1

Vacuum Fundamentals

Here is a list of things we think you should be able to do after reading this chapter:

You should be able to—

1. Use the basic terminology for vacuum technology.
2. Explain what a vacuum is.
3. Give some uses for vacuum.
4. Explain why a vacuum is necessary for some processes.
5. Discuss the two important types of gas flow.
6. Describe the effect of temperature and pressure on a volume of gas.
7. Recognize and use pressure units correctly.
8. Use the term "throughput" to describe vacuum system, pump operation and gas load.

Introduction

In the first part of this chapter, we will introduce you to vacuum:

- What it is
- How it relates to pressure
- How it is produced
- The different types of vacuum
- Where it is used
- Why we need it

Then, you will learn about the way we express very large and very small numbers. You will also learn about temperature as a factor in vacuum work and the types of pressure and how it is measured.

Finally, we will discuss some of the basic concepts used in vacuum work. These are:

- The effects of pressure
- Pressure ranges in vacuum systems
- Some basic laws about the behavior of gases
- Some types of gas flow
- How we measure the work done by vacuum systems

The Nature of Vacuum

What Is Vacuum?

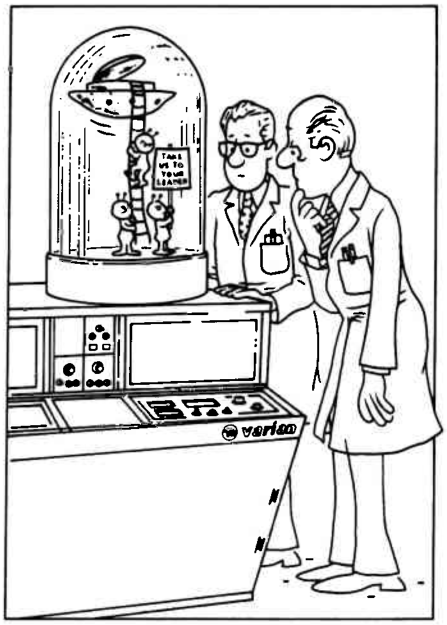
vacuum

work chamber

The word *vacuum* comes from the Latin "vacua," which means "empty." Actually, vacuum is only partially empty space. In a vacuum, some of the air and other gases have been removed from a contained volume. This volume is usually called the *work chamber*. It separates the vacuum from the outside world.

A more practical definition for vacuum is what exists in any contained volume where there is less gas than there is in the surrounding atmosphere.

We shall see that these gases exert a force on the surface area of the container. This force is called *pressure*. We can measure the pressure in the chamber by comparing it to the atmospheric pressure on the outside. In this way, we can find out how much gas is left in the vacuum.



What About Pressure?

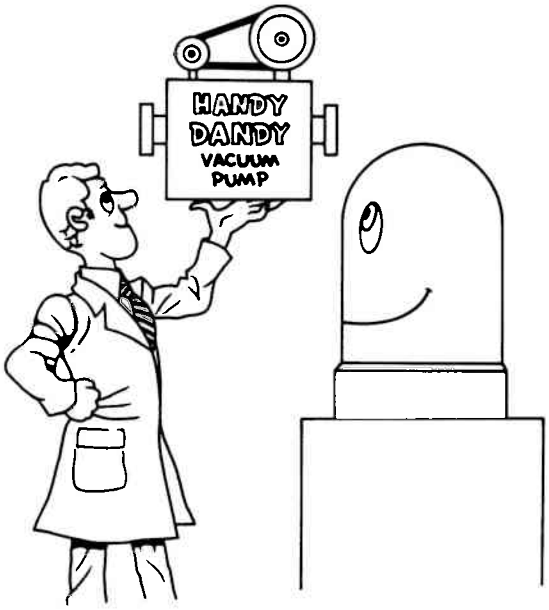
pressure

pressure measurement

Pressure is defined as force per unit area. Gases are composed of small particles. These gas particles are in constant motion. As these particles move around in space, they hit objects. When they hit something, they exert a force, or pressure. We can take a unit of area and measure the number and intensity of particle impacts on that surface. The result is a *pressure measurement.*

How Is a Vacuum Produced?

A vacuum is made by removing air and other gases from the work chamber. We remove the air and other gases by using special pumps, called vacuum pumps.

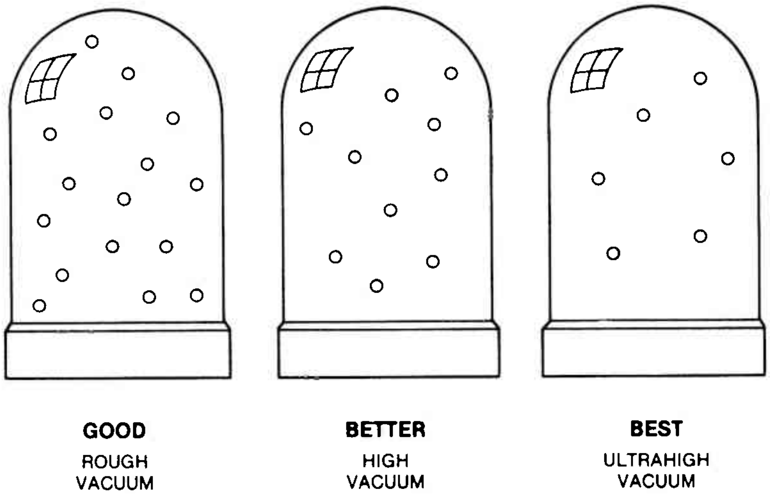


vacuum pumps

There are many, and very different, kinds of *vacuum pumps*. Some of them actually remove the gases. Other pumps trap the gases or change their form. In any case, the pump's job is to take as many gases out of circulation as necessary.

Different Types of Vacuum

There are different degrees of vacuum, called rough vacuum, high vacuum, and ultrahigh vacuum. Which one is used depends on the application. As the chambers below show, the better (or higher) the vacuum is, the less air and gas are present.



Where Is Vacuum Used?

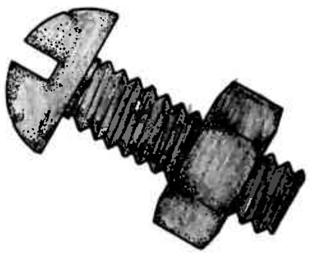
Vacuum is used for many products and processes. Some of them are:

Rough Vacuum	High Vacuum	Ultrahigh Vacuum
Food processing	Tube processing	Space research
Evaporation	Heat treating	Materials research
Freeze drying	Integrated circuit manufacture	Metallurgy
Distillation	Decorative coating	Physics research
Sputtering	Particle acceleration	Surface analysis
Electrical conduction (neon lights)	Chemistry research	Molecular beam epitaxy
	E-beam welding	
	Vapor deposition	
	Ion implantation	
	Insulation (thermal)	

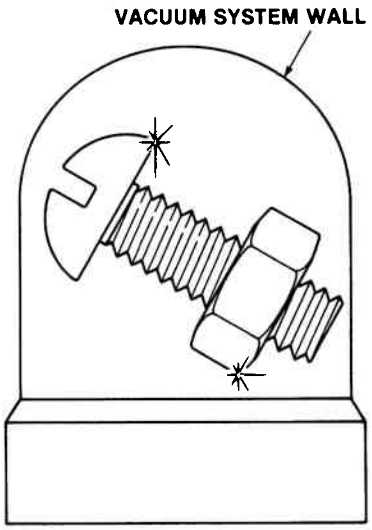
Why Is Vacuum Needed?

We use a vacuum when we need a space that is very *clean.* It must be free of gases that can interfere with what we want to do.

Let's take iron, for example. When iron is left out in air, it reacts with the gases in the air, and the result is rust. This wouldn't happen in a vacuum.



RUSTY



CLEAN

Another example is television. If gases are not removed from a TV tube, the electrons are blocked from reaching the screen— no picture!

The easiest way to define "clean" is to say that everything is contaminated, or dirty, to some degree. It is a matter of how much contamination is present. The less contamination, the "cleaner" something is.

Let's look at some of this contamination that we are trying to remove.

DRY ATMOSPHERIC AIR IS A MIXTURE OF GASES

Gas	Percent by Volume
Nitrogen	78.08
Oxygen	20.95
Argon	0.93
Carbon Dioxide	0.03
Neon	0.0018
Helium	0.0005
Krypton	0.0001
Hydrogen	0.00005
Xenon	0.0000087

Atmospheric air is a mixture of gases. Over 99% of atmosphere is nitrogen and oxygen. All other gases make up less than 1%.

Water vapor, another common gas, is not listed above because the amount changes with atmospheric pressure and temperature. Water vapor, which varies from 0.6% to 6% by volume, is one of the biggest sources of vacuum contamination, or "dirt."

Large and Small Numbers

Powers of Ten

powers of ten

You may already be familiar with the *powers of ten*. It is a way of describing very large and very small numbers. It is called exponential notation, scientific notation, logarithmic numbers, or simply "powers of ten." Powers of ten is a simple, convenient way for writing and working with very large and very small numbers. For example, one million = 1×10^6, and one-millionth = 1×10^{-6}.

Some Powers of Ten

$1 \times 10^6 = 1{,}000{,}000$
$1 \times 10^5 = 100{,}000$
$1 \times 10^4 = 10{,}000$
$1 \times 10^3 = 1{,}000$
$1 \times 10^2 = 100$
$1 \times 10^1 = 10$
$1 \times 10^0 = 1$

$1 \times 10^{-1} = 0.1$
$1 \times 10^{-2} = 0.01$
$1 \times 10^{-3} = 0.001$
$1 \times 10^{-4} = 0.0001$
$1 \times 10^{-5} = 0.00001$
$1 \times 10^{-6} = 0.000001$

In practice, a number is written as some value from 1 and up to 10, but not including 10. Then, it is multiplied by either a positive or negative power of ten. For example, $7.6 \times 10^2 = 760$.

The small 2 to the upper right of the 10 is called an exponent, or power. The exponent is the number of times the first number is multiplied by 10 (2 in the example above). Where the exponent is a *minus*, it is the number of times the first number is divided by 10.

You may be interested in these very large numbers—

Approximate number of particles in:	
Atmosphere	$\approx 10^{40}$
Earth	$\approx 10^{60}$
Visible Universe	$\approx 10^{100}$

and in some very small numbers—

Typical Molecule Diameter	$\approx 10^{-8}$ in.
Bacteria	$\approx 10^{-3}$ in.

Using the Powers of Ten

Let's try a few examples using the powers of ten. But first of all, the rules of the game.

1. *To add or subtract:* First, adjust the numbers to make the exponents the same value. Then, add or subtract.

Adding—No adjustment needed

$$\begin{array}{r} 2 \times 10^{-3} \\ + \; 3 \times 10^{-3} \\ \hline 5 \times 10^{-3} \end{array}$$

Adding—Adjustment needed

$$\begin{array}{r} 2 \times 10^{-4} \\ + \; 3 \times 10^{-3} \\ \hline ? \end{array}$$

(continued on next page)

Adjusting gives you:

$$\begin{array}{r} 0.2 \times 10^{-3} \\ +\ 3.0 \times 10^{-3} \\ \hline 3.2 \times 10^{-3} \end{array}$$

To adjust, we changed the 10^{-4} exponent by *one* power to 10^{-3}. We then moved the decimal in the whole number *one* place to the left.

Here's another example:

$$\begin{array}{r} 2 \times 10^{-5} \\ +\ 3 \times 10^{-3} \\ \hline ? \end{array}$$

Adjusting gives you:

$$\begin{array}{r} .02 \times 10^{-3} \\ +\ 3.00 \times 10^{-3} \\ \hline 3.02 \times 10^{-3} \end{array}$$

To adjust, we changed the 10^{-5} exponent by *two* powers—to 10^{-3}. We then moved the decimal in the whole number *two* places to the left.

Subtracting—No adjustment needed

$$\begin{array}{r} 6 \times 10^{-4} \\ -\ 5 \times 10^{-4} \\ \hline 1 \times 10^{-4} \end{array}$$

Subtracting—Adjustment needed

$$\begin{array}{r} 6 \times 10^{-4} \\ -\ 5 \times 10^{-5} \\ \hline ? \end{array}$$

Adjusting gives you:

$$\begin{array}{r} 6.0 \times 10^{-4} \\ -\ 0.5 \times 10^{-4} \\ \hline 5.5 \times 10^{-4} \end{array}$$

2. *To multiply:* Add exponents.

   a) $10^1 \times 10^2 = 10^3$
   b) $10^{-1} \times 10^2 = 10^1$
   c) $(2 \times 10^1) \times (3 \times 10^2) = 6 \times 10^3$

3. *To divide:* Subtract exponents.

   a) $\frac{10^3}{10^2} = 10^1$
   b) $\frac{10^2}{10^3} = 10^1$
   c) $\frac{4 \times 10^3}{2 \times 10^2} = 2 \times 10^1$

4. *To raise to a power:* Multiply exponent by power.

   a) $(10^1)^3 = 10^3$
   b) $(10^2)^2 = 10^4$
   c) $(2 \times 10^1)^3 = 8 \times 10^3$

(continued on next page)

5. *To find a root:* Divide by root.

a) $\sqrt{10^2} = 10^1$ b) $\sqrt[3]{10^6} = 10^2$

c) $\sqrt[3]{9 \times 10^3} = 3 \times 10^1$

Here is a statement which results from division:

A pressure of 10^{-3} torr is 1 million times greater than 10^{-9} torr.

$$\frac{1 \times 10^{-3}}{1 \times 10^{-9}} = 1 \times 10^6 \text{ (which is 1 million)}$$

Two more examples of division:

$$\frac{10^2}{10^2} = 10^0 = 1 \qquad \frac{3 \times 10^3}{1.5 \times 10^{-7}} = 2 \times 10^{10}$$

Powers of Ten and Number of Decimal Places

When you write the number "1", it is taken for granted that you are really writing "1." with a decimal point to the right.

When the decimal point is on the right side of "1.", it is said to be in the "zero" position and so, $1 \times 10^0 = 1$. If it is one more position to the right, it is in the "one" position, so $1 \times 10^1 = 10$.

Likewise, when the decimal point is on the left side of one, "0.1", it is in the minus one position and $1 \times 10^{-1} = 0.1$. Notice that the minus exponent also means "one divided by that number."
Thus: $1 \times 10^{-1} = 1/10$.

Temperature

We have mentioned temperature already in our discussion. Most of us are familiar with the Fahrenheit (°F) and the Celsius or Centigrade (°C) scales of temperature measurement. In the world of vacuum, we are also concerned with the absolute temperature as well.

temperature

Temperature is a qualitative measurement of energy. The hotter something is, the more energy it contains. Or, if we want to get rid of gases, we could pump the energy out of them until they become frozen. That is, we have lowered the temperature of the gases.

absolute temperature

Calculations of heat and energy do not work well in the Celsius and Fahrenheit scales because of the negative numbers. This is where the *absolute* or Kelvin scale comes in. Let's compare some temperatures and conversion factors.

°F	°C	°K	
212	100	373	Boiling point of water
32	0	273	Freezing point of water
−321	−196	77	LN_2 temperature
−437	−261	12	Cold head temperature
−459	−273	0	Absolute zero

Conversion factors

$$°C = \frac{5}{9}(F - 32) \qquad °K = C + 273$$

$$°F = \frac{9}{5}C + 32 \qquad °K = \frac{5}{9}(F - 32) + 273$$

Now let's discuss some information about gases.

Pressure

Earlier we defined pressure. Now, we'll explain the kinds of pressure vacuum is concerned with. We'll also describe how we measure pressure. First, let's look at what a gas is.

What Is Gas?

gas

What is a *gas?* It is a state of matter where the individual particles are free to move in any direction and tend to expand uniformly to fill the confines of a container. The gas particles are very small and freely moving. Some, like hydrogen and oxygen, are very reactive and easily form stable chemical compounds with other gases or elements. Other gases, such as helium and argon, are inert. These are sometimes known as the noble (inert) gases. They do not tend to form compounds.

pressure

All gases have mass and are thus attracted to the earth by the force of gravity. This "ocean" of gas we call "air" has weight. This weight pushing on the earth's surface is called atmospheric pressure. By definition, *pressure* (P) is the force (F) exerted on some particular area (A), such as a square inch, square foot, or square centimeter. Put into mathematical terms,

$$P = \frac{F}{A} \text{ (Pressure = Force per Unit Area)}$$

standard atmosphere

At 45° N latitude and at sea level, the average pressure exerted on the earth's surface is 14.69 pounds per square inch (absolute), or 14.69 psia. When the temperature is 0°C, this 14.69 psia is called a *standard atmosphere* (1 std atm). Gas behavior is usually described with reference to "standard conditions" of temperature and pressure (stp).

Atmospheric Pressure

We use several different pressure scales. Here are four readings, all at standard conditions.

14.7 psia = 760 torr = 1 std atm = 101,325 pascal

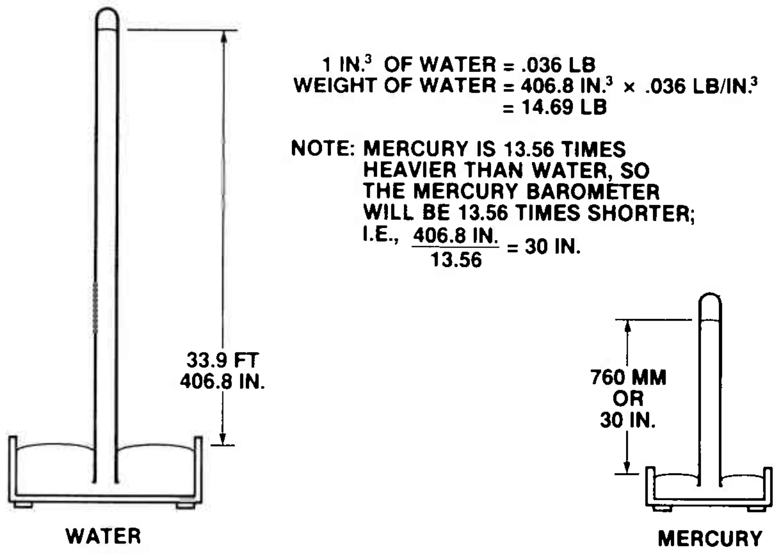
The average atmospheric pressure at sea level (45° N latitude) is 14.7 psia, 760 torr, or 101,325 Pa. Vacuum processes are usually done at pressures much lower than atmospheric pressure. Atmospheric pressure changes with distance above sea level (altitude) and changes in our weather.

AVERAGE PRESSURE AT VARIOUS ALTITUDES

Altitude (Ft)	Pressure (Torr)	Altitude (Ft)	Pressure (Torr)	Altitude (Ft)	Pressure (Torr)
– 1,000	787.87	7,000	586.49	25,000	282.40
– 500	773.83	7,500	575.45	27,500	253.00
0	760.00	8,000	564.58	30,000	226.13
500	746.37	8,500	553.88	35,000	179.33
1,000	732.93	9,000	543.34	40,000	141.18
1,500	719.70	9,500	532.97	45,000	111.13
2,000	706.66	10,000	522.75	50,000	87.497
2,500	693.81	11,000	502.80	55,000	68.889
3,000	681.15	12,000	483.48	60,000	54.236
3,500	668.69	13,000	464.76	70,000	33.662
4,000	656.40	14,000	446.63	80,000	21.010
4,500	644.30	15,000	429.08	90,000	13.208
5,000	632.38	17,500	387.65	100,000	8.356
5,500	620.65	20,000	349.53	120,000	3.446
6,000	609.09	22,500	314.51	140,000	1.508
6,500	597.70				

Source: U.S. Standard Atmosphere, 1962 (NASA)

A way to measure the force exerted by the atmosphere was developed in the mid-1600s by Evangelista Torricelli. It consisted of balancing a fluid of known weight against the weight of air. The first fluid used was water. Later, mercury was used. The measurement was made using an instrument called a barometer. We have named a pressure unit, torr, in Torricelli's honor.



1 IN.^{3} OF WATER = .036 LB
WEIGHT OF WATER = 406.8 IN.^{3} × .036 LB/IN.^{3}
= 14.69 LB

NOTE: MERCURY IS 13.56 TIMES HEAVIER THAN WATER, SO THE MERCURY BAROMETER WILL BE 13.56 TIMES SHORTER; I.E., $\frac{406.8 \text{ IN.}}{13.56} = 30$ IN.

THE BAROMETER

Pressure Measurement

millimeters of mercury
torr
microns
pascal

There are several different scales for pressure measurement. *Millimeters of mercury, torr,* and *microns* are all commonly used. *Pascal (Pa)* is the metric unit for pressure measurement and is the international standard.

The following table shows some of the common scales. The values for these scales are all listed at the same pressure— one standard atmosphere (1 std atm).

PRESSURE EQUIVALENTS

Atmospheric Pressure (Standard) =	
0	psig (gauge pressure)
14.7	pounds per square inch (psia)
760	mm of mercury
760	torr
760,000	millitorr or microns
101,325	pascal
1.013	bar
1013	millibar

Here is a table for the equivalent values for one torr and one millitorr (mtorr).

One Torr =	**One Millitorr =**
$\frac{1}{760}$ atmosphere	$\frac{1}{1000}$ torr
1 mm of mercury	$\frac{1}{1000}$ mm of mercury
1000 microns or millitorr	10^{-3} torr
10^3 microns or millitorr	0.001 torr
133 pascal	1 millitorr
	0.133 pascal

A conversion table and equivalents for the different measurement scales are provided in the Appendix.

Partial Pressure

total pressure
partial pressure

The *total pressure* of a mixture of gases is the sum of each of the individual gas pressures in the mixture. This is known as Dalton's Law of Partial Pressure. Each individual gas pressure in a mixture is called a *partial pressure.*

PARTIAL PRESSURES OF GASES CORRESPOND TO THEIR RELATIVE VOLUMES

			Partial Pressure	
Gas (Air)	**Symbol**	**Percent by Volume**	**Torr**	**Pascal**
Nitrogen	N_2	78	593	79,000
Oxygen	O_2	21	159	21,000
Argon	Ar	0.93	7.1	940
Carbon Dioxide	CO_2	0.03	0.25	33
Neon	Ne	0.0018	1.4×10^{-2}	1.8
Helium	He	0.0005	4.0×10^{-3}	5.3×10^{-1}
Krypton	Kr	0.0001	8.7×10^{-4}	1.1×10^{-1}
Hydrogen	H_2	0.00005	4.0×10^{-4}	5.1×10^{-2}
Xenon	Xe	0.0000087	6.6×10^{-5}	8.8×10^{-3}
Water	H_2O	Variable	(5 to 50 torr typically)	Variable

At standard conditions (760 torr, 0°C), each gas exerts a pressure relative to its percent of the total volume: for example, $N_2 = 78\% = 0.78 \times 760 = 593$ torr.

Vapor Pressure

evaporation
vapor
vapor pressure
condensation
sublimation

When a liquid or solid becomes a gas, we call that process *evaporation.* The gas produced, we call a *vapor.* It, of course, exerts a pressure. This pressure, we refer to as the *vapor pressure* for that particular material. The act of turning the gas back into a liquid, we call *condensation.* When a solid evaporates to a gas directly, we call that process *sublimation.*

In general usage, vapors are gases that tend to condense back to the liquid state at moderate temperatures and pressures. All substances have a characteristic saturation vapor pressure that varies directly with temperature.

The lower the temperature, the lower the vapor pressure. This is true for all substances.

Water deserves special attention because of its behavior in the vacuum system. It is present in air as a gas in relatively large quantities. In the vacuum system, it is hard to remove condensed water vapor from surfaces at room temperatures.

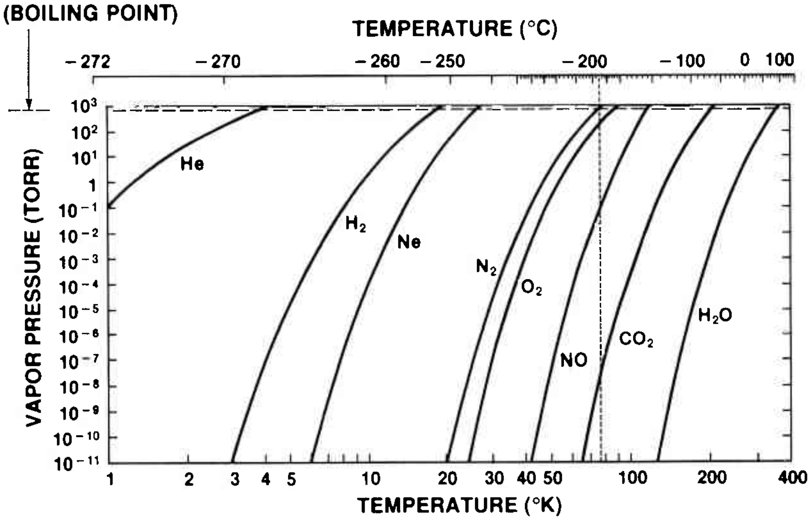
VAPOR PRESSURE OF WATER AT VARIOUS TEMPERATURES

T °C		P Torr
100	(Boiling)	760
50		93
25		24
0	(Freezing)	4.8
−40		0.1
−78.5	(Dry Ice)	5×10^{-4}
−196	(LN_2)	10^{-24}

VAPOR PRESSURES OF SOME LIQUIDS

Liquid	Vapor Pressure Torr at 20 °C (68 °F)
Benzene	74.6
Ethyl Alcohol	43.9
Methyl Alcohol	96.0
Acetone	184.8
Turpentine	4.4
Water	17.5
Carbon Tetrachloride	91.0
High Vacuum Pump Oil	10^{-7}

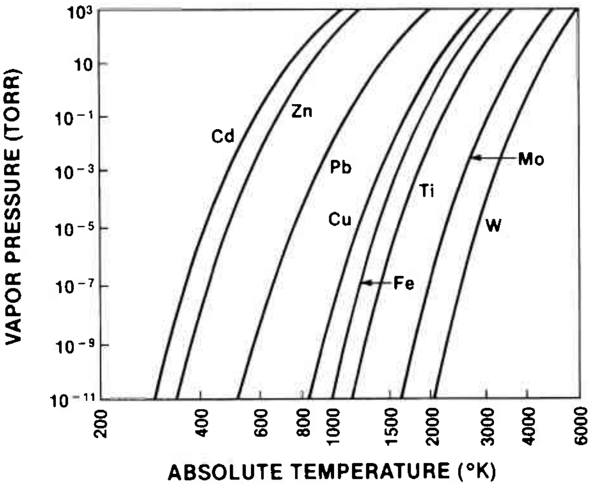
Acetone has the highest vapor pressure of the liquids on this list. It evaporates the fastest of those substances on the list. It releases the most gas into the chamber in a given length of time. High vacuum pump oil is the least volatile liquid on the list. It will take the longest time to evaporate.



VAPOR PRESSURES OF COMMON GASES

When gases become cooled sufficiently, they liquify and/or freeze. These curves give the vapor pressure for selected gases when they are liquids or solids. Curves to the right of the vertical dotted line (77°K, -196°C) indicate low vapor pressures at this temperature. Curves to the left show high vapor pressures at this temperature, which is the boiling point of liquid nitrogen.

Gases at the left side of the chart have high vapor pressures at extremely low temperatures. *Note:* Vapor pressure of all gases is the *same* at the boiling point in atmosphere (760 torr) even though they boil at different temperatures.



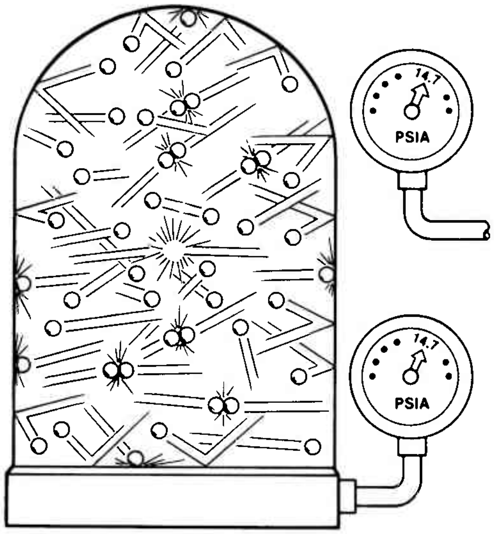
VAPOR PRESSURES OF SOME COMMON MATERIALS NORMALLY CONSIDERED SOLID

All materials have a vapor pressure, even though it may be very small. Note that, for some of these materials, their vapor pressure may be high enough to be a problem in some vacuum systems.

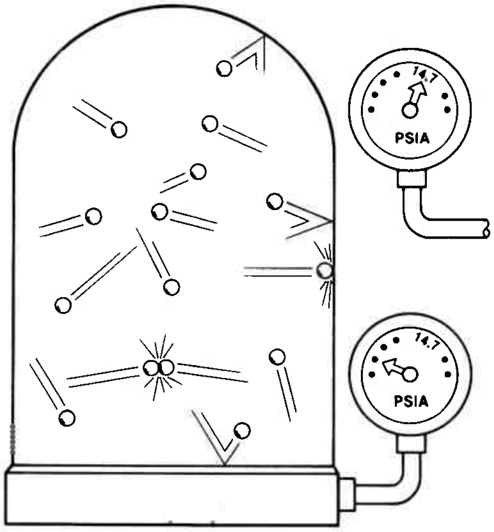
Effects of Pressure

absolute pressure

Before the air and other gases are pumped from the work chamber, constant, high-speed motion makes the particles bump into each other and into the chamber walls. This activity develops a total actual (absolute) pressure of 14.7 pounds per square inch (psia). As we have already seen, 14.7 psia is the average atmospheric pressure at sea level. Therefore, the pressure is the same inside and outside the chamber.



As air is pumped out of the chamber, pressure drops. However, we can never remove all particles from the chamber.



desorption
outgassing

After most of the free-moving gas (sometimes called the volume gas) is removed, there are still other sources of gas entering the system. Gases come off of surfaces in the vacuum system or out of the materials inside the work chamber. This is called *desorption* or *outgassing.*

implode

Vacuum systems can *implode* because of the external atmospheric pressure, causing the walls to collapse inward.

Pressure Ranges

These are the pressure ranges generally used in vacuum work:

rough vacuum
high vacuum
ultrahigh vacuum

Rough (low) vacuum	759 to 1×10^{-3} torr (approx.)
High vacuum	1×10^{-3} torr to 1×10^{-8} torr (approx.)
Ultrahigh vacuum	Less than 1×10^{-8} torr

Gas Particles

atoms

Let's talk about the nature of the gases that exert this pressure. They are made from naturally occurring chemical elements. These elements are shown in the periodic table on the next page. These elements are the building blocks of earthly matter. The smallest identifiable part of an element is one of its *atoms.*

nucleus
protons
neutrons

An atom has a dense center portion known as the *nucleus.* This nucleus has particles called *protons* and *neutrons.* The protons have a positive electrical charge. Neutrons are neutral. This electrical charge in the nucleus is different for each element.

electrons

Under normal conditions, the nucleus is surrounded by a number of electrons. *Electrons* have a negative electrical charge. The number of electrons balances the positive charge and this makes the atom electrically neutral.

masses
atomic mass units (amu)

Neutrons and protons weigh the same and make up the bulk of the atom. The atoms of the different elements have different numbers of protons and neutrons. They thus have different *masses.* This means they have different weights (masses). They are classified by their atomic mass or weight. We call this *atomic mass units*, or *amu.*

PERIODIC CHART OF THE ELEMENTS

1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A		
								1 **H** 1.008_0									2 **He** 4.00260	2
3 **Li** 6.94_1	4 **Be** 9.01218											5 **B** 10.81	6 **C** 12.011	7 **N** 14.0067	8 **O** 15.999_4	9 **F** 18.9984	10 **Ne** 20.17_9	2 8
11 **Na** 22.9898	12 **Mg** 24.305											13 **Al** 26.9815	14 **Si** 28.08_6	15 **P** 30.9738	16 **S** 32.06	17 **Cl** 35.453	18 **Ar** 39.94_8	2 8 8
19 **K** 39.10_2	20 **Ca** 40.08	21 **Sc** 44.9559	22 **Ti** 47.9_0	23 **V** 50.941_4	24 **Cr** 51.996	25 **Mn** 54.9380	26 **Fe** 55.84_7	27 **Co** 58.9332	28 **Ni** 58.7_1	29 **Cu** 63.54_6	30 **Zn** 65.3_7	31 **Ga** 69.72	32 **Ge** 72.5_9	33 **As** 74.9216	34 **Se** 78.9_6	35 **Br** 79.904	36 **Kr** 83.80	2 8 18 8
37 **Rb** 85.467_8	38 **Sr** 87.62	39 **Y** 88.9059	40 **Zr** 91.22	41 **Nb** 92.9064	42 **Mo** 95.9_4	43 **Tc** 98.9062	44 **Ru** 101.0_7	45 **Rh** 102.9055	46 **Pd** 106.4	47 **Ag** 107.868	48 **Cd** 112.40	49 **In** 114.82	50 **Sn** 118.6_9	51 **Sb** 121.7_5	52 **Te** 127.6_0	53 **I** 126.9045	54 **Xe** 131.30	2 8 18 18 8
55 **Cs** 132.9055	56 **Ba** 137.3_4	57- 71 see La series	72 **Hf** 178.4_9	73 **Ta** 180.947_9	74 **W** 183.8_5	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2_2	78 **Pt** 195.0_9	79 **Au** 196.9665	80 **Hg** 200.5_9	81 **Tl** 204.3_7	82 **Pb** 207.2	83 **Bi** 208.9806	84 **Po**	85 **At**	86 **Rn**	2 8 18 32 18 8
87 **Fr**	88 **Ra** 226.0254	89- 103 see Ac series																

La Series	57 **La** 138.905_5	58 **Ce** 140.12	59 **Pr** 140.9077	60 **Nd** 144.2_4	61 **Pm**	62 **Sm** 150.4	63 **Eu** 151.96	64 **Gd** 157.2_5	65 **Tb** 158.9254	66 **Dy** 162.5_0	67 **Ho** 164.9303	68 **Er** 167.2_6	69 **Tm** 168.9342	70 **Yb** 173.0_4	71 **Lu** 174.97	2 8 18 32 9 2
Ac Series	89 **Ac**	90 **Th** 232.0381	91 **Pa** 231.0359	92 **U** 238.029	93 **Np** 237.0482	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**	

molecules

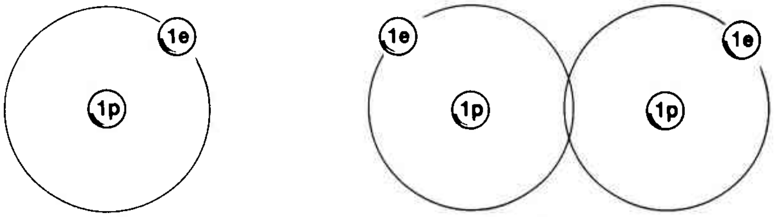
Molecules simply consist of one or more atoms joined together, with definite chemical and physical characteristics.

molecular weight

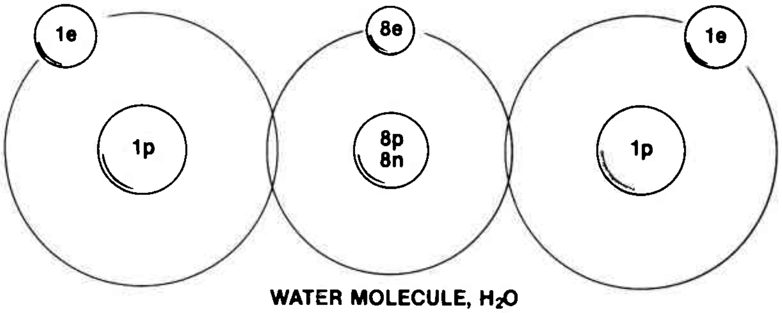
Molecules are likewise classified by their *molecular weight* (or mass). This is simply the sum total of the individual atomic weights that make up the molecule.

Some of the elements usually exist as gases. Some of these, like hydrogen, nitrogen and oxygen, travel as molecules with two or three atoms bound together.

Some gases are composed of more than one element, such as water.



HYDROGEN ATOM, H **HYDROGEN MOLECULE, H_2**



WATER MOLECULE, H_2O

HYDROGEN ATOM, HYDROGEN MOLECULE, AND WATER MOLECULE

For instance, the atomic weight of hydrogen (H) is 1 amu. Its molecule is made up of two hydrogen atoms (H_2) so its molecular weight or mass is 2 amu.

The atomic weight of oxygen is 16 amu. Thus, the molecular weight of water (H_2O) is 18 amu. That is the mass of two hydrogen atoms plus the mass of one oxygen atom (1 + 1 + 16).

ion

Under certain conditions, an atom or a molecule can become electrically charged. It is then referred to as an *"ion."* This process will be considered in more detail in the discussion on "Ionization."

Gas Laws

Let's look at what happens to gases as we use them in our vacuum system. We first assume that gases are perfect—and in general, they are. So we can apply some "laws" to their behavior. Let's look at some of these laws.

Avogadro's Law

mole

Under the same conditions of pressure and temperature, equal volumes of all gases have the same number of particles (molecules, actually). We call this a *mole*.

One mole of any gas has 6.023 × 10^{23} particles, under standard conditions (760 torr, 273°K), occupies 22.4 liters, and weighs one molecular weight.

Avogadro's Law

We know this as *Avogadro's Law*.

1. How many particles would be in a standard liter?

$$\frac{6.023 \times 10^{23}\text{ particles}}{22.4\ \ell} = 2.69 \times 10^{22}\text{ particles}/\ell$$

standard cubic centimeter

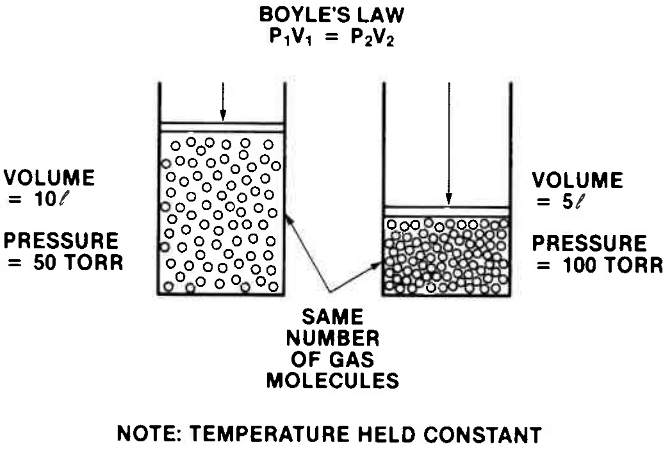
2. How many in a standard cubic centimeter?

$$\frac{6.023 \times 10^{23}\text{ particles}}{22.4\ \ell} \times \frac{10^{-3}\ \ell}{1\text{ cc}} = 2.69 \times 10^{19}\text{ particles/cc}$$

Boyle's Law

Boyle's Law

Boyle's Law, $P_1V_1 = P_2V_2$, or original pressure times original volume equals new pressure times new volume. Reduce the volume by half, the pressure is doubled. This equation predicts new pressure or new volume whenever the other is changed by any amount, providing that the temperature remains the same.



Gas Expansion

Gas expands tremendously under vacuum (from Boyle's Law). This happens to gas absorbed in fingerprints and dirt in general. Water and solvents are also sources of large gas loads. The large volumes these materials produce are a major part of "outgassing."

Suppose you have a chamber which has a volume of 100 ℓ at a pressure of 1×10^{-4} torr. If 1 std cc of gas is suddenly added, what will be the pressure?

Let's use Boyle's Law, $P_1V_1 = P_2V_2$.

Note that we are really calculating a new pressure, not a new volume. Also, the partial pressure of the gas we are adding will add to the gas pressure already there.

$$P_1V_1 = P_2V_2$$

For the gas we are adding to the chamber:

$$760 \text{ torr} \times 1 \text{ cc} = P_2 \times 100 \,\ell$$

Solving for P_2 and converting cubic centimeters to liters:

$$P_2 = \frac{760 \text{ torr} \times 1 \text{ cc}}{100 \,\ell} \times \frac{10^{-3} \,\ell}{1 \text{ cc}}$$

$$P_2 = 7.6 \times 10^{-3} \text{ torr}$$

Now the total pressure in the container is the sum of the pressure there (1×10^{-4} torr) plus the pressure from the gas we added (7.6×10^{-3} torr).

$$P_{Total} = P_{Chamber} + P_2$$

$$= 1 \times 10^{-4} \text{ torr} + 7.6 \times 10^{-3} \text{ torr}$$

$$= 7.7 \times 10^{-3} \text{ torr}$$

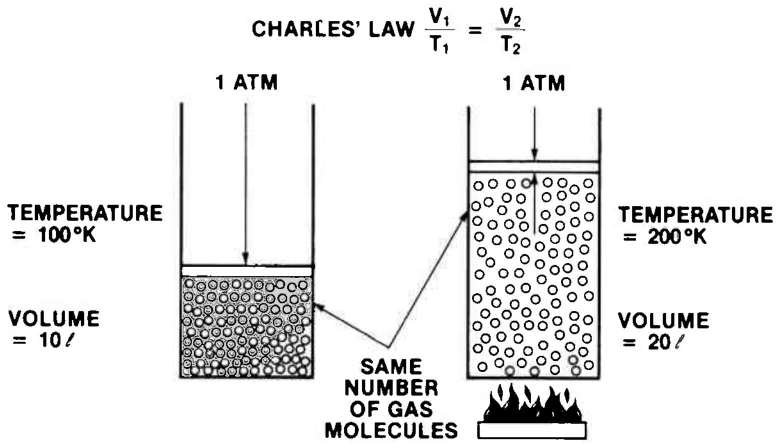
We see that the 1 cc of gas at atmospheric pressure contributed much more to the pressure in the chamber than the gas already there!

Charles' Law

Charles' Law

Let's look at what happens to the volume of gas as we change the temperature. As we cool a gas, its volume gets smaller. If we heat the gas, its volume increases. We call this *Charles' Law*. The equation looks like this:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$



AMOUNT OF GAS DOES NOT CHANGE
NOTE: PRESSURE HELD CONSTANT

Charles' Law states that if the absolute temperature is doubled, the volume of gas is doubled providing that the pressure is unchanged.

Law of Gay-Lussac

If Charles' Law is examined carefully, a more specific relationship develops.

Gay-Lussac's Law

If the temperature of a volume of gas at 0°C is changed by 1°C, the volume will change (plus or minus) by 1/273 of its original value. This is *Gay-Lussac's Law*. Thus:

$$V = V_0 + \left(\frac{°C}{273}\right) \times V_0$$

Rearranging this equation gives us:

$$V = V_0 \left(1 + \frac{°C}{273}\right)$$

Lord Kelvin used this relationship to develop the absolute temperature scale.

General Gas Law

general gas law

We can combine these laws to get a *general gas law* (Boyle's and Charles' combined):

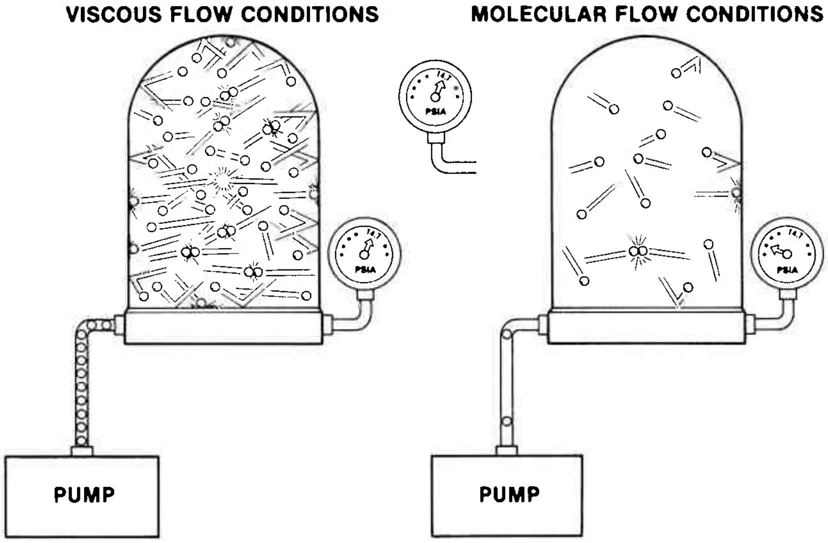
$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

The general gas law combines pressure, volume, and temperature in a single equation.

Note: The temperature in Charles' Law and the general gas law is expressed in the absolute scale, or degrees Kelvin; to convert from °C to °K, add 273° to °C; thus, 100°C + 273° = 373°K.

Gas Flow

Since we want to move gas molecules out of the vacuum chamber, we should know how gas flows. Of the many types of gas flow, we will discuss two kinds: viscous flow and molecular flow. Both types of flow have to do with how tightly molecules fill a space.



GASEOUS FLOW CONDITIONS

Viscous Flow

viscous flow

Generally, gas molecules occupying a space at a pressure greater than 1 × 10^{-2} torr act very much like a fluid, so this is called *viscous flow*. In the viscous flow range, the molecules are constantly bumping into each other. The molecules are so closely packed together that as our vacuum pump moves some of them out of the chamber, others will rush to fill up that empty space.

In viscous flow conditions, molecular movement is predictable. When a molecule is hit or hits a surface, we can predict its movement after impact with reasonable accuracy.

Because the molecules are tightly packed and move predictably, we can use smaller diameter hoses and tubulations for rough pumping operations.

Viscous flow conditions will generally allow us to move great quantities of molecules per unit time from one place to another.

Molecular Flow

molecular flow

Molecular flow occurs when the molecules are so far apart that they no longer have any influence on each other. Their motion is strictly random. This occurs at low pressures where fewer molecules are present.

Depending on the pressure, a gas molecule might travel inches, feet, or even miles before it strikes another molecule. This means we can't depend on molecular interaction to push or start a flow pattern.

In the molecular flow range, molecular movement is unpredictable. This is why we have such large inlets in high vacuum pumps.

The use of large inlets increases the probability that one of these randomly moving molecules will move into the pump.

In molecular flow, the molecular motion is explained by kinetic theory, which uses statistics (chance) to describe the condition.

The difference between viscous flow and molecular flow does not depend upon the pressure alone. It also depends upon the dimensions of the vacuum container (pipes, chamber, etc.). Basically, it depends upon the mean free path and whether it is longer or shorter than the container dimensions. Let's take a look at what is meant by "mean free path."

Mean Free Path

mean free path

As we lower the pressure in the vacuum chamber, the amount of space between the gas particles increases. The particles bump into each other less frequently. The average distance a particle moves before it bumps another particle is the *mean free path.*

MOLECULAR DENSITY AND MEAN FREE PATH

	7.6 × 10^2 Torr (atm)	**1 × 10^{-3} Torr**	**1 × 10^{-9} Torr**
# mol/cm^3	3 × 10^{19} (30 million trillion)	4 × 10^{13} (40 trillion)	4 × 10^7 (40 million)
MFP	2 × 10^{-6} in.	2 in.	30 mi

At atmosphere, the mean free path is extremely short, about two millionths of an inch. Under vacuum, fewer molecules remain, and the mean free path is longer. Its length depends on the number of molecules present, and therefore on the pressure. The mean free path for air can be estimated from the relationship:

$$\text{Mean Free Path} = \frac{5 \times 10^{-3}\ \text{torr cm}}{P_{\text{torr}}}$$

From this, we can see that as the pressure gets lower, the mean free path gets longer. Likewise, as the pressure gets lower, there are fewer molecules of gas present, so there is less chance of them running into each other.

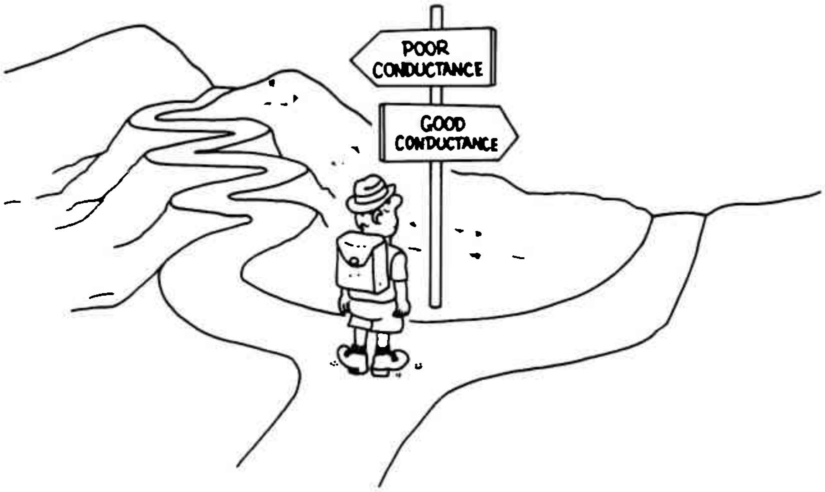
gas density
(molecular density)

In 1 cc of gas at standard conditions (760 torr at 0°C), there are about 3×10^{19} gas molecules and the mean free path is about 2×10^{-6} cm (a few millionths of an inch). At 1×10^{-9} torr, there are about 4×10^{7} molecules/cc, and the mean free path is about 30 miles or 50 kilometers. The number of molecules per unit volume (in this example cubic centimeters) is called the *gas density.*

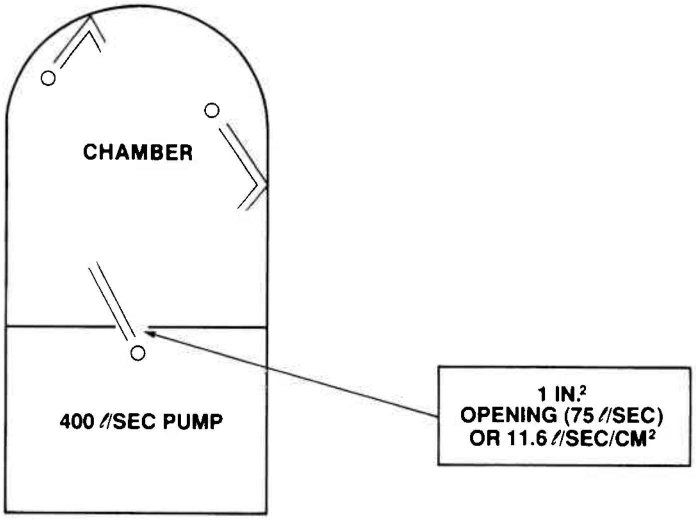
Conductance

conductance

When we talk about moving a gas through a vacuum system, we use the term conductance. *Conductance* is the ability of an opening or pipe to allow a given volume of gas to pass through in a given time. It is expressed in such units as liters per second, cubic feet per minute or cubic meters per hour.



In molecular flow, a good conductance path is wide and short. It has few turns, thus allowing free gas flow. In viscous flow, these conditions are not so important. This is because the molecules tend to push one another along under the influence of a pressure difference.



MOLECULAR FLOW

In the molecular flow range, a 1 in.^{2} opening has a 75 ℓ/sec conductance. The pump speed, in this case 400 ℓ/sec, is really 75 ℓ/sec as far as the chamber is concerned because the molecules must go through the hole before they can be pumped. To improve system performance, the conductance must first be improved. (Make the hole bigger!) To repeat: In the molecular flow range, a pump works only when molecules migrate into the pump by chance.

Conductance in Viscous Flow

The volume of gas that can flow per unit of time through a pipe under viscous flow conditions is related to the *fourth* power of the pipe diameter and is inversely related to the length of the pipe.

For example, if you use a pipe with a diameter twice that of the pipe presently being used, it will allow 2^4 or sixteen times as much gas to flow through it, assuming that the length of the pipe is the same.

Now let's compare this to molecular flow conditions.

Conductance in Molecular Flow

The volume of gas that can flow per unit of time through a pipe under molecular flow conditions is related to the cube of the diameter and inversely to the length of the pipe.

Using the same pipe as in the viscous flow example, doubling the diameter of the pipe will, at most, allow 2^3 or eight times the flow for the same length of pipe.

In either case of viscous flow or molecular flow, making the pipe shorter will increase the flow of gas through the pipe. Please note that these are gross statements that are subject to all kinds of qualifications.

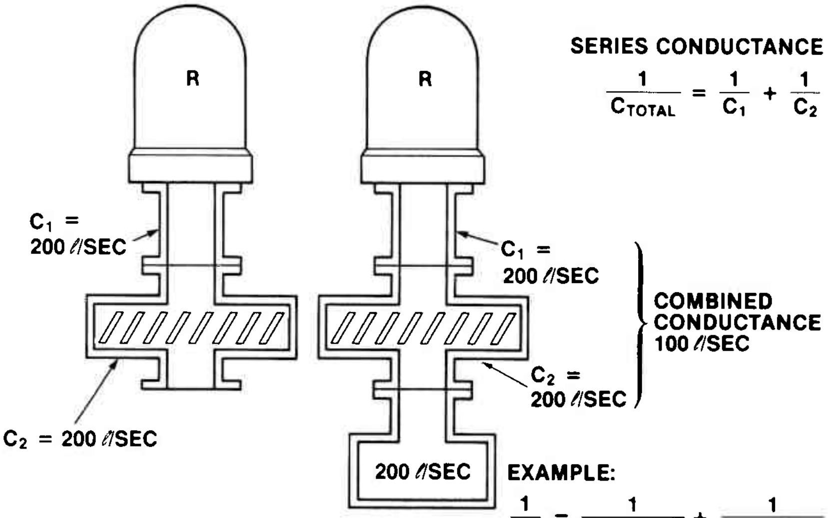
transition range

There is another region where we approach molecular flow, but the flow is not really viscous either. This region is called the *transition range*. There is another set of calculations to be used for the transition range, but we will not discuss them in this text.

Please see the appendix if you need further details on how to calculate conductances.

Series Conductance

When you place components in series in a vacuum system, the total conductance is less than the smallest of the conductances in series.



SERIES CONDUCTANCE

$$\frac{1}{C_{TOTAL}} = \frac{1}{C_1} + \frac{1}{C_2}$$

EXAMPLE:

$$\frac{1}{C_T} = \frac{1}{200\ \ell/SEC} + \frac{1}{200\ \ell/SEC}$$

$$C_T = 100\ \ell/SEC$$

Let's look at the result (point "R" at the vacuum chamber) of adding a pump (shown in the drawing) with a speed (S) of 200 ℓ/sec to the combined 100 ℓ/sec series conductance.

The pump can be represented by another conductance of 200 ℓ/sec in the line. In this case, we call the total conductance, R, the combined pipe conductance, C, and the conductance of the pump, S. So:

$$\frac{1}{R} = \frac{1}{C} + \frac{1}{S}$$

If we play with this a bit, we get:

$$R = \frac{CS}{C + S}$$

Thus:

$$R = \frac{\frac{100\ \ell}{sec} \times \frac{200\ \ell}{sec}}{(100 + 200)\ \ell/sec}$$

$$= 66.6\ \ell/sec$$

Thus our 200 ℓ/sec pump is effectively delivering only one-third of its speed to pump the work chamber.

What would be the effect of changing to a 2,000 ℓ/sec pump?

Going through a similar calculation:

$$R = \frac{\frac{100\,\ell}{\text{sec}} \times \frac{2{,}000\,\ell}{\text{sec}}}{(100 + 2{,}000)\ \ell/\text{sec}}$$

$$= 95\ \ell/\text{sec}$$

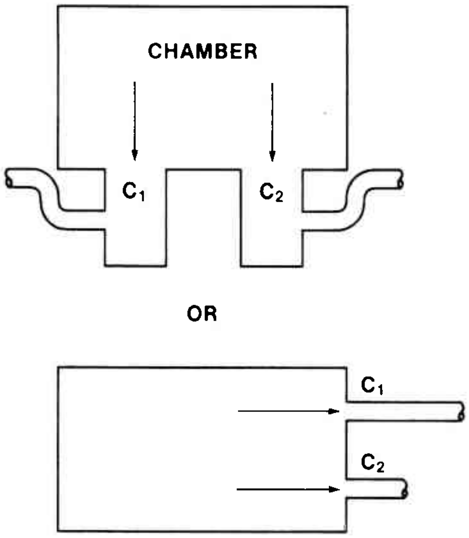
An amazing improvement of 29 ℓ/sec! (But only about 5% of its speed is being used!)

conductance-limited

"The pump is no better than the pipe!!" Remember that we cannot pump the gas until it reaches the pump. We are *conductance-limited* here.

Parallel Conductance

PARALLEL CONDUCTANCE



In parallel conductance,

$$C_{\text{total}} = C_1 + C_2$$

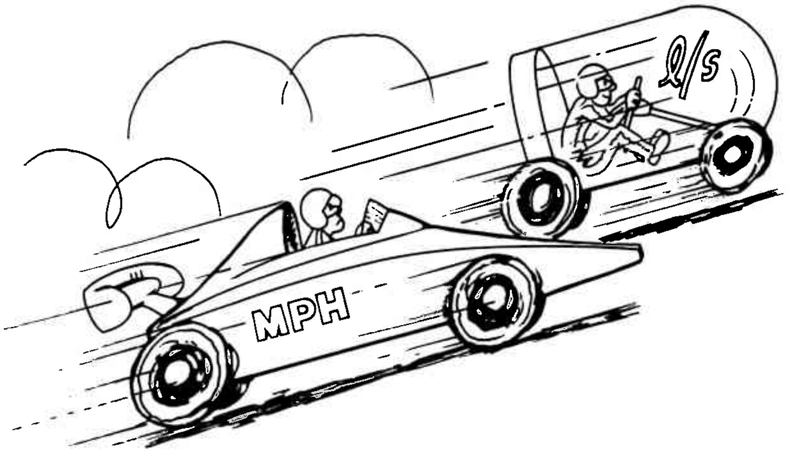
We simply add parallel conductances to get the total.

Let's go on, now, to see what kind of work our vacuum system does.

Measuring Work Performed by Vacuum Systems

pumping speed

We have many different ways to measure things. We may measure the performance of our car by how fast it will go, for instance. We measure how fast a vacuum pump is by stating its *pumping speed.* (More explicitly, by its volumetric pumping capacity.)



Pumping speed is rated in liters per second, or cubic feet per minute. Pumping speed alone does not tell us what we want to know about vacuum system work. We are really interested in getting the molecules out—not in pumping an "empty volume." Our liters per second or cubic feet per minute tells us nothing about how many molecules are being removed from our vacuum chamber.

throughput

Air is easily removed from a chamber at high pressures. After a short while, not much gas is left, so pumping speed doesn't tell us what we want to know about vacuum system work per unit time. We need a new term: *throughput,* which is vacuum pumping capacity. The throughput tells us how many molecules we are pumping. Let's look at this in more detail.

Quantity of Gas

gas load

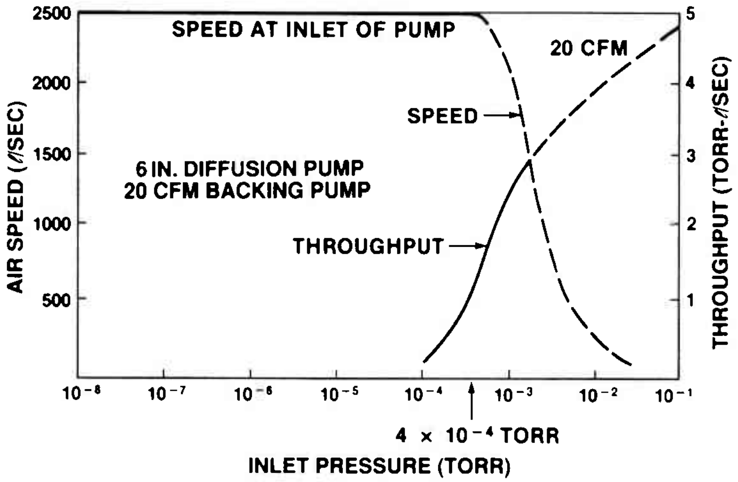
The amount of gas present in a system is determined by multiplying the pressure (torr) times the volume (liters). This tells us the actual number of gas molecules contained in a particular enclosure. We also call this the *gas load.* The usual units are torr-liters or pascal-liters.

In vacuum, we are interested in how much work a pump has to do to transfer a mass of gas from one place to another. Pressure times the volume (PV) is a measure of this work. A point of even more interest is the time it takes to do this work, or (PV/t), which is the capacity of a pump. This is called the *throughput.* Typical units for throughput are torr-liters per second.

Throughput
Q = PS

Throughput is called Q. So throughput (or Q) equals pump speed times pressure per unit time, or quantity of gas flow. This more realistically helps define pumping work. (The lower the pressure, the less gas remains.) Speed in liters per second, times pressure, in torr, gives us Q in *torr-liters per second.*

Since pumping speed (S) is volume per unit time (V/t), then Q = PV/t. Torr-liters per second are the common units. You could also use pascal-liters per second or atm ft^3/minute if you so desired. Let's look at a typical use for the pumping speed and throughput.



DIFFUSION PUMP SPEED AND THROUGHPUT CURVES

Q = pressure times pump speed per unit time. At a pressure of 4×10^{-4} torr and a rated pumping speed of 2,500 ℓ/sec, we find

$$Q = 2.5 \times 10^{3} \frac{\ell}{\text{sec}} \times 4 \times 10^{-4} \text{ torr}$$

$$= 1 \text{ torr-}\ell/\text{sec}$$

Pick out additional points on the horizontal axis of the chart to see how Q is affected as the pumpdown continues. Note that the throughput will continue to decrease as the pressure decreases. This is true even though the pump speed is constant. The throughput is telling us that it is getting harder to remove molecules because there are fewer of them per unit volume.

How Q = PS Is Used

If the Q in a system is 1 torr-ℓ/sec and we had a 1,000 ℓ/sec pump, what pressure could be reached?

$$Q = PS$$

$$\frac{1 \text{ torr-}\ell}{\text{sec}} = P \times \frac{1{,}000\ \ell}{\text{sec}}$$

Now, let's solve for P:

$$P = \frac{1 \text{ torr-}\ell}{\text{sec}} \times \frac{\text{sec}}{1{,}000\ \ell}$$

$$= 10^{-3} \text{ torr}$$

or

If you wanted a pressure of 1×10^{-8} torr, what pumping speed is needed (assuming the same Q as above, 1 torr-ℓ/sec)?

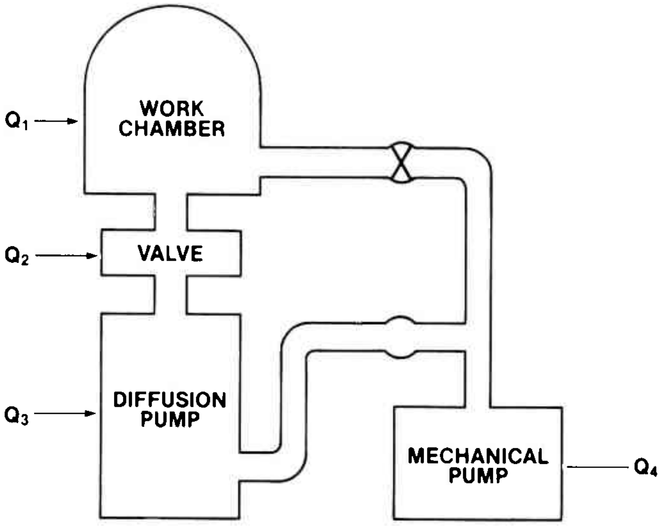
$$\frac{1 \text{ torr-}\ell}{\text{sec}} = 1 \times 10^{-8} \text{ torr} \times S$$

Solving for S:

$$S = \frac{1 \text{ torr-}\ell/\text{sec}}{1 \times 10^{-8} \text{ torr}}$$

$$= 1 \times 10^{8}\ \ell/\text{sec}$$

That's ridiculous! 100 million ℓ/sec (1×10^8 ℓ/sec)! Nobody makes a pump that big– so what do you do?? We will have to change something– most likely our expectations!



$Q_1 = Q_2 = Q_3 = Q_4$

In steady-state or equilibrium conditions, throughput is the same at one end of a vacuum system as it is at the other. Speeds and pressures may vary from point to point, but they combine to give the same throughput through all of the system. (This is important when selecting pumps to work together– more on this point later.)

Gas Load

Another name for Q, the throughput, is gas load. Where does the gas load, "Q," come from? It comes from several places: leaks, outgassing, and contamination are all contributing to the gas load.

In the preceding problem, if we could fix the leaks, heat the surfaces, use the right materials, and clean up the system, the gas load, Q, could probably be reduced to about 1×10^{-5} torr-ℓ/sec. Let's calculate the needed pump speed for this (remember, we want to pump to 1×10^{-8} torr):

$$\frac{1 \times 10^{-5}\ \text{torr-}\ell}{\text{sec}} = 1 \times 10^{-8}\ \text{torr} \times S$$

Solving for S:

$$S = \frac{1 \times 10^{-5}\ \text{torr-}\ell/\text{sec}}{1 \times 10^{-8}\ \text{torr}}$$

$$= 1 \times 10^{3}\ \ell/\text{sec}$$

That's more like it! This is a much more realistic value for the pump speed.

"Q" and Power

As mentioned before, Q is work per unit time or power. As such, it can be expressed in watts. If you want more throughput (power), you need more electricity (power). That is, you need higher power heaters and motors. The conversion is

$$7.50\ \text{torr-}\ell/\text{sec} = 1\ \text{watt} = 1{,}000\ \text{Pa}\ \ell/\text{sec}$$

For example, a 1000 ℓ/sec pump operating at 5×10^{-5} torr is 0.05 torr-ℓ/sec or much less than one watt of power.

Summary

Vacuum is an environmental condition produced in a suitable container. It is produced by reducing the number of gas particles per unit volume to below that which exists on the outside. The removal of gas particles is done by means of devices known as vacuum pumps. The number and temperature of the gas molecules in the container are responsible for the force exerted on the walls of the container. The force per unit area is called the pressure. The standard atmospheric pressure is 14.69 pounds per square inch absolute. This standard pressure is what air molecules would exert on the surface of the earth at 45° N latitude on a clear day at sea level.

The word *vacuum* comes from the Latin "vacua," which means "empty." Actually, the container is only partially empty, and varying degrees of emptiness are required for various types of work. Complete emptiness is not attainable. In other words, there is no such thing as a "perfect vacuum."