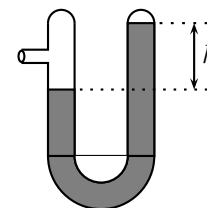


Figure 1: Gauges used in various pressure ranges.

## 1 Pressure

Many modern physics experiments are carried out in a reduced pressure environment, usually to isolate a sample of interest from outside influences. For example, a metal surface might become covered with molecules adsorbed from the gas phase, or the particle beam in an accelerator might be attenuated by collisions with background gas in the beam pipe: the solution is to pump away the gas. This section deals with techniques used to measure pressure from atmospheric pressure down to the lowest pressures that can be produced in a laboratory, a range of roughly fifteen orders of magnitude. Figure 1 shows approximate ranges for a selection of commonly used pressure gauges.

Two of the gauges shown in figure 1 measure pressure directly, the rest use a secondary physical process to measure something that is related to the pressure. The direct gauges are the mercury manometer, shown in the figure to the right, and the capacitance manometer, shown in figure 3. In a mercury manometer, gas is allowed in to one arm of a U-shaped tube filled with liquid mercury. The other arm is evacuated. Reflection of the gas molecules at the mercury surface involves momentum exchange, and this results in a pressure. The height difference between the two arms is a direct measure of the pressure difference, and is given in mmHg or Torr. Atmospheric pressure will support a column of mercury 760 mm high. Such an apparatus is bulky and can be messy.



In Otto Stern's laboratory in Hamburg in the 1930's, mercury manometers were used as detectors in atomic and molecular beam scattering experiments. A figure from one of Stern's papers is shown in figure 2. Through a combination of clever compensation and careful circuit construction it seems that Stern and

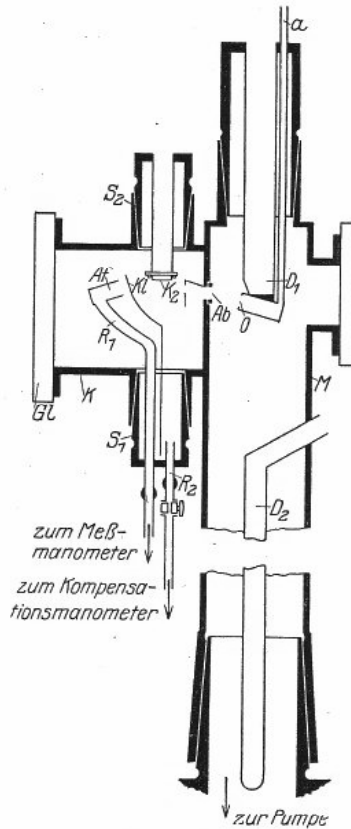


Fig. 7. Neue Anordnung.

Figure 2: Early beam-surface scattering, from Estermann and Stern, ZS f. Phys. 61 95 (1930).

coworkers were able to measure pressure differences at the astonishing level of  $10^{-8}$  mmHg! This is roughly the thickness of one atomic layer of Hg. Damn, those guys were good. The apparatus shown in figure 2 was used to observe the diffraction of helium from a crystalline LiF surface and was the first experimental demonstration of the de Broglie wave character of something heavier than an electron. This marked the beginning of the field of atom optics.

A second type of absolute pressure gauge is the capacitance manometer shown schematically in figure 3. It consists of two parallel discs, one fixed and one flexible that form the plates of a capacitor. The fixed disc is gas permeable and the flexible one is not. A pressure difference between the two sides (ref and sig in the figure), will cause the flexible membrane to bow and the capacitance to change. Capacitance manometers can be very accurate but are fairly expensive. A typical pressure head covers 5 orders of magnitude and can be purchased (with different disc thicknesses) for different ranges.

For a circular membrane, clamped around the rim, the displacement (from flatness) as a function of radial position ( $r$ ) and pressure ( $P$ ) is given by:

$$w(r) = \frac{Pa^4}{6D} \left[ 1 - \left( \frac{r}{a} \right)^2 \right]$$

with

$$D = \frac{Eh^3}{12(1 - \nu^2)}$$

where the variables are:  $a$  the plate radius,  $h$  the plate thickness,  $E$  is Young's modulus, and  $\nu$  is Poisson's ratio. The material properties appearing in this equation are well measured and the rest of the terms are geometry. Thus, this device qualifies as an absolute instrument not requiring calibration. Potential problems

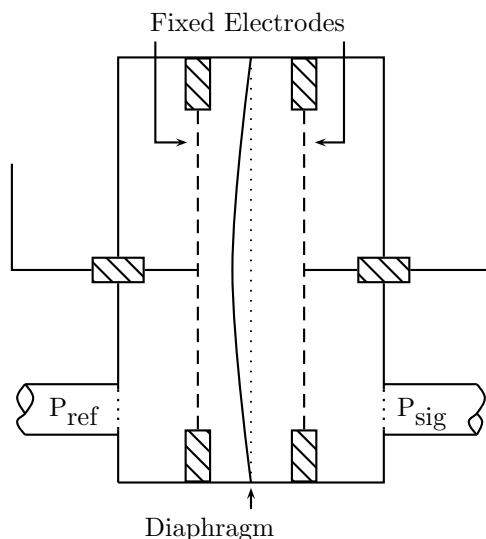


Figure 3: Schematic of a capacitance manometer head.

include measurements involving condensable gasses (e.g. water, which can have a big effect because of its large dielectric constant), and mechanical resonances (think of the flexible membrane as a drum head). The resonant frequency is give by  $\nu = \frac{1.2}{\pi a} \sqrt{s/\rho g}$ , where  $s$  is the radial tension (force per unit length) on the disc.

A modern day version of a diaphragm pressure gauge is shown in figure 4. Here a deep depression is fabricated in a single crystal silicon wafer and a second, flat piece of silicon is bonded over it. A hole in the bottom piece lets in gas. The top piece has two pizeoresistors fabricated on in by ion implantation (since silicon is not a piezoelectric material). The resistance of these is dependent on the *stress* in the material. One the these resistors ( $R_2$ , the reference) is placed over the thick supporting material and the other ( $R_1$ ) is placed over the thin membrane. If the pressure difference across the thin membrane is different from zero, the membrane will distort and the resistance of  $R_1$  will change. A second structure used as a reference is fabricated on the same silicon wafer but not connected to any gas sample. The resistors are connected to form a Wheatstone bridge, with amplification also built into the chip. Such devices are in widespread use in air conditioning systems and in automobiles and can be purchased for a few dollars or less.

A similar pressure gauge in which the inductance is measured instead of the capacitance is shown in figure 5. The dark areas between the horizontal bars of the “E” represent a coil of wire with the windings coming out of and going into the page. The magnetic field lines then circulate in the plane of the page. Most of the path for the field lines is within the gray area of the figure which is a material with high magnetic permeability. However there is a small air gap; this gap is effectively a volume with a high magnetic “resistance”, that is the inductance is dominated by the spacing of the gap. When the pressure is changed, the thin plate on the right deforms and the inductance of a circuit containing the element changes. This change is calibrated to the pressure. Usually two of the “E” structures are sandwiched together and one is used as a reference. This is shown in figure 6.

The spinning rotor gauge (sometimes called a viscosity gauge) is shown in figure 7. Several sets of electromagnets are used to rotate a magnetic ball, usually at 400 Hz (a secondary standard for transformers). Another set of magnetic coils is used to monitor the rotation. The ball is spun and then allowed to drift for a period of time, and the decay of the rotation is monitored. Collisions with gas molecules slow the rotation rate during the drift time. The rate of change of the rotation frequency is given by:

$$-\frac{\dot{\omega}}{\omega} = \frac{10}{\pi} \frac{1}{ad} \frac{p}{\bar{c}}$$

where  $a$  is ball radius,  $d$  the ball density,  $p$  is the gas pressure and  $\bar{c}$  is the average gas speed. This expression is based on two assumptions. One, the angular distribution of the molecules leaving the surface of the rotor is symmetric about the surface normal, an assumption that appears to be quite well obeyed for

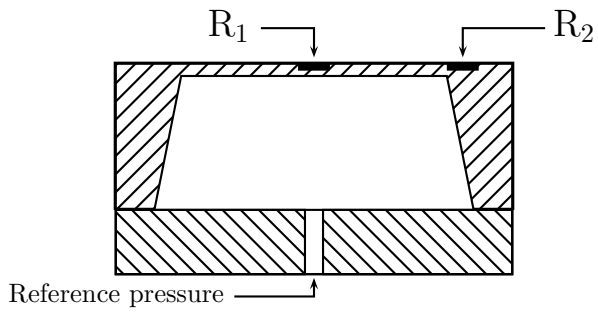
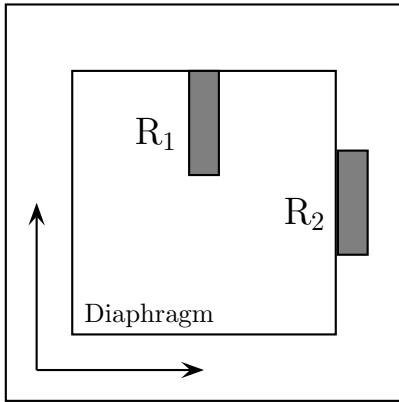


Figure 4: Schematic of piezoresistors on a silicon diaphragm.

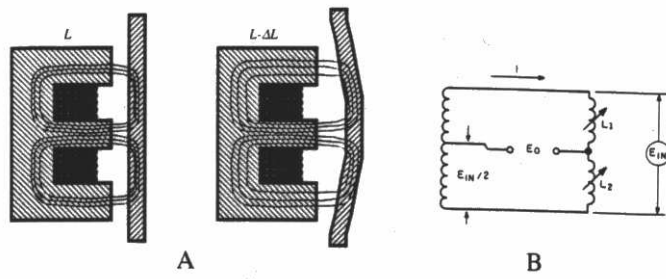


Figure 5: Variable reluctance pressure sensor. A: basic principle of operation; B an equivalent circuit. From reference [1].

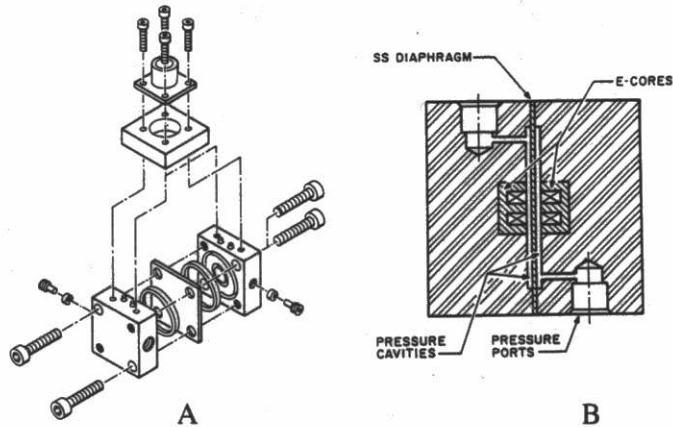
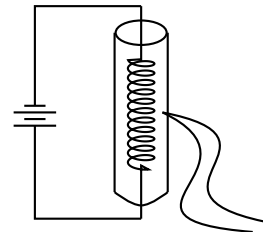


Figure 6: Construction of a VPR sensor for low pressure measurements. A: assembly of the sensor; B: double E-core at both sides of the cavity. From reference [1].

a “real” (microscopically rough, adsorbate covered) surface. The second assumption is that the gas is in the free molecular flow regime, that is that a gas molecule travels from the walls to the rotor without colliding with other gas molecules.

Note that the expression given above involves no calibration (as all the pressure gauges discussed in what follows), so the SRG is arguably an absolute gauge. In addition it is linear in the pressure. It is used in the range from about  $10^{-2}$  down to  $10^{-7}$  torr. At higher pressures the gauge becomes nonlinear because of collective motion in the gas flow.

A thermal conductivity or thermocouple gauge (illustrated at the right) uses heat transport to measure gas pressure. A thermocouple is placed near a heated filament and then one of two things is measured. (1) the temperature of the thermocouple is measured for fixed power dissipation in the filament; or (2) the filament power required to maintain a constant thermocouple voltage.



Energy transfer from such a heated filament versus the gas pressure is plotted in figure 8; an equivalent and more insightful scale for the x-axis in this figure is the Knudsen number, which is the ratio of the mean free path to some relevant apparatus dimension. Three regimes are readily identified in the figure which demarcate the useful pressure range of a thermocouple gauge. At low pressure, energy transfer is all radiative and the gauge is insensitive to the gas pressure. At intermediate pressure, heat transfer is conductive. The gas is in free molecular flow, collisions are with the surfaces of the filament and thermocouple, and gas phase collisions are negligible. This is the linear central portion of the graph. At higher pressures, heat transfer is by convection, and gas phase collisions become important. In this range, the heat transfer still varies with gas pressure, but at a much slower rate and it becomes very dependent on the gas species. This latter effect is shown in figure 9.

A recent improvement on the thermocouple gauge is called the convectron gauge. According to the manufacturer it uses a large gauge volume to enhance convective energy transfer and can be used up higher pressures, even up to atmospheric pressure although the dependence of the response becomes extreme. However these gauges are very robust and have become the instrument of choice for use on forelines in high vacuum systems.

A breakthrough of sorts occurred in the 1950's with the invention of the hot filament ionization gauge. This allowed the lowest pressure that could be measured to be extended into the  $10^{-8}$  torr range, and with future enhancements, into down to  $10^{-11}$  torr.

The layout of the Bayard-Alpert (the inventors) gauge is shown in figure 10. A filament (tungsten or

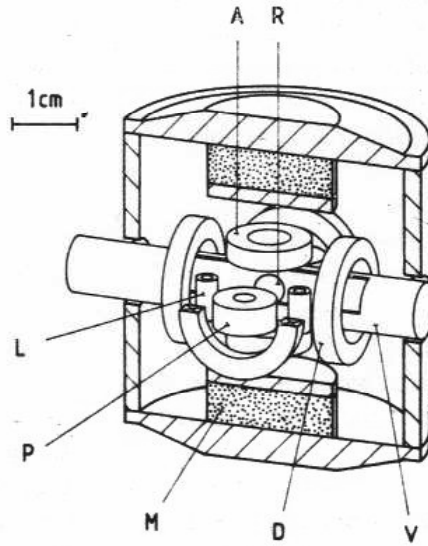


Figure 7: Spinning rotor gauge. R - rotor; V - vacuum enclosure (partially cut away for illustration); M - one of two permanent magnets; A - one of two pickup coils for control of axial rotor position; L - one of four coils for lateral damping; D - one of four drive coils; P - one of two pickup coils. From J. K. Fremerey, *JVST A*, **3** 1715 (1985).

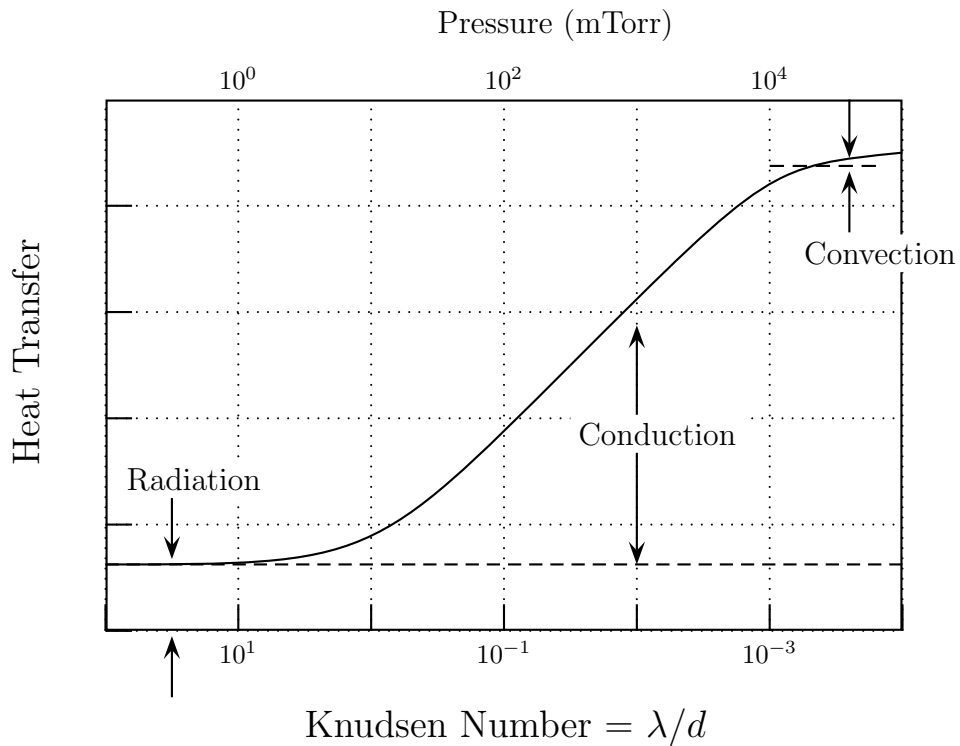


Figure 8: Heat transfer regimes typical of a thermal conductivity gauge.

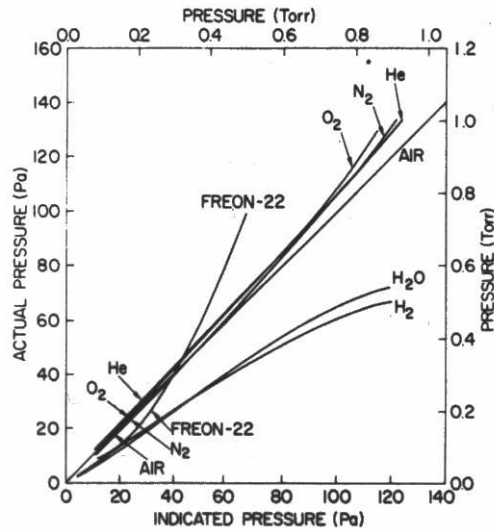


Figure 9: Calibration curves for a thermocouple gauge tube.

tungsten doped with thorium) is heated sufficiently hot (1700-1800 K) to generate electrons by thermionic emission. The electrons are accelerated by a potential difference of 100 volts (typical) toward a grid. The grid is biased at +180 V with respect to ground. Inside the grid ions are produced by collisions:  $e^- + A \rightarrow 2e^- + A^+$ . In the center of the grid is a bare metal wire (the collector) connected to ground via a sensitive current meter. An ion is therefore attracted to the collector. When a positive ion nears a metal surface it is neutralized with essentially unity probability. The electron required to do this neutralization is measured by the ammeter.

Both the rate of ionization and the conversion of ions to electrons at the collector are linear in the pressure for pressures below about  $10^{-4}$  torr. For pressures above this, a collisional cascade starts to occur. The filament in the ion gauge is biased about +80 volts with respect to ground so that the thermally emitted electrons go to the grid and nowhere else (such as the chamber walls). These electrons oscillate multiple times in the potential well produced by the grid before eventually being neutralized. The current between the filament and grid is measured as a feedback signal to control the filament heating power. It is also used to detect an overpressure condition where the filament is hot but no electrons are reaching the grid: in this case the filament is shot off to prevent burnout.

The lower limit on the pressure that can be measured by an ionization gauge is called the X-ray limit and results from the following process. Electrons that hit the grid have sufficient kinetic energy to cause photon emission, a process called inverse photoemission. The tail of the energy of these photons extends into the UV and X-ray region of the spectrum. A small fraction of these higher energy photons hit the collector and cause photoemission. The electrons head straight for the grid, but the loss of electrons at the collector looks just like ion neutralization, and leads to a background current in the ammeter. For a grid constructed of fine wire, this dark current corresponds to a pressure of about  $3 \times 10^{-11}$  torr, the X-ray limit. To measure lower pressures requires a mass spectrometer, which is the subject of section 2.

The ionization probability depends on the both the gas identity and the electron energy. The dependence on gas species is shown in table 1 and essentially tracks the ionization potential of the atom or molecule. Thus, the gauge is less sensitive to hydrogen and helium and more sensitive to  $\text{CO}_2$  and krypton. An ion gauge built to standard specifications commonly has a sensitivity ( $s$ ) of 10/torr. The collector current is then  $i_+ = s i_e P$  where  $i_e$  is the emission current and is typically 10 milliamps. This puts  $i_+$  in the range of nanoamps which is easily measured.

For reactive species, the ions are actually implanted in the collector so the gauge functions as a kind of pump (not too different than an ion pump), albeit with a low pumping speed of a fraction of a liter per second.

The hot filament in a Bayard-Alpert ionization gauge can result in contamination when used to measure

Table 1: Experimental Total Ionization Cross Sections at 70 eV Electron Energy (Normalized to Nitrogen)

Gas	Relative Cross Section
H <sub>2</sub>	0.42
He	0.14
CH <sub>4</sub>	1.57
Ne	0.22
N <sub>2</sub>	1.00
CO	1.07
C <sub>2</sub> H <sub>4</sub>	2.44
NO	1.25
O <sub>2</sub>	1.02
Ar	1.19
CO <sub>2</sub>	1.36
N <sub>2</sub> O	1.48
Kr	1.81
Xe	2.20
SF <sub>6</sub>	2.42

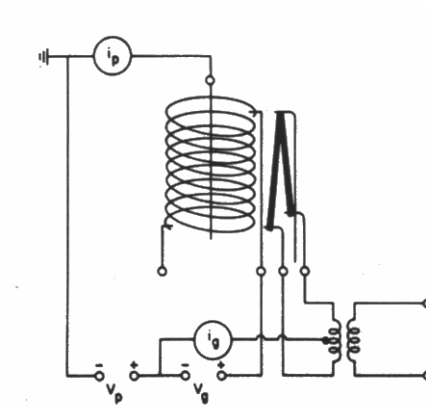


Figure 10: Schematic circuit for a Bayard-Alpert ionization gauge.

the pressure of more reactive gases as they can be decomposed on the filament. An alternative is the cold cathode or Penning gauge shown schematically in figure 11. Here a high voltage difference is applied between two electrodes and electrons can escape the negative terminal. A magnetic field along the axis of the device causes the electrons to travel along a spiral path where they can cause collisional ionization of the background gas. The ions don't curve as much in the magnetic field and travel to the negative electrode where they are neutralized and measured. These devices tend to be very robust particularly against sudden pressure bursts, not having any hot filament.



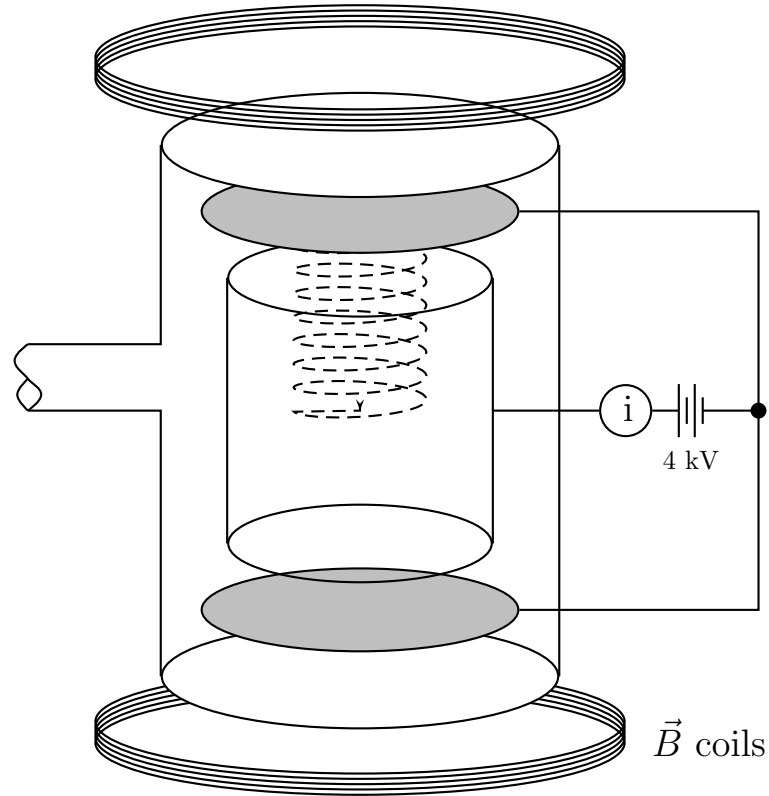


Figure 11: Schematic of a cold cathode ionization gauge.

## References

- [1] Jacob Fraden, "Handbook of Modern Sensors," Springer Verlag, New York, 1996.

## Appendix: Reference Results from the Kinetic Theory of Gases

Maxwell-Boltzmann speed distribution:

$$dN = 4\pi \left( \frac{m}{2\pi kT} \right)^{3/2} \exp \left( \frac{-mc^2}{2kT} \right) c^2 dc$$

where  $c$  is the speed,  $m$  is the mass,  $T$  is the temperature in Kelvin, and  $k$  is Boltzmann's constant,  $k = 1.381 \times 10^{-23} \text{ J/K} = 8.631 \times 10^{-5} \text{ eV/K}$ .

The average speed is

$$\bar{c} = \left( \frac{8kT}{\pi m} \right)^{1/2}$$

The mean free path is

$$\lambda = \frac{1}{\sqrt{2}\rho d^2}$$

where  $\rho$  is the density and  $d$  is the effective particle diameter, typically around 0.3 nm. The rate of collisions with a surface is

$$Z_{\text{wall}} = \frac{1}{4}\rho\bar{c}$$

For an ideal gas, the average kinetic energy is

$$E_k = \frac{3}{2}kT$$

Pressure and kinetic energy are related according to

$$p = \frac{\rho\bar{c}^2}{3}$$

At room temperature  $kT = 25$  meV.

Conversion factors:

1 Pa = 1.45x10<sup>-4</sup> lb/in<sup>2</sup> = 9.869x10<sup>-6</sup> atm = 7.5x10<sup>-3</sup> mm Hg.

Flux near centerline from an effusive beam

$$\dot{n} = \frac{\rho\bar{c}}{4} \frac{A_s A_c}{\pi d_c^2} = \frac{P}{(2\pi M_g k_B T_g)^{1/2}} \frac{A_s A_c}{\pi d_c^2}$$

Beam intensity at a target

$$I_B = \frac{\rho\bar{c}}{4} \frac{A_s}{\pi d_t^2} = \frac{P}{(2\pi M_g k_B T_g)^{1/2}} \frac{A_s}{\pi d_t^2}$$

Table 2: Typical numbers for N<sub>2</sub> at 298 K ( $\bar{c} = 475$  m/s, d=0.316 nm)

Pressure	Density (cm <sup>-3</sup> )	Mean Free Path	$Z_{\text{wall}}$ cm <sup>-2</sup> s <sup>-1</sup>	ML time
10 <sup>-6</sup> torr	3.24x10 <sup>10</sup>	69.6 m	3.85x10 <sup>14</sup>	0.385 s
10 <sup>-3</sup> torr	3.24x10 <sup>13</sup>	69.6 mm	3.85x10 <sup>17</sup>	0.385 ms
1 torr	3.24x10 <sup>16</sup>	69.6 μm	3.85x10 <sup>20</sup>	0.385 μs
1000 torr	3.24x10 <sup>19</sup>	69.6 nm	3.85x10 <sup>23</sup>	0.385 ns