The US Particle Accelerator School
Pressure Measuring Devices

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Vacuum Measurement Considerations

- Large measurement range: $760 - 10^{-13}$ Torr (16 orders of magnitude)
- Pressure is the descriptive term, rarely the important one
- High accuracy is impractical, ± 10% good enough
- Some gauges do not measure pressure directly
- Some gauges are gas species dependent
- Measured environment is usually a dynamic one
- Placement of gauge will influence its response
Vacuum Measurement

- **Total pressure gauges**
  - *Direct measurement*
    - Liquid column level
    - Solid wall movement
  - *Indirect measurement*
    - Thermal conductivity
    - Viscosity
    - Ionization

- **Partial pressure gauges**
  - *Indirect only:* ionization & mass filtering
The pressure range measured in most vacuum systems is too broad to be measured with a single gauge!

\[
\begin{align*}
1 \times 10^{-10} \text{ Torr} & \quad \text{Base Vacuum Pressure} \\
760 \text{ Torr} & \quad \text{Atmospheric Pressure}
\end{align*}
\]

1 unit is \(\sim 11,000,000,000\) [11 billion] times the other!

\[
\begin{align*}
10 \text{ meters} & \quad \text{The dimension of a room.} \\
10^9 \text{ km} & \quad \text{Distance between Earth and Saturn}
\end{align*}
\]

It is not practical to measure both with the same device.
**Units of Pressure Often Used in Vacuum Technology**

Atmospheric Pressure (Standard) =

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>760</td>
<td>Torr</td>
</tr>
<tr>
<td>760</td>
<td>mm of mercury (Hg)</td>
</tr>
<tr>
<td>29.9</td>
<td>inches of Hg</td>
</tr>
<tr>
<td>14.7</td>
<td>lbs. per square inch – abs. (psia)</td>
</tr>
<tr>
<td>0</td>
<td>psig (psi at gauge)</td>
</tr>
<tr>
<td>760,000</td>
<td>Millitorr or “microns” of Hg</td>
</tr>
<tr>
<td>101,000</td>
<td>Pascal (Newton/m²)</td>
</tr>
<tr>
<td>1.01</td>
<td>Bar</td>
</tr>
<tr>
<td>1010</td>
<td>Millibar</td>
</tr>
</tbody>
</table>
Types of Vacuum Gauges

Direct Gauges
(Displacement of a wall)

Solid Wall
- Diaphragm
- Bourdon Type
- Capacitance Diaphragm

Liquid Wall
- McLeod
- U-Tube Manometer
Types of Vacuum Gauges

Indirect Gauges
(Measurement of a gas property)

Charge Generation (Ionization) Energy Transfer (Heat Loss) Momentum Transfer (Viscosity)

Thermocouple Pirani CONVECTRON

Spinning Rotor

Cold Cathode

Penning Inverted Magnetron

Hot Cathode

Triode Schulz-Phelps Bayard-Alpert STABIL-ION
## Gauge Summary

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Measurement Mechanism</th>
<th>Operating range (Torr)</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bourdon tube/diaphragm</td>
<td>solid wall movement</td>
<td>1000s-1</td>
<td>low</td>
</tr>
<tr>
<td>Capacitance manometer</td>
<td>solid wall movement</td>
<td>10,000-10^-6</td>
<td>high</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>thermal conductivity</td>
<td>1-10^-3</td>
<td>medium</td>
</tr>
<tr>
<td>Pirani</td>
<td>thermal conductivity</td>
<td>1-10^-4</td>
<td>medium</td>
</tr>
<tr>
<td>Bayard-Alpert</td>
<td>ionization</td>
<td>10^-2-10^-11</td>
<td>medium</td>
</tr>
<tr>
<td>Penning</td>
<td>ionization</td>
<td>10^-2-10^-6</td>
<td>medium</td>
</tr>
<tr>
<td>Inverted magnetron</td>
<td>ionization</td>
<td>10^-3-10^-12</td>
<td>medium</td>
</tr>
<tr>
<td>Spinning rotor</td>
<td>momentum transfer</td>
<td>760-10^-7</td>
<td>high</td>
</tr>
</tbody>
</table>
Medium and Low Vacuum: $10^{-3}$ Torr to 1000 Torr

- Direct Gauges - Displacement of a Solid Wall
  - Capacitance Diaphragm Gauge
- Indirect Gauges - Heat-Loss Gauges
  - Thermocouple Gauge
  - Pirani Gauge
  - CONVECTRON Gauge (Convection-Enhanced Pirani)

Ultra-High and High Vacuum: $10^{-11}$ Torr to $10^{-3}$ Torr

- Indirect Gauges - Ionization Gauges
  - Hot Cathode Gauge
  - Cold Cathode Gauge
Bourdon Tube & Diaphragm Gauges

Distinguishing features & operating characteristics:

- Measures pressure directly
- Operating range above atm pressure to 1 Torr
- Indicated value is independent of gas specie being measured
- System of gears & levers transmit the movement of a small tube or wall to a pointer
- Can be constructed such that all parts exposed to vacuum are stainless steel
- Optionally configured as a compound gauge
- Bourdon tube often used as an indicator of system status
- For safety reasons: Bourdon tube recommended for most systems
Bourdon Tube Gauge Components

- Scale
- Pointer
- Bourdon Tube
- Gear Sector
- Pinion
- Hair Spring
- Gear Sector & Pinion
- Base
- Connecting Link
- To Vacuum System

Image of Bourdon tube gauges.
Diaphragm Gauge Components

- Pointer & Pointer Gear
- Sector Gear
- Fixed Block
- Flexure Pivot
- Counterweight
- Connecting Rod
- Capsule
Operating Ranges for Heat-Loss Gauges

Pressure Range Comparison of Heat-Loss Sensors

Thermocouple

Pirani

CONVECTRON

Pressure Range

Torr

atmosphere

0 200 400 600 800 1000
Heat-Loss or Energy Transfer

- Heated element cools as molecules strike.

- Higher pressure means increased cooling of sensor.

- Gas species dependent.
Thermocouple gauge

Distinguishing features & operating characteristics:

- Indirectly measures pressure via thermal conductivity of gases
- Operating range 1 Torr to $10^{-3}$ Torr
- Indicated value is gas dependent
- Constant current is delivered to a wire & it’s temperature is measured by a thermocouple
- Thermocouple voltage is read on a pressure scale
- Not capable of good measurements above 1 Torr
- Rugged design, inexpensive, however somewhat inaccurate
Thermocouple Gauges

- Constant current through the heater (sensor).

- TC junction measures temperature changes.

- Slow response time.
Pirani Gauges

Distinguishing features & operating characteristics:

- Indirectly measures pressure via thermal conductivity of gases
- Operating range 1 to $10^{-4}$ Torr
- Indicated value is gas dependent
- Resistance heated wire which is part of a Wheatstone bridge
- Pirani gauge that is sensitive to convection heat losses is available
- This gauge's operating range is 1000 to $10^{-4}$ Torr
Pirani Gauge

- Wheatstone bridge with sensor as one leg of bridge.
- Current through sensor changes to maintain balance.
- Reads to ~100 Torr.
Convection Enhanced Pirani Gauge – CONVECTRON® Gauge

- Similar principle to pirani.
  - Conductive heat loss (10^{-3} Torr to ~100 Torr)
  - Adds convective heat loss (~100 Torr to 1000 Torr.)

- Improved temperature compensation.

- Gold plated tungsten sensor.
CONVECTRON Gauge Benefits

- **Wide Measurement Range:**
  \[10^{-3} \text{ Torr} - 1000 \text{ Torr}\].
- Individual calibration.
- Accurate, fast measurement.
- Long term stability.
- Recalibrate for contaminated gauge or after cleaning gauge.
- Very reliable - industry standard.
CONVECTRON Gauges - Drawbacks

- Gas dependent
- Sensitive to orientation
- S-curve, analog output
- Fragile
- Corrosive gases - attacked by fluorine, chlorine, mercury
Capacitance Manometers

Distinguishing features & operating characteristics:

- Measures pressure directly
- Operating range 10,000 to $10^{-6}$ Torr, with different ranged sensors
- Indicated value is independent of gas being measured
- Diaphragm gauge that senses the change in capacitance of a circuit which contains the diaphragm wall as an active element
- Deflections of the diaphragm as small as one Å can be sensed
- Available in several ranges with differing resolution
- Measurements requiring a high degree of accuracy use heated sensors
- High precision work requires frequent "zeroing"
Ionization of Gases

- Gas atoms and molecules are normally without charge or "neutral", they have equal numbers of protons and electrons.

- If one or more electrons are removed from an atom it becomes positively charged and we call it an ion.

- Numerous processes in vacuum technology utilize energetic free electrons to strip atoms of some of their electrons, thus creating ions.

- Ions, being positively charged, can be manipulated by magnetic and electrical fields.

- An atom has a probability of being ionized that is dependent on the atom itself and the energy of the colliding electron. The ionization cross section quantifies the probability of ionization.
Ionization Gauges

- At pressures below $10^{-5}$ Torr (high vacuum) direct measurement of pressure is very difficult

- Thermal conductivity gauges have exceeded their operational limits

- Primary method for pressure measurement from $10^{-4}$ to $10^{-12}$ Torr is gas ionization & ion collection/measurement

- These gauges can be divided into hot & cold cathode types

- Most common high vacuum gauge today is the Bayard-Alpert
Ionization Gauge Principle of Operation

- Incident electron current
- Gas molecules
- Ions
- Ion collector
- Electrometer
- Ion current
- Collector bias
Hot Cathode Ionization Gauge, Basics

- Hot filament (cathode) emits electrons.
- Molecules are ionized and collected.
- Pressure reading is determined by the electronics from the collector current.
Gauge Sensitivity

**Gauge Sensitivity:** A constant that indicates how well a gauge creates ions.

- **Ion gauge equation:**
  
  \[ P = \frac{i_+}{i_e \cdot S} \]

  where:
  
  \[ i_+ = \text{ion current} \]
  
  \[ i_e = \text{emission current} \]
  
  \[ S = \text{sensitivity} \]

- **Sensitivities of B-A Gauges**
  
  - Glass Gauge and Standard Nude Gauge \( \sim 10/\text{Torr} \)
  
  - UHV Nude Gauge \( \sim 25/\text{Torr} \)
Emission Current

- Emission current = Electron Current ≈ No. of electrons

- A variable controlled by the electronics

\[ P = \frac{i_+}{i_e \cdot S} \]
What Emission Current Should Be Used?

- Selected, based on measurement range

- Typical emission settings for B-A gauges:
  - High pressure: \( i_e = 0.1 \text{ mA} \)
  - Widest pressure range: \( i_e = 1 \text{ mA} \) (default)
  - UHV range: \( i_e = 10 \text{ mA} \)

- Typical problems:
  - High emission + high pressure = gauge off
  - Low emission + low pressure = “nervous” display
X-Ray Limit

- Lower limit of the gauge
- Low accuracy readings near the x-ray limit
- Select gauge with x-ray limit 5 to 10 times lower than lowest pressure
- Only an issue for UHV measurement at $P < 1 \times 10^{-9}$ Torr
Filament Selection

- **Thoria-coated Iridium**
  - General purpose
  - Operates cooler (~900° C)
  - Burn-out resistant

- **Tungsten**
  - Special purpose
  - Operates hotter (~1200° C)
  - Burns out easily and oxidizes when exposed to atmosphere
Granville-Phillips Series 274: Glass B-A Gauge

- Filaments: single thoria-coated iridium, or dual tungsten
- Sensitivity: 10/Torr.
- Helical grid: EB or I²R degas.
- X-ray limit: < 3 x 10⁻¹⁰ Torr
- Port diameter: 3/4 in. or 1 in.
- Vacuum connections: straight tube, NW25, 1.33 in. ConFlat-type (16CF), 2.75 in. ConFlat-type (35CF)
Granville-Phillips Series 274:
Nude B-A Gauge

- Filaments: single thoria-coated iridium, replaceable
- Sensitivity: 10/Torr
- Helical grid: EB or resistive degas
- X-ray limit: about 4 x 10^{-10} Torr
- Flanges: NW40, 2.75 in. ConFlat-type (35CF)
- Available with pin-guard
Granville-Phillips Series 274: UHV Nude B-A Gauge

- Filaments: dual thoria-coated iridium, or dual tungsten, replaceable.
- Enclosed grid: EB degas only
- X-ray limit: about $2 \times 10^{-11}$ Torr
- Flanges: NW40, 2.75 in. ConFlat-type (35CF)
- Available with pin-guard
STABIL-ION Gauge Design

- Rugged Steel Enclosure
- Guard
- Self-aligning Connector
- Port Shield
- Tensioned Filaments
- Precision-wound Grid
**STABIL-ION Gauge Types**

- **Extended Range Gauge**
  - $1 \times 10^{-9}$ to $2 \times 10^{-2}$ Torr
  - x ray limit: $< 2 \times 10^{-10}$ Torr
  - Highest accuracy & stability
  - Sensitivity: 50/Torr

- **UHV Gauge**
  - $10^{-11}$ to $10^{-3}$ Torr
  - x ray limit: $< 2 \times 10^{-11}$ Torr
  - Less accurate & stable than Extended Range Gauge
  - Sensitivity: 20/Torr

Only design difference is collector diameter

- Extended Range: 0.040 inches
- UHV: 0.005 inches
Advertised Accuracy of $\textit{STABIL-ION}$ Gauge

- 370120 with 370 controller = +/-4% of reading
- 360120 with 360 controller = +/-6% of reading [mid-scale pressures]
- 360120 with other controllers such as 347 module or older style Series 303, 307, or 350 = ~+/-15% of reading
- Independent Labs [Sandia & PTB] report better accuracy levels than the manufacturer
MICRO-ION™ Gauge Design

Electrode Assembly
  Grid Top End Cap
  Grid Supports (2)
  Ion Collectors (2)
  Grid Bottom End Cap
  Collector Shield
MICRO-ION™ Gauge: Wide Measurement Range

- X-ray limit: < 3 x 10^{-10} Torr (< 4 x 10^{-10} mbar).
- Upper pressure limit: 5 x 10^{-2} Torr/mbar.
- Stable behavior at pressures > 1x10^{-3} Torr/mbar.
- Useable in place of glass and nude B-A gauges.
- Good overlap with low vacuum (> 1x10^{-3} Torr/mbar) gauges such as CONVECTRON.
Bayard-Alpert Ionization gauge

Distinguishing features & operating characteristics:

- Measures pressure indirectly
- Operating range is $10^{-3}$ to $10^{-11}$ Torr
- Indicated value is gas dependent
- Gas ionization from electron impact & then ion collection
- Three electrode geometry
- Hot cathode (filament)
- Two configurations available, tubulated & nude
Bayard-Alpert gauge (continued)

Pressure \( (P) = \left( \frac{1}{S} \right) \left( \frac{i_c}{i_e} \right) \)

\( S \) = sensitivity of the gauge, units are reciprocal pressure

Different sensitivities for different gas species

Accurate to +/- 50%, better with calibration

Low pressure measurement limited by residual currents
  X-ray effect
  EID
  Insulator leakage
Bayard-Alpert gauge components

Bayard-Alpert Gage
Side-By-Side Filaments

Bayard-Alpert Gage
Opposed Filaments
Ionization Gauges

- Glass tubulated
  - Pumping capacity can mask true pressure
  - About one third the price of a nude gauge
- Nude
  - More robust
  - Placed directly into environment, pumping is minimized
  - Filaments are replaceable
  - Higher sensitivities & can measure lower pressures (UHV)
  - Larger variation in sensitivity
Penning gauge

- Measures pressure indirectly
- Operating range $10^{-2}$ to $10^{-7}$ Torr
- Indicated value is gas dependent
- Cold cathode (no hot filament)
- Penning discharge: crossed electrical & magnetic fields to enhance ionization efficiency
- Discharge current is used as a measure of pressure
- $S = \frac{I_c}{p^n}$ \hspace{1cm} $1.1 < n < 1.4$ \hspace{1cm} pressure-current relationship is nonlinear
- Does not produce gases like a hot filament gauge
- Difficult to start & maintain discharge at pressures $< 10^{-6}$ Torr
- Discharge mode “hopping” may confuse pressure indication
- Less accurate and less stable than a B-A gauge
Penning gauge (cutaway and circuit)
Spinning Rotor Gauge (SRG)

- Also called the molecular drag gauge (MDG)
- Measures pressure indirectly
- Operating range $10^{-2}$ to $10^{-7}$ Torr
- Indicated value is gas dependent (viscosity)
- Works by the principle of momentum transfer
- Utilizes a magnetically levitated, spinning, steel 4mm ball
- Ball rotation is slowed by gas collisions & measured
- Vibration sensitive
- Requires 30 seconds to 5 minutes to make a measurement
- Very good accuracy and linearity
- Often used in laboratories for calibration transfer standard
Spinning Rotor Gauge (SRG)

From *Handbook of Vacuum Science and Technology*, Hoffman
Inverted Magnetron Gauge

- Measures pressure indirectly
- Operating range $10^{-3}$ to $10^{-12}$ Torr (note low pressure)
- Indicated value is gas dependent

- Cold cathode (no hot filament)
- Ion current & pressure are not linearly related
- Same advantages as Penning, improvement on drawbacks
- Electrode geometry evolved from Penning configuration
- Anode changed to a rod and auxiliary (shield) cathode added
- Less accurate & reproducible than Bayard-Alpert
Inverted Magnetron Cut-away with Circuitry

- **Anode**
- **Auxiliary cathode**
- **Ion collector**
- **Ion current amplifier**

5-10 kV

B
Partial Pressure Gauges

- Determine the composition of gases in a vacuum environment
- Usually qualitatively, sometimes quantitatively
- Mass spectrometer
- Amount of ions vs. mass/charge ratio (m/e or m/q)
- AMU - atomic mass unit  $C_{12}$ is exactly 12 AMU
- PPA & RGA
- Analytical mass spectrometer
- $N_2^+$ m/e = 28.0061  $CO^+$ m/e = 27.9949
Partial Pressure Gauges (continued)

- PPA components
  - Ionizer
  - Mass filter
  - Detector
- Common types of PPAs
  - Quadrupole
  - Magnetic sector
  - Time of flight
Quadrupole mass filter.
Analysis of Mass Spectra

- Fragmentation or cracking patterns
  - Dissociative ionization
  - Isotopes
  - Multiple ionization
  - Combined effects
- Cracking patterns are dependent on instrumental parameters
- Be careful with tabulated patterns
- Beware of instruments that convert ion currents to partial pressures