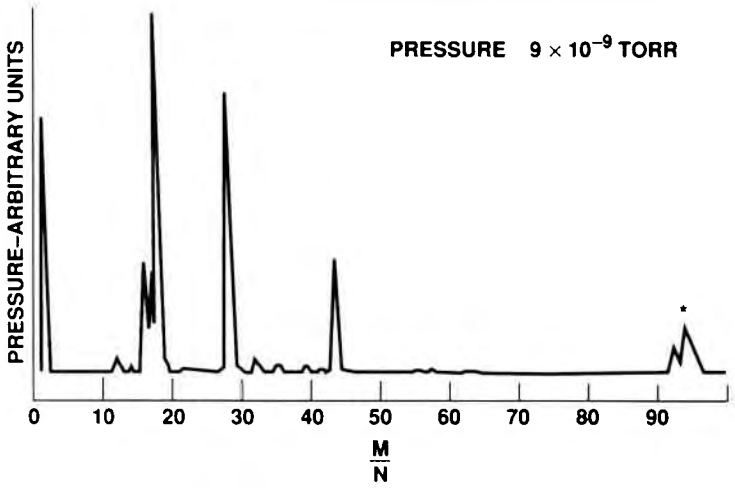


MASS SPECTRUM OF UNBAKED TURBO PUMP SYSTEM

*RHENIUM PEAK (FROM FILAMENT IN RGA)

Pump Base Pressure

Ultimate or base pressure is defined as the lowest pressure measured in the standard test dome within 48 hours after the prescribed bakeout is finished, per international test procedures (DIN Norm #28428).

To achieve the lowest base pressure in a system then, it is necessary to bake out the system and the turbo pump. Many people accept the pressure reached without a bakeout as their base pressure.

Care must be taken to ensure the temperature of the turbo pump never exceeds the manufacturer's maximum allowable temperature at the inlet flange, typically 80°–120°C.

Most manufacturers supply heating mantles to give the turbo pump inlet a mild bakeout. The chamber can be baked out with strip heaters or a small clamshell oven.

Potential Problems

The most common failures of turbo pumps are due to particulates, lack of bearing lubrication, and shock.

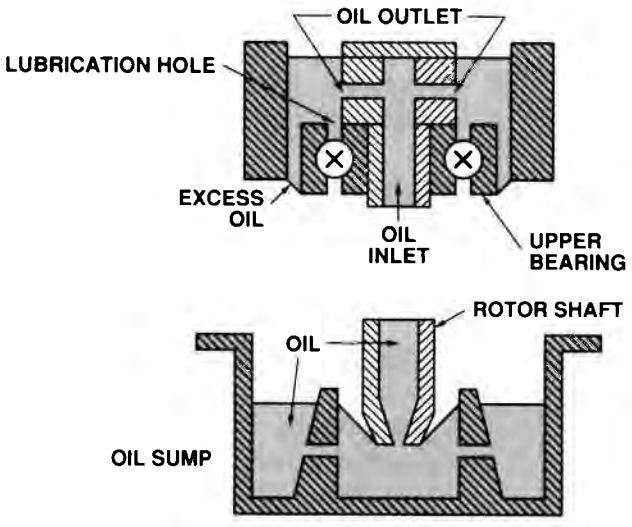
Lubricating Systems

There are a variety of methods used to deliver lubrication to the bearings. The most common are described below.

Circulating Oil

Oil is drawn up the shaft during operation and ejected over the bearings. This method provides a continuous flushing of the bearings, removing any particulates that have accumulated, and provides a continuous flow of lubricating oil. The oil also helps to cool the bearing.

Circulating oil is the most reliable method of bearing lubrication; however, it requires a vertical mounting of the pump and water cooling. In addition to superior reliability, it allows a visible indication of the oil quality and quantity through a transparent oil sump.

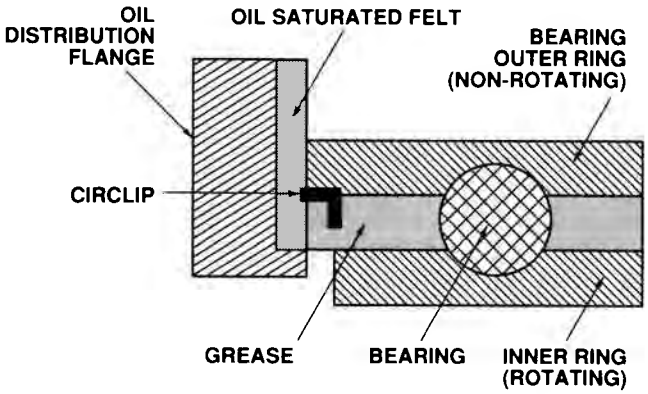


OIL LUBRICATION OF TURBO PUMP BEARINGS

Grease-Lubricated Pumps

In this method, the bearings are packed in grease, which contains a lubricating oil. Periodically, oil must be injected into the pump lubrication port to replenish the consumed oil.

Advantages of this method are that the pumps can be mounted in any orientation and usually can be air-cooled. Disadvantages are that the status of the lubrication cannot be determined as with the oil-lubricated pumps.



VARIAN GREASE-LUBRICATED PUMP OIL DISTRIBUTION DEVICE (SIDE VIEW)

Shock

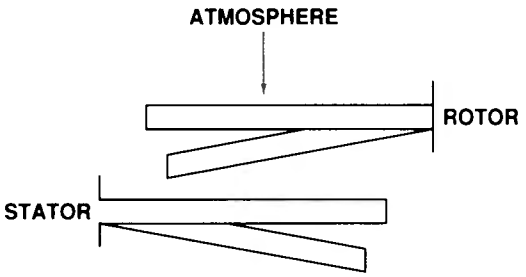
Since a turbo pump incorporates a precisely balanced high-speed rotating turbine, it should never be moved or jolted while it is in operation. This will help prevent a catastrophic crash (rotating rotor touching a stator and destroying the turbine).

There are two other modes of shock damage that should be avoided. One mode is that the system dumps to atmosphere while the pump is rotating. The second is improper venting. Let's look at these modes in further detail.

System Dumps to Atmosphere While Pump Is Rotating

Most well-designed turbos can withstand infrequent dumps to atmosphere without suffering a pump crash, although it is certainly recommended that one avoid this whenever possible!

The pump blades will flex when a gas load is dumped into the pump. If the rotor and stator blades come in contact with each other under these conditions, a catastrophic failure mode will occur. This is "fondly" called a crash. Proper valving procedures will help prevent this occurrence.



SYSTEM DUMPED TO ATMOSPHERE WHILE THE PUMP IS ROTATING

Venting

One should always vent the turbo pump while the rotor is still spinning.

If the pump is still in rotation when vented, rotational lift (like the way a helicopter blade produces lift) will minimize the loading on the bearings. If the balls in the bearings are not rotating, "dimples" can result as the impact on the balls permanently deforms the bearing race. Once this occurs, bearing failure can occur at any time due to the damaged bearing surface.

The proper location for the vent valve is at the turbo inlet, or at an interstage vent port, if available. Venting through the foreline is not recommended, as accumulated mechanical pump oil vapors can be forced into the high vacuum area of the pump by the inrushing air, eventually migrating to the system chamber if done

repetitively. This is the prime cause of contamination in a turbo pump vacuum system.

See the chapter on System Operation for more detail on how to vent a turbo pump properly.

Additional Concerns

Turbomolecular pumps must be protected against mechanical damage as well as against the loss of cooling water because the pump is a high-speed device with considerable stored energy. If a large, solid particle enters the rotor or a bearing seizes, serious damage may be done to the pump.

A splinter shield or screen located at the pump inlet adequately protects the rotors and stators from physical damage with some loss in pumping speed. Some pumps are available with side inlet ports. Water cooling is preferred in both oil-lubricated or grease-packed bearings. Proper cooling is necessary to remove heat from the bearings and to extend bearing life.

Turbomolecular pumps will give reliable, trouble-free operation if they are adequately lubricated and protected against cooling-water failure, power failure, mechanical damage, and excessive torque.

Backstreaming of mechanical pump oil can occur. Stopping the pump with the forepump operating and the work chamber under vacuum will result in rapid backstreaming of oil vapors from the foreline to the clean side of the pump. To minimize this back-streaming, you should always vent the turbomolecular pump from the inlet during shutdown.

The pump should be vented with dry gas in such a way that it will flow toward the foreline through at least a portion of a rotor and stator assembly. Oil vapors in the foreline are then flushed away from the high vacuum chamber. The pump must never be vented from the foreline because oil vapors will be forced back toward the pump inlet and the high vacuum chamber.

Vacuum System Use

Most system designs use the turbo pump coupled with a high vacuum valve. This design is similar to a diffusion pump system using a common roughing and foreline pump. It is possible, however, to rough pump a chamber right through the turbo; in this case, the turbo will gain speed as chamber pressure is reduced.

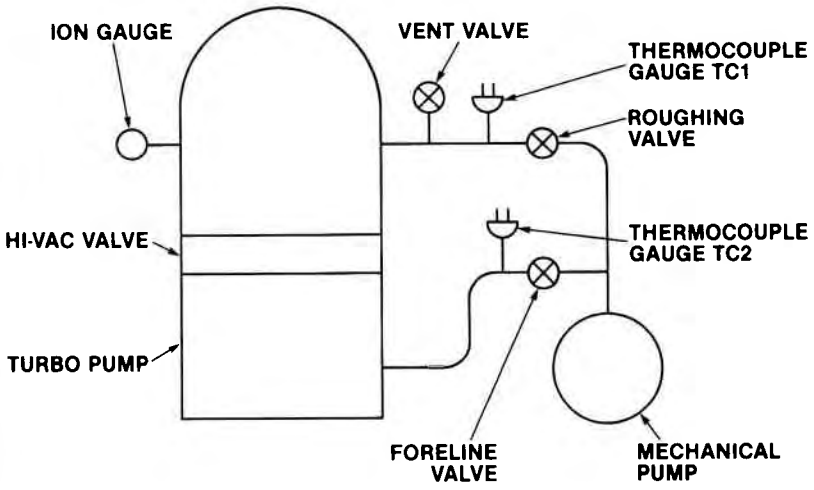
This type of system design shouldn't be used if the work chamber needs to be vented to high pressure very often, or if rapid pump-down to low pressure is required.

Turbo pumps can also be placed in series with cryotraps to promote high-speed pumping of water vapor and other condensables.

It is desirable to use a high vacuum isolation valve to isolate the turbo pump if roughing the chamber through a separate roughing line, similar to the way diffusion pump systems are manifolded.

This is especially true on fast cycling applications such as load locks, where it is desired to cycle the load lock at a rate approaching the start-up time of the turbo pump. To achieve the fastest cycle time, it is necessary first to rough the chamber through a roughing line and then transfer to the turbo pump (which is rotating at full speed). As a general rule of thumb, it is advisable to use a valved system if the chamber is going to be repetitively cycled from atmosphere to vacuum to atmosphere, with a total cycle time of less than ten minutes.

A valved system as shown here should also be used when evacuating a large vacuum chamber. Roughing the chamber through the turbo pump will be slower, since the turbo pump will have rather large conductance losses due to the small exhaust port on the turbo pump.

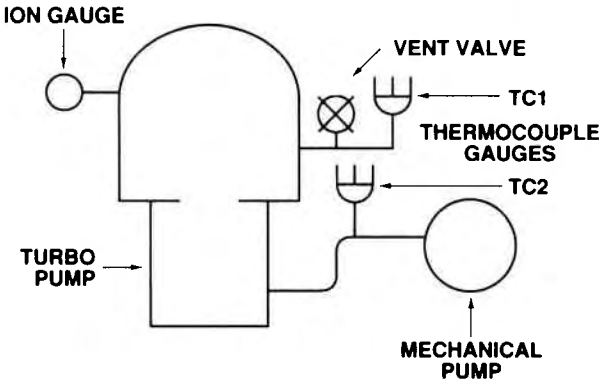


TURBO PUMP SYSTEM

Turbo pumps allow great flexibility in the choice of vacuum manifolding. For moderately sized chambers, the turbo pump can be mounted directly to the chamber without a high vacuum isolation valve. In this case, the turbo pump is cycled from atmosphere to high vacuum along with the chamber, and the chamber is roughed through the turbo. Usually, the turbo pump and

mechanical pump are started and stopped simultaneously. Most modern turbo controllers have provisions for switching the mechanical pump contactor on and off with single switch control of both mechanical pump and turbo pump from the front panel.

Alternatively, if the chamber is larger and cannot be roughed through the turbo pump to several hundred millitorr within the turbo pump start-up time, a delayed start can be employed by using a thermocouple gauge set point to delay starting the turbo pump until the pressure falls into the high millitorr range. The advantage of roughing through the turbo is that a simple system with minimal valving can be built. A disadvantage is the increased time required to reach high vacuum pressure levels.



TURBO PUMP SYSTEM ROUGHED THROUGH TURBO PUMP

Maintenance

If the pump and/or vacuum system become contaminated with forepump oil or bearing oil, it may prevent pumping below 10^{-5} torr. The pump and system should be cleaned with the appropriate solvents. Contact the pump manufacturer for the proper solvents and procedure.

Bearing wear is expected. Due to the precision balance and tolerances involved, bearings are normally replaced by factory-trained personnel. Turbos must generally be rebuilt every 2 to 5 years, if operated continuously. Typical turbo pump maintenance includes periodic changes of the lubricating oil for circulating oil-lubricated pumps, and relubrication by injecting the lubricant via syringe for grease-lubricated pumps. The manufacturer's recommended intervals should be followed. If an oil-lubricated pump is used, the oil should also be changed if it becomes discolored.

The manufacturer's relubrication or oil change schedule must be followed to ensure reliable lubrication of the rotor bearings. A lack of lubrication will result in bearing seizure and failure of the pump.

When the turbine speed drops to less than 60% of its nominal speed, gas or oil molecules can make their way from the foreline, past the inlet, and into the chamber. This can contaminate the pump and the product or process. Typical causes can be loss of power to the motor or controller or motor failure. Another cause can be an overpressure condition in either the chamber inlet or pump foreline.

The worst situation for a turbo pump is a hardware "crash." This is usually caused by debris falling into the pump inlet and touching the rotor blades. A "crash" literally destroys the internal pump stages. The pump must usually be replaced after this experience.

Contamination of the turbo pump rotor blades may occur, especially if the foreline is frequently air-released, as this will force mechanical pump oil vapor into the turbo pump. When contamination occurs, it will usually be evident by extended pumpdown times or an inability to reach accustomed base pressures. If this occurs, the pump and system should be cleaned with appropriate solvents. Typically, manufacturers recommend lowering a turbo pump inlet down into a solvent bath, making sure that the solvent does not reach the pump motor or bearings. Consult the manufacturer or turbo pump manual for explicit instructions and solvent to use.

As with any high-speed rotating bearing, wear will occur and require bearing replacement and rebalancing. Due to the precise balancing of the turbo pump required to achieve long bearing life, bearing replacement is usually done by factory-trained personnel.

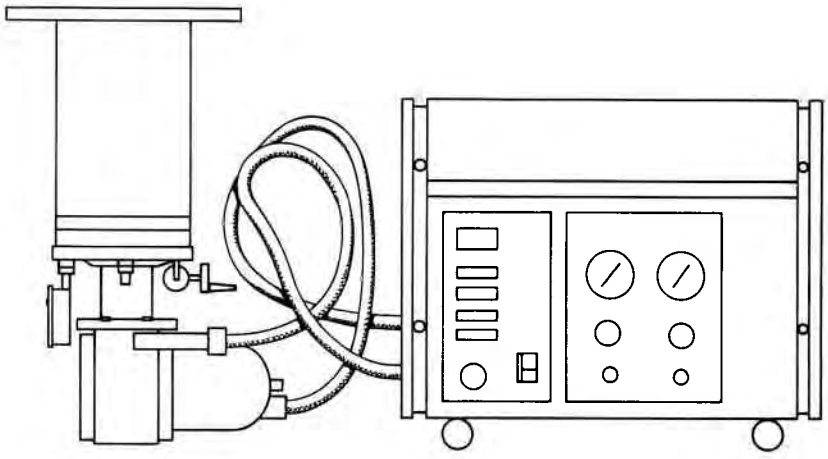
It is impossible to accurately predict bearing life due to such variations as cycling frequency, loading due to atmospheric dumps, and lubrication quality.

The bearings should be replaced when there is an increased level of noise and vibration. Worn bearings generate more noise which is more harsh in tone. You may also note an increased vibration level in your sensitive instruments.

Normal bearing replacement should be scheduled after 15,000 hours of operation.

Cryopump

The cryopump (also called mechanical cryopump) is unique in that it pumps by getting gases so cold that they freeze out and are stored, or captured, in the pump. It is extremely clean– it uses no oils, and has no moving parts in vacuum. It also has very high throughput. The cryopump is used in the high vacuum range in industrial applications where hydrocarbons cannot be tolerated. Models are available for UHV use as well.



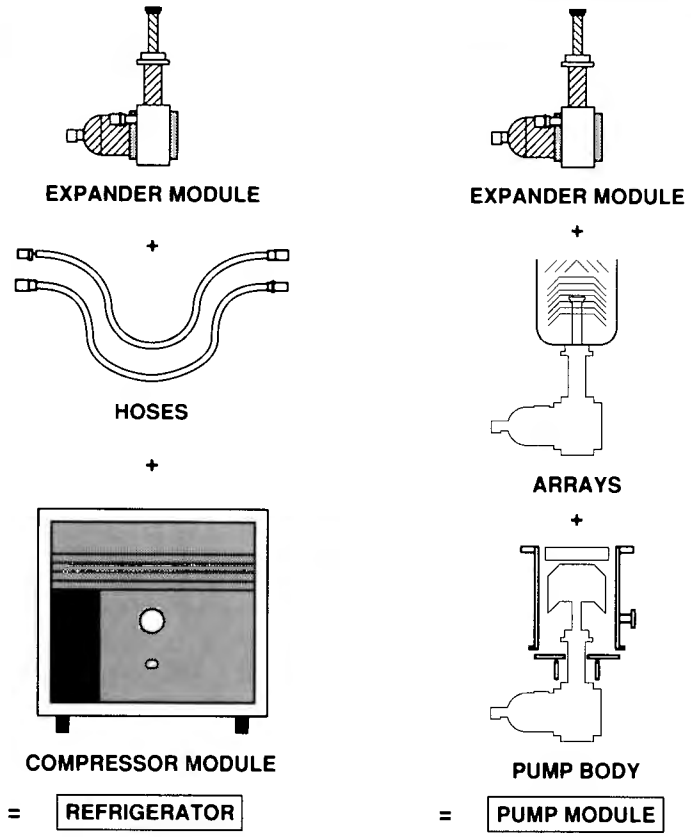
CRYOPUMP **COMPRESSOR**

closed-loop refrigeration system

A mechanical cryopump is made up of two main components: a gaseous helium compressor and a pump consisting of a cold head, baffle, pump body and sometimes an integral high vacuum valve. The compressor and cold head operate much like a household refrigerator, except that much lower temperatures are reached. The cryopump is a *closed-loop refrigeration system*, since the coolant does not vent to atmosphere.

Components

A mechanical cryopump consists of a pump module and a compressor module. These two modules are connected by flexible hoses to form a closed-loop refrigeration system. The main components of the pump module are the expander module, arrays and pump body. The compressor module, expander module and the flexible hoses that connect them form a refrigerator. Gaseous helium is circulated between the compressor and expander. Sometimes an integral high vacuum valve is included with the pump module.



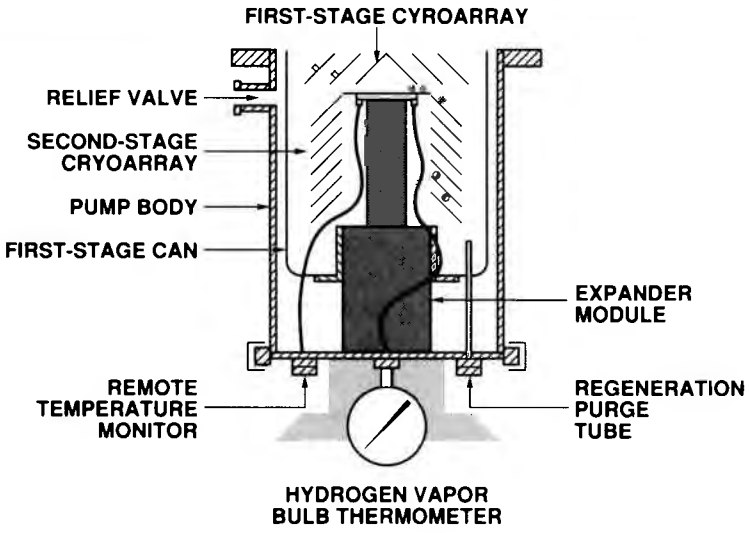
Pump Module

The pump module consists of the following major components: the expander module, the first- and second-stage cryoarrays, the pump body, the second-stage temperature monitors (remote sensor and/or hydrogen vapor bulb thermometer) and the pressure relief valve.

The expander is where refrigeration is produced. High-pressure helium gas is supplied by the compressor. This gas is expanded in two stages to produce cryogenic temperatures. The actual operating temperatures of the two stages will vary, depending on thermal and gas loads that are imposed. Typically, the first stage operates between 50° and 80°K, and the second stage, or cold head, operates between 10° and 20°K.

The cryoarrays are the pumping surfaces which are cooled by the expander. It is on these cryoarrays that gases from the vacuum chamber are condensed or adsorbed.

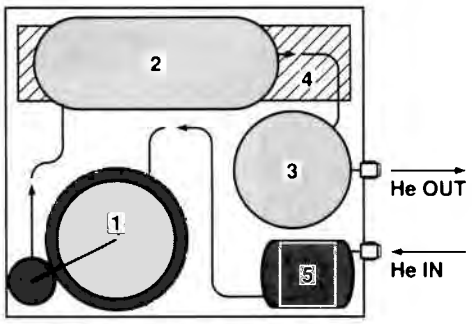
The pump body forms the vacuum-tight envelope which attaches the pump to the vacuum chamber.



THE PUMP MODULE

Compressor Module

The compressor module supplies high-pressure, high-purity, room-temperature helium gas to the expander module. The compressor module consists of an air- or a water-cooled, oil-lubricated compressor capsule, a two-stage filtering (coalescer and adsorber) system which removes vaporized oil from the high-pressure helium stream, a surge volume to reduce the returning pressure fluctuations, an interlock system to prevent damage to the compressor, and a power supply to run the compressor and expander.



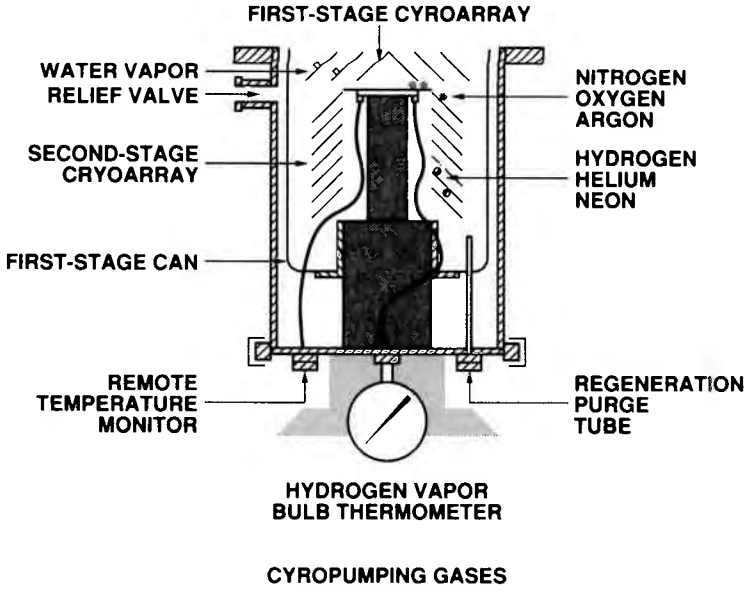
1. Compressor Capsule
2. Coalescer
3. Adsorber
4. Power Supply
5. Surge Volume

THE COMPRESSOR MODULE

How the Pump Works

In cryopump operation, helium is compressed, and gives up its heat to the surrounding walls of the compressor. This heat is removed by water or air cooling, which cools the helium. The cooled, compressed helium then goes to the pump cold head. In the expander at the cold head, a valving system allows the helium to expand. The expanded helium now takes in heat from the cold head and baffle array. This chills the cold head and baffle array to around 12°K and 70°K, respectively.

These chilled surfaces pump gases from the chamber. Chilled surfaces, in a vacuum, pump gases in two ways: The gases are either condensed (called cryocondensation) or adsorbed (called cryosorption) on the cryoarrays.

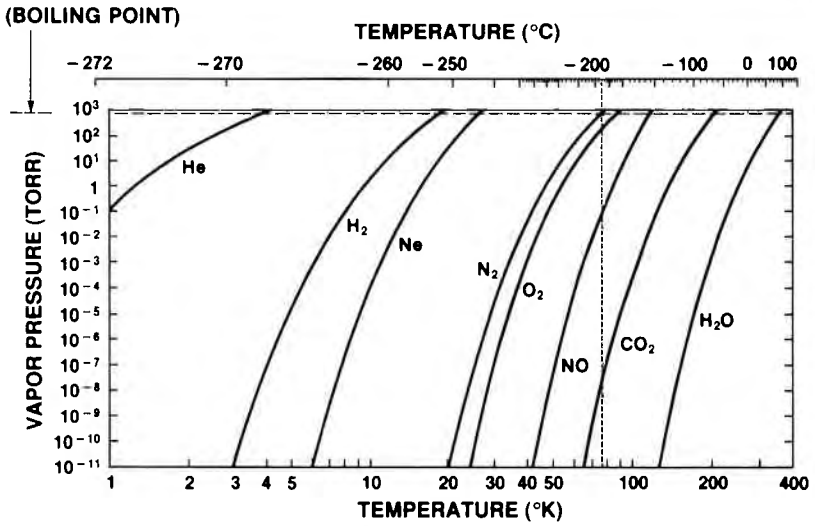


Cyrocondensation

cryocondensation

The cryopump pumps most gases the same way a household refrigerator "pumps" water vapor. That is, it condenses the gases to solids. This process is called *cryocondensation.*

The likelihood that most gases will stick to a surface in an ice-like condition at less than 20°K is quite high. At this temperature, the combination of partial pressures of most gases is around 10^{-11} torr or lower.



VAPOR PRESSURES OF COMMON GASES

Most gases are condensed on the first- and-second stage cryoarrays The first-stage array is cold enough to pump water vapor by cryocondensation. The second-stage array is cold enough to pump nitrogen, oxygen, argon and most other gases by cryocondensation.

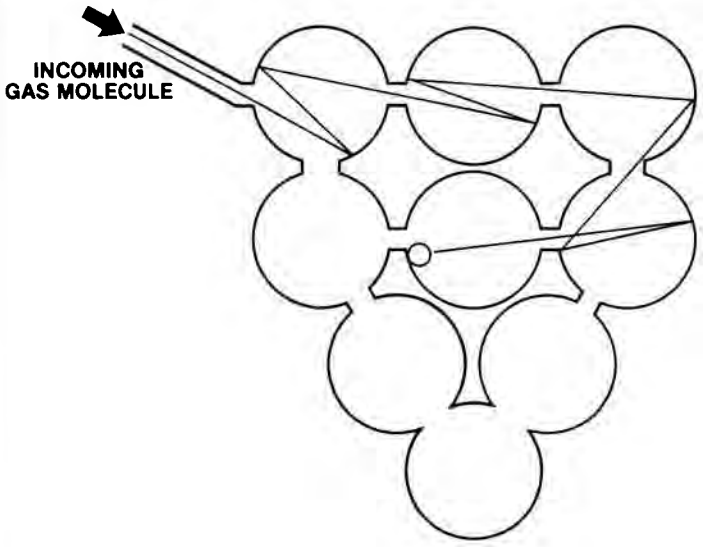
Cryosorption

cryosorption

The arrays are not cold enough to pump helium, hydrogen and neon by condensing them. So, we use another method to remove them. This method is called *cryosorption.*

Unlike cryocondensation, cryosorption is a surface-related phenomenon: the greater the available surface area at cryogenic temperatures, the more likely that gas molecules will stick to it. Although most gases are frozen or condensed between 12°K and 20°K, three gases are still very active at these temperatures: helium, hydrogen and neon. If we did not have some way to remove them, their partial pressures would continue to rise—perhaps to a point where the total system pressure would be unacceptable.

A very porous material is attached to the second-stage (coldest) cryoarray. This material is usually activated charcoal. Helium, hydrogen and neon are trapped on the maze-like structures and spaces of the charcoal. This is similar to a sponge soaking up water vapor at room temperature. This process is called cryosorption.



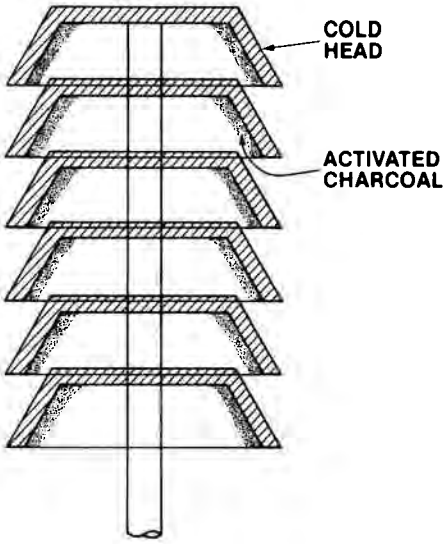
CRYOSORPTION

The use of porous material ensures three things:

1. Tremendous surface area is available on which to trap gases. The charcoal has an enormous surface-to-volume ratio: about 8,000 ft^2/cc.

2. Gases progressively lose thermal energy as they bounce around, and finally stick to these surfaces.

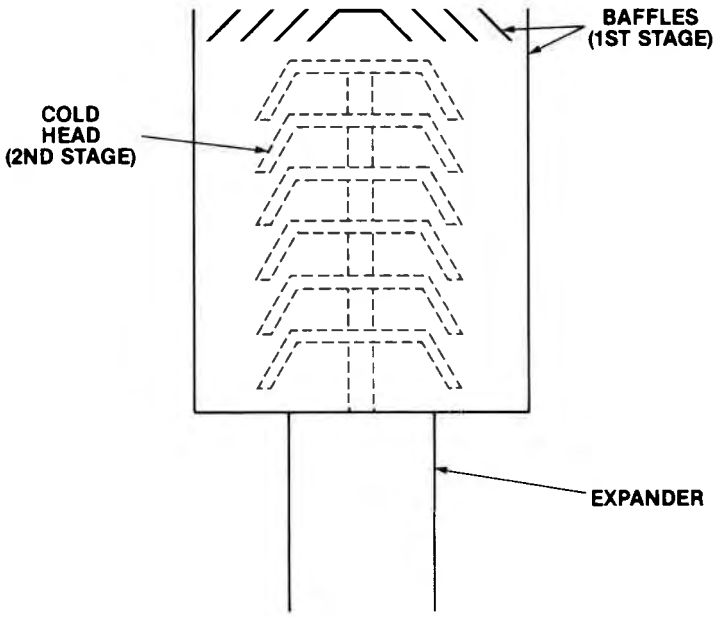
3. It is likely that once inside the "maze," the hard-to-trap gases will not wander out of the pump.



CHARCOAL PLACEMENT

Activated charcoal is bonded to the inner surface of the cold head or second-stage cryoarray. Since the charcoal gives plenty of

surface for helium, hydrogen and neon, it can also trap the easier-to-pump gases. Therefore, some means are required to keep the charcoal for the hard-to-pump gases only.



To keep the charcoal surfaces available for the harder-to-pump gases, the outer surface of the cold head is left uncoated. This provides adequate surface on which to condense the easy-to-pump gases. The charcoal is therefore less accessible to the easy-to-pump condensable gases. Finally, a baffle or first-stage cryo-array is placed around the cold head to limit the conductance to the charcoal surfaces.

The baffle also protects the much colder cold head from sudden temperature changes. Such sudden changes can be caused by gas loads and radiated heat from the pump body surfaces. This ensures that the gases trapped on the charcoal surfaces will not be released in the system inappropriately.

Start-Up

WARNING
The pressure relief valve is designed to prevent built-up pressure. Never alter, restrain, or remove the pressure relief valve.

Trying to start the cryopump at atmospheric pressure is like leaving the door open on your (household) refrigerator– the unit runs fine, but you are trying to cool down the whole room!

So, after we connect the power and water to our cryopump, the first thing to do is get the air out of the cryopump body. That is, we rough out the pump, using a well-trapped or an oil-free mechanical vacuum pump. This rough vacuum insulates our refrigerator from the "hot" air outside the pump—very much like a thermos bottle. Now the pump surfaces can get cold.

We then start chilldown. We valve off the roughing pump. (It will be used later for rough pumping the vacuum chamber.) We then turn on the compressor and let the pump chill down to operating temperatures. We can check this process by watching the temperature of the pump at either of two places. We can check either the hydrogen bulb thermometer or the solid-state sensor remote display—whichever is provided on the system.

Once the second-stage array is cold (below 20°K), our pump is ready to go to work. When the pump is operating, we can indeed treat it much like a refrigerator—let it run.

Crossover

crossover

Once the cryopump has cooled to operating temperatures (second stage less than 20°K), it has reached its full pumping speed and its capacity for retaining all gases. It is ready to be valved into the system. This is called *crossover.*

Cryopumps have the unique and desirable ability to pump larger-than-usual gas loads when being valved into the system. This is called the impulsive throughput capability of the pump. This provides shorter roughing times by allowing the roughing pump to be valved off at high pressures. It also reduces the probability of roughing pump oil migrating into the chamber.

The crossover pressure is the pressure in the vacuum chamber at which the roughing pump is valved off and the cryopump is valved in without adversely affecting the pump, the pressure or the process. The crossover pressure is high for cryopumps. It can be calculated by dividing the maximum impulsive throughput by the chamber volume:

$$\text{Crossover Pressure (torr)} = \frac{\text{Maximum Impulsive Throughput (torr-liters)}}{\text{Chamber Volume (liters)}}$$

You can find the impulsive gas load the cryopump can handle in your cryopump data sheet.

Steady-State Operation

After the cryopump is properly valved into the process chamber, the cryopump operating temperature should be maintained below 20°K for optimum performance. At chamber pressures less than 1×10^{-4} torr and/or when the high vacuum valve is closed, the second-stage temperature should normally be 14°K or less. For

steady-state operating parameters such as pump speed, capacity and throughput, check your cryopump data sheet.

Regeneration

regeneration

Cryopumps capture gases rather than compressing and expelling them, and they will eventually be filled up. We "empty" them by warming them to room temperature or above with heated, dry nitrogen gas. This process is called *regeneration.*

Regeneration, or emptying the cryopump, must be done periodically because the pump, like most refrigerators, will fill up with "frost," so "defrosting" or regeneration is needed.

Regeneration Process

Remember, a cryopump captures and retains gases on its internal cold surfaces— it has a storage limit. When the level of stored gas approaches capacity, pumping speeds lessen. When that happens, the cryopumping surfaces need to be emptied or regenerated.

Regeneration is a process whereby the captured gases are released and expelled. In effect, the pumping surfaces are renewed for further service. For cryopumps, the regeneration process consists of four steps:

1. Isolate the pump from the process chamber and turn off the compressor.

2. Warm the pump while purging with dry, perhaps heated, nitrogen (maximum temperature 120°C). The stored gases will be flushed from the pump through the pressure relief valve. If the pump has been used for toxic or caustic gases, precautions must be taken to vent the relief valve to a scrubber or other approved manner. As the pump is being regenerated, the sieve traps can be heated (baked out) to regenerate them. This should continue until the second-stage cryoarray reaches room temperature: 290°–295°K.

   No gauges should be placed on the pump body to read the pump pressure. During regeneration, the gauge may furnish a source of ignition to the potentially explosive gas mixture (hydrogen and oxygen) in the pump chamber.

3. Evacuate the pump with a roughing pump to remove the remaining gases and to create an insulating vacuum between the arrays and the pump body.

4. Chill the pump to operating temperature, then place it back into operation.

Please refer to the operator's manual for the details of regeneration for your particular cryopump.

Tips on Regeneration

Here are some tips for proper regeneration. These tips should be used to help keep your cryopump in good operating condition.

- *When to regenerate.* For a cryopump system, find out the length of time to reach an unsatisfactory base pressure or operating pressure. Routinely regenerate at 60% of that time. For example, if it takes 20 working days before a system pressure becomes unacceptable, regenerate once every two weeks.

- *The number of hours between regeneration cycles can also be calculated* in the case of a continuous gas flow of a known gas species.

  A = duration of operation with a continuous gas flow (hours)

  B = gas flow (sccm)

  C = Varian cryopump capacity for the particular gas species being pumped (std liters)

  $$A = \frac{16.6 \times C}{B}$$

  Example: For a sputtering application (Varian FS-8 pump) of continuously flowing argon gas at 70 sccm, the duration of continuous operation would be:

  $$A = \frac{16.6 \times 1{,}500 \text{ std liters}}{70 \text{ sccm}} = 356 \text{ hours}$$

- *Pressure relief valve.* The pressure relief valve opens at 7–9 psig and is located just below the top of the cryopump body. **Never defeat or limit this valve.**

- *Use of the purge tube.* Purging with heated (100°–120°C) nitrogen at the required pressure (15 psig) will insure that the second-stage array will be kept clean of water vapor; also, the nitrogen purge will insure dilution of any toxic gases collected in the pump.

- *Don't shorten regeneration time.* Follow the operator's manual for proper regeneration procedure and times.

- *Regenerate the sieve trap.* Regenerating the sieve trap prior to regenerating the cryopump will assure maximum protection from roughing pump oil.

Sieve Trap Use/Regeneration

When an oil-sealed mechanical roughing pump is used, a sieve trap is needed to prevent roughing pump oil from migrating back into the cryopump and the work chamber. A sieve trap is basically a cannister filled with molecular sieve material. It is installed into the roughing manifold. The sieve material consists of small, porous granules with a very large effective surface area—approximately 8,000 ft^2/gram.

The migrating roughing pump oil and other contaminants are filtered out by the trap. When the trap becomes saturated with oil or water vapor, it becomes ineffective as a filter and needs to be regenerated. Regeneration consists of heating the trap to about 250°C, while roughing and purging the trap with dry nitrogen at a pressure of about 2 torr. The nitrogen sweeps the evolving contaminants toward the roughing pump.

The cryopump roughing line sieve trap should be isolated between two valves after this bakeout to protect it and the cryopump from contamination. The valves are only opened during cryopump roughing so the trap will stay clean during normal system operation. The trap will not be exposed to the constant operation of the system roughing pump. (Note that the chamber roughing line sieve trap is not usually isolated in this fashion. The frequent cycling of the chamber makes this impractical. Thus, the roughing line trap should be regenerated with greater frequency.)

As a rule of thumb, the sieve trap should be regenerated just before the cryopump is regenerated. In automated systems, the microprocessor controls the regeneration procedures. The sieve trap bakeout is part of that cycle. The general procedure for regeneration of the sieve trap is as follows:

1. Isolate the sieve trap from the cryopump/work chamber.

2. With the roughing pump on and the gas ballast valve open, set up a nitrogen flow to raise the trap pressure to 2 torr through the trap. Turn on the bakeout heater(s) for the sieve trap(s).

3. When the sieve trap has reached 250°C (about 20 to 30 minutes after turning the heater on), maintain the temperature and continue to purge and pump on it for 45 minutes.

4. Turn off the bakeout heater.

5. Continue pumping and purging the trap for about 1 hour or until it has cooled.

6. Turn off the nitrogen flow and isolate the clean trap from the mechanical pump.

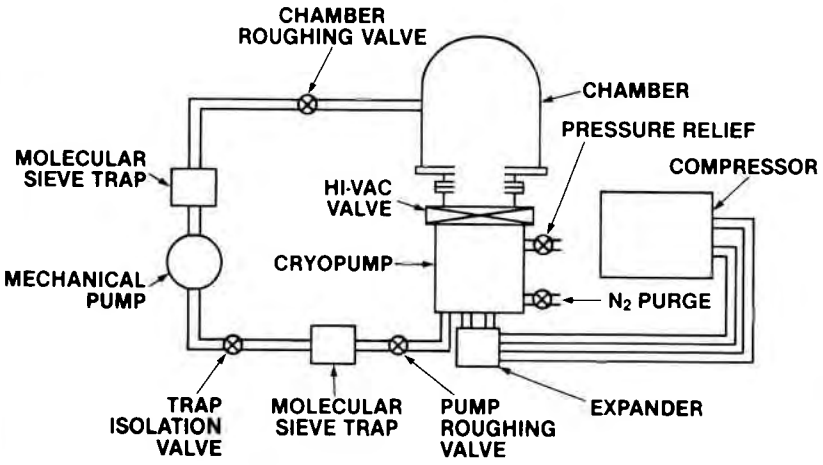
Shutdown

The cryopump can be shut down by simply closing the high vacuum isolation valve and shutting off the compressor. However, warm-up time to room temperature can be quite long (from 12 to 24 hours). Also, without proper regeneration, water vapor condensed on the first stage can migrate to the second-stage charcoal and decrease charcoal capacity.

Therefore, it is best to warm up the pump as described under "Regeneration." Warm the pump while purging with dry, perhaps heated, nitrogen (maximum temperature 120°C). The stored gases will be flushed from the pump through the pressure relief valve. This should continue until the second-stage cryoarray reaches room temperature: 290°–295°K. Once this temperature has been reached, shut off the purge gas heater (if used), close and turn off the nitrogen supply. This will ensure a dry atmosphere in the pump until further use.

Vacuum System Use

Mechanical cryopumps are currently gaining in popularity. They are used on vacuum systems wherever an ultraclean high vacuum and high throughput are required. Their use is limited by high heat processes and the presence of great quantities of hard-to-pump gases like helium, hydrogen and neon.



CRYOPUMP SYSTEM

Maintenance

Only cryopump maintenance procedures that can safely be performed in the user's facility are described here.

Most maintenance performed at the user's facility is not on the high-pressure portion of the cryopump. Any problem relating to the pressurized helium system of the expander, hoses or compressor (except for recharging the compressor) should only be checked at a service center. When the cryopump does not operate as specified, refer to the pump operator's manual. When the cause of the problem has been found, the operator's manual indicates whether maintenance and/or repair can be done immediately or at a service center.

As-Required Maintenance

You may perform the following maintenance items when they are required.

1. Clean pressure relief valve.
2. Replace cryoarrays.
3. Recharge refrigerator with high purity (99.995% or better) helium.
4. Replace the hydrogen bulb thermometer.
5. Replace the solid-state temperature sensor.
6. Clean and replace the Aeroquip fitting hose gasket.

If the charcoal-covered arrays on the cold head have been contaminated with mechanical pump oil, they must be removed and replaced with new arrays, and all internal pump surfaces cleaned.

The pressure of the system helium supply must be maintained. It should be checked only when the pump is at room temperature (chilled gases take up less volume). If the pressure is low, the system should be charged only with ultrapure helium—99.995% or better. Severe pump damage can occur if the wrong grade of helium is used or if the helium supply is contaminated with oil, water, grease, etc. Follow manufacturer's recommendations for proper charging techniques.

For more detailed maintenance, such as removing and cleaning pump surfaces, more detailed training beyond the scope of this course and manual is necessary.

Log Book

Check the vacuum system and cryopump on a regular basis for normal operating parameters. Record these in a log book. This should include such items as:

1. Base pressure
2. Operating pressure
3. Helium pressure
4. Expander temperature
5. Water flow
6. Cryopump regeneration cycle time
7. Sieve trap regeneration cycle time
8. Time when compressor adsorber was last changed

This is by no means a complete list of items to place in your log book, just a minimal list of items which will help in maintaining and troubleshooting your cryopump.

Regular Maintenance

The following procedures should be done on a regularly scheduled basis. Enter the date and time these procedures are done in your log book for future reference.

Cryopump Regeneration

Regenerate the cryopump. The gas load generated by your process determines how often you should regenerate. Cryopumped serial coaters are typically regenerated once a week. Ion implanters, perhaps every two weeks, or monthly.

Sieve Trap Regeneration

Regenerate the sieve trap. When automatic regeneration controllers are used, sieve trap regeneration is a part of the automated pump regeneration procedure. If hydrocarbon contamination of your vacuum system is a concern, regenerate the sieve trap(s) every time you regenerate the cryopump. *Remember:* Cryopumps and oil vapors are not compatible!

Pump Parameters Check

Check and record pump parameters weekly. These are listed above under "Log Book."

Adsorber Capsule Change

Change the compressor module adsorber capsule as specified by the operator's manual: Varian's original VK™ and Cryostack™ adsorbers after 9,000 hours, and thereafter every 13,500 hours; HV, VS, and FS series every 13,500 hours.

Molecular Sieve Change

Change the molecular sieve material and solvent clean the sieve trap body once a year. Follow the procedure in the operator's manual. Periodic sieve trap maintenance is important if you must keep all hydrocarbons out of your system.

4 Ultrahigh Vacuum Pumps

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

You should be able to—

1. Describe the major components of each type of ultrahigh vacuum pump.
2. Explain how the major types of ultrahigh vacuum pumps work.
3. Describe the place of these pumps in vacuum system use.
4. Describe in general how these pumps are maintained.

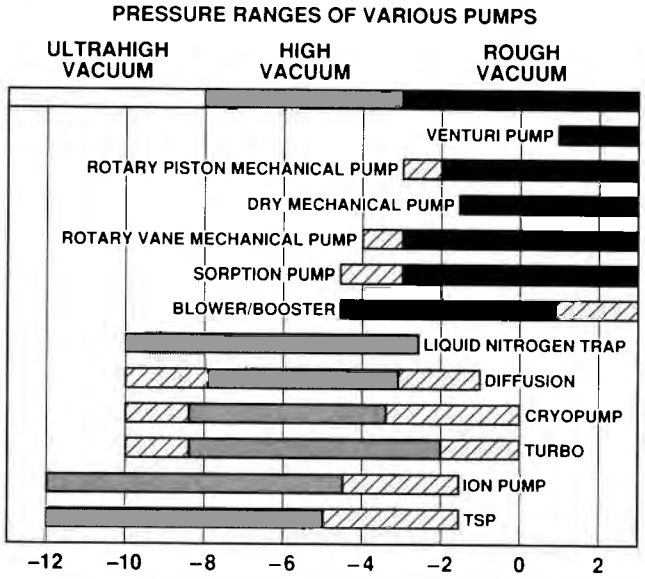
Introduction

You have seen some unique varieties of high vacuum pumps—pumps with no moving parts, pumps that aren't really considered pumps, and pumps that get quite hot or quite cold! But we aren't done yet. There's more to come in ultrahigh vacuum pumps!

bakeout

We should also state here that any high vacuum pumps that we have discussed in the previous chapter can operate in the UHV region. Generally what distinguishes UHV from other vacuum uses is, of course, the lower pressure. Another distinction is the need to *bakeout* the system to accelerate the release of gases and the need to minimize the number of permeable membranes (O-rings) in order to minimize the gas load on the pumps. The pumps that we will discuss in this chapter work very well for UHV systems—they also could be and indeed are used as high vacuum pumps as well.

In this chapter we will explain how ultrahigh vacuum pumps work and the general ways they are used. We will also discuss the major pump components and how the pumps are maintained. We will give an overview of how they fit into vacuum systems. System operation is explained in more detail in a later chapter.



This chart shows typical operating ranges for a variety of vacuum pumps. See the beginning of chapter 2 for a brief discussion of pressure ranges of pumps.

Operating the ultrahigh vacuum pumps above their normal operating range usually results in a very short operating life of the pump.

The ultrahigh vacuum pumps discussed in this chapter are:

Titanium Sublimation Pump
Non-Evaporable Getter Pump
Ion Pump

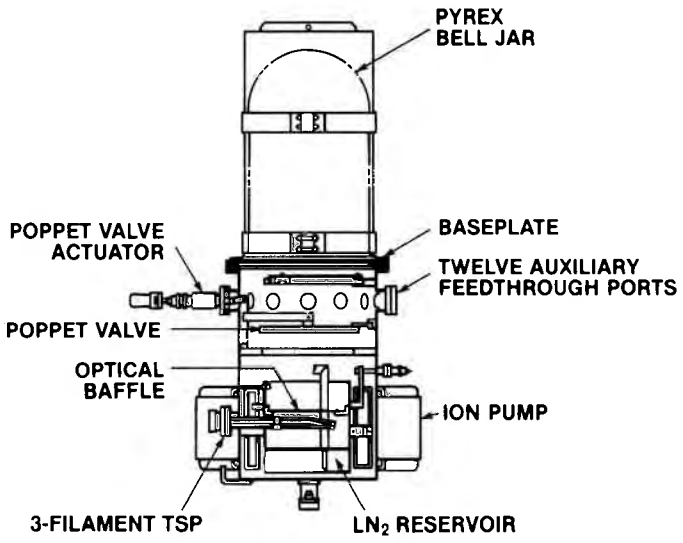
The titanium sublimation, non-evaporable getter and ion pumps are ultrahigh vacuum devices. They operate on completely different principles from those we've seen thus far. Their pumping is done mainly by chemical combination or by electrical means.

Titanium Sublimation Pump

gettering

The titanium sublimation pump is another type of gas capture or storage pump. In titanium sublimation pumping (TSP), titanium pumps gases by chemically reacting with the gas molecules, forming solid compounds. This reaction removes the molecules from the vacuum system. This method of removing gases is called *gettering*. Pumps that chemically react with gases are called getter pumps.

TSP pumps are used in vacuum system applications where no hydrocarbon or other vapors or contaminants can be tolerated; where a large pumping area or sump which is well baffled from the chamber is available; and where the presence of titanium will not interfere with the product or process.



Components

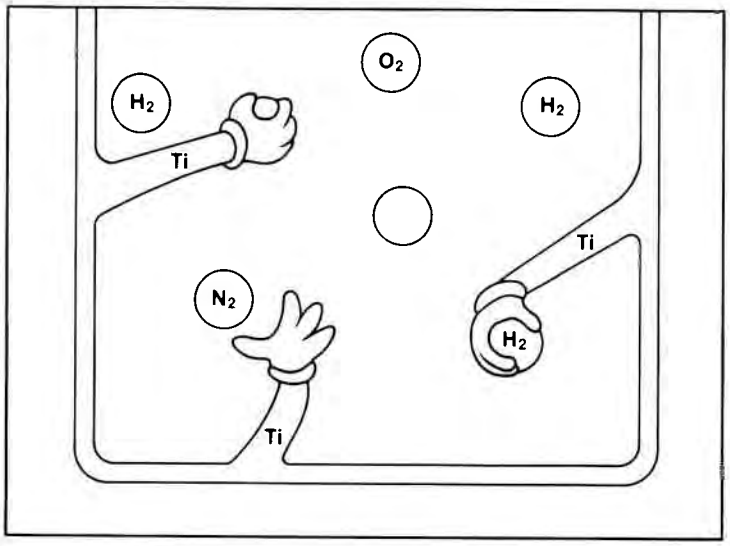
A titanium sublimation pump consists of a source of titanium, a source of heat, and surrounding surfaces on which a titanium film can be deposited.

How the Pump Works

Pump Operation

sublimes

Like many substances, titanium can skip the liquid state. When properly heated, it *sublimes*. That is, it goes directly from the solid to the vapor state. This vapor deposits on the surrounding surfaces.



Chemically, titanium is a very reactive substance. The deposited film combines readily with many gases, changing them into solid compounds such as titanium hydrides, oxides and nitrides. This is a form of chemical pumping. When the film of titanium becomes saturated, a fresh film is deposited, and the chemical pumping action resumes.

TYPICAL PUMPING SPEEDS PER SQUARE INCH OF TITANIUM SUBLIMATION SURFACE FOR VARIOUS GASES
(Liters per Second per Square Inch)

Surface Temperature	H_2	N_2	O_2	CO	CO_2	H_2O
20°C	20	30	60	60	50	20
– 195°C	65	65	70	70	60	90

Pumping Speed

Typical TSP pumping speeds for room temperature and LN_2 temperature are shown on the previous page. As can be seen, TSP pumping speeds improve significantly at LN_2 temperatures. This is due to the improved sticking coefficients. (A sticking coefficient is related to the amount of time available for a chemical reaction to occur as the gas molecules hit the titanium-covered sump walls.) The colder temperatures mean molecules will spend a bit more time on the wall surface. This, therefore, increases the time in which a chemical reaction can occur.

TSP pumping is very effective on reactive gases such as nitrogen, oxygen, hydrogen, carbon monoxide, carbon dioxide and water vapor. These are all common gases in vacuum systems.

TSPs will not pump inert gases or methane very well. If operated above 10^{-3} torr, two things generally happen:

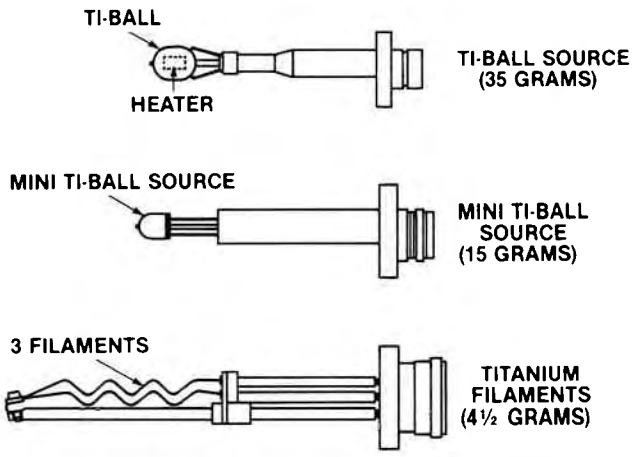
1. Oxide and hydride formation on the surface of the titanium source will work against sublimation.

2. The titanium that does manage to leave the source will tend to react with gas molecules before it can be deposited on the walls. This usually results in particulates, or "flakes." Although the flakes normally settle at the sump floor, they may be stirred up to become a process contamination source during the next roughing cycle.

Continuous deposition of titanium is unnecessary, and, in fact, is wasteful. A film of titanium can pump for extended periods at low pressures. If pumping doesn't improve following deposition of a fresh layer of titanium, it's likely that the previous layer wasn't fully "used up." The operator should watch the system gauges. After a titanium deposition, he should wait until the pressure drops and stabilizes before activating the titanium source again.

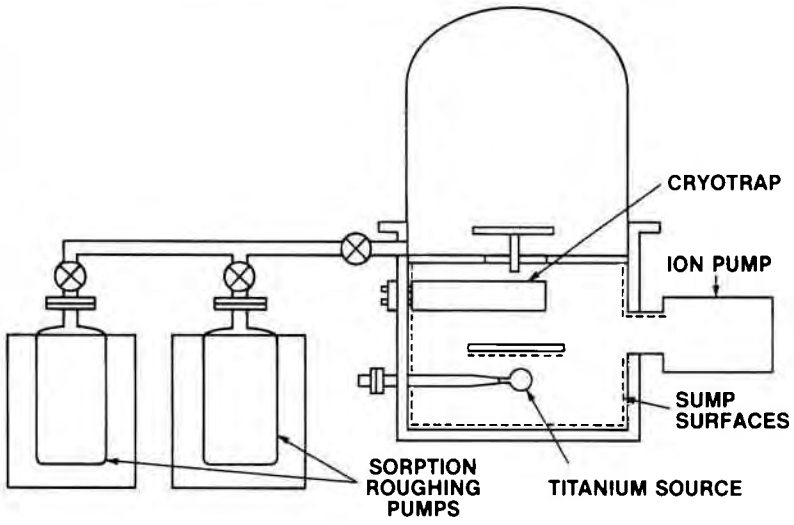
The Titanium Source

The titanium source is a compact unit; most models are mounted on a 2-3/4 in. ConFlat® Flange.



There are various titanium sources. Varian manufactures a three-filament source, a Ti-Ball Source, and a mini Ti-Ball Source. The Ti-Ball Source produces about 750 watts of heat at full power and 200 watts on standby power; the other two sources produce about 380 watts at full power. The mini Ti-Ball standby power is 95 watts; the filament source is simply turned off when not operating. The heat radiated to nearby surfaces may cause excessive outgassing in small volumes.

Vacuum System Use



Typically, UHV systems require an ultraclean environment. Because of this, TSP pumping is often used together with ion pumps and LN_2 traps or baffles. These systems are usually rough pumped by sorption pumps.

Maintenance

Titanium sources must be replaced when the titanium available for sublimation has been exhausted or when the internal heating coil (in the "ball" sources) has failed. Eventually, the sump surfaces are heavily coated and begin flaking. The sump must then be carefully cleaned.

Non-Evaporable Getter Pump

The non-evaporable getter (NEG) pump is just what its name says— a pump that reacts with gases to trap them on and within its surfaces. NEG pumps are typically used along with ion pumps to assist in pumping hydrogen at UHV (i.e., 10^{-9} torr and less). One of its advantages is that the NEG will release its gas load when heated to high temperatures (350°C). This makes it, for the most part, a regenerable pump much like a sorption or cryopump. This is in contrast to the TSP, which cannot be regenerated— we simply evaporate another layer of fresh titanium surface over the used surface.

Components

The NEG is an alloy containing zirconium, vanadium and iron (Zr-V-Fe) which is placed on a constantan strip and then formed into a cartridge for use. The cartridges may be placed in the system chamber or inside of a larger-size ion pump.

How the Pump Works

Pump Operation

The NEG is a getter pump, which means that it will pump chemically reactive gases, just as the TSP does. The pump speed for most reactive gases, such as 0_2, N_2, CO, decreases as the NEG surface fills up with the gases. The speed for hydrogen, however, remains relatively constant even when the pump is "full" of other gases. This is a great advantage at UHV pressures because the largest gas load is usually hydrogen. Thus the NEG pump can effectively double the pumping speed compared to the ion pump alone.

The NEG is essentially pumping all the time at room temperature, and when using one, it must be regenerated after installation into the system. There is no action that needs to be taken to "turn it on." It will need to be periodically regenerated in order to keep pumping effectively.

Regeneration

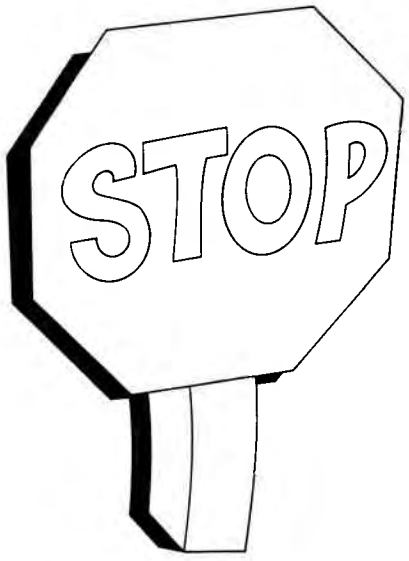
Regeneration consists of turning on the heater, the heater being the constantan strip which holds the alloy, and heating it to 350°C for approximately 1 hour. A very convenient time to do this is as a part of the bakeout cycle during pumpdown. The gases evolved from the NEG are repumped by the ion pump, the TSP, or a roughing pump at higher pressure.

Vacuum System Use

NEG pumps are used in ion pumps. Refer to the section on ion pumps later in this chapter for ion pump vacuum system use.

Maintenance

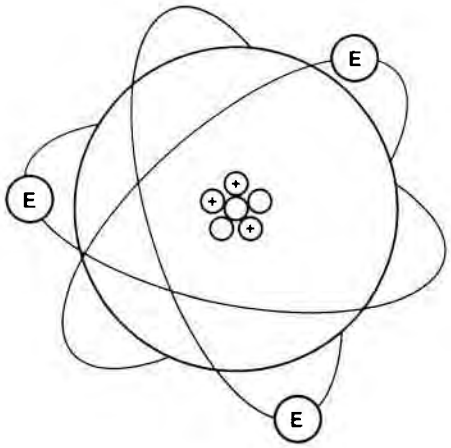
No maintenance is required of the NEG other than regeneration. After thirty or more regeneration cycles, the pump will probably need to be replaced with a fresh NEG pump. For typical UHV work, NEG life is several years because the system is kept at UHV conditions for long periods of time.



Review of the Nature of Gases

Before continuing, a few basic facts about the atomic and molecular nature of gases should be reviewed. Some of this information was discussed in chapter 1. These facts will be useful for understanding how ion pumps operate. Let's review them briefly here.

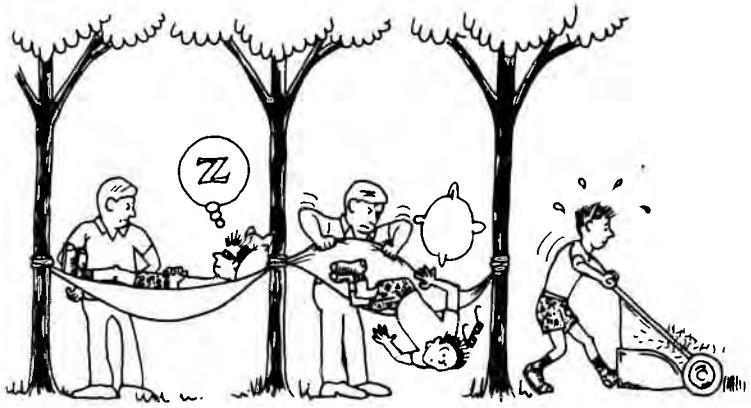
An atom is the smallest particle of matter that can exist and still retain the basic characteristics of the material or element from which it came. Molecules are simply one atom or two or more atoms joined together; many gases exist as molecules.



ion

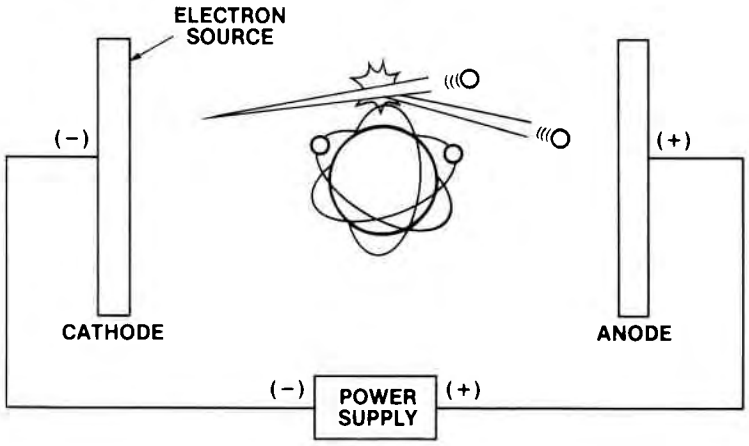
ionization

Atoms and molecules normally have an equal number of protons (positively charged particles) and electrons (negatively charged particles). The neutrons in the nucleus contribute to the weight (mass) of the atom but not to the charge. The atoms are thus neutral, or electrically balanced. If this balance is upset, useful work can be produced. If we remove electrons from the atom, we have made a positively charged atom or molecule we call an *ion*. This process of creating ions is called *ionization*. We can put these charged particles to work because we can direct their motion using a magnetic or electrical field.



Ion Pump

Let's now make our ion pump by connecting two electrodes to a high-voltage supply. Electron flow will be from cathode to anode as in this drawing. Ions will carry current from anode to cathode. Fewer ions than electrons will be produced so that we can say that the current through the pump is the "ion current."



sputtering

In this drawing, a free electron is attracted to a positively charged anode. On the way to the anode, it collides with a neutral atom, ionizing it. Now two electrons are free to continue toward the anode, increasing the probability of still further ionization. The positively charged ions are then accelerated toward the negatively charged cathode. They may impact the cathode with such force that they stick to the cathode material, and are thereby pumped. As one gas molecule is driven into the cathode, one or more molecules of the cathode is usually released from this surface. This process is called *sputtering*.

The ion pump is also a gas capture pump. It is not designed to pump heavy gas loads. For this reason, it is not generally used alone in high-production applications. Instead, it is more often used in research and analytical applications where there is no need to repeatedly and rapidly cycle the work chamber to atmosphere. When combined with a TSP, it also provides adequate pumping for these applications.

Ion pumps are clean operating devices. They are electronic devices which use no moving parts or oils. It is possible to achieve pressures in the 10^{-11} torr range, with overnight bakeout of the system. The bakeout process drives residual gas off walls. This gas is then pumped by the ion pumps.

In research and analytical applications, the ion pump's cleanliness, bakeability, low power consumption, vibration-free operation and long life make it the pump of choice for most ultrahigh vacuum uses.

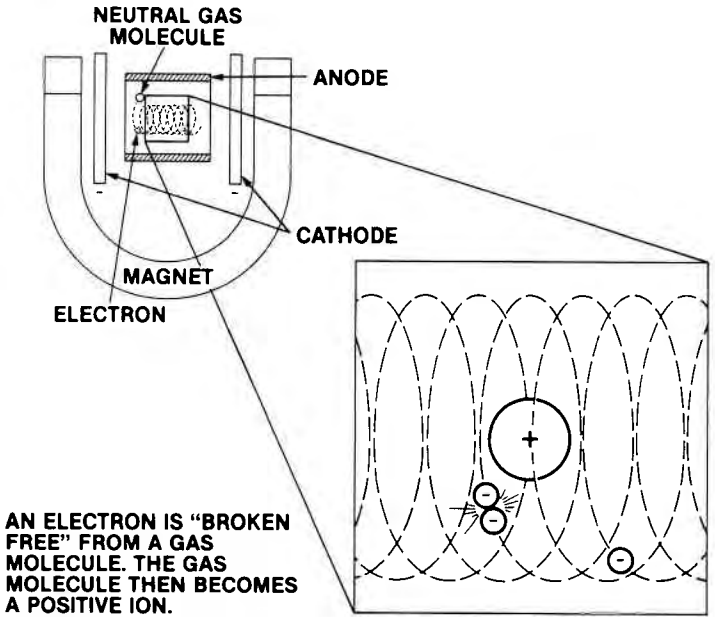
Ion pumps come in various sizes. A small appendage ion pump is used not for pumping down, but for maintaining vacuum conditions in operating devices such as transmitting tubes.

Larger pumps can be used to evacuate small chambers, or several can be connected in parallel with other ion pumps to pump down larger chambers.

Components

A basic ion pump cell consists of two titanium cathodes and an anode. All are placed between the poles of a strong permanent magnet.

How the Pump Works

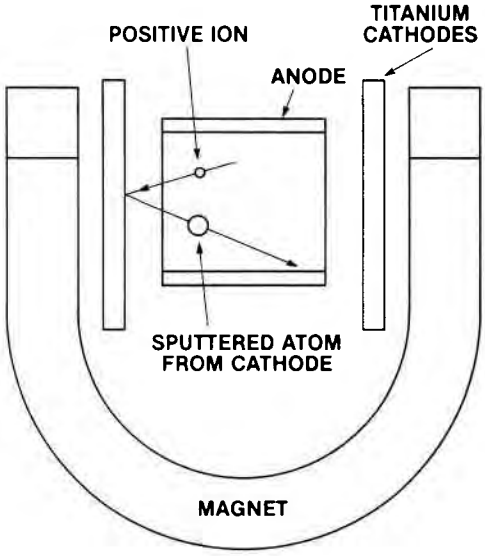


Pump Operation

The magnetic field forces the free electrons to travel in long helical paths instead of straight lines. This increases the probability of collision with molecules on their way to the positively charged anode. This, in turn, increases the ionization probability, and therefore the amount of useful pumping action that can be performed by the pump.

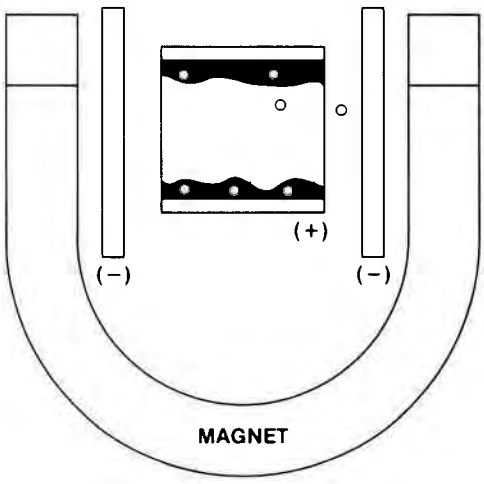
cold cathode discharge

Because of the action of the magnetic field, the electrons do not easily come in contact with the anode. As a result, a "cloud" of electrons is formed in the anode area. This electron cloud becomes fairly stable during pump operation. The electron density is high enough for efficient ionization of gas molecules. Therefore, a hot filament electron source is not needed. So, the name for this process is *cold cathode discharge*.



The positively charged ions, which are relatively heavy particles, are accelerated into the negatively charged titanium cathodes. This impact causes sputtering, or chipping away of the titanium cathode material.

Sputtered titanium deposits onto the internal structure of the pump. There it is available for chemical combination with gas molecules to convert them to solids. Thus we have the needed pumping action.



In addition, a second pumping action takes place. Some of the ionized molecules impact the cathodes with enough force to become buried in them. This burial prevents them from re-combining and becoming a free gas again.

Still another pumping process occurs in the case of hydrogen, which diffuses directly into and reacts with the cathode plate. Also, neutral molecules in the anode regions can literally be buried or "plastered over" by the sputtered cathode material. Complex molecules may also be split in the discharge to smaller, more readily pumped molecules.

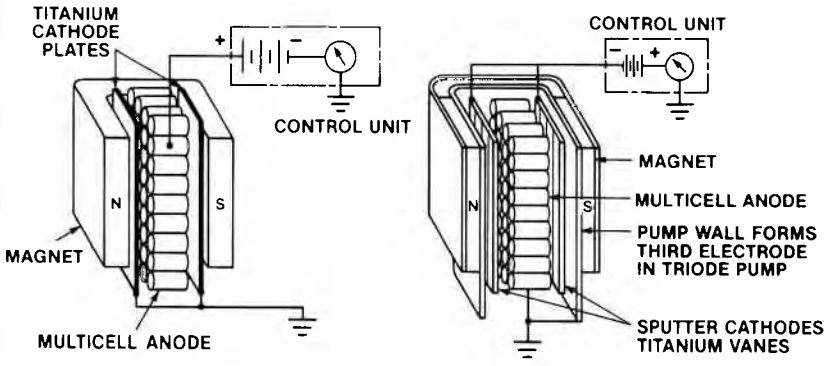
There is a problem with the pump design we have described (also called a diode configuration). Some of the buried molecules can be released again into the vacuum system. This re-release can be caused by heating of the cathodes or reduction of cathode material due to sputtering. It can also be caused by a molecule or atom being physically separated from the sputtered film.

Pumping Characteristics of Different Configurations

Ion pumps are available in different design configurations. Each design has its own special pumping characteristics.

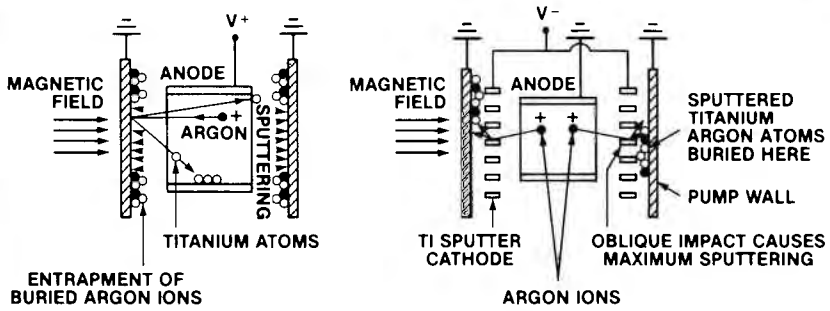
In the diode pump, as we have seen, the ions strike the cathode plate and react with the sputtered titanium.

The triode pump, which is a variation on the diode pump, improves inert or noble gas pumping. Titanium cathodes are in the form of grids. Ions sputter titanium onto the pump walls. This angled impact sputters more titanium than in the diode model and thus furnishes more material for argon or noble gas burial. Because of the electrical arrangement of the pump components, the glow discharge that happens in "starting" the diode pump is typically confined in the triode pump. As a result, the triode pump can be started at slightly higher pressure.



ION PUMP SCHEMATICS

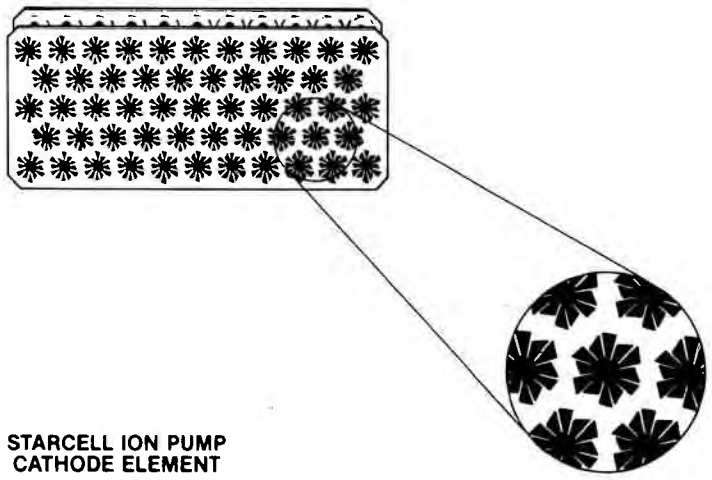
(A) DIODE PUMP (B) TRIODE PUMP



PUMPING MECHANISMS

(A) DIODE ION PUMP **(B) TRIODE ION PUMP**

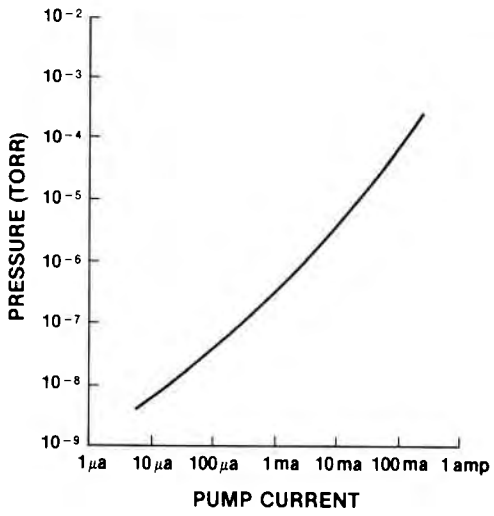
The StarCell™ ion pump provides more noble gas pumping than a triode pump and a stability which is not attainable with a diode element. The StarCell™ pump has an anode structure and two cathode plates. Radially symmetrical, finned cells in the cathode plates are concentric with the anode cells. This increases the probability of higher rebound energy noble gas molecules– an improvement in the efficiency of the noble gas pumping mechanism. Its useful life is greater than diode- or triode-type pumps.



STARCELL ION PUMP CATHODE ELEMENT

Other Characteristics

The ion pump is self-regulating. At the higher pressures, where much ionization takes place, more current flows. At low pressures, less current flows. This characteristic current drain can be used to measure the pressure, or degree of vacuum achieved with the pump. This feature eliminates the need for an ion gauge on the system.



Ion pumps are long lived; the lower the pressure, the longer the life. Once they begin pumping, they quickly lower the pressure to the long-life region. As long as they are not pumping against a leak, they will last for years. Ideally, ion pumps should be started at pressures approaching 10^{-5} torr. At higher pressures, the plasma discharge that is generated minimizes pumping speed and reduces cathode life. A more common and practical approach is to sorption rough the pump to less than 10^{-2} torr before applying the ion pump power. At very low pressures, the time taken to begin the ionization process may be excessively long.

TYPICAL DIODE PUMP SERVICE LIFE

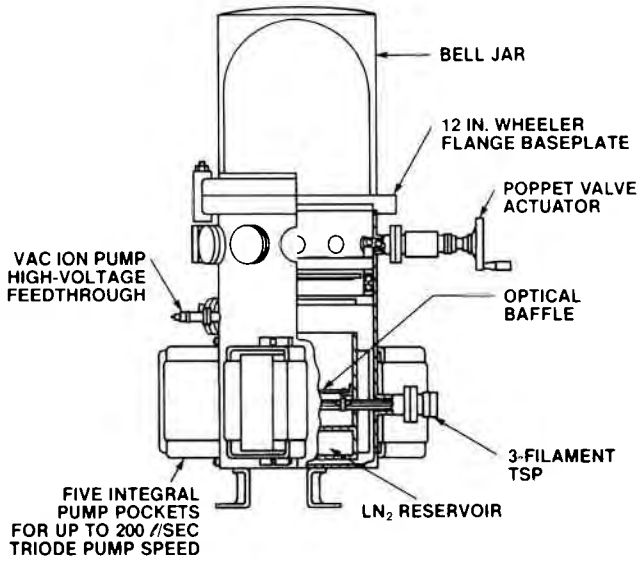
Pressure (Torr)	Life (Hours)
10^{-3}	20
10^{-4}	200
10^{-5}	2,000
10^{-7}	200,000 (over 20 years of constant operation)

Life (Pumping N_2 at 10^{-6} Torr)	
Triode	35,000 hours — approx. 4 years
Diode	50,000 hours — approx. 6 years
StarCell	80,000 hours — approx. 9 years

Vacuum System Use

Ion pumps are typically used in systems which demand ultra-clean, ultrahigh vacuum. This type of vacuum system is pumped to high vacuum or lower pressure and then kept in that condition

for long periods of time. A load-lock chamber is often built on the system to allow access to the chamber without bringing the chamber back to air. Typical uses are for electron microscopes, mass spectrometers, and surface analysis, to mention a few.



Maintenance

Very little maintenance can be performed on ion pumps other than an occasional bakeout. When pumping eventually deteriorates to the point where operating pressures can no longer be attained, pump replacement or sometimes anode/cathode assembly replacement is necessary.

Summary

We have discussed the pressure ranges of vacuum pumps and the major types of pumps in each range. By now, you should be familiar with the different types of vacuum pumps—what their major components are and how they work. You have also learned how they are placed in vacuum systems and some general maintenance information.

Let's go on now to gauges. These are major vacuum components that tell you what is going on inside your vacuum system.

5

Gauges

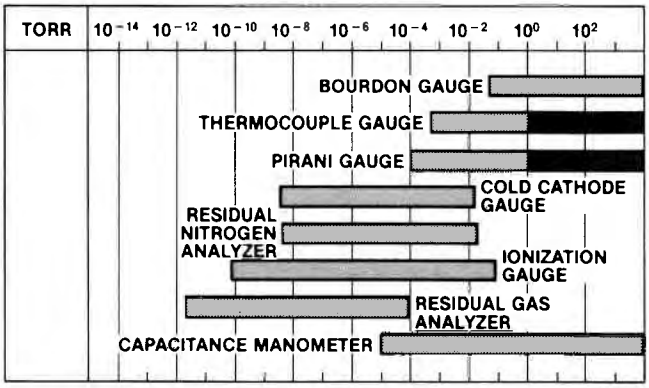
In this chapter, you will learn to do the following:

1. List the commonly used vacuum gauges.
2. Give the pressure range in which each of these gauges operates.
3. Explain how these gauges work.
4. Describe how these gauges are maintained.

Introduction

Gauges are an important part of your vacuum system. You rely on them to tell you what is happening inside the system. If you have worked with vacuum systems, you know that you must read several gauges— not just one. The pressure range is too great for any one gauge to read. The various gauges all have limited useful ranges. As a result, we must use several different types of gauges in order to read all the pressure ranges. Many gauges measure pressure. Only the commonly used ones are covered here. For example, the Bourdon, thermocouple, ionization, and cold cathode gauges, residual nitrogen analyzer, capacitance manometer, and residual gas analyzer. This chart shows typical pressure ranges of the gauges.

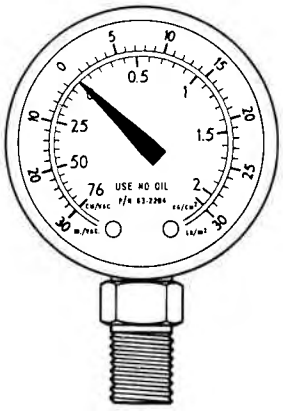
TYPICAL GAUGE PRESSURE RANGES



The gauges cover the entire operating range of all vacuum pumps covered in the previous chapters. We will start with rough vacuum gauges and work our way to the high vacuum gauges.

We would like our gauge to respond to total pressure— force per unit area— in order to be able to read the pressure in our vacuum system. We will see that for most vacuum gauges, the actual force per unit area is not what is measured. The gauge senses some other property. This reading is then converted to a pressure reading. Let's look at some rough vacuum gauges now.

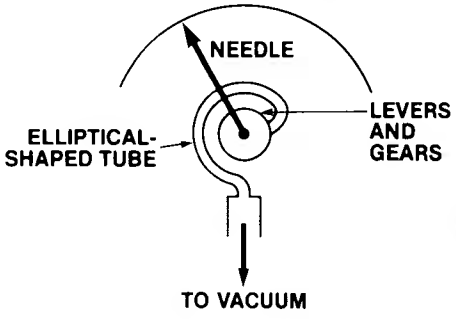
Bourdon Gauge

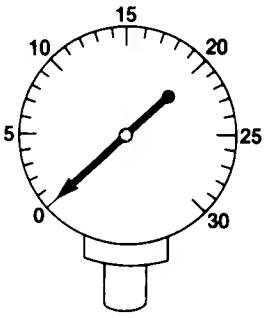


The Bourdon gauge is rugged and reliable. It can be used for measuring pressures above and below atmospheric pressure. Notice that it resembles a vacuum pressure gauge used in automotive tune-ups—same principle!

Generally, the accuracy of the Bourdon gauge is not high, but it is simple and reliable. At the lower end of its range, it really is not very sensitive. It stops reading around 1 to 0.1 torr.

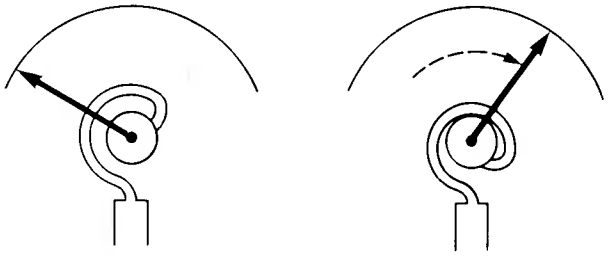
How the Gauge Works





The Bourdon gauge measures relative pressure. Here's how it works. A tube in the Bourdon gauge is bent into an arc. One end is open to the vacuum chamber. Its other end is sealed and connected to an indicator needle. The meter scale is calibrated in inches of vacuum: zero is atmospheric pressure, and 30 inches corresponds to the low end of its range. This, of course, means that it is reading the relative pressure, or gauge pressure. It is comparing the pressure inside the tube to the pressure outside the tube. The gauge does respond to changes in pressure; but these

are the changes inside relative to the pressure outside. Since the pressure outside is always changing, by as much as ±10% from the average pressure, its accuracy is only moderately good.



The inside of the tube is open to the chamber, and the outside is at atmosphere. As the chamber is pumped out, the pressure difference between the inside of the tube and the outside of the tube causes the curvature of the tube to change. A system of levers and gears moves the needle according to the change in the bend of the tube.

Maintenance

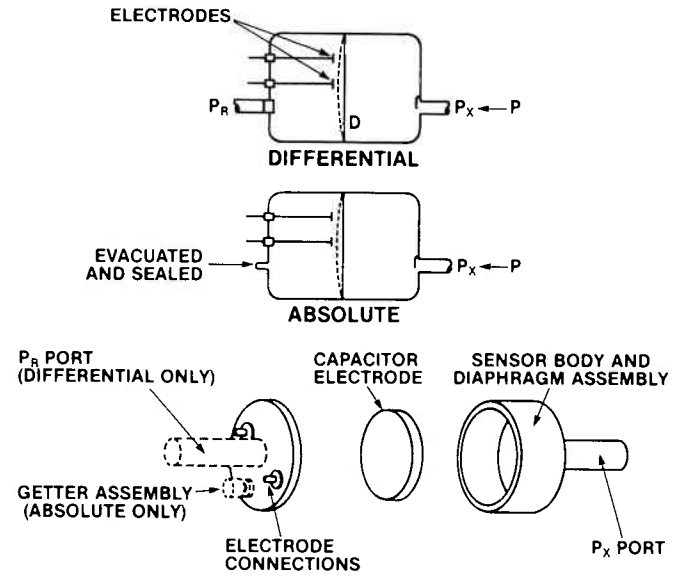
Bourdon gauges typically do not get any maintenance. The more expensive varieties may have mechanical adjustments that can be made. In general, the gauge is replaced rather than repaired.

Capacitance Manometer

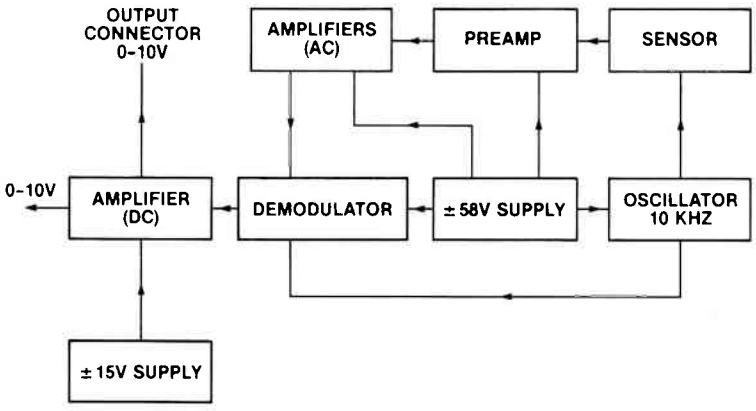
The capacitance manometer is another pressure gauge which can be used in the rough vacuum range. It is capable of measuring the absolute pressure or relative pressure, depending on the gauge model used. It does respond to the total pressure. It is not sensitive to changes in gas mixture as are many other gauges.

The sensing unit contains a tensioned metal diaphragm, one side of which is exposed to the gas whose pressure is to be measured. For absolute pressure measurement, the other (reference) side contains an electrode assembly placed in a sealed high vacuum reference cavity. Since the electrodes in the absolute pressure gauge are not exposed to the gases being measured, this gauge is not affected by oil or water vapors, or by corrosive or other chemically-active process gases.

How the Gauge Works



The diaphragm deflects with changing pressure– force per unit area– independent of the composition of the measured gas. This causes a capacitance change between the diaphragm and the adjacent electrode assembly. The capacitance change is sensed in an oscillator circuit and converted to a frequency change proportional to the diaphragm deflection.



This frequency change, in turn, is converted in the unit to be displayed as the pressure reading. The sensor unit may be constructed of materials such as inconel and stainless steel, allowing the gauge to be used with corrosive gases.

This gauge is sufficiently accurate (about 1% of reading) and precise that one can worry about the effects of temperature changes (Charles' Law) on the pressure readings. The sensor head may be placed in a constant temperature oven as a result.

This gauge is often used as a flow controller because of its fast response (milliseconds) to pressure changes. If you desire to use a capacitance manometer over a wide range, you may need several units. The gauge is constructed to read over three or four orders of magnitude. If you wish to read from atmosphere (7.6×10^2 torr) into the high vacuum range (1×10^{-5} torr), that is seven orders of magnitude. Therefore, you need several different gauge units. These gauges can be constructed so that pressures from 10,000 (10^5) torr to 10^{-5} torr may be sensed, but any particular gauge is limited to about four orders of magnitude of that range. Below 1 mtorr (10^{-3} torr), the accuracy falls dramatically.

Maintenance

The capacitance manometer may receive more maintenance than many gauges because of its ability to read accurate and precise pressure values. It may periodically be taken to the calibration lab for a check against some standard gauge. When it is used in dirty or corrosive gas systems, the sensing side of the gauge head may be flushed with an appropriate solvent.

Overpressuring the gauge (20% over full scale) may shift the reading or permanently damage it. An isolation valve is often used to prevent this.

Heat Transfer

Well, we are finished with "real" pressure gauges. The rest of the gauges we will be discussing sense some property of the gas present in our vacuum system and convert it to a pressure reading. One of these properties we will be using is the thermal conductivity of gases. Let's take a minute to discuss the concept of heat transfer.

You have probably learned somewhere that heat can be transferred three ways: conduction, convection, and radiation. Let's look at these three ways on a molecular scale.

conduction

To transfer heat, or energy, by *conduction*, molecules need to touch a surface or another molecule in order to transfer the heat. This principle is used in gauges between 2 torr and 10^{-3} torr.

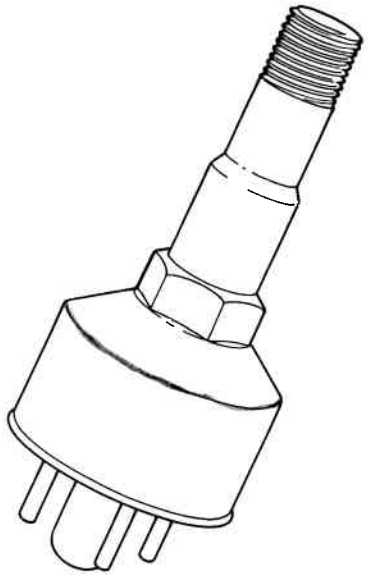
convection

To transfer heat by *convection*, we need massive numbers of molecules flowing. Your hot-air furnace heats by convection. Some gauges use this principle between 760 torr and 2 torr but are generally less accurate in this pressure range.

radiation

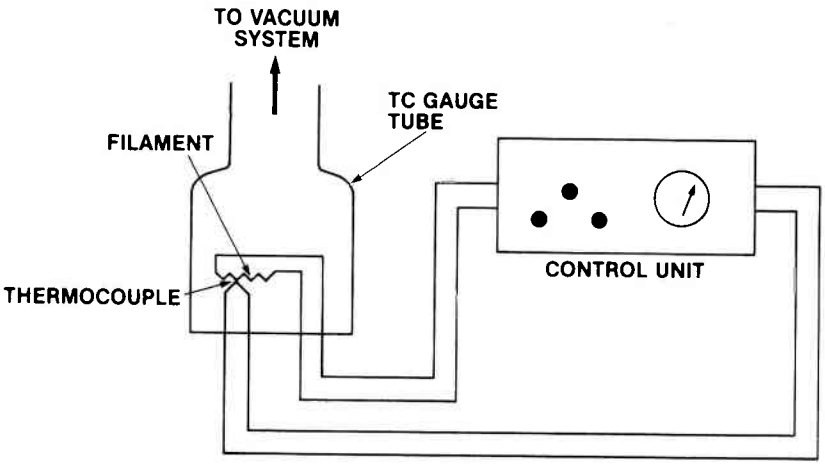
To transfer heat by *radiation*, we need light energy. Not the kind of light that you see, but typically infrared light. The heat you feel when standing in front of a fireplace is mostly the radiated heat. No gas molecules need be involved; that is, radiation is independent of the number of gas molecules present. Radiated heat is the only way to transfer heat inside of a vacuum system at high vacuum. There are insufficient molecules present to provide heat transfer by either conduction or convection. Now, let's go on to discuss gauges that depend on heat transfer to work.

Thermocouple Gauge



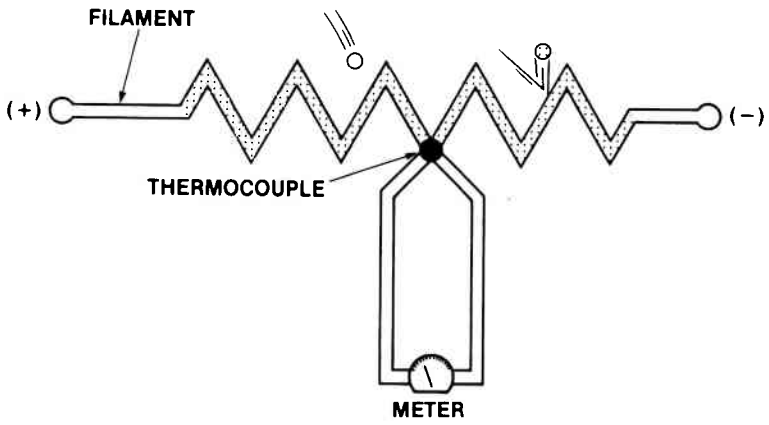
The thermocouple, or TC, gauge is another rugged, simple instrument. It is used to measure pressures in the rough vacuum range. It does its work well under less than ideal conditions. The TC gauge measures temperature and converts it to a pressure reading. Many modern thermocouple gauges have been modified to use convection as well as conduction principles. This effectively extends their useful range to atmosphere. It is typically considered as a very approximate device. Let's take a look at how it works.

How the Gauge Works



A thermocouple gauge consists of a gauge tube and control unit. Within the gauge tube is a heated filament. Spot welded to the filament is a thermocouple that measures the temperature of the hot wire. The meter is calibrated in pressure units, not in temperature.

THERMOCOUPLE GAUGE PRINCIPLE



At atmospheric pressure, there will be many molecular collisions with the heated filament. The gas molecules conduct heat away from the filament. The amount of heat removal can be related to the amount of gas in the chamber. At higher pressures, with lots of molecules, much heat will be conducted away from the wire. Therefore, the wire will be at a lower temperature (cooler). When we pump away the gas, there are fewer molecules to collide with the wire. The wire is therefore at a higher temperature (hotter).

There is not a linear relationship between wire temperature and pressure, so the pressure scale on your TC gauge is not linear. The gauge stops responding at about 1 mtorr (10^{-3} torr) because the heat loss through radiation is now the largest factor. The heat lost through radiation is also constant. Therefore, the gauge reads "zero." Compared to other gauges, the TC gauge has a slow response time. This is because the wire must have time to heat up or cool down as the pressure changes. Some newer gauges speed up the response time by operating the gauge at constant temperature and measuring the change in current required to hold the temperature constant.

Maintenance

If the sensing unit, or gauge head, gets dirty, it may be cleaned with an appropriate solvent. Most people will simply discard the TC gauge and install a new one in its place.

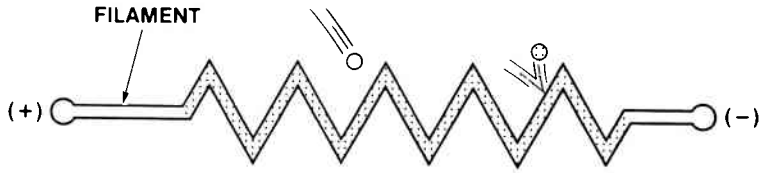
Whenever you clean or replace a TC gauge, it should be adjusted to read the proper values. To do this, you expose the gauge head to a pressure of 10^{-4} torr or less and adjust the control unit to read zero on the pressure gauge. If for some reason you cannot obtain a pressure below 10^{-4} torr, then install a "good" gauge and set the system gauge to read the same pressure.

Please check the operation manual for your particular unit for adjustment instructions, because they do vary in detail.

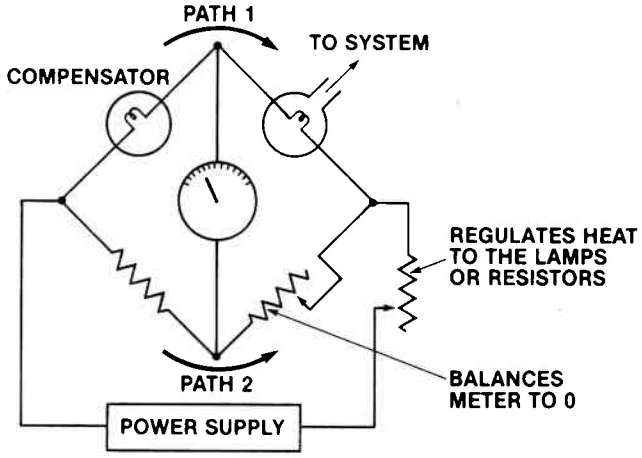
Pirani Gauge

The Pirani gauge operates similarly to the thermocouple gauge. It will read pressures best from about 2 torr to 0.001 torr. The appeal of this gauge is based mostly on its faster response time and range. Because of its more complex design, it is larger and more costly than the thermocouple gauge.

How the Gauge Works



In the Pirani gauge, gas molecules also conduct heat away from a hot filament. In this gauge, we depend on the change in resistance as the temperature changes. The temperature change causes a change in the filament resistance. The filament is part of a bridge circuit that drives the pressure meter. A simplified explanation of this circuit is given below.



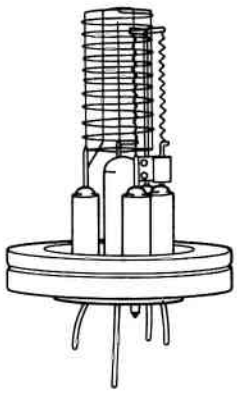
In a balanced bridge circuit, the current flow in Path Number One equals the current flow in Path Number Two. A meter, placed in the center as shown, indicates zero. When heat is conducted away from the filament, its resistance is changed, and this balance is upset. This unbalance develops a voltage difference at the meter connections, and current flows through it. Again, the meter is calibrated in pressure units. The hotter the filament, the more resistance it has. The compensator, which is a very similar filament, remains at a constant temperature and pressure. Therefore, its resistance is relatively constant. Ambient temperature changes do affect the gauge significantly below 10^{-3} torr.

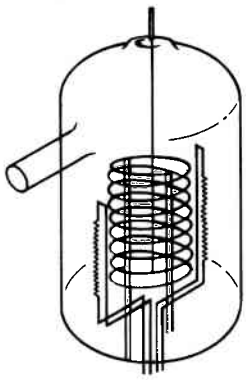
Maintenance

Pirani gauge maintenance includes adjusting and cleaning. A Pirani gauge can be adjusted. Please consult your manual for the gauge to determine the proper procedure.

Ionization Gauge

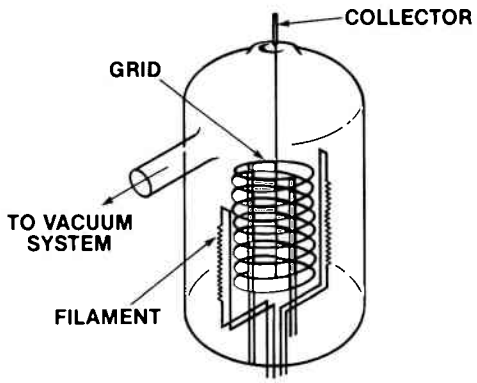
The ionization gauge works on yet another property of molecules. They use the property that if you can energize an atom or molecule, it may lose an electron and become charged. These charged molecules (ions) can be attracted and "counted" as they pick up an electron to become neutral again. This is very similar to the way the ion pump works. Let's look at how this is accomplished as we discuss the gauge.

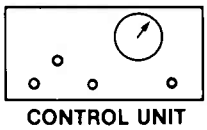




The ionization gauge is perhaps unique in that it can be used over a pressure range spanning eight orders of magnitude (10^{-3} to 10^{-11} torr). It is commonly used over seven orders of magnitude (10^{-3} to 10^{-10}) and expected to be within ±20% of the correct value over that range. This makes it the most widely used gauge for high vacuum work. Models include both glass and metal envelopes as well as "nude" gauges which mount directly in the chamber.

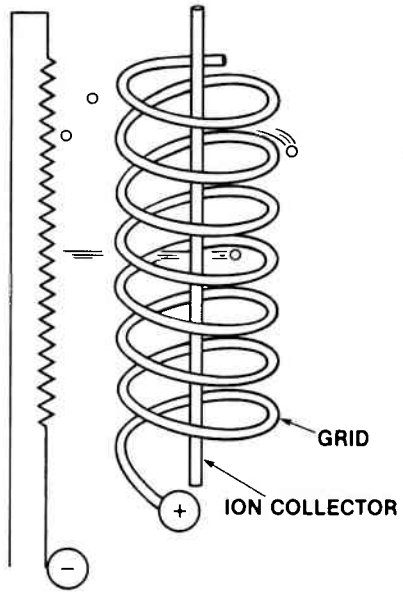
How the Gauge Works



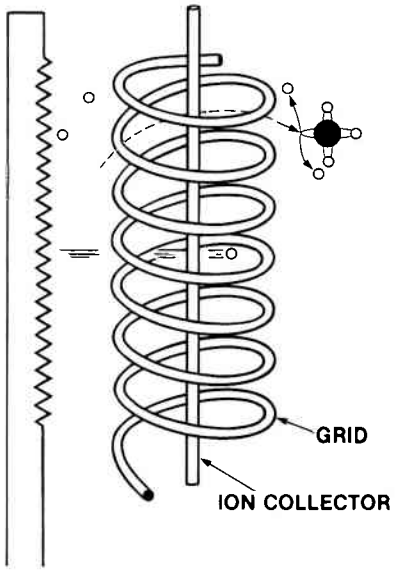


hot cathode ionization gauge

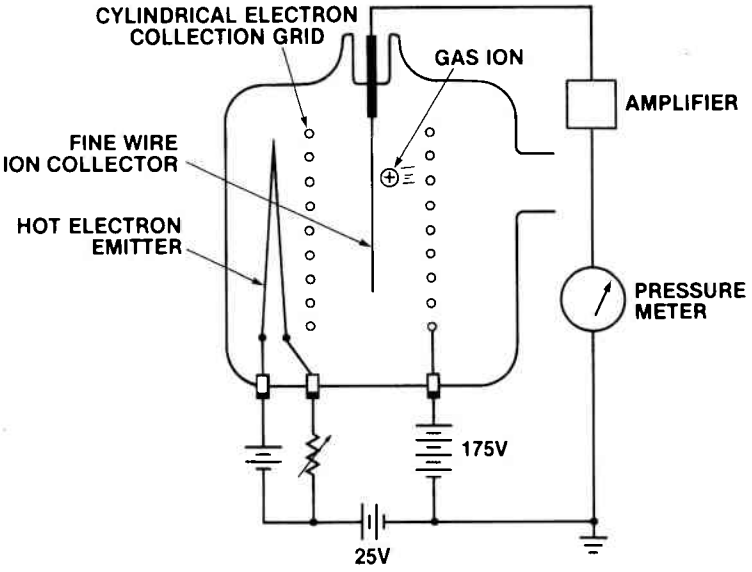
One *ionization gauge* has a hot filament, a grid and an ion collector. A control unit provides power, amplification, and metering. The hot filament supplies ionizing electrons. The grid attracts these electrons. The ion collector attracts the ions and gives up electrons as ions are neutralized. This process creates a small "ion current" which is then amplified.



Let's look at the process in more detail. Electrons emitted by the hot filament are attracted to the positive grid. However, many electrons miss the loosely wound grid and swing past it several times before finally striking it. Because of the large number of electrons emitted by the filament, a fairly constant "electron cloud" is present about the grid in the gauge tube.



On their long, round-about flight to the grid, electrons may collide with gas molecules, ionizing them and releasing more electrons. The longer the flight of these electrons, the greater the chance of collision. Therefore, a stronger, more usable signal is produced.



The positively ionized gas molecules are attracted to the collector. This produces an ion current proportional to the pressure in the chamber. To get meaningful pressure readings, the sensitivity of the gauge must be known, and the emission current must be well regulated. The "sensitivity" selector on the controller must be set the same as the rated sensitivity of the gauge tube. If this "matching" is not done, you will get inaccurate pressure readings.

The sensitivity of the ion gauge is obtained from the relationship

$$P = \frac{1}{S} \times \frac{i_p}{i_e},$$

where P is pressure,
S is gauge sensitivity,
i_p is the positive ion current,
i_e is the emission current.

As you can see from the ratio i_p/i_e, there are two variables, not one. If the emission current varies, it will cause a variation in the ionization current and therefore the pressure. Most manufacturers of ion gauges go to great pains to insure that i_e is constant. Varian uses a patented Ratiomatic™ circuit to directly measure the ratio of the ion current to the emission current. This allows small variations in the emission current to occur without affecting the gauge reading.

The ion gauge has limits like any of the other gauges. The x-ray limit determines the low end of the ion gauge range. Low-energy

x-rays are created when electrons strike the grid. They are always being produced. Those x-rays that strike the collector release photoelectrons and cause a constant error signal. This x-ray current is insignificant until about 10^{-10} torr. There, the value of pressure-related ion current approaches the x-ray current. To read low pressures, we must make a correction for the x-ray current. Doing this makes it possible to read pressures below 10^{-11} torr.

If you look at the manual for your ion gauge, you will find a table of correction factors. Some modern gauges allow you to put a correction factor or two into the control unit. These correction factors have to do with the fact that some molecules are easier to ionize than others. They will therefore give an incorrect pressure reading. The gauge unit is calibrated using nitrogen gas (or perhaps air). If you now use a different gas in your vacuum system, you should apply the proper correction factor to get "correct" pressure readings. You can, of course, do as many people do and "use the pressure that works."

Maintenance

Ion gauges can sometimes be cleaned using appropriate solvents, though we do not advise it. Most people will use the degas control as a cleaning procedure. The degas heats up the grid so that it bakes the walls of the gauge tube. This baking drives any molecules collected on the walls back into the vacuum system where they may be pumped away. Degassing a tube that is contaminated with silicone-based pump oils permanently affects it.

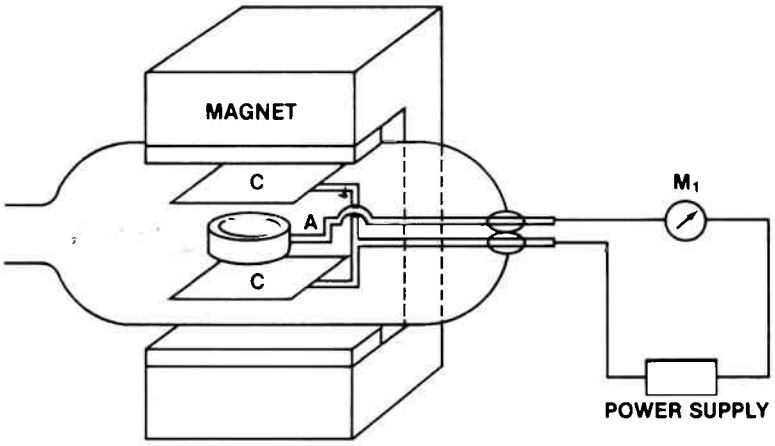
Attempts to clean a gauge tube are not always successful. But if you choose to clean your gauge head with solvents, be certain to thoroughly clean and dry the gauge before installing it. Operating the degas function, which heats the grid, can cause enough outgassing of volatile solvents to create a plasma discharge. The resulting "short" could cause severe electrical shock or death if the system and controller are not adequately grounded. Be sure the gauge has thoroughly dried before reinstallation and subsequent operation.

The ion gauge will need periodic adjustments of the control unit. Refer to the manual for your specific gauge as to how to carry out the procedure. The gauge unit in some installations will require calibration. This involves checking the gauge head and control unit versus a standard or known gauge. The gauge is adjusted to indicate the same pressure as the standard. It is then typically "certified." The National Institute of Standards and Technology will now provide this service for a fee.

Cold Cathode Gauge

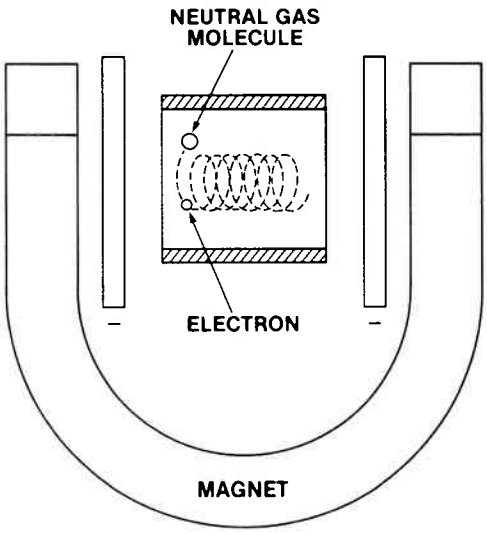
cold cathode ionization gauge

Another high vacuum gauge is the *cold cathode ionization gauge.* It also depends on the ability to ionize molecules.

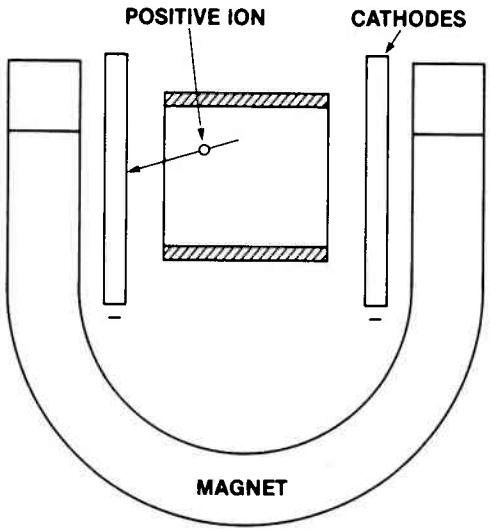


A cold cathode gauge consists of a gauge tube and control unit. The gauge tube has a central anode and two cathodes or a cylindrical cathode. A strong permanent magnet surrounds these elements. Its accuracy is approximately ±50% of the true pressure.

How the Gauge Works



A dc voltage of about 2,000 volts attracts electrons in the gauge tube to the positively charged anode. The magnetic field forces the electrons into long helical paths. This increases the probability of electron-molecular collisions. The collisions produce ions. This, in turn, produces a glow discharge.



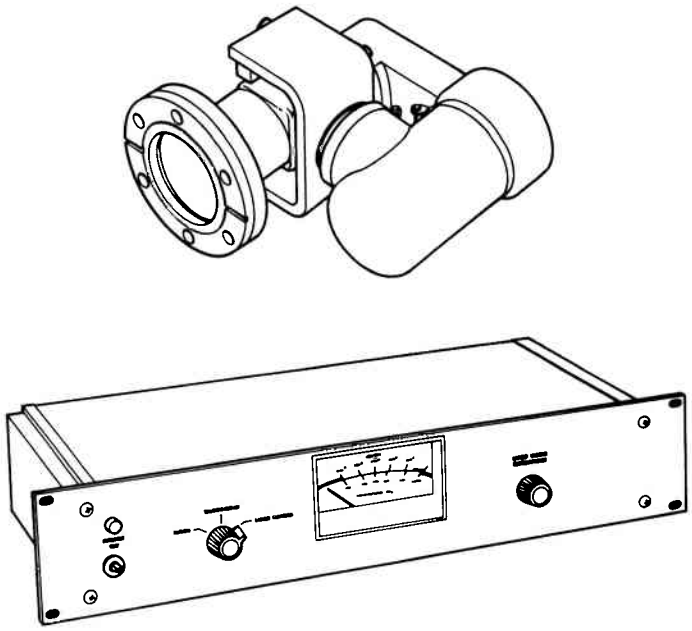
The positive gas ions are now attracted to the negatively charged cathode. The resulting ion current is measured and calibrated in units of pressure. (Note the similarity between this gauge and the ion pump—the cold cathode gauge is an ion pump with non-gettering cathode material.)

The gauge extinguishes when the pressure (gas density) gets too high (about 10^{2} torr) to support a gas discharge. It also extinguishes when the pressure gets too low (about 10^{-8} torr) to support a discharge. Most cold cathode gauges are constructed so that they may be taken apart for cleaning. An advantage of this gauge is that there is no filament to burn out. This makes it a more rugged gauge that takes more abuse but is less accurate.

Maintenance

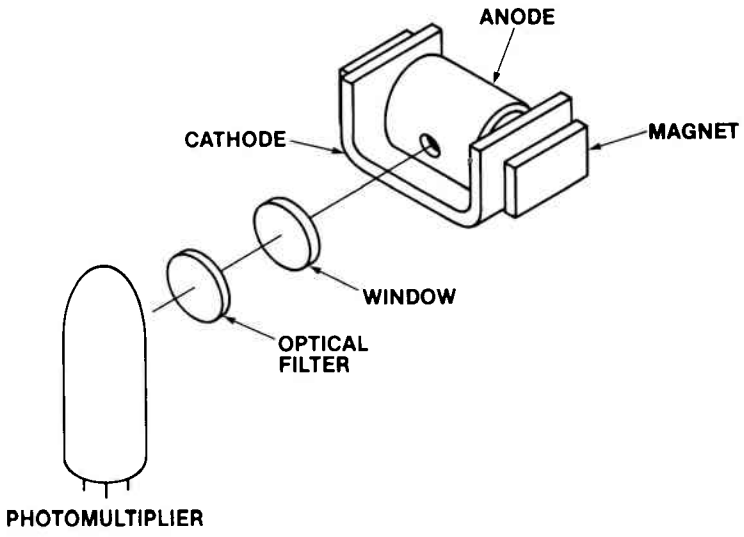
The cold cathode gauge usually does not need calibration or adjustment. It depends completely on the ion current being proportional to the pressure. It is quite rugged because of its all-metal construction. An adaptation of the cold cathode gauge is the residual nitrogen analyzer, which we'll look at next.

Residual Nitrogen Analyzer



The residual nitrogen analyzer (RNA) reads the total pressure and the nitrogen partial pressure. It operates in the high vacuum range.

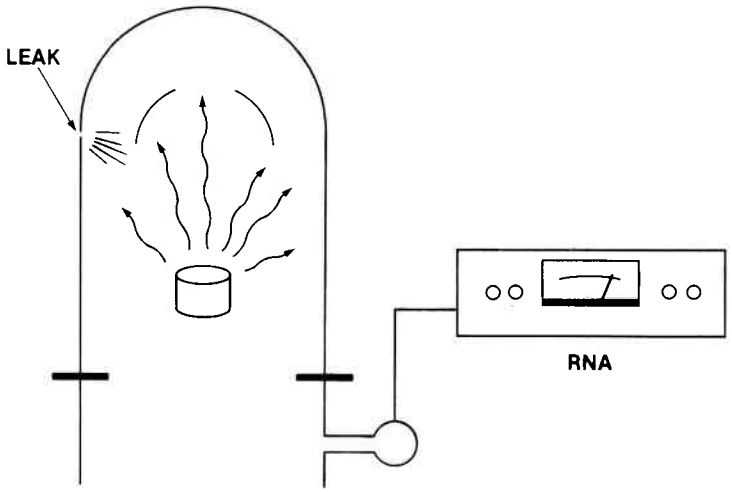
How the RNA Works



The RNA is a cold cathode gauge that also includes a window, an optical filter, and photomultiplier tube. Ionization produces light. This light has various colors, depending on the gases producing it. The filter passes nitrogen light and blocks the light from other ionized gases. Thus, the gauge reads only the nitrogen pressure. In the "normal" mode, this cold cathode gauge also reads the total pressure. We can use this to help us in determining the condition of our vacuum system.

Gases are pumped at different rates. Nitrogen is relatively easy to pump, so its percentage in a pumped-out system is lower than it is at atmosphere. A leak, on the other hand, admits an abundance of nitrogen. The RNA, which is tuned to nitrogen, senses this abnormality, and identifies an air leak.

For example, the percentage of nitrogen remaining in a normal evacuated leak-free system at 5×10^{-6} torr may be about 10%. An air leak can change this percentage to about 80%. A low nitrogen reading upsets the normal balance in the other direction, and is a good indication of outgassing or an internal leak in the system. The gauge is a simple way to diagnose a system problem. It answers a very important diagnostic question– does the system have a real leak or a virtual leak?



For example, coating material builds up with time, outgasses and raises the pressure. The RNA can tell the difference between outgassing, which may be still within acceptable limits, and an air leak, which is not.