Introduction to
Surface and **Thin Film Processes**

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2 Surfaces in vacuum: ultra-high vacuum techniques and processes

This chapter presents a practically oriented introduction to modern vacuum techniques, in the context of studying surface and thin film processes. The following sections review the science behind the technologies, and give a few worked examples, which we refer to later. Section 2.1 reviews the kinetic theory concepts on which vacuum systems are based; section 2.2 outlines the basic ideas involved in ultra-high vacuum (UHV) system design. The next section 2.3 deals with vacuum system hardware, in order to make sense of the large range of chambers, flanges, pumps and gauges which make up a complete system. It is assumed that the reader is already familiar with a basic vacuum system and its components, so that only a few figures of apparatus are needed. Section 2.4 describes the procedures used in performing experiments under UHV conditions, and discusses some of the challenges involved in scaling these procedures up to manufacturing processes. Finally, section 2.5 briefly lists some of the more commonly used thin film deposition techniques, and describes where more information on such processes can be found.

2.1 Kinetic theory concepts

2.1.1 Arrival rate of atoms at a surface

The arrival rate R of atoms at a surface in a vacuum chamber is related to the molecular density n, the mean speed of the molecules $\bar{v}$ and the pressure p, via the standard kinetic theory formulae (Dushman & Lafferty 1992, Hudson 1992)

$$R = n\bar{v}/4 \text{ per unit area} = p/(2\pi mkT)^{1/2}\,; \tag{2.1}$$

you may also need $n = p/kT$ and $\bar{v} = (8kT/\pi m)^{1/2}$, which are required to connect the two versions of the above formula. The notation can be confusing: R is sometimes called the deposition flux, F, and $\bar{v}$ is sometimes written v, c or $\bar{c}$.

Now let us work through an example to find the molecular density n, the mean free path λ, and the monolayer arrival time, τ. We take, as a typical example, the residual gas in a vacuum system, which is often a mixture of CO, H_2 and H_2O; the following calculations are for carbon monoxide, CO, which has molecular weight 28. Then the molecular mass, $m = 28 \times 1.6605 \times 10^{-27}$ kg; Boltzmann's constant $k = 1.3807 \times 10^{-23}$ J/K; and $T = 293$ K (UK, if you're lucky), or 300 K (Arizona, ditto); we shall also need the molecular diameter of CO, $\sigma = 0.316$ nm.

The question of units, especially of pressure, is important. The SI unit is the pascal (Nm^{-2}). One bar $= 10^5$ Pa, and modern vacuum gauges are calibrated in millibar: 1 mbar = 100 Pa. The older unit torr (mm Hg) is named after the inventer of the mercury barometer, Torricelli, who worked with Galileo in the seventeenth century: 1 Torr = 1.333 mbar (760 Torr = 1013 mbar = 1 atmosphere). These units and conversion factors are collected in Appendix C.

2.1.2 *The molecular density, n*

At low pressures $n = Ap$. With n per cm^3 and p in mbar, we have the constant $A = (100)/(kT \times 10^6)$. This gives

$$n = p/kT = 7.2464 \times 10^{18}/T. \tag{2.2}$$

Roth (1990, chapter 1) for example, has suitable diagrams and tables which spell this relationship out for air at 25 °C. Don't forget that in all these equations, T is the absolute *Kelvin* temperature (K): $T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273.15$. For our example of CO, a typical number to get hold of is that at 10^{-6} mbar there are 2.42×10^{10} molecules/ cm^3 in Arizona and 2.47×10^{10} in the UK. Just checking: it's the temperature! There are still lots of molecules around, even in the best vacuum.

2.1.3 *The mean free path, λ*

The mean free path between molecular collisions in the gas phase is inversely related to the density n and the molecular cross section proportional to σ^2. The proportionality constant f in the equation $\lambda = f/n\sigma^2$ was solved by Maxwell in 1860 (for a historical account see Garber *et al.* 1986): $f = 1/\pi\sqrt{2} = 0.225$. Thus for CO, with σ^2 almost exactly equal to 0.1 nm^2, we have

$$\lambda = 2.25 \times 10^{14}/n \text{ (cm)}, \tag{2.3}$$

where n is expressed as in (2.2); the mean free path at 10^{-6} mbar is of order 100 m at room temperature. Thus λ is much greater than the typical dimensions of a UHV chamber, operating, say, below 10^{-9} mbar; the gas molecules will travel from wall to wall, or from wall to sample, without intermediate collisions.

Higher pressure gas reactors, operating at 10^{-3} mbar and above, start to run into gas collision and diffusion effects, but the UHV community largely ignore this, except for particle accelerators where particles circulate at close to the velocity of light for many hours. At a large installation, such as CERN or FermiLab, the accelerated particles are constrained to miss the walls, but of course they hit the residual gas molecules. There are other effects, such as high power (up to several kW/m of path) synchrotron radiation produced when the beam travels in a circle, which desorbs molecules from the walls;

on sufficiently long timescales, this initially bad effect can be turned to advantage, in the form of beam cleaning. One of the challenging aspects of the (late) superconducting supercollider was how to design a toroidal pipe some 80 km long and say 0.15 m in diameter with a vacuum everywhere better than 10^{-12} mbar. The large electron–positron (LEP) storage ring at CERN (*only* 26.7 km in circumference) has an only marginally less severe specification, and beam conditioning effects are an important aspect of the operation (Reinhard 1983, Dylla 1996). Vacuum design and procedures have to be taken rather seriously!

2.1.4 The monolayer arrival time, τ

If N_0 is the number of atoms in a monolayer (the ML unit) then $R\tau = N_0$. We have already had that $R = Cp$ with $C = (2\pi mkT)^{-1/2}$. Now we need the conversion from millibars to pascal, T and the other constants. For CO, R in atoms·m^{-2}·s^{-1}, and p in mbar, C is then 2.876×10^{24} for $T = 300$ K, or $R = 2.876 \times 10^{18}$ atoms·m^{-2}·s^{-1} at 10^{-6} mbar, i.e. of order 3×10^{14} at 10^{-10} mbar, a typically (good) UHV pressure. Watch out for whether cm^{-2} are used in place of m^{-2} as (area)$^{-1}$ units; factors of 10^4 are significant!

The definition of N_0 requires above all consistency. It can be defined in terms of the substrate, the deposit or the gas molecules, but it must be done consistently, and the ML unit needs definition, essentially in each paper or description: there is no accepted standard. For example, consider condensation on Ag(111), with a (1×1) structure. It is perfectly reasonable to define N_0 as the number of Ag atoms per unit area. With the bulk lattice parameter $a_0 = 0.4086$ nm, the surface mesh area is $(\sqrt{3}/2)a^2$, where the surface lattice constant $a = a_0/\sqrt{2}$. Thus $N_0 = 1.383 \times 10^{19}$ atoms·m^{-2}. With this definition, $\tau = 4.81$ s at 10^{-6} mbar (CO) and 13.4 hours at 10^{-10} mbar. This is, of course, the reason for doing experiments in UHV conditions; only at low pressures can one maintain a clean surface for long enough to do the experiment.

However, the above definition of the monolayer arrival time only makes sense if we have a well-defined substrate. If the substrate N_0 is ill-defined or irrelevant (e.g. the inside of a stainless steel vacuum chamber, or for an incommensurate deposit), then a definition in terms of the deposit makes more sense. In our case we might use a close-packed monolayer of condensed CO; with $a = 0.316$ nm, the corresponding values of $\tau = 4.02$ s at 10^{-6} mbar (CO) and 11.2 hours at 10^{-10} mbar. Although these are of the same order, they are not the same. Thus for quantitative work, it is important *either* to define the ML unit explicitly, *or* to work with a value of R expressed in atoms·m^{-2}·s^{-1}, rather than in ML/s. Note also that had the deposit been something other than CO, and we wanted to track the result in terms of pressure, then we have to use the correct m and T in the constant C.

To summarize: (1) the density n is still high even in UHV; (2) the mean free path $\lambda \gg$ apparatus dimensions; (3) the monolayer arrival time τ is greater than 1 h only for $p < 10^{-9}$ mbar; and for good measure (4) the monolayer (ML) unit, if used, needs to be defined consistently. The various quantities calculated in this section are displayed in figure 2.1.

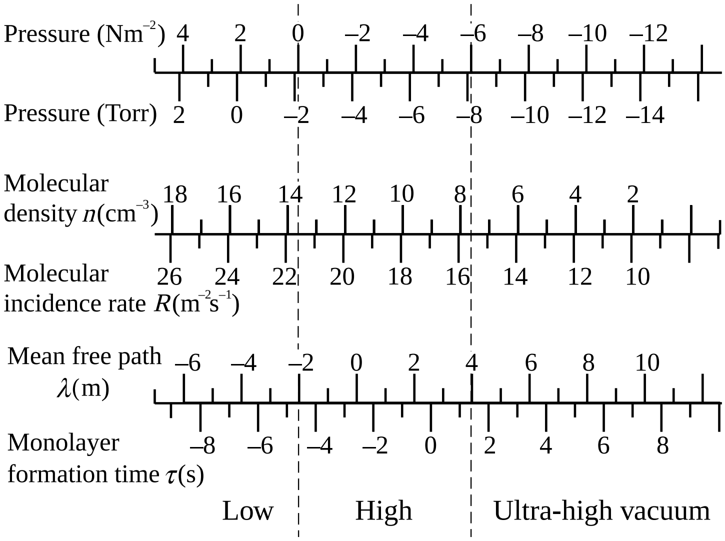

Figure 2.1. Plot of n (cm^{-3}), R (atoms·m^{-2}·s^{-1}), λ (m) and τ (s) for CO at temperature $T = 300\,\mathrm{K}$, as a function of pressure p, on a logarithmic scale in units of 1 mbar = 100 Pascal or Nm^{-2}, and the older unit 1 Torr = 1.333 mbar. The division into low, high and ultra-high vacuum regimes are approximate terms based on usage.

2.2 Vacuum concepts

2.2.1 System volumes, leak rates and pumping speeds

The system to be pumped has a system volume, V, measured in liters, at pressure p (mbar or torr), as indicated schematically in figure 2.2. It is pumped by a pump, with a pumping speed, S (liter/s). The pump-down equation for a constant volume system, with a leak rate Q into the system, is then:

$$pS = -V\mathrm{d}p/\mathrm{d}t + Q. \tag{2.4}$$

The leak rate is composed of two elements: $Q = Q_l + Q_o$, where Q_l is the *true* leak rate (i.e. due to a hole in the wall) and Q_o is a *virtual* leak rate. A virtual leak is one which originates inside the system volume; it can be caused by degassing from the walls, or from trapped volumes, which are to be avoided strongly.

The solution of the pump-down equation, assuming everything except the pressure is constant, separates into:

(a) a short time limit: $p = p_0\exp(-t/\tau)$, with $\tau = V/S$, (2.5a)
where the leak rate is negligible. This stage will be essentially complete in 10τ. Typical values 10×50 liter/ 50 liters/s = 10 s. It isn't quite this short in practice, but it is short;

(b) a long time limit: p_u, the ultimate pressure $= Q/S$. (2.5b)
When the true leak rate is negligible, $Q \rightarrow Q_o$, which depends on the surface area A, material and the treatment of the surface. For example, if the system volume

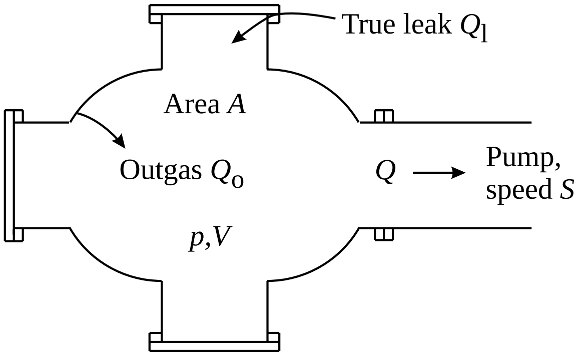

Figure 2.2. Schematic diagram of a pumping system, comprising the volume V, internal area A, pumping speed S and leak rate Q, comprising outgas Q_o and true leaks Q_l. See text for discussion.

$V = 50$ liter (e.g. $50 \times 20 \times 50$ cm^3), then A is ~ 1 m^2. We can take $Q_o = qA$, so with a typical (good) value for q around 10^{-8} mbar·liter·m^{-2}·s^{-1}, we deduce from (2.5b) that $p_u = 2 \times 10^{-10}$ mbar.

This value is a typical pressure to aim for after bakeout. The bakeout is required to desorb gases, particularly H_2O, from the walls. Water is particularly troublesome because it is always present and desorbs so slowly; it is essentially impossible (with standard stainless steel/glass systems) to achieve pressures below 10^{-8} mbar in a sensible time without baking. The role of water vapor in vacuum systems has been reviewed by Berman (1996). Practical bakeout procedures are indicated by Lüth (1993/5 Panel I) and Yates (1997) with comments here in section 2.3.

It is worth remembering, throughout this chapter, that both design and preparation procedures are lengthy; they can be disastrous, and very expensive, if they are not thought through or go wrong. Thus we should give even the simple models described here due respect! It is also important not to use these simple calculations blindly, and to check with experts who have a feel for the points which are difficult to quantify. An example is the following.

In applying the pump-down equation (2.4), there is some possibility of confusion, as it can be used too uncritically, and used to deduce answers which run counter to practical experience. To deduce, via (2.5a) above, that you can get down to 10^{-6} mbar, say, in a minute or so, is not correct. It is, however, correct to deduce that in that time the term $-V\mathrm{d}p/\mathrm{d}t$ becomes smaller in magnitude than $+Q$; but Q itself varies (decreases) with time, as the walls outgas, and S is also, in general, a function of pressure. This means that for almost all UHV situations we are interested in the long time limit (2.5b), but with variable Q, depending on the bakeout and other treatments of the vacuum system, and with variable S, depending on the type of pump and the pressure. Manufacturers' catalogues typically give a plot of how S varies with p. As the pump approaches its ultimate pressure limit, the speed S drops off to an ineffective value.

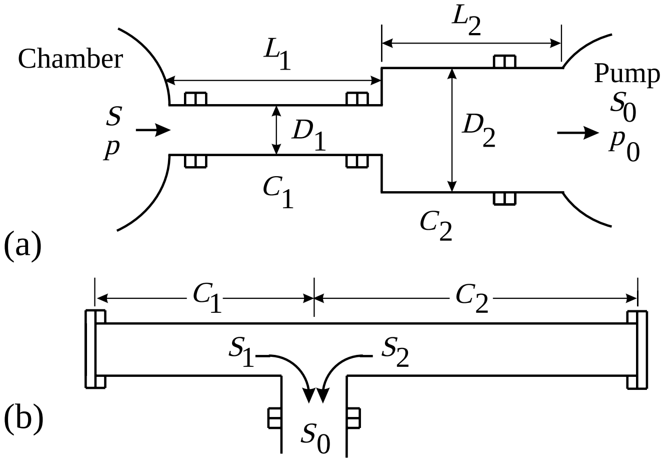

Figure 2.3. The effect on pumping speeds S of pipe conductances C_i: (a) in series, and (b) in parallel with a pump of speed S_0.

2.2.2 *The idea of conductance*

The pumping speed of the pump is reduced by the high impedance, or low conductance, of the pipework between the pump and the vacuum chamber, as shown in figure 2.3. The conductance of a pipe is defined as the flow rate through it, divided by the pressure difference between the two ends. But, of course, large pipes increase both the system volume and the internal surface area. So, one needs to take care in the design of the system, to avoid obvious pitfalls. Individual pipes have a conductance C_i, and several of these, with different lengths and diameters, may be in series with the pump. Then with the pump speed as S_0, we have the effective pumping speed S at the chamber given by

$$S^{-1}=\Sigma_i C_i^{-1}+S_0^{-1}, \tag{2.6}$$

where the C_i are measured in liters/s. Thus we need to choose the C_i large enough so that S is not $\ll S_0$; or equivalently, if S is sufficient, we can economize on the size (S_0) of the pump. As with all design problems, we need to have enough in hand so that our solution works routinely and is reliable. On the other hand, over-provision is (very) expensive. We consider actual values of C in section 2.3 and Appendix F.

Sometimes, if high pumping speed is essential, or if the geometrical aspect ratio is unfavorable (as in the accelerator examples cited in section 2.2.1), we would use multiple pumps distributed along the length of the apparatus. In this case the conductances are distributed in parallel, and

$$S=\Sigma_i S_i,\ C=\Sigma_i C_i. \tag{2.7}$$

Whether this is a good solution should be clear from geometry. Obviously, a solution involving one UHV pump is simpler, if possible. Sometimes we use more than one pump because different pumps have different characteristics, as described in section 2.3.

2.2.3 *Measurement of system pressure*

One can measure pressure at various points in the system volume, and these pressures will not necessarily be the same. There is a tendency, understandable of course, to put the pressure gauge very close to the pump, where the pressure (p_0) is lowest. This is useful for tests on small systems, but the pressure p in a large system volume will be worse because of the intervening conductance C, as indicated in figure 2.3.

By continuity, we have $p_0S_0 = pS = Q$, the flow rate. But the flow rate is also equal to $C(p - p_0)$, as this is the definition of the conductance. So, rearranging, we can deduce that

$$p - p_0 = p_0S_0/C \text{ and hence } p = p_0(1 + S_0/C). \tag{2.8}$$

Thus there is a big error in the measurement of p at position p_0, if S_0 is large and/or C small. One can also use the above relations to prove (2.6).

Note that in general both S and C can be functions of pressure. In the molecular flow regime, at low p where the gas molecules only collide with the walls, and where we are not near the ultimate pressure of the pump, then they are, in fact, both constant. The parameter most commonly used to distinguish different flow regimes is the Knudsen number K_n, which is simply the ratio of the the mean free path λ to the the pipe diameter D. Molecular flow, considered here, is valid for $K_n > 1$. The viscous flow regime, valid at high pressures, arises when $K_n < 0.01$. There is an intermediate regime, named after Knudsen, when $0.01 < K_n < 1$, in which the flow is turbulent. Backing pumps may operate in the turbulent regime during the initial pump down phase from atmospheric pressure, with $Q > 200D$ (D in cm), but otherwise this regime is unimportant for UHV systems (Roth 1990, Delchar 1993).

2.3 UHV hardware: pumps, tubes, materials and pressure measurement

2.3.1 *Introduction: sources of information*

It is not really possible to do justice to the subjects of hardware and experimental design practices in a book; it takes too much space, so let me first comment on additional sources of information. Of the general surface science textbooks, Lüth (1993/5) has used his Panel I to convey the feel of UHV equipment. Detailed books on vacuum technology exist, including O'Hanlon (1989), Roth (1990) and Dushman & Lafferty (1992), and there are several concise summaries including Delchar (1993) and Chambers *et al.* (1998). A highly regarded general text on experimental design is that by Moore *et al.* (1989), which has a chapter on vacuum and a short section on UHV design. A useful compendium of designs and know-how for experimental surface science has been compiled by Yates (1997).

Manufacturers' catalogues are useful, assuming that you know that they are attempting to get you to buy something (in the long run). Although all such catalogues provide detailed information about the products, the Leybold-Heraeus catalogue has traditionally included a tutorial section which helps one understand what the products are doing, and what choices the purchaser needs to make. Relatively small performance improvements in vacuum components can cause quite a commercial stir. So one always needs to consider what the latest model is really doing. The physical principles on which these devices are based are emphasized here, in the hope that these do not change too fast.

2.3.2 *Types of pump*

There are many types of pump, but the ones used to create UHV conditions are typically one or more of the following: turbomolecular, diffusion, ion or sputter ion, sublimation or getter, or cryo-pumps. In choosing a pump for a system, you need to know, first of all, its general characteristics.

Turbopumps are extremely useful general purpose pumps, with high throughput, and produce a pressure ratio between their input and output ends. They are poor for low mass molecules, especially hydrogen, because they work by giving an additional velocity, in the required direction, to the molecules, and thus are less effective when the molecular speed is high. The ultimate pressure depends on the backing pressure, and so p_u can be improved using two pumps in series. There are newer versions with magnetic levitation bearings which make the pumps contamination free and much quieter than earlier versions. The rotor of a small pump typically turns at over 100000 revs/min, with tip speeds in excess of 250 m/s; these high speeds means that the lightness and tensile strength, as well as the geometric form of the rotor blades are important materials parameters (Becker & Bernhardt 1983, Bernhardt 1983). Turbopumps are used extensively in semiconductor manufacturing facilities, the ‘Fabs’ of the silicon age. UHV pumps constitute a major cost of these facilities. There is an active current effort (Helmer & Levi 1995, Schneider *et al.* 1998) in modeling the performance of such pumps, with the goal of making less expensive (rather than simply more powerful) turbopumps for future facilities.

Diffusion pumps are the workhorses of standard high vacuum systems. For UHV use, they are always fitted with a liquid nitrogen cooled trap, in order to stop oil entering the vacuum chamber. This trap is situated behind a valve that can be sealed off should the trap need to be warmed up, or if any disaster occurs. One of the claims in favor of diffusion pumps is that the cost for a given pumping speed is lower than for other types of pump; they also pump hydrogen and helium well.

Ion, sputter-ion, sublimation, getter and cryo-pumps are characterized as capture pumps, since they trap the gas inside the system (Welch 1994). Thus they are not good if there is a heavy gas load, but can be very good for a static vacuum under clean conditions. Chemical pumps comprise those capture pumps which work primarily via chemical reactions at the internal surfaces; these pumps are poor for rare gases. Getters are chemical pumps which have been traditionally been used in static vacua such as lamp bulbs, cathode ray and TV tubes, and they are also used in accelerators such as LEP (Reinhard 1983, Ferrario 1996).

Cryopumps have very high speed, but produce vibration from the closed cycle displacer motor used for refrigeration, and are quite expensive. Specific characteristics of all these pumps can perhaps best be assessed by visiting a laboratory or facility, or by visiting a trade show at a conference. The important points to understand in advance are the principles of their operation.

2.3.3 *Chambers, tube and flange sizes*

The second type of decision concerns pumping speed and flange sizes. These design requirements affect the size, weight and cost, and via these factors, the viability of the apparatus. Tubes and flange sizes are standard, as can be seen from the manufacturers' catalogues. The standard sizes are in Appendix F, and their conductance per meter length, and with a 10 cm end into the chamber, is given. The conductance calculations are then sufficient to make estimates which will enable you to sketch a reasonable design. Then, one typically needs to discuss it with someone who has done a design previously; it may be the most important factor in your experiment, and should not be done blind.

Useful formulae for conductances are the following. For an aperture, diameter D (cm),

$$C = 2.86\,(T/M)^{1/2}\,D^2 \text{ liter/s,} \tag{2.9}$$

with M the molecular weight, and T (K). For a long or short pipe, with length L in cm also,

$$C = 3.81\,(T/M)^{1/2}\,D^3/(L + 1.33D) \text{ liter/s.} \tag{2.10}$$

The flanges are typically made of stainless steel, and are sealed with copper gaskets. They are loosely referred to as conflat flanges, though Conflat® is a trade mark of Varian, Inc.; they are available from many suppliers. These tubes/flanges are referred to as ports on the central chamber. Even if one has access to a good machine shop, it is not particularly cost-effective to try to make one's own vacuum components: there are several specialist firms who make tubes, flanges and chambers on a routine basis in both North America and Europe, at least. What we then have to do is to 'pick and mix' accessories for our needs, typically around a special chamber which has been designed for the job in hand, and made by one of these firms. Many of the accessories relate to particular measurement or sample handling techniques, which are the subject of section 2.4.

We need to match pump speeds to pipe dimensions and conductances, as set out in Appendix F, table F2. A rule of thumb is that you need 1 liter/s of pump speed for every 100 cm^2 of wall area. This can be seen by taking a value for q (see section 2.2.1) $= 2 \times 10^{-12}$ $\text{mbar·liter·s}^{-1}\text{·cm}^{-2}$ or 2×10^{-8} $\text{mbar·liter·s}^{-1}\text{·m}^{-2}$, which is a reasonably conservative design figure.

Both sublimation and cryopump designs can trap a large fraction of the gas which enters the throat of the pump; in practice certainly greater than a quarter. This means that $S > C/4$, where C is the aperture conductance, which can be high, e.g. for 4–8 inch diameter pipes in the range 400–3000 liter/s, depending on the precise flanging arrangements. A titanium sublimation pump (TSP) chamber can be designed relatively easily

Table 2.1. *Manufacturer's quoted information for TSP pumping speeds (liter·s^{-1}·cm^{-2})*

Wall T	H_2	N_2	O_2	CO	CO_2	H_2O	CH_4/Inert
20 °C	3	4	2	9	8	3	0
77 K	10	10	6	11	9	14	0

for these needs, using data from table 2.1. For example, a tube 20 cm long and 20 cm (8 inch) diameter has an internal area of about 1200 cm^2. If we take a pessimistic view that, with the wall at 20 °C, the average for all relevant gases is 2 liter·s^{-1}·cm^{-2}, this still gives us a pumping speed $S = 2 \times 1200 = 2400$ liter/s, which is quite large enough to be greater than, or around, $C/4$ for a reasonable pump aperture.

But we should note some other points too. A TSP outgasses when it is being 'fired', and the pressure therefore goes up before coming down; if the walls are too close to the hot filament, this problem is worse. Second, these pumps do not pump unreactive gases at all well. Cooling the walls with liquid nitrogen helps; even water cooling is quite effective in improving the performance, but it still doesn't pump unreactive gases. The result of such concerns means that you should not economize on the wall area, and you should use a somewhat larger diameter tube than you might calculate on the simplest basis.

2.3.4 Choice of materials

UHV experiments require the use of materials with low vapor pressures, and it is helpful to have your own notes and diagrams which give you easy access to such information (see Appendix G for some pointers). Since the outgas leak rate $Q_o = qA$, we should use low q materials, and minimize the area A of the design. As materials and accessories have improved there is a tendency to put more and more equipment into the vacuum system. This may make life more difficult in the long run: to try to do everything often means you may achieve nothing.

There are lists of q (sometimes called q_d to represent desorption) values for different materials and treatments in vacuum books and review articles, but they need to be treated as general guides only. If you need to make measurements of q for particular materials, this is not without pitfalls (Redhead 1996), and is rarely done for small scale applications. The main materials, stainless steel, copper, aluminum, ceramics, all produce values below 2×10^{-12} mbar·liter·s^{-1}·cm^{-2} after a modest bakeout at around 200 °C for 12–24 h. These values are satisfactory for most purposes, and the trend is to avoid more stringent bakeouts at higher temperatures or over longer times.

It is imperative that you know what is in your system before you bakeout, or this important stage in your experiment may cause irreversible damage, and repairs may be very expensive. In particular, *do not* bakeout your system to temperatures which seem routine from the research literature (Redhead *et al.* 1968, Hobson 1983, 1984)! Some equipment contains materials, particularly high temperature plastics, e.g. for insulating electrical

Table 2.2. *Classification of vacuum gauges*

Physical property involved	Kind of gauge	Kind of pressure recorded
(1) Pressure exerted by the gas	Bourdon, capacitance	Total pressure, all gases
	McCleod (gas compression)	Pressure, non-condensable gas
(2) Viscosity of the gas	Spinning rotor	Total, depends on gas
(3) Momentum transfer	Radiometer, Knudsen gauge	Total, ~independent of gas
(4) Thermal conductivity	Pirani, thermocouple gauge	Total, depends on gas
(5) Ionization	Bayard–Alpert gauge	Total, depends on gas
	Partial pressure analyzers	Partial pressure

wires, which are very sensitive to the exact bakeout temperature, say between 150 and 220 °C. Despite this caution, the availability of such plastics, coated wires, and even electric motors which work under UHV, has made surface science techniques much more widespread and routine.

2.3.5 Pressure measurement and gas composition

As with pumps, the practitioner needs to know what the different types of gauge can do, and what principles they are based on. There are three general purpose gauges for accurate pressure measurement: the ion gauge, the Pirani gauge and the capacitance gauge. The ion gauge works by ionization of the gas molecules, and the fine wire collector reduces the low pressure limit due to X-ray emission of electrons, which mimics an ion current. It should only be used below 10^{-1} mbar, works well below 10^{-3} mbar, and has a lower limit typically below 10^{-11} mbar, depending on the design. The cold cathode (Penning) gauge also works by ionizing the gas molecules, and works over the range $5 \cdot 10^{-8}$ to 10^{-2} mbar; but it also functions as a sputter ion pump to some extent, and so the pressure tends to be underestimated.

The Pirani gauge utilizes the thermal conductivity of the gas molecules, and works over a range from about 10^{-3} to 10^{2} mbar; it typically is used for semi-quantitative monitoring of the fore-vacuum. A capacitance gauge is extremely precise above 10^{-4} mbar, but requires different heads for different pressure ranges. This is sometimes referred to as a baratron, but (spelt with a capital B) this is the trade name of a company making such equipment; these gauges are used very widely in all aspects of pressure measurement, process and flow control, for example in chemical vapor deposition (CVD) reactors. An outline description of such process equipment is given by Lüth (1993/5, section 2.5); more details are given in various sections of Glocker & Shah (1995).

A list of such gauges is given in table 2.2. There are some relatively new ones, including the spinning rotor gauge, based on gas viscosity, which has been developed and marketed over the last ten years. To find out more about such a development requires a two-pronged approach. One needs manufacturer's catalogues to find out what is actually available commercially. The second line of enquiry is to search the vacuum