdon tube pressure gauge**	Reference or working standard	Burdon tube pressure gauge	
(2) **Electrical pressure gauge**	Reference or working standard	Voltage source p / U, I, f p Indication	
(3) **Pressure transmitter with electrical output**	Reference or working standard	p / U, I, f	Auxiliary power Indication

Notes

1- auxiliary measuring devices of the DKD laboratory must be used for the calibration of pressure transmitters with electrical output (3). These devices serve to convert the electrical signal into a readable indication.

2- To ensure traceability, the auxiliary measuring devices must have been calibrated and a statement on the measurement uncertainty to be attributed to the measurement values must be available.

3- If the calibration item has a digital interface (e.g. RS232, RS485, IEEE488, etc.), this interface can be used in the place of the indication. It is to be ensured that the data read out are unequivocally interpreted and processed.

➢ Calibration Capability

suitability of the calibration item

the state of the calibration item at the time of calibration should comply with the generally accepted rules of technology and with the particular specifications of the manufacturer's documentation.

The calibratability is to be ascertained by external inspections and function tests.

External inspections

- visual inspection for damage (pointer, threads, sealing surface, pressure channel)
- contamination and cleanness
- visual inspections of inscriptions, readability of indications
- test whether the documents necessary for calibration (technical data, operating instructions) have been submitted.

Function tests :

- tightness of tube system of calibration item
- electrical function
- perfect function of actuators (e.g. zero adjustability)
- setting elements in defined position
- faultless execution of self-checking and/or self-setting functions; if needed, internal reference values are to be read out via the EDP interface
- torque dependence (zero signal) during mounting

Note:

If repair or adjustment work has to be carried out to ensure calibratability, this work has to be agreed upon between customer and calibration laboratory.

➢ Ambient conditions

The calibration is to be carried out after temperature equalization between calibration item and environment.
A period for warming up the calibration item or potential warming-up of the calibration item due to the supply voltage is to be taken into account.

The calibration is to be performed at an ambient temperature stable to within ±1 K; this temperature must lie between 18° C and 28° C and is to be recorded.

Note:

If the air density has an effect on the calibration result, not only the ambient temperature but also the atmospheric pressure and the relative humidity are to be recorded.

➢ 7: Calibration methods

-The pressure gauge is to be calibrated as a whole (measuring chain), if possible.

- The specified mounting position is to be taken into consideration

- The calibration is to be carried out in measurement points uniformly distributed over the calibration range.

- Depending on the measurement uncertainty aimed at, one or several measurement series are necessary.

- If the behavior of the calibration item as regards the influence of the torque during mounting is not sufficiently known, the calibration item has to be clamped once again to determine the reproducibility. In this case, the torque is to be measured and documented.

The comparison between the measurement values for calibration item and reference or working standard can be performed by two different methods:

-adjustment of the pressure according to the indication of the calibration item,

-adjustment of the pressure according to the indication of the standard

Calibration sequences table

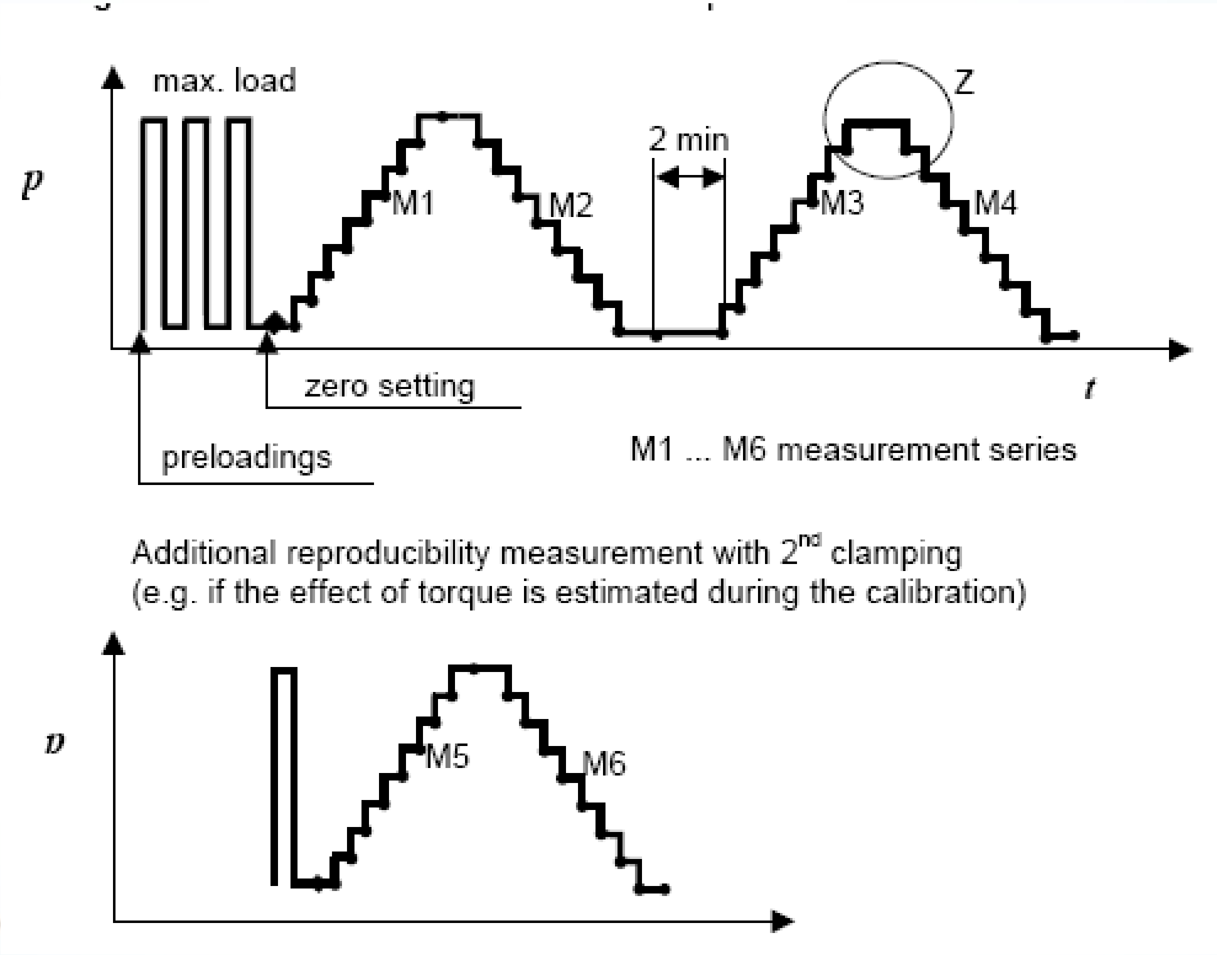
Calibration sequence	Measurement uncertainty aimed at, in % of the measurement span (*)	Number of measurement points with zero up/down	Number of pre-loadings	Load change + waiting time (**) seconds	Waiting time at upper limit of measurement range (***) minutes	Number of measurement series up	Number of measurement series down
A	< 0,1	9	3	> 30	2	2	2
B	0,1 ... 0,6	9	2	> 30	2	2	1
C	> 0,6	5	1	> 30	2	1	1

(*) the accuracy specifications of the manufacturers are usually related to the measurement span.

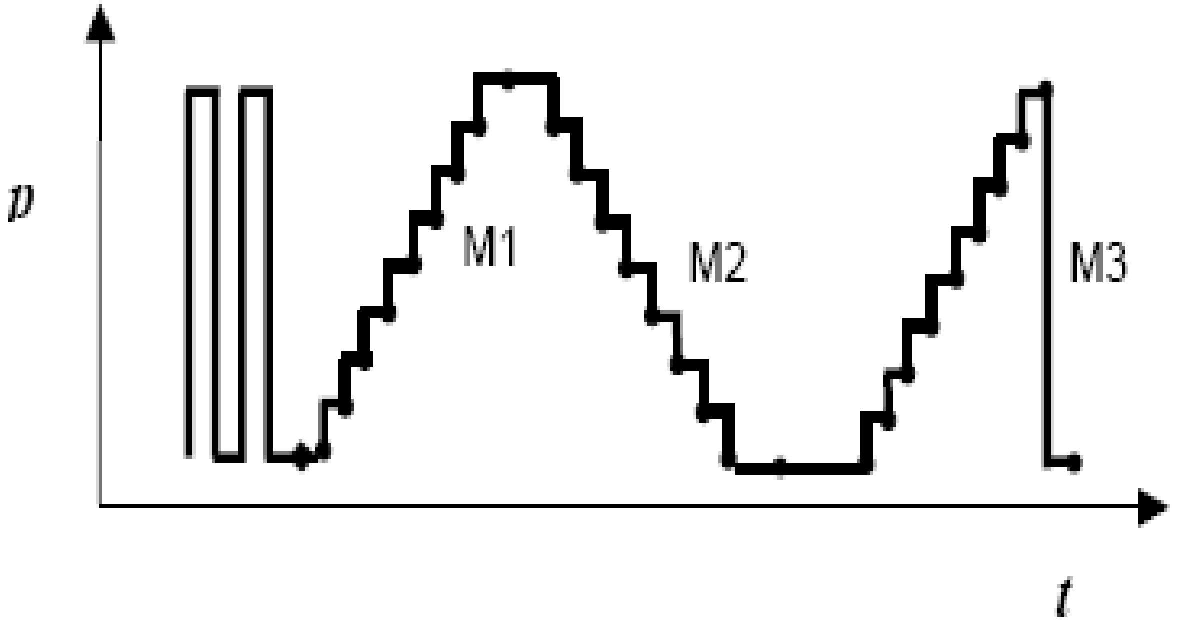
(**) One has to wait until steady-state conditions (sufficiently stable indication of standard and calibration item) are reached.

(***) For Bourdon tube pressure gauges, a waiting time of five minutes is to be observed. the waiting times can be reduced.

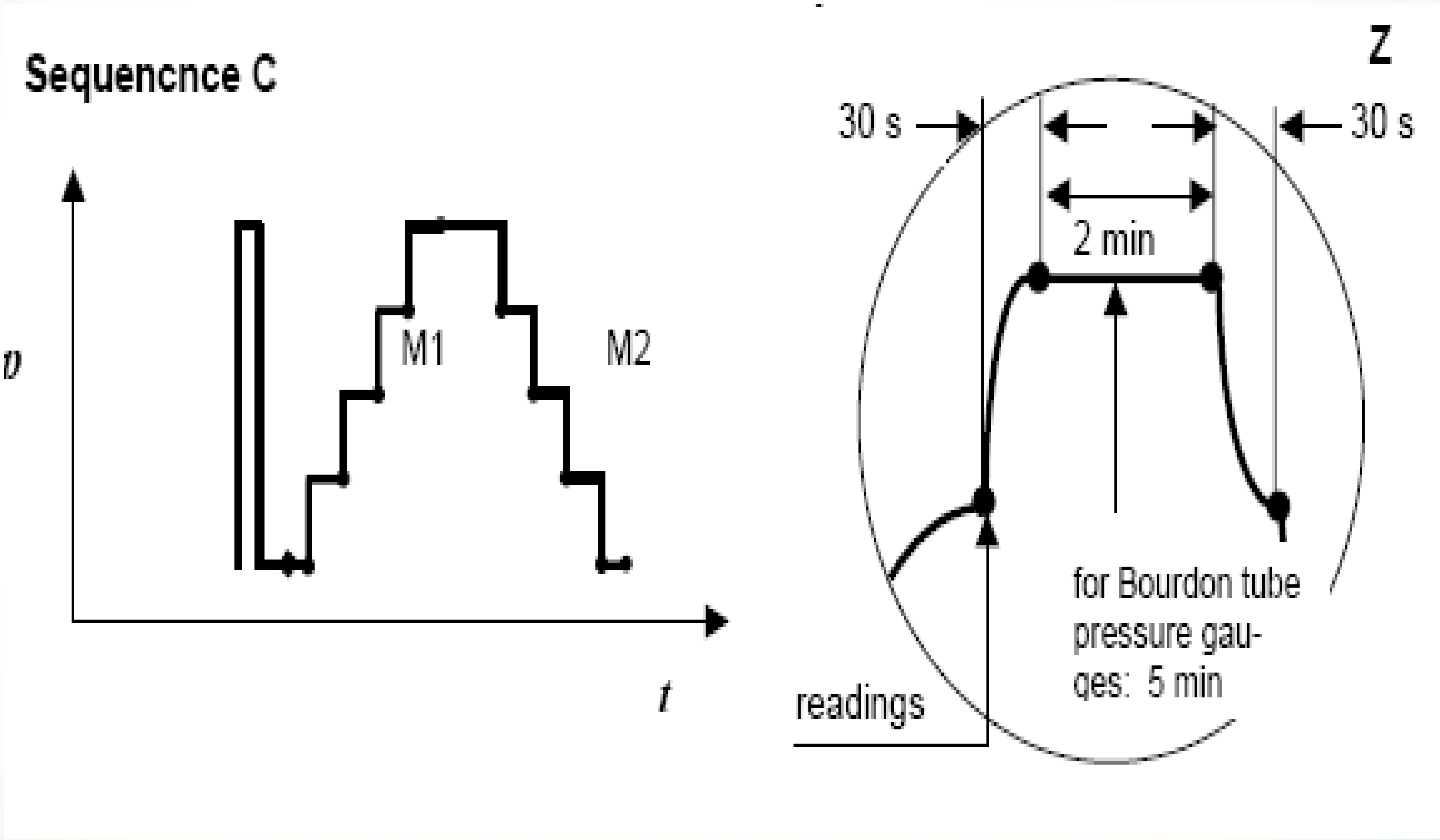
Calibration sequence A



Calibration sequence B



Calibration sequence C



Notes:

1- For the calibration of items with a range of measurement greater than 2500 bar, calibration sequence A is in principle to be used. If clamping effects are observed, the calibration is to be repeated clamping the calibration item anew.

2- Especially Bourdon tube pressure gauges have to be slightly tapped to minimize any frictional effect of the pointer system.

Period of validity (recommended)

It is the user who is responsible for fixing, and complying with, an appropriate period for repeating the calibration.

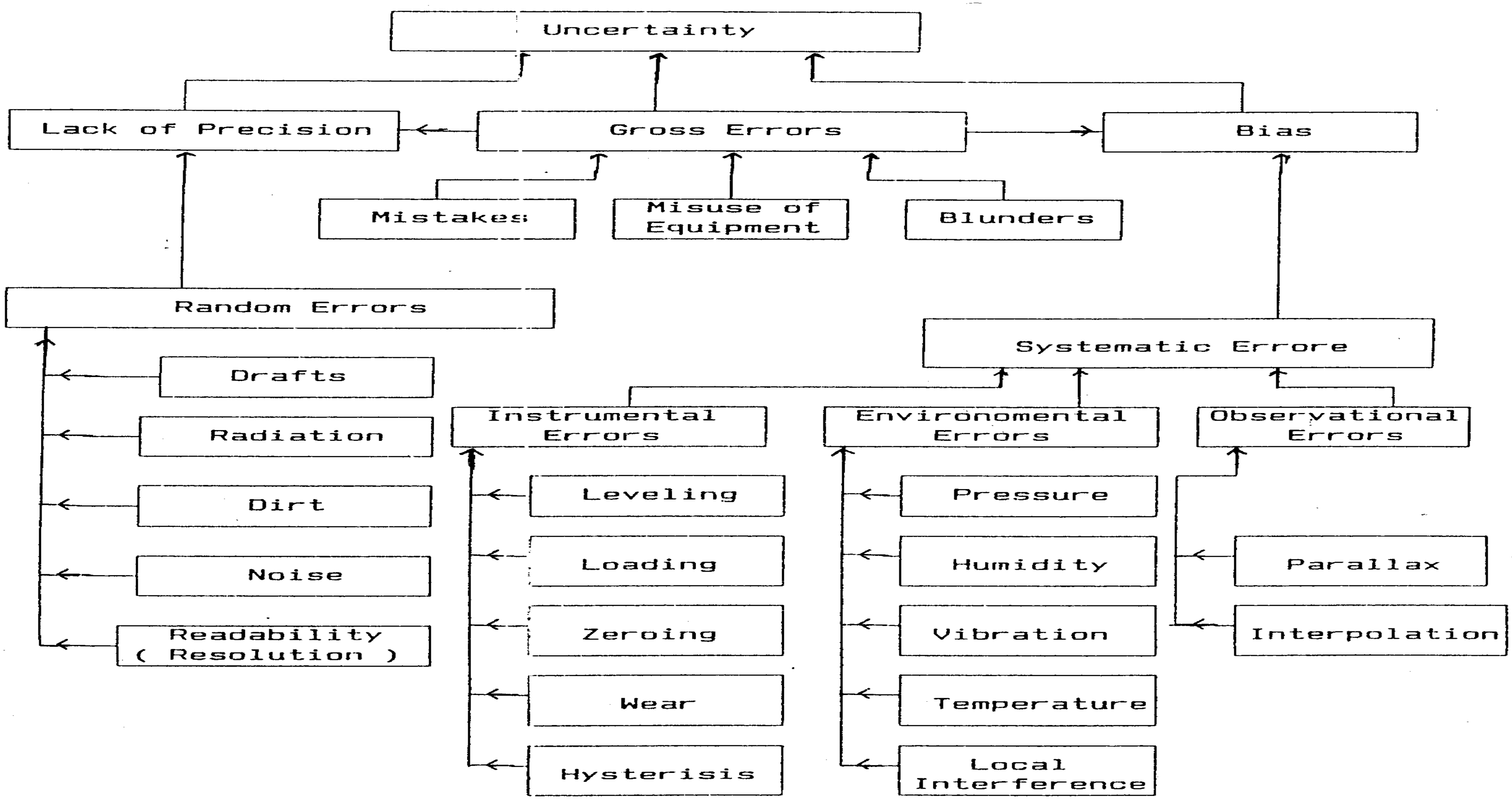
The recommended:

Pressure balances	5 years
Bourdon tube pressure gauges, class >0,6	2 years
Electrical pressure gauges > 0,5% of measurement span	2 years
Pressure transmitters with electrical output > 0,5% of measurement span	2 years
Bourdon tube pressure gauges, class ≤ 0,6	1 year
Electrical pressure gauges £ 0,5% of measurement span	1 year
Pressure transmitters with electrical output £ 0,5% of measurement span	1 year

Independently of these periods, the calibration item is to be **recalibrated**, among other things, if it has been **subjected to an overload outside its overload limits, after a repair**, **after improper handling** which might have an **effect on the measurement uncertainty** or for other reasons.

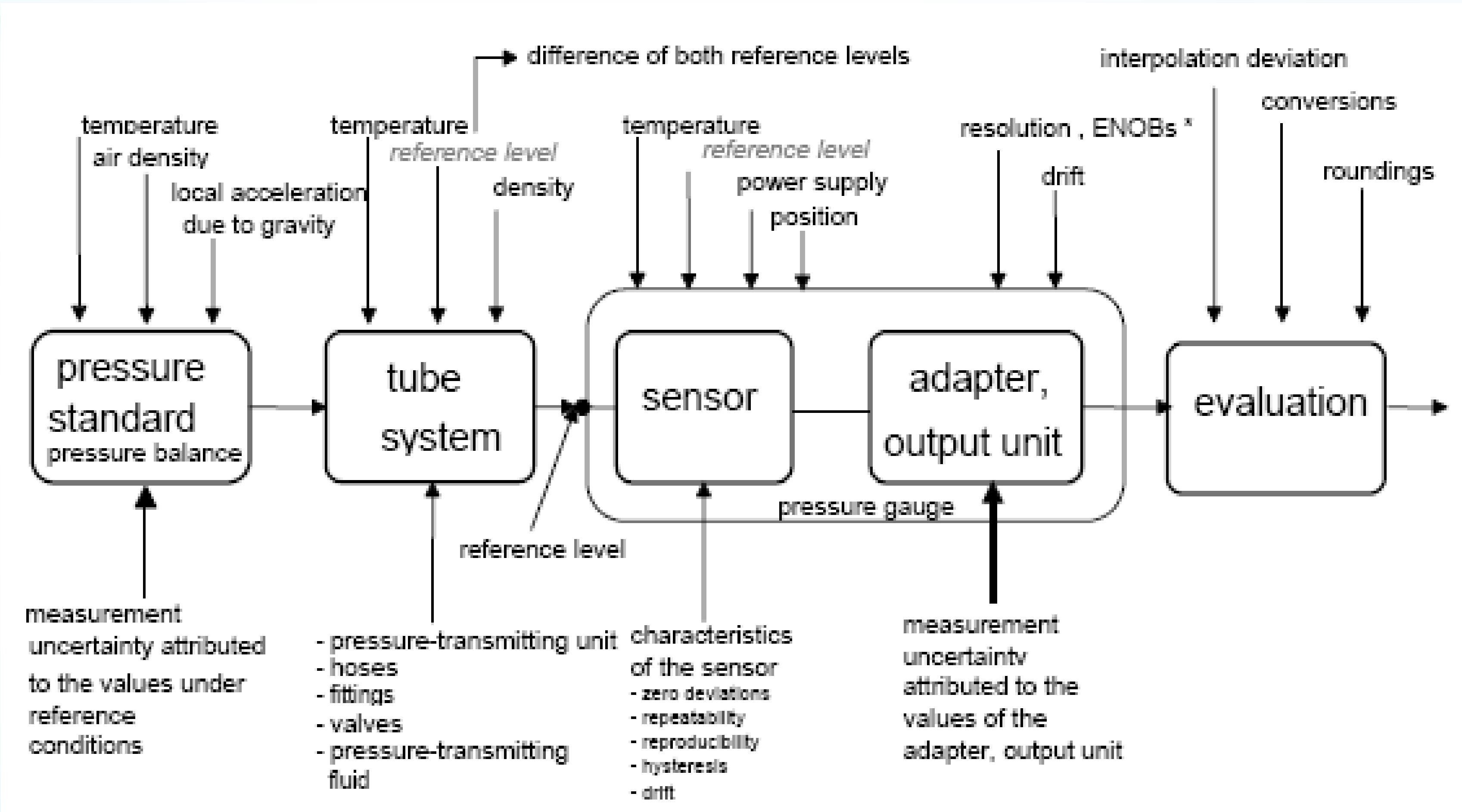
٧ - مصادر الأخطاء وحساب اللايقين

Source of Error مصادر الأخطاء



Classiffication of Measurement Errors

Influence quantities in the calibration Process



What is uncertainty of measurement?

- The uncertainty of a measurement tells us some thing about QUALITY.
- Uncertainty of measurement is the doubt which exists about the result of any measurement.
- For every measurement - even the most careful – there is always a margin of doubt.

Definitions

Uncertainty of Measurement

"parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand."

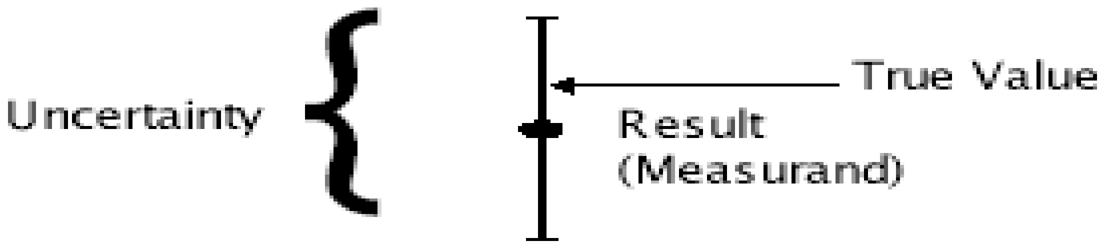
"measurand" refers to the quantity that is to be measurand

Definitions

- Uncertainty of Measurement
- An alternative definition is given in the forward to the BSI version of VIM:
  - "result of the evaluation aimed at characterising the range within which the true value of a measurand is estimated to lie, generally with a given confidence"

Definitions

- Measurement Uncertainty



Knowing then that all measurements contain error, our job is to quantify in what range do we expect our True Value to lie, and with a 95% confidence.

Expressing uncertainty of measurement

- Since there is always a margin of doubt about any measurement, we need to ask;

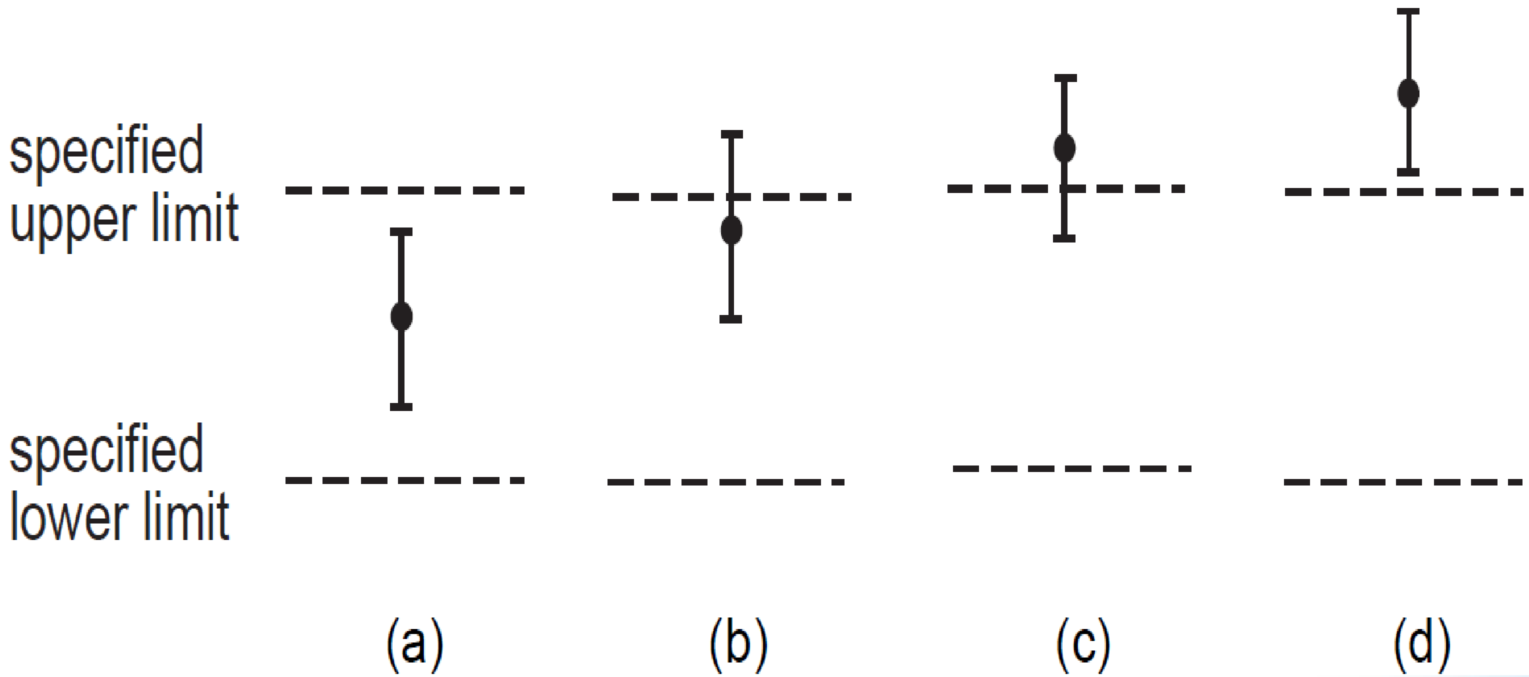
  - How big is the margin?

  - How bad is the doubt?

- Thus we need two number in order to quantify an uncertainty;

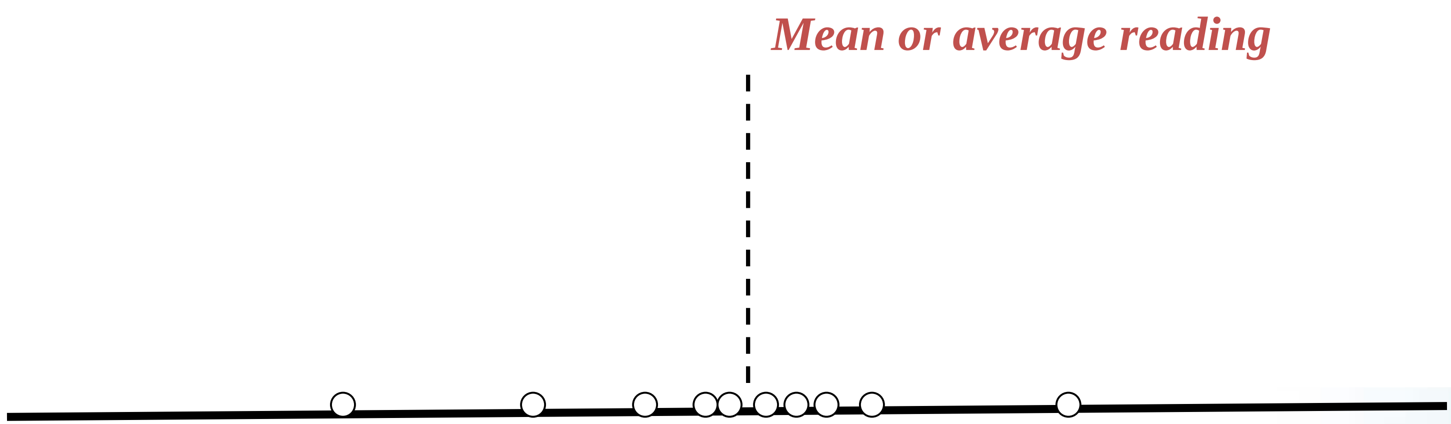
  - The width of the margin,

  - The confidence level


specified
upper limit
specified
lower limit
(a)
(b)
(c)
(d)

Average

When there is variation in reading when they are repeated, It is best to take many readings and take an average. An average gives you an estimate of the 'true' value.



How many readings do you need to find an average?

- ***The more measurements you use, the better the estimate you will have.***
- ***The more results you use, the closer you get to that ideal estimate of the mean.***

Between 4 and 10 reading is sufficient

Standard Deviation "*s*" … Spread

- When repeated measurements give different results, we want to know how widely spread the readings are.
- The spread of values tells us something about the uncertainty of a measurement.
- Sometimes it is enough to know the range between the highest and lowest values.
- The usual way to quantify spread is standard deviation.
- Roughly two thirds of all readings will fall between plus and minus (±) one standard deviation of the average.
- Roughly 95% of all readings will fall within two standard deviations.

Example

- Type A and Type B contributions
  - Type A ‘evaluated by statistical means’
    - Standard deviation

$$s \equiv \sqrt{\frac{1}{(n-1)}\sum_{j=1}^{j=n}(x_j - \bar{x})^2}$$

Where do errors and uncertainties come from?

- ***The measuring instrument:*** instruments can suffer from errors including bias, changes due to ageing, wear, or other kinds of drift, poor readability, noise, …etc.
- ***The item being measured:*** which may not be stable?
- ***The measurement process:*** the measurement itself may be difficult to make.
- ***Imported uncertainties:*** calibration of your instrument has an uncertainty which is then built into the uncertainty of the measurements you make.
- ***Operator skill:*** some measurements depend on the skill and judgment of the operator.
- ***Sampling issues:*** the measurements you make must be properly representative of the process you are trying to assess.
- ***The environment:*** temperature, air pressure, humidity and many other conditions can affect the measuring instrument or the item being measured.

The general kinds of uncertainty in any measurement

1) Random or systematic

The effects which give rise to uncertainty in measurement can be either:

- ***Random*** – where repeating the measurement gives a randomly different result. If so, the more measurements you make, and then average, the better estimate you generally can expect to get.

or

- ***Systematic*** – where the same influence affects the result for each of the repeated measurements.

The general kinds of uncertainty in any measurement

2) Distribution – the 'shape' of the errors

The spread of a set of values can take different forms, or *probability distributions*.

- ***Normal or Gaussian distribution***

If a set of readings are more likely to fall near the average than further away. This is typical of a *normal* or *Gaussian* distribution.

Example : Examined the heights in a large group of men !!!

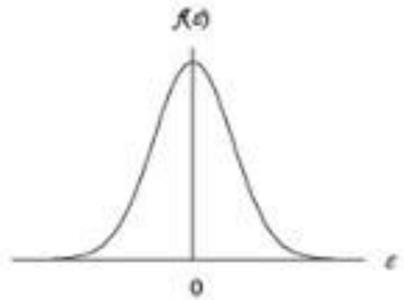
- ***Uniform or rectangular distribution***

When the measurements are quite equally spread between the highest and the lowest values, a *rectangular* or *uniform* distribution is produced.

- ***other distribution;***

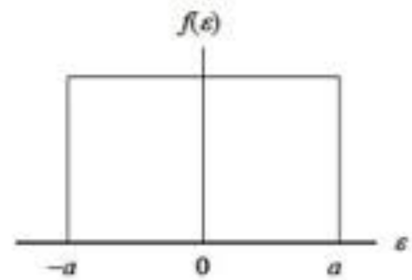
More rarely as, *triangular, M-shaped or lop-sided.*

Normal



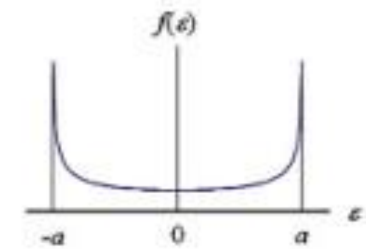
$$u = \frac{a}{k}$$

Uniform



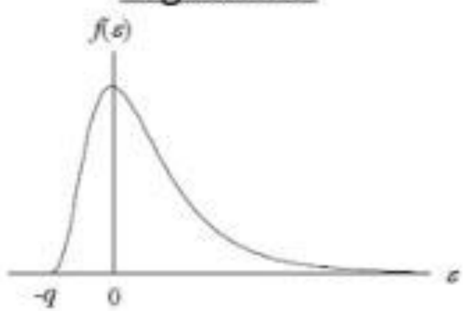
$$u = \frac{a}{\sqrt{3}}$$

U-Shaped



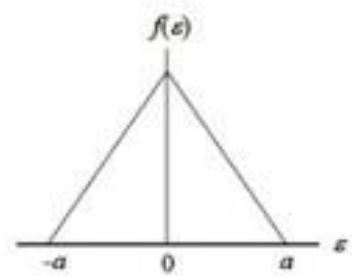
$$u = \frac{a}{\sqrt{2}}$$

Log Normal



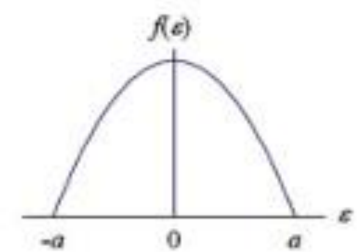
$$u = |m + q| e^{\frac{\lambda^2}{2}} \sqrt{e^{\lambda^2} - 1}$$

Triangle



$$u = \frac{a}{\sqrt{6}}$$

Quadratic



$$u = \frac{a}{\sqrt{5}}$$

What is not a measurement uncertainty?

- *Tolerances* are not uncertainties
- *Specifications* are not uncertainties
- *Accuracy (or rather inaccuracy)* is not the same as uncertainties
- *Errors* are not the same as uncertainties
- *Statistical analysis* is not the same as uncertainties

How to calculate uncertainty of measurement?

- **Identify the sources of uncertainty in the measurement.**
- **Estimate the size of the uncertainty from each source.**
- **Finally; combined the individual uncertainties to give an overall figure.**

The two ways to estimate uncertainties

There are two approaches to estimating them:

- Type A evaluations – uncertainty estimates using statistics (repeated readings)

- Type B evaluations - uncertainty estimates from any other information (experience, calibration certificates, manufacturer's specifications, calculations, published information and from common sense)

Eight main steps to evaluating uncertainty

1) Decide what you need to find out from your measurements.

   Decide what actual measurements and calculations are needed to produce the final result.

2) Carry out the measurements needed.

3) Estimate the uncertainty of each input quantity that feeds into the final results.

4) Decide whether the errors of the input quantities are independent of each other. If you think not, then some extra calculations or information are needed.

Eight main steps to evaluating uncertainty..

5) Calculate the result of your measurement (including any known corrections for things such as calibration).

6) Find the combined standard uncertainty from all the individual aspects.

7) Express the uncertainty in terms of a coverage factor, together with a size of the uncertainty interval, and state a level of confidence.

8) Write down the measurement result and the uncertainty, and state how got both of these.

Important things you should know before making an uncertainty calculation

Standard *uncertainty* ;

All contributing uncertainties should be expressed at the same confidence level, by converting them into standard uncertainties.

1) Standard uncertainty for type A evaluation, is calculated from:

$$u = \frac{s}{\sqrt{n}}$$

Where ‘s’ is the standard deviation of the mean

‘n’ is the number of measurements in the set.

Important things you should know before making an uncertainty calculation

2) Standard uncertainty for type B evaluation is calculated from:

Where the information is more scarce (in some Type B estimates), you might only be able to estimate the upper and lower limits of uncertainty. You may then have to assume the value is equally to fall anywhere in between, i.e. a rectangular or uniform distribution then;

$$u = \frac{a}{\sqrt{3}}$$

Where a is the semi-range (or half-width) between the upper and lower limits.

Rectangular or uniform distributions occur quite commonly but not all cases.

Important things you should know before making an uncertainty calculation

3) Converting uncertainties from one unit of measurement to another

Uncertainty contributions must be in the same units before they are combined

Important things you should know before making an uncertainty calculation

Combining standard uncertainties

- Summation in quadrate for addition and subtraction

$$U_{combined} = \sqrt{a^2 + b^2 + c^2 ...etc}$$

- Summation in quadrate for multiplication or division;

For more complicated cases, it can be useful to work,

The relative uncertainty u (A)/A

$$u(A)/A = \sqrt{(\frac{u(L)}{L})^2 + (\frac{u(W)}{W})^2}$$

Important things you should know before making an uncertainty calculation

Coverage factor k

k= 1 for confidence level of approximately 68 percent,

k=2.58 for confidence level of approximately 99 percent,

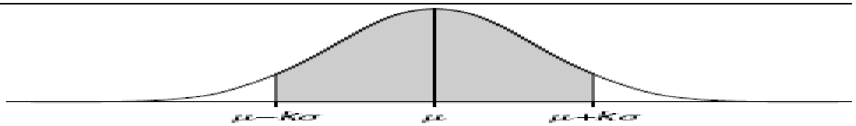
k=3 for confidence level of approximately 99.7 percent

Most commonly we scale the overall uncertainty by using the coverage factor k = 2, to give a level of confidence of approximately 95 percent.

Important things you should know before making an uncertainty calculation

Table 2.1 Area under the normal probability distribution

The percentage probability of finding x within $\mu \pm k\sigma$



k	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.00	0.80	1.60	2.39	3.19	3.99	4.78	5.58	6.38	7.17
0.1	7.97	8.76	9.55	10.34	11.13	11.92	12.71	13.50	14.28	15.07
0.2	15.85	16.63	17.41	18.19	18.97	19.74	20.51	21.28	22.05	22.82
0.3	23.58	24.34	25.10	25.86	26.61	27.37	28.12	28.86	29.61	30.35
0.4	31.08	31.82	32.55	33.28	34.01	34.73	35.45	36.16	36.88	37.59
0.5	38.29	38.99	39.69	40.39	41.08	41.77	42.45	43.13	43.81	44.48
0.6	45.15	45.81	46.47	47.13	47.78	48.43	49.07	49.71	50.35	50.98
0.7	51.61	52.23	52.85	53.46	54.07	54.67	55.27	55.87	56.46	57.05
0.8	57.63	58.21	58.78	59.35	59.91	60.47	61.02	61.57	62.11	62.65
0.9	63.19	63.72	64.24	64.76	65.28	65.79	66.29	66.80	67.29	67.78
1.0	68.27	68.75	69.23	69.70	70.17	70.63	71.09	71.54	71.99	72.43
1.1	72.87	73.30	73.73	74.15	74.57	74.99	75.40	75.80	76.20	76.60
1.2	76.99	77.37	77.75	78.13	78.50	78.87	79.23	79.59	79.95	80.29
1.3	80.64	80.98	81.32	81.65	81.98	82.30	82.62	82.93	83.24	83.55
1.4	83.85	84.15	84.44	84.73	85.01	85.29	85.57	85.84	86.11	86.38
1.5	86.64	86.90	87.15	87.40	87.64	87.89	88.12	88.36	88.59	88.82
1.6	89.04	89.26	89.48	89.69	89.90	90.11	90.31	90.51	90.70	90.90
1.7	91.09	91.27	91.46	91.64	91.81	91.99	92.16	92.33	92.49	92.65
1.8	92.81	92.97	93.12	93.28	93.42	93.57	93.71	93.85	93.99	94.12
1.9	94.26	94.39	94.51	94.64	94.76	94.88	95.00	95.12	95.23	95.34
2.0	95.45	95.56	95.66	95.76	95.86	95.96	96.06	96.15	96.25	96.34
2.1	96.43	96.51	96.60	96.68	96.76	96.84	96.92	97.00	97.07	97.15
2.2	97.22	97.29	97.36	97.43	97.49	97.56	97.62	97.68	97.74	97.80
2.3	97.86	97.91	97.97	98.02	98.07	98.12	98.17	98.22	98.27	98.32
2.4	98.36	98.40	98.45	98.49	98.53	98.57	98.61	98.65	98.69	98.72
2.5	98.76	98.79	98.83	98.86	98.89	98.92	98.95	98.98	99.01	99.04
2.6	99.07	99.09	99.12	99.15	99.17	99.20	99.22	99.24	99.26	99.29
2.7	99.31	99.33	99.35	99.37	99.39	99.40	99.42	99.44	99.46	99.47
2.8	99.49	99.50	99.52	99.53	99.55	99.56	99.58	99.59	99.60	99.61
2.9	99.63	99.64	99.65	99.66	99.67	99.68	99.69	99.70	99.71	99.72
3.0	99.73	—	—	—	—	—	—	—	—	—
3.5	99.95	—	—	—	—	—	—	—	—	—
4.0	99.994	—	—	—	—	—	—	—	—	—
4.5	99.9993	—	—	—	—	—	—	—	—	—
5.0	99.99994	—	—	—	—	—	—	—	—	—

Mainly 6 common sources of Uncertainty

3 sources from Under test

- Repeatability
- Hystresis
- Resolution

3 sources from Standard

- Standard
- Uncorrected error
- Drift of Standard

Examples

Uncertainty in Pressure Gauge

A pressure Gauge of working range 100 bar was calibrated the following Data are collected:

- Resolution of 0.5 bar
- No Diff between up and down reading
- The unc. Of Pressure Calibrator = 0.01 bar
- With drift in the calibrator =10 mbar
- The uncorrected error of standard = 17 mbar
- The repeatability of measurement gives standard deviation = 0.6 bar

Estimate the Uncertainty of the calibration of this Gauge??

Uncertainty in Pressure Gauge…

Label	Unc. Source	Value (mg)	Dist Prob.	Divisor	Ci	U (Wx) ±mg
U_{Rep}	repeatability	$\frac{0.6}{\sqrt{5}}$	Normal	1	1	0.268
U_{Rs}	Resolution	0.5×0.2	Rectangle	$\sqrt{3}$	1	0.0577
U_{hy}	Hystresis	0	Rectangle	$\sqrt{3}$	1	0
U_{Std}	standard	0.01	Normal	2	1	0.005
U_{Drif}	Drift in standard	0.01	Rectangle	$\sqrt{3}$	1	0.0058
U_{uncorr}	Uncorr. error	0.017	Rectangle	$\sqrt{3}$	1	0.0098
Uc	Combined Unc.		Normal			0.2744
UExp	Expanded Unc.		Normal			0.5488

Uncertainty in Pressure balance

- standard uncertainties for gauge mode oil piston gauge calibration at 5 MPa, REF piston gauge is PG42, of nominal area 8.4×10^{-5} m^2, and Spinesstic oil as pressure fluid. Relative combined standard uncertainty is 1.20×10^{-5} (12.0 ppm).

Uncertainty in Pressure balance ….

Uncertainty term				Sensitivity coefficient divided by $A_{e,T}$			Standard uncertainty		Rel. unc.
Name	Symbol	Value	Units	Definition	Abs Value	Units	Value	Units	on $A_{e,T}$
REF Area	$A_{e,R}$	8.402E-05	m^2	$1/A_{e,R}$	11901.89	m^{-2}	9.24E-10	m^2	**1.10E-05**
REF Mass	M_R	42.86	kg	$-1/M_R$	2.33E-02	kg^{-1}	1.24E-04	kg	**2.89E-06**
TEST Mass	M_T	42.85	kg	$1/M_T$	2.33E-02	kg^{-1}	1.24E-04	kg	**2.89E-06**
Ambient density	ρ_a	1.18	kg/m^3	$\Delta\rho_M/(\rho_{MT}\rho_{MR})$ - gh/p_T	9.80E-08	m^3/kg	0.030	kg/m^3	2.94E-09
REF mass dens.	ρ_{MR}	7800	kg/m^3	$(\rho_{a,cal}-\rho_a)/\rho_{MR}^2$	4.93E-10	m^3/kg	45.0	kg/m^3	2.22E-08
TEST mass dens.	ρ_{MT}	7800	kg/m^3	$(\rho_a-\rho_{a,cal})/\rho_{MT}^2$	4.93E-10	m^3/kg	45.0	kg/m^3	2.22E-08
Surface tension	γ	3.06E-02	N/m	$C_R/(M_R g)(D_R/D_T-1)$	9.33E-09	m/N	1.77E-03	N/m	1.65E-11
REF piston circ.	C_R	3.25E-02	m	$-\gamma/(M_R g)$	7.28E-05	1/m	3.25E-05	m	2.37E-09
TEST piston circ.	C_T	3.25E-02	m	$\gamma/(M_T g)$	7.29E-05	1/m	3.25E-05	m	2.37E-09
Gravity	g	9.801011	m/s^2	$(\rho_f-\rho_a)h/p_T$	8.57E-06	s^2/m	2.00E-06	m/s^2	1.71E-11
REF therm. exp.	$\alpha_{p,R}+\alpha_{c,R}$	9.10E-06	C^{-1}	$T_R - 23.00$	0.50	C	5.25E-07	C^{-1}	2.63E-07
TEST therm. exp.	$\alpha_{p,T}+\alpha_{c,T}$	9.10E-06	C^{-1}	$-(T_T - 23.00)$	0.50	C	5.25E-07	C^{-1}	2.63E-07
REF temperature	T_R	23.50	C	$\alpha_{p,R}+\alpha_{c,R}$	9.10E-06	C^{-1}	0.058	C	5.25E-07
TEST temperature	T_T	23.50	C	$-(\alpha_{p,T}+\alpha_{c,T})$	9.10E-06	C^{-1}	0.058	C	5.25E-07
Fluid density	ρ_f	857.8	kg/m^3	gh/p_T	9.80E-08	m^3/kg	9.91	kg/m^3	9.71E-07
Height difference	h	0.05	m	$(\rho_f-\rho_a)g/p_T$	1.68E-03	1/m	0.001	m	**1.68E-06**
Press. equilibrium	ΔP	0.00	Pa	$-1/p_T$	2.00E-07	1/Pa	5.83	Pa	**1.17E-06**
					Relative combinded standard unc.				**1.20E-05**

Thank You