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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?

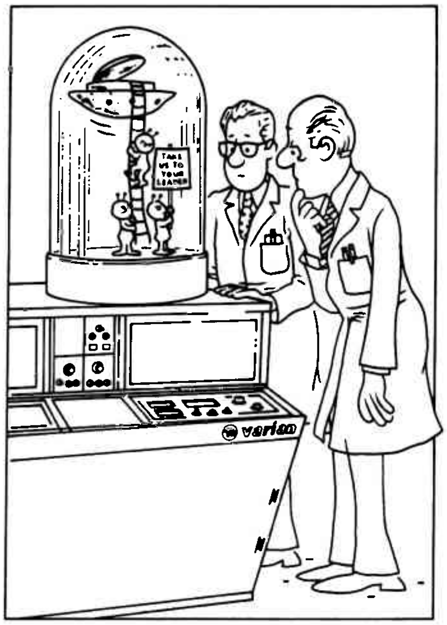
vacuum

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?

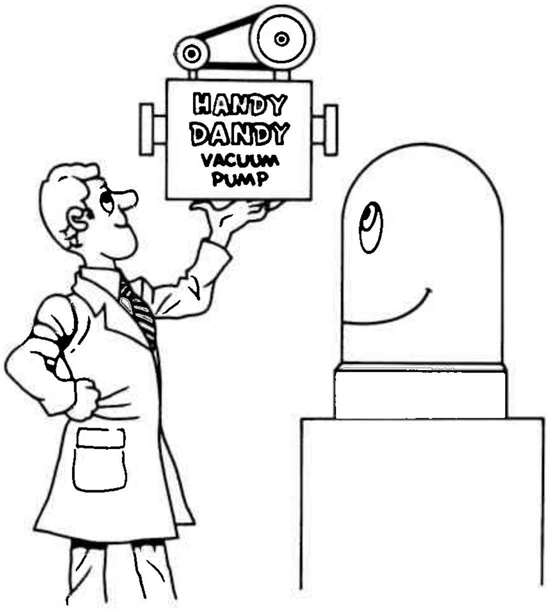
pressure

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.

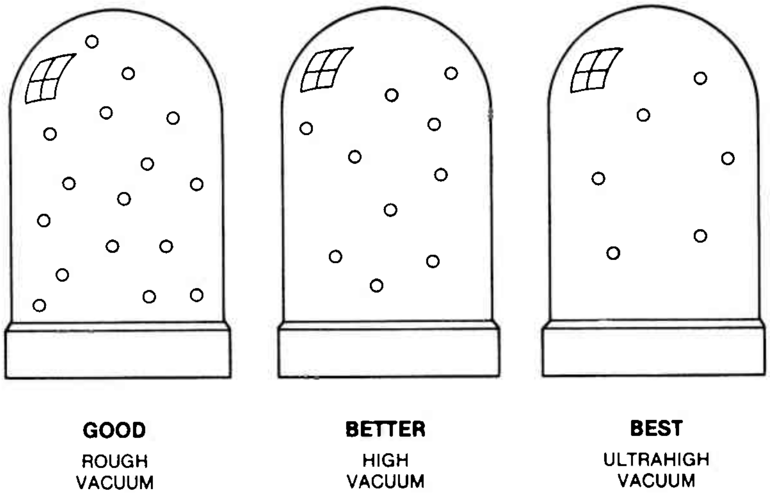


vacuum pumps

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?

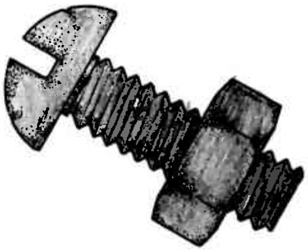
Vacuum is used for many products and processes. Some of them are:

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)	

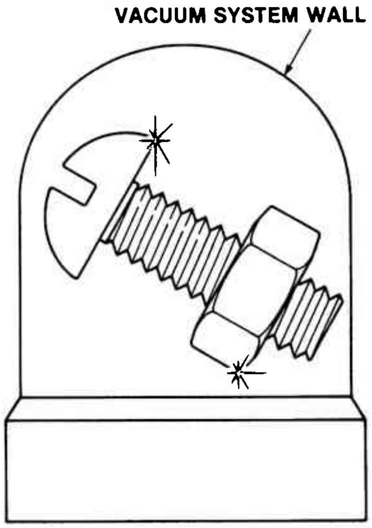
Why Is Vacuum Needed?

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

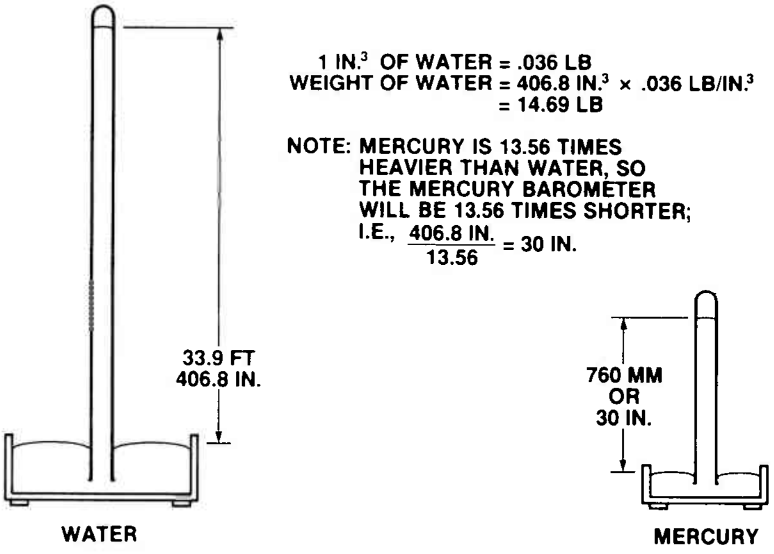
The average atmospheric pressure at sea level (45° N latitude) is 14.7 psia, 760 torr, or 101,325 Pa. Vacuum processes are usually done at pressures much lower than atmospheric pressure. Atmospheric pressure changes with distance above sea level (altitude) and changes in our weather.

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.

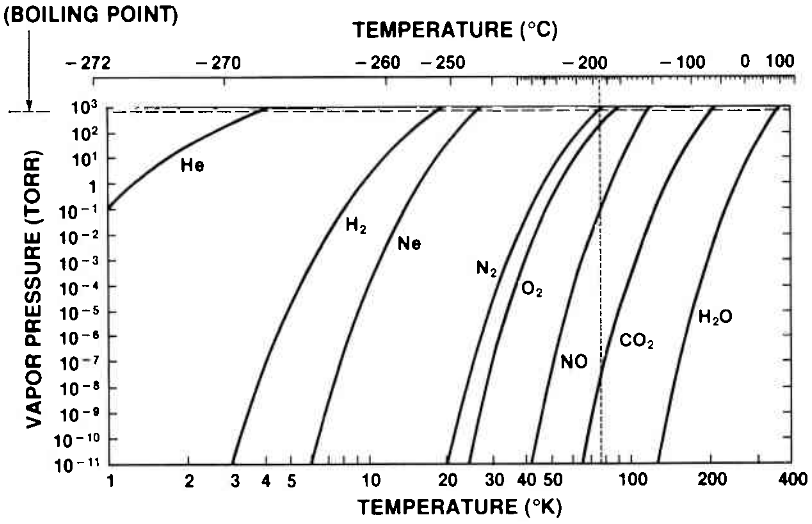
VAPOR PRESSURE OF WATER AT VARIOUS TEMPERATURES

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}

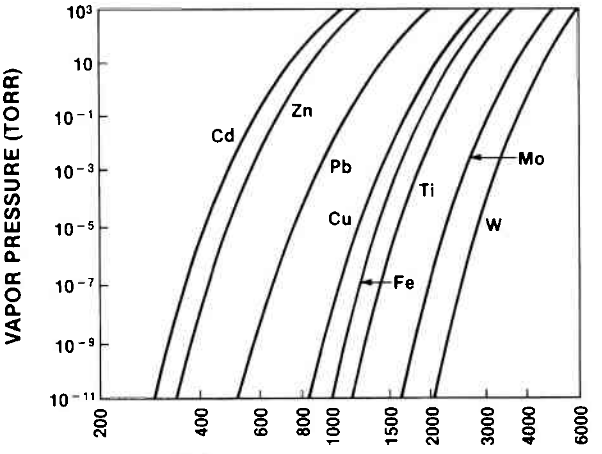
Acetone has the highest vapor pressure of the liquids on this list. It evaporates the fastest of those substances on the list. It releases the most gas into the chamber in a given length of time. High vacuum pump oil is the least volatile liquid on the list. It will take the longest time to evaporate.



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.



ABSOLUTE TEMPERATURE (°K)

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.