Technical Information

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What Is Vacuum?

Commonly, the word “vacuum” is applied to an enclosed volume containing gas at a lower pressure than the surrounding atmospheric pressure. So many applications, processes, and products involve vacuum that attempting to classify them appears futile. However, using very broad definitions, vacuum applications fit into six headings...

Large Hadron Colliders

Moving electrons (or ions) from here to there as in x-ray tubes, beam lines, mass spectrometers, etc, demands high vacuum. Why? Because electrons/ions will be deflected by, attach to, or ionize any residual gas molecules they encounter. *Vacuum creates conditions in which charged or uncharged particles can be moved around without collision.*

Mirrors

Evaporating aluminum as a thin coating on glass or plastic makes a wonderful headlamp reflector, DVD, or rear-view mirror. But try evaporating aluminum in air and the result is aluminum oxide, a white substance not noted for its reflective properties. *Vacuum prevents chemical reaction with air.*

Cameras

All good camera lenses are coated with an anti-reflective layer so the maximum amount of light arrives at the film or digital processor. By contrast, architectural glass is coated with partially reflective layers for visible or infra-red wavelengths. Any oil or water vapor absorbed on the glass surface prior to coating ruins the process. *Vacuum helps removes absorbed contamination from surfaces.*

Halloween Masks

Vacuum forming is a common process for making plastic Halloween masks, compartmented lunch trays, and disposable razors. The plastic sheet is heated to a deforming temperature and the air removed between it and a metal mold. *Vacuum removes air to create a differential pressure.*

Neon Signs

Neon signs contain...neon (and other gases for different colors); electrical switchgear is backfilled with SF_6 to prevent arcs; and all fluorescent lights are backfilled with mercury vapor. *Vacuum removes air in preparation for backfilling with an appropriate gas, vapor, or liquid.*

Clean Surfaces

Tribology experiments (the science of wear and friction of *clean* surfaces) often starts with breaking a crystal under vacuum to get a clean surface that has no absorbed contaminants. If the chamber's pressure is one millionth of an atmosphere, the initially clean surface is coated with a mono-layer of residual gas within ~1 second. If the chamber is at one billionth of an atmosphere, the time increases to ~1000 seconds. *Vacuum reduces the flux of the residual gas on a surface.*

What is Pressure?

Since vacuum is described as a “reduced pressure” we must have some understanding of what pressure means. There are two ways of presenting it: (a) every-day experience with atmospheric pressure; and (b) what is really happening at the molecular level.

Grand Scale

The layer of air surrounding the earth is not thick (roughly 100 km, compared to the earth's diameter of 12,800 km). However, a column of air 1” square (6.45 cm^2) at sea level projected to the top of the atmosphere weighs about 14.7 pounds (6.7 kg) on the average day. Expressed another way, this air column creates a pressure at sea level of 14.7 pounds per square inch (psi) (1.035 kg/cm^2). But air is a fluid and 14.7 psi applies to all surface no matter what their orientation. If we evacuate a 1” cubic box at sea level, then the top (horizontal) surface will experience 14.7 psi pushing down and the bottom (horizontal) surface will experience 14.7 psi pushing up. Equally, opposite sides of the cube experience forces of 14.7 psi pushing left and right. So the cube experiences no net force pushing it in any direction (other than gravity, of course).

Nano Scale

Air is a mixture of molecules (nitrogen, oxygen, carbon dioxide, etc) and atoms (argon, helium, etc), which at normal temperatures are all moving at high speed, making a huge number of elastic collisions with each other in a gas phase and non-elastic collisions with surfaces. At room temperature, the average nitrogen molecule is traveling at ~900 mph (474 m/s.). At any moment, ~90% of the N_2 molecules have velocities between 100 mph and 1,800 mph. But N_2 has the mass of only 4.8×10^{-23} gm, so despite its high velocity its kinetic energy is unnoticeably small. However, as noted in *Number Density* (below), 1 cubic centimeter (cc) of air contains a gigantic number of atoms/molecules.

It is the force generated by the high speed surface bombardment of those myriad tiny particles that we experience as pressure.

Pressure Unit

All pressure measurement units are of the form - force per unit area. However, for many units this relationship is hard to identify. A few of the more commonly used pressure units in vacuum applications are noted here with approximate conversion factors to 1 atmosphere pressure (1 atm) to show their relative magnitude.

- millimeter of mercury: 760 mmHg = 1 atm
- Torr*: 760 Torr = 1 atm
- millitorr: 760000 mTorr = 1 atm
- micron of mercury: 760000 µHg = 1 atm
- bar: 1.013 bar = 1 atm
- millibar: 1013 mbar = 1 atm
- pascal**: 101325 Pa= 1 atm

*Preferred unit in the USA and used throughout these notes

*SI units (1 Pa = 1 newton/m^2)

Basic Vacuum Concepts

Our concept of solids and liquids depends largely on our ability to see/touch them. If we have two lumps of solid, roughly the same volume and one lump is light while the other is heavy, we say the heavy lump has a higher density - mass per unit volume (lb/in^3, g/cc, kg/m^3, etc.). Gases present a challenge to our ability to see/touch and new terms have been introduced to describe the “gaseous state”.

(The gas laws used to derive the values quoted below are correct only for ***ideal*** *gases. However, in room temperature chambers as pressure decreases, all gases approach ideal behavior. For vacuum applications, the appropriately scaled value - to allow for pressure change - will be sufficiently accurate for precise calculations.)*

Number Density

Avogadro determined that equal volumes of gas at the same temperature and pressure contained equal numbers of molecules. It does not matter if the gas is pure N_2, CO_2, Ar, H_2, or a mixture of all four. Later, Loschmidt determined that 22.4 liters of gas at 760 Torr and 0º C contain 6.022×10^{23} molecules (the present day value, often called Avogadro's number).

Since gas fills any volume that contains it, its “density” (in g/cc units) depends on that volume, the gas composition, and molecular weights of the components. If instead of density (mass per unit volume) we use *number density* (number of molecules in 1 cc) we can describe a “quantity” of gas without knowing anything about composition or molecular weights. From Avogadro's number (which refers to 22.4 liters) we know the number density (which refers to 1 cc) of any gas at 760 Torr and 0° C is 2.69×10^{19} cm^{-3}.

Mean Free Path

The huge number density at atmospheric pressure and the high velocities of the gas molecules mean that in each cc there are many, many gas phase collisions every second. Expressed another way, even though a molecule travels at high speed, on average it travels a very short distance before hitting another gas phase molecule. This average distance is called the *mean free path* (mfp). For air at 760 Torr the mfp is 6.5 x 10^{-6} cm.

Particle Flux

In addition to colliding with each other in the gas phase, gas molecules hit the containing vessel walls and every other surface inside the enclosure. The rate at which they hit these surfaces, called *particle flux*, depends on the gas's number density. The flux of air at 760 Torr and 0º C is 2.9 x 10^{23} cm^{-2} s^{-1}.

Reducing Pressure

If we remove some molecules from an enclosed container initially at 760 Torr, what happens to number density, mfp, and particle flux? The easiest quantity to understand is number density. If we remove half of the molecules from the container, the number density goes from 2.7 x 10^{19} cm^{-3} to 1.35 x 10^{19} cm^{-3}. If we remove 99% of the original molecules, the number density is 2.7 x 10^{17} cm^{-3}, still a huge number. The table shows the relationship between pressure, number density, mean free path, flux, and the time taken to completely cover a clean surface with a monolayer, for air at room temperature.

With respect to the monolayer coverage, it depends on: particle flux, molecular diameter, and the sticking coefficient of the gas molecules on the surface. The numbers given are for air which has an average molecular diameter of 3.7 Å and the sticking coefficient is ~1 on a clean, unheated surface.

Base Pressure

When a chamber has no leaks, has no gas deliberately flowing into it, and has been pumped for several days, the pressure reaches an equilibrium value called the *base pressure*. In truth, because the pressure approaches equilibrium asymptotically and the outgassing rate undergoes exponential decay, even after a long time under vacuum, the chamber, theoretically, will never quite reach a stable pressure. But variations in vacuum gauge calibration, room temperature, pumping speed, backstreaming from the pump, etc., mask or counter any real pressure reduction and the chamber appears to have reached a steady state. Often what happens is: the operator pumps the chamber for a few hours, grows tired of waiting, and claims the chamber is at base pressure.

This is not necessarily wrong. After all, if the pressure falls from 5x10^{-7} Torr to 4x10^{-7} Torr by waiting another ten hours, is all that much gained? Perhaps it doesn't conform to formal definition, but in a sense the base pressure is reached whenever the operator says it is and starts using the chamber.

Working Pressure

The term *base pressure* defines conditions where no gas is deliberately flowing into the system. But sometimes the chamber is first pumped to its base pressure (to check for leaks or remove contamination) and then back-filled with a gas to an intermediate pressure. This is how processes such as sputter deposition, plasma etching, and CVD are done. This intermediate pressure is called the *working pressure*. To establish and maintain a working pressure, it is rarely sufficient to just close the pumping port, back-fill with gas, and walk away. Most back-fill applications require a flow of fresh gas to sweep away contaminants desorbing from the chamber walls. Often the back-fill pressure is stabilized with a feedback control system.

Reducing Pressure

Pressure (Fractions of an Atmosphere)	Pressure (Torr)	Number Density (cm^{-3})	Mean Free Path (cm)	Particle Flux (cm^{-2} sec^{-1})	Time for a Monolayer (sec)
1/1,000	0.76	2.7 x 10^{16}	0.0065	2.9 x 10^{20}	3 x 10^{-6}
1/10,000	7.6 x 10^{-2}	2.7 x 10^{15}	0.065	2.9 x 10^{19}	3 x 10^{-5}
1/100,000	7.6 x 10^{-3}	2.7 x 10^{14}	0.65	2.9 x 10^{18}	3 x 10^{-4}
1/1,000,000	7.6 x 10^{-4}	2.7 x 10^{13}	6.5	2.9 x 10^{17}	3 x 10^{-3}
1/10,000,000	7.6 x 10^{-5}	2.7 x 10^{12}	65	2.9 x 10^{16}	3 x 10^{-2}
1/100,000,000	7.6 x 10^{-6}	2.7 x 10^{11}	650	2.9 x 10^{15}	3 x 10^{-1}

Ultimate Pressure

Vacuum pump manufacturers gives two specifications: pumping speed and *ultimate pressure* (also called ultimate vacuum). The ultimate pressure is measured by capping the pump's inlet and finding the equilibrium pressure after operating the pump for many hours. Because it is measured under "ideal" circumstances, it is crucial to remember that a chamber connected to this pump will never reach the quoted ultimate pressure! Perhaps worse, pump manufacturers measure the ultimate pressure of mechanical pumps using a McLeod gauge that cannot measure vapors such as pump oil and water. Consequently, the so-called *ultimate (partial) pressure* of a rotary vane pump may be quoted in the 10^{-5} Torr range, causing much confusion when the practical ultimate pressure (using a gauge that responds to oil and water vapor) is two decades higher.

Flow Regimes

The mean free path (described above) and the chamber/component dimensions determine the gas's flow conditions or *flow regime*. If the mfp is:

- Very short compared with the chamber's 'characteristic dimension's', the gas is in *continuum* flow
- Shorter than the chamber's characteristic dimensions but approaches them, the gas is in *transitional* flow
- Equal to or longer than the chamber's characteristic dimensions then the gas is in *molecular* flow

The flow regime is used to identify the appropriate equations needed to calculate conductances, pump down times, and other characteristics.

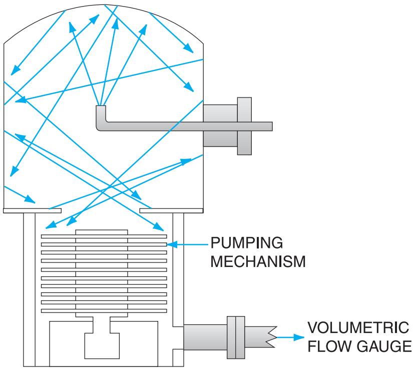
Vacuum Doesn't Suck!

There is a common misunderstanding that vacuum pumps suck. *There is no such force as suction.* If the gas molecules in one "section" of a vacuum volume could be instantaneously removed, molecules from the remaining section, in their normal high-speed flight, would randomly collide and bounce off walls until they filled the whole volume at a lower pressure.

For vacuum pumping this means, until a gas molecule in its random flight enters the pumping mechanism, that molecule cannot be removed from the volume. In effect the pump acts like a one-way valve: gas molecules may enter but not return. But for that to happen, molecules must first arrive at the pump...it can not reach out and grab them. Understanding that *vacuum doesn't suck* makes the basic aspects of vacuum technology much easier to grasp.

■ *Conductance*

Vacuum technology novices have difficulty distinguishing *conductance* from *pumping speed* (discussed later). These terms seem to describe similar concepts and use identical flow units of volume per unit time. But they should not be confused.



Definition of Conductance

The formal definition of conductance is:

- The ratio of throughput, under steady-state conservation conditions, to the pressure differential between two specified isobaric sections inside the pumping system.

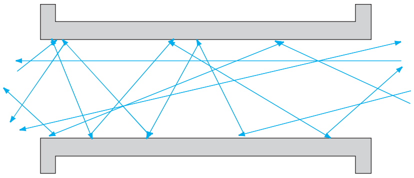
Practical Interpretation

The conductance of a ‘passive’ vacuum component (e.g. tube, nipple, elbow, tee, valve, non-cooled baffle, etc.) is a measure of that component’s ability to transmit gas molecules from end-to-end in some given time. High conductance is of paramount importance in achieving rapid chamber pump down times and low base pressures.

One characteristic that determines conductance is the clear diameter of the opening through the component. A wide opening offers a bigger target for molecules to enter during their random flights around the chamber and, obviously, until a molecule enters the component it cannot be transmitted.

Another characteristic is the number of wall collisions molecules make during their transmission through the component. When molecules hit surfaces they are not reflected like light from mirror. Rather, they “stick”, often for a very short time, lose all information about their arrival direction, and desorb following a *cosine distribution*. This distribution gives the molecules an equal chance of heading in either direction along the tube and a maximum probability of heading diametrically across the tube. The more surface hits a molecule makes, the less likely it is to complete the journey quickly and the lower is that component’s conductance.

So the practical interpretation of conductance is that molecules pass more readily through a tube that is wide bore, straight, and short. Components with these characteristics have high conductance.


GAS CONDUCTANCE OF A PASSIVE COMPONENT

Conductance Units

Conductance is a volumetric flow measured in units of *volume per unit time,* specifically: liters per second (L/s); cubic meters per hour (m^3/h); cubic feet per minute (cfm); liters per minute (L/m); etc. Expressing conductances as volumetric flows has two benefits: (a) conductances can be combined by simple math (see below) and (b) in the molecular flow regime, a component’s conductance is constant and independent of pressure.

Calculating Conductances

The time to calculate conductances is before any vacuum component is purchased. The approximate operating characteristics of a soon-to-be-built or about-to-be-modified system should be known while it is still a scratch-pad idea. When the system is constructed, it is a trivial matter to reduce conductance but an expensive re-build to increase conductances that are too low.

Manual Calculation

Since conductance in molecular flow is independent of pressure and since most high vacuum applications are in molecular flow, the calculations discussed here and in the sidebar are appropriate only for that flow regime. Two books edited by J.M. Lafferty are invaluable when making conductance calculations. The first is *Scientific Foundations of Vacuum Technique*, by Saul Dushman, 2nd ed., J.M. Lafferty, editor, from which we have reprinted a table from p.99 with permission from John Wiley & Sons ©1962. The second is *Scientific Foundations of Vacuum Science and Technology*, J.M. Lafferty, editor, John Wiley & Sons ©1998 which has a chapter by R. Gordon Livesey with a wealth of information and equations for calculating conductances in molecular, transitional, and continuum flow regimes.

Examples of conductance calculations for straight cylindrical components using Dushman’s table are given in the sidebar. To calculate conductances of non-cylindrical components, find the appropriate equation in Lafferty’s 2nd book or, for less accurate estimates, use Dushman’s table and some rules of thumb:

- Right-Angle Bends: Measure the tube length “L” as the shortest distance (along the inside of the bend). Calculate the conductance from the table as if the tube were straight, then divide by 2 for every right-angle bend.
- Non-Cylindrical Cross-Section: Calculate the “open” area of the tube or annulus and find the radius of a cylindrical tube with an equal area. Calculate the conductance of this “equivalent tube”.
- Diameter Changes: If a tube changes diameter along its length, the safest way to calculate conductance is to use the smaller diameter to calculate “a” (the radius). But if the smaller diameter portion is short compared to the total tube length, the underestimation may be extreme. In such cases, calculate the conductance of the small diameter and large diameter section as separate tubes and combine them in series (see *Combining Conductances*).

Dushman’s Table for Conductance Values

		F_t—Conductance of Tube (liters sec.$^{-1}$) for air at 25° C						
a (cm)	F_O	L/a = 1	2	4	8	12	16	30
		K = 0.672	0.514	0.359	0.232	0.172	0.137	0.080
0.1	0.367	0.246	0.188	0.132	0.085	0.063	0.050	0.029
0.2	1.466	0.986	0.753	0.527	0.340	0.252	0.200	0.117
0.3	3.300	2.217	1.664	1.184	0.764	0.567	0.451	0.263
0.4	5.866	3.943	3.013	2.106	1.358	1.008	0.802	0.468
0.5	9.166	6.160	4.708	3.291	2.122	1.575	1.253	0.731
0.6	13.200	8.872	6.779	4.739	3.057	2.269	1.805	1.052
0.7	17.970	12.080	9.228	6.449	4.161	3.088	2.457	1.432
0.8	23.470	15.770	12.050	8.424	5.436	4.033	3.208	1.871
0.9	29.700	19.960	15.250	10.660	6.879	5.105	4.061	2.368
1.0	36.660	24.640	18.830	13.160	8.492	6.302	5.013	2.922
2.0	146.600	98.560	75.340	52.650	33.970	25.210	20.050	11.690
3.0	330.000	221.700	166.400	118.400	76.420	56.710	45.110	26.300
4.0	586.600	394.300	301.300	210.600	135.800	100.800	80.210	46.770
5.0	916.600	616.000	470.800	329.100	212.200	157.500	125.300	73.100
6.0	1,320.000	887.200	677.900	473.900	305.700	226.900	180.500	105.200
7.0	1,797.000	1,208.000	922.800	644.900	416.100	308.800	245.700	143.200
8.0	2,347.000	1,577.000	1,205.000	842.400	543.600	403.300	320.800	187.100
9.0	2,970.000	1,996.000	1,525.000	1,066.000	687.900	510.500	406.100	236.800
10.0	3,666.000	2,464.000	1,883.000	1,316.000	849.200	630.200	501.300	292.200

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Combining Conductances

Since a component's conductance in molecular flow is independent of pressure and is quoted as a volumetric flow, conductances for various components can be combined in series or parallel. If two chambers are connected together by: (a) a narrow tube on chamber 1; (b) a right angle valve; and (c) a large port on chamber 2, their separate conductances can be combined as reciprocals to give a total conductance between the two chambers (see sidebar *Series Conductances*). Notice that the total conductance is much less than any individual conductance. In addition, look at the table. Here, just two conductances, one variable and the other fixed at 10 L/s, are added together. The Total Conductance column demonstrates a critical rule in series conductances– *the smallest conductance rules.*

Alternatively, if two chambers are connected by two tubes of different diameters, each tube has its own conductance. To determine the total conductance between chambers simply add the conductances together (see sidebar *Parallel Conductances*).

Computer Calculations

A component's conductance in continuum or transitional flow depends on gas pressure and uses different equations than those governing molecular flow. Calculating conductances from atmospheric pressure to high vacuum requires iterative processes ideally suited to computer calculation. PEC's VacTran, described on page 17-21, is an exceptionally powerful program for vacuum technology calculations including the calculation of series and parallel conductances for any pressure range and many different cross-sectional shapes (cones, slots, ovals, annuli, and triangles).

Calculating Conductance

The conductance of an **orifice**—a hole in an infinitely thin plate—is determined as follows:

- Measure the orifice's radius in centimeters.
- Enter the table at the appropriate "a" (radius) row. Go right to the F_0 column and read the conductance in L/s.

The conductance of a **straight cylindrical tube** is calculated as follows:

- Measure the (overall) length of the tube in any convenient units.
- Measure the tube's I.D. in the same units.
- Divide the I.D. by 2 to give the radius.
- Divide the length by the radius (this gives the "L/a" ratio used in the table).
- Convert the radius to centimeters (this gives "a" (cm) to use in the table).
- Enter the table at the appropriate "a" row.

Go right until under the value of the calculated "L/a" ratio. If the exact match is not available, use the next larger "L/a" value or interpolate.

Pumping

Pumping Speed Definition

The formal definition of pumping speed is:

- The ratio of the throughput of a given gas to the partial pressure of that gas at a specific point near the inlet port of the pump.

Pumping Interpretation

With less formality, but perhaps more clarity, pumping speed is a measure of the pump's ability to permanently remove gas from its inlet port.

Conductance C1	Conductance C2	Total Conductance 1/(1/C1 + 1/C2)
10	10	5 L/sec.
10	100	9.1 L/sec.
10	1,000	9.9 L/sec.
10	10,000	9.99 L/sec.
10	100,000	9.999 L/sec.
10	1,000,000	9.9999 L/sec.

Series Conductances

Series conductances are added as reciprocals:

1/Ctotal = 1/C1 + 1/C2 + 1/C3

Given:

Narrow Tube—120 L/s (C1)

Angle Valve—230 L/s (C2)

Large Port—1,400 L/s (C3)

The total conductance is:

$1/C_{total} = 1/120 + 1/230 + 1/1{,}400$

$1/C_{total} = 0.0083 + 0.0043 + 0.0007$

$1/C_{total} = 0.01339$

$C_{total} = 1/\ 0.01339$

Total Series Conductance = 74.6 L/s

Parallel Conductances

Using two conductances simultaneously between two chambers or between a chamber and pump is not common but such arrangements do occur and are easily calculated. Suppose the two tubes have conductances of 1,800 L/s and 2,300 L/s. The total conductance is:

$C_{total} = C1 + C2$

$C_{total} = 1{,}800 + 2{,}300$

Total Parallel Conductance = 4,100 L/s

Pumping Speed Units

Pumping speed is a volumetric flow measured in units of *volume per unit time* – specifically: liters per second (L/s); cubic feet per minute (cfm); cubic meters per hour (m^3/h); or liters per minute (L/m). As with conductance, expressing pumping speed as volumetric flows has the benefits that pumping speed and conductances can be combined by simple math (see *Effective Pumping Speed*).

Pumping Speed Curves

Various standards organizations in the US, Europe, and Asia have specified methods for measuring *pumping speed*. As far as we are aware, all suggest capping the pump with a small volume dome at its inlet port and monitoring the pressure at various gas flow rates into the dome (from a calibrated mass flow controller). The results are plotted as *pumping speed* vs *pressure* as shown in Figure 2. Because a pump's pumping speed is measured under ideal conditions, its numerical value will be unobtainable in a practical system–the connection between any pump and any chamber affects the pumping speed (see *Effective Pumping Speed*).

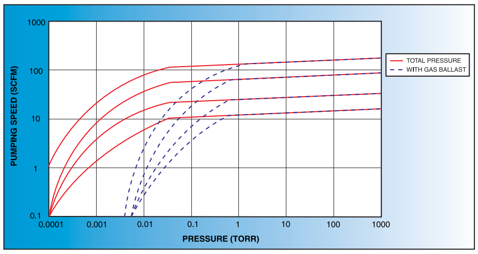


Figure 2

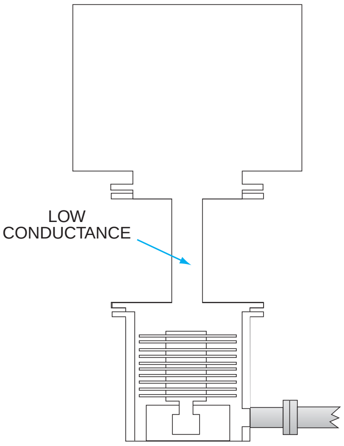
Displacement and Capacity

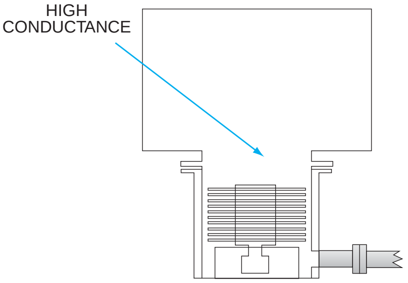
Unfortunately, many mechanical pump manufacturers quote a value called *free air displacement* or *capacity* for their pumps. The units are volumetric flow rate and the value is easily mistaken for a measured pumping speed. However, displacement/capacity appears to be a theoretical pumping speed the pump might have if the gas had no mass or viscocity; negotiated the entrance port and constrictions into the pumping mechanism instantaneously; and did so without turbulence or boundary layer effects. Why pump manufacturers indulge in such an exaggeration is unknown. It only confuses those attempting vacuum calculations. We strongly suggest displacement/capacity values be ignored or, in the absence of a measured pumping speed, multiplying displacement by ~0.75 to get an approximation of the real pumping speed.

Effective Pumping Speed (EPS)

What is EPS?

As pointed out above, a pump's quoted pumping speed is the maximum value measured under ideal conditions. In practical situations, a pump is connected to a chamber via a series of passive components such as a tube, valve, and perhaps a trap. Each passive device has its own ability to transfer gas, and clearly that ability will affect the flow of gas from chamber to pump inlet. It is the combination of the conductances of these passive devices and the pumping speed of the pump that determines the overall pumping speed from the chamber, called the *effective pumping speed* (EPS) or sometimes the *delivered pumping speed.* (We will use the former.) The EPS's value is critical since it determines the chamber's pump-down characteristics and base pressure.





EPS Units

Since EPS is a combination of conductance and pumping speed, it retains the units of *volume per unit time*, such as: liters per second (L/s); cubic feet per minute (cfm); cubic meters per hour (m^3/h); or liters per minute (L/m).

Calculating EPS

Consider a 500 L/s high vacuum pump connected to a chamber by a pumping port of 4" (10 cm) internal diameter x 4" (10 cm) long. Calculating the port's conductance from Dushman's table gives ~500 L/s. Pumping speed and conductance are combined to give the EPS in exactly the same way two series conductances are combined.

$$1/EPS = 1/PS + 1/C$$

So a 500 L/s pump and a 500 L/s port combine as 1/500 + 1/500. That is, the EPS from the chamber is 250 L/s. The simplest connection between pump and chamber halved the pump's quoted pumping speed.

Obviously, this is a serious issue and adding a trap or valve to the connection can only further reduce the pumping speed from the chamber. Unfortunately, all too often we see connections between pump and chamber that are just plain silly. For example, a 500 L/s diffusion pump connected to a chamber by a 0.7" (1.8 cm) I.D. x 1.42" (3.6 cm) long tube. Dushman's table gives the tube's conductance as ~10.7 L/s. Combining this with the pump (1/500 + 1/10.7) gives an EPS of ~10.5 L/s. There is no clearer illustration of the maxim: the smallest conductance rules.

Measuring EPS

One method of measuring EPS uses the fact that in molecular flow the system follows first-order reaction kinetics:

$$P_{final} = P_{original} \times e^{-kt}$$

Integrating with respect to time

$$EPS = V/t \times \log_e(P_o/P_f)$$

Where V is chamber volume, t is time, and P_o and P_f are the start and final pressures.

Example: a 150 L chamber has a base pressure of 1×10^{-8} Torr. Gas is injected through a valve at a rate that keeps the pressure at 4×10^{-4} Torr with the pumps operating. The valve is shut at time zero 0 s and 16 s later the chamber has reached 6×10^{-6} Torr.

$$EPS = 150/16 \times \log_e(4 \times 10^{-4}/6 \times 10^{-6})$$
$$EPS = 9.38 \times \log_e 66.67$$
$$EPS = 9.38 \times 4.2$$
$$\mathbf{EPS = 39\ L/sec.}$$

Limitations to measuring the EPS this way:

- Formula only works for molecular flow conditions.
- Results are invalid if P_o edges into transitional flow.
- If P_f is <50x the chamber's base pressure, wall outgassing will affect the time measurement.

Other measurement methods are under Tech Info at www.lesker.com.

Gas Load

What is Gas Load?

When discussing pressures and pumping, we are really speaking about molecules in the gas-phase, which are the only ones we can measure or pump. However, if we could remove all gas-phase molecules instantaneously from a vacuum vessel, the result would not be zero pressure. Molecules are continuously entering the gas phase from various sources which can be summarized as:

- **Real leaks** at welds, gaskets, flanges, or porous construction materials
- **Virtual leaks** such as trapped volumes at welds, screw threads, or mating surfaces
- **Outgassing**, which includes gas/vapor...
  —**Desorbing** from the wall surfaces (which is important enough to warrant its own section)
  —**Diffusing** from the wall matrix
- **Evaporation** of materials with high vapor pressure
- **Permeation** through elastomeric gaskets
- **Permeation** through the glass or walls
- **Backstreaming gases** from the pump
- **Backstreaming oil vapor** from an oil-sealed pump
- **Backstreaming condensable vapors** (eg solvents) coming out of the pump oil
- **Desorbing gas** from a saturated trap
- **Desorbing gas** from a cryogenic trap with a falling cryogen level
- **Deliberately injected gas** required by the process

The rate at which molecules enter into the chamber's gas phase from all these sources is called the chamber's gas load.

Gas Load Units

Gas load is a mass flow rate and is measured in units of **volume x pressure per unit time**, such as: Torr.liters per second (T.L/s); mbar.liters per second (mbar.L/s); Pascal.cubic meters per hour ($Pa.m^3/h$); Torr.liters per minute (T.L/m); or std.cubic centimeters per minute (sccm).

Outgassing

What is Outgassing?

In a well-designed, well-constructed vacuum system, in the absence of deliberately injected gas, the major contributor to the gas load is the desorption of gases/vapors from the vacuum surfaces - *outgassing*. More specifically, the outgassing rate is the amount of gas leaving some unit area of surface in unit time.

Outgassing Rate Units

Any combination of units for pressure, volume, area, and time, can be used but there are just three combinations commonly quoted:

- Torr x liter per square centimeter per second (mostly in the USA)
- millibar x liter per square centimeter per second (mostly in Europe)
- pascal x cubic meter per square meter per second (the SI unit)

Note: by manipulating units the last combination can be transformed into the seemingly bizarre but correct W/m^2 *and is quoted this way in some literature collections. To transform rates in W/m*^{2} *into Torr-L/(cm*^{2}*-s) divide the former value by 1,333.2*

Outgassing Sources

Surfaces are active places that absorb gases and vapors to reduce the 'unfulfilled' bonding forces of the surface atoms. This means that all surfaces, no matter what material is under consideration, outgas under vacuum. Some of the worst materials are: plastics, elastomers, and glues; porous ceramics and porous metals; lubricating, sealing, or heat transfer greases; and us (fingerprints, hair, skin cells, dust mites, spittle droplets when talking, and food)!

The most common gases/vapors outgassing from surfaces are: water vapor; oil and grease vapors; solvents and volatile organic materials; and (when approaching ultrahigh vacuum pressures) hydrogen and carbon monoxide from stainless steel used in the chamber's construction.

Reducing Outgassing

As stated above, nothing can be pumped from the chamber until it is in the gaseous phase. The outgassing rate is reduced by methods that cause adsorbed gas/vapor to enter the gaseous phase:

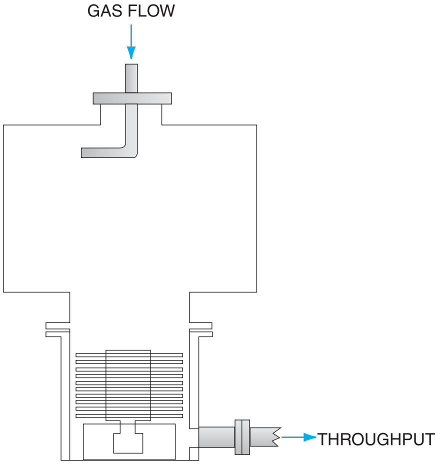
- Heat: baking the chamber increases the desorption rate of the gas/vapor
- Light: intense short wavelength UV breaks bonds between surface and adsorbed gas/vapor
- Plasma: active plasma products break bonds and react with adsorbed gas/vapor forming more volatile compounds
- Chemistry: reactive chemical vapors convert adsorbed water into HCl (very limited utility)

Throughput

What is Throughput?

Pump manufacturers supply pumping speed vs pressure curves for each pump. Multiplying pumping speed at some pressure by that pressure gives a measurement called *throughput* (or sometimes *pump throughput*).

It is essentially a measure of the *quantity* of gas the pump removes from its inlet in unit time, where the word *quantity* can be substituted by *amount, mass,* or *number of molecules.*



Throughput Units

Throughput is a mass flow rate and is measured in units of **volume x pressure per unit time**, such as: Torr.liters per second (T.L/s); mbar.liters per second (mbar.L/s); Pascal.cubic meters per hour (Pa.m^3/h); Torr.liters per minute (T.L/m); or std.cubic centimeters per minute (sccm).

Measuring Throughput

One method of measuring/calculating *(effective) throughput* is to measure/calculate the EPS from the chamber (see above) and multiply that value by the chamber pressure. As an example: the measured EPS is 83 L/s when the chamber's working pressure is 5 x 10^{-6} Torr.

The effective throughput is then:

83 L/s x 5 x 10^{-6} Torr which is **4.15 x 10^{-4} Torr.L/s**

Another measurement method is listed under Tech Info at www.lesker.com.

Gas Load & Throughput

Comparison & Calculations

The *gas load* was defined above as the total amount of gas entering the system while *throughput* is the total amount of gas leaving the system. Both have units of *volume x pressure per unit time*. The critical point here is to recognize that when the chamber's pressure is constant, *gas load* must equal *throughput*. To express the concept fully: the mass of gas entering the system in a given time must equal the mass of gas leaving the system in the same time or the pressure will change. To use a less rigorous but more memorable expression, at constant pressure:

Gas In = Gas Out

This identity is used when sizing pumps for applications that have known mass flow of gas injected. The common unit for measuring mass flows of gas is *standard cubic centimeters* per *minute* or *sccm*, popularly called "skims". (Note the units: *standard* refers to 760 Torr or 1013.2 mbar at 0° C; *cubic centimeters* is a volume; and *minute* is, obviously, time.) As an example, let us calculate the pumping speed needed to maintain a working pressure of ~13 mTorr when injecting 100 sccm of argon. First we convert the gas flow units (sccm) into pump flow units (say L/s if we are dealing with a high vacuum pump situation or cfm, L/m, etc. for a roughing pump). Here we will consider just a high vacuum pump:

100 sccm = 100 x 760 Torr.ccm
= (100 x 760)/1000 Torr.liter/min
= (100 x 760)/(1000 x 60) Torr.liter/sec
Gas In = 1.27 T.L/s

Since ***Gas Out*** must also equal 1.27 T.L/s and we know the chamber pressure must be ~13 mTorr with the gas flowing, we calculate the minimum effective pumping speed by dividing 1.27 T.L/s by 0.013 T:

1.27/0.013 = ~100 L/s
Minimum effective pumping speed 100 L/s

Clearly, the pump's quoted pumping speed must be higher than this since the pumping port's conductance will reduce it. However, it can be much higher and simply trimmed to 100 L/s using a throttle valve between chamber and pump.

Pump-Down Times

Manual Calculations

Can pump-down time be calculated? The short answer is yes. But the longer answer is: this is an iterative process involving exponential decay and manual calculation can be involved and tedious, even using a spreadsheet program.

Computer Calculations

Over the years, computer algorithms have been developed for iterative techniques needed to calculate conductances, throughputs, gas loads, effective pumping speeds, and pump-down times across continuum, transitional, and molecular flow regimes using the available formulas from vacuum technology. Typically, the user keys in the pump's pumping speed curve, chamber dimensions, surface outgassing rates, start/finish pressure, etc., and the calculations are done automatically with the program choosing the appropriate formula at each iteration.

We have used successive updates of the **VacTran**® program (from Professional Engineering Computations) for over 17 years. We find it invaluable and, of the programs we have examined, the easiest to use and most versatile.

VacTran® is particularly valuable during system re-design. The existing system's measured pump-down characteristics determine the real gas load which is used for the model. The designer then makes the proposed design changes on the model and re-runs pump-down iterations. Since the model's gas load reflects reality, the calculated results closely parallel real-world experience when the re-design changes are made.

If you have a one-time question to which **VacTran**® can be applied, try our Tech Info service at **techinfo@lesker.com** and we may be able to help. If you are facing vacuum design issues that involve a number of 'what if' conditions, we urge you to buy this program. But note, successful computer modeling depends on the nature of the problem and the operator's understanding of vacuum technology.

Slow Pumpdown

At techinfo@lesker.com a frequently asked question runs along these lines: "Pumping from atmosphere to 1 x 10^{-6} Torr is taking over five hours. What's the problem?" Obviously, there is no hope of answering without a long assessment that could easily be made by the questioner:

- Given the chamber's volume, cleanliness, pumps used, conductance from chamber to pumps, is a pump-down time of <5 hours reasonable?
- Is this the first time the chamber has been pumped down?
- Does it take five hours for every pump down?
- Has the time slowly increased?
- Has the time suddenly increased?

Let's examine each of these questions.

"Chamber volume . . . "

A. Is the chamber volume very large and the rough pump speed very small?

B. Does the chamber contain very large surface areas and is the high vacuum pump small?

C. Is the high vacuum pump's base pressure close to 1 x 10^{-6} Torr?

D. Are the chamber walls clean or dirty, oily, pitted, or corroded?

E. Does the high vacuum pumping port have the same I.D. as the high vacuum pump inlet?

F. Is the high vacuum pumping port's length more than 3 times its I.D.?

"First pump-down"

A. Patience! The initial pump-down removes the loosely bound vapor layers absorbed on every surface. Regard it as 'vacuum conditioning'. Pump the system for several hours, let up to atmosphere with dry nitrogen and pump-down again. Then, if the pumpdown still takes five hours, consider B and C.

B. Examine the simple things that can cause long pump-down: check for leaks with a leak detector; regenerate the foreline trap; check that gas inlet valves are fully closed; consider the outgassing characteristics of the construction materials; check that the cross-over pressure is appropriate for both rough and high vacuum pumps; check if the foreline pressure is at an acceptable value for the high vacuum pump.

C. Did someone goof in the original design? Check using a computer modeling program such as **VacTran**®. When you allow for typical outgassing rates, are the results consistent with the measured pump-down time?

"Five hours every time"

Convince yourself the system does not leak and then, using **VacTran**®, model the system. Check that the calculated pump-down time is similar to the measured one.

If not, add outgassing sources (roughly modeling the real parts in the chamber) until the pump-down time equals 5 hours. Now you have two options:

A. Reduce the gas load by either:
(a) modeling the removal of non-essential components or reducing surface areas; or (b) modeling a reduced outgassing rate achieved by baking or plasma cleaning; this is usually the least expensive option to improving pump-down times

B. If little can be done about the total gas load, play 'what if' games with the model by changing pumps and conductances to see what must be done to improve the pump-down time. This is always an expensive option.

"Slowly gotten worse"

Time to consider maintenance issues:

A. Is the fluid in any oil-sealed pump contaminated with a vapor?

B. Are the foreline or system traps overloaded?

C. Is something inside the chamber thermally decomposing?

D. Have the fill-full sensors of an LN_2 trap changed position?

E. Are the chamber walls contaminated with oil from the pumps?

F. Are o-rings aging due to high temperatures?

G. Does the cryo-pump need regeneration?

More potential issues can be added but the real question is, can the main cause be detected? Fortunately, in most cases the answer is yes, so attach an RGA. Of course, there are drawbacks: RGAs are not cheap and you must learn to interpret spectra. But, as a vacuum diagnostics tool, the RGA has no equal.

"Suddenly gotten worse"

A. Check your vacuum system's logbook. What did you last do? Change a flange or gasket? Add a component? Change the pump fluid? Then check that the change did not cause a leak, increase the outgassing rate, or reduce the effective pumping speed.

B. If the sudden increase in base pressure occurs after the first chamber bakeout or after three or four pump-downs following system commissioning (when no changes have been made), then make another leak check of the whole system. Real leaks are easily blocked by ice (the effect of vacuum on water trapped in the leak during the final chamber cleaning) or a combination of machining oils and "residues." When the blockage evaporates or disperses, suddenly the chamber has a leak that was previously not there.

Unit Conversion Tables

Pressure Units

Pressure Units	Atmosphere	Bar	dynes/cm^2	in. Hg	in. Water	kg/cm^2	mbar	mTorr	Pa	psi	Torr
1 atm.	1	1.01325	1.01325 x 10^{6}	29.9212	406.78	1.03322	1013.25	7.6 x 10^{5}	1.01325 x 10^{5}	14.696	760
1 bar	0.9869	1	1 x 10^{6}	29.53	401.46	1.0197	1,000	7.5006 x 10^{5}	1 x 10^{5}	14.504	750.06
1 dyne/cm^2	9.869 x 10^{-7}	1 x 10^{-6}	1	2.953 x 10^{-5}	4.0146 x 10^{-4}	1.0197 x 10^{-6}	1 x 10^{-3}	0.75006	0.1	1.4504 x 10^{-5}	7.5006 x 10^{-4}
1 in. Hg	3.342 x 10^{-2}	3.386 x 10^{-2}	3.386 x 10^{4}	1	13.595	3.4532 x 10^{-2}	33.863	2.54 x 10^{4}	3.3864 x 10^{3}	0.4912	25.4
1 in. water	2.458 x 10^{-3}	2.491 x 10^{-3}	2.491 x 10^{3}	7.356 x 10^{-2}	1	2.54 x 10^{-3}	2.4909	1.868 x 10^{3}	2.4909 x 10^{2}	3.613 x 10^{-2}	1.868
1 kg/cm^2	0.9678	0.9807	9.807 x 10^{5}	28.959	3.937 x 10^{2}	1	9.8067 x 10^{2}	7.3556 x 10^{5}	9.8067 x 10^{4}	14.223	7.3556 x 10^{2}
1 mbar	9.869 x 10^{-4}	1 x 10^{-3}	1 x 10^{3}	2.953 x 10^{-2}	0.4015	1.0197 x 10^{-3}	1	7.5006 x 10^{2}	100	1.450 x 10^{-2}	0.75006
1 mTorr	1.316 x 10^{-6}	1.3332 x 10^{-6}	1.3332	3.927 x 10^{-5}	5.352 x 10^{-4}	1.3595 x 10^{-6}	1.3332 x 10^{-3}	1	0.13332	1.934 x 10^{-5}	1 x 10^{-3}
1 Pa	9.869 x 10^{-6}	1 x 10^{-5}	10	2.953 x 10^{-4}	4.0146 x 10^{-3}	1.0197 x 10^{-5}	0.01	7.5006	1	1.4504 x 10^{-4}	7.5006 x 10^{-3}
1 psi	6.805 x 10^{-2}	6.895 x 10^{-2}	6.895 x 10^{4}	2.036	27.68	7.031 x 10^{-2}	68.95	5.1715 x 10^{4}	6.8948 x 10^{3}	1	51.715
1 Torr	1.316 x 10^{-3}	1.333 x 10^{-3}	1.333 x 10^{3}	3.937 x 10^{-2}	0.5352	1.360 x 10^{-3}	1.3332	1 x 10^{3}	1.3332 x 10^{2}	1.934 x 10^{-2}	1

Pumping Speed Units

Flow	CFM	L/min	L/s	m^3/hr	m^3/min
1 CFM	1	28.317	0.47195	1.69902	2.8317x10^{-2}
1 L/min	3.5311x10^{-2}	1	1.6667x10^{-2}	6.0x10^{-2}	0.001
1 L/s	2.11887	60	1	3.6	0.06
1 m^3/hr	0.5885	16.667	0.27778	1	1.6667x10^{-2}
1 m^3/min	35.311	1,000	16.667	60	1

Mass Flow Units

Mass Flow	sccm	micron.L/s	molecules/s	Pa.L/s	Torr.L/s
1 sccm	1	12.667	4.4807x10^{17}	1.6887	1.2667x10^{-2}
1 micron.L/s	7.895x10^{-2}	1	3.5374x10^{16}	0.1333	0.001
1 molecules/s	2.232x10^{-18}	2.827x10^{-17}	1	3.769x10^{-18}	2.827x10^{-20}
1 Pa.L/s	0.5922	7.50	2.653x1017	1	7.5x10^{-3}
1 Torr.L/s	78.95	1,000	3.537x1019	1.333x10^{2}	1

(Note: 1sccm = 1.0916 atm.cc/min at 25º C)

Leak Rate Units

Leak Rate	atm.cc/s	Pa.m^3/s	Torr.L/s	mbar.L/s	micron.L/s
1 atm.cc/s	1	0.1013	0.76	1.013	7.6x10^{2}
1 Pa.m3/s	9.869	1	7.50	10	7.50x10^{3}
1 Torr.L/s	1.316	0.1333	1	1.333	1000
1 mbar.L/s	0.9869	0.1	0.75	1	7.50x10^{2}
1 micron.L/s	1.316x10^{-3}	1.333x10^{-4}	0.001	1.333x10^{-3}	1

Outgassing Rate Units

Outgas Rate	mbar.L/(cm^2.s)	Pa.L/(m^2 .s)	Pa.m^3/(m^2.s)	W/m^2	Torr.L/(cm^2.s)
1 mbar.L/(cm^2.s)	1	1x10^{6}	1x10^{3}	1x10^{3}	0.75
1 Pa.L/(m^2 .s)	1x10^{-6}	1	1x10^{-3}	1x10^{-3}	7.5x10^{-7}
1 Pa.m^3/(m^2.s)	1x10^{-3}	1x10^{3}	1	1	7.50x10^{-4}
1 W/m^2	1x10^{-3}	1x10^{3}	1	1	7.50x10^{-4}
1 Torr.L/(cm^2.s)	1.333	1.333x10^{6}	1.333x10^{3}	1.333x10^{3}	1

Unit Conversion Tables (continued)

Weights & Measures

To Convert	Into	Multiply By
ampere-turn	gilbert	1.257
ampere-turn/cm	ampere-turn/in	2.54
ampere-turn/in	gilbert/cm	0.495
ampere-turn/in	ampere-turn/cm	0.3937
ampere/cm^2	ampere/in^2	6.452
angstrom	microinch	0.00393
angstrom	millimicron	0.1
angstrom	cm	10^{-8}
angstrom	nanometer	0.1
angstrom	micron	10^{-4}
b/mil ft	grams/cm^3	2.306x10^{6}
Btu	joule	1054
Btu	kilowatt-hour	2.929x10^{-4}
Btu	ft-lb	777.6
Btu/minute	watt	17.57
calorie (kg)	joule	4184
calorie (kg)	Btu	3.968
calorie (kg)	horsepower hr	1.558x10^{-3}
calorie (kg)	ft-lb	3086
calories (kg)	kilowatt-hour	1.162x10^{-3}
circular mil	cm^2	5.067x10^{-6}
circular mil	in^2	7.854x10^{-7}
circular mil sq	mil	0.7854
cm	mil	393.7
cm	inch	0.3937
cm	angstrom	10^{8}
cm^2	ft^2	1.076x10^{-3}
cm^2	circular mil	1.974x10^{5}
cm^2	in^2	0.155
cm^3	gallon	2.642x10^{-4}
cm^3	in^3	6.102x10^{-2}
cm^3	quarts (liquid)	1.057x10^{-3}
cm^3	liter	10^{-3}
cm^3	ft^3	3.531x10^{-5}
cm^3	pints (liquid)	2.113x10^{-3}
coulombs/in^2	coulombs/cm^2	0.155
degree (angle)	minute	60
degree (angle)	second	3600
degree (angle)	radian	0.01745
degree/sec	radian/sec	0.01745
degree/sec	revolution/sec	0.002778
degree/sec	rpm	0.1667
dyne	pound	2.248x10^{-6}
dyne	gram	1.020x10^{-3}
dynes/cm^2	bar	10^{-6}
erg	dyne-cm	1
erg	kg-meter	1.020x10^{-8}
erg	gram-cm	1.020x10^{-3}
erg	ft-lb	7.376x10^{-8}
erg	kg-calorie	2.390x10^{-11}
erg	joule	10^{-7}
erg	Btu	9.486x10^{-11}
ergs/sec	Btu/min	5.691x10^{-9}
ergs/sec	kilowatt	10^{-10}
ergs/sec	ft-lb/min	4.42x10^{-6}
feet	cm	30.48
feet	meter	0.3048
ft-lb	meter-kilogram	0.1383
ft-lb	cm-gram	13.826
ft-lb	cm-dyne	1.356x10^{7}

To Convert	Into	Multiply By
ft^2	in^2	144
ft^2	m^2	0.0929
ft^2	cm^2	929
ft^3	lb. water	62.4
ft^3	liter	28.32
ft^3	pint (liquid)	59.84
ft^3	cm^3	2.832x10^{4}
ft^3	in^3	1728
ft^3	m^3	0.02832
ft^3	quart (liquid)	29.92
ft^3	gallon	7.481
ft^3	yd^3	0.03704
ft^3/min	gallon/sec	0.1247
ft^3/min	cm^3/sec	471.9
ft^3/min	liter/sec	0.4719
gallon	quart (liquid)	4
gallon	liter	3.785
gallon	cm^3	3785
gallon	pint (liquid)	8
gallon	ft^3	0.1337
gallon	lb. water	8.34
gallon	in^3	231
gallon	m^3	3.785x10^{-3}
gallon/min	liter/sec	0.064
gallon/min	ft^3/sec	2.228x10^{-3}
gauss	lines/in^2	6.452
gilbert	ampere-turn	0.7958
gram	oz	0.03527
gram	dyne	980.7
gram	lb	2.205x10^{-3}
gram-calorie	Btu	3.968x10^{-3}
gram-cm	kg-meter	10^{-5}
gram-cm	joule	9.807x10^{-5}
gram-cm	ft-lb	7.233x10^{-5}
gram-cm	erg	980.7
gram-cm	Btu	9.302x10^{-8}
gram-cm	kg-calorie	2.344x10^{-8}
gram/cm	lb/in	5.6x10^{-3}
gram/cm^3	lb/circular mil ft	3.405x10^{-7}
gram/cm^3	lb/in^3	0.03613
gram/cm^3	lb/ft^3	62.43
horsepower	horsepower(metric)	1.014
horsepower	watt	745.7
in^2	ft^2	6.944x10^{-3}
in^2	cm^2	6.452
in^2	sq mil	10^{6}
in^2	mm^2	645.2
in^2	circular mil	1.273x10^{6}
in^3	pint (liquid)	0.0346322
in^3	quart (liquid)	0.01732
in^3	liter	1.639x10^{-2}
in^3	gallon	4.329x10^{-3}
in^3	m^3	1.639x10^{-5}
in^3	ft^3	5.787x10^{-4}
in^3	cm^3	16.39
inch	angstrom	2.54x10^{8}
inch	cm	2.54
joule	watt-hour	2.778x10^{-4}
joule	kg-meter	0.102
joule	kg-calorie	2.390x10^{-4}

To Convert	Into	Multiply By
joule	ft-lb	0.7377
joule	erg	10^{7}
joule	Btu	9.486x10^{-4}
kilogram	tons (short)	1.102x10^{-3}
kilogram	lb	2.2046
kilogram (force)	dyne	980665
kilogram-meter	kilowatt-hour	2.724x10^{-6}
kiloline	maxwell	10^{3}
kilometer	mile	0.6214
kilometer	feet	3281
kilowatt	ft-lb/sec	737.6
kilowatt	ft-lb/min	4.425x10^{4}
kilowatt	Btu/minute	56.92
kilowatt-hour	kilogram-meter	3.671x10^{5}
kilowatt-hour	joule	3.6x10^{6}
kilowatt-hour	ft-lb	2.655x10^{6}
kilowatt-hour	Btu	3415
km/hour	m/min	16.67
km/hour	mile/hour	0.6214
km/hour	ft/sec	0.9113
km/hour	ft/min	54.68
km/hour	cm/sec	27.78
km^2	ft^3	1.076x10^{7}
lb water	gallon	0.1198
lb water	in^3	27.68
lb water	ft^3	0.01602
lb water/min	ft^3/sec	2.669x10^{-4}
lb/ft	kg/meter	1.488
lb/ft^2	kg/m^2	4.882
lb/ft^2	ft. water	0.01602
lb/ft^2	lb/in^2	6.944x10^{-3}
lb/in	grams/cm	178.6
lb/in^2	lb/ft^2	144
lb/in^2	kg/m^2	703.1
lb/in^2	in. Hg	2.036
lb/in^2	ft. water	2.307
lb/in^2	atmosphere	0.06804
lines/cm^2	gauss	1
lines/in^2	gauss	0.155
liter	quart (liquid)	1.057
liter	pint (liquid)	2.113
liter	gallon	0.2642
liter	in^3	61.02
liter	ft^3	0.03531
liter/min	gallon/sec	4.403x10^{-3}
liter/min	ft^3/sec	5.885x10^{-4}
lumen/ft^2	foot-candle	1
m/min	miles/hour	0.03728
m/min	km/hour	0.06
m/min	ft/sec	0.05468
m/sec	miles/min	0.03728
m/sec	km/min	0.06
m/sec	km/hr	3.6
m/sec	ft/sec	3.281
m/sec	ft/min	196.8
m/sec	miles/hour	2.237
m^2	sq mile	3.861x10^{-7}
m^2	ft^2	10.764
m^3	quarts (liquid)	1057
m^3	pints (liquid)	2113

Weights & Measures

To Convert	Into	Multiply By
m^3	gallon	264.2
m^3	in^3	61024
m^3	ft^3	35.31
m^3	cm^3	10^6
maxwell	kiloline	36802
megaline	maxwell	10^6
meter	inch	39.37
meter	feet	3.2808
meter	angstrom	10^{10}
mhos/mil ft	megmhos/in^3	15.28
mhos/mil ft	megmhos/cm^3	6.015
microhm/cm^3 ohms/mil	ft	6.015
microhm/cm^3	microhms/in^3	0.3937
microhm/in^3	microhm/cm^3	2.54
microinch	angstrom	254
micromicron	angstrom	0.01
micron	angstrom	10000
mil	inch	36802
mil	cm	0.0025
milliliter	cm^3	1
millimeter	mil	39.37
millimeter	micron	1000
millimeter	inch	0.03937
millimeter	angstrom	10^7
millimicron	angstrom	10
minute	seconds (angle)	60
minutes (angle)	radian	2.909x10^{-4}
mm^2	in^2	1.55x10^{-3}
mm^2	cm^2	0.01
mm^2 circular	mil	1.974x10^3
nanometer	micron	10^{-3}
ohms/mil ft	microhm/in^3	0.06524
ohms/mil ft	microhm/cm^3	0.1662
ounces (fluid)	liter	0.02957
ounces (fluid)	in^3	1.805
oz/in^2	psi	0.0625
pints (liquid)	in^3	28.88
pints (dry)	in^3	33.6
pound	oz	16
pound	gram	453.6
pound (force)	dyne	444823
quadrants (angle)	radian	1.571
quadrants (angle)	minute	5400
quadrants (angle)	degree	90
quart fluid	ounce	32
quarts (liquid)	in^3	57.75
quarts (dry)	in^3	67.2
radian	degrees/sec	57.3
radian	quandrant	0.637
radian	minute	3438
radian	degree	57.3
radians/sec	revolutions/sec	0.1592
radians/sec	rpm	9.549
revolution	radian	6.283
revolution	quadrant	4
revolution	degree	360
revolutions/sec	rpm	60
revolutions/sec	radians/sec	6.283
revolutions/sec	degrees/sec	360
rpm	revolutions/sec	0.01667
rpm	radians/sec	0.1047
rpm	degrees/sec	6
seconds (angle)	radian	4.848x10^{-6}
spheres (solid angle)	steradian	12.57
spherical rt. angle	steradian	1.571
spherical rt. angle	sphere	0.125
spherical rt. angle	hemisphere	0.25
steradian	sphere	0.07958
steradian	hemisphere	0.1592
stere	liter	10^3
tons (short)	lb	2000
tons (short)	kg	907.2
tons (metric)	lb	2205
tons (metric)	kg	10^3
tons (long)	lb	2240
tons (long)	kg	1016
watt	kilowatt	36802
watt	ft-lb/sec	0.7376
watt	ft-lb/min	44.25
watt	ergs/sec	10^7
watt	Btu/min	0.05692
watt-hour	kilogram-meter	367.1
watt-hour	ft-lb	2655
watt-hour	Btu	3.414
weber	maxwell	10^8

Material Deposition

Key to Symbols: * influenced by composition; ** Cr-plated rod or strip; ***all metals alumina coated; **C** = carbon; **Gr** = graphite; **Q** = quartz; **Incl** = Inconel; **VC** = vitreous carbon; **SS** = stainless steel; **Ex** = excellent; **G** = good; **F** = fair; **P** = poor; **S** = sublimes; **D** = decomposes; **RF** = RF sputtering is effective; **RF-R** = reactive RF sputter is effective; **DC** = DC sputtering is effective; **DC-R** = reactive DC sputtering is effective

Material	Symbol	MP (° C)	S/D	g/cm³	Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques					Sputter	Comments
									Thermal Sources					
					10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible		
Aluminum	Al	660	—	2.70	677	821	1,010	Ex	—	—	W	TiB_2-BN, ZrB_2, BN	DC	Alloys W/Ta/Mo. Flash evap or use BN crucible
Aluminum Antimonide	AlSb	1,080	—	4.3	—	—	—	—	—	—	—	—	RF	—
Aluminum Arsenide	AlAs	1,600	—	3.7	—	—	~ 1,300	—	—	—	—	—	RF	—
Aluminum Bromide	$AlBr_3$	97	—	2.64	—	—	~ 50	—	Mo	—	—	Gr	—	—
Aluminum Carbide	Al_4C_3	~1,400	D	2.36	—	—	~ 800	F	—	—	—	—	RF	n 2.7
Aluminum, 2% Copper	Al2%Cu	640	—	2.82	—	—	—	—	—	—	—	—	DC	Wire feed & flash. Co-evap difficult
Aluminum Fluoride	AlF_3	1,291	S	2.88	410	490	700	P	Mo, W, Ta	—	—	Gr	RF	—
Aluminum Nitride	AlN	>2,200	S	3.26	—	—	~1,750	F	—	—	—	—	RF-R	Decomposes. R-evap Al in 10^{-3} T N_2 with glow discharge.
Aluminum Oxide	Al_2O_3	2,072	—	3.97	—	—	1,550	Ex	W	—	W	—	RF-R	Forms smooth, hard films. n 1.66
Aluminum Phosphide	AlP	2,000	—	2.42	—	—	—	—	—	—	—	—	RF	—
Aluminum, 2% Silicon	Al2%Si	640	—	2.69	—	—	1,010	—	—	—	—	TiB2-BN	RF, DC	Wire feed & flash. Co-evap difficult
Antimony	Sb	630	S	6.68	279	345	425	P	Mo*** Ta***	Mo, Ta	Mo, Ta	BN, C, Al_2O_3	RF, DC	Sublimes rapidly at low temp
Antimony Oxide	Sb_2O_3	656	S	5.2	—	—	~300	G	Pt	—	Pt	BN, Al_2O_3	RF-R	Decomposes on W. n 2.09, 2.18, 2.35
Antimony Selenide	Sb_2Se_3	611	—	—	—	—	—	—	Ta	—	—	C	RF	Composition variable
Antimony Sulfide	Sb_2S_3	550	—	4.64	—	—	~200	G	Mo, Ta	—	Mo, Ta	Al_2O_3	—	No decomposition. n 3.19, 4.06, 4.3
Antimony Telluride	Sb_2Te_3	629	—	6.50	—	—	600	—	—	—	—	C	RF	Decomposes over 750° C
Arsenic	As	817	S	5.73	107	150	210	P	C	—	—	Al_2O_3, BeO, VC	—	Dedicated vacuum system. Sublimes rapidly at low temp.
Arsenic Oxide	As_2O_3	312	—	3.74	—	—	—	—	—	—	—	—	—	—
Arsenic Selenide	As_2Se_3	~360	—	4.75	—	—	—	—	—	—	—	Al_2O_3, Q	RF	—
Arsenic Sulfide	As_2S_3	300	—	3.43	—	—	~400	F	Mo	—	—	Al_2O_3, Q	RF	n 2.4, 2.81, 3.02
Arsenic Telluride	As_2Te_3	362	—	—	—	—	—	—	—	—	—	—	—	Flash. See JVST. 1973; 10:748
Barium	Ba	725	—	3.51	545	627	735	F	W, Ta, Mo	W	W	Metals	RF	Wets without alloying; reacts with ceramics
Barium Chloride	$BaCl_2$	963	—	3.92	—	—	~650	—	Ta, Mo	—	—	—	RF	Preheat gently to outgas. n 1.73
Barium Fluoride	BaF_2	1,355	S	4.89	—	—	~700	G	Mo	—	—	—	RF	n 1.47
Barium Oxide	BaO	1,918	—	5.72	—	—	~1,300	P	Pt	—	Pt	Al_2O_3	RF, RF-R	Decomposes slightly. n 1.98
Barium Sulfide	BaS	1,200	—	4.25	—	—	1,100	—	Mo	—	—	—	RF	n 2.16
Barium Titanate	$BaTiO_3$	—	D	6.02	—	—	—	—	—	—	—	—	RF	Gives Ba. Co-evap OK. Sputter OK. n 2.40
Beryllium	Be	1,278	—	1.85	710	878	1,000	Ex	W, Ta	W	W	BeO, C, VC	DC	Wets W/Ta/Mo. Evaporates easily
Beryllium Carbide	Be_2C	>2,100	D	1.90	—	—	—	—	—	—	—	—	—	—
Beryllium Chloride	$BeCl_2$	405	—	1.90	—	—	~150	—	—	—	—	—	RF	—
Beryllium Fluoride	BeF_2	800	S	1.99	—	—	~200	G	—	—	—	—	—	n <1.33
Beryllium Oxide	BeO	2,530	—	3.01	—	—	1,900	G	—	—	W	—	RF, RF-R	No decomposition from E-beam. n 1.72
Bismuth	Bi	271	—	9.80	330	410	520	Ex	W, Mo, Ta	W	W	Al_2O_3, VC	DC	Resistivity high.
Bismuth Fluoride	BiF_3	727	S	5.32	—	—	~300	—	—	—	—	Gr	RF	n 1.74
Bismuth Oxide	Bi_2O_3	860	—	8.55	—	—	~1,400	P	Pt	—	Pt	—	RF, RF-R	n 1.91
Bismuth Selenide	Bi_2Se_3	710	D	6.82	—	—	~650	G	—	—	—	Gr, Q	RF	Co-evap OK. Sputter OK
Bismuth Sulfide	Bi_2S_3	685	D	7.39	—	—	—	—	—	—	—	—	RF	n 1.34, 1.46
Bismuth Telluride	Bi_2Te_3	573	—	7.7	—	—	~600	—	W, Mo	—	—	Gr, Q	RF	Co-evap OK. Sputter OK
Bismuth Titanate	$Bi_2Ti_2O_7$	—	D	—	—	—	—	—	—	—	—	—	RF	Sputter OK. R-co-evap in 10^{-2} T O_2
Boron	B	2,079	—	2.34	1,278	1,548	1,797	Ex	C	—	—	C, VC	RF	Forms carbide with container
Boron Carbide	B_4C	2,350	—	2.52	2,500	2,580	2,650	Ex	—	—	—	—	RF	—
Boron Nitride	BN	~3,000	S	2.25	—	—	~1,600	P	—	—	—	—	RF, RF-R	Decomposes. R-sputter preferred
Boron Oxide	B_2O_3	~450	—	1.81	—	—	~1,400	G	Pt, Mo	—	—	—	—	n 1.48
Boron Sulfide	B_2S_3	310	—	1.55	—	—	800	—	—	—	—	Gr	RF	—
Cadmium	Cd	321	—	8.64	64	120	180	P	W, Mo, Ta	—	W, Mo, Ta	Al_2O_3, Q	RF, DC	Dedicated vacuum system. High VP. Low sticking coeff
Cadmium Antimonide	Cd_3Sb_2	456	—	6.92	—	—	—	—	—	—	—	—	—	—
Cadmium Arsenide	Cd_3As_2	721	—	6.21	—	—	—	—	—	—	—	Q	RF	—
Cadmium Bromide	$CdBr_2$	567	—	5.19	—	—	~300	—	—	—	—	—	—	—
Cadmium Chloride	$CdCl_2$	568	—	4.05	—	—	~400	—	—	—	—	—	—	—
Cadmium Fluoride	CdF_2	1,100	—	6.64	—	—	~500	—	—	—	—	—	RF	n 1.56
Cadmium Iodide	CdI_2	387	—	5.67	—	—	~250	—	—	—	—	—	—	—
Cadmium Oxide	CdO	>1,500	D	6.95	—	—	~530	—	—	—	—	—	RF-R	Decomposes. n 2.49
Cadmium Selenide	CdSe	>1,350	S	5.81	—	—	540	G	Mo, Ta	—	—	Al_2O_3, Q	RF	Evaporates easily. n 2.4
Cadmium Sulfide	CdS	1,750	S	4.82	—	—	550	F	W, Mo, Ta	—	W	Al_2O_3, Q	RF	Substrate temp. affects sticking coeff Composition varies. n 2.51, 2.53

Chromium Pieces

Copper Pellets

Boron Nitride Target

					Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques						
									Thermal Sources					
Material	Symbol	MP (° C)	S/D	g/cm^3	10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible	Sputter	Comments
Cadmium Telluride	CdTe	1,121	—	5.85	—	—	450	—	W, Mo, Ta	W	W, Ta, Mo	—	RF	Substrate temp. affects composition. n~2.6
Calcium	Ca	839	S	1.54	272	357	459	P	W	W	W	Al_2O_3, Q	—	Film reacts in air.
Calcium Fluoride	CaF_2	1,423	—	3.18	—	—	~1,100	—	W, Mo, Ta	—	W, Mo, Ta	Q	RF	Rate control important. Preheat gently to outgas. n 1.43
Calcium Oxide	CaO	2,614	—	~3.3	—	—	~1,700	—	W, Mo	—	—	ZrO_2	RF-R	Forms volatile oxides with W/Mo. n 1.84
Calcium Silicate	$CaSiO_3$	1,540	—	2.91	—	—	—	G	—	—	—	Q	RF	n 1.61, 1.66
Calcium Sulfide	CaS	—	D	2.5	—	—	1,100	—	Mo	—	—	—	RF	Decomposes. n 2.14
Calcium Titanate	$CaTiO_3$	1,975	—	4.10	1,490	1,600	1,690	P	—	—	—	—	RF	Decomposes in evap. Sputter OK. n 2.34
Calcium Tungstate	$CaWO_4$	—	—	6.06	—	—	—	G	W	—	—	—	RF	n 1.92
Carbon	C	~3,652	S	1.8–2.1	1,657	1,867	2,137	Ex	—	—	—	—	PDC	E-beam or Arc evap. Poor film adhesion.
Cerium	Ce	798	—	~6.70	970	1,150	1,380	G	W, Ta	W	W, Ta	Al_2O_3, BeO, VC	DC, RF	—
Cerium Fluoride	CeF_3	1,460	—	6.16	—	—	~900	G	W, Mo, Ta	—	Mo, Ta	—	RF	Preheat gently to outgas. n ~ 1.7
Cerium (III) Oxide	Ce_2O_3	1,692	—	6.86	—	—	—	F	W	—	—	—	—	Alloys. Use thick W boat. n 1.95
Cerium (IV) Oxide	CeO_2	~2,600	—	7.13	1,890	2,000	2,310	G	W	—	—	—	RF, RF-R	Little decomposition.
Cesium	Cs	28	—	1.88	-16	22	80	—	SS	—	—	Q	—	—
Cesium Bromide	CsBr	636	—	3.04	—	—	~400	—	W	—	—	—	RF	n 1.70
Cesium Chloride	CsCl	645	—	3.99	—	—	~500	—	W	—	—	—	RF	n 1.64
Cesium Fluoride	CsF	682	—	4.12	—	—	~500	—	W	—	—	—	RF	n 1.48
Cesium Hydroxide	CsOH	272	—	3.68	—	—	550	—	Pt	—	—	—	—	—
Cesium Iodide	CsI	626	—	4.51	—	—	~500	—	W	—	—	Pt, Q	RF	n 1.79
Chiolote	$Na_5Al_3F_{14}$	—	—	2.9	—	—	~800	—	Mo, W	—	—	—	RF	n 1.33
Chromium	Cr	1,857	S	7.20	837	977	1,157	G	**	W	W	VC	DC	Films very adherent. High rates possible.
Chromium Boride	CrB	2,760(?)	—	6.17	—	—	—	—	—	—	—	—	RF	—
Chromium Bromide	$CrBr_2$	842	—	4.36	—	—	550	—	Incl	—	—	—	RF	—
Chromium Carbide	Cr_3C_2	1,980	—	6.68	—	—	~2,000	F	W	—	—	—	RF	—
Chromium Chloride	$CrCl_2$	824	—	2.88	—	—	550	—	Fe, Incl	—	—	—	RF	—
Chromium Oxide	Cr_2O_3	2,266	—	5.21	—	—	~2,000	G	W, Mo	—	W	—	RF, RF-R	Loses O_2, reoxidizes at 600° C in air. n 2.55
Chromium Silicide	$CrSi_2$	1,490	—	5.5	—	—	—	—	—	—	—	—	RF	—
Chromium-Silicon Monoxide	Cr-SiO	—	S	*	*	*	*	G	W	—	W	—	RF	Flash evap
Cobalt®	Co	1,495	—	8.9	850	990	1,200	Ex	W, Nb	—	W	Al_2O_3, BeO	DC	Alloys with W/Ta/Mo
Cobalt Bromide	$CoBr_2$	678	D	4.91	—	—	400	—	Incl	—	—	—	RF	—
Cobalt Chloride	$CoCl_2$	724	D	3.36	—	—	472	—	Incl	—	—	—	RF	—
Cobalt Oxide	CoO	1,795	—	6.45	—	—	—	—	—	—	—	—	DC-R, RF-R	Sputter preferred.
Copper	Cu	1,083	—	8.92	727	857	1,017	Ex	Mo	W	W	Al_2O_3, Mo, Ta	DC	Adhesion poor. Use interlayer (Cr). Evap OK.
Copper Chloride	CuCl	430	—	4.14	—	—	~600	—	—	—	—	—	RF	n 1.93
Copper Oxide	Cu_2O	1,235	S	6.0	—	—	~600	G	Ta	—	—	Al_2O_3	DC-R, RF-R	n 2.71
Copper Sulfide	Cu_2S	1,100	—	5.6	—	—	—	—	—	—	—	—	—	—
Cryolite	Na_3AlF_6	1,000	—	2.9	1,020	1,260	1,480	Ex	W, Mo, Ta	—	W, Mo, Ta	VC	RF	Large chunks reduce spitting Little decomposition
Dysprosium	Dy	1,412	—	8.55	625	750	900	G	Ta	—	—	—	DC	—
Dysprosium Fluoride	DyF_3	1,360	S	—	—	—	~800	G	Ta	—	—	—	RF	—
Dysprosium Oxide	Dy_2O_3	2,340	—	7.81	—	—	~1,400	—	Ir	—	—	—	RF, RF-R	Loses O_2.
Erbium	Er	1,529	S	9.07	650	775	930	G	W, Ta	—	—	—	DC	—
Erbium Fluoride	ErF_3	1,350	—	—	—	—	~750	—	Mo	—	—	—	RF	See JVST. 1985; A3(6):2320.
Erbium Oxide	Er_2O_3	—	—	8.64	—	—	~1,600	—	Ir	—	—	—	RF, RF-R	Loses O_2.
Europium	Eu	822	S	5.24	280	360	480	F	W, Ta	—	—	Al_2O_3	DC	Low Ta solubility
Europium Fluoride	EuF_2	1,380	—	6.50	—	—	~950	—	Mo	—	—	—	RF	—
Europium Oxide	Eu_2O_3	—	—	7.42	—	—	~1,600	G	Ir, Ta, W	—	—	ThO_2	RF, RF-R	Loses O_2. Films clear and hard.
Europium Sulfide	EuS	—	—	5.75	—	—	-	G	—	—	—	—	RF	—

Materials Deposition

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					Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques						
									Thermal Sources					
Material	Symbol	MP (° C)	S/D	g/cm³	10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible	Sputter	Comments
Gadolinium®	Gd	1,313	—	7.90	760	900	1,175	Ex	Ta	—	—	Al_2O_3	DC	High Ta solubility
Gadolinium Carbide	GdC_2	—	—	—	—	—	1,500	—	—	—	—	C	RF	Decomposes under sputtering
Gadolinium Oxide	Gd_2O_3	2,330	—	7.41	—	—	—	F	Ir	—	—	—	RF, RF-R	Loses O_2.
Gallium	Ga	30	—	5.90	619	742	907	G	—	—	—	Al_2O_3, BeO, Q	—	Alloys with W/Ta/Mo. E-beam OK.
Gallium Antimonide	GaSb	710	—	5.6	—	—	—	F	W, Ta	—	—	—	RF	Flash evap
Gallium Arsenide	GaAs	1,238	—	5.3	—	—	—	G	W, Ta	—	—	C	RF	Flash evap
Gallium Nitride	GaN	800	S	6.1	—	—	~200	—	—	—	—	Al_2O_3	RF, RF-R	R-evap Ga in 10^{-3} T N_2
Gallium Oxide	Ga_2O_3	1,900	—	6.44	—	—	—	—	Pr, W	—	—	—	RF	Loses O_2. n 1.92
Gallium Phosphide	GaP	1,540	—	4.1	—	770	920	—	W, Ta	—	W	Q	RF	No decomposition. Rate control important.
Germanium	Ge	937	—	5.35	812	957	1,167	Ex	W, C, Ta	—	—	Q, Al_2O_3	DC	E-beam film excellent
Germanium Nitride	Ge_3N_2	450	S	5.2	—	—	~650	—	—	—	—	—	RF-R	Sputter preferred
Germanium (II) Oxide	GeO	710	S	—	—	—	500	—	—	—	—	Q	RF	n 1.61
Germanium (III) Oxide	GeO_2	1,086	—	6.24	—	—	~625	G	Ta, Mo	—	W, Mo	Q, Al_2O_3	RF-R	Loses O_2; Film mostly GeO
Germanium Telluride	GeTe	725	—	6.20	—	—	381	—	W, Mo	—	W	Q, Al_2O_3	RF	
Glass, Schott® 8329	—	—	—	2.20	—	—	—	Ex	—	—	—	—	RF	Melt in air before evaporating.
Gold	Au	1,064	—	19.32	807	947	1,132	Ex	W***Mo***W	—	—	Al_2O_3, BN, VC, W	DC	Films soft; Adhesion poor. Use Cr interlayer
Hafnium	Hf	2,227	—	13.31	2,160	2,250	3,090	G	—	—	—	—	DC	—
Hafnium Boride	HfB_2	3,250	—	10.5	—	—	—	—	—	—	—	—	DC, RF	—
Hafnium Carbide	HfC	~3,890	S	12.20	—	—	~2,600	—	—	—	—	—	RF	—
Hafnium Nitride	HfN	3,305	—	—	—	—	—	—	—	—	—	—	RF, RF-R	—
Hafnium Oxide	HfO_2	2,758	—	9.68	—	—	~2,500	F	W	—	—	—	RF, RF-R	Loses O_2. Film HfO
Hafnium Silicide	$HfSi_2$	1,750	—	7.2	—	—	—	—	—	—	—	—	RF	—
Holmium	Ho	1,474	—	8.80	650	770	950	G	W, Ta	W	W	—	—	—
Holmium Fluoride	HoF_3	1,143	—	—	—	—	~800	—	—	—	—	Q	DC, RF	—
Holmium Oxide	Ho_2O_3	2,370	—	8.41	—	—	—	—	Ir	—	—	—	RF, RF-R	Loses O_2
Inconel	Ni/Cr/Fe	1,425	—	8.5	—	—	—	G	W	W	W	—	DC	Fine wire wrapped on W Low rate for smooth films
Indium	In	157	—	7.30	487	597	742	Ex	W, Mo	—	W	Gr, Al_2O_3	DC	Wets W and Cu. Mo liner OK.
Indium Antimonide	InSb	535	—	5.8	—	—	—	—	W	—	—	—	RF	Decomposes. Sputter preferred; Co-evap OK.
Indium Arsenide	InAs	943	—	5.7	780	870	970	—	W	—	—	—	RF	—
Indium Nitride	InN	1,200	—	7.0	—	—	—	—	—	—	—	—	—	—
Indium (I) Oxide	In_2O	~600	S	6.99	—	—	650	—	—	—	—	—	RF	Decomposes under sputtering
Indium (III) Oxide	In_2O_3	850	—	7.18	—	—	~1,200	G	W, Pt	—	—	Al_2O_3	—	—
Indium Phosphide	InP	1,070	—	4.8	—	630	730	—	W, Ta	—	W, Ta	Gr	RF	Films are P rich
Indium Selenide	In_2Se_3	890	—	5.67	—	—	—	—	—	—	—	—	RF	Sputter preferred; Co-evap OK. Flash evap
Indium (I) Sulfide	In_2S	653	—	5.87	—	—	650	—	—	—	—	Gr	RF	—
Indium (II) Sulfide	InS	692	S	5.18	—	—	650	—	—	—	—	Gr	RF	—
Indium (III) Sulfide	In_2S_3	1,050	S	4.90	—	—	850	—	—	—	—	Gr	RF	Decomposes. Film In_2S
Indium (II) Telluride	InTe	696	—	6.29	—	—	—	—	—	—	—	—	—	—
Indium (III) Telluride	In_2Te_3	667	—	5.78	—	—	—	—	—	—	—	—	RF, DC-R	Sputter preferred; Co-evap OK. Flash evap
Indium Tin Oxide	$In_2O_3–SnO_2$	1,800	S	—	—	—	—	—	—	—	—	—	—	—
Iridium	Ir	2,410	—	22.42	1,850	2,080	2,380	F	—	—	—	ThO_2	DC	—
Iron®	Fe	1,535	—	7.86	858	998	1,180	Ex	W	W	W	Al_2O_3, BeO	DC	Attacks W. Films hard, smooth. Preheat gently to outgas.
Iron Bromide	$FeBr_2$	684	D	4.64	—	—	561	—	—	—	—	Fe	RF	—
Iron Chloride	$FeCl_2$	670	S	3.16	—	—	300	—	—	—	—	Fe	RF	n 1.57
Iron Iodide	FeI_2	—	—	5.32	—	—	400	—	—	—	—	Fe	RF	—
Iron (II) Oxide	FeO	1,369	—	5.7	—	—	—	P	—	—	—	—	RF, RF-R	Decomposes; sputter preferred. n 2.32
Iron (III) Oxide	Fe_2O_3	1,565	—	5.24	—	—	—	G	W	—	W	—	—	Decomposes to Fe_3O_4 at 1,530° C. n 3.01
Iron Sulfide	FeS	1,193	D	4.74	—	—	—	—	—	—	—	Al_2O_3	RF	Decomposes

Lanthanum Hexaboride Target

Indium Tin Oxide Pieces

Gold Pellets

Lead Shot

Hafnium Target

					Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques						
									Thermal Sources					
Material	Symbol	MP (° C)	S/D	g/cm^3	10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible	Sputter	Comments
Kanthal	FeCrAl	—	—	7.1	—	—	—	—	W	W	W	—	DC	—
Lanthanum	La	921	—	6.15	990	1,212	1,388	Ex	W, Ta	—	—	Al_2O_3	RF	Films react in air
Lanthanum Boride	LaB_6	2,210	D	2.61	—	—	—	G	—	—	—	—	RF	—
Lanthanum Bromide	$LaBr_3$	783	—	5.06	—	—	—	—	—	—	Ta	—	RF	Films hygroscopic. n 1.94
Lanthanum Fluoride	LaF_3	1,490	S	~6.0	—	—	900	G	Ta, Mo	—	Ta	—	RF	No decomposition. n ~1.6
Lanthanum Oxide	La_2O_3	2,307	—	6.51	—	—	1,400	G	W, Ta	—	—	—	RF	Loses O_2. n~1.73
Lead	Pb	328	—	11.34	342	427	497	Ex	W, Mo	W	W, Ta	Al_2O_3, Q	DC	—
Lead Bromide	$PbBr_2$	373	—	6.66	—	—	~300	—	—	—	—	—	—	—
Lead Chloride	$PbCl_2$	501	—	5.85	—	—	~325	—	Pt	—	—	Al_2O_3	RF	Little decomposition
Lead Fluoride	PbF_2	855	S	8.24	—	—	~400	—	W, Pt, Mo	—	—	BeO	RF	n 1.75
Lead Iodide	PbI_2	402	—	6.16	—	—	~500	—	Pt	—	—	Q	—	—
Lead Oxide	PbO	886	—	9.53	—	—	~550	—	Pt	—	—	Q, Al_2O_3	RF-R	No decomposition. n ~2.6
Lead Selenide	PbSe	1,065	S	8.10	—	—	~500	—	W, Mo	—	W	Gr, Al_2O_3	RF	—
Lead Stannate	$PbSnO_3$	1,115	—	8.1	670	780	905	P	Pt	—	Pt	Al_2O_3	RF	Decomposes
Lead Sulfide	PbS	1,114	S	7.5	—	—	500	—	W	—	W, Mo	Q, Al_2O_3	RF	Little decomposition. n 3.92
Lead Telluride	PbTe	917	—	8.16	780	910	1,050	—	Mo, Pt, Ta	—	—	Al_2O_3, Gr	RF	Film is Te rich. Sputter preferred; Co-evap OK.
Lead Titanate	$PbTiO_3$	—	—	7.52	—	—	—	—	Ta	—	—	—	RF	—
Lithium	Li	181	—	0.53	227	307	407	G	Ta, SS	—	—	Al_2O_3, BeO	—	Film reacts in air
Lithium Bromide	LiBr	550	—	3.46	—	—	~500	—	Ni	—	—	—	RF	n 1.78
Lithium Chloride	LiCl	605	—	2.07	—	—	400	—	Ni	—	—	—	RF	Preheat gently to outgas. n 1.66
Lithium Fluoride	LiF	845	—	2.64	875	1,020	1,180	G	Ni, Ta, Mo, W	—	—	Al_2O_3	RF	Optical films require rate control. Preheat gently to outgas. n 1.39
Lithium Iodide	LiI	449	—	4.08	—	—	400	—	Mo, W	—	—	—	RF	n 1.96
Lithium Oxide	Li_2O	>1,700	—	2.01	—	—	850	—	Pt, Ir	—	—	—	RF	n 1.64
Lutetium	Lu	1,663	—	9.84	—	—	1,300	Ex	Ta	—	—	Al_2O_3	RF, DC	—
Lutetium Oxide	Lu_2O_3	—	—	9.42	—	—	1,400	—	Ir	—	—	—	RF	Decomposes

Materials Deposition

Key to Symbols: * influenced by composition; ** Cr-plated rod or strip; ***all metals alumina coated; **C** = carbon; **Gr** = graphite; **Q** = quartz; **Incl** = Inconel; **VC** = vitreous carbon; **SS** = stainless steel; **Ex** = excellent; **G** = good; **F** = fair; **P** = poor; **S** = sublimes; **D** = decomposes; **RF** = RF sputtering is effective; **RF-R** = reactive RF sputter is effective; **DC** = DC sputtering is effective; **DC-R** = reactive DC sputtering is effective

Material	Symbol	MP (° C)	S/D	g/cm^3	Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques					Sputter	Comments
									Thermal Sources					
					10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible		
Magnesium	Mg	649	S	1.74	185	247	327	G	W, Mo, Ta, CbW		W	Al_2O_3, VC	DC	Extremely high rates possible
Magnesium Aluminate	$MgAl_2O_4$	2,135	—	3.6	—	—	—	G	—	—	—	—	RF	(Natural spinel) n 1.72
Magnesium Bromide	$MgBr_2$	700	—	3.72	—	—	~450	—	Ni	—	—	—	RF	Decomposes
Magnesium Chloride	$MgCl_2$	714	—	2.32	—	—	400	—	Ni	—	—	—	RF	Decomposes. n 1.67
Magnesium Fluoride	MgF_2	1,261	—	2.9–3.2	—	—	1,000	Ex	Mo, Ta	—	—	Al_2O_3	RF	Substrate temp and rate control important. Reacts with W. Mo OK. n 1.38
Magnesium Iodide	MgI_2	<637	D	4.43	—	—	200	—	Ir	—	—	—	RF	—
Magnesium Oxide	MgO	2,852	—	3.58	—	—	1,300	G	—	—	—	C, Al_2O_3	RF, RF-R	R-Evap in 10^{-3} T O_2. W gives volatile oxides. n~1.7
Manganese	Mn	1,244	S	7.20	507	572	647	G	W, Ta, Mo	W	W	Al_2O_3, BeO	DC	—
Manganese Bromide	$MnBr_2$	—	D	4.39	—	—	500	—	Incl	—	—	—	RF	—
Manganese Chloride	$MnCl_2$	650	—	2.98	—	—	450	—	Incl	—	—	—	RF	—
Manganese (III) Oxide	Mn_2O_3	1,080	—	4.50	—	—	—	—	—	—	—	—	—	—
Manganese (IV) Oxide	MnO_2	535	—	5.03	—	—	—	P	W	—	W	—	RF-R	Loses O_2 at 535° C
Manganese Sulfide	MnS	—	D	3.99	—	—	1,300	—	Mo	—	—	—	RF	Decomposes. n 2.70
Mercury	Hg	-39		13.55	-68	-42	-6	—	—	—	—	—	—	—
Mercury Sulfide	HgS	584	S	8.10	—	—	250	—	—	—	—	Al_2O_3	RF	Decomposes. n 2.85, 3.20
Molybdenum	Mo	2,617	—	10.2	1,592	1,822	2,117	Ex	—	—	—	—	DC	Films smooth, hard. Preheat gently to outgas.
Molybdenum Boride	MoB_2	2,100	—	7.12	—	—	—	P	—	—	—	—	RF	—
Molybdenum Carbide	Mo_2C	2,687	—	8.9	—	—	—	F	—	—	—	—	RF	Evaporation of $Mo(CO)_6$ yields Mo_2C.
Molybdenum Disulfide	MoS_2	1,185	—	4.80	—	—	~50	—	—	—	—	—	RF	—
Molybdenum Oxide	MoO_3	795	S	4.69	—	—	~900	—	Mo, Pt	—	Mo	Al_2O_3, BN	RF	Slight O_2 loss. n 1.9
Molybdenum Silicide	$MoSi_2$	2,050	—	6.31	—	—	—	—	W	—	—	—	RF	Decomposes
Neodymium	Nd	1,021	—	7.01	731	871	1,062	Ex	Ta	—	—	Al_2O_3	DC	Low W solubility
Neodymium Fluoride	NdF_3	1,410	—	6.5	—	—	~900	G	Mo, W	—	Mo, Ta	Al_2O_3	RF	Little decomposition. n 1.6
Neodymium Oxide	Nd_2O_3	~1,900	—	7.24	—	—	~1,400	G	Ta, W	—	—	ThO_2	RF, RF-R	Loses O_2; films clear. E-beam OK. n 1.79
Nichrome IV®	Ni/Cr	1,395	—	8.50	847	987	1,217	Ex	***	W	W, Ta	Al_2O_3, VC, BeO	DC	Alloys with W/Ta/Mo
Nickel®	Ni	1,453	—	8.90	927	1,072	1,262	Ex	W	W	W	Al_2O_3, BeO, VC	DC	Alloys with W/Ta/Mo. Smooth adherent films
Nickel Bromide	$NiBr_2$	963	S	5.10	—	—	362	—	Incl	—	—	—	RF	—
Nickel Chloride	$NiCl_2$	1,001	S	3.55	—	—	444	—	Incl	—	—	—	RF	—
Nickel Oxide	NiO	1,984	—	6.67	—	—	~1,470	—	—	—	—	Al_2O_3	RF-R	Decomposes on heating. n 2.18
Nimendium®	Ni3%Mn	1,425	—	8.8	—	—	—	—	—	—	—	—	DC	
Niobium	Nb	2,468	—	8.57	1,728	1,977	2,287	Ex	W	—	—	—	DC	Attacks W. n 1.80
Niobium Boride	NbB_2	2,900	—	6.97	—	—	—	—	—	—	—	—	RF	—
Niobium Carbide	NbC	3,500	—	7.6	—	—	—	F	—	—	—	—	RF	—
Niobium Nitride	NbN	2,573	—	8.4	—	—	—	—	—	—	—	—	RF, RF-R	R-evap Nb in 10^{-3} T N_2
Niobium (II) Oxide	NbO	—	—	7.30	—	—	1,100	—	Pt	—	—	—	RF	—
Niobium (III) Oxide	Nb_2O_3	1,780	—	7.5	—	—	—	—	W	—	W	—	RF, RF-R	—
Niobium (V) Oxide	Nb_2O_5	1,485	—	4.47	—	—	—	—	W	—	W	—	RF, RF-R	n 1.95
Niobium Telluride	NbTeX	—	—	7.6	—	—	—	—	—	—	—	—	RF	Composition variable
Niobium-Tin	Nb_3Sn	—	—	—	—	—	—	Ex	—	—	—	—	DC	Co-evap OK
Osmium	Os	3,045	—	22.48	2,170	2,430	2,760	F	—	—	—	—	DC	—
Osmium Oxide	OsO_2	—	D	—	—	—	—	—	—	—	—	—	—	—
Palladium	Pd	1,554	S	12.02	842	992	1,192	Ex	W	W	W	Al_2O_3, BeO	DC	Alloys W/Ta/Mo. Rapid evap suggested.
Palladium Oxide	PdO	870	—	9.70	—	—	575	—	—	—	—	Al_2O_3	RF-R	Decomposes
Parylene	C_8H_8	300–400	—	1.1	—	—	—	—	—	—	—	—	—	(Vapor-depositable plastic)
Permalloy®	Ni/Fe	1,395	—	8.7	947	1,047	1,307	G	W	—	—	Al_2O_3, VC	DC	Film low in Ni
Phosphorus	P	44.1	—	1.82	327	361	402	—	—	—	—	Al_2O_3	—	Film ignites in air. n 2.14
Phosphorus Nitride	P_3N_5	—	—	2.51	—	—	—	—	—	—	—	—	RF, RF-R	—
Platinum	Pt	1,772	—	21.45	1,292	1,492	1,747	Ex	W	W	W	C, ThO_2	DC	Alloys W/Ta/Mo. Films soft, poor adhesion.


Silicon Pieces


Palladium Target


Magnesium Target


Manganese Pieces


Nickel Pellets

					Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques						
									Thermal Sources					
Material	Symbol	MP (° C)	S/D	g/cm^3	10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible	Sputter	Comments
Platinum Oxide	PtO_2	450	—	10.2	—	—	—	—	—	—	—	—	RF-R	—
Plutonium	Pu	641	—	19.84	—	—	—	—	W	—	—	—	—	—
Polonium	Po	254	—	9.4	117	170	244	—	—	—	—	Q	—	—
Potassium	K	63	—	0.86	23	60	125	—	Mo	—	—	Q	—	Film reacts in air. Preheat gently to outgas.
Potassium Bromide	KBr	734	—	2.75	—	—	~450	—	Ta, Mo	—	—	Q	RF	Preheat gently to outgas. n 1.559
Potassium Chloride	KCl	770	S	1.98	—	—	510	G	Ta, Ni	—	—	—	RF	Preheat gently to outgas. n 1.49
Potassium Fluoride	KF	858	—	2.48	—	—	~500	—	—	—	—	Q	RF	Preheat gently to outgas. n 1.363
Potassium Hydroxide	KOH	360	—	2.04	—	—	~400	—	Pt	—	—	—	—	Preheat gently to outgas
Potassium Iodide	KI	681	—	3.13	—	—	~500	—	Ta	—	—	—	RF	Preheat gently to outgas. n 1.677
Praseodymium	Pr	931	—	6.77	800	950	1,150	G	Ta	—	—	—	DC	—
Praseodymium Oxide	Pr_2O_3	—	D	7.07	—	—	1,400	G	Ir	—	—	ThO_2	RF, RF-R	Loses O_2
Radium	Ra	700	—	5 (?)	246	320	416	—	—	—	—	—	—	—
Rhenium	Re	3,180	—	20.53	1,928	2,207	2,571	P	—	—	—	—	DC	—
Rhenium Oxide	ReO_3	—	D	~7	—	—	—	—	—	—	—	—	RF	R-evap in 10^{-3} T O_2
Rhodium	Rh	1,966	—	12.4	1,277	1,472	1,707	G	W	W	W	ThO_2, VC	DC	E-beam OK
Rubidium	Rb	39	—	1.48	-3	37	111	—	—	—	—	Q	—	—
Rubidium Chloride	RbCl	718	—	2.09	—	—	~550	—	—	—	—	Q	RF	n 1.493
Rubidium Iodide	RbI	647	—	3.55	—	—	~400	—	—	—	—	Q	RF	n 1.647
Ruthenium	Ru	2,310	—	12.3	1,780	1,990	2,260	P	W	—	—	—	DC	—
Samarium	Sm	1,074	—	7.52	373	460	573	G	Ta	—	—	Al_2O_3	DC	—
Samarium Oxide	Sm_2O_3	2,350	—	8.35	—	—	—	G	Ir	—	—	ThO_2	RF, RF-R	Loses O_2. Films smooth, clear.
Samarium Sulfide	Sm_2S_3	1,900	—	5.73	—	—	—	G	—	—	—	—	—	—
Scandium	Sc	1,541	—	2.99	714	837	1,002	Ex	W	—	—	Al_2O_3, BeO	RF	Alloys with Ta.
Scandium Oxide	Sc_2O_3	2,300	—	3.86	—	—	~400	F	—	—	—	—	RF, RF-R	—
Selenium	Se	217	—	4.81	89	125	170	G	W, Mo	W, Mo	W, Mo	A_2O_3, VC	—	Dedicated vacuum system. High V.P.
Silicon	Si	1,410	—	2.32	992	1,147	1,337	F	W, Ta	—	—	BeO, Ta, VC	DC, RF	Alloys with W; use thick boat. E-beam OK
Silicon Boride	SiB_6	—	—	—	—	—	—	P	—	—	—	—	RF	—
Silicon Carbide	SiC	~2,700	S, D	3.22	—	—	1,000	—	—	—	—	—	RF	Sputter preferred. n 2.654, 2.697
Silicon Nitride	Si_3N_4	1,900	—	3.44	—	—	~800	—	—	—	—	—	RF, RF-R	—
Silicon (II) Oxide	SiO	>1,702	S	2.13	—	—	850	F	Ta	W	W	Ta	RF, RF-R	Use baffle box and low evap rate. n 1.6
Silicon (IV) Oxide	SiO_2	1,610	—	~2.65	*	*	1,025*	Ex	—	—	—	Al_2O_3	RF	Quartz excellent in E-beam. n 1.544, 1.553
Silicon Selenide	SiSe	—	—	—	—	—	550	—	—	—	—	Q	RF	—
Silicon Sulfide	SiS	940	S	1.85	—	—	450	—	—	—	—	Q	RF	n 1.853

Materials Deposition

Key to Symbols: * influenced by composition; ** Cr-plated rod or strip; ***all metals alumina coated; **C** = carbon; **Gr** = graphite; **Q** = quartz; **Incl** = Inconel; **VC** = vitreous carbon; **SS** = stainless steel; **Ex** = excellent; **G** = good; **F** = fair; **P** = poor; **S** = sublimes; **D** = decomposes; **RF** = RF sputtering is effective; **RF-R** = reactive RF sputter is effective; **DC** = DC sputtering is effective; **DC-R** = reactive DC sputtering is effective

Material	Symbol	MP (° C)	S/D	g/cm^3	Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques					Sputter	Comments
					10^{-8}	10^{-6}	10^{-4}	E-Beam	Thermal Sources					
									Boat	Coil	Basket	Crucible		
Silicon Telluride	$SiTe_2$	—	—	4.39	—	—	550	—	—	—	—	Q	RF	—
Silver	Ag	962	—	10.5	580	690	820	Ex	W	Mo	Ta, Mo	Al_2O_3, W	DC	Adhesion poor. Use Cr interlayer
Silver Bromide	AgBr	432	D	6.47	—	—	~380	—	Ta	—	—	Q	RF	n 2.253
Silver Chloride	AgCl	455	—	5.56	—	—	~520	—	Mo, Pt	—	Mo	Q	RF	n 2.07
Silver Iodide	AgI	558	—	6.01	—	—	~500	—	Ta	—	—	—	RF	n 2.21
Sodium	Na	98	—	0.97	74	124	192	—	Ta, SS	—	—	Q	—	Preheat gently to outgas. Film reacts in air. n 4.22
Sodium Bromide	NaBr	747	—	3.20	—	—	~400	—	—	—	—	Q	RF	Preheat gently to outgas. n 1.641
Sodium Chloride	NaCl	801	—	2.17	—	—	530	G	Ta, W, Mo	—	—	Q	RF	Copper oven; little decomposition Preheat gently to outgas. n 1.544
Sodium Cyanide	NaCN	564	—	—	—	—	~550	—	Ag	—	—	—	RF	Preheat gently to outgas. n 1.452
Sodium Fluoride	NaF	993	—	2.56	—	—	~1,000	G	Mo, Ta, W	—	—	BeO	RF	Preheat gently to outgas. No decomposition. n 1.336
Sodium Hydroxide	NaOH	318	—	2.13	—	—	~470	—	Pt	—	—	—	—	Preheat gently to outgas. n 1.358
Spinel	$MgAl_2O_4$	—	—	8.0	—	—	—	G	—	—	—	—	RF	n 1.72
Strontium	Sr	769	—	2.6	239	309	403	P	W, Ta, Mo	W	W	VC	RF	Wets but no alloy with W/Ta/Mo. Film reacts in air.
Strontium Chloride	$SrCl_2$	875	—	3.05	—	—	—	—	—	—	—	—	—	n 1.650
Strontium Fluoride	SrF_2	1,473	—	4.24	—	—	~1,000	—	—	—	—	Al_2O_3	RF	n 1.442
Strontium Oxide	SrO	2,430	S	4.7	—	—	1,500	—	Mo	—	—	Al_2O_3	RF	Reacts with W/Mo. n 1.810
Strontium Sulfide	SrS	>2,000	—	3.70	—	—	—	—	Mo	—	—	—	RF	Decomposes. n 2.107
Sulfur	S	113	—	2.07	13	19	57	P	W	—	W	Q	—	Dedicated vacuum system. High VP. n 1.957
Supermalloy®	Ni/Fe/Mo	1,410	—	8.9	—	—	—	G	—	—	—	—	DC	Sputter preferred; Co-evap Ni/Fe and Mo
Tantalum	Ta	2,996	—	16.6	1,960	2,240	2,590	Ex	—	—	—	—	DC	Forms good films
Tantalum Boride	TaB_2	3,000(?)	—	11.15	—	—	—	—	—	—	—	—	RF	—
Tantalum Carbide	TaC	3,880	—	13.9	—	—	~2,500	—	—	—	—	—	RF	—
Tantalum Nitride	TaN	3,360	—	16.30	—	—	—	—	—	—	—	—	RF, RF-R	Evap Ta in 10^{-3} T N_2
Tantalum Pentoxide	Ta_2O_5	1,872	—	8.2	1,550	1,780	1,920	G	Ta	W	W	VC	RF, RF-R	Slight decomposition. Evap Ta in 10^{-3} T O_2. n 2.6
Tantalum Sulfide	TaS_2	>1,300	—	—	—	—	—	—	—	—	—	—	RF	—
Technetium	Tc	2,200	—	11.5	1,570	1,800	2,090	—	—	—	—	—	—	—
Teflon®	PTFE	330	—	2.9	—	—	—	—	W	—	—	—	RF	Baffled source. Film structure doubtful.
Tellurium	Te	449	—	6.25	157	207	277	P	W, Ta	W	W, Ta	Al_2O_3, Q	RF	Wets W/Ta without alloying. n1.002
Terbium	Tb	1,356	—	8.23	800	950	1,150	Ex	Ta	—	—	Al_2O_3	RF	—
Terbium Fluoride	TbF_3	1,172	—	—	—	—	~800	—	—	—	—	—	RF	—
Terbium Oxide	Tb_2O_3	2,387	—	7.87	—	—	1,300	—	Ir	—	—	—	RF	Partially decomposes
Terbium Peroxide	Tb_4O_7	—	D	—	—	—	—	—	Ta	—	—	—	RF	Loses O_2. Films are mostly TbO
Thallium	Tl	304	—	11.85	280	360	470	P	W, Ta	—	W	Al_2O_3, Q	DC	Wets freely
Thallium Bromide	TlBr	480	S	7.56	—	—	~250	—	Ta	—	—	Q	RF	n 2.4 - 2.8
Thallium Chloride	TlCl	430	S	7.00	—	—	~150	—	Ta	—	—	Q	RF	n 2.247
Thallium Iodide	TlI	440	S	7.1	—	—	~250	—	—	—	—	Q	RF	n 2.78
Thallium Oxide	Tl_2O_2	717	—	10.19	—	—	350	—	—	—	—	—	RF	Decomposes at 850° C to Tl_2O
Thorium	Th	1,750	—	11.7	1,430	1,660	1,925	Ex	W, Ta, Mo	W	W	—	—	—
Thorium Bromide	$ThBr_4$	610	S	5.67	—	—	—	—	Mo	—	—	—	—	n 2.47
Thorium Carbide	ThC_2	2,655	—	8.96	—	—	~2,300	—	—	—	—	C	RF	—
Thorium Fluoride	ThF_4	>900	—	6.32	—	—	~750	F	Mo	—	W	VC	RF	—
Thorium Oxide	ThO_2	3,220	—	9.86	—	—	~2,100	G	W	—	—	—	RF, RF-R	—
Thorium Oxyfluoride	$ThOF_2$	900	—	9.1	—	—	—	—	Mo, Ta	—	—	—	—	n 1.52
Thorium Sulfide	ThS_2	1,925	—	7.30	—	—	—	—	—	—	—	—	RF	Sputter preferred; Co-evap OK
Thulium	Tm	1,545	S	9.32	461	554	680	G	Ta	—	—	Al_2O_3	DC	—
Thulium Oxide	Tm_2O_3	—	—	8.90	—	—	1,500	—	Ir	—	—	—	RF	Decomposes
Tin	Sn	232	—	7.28	682	807	997	Ex	Mo	W	W	Al_2O_3	DC	Wets Mo. Low sputter power. Ta liner for E-beam.
Tin Oxide	SnO_2	1,630	S	6.95	—	—	~1,000	Ex	W	W	W	Q, Al_2O_3	RF, RF-R	Using W, films low in O; Oxidize in air. n 2.0
Tin Selenide	SnSe	861	—	6.18	—	—	~400	G	—	—	—	Q	RF	—
Tin Sulfide	SnS	882	—	5.22	—	—	~450	—	—	—	—	Q	RF	—
Tin Telluride	SnTe	780	D	6.48	—	—	~450	—	—	—	—	Q	RF	—
Titanium	Ti	1,660	—	4.5	1,067	1,235	1,453	Ex	W	—	—	TiC	DC	Alloys with W/Ta/Mo; Outgas is high on first heating
Titanium Boride	TiB_2	2,900	—	4.50	—	—	—	P	—	—	—	—	RF	—

Yttrium Fluoride Pieces

Zinc Oxide Tablets

Tungsten Oxide Target

					Temp. (° C) for Given Vap. Press. (Torr)			Evaporation Techniques						
									Thermal Sources					
Material	Symbol	MP (° C)	S/D	g/cm^3	10^{-8}	10^{-6}	10^{-4}	E-Beam	Boat	Coil	Basket	Crucible	Sputter	Comments
Titanium Carbide	TiC	3,140	—	4.93	—	—	~2,300	—	—	—	—	—	RF	—
Titanium Nitride	TiN	2,930	—	5.22	—	—	—	G	Mo	—	—	—	RF, RF-R	Sputter preferred. Decomposes with thermal evap.
Titanium (II) Oxide	TiO	1,750	—	4.93	—	—	~1,500	G	W, Mo	—	—	VC	RF	Preheat gently to outgas. n 2.2
Titanium (III) Oxide	Ti_2O_3	2,130	D	4.6	—	—	—	G	W	—	—	—	RF	Decomposes
Titanium (IV) Oxide	TiO_2	1,830	—	4.26	—	—	~1,300	F	W, Mo	—	W	—	RF, RF-R	Loses O_2. Oxides in air. Ta gives films TiO/Ti. n 2.616, 2.903
Tungsten	W	3,410	—	19.35	2,117	2,407	2,757	G	—	—	—	—	DC	Films hard and adherent.
Tungsten Boride	WB_2	~2,900	—	10.77	—	—	—	P	—	—	—	—	RF	—
Tungsten Carbide	W_2C	2,860	—	17.15	1,480	1,720	2,120	Ex	C	—	—	—	RF	—
Tungsten Disulfide	WS_2	1,250	D	7.5	—	—	—	—	—	—	—	—	RF	—
Tungsten Oxide	WO_3	1,473	S	7.16	—	—	980	G	W, Pt	—	—	—	RF-R	Preheat gently to outgas. W gives O_2 loss. n 1.68
Tungsten Selenide	WSe_2	—	—	9.0	—	—	—	—	—	—	—	—	RF	—
Tungsten Silicide	WSi_2	>900	—	9.4	—	—	—	—	—	—	—	—	RF	—
Tungsten Telluride	WTe_2	—	—	9.49	—	—	—	—	—	—	—	Q	RF	—
Uranium	U	1,132	—	19.05	1,132	1,327	1,582	G	Mo, W	W	W	—	—	Films reacts in air
Uranium Carbide	UC_2	2,350	—	11.28	—	—	2,100	—	—	—	—	C	RF	Decomposes
Uranium Fluoride	UF_4	960	—	6.70	—	—	300	—	Ni	—	—	—	RF	—
Uranium (III) Oxide	U_2O_3	1,300	D	8.30	—	—	—	—	W	—	W	—	RF-R	Decomposes at 1,300° C to UO_2
Uranium (IV) Oxide	UO_2	2,878	—	10.96	—	—	—	—	W	—	W	—	RF	Ta causes decomposition
Uranium Phosphide	UP_2	—	—	8.57	—	—	1,200	—	Ta	—	—	—	RF	Decomposes
Uranium (II) Sulfide	US	>2,000	—	10.87	—	—	—	—	—	—	—	—	—	—
Uranium (IV) Sulfide	US_2	>1,100	—	7.96	—	—	—	—	W	—	—	—	RF	Slight decomposition
Vanadium	V	1,890	—	5.96	1,162	1,332	1,547	Ex	W, Mo	—	—	—	DC	Wets Mo. E-beam preferred. n 3.03
Vanadium Boride	VB_2	2,400	—	5.10	—	—	—	—	—	—	—	—	RF	—
Vanadium Carbide	VC	2,810	—	5.77	—	—	~1,800	—	—	—	—	—	RF	—
Vanadium Nitride	VN	2,320	—	6.13	—	—	—	—	—	—	—	—	RF, RF-R	—
Vanadium (IV) Oxide	VO_2	1,967	S	4.34	—	—	~575	—	—	—	—	—	RF, RF-R	Sputter preferred.
Vanadium (V) Oxide	V_2O_5	690	D	3.36	—	—	~500	—	—	—	—	Q	RF	n 1.46, 1.52, 1.76
Vanadium Silicide	VSi_2	1,700	—	4.42	—	—	—	—	—	—	—	—	RF	—
Ytterbium	Yb	819	S	6.96	520	590	690	G	Ta	—	—	—	—	—
Ytterbium Fluoride	YbF_3	1,157	—	—	—	—	~800	—	Mo	—	—	—	RF	—
Ytterbium Oxide	Yb_2O_3	2,346	S	9.17	—	—	~1,500	—	Ir	—	—	—	RF, RF-R	Loses O_2
Yttrium	Y	1,522	—	4.47	830	973	1,157	Ex	W, Ta	W	W	Al_2O_3	RF, DC	High Ta solubility
Yttrium Alum Oxide	$Y_3Al_5O_{12}$	1,990	—	—	—	—	—	G	—	W	W	—	RF	Films not ferroelectric
Yttrium Fluoride	YF_3	1,387	—	4.01	—	—	—	—	—	—	—	—	RF	—
Yttrium Oxide	Y_2O_3	2,410	—	5.01	—	—	~2,000	G	W	—	—	C	RF, RF-R	Loses O_2; films smooth and clear. n 1.79
Zinc	Zn	420	—	7.14	127	177	250	Ex	Mo, W, Ta	W	W	Al_2O_3 Q	DC	Evaporates well, over wide range of conditions
Zinc Antimonide	Zn_3Sb_2	570	—	6.33	—	—	—	—	—	—	—	—	RF	—
Zinc Bromide	$ZnBr_2$	394	—	4.20	—	—	~300	—	W	—	—	C	RF	Decomposes. n 1.545
Zinc Fluoride	ZnF_2	872	—	4.95	—	—	~800	—	Pt, Ta	—	—	Q	RF	—
Zinc Nitride	Zn_3N_2	—	—	6.22	—	—	—	—	Mo	—	—	—	RF	Decomposes
Zinc Oxide	ZnO	1,975	—	5.61	—	—	~1,800	F	—	—	—	—	RF-R	n 2.008, 2.029
Zinc Selenide	ZnSe	>1,100	—	5.42	—	—	660	—	Ta, W, Mo	W, Mo	W, Mo	Q	RF	Dedicated vacuum system. Preheat gently to outgas. Evaporates well. n 2.89
Zinc Sulfide	ZnS	1,700	S	3.98	—	—	~800	G	Ta, Mo	—	—	—	RF	Dedicated vacuum system. Preheat gently to outgas. Films partially decompose. Substrate temp affects sticking coeff. n 2.356
Zinc Telluride	ZnTe	1,239	—	6.34	—	—	~600	—	Mo, Ta	—	—	—	RF	Preheat gently to outgas. n 3.56
Zirconium	Zr	1,852	—	6.49	1,477	1,702	1,987	Ex	W	—	—	—	DC	Alloys W. Films react in air.
Zirconium Boride	ZrB_2	~3,200	—	6.09	—	—	—	G	—	—	—	—	RF	—
Zirconium Carbide	ZrC	3,540	—	6.73	—	—	~2,500	—	—	—	—	—	RF	—
Zirconium Nitride	ZrN	2,980	—	7.09	—	—	—	—	—	—	—	—	RF, RF-R	R-evap in 10^{-3} T N_2.
Zirconium Oxide	ZrO_2	~2,700	—	5.89	—	—	~2,200	G	W	—	—	—	RF, RF-R	Loses O_2. Films clear and hard. n 2.13, 2.19, 2.20
Zirconium Silicate	$ZrSiO_4$	2,550	—	4.56	—	—	—	—	—	—	—	—	RF	n 1.92–1.96; 1.97–2.02
Zirconium Silicide	$ZrSi_2$	1,700	—	4.88	—	—	—	—	—	—	—	—	RF	—

Modern Vacuum Practice
by Nigel Harris

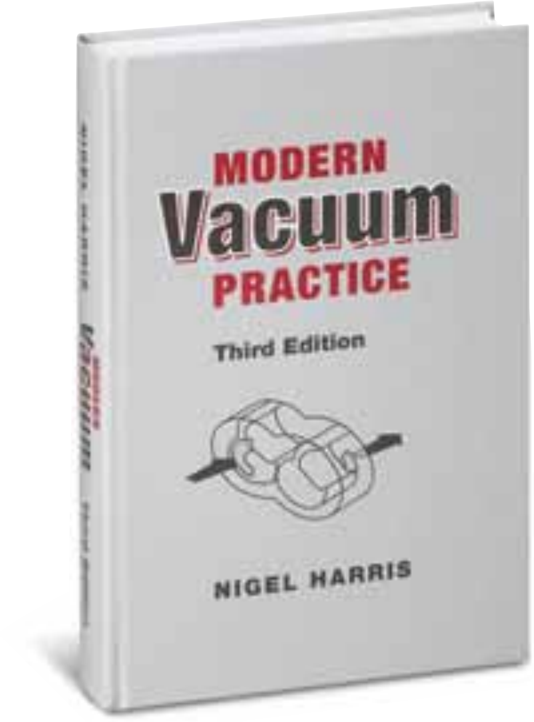
Self-Published, 3rd Edition (2005), 457 pp.

Harris has written the introductory book every vacuum novice needs. Without mathematics or reference to the kinetic theory of gases, it is an excellent, practical, and understandable guide written in clear English, and full of clean, easy-to-understand drawings. It even has a series of sketches showing how to assemble flanges.

Harris opens with a simple description of vacuum and its applications, and then has a delightfully slim chapter on "Some Relevant Physical Concepts." It gives the novice enough to absorb and understand without baffling him or her on the more arcane details. He follows this with two chapters on pressure measurements and residual gas identification, again managing to hit the simple truths rather than plowing through the minutia.

The central third of the book gives an excellent description and comparison of the important rough and high vacuum pumps. The depth of explanation is good without being stodgy. Each pump has its own practical troubleshooting chart describing what might cause the observed, faulty system behavior when evacuated by that type of pump. These tables alone are worth the price of the book to the vacuum user or maintenance staff person.

A separate 31-page chapter on leak detection has to be one of the most comprehensive every written. A chapter on "Safe Uses of Vacuum Equipment" is a very welcome first and should be required reading for all vacuum practitioners.



Given the extent and clarity of the drawings, it is perhaps churlish to point out one of them is wrong. The wobble bellows rotary drive, as pictured on page 220, might wobble, but is unable to rotate.

Description	Part No.	Price
Modern Vacuum Practice Book (3rd ed.)	BK401003	**Call**

A User's Guide to Vacuum Technology
by J. O'Hanlon

Wiley-Interscience, 3rd Edition (2003), 516 pp.

This is a comprehensive guide to vacuum technology, but not an introductory book. Although it does not presume the reader has prior knowledge, the depth to which it plumbs each facet of vacuum technology may leave a newcomer stranded. It is, however, a vital text-book for all those technicians, engineers, and researchers who, from daily contact, have some familiarity with vacuum systems, but must know more.

O'Hanlon divides the subject of Vacuum into four main sections: **Its Basis, Production, Materials,** and **Systems**. It concludes with good Appendixes that, in this reviewer's copy, are so worked-over they are dog-eared with pages falling out.

The largest section, **Its Basis**, covers in suitable depth (including the math) the kinetic theory of gases, gas flow, outgassing, pressure measurement, etc. The **Production** section is an in-depth look at the major pumps and pumping mechanism used in modern vacuum technology.

The **Materials** section is good, emphasizing how the choice of materials and components influences the ultimate pressure. It then discusses joints, flanges, seals, and various components. It concludes with an interesting chapter on vacuum lubrication that gives references to a variety of liquid, grease, and dry lubricants.

The **Systems** section contains chapters on rough vacuum, high vacuum, ultraclean vacuum, high flow, and multi-chamber systems. The final chapter is a good introduction to leak detection methods.

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A User's Guide to Vacuum Technology Book (3rd ed.)	BK551033	**Call**

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Professional Engineering Computations introduced VacTran vacuum calculation software some 18 years ago. The current version, **VacTran 3**, both continues the traditional calculations and significantly advances the program's capabilities.

As the pressure decreases during the pump down of any vacuum vessel, the flow regimes through chamber and ducts change from continuum, through transitional, to molecular flow. As the flow regime changes so do formulas for conductances and pumping speeds. Further complicating this picture is the outgassing rates of the various materials which decay exponentially with time. Modeling these interactions, even with a spreadsheet doing the math, is tedious and rarely attempted. **VacTran 3** is a fast, convenient way to perform a variety of calculations at the 'what-if' design stage to investigate and maximize a vacuum system's performance.

With **VacTran 3**'s easy-to-use interface, the designer can readily adjust any parameter knowing that the appropriate formulas will be applied automatically to allow her/him to:

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- Enter raw data for gas loads or use the outgassing rate library of literature values
- Model the outgassing of multiple surfaces, permeation through o-rings, and known gas flows into the chamber
- Compare the gas loads from these sources
- Create professional-looking graphs
- Avoid vacuum 'surprises'

The major new features in **VacTran 3** include:

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- Six stations for different pump/conductance combinations on any one system
- Calculation of conductances that are: circular, annular, elliptical, triangular, rectangular, conical, and slit- or orifice-shaped
- Calculation for chamber volumes/surface areas: box, sphere, bell jar, cylinder, torus, 4-way and 6-way intersections and crosses, etc

- A gallery to which calculated curves can be automatically saved
- An option that graphs the rate of pressure rise expected during 'leak back' checks
- An excellent interactive e-Help manual that provides valuable vacuum technology training

Our extensive practical experience (almost daily use for 17 years) with all versions of the **VacTran** program have convinced us of its practicality and utility for vacuum system modeling.

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