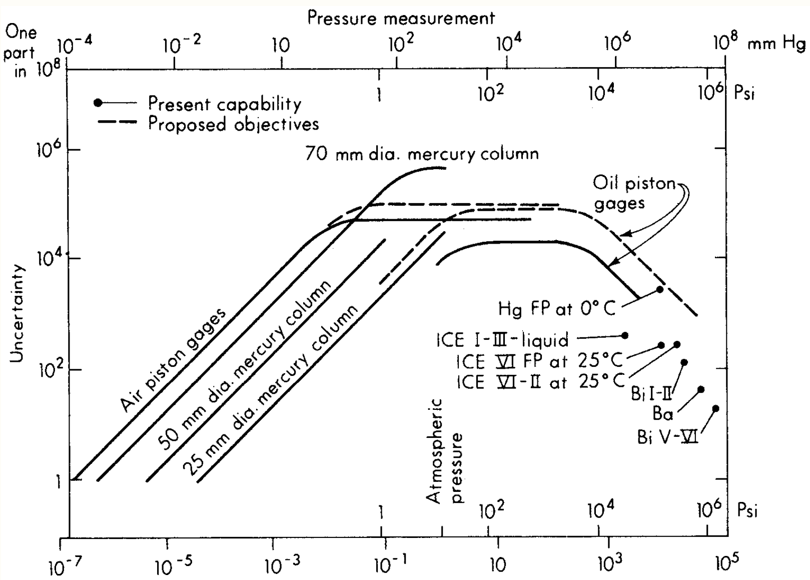
NTU50235100

# PRESSURE MEASUREMENT

04/23 周元昉

NTU50235100

## Standards and Calibration

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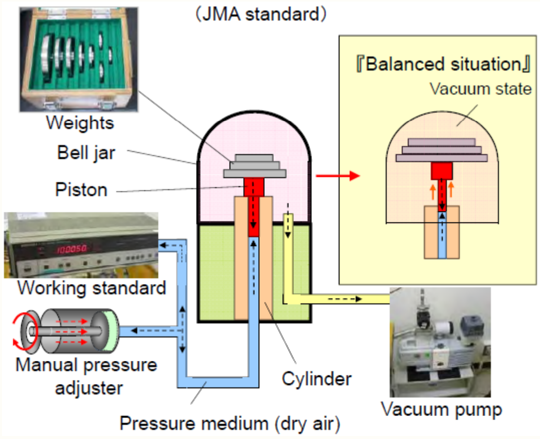
# Air piston gage

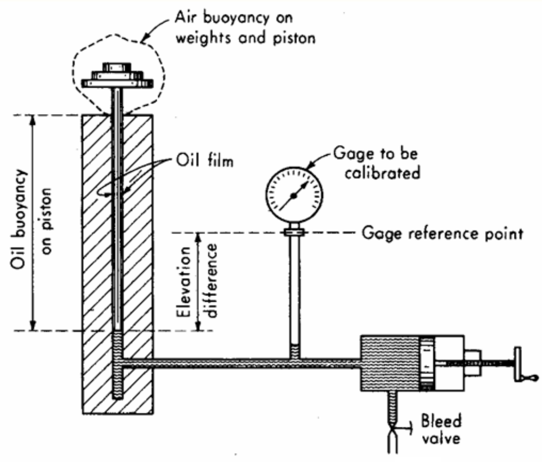



It produces an accurate level of pressure by balancing the vacuum section (the upper part) and the constant-pressure section (the lower part). Pressure in the lower section is determined by placing an approved high accuracy weight on the upper section. Pressure in the lower section is adjusted with the vacuum pump and pressure adjuster so that it balances with the weight on the upper section. The pressure in the lower section is led to the air inlet of the pressure gauge to be calibrated.





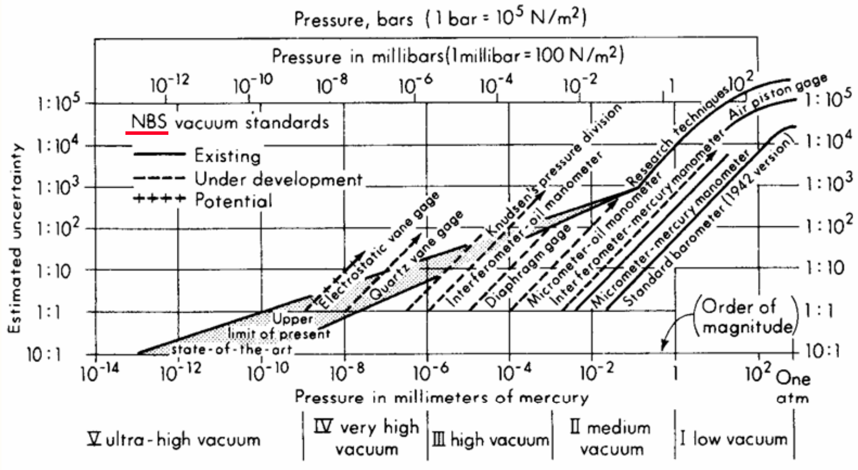
# Oil piston gage




The pressure under the piston

$$p = \frac{Mg(1 - \rho_a/\rho_m) + \gamma C}{A_0[1 + (\alpha_c + \alpha_p)(T - T_r)](1 + bp_n)[1 + d(p_z - p_j)]}$$

Ref: Vern E. Bean, *NIST MEASUREMENT SERVICES: NIST Pressure Calibration Service*, NIST Special Publication 250-39, 1994.




Note: The National Bureau of Standards (NBS) of US was established by US Congress in 1901.
Its name was changed to the National Institute of Standards and Technology (NIST) in 1988.



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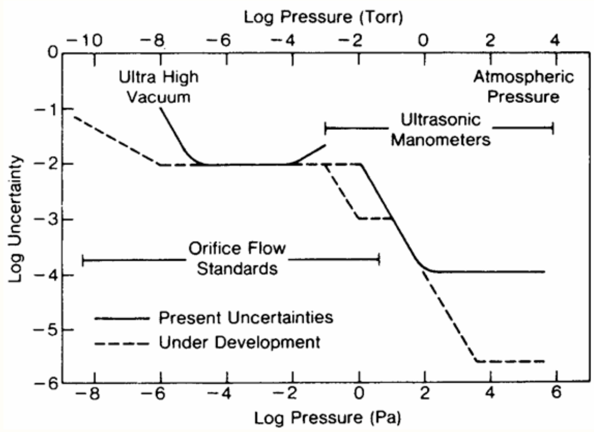
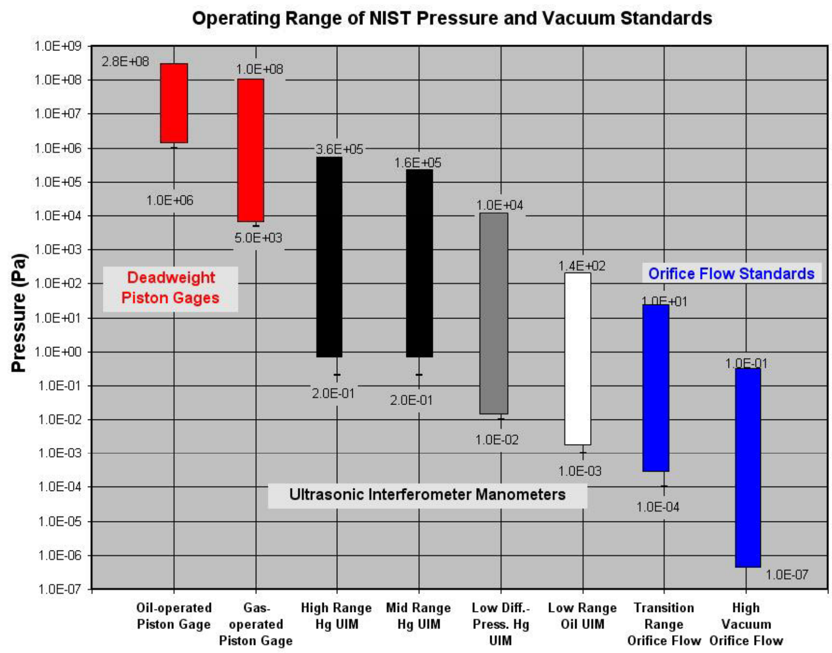



High vacuum calibration system
(Sandia National Lab.)

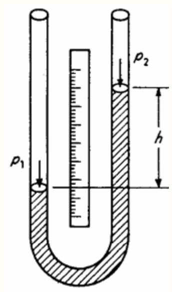




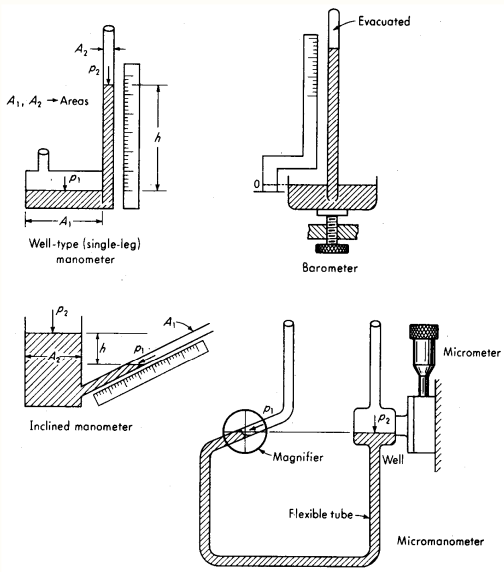



# Pressure Gages

- Direct reading gages
  - Manometers

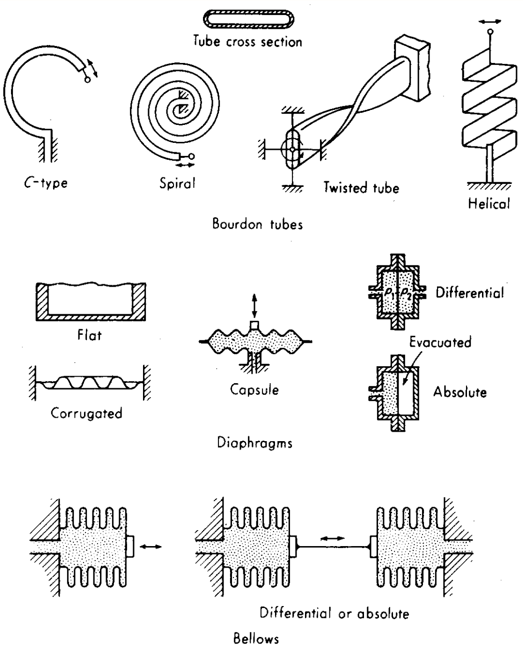



$$h = \frac{p_1 - p_2}{\rho g}$$

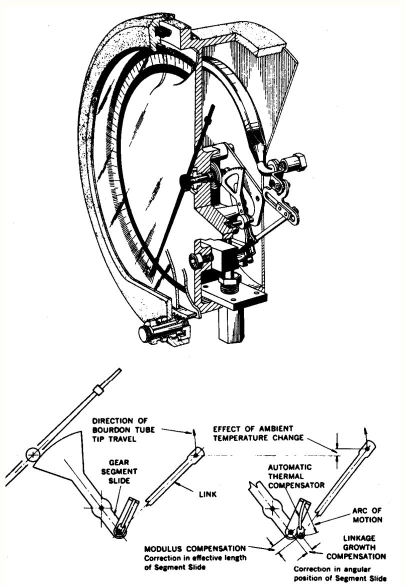



- Different fluid provides different uncertainty

• Elastic pressure transducers



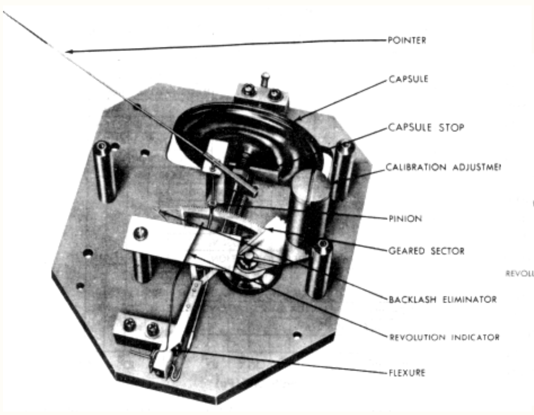

Bourdon-tube gage (0.1% accuracy)



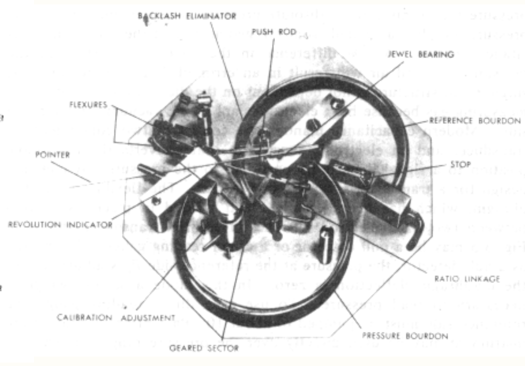




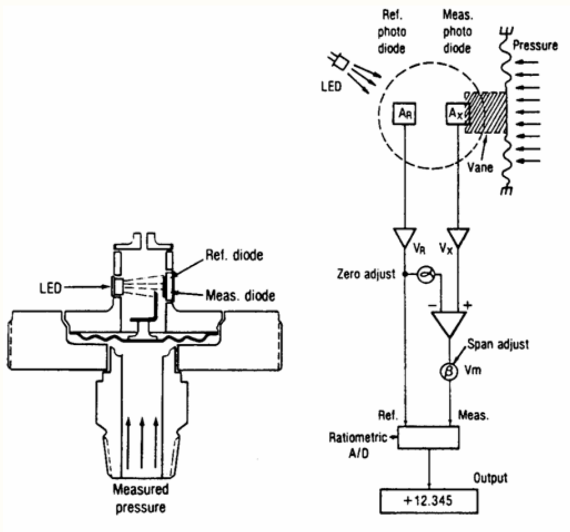

• Diaphragm and Bourdon gages



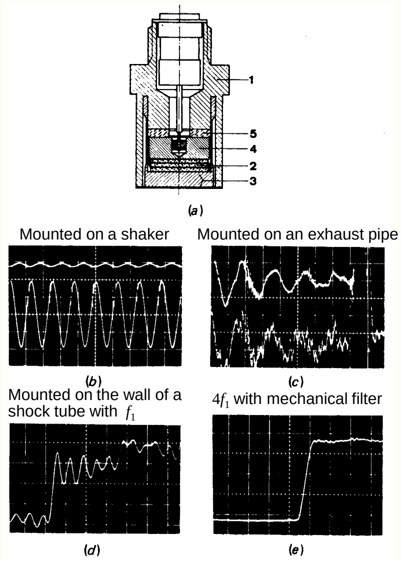

Diaphragm gage




Bourdon gauge




Electro-optic pressure transducer




Piezoelectric transducer with acceleration compensation





- Strain gage pressure sensors

$$p = \frac{16Et^4}{3R^4(1-\nu^2)}\left[\frac{y_c}{t} + 0.488\left(\frac{y_c}{t}\right)^3\right]$$

where
$p \triangleq$ pressure difference across diaphragm
$E \triangleq$ modulus of elasticity
$t \triangleq$ diaphragm thickness
$\nu \triangleq$ Poisson's ratio
$R \triangleq$ diaphragm radius to clamped edge

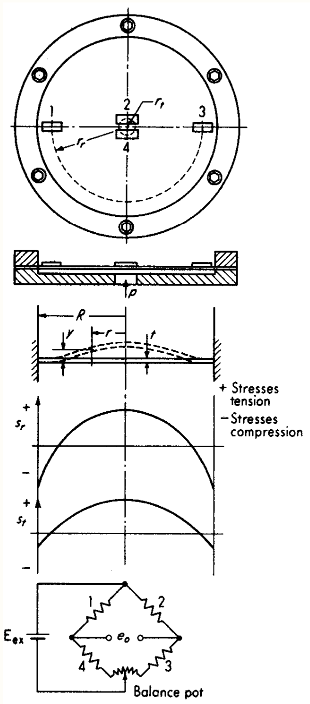
$$s_r = \frac{3pR^2\nu}{8t^2}\left[\left(\frac{1}{\nu}+1\right) - \left(\frac{3}{\nu}+1\right)\left(\frac{r}{R}\right)^2\right]$$

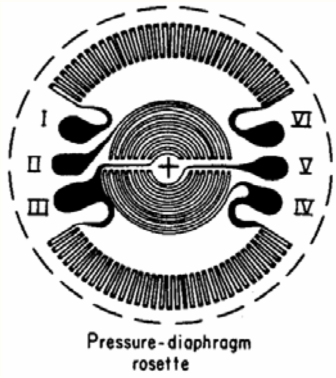
$$s_t = \frac{3pR^2\nu}{8t^2}\left[\left(\frac{1}{\nu}+1\right) - \left(\frac{1}{\nu}+3\right)\left(\frac{r}{R}\right)^2\right]$$

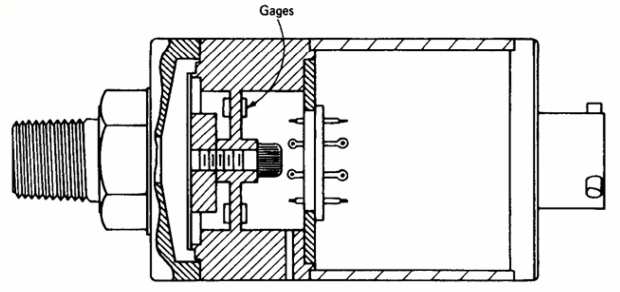
$$y = \frac{3p(1-\nu^2)(R^2-r^2)^2}{16Et^3}$$

$$\omega_n = \frac{10.21}{CR^2}\sqrt{\frac{Et^2}{12\rho_d(1-\nu^2)}} \quad \text{rad/s}$$

$$C \triangleq \sqrt{1 + 0.669\frac{\rho_f}{\rho_d}\frac{R}{t}}$$



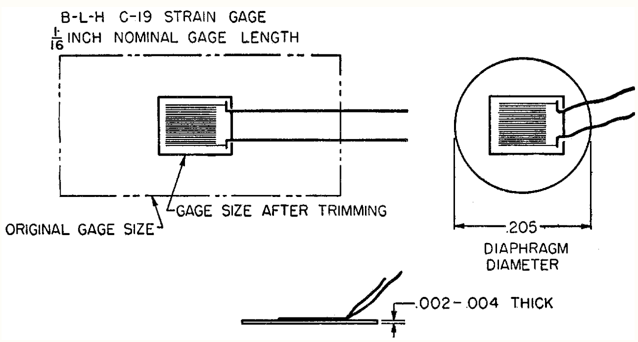


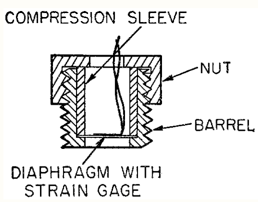



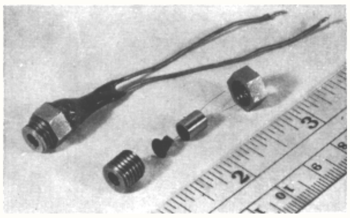





- Miniature pressure transducer

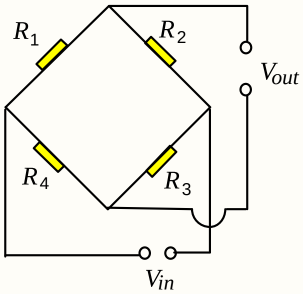


# •The Wheatstone Bridge

Bridge output $V_{out} = \dfrac{R_1R_3 - R_2R_4}{(R_1+R_2)(R_3+R_4)}V_{in}$




For a balanced bridge

$R_1R_3 = R_2R_4$ and $V_{out} = 0$

Resistance change $\Delta R_1, \Delta R_2, \Delta R_3, \Delta R_4$

$$V_{out} = \frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)(1-\eta)V_{in}$$

where $\eta = \dfrac{1}{1 + \dfrac{1+r}{\left(\dfrac{\Delta R_1}{R_1} + \dfrac{\Delta R_4}{R_4}\right) + r\left(\dfrac{\Delta R_2}{R_2} + \dfrac{\Delta R_3}{R_3}\right)}}$ and $r = \dfrac{R_2}{R_1} = \dfrac{R_3}{R_4}$





For $\Delta R << R$ , that is $\eta \to 0$

$$V_{out} = \frac{r}{(1+r)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)V_{in}$$

• Constant current source

$$V_{out} = \frac{R_1R_3 - R_2R_4}{R_1 + R_2 + R_3 + R_4}I_{in}$$

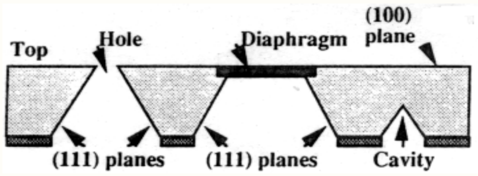
$$V_{out} = \frac{R_1R_3}{\Sigma R + \Sigma\Delta R}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} + \frac{\Delta R_1}{R_1}\frac{\Delta R_3}{R_3} - \frac{\Delta R_2}{R_2}\frac{\Delta R_4}{R_4}\right)I_{in}$$

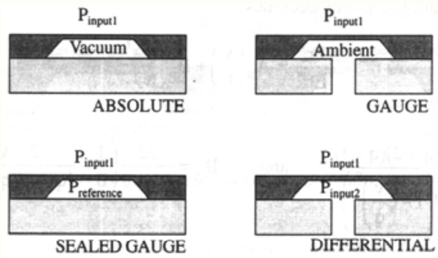
$\Sigma R = R_1 + R_2 + R_3 + R_4$ $\Sigma\Delta R = \Delta R_1 + \Delta R_2 + \Delta R_3 + \Delta R_4$

For $\Delta R << R$ , $V_{out} = \dfrac{R_1R_3}{\Sigma R}\left(\dfrac{\Delta R_1}{R_1} - \dfrac{\Delta R_2}{R_2} + \dfrac{\Delta R_3}{R_3} - \dfrac{\Delta R_4}{R_4}\right)I_{in}$

• Silicon based piezoresistor pressure sensors

Anisotropic etching of single crystalline silicon

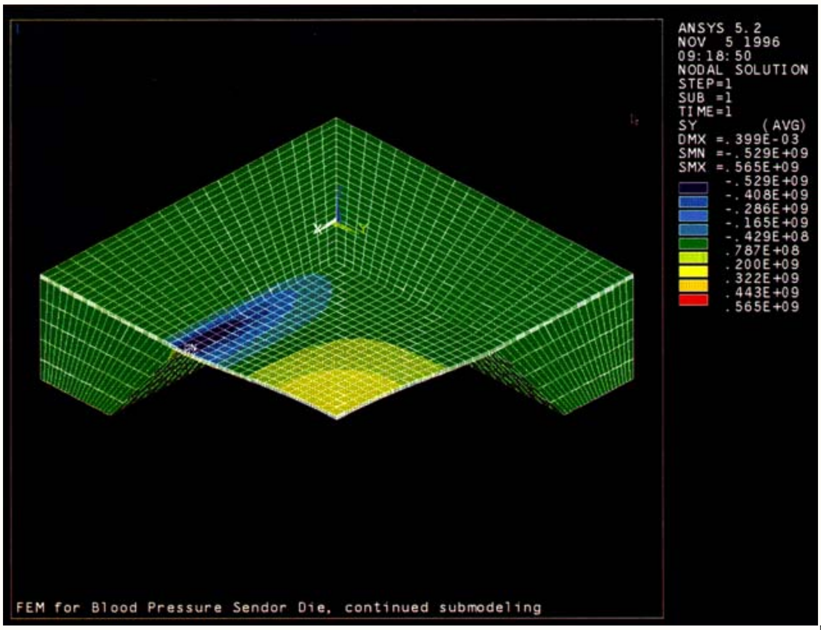


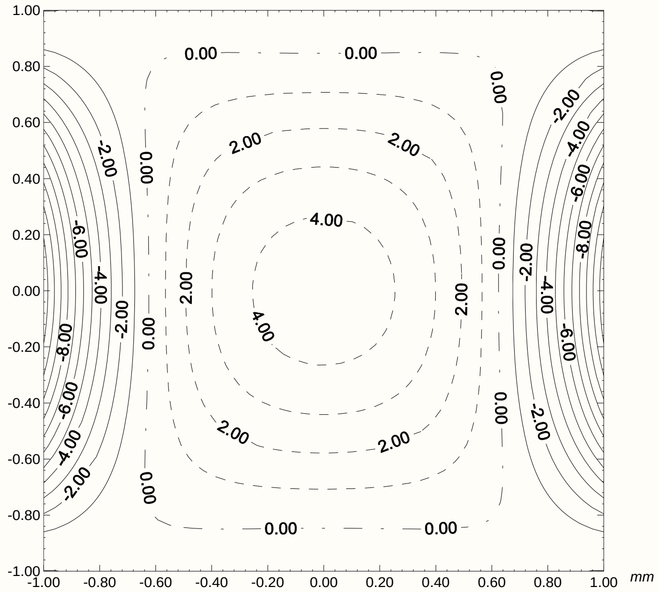





Normal stress distribution of a square plate



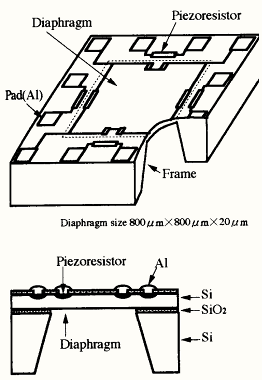
Contour of normal stress in [011] direction ($MPa$)



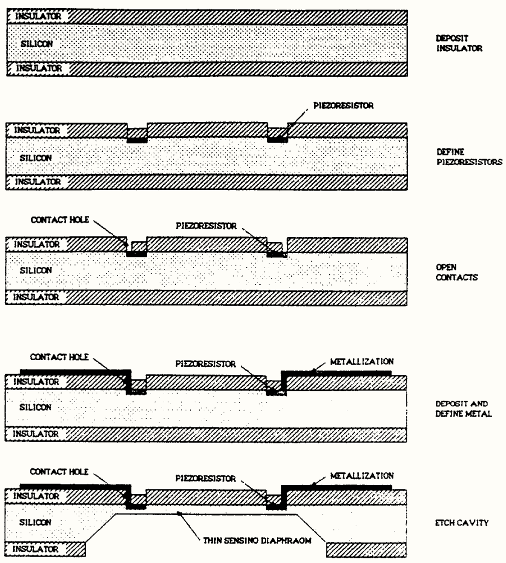





- Fabrication of silicon based piezoresistor pressure sensors




(Lee et. al., Transducers ’95, 379-C9, 1995)




(Brysek et. al., *Silicon Sensors and Microstructures*, Nova sensor, 1990 )

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• General Design Considerations

- Plate dimensions – sensitivity, strength, frequency response
  - maximize *a/h*: large aspect ratios give the best pressure sensitivities
  - $h_{\min} < h$ : fabrication considerations
  - $h < 0.1a$ : thin plate theory valid
  - $a_{\min} < a$ : $a_{\min}$ is determined by the geometry of piezoresistors and the ability to place resistors on the plate
  - maximum bending stresses must not exceed fracture stress
  - $w_{\max} < 0.2h$ : avoid nonlinear behavior
  - check resonant frequency

- Resistor placement: high signal level, sufficient impedance, and insensitive to alignment and patterning error
  - High signal level: positions of largest stresses (or strains)
  - High impedance: a) narrower resistors,
    b) more resistor segments, and
    c) higher resistivity.

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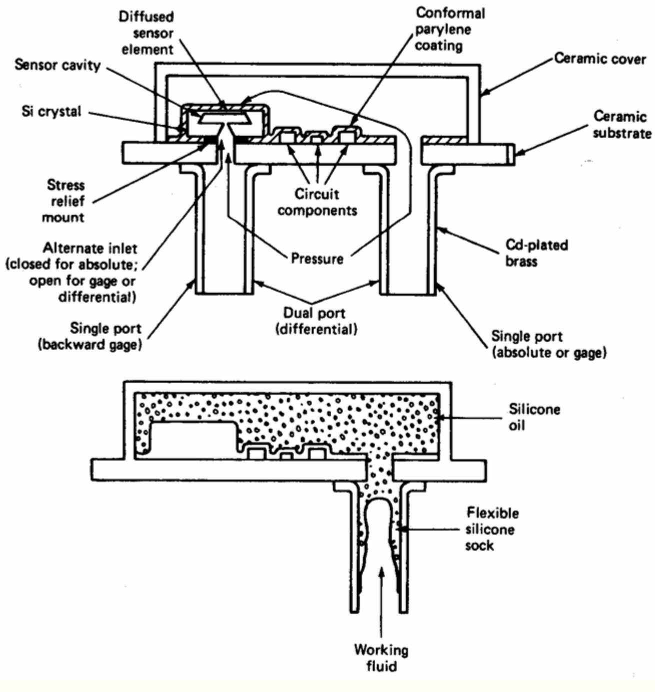


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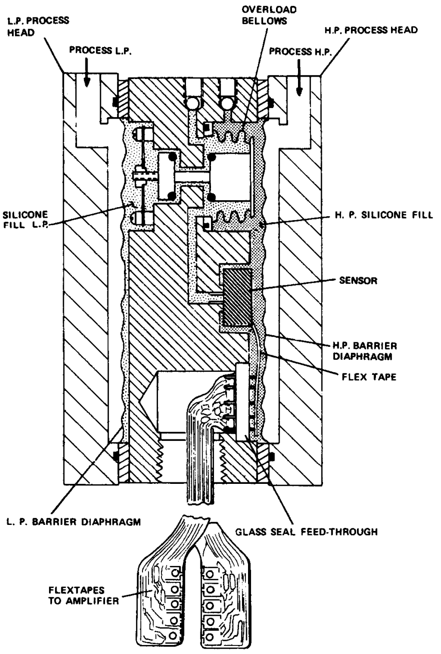
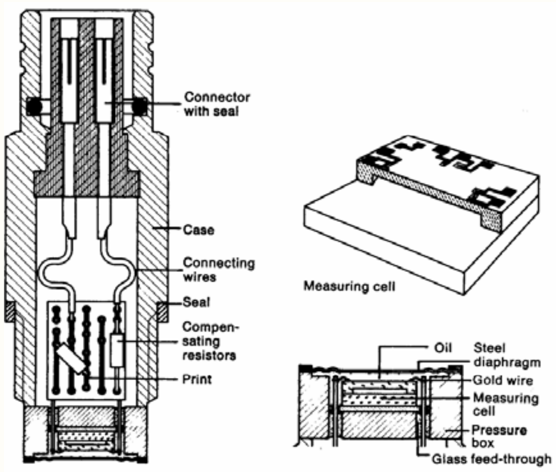



Differential-pressure transmitter

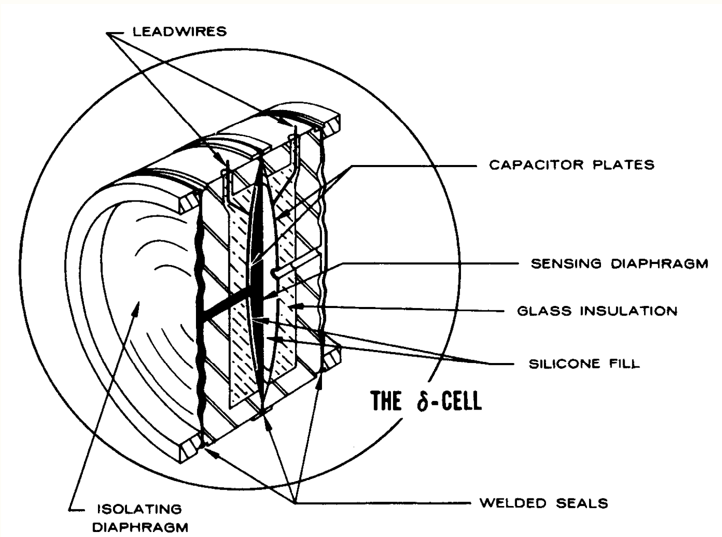



“Diffused” strain-gage transducers





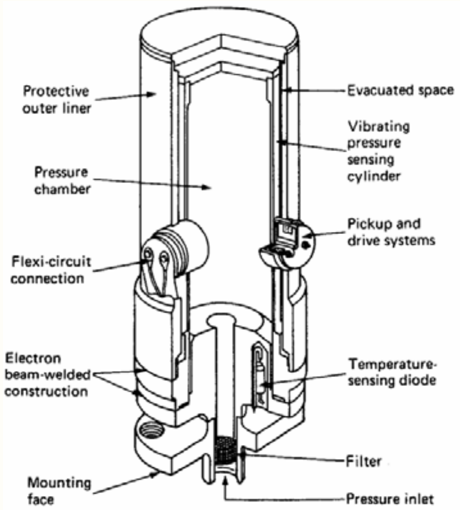
• Capacitive differential-pressure transmitter



## •Resonant transducers

$$\omega^2 = \frac{Eg}{(1-\nu^2)\gamma r^2}\left[\frac{(1-\nu^2)\lambda^4}{(n^2+\lambda^2)^2} + \frac{t^2}{12r^2}(n^2+\lambda^2)^2 + \frac{(1-\nu^2)r}{Et}\left(n^2+\frac{\lambda^2}{2}\right)\right]p$$

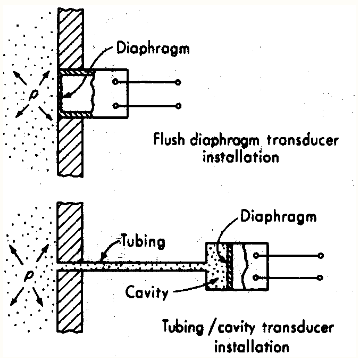
where
- $\omega \triangleq$ natural frequency
- $L \triangleq$ cylinder length
- $r \triangleq$ cylinder mean radius
- $E \triangleq$ elastic modulus
- $p \triangleq$ pressure
- $t \triangleq$ wall thickness
- $\gamma \triangleq$ specific weight
- $\nu \triangleq$ Poisson's ratio
- $g \triangleq$ acceleration of gravity
- $n \triangleq$ circumferential mode no. $= 2, 3, \ldots$
- $m \triangleq$ longitudinal mode no. $= 1, 2, \ldots$
- $\lambda \triangleq \frac{\pi r(m+0.3)}{L}$

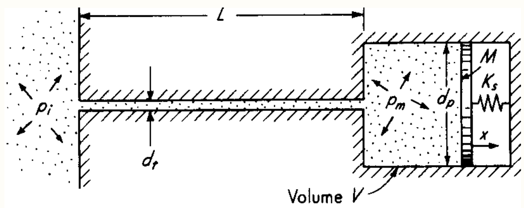






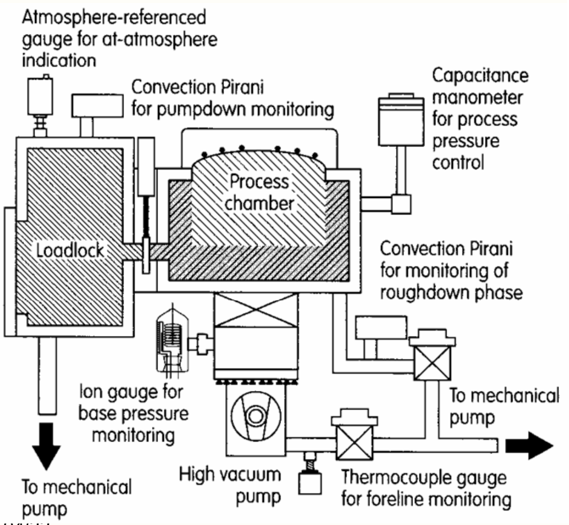

## •Cavity effects

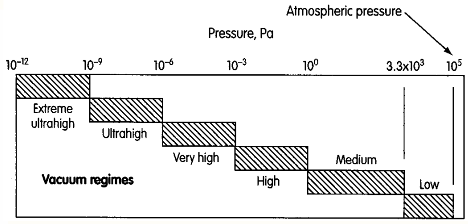


# Vacuum Gages

•A typical vacuum system

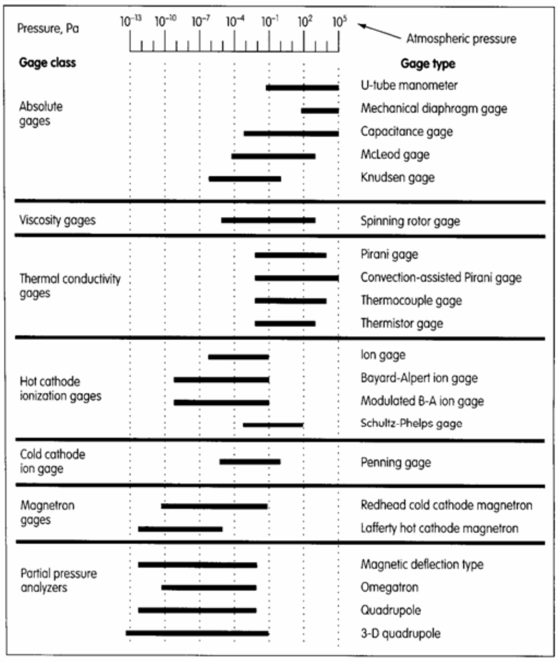




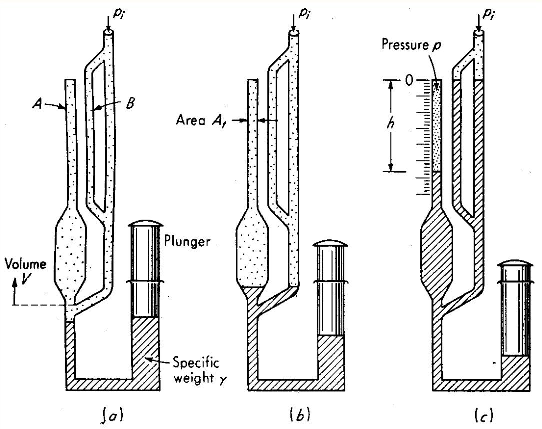



• Pressure ranges for various gages



McLeod gage

Served as a vacuum standard

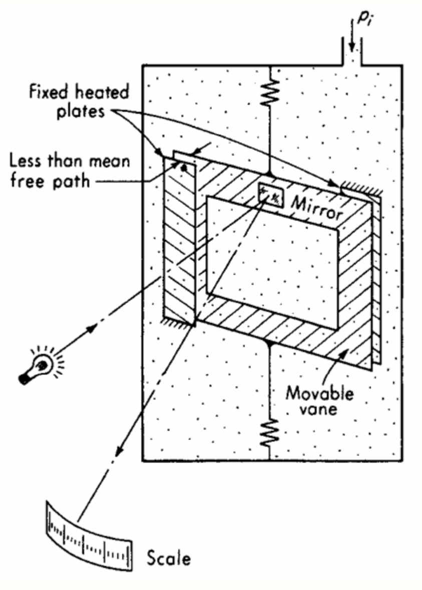



$$p_iV = pA_ih$$
$$p = p_i + h\gamma$$
$$p_i = \frac{\gamma A_i h^2}{V - A_i h} \approx \frac{\gamma A_i h^2}{V} \quad \text{if} \quad V >> A_i h$$

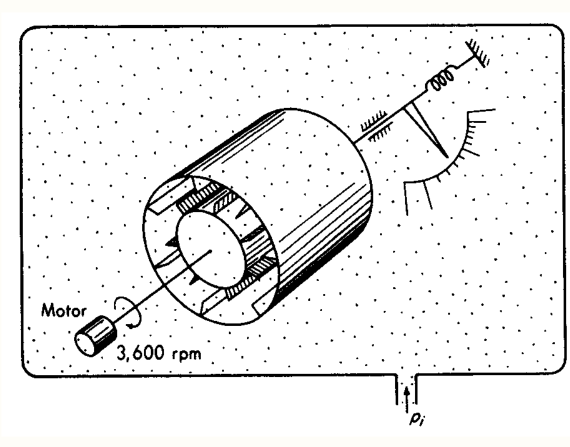




- Kundsen gage

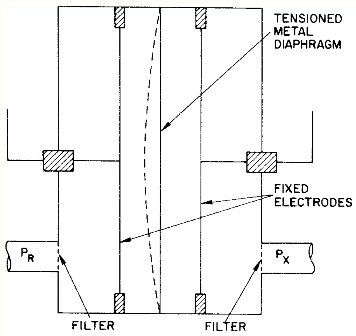



- Momentum transfer (Viscosity) gage

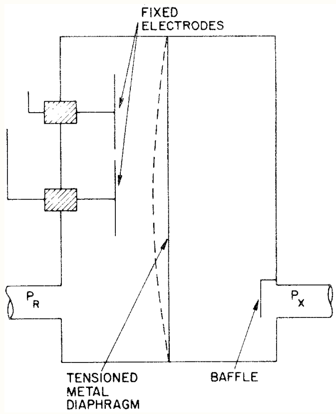


• Capacitance manometer

-A diaphragm gauge in which the deflection of the diaphragm is measured by observing the change in capacitance between it and a fixed counter electrode


Double-sided capacitance manometer

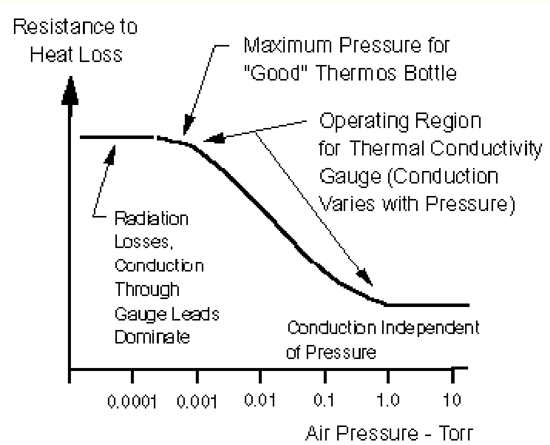



Single-sided capacitance manometer



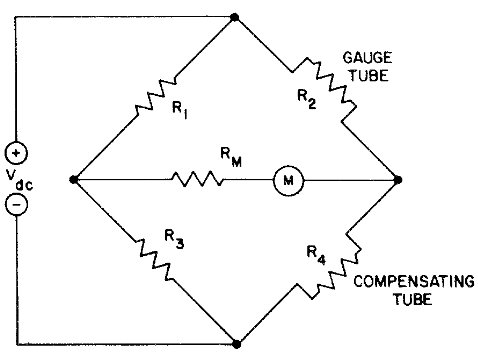


# Thermal conductivity gages

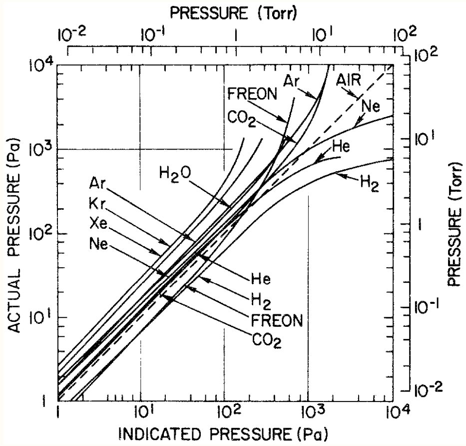


• Pirani gauge

- the electrical resistance of the wire being proportional to its temperature
- the heated wire forms one arm of a Wheatstone bridge




Basic Pirani gauge circuit




Calibration curves for a Pirani gauge





• Thermocouple gauge

• Indirect pressure measurement: measures pressure-dependent heat flow

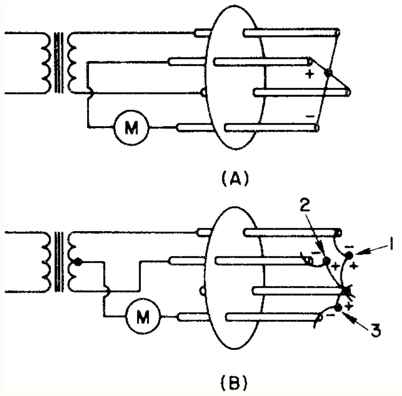
• Based on change in thermal conductivity of a gas: at low pressure, linear relationship between conductivity and pressure

• Constant current is delivered to heat a filament that a tiny thermocouple is spot welded to its midpoint

• As pressure decreases, gas impingement rate decreases and less heat is transferred from filament

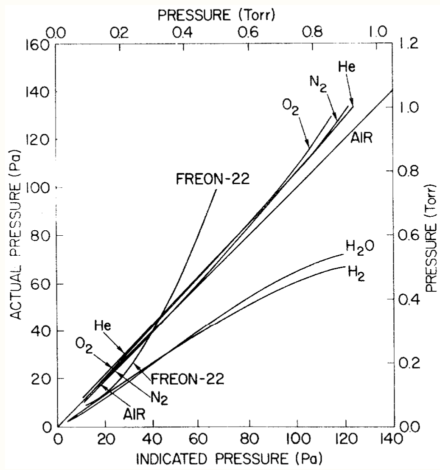
• Measured filament temperature (thermocouple potential) is transformed into pressure units at the controller

(Teledyne Hastings Instruments, THI)




(A) Uncompensated, (B) Compensated

A temperature shift in the AC heated thermocouples 1 and 2 (Fig. B). The resultant temperature shift causes a change in the DC output from couples 1 and 2 inversely with pressure changes. The DC thermocouple 3 (when installed) is in series with the circuit load. Thermocouple 3 provides compensation for transient changes in ambient temperature.




Calibration curve

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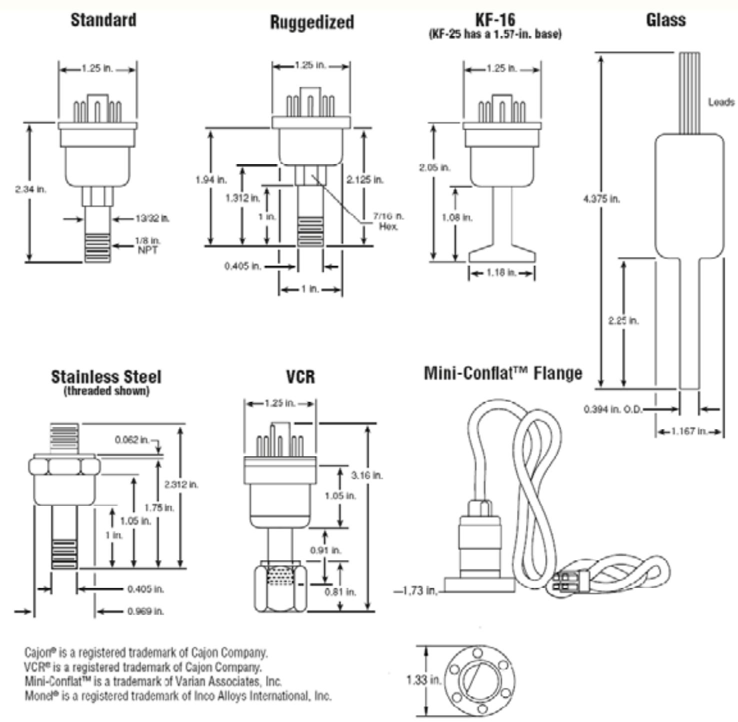
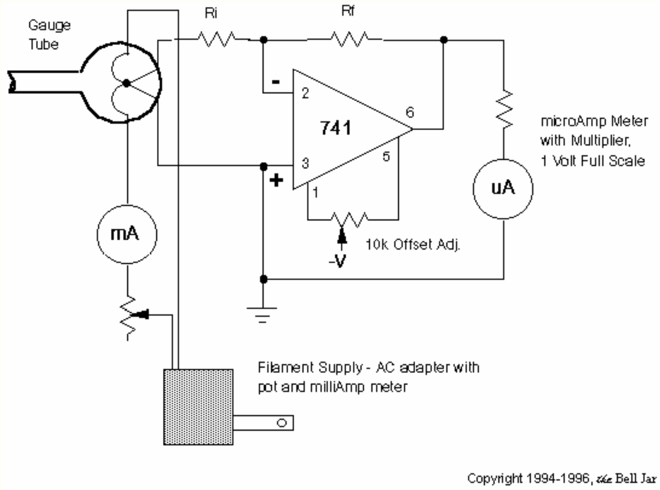


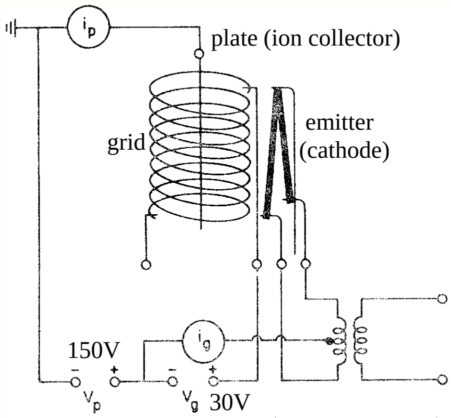







# Ionization gauges

• Hot cathode gauge




p: plate g: grid

Circuit for a Bayard-Alpert ionization gauge

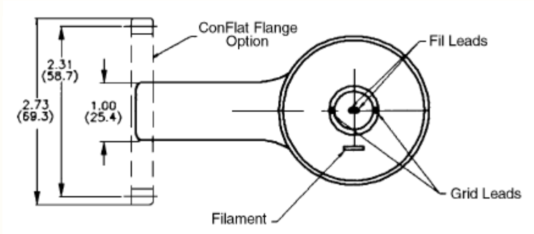
| Gas | Relative Sensitivity |
|---|---|
| $H_2$ | 0.42 - 0.53 |
| He | 0.18 |
| $H_2O$ | 0.9 |
| Ne | 0.25 |
| $N_2$ | 1.00 |
| CO | 1.05 - 1.1 |
| $O_2$ | 0.8 - 0.9 |
| Ar | 1.2 |
| Hg | 3.5 |
| Acetone | 5 |

Sensitivity $S = \frac{(I+)}{(I-)} \frac{1}{P}$

I+ = Ion Current in Amperes (from collector)
I– = Emission Current in Amperes (from filament)
P = Pressure in torr

**Sensitivity**
10 (torr)-1 (mbar)-1 (typical)
**Operating Ratings**
- 0 VDC (collector)
- +180 VDC to ground (grid)
- + 30 VDC to ground
- 5 VAC nominal (filament)

**X-Ray Limit**
2 x 10-10 torr
(2.6 x 10-10 mbar)
**Operating Pressure**
2 x 10-10 torr to 1 x 10-3 torr
(2.7 x 10-10 mbar to 1 x 10-3 mbar)






- Cold cathode gauge

Wire anode loop: 2-10kV
Permanent magnet: 0.1-0.2 Tesla
Output current: 10-50 mA/Pa
Operation range: 1-$10^{-6}$ Pa

Higher ionization efficiency
than hot cathode gage