Kurt J. Lesker Company®

➤ *Pump Classifications*

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Pumps

◼ Transfer vs. Capture

Vacuum pumps are divided into two groups: gas transfer or gas capture. Transfer pumps force gas molecules in a preferred direction by positive displacement or momentum exchange. Ultimately, the gas is compressed until slightly above atmospheric pressure when it is ejected into the atmosphere. By contrast, capture pumps immobilize gas molecules on special surfaces within the vacuum system. To generalize their applications, transfer pumps are used for high gas loads while capture pumps produce oil-free vacuums and UHV pressures.

Pump Applications: Transfer vs. Capture

1. With the exception of diffusion pumps, all transfer pumps exhibit some kind of mechanical motion, which implies they vibrate to some degree. By contrast, most capture pumps, with the exception of cryogenic pumps, have no moving parts. Capture pumps are therefore preferred in the optical coatings industry where even minimal vibrations to the vacuum system are unacceptable.

2. Car headlight reflectors are made by flash evaporating aluminum onto formed plastic parts in a batch coater. For cost-effective production, the production can only be a few minutes. The high gas load conditions make capture pumps an unlikely first choice.

◼ Operating Pressure Range

The mechanics of the pump design inherently dictate the pressure range at which the pump is able to operate. The vacuum industry recognizes the following pressure regimes:

• Coarse Vacuum — 760–1 Torr

• Medium Vacuum — 1 Torr–10^{-3} Torr

• High Vacuum — 10^{-4}–10^{-8} Torr

• Ultra High Vacuum — 10^{-9}–10^{-12} Torr

The transition from atmospheric pressure to the bottom of the UHV range (approx. 1 x 10^{-12} Torr) is a dynamic range of almost 10^{15} and well beyond the capabilities of any single pump. Indeed, to get to any pressure below 10^{-4} Torr requires more than one pump. While the distinction between gas transfer and gas capture is important for applications, classification into vacuum degree is more helpful in pump selection.

NOTE: While other pump classification criteria are listed below, pumps are ultimately organized according to the operating principle/pumping mechanism that, again, loosely groups pumps into one of the aforementioned pressure ranges.

◼ Ultimate Pressure and Pumping Speed

A pump's ultimate pressure, often called its ultimate vacuum, is a value measured when the pump's design is finalized and an example built. In general terms, it is measured by blanking the pump's inlet with a pressure gauge, operating the pump for some time, recording the pressure achieved, and calling that the ultimate pressure. Because there are many pressure units, you will see ultimate pressures quoted in Torr, millibar, Pascal, inches of mercury, etc.

Pumping speed is formally defined as the ratio of the throughput of a given gas to the partial pressure of that gas at a specific point near the inlet port of the pump. With less formality, but more clarity, it is the volume of gas (at any pressure) that is removed from the system by the pump in unit time. In short, pumping speed is a measure of the pump's capacity to remove gas from the chamber. It is measured in liters per second (L/sec.), cubic feet per minute (cfm), or cubic meters per hour (m^3/hr.).

There are several points to note when comparing pumps based on their rated pumping speed. First, pumping speed is measured under the same ideal conditions used to measure ultimate pressure-minimum volume, right at the pump inlet, lowest possible outgassing rate, ideal conditions, etc. Second, pumping speed is specified by the manufacturer as the highest value over the entire operating pressure range of the pump. The pumping speed curve shown below illustrates the characteristic differences between roots pumps, mechanical pumps, and high vacuum pumps.
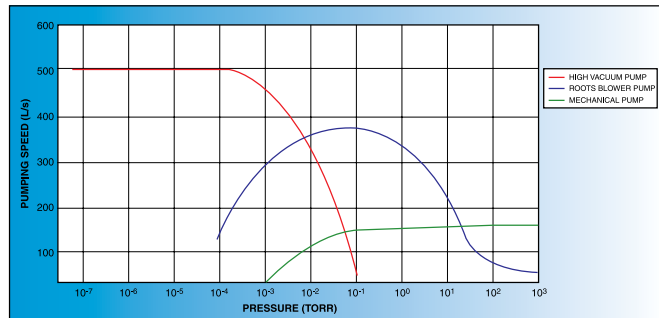
◼ Wet vs. Dry

A wet pump uses low vapor pressure oil in the pumping mechanism. A diffusion pump, for example, uses oil vapor flow as the pumping mechanism while a rotary vane pump uses oil to lubricate and seal sliding joints between vanes and casing. So, in any wet pump, oil liquid and vapor coexist in the pumps vacuum volume.

A dry pump has no gas sealing fluid. Some dry pumps may truly have no lubricants while other dry pumps may have lubricated gears/bearings sealed from the vacuum track by o-rings. The latter, "somewhat dry pump," doesn't use oil/grease to seal but does use it to lubricate gears or bearings outside the vacuum volume (as in roots pumps, screw pumps, claw pumps) or at the pump's high-pressure end (as in ceramic ball-bearing turbo pumps). For roots, screw, or claw pumps, shaft-seals prevent vapors re-entering the vacuum volume. For turbo pumps, the pumping mechanism prevents the vapors traveling backwards. The former, "really dry pumps," don't have lubricants anywhere close to the vacuum volume. Capture pumps fall into this category, as do transfer pumps using PTFE as a sliding lubricant (as in scroll pumps, reciprocating piston pumps) or as the gas seal (as in diaphragm pumps). But solid lubricants lack the lubricity of fluid lubricants and their lifetimes are not as long.

PLEASE NOTE: An oil-free system is never achieved by simply replacing existing oil-sealed pumps with dry pumps. All surfaces in the chamber and pumping lines will be contaminated with an oil film that will act as a secondary source unless rigorously cleaned or replaced.

➤ *Pump Classifications*

■ Normal vs. Corrosive

Pumping aggressive gases can severely affect the pump's lifetime depending on the construction of the pump's critical internal components. Pump manufacturers offer chemical (a.k.a. corrosion or corrosive) versions of their pumps that feature some added degree of protection. Because there are no standards covering the chemical resistance of a pump, each pump manufacturer devises its own anti-corrosion strategies.

For various reasons depending on the pumping mechanism involved, capture pumps aren't rated for pumping corrosive gases. Those transfer pumps that are rated for corrosive gases typically have special coatings for shaft bearings: Viton® o-rings and gaskets, gas ballasts, gas bubbles, and use inert fluids where applicable (**see sidebar, at right**).

■ Rotary Vane Pumps

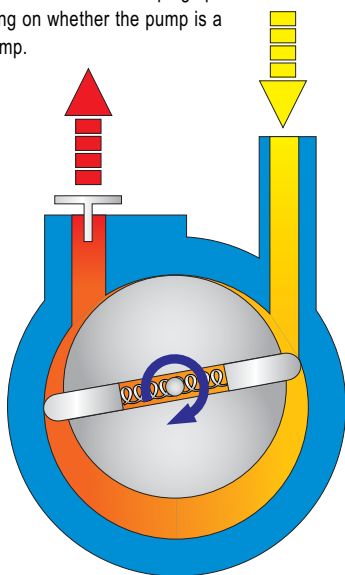**Vacuum Level:** Coarse Vacuum or Medium Vacuum (design dependent)

Gas Removal Method: Gas Transfer

Pump Design: Oil-Sealed (wet)

There are two different types of rotary vane pumps—those for coarse vacuum applications and those for medium vacuum applications. The major distinctions between the rotary vane mechanism for coarse pumps and rough pumps are the number of vanes, their tolerances, and the trapping of exhaust oil vapors.

In all rotary vane pumps, gas from the chamber enters the inlet port and is trapped between the rotor vanes and the pump body. The eccentrically mounted rotor compresses the gas and sweeps it toward the discharge port. When gas pressure exceeds atmospheric, the exhaust valve opens and gas is expelled. Oil is used as a lubricant, coolant, and gas sealant for the vanes. Single-stage rough rotary vane pumps have ultimate pressures around 10^{-2} Torr range while two-stage medium vacuum vane pumps reach 10^{-3} Torr. Pumping speeds vary from 1–650 cfm, depending on whether the pump is a coarse vane or rough vane pump.

Rough vane pumps are used primarily as backing pumps for roots or high-vacuum gas transfer pumps such as turbomolecular and diffusion in all vacuum applications. Coarse vane pumps are used in freeze drying, vacuum filtering, vacuum impregnation, materials handling, meat packing, and "house" vacuum systems.

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Pumps

■ Diaphragm Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Dry

A flexible metal or polymeric diaphragm seals a small volume at one end. At the other end are two spring-loaded valves, one opening when the volume's pressure falls below the "outside" pressure, the other opening when the volume's pressure exceeds the "outside" pressure. A cam on a motor shaft rapidly flexes the diaphragm, causing gas transfer in one valve and out the other.
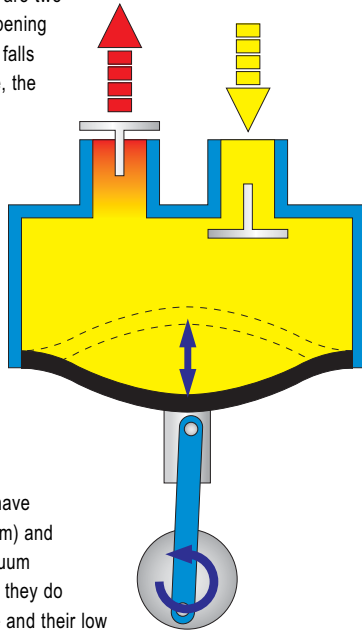
Diaphragm pumps often have two stages in series— to produce a lower vacuum, or in parallel, to produce a higher pumping speed. In general, diaphragm pumps have low pumping speeds (<10 cfm) and produce a poor ultimate vacuum (1 Torr to 10 Torr). However, they do exhaust into the atmosphere and their low costs make them attractive roughing pumps.

In part, hybrid pumps were developed to accept the poor foreline pressure diaphragm pumps produce. Diaphragm pumps are also used for simple vacuum filtration, thin film evaporation, distillation, gel drying applications, and as sample movers for gas analyzers, membrane filtration, and sample extraction.

■ Cryosorption Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Dry

Cryosorption pumps are essentially closed-ended tubes filled with molecular sieve pellets. The tubes are often internally finned or re-entrant to aid heat transfer. The pumping action is created by cooling the molecular sieve with LN_2 in a surrounding dewar. A correctly sized cryosorption pump will evacuate a chamber from atmosphere to approximately 10^{-4} Torr in a few minutes. But it is a one-time operation and the pump needs regeneration before further use. To achieve the lowest pressures, two or more cryosorption pumps are operated in sequence. They are low-cost, trouble-free, and completely dry. Before the advent of dry mechanical pumps, they were often used for the initial rough down of infrequently vented ion-pumped UHV systems. Their simple blow-off rubber stopper valves make the first part of regeneration automatic. More effective regeneration requires heating one pump while it is pumped by another.

■ Reciprocating Piston Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Dry

The mechanism, patented by CSIRO Australia, moves a reciprocating piston in a metal cylinder lined with a composite PTFE wall honed to a 3-micron finish. A combination of poppet and slide valves, similar in concept to those of the 4-stroke and 2-stroke internal combustion engines, directs gas flow to and from the cylinder. The pumps are built with up to 4 stages, often connected in parallel or series to achieve an ultimate vacuum of 2×10^{-2} Torr or pumping speeds from 6–32 cfm while exhausting at atmospheric pressure. They are used in clean, dry applications that do not contain aggressive gases, water vapor, or dust. A typical application is roughing load locks in MBE and UHV processing systems.
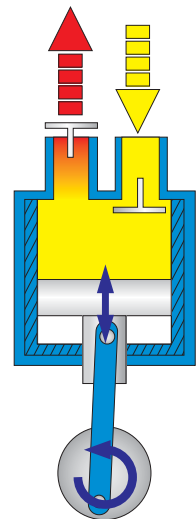
■ Scroll Pumps

Vacuum Level: Medium Vacuum

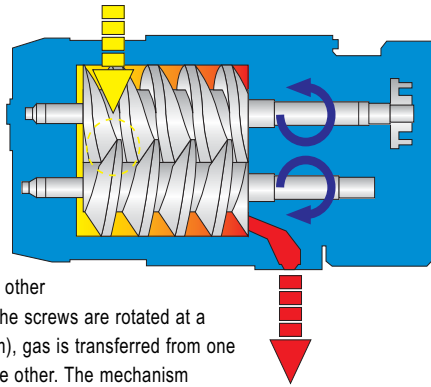**Gas Removal Method:** Gas Transfer

Pump Design: Dry

Two open spiral metal strips are nested together. One spiral is fixed while the other "orbits"—its center point describes a small circle but the spiral does not rotate. As the moving spiral orbits, it touches the stationary spiral at everchanging positions. The shape of the spirals means at one orbital point there is an open (crescent-shaped) volume connected to the inlet. A little later in the orbit, the connection with the inlet closes, trapping a volume of gas. Continuing the orbit causes this volume to decrease, compressing the gas until it reaches a minimum volume and maximum pressure at the spirals' center, where the outlet is located. In this orbital position, the inlet is again connected to the large open volume. Typically, two such nested spiral stages are mounted in series, producing an ultimate vacuum in the 10^{-2} Torr range and pumping speed of roughly 12–25 cfm while exhausting at atmospheric pressure. Scroll pumps are used in clean, dry processes and as dry backing pumps for high vacuum pumps. They should not be used outside an ambient temperature range of 5–40º C.

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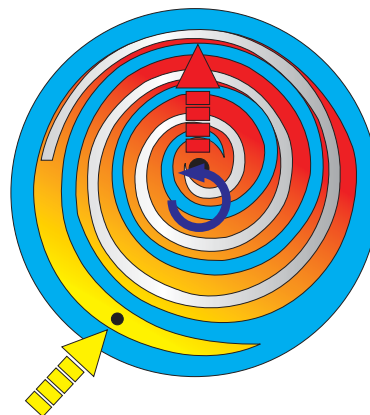
Pumps

■ Screw Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Dry

Two contra-rotating, left- and right-handed "screws" mesh with each other but do not touch. When the screws are rotated at a modest speed (3,600 rpm), gas is transferred from one end of the structure to the other. The mechanism produces an ultimate pressure in the 10^{-3} Torr range, yet can operate with the inlet at atmospheric pressure. Pumping speeds from 30–318 cfm are available. The construction materials are chosen to enable the screw pump to operate in the harsh environments of aggressive gases and particulates found in semiconductor etching and CVD processes. They are also used for roughing dry, high vacuum transfer pumps or initial pumpdown for capture pumps.

■ Hook and Claw Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Dry

Two contra-rotating impellers, which in cross-sectional shape look like claws, mesh along their length without touching. The rotary action is not unlike the lobe pump but the claw pump's inlet and outlet ports are in the casing's end wall and are covered or exposed by the end of the impeller shaft. One advantage of this pump is its ability to accept high temperature gases, giving it good water vapor pumping characteristics. Design features such as blowing compressed air into the bearings provide protection against particulates or aggressive gas. Claw pumps have ultimate pressures of just below 10^{-1} Torr and pumping speeds from 50–250 cfm while exhausting into atmospheric pressure. Claw pumps are used in harsh industrial environments, particularly in claw pump semiconductor processing and where water vapor content is high.

■ Rotary Piston Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Oil-Sealed (wet)

This mechanism is best at pumping high gas loads at pressures lower than 0.1 Torr. The mechanism is complex, but also rugged and can withstand much abuse. Gas from the chamber enters the pump body through a sliding sleeve valve. An eccentrically mounted cylinder rocks (orbits) around the inside of the pump body without rotating. It compresses the gas out through the exhaust valve into the atmosphere. Rotary pistons are used extensively for backing large roots pumps and/or diffusion pumps attached to production-sized vacuum furnaces.
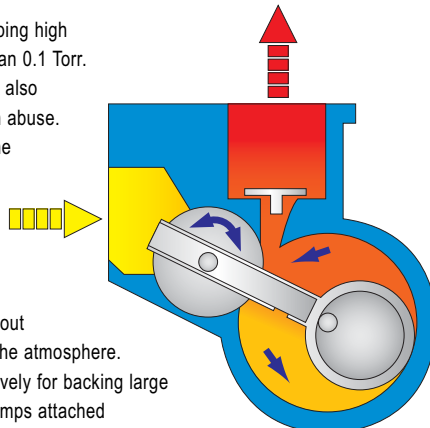
■ Roots (Rotary Lobe) Pumps

Vacuum Level: Medium Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Oil-Sealed (wet)

The roots (or rotary lobe) action is excellent for moving huge quantities of gas at pressures between 0.01–10 Torr. In cross-section, the two lobes are figure-eights that mesh without touching and counter-rotate to continuously transfer gas in one direction through the pump. The compression ratio (outlet pressure divided by inlet pressure) is between 10 and 100, and single-stage lobe pumps must be backed by rotary vane or piston pumps. The compression ratio also varies with the molecular weight of the gas, the higher velocities of the light gases enabling them to return more easily to the chamber. The pump's ultimate pressure is typically 10^{-4} Torr when backed by a pump pulling 10^{-3} Torr. Roots pumps handle very high gas loads and will cycle large batch process chambers quickly. They are favored in high throughput process applications such as diffusion bonding, distillation towers, and IC fabrication lines.
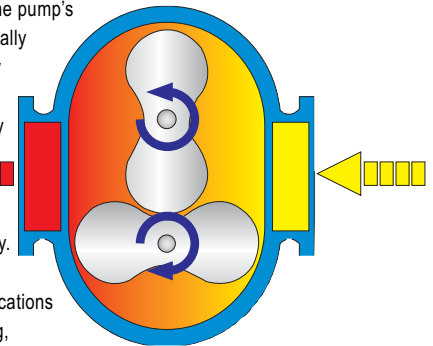
Roots Pumps and High Pressures

The Roots' pressure range is from ~20 Torr to ~10^{-4} Torr. Pumping a chamber from atmosphere leads to two non-obvious issues:

- Operating the Roots at full speed generates heat (by gas compression) and requires a power level that damages the motor.
- Leaving the pump off introduces a huge conductance loss.

Roots manufacturers counteract these problems in three ways.

1. A variable speed motor is monitored and a feedback loop keeps its power at an acceptable level to avoid overheating. As the pressure decreases, the same power rotates the rotors faster. At ~20 Torr, the rotors are at full speed.

2. The pump operates at full speed. However, an (automatic) "back" by-pass valve connects downstream- and upstream-sides. If the downstream pressure is too high, the valve opens and gas flows back to the upstream-side effectively equilibrating pressures. At ~20 Torr the downstream pressure is no longer high enough to force the valve open.

3. The motor operates at full speed, but a fluid drive connects it and the rotors. At high pressure, the rotors cannot be driven at motor speed and there is slippage in the fluid drive. At ~20 Torr, the rotors are at full speed.
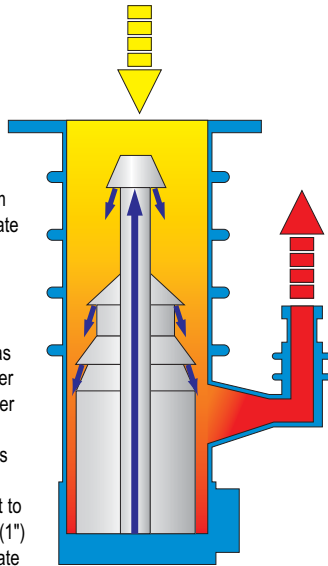
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Pumps

■ Diffusion Pumps

Vacuum Level: High Vacuum

Gas Removal Method: Gas Transfer

Pump Design: Oil-Sealed (wet)

Diffusion pumps were the first high vacuum pumps in operation. Diffusion pumps operate by boiling a low vapor pressure, high molecular weight, non-reactive fluid and forcing a dense vapor stream up a central column and out as a conical vapor curtain, through jets that are angled downward. Gas molecules from the chamber randomly enter the curtain and are pushed toward the boiler by momentum transfer from the fluid molecules. When the vapor curtain reaches the cold wall, the temperature change of perhaps 200–250º C immediately returns it to liquid form at a low vapor pressure. Small (1") and large (36") diameter pumps give ultimate vacuums in the 10^{-4} Torr range. Mid-sized pumps, with an LN_2 trap, reach the 10^{-7} Torr range. Pumping speeds range from perhaps 30 L/s to 50,000 L/s.

Diffusion pumps tolerate operating conditions (e.g., excess particles or reactive gases) that would destroy other high vacuum pumps. They have high pumping speeds for a relatively low cost, and are vibration- and noise-free. Unfortunately, they continuously backstream oil vapor and instantly turn a simple operating error into a major system disaster with oil everywhere. For this reason, diffusion pumps have decreased in popularity but are still seen in applications requiring huge pumping speeds such as molecular beam systems, large scale vacuum furnace processing, and space simulation chambers.

■ Turbomolecular Pumps

Vacuum Level: High Vacuum & Ultra High Vacuum (design dependent)

Gas Removal Method: Gas Transfer

Pump Design: Dry

Turbo pumps, as they are commonly called, resemble jet engines. A stack of rotors, each having multiple, angled blades, rotate at very high speeds between a stack of stators. Gas molecules randomly entering the mechanism and colliding with the underside of the spinning rotor blade are given momentum toward the pump's exhaust. The compression ratio for N_2 across the pump may exceed 10^8. That is, if the partial pressure in the foreline is 10^{-4} Torr, the chamber partial pressure may be 10^{-12} Torr, 10^8 times lower. (The actual partial pressure depends on many factors not related to compression ratio.) Compression ratios for H_2 and He are much lower, sometimes less than 10^3, which suggests the turbo mechanism alone is not good at producing low chamber pressures when H_2 or He is present.

The ultimate vacuum of most turbos lies between 10^{-7} Torr and 10^{-10} Torr. However, UHV pressures are achieved by backing a large turbo by a small turbo (which, in turn, is backed by a mechanical pump). Turbo pumping speeds range from 50 L/s to 3,500 L/s for normal commercial pumps. Correctly operated and vented, the turbo mechanism prevents vapor backstreaming from the greased rotor bearings. For truly dry chambers, a turbo with magnetically levitated bearings backed by a dry mechanical pump are used. With proper venting, the turbo mechanism stops in less than a minute, which may mean chamber venting is accomplished without the need for a valve separating pump and chamber. Also, a separate roughing line is usually unnecessary because the chamber can be roughed through the stationary or accelerating turbo.

Turbo pumps are used in all vacuum applications between 10^{-4} and 10^{-10} Torr and are replacing diffusion pumps as general workhorses. Turbo pumps are not used on dusty processes or those for which small high frequency vibration might be a problem. However, some turbo pumps are built to resist corrosion from reactive gases.

■ Molecular Drag Pumps

Vacuum Level: High Vacuum & Ultra High Vacuum (design dependent)

Gas Removal Method: Gas Transfer

Pump Design: Dry

The drag pump has a smooth, high speed tubular rotor, capped at its top end, spinning between closely spaced, cylindrical walls, one outside and one inside the rotor. The stationary walls are helically grooved on the surface facing the rotor. The rotor is driven at tangential velocities, approaching the average velocity of gas molecules. The pumping action is caused by momentum transfer from the rotor to the gas molecules with the spiral grooves providing a preferred flow direction toward the exhaust port. Its compression ratios are typically 10^9 for N_2, 10^4 for He, and 10^3 for H_2. But the mechanism's low pumping speed (less than 10 L/s) means the ultimate vacuum may be only 10^{-6} Torr. The maximum continuous inlet pressure is 0.1 Torr, but its exhaust pressure can be as high as 10 to 40 Torr. That is, the diaphragm pump is an adequate backing pump. Drag pumps are used where relatively low cost, low pumping speeds, and modest ultimate vacuum are demanded.
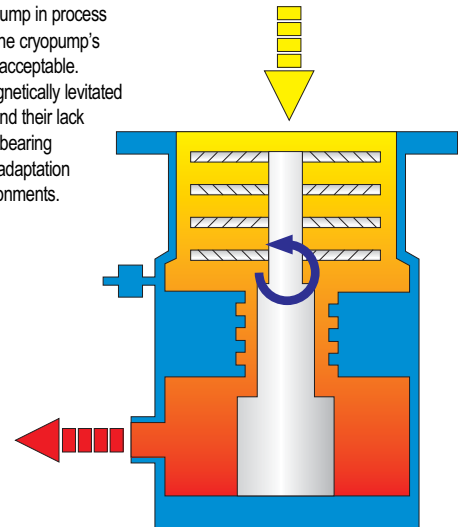
■ Turbo-Drag Hybrid Pumps

Vacuum Level: High Vacuum & Ultra High Vacuum (design dependent)

Gas Removal Method: Gas Transfer

Pump Design: Dry

The hybrid pump (also called a combination pump or sometimes just turbo pump) combines the input stage of a standard turbo pump with the output stage of a drag pump. The resulting hybrid has a much higher pumping speed than a molecular drag pump yet operates at high foreline pressures often requiring only a diaphragm pump. The compression ratio for hybrid pumps can reach 1,010 for N_2 and more than 10^4 for H_2. Their ultimate pressure is 10^{-11} Torr when backed by a pump giving a low foreline pressure and pumping speed ranges from 50 L/s to 3,200 L/s.

The hybrid pump appears to be rapidly replacing the regular turbo for all R&D applications requiring 10^{-9} Torr, and the cryopump in process applications for which the cryopump's regeneration time is unacceptable. Hybrid pumps with magnetically levitated bearings are truly dry and their lack of lubricated "physical" bearing surfaces enables their adaptation to fairly corrosive environments.

■ Cryogenic Pumps

Vacuum Level: High Vacuum & Ultra High Vacuum (design dependent)

Gas Removal Method: Gas Capture

Pump Design: Dry

Cryogenic pumps (commonly called cryopumps) are similar in principle to cryosorption pumps, except they are held at lower temperatures. Essentially, there are three surfaces. An outer surface, which is held at 80K and includes an optically opaque chevron baffle, pumps mostly water vapor. It surrounds (and thermally insulates) an inverted cup-shaped inner surface held at 15K to 20K that traps the common atmospheric gases. The underside of the cup is coated with activated carbon and provides hydrogen pumping. All surfaces are cooled by a closed cycle helium cryocompressor attached to the pump by insulated tubes. Cryopumps are particularly suited to pumping atmospheric gases and high melting point vapors (H_2O) in the 10^{-6} to 10^{-9} Torr range. The major disadvantages are poor helium pumping and vibration transmitted from the compressor.
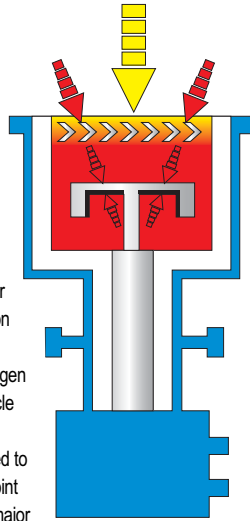
This mechanism is less susceptible to operational errors than other high vacuum pumps. If exposed to the chamber when the quantity of gas (Pressure x Volume) exceeds the manufacturer's recommended number, the pump simply warms, temporarily losing its ability to pump. After the gas load is reduced and the pump cooled, it is again operational. The quantity of gas pumped before regeneration is needed varies from several hundred atm. liters for Ar to a few atm. liters for H_2.
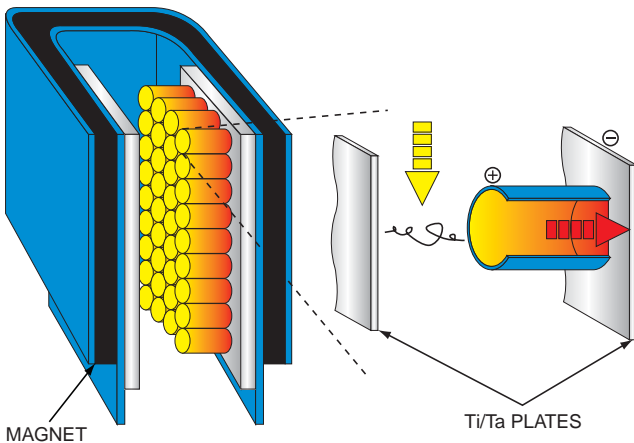
Cryopumps have found great success in non-aggressive semiconductor processes where oil-free operation and high pumping speeds are essential.

■ Ion Pumps

Vacuum Level: Ultra High Vacuum

Gas Removal Method: Gas Capture

Pump Design: Dry

MAGNET

Ti/Ta PLATES

Ion pumps are the primary choice for all true UHV chambers. They are clean, bakeable, vibration-free, operate from 10^{-6} Torr to 10^{-11} Torr with low power consumption, and have long operating lives. All ion pumps have the same basic components: a parallel array of short, stainless steel tubes, two plates (Ti or Ta)

spaced a short distance from the open ends of the tubes, and a strong magnetic field parallel to the tubes' axes.

Electrons from the (cathodic) plates move along tight helical trajectories in the magnetic field through the (anodic) tubes. When a gas molecule is ionized by an electron in a tube, it is strongly attracted to a cathode that it strikes with force sufficient to sputter titanium. The sputtered Ti coats everything: tubes, plates, and pump casing. Several pumping mechanisms are possible, including chemical reaction (getter action), ion burial, and neutral burial (the last two accounting for the pump's ability to pump inert gases).

The ion pump's characteristics are determined by the plate material, its physical form, and the voltage supplied. In the "diode" pump, the Ti plates are grounded and the tubes have a high positive voltage. The diode has high pumping speed for H_2, O_2, N_2, CO_2, CO, and other getterable gases. The "noble diode" pump has the same electrical supply as the diode, but Ta is substituted for one Ti plate. This reduces the pump's H_2 pumping speed, but enables higher pumping speed and greater stability for Ar and He. In the "triode" pump, the plates are slotted or penetrated in some manner and connected to a high negative voltage. Both the tubes and the pump casing (acting as a third electrode) are grounded. Sputtering from the slotted plates deposits Ti not only on the tubes and plates but also on the pump casing. Inert gases and methane burial on the casing are less susceptible to later ion bombardment, even at high pressures when plates are heavily bombarded.

■ Titanium Sublimation Pumps

Vacuum Level: Ultra High Vacuum

Gas Removal Method: Gas Capture

Pump Design: Dry

Titanium sublimation pumps (abbreviated as TSP) are evaporable getter-style pumps. The term getter is applied to any active metal that chemically reacts with gases to form a stable, nonvolatile product. There are two types of getters: evaporable and non-evaporable. Both are used as vacuum augmentation devices—they maintain or improve the vacuum level achieved by some other high vacuum or UHV pumping mechanism.

Titanium Sublimation Pumps use multiple thin film evaporations to keep the surface active. Their pumping speeds depend on the surface area of the getter film. Titanium pumps H_2, O_2, N_2, and H_2O well, but has no effect on inert gases or methane. It is used from 10^{-6} Torr to UHV to remove the H_2 residual gas, often as an addition to an ion pump. The adverse effect of a Ti film on any electrical insulator is a major disadvantage. This is where non-evaporable getter pumps like those with getter films made of Zr-Al-Fe are used.