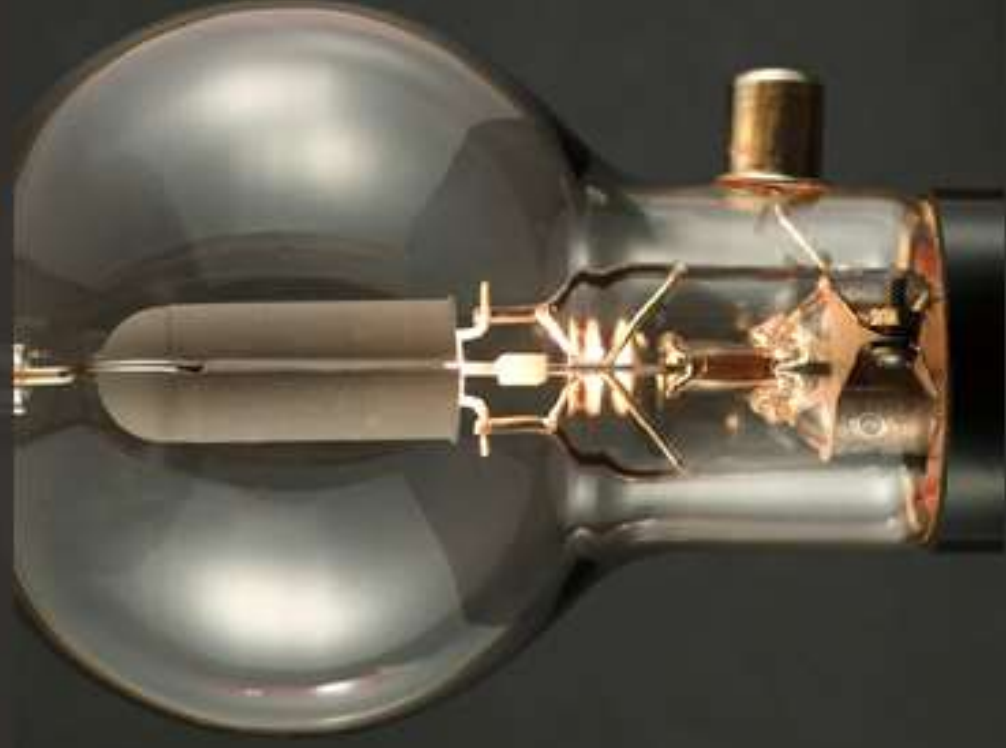


Vacuum

Physics and Engineering



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WORLD TECHNOLOGIES

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Chapter- 1

Introduction to Vacuum



Pump to demonstrate vacuum

In everyday usage, **vacuum** is a volume of space that is essentially empty of matter, such that its gaseous pressure is much less than atmospheric pressure. The word comes from the Latin term for "empty". Even putting aside the complexities of the quantum vacuum, the classical notion of a **perfect vacuum** with gaseous pressure of exactly zero is only a philosophical concept and is never observed in practice. Physicists often discuss ideal test results that would occur in a perfect vacuum, which they simply call "vacuum" or "free

space", and use the term **partial vacuum** to refer to real vacuum. The Latin term **in vacuo** is also used to describe an object as being in what would otherwise be a vacuum.

The *quality* of a vacuum refers to how closely it approaches a perfect vacuum. Residual gas pressure is a primary indicator of quality, and is most commonly measured in units called torr, even in metric contexts. Lower pressures indicate higher quality, although other variables must also be taken into account.

Vacuum has been a frequent topic of philosophical debate since Ancient Greek times, but was not studied empirically until the 17th century. Evangelista Torricelli produced the first laboratory vacuum in 1643, and other experimental techniques were developed as a result of his theories of atmospheric pressure. A **torricellian vacuum** is created by filling a tall glass container closed at one end with mercury and then inverting the container into a bowl to contain the mercury.

Vacuum became a valuable industrial tool in the 20th century with the introduction of incandescent light bulbs and vacuum tubes, and a wide array of vacuum technology has since become available. The recent development of human spaceflight has raised interest in the impact of vacuum on human health, and on life forms in general.



A large vacuum chamber

Etymology

From Latin **vacuum** (*an empty space, void*) noun use of neuter of *vacuus* (*empty*) related to *vacare* (*be empty*).

"Vacuum" is one of the few words in the English language that contains two consecutive 'u's.

Uses



Light bulbs contain a partial vacuum, usually backfilled with argon, which protects the tungsten filament

Vacuum is useful in a variety of processes and devices. Its first widespread use was in the incandescent light bulb to protect the filament from chemical degradation. The chemical inertness produced by a vacuum is also useful for electron beam welding, cold welding, vacuum packing and vacuum frying. Ultra-high vacuum is used in the study of atomically clean substrates, as only a very good vacuum preserves atomic-scale clean surfaces for a

reasonably long time (on the order of minutes to days). High to ultra-high vacuum removes the obstruction of air, allowing particle beams to deposit or remove materials without contamination. This is the principle behind chemical vapor deposition, physical vapor deposition, and dry etching which are essential to the fabrication of semiconductors and optical coatings, and to surface science. The reduction of convection provides the thermal insulation of thermos bottles. Deep vacuum lowers the boiling point of liquids and promotes low temperature outgassing which is used in freeze drying, adhesive preparation, distillation, metallurgy, and process purging. The electrical properties of vacuum make electron microscopes and vacuum tubes possible, including cathode ray tubes. The elimination of air friction is useful for flywheel energy storage and ultracentrifuges.

Vacuum driven machines

Vacuums are commonly used to produce suction, which has an even wider variety of applications. The Newcomen steam engine used vacuum instead of pressure to drive a piston. In the 19th century, vacuum was used for traction on Isambard Kingdom Brunel's experimental atmospheric railway. Vacuum brakes were once widely used on trains in the UK but, except on heritage railways, they have been replaced by air brakes.

Manifold vacuum can be used to drive accessories on automobiles. The best-known application is the vacuum servo, used to provide power assistance for the brakes. Obsolete applications include vacuum-driven windscreen wipers and fuel pumps.

Quantum-mechanical definition

In quantum mechanics, the vacuum is defined as the state (i.e. solution to the equations of the theory) with the lowest energy. To first approximation, this is simply a state with no particles, hence the name.

Even an ideal vacuum, thought of as the complete absence of anything, will not in practice remain empty. Consider a vacuum chamber that has been completely evacuated, so that the (classical) particle concentration is zero. The walls of the chamber will emit light in the form of black body radiation. This light carries momentum, so the vacuum does have a radiation pressure. This limitation applies even to the vacuum of interstellar space. Even if a region of space contains no particles, the cosmic microwave background fills the entire universe with black body radiation.

An ideal vacuum cannot exist even inside of a molecule. Each atom in the molecule exists as a probability function of space, which has a certain non-zero value everywhere in a given volume. Thus, even "between" the atoms there is a certain probability of finding a particle, so the space cannot be said to be a vacuum.

More fundamentally, quantum mechanics predicts that vacuum energy will be different from its naive, classical value. The quantum correction to the energy is called the zero-point energy and consists of energies of virtual particles that have a brief existence. This

is called vacuum fluctuation. Vacuum fluctuations may also be related to the so-called cosmological constant in cosmology. The best evidence for vacuum fluctuations is the Casimir effect and the Lamb shift.

In quantum field theory and string theory, the term "vacuum" is used to represent the ground state in the Hilbert space, that is, the state with the lowest possible energy. In free (non-interacting) quantum field theories, this state is analogous to the ground state of a quantum harmonic oscillator. If the theory is obtained by quantization of a classical theory, each stationary point of the energy in the configuration space gives rise to a single vacuum. String theory is believed to have a huge number of vacua - the so-called string theory landscape.

Outgassing

Outgassing (sometimes called **offgassing**, particularly when in reference to indoor air quality) is the release of a gas that was dissolved, trapped, frozen, absorbed or adsorbed in some material. It can include sublimation and evaporation which are phase transitions of a substance into a gas, as well as desorption, seepage from cracks or internal volumes and gaseous products of slow chemical reactions. Boiling is generally thought of as a separate phenomenon from outgassing because it consists of a phase transition of a liquid into a vapor made of the same substance.

Outgassing in a vacuum

Outgassing is a challenge to creating and maintaining clean high-vacuum environments. NASA maintains a list of low-outgassing materials to be used for spacecraft, as outgassing products can condense onto optical elements, thermal radiators, or solar cells and obscure them. Materials not normally considered absorbent can release enough light-weight molecules to interfere with industrial or scientific vacuum processes. Moisture, sealants, lubricants, and adhesives are the most common sources, but even metals and glasses can release gases from cracks or impurities. The rate of outgassing increases at higher temperatures because the vapour pressure and rate of chemical reaction increases. For most solid materials, the method of manufacture and preparation can reduce the level of outgassing significantly. Cleaning surfaces or baking individual components or the entire assembly before use can drive off volatiles.

NASA's Stardust spaceprobe suffered reduced image quality due to an unknown contaminant that had condensed on the CCD sensor of the navigation camera. A similar problem affected the Cassini-Huygens spaceprobe's Narrow Angle Camera, but was corrected by repeatedly heating the system to 4 degrees Celsius.

Outgassing from rock

Outgassing is the source of many tenuous atmospheres of terrestrial planets or moons. Many materials are volatile relative to the extreme vacuum of space, such as around the

Earth's Moon, and may evaporate or even boil at ambient temperature. Materials on the lunar surface have completely outgassed and been ripped away by solar winds long ago, but volatile materials may remain at depth. Once released, gases almost always are less dense than the surrounding rocks and sand and seep toward the surface. The lunar atmosphere probably originates from outgassing of warm material below the surface. At the Earth's tectonic divergent boundaries where new crust is being created, helium and carbon dioxide are some of the volatiles being outgassed from mantle magma.

Outgassing in a closed environment

Outgassing can be significant if it collects in a closed environment where air is stagnant or recirculated. This is, for example, the origin of new car smell. Even a nearly odourless material such as wood may build up a strong smell if kept in a closed box for months. There is some concern that softeners and solvents that are released from many industrial products, especially plastics, may be harmful to human health.. Some types of RTV sealants outgas the poison cyanide for weeks after application. These outgassing poisons are of great concern in the design of submarines and space stations.

Quality

The quality of a vacuum is indicated by the amount of matter remaining in the system, so that a high quality vacuum is one with very little matter left in it. Vacuum is primarily measured by its absolute pressure, but a complete characterization requires further parameters, such as temperature and chemical composition. One of the most important parameters is the **mean free path** (MFP) of residual gases, which indicates the average distance that molecules will travel between collisions with each other. As the gas density decreases, the MFP increases, and when the MFP is longer than the chamber, pump, spacecraft, or other objects present, the continuum assumptions of fluid mechanics do not apply. This vacuum state is called *high vacuum*, and the study of fluid flows in this regime is called particle gas dynamics. The MFP of air at atmospheric pressure is very short, 70 nm, but at 100 mPa ($\sim 1 \times 10^{-3}$ Torr) the MFP of room temperature air is roughly 100 mm, which is on the order of everyday objects such as vacuum tubes. The Crookes radiometer turns when the MFP is larger than the size of the vanes.

Vacuum quality is subdivided into ranges according to the technology required to achieve it or measure it. These ranges do not have universally agreed definitions, but a typical distribution is as follows:

	pressure (Torr)	pressure (Pa)
Atmospheric pressure	760	101.3 kPa
Low vacuum	760 to 25	100 kPa to 3 kPa
Medium vacuum	25 to 1×10^{-3}	3 kPa to 100 mPa
High vacuum	1×10^{-3} to 1×10^{-9}	100 mPa to 100 nPa
Ultra high vacuum	1×10^{-9} to 1×10^{-12}	100 nPa to 100 pPa

Extremely high vacuum	$<1 \times 10^{-12}$	<100 pPa
Outer Space	1×10^{-6} to $<3 \times 10^{-17}$	100 μ Pa to <3 fPa
Perfect vacuum	0	0 Pa

- **Atmospheric pressure** is variable but standardized at 101.325 kPa (760 Torr)
- **Low vacuum**, also called *rough vacuum* or *coarse vacuum*, is vacuum that can be achieved or measured with rudimentary equipment such as a vacuum cleaner and a liquid column manometer.
- **Medium vacuum** is vacuum that can be achieved with a single pump, but the pressure is too low to measure with a liquid or mechanical manometer. It can be measured with a McLeod gauge, thermal gauge or a capacitive gauge.
- **High vacuum** is vacuum where the MFP of residual gases is longer than the size of the chamber or of the object under test. High vacuum usually requires multi-stage pumping and ion gauge measurement. Some texts differentiate between high vacuum and *very high vacuum*.
- **Ultra high vacuum** requires baking the chamber to remove trace gases, and other special procedures. British and German standards define ultra high vacuum as pressures below 10^{-6} Pa (10^{-8} Torr).
- **Deep space** is generally much more empty than any artificial vacuum. It may or may not meet the definition of high vacuum above, depending on what region of space and astronomical bodies are being considered. For example, the MFP of interplanetary space is smaller than the size of the solar system, but larger than small planets and moons. As a result, solar winds exhibit continuum flow on the scale of the solar system, but must be considered as a bombardment of particles with respect to the Earth and Moon.
- **Perfect vacuum** is an ideal state that cannot be obtained in a laboratory, nor can it be found or obtained anywhere else in the universe, apart from possibly the singularity of a black hole, or the (potentially large) spaces between atoms in lesser vacuums.
- **Hard vacuum** and **Soft vacuum** are terms that are defined with a dividing line defined differently by different sources, such as 5 psia, one Torr, or 0.1 Torr the common denominator being that a hard vacuum is a higher vacuum than a soft one.

Examples

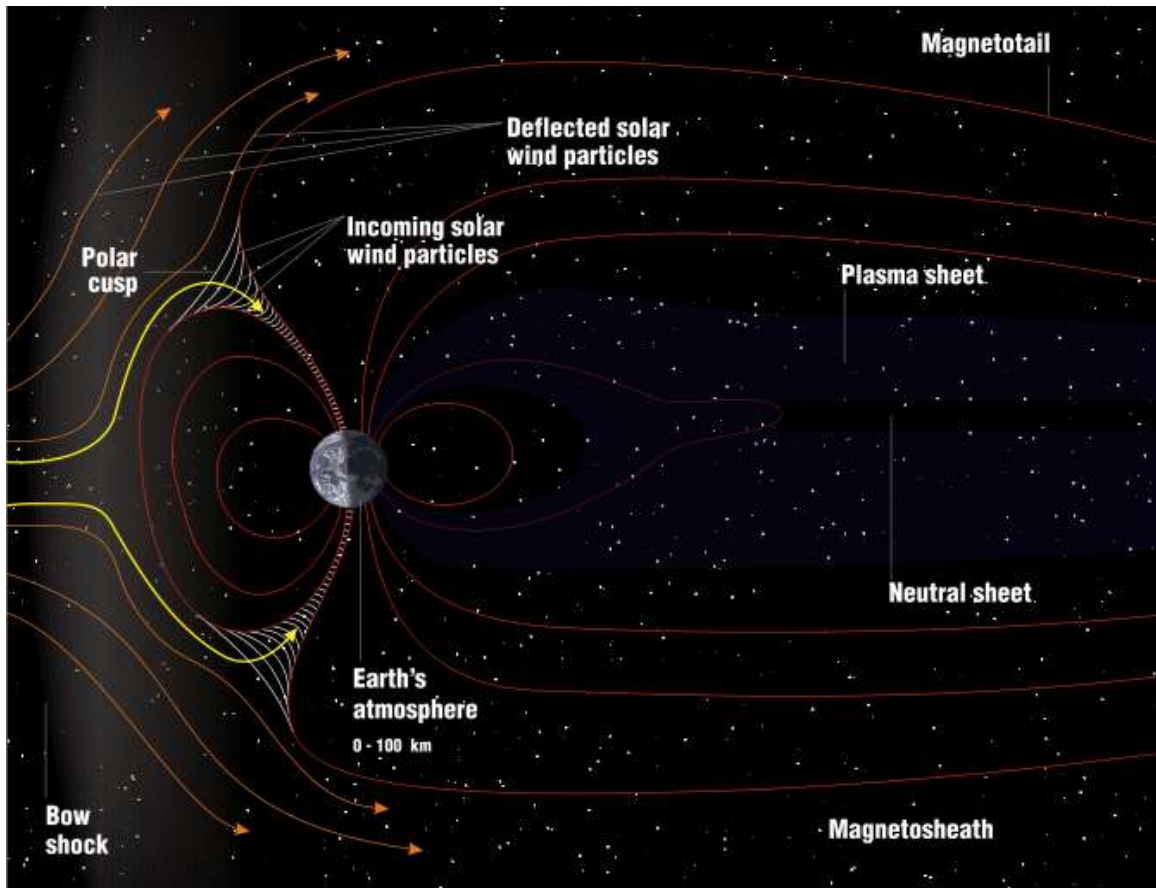
	pressure (Pa)	pressure (Torr)	mean free path	molecules per cm^3
Vacuum cleaner	approximately 80 kPa	600	70 nm	10^{19}
liquid ring vacuum pump	approximately 3.2 kPa	24		
freeze drying	100 to 10 Pa	1 to 0.1	100 μ m to 1 mm	10^{16} to 10^{15}

rotary vane pump	100 Pa to 100 mPa	1 to 10^{-3}	100 μm to 10 cm	10^{16} to 10^{13}
Incandescent light bulb	10 to 1 Pa	0.1 to 0.01	1 mm to 1 cm	10^{15} to 10^{14}
Thermos bottle	1 to 0.01 Pa	10^{-2} to 10^{-4}	1 cm to 1 m	10^{14} to 10^{12}
Earth thermosphere	1 Pa to 100 nPa	10^{-2} to 10^{-9}	1 cm to 100 km	10^{14} to 10^7
Vacuum tube	10 μPa to 10 nPa	10^{-7} to 10^{-10}		
Cryopumped MBE chamber	100 nPa to 1 nPa	10^{-9} to 10^{-11}	100 to 10,000 km	10^7 to 10^5
Pressure on the Moon	approximately 1 nPa	10^{-11}		4×10^5
Interplanetary space				10
Interstellar space				1
Intergalactic space				

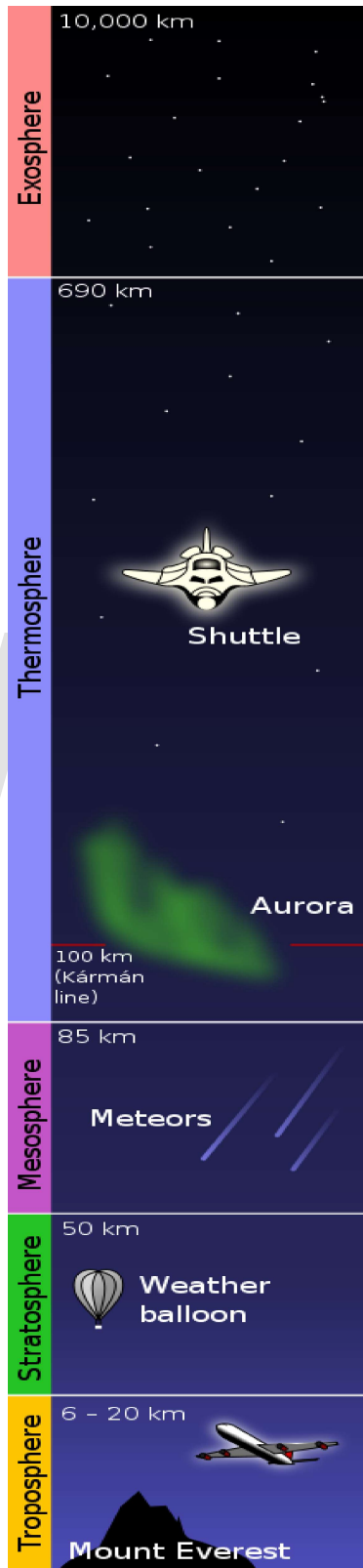


Chapter- 2

Outer Space



Outer space is not a perfect vacuum, but a tenuous plasma awash with charged particles, electromagnetic fields, and the occasional star.



The boundaries between the Earth's surface and outer space, at the Kármán line, 100 km (62 mi) and exosphere at 690 km (430 mi).

Outer space (often simply called **space**) is the void that exists beyond any celestial body including the Earth. It is not completely empty (i.e. a perfect vacuum), but contains a low density of particles, predominantly hydrogen plasma, as well as electromagnetic radiation, magnetic fields, and neutrinos. Theoretically, it also contains dark matter and dark energy.

Discovery

In 350 BC, Greek philosopher Aristotle suggested that *nature abhors a vacuum*, a principle that became known as the *horror vacui*. Based on this idea that a vacuum could not exist, it was widely held for many centuries that space could not be empty. As late as the seventeenth century, the French philosopher René Descartes argued that the entirety of space must be filled. It became known to Galileo Galilei that air had weight and so was subject to gravity. He also demonstrated that there was an established force that resisted the formation of a vacuum. However, it would remain for his pupil Evangelista Torricelli to create an apparatus that would produce a vacuum. At the time this experiment created a scientific sensation in Europe. The French mathematician Blaise Pascal reasoned that if the column of mercury was suspended by air then the column ought to be shorter at higher altitude. His brother in law, Florin Périer, repeated the experiment on the Puy-de-Dôme mountain in central France and found that the column was shorter by three inches. This decrease in pressure was further demonstrated by carrying a half-full balloon up a mountain and watching it gradually inflate, then deflate upon descent. These and other experiments were used to overthrow the principle of *horror vacui*.

Further work on the physics of the vacuum was performed by Otto von Guericke. He correctly noted that the atmosphere of the Earth surrounds the planet like a shell, with the density gradually declining with altitude. He concluded that there must be a vacuum between the Earth and the Moon.

Early speculations as to the infinite dimension of space was performed in the sixteenth century by the Italian philosopher Giordano Bruno. He extended the Copernican heliocentric cosmology to the concept of an infinite universe that is filled with a substance he called aether, which did not cause resistance to the motions of heavenly bodies. English philosopher William Gilbert arrived at a similar conclusion, arguing that the stars are visible to us only because they are surrounded by a thin aether or a void. This concept of an aether originated with ancient Greek philosophers, including Aristotle, who conceived of it as the medium through which the heavenly bodies moved.

The concept of a universe filled with a luminiferous aether remained in vogue among some scientists up until the twentieth century. This form of aether was viewed as the medium through which light could propagate. In 1887, the Michelson-Morley experiment was carried out as an attempt to detect the Earth's motion through this medium by looking for changes in the speed of light based on the direction of the planet's motion. However, the null result indicated something was wrong with the concept. Since then the idea of the luminiferous aether had essentially been abandoned, to be replaced by Albert Einstein's

theory of special relativity. The latter held that the speed of light is a constant in a vacuum, regardless of the observer's motion or frame of reference.

The first professional astronomer to support the concept of an infinite universe was the Englishman Thomas Digges in 1576. However, the true scale of the universe remained unknown until the first successful measurement of the distance to a nearby star was performed in 1838 by the German astronomer Friedrich Bessel. He showed that the star 61 Cygni had a parallax of just 0.31 arcseconds (compared to the modern value of 0.287"). This corresponded to a distance of over 10 light years. The distance scale to the Andromeda galaxy was determined in 1923 by American astronomer Edwin Hubble when he measured the brightness of cepheid variables within that galaxy. This established that the Andromeda galaxy, and by extension all galaxies, lay well outside the Milky Way.

The modern concept of outer space is based upon the Big Bang cosmology, which was first proposed in 1931 by the Belgian physicist Georges Lemaître. This theory holds that the observable universe originated from a very compact form that has since undergone continuous expansion. Matter that remained following the initial expansion has since undergone gravitational collapse to create stars, galaxies and other astronomical objects, leaving behind a deep vacuum that forms what is now called outer space.

The term *outer space* was first recorded by the English poet Lady Emmeline Stuart-Wortley in her poem "The Maiden of Moscow" in 1842, and later popularized in the writings of HG Wells in 1901. The shorter term *space* is actually older, first used to mean the region beyond Earth's sky in John Milton's *Paradise Lost* in 1667.

Environment

Outer space is the closest natural approximation of a perfect vacuum. It has effectively no friction, allowing stars, planets and moons to move freely along ideal gravitational trajectories. However, even in the deep vacuum of intergalactic space there are still a few hydrogen atoms per cubic meter. By comparison, the air we breathe contains about 10^{25} molecules per cubic meter. The sparse density of matter in outer space means that electromagnetic radiation can travel great distances without being scattered; the mean free path for a photon in intergalactic space is about 10^{23} km, or 10 billion light years. The deep vacuum of space could make it an attractive environment for certain industrial processes, for instance those that require ultraclean surfaces.

Stars, planets, asteroids and moons keep their atmospheres by gravitational attraction, and as such, atmospheres have no clearly delineated boundary: the density of atmospheric gas simply decreases with distance from the object. The Earth's atmospheric pressure drops to about 1 Pa at 100 kilometres (62 mi) of altitude. This is known as the Kármán line, a common definition of the boundary with outer space. Beyond this line, isotropic gas pressure rapidly becomes insignificant when compared to radiation pressure from the Sun and the dynamic pressure of the solar wind, so the definition of pressure becomes difficult to interpret. The thermosphere in this range has large gradients of pressure,

temperature and composition, and varies greatly due to space weather. Astrophysicists prefer to use number density to describe these environments, in units of particles per cubic centimeter.

Temperature

All of the observable Universe is filled with photons that were created during the Big Bang, which is known as the cosmic microwave background radiation (CMB). There is quite likely a correspondingly large number of neutrinos called the cosmic neutrino background. The current black body temperature of this photon radiation is about 3 K ($-270\text{ }^{\circ}\text{C}$; $-454\text{ }^{\circ}\text{F}$). Some regions of outer space can contain highly energetic particles that have a much higher temperature than the CMB.

Effect on human bodies

Contrary to popular belief, a person suddenly exposed to the vacuum would not explode, freeze to death or die from boiling blood. Air would immediately leave the lungs due to the enormous pressure gradient. Any oxygen dissolved in the blood would empty into the lungs to try to equalize the partial pressure gradient. Once the deoxygenated blood arrived at the brain, death would quickly follow.

Humans and animals exposed to vacuum will lose consciousness after a few seconds and die of hypoxia within minutes. Blood and other body fluids do boil when their pressure drops below 6.3 kPa, the vapor pressure of water at body temperature. This condition is called ebullism. The steam may bloat the body to twice its normal size and slow circulation, but tissues are elastic and porous enough to prevent rupture. Ebullism is slowed by the pressure containment of blood vessels, so some blood remains liquid. Swelling and ebullism can be reduced by containment in a flight suit. Shuttle astronauts wear a fitted elastic garment called the Crew Altitude Protection Suit (CAPS) which prevents ebullism at pressures as low as 2 kPa. Water vapor would also rapidly evaporate off from exposed areas such as the lungs, cornea of the eye and mouth, cooling the body. Rapid evaporative cooling of the skin will create frost, particularly in the mouth, but this is not a significant hazard. Space may be cold, but it's mostly vacuum and transfers heat ineffectively; as a result the main temperature regulation concern for space suits is how to get rid of naturally generated body heat.

Cold or oxygen-rich atmospheres can sustain life at pressures much lower than atmospheric, as long as the density of oxygen is similar to that of standard sea-level atmosphere. The colder air temperatures found at altitudes of up to 3 kilometres (1.9 mi) generally compensate for the lower pressures there. Above this altitude, oxygen enrichment is necessary to prevent altitude sickness, and spacesuits are necessary to prevent ebullism above 19 kilometres (12 mi). Most spacesuits use only 20 kPa of pure oxygen, just enough to sustain full consciousness. This pressure is high enough to prevent ebullism, but simple evaporation of blood can still cause decompression sickness and gas embolisms if not managed.

Rapid decompression can be much more dangerous than vacuum exposure itself. Even if the victim does not hold his breath, venting through the windpipe may be too slow to prevent the fatal rupture of the delicate alveoli of the lungs. Eardrums and sinuses may be ruptured by rapid decompression, soft tissues may bruise and seep blood, and the stress of shock will accelerate oxygen consumption leading to hypoxia. Injuries caused by rapid decompression are called barotrauma. A pressure drop as small as 13 kPa, which produces no symptoms if it is gradual, may be fatal if it occurs suddenly.

Boundary

There is no clear boundary between Earth's atmosphere and space, as the density of the atmosphere gradually decreases as the altitude increases. There are several designated scientific boundaries, namely:

- The Fédération Aéronautique Internationale has established the Kármán line at an altitude of 100 kilometres (62 mi) as a working definition for the boundary between aeronautics and astronautics. This is used because above an altitude of roughly 100 km, as Theodore von Kármán calculated, a vehicle would have to travel faster than orbital velocity in order to derive sufficient aerodynamic lift from the atmosphere to support itself.
- The United States designates people who travel above an altitude of 50 miles (80 km) as astronauts.
- NASA's mission control uses 76 miles (122 km) as their re-entry altitude, which roughly marks the boundary where atmospheric drag becomes noticeable (depending on the ballistic coefficient of the vehicle), thus leading shuttles to switch from steering with thrusters to maneuvering with air surfaces.

In 2009, scientists at the University of Calgary reported detailed measurements with an instrument called the Supra-Thermal Ion Imager (an instrument that measures the direction and speed of ions), which allowed them to determine that space begins 118 kilometres (73 mi) above Earth. The boundary represents the midpoint of a gradual transition over tens of kilometers from the relatively gentle winds of the Earth's atmosphere to the more violent flows of charged particles in space, which can reach speeds well over 600 miles per hour (1,000 km/h).

This was only the second time that direct measurements of charged particle flows have been conducted at this region, which is too high for balloons and too low for satellites. It was however the first study to include all the relevant elements for this kind of determination – for example, the upper atmospheric winds.

The instrument was carried by the JOULE-II rocket on January 19, 2007, and traveled to an altitude of about 124 miles (200 km). From there it collected data while it was moving through the "edge of space".

Legal status

The Outer Space Treaty provides the basic framework for international space law. This treaty covers the legal use of outer space by nation states, and includes in its definition of *outer space* the Moon and other celestial bodies. The treaty states that outer space is free for all nation states to explore and is not subject to claims of national sovereignty. It also prohibits the deployment of nuclear weapons in outer space. The treaty was passed by the United Nations General Assembly in 1963 and signed in 1967 by the USSR, the United States of America and the United Kingdom. As of January 1, 2008 the treaty has been signed by 98 states and ratified by an additional 27 states.

Between 1958 and 2008, outer space has been the subject of multiple resolutions by the United Nations General Assembly. Of these, more than 50 have been concerning the international co-operation in the peaceful uses of outer space and preventing an arms race in space. Four additional space law treaties have been negotiated and drafted by the UN's Committee on the Peaceful Uses of Outer Space. The 1979 Moon Treaty turned the jurisdiction of all heavenly bodies (including the orbits around such bodies) over to the international community. However, this treaty has not been ratified by any nation that currently practices manned spaceflight.

Space versus orbit

To perform an orbit, a spacecraft must travel faster than a sub-orbital spaceflight. A spacecraft has not entered orbit until it is traveling with a sufficiently great horizontal velocity such that the acceleration due to gravity on the spacecraft is less than or equal to the centripetal acceleration being caused by its horizontal velocity. So to enter orbit, a spacecraft must not only reach space, but must also achieve a sufficient orbital speed (angular velocity). For a low-Earth orbit, this is about 7,900 m/s (28,400 km/h; 17,700 mph); by contrast, the fastest airplane speed ever achieved (excluding speeds achieved by deorbiting spacecraft) was 2,200 m/s (7,900 km/h; 4,900 mph) in 1967 by the North American X-15.

Konstantin Tsiolkovsky was the first person to realize that, given the energy available from any available chemical fuel, a several-stage rocket would be required. The escape velocity to pull free of Earth's gravitational field altogether and move into interplanetary space is about 11,000 m/s (39,600 km/h; 24,600 mph) The energy required to reach velocity for low Earth orbit (32 MJ/kg) is about twenty times the energy required simply to climb to the corresponding altitude (10 kJ/(km·kg)).

There is a major difference between sub-orbital and orbital spaceflights. The minimum altitude for a stable orbit around Earth (that is, one without significant atmospheric drag) begins at around 350 kilometres (220 mi) above mean sea level. A common misunderstanding about the boundary to space is that orbit occurs simply by reaching this altitude. Achieving orbital speed can theoretically occur at any altitude, although atmospheric drag precludes an orbit that is too low. At sufficient speed, an airplane would

need a way to keep it from flying off into space, but at present, this speed is several times greater than anything within reasonable technology.

A common misconception is that people in orbit are outside Earth's gravity because they are "floating". They are floating because they are in "free fall": they are accelerating toward Earth, along with their spacecraft, but are simultaneously moving sideways fast enough that the "fall" away from a straight-line path merely keeps them in orbit at a constant distance above Earth's surface. Earth's gravity reaches out far past the Van Allen belt and keeps the Moon in orbit at an average distance of 384,403 kilometres (238,857 mi).

Regions

Space is not a perfect vacuum: its different regions are defined by the various atmospheres and "winds" that dominate within them, and extend to the point at which those winds give way to those beyond. Geospace extends from Earth's atmosphere to the outer reaches of Earth's magnetic field, whereupon it gives way to the solar wind of interplanetary space. Interplanetary space extends to the heliopause, whereupon the solar wind gives way to the winds of the interstellar medium. Interstellar space then continues to the edges of the galaxy, where it fades into the intergalactic void.

Geospace



Aurora australis observed by *Discovery*, on STS-39, May 1991 (orbital altitude: 260 km)

Geospace is the region of outer space near the Earth. Geospace includes the upper region of the atmosphere, as well as the ionosphere and magnetosphere. The Van Allen radiation belts also lie within the geospace. The region between Earth's atmosphere and the Moon is sometimes referred to as **cis-lunar space**.

Although it meets the definition of outer space, the atmospheric density within the first few hundred kilometers above the Kármán line is still sufficient to produce significant drag on satellites. Most artificial satellites operate in this region called low earth orbit and must fire their engines every few days to maintain orbit. The drag here is low enough that it could theoretically be overcome by radiation pressure on solar sails, a proposed propulsion system for interplanetary travel.

Geospace is populated by electrically charged particles at very low densities, the motions of which are controlled by the Earth's magnetic field. These plasmas form a medium from which storm-like disturbances powered by the solar wind can drive electrical currents into the Earth's upper atmosphere.

During geomagnetic storms two regions of geospace, the radiation belts and the ionosphere, can become strongly disturbed. These storms increase fluxes of energetic electrons that can permanently damage satellite electronics, disrupting telecommunications and GPS technologies, and can also be a hazard to astronauts, even in low-Earth orbit. They also create aurorae seen near the magnetic poles.

Geospace contains material left over from previous manned and unmanned launches that are a potential hazard to spacecraft. Some of this debris re-enters Earth's atmosphere periodically.

The absence of air makes geospace (and the surface of the Moon) ideal locations for astronomy at all wavelengths of the electromagnetic spectrum, as evidenced by the spectacular pictures sent back by the Hubble Space Telescope, allowing light from about 13.7 billion years ago — almost to the time of the Big Bang — to be observed.

The outer boundary of geospace is the interface between the magnetosphere and the solar wind. The inner boundary is the ionosphere. Alternately, geospace is the region of space between the Earth's upper atmosphere and the outermost reaches of the Earth's magnetic field.

Interplanetary

Interplanetary space, the space around the Sun and planets of the Solar System, is the region dominated by the interplanetary medium, which extends out to the heliopause where the influence of the galactic environment starts to dominate over the magnetic field and particle flux from the Sun. Interplanetary space is defined by the solar wind, a continuous stream of charged particles emanating from the Sun that creates a very tenuous atmosphere (the heliosphere) for billions of miles into space. This wind has a particle density of 5–10 protons/cm³ and is moving at a velocity of 350–400 km/s. The

distance and strength of the heliopause varies depending on the activity level of the solar wind. The discovery since 1995 of extrasolar planets means that other stars must possess their own interplanetary media.

The volume of interplanetary space is an almost pure vacuum, with a mean free path of about one astronomical unit at the orbital distance of the Earth. However, this space is not completely empty, and is sparsely filled with cosmic rays, which include ionized atomic nuclei and various subatomic particles. There is also gas, plasma and dust, small meteors, and several dozen types of organic molecules discovered to date by microwave spectroscopy.

Interplanetary space contains the magnetic field generated by the Sun. There are also magnetospheres generated by planets such as Jupiter, Saturn and the Earth that have their own magnetic fields. These are shaped by the influence of the solar wind into the approximation of a teardrop shape, with the long tail extending outward behind the planet. These magnetic fields can trap particles from the solar wind and other sources, creating belts of magnetic particles such as the Van Allen Belts. Planets without magnetic fields, such as Mars and Mercury, but excluding Venus, have their atmospheres gradually eroded by the solar wind.

Interstellar

Interstellar space is the physical space within a galaxy not occupied by stars or their planetary systems. The interstellar medium resides—by definition—in interstellar space.

Intergalactic

Intergalactic space is the physical space between galaxies. Generally free of dust and debris, intergalactic space is very close to a total vacuum. The space between galaxy clusters, called the voids, is probably nearly empty. Some theories put the average density of the Universe as the equivalent of one hydrogen atom per cubic meter. The density of the universe, however, is clearly not uniform; it ranges from relatively high density in galaxies (including very high density in structures within galaxies, such as planets, stars, and black holes) to conditions in vast voids that have much lower density than the universe's average.

Surrounding and stretching between galaxies, there is a rarefied plasma that is thought to possess a cosmic filamentary structure and that is slightly denser than the average density in the universe. This material is called the *intergalactic medium (IGM)* and is mostly ionized hydrogen; i.e. a plasma consisting of equal numbers of electrons and protons. The IGM is thought to exist at a density of 10 to 100 times the average density of the universe (10 to 100 hydrogen atoms per cubic meter). It reaches densities as high as 1000 times the average density of the universe in rich clusters of galaxies.

The reason the IGM is thought to be mostly ionized gas is that its temperature is thought to be quite high by terrestrial standards (though some parts of it are only "warm" by

astrophysical standards). As gas falls into the Intergalactic Medium from the voids, it heats up to temperatures of 10^5 K to 10^7 K, which is high enough for the bound electrons to escape from the hydrogen nuclei upon collisions. At these temperatures, it is called the Warm-Hot Intergalactic Medium (WHIM). Computer simulations indicate that on the order of half the atomic matter in the universe might exist in this warm-hot, rarefied state. When gas falls from the filamentary structures of the WHIM into the galaxy clusters at the intersections of the cosmic filaments, it can heat up even more, reaching temperatures of 10^8 K and above.

WWT

Types

Pumps can be broadly categorized according to three techniques:

- **Positive displacement** pumps use a mechanism to repeatedly expand a cavity, allow gases to flow in from the chamber, seal off the cavity, and exhaust it to the atmosphere.
- **Momentum transfer** pumps, also called **molecular pumps**, use high speed jets of dense fluid or high speed rotating blades to knock gas molecules out of the chamber.
- **Entrapment** pumps capture gases in a solid or adsorbed state. This includes **cryopumps**, **getters**, and **ion pumps**.

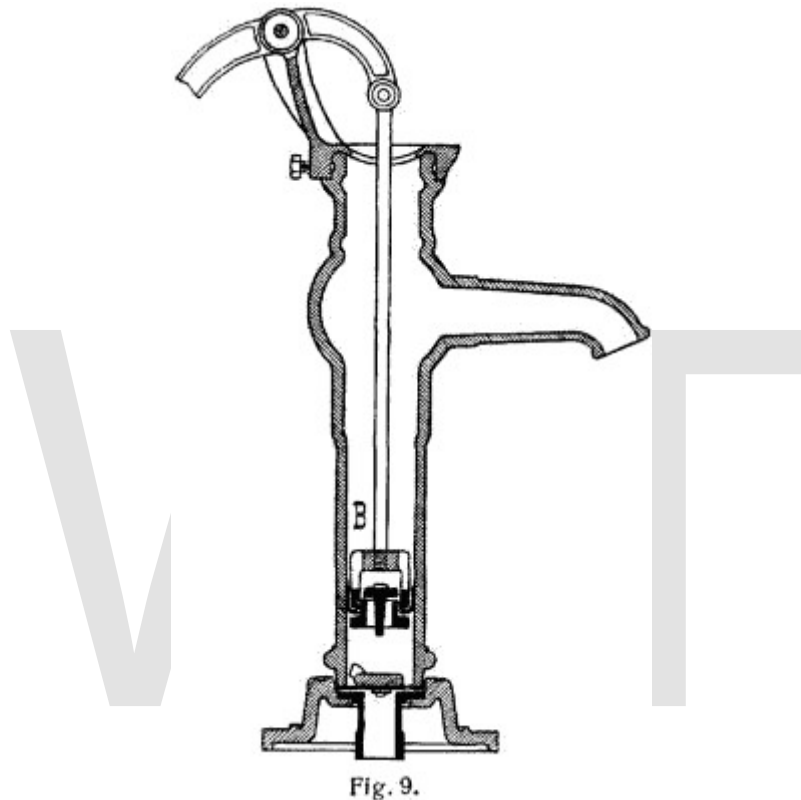
Positive displacement pumps are the most effective for low vacuums. Momentum transfer pumps in conjunction with one or two positive displacement pumps are the most common configuration used to achieve high vacuums. In this configuration the positive displacement pump serves two purposes. First it obtains a rough vacuum in the vessel being evacuated before the momentum transfer pump can be used to obtain the high vacuum, as momentum transfer pumps cannot start pumping at atmospheric pressures. Second the positive displacement pump backs up the momentum transfer pump by evacuating to low vacuum the accumulation of displaced molecules in the high vacuum pump. Entrapment pumps can be added to reach ultrahigh vacuums, but they require periodic regeneration of the surfaces that trap air molecules or ions. Due to this requirement their available operational time can be unacceptably short in low and high vacuums, thus limiting their use to ultrahigh vacuums. Pumps also differ in details like manufacturing tolerances, sealing material, pressure, flow, admission or no admission of oil vapor, service intervals, reliability, tolerance to dust, tolerance to chemicals, tolerance to liquids and vibration.

Performance measures

- **Pumping speed** refers to the volume flow rate of a pump at its inlet, often measured in volume per unit of time. Momentum transfer and entrapment pumps are more effective on some gases than others, so the pumping rate can be different for each of the gases being pumped, and the average volume flow rate of the pump will vary depending on the chemical composition of the gases remaining in the chamber.
- **Throughput** refers to the pumping speed multiplied by the gas pressure at the inlet, and is measured in units of pressure·volume/unit time. At a constant temperature, throughput is proportional to the number of molecules being pumped per unit time, and therefore to the mass flow rate of the pump. When discussing a leak in the system or backstreaming through the pump, **throughput** refers to the volume leak rate multiplied by the pressure at the vacuum side of the leak, so the leak throughput can be compared to the pump throughput.

Positive displacement and momentum transfer pumps have a constant volume flow rate, (pumping speed,) but as the chamber's pressure drops, this volume contains less and less mass. So although the pumping speed remains constant, the throughput and mass flow rate drop exponentially. Meanwhile, the leakage, evaporation, sublimation and backstreaming rates continue to produce a constant throughput into the system.

Positive displacement



The manual water pump draws water up from a well by creating a vacuum that water rushes in to fill. In a sense, it acts to evacuate the well, although the high leakage rate of dirt prevents a high quality vacuum from being maintained for any length of time.



Mechanism of a scroll pump

Fluids cannot be pulled, so it is technically impossible to create a vacuum by suction. Suction is the movement of fluids into a vacuum under the effect of a higher external pressure, but the vacuum has to be created first. The easiest way to create an artificial vacuum is to expand the volume of a container. For example, the diaphragm muscle expands the chest cavity, which causes the volume of the lungs to increase. This expansion reduces the pressure and creates a partial vacuum, which is soon filled by air pushed in by atmospheric pressure

To continue evacuating a chamber indefinitely without requiring infinite growth, a compartment of the vacuum can be repeatedly closed off, exhausted, and expanded again. This is the principle behind *positive displacement pumps*, like the manual water pump for example. Inside the pump, a mechanism expands a small sealed cavity to create a deep vacuum. Because of the pressure differential, some fluid from the chamber (or the well, in our example) is pushed into the pump's small cavity. The pump's cavity is then sealed from the chamber, opened to the atmosphere, and squeezed back to a minute size.

More sophisticated systems are used for most industrial applications, but the basic principle of cyclic volume removal is the same:

- Rotary vane pump, the most common
- Diaphragm pump, zero oil contamination
- Liquid ring pump
- Piston pump, cheapest
- Scroll pump, highest speed dry pump
- Screw pump (10 Pa)
- Wankel pump
- External vane pump
- Roots blower, also called a **booster pump**, has highest pumping speeds but low compression ratio
- Multistage Roots pump that combine several stages providing high pumping speed with better compression ratio
- Toepler pump
- Lobe pump

The base pressure of a rubber- and plastic-sealed piston pump system is typically 1 to 50 kPa, while a scroll pump might reach 10 Pa (when new) and a rotary vane oil pump with a clean and empty metallic chamber can easily achieve 0.1 Pa.

A positive displacement vacuum pump moves the same volume of gas with each cycle, so its pumping speed is constant unless it is overcome by backstreaming.

Momentum transfer



A cutaway view of a turbomolecular high vacuum pump

In a **momentum transfer** pump, gas molecules are accelerated from the vacuum side to the exhaust side (which is usually maintained at a reduced pressure by a positive displacement pump). Momentum transfer pumping is only possible below pressures of about 0.1 kPa. Matter flows differently at different pressures based on the laws of fluid dynamics. At atmospheric pressure and mild vacuums, molecules interact with each other and push on their neighboring molecules in what is known as viscous flow. When the distance between the molecules increases, the molecules interact with the walls of the chamber more often than the other molecules, and **molecular pumping** becomes more effective than positive displacement pumping. This regime is generally called **high vacuum**.

Molecular pumps sweep out a larger area than mechanical pumps, and do so more frequently, making them capable of much higher pumping speeds. They do this at the expense of the seal between the vacuum and their exhaust. Since there is no seal, a small

pressure at the exhaust can easily cause backstreaming through the pump; this is called **stall**. In high vacuum, however, pressure gradients have little effect on fluid flows, and molecular pumps can attain their full potential.

The two main types of molecular pumps are the diffusion pump and the turbomolecular pump. Both types of pumps blow out gas molecules that diffuse into the pump by imparting momentum to the gas molecules. Diffusion pumps blow out gas molecules with jets of oil or mercury, while turbomolecular pumps use high speed fans to push the gas. Both of these pumps will stall and fail to pump if exhausted directly to atmospheric pressure, so they must be exhausted to a lower grade vacuum created by a mechanical pump.

As with positive displacement pumps, the base pressure will be reached when leakage, outgassing, and backstreaming equal the pump speed, but now minimizing leakage and outgassing to a level comparable to backstreaming becomes much more difficult.

- Diffusion pump
- Turbomolecular pump

Entrapment

Entrapment pumps may be cryopumps, which use cold temperatures to condense gases to a solid or adsorbed state, **chemical** pumps, which react with gases to produce a solid residue, or ionization pumps, which use strong electrical fields to ionize gases and propel the ions into a solid substrate. A cryomodule uses cryopumping.

- Ion pump
- Cryopump
- Sorption pump
- Non-evaporative getter

Other pump types

- Venturi vacuum pump (aspirator) (10 to 30 kPa)
- Steam ejector (vacuum depends on the number of stages, but can be very low)

Techniques

Vacuum pumps are combined with chambers and operational procedures into a wide variety of vacuum systems. Sometimes more than one pump will be used (in series or in parallel) in a single application. A partial vacuum, or rough vacuum, can be created using a positive displacement pump that transports a gas load from an inlet port to an outlet (exhaust) port. Because of their mechanical limitations, such pumps can only achieve a low vacuum. To achieve a higher vacuum, other techniques must then be used, typically in series (usually following an initial fast pump down with a positive displacement

pump). Some examples might be use of an oil sealed rotary vane pump (the most common positive displacement pump) backing a diffusion pump, or a dry scroll pump backing a turbomolecular pump. There are other combinations depending on the level of vacuum being sought.

Achieving high vacuum is difficult because all of the materials exposed to the vacuum must be carefully evaluated for their outgassing and vapor pressure properties. For example, oils, and greases, and rubber, or plastic gaskets used as seals for the vacuum chamber must not boil off when exposed to the vacuum, or the gases they produce would prevent the creation of the desired degree of vacuum. Often, all of the surfaces exposed to the vacuum must be baked at high temperature to drive off adsorbed gases.

Outgassing can also be reduced simply by desiccation prior to vacuum pumping. High vacuum systems generally require metal chambers with metal gasket seals such as Klein flanges or ISO flanges, rather than the rubber gaskets more common in low vacuum chamber seals. The system must be clean and free of organic matter to minimize outgassing. All materials, solid or liquid, have a small vapour pressure, and their outgassing becomes important when the vacuum pressure falls below this vapour pressure. As a result, many materials that work well in low vacuums, such as epoxy, will become a source of outgassing at higher vacuums. With these standard precautions, vacuums of 1 mPa are easily achieved with an assortment of molecular pumps. With careful design and operation, 1 μ Pa is possible.

Several types of pumps may be used in sequence or in parallel. In a typical pumpdown sequence, a positive displacement pump would be used to remove most of the gas from a chamber, starting from atmosphere (760 Torr, 101 kPa) to 25 Torr (3 kPa). Then a sorption pump would be used to bring the pressure down to 10^{-4} Torr (10 mPa). A cryopump or turbomolecular pump would be used to bring the pressure further down to 10^{-8} Torr (1 μ Pa). An additional ion pump can be started below 10^{-6} Torr to remove gases which are not adequately handled by a cryopump or turbo pump, such as helium or hydrogen.

Ultra high vacuum generally requires custom-built equipment, strict operational procedures, and a fair amount of trial-and-error. Ultra-high vacuum systems are usually made of stainless steel with metal-gasketed conflat flanges. The system is usually baked, preferably under vacuum, to temporarily raise the vapour pressure of all outgassing materials in the system and boil them off. If necessary, this outgassing of the system can also be performed at room temperature, but this takes much more time. Once the bulk of the outgassing materials are boiled off and evacuated, the system may be cooled to lower vapour pressures to minimize residual outgassing during actual operation. Some systems are cooled well below room temperature by liquid nitrogen to shut down residual outgassing and simultaneously cryopump the system.

In ultra-high vacuum systems, some very odd leakage paths and outgassing sources must be considered. The water absorption of aluminium and palladium becomes an unacceptable source of outgassing, and even the absorptivity of hard metals such as

stainless steel or titanium must be considered. Some oils and greases will boil off in extreme vacuums. The porosity of the metallic chamber walls may have to be considered, and the grain direction of the metallic flanges should be parallel to the flange face.

The impact of molecular size must be considered. Smaller molecules can leak in more easily and are more easily absorbed by certain materials, and molecular pumps are less effective at pumping gases with lower molecular weights. A system may be able to evacuate nitrogen (the main component of air) to the desired vacuum, but the chamber could still be full of residual atmospheric hydrogen and helium. Vessels lined with a highly gas-permeable material such as palladium (which is a high-capacity hydrogen sponge) create special outgassing problems.

Uses of vacuum pumps

Vacuum pumps are used in many industrial and scientific processes including:

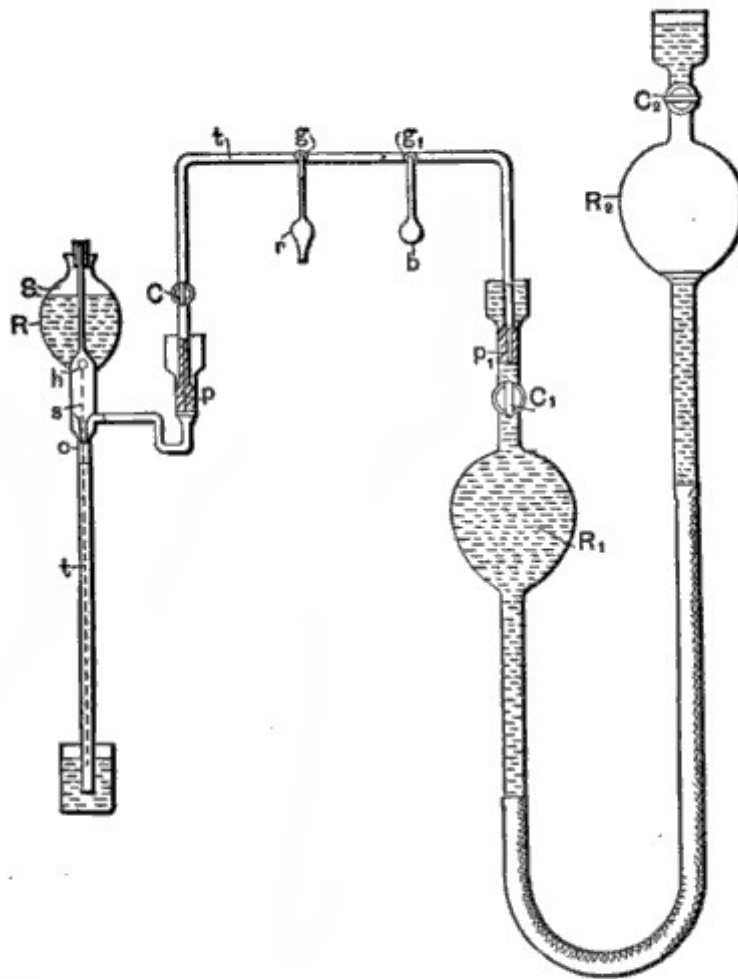
- Composite Plastic moulding processes (VRTM)
- Driving some of the flight instruments in most aircraft.
- The production of most types of electric lamps, vacuum tubes, and CRTs where the device is either left evacuated or re-filled with a specific gas or gas mixture
- Semiconductor processing, notably ion implantation, dry etch and PVD, ALD, PECVD and CVD deposition and soon in photolithography
- Electron microscopy
- Medical processes that require suction
- Medical applications such as such Radiotherapy, Radiosurgery, Radiopharmacy
- Analytical instrumentation to analyse gas, liquid, solid, surface and bio materials
- Mass spectrometers to create an ultra high vacuum between the ion source and the detector
- Vacuum Coating for decoration, for durability, for energy saving
- Glass coating for low e glass
- Hard coating for engine (as in Formula One)
- Ophthalmic coating
- Milking Machines
- Air conditioning service - removing all contaminants from the system before charging with refrigerant
- Trash compactor
- Vacuum engineering
- Sewage systems
- Freeze Drying
- As the main source of vacuum in dairy shed plant

Vacuum may be used to power, or provide assistance to mechanical devices. In diesel engined motor vehicles, a pump fitted on the engine (usually on the camshaft) is used to produce vacuum. In petrol engines, instead, vacuum is obtained as a side-effect of the operation of the engine and the flow restriction created by the throttle plate. This vacuum may then be used to power:

- The vacuum servo booster for the hydraulic brakes
- Motors that move dampers in the ventilation system
- The throttle driver in the cruise control servomechanism

In an aircraft, the vacuum source is often used to power gyroscopes in the various flight instruments. To prevent the complete loss of instrumentation in the event of an electrical failure, the instrument panel is deliberately designed with certain instruments powered by electricity and other instruments powered by the vacuum source.

History of the vacuum pump



APPARATUS USED FOR OBTAINING HIGH DEGREES OF EXHAUSTION.

The predecessor to the vacuum pump was the suction pump, which was known to the romans. Dual-action suction pumps were found in the city of Pompeii. Arabic engineer Al-Jazari also described suction pumps in the 13th century. He said that his model was a

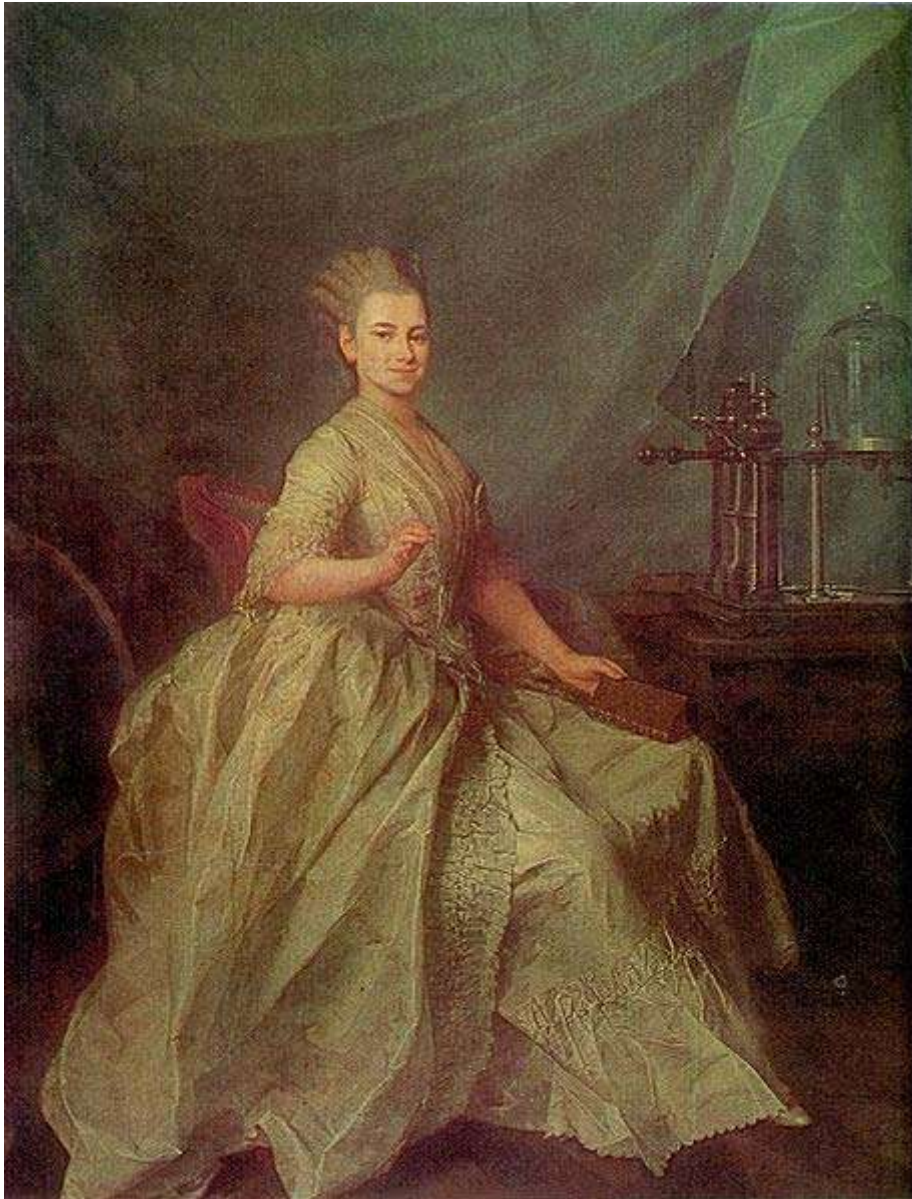
larger version of the siphons the Bizantines used to discharge the Greek fire. The suction pump later reappeared in Europe from the 15th century.

By the 17th century, water pump designs had improved to the point that they produced measurable vacuums, but this was not immediately understood. What was known was that suction pumps could not pull water beyond a certain height: 18 Florentine yards according to a measurement taken around 1635. (The conversion to metres is uncertain, but it would be about 9 or 10 metres.) This limit was a concern to irrigation projects, mine drainage, and decorative water fountains planned by the Duke of Tuscany, so the Duke commissioned Galileo to investigate the problem. Galileo advertised the puzzle to other scientists, including Gaspar Berti who replicated it by building the first water barometer in Rome in 1639. Berti's barometer produced a vacuum above the water column, but he could not explain it. The breakthrough was made by Evangelista Torricelli in 1643. Building upon Galileo's notes, he built the first mercury barometer and wrote a convincing argument that the space at the top was a vacuum. The height of the column was then limited to the maximum weight that atmospheric pressure could support. Some people believe that although Torricelli's experiment was crucial, it was Blaise Pascal's experiments that proved the top space really contained vacuum.

In 1654, Otto von Guericke invented the first vacuum pump and conducted his famous Magdeburg hemispheres experiment, showing that teams of horses could not separate two hemispheres from which the air had been evacuated. Robert Boyle improved Guericke's design and conducted experiments on the properties of vacuum. Robert Hooke also helped Boyle produce an air pump which helped to produce the vacuum. The study of vacuum then lapsed until 1855, when Heinrich Geissler invented the mercury displacement pump and achieved a record vacuum of about 10 Pa (0.1 Torr). A number of electrical properties become observable at this vacuum level, and this renewed interest in vacuum. This, in turn, led to the development of the vacuum tube.

In the 19th century, Nikola Tesla designed the apparatus, imaged to the right, that contains a Sprengel Pump to create a high degree of exhaustion.

Hazards



Student of Smolny Institute Catherine Molchanova with vacuum pump, by Dmitry Levitzky, 1776

Old vacuum-pump oils that were produced before circa 1980 often contain a mixture of several different dangerous polychlorinated biphenyls (PCBs), which are highly toxic, carcinogenic, persistent organic pollutants.

Chapter- 4

Pressure Measurement



The construction of a bourdon tube gauge, construction elements are made of brass

Many techniques have been developed for the measurement of pressure and vacuum. Instruments used to measure pressure are called **pressure gauges** or **vacuum gauges**.

A **manometer** could also be referring to a pressure measuring instrument, usually limited to measuring pressures near to atmospheric. The term *manometer* is often used to refer specifically to liquid column hydrostatic instruments.

A **vacuum gauge** is used to measure the pressure in a vacuum—which is further divided into two subcategories: high and low vacuum (and sometimes ultra-high vacuum). The applicable pressure range of many of the techniques used to measure vacuums have an overlap. Hence, by combining several different types of gauge, it is possible to measure system pressure continuously from 10 mbar down to 10^{-11} mbar.

Absolute, gauge and differential pressures - zero reference

Although pressure is an absolute quantity, everyday pressure measurements, such as for tire pressure, are usually made relative to ambient air pressure. In other cases measurements are made relative to a vacuum or to some other ad hoc reference. When distinguishing between these zero references, the following terms are used:

- **Absolute pressure** is zero referenced against a perfect vacuum, so it is equal to gauge pressure plus atmospheric pressure.
- **Gauge pressure** is zero referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted.
- **Differential pressure** is the difference in pressure between two points.

The zero reference in use is usually implied by context, and these words are only added when clarification is needed. Tire pressure and blood pressure are gauge pressures by convention, while atmospheric pressures, deep vacuum pressures, and altimeter pressures must be absolute. Differential pressures are commonly used in industrial process systems. Differential pressure gauges have two inlet ports, each connected to one of the volumes whose pressure is to be monitored. In effect, such a gauge performs the mathematical operation of subtraction through mechanical means, obviating the need for an operator or control system to watch two separate gauges and determine the difference in readings. Moderate vacuum pressures are often ambiguous, as they may represent absolute pressure or gauge pressure without a negative sign. Thus a vacuum of 26 inHg gauge is equivalent to an absolute pressure of 30 inHg (typical atmospheric pressure) $- 26 \text{ inHg} = 4 \text{ inHg}$.

Atmospheric pressure is typically about 100 kPa at sea level, but is variable with altitude and weather. If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes. For example, when a car drives up a mountain (atmospheric air pressure decreases), the (gauge) tire pressure goes up. Some standard values of atmospheric pressure such as 101.325 kPa or 100 kPa have been defined, and some instruments use one of these standard values as a constant zero reference instead of the actual variable ambient air pressure. This impairs the accuracy of these instruments, especially when used at high altitudes.

Use of the atmosphere as reference is usually signified by a (g) after the pressure unit e.g. 30 psi g, which means that the pressure measured is the total pressure minus atmospheric pressure. There are two types of gauge reference pressure: vented gauge (vg) and sealed gauge (sg).

A vented gauge pressure transmitter for example allows the outside air pressure to be exposed to the negative side of the pressure sensing diaphragm, via a vented cable or a hole on the side of the device, so that it always measures the pressure referred to ambient barometric pressure. Thus a vented gauge reference pressure sensor should always read zero pressure when the process pressure connection is held open to the air.

A sealed gauge reference is very similar except that atmospheric pressure is sealed on the negative side of the diaphragm. This is usually adopted on high pressure ranges such as hydraulics where atmospheric pressure changes will have a negligible effect on the accuracy of the reading, so venting is not necessary. This also allows some manufacturers to provide secondary pressure containment as an extra precaution for pressure equipment safety if the burst pressure of the primary pressure sensing diaphragm is exceeded.

There is another way of creating a sealed gauge reference and this is to seal a high vacuum on the reverse side of the sensing diaphragm. Then the output signal is offset so the pressure sensor reads close to zero when measuring atmospheric pressure.

A sealed gauge reference pressure transducer will never read exactly zero because atmospheric pressure is always changing and the reference in this case is fixed at 1 bar.

An absolute pressure measurement is one that is referred to absolute vacuum. The best example of an absolute referenced pressure is atmospheric or barometric pressure.

To produce an absolute pressure sensor the manufacturer will seal a high vacuum behind the sensing diaphragm. If the process pressure connection of an absolute pressure transmitter is open to the air, it will read the actual barometric pressure.

Units

Pressure units						
	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Atmosphere (atm)	Torr (Torr)	Pound- force per square inch (psi)
1 Pa	$\equiv 1 \text{ N/m}^2$	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	$\equiv 10^6 \text{ dyn/cm}^2$	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	$\equiv 1 \text{ kgf/cm}^2$	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	$\equiv 1 \text{ atm}$	760	14.696
1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	$\equiv 1 \text{ Torr};$ $\approx 1 \text{ mmHg}$	19.337×10^{-3}
1 psi	6.894×10^3	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	$\equiv 1 \text{ lbf/in}^2$

Example reading: $1 \text{ Pa} = 1 \text{ N/m}^2 = 10^{-5} \text{ bar} = 10.197 \times 10^{-6} \text{ at} = 9.8692 \times 10^{-6} \text{ atm} = 7.5006 \times 10^{-3} \text{ torr} = 145.04 \times 10^{-6} \text{ psi}$ etc.

The SI unit for pressure is the pascal (Pa), equal to one newton per square metre ($\text{N}\cdot\text{m}^{-2}$ or $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$). This special name for the unit was added in 1971; before that, pressure in SI was expressed in units such as N/m^2 . When indicated, the zero reference is stated in parenthesis following the unit, for example 101 kPa (abs). The pound per square inch (psi) is still in widespread use in the US and Canada, notably for cars. A letter is often appended to the psi unit to indicate the measurement's zero reference; psia for absolute, psig for gauge, psid for differential, although this practice is discouraged by the NIST.

Because pressure was once commonly measured by its ability to displace a column of liquid in a manometer, pressures are often expressed as a depth of a particular fluid (e.g. inches of water). The most common choices are mercury (Hg) and water; water is nontoxic and readily available, while mercury's density allows for a shorter column (and so a smaller manometer) to measure a given pressure.

Fluid density and local gravity can vary from one reading to another depending on local factors, so the height of a fluid column does not define pressure precisely. When 'millimetres of mercury' or 'inches of mercury' are quoted today, these units are not based on a physical column of mercury; rather, they have been given precise definitions that can be expressed in terms of SI units. The water-based units usually assume one of the older definitions of the kilogram as the weight of a litre of water.

Although no longer favoured by measurement experts, these **manometric units** are still encountered in many fields. Blood pressure is measured in millimetres of mercury in most of the world, and lung pressures in centimeters of water are still common. Natural gas pipeline pressures are measured in inches of water, expressed as "'WC' ('Water Column'). Scuba divers often use a manometric rule of thumb: the pressure exerted by ten metres depth of water is approximately equal to one atmosphere. In vacuum systems, the units torr, micrometre of mercury (micron), and inch of mercury (inHg) are most commonly used. Torr and micron usually indicates an absolute pressure, while inHg usually indicates a gauge pressure.

Atmospheric pressures are usually stated using kilopascal (kPa), or atmospheres (atm), except in American meteorology where the hectopascal (hPa) and millibar (mbar) are preferred. In American and Canadian engineering, stress is often measured in kip. Note that stress is not a true pressure since it is not scalar. In the cgs system the unit of pressure was the barye (ba), equal to $1 \text{ dyn}\cdot\text{cm}^{-2}$. In the mts system, the unit of pressure was the pieze, equal to 1 sthene per square metre.

Many other hybrid units are used such as mmHg/cm² or grams-force/cm² (sometimes as kg/cm² and g/mol² without properly identifying the force units). Using the names kilogram, gram, kilogram-force, or gram-force (or their symbols) as a unit of force is forbidden in SI; the unit of force in SI is the newton (N).

Static and dynamic pressure

Static pressure is uniform in all directions, so pressure measurements are independent of direction in an immovable (static) fluid. Flow, however, applies additional pressure on surfaces perpendicular to the flow direction, while having little impact on surfaces parallel to the flow direction. This directional component of pressure in a moving (dynamic) fluid is called dynamic pressure. An instrument facing the flow direction measures the sum of the static and dynamic pressures; this measurement is called the total pressure or stagnation pressure. Since dynamic pressure is referenced to static pressure, it is neither gauge nor absolute; it is a differential pressure.

While static gauge pressure is of primary importance to determining net loads on pipe walls, dynamic pressure is used to measure flow rates and airspeed. Dynamic pressure can be measured by taking the differential pressure between instruments parallel and perpendicular to the flow. Pitot-static tubes, for example perform this measurement on airplanes to determine airspeed. The presence of the measuring instrument inevitably acts to divert flow and create turbulence, so its shape is critical to accuracy and the calibration curves are often non-linear.

Applications

- Altimeter
- Barometer
- MAP sensor
- Pitot tube
- Sphygmomanometer

Instruments

Many instruments have been invented to measure pressure, with different advantages and disadvantages. Pressure range, sensitivity, dynamic response and cost all vary by several orders of magnitude from one instrument design to the next. The oldest type is the liquid column (a vertical tube filled with mercury) manometer invented by Evangelista Torricelli in 1643. The U-Tube was invented by Christian Huygens in 1661.

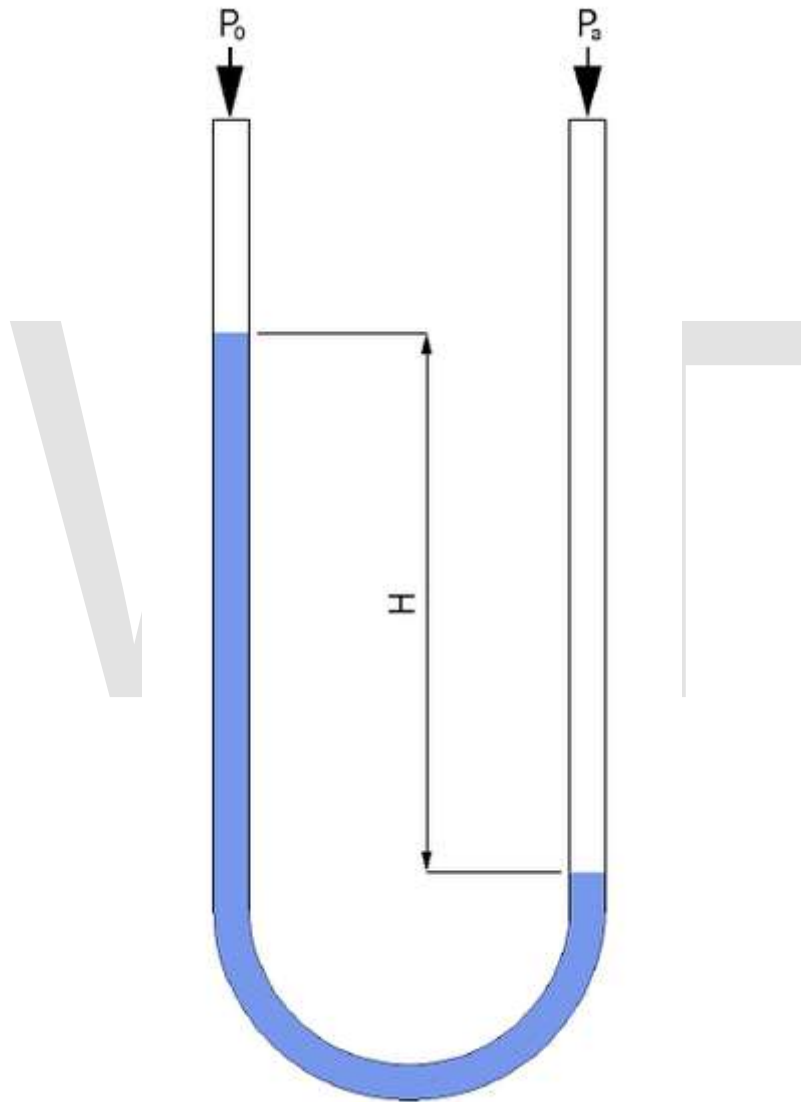
Hydrostatic

Hydrostatic gauges (such as the mercury column manometer) compare pressure to the hydrostatic force per unit area at the base of a column of fluid. Hydrostatic gauge measurements are independent of the type of gas being measured, and can be designed to have a very linear calibration. They have poor dynamic response.

Piston

Piston-type gauges counterbalance the pressure of a fluid with a solid weight or a spring. Another name for piston gauge is deadweight tester. For example, dead-weight testers used for calibration or tire-pressure gauges.

Liquid column



The difference in fluid height in a liquid column manometer is proportional to the

pressure difference.

$$H = \frac{P_a - P_o}{g\rho}$$

Liquid column gauges consist of a vertical column of liquid in a tube whose ends are exposed to different pressures. The column will rise or fall until its weight is in equilibrium with the pressure differential between the two ends of the tube. A very simple version is a U-shaped tube half-full of liquid, one side of which is connected to the region of interest while the reference pressure (which might be the atmospheric pressure or a vacuum) is applied to the other. The difference in liquid level represents the applied pressure. The pressure exerted by a column of fluid of height h and density ρ is given by the hydrostatic pressure equation, $P = h\rho g$. Therefore the pressure difference between the applied pressure P_a and the reference pressure P_0 in a U-tube manometer can be found by solving $P_a - P_0 = h\rho g$. If the fluid being measured is significantly dense, hydrostatic corrections may have to be made for the height between the moving surface of the manometer working fluid and the location where the pressure measurement is desired.

Although any fluid can be used, mercury is preferred for its high density (13.534 g/cm^3) and low vapour pressure. For low pressure differences well above the vapour pressure of water, water is commonly used (and "inches of water" is a common pressure unit). Liquid-column pressure gauges are independent of the type of gas being measured and have a highly linear calibration. They have poor dynamic response. When measuring vacuum, the working liquid may evaporate and contaminate the vacuum if its vapor pressure is too high. When measuring liquid pressure, a loop filled with gas or a light fluid must isolate the liquids to prevent them from mixing. Simple hydrostatic gauges can measure pressures ranging from a few Torr (a few 100 Pa) to a few atmospheres. (Approximately 1,000,000 Pa)

A single-limb liquid-column manometer has a larger reservoir instead of one side of the U-tube and has a scale beside the narrower column. The column may be inclined to further amplify the liquid movement. Based on the use and structure following type of manometers are used

1. Simple Manometer
2. Micromanometer
3. Differential manometer
4. Inverted differential manometer



A McLeod gauge, drained of mercury

McLeod gauge

A McLeod gauge isolates a sample of gas and compresses it in a modified mercury manometer until the pressure is a few mmHg. The gas must be well-behaved during its compression (it must not condense, for example). The technique is slow and unsuited to continual monitoring, but is capable of good accuracy.

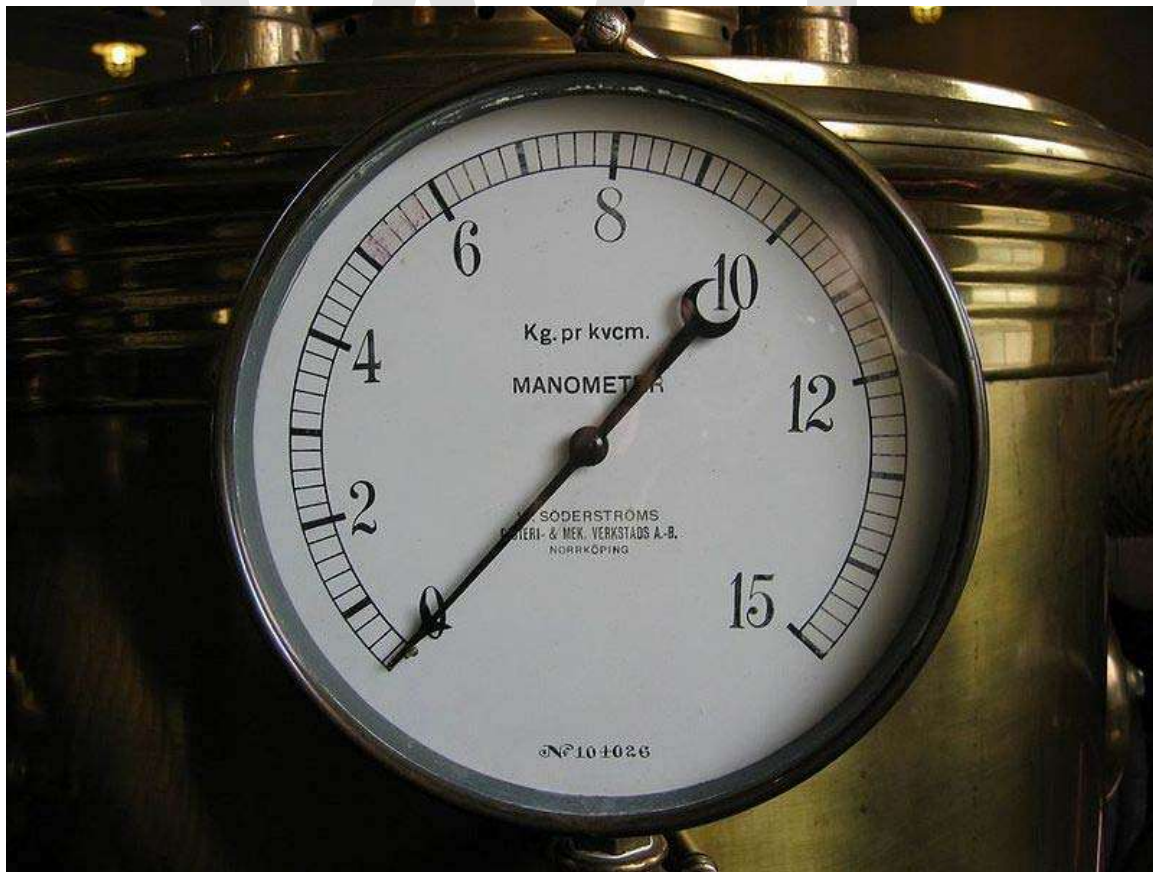
Useful range: above 10^{-4} torr (roughly 10^{-2} Pa) as high as 10^{-6} Torr (0.1 mPa),

0.1 mPa is the lowest direct measurement of pressure that is possible with current technology. Other vacuum gauges can measure lower pressures, but only indirectly by measurement of other pressure-controlled properties. These indirect measurements must be calibrated to SI units via a direct measurement, most commonly a McLeod gauge.

Aneroid

Aneroid gauges are based on a metallic pressure sensing element which flexes elastically under the effect of a pressure difference across the element. "Aneroid" means "without fluid," and the term originally distinguished these gauges from the hydrostatic gauges described above. However, aneroid gauges can be used to measure the pressure of a liquid as well as a gas, and they are not the only type of gauge that can operate without fluid. For this reason, they are often called **mechanical** gauges in modern language. Aneroid gauges are not dependent on the type of gas being measured, unlike thermal and ionization gauges, and are less likely to contaminate the system than hydrostatic gauges. The pressure sensing element may be a **Bourdon tube**, a diaphragm, a capsule, or a set of bellows, which will change shape in response to the pressure of the region in question. The deflection of the pressure sensing element may be read by a linkage connected to a needle, or it may be read by a secondary transducer. The most common secondary transducers in modern vacuum gauges measure a change in capacitance due to the mechanical deflection. Gauges that rely on a change in capacitances are often referred to as Baratron gauges.

Bourdon



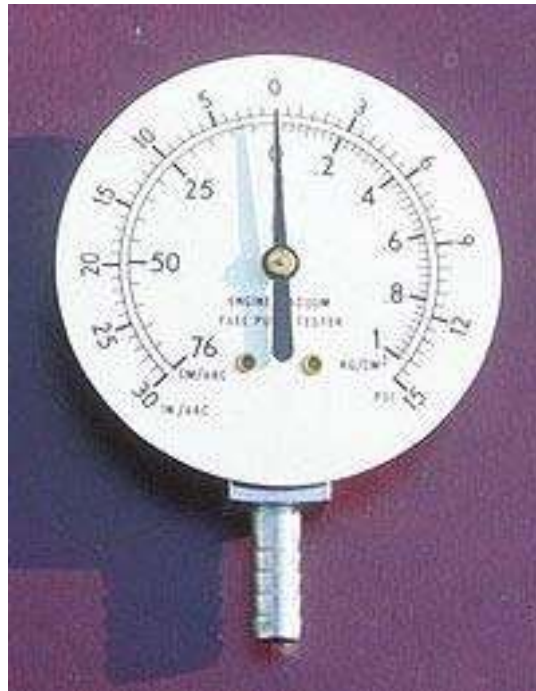
Membrane-type manometer

The Bourdon pressure gauge uses the principle that a flattened tube tends to change to a more circular cross-section when pressurized. Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized. Eugene Bourdon patented his gauge in France in 1849, and it was widely adopted because of its superior sensitivity, linearity, and accuracy; Edward Ashcroft purchased Bourdon's American patent rights in 1852 and became a major manufacturer of gauges. Also in 1849, Bernard Schaeffer in Magdeburg, Germany patented a successful diaphragm (see below) pressure gauge, which together with the Bourdon gauge, revolutionized pressure measurement in industry. But in 1875 after Bourdon's patents expired, his company Schaeffer and Budenberg also manufactured Bourdon tube gauges.

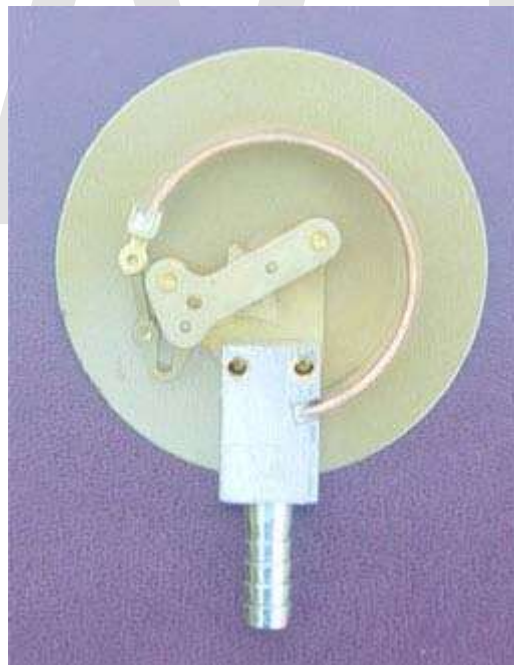
In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a (segment of a) gear by a connecting link which is usually adjustable. A small diameter pinion gear is on the pointer shaft, so the motion is magnified further by the gear ratio. The positioning of the indicator card behind the pointer, the initial pointer shaft position, the linkage length and initial position, all provide means to calibrate the pointer to indicate the desired range of pressure for variations in the behaviour of the Bourdon tube itself. Differential pressure can be measured by gauges containing two different Bourdon tubes, with connecting linkages.

Bourdon tubes measure gauge pressure, relative to ambient atmospheric pressure, as opposed to absolute pressure; vacuum is sensed as a reverse motion. Some aneroid barometers use Bourdon tubes closed at both ends (but most use diaphragms or capsules, see below). When the measured pressure is rapidly pulsing, such as when the gauge is near a reciprocating pump, an orifice restriction in the connecting pipe is frequently used to avoid unnecessary wear on the gears and provide an average reading; when the whole gauge is subject to mechanical vibration, the entire case including the pointer and indicator card can be filled with an oil or glycerin. Typical high-quality modern gauges provide an accuracy of $\pm 2\%$ of span, and a special high-precision gauge can be as accurate as 0.1% of full scale.

In the following illustrations the transparent cover face of the pictured combination pressure and vacuum gauge has been removed and the mechanism removed from the case. This particular gauge is a combination vacuum and pressure gauge used for automotive diagnosis:



Indicator side with card and dial

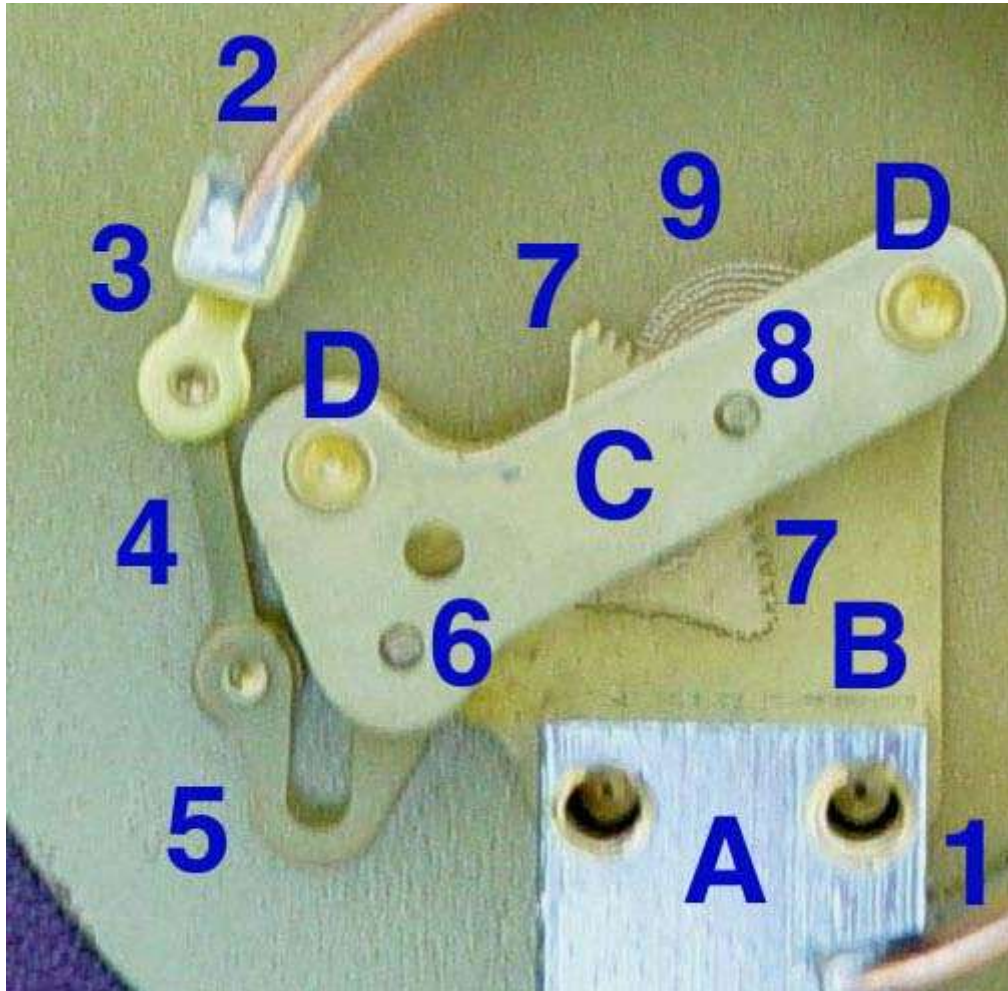


Mechanical side with Bourdon tube

- the left side of the face, used for measuring manifold vacuum, is calibrated in centimetres of mercury on its inner scale and inches of mercury on its outer scale.

- the right portion of the face is used to measure fuel pump pressure and is calibrated in fractions of 1 kgf/cm² on its inner scale and pounds per square inch on its outer scale.

Mechanical details



Mechanical details

Stationary parts:

- A: Receiver block. This joins the inlet pipe to the fixed end of the Bourdon tube (1) and secures the chassis plate (B). The two holes receive screws that secure the case.
- B: Chassis plate. The face card is attached to this. It contains bearing holes for the axles.
- C: Secondary chassis plate. It supports the outer ends of the axles.
- D: Posts to join and space the two chassis plates.

Moving Parts:

1. Stationary end of Bourdon tube. This communicates with the inlet pipe through the receiver block.
2. Moving end of Bourdon tube. This end is sealed.
3. Pivot and pivot pin.
4. Link joining pivot pin to lever (5) with pins to allow joint rotation.
5. Lever. This an extension of the sector gear (7).
6. Sector gear axle pin.
7. Sector gear.
8. Indicator needle axle. This has a spur gear that engages the sector gear (7) and extends through the face to drive the indicator needle. Due to the short distance between the lever arm link boss and the pivot pin and the difference between the effective radius of the sector gear and that of the spur gear, any motion of the Bourdon tube is greatly amplified. A small motion of the tube results in a large motion of the indicator needle.
9. Hair spring to preload the gear train to eliminate gear lash and hysteresis.

Diaphragm



A pile of pressure capsules with corrugated diaphragms in an aneroid barograph

A second type of aneroid gauge uses the deflection of a flexible membrane that separates regions of different pressure. The amount of deflection is repeatable for known pressures so the pressure can be determined by using calibration. The deformation of a thin diaphragm is dependent on the difference in pressure between its two faces. The reference face can be open to atmosphere to measure gauge pressure, open to a second port to measure differential pressure, or can be sealed against a vacuum or other fixed reference pressure to measure absolute pressure. The deformation can be measured using mechanical, optical or capacitive techniques. Ceramic and metallic diaphragms are used.

Useful range: above 10^{-2} Torr (roughly 1 Pa)

For absolute measurements, welded pressure capsules with diaphragms on either side are often used.

Shape:

- Flat
- corrugated
- flattened tube
- capsule

Bellows

In gauges intended to sense small pressures or pressure differences, or require that an absolute pressure be measured, the gear train and needle may be driven by an enclosed and sealed bellows chamber, called an **aneroid**, which means "without liquid". (Early barometers used a column of liquid such as water or the liquid metal mercury suspended by a vacuum.) This bellows configuration is used in aneroid barometers (barometers with an indicating needle and dial card), altimeters, altitude recording barographs, and the altitude telemetry instruments used in weather balloon radiosondes. These devices use the sealed chamber as a reference pressure and are driven by the external pressure. Other sensitive aircraft instruments such as air speed indicators and rate of climb indicators (variometers) have connections both to the internal part of the aneroid chamber and to an external enclosing chamber.

Electronic pressure sensors

- ***Piezoresistive Strain Gage***

Uses the piezoresistive effect of bonded or formed strain gauges to detect strain due to applied pressure.

- ***Capacitive***

Uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure.

- ***Magnetic***

Measures the displacement of a diaphragm by means of changes in inductance (reluctance), LVDT, Hall Effect, or by eddy current principal.

- ***Piezoelectric***

Uses the piezoelectric effect in certain materials such as quartz to measure the strain upon the sensing mechanism due to pressure.

- ***Optical***

Uses the physical change of an optical fiber to detect strain due applied pressure.

- ***Potentiometric***

Uses the motion of a wiper along a resistive mechanism to detect the strain caused by applied pressure.

- ***Resonant***

Uses the changes in resonant frequency in a sensing mechanism to measure stress, or changes in gas density, caused by applied pressure.

Thermal conductivity

Generally, as a real gas increases in density -which may indicate an increase in pressure- its ability to conduct heat increases. In this type of gauge, a wire filament is heated by running current through it. A thermocouple or Resistance Temperature Detector (RTD) can then be used to measure the temperature of the filament. This temperature is dependent on the rate at which the filament loses heat to the surrounding gas, and therefore on the thermal conductivity. A common variant is the Pirani gauge which uses a single platinum filament as both the heated element and RTD. These gauges are accurate from 10 Torr to 10^{-3} Torr, but they are sensitive to the chemical composition of the gases being measured.

Two wire

One wire coil is used as a heater, and the other is used to measure nearby temperature due to convection.

Pirani (one wire)

A Pirani gauge consists of a metal wire open to the pressure being measured. The wire is heated by a current flowing through it and cooled by the gas surrounding it. If the gas pressure is reduced, the cooling effect will decrease, hence the equilibrium temperature of the wire will increase. The resistance of the wire is a function of its temperature: by measuring the voltage across the wire and the current flowing through it, the resistance (and so the gas pressure) can be determined. This type of gauge was invented by Marcello Pirani.

Thermocouple gauges and **thermistor gauges** work in a similar manner, except a thermocouple or thermistor is used to measure the temperature of the wire.

Useful range: 10^{-3} - 10 Torr (roughly 10^{-1} - 1000 Pa)

Ionization gauge

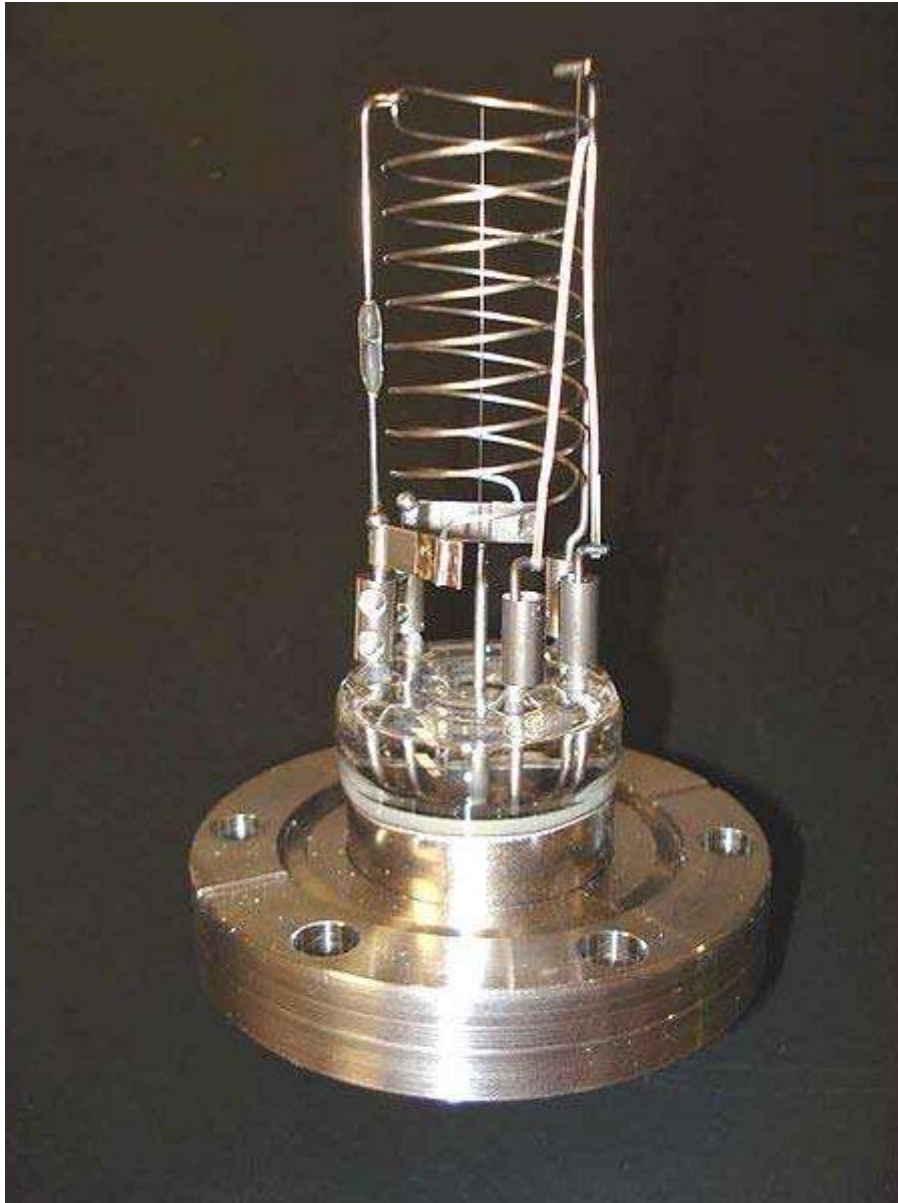
Ionization gauges are the most sensitive gauges for very low pressures (also referred to as hard or high vacuum). They sense pressure indirectly by measuring the electrical ions produced when the gas is bombarded with electrons. Fewer ions will be produced by lower density gases. The calibration of an ion gauge is unstable and dependent on the nature of the gases being measured, which is not always known. They can be calibrated against a McLeod gauge which is much more stable and independent of gas chemistry.

Thermionic emission generate electrons, which collide with gas atoms and generate positive ions. The ions are attracted to a suitably biased electrode known as the collector. The current in the collector is proportional to the rate of ionization, which is a function of the pressure in the system. Hence, measuring the collector current gives the gas pressure. There are several sub-types of ionization gauge.

Useful range: 10^{-10} - 10^{-3} torr (roughly 10^{-8} - 10^{-1} Pa)

Most ion gauges come in two types: hot cathode and cold cathode, a third type exists which is more sensitive and expensive known as a spinning rotor gauge, but is not discussed here. In the hot cathode version an electrically heated filament produces an electron beam. The electrons travel through the gauge and ionize gas molecules around them. The resulting ions are collected at a negative electrode. The current depends on the number of ions, which depends on the pressure in the gauge. Hot cathode gauges are accurate from 10^{-3} Torr to 10^{-10} Torr. The principle behind cold cathode version is the same, except that electrons are produced in the discharge of a high voltage. Cold Cathode gauges are accurate from 10^{-2} Torr to 10^{-9} Torr. Ionization gauge calibration is very sensitive to construction geometry, chemical composition of gases being measured, corrosion and surface deposits. Their calibration can be invalidated by activation at atmospheric pressure or low vacuum. The composition of gases at high vacuums will usually be unpredictable, so a mass spectrometer must be used in conjunction with the ionization gauge for accurate measurement.

Hot cathode



Bayard-Alpert hot cathode ionization gauge

A hot cathode ionization gauge is mainly composed of three electrodes acting together as a triode, where the cathode is the filament. The three electrodes are a collector or plate, a filament, and a grid. The collector current is measured in picoamps by an electrometer. The filament voltage to ground is usually at a potential of 30 volts while the grid voltage at 180–210 volts DC, unless there is an optional electron bombardment feature, by heating the grid which may have a high potential of approximately 565 volts. The most common ion gauge is the hot cathode **Bayard-Alpert gauge**, with a small ion collector inside the grid. A glass envelope with an opening to the vacuum can surround the electrodes, but usually the **Nude Gauge** is inserted in the vacuum chamber directly, the

pins being fed through a ceramic plate in the wall of the chamber. Hot cathode gauges can be damaged or lose their calibration if they are exposed to atmospheric pressure or even low vacuum while hot. The measurements of a hot cathode ionization gauge are always logarithmic.

Electrons emitted from the filament move several times in back and forth movements around the grid before finally entering the grid. During these movements, some electrons collide with a gaseous molecule to form a pair of an ion and an electron (Electron ionization). The number of these ions is proportional to the gaseous molecule density multiplied by the electron current emitted from the filament, and these ions pour into the collector to form an ion current. Since the gaseous molecule density is proportional to the pressure, the pressure is estimated by measuring the ion current.

The low pressure sensitivity of hot cathode gauges is limited by the photoelectric effect. Electrons hitting the grid produce x-rays that produce photoelectric noise in the ion collector. This limits the range of older hot cathode gauges to 10^{-8} Torr and the Bayard-Alpert to about 10^{-10} Torr. Additional wires at cathode potential in the line of sight between the ion collector and the grid prevent this effect. In the extraction type the ions are not attracted by a wire, but by an open cone. As the ions cannot decide which part of the cone to hit, they pass through the hole and form an ion beam. This ion beam can be passed on to a

- Faraday cup
- Microchannel plate detector with Faraday cup
- Quadrupole mass analyzer with Faraday cup
- Quadrupole mass analyzer with Microchannel plate detector Faraday cup
- ion lens and acceleration voltage and directed at a target to form a sputter gun. In this case a valve lets gas into the grid-cage.

Cold cathode

There are two subtypes of cold cathode ionization gauges: the **Penning gauge** (invented by Frans Michel Penning), and the **Inverted magnetron**, also called a **Redhead gauge**. The major difference between the two is the position of the anode with respect to the cathode. Neither has a filament, and each may require a DC potential of about 4 kV for operation. Inverted magnetrons can measure down to 1×10^{-12} Torr.

Such gauges cannot operate if the ions generated by the cathode recombine before reaching the anodes. If the mean-free path of the gas within the gauge is smaller than the gauge's dimensions, then the electrode current will essentially vanish. A practical upper-bound to the detectable pressure is, for a Penning gauge, of the order of 10^{-3} Torr.

Similarly, cold cathode gauges may be reluctant to start at very low pressures, in that the near-absence of a gas makes it difficult to establish an electrode current - particularly in Penning gauges which use an axially symmetric magnetic field to create path lengths for ions which are of the order of metres. In ambient air suitable ion-pairs are ubiquitously

formed by cosmic radiation; in a Penning gauge design features are used to ease the set-up of a discharge path. For example, the electrode of a Penning gauge is usually finely tapered to facilitate the field emission of electrons.

Maintenance cycles of cold cathode gauges are generally measured in years, depending on the gas type and pressure that they are operated in. Using a cold cathode gauge in gases with substantial organic components, such as pump oil fractions, can result in the growth of delicate carbon films and shards within the gauge which eventually either short-circuit the electrodes of the gauge, or impede the generation of a discharge path.

Calibration

Pressure gauges are either direct- or indirect-reading. Hydrostatic and elastic gauges measure pressure are directly influenced by force exerted on the surface by incident particle flux, and are called direct reading gauges. Thermal and ionization gauges read pressure indirectly by measuring a gas property that changes in a predictable manner with gas density. Indirect measurements are susceptible to more errors than direct measurements.

- Dead weight tester
- McLeod
- mass spec + ionization

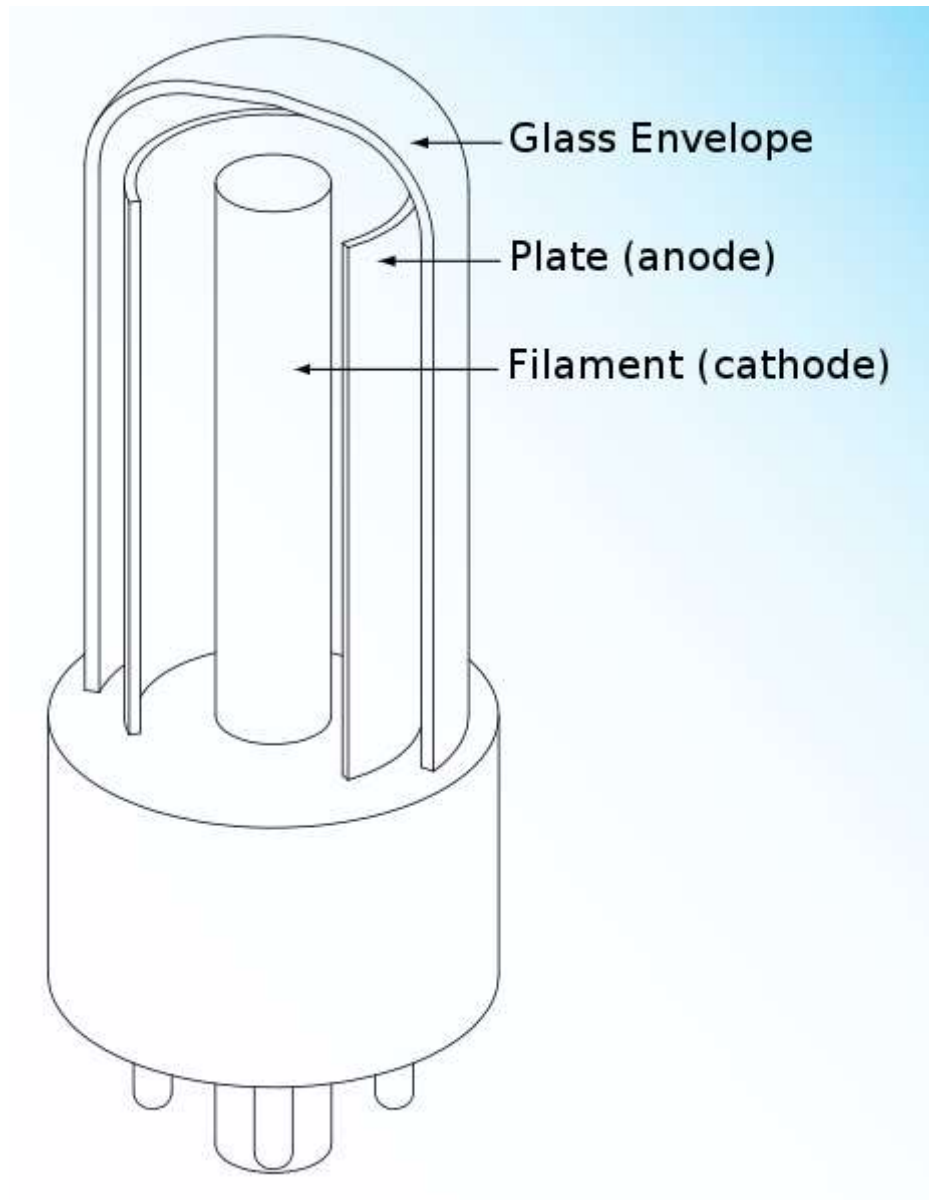
Dynamic transients

When fluid flows are not in equilibrium, local pressures may be higher or lower than the average pressure in a medium. These disturbances propagate from their source as longitudinal pressure variations along the path of propagation. This is also called sound. Sound pressure is the instantaneous local pressure deviation from the average pressure caused by a sound wave. Sound pressure can be measured using a microphone in air and a hydrophone in water. The effective sound pressure is the root mean square of the instantaneous sound pressure over a given interval of time. Sound pressures are normally small and are often expressed in units of microbar.

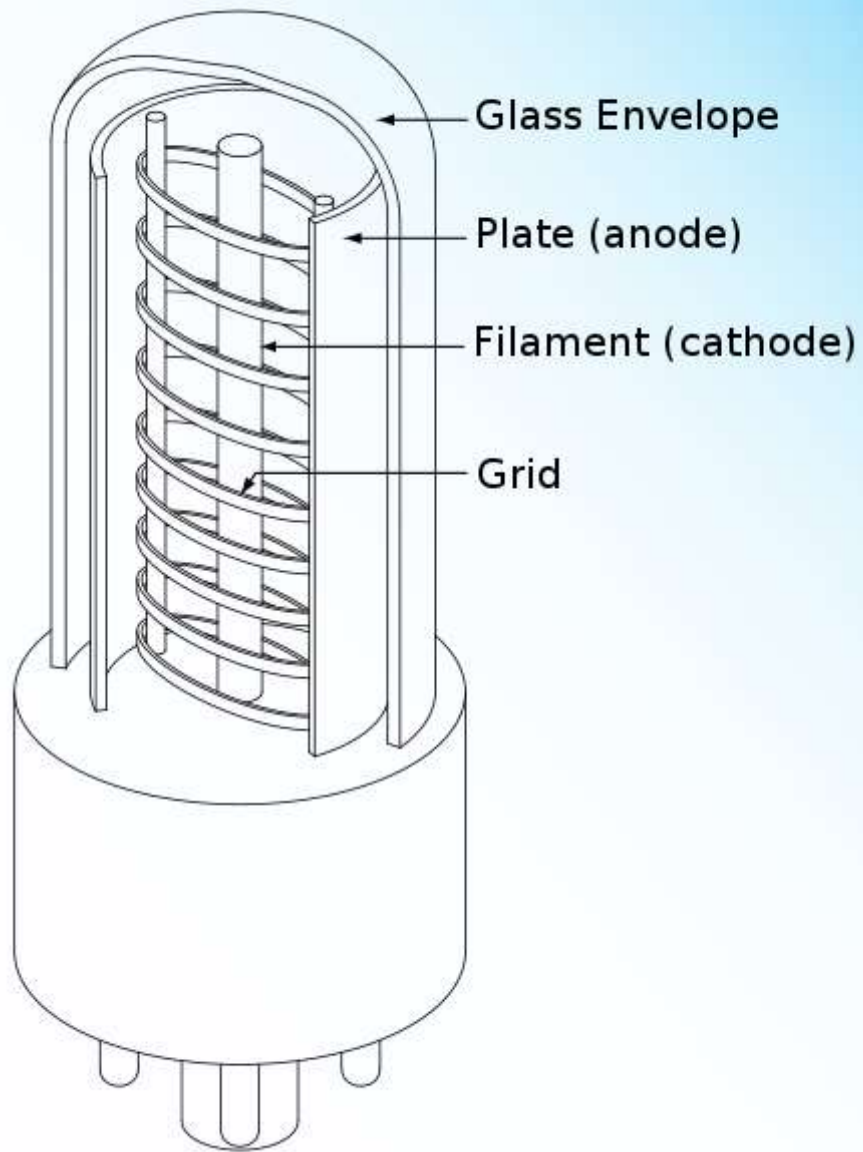
- frequency response of pressure sensors
- resonance

Chapter- 5

Vacuum Tube



Structure of a vacuum tube diode



Structure of a vacuum tube triode



An RCA triode vacuum tube, type 808

In electronics, a **vacuum tube**, **electron tube** (in North America), or **thermionic valve** (elsewhere, especially in Britain) is a device used to amplify, switch, otherwise modify, or create an electrical signal by controlling the movement of electrons in a low-pressure space. Some special function vacuum tubes are filled with low-pressure gas: these are so-called soft tubes as distinct from the hard vacuum type which have the internal gas pressure reduced as far as possible. Almost all tubes depend on the thermionic emission of electrons.

Description

A vacuum tube consists of electrodes in a vacuum in an insulating heat-resistant envelope which is usually tubular. Many tubes have glass envelopes, though some types such as power tubes may have ceramic or metal envelopes. The electrodes are attached to leads which pass through the envelope via an airtight seal. On most tubes, the leads are designed to plug into a tube socket for easy replacement.

The simplest vacuum tubes resemble incandescent light bulbs in that they have a filament sealed in a glass envelope which has been evacuated of all air. When hot, the filament releases electrons into the vacuum: a process called thermionic emission. The resulting negatively charged cloud of electrons is called a space charge. These electrons will be drawn to a metal plate inside the envelope, if the plate (also called the anode) is positively charged relative to the filament (or cathode). The result is a flow of electrons from filament to plate. This cannot work in the reverse direction because the plate is not heated and does not emit electrons. This very simple example described can thus be seen to operate as a diode: a device that conducts current only in one direction. The vacuum tube diode conducts conventional current from plate (anode) to the filament (cathode); this is the opposite direction to the flow of electrons (called electron current).

Vacuum tubes require a large temperature difference between the hot cathode and the cold anode. Because of this, vacuum tubes are inherently power-inefficient; enclosing the tube within a heat-retaining envelope of insulation would allow the entire tube to reach the same temperature, resulting in electron emission from the anode that would counter the normal one-way current. Because the tube requires a vacuum to operate, convection cooling of the anode is not generally possible unless the anode forms a part of the vacuum envelope (in which case the cooling is by conduction through the anode material and then convection outside the vacuum envelope). Thus anode cooling occurs in most tubes through black-body radiation and conduction of heat to the outer glass envelope via the anode mounting frame. Cold cathode tubes do not rely on thermionic emission at the cathode and usually have some form of gas discharge as the operating principle; such tubes are used for lighting (neon lamps) or as voltage regulators.

Sometimes another electrode, called a control grid, is added between the cathode and the anode. The vacuum tube is then known as a "triode." A triode is a *voltage-controlled device*, in that a voltage that is applied as an input to the grid can be used to modulate the rate of electron flow between anode and cathode. The relationship between this input voltage and the output current is determined by a transconductance function. Control grid current is practically negligible in most circuits. The solid-state device most closely analogous to the vacuum tube is the JFET, although the vacuum tube typically operates at far higher voltage (and power) levels than the JFET.

History and development



Inside of a vacuum tube with plate cut open

The 19th century saw increasing research with evacuated tubes, such as the Geissler and Crookes tubes. Scientists who experimented with such tubes included Eugen Goldstein, Nikola Tesla, Johann Wilhelm Hittorf, Thomas Edison, and many others. These tubes were mostly for specialized scientific applications, or were novelties, with the exception of the light bulb. The groundwork laid by these scientists and inventors, however, was critical to the development of vacuum tube technology.

Though the thermionic emission effect was originally reported in 1873 by Frederick Guthrie, it is Thomas Edison's 1884 investigation of the Edison Effect that is more often mentioned. Edison patented what he found, but he did not understand the underlying physics, or the potential value of the discovery. It wasn't until the early 20th century that this effect was put to use, in applications such as John Ambrose Fleming's diode used as a radio detector, and Lee De Forest's 1906 "audion" (soon improved by others as the triode in 1908) used in the first telephone amplifiers. These developments led to great improvements in telecommunications technology, particularly the first coast-to-coast telephone line in the US, and the birth of broadcast radio.

Diodes and triodes

The English physicist John Ambrose Fleming worked as an engineering consultant for firms, including Edison Telephone and the Marconi Company. In 1904, as a result of experiments conducted on Edison effect bulbs imported from the USA, he developed a device he called an "oscillation valve" (because it passes current in only one direction).

Later known as the Fleming valve, it could be used as a rectifier of alternating current and as a radio wave detector.

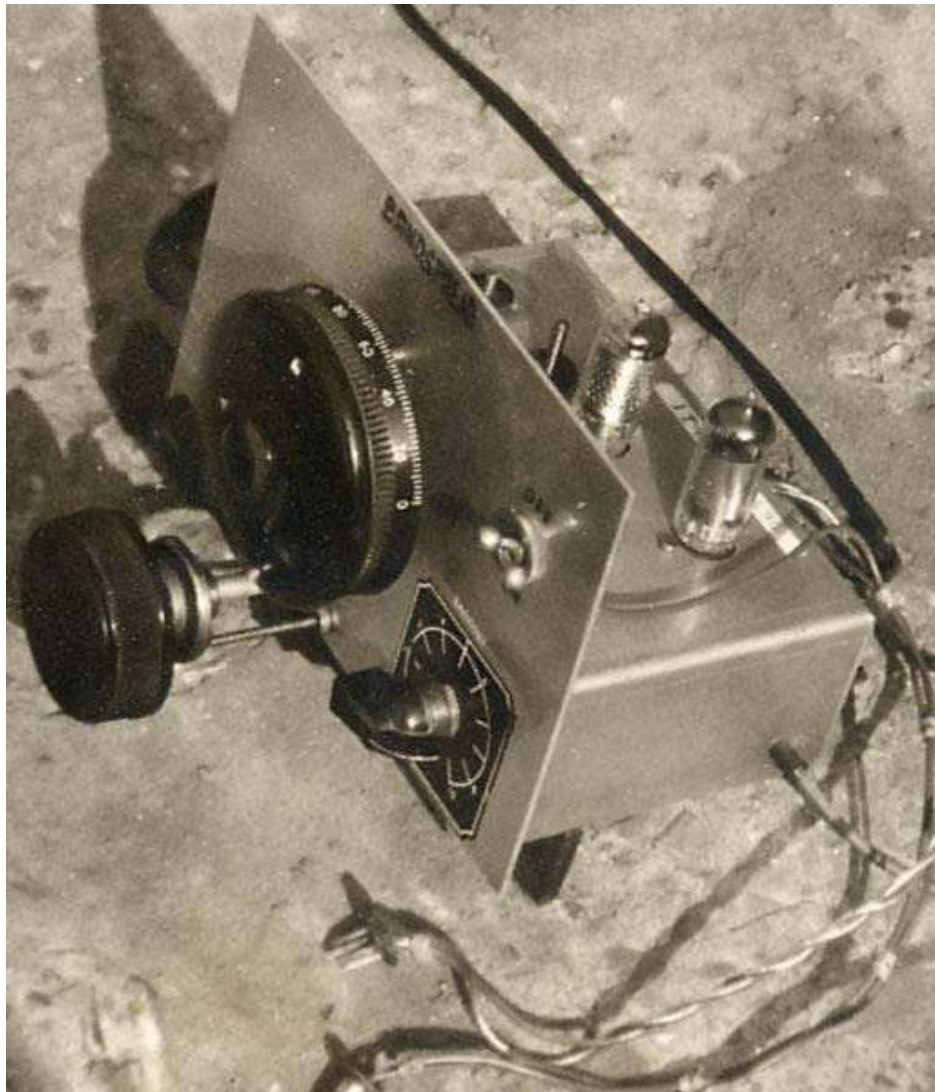
In 1906 Robert von Lieben filed for a three-electrode amplifying vacuum tube. His invention also included a beam-focusing electromagnet.

In 1907 Lee De Forest placed a bent wire serving as a screen, later known as the "grid" electrode, between the filament and plate electrode. As the voltage applied to the grid was varied from negative to positive, the number of electrons flowing from the filament to the plate would vary accordingly. Thus the grid was said to electrostatically "control" the plate current. The resulting three-electrode device was therefore an excellent and very sensitive amplifier of voltages. De Forest called his invention the "Audion". In 1907, De Forest filed for a three-electrode version of the Audion for use in radio communications. The device is now known as the triode. De Forest's device was not strictly a vacuum tube, but clearly depended for its action on ionisation of the relatively high levels of gas remaining after evacuation. The De Forest company, in its Audion leaflets, warned against operation which might cause the vacuum to become too hard. The Finnish inventor Eric Tigerstedt significantly improved on the original triode design in 1914, while working on his sound-on-film process in Berlin, Germany. The first true vacuum triodes were the Pliotrons developed by Irving Langmuir at the General Electric research laboratory (Schenectady, New York) in 1915. Langmuir was one of the first scientists to realize that a harder vacuum would improve the amplifying behaviour of the triode. Pliotrons were closely followed by the French 'R' Type which was in widespread use by the allied military by 1916. These two types were the first true *vacuum* tubes. Historically, vacuum levels in production vacuum tubes typically ranged between 10 μPa to 10 nPa.

The non-linear operating characteristic of the triode caused early tube audio amplifiers to exhibit harmonic distortions at low volumes. This is not to be confused with the

overdrive that tube amplifiers exhibit at high volume levels (known as the tube sound). To remedy the low-volume distortion problem, engineers plotted curves of the applied grid voltage and resulting plate currents, and discovered that there was a range of relatively linear operation. In order to use this range, a negative voltage had to be applied to the grid to place the tube in the "middle" of the linear area with no signal applied. This was called the idle condition, and the plate current at this point the "idle current". Today this current would be called the quiescent or standing current. The controlling voltage was superimposed onto this fixed voltage, resulting in linear swings of plate current for both positive and negative swings of the input voltage. This concept was called *grid bias*.

Tetrodes and pentodes



A two-tube homemade radio from 1958. The tubes are the two columns with the dark tops. The flying leads connect to the low-voltage filament and high-voltage anode supplies.

When triodes were first used in radio transmitters and receivers, it was found that they had a tendency to oscillate due to parasitic anode-to-grid capacitance. Many circuits were developed to reduce this problem (e.g. the Neutrodyne amplifier), but proved unsatisfactory over wide ranges of frequencies. It was discovered that the addition of a second grid, located between the control grid and the plate and called a *screen grid* could solve these problems. ("Screen" implies shielding, not physical construction.) A positive voltage slightly lower than the plate voltage was applied to it, and the screen grid was bypassed (for high frequencies) to ground with a capacitor. This arrangement decoupled the anode and the first grid, completely eliminating the oscillation problem. An additional side effect of this second grid is that the Miller capacitance is also reduced, which improves gain at high frequency. This two-grid tube is called a *tetrode*, meaning four active electrodes, and was common by 1926.



Radio transmitter high-power vacuum tube. The braided copper leads provide heater current for the cathode. The tube also has a heat sink. Dubendorf Museum of Military Aviation.

However, the tetrode has some new problems. In any tube, electrons strike the anode hard enough to knock out secondary electrons. In a triode these (less energetic) electrons cannot reach the grid or cathode, and are re-captured by the anode. But in a tetrode, they can be captured by the second grid, reducing the plate current and the amplification of the circuit. Since secondary electrons can outnumber the primary electrons, in the worst case, particularly when the plate voltage dips below the screen voltage, the plate current can actually go down with increasing plate voltage. This is negative-resistance behavior. This is the "tetrode kink". Another consequence of this effect is that under severe overload, the current collected by the screen grid can cause it to overheat and melt, destroying the tube.

Again, the solution was to add another grid, called a suppressor grid. This third grid was biased at either ground or cathode voltage and its negative voltage (relative to the anode) electrostatically suppressed the secondary electrons by repelling them back toward the

anode. This three-grid tube is called a pentode, meaning five electrodes. The pentode was invented in 1928 by Bernard D. H. Tellegen.

Improvements in construction and performance

The very earliest vacuum tubes strongly resembled incandescent light bulbs and were made by lamp manufacturers, who had the equipment for manufacture of glass envelopes and the powerful vacuum pumps required to evacuate the enclosures. After World War I, specialized manufacturers using more economical construction methods were set up to fill the growing demand for broadcast receivers. Bare tungsten filaments operated at a temperature of around 2200 °C. The development of oxide-coated filaments in the mid 1920s reduced filament operating temperature to a dull red heat (around 700 °C), which in turn reduced thermal distortion of the tube structure and allowed closer spacing of tube elements. This in turn improved tube gain, since the gain of a triode is inversely proportional to the spacing between grid and cathode. Development of the indirectly-heated cathode, with the filament inside a cylinder of oxide-coated nickel, further reduced distortion of the tube elements and also allowed the cathode heaters to be run from an AC supply.



Heat transfer and appearance of tubes



The anode of this tube has been designed to dissipate heat

Many types of vacuum tubes can be recognized from their appearance. A considerable amount of heat is produced when tubes operate. In most circuits the tube is about 30-60% efficient dependent on the class of operation (classes A, B, or C), which means that 40-70 % of input power to the stage is lost as heat. The requirements for heat removal significantly change the appearance of high-power vacuum tubes.

Most tubes contain two sources of heat when operating. The first one of these is the filament or heater. Some types contain a *directly heated cathode*. This is a filament

similar to an incandescent electric lamp and some types glow brightly like a lamp, but most glow dimly. (The "bright emitter" types possess a tungsten filament alloyed with 1-3 % thorium which reduces the work function of the metal, giving it the ability to emit sufficient electrons at about 2000 degrees Celsius. The "dull emitter" types also possess a tungsten filament but it is coated in a mixture of calcium, strontium and barium oxides, which emit electrons easily at much lower temperatures due to a monolayer of mixed alkali earth metals coating the tungsten when the cathode is heated to about 800-1000 degrees Celsius.)

The second form of cathode is the *indirectly heated* form which usually consists of a nickel tube, coated on the outside with the same strontium, calcium, barium oxide mix used in the "dull emitter" directly heated types, and fitted with a tungsten filament inside the tube to heat it. This tungsten filament is usually uncoiled and coated in a layer of alumina, (aluminium oxide), to insulate it from the nickel tube of the actual cathode. This form of construction allows for a much greater electron emitting area and, because the heater is insulated from the cathode, the cathode can be positioned in a circuit at up to 150 volts more positive than the heater or 50 volts more negative than the heater for most common types. It also allows all the heaters to be simply wired in series or parallel rather than some requiring special *isolated* power supplies such as specially insulated windings on power transformers or separate batteries. For small-signal tubes such as used in radio receivers, heaters are rated from 50 mW to 5 watts, (directly heated), and about 500 mW to 8 watts for indirectly heated types. Once filament/heater power is included in total power consumption, small tubes have very poor efficiencies. A 6BM8/ECL82 audio stage consumes a total power of some 15 watts for 3.5 watts of useful audio power, giving an efficiency of around 23%. Some signal amplifiers, particularly high-frequency amplifiers such as the 6BA6, consume some 5.9 watts of power in normal operation and deliver only 1.1 watts of power at the plate.

The second source of heat is generated at the anode, when electrons, accelerated by the voltage applied to the anode, strike the anode and impart a considerable fraction of their energy to it, raising its temperature. In tubes used in power amplifier or transmitting circuits, this source of heat will exceed the power dissipated in the cathode heater. (The plates or anodes of 6L6 devices used in guitar amplifiers can sometimes be seen to reach red heat if the *bias* is set too high, they should not emit any visible radiation when driven at maximum ratings.) No tubes in domestic, music, or studio equipment should operate with glowing anodes.

This heat usually escapes the device by black body radiation from the anode/plate as infra red light. Some is conducted away through the connecting wires going to the base but none is convected in most types of tube because of the vacuum and the absence of any gas inside the bulb to convect. It is the way tubes get rid of heat which most affects their overall appearance, next to the type of unit (triode, pentode, etc.) they contain, or whether they contain more than one of these basic units. For devices required to radiate more than 500 mW or so, usually indirectly heated cathode types, the anode or plate is often treated to make its surface less shiny, and to make it darker, either gray or black. This helps it radiate the generated heat and maintain the anode or plate at a temperature significantly

lower than the cathode, a requirement for proper operation. Types 6BQ5/EL84 and 6BM8/ECL82 are examples of indirectly heated types with gray anodes.

Other internal elements of high-power tubes, such as control grids and screen grids, may also dissipate heat if carrying large currents. Limits to grid dissipation are listed for such devices, to prevent distortion and failure of the grids.

Tubes used as power amplifier stages for radio transmitters may have additional heat exchangers, cooling fans, radiator fins, or other measures to improve heat transfer at the anode. Broadcast transmitters may use water-cooling or evaporative cooling for tube anodes. The water cooling system must withstand the high voltages present on the anode.

Low power rated tubes, such as the 1.4 volt filament, directly heated tubes, designed for use in battery powered equipment, often retain shiny metal anodes as they produce so little heat. 1T4, 1R5 and 1A7 are examples of devices with shiny untreated anodes. Gas filled tubes, such as thyratrons, although they possess a greater plate dissipation than a "1 volt battery type", still often possess a shiny metal anode finish as the gas filling conducts and convects the heat to the bulb wall. Types 884 and 2D21 are typical examples.

The outer electrode in most tubes is usually the anode. Some small signal types, such as sharp and remote cut-off R.F. and A.F. pentodes and some pentagrid converters have a shield fitted around all the electrodes enclosing the anode. This shield is sometimes a solid metal sheet, treated to make it dull and gray like an anode or plate, and sometimes it is fabricated from expanded metal mesh, acting as a Faraday cage but allowing sufficient heat from the anode beneath to escape. Types 6BX6/EF80 and 6BK8/EF86 are typical examples of this shielded type commonly using expanded mesh. Types 6AU6/EF94 and 6BE6/EK90 are examples using a gray sheet metal cylindrical shield giving them a very similar overall appearance.

Indicators such as some "magic eye" tubes and the type 6977 fluorescent-anode type have glowing electrodes.

Other variations



12SA7 Pentagrid converter tube

Frequency conversion can be accomplished by various methods in superheterodyne receivers. Tubes with 5 grids, called pentagrid converters, were generally used, although alternatives such as using a combination of a triode with a hexode were also used. Even octodes have been used for frequency conversion. The additional grids are either control grids, with different signals applied to each one, or screen grids. In many designs a special grid acted as a second 'leaky' plate to provide a built-in oscillator, which then coupled this signal with the incoming radio signal. These signals create a single, combined effect (equivalent to a crude analog multiplier) on the plate current (and thus

the signal output) of the tube circuit. The useful component of the output was the difference frequency between that of the incoming signal and that of the oscillator.

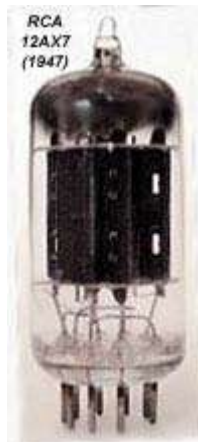
The heptode, or pentagrid converter, was the most common of these. 6BE6 is an example of a heptode (note that the first number in the tube ID indicates the filament voltage). Octodes were rare in the US, the 7A8 was one example, but much more common in Europe particularly in battery operated radios where the lower power consumption was an advantage.

Toward the end of the tube era, precision control and screen grids, called frame grids, offered enhanced performance. Instead of the typically elliptical fine-gauge wire supported by two larger wires, a frame grid was a metal stamping with rectangular openings that surrounded the cathode. The grid wires were in a plane defined by the stamping, and the control grid was placed much closer to the cathode surface than traditional construction would permit.

To reduce the cost and complexity of radio equipment, by 1940 it was common practice to combine more than one function, or more than one set of elements in the bulb of a single tube. The only constraint was where patents, and other licencing considerations required the use of multiple tubes.

For example, the RCA Type 55 was a double diode triode used as a detector, automatic gain control rectifier and audio preamp in early AC powered radios. The same set of tubes often included the 53 Dual Triode Audio Output.

Another early type of multi-section tube, the 6SN7, is a "dual triode" which, for most purposes, can perform the functions of two triode tubes, while taking up half as much space and costing less.



An RCA 12AX7 dual-triode tube (1947)

The 12AX7 is a dual high-gain triode widely used in guitar amplifiers, audio preamps, and instruments.

The invention of the 9-pin miniature tube base, besides allowing the 12AX7 family, also allowed many other multi section tubes, such as the 6GH8 triode pentode. Along with a host of similar tubes, the 6GH8 was quite popular in television receivers. Some color TV sets used exotic types like the 6JH8 which had two plates and beam deflection electrodes (it was known as the 'sheet beam' tube). Vacuum tubes used like this were designed for demodulation of synchronous signals, an example of which is color demodulation for television receivers.



Modern 12AX7 miniature vacuum tube (manufactured in Russia)

The desire to include many functions in one envelope resulted in the General Electric Compactron. A typical unit, the 6AG11 Compactron tube contained two triodes and two diodes, but many in the series had triple triodes.

An early example of multiple devices in one envelope was the Loewe 3NF. This 1920s device had 3 triodes in a single glass envelope together with all the fixed capacitors and resistors required to make a complete radio receiver. As the Loewe set had only one tube socket, it was able to substantially undercut the competition since, in Germany, state tax was levied by the number of sockets. However, reliability was compromised, and production costs for the tube were much greater. In a sense, these were akin to integrated circuits. In the US, Cleartron briefly produced the "Multivalve" triple triode for use in the Emerson Baby Grand receiver. This Emerson set also had a single tube socket, but

because it used a four-pin base, the additional element connections were made on a "mezzanine" platform at the top of the tube base.

Loewe were to also offer the 2NF (two tetrodes plus passive components) and the WG38 (two pentodes, a triode and the passive components).



Vacuum tubes in an Australian radio of the late 1930s

The beam power tube is usually a tetrode with the addition of beam-forming electrodes, which take the place of the suppressor grid. These angled plates focus the electron stream onto certain spots on the anode which can withstand the heat generated by the impact of massive numbers of electrons, while also providing pentode behavior. The positioning of the elements in a beam power tube uses a design called "critical-distance geometry", which minimizes the "tetrode kink", plate-grid capacitance, screen-grid current, and secondary emission effects from the anode, thus increasing power conversion efficiency. The control grid and screen grid are also wound with the same pitch, or number of wires per inch.

Aligning the grid wires also helps to reduce screen current, which represents wasted energy. This design helps to overcome some of the practical barriers to designing high-power, high-efficiency power tubes. 6L6 was the first popular beam power tube, introduced by RCA in 1936. Corresponding tubes in Europe were the KT66, KT77 and KT88 by GEC (the KT standing for "Kinkless Tetrode").

Variations of the 6L6 design are still widely used in guitar amplifiers, making it one of the longest lived electronic device families in history. Similar design strategies are used in the construction of large ceramic power tetrodes used in radio transmitters.

Special-purpose tubes

Some special-purpose tubes are constructed with particular gases in the envelope. For instance, voltage regulator tubes contain various inert gases such as argon, helium or neon, and take advantage of the fact that these gases will ionize at predictable voltages. The thyatron is a special-purpose tube filled with low-pressure gas or mercury, some of which vaporizes. Like other tubes, it contains a hot cathode and an anode, but also a control electrode, which behaves somewhat like the grid of a triode. When the control electrode starts conduction, the gas ionizes, and the control electrode no longer can stop the current; the tube "latches" into conduction. Removing plate (anode) voltage lets the gas de-ionize, restoring its non-conductive state. Some thyatrons can carry large currents for their physical size. One example is the miniature type 2D21, often seen in 1950s jukeboxes as control switches for relays. A cold-cathode version of the thyatron, which uses a pool of mercury for its cathode, is called an Ignitron (tm). It can switch thousands of amperes in its largest versions. Thyatrons containing hydrogen have a very consistent time delay between their turn-on pulse and full conduction, and have long been used in radar transmitters. Thyatrons behave much like silicon-controlled rectifiers, or to be more chronologically precise, silicon controlled rectifiers mimic some of the behaviours of Thyatrons.

Tubes usually have glass envelopes, but metal, fused quartz (silica), and ceramic are possible choices. The first version of the 6L6 used a metal envelope sealed with glass beads, while a glass disk fused to the metal was used in later versions. Metal and ceramic are used almost exclusively for power tubes above 2 kW dissipation. The nuvistor is a tiny tube made only of metal and ceramic. In some power tubes, the metal envelope is also the anode. The 4CX1000A is an external anode tube of this sort. Air is blown through an array of fins attached to the anode, thus cooling it. Power tubes using this cooling scheme are available up to 150 kW dissipation. Above that level, water or water-vapor cooling are used. The highest-power tube currently available is the Eimac 4CM2500KG, a forced water-cooled power tetrode capable of dissipating 2.5 megawatts. (By comparison, the largest power transistor can only dissipate about 1 kilowatt.) Another very high power tube is the Eimac 8974, a 1.25 megawatt tetrode used in military and commercial radio-frequency installations.

An extremely specialized tube is the Krytron, which is used for extremely precise, rapid high-voltage switching. Due to their intended purpose, the initiation of the precise sequence of detonations used to set off a nuclear weapon, they are heavily controlled at an international level.



X-ray tube insert

Medical imaging equipment, such as radiographic and nuclear imaging, use special vacuum tubes. Radiographic, fluoroscopic, and CT X-ray imaging equipment use a specially designed vacuum tube diode, which has a rotating anode to dissipate the large amounts of heat developed during operation, and a focused cathode. They are housed in an aluminum housing which is filled with a dielectric oil. Nuclear imaging equipment uses photomultiplier tube arrays to detect radiation.

Miniature tubes

The miniature vacuum tube made tubes smaller by eliminating the Bakelite base. It was invented in 1938. Instead of the separate base, the pins are fused in the glass base of the envelope. This forces the sealing tip to the top of the envelope. Making tubes smaller reduced the voltage that they could work at, and also the power of the filament, so the older style continued to be used for high power rectifiers, valve amplifier output stages and certain transmitting tubes. Miniature tubes with a size roughly that of half a cigarette were used in hearing-aid amplifiers.

Development continued, and led to the sub miniature tubes and the "acorn" valve (named due to its shape).

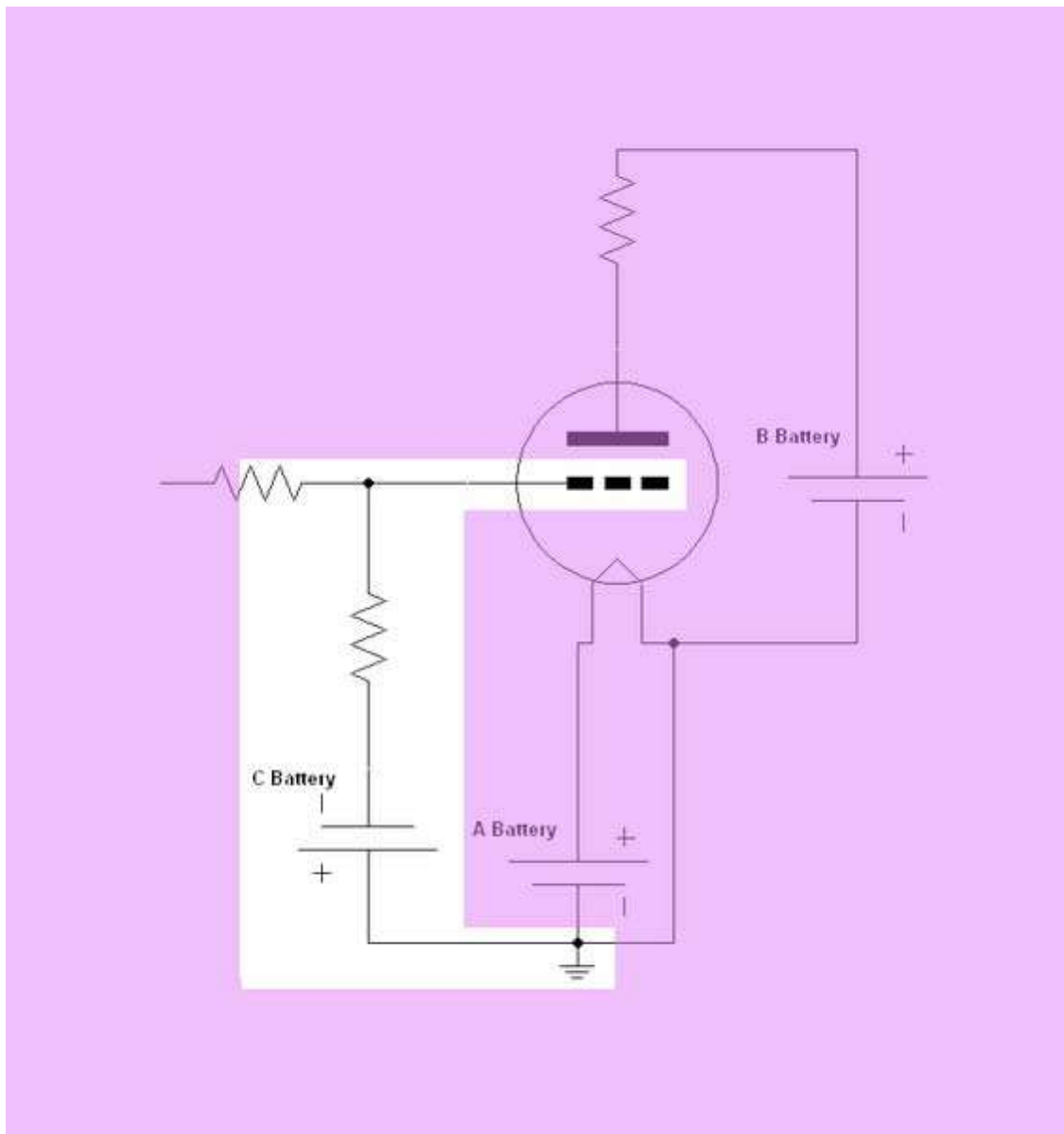
Powering the tube

Batteries

Batteries provided the voltages required by tubes in early radio sets. As many as three different voltages were required, using three different batteries. The "A" batteries or LT (low-tension) battery provided the filament voltage. Tube heaters were designed for single, double or triple-cell lead-acid batteries, giving nominal heater voltages of 2 V, 4 V or 6 V. In portable radios, dry batteries were sometimes used with 1.5 or 1 V heaters. Reducing filament consumption improved the life span of batteries. By 1955, receiving tubes using 50 mA down to as little as 10 mA for the heaters had been developed, but they were swept aside by development of the transistor.

The plate voltage was provided by "B" batteries or the HT (high-tension) supply or battery. These were generally of dry cell construction, containing many small 1.5 volt cells in series. They typically came in ratings of 22.5, 45, 67.5, 90 or 135 volts.

Some sets used a grid bias battery or "C" batteries, although many circuits used grid leak resistors, voltage dividers or cathode bias to provide proper tube bias. These batteries had very low drain.



Batteries for a vacuum tube circuit. The C battery is highlighted.

AC power

Replacement of batteries was a major cost of operation for early radio receiver users. The development of the battery eliminator, and, in 1925, batteryless receivers operated by household power, reduced operating costs and contributed to the growing popularity of radio. A power supply using a transformer with several windings, one or more rectifiers (which may themselves be vacuum tubes), and large filter capacitors provided the required direct current voltages from the alternating current source.

As a cost reduction measure, especially in high-volume consumer receivers, all the tube heaters could be connected in series across the AC supply, and the plate voltage derived from a half-wave rectifier directly connected to the AC input, eliminating the need for a heavy power transformer. As an additional feature, these radios could be operated on AC or DC mains. While this arrangement limited the plate voltage (and so, indirectly, the output power) that could be obtained, the resulting supply was adequate for many purposes. A filament tap on the rectifier tube provided the 6 volt, low current supply needed for a dial light. The so-called *series string* approach did have one safety defect: the chassis of the receiver was connected to one side of the power supply, presenting a shock hazard. Engineers reduced this hazard by enclosing the chassis in a plastic case, making the back out of particle board, and riveting the power cord chassis plug to the back so that consumers would not be able to power the radio while the chassis was accessible. (Technicians and tinkerers routinely bypassed this by using a separate cord, known colloquially as a "cheater cord" or "widowmaker.") Many consumer AM radio manufacturers of the era used a virtually identical circuit with the tube complement of 12BA6, 12BE6, 12AV6, 35W4, and 50C5, giving these radios the nickname All American Five or simply "Five Tube Radio." Although millions of such receivers were produced, they have now become collector's items.

Direct and indirect heating



Directly heated RS242 triodes

It became common to use the filament to heat a separate electrode called the cathode, and to use this cathode as the source of electron flow in the tube rather than the filament itself. This minimized the introduction of hum when the filament was energized with alternating current. In such tubes, the filament is called a heater to distinguish it as an inactive element. Development of vacuum tubes that could use alternating current for the heater supply allowed elimination of one rectifier element.

Reliability



Tube tester manufactured in 1930

One reliability problem of tubes with oxide cathodes is the possibility that the cathode may slowly become "poisoned" by gas molecules from other elements in the tube, which reduce its ability to emit electrons. Trapped gases or slow gas leaks can also damage the cathode or cause plate-current run away due to ionization of free gas molecules. Vacuum hardness and proper selection of construction materials are the major influences on tube lifetime. Depending on the material, temperature and construction, the surface material of the cathode may also diffuse onto other elements. The resistive heaters that heat the

cathodes may break in a manner similar to incandescent lamp filaments, but rarely do, since they operate at much lower temperatures than lamps.

The heater's failure mode is typically a stress-related fracture of the tungsten wire or at a weld point and generally occurs after accruing many thermal (power on-off) cycles. Tungsten wire has a very low resistance when at room temperature. A negative temperature coefficient device, such as a thermistor, may be incorporated in the equipment's heater supply or a ramp-up circuit may be employed to allow the heater or filaments to reach operating temperature more gradually than if powered-up in a step-function. Low-cost radios had tubes with heaters connected in series, with a total voltage equal to that of the line (mains). Following World War II, tubes intended to be used in series heater strings were redesigned to all have the same ("controlled") warm-up time. Earlier designs had quite-different thermal time constants. The audio output stage, for instance, had a larger cathode, and warmed up more slowly than lower-powered tubes. The result was that heaters that warmed up faster also temporarily had higher resistance, because of their positive temperature coefficient. This disproportionate resistance caused them to temporarily operate with heater voltages well above their ratings, and shortened their life.

Another important reliability problem is caused by air leakage into the tube. Usually oxygen in the air reacts chemically with the hot filament or cathode, quickly ruining it. Designers developed tube designs that sealed reliably. This was why most tubes were constructed of glass. Metal alloys (such as Cunife and Fernico) and glasses had been developed for light bulbs that expanded and contracted in similar amounts, as temperature changed. These made it easy to construct an insulating envelope of glass, while passing connection wires through the glass to the electrodes.

When a vacuum tube is overloaded or operated past its design dissipation, its anode (plate) may glow red. In consumer equipment, a glowing plate is universally a sign of an overloaded tube. However, some large transmitting tubes are designed to operate with their anodes at red, orange, or in rare cases, white heat.

Vacuum

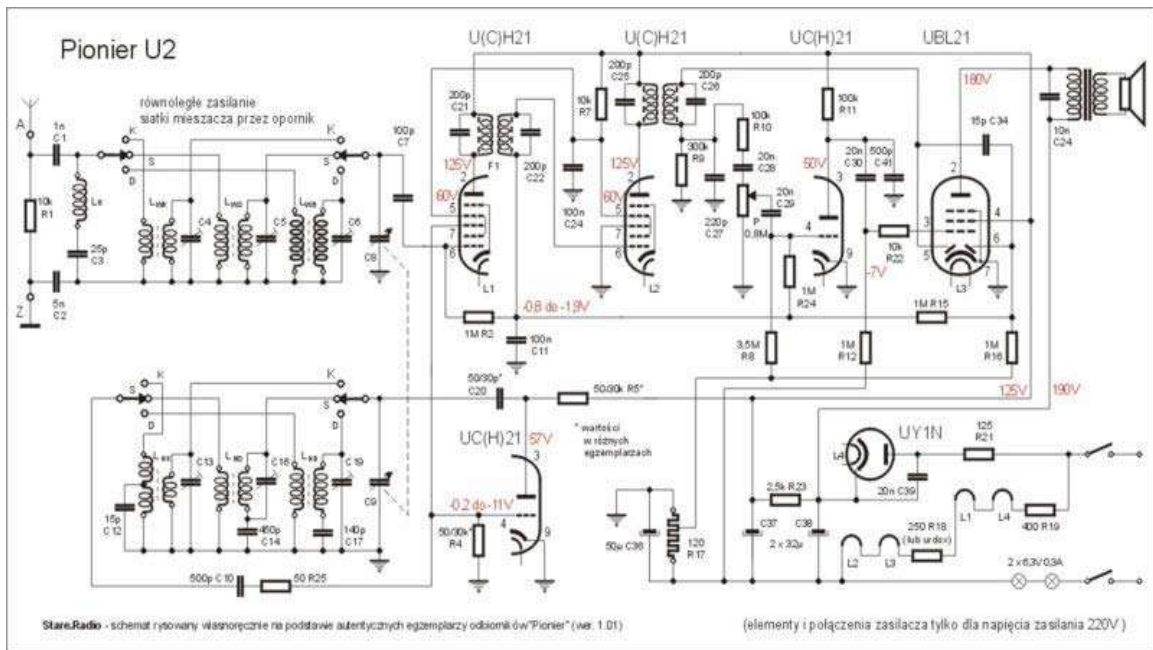


A valve in a modern guitar amplifier, glowing blue. This can indicate a "gassy" tube; however, this effect is commonly the result of electron bombardment of impurities in the glass envelope.

The vacuum inside the envelope must be as perfect, or "hard", as possible. Any gas atoms remaining might be ionized at operating voltages, and will conduct electricity between the elements in an uncontrolled manner. This can lead to erratic operation or even catastrophic destruction of the tube and associated circuitry. Unabsorbed free air sometimes ionizes and becomes visible as a pink-purple glow discharge between the tube elements.

To prevent any remaining gases from remaining in a free state in the tube, modern tubes are constructed with "getters", which are usually small, circular troughs filled with metals that oxidize quickly, with barium being the most common. While the tube envelope is being evacuated, the internal parts except the getter are heated by RF induction heating to extract any remaining gases from the metal. The tube is then sealed and the getter is heated to a high temperature, again by radio frequency induction heating. This causes the material to evaporate, absorbing/reacting with any residual gases and usually leaving a silver-colored metallic deposit on the inside of the envelope of the tube. The getter continues to absorb any gas molecules that leak into the tube during its working life. If a

tube develops a crack in the envelope, this deposit turns a white color when it reacts with atmospheric oxygen. Large transmitting and specialized tubes often use more exotic getter materials, such as zirconium. Early gettered tubes used phosphorus based getters and these tubes are easily identifiable, as the phosphorus leaves a characteristic orange or rainbow deposit on the glass. The use of phosphorus was short-lived and was quickly replaced by the superior barium getters. Unlike the barium getters, the phosphorus did not absorb any further gases once it had fired.



Schematic diagram of a 1948 vacuum tube radio from Poland

Transmitting tubes

Large transmitting tubes have carbonized tungsten filaments containing a small trace (1% to 2%) of thorium. An extremely thin (molecular) layer of thorium atoms forms on the outside of the wire's carbonized layer and, when heated, serve as an efficient source of electrons. The thorium slowly evaporates from the wire surface, while new thorium atoms diffuse to the surface to replace them. Such thoriated tungsten cathodes usually deliver lifetimes in the tens of thousands of hours. The end-of-life scenario for a thoriated-tungsten filament is when the carbonized layer has mostly been converted back into another form of tungsten carbide and emission begins to drop off rapidly; a complete loss of Thorium has never been found to be a factor in the end-of-life in a tube with this type of emitter. The highest reported tube life is held by an Eimac power tetrode used in a Los Angeles radio station's transmitter, which was removed from service after 80,000 hours (~9 years) of operation. It has been said that transmitters with vacuum tubes are better able to survive lightning strikes than transistor transmitters do. While it was commonly believed that at rf power levels above approx. 20 kilowatts, vacuum tubes were more efficient than solid state circuits, this is no longer the case especially in medium wave (AM broadcast) service where solid state transmitters at nearly all power

levels have measurably higher efficiency. FM broadcast transmitters with solid state PA's up to approx. 15 kW also show better overall mains-power efficiency than tube-based PA's and with the advent of newer, more efficient transistors this power level will certainly increase.

Receiving tubes

Cathodes in small "receiving" tubes are coated with a mixture of barium oxide and strontium oxide, sometimes with addition of calcium oxide or aluminium oxide. An electric heater is inserted into the cathode sleeve, and insulated from it electrically by a coating of aluminium oxide. This complex construction causes barium and strontium atoms to diffuse to the surface of the cathode when heated to about 780 degrees Celsius, thus emitting electrons.

Failure modes

Catastrophic failures

A catastrophic failure is one which suddenly makes the vacuum tube unusable. A crack in the glass envelope will allow air into the tube and destroy it. Cracks may result from stress in the glass, bent pins or impacts; tube sockets must allow for thermal expansion, to prevent stress in the glass at the pins. Stress may accumulate if a metal shield or other object presses on the tube envelope and causes differential heating of the glass. Glass may also be damaged by high-voltage arcing.

Tube heaters may also fail without warning, especially if exposed to over voltage or as a result of manufacturing defects. Tube heaters don't normally fail by evaporation like lamp filaments, since they operate at much lower temperature. The surge of inrush current when the heater is first energized causes stress in the heater, and can be avoided by slowly warming the heaters, gradually increasing current. Some tubes intended for series string operation of the heaters across the supply will have a definite controlled warm-up time to avoid excess voltage on some heaters as others warm up. Directly-heated filament-type cathodes as used in battery-operated tubes or some rectifiers may fail if the filament sags, causing internal arcing. Excess heater-to-cathode voltage in indirectly heated cathodes can break down the insulation between elements and destroy the heater.

Arcing between tube elements can destroy the tube. An arc can be caused by applying plate potential before the cathode has come up to operating temperature, or by drawing excess current through a rectifier which damages the emission coating. Arcs can also be initiated by any loose material inside the tube, or by excess screen voltage. An arc inside the tube allows gas to evolve from the tube materials, and may deposit conductive material on internal insulating spacers.

Degenerative failures

Degenerative failures cause the performance of the tube to slowly deteriorate with time.

Overheating of internal parts, such as control grids or mica spacer insulators, can result in trapped gas escaping into the tube; this can reduce performance. A getter is used to absorb gases evolved during tube operation, but has only a limited ability to combine with gas. Control of the envelope temperature prevents some types of gassing. A tube with very bad internal gas may have a visible blue glow when plate voltage is applied.

Gas and ions within the tube contribute to grid current which can disturb operation of a vacuum tube circuit. Another effect of overheating is the slow deposit of metallic vapors on internal spacers, resulting in inter-element leakage.

Tubes on standby for long periods, with heater voltage applied, may develop high cathode interface resistance and display poor emission characteristics. This effect occurred especially in pulse and digital circuits, where tubes had no plate current flowing for extended times.

Cathode depletion describes the loss of emission after thousands of hours of normal use. Sometimes emission can be restored for a time by raising heater voltage either for a short time or a permanent increase of a few percent. Cathode depletion was uncommon in signal tubes but was a frequent cause of failures of monochrome television cathode-ray tubes.

Other failures

Vacuum tubes may have or develop defects in operation that makes an individual tube useless in one device, but which may not prevent its satisfactory operation in another system. *Microphonics* refers to internal vibration of tube elements, which modulates the signal from the tube in an undesirable way; sound or vibration pick-up may affect the signals, or even cause uncontrolled howling if a feedback path develops between a microphonic tube and, for example, a loudspeaker. Leakage current between AC heaters and the cathode may couple into the circuit, or electrons emitted directly from the ends of the heater may also inject hum into the signal. Leakage current due to internal contamination may also inject noise.



Tubes from a 1950s computer

Computer vacuum tubes

Colossus

Colossus (and its successor Colossus Mk2) was built by the British during World War II to substantially speed up the task of breaking the German high level Lorenz encryption. Based on 1500 vacuum tubes, Colossus replaced an earlier machine based on relay and switch logic (the Heath Robinson). Colossus was able to break in a matter of hours messages that had previously taken several weeks. Colossus Mk2 used a total of around 2000 vacuum tubes. Colossus was the first ever use of vacuum tubes on such a large scale for a single machine. The largest project previously had used just 150 tubes and had proven to be extremely unreliable. The main design problem at Colossus's inception was how to make vacuum tube based equipment reliable when the tubes were used in large numbers.

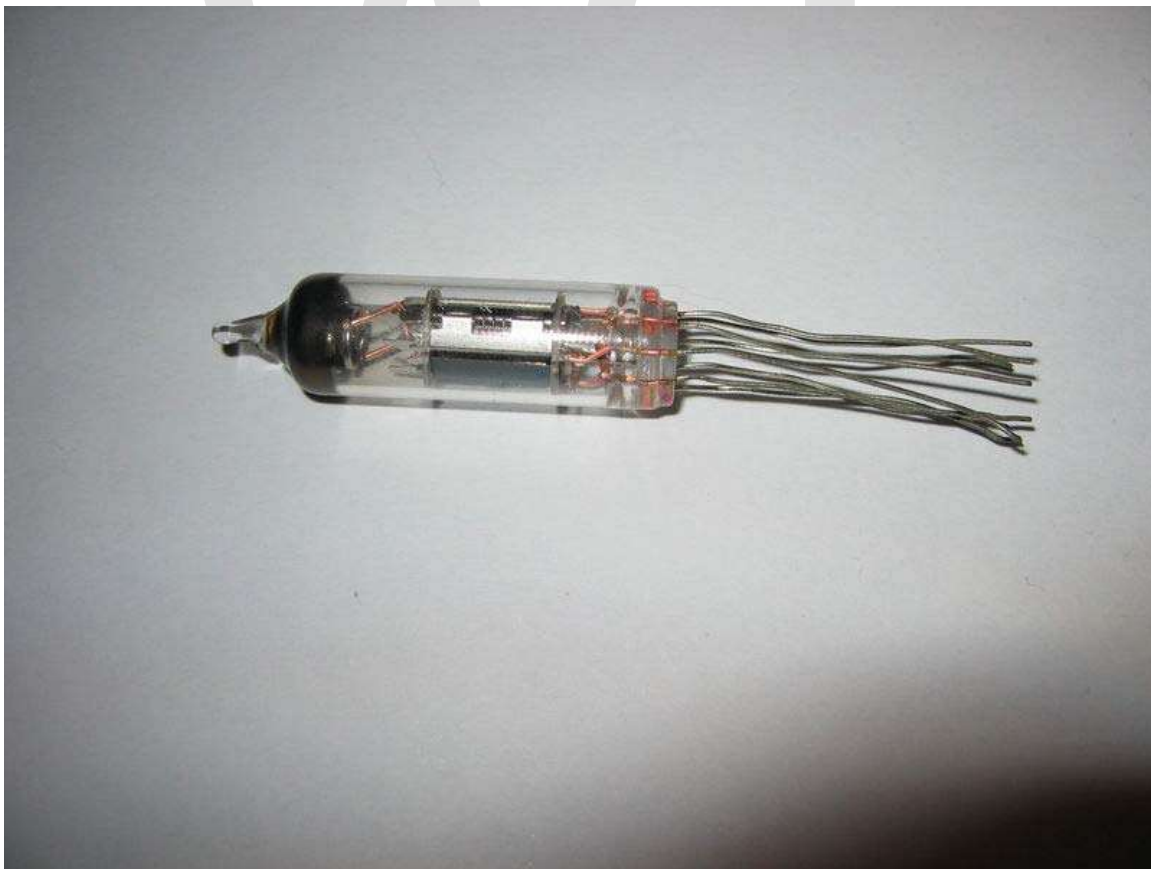
The Colossus computer's designer, Dr. Tommy Flowers, had a theory that most of the unreliability was caused during power down and (mainly) power up. Once Colossus was built and installed, it was switched on and left switched on running from dual redundant diesel generators (the wartime mains supply being considered too unreliable). The only time it was switched off was for conversion to the Colossus Mk2 and the addition of another 500 or so tubes. Another 9 Colossus Mk2s were built, and all 10 machines ran

with a surprising degree of reliability. The 10 Colossi consumed 15 kilowatts of power each, 24 hours a day, 365 days a year—nearly all of it for the tube heaters.

Whirlwind

To meet the reliability requirements of the early digital computer Whirlwind, it was necessary to build special "computer vacuum tubes" with extended cathode life. The problem of short lifetime was traced to evaporation of silicon, used in the tungsten alloy to make the heater wire easier to draw. Elimination of the silicon from the heater wire alloy (and paying extra for more frequent replacement of the wire drawing dies) allowed production of tubes that were reliable enough for the Whirlwind project. The tubes developed for Whirlwind later found their way into the giant SAGE air-defense computer system. High-purity nickel tubing and cathode coatings free of materials that can poison emission (such as silicates and aluminium) also contribute to long cathode life. The first such "computer tube" was Sylvania's 7AK7 of 1948. By the late 1950s it was routine for special-quality small-signal tubes to last for hundreds of thousands of hours, if operated conservatively. This reliability made mid-cable amplifiers in submarine cables possible.

World War II



A CV4501 subminiature tube for use in a military radio set. The tube is a special quality type based on the EF72, 35 mm long and 10 mm in diameter (excluding leads).

Near the end of World War II, to make radios more rugged, some aircraft and army radios began to integrate the tube envelopes into the radio's cast aluminium or zinc chassis. The radio became just a printed circuit with non-tube components, soldered to the chassis that contained all the tubes. During WWII in 1942, rugged metal vacuum tubes were mounted in anti-aircraft shells. These proximity fuzes made anti-aircraft shells 6 times more effective. In the fall of 1944, artillery shells with proximity fuses were used. The tiny tubes were later known as "subminiature" types. They were widely used in 1950s military and aviation electronics.

Applications

Vacuum tubes were critical to the development of electronic technology, which drove the expansion and commercialization of radio broadcasting, television, radar, sound reproduction, large telephone networks, analog and digital computers, and industrial process control. Some of these applications pre-dated electronics, but it was the vacuum tube that made them widespread and practical.

Tubes were heavily used in the early generations of electronic devices, such as radios, televisions, and early computers such as the Colossus which used 2000 tubes, the ENIAC which used nearly 18,000 tubes, and the IBM 700 series.

For most purposes, the vacuum tube has been replaced by solid-state devices such as transistors and solid-state diodes. Solid-state devices last much longer, are smaller, more efficient, more reliable, and cheaper than equivalent vacuum tube devices. However, tubes are still used in specialized applications: for engineering reasons, as in high-power radio frequency transmitters; or for their aesthetic appeal and distinct sound signature, as in audio amplification. Cathode ray tubes are still used as display devices in television sets, video monitors, and oscilloscopes, although they are being replaced by LCDs and other flat-panel displays. A specialized form of the electron tube, the magnetron, is the source of microwave energy in microwave ovens and some radar systems. The klystron, a powerful but narrow-band radio-frequency amplifier, is commonly deployed by broadcasters as a high-power UHF television transmitter.

Vacuum tubes are less susceptible than corresponding solid-state components to the electromagnetic pulse effect of nuclear explosions. This property kept them in use for certain military applications long after transistors had replaced them elsewhere. Vacuum tubes are still used for very high-powered applications such as industrial radio-frequency heating, generating large amounts of RF energy for particle accelerators, and power amplification for broadcasting. In microwave ovens, cost-engineered magnetrons efficiently generate microwave power on the order of hundreds of watts.



Russian 12AX7 tubes inside a modern guitar amplifier

Many audiophiles, professional audio engineers, and musicians prefer the tube sound of audio equipment based on vacuum tubes over electronics based on transistors. There are companies which still make specialized audio hardware featuring tube technology. A common usage is in the high-end microphone preamplifiers preferred by professional music recording studios, and in electric guitar amplification. The sound produced by a tube based amplifier with the tubes overloaded (overdriven) has defined the texture of some genres of music such as classic rock and blues. Guitarists often prefer tube amplifiers for the warmth of their tone and the natural compression effect they can apply to an input signal.

Cathode-ray tubes (CRTs) are a highly-evolved type of vacuum tube, described elsewhere.

In 2002, computer motherboard maker AOpen brought back the vacuum tube for modern computer use by releasing the AX4GE Tube-G motherboard. This motherboard uses a Sovtek 6922 vacuum tube (a version of the 6DJ8) as part of AOpen's TubeSound Technology. AOpen claims that the vacuum tube brings superior sound.

Cooling



A 12AX7 preamp tube, EL84 power tube (with dampener rings) and a GZ34 rectifier tube in a guitar amplifier.

Like any electronic device, vacuum tubes produce heat while operating. This waste heat is one of the principal factors that affect tube life. The majority of this waste heat originates in the anode though some grids may also require cooling to remove excess heat. For example, the cooling of the screen grid in an EL34 is facilitated by the addition of two small radiators or "wings," located near the top of the tube. The heater (filament) also contributes to the total waste heat. A tube's data sheet will normally identify the maximum amount of heat each element may dissipate.

The method of anode cooling is dependent on the construction of the tube itself. For tubes with internal anodes such as the 12AX7 or EL34, the cooling occurs by radiating the heat by black body radiation from the anode to the glass envelope. Natural air circulation, convection, then removes the heat from the envelope. Tube shields that aided heat dispersal could be retrofitted on certain select types of tubes. These shields act by improving heat conduction from the surface of the tube to the shield itself by means of tens of copper tongues in contact with the glass tube, and have an opaque, black outside finish for improved heat radiation. The ability to remove heat may be further increased by implementing forced air cooling, adding fins to the anode, and operating the anode at red hot temperatures. All of these measures are implemented in the 4-1000A transmitting tube.

The amount of heat that may be removed from a tube with an internal anode is limited. Tubes with external anodes may be cooled using forced air, water, vapor, and multiphase. The 3CX10,000A7 is an example of a tube with an external anode cooled by forced air. The water, vapor, and multiphase cooling techniques all depend on the high specific heat and latent heat of water. The 8974 is an example of a water cooled tube and is among the largest commercial tube available today.

In a water cooled tube, the anode voltage appears directly on the cooling water surface, thus requiring the water to be an electrical insulator. Otherwise the high voltage can be conducted through the cooling water to the radiator system; hence the need for deionized water. Such systems usually have a built-in water-conductance monitor which will shut down the high-tension supply (often tens of kilovolts) if the conductance becomes too high.

Other vacuum tube devices

Many devices were built during the 1920–1960 period using vacuum-tube techniques. Most such tubes were rendered obsolete by semiconductors; some techniques for integrating multiple devices in a single module, sharing the same glass envelope have been discussed above, such as the Loewe 3NF. Vacuum-tube electronic devices still in common use include the magnetron, klystron, photomultiplier, x-ray tube, traveling-wave tube and cathode ray tube. The magnetron is the type of tube used in all microwave ovens. In spite of the advancing state of the art in power semiconductor technology, the vacuum tube still has reliability and cost advantages for high-frequency RF power generation. Photomultipliers are still the most sensitive detectors of light. Many televisions, oscilloscopes and computer monitors still use cathode ray tubes, though flat panel displays are becoming more popular as prices drop.

Many of the better tube radios had so-called "tuning eye" indicator tubes behind their front panels, with just the top of the tube showing. These tubes were used as a visual indication of received signal strength, and an aid to properly tuning in a station.

Secondary emission is the term for what happens when electrons in a vacuum strike certain materials, and the impacts cause electrons to be emitted. For some materials, more electrons are emitted than originally hit the surface. Such devices, called electron multipliers, amplify the current represented by the incoming electrons. Several stages (as many as 15 or so) can be cascaded for high gain, and are essential parts of very sensitive phototubes, usually called photomultipliers or multiplier phototubes. The image orthicon TV studio camera tubes also used multistage photomultipliers.

For decades, electron-tube designers tried to use secondary emission to obtain more amplification in vacuum tubes with hot cathodes, but they suffered from short life because the material used for the secondary-emission electrode (called a dynode) "poisoned" the tube's hot cathode. (For instance, the interesting RCA 1630 secondary-emission tube was marketed, but did not last.) However, eventually, Philips of The Netherlands developed the EFP60 tube that had a satisfactory lifetime, and was used in at

least one product, a laboratory pulse generator. However, transistors were rapidly improving, and eclipsed tubes in general.

A variant, called a channel electron multiplier, is a curved tube, such as a helix, coated on the inside with material with good secondary emission. One type had a little funnel to capture incoming electrons. The tube was resistive, and its ends were connected to enough voltage to create repeated cascades of electrons.

Tektronix made a high-performance wideband oscilloscope CRT with a channel electron multiplier plate behind the phosphor layer. This plate was a bundled array of a huge number of short individual c.e.m. tubes that accepted a low-current beam and intensified it to provide a display of practical brightness. (The electron optics of the wideband electron gun could not provide enough current to directly excite the phosphor.)

The fluorescent displays commonly used on videocassette recorders, some microwave oven control panels, and automotive dashboards are vacuum tubes, using phosphor-coated anodes to form the display characters, and a heated filamentary cathode as an electron source. These are referred to as "VFDs", or vacuum fluorescent displays. Because the filaments are in view, they must be operated at temperatures where the filament does not glow visibly. Often found in automotive applications, their high brightness allows reading the display in daylight. VFD tubes are flat and rectangular, as well as relatively thin. Typical VFD phosphors emit a broad-spectrum greenish-white light, permitting use of color filters. This type of phosphor provides a bright glow with only modest operating voltage, low tens of volts.

Some tubes, such as magnetrons, traveling-wave tubes, carcinotrons, and klystrons, combine magnetic and electrostatic effects. These are efficient (usually narrow-band) RF producers and still find use in radar, microwave ovens and industrial heating. Traveling-wave tubes (TWTs) are very good amplifiers; they are used in some communications satellites. High-powered klystron amplifier tubes can provide hundreds of kilowatts in the UHF range.

Gyrotrons or vacuum masers, used to generate high-power millimetre band waves, are magnetic vacuum tubes in which a small relativistic effect, due to the high voltage, is used for bunching the electrons. Gyrotrons can generate very high powers (hundreds of kilowatts). Free electron lasers, used to generate high-power coherent light and perhaps even X rays, are highly relativistic vacuum tubes driven by high-energy particle accelerators.

Particle accelerators can be considered vacuum tubes that work backward, the electric fields driving the electrons, or other charged particles. In this respect, a cathode ray tube is a particle accelerator.

A tube in which electrons move through a vacuum (or gaseous medium) within a gas-tight envelope is generically called an *electron tube*.

Some condenser microphone designs use built-in vacuum tube preamplifiers.

As of 2008, scores of small companies are manufacturing audiophile amplifiers and preamps that use vacuum tubes.

Vacuum tubes using field electron emitters

In the early years of the 21st century there has been renewed interest in vacuum tubes, this time with the electron emitter formed on a flat silicon substrate, as in integrated circuit technology. This subject is now called vacuum nanoelectronics. The most common design uses a cold cathode in the form of a large-area field electron source (for example a field emitter array). With these devices, electrons are field-emitted from a large number of closely spaced individual emission sites.

Their claimed advantages include greatly enhanced robustness combined with the ability to provide high power outputs at low power consumptions. Operating on the same principles as traditional tubes, prototype device cathodes have been fabricated in several different ways. Although a common approach is to use a field emitter array, one interesting idea is to etch electrodes to form hinged flaps – similar to the technology used to create the microscopic mirrors used in Digital Light Processing) that are stood upright by an electrostatic charge.

Such integrated microtubes may find application in microwave devices including mobile phones, for Bluetooth and Wi-Fi transmission, in radar and for satellite communication. Presently they are being studied for possible applications in field emission display technology, but significant production problems seem to exist.

Chapter- 6

Ultra-High Vacuum

Ultra-high vacuum (UHV) is the vacuum regime characterised by pressures lower than about 10^{-7} pascal or 100 nanopascals (10^{-9} mbar, $\sim 10^{-9}$ torr). UHV requires the use of unusual materials in construction and by heating the entire system to 180°C for several hours ("baking") to remove water and other trace gases which adsorb on the surfaces of the chamber. At these low pressures the mean free path of a gas molecule is approximately 40 km, so gas molecules will collide with the chamber walls many times before colliding with each other. Almost all interactions therefore take place on various surfaces in the chamber.

Concepts involved

- Sorption of gases
- Kinetic theory of gases
- Gas transport and pumping
- Vacuum pumps and systems
- Vapour pressure

Material limitations

Materials which are not allowed due to high vapour pressure:

- majority of organic compounds cannot be used:
 - plastics other than teflon and PEEK: gaskets are made of copper, and are single-use; plastics in other uses are replaced with ceramics or metals
 - glues: special glues for high vacuum must be used
- common steel: due to oxidizing, which greatly increases adsorption area, only stainless steel is used
- lead: soldering is performed using lead-free solder
- indium: Indium is commonly used as a deformable gasket material for vacuum seals, especially in cryogenic apparatus, but its low melting point prevents use in baked systems.
- zinc, cadmium: High vapor pressures during system bake-out.

Technical limitations:

- screws: threads have a high surface area and tend to "trap" gases, therefore are avoided
- welding: standard welding cannot be used due to high surface area and introduction of gas chambers, which would collect gas at atmospheric pressure, and release it slowly during evacuation (removal of gas).

Typical uses for ultra-high vacuum

Ultra-high vacuum is necessary for many surface analytic techniques such as:

- X-ray photoelectron spectroscopy (XPS)
- Auger electron spectroscopy (AES)
- Secondary ion mass spectrometry (SIMS)
- Thermal desorption spectroscopy (TPD)
- Thin film growth and preparation techniques with stringent requirements for purity, such as molecular beam epitaxy (MBE), UHV chemical vapor deposition (CVD) and UHV pulsed laser deposition (PLD)
- Angle resolved photoemission spectroscopy (ARPES)

UHV is necessary for these applications to reduce surface contamination, by reducing the number of molecules reaching the sample over a given time period. At 0.1 mPa (10^{-6} Torr), it only takes 1 second to cover a surface with a contaminant, so much lower pressures are needed for long experiments.

UHV is also required for:

- Particle accelerators
- Gravitational wave detectors such as LIGO, VIRGO, GEO 600, and TAMA 300.
- Atomic physics experiments which use cold atoms, such as ion trapping or making Bose-Einstein condensates

and, while not compulsory, can prove beneficial in applications such as:

- Atomic force microscopy. High vacuum enables high Q factors on the cantilever oscillation.
- Scanning tunneling microscopy. High vacuum reduces oxidation and contamination, hence enables imaging and the achievement of atomic resolution on clean metal and semiconductor surfaces, e.g. imaging the surface reconstruction of the unoxidized silicon surface.

Achieving ultra-high vacuum

Extraordinary steps are required to reach UHV, including the following:

- High pumping speed — possibly multiple vacuum pumps in series and/or parallel

- Minimize surface area in the chamber
- High conductance tubing to pumps — short and fat, without obstruction
- Use low-outgassing materials such as certain stainless steels
- Avoid creating pits of trapped gas behind bolts, welding voids, etc.
- Electropolish all metal parts after machining or welding
- Use low vapor pressure materials (ceramics, glass, metals, teflon if unbaked)
- Bake the system to remove water or hydrocarbons adsorbed to the walls
- Chill chamber walls to cryogenic temperatures during use
- Avoid all traces of hydrocarbons, including skin oils in a fingerprint — always use gloves

Outgassing is a significant problem for UHV systems. Outgassing can occur from two sources: surfaces and bulk materials. Outgassing from bulk materials is minimized by careful selection of materials with low vapor pressures (such as glass, stainless steel, and ceramics) for everything inside the system. Even materials which are not generally considered absorbent can outgas, including most plastics and some metals. For example, vessels lined with a highly gas-permeable material such as palladium (which is a high-capacity hydrogen sponge) create special outgassing problems.

Outgassing from surfaces is a subtler problem. At extremely low pressures, more gas molecules are adsorbed on the walls than are floating in the chamber, so the total surface area inside a chamber is more important than its volume for reaching UHV. Water is a significant source of outgassing because a thin layer of water vapor rapidly adsorbs to everything whenever the chamber is opened to air. Water evaporates from surfaces too slowly to be fully removed at room temperature, but just fast enough to present a continuous level of background contamination. Removal of water and similar gases generally requires baking the UHV system at 200 to 400 °C while vacuum pumps are running. During chamber use, the walls of the chamber may be chilled using liquid nitrogen to reduce outgassing further.

Hydrogen and helium are the most common background gases in a well-designed, well-baked UHV system. Hydrogen diffuses out from the grain boundaries in stainless steel. Helium can diffuse through the steel and glass from the outside air.

There is no single vacuum pump that can operate all the way from atmospheric pressure to ultra-high vacuum. Instead, a series of different pumps is used, according to the appropriate pressure range for each pump. Pumps commonly used to achieve UHV include:

- Turbomolecular pumps (especially compound and/or magnetic bearing types)
- Ion pumps
- Titanium sublimation pumps
- Non-evaporable getter (NEG) pumps
- Cryopumps

UHV pressures are measured with an ion gauge, either a hot filament or an inverted magnetron type.

Finally, special seals and gaskets must be used between components in a UHV system to prevent even trace leakage. Nearly all such seals are all metal, with knife edges on both sides cutting into a soft, copper gasket. This all-metal seal can maintain pressures down to 100 pPa ($\sim 10^{-12}$ Torr).

Measuring high vacuum

Measurement of high vacuum is done using a *nonabsolute gauge* that measures a pressure-related property of the vacuum, for example, its thermal conductivity. See, for example, Pacey. These gauges must be calibrated. The gauges capable of the measuring the lowest pressures are magnetic gauges based upon the pressure dependence of the current in a spontaneous gas discharge in intersecting electric and magnetic fields.

UHV manipulator

A **UHV manipulator** allows an object which is inside a vacuum chamber and under vacuum to be mechanically positioned. It may provide rotary motion, linear motion, or a combination of both. The most complex devices give motion in three axes and rotations around two of those axes. To generate the mechanical movement inside the chamber, two basic mechanisms are commonly employed: a mechanical coupling through the vacuum wall (using a vacuum-tight seal around the coupling), or a magnetic coupling that transfers motion from air-side to vacuum-side. Various forms of motion control are available for manipulators, such as knobs, handwheels, motors, stepping motors, piezoelectric motors, and pneumatics.

The manipulator or sample holder may include features which allow additional control and testing of a sample, such as the ability to apply heat, cooling, voltage, or a magnetic field. Sample heating can be accomplished by electron bombardment or thermal radiation. For electron bombardment, the sample holder is equipped with a filament which emits electrons when biased at a high negative potential. The impact of the electrons bombarding the sample at high energy causes it to heat. For thermal radiation, a filament is mounted close to the sample and resistively heated to high temperature. The infrared energy from the filament heats the sample.

Chapter- 7

Vacuum Flange



A KF-25 tee, o-ring, and clamp.

A **vacuum flange** is a flange at the end of a tube used to connect vacuum chambers, tubing and vacuum pumps to each other.

Vacuum flange types



A CF (conflat) pipe and flange with copper gasket.

Several vacuum flange standards exist, and the same flange types are called by different names by different manufacturers and standards organizations.

KF/QF

The ISO standard quick release flange is known by the names Quick Flange (QF), Klein Flange (KF) or NW, sometimes also as DN. The KF designation has been adopted by ISO, DIN, and Pneurop. KF flanges are made with a chamfered back surface that attached with a circular clamp and an elastomeric o-ring that is mounted in a metal centering ring. Standard sizes are indicated by the nominal inner diameter in millimeters for flanges 16 through 50 mm in diameter.

- DN16KF
- DN25KF
- DN40KF
- DN50KF

ISO

The ISO large flange standard is known as LF, LFB, MF or sometimes just ISO flange. As in KF-flanges, the flanges are joined by a centering ring and an elastomeric o-ring. An extra spring-loaded circular clamp is often used around the large diameter o-rings to prevent them from rolling off from the centering ring during mounting.

The ISO large flanges come in two varieties. The ISO-K (or ISO LF) flanges are joined with double claw clamps which clamp to a circular groove on the tubing side of the flange. The ISO-F (or ISO LFB) flanges have holes for attaching the two flanges with bolts. Two tubes with ISO-K and ISO-F flanges can be joined together by clamping the ISO-K side with single claw clamps which are then bolted to the holes on the ISO-F side.

ISO large flanges are available in sizes from 63 to 500 mm nominal tube diameter).

- DN63LF (63.5 mm)
- DN100LF (102 mm)
- DN160LF (160 mm)
- DN200LF (200 mm)
- DN250LF (254 mm)
- DN320LF (316 mm)
- DN400LF (400 mm)
- DN500LF (500 mm)

CF (Conflat)

CF (ConFlat) flanges use a copper gasket and knife-edge flange to achieve an ultrahigh vacuum seal. The term "ConFlat" is a registered trademark of Varian, Inc., so "CF" is commonly used by other flange manufacturers. Each face of the two mating CF flanges has a knife edge which cuts into the softer metal gasket, providing an extremely leak-tight, metal-to-metal seal. Deformation of the metal gasket fills small defects in the flange, allowing Conflat flanges operate down to 10^{-13} torr (10^{-11} Pa) pressure. The gasket is partially recessed in a groove in each flange. The groove helps hold the gasket in place, which aligns the two flanges and also reduces gasket expansion during bake-out. For stainless steel conflat flanges baking temperatures of 450°C can be achieved; the temperature is limited by the choice of gasket material. CF flanges are sexless and interchangeable. North American flange sizes are given by flange outer diameter in inches while in Europe and Asia, sizes are given by tube inner diameter in millimeters:

European, Asian size North American size [inches]

DN10	1
DN16	1½ ("mini")
DN25	2⅛
DN40 (or: DN35)	2¾
DN50	3⅜

DN63	4½
DN75	4⅝
DN100	6
DN125	6¾
DN160 (or: DN150)	8
DN200	10
DN250	12
	13¼
	14
	16½



A 60 kV high voltage electrical feedthrough on a 4-1/2 inch (or DN63) conflat flange

ConFlat gaskets were originally invented by William Wheeler and other engineers at Varian in an attempt to build a flange that would not leak after baking.

Wheeler

A Wheeler flange is a large wire seal flange often used on large vacuum chambers.

ASA

ANSI has a flange standard called ASA. These flanges are elastomeric o-ring seal and can be used for both vacuum and pressure applications. Flange sizes are indicated by tube nominal inner diameter or by flange outer diameter (in inches): 1 (4.25 O.D.), 1.5 (5.00 O.D.), 2 (6.00 O.D.), 3 (7.50 O.D.), 4 (9.00 O.D.), 6 (11.00 O.D.), 8 (13.5 O.D.), 10 (16.00 O.D.).

Vacuum gaskets

To achieve a vacuum seal, a gasket is required. An elastomeric o-ring gasket can be made of Buna rubber, viton fluoropolymer, silicon rubber or teflon. O-rings can be placed in a groove or may be used in combination with a centering ring or as a "captured" o-ring that is held in place by separate metal rings. Metal gaskets are used in ultra-high vacuum systems where the outgassing of the elastomer could be a significant gas load. A copper ring gasket is used with conflat flanges. Metal wire gaskets made of copper, gold or indium can be used.

Vacuum feedthrough

A vacuum feedthrough is a flange that contains a vacuum-tight electrical, physical or mechanical connection to the vacuum chamber. An electrical feedthrough allows voltages to be applied to components under vacuum, for example a filament or heater. An example of a physical feedthrough is a vacuum tight connection for cooling water. A mechanical feedthrough is used for rotation and translation of components under vacuum. A wobble stick is a mechanical feedthrough device that can be used to pick up, move and otherwise manipulate objects in the vacuum chamber.

Chapter- 8

Vacuum Packing and Vacuum Evaporation

Vacuum packing

Vacuum packing is a method of storing food and presenting it for sale. Appropriate types of food are stored in an airless environment, usually in an air-tight pack or bottle to prevent the growth of microorganisms. The vacuum environment removes atmospheric oxygen, protecting the food from spoiling by limiting the growth of aerobic bacteria or fungi, and preventing the evaporation of volatile components. Vacuum packing is commonly used for long-term storage of dry foods such as cereals, nuts, cured meats, cheese, smoked fish, coffee, and potato chips (crisps). It is also for storage of fresh foods such as vegetables, meats, and liquids such as soups in a shorter term because vacuum condition cannot stop bacteria from getting water which can promote their growth. Vacuum packaging food can extend its life by up to 3-5 times.

Vacuum packing is also used to reduce greatly the bulk of non-food items. For example, clothing and bedding can be stored in bags evacuated with a domestic vacuum cleaner or a dedicated vacuum sealer. This technique is sometimes used to compact household waste, for example where a charge is made for each full bag collected. Vacuum packing can be used to reduce bulk of inflatable items as well.

Vacuum packaging products using plastic bags, canisters, bottles, or mason jars are available for home use.

Vacuum packaging delicate food items can be done by using an inert gas kit, typically available on chamber vacuum sealers. After air has been removed, an inert gas (such as nitrogen) is added to maintain the preservation of packaged food while preventing damage. An example of inert gas for packaging delicate foods is potato chips.

External Sealers

External vacuum sealers involve a bag being attached to the vacuum-sealing machine externally. The machine will remove the air and seal the bag, which is all done outside the machine.

Chamber Sealers

Chamber sealers require the entire product to be placed within the machine. Like external sealers, a plastic bag is typically used for packaging. Once the product is placed in the machine, the lid is closed and air is removed. Once the air is removed, the bag is sealed and the atmosphere within the chamber is returned back to normal. The lid is then opened and the product removed. Chamber sealers are typically used for higher-volume packaging.

Manufacturers of chamber type vacuum packing machines include: Cryovac, Multivac, Sammic, VC999, New Diamond Vac , Jaw Feng Machinery ,Sevana and several others.

Preventing Freezer Burn

When foods are frozen without preparation, freezer burn can occur. It happens when the surface of the food is dehydrated, and this leads to a dried and leathery appearance. Freezer burn also ruins the flavor and texture of foods. Vacuum packing prevents freezer burn by preventing the food from exposure to the cold, dry air.

Sous-vide Cooking

Vacuum packaging also allows for a special cooking method, Sous-vide. Sous-vide, meaning "under vacuum" in French, involves poaching food that is vacuum sealed in a plastic bag.

Security

Due to an oxygen-poor environment, anaerobic microorganism can proliferate, so vacuum packing is often used in combination with other treatment.

Vacuum evaporation

Vacuum evaporation is the process of causing the pressure in a liquid-filled container to be reduced below the vapor pressure of the liquid, causing the liquid to evaporate at a lower temperature than normal. Although the process can be applied to any type of liquid at any vapor pressure, it is generally used to describe the boiling of water by lowering the container's internal pressure below standard atmospheric pressure and causing the water to boil at room temperature.

When the process is applied to food and the water is evaporated and removed, the food can be stored for long periods of time without spoiling. It is also used when boiling a

substance at normal temperatures would chemically change the consistency of the product, such as egg whites coagulating when attempting to dehydrate the albumen into a powder.

This process was invented by Henri Nestlé in 1866, of Nestlé Chocolate fame, although the Shakers were already using a vacuum pan earlier than that.

This process is used industrially to make such food products as evaporated milk for milk chocolate, and tomato paste for ketchup.

Vacuum evaporation is also a form of physical vapor deposition used in the semiconductor, microelectronics, and optical industries and in this context is a process of depositing thin films of material onto surfaces. Such a technique consists of pumping a vacuum chamber to pressures of less than 10^{-5} torr and heating a material to produce a flux of vapor in order to deposit the material onto a surface. The material to be vaporized is typically heated until its vapor pressure is high enough to produce a flux of several Angstroms per second by using an electrically resistive heater or bombardment by a high voltage beam.



Chapter- 9

Vacuum Deposition and Vacuum Chamber

Vacuum deposition

Vacuum deposition is a family of processes used to deposit layers atom-by-atom or molecule-by-molecule at sub-atmospheric pressure (vacuum) on a solid surface. The layers may be as thin as one atom to millimeters thick (freestanding structures). There may be multiple layers of different materials (e.g. optical coatings). A thickness of less than one micrometre is generally called a thin film while a thickness greater than one micrometre is called a coating. The vacuum environment may serve one or more purposes including:

- reducing the particle density so that the mean free path for collision is long
- reducing the particle density of undesirable atoms and molecules (contaminants)
- providing a low pressure plasma environment
- providing a means for controlling gas and vapor composition
- providing a means for mass flow control into the processing chamber.

Condensing particles may come from a variety of sources including:

- thermal evaporation, Evaporation (deposition)
- sputtering
- cathodic arc vaporization
- laser ablation
- decomposition of a chemical vapor precursor, chemical vapor deposition

When the vapor source is from a liquid or solid material the process is called *physical vapor deposition* (PVD). When the source is from a chemical vapor precursor the process is called *low pressure chemical vapor deposition* (LPCVD) or, if in a plasma, *plasma enhanced CVD* (PECVD) or "plasma assisted CVD" (PACVD). Often a combination of PVD and CVD processes are used in the same or connected processing chambers.

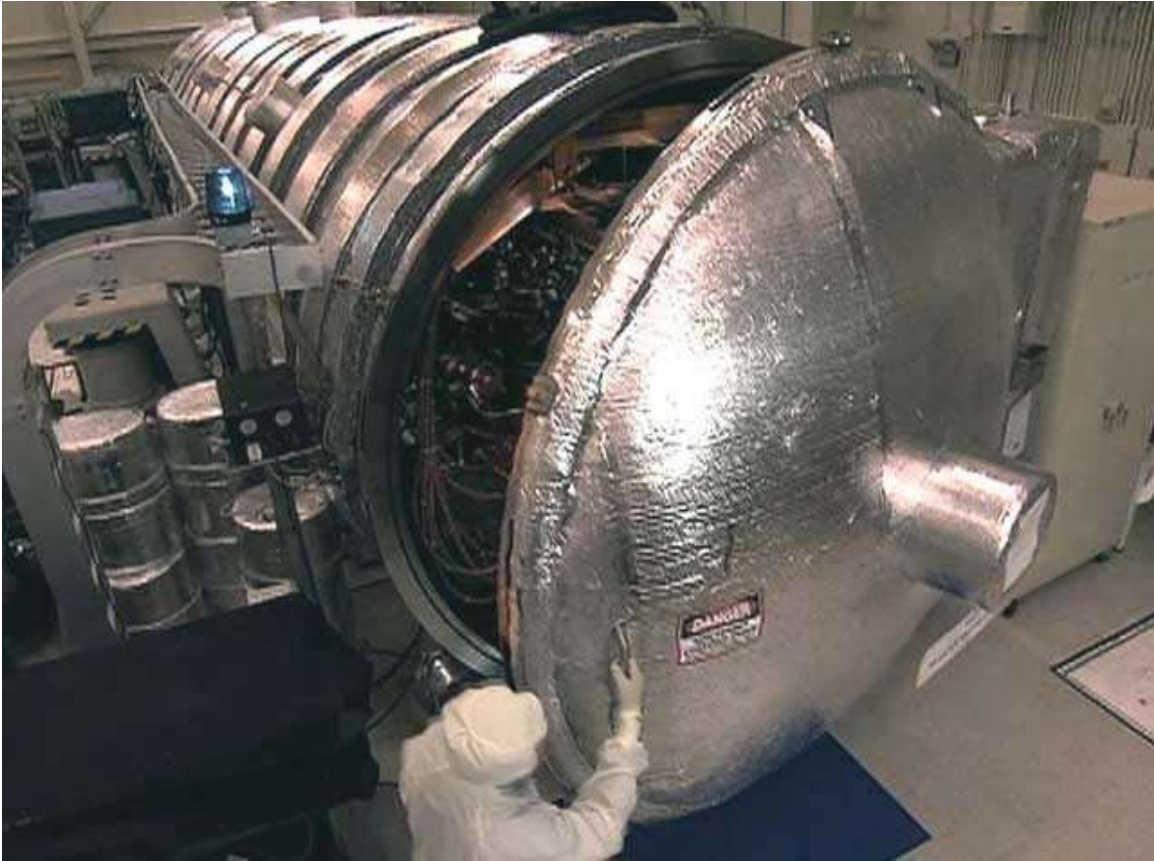
In reactive deposition the depositing material reacts either with a component of the gaseous environment ($\text{Ti} + \text{N} \rightarrow \text{TiN}$) or with a co-depositing species ($\text{Ti} + \text{C} \rightarrow \text{TiC}$). A plasma environment aids in activating gaseous species ($\text{N}_2 \rightarrow 2\text{N}$) and in decomposition of chemical vapor precursors ($\text{SiH}_4 \rightarrow \text{Si} + 4\text{H}$). The plasma may also be used to provide ions for vaporization by sputtering or for bombardment of the substrate for sputter

cleaning and for bombardment of the depositing material to densify the structure and tailor properties (ion plating).

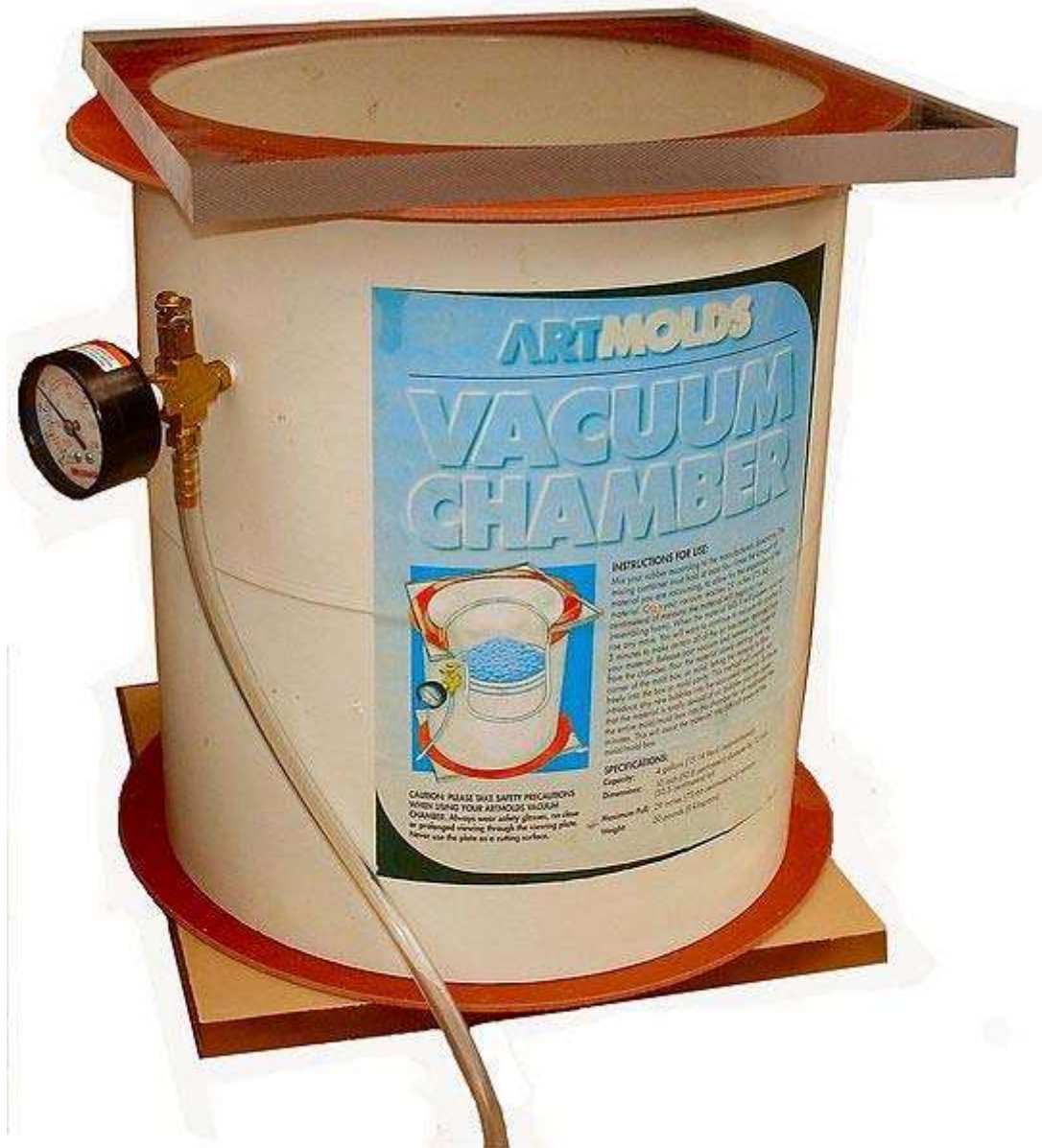
Applications

- Electrical conduction: metallic films, transparent conductive oxides (TCO), superconducting films & coatings
- Semiconductor devices: semiconductor films, electrically insulating films
- Solar cells.
- Optical films: antireflective coatings, optical filters
- Reflective coatings: mirrors, heat mirrors
- Tribological coating: hard coatings, erosion resistant coatings, solid film lubricants
- Energy conservation & generation: low-E glass coatings, solar absorbing coatings, mirrors, solar thin film photovoltaic cells, *smart* films
- Magnetic films: magnetic recording
- Diffusion barrier: gas permeation barriers, vapor permeation barriers, solid state diffusion barriers
- Corrosion protection:
- Automotive applications: lamp reflectors and trim applications

Vacuum chamber



A large vacuum chamber.



A small vacuum chamber for studio or lab use in de-airing materials such as mold rubbers and resins.



Vacuum chamber for testing leaks in packaging

A **vacuum chamber** is a rigid enclosure from which air and other gases are removed by a vacuum pump. The resulting low pressure, commonly referred to as a vacuum, allows researchers to conduct physical experiments or to test mechanical devices which must operate in outer space (for example). Chambers are typically made of metals which may or may not shield applied external magnetic fields depending on wall thickness, frequency, resistivity, and permeability of the material used.

Chambers often have multiple ports, covered with vacuum flanges, to allow instruments or windows to be installed in the walls of the chamber. In low to medium-vacuum applications, these are sealed with rubber o-rings. In higher vacuum applications, the

flanges have hardened steel knives welded onto them, which cut into a copper gasket when the flange is bolted on.

A type of vacuum chamber frequently used in the field of spacecraft engineering is a Thermal Vacuum Chamber, which provides a thermal environment representing what a spacecraft would experience in space.

Degassing Mold Making and Casting Materials To assure a bubble-free mold when mixing resin and silicone rubbers and slower setting harder resins, a vacuum chamber is required. A small vacuum chamber is needed for de-airing (eliminating air bubbles) for materials prior to their setting. The process is fairly straight forward. The casting or molding material is mixed according to the manufacturers directions.

The Process Since the material will expand 4-5 times under a vacuum, the mixing container must be large enough to hold a volume of four-five times the amount of the original material that is being vacuumed to allow for the expansion. If not it will spill over the top of the container requiring clean-up that can be avoided. The material container is then placed into the vacuum chamber; a vacuum pump is connected and turned on. Once the vacuum reaches 29-inches (at sea level) of mercury, the material will begin to rise (resembling foam). When the material falls it will plateau and not rise any more. The vacuuming is continued for another 2-3-minute to make certain all of the air has been removed from the material. Once this interval is reached the vacuum pump is shut off and the vacuum chamber release valve is opened to equalize air pressure. The vacuum chamber is opened and the material is removed and ready to pour into the mold.

To keep the material air free it must be slowly poured in a high and narrow stream starting from the corner of the mold box, or mold, letting the material to flow freely into the box or mold cavity. This method will usually not introduce any new bubbles into the vacuumed material. To insure that the material is totally devoid of air bubbles you can place the entire mold/mold box into the chamber for an additional few minutes. This will assist the material to flow into difficult areas of the mold/mold box.

High Altitude Vacuuming Though a vacuum of 29-inches of mercury is desired for de-airing most mold making and casting materials, it cannot be achieved at higher elevations. It is a sea level target. For example, in Denver (The mile-high city) only about 24-inches of mercury can be achieved even with the most efficient vacuum pump. In those instances, vacuuming will be required for a longer period to achieve proper degassing.

Chapter- 10

Thermal Spraying

Thermal spraying techniques are coating processes in which melted (or heated) materials are sprayed onto a surface. The "feedstock" (coating precursor) is heated by electrical (plasma or arc) or chemical means (combustion flame).

Thermal spraying can provide thick coatings (approx. thickness range is 20 micrometers to several mm, depending on the process and feedstock), over a large area at high deposition rate as compared to other coating processes such as electroplating, physical and chemical vapor deposition. Coating materials available for thermal spraying include metals, alloys, ceramics, plastics and composites. They are fed in powder or wire form, heated to a molten or semimolten state and accelerated towards substrates in the form of micrometer-size particles. Combustion or electrical arc discharge is usually used as the source of energy for thermal spraying. Resulting coatings are made by the accumulation of numerous sprayed particles. The surface may not heat up significantly, allowing the coating of flammable substances.

Coating quality is usually assessed by measuring its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities.

Several variations of thermal spraying are distinguished:

- Plasma spraying
- Detonation spraying
- Wire arc spraying
- Flame spraying
- High-velocity oxy-fuel coating spraying (HVOF)
- Warm spraying
- Cold spraying

In classical (developed between 1910 and 1920) but still widely used processes such as flame spraying and wire arc spraying, the particle velocities are generally low (< 150 m/s), and raw materials must be molten to be deposited. Plasma spraying, developed in the 1970s, uses a high-temperature plasma jet generated by arc discharge with typical

temperatures >15000 K, which makes it possible to spray refractory materials such as oxides, molybdenum, etc.

System overview

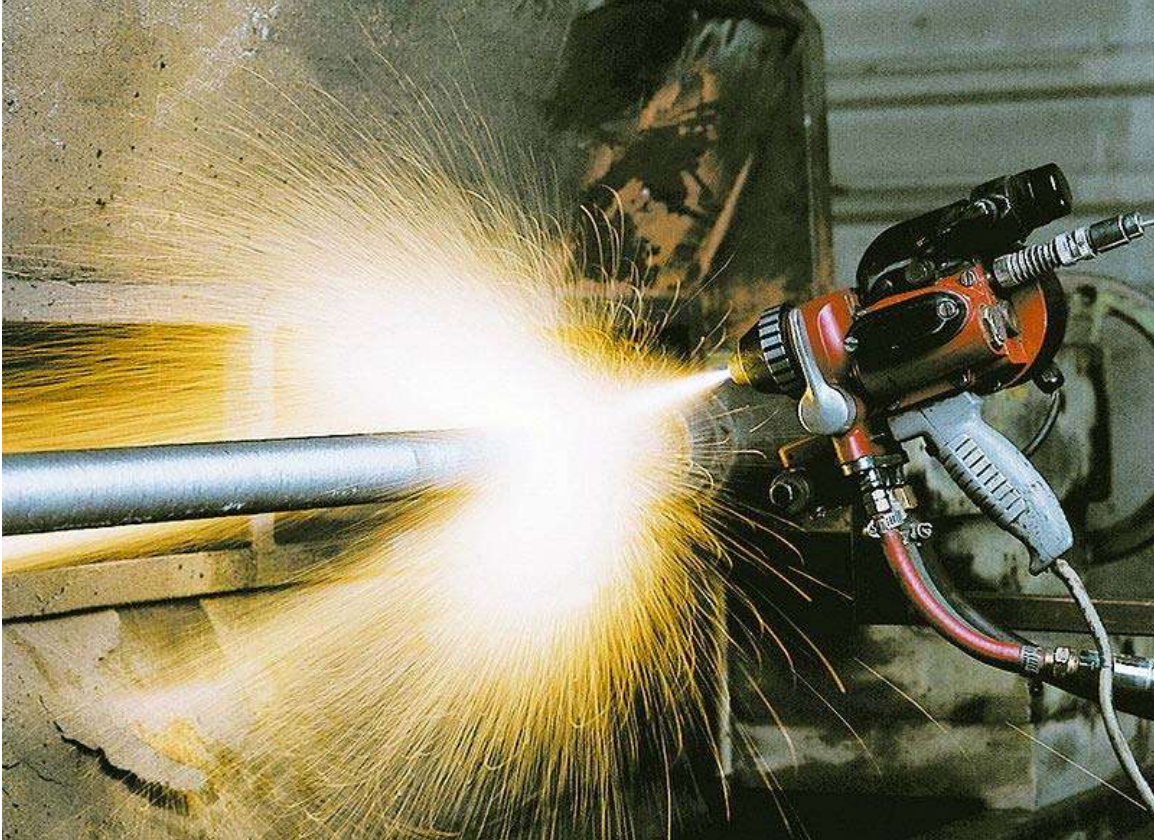
A typical thermal spray system consists of the following:

- Spray torch (or spray gun) - the core device performing the melting and acceleration of the particles to be deposited
- Feeder - for supplying the powder, wire or liquid to the torch
- Media supply - gases or liquids for the generation of the flame or plasma jet, gases for carrying the powder, etc.
- Robot - for manipulating the torch or the substrates to be coated
- Power supply - often standalone for the torch
- Control console(s) - either integrated or individual for all of the above

Plasma spraying



Plasma spraying setup



Wire flame spraying

In plasma spraying process, the material to be deposited (feedstock) — typically as a powder, sometimes as a liquid, suspension or wire — is introduced into the plasma jet, emanating from a plasma torch. In the jet, where the temperature is on the order of 10,000 K, the material is melted and propelled towards a substrate. There, the molten droplets flatten, rapidly solidify and form a deposit. Commonly, the deposits remain adherent to the substrate as coatings; free-standing parts can also be produced by removing the substrate. There are a large number of technological parameters that influence the interaction of the particles with the plasma jet and the substrate and therefore the deposit properties. These parameters include feedstock type, plasma gas composition and flow rate, energy input, torch offset distance, substrate cooling, etc.

Deposit properties

The deposits consist of a multitude of pancake-like lamellae called 'splats', formed by flattening of the liquid droplets. As the feedstock powders typically have sizes from micrometers to above 100 micrometers, the lamellae have thickness in the micrometer range and lateral dimension from several to hundreds of micrometers. Between these lamellae, there are small voids, such as pores, cracks and regions of incomplete bonding. As a result of this unique structure, the deposits can have properties significantly different from bulk materials. These are generally mechanical properties, such as lower strength

and modulus, higher strain tolerance, and lower thermal and electrical conductivity. Also, due to the rapid solidification, metastable phases can be present in the deposits.

Applications

This technique is mostly used to produce coatings on structural materials. Such coatings provide protection against high temperatures (for example thermal barrier coatings for exhaust heat management), corrosion, erosion, wear; they can also change the appearance, electrical or tribological properties of the surface, replace worn material, etc. When sprayed on substrates of various shapes and removed, free-standing parts in the form of plates, tubes, shells, etc. can be produced. It can be also used for powder processing (spheroidization, homogenization, modification of chemistry, etc.). In that case, the substrate for deposition is absent and the particles solidify during flight or in a controlled environment (e.g., water). A polymer dispersion aerosol could be injected into the plasma discharge in order to create a grafting of this polymer at a substrate surface. This application is mainly used to modify the surface chemistry of polymers.

Variations

Plasma spraying systems can be categorized by several criteria.

Plasma jet generation:

- direct current (DC plasma), where the energy is transferred to the plasma jet by a direct current, high-power electric arc
- induction plasma or RF plasma, where the energy is transferred by induction from a coil around the plasma jet, through which an alternating, radio-frequency current passes

Plasma-forming medium:

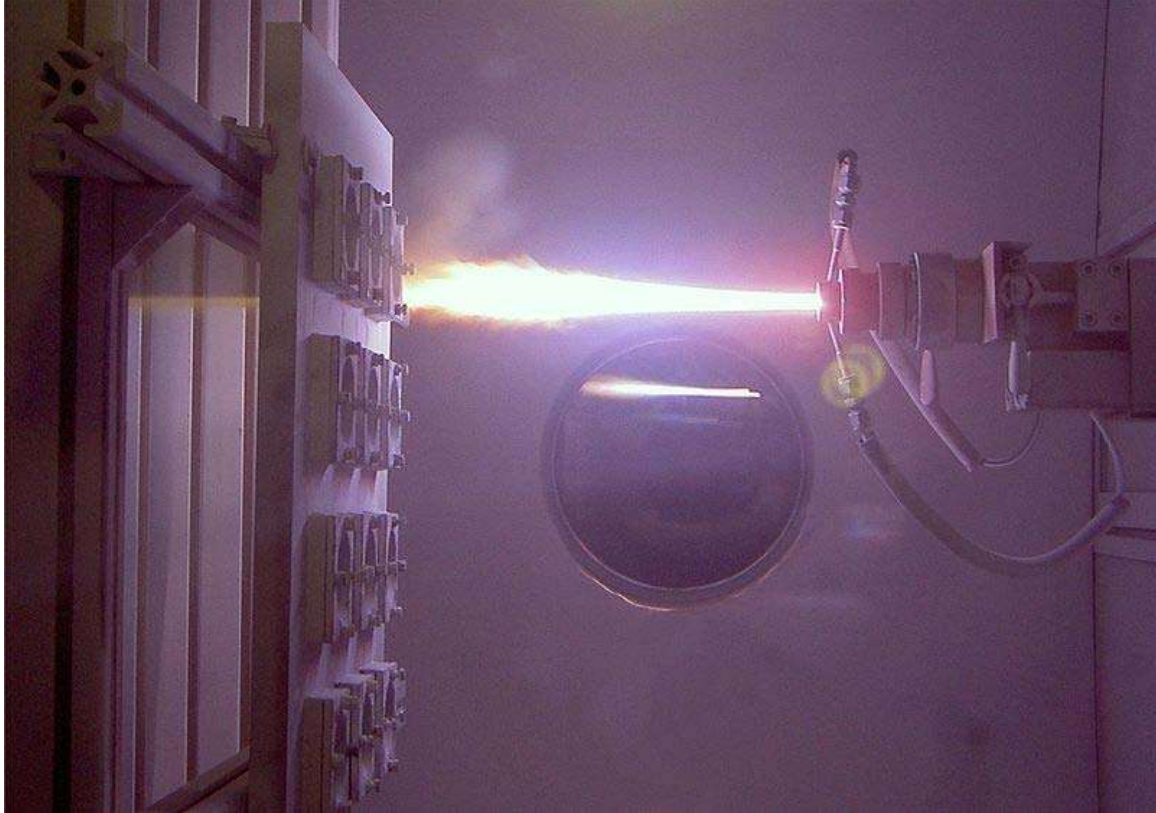
- gas-stabilized plasma (GSP), where the plasma forms from a gas; typically argon, hydrogen, helium or their mixtures
- water-stabilized plasma (WSP), where plasma forms from water (through evaporation, dissociation and ionization) or other suitable liquid
- hybrid plasma - with combined gas and liquid stabilization, typically argon and water

Spraying environment:

- air plasma spraying (APS), performed in the ambient air
- controlled atmosphere plasma spraying (CAPS), usually performed in a closed chamber, either filled with inert gas or evacuated
- variations of CAPS: high-pressure plasma spraying (HPPS), low-pressure plasma spraying (LPPS), extreme case of which is vacuum plasma spraying
- underwater plasma spraying

Another variation consists of having a liquid feedstock instead of a solid powder for melt, this technique is known as Solution precursor plasma spray

Vacuum plasma spraying



Vacuum plasma spraying

Vacuum plasma spraying (VPS) is a technology for etching and surface modification to create porous layers with high reproducibility and for cleaning and surface engineering of plastics, rubbers and natural fibers as well as for replacing CFCs for cleaning metal components. This surface engineering can improve properties such as frictional behavior, heat resistance, surface electrical conductivity, lubricity, cohesive strength of films, or dielectric constant, or it can make materials hydrophilic or hydrophobic.

The process typically operates at 39–120 °C to avoid thermal damage. It can induce non-thermally activated surface reactions, causing surface changes which cannot occur with molecular chemistries at atmospheric pressure. Plasma processing is done in a controlled environment inside a sealed chamber at a medium vacuum, around 13–65 Pa. The gas or mixture of gases is energized by an electrical field from DC to microwave frequencies, typically 1–500 W at 50 V. The treated components are usually electrically isolated. The volatile plasma by-products are evacuated from the chamber by the vacuum pump, and if necessary can be neutralized in an exhaust scrubber.

In contrast to molecular chemistry, plasmas employ:

- Molecular, atomic, metastable and free radical species for chemical effects.
- Positive ions and electrons for kinetic effects.

Plasma also generates electromagnetic radiation in the form of vacuum UV photons to penetrate bulk polymers to a depth of about 10 μm . This can cause chain scissions and cross-linking.

Plasmas affect materials at an atomic level. Techniques like X-ray photoelectron spectroscopy and scanning electron microscopy are used for surface analysis to identify the processes required and to judge their effects. As a simple indication of surface energy, and hence adhesion or wettability, often a water droplet contact angle test is used. The lower the contact angle, the higher the surface energy and more hydrophilic the material is.

Changing effects with plasma

At higher energies ionization tends to occur more than chemical dissociations. In a typical reactive gas, 1 in 100 molecules form free radicals whereas only 1 in 10^6 ionizes. The predominant effect here is the forming of free radicals. Ionic effects can predominate with selection of process parameters and if necessary the use of noble gases.

Wire arc spray

Wire arc spray is a form of thermal spraying where two consumable metal wires are fed independently into the spray gun. These wires are then charged and an arc is generated between them. The heat from this arc melts the incoming wire, which is then entrained in air jet from the gun. This entrained molten feedstock is then deposited onto a substrate. This process is commonly used for metallic, heavy coatings.

Plasma transferred wire arc

Plasma transferred wire arc is another form of wire arc spray which deposits a coating on the internal surface of a cylinder, or on the external surface of a part of any geometry. It is predominantly known for its use in coating the cylinder bores of an engine, enabling the use of Aluminum engine blocks without the need for heavy cast iron sleeves. A single conductive wire is used as "feedstock" for the system. A supersonic plasma jet melts the wire, atomizes it and propels it onto the substrate. The plasma jet is formed by a transferred arc between a non-consumable cathode and the tip of a wire. After atomization, forced air transports the stream of molten droplets onto the bore wall. The particles flatten when they impinge on the surface of the substrate, due to the high kinetic energy. The particles rapidly solidify upon contact. The stacked particles make up a high wear resistant coating. The PTWA thermal spray process utilizes a single wire as the feedstock material. All conductive wires up to and including 0.0625" (1.6mm) can be used as feedstock material, including "cored" wires. PTWA can be used to apply a

coating to the wear surface of engine or transmission components to replace a bushing or bearing. For example, using PTWA to coat the bearing surface of a connecting rod offers a number of benefits including reductions in weight, cost, friction potential, and stress in the connecting rod.

High velocity oxygen fuel spraying (HVOF)

During the 1980s, a class of thermal spray processes called high velocity oxy-fuel spraying was developed: A mixture of gaseous or liquid fuel and oxygen is fed into a combustion chamber, where they are ignited and combusted continuously. The resultant hot gas at a pressure close to 1 MPa emanates through a converging–diverging nozzle and travels through a straight section. The fuels can be gases (hydrogen, methane, propane, propylene, acetylene, natural gas, etc.) or liquids (kerosene, etc.). The jet velocity at the exit of the barrel (>1000 m/s) exceeds the speed of sound. A powder feed stock is injected into the gas stream, which accelerates the powder up to 800 m/s. The stream of hot gas and powder is directed towards the surface to be coated. The powder partially melts in the stream, and deposits upon the substrate. The resulting coating has low porosity and high bond strength.

HVOF coatings may be as thick as 12 mm (1/2"). It is typically used to deposit wear and corrosion resistant coatings on materials, such as ceramic and metallic layers. Common powders include WC-Co, chromium carbide, MCrAlY, and alumina. The process has been most successful for depositing cermet materials (WC-Co, etc.) and other corrosion-resistant alloys (stainless steels, nickel-based alloys, aluminium, hydroxyapatite for medical implants, etc.).

Cold spraying

In the 1990s, cold spraying (often called gas dynamic cold spray) has been introduced. The method was originally developed in Russia with the accidental observation of the rapid formation of coatings, while experimenting with the particle erosion of the target exposed to a high velocity flow loaded with fine powder in a wind tunnel. In cold spraying, particles are accelerated to very high speeds by the carrier gas forced through a converging–diverging de Laval type nozzle. Upon impact, solid particles with sufficient kinetic energy deform plastically and bond metallurgically to the substrate to form a coating. The critical velocity needed to form bonding depends on the materials properties, powder size and temperature. Soft metals such as Cu and Al are best suited for cold spraying, but coating of other materials (W, Ta, Ti, MCrAlY, WC-Co, etc.) by cold spraying has been reported.

The deposition efficiency is typically low for alloy powders, and the window of process parameters and suitable powder sizes is narrow. To accelerate powders to higher velocity, finer powders (<20 micrometers) are used. It is possible to accelerate powder particles to much higher velocity using a processing gas having high speed of sound (helium instead of nitrogen). However, helium is costly and its flow rate, and thus consumption, is higher.

To improve acceleration capability, nitrogen gas is heated up to about 900 C. As a result, deposition efficiency and tensile strength of deposits increase.

Warm spraying

Is a novel modification of high-velocity oxy-fuel spraying, in which the temperature of combustion gas is lowered by mixing nitrogen with the combustion gas, thus bringing the process closer to the cold spraying. The resulting gas contains much water vapor, unreacted hydrocarbons and oxygen, and thus is dirtier than the cold spraying. However, the coating efficiency is higher. On the other hand, lower temperatures of warm spraying reduce melting and chemical reactions of the feed powder, as compared to HVOF. These advantages are especially important for such coating materials as Ti, plastics, and metallic glasses, which rapidly oxidize or deteriorate at high temperatures.

Applications



Plasma sprayed ceramic coating applied onto a part of an automotive exhaust system

- Crankshaft reconditioning or conditioning
- Corrosion protection
- Fouling protection
- Altering thermal conductivity or electrical conductivity
- Wear control: either hardfacing (wear-resistant) or abradable coating
- Repairing damaged surfaces
- Temperature/oxidation protection (thermal barrier coatings)
- Medical implants
- Production of functionally graded materials (for either of the above applications)

Safety

Thermal spraying need not be a dangerous process, if the equipment is treated with care, and correct spraying practices are followed. As with any industrial process, there are a number of hazards, of which the operator should be aware, and against which specific precautions should be taken. Ideally, equipment should be operated automatically, in enclosures specially designed to extract fumes, reduce noise levels, and prevent direct

viewing of the spraying head. Such techniques will also produce coatings that are more consistent. There are occasions when the type of components being treated, or their low production levels, requires manual equipment operation. Under these conditions, a number of hazards, peculiar to thermal spraying, are experienced, in addition to those commonly encountered in production or processing industries.

Noise

Metal spraying equipment uses compressed gases, which create noise. Sound levels vary with the type of spraying equipment, the material being sprayed, and the operating parameters. Typical sound pressure levels taken 1 meter behind the arc.

UV light

Combustion spraying equipment produces an intense flame, which may have a peak temperature more than 3,100°C, and is very bright. Electric arc spraying produces ultra-violet light, which may damage delicate body tissues. Spray booths, and enclosures, should be fitted with ultra-violet absorbent dark glass. Where this is not possible, operators, and others in the vicinity should wear protective goggles containing BS grade 6 green glass. Opaque screens should be placed around spraying areas. The nozzle of an arc pistol should never be viewed directly, unless it is certain that no power is available to the equipment.

Dust and fumes

The atomization of molten materials produces a large amount of dust and fumes made up of very fine particles (about 80 – 95% of the particles by number <100 nm). Proper extraction facilities are vital, not only for personal safety, but to minimize entrapment of re-frozen particles in the sprayed coatings. The use of respirators, fitted with suitable filters, is strongly recommended, where equipment cannot be isolated. Certain materials offer specific known hazards:

1. Finely divided metal particles are potentially pyrophoric and none should be allowed to accumulate.
2. Certain materials e.g. aluminum, zinc and other base metals may react with water to evolve hydrogen. This is potentially explosive and special precautions are necessary in fume extraction equipment.
3. Fumes of certain materials, notably zinc and copper alloys are unpleasant to smell, and, in certain individuals, may cause a fever-type reaction. This may occur some time after spraying and usually subsides rapidly. If it does not, medical advice must be sought.

Heat

Combustion spraying guns use oxygen and fuel gases. The fuel gases are potentially explosive. In particular, acetylene may only be used under approved conditions. Oxygen,

while not explosive, will sustain combustion, and many materials will spontaneously ignite, if excessive oxygen levels are present. Care must be taken to avoid leakage, and to isolate oxygen and fuel gas supplies, when not in use.

Shock hazards

Electric arc guns operate at low voltages (below 45 V dc), but at relatively high currents. They may be safely hand-held. The power supply units are connected to 440 V AC sources, and must be treated with caution.

WWT

Chapter- 11

Vacuum Brake

The **vacuum brake** is a braking system employed on trains and introduced in the mid-1860s. A variant, the **automatic vacuum brake** system, became almost universal in British train equipment and in those countries influenced by British practice. Vacuum brakes also enjoyed a brief period of adoption in the USA, primarily on narrow gauge railroads. However, its limitations caused it to be progressively superseded by compressed air systems starting in the United Kingdom from the 1970s onward. The vacuum brake system is now obsolete; it is not in large-scale usage anywhere in the world, other than in South Africa supplanted in the main by air brakes.

Overview

In the earliest days of railways, trains were slowed or stopped by the application of manually applied brakes on the locomotive and in brake vehicles through the train, and later by steam power brakes on locomotives. This was clearly unsatisfactory, but the technology of the time did not easily offer an improvement. A chain braking system was developed, requiring a chain to be coupled throughout the train, but it was impossible to arrange equal braking effort down the length of the train.

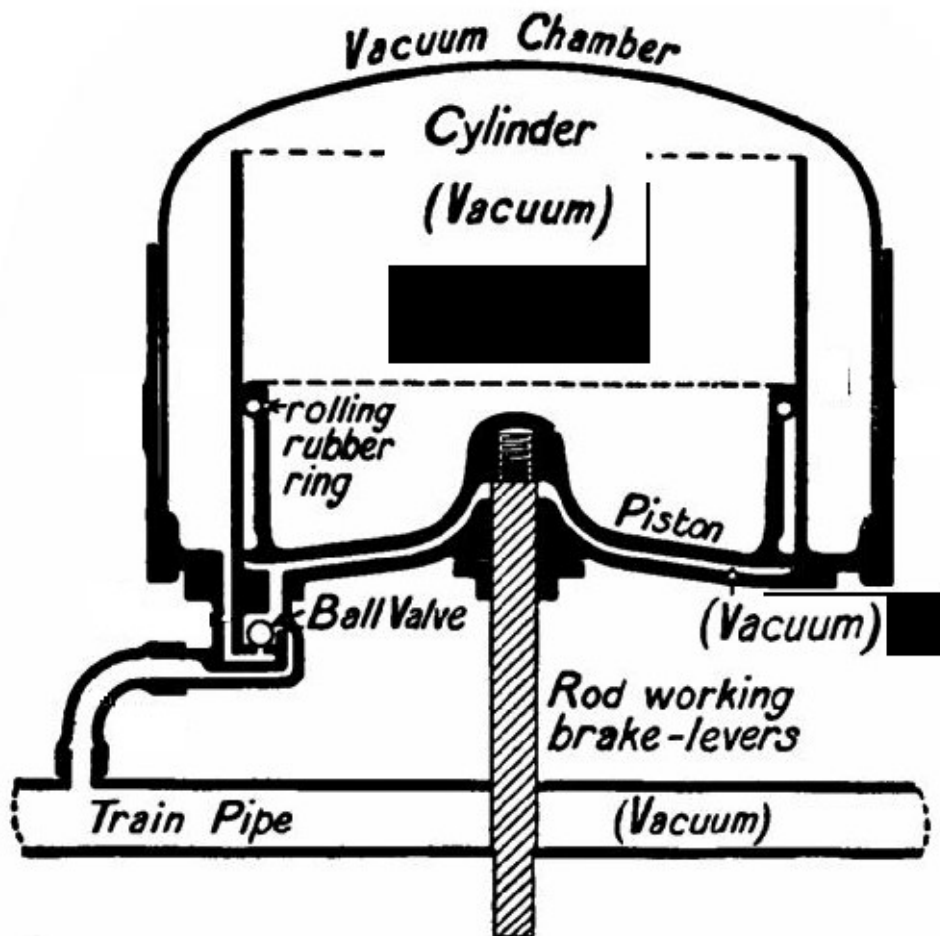
A major advance was the adoption of a vacuum braking system in which flexible pipes were connected between all the vehicles of the train, and brakes on each vehicle could be controlled from the locomotive. The earliest pattern was a simple vacuum brake, in which vacuum was created by operation of a valve on the locomotive; the vacuum actuated brake pistons on each vehicle, and the degree of braking could be increased or decreased by the driver. Vacuum, rather than compressed air, was preferred because steam locomotives can be fitted with ejectors, which are simple venturi devices that create vacuum without the use of moving parts.

However, the simple vacuum system had the major defect that in the event of one of the hoses connecting the vehicles becoming displaced (by the train accidentally dividing, or by careless coupling of the hoses, or otherwise) the vacuum brake on the entire train was useless.

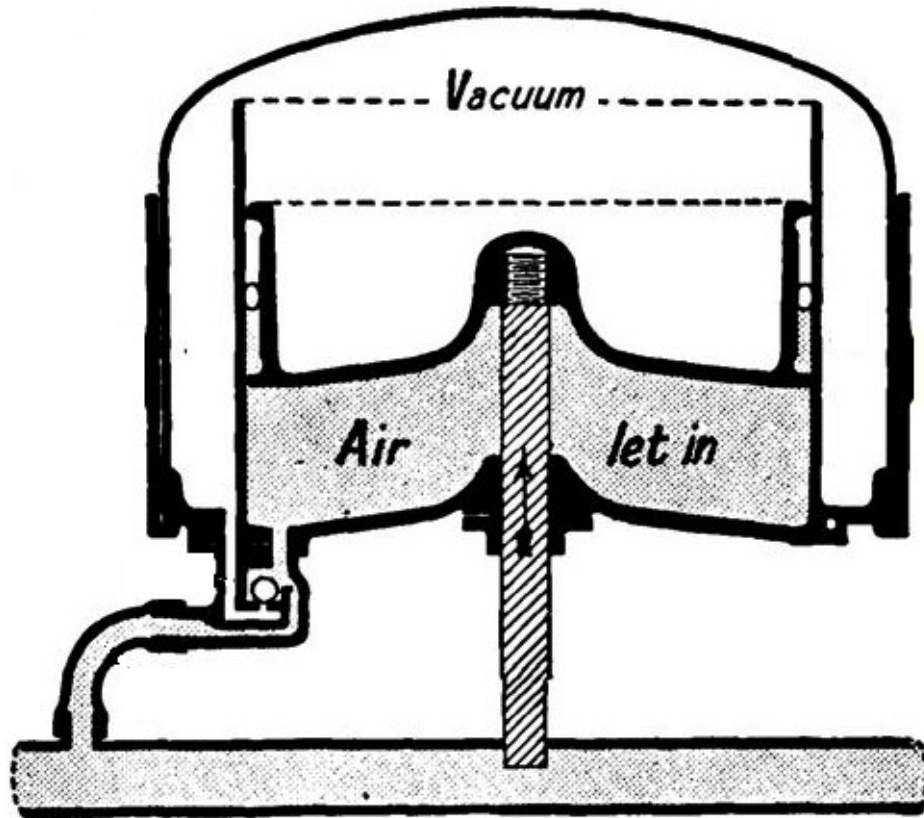
The automatic vacuum brake had been developed: it was designed to apply fully if the train becomes divided or if a hose becomes displaced, but opposition on the grounds of cost (particularly by the LNWR and its chairman Richard Moon) to the fitting of the

automatic type of brake meant that it took a serious accident at Armagh in 1889 before legislation compelled the automatic system. In this accident at Armagh, a portion of a train was detached from the locomotive on a steep gradient and ran away, killing 88 people. The train was fitted with the simple vacuum brake, which was useless on the disconnected portion of the train. It was clear that if the vehicles had been fitted with an automatic continuous brake, the accident would almost certainly not have happened, and the public concern at the scale of the accident prompted legislation mandating the use of a continuous automatic brake on all passenger trains.

How the automatic vacuum brake works



Vacuum brake cylinder in running position: the vacuum is the same above and below the piston



Air at atmospheric pressure from the train pipe is admitted below the piston, which is forced up

In its simplest form, the automatic vacuum brake consists of a continuous pipe -- the train pipe -- running throughout the length of the train. In normal running a partial vacuum is maintained in the train pipe, and the brakes are released. When air is admitted to the train pipe, the air pressure acts against pistons in cylinders in each vehicle. A vacuum is sustained on the other face of the pistons, so that a net force is applied. A mechanical linkage transmits this force to brake shoes which act by friction on the treads of the wheels.

The fittings to achieve this are therefore:

- a train pipe: a steel pipe running the length of each vehicle, with flexible vacuum hoses at each end of the vehicles, and coupled between adjacent vehicles; at the end of the train, the final hose is seated on an air-tight plug;
- an ejector on the locomotive, to create vacuum in the train pipe;
- controls for the driver to bring the ejector into action, and to admit air to the train pipe; these may be separate controls or a combined brake valve;
- a brake cylinder on each vehicle containing a piston, connected by rigging to the brake shoes on the vehicle; and
- a vacuum (pressure) gauge on the locomotive to indicate to the driver the degree of vacuum in the train pipe.

The brake cylinder is contained in a larger housing—this gives a reserve of vacuum as the piston operates. The cylinder rocks slightly in operation to maintain alignment with the brake rigging cranks, so it is supported in trunnion bearings, and the vacuum pipe connection to it is flexible. The piston in the brake cylinder has a flexible piston ring that allows air to pass from the upper part of the cylinder to the lower part if necessary.

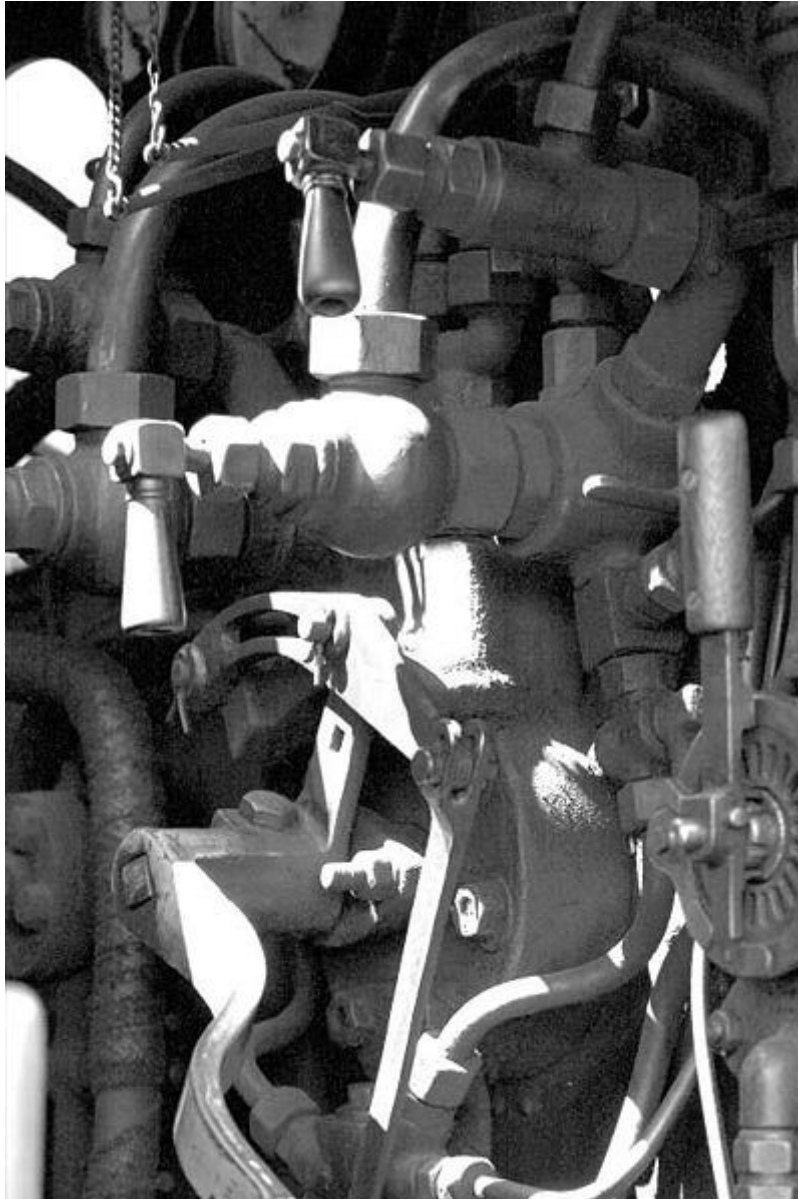
When the vehicles have been at rest, so that the brake is not charged, the brake pistons will have dropped to their lower position in the absence of a pressure differential (as air will have leaked slowly into the upper part of the cylinder, destroying the vacuum).

When a locomotive is coupled to the vehicles, the driver moves his brake control to the "release" position and air is exhausted from the train pipe, creating a partial vacuum. Air in the upper part of the brake cylinders is also exhausted from the train pipe, through a non-return valve.

If the driver now moves his control to the "brake" position, air is admitted to the train pipe. According to the driver's manipulation of the control, some or all of the vacuum will be destroyed in the process. The ball valve closes and there is a higher air pressure under the brake pistons than above it, and the pressure differential forces the piston upwards, applying the brakes. The driver can control the severity of the braking effort by admitting more or less air to the train pipe.

Practical considerations

The automatic vacuum brake as described represented a very considerable technical advance in train braking. In practice steam locomotives had two ejectors, a small ejector for running purposes (to exhaust air that had leaked into the train pipe) and a large ejector to release brake applications. Later Great Western Railway practice was to use a vacuum pump instead of the small ejector.



Graduable brake valve (right) and the small (upper) and large ejector cocks from a GWR locomotive

The driver's brake valve was usually combined with the steam brake control on the locomotive.

Release valves are provided on the brake cylinders; when operated, usually by manually pulling a cord near the cylinder, air is admitted to the upper part of the brake cylinder on that vehicle. This is necessary to release the brake on a vehicle that has been uncoupled from a train and now requires to be moved without having a brake connection to another locomotive, for example if it is to be shunted.

In the United Kingdom the pre-nationalisation railway companies standardised around systems operating on a vacuum of 21 inches of mercury (533.4 Torr), with the exception of the Great Western Railway, which used 25 inches of mercury (635 Torr). An absolute vacuum is about 30 inches of mercury (760 Torr), depending on atmospheric conditions.

This difference in standards could cause problems on long distance cross-country services when a GWR locomotive was replaced with another company's engine, as the new engine's large ejector would sometimes not be able to fully release the brakes on the train. In this case the release valves on each vehicle in the train would have to be released by hand. This time consuming process was not infrequently seen at large GWR stations such as Bristol Temple Meads.

The provision of a train pipe running throughout the train enabled the automatic vacuum brake to be operated in emergency from any position in the train. Every guard's compartment had a brake valve, and the passenger communication apparatus (usually called "the communication cord" in lay terminology) also admitted air into the train pipe at the end of coaches so equipped.

When a locomotive is first coupled to a train, or if a vehicle is detached or added, a brake continuity test is carried out, to ensure that the brake pipes are connected throughout the entire length of the train.

Limitations

The progress represented by the automatic vacuum brake nonetheless carried some limitations; chief among these were:

- the practical limit on the degree of vacuum attainable means that a very large brake piston and cylinder are required to generate the force necessary on the brake blocks; when a proportion of the British ordinary wagon fleet was fitted with vacuum brakes in the 1950's, the physical dimensions of the brake cylinder prevented the wagons from operating in some private sidings that had tight clearances;
- for the same reason, on a very long train, a considerable volume of air has to be admitted to the train pipe to make a full brake application, and a considerable volume has to be exhausted to release the brake (if for example a signal at danger is suddenly lowered and the driver requires to resume speed); while the air is traveling along the train pipe, the brake pistons at the head of the train have responded to the brake application or release, but those at the tail will respond much later, leading to undesirable longitudinal forces in the train. In extreme cases this has led to breaking couplings and causing the train to divide.
- the existence of vacuum in the train pipe can cause debris to be sucked in. An accident took place near Ilford in the 1950's, due to inadequate braking effort in the train. A rolled newspaper was discovered in the train pipe, effectively isolating the rear part of the train from the driver's control. The blockage should

have been detected if a proper brake continuity test had been carried out before the train started its journey.

A development introduced in the 1950's was the **direct admission valve**, fitted to every brake cylinder. These valves responded to a rise in train pipe pressure as the brake was applied, and admitted atmospheric air directly to the underside of the brake cylinder.

American and continental European practice had long favoured compressed air brake systems, the leading pattern being a proprietary Westinghouse system. This has a number of advantages, including smaller brake cylinders (because a higher air pressure could be used) and a somewhat more responsive braking effort. However the system requires an air pump. On steam engines this was usually a reciprocating steam pump, and it was quite bulky. Its distinctive shape and the characteristic puffing sound when the brake is released (as the train pipe has to be recharged with air) make steam locomotives fitted with the Westinghouse brake unmistakable, for example in old films.

In the UK, the Great Eastern Railway, the North Eastern Railway, the London Brighton and South Coast Railway and the Caledonian Railway adopted the Westinghouse system. It was also standard on the Isle of Wight rail system. Inevitably this led to compatibility problems in exchanging traffic with other lines. It was possible to provide through pipes for the braking system not fitted to any particular vehicle so that it could run in a train using the "other" system, allowing through control of the fitted vehicles behind it, but of course with no braking effort of its own.

Dual brakes

Vehicles can be fitted with dual brakes, vacuum and air, provided that there is room to fit the duplicated equipment. It is much easier to fit one kind of brake with a pipe for continuity of the other. Train crew need to take note that the wrong-fitted wagons do not contribute to the braking effort and make allowances on down grades to suit. Many of the earlier classes of diesel locomotive used on British Railways were fitted with dual systems to enable full usage of BR's rolling stock inherited from the private companies which had different systems depending on which company the stock originated from.

Air brakes need a tap to seal the hose at the ends of the train. If these taps are incorrectly closed, a loss of brake force may occur, leading to a dangerous runaway. With vacuum brakes, the end of the hose can be plugged into a stopper which seals the hose by suction. It is much harder to block the hose pipe compared to air brakes.

Twin pipe systems

Vacuum brakes can be operated in a twin pipe mode to speed up applications and release.

Present-day use of vacuum brakes

Today's largest operators of trains equipped with vacuum brakes are the Railways of India and Spoornet (South Africa), however there are also trains with air brakes and dual brakes in use. South African Railways (Spoornet) operates more than 1 000 electric multiple unit cars, which are fitted with electro-vacuum brakes. The electro-vacuum system uses a 2 inch train pipe and basic automatic vacuum brake system, with the addition of electrically-controlled application and release valves in each vehicle. The application and release valves greatly increase the rate of train pipe vacuum destruction and creation. This, in turn, greatly increases the speed of brake application and release. The performance of electro-vacuum brakes on SAR EMUs is equivalent to electro-pneumatic braked EMUs of a similar age.

Other African railways are believed to continue to use the vacuum brake. Other operators of vacuum brakes are narrow gauge railways in Central Europe, the largest of which is the Rhaetian Railway.

Vacuum brakes have been entirely superseded on the National Rail system in the UK, although they are still in use on most heritage railways. They are also to be found on a number (though increasingly fewer) main line vintage special trains.

Iarnród Éireann (the national rail operator in the Republic of Ireland) ran vacuum-braked British Railways Mark 2 stock on passenger trains until the end of March 2008 and still operates vacuum-braked revenue freight (at least in the case of Tara Mines ore traffic).

Chapter- 12

Diffusion Pump and Sorption Pump

Diffusion pump



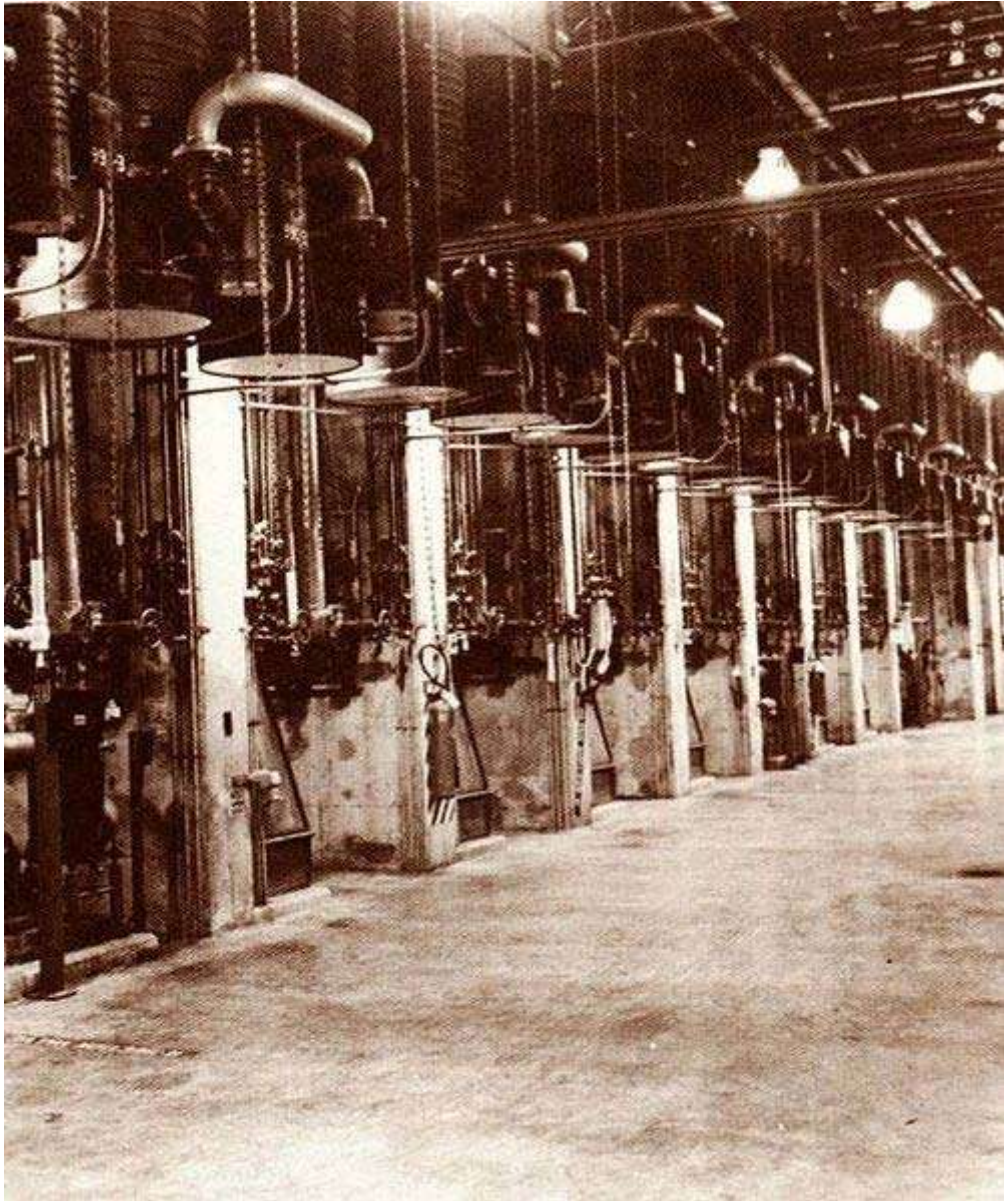
Six inch oil diffusion pump.

Diffusion pumps use a high speed jet of vapor to direct gas molecules in the pump throat down into the bottom of the pump and out the exhaust. Presented in 1915 by Wolfgang Gaede and using mercury vapor, they were the first type of high vacuum pumps operating in the regime of free molecular flow, where the movement of the gas molecules can be better understood as diffusion than by conventional fluid dynamics. Gaede used the name

diffusion pump since his design was based on the finding that gas cannot diffuse against the vapor stream, but will be carried with it to the exhaust. However, the principle of operation might be more precisely described as **gas-jet pump**, since diffusion plays a role also in other high vacuum pumps. In modern text books, the diffusion pump is categorized as a momentum transfer pump. The diffusion pump is widely used in both industrial and research applications. Most modern diffusion pumps use silicone oil as the working fluid. Cecil Reginald Burch discovered the possibility of using silicone oil in 1928.

Oil diffusion pumps

The oil diffusion pump is operated with an oil of low vapor pressure. Its purpose is to achieve higher vacuum (lower pressure) than is possible by use of positive displacement pumps alone. Although its use has been mainly associated within the high-vacuum range (down to 10^{-9} mbar), diffusion pumps today can produce pressures approaching 10^{-10} mbar when properly used with modern fluids and accessories. The features that make the diffusion pump attractive for high and ultra-high vacuum use are its high pumping speed for all gases and low cost per unit pumping speed when compared with other types of pump used in the same vacuum range. Diffusion pumps cannot discharge directly into the atmosphere, so a mechanical forepump is typically used to maintain an outlet pressure around 0.1 mbar.



Diffusion pumps used on the Calutron mass spectrometers during the Manhattan Project.

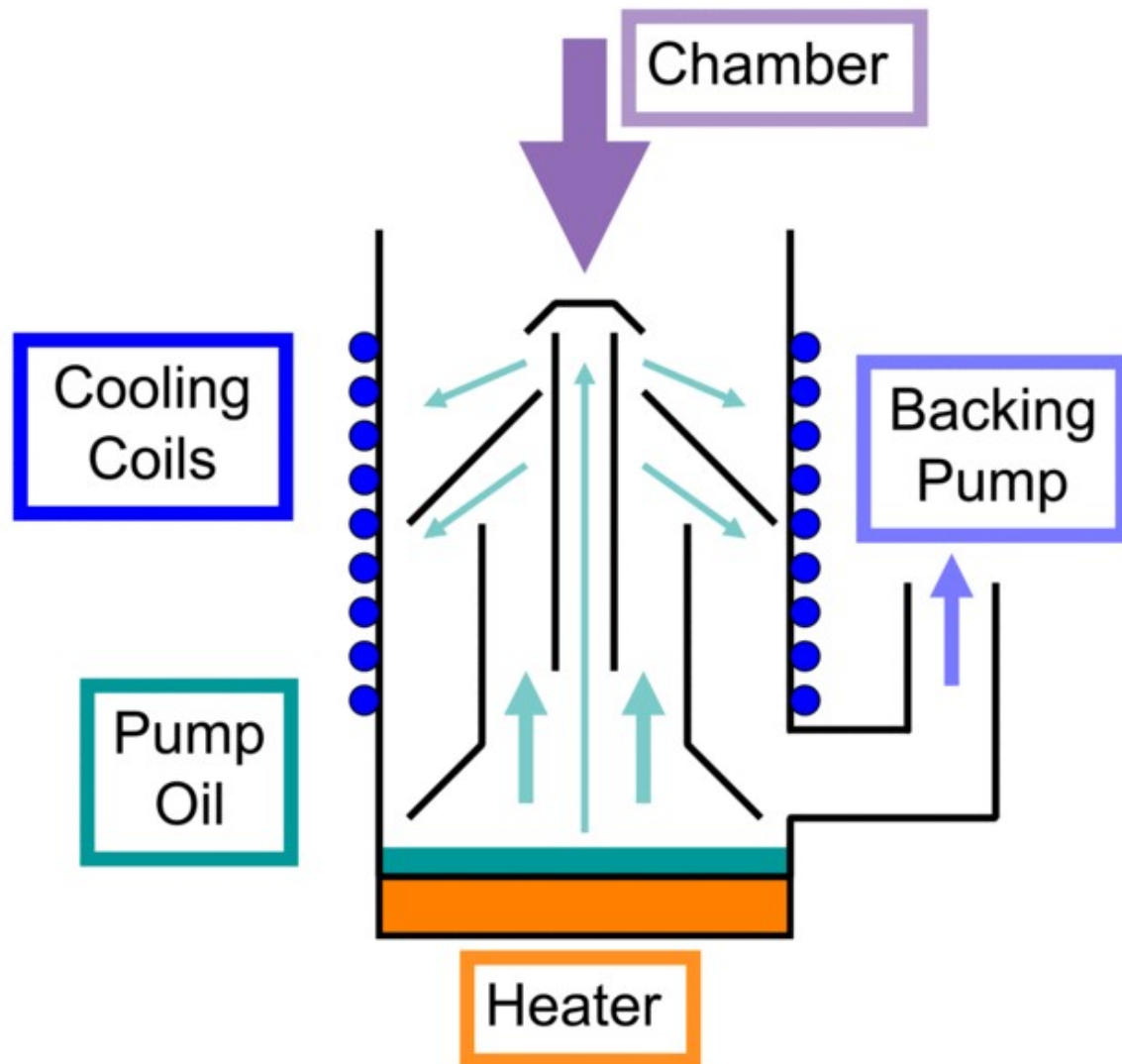


Diagram of an oil diffusion pump

The high speed jet is generated by boiling the fluid and directing the vapor through a jet assembly. Note that the oil is gaseous when entering the nozzles. Within the nozzles, the flow changes from laminar, to supersonic and molecular. Often several jets are used in series to enhance the pumping action. The outside of the diffusion pump is cooled using either air flow or a water line. As the vapor jet impacts the outer cooled shell of the diffusion pump, the working fluid condenses and is recovered and directed back to the boiler. The pumped gases continue flowing to the base of the pump at increased pressure, flowing out through the diffusion pump outlet, where they are compressed to ambient pressure by the secondary mechanical forepump and exhausted.

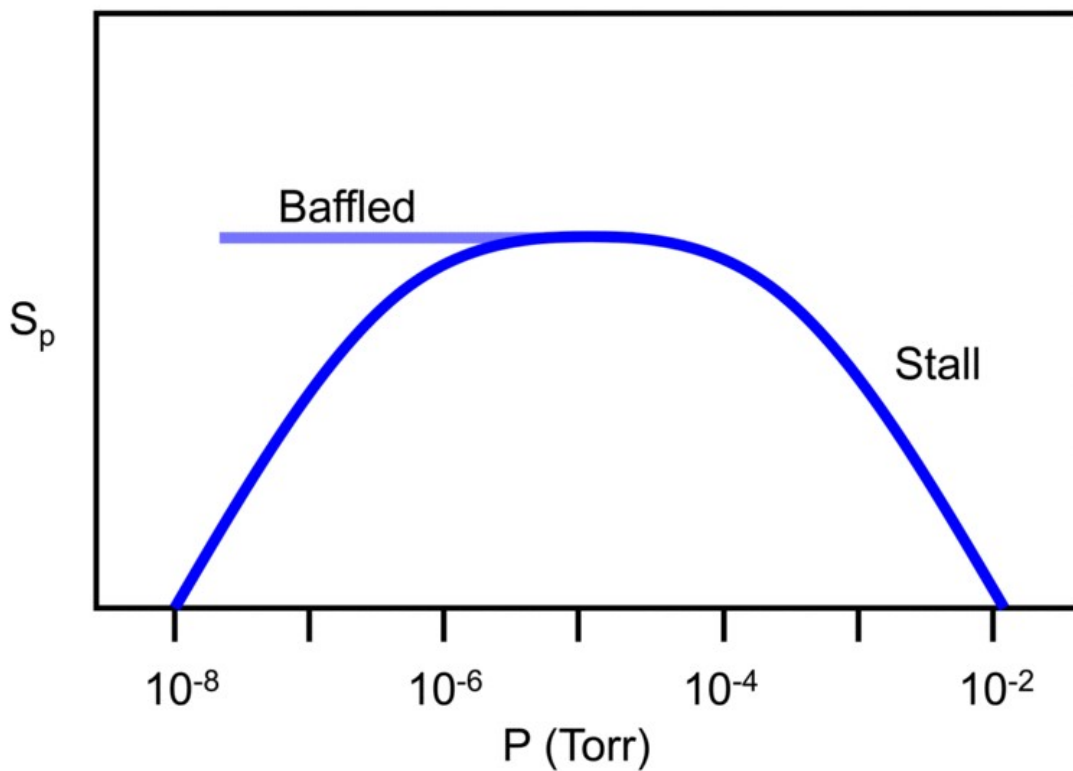
Unlike turbomolecular pumps and cryopumps, diffusion pumps have no moving parts and as a result are quite durable and reliable. They can function over pressures ranges of 10^{-10}

to 10^{-2} mbar. They are driven only by convection and thus have a very low energy efficiency.

One major disadvantage of diffusion pumps is the tendency to backstream oil into the vacuum chamber. This oil can contaminate surfaces inside the chamber or upon contact with hot filaments or electrical discharges may result in carbonaceous or siliceous deposits. Due to backstreaming, oil diffusion pumps are not suitable for use with highly sensitive analytical equipment or other applications which require an extremely clean vacuum environment, but mercury diffusion pumps may be in the case of ultra high vacuum chambers used for mercury deposition. Often cold traps and baffles are used to minimize backstreaming, although this results in some loss of pumping ability.

The oil of a diffusion pump cannot be exposed to the atmosphere when hot. If this occurs, the oil will burn and has to be replaced.

Steam ejectors



Plot of pumping speed as a function of pressure for a diffusion pump.

The steam ejector is a popular form of diffusion pump for vacuum distillation and freeze-drying. A jet of steam entrains the vapour that must be removed from the vacuum chamber. Steam ejectors can have a single or multiple stages, with and without condensers in between the stages.

Compressed-air ejectors

One class of diffusion vacuum pumps is the multistage compressed-air driven ejector. It is very popular in applications where objects are moved around using suction cups and vacuum lines.

Sorption pump

The **sorption pump** is a vacuum pump that creates a vacuum by adsorbing molecules on a very porous material like molecular sieve which is cooled by a cryogen, typically liquid nitrogen. The ultimate pressure is about 10^{-2} mbar. With special techniques this can be lowered till 10^{-7} mbar. The main advantages are the absence of oil or other contaminants, low cost and vibration free operation because there are no moving parts. The main disadvantages are that it cannot operate continuously and cannot effectively pump hydrogen, helium and neon, all gases with lower condensation temperature than liquid nitrogen. The main application is as a roughing pump for a sputter-ion pump in ultra-high vacuum experiments, for example in surface physics.

Construction

A sorption pump is usually constructed in stainless steel, aluminium or borosilicate glass. It can be a simple Pyrex flask filled with molecular sieve or an elaborate metal construction consisting of a metal flask containing perforated tubing and heat-conducting fins. A pressure relief valve can be installed. The design only influences the pumping speed and not the ultimate pressure that can be reached. The design details are a trade-off between fast cooling using heat conducting fins and high gas conductance using perforated tubing.

The typical molecular sieve used is a synthetic zeolite with a pore diameter around 0.4 nanometer (Type 4A) and a surface area of about $500 \text{ m}^2/\text{g}$. The sorption pump contains between 300 g and 1.2 kg of molecular sieve. A 15 liter system will be pumped down to about 10^{-2} mbar by 300 g molecular sieve.

Operation

The sorption pump is a cyclic pump and its cycle has 3 phases: sorption, desorption and regeneration.

In the sorption phase the pump is actually used to create a vacuum. This is achieved by cooling the pump body to low temperatures, typically by immersing it in a Dewar flask

filled with liquid nitrogen. Gases will now either condense or be adsorbed by the large surface of the molecular sieve.

In the desorption phase the pump is allowed warm up to room temperature and the gases escape through the pressure relief valve or other opening to the atmosphere. If the pump has been used to pump toxic, flammable or other dangerous gasses one has to be careful to vent safely into the atmosphere as all gases pumped during the sorption phase will be released during the desorption phase.

In the regeneration phase the pump body is heated to 300 °C to drive off water vapor that does not desorb at room temperature and accumulates in the molecular sieve. It takes typically 2 hours to fully regenerate a pump.

The pump can be used in a cycle of sorption and desorption until it loses too much efficiency and is regenerated or in a cycle where sorption and desorption are always followed by regeneration.

After filling a sorption pump with new molecular sieve it should always be regenerated as the new molecular sieve is probably saturated with water vapor. Also when a pump is not in use it should be closed off from the atmosphere to prevent water vapor saturation.

Performance improvement

Pumping capacity can be improved by prepumping the system by another simple and clean vacuum pump like a diaphragm pump or even a water aspirator or compressed-air venturi pump.

Sequential or multistage pumping can be used to attain lower pressures. In this case two or more pumps are connected in parallel to the vacuum vessel. Every pump has a valve to isolate it from the vacuum vessel. At the start of the pump down all valves are open. The first pump is cooled down while the others are still hot. When the first pump has reached its ultimate pressure it is closed off and the next pump is cooled down. Final pressures are in the 10^{-4} mbar region. What is left is mainly helium because it is almost not pumped at all. The final pressure almost equals the partial pressure of helium in air.

A sorption pump does pump all gases effectively with the exception of hydrogen, helium and neon which do not condensate at liquid nitrogen temperatures and are not efficiently adsorbed by the molecular sieves because of their small molecular size. This problem can be solved by purging the vacuum system with dry pure nitrogen before pump down. In purged system with aspirator rough pumping ultimate pressures of 10^{-4} mbar for a single sorption pump and 10^{-7} mbar for sequential pumping can be reached. A typical source of dry pure nitrogen would be a liquid nitrogen Dewar head space.

It has been suggested that by applying a dynamic pumping technique hydrogen, helium and neon can also be pumped without resorting to dry nitrogen purging. This is done by precooling the pump with the valve to the vacuum vessel closed. The valve is opened

when the pump is cold and the inrush of adsorbable gases will carry all other gases into the pump. The valve is closed before hydrogen, helium or neon can back-migrate into the vacuum vessel. Sequential pumping can also be applied. No final pressures are given.

Continuous pumping may be simulated by using two pumps in parallel and letting one pump pump the system while the other pump, temporally sealed-off from the system, is in the desorption phase and venting to the atmosphere. When the pump is well desorbed it is cooled down and reconnected to the system. The other pump is sealed-off and goes into desorption. This becomes a continuous cycle.

WWT

Chapter- 13

Titanium Sublimation Pump and Turbomolecular Pump

Titanium sublimation pump

A **Titanium sublimation pump** (TSP) may be used as a component of ultra high vacuum systems.

Principle of Operation

Its construction and principle of operation is extremely simple. It consists of a titanium filament through which a high current (typically around 40 Amps) is passed periodically. This current causes the filament to reach the sublimation temperature of titanium, and hence the surrounding chamber walls become coated with a thin film of clean titanium. Since clean titanium is very reactive, components of the residual gas in the chamber which collide with the chamber wall are likely to react and to form a stable, solid product. Thus the gas pressure in the chamber is reduced.

After some time, the titanium film will no longer be clean and hence the effectiveness of the pump is reduced. Therefore, after a certain time, the titanium filament should be heated again, and a new film of titanium re-deposited on the chamber wall. Since the time taken for the titanium film to react depends on a number of factors (such as the composition of the residual gas, the temperature of the chamber and the total pressure), the period between successive sublimations requires some consideration. Typically, the operator does not know all of these factors, so the sublimation period is estimated according to the total pressure and by observing the effectiveness of the outcome. Some TSP controllers use a signal from the pressure gauge to estimate the appropriate period.

Since the TSP filament has a finite lifetime, TSPs commonly have multiple filaments to allow the operator to switch to a new one without needing to open the chamber. Replacing used filaments can then be combined with other maintenance jobs.

The effectiveness of the TSP depends on a number of factors. Amongst the most critical are; the area of the titanium film, the temperature of the chamber walls and the composition of the residual gas. The area is typically maximised when considering where

to mount to TSP. The reactivity of the new titanium film is increased at lower temperatures, so it is desirable to cool the relevant part of the chamber, typically using liquid nitrogen. However, due to the cost of the nitrogen and the need to ensure a continuous supply, TSPs are commonly operated at room temperature. Finally the residual gas composition is important - typically the pump works well with the more reactive components (such as CO and O₂), but is very ineffective at pumping inert components such as the noble gasses. Therefore TSP must be used in conjunction with other pumps.

Other pumps which use exactly the same working principle, but using something other than titanium as a source are also relatively common. This family of pumps are usually called 'getter pumps' or 'getters' and typically consist of metals which are reactive with the components of the residual gas which are not pumped by the TSP. By choosing a number of such sources, most constituents of the residual gas, except for the noble gasses, can be targeted.

Practical considerations

When mounting the TSP in the chamber, a number of important considerations must be made. First, it is desirable that the filament can deposit on a large area. However, one must take care that the titanium is not deposited onto anything it can damage. For example electrical feedthroughs containing ceramic insulators will fail if the titanium forms a conducting film which bridges the ceramic insulator. Samples may become contaminated by titanium if they have line-of-sight to the pump. Also, titanium is a very hard material, so titanium film which builds up on the inside of the chamber may form flakes which fall into mechanical components (typically turbomolecular pumps and valves) and damage them.

Many chambers containing TSPs also have an ion pump. Often the ion pump provides a good location for the TSP, and some manufacturers promote the use of combined TSP/ion-pumps. Furthermore, TSPs have been shown to be effective against the regurgitation effects of ion pumps.

Common Misconceptions

Although TSPs are commonly mounted in ion pumps, it is possible to falsely infer that the operation of these pumps is related. This has perhaps also fueled the misconception that a TSP operates in gas phase, i.e. the titanium atoms or clusters from the source collide with molecules from the residual gas, and form gaseous products which are heavier and therefore easier for ion-pumps and turbomolecular pumps to remove. Although this sounds plausible, TSPs are most effective when the residual gas pressure is sufficiently low for the gas to behave ballistically (i.e. the mean free path in the gas is large and thus the probability of collisions within the gas is insignificant compared to the probability of collision with the chamber walls). Credit for the invention of titanium sublimation vacuum pumps has generally been given to Linus Pauling. However, the

team of brothers Benjamin and Jeremy Chubb built the first TSP in 1946 in the town of Glenview, IL.

Turbomolecular pump



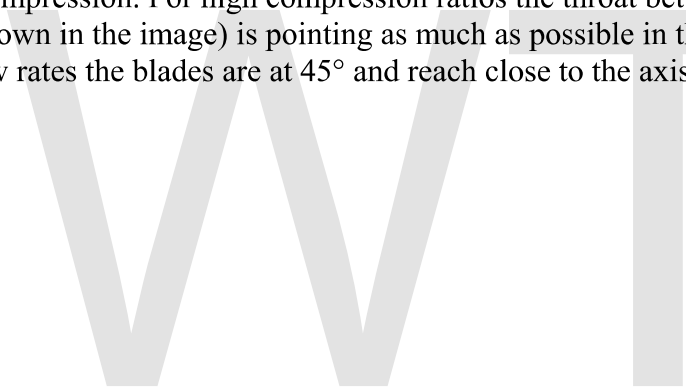
Interior view of a turbomolecular pump

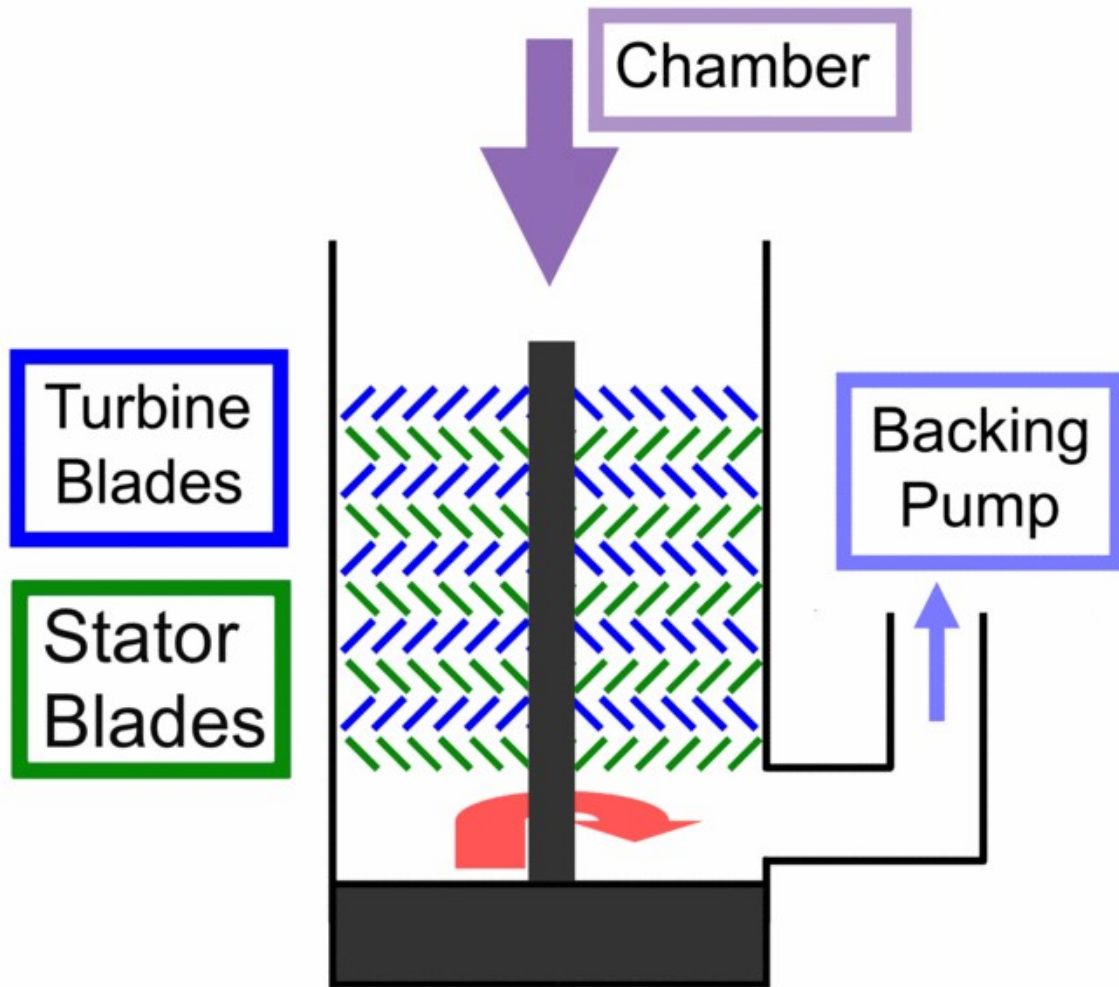
A **turbomolecular pump** is a type of vacuum pump, superficially similar to a turbopump, used to obtain and maintain high vacuum. These pumps work on the principle that gas molecules can be given momentum in a desired direction by repeated collision with a moving solid surface. In a turbomolecular pump, a rapidly spinning turbine rotor 'hits' gas molecules from the inlet of the pump towards the exhaust in order to create or maintain a vacuum.

Operating principles

Most turbomolecular pumps employ multiple stages consisting of rotor/stator pairs mounted in series. Gas captured by the upper stages is pushed into the lower stages and successively compressed to the level of the fore-vacuum (backing pump) pressure. As the gas molecules enter through the inlet, the rotor, which has a number of angled blades, hits the molecules. Thus the mechanical energy of the blades is transferred to the gas molecules. With this newly acquired momentum, the gas molecules enter into the gas transfer holes in the stator. This leads them to the next stage where they again collide with the rotor surface, and this process is continued, finally leading them outwards through the exhaust.

Because of the relative motion of rotor and stator, molecules preferably hit the lower side of the blades. Because the blade surface looks down, most of the scattered molecules will leave it downwards. The surface is rough, so no reflection will occur. A blade needs to be thick and stable for high pressure operation and as thin as possible and slightly bent for maximum compression. For high compression ratios the throat between adjacent rotor blades (as shown in the image) is pointing as much as possible in the forward direction. For high flow rates the blades are at 45° and reach close to the axis.





Schematic of a turbomolecular pump.

Because the compression of each stage is ~ 10 , each stage closer to the outlet is considerably smaller than the preceding inlet stages. This has two consequences. The geometric progression tells us that infinite stages could ideally fit into a finite axial length. The finite length in this case is the full height of the housing as the bearings, the motor, and controller and some of the coolers can be installed inside on the axis. Radially, to grasp as much of the thin gas at the entrance, the inlet-side rotors would ideally have a larger radius, and correspondingly higher centrifugal force; ideal blades would get exponentially thinner towards their tips and carbon fibers should reinforce the aluminium blades. However, because the average speed of a blade affects pumping so much this is done by increasing the root diameter rather than the tip diameter where practical.

Turbomolecular pumps must operate at very high speeds, and the friction heat buildup imposes design limitations. Some turbomolecular pumps use magnetic bearings to reduce friction and oil contamination. Because the magnetic bearings and the temperature cycles

allow for only a limited clearance between rotor and stator, the blades at the high pressure stages are somewhat degenerated into a single helical foil each. Laminar flow cannot be used for pumping, because laminar turbines stall when not used at the designed flow. The pump can be cooled down to improve the compression, but should not be so cold as to condense ice on the blades. When a turbopump is stopped, the oil from the backing vacuum may backstream through the turbopump and contaminate the chamber. One way to prevent this is to introduce a laminar flow of nitrogen through the pump. The transition from vacuum to nitrogen and from a running to a still turbopump has to be synchronized precisely to avoid mechanical stress to the pump and overpressure at the exhaust. A thin membrane and a valve at the exhaust should be added to protect the turbopump from excessive back pressure (e.g. after a power failure or leaks in the backing vacuum).

The rotor is stabilized in all of its six degrees of freedom. One degree is governed by the electric motor. Minimally, this degree must be stabilized electronically (or by a diamagnetic material, which is too unstable to be used in a precision pump bearing). Another way (ignoring losses in magnetic cores at high frequencies) is to construct this bearing as an axis with a sphere at each end. These spheres are inside hollow static spheres. On the surface of each sphere is a checkerboard pattern of inwards and outwards going magnetic field lines. As the checkerboard pattern of the static spheres is rotated, the rotor rotates. In this construction no axis is made stable on the cost of making another axis unstable, but all axes are neutral and the electronic regulation is less stressed and will be more dynamically stable. Hall effect sensors can be used to sense the rotational position and the other degrees of freedom can be measured capacitively.

Maximum pressure



A turbomolecular pump made by Edwards with attached vacuum ionization gauge for pressure measurement.

At atmospheric pressure the mean free path of air is about 70 nm. Turbomolecular blades cannot be built with anything close to such a small clearance, so this type of pump stalls if exhausted directly to the atmosphere. Nonetheless Varian, Inc. since 2006 offers a pump where the last stages have blades optimized for zero flow and can pump against a pressure of one atmosphere. Because the low pressure stages are limiting the flow, the high pressure stages can be fixed to zero flow. Theoretically centrifugal pumps could be used, but it is more compact to use a circulating flow between hollow threads in the rotor

and the stator. In other cases the exhaust is connected to a backing pump, which produces a pressure low enough for the turbomolecular pump to work efficiently. Typically, this pressure must be below 10 Pa with 1-2 Pa as common averages.

The turbomolecular pump can be a very versatile pump. It can generate many degrees of vacuum from intermediate vacuum ($\sim 10^{-2}$ Pa) up to ultra-high vacuum levels ($\sim 10^{-8}$ Pa).

Multiple turbomolecular pumps in a lab or manufacturing-plant can be connected by tubes to a small backing pump. Automatic valves and diffusion pump like injection into a large buffer-tube in front of the backing pump prevents any overpressure from one pump to stall another pump.

Practical considerations



A turbopump by Pfeiffer attached to a thin film deposition system for organic electronics research

Laws of fluid dynamics do not apply in high vacuum environments. The maximum compression varies linearly with circumferential rotor speed. In order to obtain extremely low pressures down to 1 micropascal, rotation rates of 20,000 to 90,000 revolutions per minute are often necessary. Unfortunately, the compression ratio varies exponentially with the square root of the molecular weight of the gas. Thus, heavy molecules are pumped much more efficiently than light molecules. Most gases are heavy enough to be well pumped but it is difficult to pump hydrogen and helium efficiently.

An additional drawback stems from the high rotor speed of this type of pump: very high grade bearings are required, which increase the cost.

Because turbomolecular pumps only work in molecular flow conditions, a pure turbomolecular pump will require a very large backing pump to work effectively. Thus, many modern pumps have a molecular drag stage such as a Holweck or Gaede mechanism near the exhaust to reduce the size of backing pump required.

History

The turbomolecular pump was invented in 1958 by Becker, based on the older molecular drag pumps developed by Gaede in 1913, Holweck in 1923 and Siegbahn in 1944.