

INTRODUCTION

The goal in designing or working with a vacuum system is to remove enough gas molecules from the space enclosed by the vacuum chamber to create the desired low pressure. Gas molecules may be removed from the system through a mechanical or a diffusion pump, or they may only be removed from free flight by capture and retention on surfaces. The purpose of this experiment is to familiarize the student with components and procedures used to produce a pressure in the range of 10^{-7} Torr.

One Torr is the pressure exerted by a column of mercury one millimeter high. Another common unit of pressure is the micron, abbreviated μ , which is 10^{-3} Torr. One standard atmosphere is a pressure of 760 Torr. Any pressure significantly lower than this is called a vacuum. Degrees of vacuum may be roughly classified as:

rough	760 - 1 Torr
medium	1 - 10^{-4}
high	10^{-4} - 10^{-6}
very high	10^{-6} - 10^{-9}
ultrahigh	$<10^{-9}$.

The degree of vacuum desired, and the temperatures which the components are expected to withstand, essentially determine the types of components chosen for use in a system.

The gases which must be pumped out of a system arise from various sources. The obvious one is the gas originally in the system at atmospheric pressure.

The composition of this gas may change as pressure is reduced, since some gases pump faster than others. A second obvious source is gas entering the system through leaks, usually at seals. The leak rate is expressed in Torr-liters/sec or in $l\mu$ sec (liter-micron/sec = $l\mu$ /sec). A third source is gas desorbing or "outgassing" from walls, expressed in Torr- l/cm^2 sec. A fourth major source is vapor from backstreamed pump oil or from system components. This source is determined by the type of pump oil used, the amount of backstreaming and materials used in the components. Permeation, or diffusion through walls, can be a fifth source.

Leaks, outgassing vapors, and pumping speed usually determine the pressure which exists in a given system, except for one with a mechanical pump only, where the ultimate pressure may be limited by the pump's compression ratio.

Important Basic Terminology and Definitions

There are three classes of gas flow, depending upon the pressure and the system size. At high pressure gradients, the flow is turbulent and flow lines twist in time and space. At lower pressures, flow lines are straight and parallel to the pressure gradient. This is called laminar flow. At still lower pressures, the mean free path (λ) of collisions between molecules becomes longer than the system's dimensions, and molecules collide with system walls more often than with each other. This is called "free molecule" or Knudsen flow. If the Reynolds Number = $Re = \frac{\rho v d}{\mu} \geq 2100$, flow is turbulent (ρ = mass density, v = velocity, d = characteristic system dimension, μ = viscosity); if $\lambda/d \leq 0.01$, flow is laminar; and if $\lambda/d \geq 1.00$ flow is molecular. In between the main regimes are transitional types of flow. In vacuum work one need only concern oneself with laminar flow, molecular flow, and the transition between.

Sometimes it is necessary to know v , the number of molecules incident on the unit area per second. From the kinetic theory for an ideal gas, $v = 1/4 n \bar{V}_a$, where n is the particle density and \bar{V}_a is the arithmetic average of molecular velocities $= (8kT/\pi M)^{1/2}$, where M = molecular weight. Thus, $v = (2kT/\pi M)^{1/2} n/2 = P(2\pi kTM)^{-1/2}$.

The flow rate or throughput of a system is defined as

$$Q \equiv - \frac{d(pV)}{dt} = - \frac{d(NkT)}{dt} \text{ with } Q \text{ in Torr-l/sec.}$$

The reason for the negative sign will be apparent later. Usually T is constant so that $Q = -kT \dot{N}$, which says that flow is proportional to the number of molecules/sec crossing a given plane.

At the throat of a pump the pumping speed may be calculated if the pressure is changing slowly enough to be considered constant. Then $Q = \dot{p}V$ is the volume of gas removed per second. In a closed system the volume (V) may be considered constant if the gas load from incoming gas, desorbed gas, and vapors is negligible compared to the gas present in the chamber. Then $Q = \dot{p}V$.

At the plane of a pump inlet, $-\dot{V} \equiv S \equiv$ pump speed, in liters/sec. Therefore $S = \frac{Q}{P_{\text{inlet}}}$. A real pump may act as a source of gas to the vacuum system. The pump may be characterized by a rated max. speed (S_f) and a given leak rate (Q_f). Let the pressure at the pump inlet be represented by P_i . Then the actual amount of gas removed is $Q = S_f P_i - Q_f = S_f P_i (1 - \frac{Q_f}{S_f P_i})$. When $Q = 0$, the ultimate pressure (P_u) of the pump has been reached. Thus $Q_f = S_f P_u$, and the actual pumping speed of the real pump is $S = \frac{Q}{P_i} = S_f (1 - \frac{P_u}{P_i})$.

The effective pumping speed at any other plane of the system is determined by both the actual pumping speed at the pump and the conductance between the pump inlet and the plane at which pressure is measured. Conductance between two points of a system is defined as

$$C \equiv \frac{Q}{P_1 - P_2}, \text{ in liters/sec,}$$

where P_1 and P_2 are pressures measured at the two points. Impedance is defined as

$$Z = \frac{1}{C} = \frac{P_1 - P_2}{Q}, \text{ in sec/liter.}$$

For flow through n parallel components, the conductance and impedance are given by:

$$C_p = \sum_{i=1}^n C_i \text{ and } \frac{1}{Z_p} = \sum_{i=1}^n \frac{1}{Z_i}.$$

For flow through a series of n components, the conductance and impedance are given by

$$\frac{1}{C_s} = \sum_{i=1}^n \frac{1}{C_i} \text{ and } Z_s = \sum_{i=1}^n Z_i$$

just as in electrical circuits. Formulas for calculating theoretical conductances for various simple geometries for laminar, molecular and transitioned flow may be found in the references.⁷

For a pump with real inlet pumping speed $S = \frac{Q}{P_i}$, connected to a chamber at pressure P by components of total conductance C , Q must be constant throughout. Thus, $Q = S_{\text{eff}} P$, $P - P_i = \frac{Q}{C} = \frac{Q}{S_{\text{eff}}} - \frac{Q}{S}$. Therefore, $S_{\text{eff}} = \frac{CS}{S+C}$. Note that if a pump is very fast ($S \gg C$), then $S_{\text{eff}} = C$, and the effective pumping speed is limited by the size of connecting components.

As estimate of the effective pumping speed at any point in a system may be measured using a stopwatch or other timer and a pressure gage, if the volume of the system is known. Since $S_{\text{eff}} = Q/P = -\dot{V}/P$, $S_{\text{eff}}/V = -\dot{P}/P$. Integrating gives:

$$\int_t^{t+\Delta t} \frac{S_{\text{eff}}}{V} dt = - \int_P^{P+\Delta P} \frac{dp}{p}, \text{ or}$$

$$\frac{S_{\text{eff}}}{V} \Delta t = - \ln \frac{p+\Delta p}{p} = \ln \frac{p}{p+\Delta p},$$

so that $S_{\text{eff}} = 2.3 \frac{V}{\Delta t} \log_{10} \frac{p}{p+\Delta p}.$

Adsorption, Absorption, Outgassing, and Baking

A phenomenon which is significant for high vacuum systems is adsorption (and desorption) of gas and vapor molecules on chamber walls. The desorbed gas contributes most of the gas load below 10^{-5} Torr. Adsorption is the process of molecules being attracted to and attached to solid surfaces, resulting in a layer of gas molecules a few molecules thick. Adsorption may be physical or chemical. Physical adsorption is characterized by a weak attraction, with the heat of adsorption being ≤ 8 kcal/molecule. Chemical adsorption is similar to formation of chemical compounds, and the heat of adsorption is typically 10-200 kcal/molecule. Since chemisorption produces very strong bonding, heat must be added to desorb the compound.

The number of molecules adsorbed per unit area of surface per unit time is given by $Sv = Sp(2\pi nkT)^{-1/2}$, where S is the "sticking" coefficient and v is the probability that a molecule striking a surface will be adsorbed, which is a function of molecular coverage and temperature. Barrington¹ calculates a time of 1.8 sec for a monolayer of air to form on a clean surface at 10^{-6} Torr and 15° C.

The desorption rate is given by $N_0 f / t_s$ for less than one monolayer. N_0 is the number of molecules needed for one monolayer, f is the "coverage" or the fraction of adsorption sites occupied, and t_s is the "sojourn time" or the average time spent by a molecule at an adsorption site. The temperature variation is dominated by the exponential form of $t_s = t' \exp(\frac{H_d}{RT})$, where $t' \approx 10^{-13}$ sec, and H_d is the heat of desorption. Thus, at low temperatures, adsorption is high, even for low H_d .

Absorption is the process whereby gas diffuses into a solid and stays there in a dissolved state. For gas dissolved in a solid, the equilibrium concentration is $\epsilon = bp^{1/j}$, where b is the solubility of the gas in the solid, and j is the dissociation constant of the gas ($j = 2$ for diatomic gas in metal and $j = 1$ for all gases in non-metals). Thus, as pressure is reduced, dissolved gases diffuse out and must be pumped away. Time dependent diffusion is described by $D \frac{d^2 \epsilon}{dx^2} = \frac{d\epsilon}{dt}$, where the diffusion constant $D = D_0 \exp(-\frac{H}{jRT})$, or H is the activation energy for absorption and D_0 is a function of the gas and the solid. In equilibrium flow, gas will diffuse through a wall from high pressure to low pressure at a rate equal to the diffusion into the wall on the high pressure side. This process is called permeation. The desorption or outgassing of an actual system may be described as follows. Let K be the rate at which gas appears to emanate from system walls per unit area. As a function of pumping time, K may be described empirically by $K(t) = K_u + K_1 t^{-\gamma}$, where K_1 is K at t equal to one hour, K_u is the limiting value of K , and γ is a function of time. A typical plot of K versus pumping time is shown in figure 1, with and without baking. Note that the scales are logarithmic.

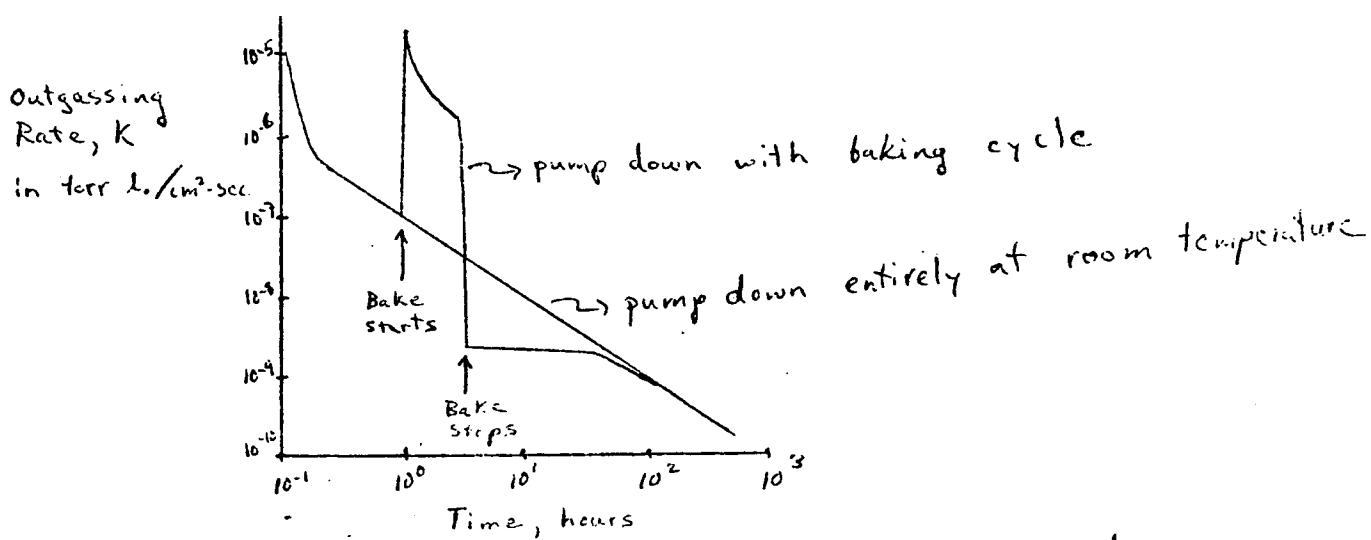


Figure 1. Outgassing Rate vs. Pumping Time, with and without Bake.

The effects of baking are to accelerate the rate of outgassing, so that a lower pressure may be reached more quickly and also to reduce the ultimate pressure which may be attained. In general, the higher the bake temperature, the greater the beneficial effects, if the system is designed to perform satisfactorily at the high temperature. Note that the bake is started after pumping down to some low pressure. It is necessary to pump out physically adsorbed gas before baking a system. Otherwise, the adsorbed gas, especially water vapor, may become chemisorbed, necessitating a prolonged high temperature bake for desorption.

Outgassing rates may also be reduced by ion bombardment or other cleaning methods. Gas evolution rates for typical vacuum materials are in the range 10^{-7} torr-l/sec-cm² for metals, 10^{-6} torr-l/sec cm² for ceramics and 10^{-5} torr-l/sec cm² for elastomers, all for unbaked systems. More specific data can be found in the reference¹⁰.

Pumps

Vacuum pumps may be divided into two general categories: those with moving parts and those without. A pump may be characterized by its pumping speed, its base (lowest possible) inlet pressure and the upper limit on pressure to which it can safely discharge.

Mechanical Pumps

The mechanical pump has two functions: (1) as a roughing pump, to attain a rough vacuum so that a diffusion pump may be started if a still lower pressure is desired and (2) as a fore pump to back a diffusion pump. A mechanical pump can discharge against atmospheric pressure. Minimum inlet pressures attainable are in the 10^{-2} to 10^{-4} torr range and are essentially limited by the compression ratio. The rating is speed at standard temperature and pressure (STP), which is displacement times revolutions per unit time for the rotary type. Speed decreases with pressure at the lower attainable pressures. A double vane rotary type pump is described below. The principle is the same for other rotary types.

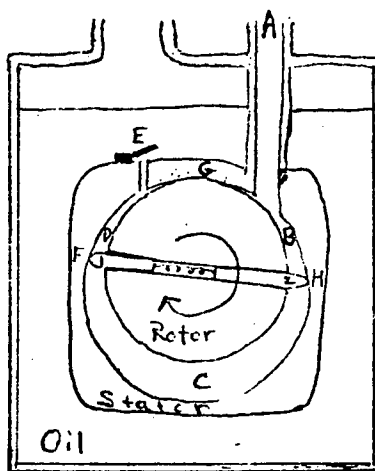


Figure 2. A Double Vane Rotary Pump.

Gas from vacuum chamber A moves into the expanding volume B swept out by one arm of the rotor. Maximum volume (C) is reached and maintained as the second arm moves past the inlet. The volume begins decreasing when the first arm moves past the exhaust part (E). The volume D decreases until pressure in D is greater than atmospheric, which causes discharge valve E to open so that the compressed gas is expelled. After operation

Gas from vacuum chamber A moves into the expanding volume B swept out by one arm of the rotor. Maximum volume (C) is reached and maintained as the second arm moves past the inlet.

The volume begins decreasing

for some time, the pressure in D will be no greater than atmospheric, even with maximum compression. Then the pump can no longer reduce the inlet pressure and base pressure has been reached.

^{Seals}~~Sales~~ at F, G, H between moving and stationary parts are maintained by an oil film. Clearances at these points are obviously very small.

Efficient pump operation depends on smoothness of sealing surfaces and the correct amount of oil flow to lubricate and seal. Surfaces can be damaged by scratches from solid particles in the oil or ~~entering~~ from the vacuum chamber. If oil flow is too great, air dissolved in the oil will raise the base pressure, and if oil flow is too small, air will leak directly into the chamber.

Oil contamination is also a problem, which is reduced by the use of "gas ballast." In the compression stage, pressure may become great enough for vapor in the gas to condense and dissolve in the oil. This vapor will then re-evaporate on the low pressure side, limiting the base pressure. Vapor may also chemically break down the oil so that sludge is formed to interfere with pump operation. "Gas ballast" involves admitting some dry air into the compression chamber so that atmospheric pressure is reached at a lower compression ratio, so that less vapor condenses.

A mechanical pump necessarily vibrates a great deal. A solid connection between the pump and the rest of the system will transfer this vibration to the whole system, creating strains which may cause leaks. A flexible connection, such as rubber or plastic tubing reduces this problem.

Mechanical Booster Pumps

A mechanical booster pump has a low compression ratio ($\sim 10/1$) as compared with a mechanical rotary pump (up to $10^5/1$) The booster pump

is most useful on large systems, in the range of 1 to 500 μ , where mechanical and diffusion pumps are least efficient. It increases pumping speed in this range when used between a mechanical pump and the vacuum chamber or diffusion pump. An important advantage is that no sealing oil is required. A Roots type mechanical booster pump is shown in fig. 3. The impellers rotate at high speed in opposite directions. Very small clearances (~ 1 mm) are maintained between impellers and between impellers and housing.

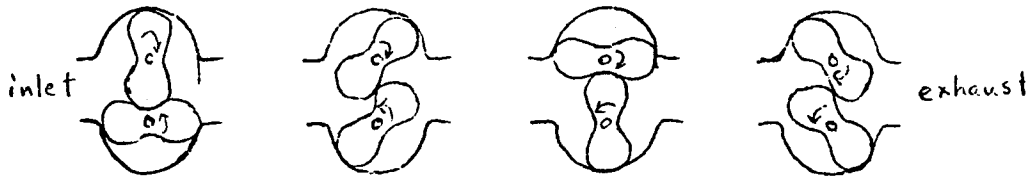


figure 3. Action of the Roots Booster Pump. Other types of mechanical pumps are described in the literature.⁸

To obtain pressures well below 10^{-3} torr the most common pump used is a vapor pump. Instead of gases being compressed and expelled to the atmosphere by a rotating mechanical member, high speed molecules are used to pump the gases from the chamber.

Diffusion or Vapor Pumps

Diffusion pumps have a maximum discharge pressure limit of about 300 μ , and therefore require a fore pump or backing pump. The inlet pressure maximum is about 20 μ when the oil is hot. The ultimate base pressure is in the range 5×10^{-3} to 10^{-9} torr, depending on the type of fluid as well as on the pump system.

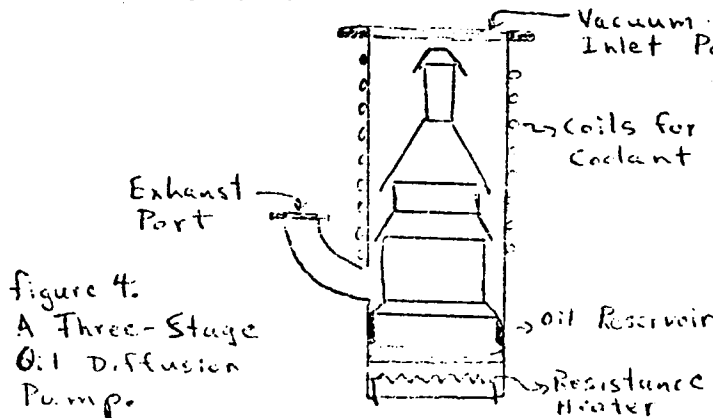


figure 4. A Three-Stage Oil Diffusion Pump.

In an oil diffusion pump (figure 4), oil is heated and evaporates. Vapor streams up the chimney and out of nozzles. Coming out of the nozzles, the vapor

has a downward-directed velocity, which is imparted to gas molecules diffusing into the inlet from the vacuum chamber. Vapor is condensed on the sides of the pump chamber, which are cooled usually by air or water, and it drains back into the oil reservoir to be re-evaporated.

If the fore pressure in the exhaust line is too high, pumping speed will be considerably reduced and "backstreaming" of oil vapor into the vacuum chamber will increase. Backstreaming is "drift of the working fluid [vapor] of a pump upstream toward the vessel being exhausted." If the fore pressure exceeds the critical limit, then pumping action stops completely and the vessel is usually drenched with oil. Most vacuum systems have a safety device which turns off the oil heater when fore pressure is above a certain limit. Fore pumping must be continued as long as the pump is hot, even after the heater is turned off.

Organic oils are subject to chemical decomposition at high temperatures or when exposed to high pressure air when hot. Decomposition increases vapor pressure and backstreaming. Silicone oils have greater resistance to decomposition than organic oils.

Mercury was originally used as the working fluid in diffusion pumps. Since it is an element, it cannot decompose, and thus can tolerate a higher fore pressure. However, it has a relatively high vapor pressure and is highly toxic. It is also adversely affected by oil diffusing back from the mechanical pump.

Baffles

Baffles, usually cooled, are placed in the line of sight (optical) path between the diffusion pump and the vacuum chamber to control backstreaming. Vapor which strikes the baffle is condensed and allowed to

drain back into the reservoir. Baffles are also often placed in the exhaust line to reduce loss of pump fluid. Conductance is reduced by baffling and thus pumping speed may suffer but a lower base pressure is usually made possible. Baffles should be designed so that conductance is reduced as little as possible while reducing backstreaming as much as possible.

Pumping by Ionization and Special Surfaces

Several types of pumps work by trapping the gas molecules within the system. Devices with such pumping action are getter pumps, ion getter pumps, adsorption pumps and traps, and cold traps and cryogenic pumps. In these pumps gas is held captive on active surfaces.

A getter pump employs metal which is heated to evaporation and deposited on the pump walls. The metal combines chemically with gases to form stable compounds with very low vapor pressure. Metals such as molybdenum, zirconium, and titanium readily form compounds with many gases; however, titanium is the most widely used. Evaporation followed by deposition of metallic film may be intermittent so that a gas monolayer may form before a new metal layer is deposited; or it may be continuous so that the metal film surface is continuously renewed.

A fresh getter film is most active before completion of a gas monolayer. Continued pumping depends on deep penetration of gas by diffusion or the formation of many monolayers.

Getters pump best with reactive gases such as oxygen, hydrogen and nitrogen. They are ineffective with inert gases like helium and argon, and complex molecules like hydrocarbons.

Ion getter pumps are of two types -- the cold cathode, also called sputter-ion or Penning pumps, and the hot cathode or evaporation-ion pump. In a sputter-ion pump, electrons emitted from a cathode in the vacuum chamber ionize gas molecules as they are accelerated toward the anode. The positively ionized molecules are accelerated to the cathode, where they are buried. The impact sputters atoms off the cathode, which is made of a getter material. An evaporation-ion pump works much the same way as a sputter-ion pump, except that getter material is also evaporated from the hot cathode.

In either ion pump, an external magnet may be used to cause the electrons to move in a helical and therefore longer path, so that they are more likely to collide with gas molecules.

Getter-ion pumps work well with reactive gases and are capable of pumping inert gases to a lesser degree. Pumping speed with argon is initially high because of ion burial at the cathode. But this mechanism saturates, causing the pumping speed to fall to about 1% of that for air. Only about one ion in 100 striking the cathode is adsorbed after saturation.

Complex molecules such as water vapor, ammonia and hydrocarbons are easily pumped by getter-ion pumps. They become dissociated, and each component is pumped according to its partial pressure. However, it is common for methane and other members of the paraffin series to be produced in a getter-ion pump. Pumping speeds relative to air for various gases in a getter-ion pump are shown below.

PUMPING SPEEDS FOR DIFFERENT GASES

	(%)
Hydrogen	270
Deuterium	190
Light hydrocarbon	90 to 160
Nitrogen	100
Carbon dioxide	100
Water vapor	100
Oxygen	57
Helium	10
Neon	4
Argon	1

The greatest advantage of getter and getter-ion pumps is the lack of pump oil, whose vapor pressure limits the ultimate pressure. Another advantage is clean pumping without needing baffles or traps. Disadvantages are that the getter material gets used up and needs replacement, and the pumping performance of getter films depends on their condition and the gases being pumped. These pumps are most effective below 10^{-5} torr and are not practical above 20 μ .

Adsorption Pumps and Traps

Materials such as charcoal, alumina, and zeolite have a great capacity for adsorbing gas, and can therefore be used as pumps. First the material is heated to release the adsorbed gases which are then pumped out by another pump. The material is then cooled under vacuum to room temperature or below (where adsorption is most efficient) and exposed to the volume to be evacuated. Adsorbing material is often placed in a pipeline as a trap for vapors entering from down stream.

Cold Traps and Cryogenic Pumping

Vapor is readily adsorbed and condensed on a cold surface. Water vapor is condensed on a surface at liquid nitrogen temperature at the rate

of 95 l/sec per square inch of exposed cold surface. If high adsorption materials are used at liquid nitrogen temperature, a small system may be reduced to 10^{-2} torr.

At liquid hydrogen temperature (20°K), all gases except helium, hydrogen and neon are condensed. At liquid helium temperature (4.2°K), all gases except He are condensed. Ultrahigh vacuum may be achieved with the help of these cryogenic liquids.

A cold trap or adsorption trap may be placed in the line between mechanical and diffusion pumps to prevent mechanical pump oil from diffusing to the diffusion pump exhaust baffles and mixing with diffusion pump oil. Mechanical pump oil decomposes readily at diffusion pump temperature and has a high vapor pressure.

Valves

25

There are several kinds of vacuum valves in common use. The gate or slide valve provides a direct optical path when open, and thus has a high conductance. As an additional advantage, it can be opened and closed very quickly. In this valve a plate is moved perpendicularly to its own plane. The plate carries an o-ring in a groove on its perimeter.

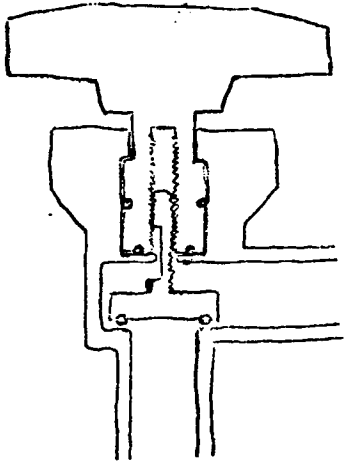
The quarter-swing butterfly valve also provides a high conductance, direct flow path, and can be opened and closed very quickly. In this valve, a disk is rotated about a horizontal shaft crossing the diameter of the circular aperture to be closed. The seal is effected by an o-ring around the perimeter of the disk.

The needle valve provides fine control over gas flow. Consequently, it has a very low conductance. The needle is moved up and down by means of a screw device which can be calibrated. The seal between needle and seat is metal to metal. It is possible to unseat the needle so that it won't close properly if the valve is opened all the way. Therefore, caution should be used.

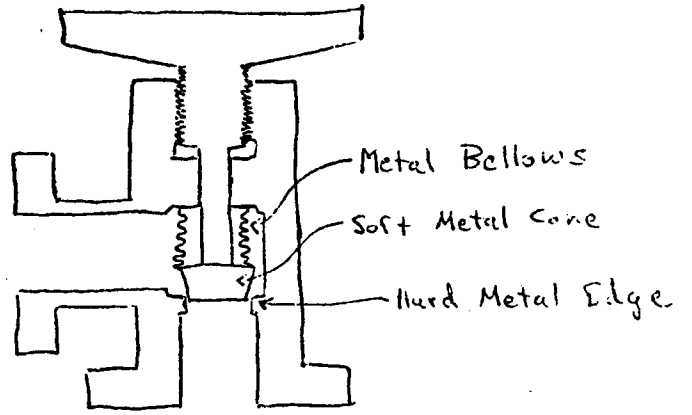
Angle valves are best described by self-explanatory diagrams in fig. 5. Figure 5a shows an angle valve which uses elastomeraseals. Figure 5b shows a modification using a one piece housing and a metal to metal closing. The closing employs one surface of soft metal such as copper which is shoved (softly) against a hard metal knife edge. A metal bellows isolates the

evacuated space from the driving mechanism, which is at higher pressure.

The only advantage of the all metal valve is its bakeability.



a. Elastome-Sealed Valve.



b. All-Metal Valve.

Figure 5. Angle Valves.

Seals

Two metal or glass flanges with smooth surfaces joined together make a good mechanical union, but narrow microscopic channels remain between them. Even channels of micron size (here 1 micron = 10^{-6} in.) can produce a considerable leak in high vacuum systems. Consequently a third, somewhat resilient part is compressed between the flanges and fills up small irregularities of the surface. Important properties to be considered for vacuum gaskets are plasticity, elasticity, permeability, vapor pressure and permissible temperature range.

The most widely used gaskets are elastomer o-rings fitted into flange grooves and are made of synthetic rubber type materials such as neoprene, butyl, silicone, teflon and viton. Viton is a very good material for high vacuum work due to its very low outgassing rates and may be heated to 150° C (without grease). Surfaces where the o-rings make contact should be inspected for minute scratches before assembling. Large compression loads are not necessary when using elastomer gaskets.

Sometimes a very thin coating of low vapor pressure vacuum grease is applied to o-rings to facilitate sealing and prolong o-ring life. Grease should not be used for any high temperature applications due to decomposition of the grease. A table of properties for Apiezon vacuum greases is shown below.

<u>Type</u>	<u>Melting Point (°C)</u>	<u>Vapor Pressure at Room Temperature (torr)</u>
L	47	$<10^{-10}$
M	44	$<10^{-7}$
N	43	$<10^{-8}$
T	125	10^{-8}

When bake temperatures above 150°C are used, gaskets must be metal. Metals commonly used are soft ones like gold, aluminum and copper. Common shapes are flat rings or circular wires. Metal gaskets require very high compression loads.

Special seals are designed to accomodate motion. The ion acoustic wave experiment employs two common types. One is an o-ring seal for reciprocating motion. The other is a swivel seal which allows both rotating and reciprocating motion. Special seals are also designed for electrical lead-ins and vacuum gage mounts.

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VAPOR PRESSURE DATA FOR A NUMBER OF COMMON GASES
 (From R. E. Honig and H. O. Hook, RCA Review 21, 360 (1960), with permission)

Symbol	Compound	Data Temp. Range, °K	Temperatures (°K) for Vapor Pressures (torr)																
			10 ⁻¹³	10 ⁻¹²	10 ⁻¹¹	10 ⁻¹⁰	10 ⁻⁹	10 ⁻⁸	10 ⁻⁷	10 ⁻⁶	10 ⁻⁵	10 ⁻⁴	10 ⁻³	10 ⁻²	10 ⁻¹	1	10 ¹	10 ²	10 ³
Ar	Argon	82-88	20.3	21.3	22.5	23.7	25.2	26.8	28.6	30.6	33.1	35.9	39.2	43.2	48.2	54.4	62.5	73.4	89.9
Br ₂	Bromine	253-331	102.0	106.5	111.0	116.5	122.0	128.5	135.5	143.5	152.5	163.0	174.5	188.5	204.	224.	248.	282.	339.
CH ₄	Methane	48-112	24.0	25.3	26.7	28.2	30.0	32.0	34.2	36.9	39.9	43.5	47.7	52.9	59.2	67.3	77.7	91.7	115.0
CO	Carbon Monoxide	56-133	20.5	21.5	22.6	23.8	25.2	26.7	28.4	30.3	32.5	35.0	38.0	41.5	45.8	51.1	57.9	67.3	84.1
CO ₂	Carbon Dioxide	107-196	59.5	62.2	65.2	68.4	72.1	76.1	80.6	85.7	91.5	98.1	106.0	114.5	125.0	137.5	153.5	173.0	198.0
COS	Carbonyl Sulfide	162-224													(124.5)	139.5	159.5	187.0	229.
CS ₂	Carbon Disulfide	194-319												(160.0)	177.5	199.5	228.	269.	329.
Cl ₂	Chlorine	162-420	66.1	69.1	72.4	76.0	80.0	84.4	89.4	95.1	101.5	109.0	117.5	127.5	140.0	155.0	173.0	201.	245.
F ₂	Fluorine	54-89													(52.2)	59.5	70.5	87.5	
H ₂	Hydrogen	14-21	2.67	2.83	3.01	3.21	3.45	3.71	4.03	4.40	4.84	5.38	6.05	6.90	8.03	9.55	11.70	15.10	21.4
HBr	Hydrogen Bromide	120-205	51.8	54.3	57.1	60.2	63.7	67.6	72.1	77.1	82.9	89.6	97.5	107.0	118.5	132.5	151.0	175.0	209.
HCl	Hydrogen Chloride	132-195	49.7	52.1	54.6	57.5	60.6	64.1	68.1	72.5	77.6	83.4	90.1	98.1	108.5	121.0	137.0	158.5	193.0
HF	Hydrogen Fluoride	240-290													(179.0)	207.	245.	301.	
H ₂ O	Water	175-380	113.0	118.5	124.0	130.0	137.0	144.5	153.0	162.0	173.0	185.0	198.5	215.	233.	256.	284.	325.	381.
H ₂ S	Hydrogen Sulfide	153-213	57.1	59.8	62.7	65.9	69.5	73.5	78.0	83.1	89.0	95.7	103.5	113.5	124.5	138.5	156.5	180.5	218.
He	Helium	0.9-5.2													0.980	1.268	1.738	2.634	4.518
I ₂	Iodine	298-456	141.5	147.5	154.0	161.5	169.5	178.5	188.5	199.5	212.	226.	243.	262.	285.	312.	345.	389.	471.
Kr	Krypton	63-121	27.9	29.4	30.9	32.7	34.6	36.8	39.3	42.2	45.5	49.4	53.9	59.4	66.3	74.8	85.9	101.0	123.5
N ₂	Nitrogen	54-128	18.1	19.0	20.0	21.1	22.3	23.7	25.2	27.0	29.0	31.4	34.1	37.5	41.7	47.0	54.0	63.4	80.0
N ₂ O	Nitrous Oxide	103-186	55.8	58.3	61.1	64.2	67.6	71.3	75.5	80.3	85.7	91.9	99.0	107.5	117.5	129.5	144.0	162.5	189.5
NO	Nitric Oxide	73-180	37.7	39.4	41.3	43.4	45.6	48.1	50.9	54.0	57.6	61.6	66.3	71.7	78.1	85.7	95.0	106.5	123.5
NH ₃	Ammonia	145-240	70.9	74.1	77.6	81.5	85.8	90.6	95.9	102.0	108.5	116.5	125.5	136.0	148.0	163.0	181.0	206.	245.
Ne	Neon	15-45	5.50	5.79	6.11	6.47	6.88	7.34	7.87	8.48	9.19	10.05	11.05	12.30	13.85	15.80	18.45	22.1	27.5
O ₂	Oxygen	57-154	21.8	22.8	24.0	25.2	26.6	28.2	29.9	31.9	34.1	36.7	39.8	43.3	48.1	54.1	62.7	74.5	92.8
SO ₂	Sulfur Dioxide	178-263	78.9	82.4	86.3	90.4	95.1	100.0	106.0	112.5	119.5	128.0	137.5	148.5	161.5	177.0	195.5	225.	269.
Xe	Xenon	110-166	38.5	40.5	42.7	45.1	47.7	50.8	54.2	58.2	62.7	68.1	74.4	82.1	91.5	103.5	118.5	139.5	170.0

⊙ Melting point for the compound

↘ Transition point for the compound

VACUUM EXPERIMENT

CHAPTER 2

GAS FLOW IN VACUUM SYSTEMS

*Turbulent, viscous and molecular flow. Conductance.
Molecular flow conductance. Combined viscous and
molecular flow. Gas flow data.*

TURBULENT FLOW

THE behaviour of a fluid as it flows through a pipe depends on the pressure at each end of the pipe, i.e. on the mean pressure and on the pressure drop along the pipe. The latter governs the flow velocity. If the pressure and flow velocity are sufficiently high, the flow is turbulent and is characterised by eddies which appear and disappear, while the fluid pressure and velocity of flow at any point fluctuate about mean values. Although irregular, the flow can nevertheless be described by laws of probability. Thus, according to Hinze^(2.1) 'turbulent fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space co-ordinates, so that statistically average values can be discerned'.

The criterion of turbulent flow is the value of the Reynolds number R which is defined by the equation

$$R = \frac{UD\rho}{\eta}$$

where U = mean fluid velocity,

D = pipe diameter,

ρ = fluid density, and

η = coefficient of viscosity.

The flow is turbulent if $R > 2200$. This leads to the result that the flow of air at room temperature through a circular pipe is turbulent if

$$PF/D > 5 \times 10^5$$

where F is the flow rate through the pipe in l./s,

P is the mean air pressure in mtorr, and

D is the pipe diameter in inches.

A study of turbulent flow would be of little practical value to the vacuum engineer, which is fortunate since the subject is somewhat complex. This type of flow can occur in the pipe between a rotary pump and a vacuum system in the early stages of pumping the system down from atmospheric pressure. Its duration will be brief enough to be neglected, however, unless the pump is fast and the pipe is narrow. Let it suffice to say that a vacuum engineer who connects a narrow pipe to a fast pump deserves a Gilbertian punishment to fit the crime.

VISCOUS FLOW

As the gas pressure is reduced and the Reynolds number decreases below 2200, the nature of the flow changes. Eddies cease to appear and the energy which is provided by the pressure gradient along the pipe is used completely in maintaining a steady flow. The gas velocity and pressure become uniform with time and the flow becomes streamline, i.e. the lines of flow are smooth and continuous and curve gently in the neighbourhood of bends and other irregularities in the pipe. Near the pipe walls the gas is almost at rest, but progressing towards the centre the layers of gas slide more quickly over one another until the velocity reaches a maximum at the centre. Now the viscosity of a fluid is defined as the tangential force per unit area of either of two horizontal planes at unit distance apart in the fluid, one plane being fixed and the other moving with unit velocity. In other words the coefficient of viscosity is a measure of the internal friction and is therefore important in determining the amount of gas passing per second through a pipe under these conditions. This type of flow therefore is generally known as 'viscous', or more rarely as 'laminar' flow and is governed by Poiseuille's law, viz.:

$$\frac{Q}{P_1 - P_2} = K \frac{D^4 P}{\eta L} \quad (2.1)$$

where Q = product of volume flow and corresponding pressure,

η = gas viscosity, and

K = numerical constant.

This equation will be put into a more practical form later.

The presence of a pressure gradient causes adjacent layers of gas to exert a pressure on each other in the direction of the negative

pressure gradient, thus setting the gas in motion as a whole, i.e. a velocity along the lines of flow is superimposed on the Maxwellian velocities. Viscous flow can occur only when the mean free path is small compared with the pipe diameter. Only those molecules near the walls will actually collide with the walls and since these will represent only a fraction of the total number of molecules present, the nature of the walls does not have an important effect on the flow rate.

MOLECULAR FLOW

If the gas pressure is lowered even further (still maintaining the pressure gradient along the pipe), then as the mean free path approaches the pipe diameter, the nature of the flow must change. The laminar nature of the flow will disappear because molecules now collide with the walls of the pipe rather than with each other. When the pressure is low enough, the molecules move about inside the pipe independently of each other and the flow is said to be 'molecular'. The pressure gradient along the tube does not now act as a driving force pushing the gas along the tube in a stream. At these low pressures the molecules move in random directions and there is a net transfer of gas from the high to the low pressure region simply because there are more molecules per unit volume at one end of the pipe than at the other. If the pressure at the left-hand end of the pipe is higher than that at the right-hand end, then more molecules will pass per second across a section perpendicular to the pipe axis from left to right than will pass in the opposite direction. Thus molecular flow can be treated as a statistical problem.

CONDUCTANCE

Any pipe or duct offers a certain resistance to gas flow of any type, causing a pressure drop along the pipe. If F is the volume of gas flowing per second across any cross-section of the pipe and P is the pressure at that section, then the quantity Q of gas passing per second is FP . The resistance R (or impedance) of a length of pipe is defined by $R = (P_1 - P_2)/Q$ where P_1 and P_2 are the pressures at the upstream and downstream ends (this is analogous to Ohm's law in an electrical circuit, i.e. $R = (V_1 - V_2)/i$). Thus R has the

dimensions of s/l . and C , the reciprocal of R , is called the conductance of the pipe in l/s . Thus

$$C = Q/\Delta P$$

Conductances in parallel

Consider two pipes in parallel having conductances C_1 and C_2 . The mass flow in each pipe is given by $Q_1 = C_1 \cdot \Delta P$ and $Q_2 = C_2 \cdot \Delta P$. The total flow $Q = Q_1 + Q_2 = (C_1 + C_2) \cdot \Delta P$. If the two pipes were to be replaced by a single pipe of conductance C_T which gives the same total flow, then $Q = C_T \cdot \Delta P$.

Thus
$$C_T = C_1 + C_2 \quad (2.2)$$

Conductances in series

Consider now two conductances C_1 and C_2 in series, e.g. a pipe joined at one end to another pipe of different diameter. Let ΔP_1 and ΔP_2 be the pressure drops along the first and second pipes and let Q_1 and Q_2 be the mass flow rates. Let ΔP_T be the total pressure drop along the two pipes in series and let Q_T be the corresponding mass flow rate. Then by definition

$$\Delta P_1 = Q_1/C_1; \quad \Delta P_2 = Q_2/C_2; \quad \Delta P_T = Q_T/C_T$$

But
$$\Delta P_T = \Delta P_1 + \Delta P_2$$

Furthermore, the mass flow rate must be the same throughout the system, otherwise there would be an accumulation of gas in the system, i.e.

$$Q_1 = Q_2 = Q_T$$

Hence
$$1/C_T = 1/C_1 + 1/C_2 \quad (2.3)$$

VISCOUS FLOW CONDUCTANCE

Round pipe

For air at 300° K Poisseuille's law (equation 2.1) can be rewritten as

$$F = \frac{(P_1^2 - P_2^2) \cdot D^4}{0.68LP}$$

Now
$$P_1^2 - P_2^2 = (P_1 + P_2)(P_1 - P_2) = 2P \cdot \Delta P$$

Hence
$$F = \frac{\Delta P \cdot D^4}{0.34L}$$

This expression enables the flow, in l/s , to be calculated in terms of the pressure gradient along the pipe. Note that F is the volume flow rate mid-way along the pipe where the pressure is P . The difference between F at the centre and at either end is usually negligible since the pressure drop ΔP along the pipe is generally small compared with the total pressure P .

Now, by definition, $C = Q/\Delta P = PF/\Delta P$

Hence
$$C = \frac{2.94PD^4}{L} \text{ l/s} \quad (2.4)$$

Rectangular duct

Let a = long side of rectangle (in),
and b = short side of rectangle (in).

Then for air at 300° K

$$C = \frac{30a^2b^2KP}{L} \text{ l/s} \quad (2.5)$$

where K is a shape factor whose value depends on b/a , as shown in Table 2.1. Thus the conductance increases rapidly as the cross-section changes from a slit to a square.

TABLE 2.1. Shape Factor for Viscous Flow Conductance of Rectangular Duct

b/a	K	b/a	K
0.1	0.032	0.6	0.126
0.2	0.059	0.7	0.133
0.3	0.081	0.8	0.137
0.4	0.100	0.9	0.139
0.5	0.115	1.0	0.140

As in the case of a round pipe, the above expression for C leads to a relation for the volume flow in terms of the pressure drop along the duct.

$$C = PF/\Delta P, \quad \text{whence } F = C \cdot \Delta P/P$$

i.e.
$$F = \frac{30a^2b^2K}{L} \cdot \Delta P \text{ l/s}$$

General

Viscous flow is difficult to treat quantitatively since it depends not only on the shape of the duct but also on the gas pressure. As a result there is very little information available on the subject. Fortunately, at the pressures which are of most interest in high vacuum technique, flow is molecular rather than viscous. On those occasions when viscous flow is of interest, conditions are usually fairly simple, e.g. when the problem is to find the time required to evacuate a tank, or volume of some sort, through a pipe which is usually circular in cross-section.

MOLECULAR FLOW CONDUCTANCE

The formulae given below refer to conductances for air at 300° K, but can be applied to any gas of molecular weight M at a temperature T ° K by multiplying the stated values by $0.31(T/M)^{1/2}$, i.e. by $\left(\frac{T}{300} \cdot \frac{29}{M}\right)^{1/2}$, taking the molecular weight of air as 29. Table 2.2 compares the conductances for various gases of a given duct with its conductance for air at the same temperature.

TABLE 2.2

Gas	$\frac{\text{Conductance for gas}}{\text{Conductance for air}}$
Hydrogen	3.8
Helium	2.7
Water vapour . . .	1.3
Carbon dioxide . .	0.81

Knudsen's formula

An expression for the mass flow rate of gas at low pressure through a long cylindrical tube of any shaped cross-section was first derived by Knudsen. By equating the momentum communicated

by molecular collisions to the wall area of a short length of the tube with the momentum produced by the pressure drop over the same length, he arrived at the result^(2.2) that the mass flow rate dG/dt through a tube of cross-sectional area A , perimeter B and length L is given by

$$\frac{dG}{dt} = \frac{8}{3} \left(\frac{2m}{\pi kT} \right)^{1/2} \frac{A^2}{BL} (P_1 - P_2)$$

where P_1 and P_2 are the pressures at the ends of the tube and m , k and T have the usual significance. Expressing the gas flow as volume flow rate $F \times$ pressure P , since from equation (1.6) mass $G = (m/kT) \cdot PV$, then

$$Q = PF = \frac{8}{3} \left(\frac{2kT}{\pi m} \right)^{1/2} \frac{A^2}{BL} (P_1 - P_2)$$

Hence the conductance of the tube is given by

$$C = \frac{8}{3} \left(\frac{2kT}{\pi m} \right)^{1/2} \frac{A^2}{BL}$$

In deriving his formula, Knudsen assumed that Maxwell's velocity distribution was approximately true for the moving gas—an assumption which may lead to appreciable error in calculation of differential effects such as, in this case, the momentum produced by the pressure drop over a short length of tube. Modern statistical treatment of the problem produces an expression for the rate of flow which involves integrals whose values depend on the geometrical form of the tube cross-section. Thus the molecular flow conductance of a long tube is written as

$$C = \frac{8}{3} K \left(\frac{2kT}{\pi m} \right)^{1/2} \frac{A^2}{BL}$$

where K is a dimensionless constant whose value depends on the geometry of the tube cross-section. When A^2 , B and L are expressed in inches,

$$C = 400 \frac{KA^2}{BL} \text{ l./s} \quad (2.6)$$

for air at 300° K.

v.r.

c

Long circular pipe

For a circular pipe, $K = 1$, $A = \pi D^2/4$, and $B = \pi D$, where D is the diameter of the pipe (in). Hence

$$C = 79D^3/L \text{ l./s} \quad (2.7)$$

A more easily memorised form of this equation is as follows. If R is the radius and L' the length of the pipe, both expressed in millimetres, then $C = R^3/L'$, C being in l./s as before.

Short circular pipe

Equation (2.7) is accurate only for pipes of infinite length. There are many cases in practice when it is important to know the conductance of a short length of pipe, in which case the conductance of the entrance aperture must be taken into account. Clausing^(2.3) studied the problem extensively but found that it was impossible to obtain an accurate formula in terms of known functions. Instead, he worked out a close approximation which enabled him to tabulate as a function of length L /diameter D of the pipe a factor α which is used to multiply the 'long pipe' formula in order to obtain the 'short pipe' conductance for that particular value of L/D . Kennard^(2.4) has given an empirical expression which reproduces Clausing's values within 1.5 per cent for all values of L/D . His expression reduces to

$$C = \frac{79D^3}{L} \cdot \alpha \text{ l./s} \quad (2.8)$$

where

$$\alpha = \frac{15L/D + 12(L/D)^2}{20 + 38L/D + 12(L/D)^2}$$

Values of α calculated from this equation are given in Table 2.3.

If the diameter of the vessel from which the gas is flowing into the short pipe is at least five times the diameter of the pipe then the formula

$$C = \frac{79D^3}{L + 1.33D} \quad (2.9)$$

gives values for the conductance of the pipe which are within about 5 per cent of those obtained from equation (2.8). This equation is derived by considering the entrance effect as an aperture of area $\pi D^2/4$ and conductance $75\pi D^2/4$ l./s in series with the conductance $79D^3/L$ l./s of the pipe itself.

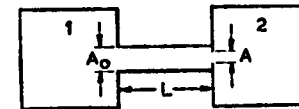
TABLE 2.3. 'Short tube' Conductance Factor

L/D	α	L/D	α
0.04	0.028	2.0	0.540
0.08	0.055	5.0	0.700
0.1	0.068	10.0	0.840
0.2	0.130	20.0	0.910
0.5	0.250	50.0	0.960
1.0	0.300	≥ 100	1

Orifice

Suppose we have a large vessel 1 connected by a pipe of cross-section A_0 and length L to a second large vessel 2 through an orifice A (Fig. 2.1). Gas moving towards the right from 1 has first

FIG. 2.1. CONDUCTANCE OF ORIFICE



of all to find the orifice A_0 . It then travels down the pipe L and has to find the orifice A in order to enter 2. The overall left-to-right conductance C_T is given by

$$1/C_T = 1/C_1 + 1/C_2 + 1/C_3$$

where C_1 = conductance of orifice A_0 within vessel 1,

C_2 = conductance of pipe L , and

C_3 = conductance of orifice A within the pipe L .

Gas moving towards the left from 2 has only to find the orifice A and flow down L in order to reach 1. The overall right-to-left conductance is simply

$$1/C_T = 1/C_4 + 1/C_2$$

where C_4 = conductance of orifice A within the vessel 2.

Under molecular flow conditions, the gas molecules in any system move in all directions. Thus, in the system of Fig. 2.1 the left-to-right and the right-to-left conductances must be equal. If they are not, then, starting from a uniform pressure throughout the

system, there would be a net gas transfer in the direction of the greater conductance, which is not possible. Thus

$$1/C_1 + 1/C_2 + 1/C_3 = 1/C_4 + 1/C_2$$

whence

$$1/C_3 = 1/C_4 - 1/C_1$$

Now it is readily shown from kinetic theory considerations (equation 2.5) that the amount of gas flowing per second through an aperture of area A in² out of a vessel which is large compared with the aperture is

$$Q = 75(P_1 - P_2)A \text{ l. mtorr/s}$$

where P_1 and P_2 are the gas pressures in mtorr on either side of the aperture. Hence the molecular flow conductance of the aperture is

$$C = 75A \text{ l./s} \quad (2.10)$$

and in the problem above, $C_1 = 75A_0$

and $C_4 = 75A$

Thus $C_3 = 75A_0 A / (A_0 - A)$

To sum up, the molecular flow conductance of an orifice of area A in² in a plate which blocks the end of a pipe of cross-sectional area A_0 in² is given by

$$C = 75A_0 A / (A_0 - A) \text{ l./s} \quad (2.11)$$

If the area of the orifice is small compared with the area of the pipe in which it is situated, then $A_0 / (A_0 - A)$ is approximately unity and

$$C = 75A \text{ (cf. equation 2.10)}$$

It is interesting to note from equation (2.11) that the molecular flow conductance of a given orifice becomes larger if the cross-sectional area of the surrounding pipe becomes smaller. For example, compare the conductance of a 2 in diameter orifice in a plate blocking a 12 in diameter pipe with its conductance when blocking a 3 in diameter pipe—242 l./s in the first case compared with 425 l./s in the second.

Loevinger has suggested that the correction factor $A_0 / (A_0 - A)$ is also applicable when the flow is viscous^(2.5).

Elliptical pipe

The conductance of a long elliptical pipe has been calculated by Turnbull^(2.6). If a and b are the semi-major and semi-minor axes,

respectively, of the elliptical cross-section and L the length of the pipe (all expressed in inches) then the conductance C_1 of the pipe is given by

$$C_1 = 632ab^2/L \text{ l./s} \quad (2.12)$$

Compare this with equation (2.6) for the conductance of a tube of any cross-section. The cross-sectional area A of an ellipse = πab and its perimeter $B = \pi[2(a^2 + b^2)]^{1/2}$ approximately. Substituting these values in equation (2.6) gives

$$\begin{aligned} C_1 &= \frac{400\pi^2 a^2 b^2 K}{\pi L [2(a^2 + b^2)]^{1/2}} \\ &= 632ab^2/L \text{ (from equation 2.12)} \end{aligned}$$

Hence the shape factor $K = \frac{632[2(a^2 + b^2)]^{1/2}}{400\pi a}$

$$= 0.71[1 + b^2/a^2]^{1/2}$$

If the elliptical pipe communicates with a large tank of cross-sectional area A_0 then the conductance C_2 of the entrance into the pipe is found from the orifice formula, equation (2.11), multiplied by the shape factor. Then if A is the cross-sectional area of the pipe ($= \pi ab$),

$$C_2 = \frac{75A_0 A}{A_0 - A} \times 0.71[1 + b^2/a^2]^{1/2}$$

and the overall conductance C is given by

$$1/C = 1/C_1 + 1/C_2$$

Rectangular duct

Consider now a rectangular duct communicating with a large tank. The conductance C_1 of the length of the duct is given by equation (2.6). If a and b are the lengths in inches of the long and short sides of the rectangle, respectively, so that the cross-sectional area $A = ab$ and the perimeter $B = 2(a + b)$, then

$$C_1 = \frac{200a^2 b^2}{(a + b)L} K$$

The shape factor K is obtained from Table 2.4, in which the values have been computed from a paper by Barrett and Bosanquet^(2.7).

TABLE 2.4. Shape Factor for Molecular Flow Conductance of Rectangular Duct

b/a	K	b/a	K
1	1.108	$\frac{1}{3}$	1.297
$\frac{2}{3}$	1.126	$\frac{1}{6}$	1.400
$\frac{1}{2}$	1.151	$\frac{1}{10}$	1.444
$\frac{1}{3}$	1.198		

Next, the conductance C_2 of the entrance into the duct is found from the orifice formula, equation (2.11), multiplied by the shape factor K . Then

$$C_2 = \frac{75A_0 A}{A_0 - A} K$$

where A_0 is the cross-sectional area of the tank in in^2 . The total conductance C is, of course, given by

$$1/C = 1/C_1 + 1/C_2$$

$$\text{whence } C = \frac{1200A^2 A_0}{16A(A_0 - A) + 3A_0 BL} \cdot K$$

Example: Determine the conductance of a rectangular duct 10 ft long with a cross-section 2 x 6 ft leading from a tank having a cross-sectional area of 16 ft^2 .

In this case $b/a = \frac{1}{3}$ so that $K = 1.2$.

$$\text{Then } C_1 = \frac{200 \times (12 \times 144)^2}{(8 \times 12)(10 \times 12)} \times 1.2 = 62,200 \text{ l./s}$$

From equation (2.11) multiplied by the shape factor,

$$C_2 = \frac{75 \times (12 \times 144) \times (16 \times 144)}{(16 \times 144) - (12 \times 144)} \times 1.2 = 622,000 \text{ l./s}$$

Then $C = 56,600 \text{ l./s}$.

Annulus formed by a thin disc within a pipe

The conductance is taken as being that of an orifice (from equation (2.10)) of area equal to that of the annulus, multiplied by

a shape factor K . Thus $C = 75AK$. If D_1 is the diameter of the thin disc and D_2 the diameter of the pipe, K has the values given in Table 2.5 (computed from Barrett and Bosanquet's paper^(2.7)).

TABLE 2.5. Shape Factor for Molecular Flow Conductance of Thin Annulus

D_1/D_2	K	D_1/D_2	K
0	1	0.707	1.254
0.259	1.072	0.866	1.430
0.500	1.154	0.966	1.675

Annular passage formed by a solid cylinder placed coaxially inside a tube

The conductance C_1 of the entrance is found from the thin plate formula indicated in the previous paragraph. The conductance C_2 of the length of the passage is found from equation (2.6) where, now,

A = cross-sectional area of annulus, in^2 ,

and B = length of outer perimeter of annulus plus length of inner perimeter, in.

K is found from Table 2.5.

$$\text{Thus, } 1/C = 1/(75AK) + BL/(400A^2K)$$

$$\text{whence } C = \frac{1200A^2K}{16A + 3BL}$$

Slit-like tube

Let a and b be the lengths in inches of the sides of the rectangular section of the tube and let $b \ll a$.

$$\text{Area } A = ab$$

$$\text{Perimeter } B = 2(a + b) = 2a \text{ approximately}$$

Thus the equation $C = (400A^2/BL)K$ becomes $C = (200ab^2/L)K$, where K is obtained from Table 2.6.

TABLE 2.6. Shape Factor for Molecular Flow Conductance of Slit-like Tube

L/b	K	L/b	K
0.1	0.036	3.0	0.520
0.2	0.068	4.0	0.600
0.4	0.130	5.0	0.670
0.8	0.220	10.0	0.940
1.0	0.260	> 10.0	$\frac{2}{3} \ln L/b$
2.0	0.400		

Bend or elbow

The resistance of a bend or elbow in a duct of circular or rectangular cross-section is usually taken to be equal to the resistance of the entrance to the bend (where it joins the straight length) plus the resistance of the bend measured along the centre line as though it were straight. Thus, the conductance of a bend of circular cross-section is the same as that of a short circular pipe of equal diameter and of a length equal to the length of the bend measured along its centre line.

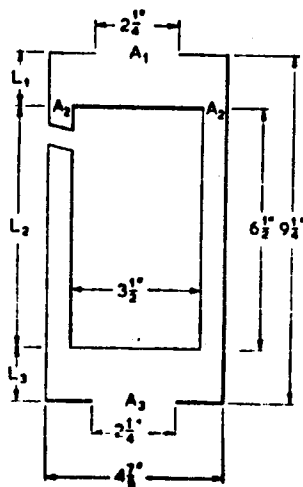


FIG. 2.2. CONDUCTANCE OF VAPOUR TRAP

Example of calculation of molecular flow conductance

Consider the vapour trap shown in Fig. 2.2. Suppose that it is mounted on top of a diffusion pump and is, in turn, surmounted by a large vessel. As gas flows from this vessel due to the pumping action, it has first of all to find the orifice A_1 in order to enter the trap. It then flows through the short length L_1 of $4\frac{7}{8}$ in. diameter pipe, after which it has to find the annular aperture A_2 in order to flow down the annular passage L_2 . All the gas flowing down L_2 finds the short length of $4\frac{7}{8}$ in. diameter pipe L_3 , so that there is no entrance effect to be taken into account here. The gas then has to find the orifice A_3 in order to leave the trap.

The successive conductances are thus as follows:

(a) C_1 , the conductance of the orifice A_1 . From equation (2.11)

$$C_1 = \frac{75A_0 A_1}{A_0 - A_1}$$

where A_0 = cross-sectional area of the body of the trap where the orifice is situated (in^2) and

A_1 = area of orifice A_1 (in^2).

$$\text{Hence } C_1 = \frac{75\pi \times 2.44^2 \times 1.13^2}{2.44^2 - 1.13^2} = 383 \text{ l./s}$$

(b) C_2 , the conductance of the pipe L_1 . From equation (2.7)

$$C_2 = 79 \times 4.88^3 / 1.38 = 6613 \text{ l./s}$$

(c) C_3 , the conductance of the annular aperture A_2 .

$$C_3 = 75A_2 K \quad (\text{see p. 25})$$

where A_2 = area of aperture (in^2) and

K = shape factor given in Table 2.5

$$= 1.3 \text{ since } D_1/D_2 = 0.72$$

$$\text{Hence } C_3 = 75\pi(2.44^2 - 1.75^2) \times 1.3 = 870 \text{ l./s.}$$

(d) C_4 , the conductance of the annular passage L_2 . From p. 25,

$$C_4 = \frac{400A_2^2}{LB} K$$

where A_2 = area of aperture as in (c),

B = total length of inner and outer perimeters of annulus (in),

L_2 = length of passage (in), and

K = shape factor as in (c).

$$\begin{aligned} \text{Hence } C_4 &= 400 \times 8.92^2 \times 1.3 / (26.3 \times 6.5) \\ &= 243 \text{ l./s} \end{aligned}$$

(c) The conductance of the pipe $L_3 = C_2$, the conductance of L_1 , since L_1 and L_3 have the same dimensions.

(f) For the same reason, the conductance of the orifice $A_3 = C_1$, the conductance of A_1 .

Thus the overall conductance C_T is given by

$$\begin{aligned} \frac{1}{C_T} &= \frac{2}{C_1} + \frac{2}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} \\ &= \frac{2}{383} + \frac{2}{6613} + \frac{1}{870} + \frac{1}{243} \end{aligned}$$

whence $C_T = 93 \text{ l./s}$

COMBINED VISCOUS AND MOLECULAR FLOW

As the gas pressure is lowered, the change of flow characteristics from viscous to molecular is by no means clear-cut^(2.8). The change is gradual and there is a transition region where the flow is partly of one type and partly of the other. This region is somewhat difficult to treat mathematically, but for most practical purposes it is sufficiently accurate to consider a duct in this pressure region as having a viscous flow conductance C_V in parallel with a molecular flow conductance C_M . Thus from equation (2.2) the total conductance C_T is given by $C_T = C_V + C_M$. If under these mixed flow conditions there are several conductances C_{T1}, C_{T2}, \dots etc., in series, then the overall conductance C_T is given by

$$1/C_T = 1/C_{T1} + 1/C_{T2} + \dots$$

i.e.
$$\frac{1}{C_T} = \frac{1}{C_{V1} + C_{M1}} + \frac{1}{C_{V2} + C_{M2}} + \dots$$

Circular pipe

It has previously been stated (equation (2.7)) that the molecular flow conductance of a long circular pipe is $79D^3/L$. This is strictly true only at low pressures. The complete expression derived by Knudsen for the molecular flow conductance of a round pipe of diameter D and length L inches ($L \gg D$) through which air at 300°K flows at a mean pressure P mtorr is

$$C = \frac{79D^3}{L} \cdot \frac{1+0.62DP}{1+0.76DP} \quad (2.13)$$

Thus, in the mixed viscous and molecular flow region, the total conductance of the pipe is

$$C_T = \frac{2.94PD^4}{L} + \frac{79D^3}{L} \cdot \frac{1+0.62DP}{1+0.76DP} \quad (2.14)$$

It is instructive to compare the magnitudes of the two conductances in a pipe through a wide pressure range from, say, 1 to 10^{-6} torr. This is done in Table 2.7 for a 1 ft length of 2 in diameter pipe. Values are for air at 300°K and the entrance effect is neglected.

The following points emerge from this table:

- (1) at high pressures C_M is almost negligible;
- (2) at low pressures C_V is negligible;
- (3) C_M varies by less than 20 per cent throughout the whole pressure range.

TABLE 2.7. Conductance per Foot Length of Two-inch Diameter Pipe

Pressure (torr)	C_V (l/s)	C_M (l/s)	C_T (l/s)
1	3910	43.3	3953
10^{-1}	391	43.4	434
10^{-2}	39.1	44.0	83
10^{-3}	3.91	47.2	51
10^{-4}	0.391	51.9	52
10^{-5}	0.039	52.9	53
10^{-6}	0.004	53.0	53

The third point is readily explained by reference to equation (2.13) which shows that the maximum value of C_M is $79D^3/L$ while the minimum is $0.62/0.76$ (i.e. 82 per cent) of the maximum.

Equation (2.14) can be used to find the lowest pressure above which only viscous flow conductance need be considered and the highest pressure below which only molecular flow need be considered. In the first case let the necessarily arbitrary criterion be that C_M shall not be greater than 10 per cent of C_V , i.e.

$$\frac{79D^3}{L} \cdot \frac{1+0.62DP}{1+0.76DP} = \frac{0.1 \times 2.94PD^4}{L}$$

Hence $P = 220/D$ mtorr. Thus for pressures above this value it can be assumed that $C_T = C_V$ with an error of not more than 10 per cent.

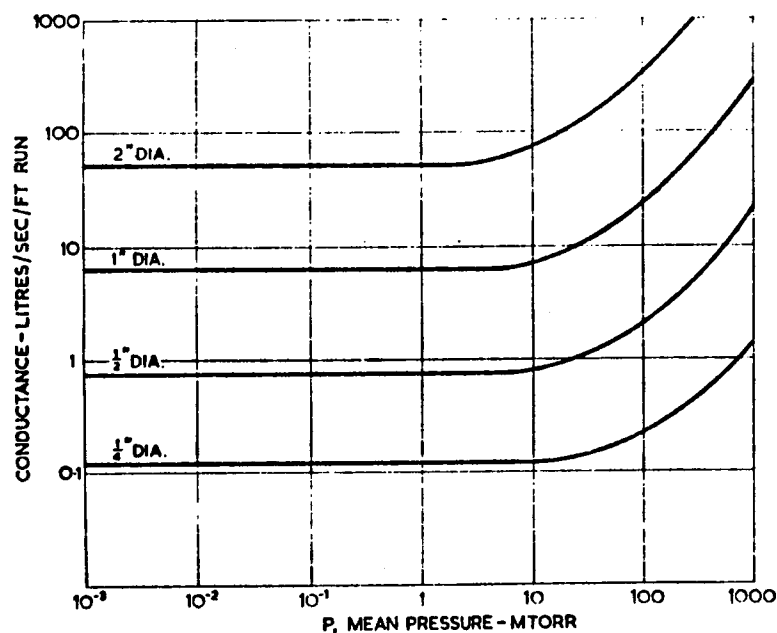


FIG. 2.3. CONDUCTANCE OF CIRCULAR PIPES

Similarly, the criterion in the second case shall be that C_V shall be not greater than 10 per cent of C_M . The limiting condition is

then that $P = 2.2D$ mtorr and for pressures below this value $C_T = C_M$ within 10 per cent. Conductance per foot run is plotted against pressure for four standard pipe diameters in Fig. 2.3.

SUMMARY OF GAS FLOW DATA

Nomenclature

P = gas pressure (mtorr)

F = gas flow rate (l./s)

D = pipe diameter (in)

L = duct length (in)

A = cross-sectional area (in²)

B = length of perimeter (in)

Turbulent flow

Air flow is turbulent if $PF/D > 5 \times 10^5$.

Conductances in parallel

$$C_T = C_1 + C_2$$

Conductances in series

$$1/C_T = 1/C_1 + 1/C_2$$

Viscous flow conductances

(i) Long circular pipe

$$C = 2.94PD^4/L \quad (\text{l./s})$$

(ii) Rectangular duct

$$C = \frac{30a^2b^2P}{L} \cdot K \quad (\text{l./s})$$

where a and b (in) are the lengths of the long and short sides of the rectangle and K is a shape factor varying from 0.032 for $b/a = 0.1$ to 0.140 for $b/a = 1$.

Molecular flow conductances

(i) Long circular pipe

$$C = 79D^3/L \quad (\text{l./s})$$

(ii) Short circular pipe

$$C = \frac{79D^3}{L+1.33D} \text{ (approx.) (l./s)}$$

(iii) Orifice of area A

$$C = 75A \text{ (l./s)}$$

(iv) Orifice of area A in a plate blocking the end of a pipe of area A_0 .

$$C = \frac{75 A_0 A}{A_0 - A} \text{ (l./s)}$$

(v) Long elliptical pipe

$$C = 632ab^2/L \text{ (l./s)}$$

where a and b (in) are the semi-major and semi-minor axes, respectively, of the elliptical cross-section.

(vi) Long rectangular duct

$$C = \frac{200a^2b^2}{(a+b)L} \cdot K \text{ (l./s)}$$

where a and b (in) are the lengths of the long and short sides of the rectangle and K is a shape factor varying from 1.444 for $b/a = 0.1$ to 1.108 for $b/a = 1$.

(vii) Annulus formed by thin disc within a pipe

$$C = 75AK \text{ (l./s)}$$

where A is the annular area and K is a shape factor varying from 1 for $D_1/D_2 = 0$ to 1.675 for $D_1/D_2 = 0.966$, D_1 and D_2 being the diameters of the disc and the pipe, respectively.

(viii) Annular passage formed by a solid cylinder placed coaxially within a tube

$$C = \frac{1200A^2K}{16A+3BL} \text{ (l./s)}$$

where A = annular area and

B = length of outer perimeter of annulus plus length of inner perimeter (in).

The shape factor K is the same as in (vii).

(ix) Slit-like tube

$$C = \frac{200ab^2}{L} \cdot K \text{ (l./s)}$$

where a and b (in) are the lengths of the sides of the rectangular section of the tube ($b \ll a$) and the shape factor K varies from 0.036 for $L/b = 0.1$ to 0.94 for $L/b = 10$.

(x) Bend or elbow. The conductance of a bend of circular cross-section is the same as that of a short circular pipe of equal diameter and of a length equal to the length of the bend measured along its centre line (see (ii) above).

Combined viscous and molecular flow conductance

Conductance of long circular pipe

$$C_T = \frac{2.94PD^4}{L} + \frac{79D^3}{L} \cdot \frac{1+0.62DP}{1+0.76DP}$$

For pressures above $220/D$ mtorr the molecular flow contribution to C_T is negligible. For pressures below $2.2/D$ mtorr the viscous flow contribution to C_T is negligible.

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- (2.3) Clausing, P. *Dissertation*. Amsterdam. 1918.
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- (2.7) Barrett, A. S. D. and Bosanquet, C. H. 'Resistance of Ducts to Molecular Flow.' *I.C.I. (Billingham Div.) Rep. BR-296* (November, 1944).
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TABLE 1.8.2. Measuring ranges of various types of vacuum gauges

Instrument	Range (Torr)												Reading	dependent or independent on nature of gas		
	720	60	10	1	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻⁵	10 ⁻⁶	10 ⁻⁷	10 ⁻⁸				
Bourdon tube	720	60												Total pressure	independent	
Liquid manometer	200	1												Total pressure	independent	
Swivel-type compression manometer	60	0.1												Partial pressure	independent	
High frequency vacuum tester			10		10 ⁻¹									Total pressure	dependent	
Alphatron L (logarithmic scale)			10		10 ⁻³									Total pressure	dependent	
McLeod compression gauge			10		10 ⁻³		10 ⁻⁴							Partial pressure	independent	
Thermal conductivity gauge			10		10 ⁻³									Total pressure	dependent	
Alphatron	1000					10 ⁻⁴								Total pressure	dependent	
Viscosity gauge					10 ⁻³	10 ⁻³								Total pressure	dependent	
PENNING gauge					10 ⁻³		10 ⁻⁶							Total pressure	dependent	
Ionization gauge					10 ⁻³		10 ⁻⁷							Total pressure	dependent	
Knudsen radiometer gauge					10 ⁻³	10 ⁻⁶								Total pressure	independent	
BAYARD-ALPERT ionization gauge						10 ⁻⁶			10 ⁻¹⁰					Total pressure	dependent	
Magnetron gauge after REDHEAD (for ultra-high vacuum)						10 ⁻⁴						10 ⁻¹²		Total pressure	dependent	
	10 ³	10 ²	10	1	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻⁵	10 ⁻⁶	10 ⁻⁷	10 ⁻⁸	10 ⁻⁹	10 ⁻¹⁰	10 ⁻¹¹	10 ⁻¹²
	coarse vacuum			medium-high vacuum			high vacuum			ultra-high vacuum						

Design pressure range: A to 10⁻¹ Torr
 Measured gauge wall.
 Reading: Advantage Disadvantage

Design pressure range: A down to 10⁻¹² Torr
 Measured Reading: Advantage Disadvantage

Design pressure range: A after von R
 Pressure a defined volume. Easily be of the device is effected besides the McLeod the operating gauge reaction
 Measured amount of Measured Reading: Advantage Disadvantage indication.

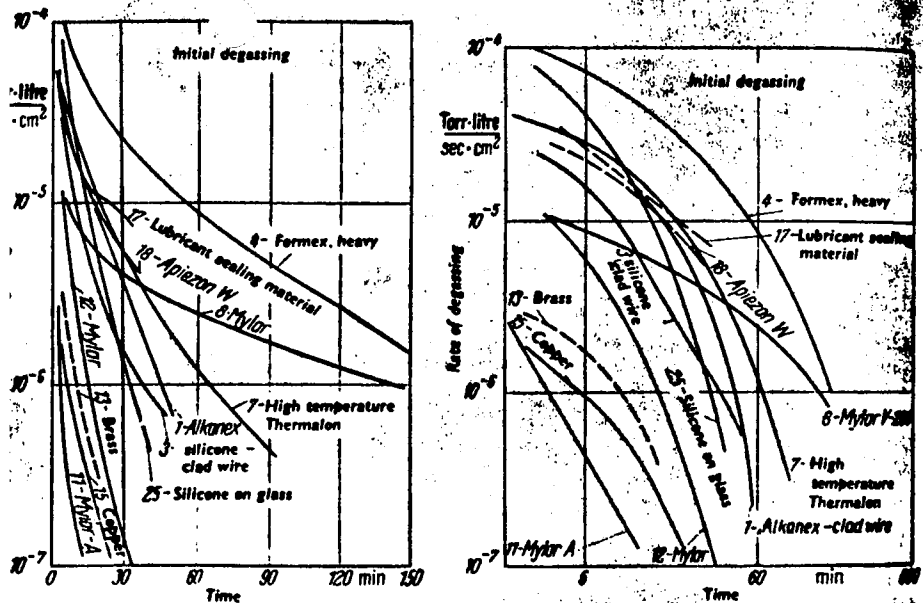


FIG. 2.4.9a and b. Gas desorption of plastic materials II (after SANTELER [21]).

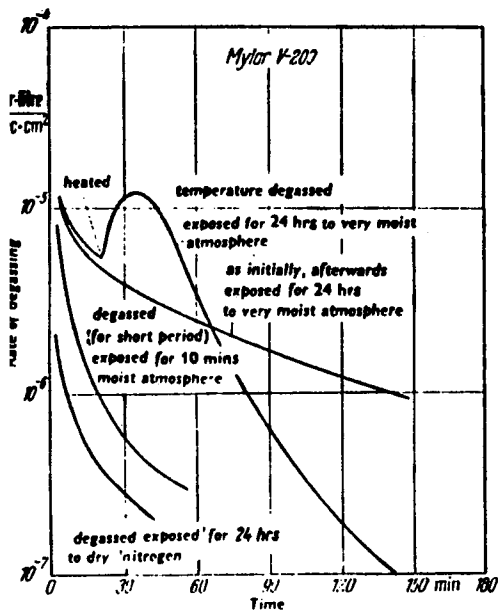


FIG. 2.4.10. Gas desorption of Mylar V-200 after various pre-treatments (after SANTELER [21]).

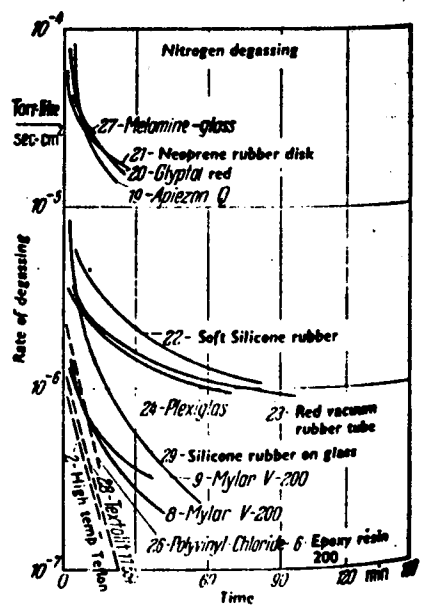


FIG. 2.4.11. Gas desorption of materials filled with nitrogen (after DAYTON et al. [37]).

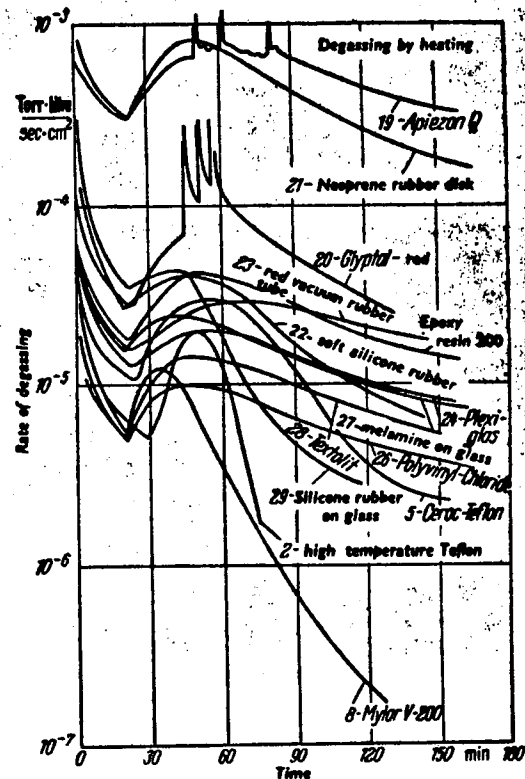


FIG. 2.4.12. Gas desorption during heating of plastic materials, which were exposed for 24 hrs to moist air (after SANTELER [21]).

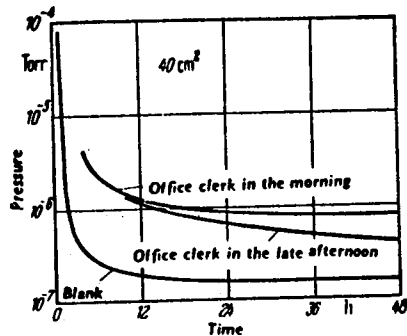


FIG. 2.4.13. Pressure-time curves for the gas desorption of finger prints on glass (after DAYTON et al. [37]).

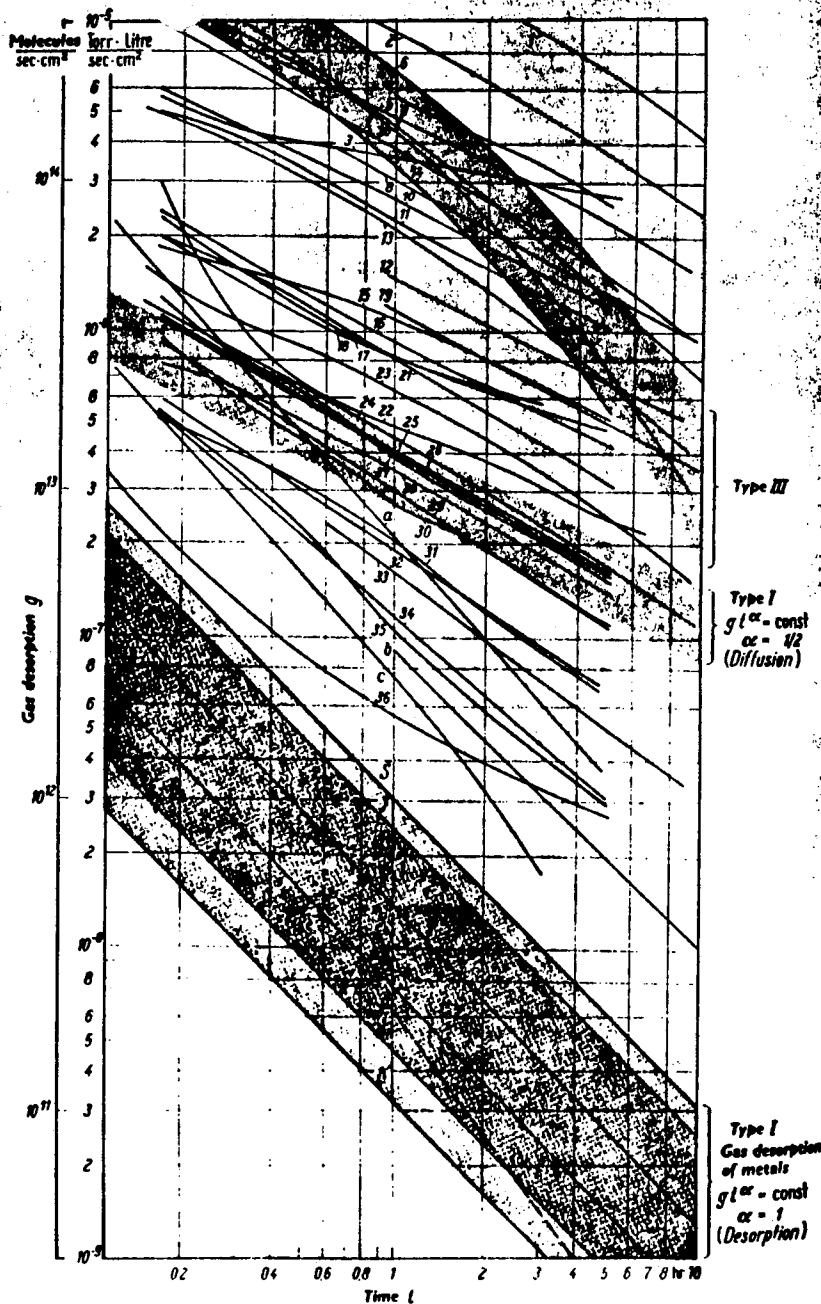
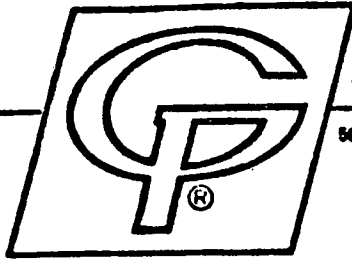


FIG. 2.4.4. Gas desorption of various substances (see notes on next page).

Curve	Material	Type	α	Author*
1	Vulkollan	I	1/2	B
2	Perbunan + Buna	I	1/2	B
3	Mowital	(I)	(1/2)	J
4	Mowilith	(I)	(1/2)	J
5	Neoprene (45/Ne 747)	I	1/2	B
		(for long periods III)	-	
6	Silicone rubber	III	-	J
7	Natural rubber	I	1/2	B
		(for long periods III)	-	
8	Perbunan	I	1/2	S
9	Perbunan	III	-	B
10	Perbunan	I	1/2	J
11	Polyamide	I	1/2	G
12	Araldite	I	1/2	B
13	Neoprene (35/Ne 746)	III	-	J
14	Silicone rubber (O-Ring)	III	-	J
15	Plexiglas	I	1/2	J
16	Polyvinylcarbazole	I	1/2	J
17	Polyvinylcarbazole	I	1/2	J
18	Polycarbonate	I	1/2	S
19	Araldite	I	1/2	B
20	Silicone (37/Si 502)	III	-	J
21	Ultramide	I	1/2	J
22	PVC	I	1/2	J
23	Viton (25/Vi 575)	I	1/2	B
24	Teflon (3/Tf 528)	I	1/2	B
25	Araldite	I	1/2	J
		(for long periods II)	-	
26	Polymethane	I	1/2	J
27	Viton	I	1/2	J
28	Viton	I	1/2	J
29	Polystyrene	I	1/2	J
30	Polystyrene	I	1/2	J
31	Polystyrene	I	1/2	J
32	Teflon	I	1/2	J
33	Teflon	I	1/2	S
34	Polyethylene	I	1/2	J
		(for long periods II)	-	
35	Polyethylene	I	1/2	J
		(for long periods II)	-	
36	Hostafion	I	1/2	J
a	Pyrophyllite	I	1	J
b	Steatite (Al ₂ O ₃)	I	1	G
c	Dogussit (Al ₂ O ₃)	I	1	J
d	Pyrex glass	I	1	S

* Continuation and footnote see p. 240.

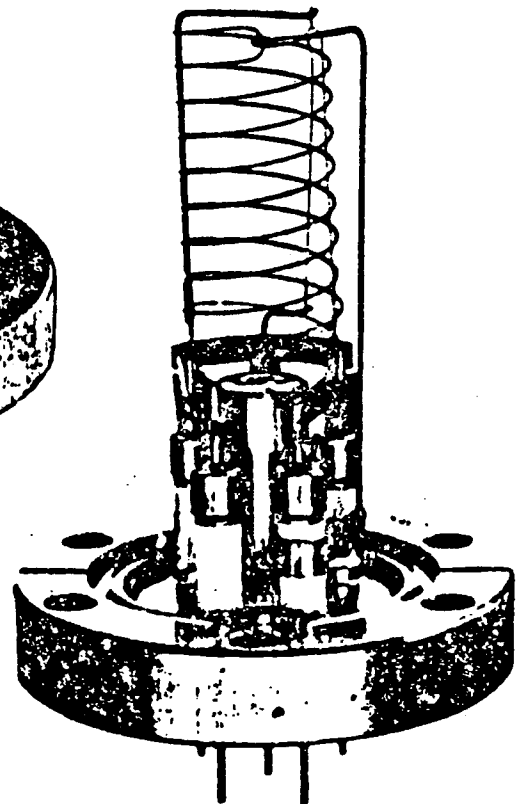
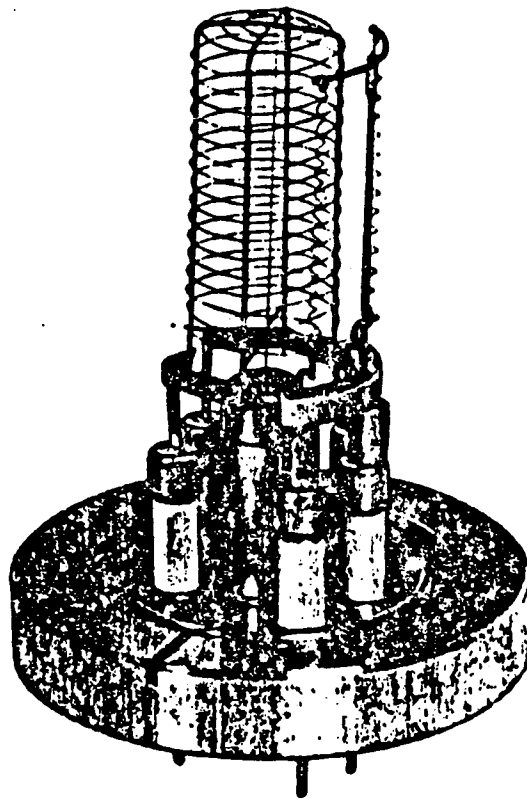
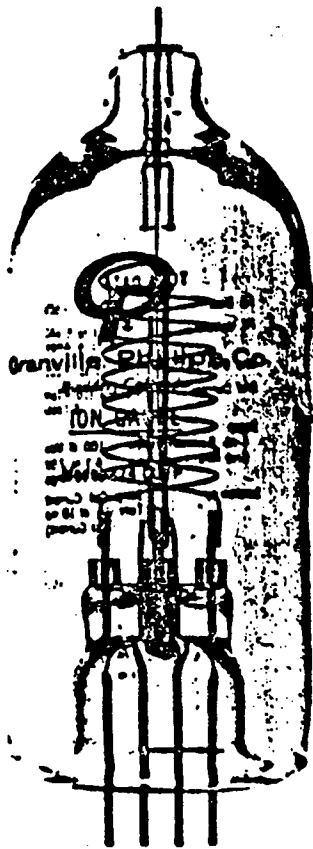


GRANVILLE-PHILLIPS COMPANY

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Installation and
Operating Instructions
274027 100
for Series 274
Bayard-Alpert Type
Ionization Gauge Tubes

Series 274



YOU SHOULD READ THIS INSTRUCTION MANUAL BEFORE INSTALLING, USING, OR SERVICING THIS EQUIPMENT

This manual is for use only with Series 274 Ionization Gauge Tubes with the following part numbers.

274002	274007	274015	274020
274003	274008	274016	274021
274005	274012	274017	274022
274006	274013	274018	274023
			274028

SAFETY INSTRUCTIONS

SAFETY PAYS. THINK BEFORE YOU ACT. UNDERSTAND WHAT YOU ARE GOING TO DO BEFORE YOU DO IT. READ THIS INSTRUCTION MANUAL BEFORE INSTALLING, USING, OR SERVICING THIS EQUIPMENT. IF YOU HAVE ANY DOUBTS ABOUT HOW TO USE THIS EQUIPMENT SAFELY, CONTACT THE GRANVILLE-PHILLIPS PRODUCT MANAGER FOR THIS EQUIPMENT AT THE ADDRESS LISTED ON THIS MANUAL.

Implosion and Explosion

Glass ionization gauges if roughly handled may implode under vacuum causing flying glass which may injure personnel. Be sure that cabling to the gauge tube has proper strain relief so that cable tension cannot break the glass. If pressurized above atmospheric pressure, glass tubes may explode, causing dangerous flying glass. A substantial shield should be placed around vacuum glassware to prevent injury to personnel.

Electrical Shock

All connections to the gauge tube pins should be covered by insulation. All gauge tube pins should be covered by connectors or by pin covers. In normal operation, 180 volts is on the grid connections. During electron bombardment degas, as much as 700 volts may be applied to some electrode pins. Do not touch any gauge tube electrodes while the tube is connected to the controller.

Temperature

During degas, the envelope of the gauge tube becomes heated much more than in normal operation. Be sure that materials that are heat sensitive are not in contact with the gauge tube, and be sure that the gauge tube is not located where personnel performing necessary system operations might come in contact with the gauge tube.

Overpressure

Do not use quick connects or other friction type connections where positive pressure will exist within the gauge tube, such as in backfilling operations.

INSTALLATION INSTRUCTIONS

Receiving Inspection

Domestic Shipments

Inspect all material received for shipping damage.

Confirm that your shipment includes all material and options ordered. If materials are missing or damaged the carrier that made the delivery must be notified within 15 days of delivery in accordance with Interstate Commerce regulations in order to file a valid claim with the carrier. Any damaged material including all containers and packing should be held for carrier inspection. Contact our Customer Service Department, 5675 East Arapahoe Avenue, Boulder, Colorado 80303, (303) 443-7660 if your shipment is not correct for reasons other than shipping damage.

International Shipments

Inspect all material received for shipping damage. Confirm that your shipment includes all material and options ordered. If items are missing or damaged the carrier making delivery to the customs broker must be notified within 15 days of delivery.

Example

If an airfreight forwarder handles the shipment and their agent delivers the shipment to customs, the claim must be filed with the airfreight forwarder.

If an airfreight forwarder delivers the shipment to a specific airline and the airline delivers the shipment to customs, the claim must be filed with the airline, not the freight forwarder.

Any damaged material including all containers and packaging should be held for carrier inspection. Contact our Customer Service Department, 5675 East Arapahoe Avenue, Boulder, Colorado 80303, U.S.A. Telex 045 791 GPVAC Bldr or telephone (303) 443-7660 if your shipment is not correct for reasons other than shipping damage.

Vacuum Connections

1. Location on system. The gauge tube should be located as close as possible to the section of the vacuum system where pressure measurement is important. Valves or other constrictions between the gauge tube and the area where pressure measurement is required may cause erroneous readings.
2. Gauge port. Pressure measurement in the high vacuum range does not require special attention to port size. However, as the pressure of interest more and more approaches the ultra-high vacuum range, a small conductance between the gauge tube and the system volume of interest can cause a significant difference in the two pressures. One inch tubulation is minimal, and at extreme vacuum the nude tube geometry is best whereby the gauge tube actually protrudes into the chamber volume.

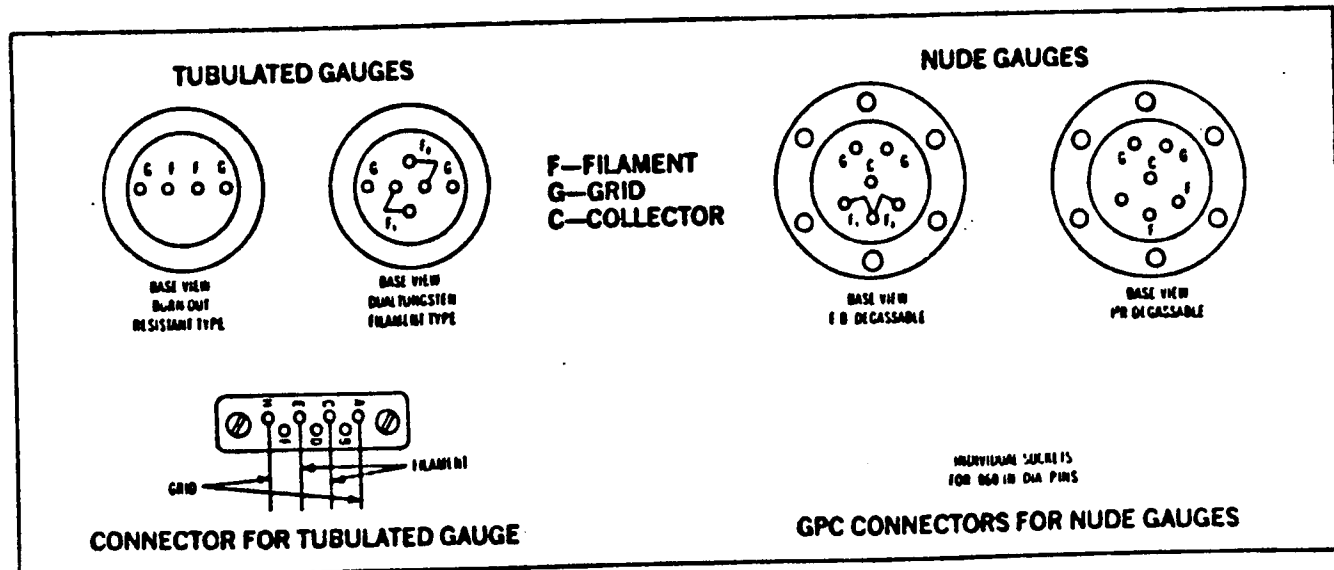


Figure 1 Gauge Tube and Cable Connector Data

3. Mounting orientation. All orientations are acceptable.
4. Connections. When using O-ring quick connects on glass tubulations, care must be used when sliding the glass tubulation into the quick connect and when gently tightening the compression ring so that the glass tubulation is not chipped or cracked. Non-rotatable flanges are ordinarily installed on glass gauge tubes because the bolt ring of rotatable flanges can inadvertently be dropped on the tube and break the glass tubulation.

Electrical Connections

Fig. 1 shows the pin connection code for the various Series 274 gauge tubes.

Do not use gauge cables with exposed conductors such as alligator clips. All gauge tube pins should be covered by connectors or by pin covers. Gauge cables should be firmly clamped to the vacuum station to provide strain relief. This helps insure there will be negligible strain transmitted to the gauge tube pins if there is relative motion between the vacuum station and the ionization gauge controller.

If the resistance heated degassable nude gauge is being used with an electron bombardment degas controller, be sure that the unused grid pin is not exposed. Cover it with a suitable insulator if necessary.

OPERATION

1. Operating Voltage Potentials

The recommended potentials are: Collector, 0V; Grid, +180V; Filament, +30V. The dependence of ion current on variations of these parameters is shown in the Specifications Section.

2. Filament Emission

As a general rule, low emission current is used in the high pressure end of the range of the gauge tube. This helps to avoid the ion current turn-around phenomenon and glow discharge. High emission current is used at ultrahigh vacuum to obtain ion currents that are large enough for convenient measurement. Typical values are 100 μ A at 10⁻³ Torr and 10 mA at 10⁻⁹ Torr. The trade-offs on emission current are that high emission current gives better readout stability and sensitivity but more gauge tube pumping if the gauge tube is clean and more gauge tube outgassing if the gauge tube is contaminated. Likewise, low emission currents minimize gauge tube outgassing (important for a contaminated gauge tube) and minimize gauge tube pumping (important for a clean gauge tube at low pressures) but yield low ion currents which are sensitive to electronic noise and are difficult to measure at lower pressures.

3. Gauge Tube Degas

The contamination level and thus the outgassing rate of a gauge tube may be greatly reduced by heating the electrodes and (as a consequence of the hot electrodes), heating the envelope thereby cleaning the tube. The two types of cleaning (degassing) used are resistive heating (I²R) of the grid, and electron bombardment (E.B.) of the grid and collector. E.B. degassing is significantly preferable only at low pressures but is more expensive. I²R heating requires longer degassing periods. Gauge tube degas is only useful at pressures below 10⁻⁴ Torr and only a few minutes degas is required at pressures above 10⁻⁶ Torr since at these higher pressures, the recontamination of surfaces occurs readily. If a system is going ultimately to the UHV range, it is useful to degas in the 10⁻⁶ Torr range and then again as the system pressure approaches the expected ultimate.

The tubulated gauge and the I²R degassable nude tube may be degassed by either I²R or E.B. degas. The E.B. degassable nude tube may be only E.B. degassed.

4. Gauge Tube Bakeout

It is also useful to externally bake the gauge tube if the entire system is expected to pump down to an ultraclean state. Gauge tubes must not be baked over 450°C as glass softening occurs just above that temperature.

5. X-ray Limit

The X ray limit refers to the lowest pressure indication which may be obtained in a Bayard-Alpert gauge when all the collector (output) current is due to X-ray induced photo-emission and there is an absence of gas. The photo-electron current has a value equivalent to a pressure indication of approximately 10⁻¹⁰ Torr in glass gauge tubes, approximately 4 x 10⁻¹⁰ Torr I²R degassable nude gauges, and approximately 2 x 10⁻¹¹ Torr in E.B. degassable nude gauge tubes.

6. Gauge Tube Accuracy

Due to geometric variations in electrode structures, a given gauge tube is accurate to within $\pm 20\%$ when reading the type for which it is specified.

TECHNICAL INFORMATION

1. Pressure Indication

Ionization gauge controllers actually measure the positive ion current in amperes from the gauge tube but the meter readout is graduated in pressure units. Even more specifically, these pressure units are direct reading only for the gas for which is specified, usually nitrogen (also air); this is called a readout of nitrogen equivalent pressure. Other gases may give much different readings from nitrogen.

2. Gauge Tube Sensitivity

To be able to present conversion tables from gas type to gauge type, the gauge tube sensitivity, K, is defined:

$$K = \frac{i_+}{i_- P} \quad \text{where } i_+ \text{ is the positive ion current to the collector, } i_- \text{ is the electron emission current from filament to grid, and } P \text{ is the pressure}$$

The glass envelope gauge tube and the I²R degassable nude gauge tube have K = 10/Torr for nitrogen (or air), and the E.B. degassable nude gauge tube has K = 25/Torr for nitrogen (or air).

Gauge tube sensitivities for various gases are tabulated in reference material in two general ways. One, directly in Torr⁻¹ and listed, for example, as K_{gas,x}, such as K_{N₂} = 10 Torr⁻¹. Two, listed as related to N₂ by r = K_{gas,x}/K_{N₂}; thus r_{N₂} = 1.0.

3. Gas Type Conversions

In general there are two ways to read the pressure of a gas other than the gas for which a gauge tube is specified. Method A, perform a mathematical conversion on the direct pressure readout (usually nitrogen equivalent pressure). Method B, use an emission current other than the value for which the ion gauge controller is set up.

Method A: To correct for an ionization gauge controller which is set up for some other sensitivity (K_{N₂,cont}) than the gauge tube (K_{N₂,tube}), the following correction to the pressure readout will yield the nitrogen equivalent pressure:

$$P_{N_2} = P_{ind} \frac{K_{N_2, cont}}{K_{N_2, tube}}$$

To convert the readout also to some other gas, the equation must also include K_{gas,x,tube}, thusly,

$$P_{gas,x} = P_{ind} \frac{K_{N_2, tube}}{K_{gas,x, tube}} \cdot \frac{K_{N_2, cont}}{K_{N_2, tube}}$$

this then can be written either

$$P_{gas,x} = P_{ind} \frac{K_{N_2, cont}}{K_{gas,x, tube}} \quad \text{or}$$

$$P_{gas,x} = \frac{P_{ind}}{r_s} \frac{K_{N_2, cont}}{K_{N_2, tube}}$$

Example: For the nude tube of $K_{N_2} = 25/\text{Torr}$ using a controller of $K_{N_2, cont} = 10/\text{Torr}$ and for r_x of argon for which $r_x = 1.2$,

$$P_{Ar} = \frac{P_{ind.}}{1.2} \frac{10}{25} = \frac{P_{ind.}}{3}$$

Method B: The usual ionization gauge controller is designed for some calibrated set-point of emission = i_- . The new emission that will correct both for controller sensitivity and for gas type is

$$i_-^* = i_- \frac{K_{N_2, cont}}{K_{gasX, tube}}$$

or

$$i_-^* = \frac{i_-}{r_x} \frac{K_{N_2, cont}}{K_{N_2, tube}}$$

If actual emission current is not read out in current units, then these equations may be expressed as fractions of full scale as

$$\frac{i_-^*}{i_-} = \frac{K_{N_2, cont}}{K_{gasX, tube}} \quad \text{and} \quad \frac{i_-^*}{i_-} = \frac{1}{r_x} \frac{K_{N_2, cont}}{K_{N_2, tube}}$$

Note that Method B is useful only for decreases in emission current or small increases.

4. Gas Sensitivity Tables

The following table lists relative gauge sensitivities for various gases. The values listed are averages of several gauges and several references from the literature. These values are from

Table II, Ionization Gauge Sensitivities As Reported in the Literature, from NASA Technical Note TND 5285, by Robert L. Summers, Lewis Research Center, National Aeronautics and Space Administration. Please see this reference for further definition of these average values and for calculations of the gauge sensitivities of other gases.

To convert ionization gauge readout from nitrogen equivalent pressure, divide the readout by the values listed for r_x .

Gas	Average Values	
	$r_x = \frac{K_{gasX}}{K_{N_2}}$	
He	0.18	
Ne	0.30	
D ₂	0.35	
H ₂	0.46	
N ₂	1.00	
Air	1.00	
O ₂	1.01	
CO	1.05	
H ₂ O	1.12	
NO	1.16	
Ar	1.29	
CO ₂	1.42	
Kr	1.94	
SF ₆	2.50	
Xe	2.87	
Hg	3.64	

ORDERING INFORMATION

Bayard-Alpert Type Gauges

Tubulated gauges with iridium coated burn-out resistant filament

	¾ in. o.d. (19.1 mm) Catalog No.	1 in. o.d. (25.4 mm) Catalog No.
Pyrex tubulation	274 002	274 005
Kovar tubulation	274 003	274 006
Kovar tubulation flanged with 2¼ in. (70mm) o.d. non-rotatable CuSeal flange	274 007	274 008
Kovar tubulation flanged with 1-5/16 in. (33mm) o.d. non-rotatable Mini-CuSeal flange	274 020	

Tubulated Gauges with dual tungsten filaments

Pyrex tubulation	274 012	274 015
Kovar tubulation	274 013	274 016
Kovar tubulation flanged with 2¼ in. (70mm) o.d. non-rotatable CuSeal flange	274 017	274 018
Kovar tubulation flanged with 1-5/16 in. (33mm) o.d. non-rotatable Mini-CuSeal flange	274 021	

Nude Gauges

With dual tungsten filaments, EB degas only, on 2¼ in. (70mm) o.d. Conflat flange, EB degas only		274 022
With dual thoria coated filaments, on 2¼ in. (70mm) o.d. Conflat flange, EB degas only		274 023
With thoria coated filament, EB or I ² R degas, on 2¼ in. (70mm) o.d. Conflat flange		274 028

REPLACEMENT PARTS AND ACCESSORIES

Replacement filament assembly, tungsten, for use with 274 022 nude gauges only	274 02-
Replacement filament assembly, thoria coated, for use with 274 023 nude gauges only	274 02!
Replacement filament assembly, thoria coated, for use with 274 028 nude gauges only	274 02!
Flange gasket for 2 1/4 in. (70 mm) o.d. CuSeal flange, OFHC copper, per box of 10	214 12!
Flange gasket for 1-5/16 in. (33 mm) o.d. Mini-CuSeal flange, per box of 10	214 71!
Flange bolt, nut and washer set, for 2 1/4 in. (70 mm) o.d. CuSeal flange, per box of 25	214 12!
Flange bolt, nut and washer set, for 1-5/16 in. (33 mm) o.d. Mini-CuSeal flange, per box of 25	214 71!

†CuSeal flanges are manufactured to geometries licensed by Varian Associates, Inc. CuSeal flanges are produced in-house by Granville-Phillips and conform to AWS Standard 3.2-1-965

SPECIFICATIONS

PHYSICAL DATA	Tubulated Gauge	Electron Bombardment Degassable Nude Gauge	Resistance Heated Degassable Nude Gauge
Tubulation	3/4 in. (19.1 mm) or 1 in. (25.4 mm) dia. x 2 1/4 in. (57 mm) long., Kovar, Pyrex, or flanged	N.A.	N.A.
Envelope	Nonex 7720 glass, 2 1/4 in. (57 mm) dia. x 5 in. (127 mm) long	Nude	Nude
Mounting Position	Any	Any	Any
Collector	Tungsten	Tungsten	Tungsten
Filament	Dual tungsten or thoria coated iridium	Dual tungsten or thoria coated iridium	Thoria coated iridium
Grid	Refractory Metals	Refractory Metals	Refractory Metals
Overall Length	6 in. (152 mm)	4-1/8 in. (105 mm)	4-1/8 in. (105 mm)
Insertion Length	N.A.	3 in. (76 mm)	3 in. (76 mm)
OPERATING DATA			
Sensitivity for N₂	10/Torr ± 20%	25/Torr ± 20%	10/Torr ± 20%
X-ray Limit	About 3 x 10 ⁻¹⁰ Torr	About 2 x 10 ⁻¹¹ Torr	About 4 x 10 ⁻¹⁰ Torr
Electron Bombardment Degas	100 watts max.	40 watts max.	100 watts max.
Resistance Heated Degas	6.3 to 7.5V at 10A	N.A.	6.3 to 7.5V at 10A
Bakeout	450°C	450°C	450°C

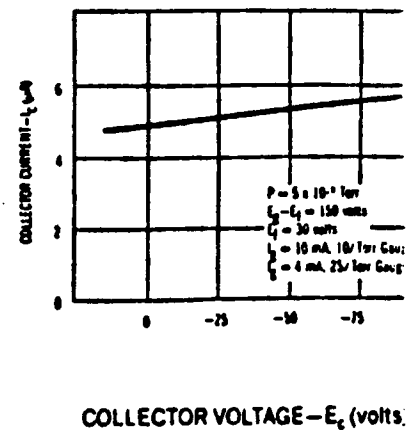
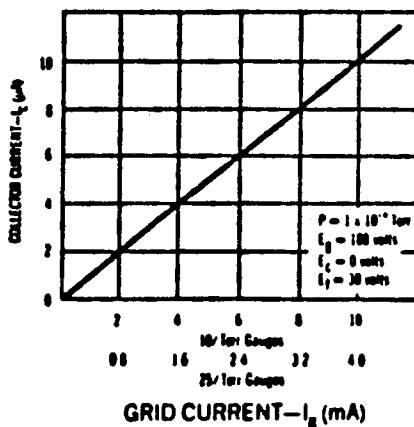
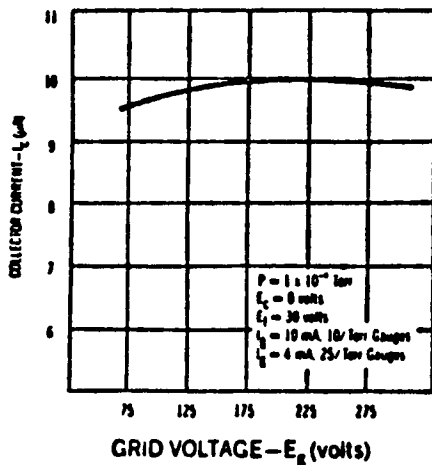


Figure 2. Operating Characteristics for Series 274 Ionization Gauge Tubes.

DIFFUSION PUMP

HS SERIES

NRC HS2

TYPE NO. 0160-0

6



*This pump is today
the best*

GENERAL

This specification sheet contains all information relating to the physical and operating characteristics of the NRC HS2 Diffusion Pump, Type No. 0160-0.

Before unpacking and installing the pump, the user should familiarize himself with the information in this specification sheet and the basic instruction manual for the HS- and HHS- series pumps.

OPERATING SPECIFICATIONS

OPTIMUM OPERATING RANGE:

2×10^{-4} torr to less than 3×10^{-5} torr

MAXIMUM PUMPING SPEED:

285 liters/second for air

MAXIMUM FOREPRESSURE:

No Load 5.5×10^{-1} torr

Full Load 4.0×10^{-1} torr

MAXIMUM THROUGHPUT:

0.5 torr liter/second

BACKSTREAMING RATE AT PUMP INLET:

0.0004 mg/cm² min (with cold cap)

POWER REQUIRED (APPROXIMATELY):

450 watts

HEAT UP TIME:

15 minutes

COOL-DOWN TIME:

5 minutes to "break" jet

10 minutes to vent pump

FLUID CHARGE:

100 cc All conventional and high performance pump fluids.

COOLING WATER REQUIREMENTS:

0.1 gpm at 60°F to 80°F inlet temperature

BACKING PUMP SIZE RECOMMENDED:

5 cfm or larger for optimum throughput.

Inlet Flange Connection:

OD	6 inches
ID	$3\frac{1}{16}$ inches
THICKNESS	$\frac{1}{2}$ inch
BOLT CIRCLE	4 $\frac{1}{2}$ diameter
NO. OF HOLES	4
SIZE OF HOLES	$\frac{1}{2}$ diameter
ORIENTATION	Straddle \odot
GASKET GROOVE	$3\frac{1}{16}$ ID x $\frac{1}{16}$ wide
GASKET O-RING	39HB-16

Foreline Connection:

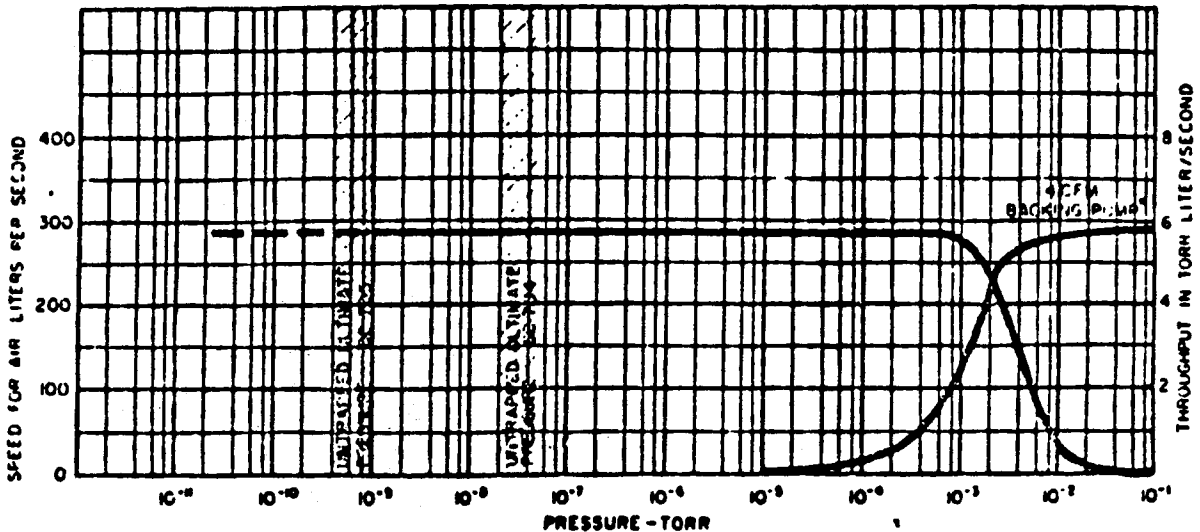
TUBING	0.840 OD*
HEIGHT	12 $\frac{1}{16}$ inches - Allow additional $3\frac{1}{2}$ " for heater removal
JET ASSEMBLY	Self-aligning, fractionating design with 3 diffusion stages and one ejector stage
FORELINE BAFFLE	Stacked half moons with snap ring retainers
COLD CAP	Conduction cooled
WATER CONNECTIONS	$\frac{1}{2}$ FPT body and quick cool.

Materials of Construction:

BODY	Stainless Steel
FLANGE	Mild Steel
JET ASSEMBLY	Aluminum
FORELINE BAFFLE	Stainless Steel
COOLING COILS	Copper, Welded to Body
HEATER REFLECTOR	Polished Aluminum
COLD CAP	Copper, Nickel Plated

* (Use $\frac{1}{4}$ ID x $1\frac{1}{2}$ OD rubber hose for vacuum service.)

SPEED CURVE



Speed Curves Based On Standard AVS Test Procedures

* Nominal backing pump speed in a typical AVS test installation

PHYSICAL SPECIFICATIONS Cont.

Heater: Cartridge Type
STD VOLTAGE (Nom.) 115V 1 ϕ
OPTION (Nom.) 220V 1 ϕ
POWER 450 Watts (Approximately)
CONNECTOR Plug-in, 115V, mates with Hubbell #5269. (220V, mates with Hubbell #5669)

EXTERIOR FINISH Green

ACTUAL WEIGHT 10 pounds

SHIPPING WEIGHT 20 pounds

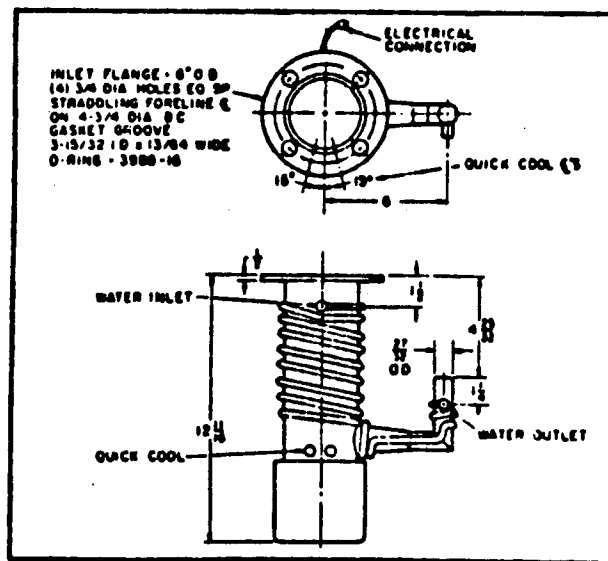
OPTIONAL COMPONENTS

6473-02-150 Heater, 450W, 240V
 8011-02-400 Cold Cap (Conduction Cooled)

When ordering replacement parts, quote type number and serial number of pump.

LIST OF REPLACEABLE PARTS

Catalog No.	Description
6473-02-125	Heater, 450W, 120V
6608-93-238	Inlet O-ring - Butyl
0181-82914	Jet Assembly
8014-02-025	Foreline Baffle
6601-56-010	Baffle Retaining Ring
8017-02-075	Heater Reflector
8015-02-010	Heater Heat Transfer Block
8018-02-025	Heater Platen
6460-18-010	Heater Clip
Standard	Heater Clip Screws 4-40 x 1/4 Rd Hd M/S Ni Plate
Standard	Reflector Nuts 10-32 Hex-S/S
Standard	Reflector Washers #10 Std Flat - S/S
Standard	Heater Screws - 1/2-20 x 1 1/2 Hex Hd C Sc/Lock washer - S/S



Norton Company reserves the right to change design and specifications without notice.

NORTON VACUUM EQUIPMENT DIVISION
 FORMERLY NRC EQUIPMENT CORP.
 160 CHARLEMONT ST. NEWTON, MASS. 02461

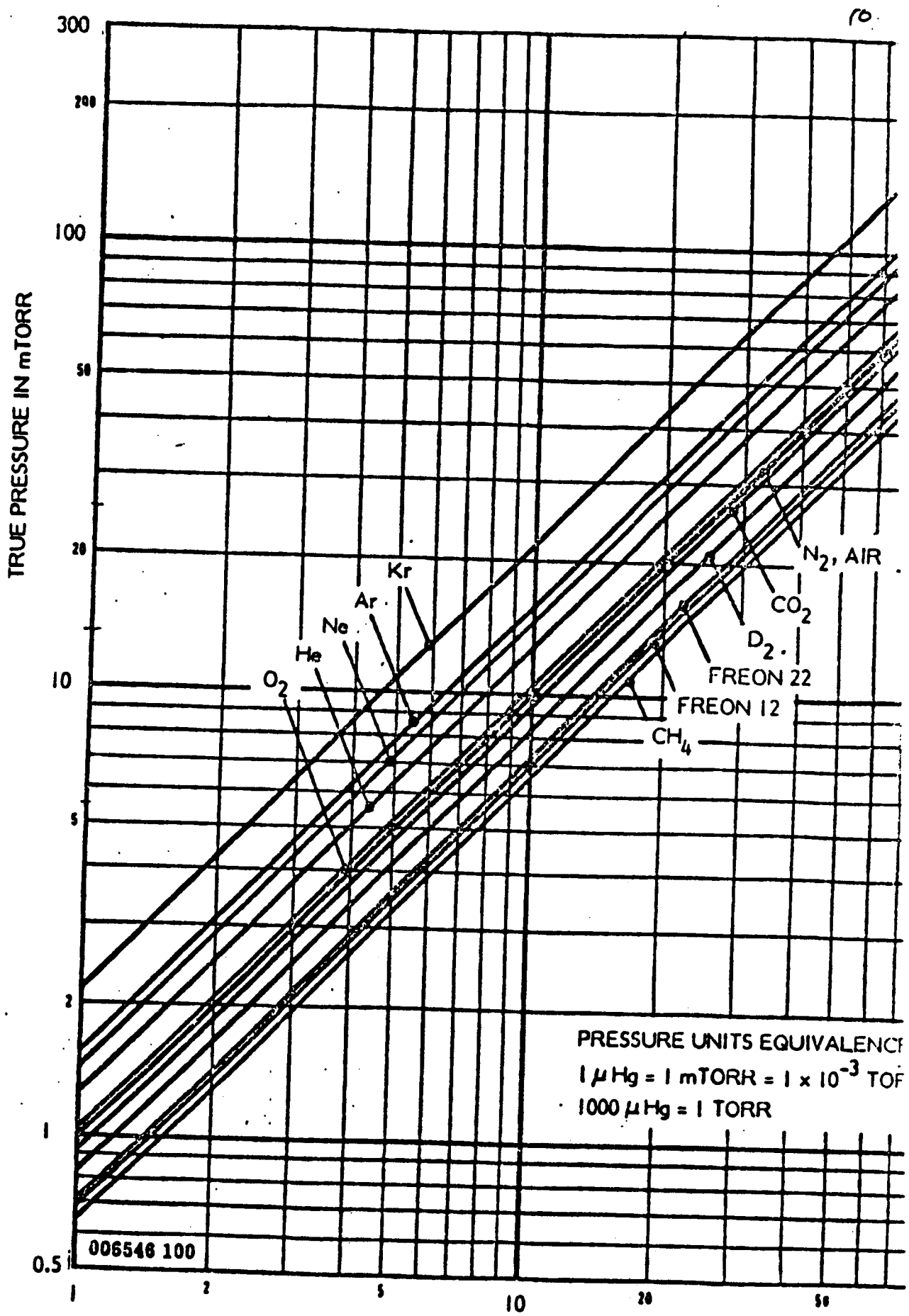
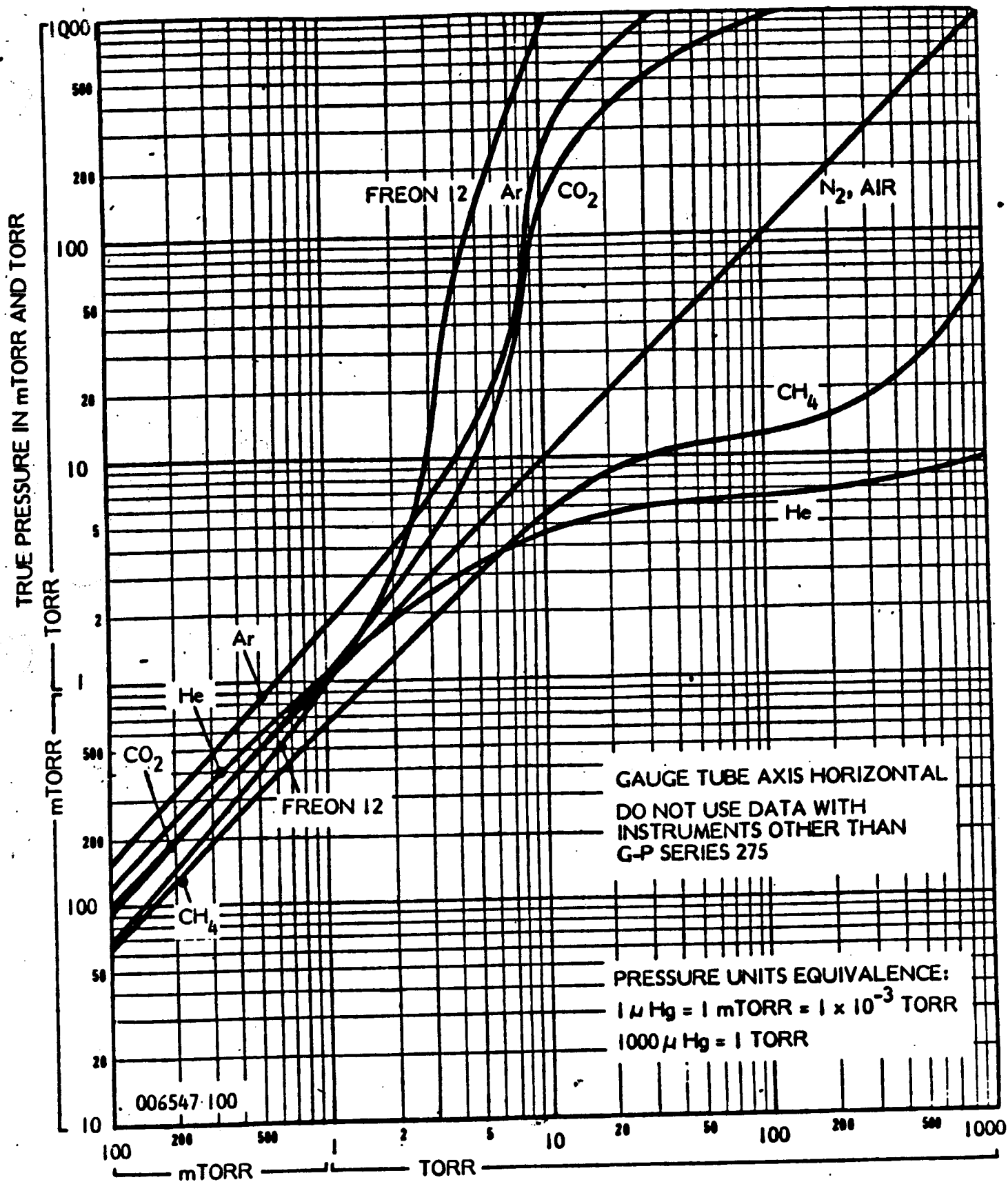


FIG. 6-1



INDICATED PRESSURE IN mTORR AND TORR
(N₂ EQUIVALENT)

FIG. 6-2

1402 160 L/M

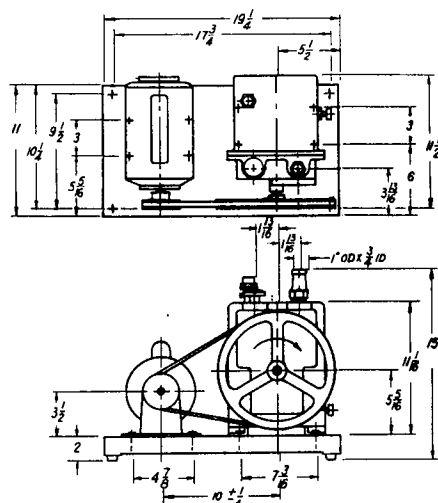
Guaranteed Pressure
0.1 micron (McLeod Gauge)
0.0001 mm Hg (1×10^{-4} torr)

Free Air Displacement
160 liters/minute, 5.6 CFM
(9.6 M³/hr)

Specifications:

Number of Stages 2
Guaranteed Ultimate Pressure
 1×10^{-4} Torr (McLeod Gauge)
Pump Speed 525 RPM
Motor 1/2 HP
Motor Speed 1725 RPM
Drive 1 V-Belt
Oil Capacity 2 1/4 Qts. (2.13 liters)
Tubing Required
13/16 in. I.D. (20.6 mm)
Intake Connection
Nipple Thread Type, 1-20
3/4 in. I.D. (19 mm)
Exhaust Connection
Thread Type, 1-20
Weight (pump only)
75 Pounds (34 kg)
Shipping Weight (pump only)
82 Pounds (37.2 kg)
Weight (pump, motor, base, drive)
112 Pounds (50.8 kg)
Shipping Weight (pump, motor, base, drive) 125 Pounds (56.7 kg)

Overall Dimensions
19 1/4" L x 12 1/4" W x 15 5/8" H
(48.9 x 31.1 x 39.7 cm)
Exhaust Filter Optional, 1417A
Filter Element 1417G
Vented Exhaust Standard
Belt Guard Standard
Quick Disconnect Coupling
Optional, 1393C



1402 Pump, Only Without base, motor and belt.

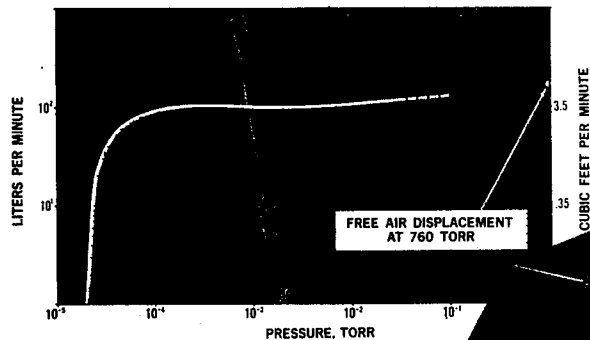
1402B-01 Pump Complete with base, motor, oil, belt, belt guard and cord with line switch and plug. For operation from 115/230 volt, 60 Hz power, wired for 115 volt operation.

1402C-01 Pump Identical with 1402B-01 but for operation from 230 volt, 60 Hz power.

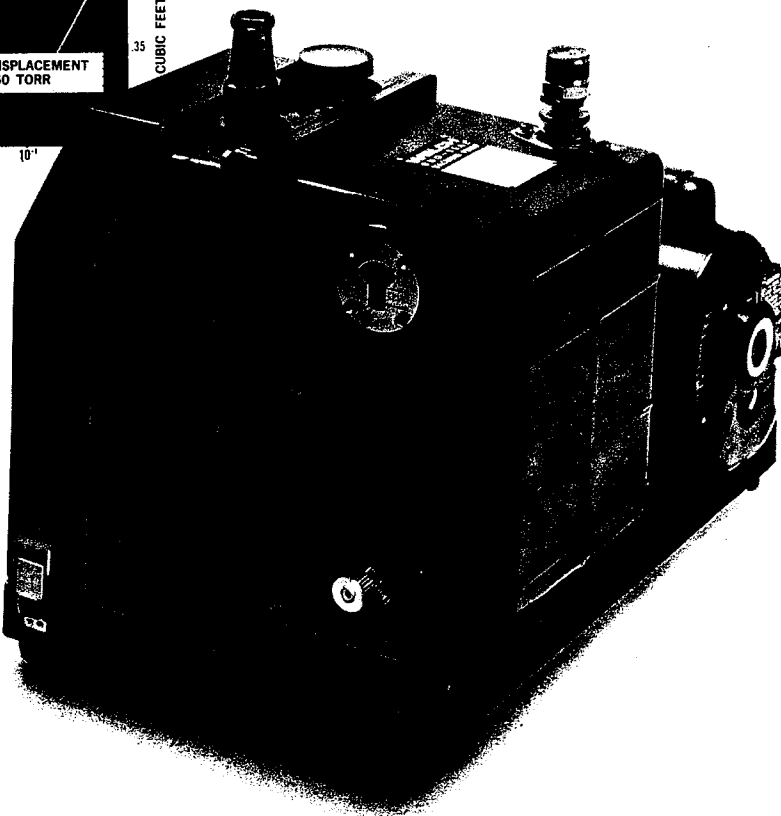
1402K-01 Pump Similar to 1402B-01 but for special helium transfer and not equipped with vented exhaust. For operation from 115/230 volt, 60 Hz power, wired for 115 volt operation.

1402L-01 Pump Identical with 1402B-01 but for operation from 110/220 volt, 50 Hz power.

1402M-01 Pump Identical with 1402B-01 but for operation from 3 phase, 230/460 volt, 60 Hz power.



This model is available with many other motors than those listed above, including totally enclosed and explosion proof types.



9/82 to Rebuild.
363 # 1402
to DAS to two weeks