VACUUM

(There’s nothing to it…)

My background: semiconductor manufacturing equipment utilizing various levels of vacuum:

- No Vacuum:
  - APCVD (Atmospheric Pressure Chemical Vapor Deposition)
- Low Vacuum:
  - Oxygen Ashers / RF Plasma Etchers / LPCVD (Low Pressure Chemical Vapor Deposition) Diffusion Furnaces
- High Vacuum:
  - Ion Implanters
  - Aluminum Sputtering Systems
  - Gold Evaporators

Definitions of Vacuum

- Nothing at all?
    - No electromagnetic radiation?
    - No photons?
    - No gravity / gravitons?
    - No neutrinos?
    - No dark matter?
    - No space?
    - No time?
    - No properties?
        - Speed of light not constant?

Distortion and dragging of space by earth's gravity proved by…

…the Gravity Probe B spacecraft.

"Restoring the aether is not a completely silly point of view." Francis Everitt, Principal Investigator, Gravity Probe B experiment.

Definitions

- A perfect vacuum: or free space is a volume of space that is essentially empty of matter.
- Practical definition: A vacuum is a volume of space with less than a reference pressure.

Vacuum measurement

Sea level

= 1 atmosphere

= 1 Bar

= 1,000 milliBar (mb)

= 101.3 kPa

= 14.7 psi

= 33.9 ft H2O

= 29.92 in Hg

= 760 mm Hg

= 760 Torr (named after Evangelista Torricelli, inventor of the mercury barometer)

Going down:

- Low vacuum: 760 Torr to 1 x 10^{-3} Torr
  - Vacuum cleaner: to 600 Torr
  - Thermos bottle 10^{-3} Torr
- High vacuum: 10^{-3} to 10^{-9} Torr
  - Electron microscope
  - Ion Implanter
  - Evaporator
  - Sputterer
- Ultra high vacuum: 10^{-9} to 10^{-12} Torr
  - CERN LHC: 1 x 10^{-10} Torr
  - Moon's surface: 1 x 10^{-11} Torr
- Deep Space 1 x 10^{-17} Torr = 0.000,000,000,000,000,01 Torr


EVANGELISTA TORRICELLI

Evangelista Torricelli

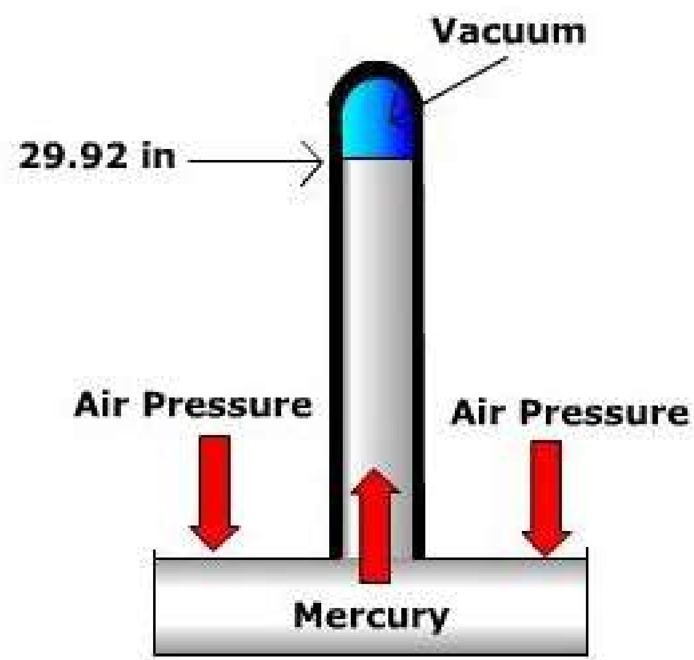
- Torricelli's chief invention was the mercury barometer, which arose from solving a practical problem. Pump makers of the Grand Duke of Tuscany attempted to raise water to a height of 12 meters or more, but found that 10 meters was the limit with a suction pump. Torricelli employed mercury, fourteen times heavier than water. In 1643 he created a tube approximately one meter long, sealed at the top, filled it with mercury, and set it vertically into a basin of mercury. The column of mercury fell to about 76 cm, leaving a Torricellian vacuum above. As we now know, the column's height fluctuated with changing atmospheric pressure; this was the first barometer. This discovery perpetuated his fame, and the Torr, a unit used in vacuum measurements, has been named for him.

Mercury Barometer No More!

By Martin Banks in Brussels, and George Jones 06 Jun 2007

- Britain's traditional barometer makers and restorers were facing closure last night after the European Parliament voted to uphold a ban on the use of mercury. The decision effectively consigns more than 350 years of unique British tradition and craft to history.

- After a two-year phase-out period, production of thermometers and barometers containing mercury will be banned, ostensibly to prevent the toxic metal entering the food chain.



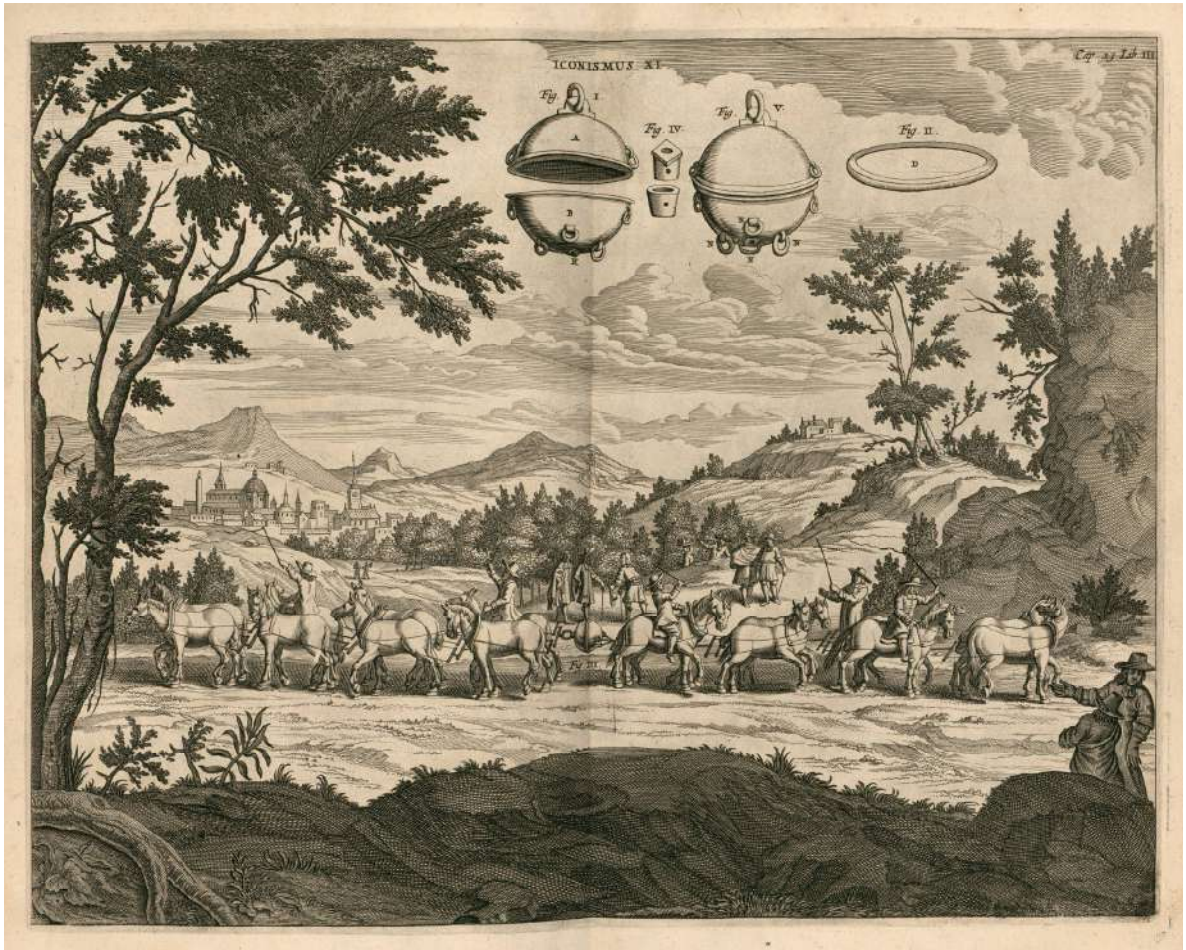
Otto von Guericke

- **Born** November 20, 1602
  Magdeburg, Germany
- **Died** May 11, 1686 (aged 83)
  Hamburg, Germany
- **Fields** Physicist, Politician
- **Known for** Research and experiment for vacuums

Otto von Guericke

- In 1650 he invented a vacuum pump consisting of a piston and an air gun cylinder with two-way flaps designed to pull air out of whatever vessel it was connected to, and used it to investigate the properties of the vacuum in many experiments. Guericke demonstrated the force of air pressure with dramatic experiments. He had joined two copper hemispheres of 51 cm diameter (Magdeburg hemispheres) and pumped the air out of the enclosure. Then he harnessed a team of eight horses to each hemisphere and showed that they were not able to separate the hemispheres. When air was again let into the enclosure, they were easily separated. He repeated this demonstration in 1663 at the court of Friedrich Wilhelm I of Brandenburg in Berlin, using 24 horses.
- With his experiments Guericke disproved the hypothesis of "horror vacui", that nature abhors a vacuum, which for centuries was a problem for philosophers and scientists. Guericke proved that substances were not pulled by a vacuum, but were pushed by the pressure of the surrounding fluids.
- Other research: Guericke applied the barometer to weather prediction and thus prepared the way for meteorology.

Magdeburg Hemispheres



Uses of Vacuum

- incandescent light bulb
- electron beam welding
- cold welding
- vacuum packing
- vacuum frying
- To study atomically clean substrates
- Semiconductors: particle beams and low pressure gases deposit or remove materials
  - vapor deposition
  - ion implantation
  - sputtering
  - dry etching
  - ashing (cleaning)
- optical coatings
- surface science
- thermos bottles
- Lowers the boiling point of liquids and promotes low temperature outgassing
  - freeze drying
  - adhesive preparation
  - distillation
  - metallurgy
  - process purging
- Electrical properties
  - electron microscopes
  - vacuum tubes
  - cathode ray tubes
- Elimination of air friction
  - flywheel energy storage
  - ultracentrifuges

Outer Space

- The Kármán line at an altitude of 62 miles (100 km), is considered Earth's approximate boundary with outer space, where the pressure = 1 Pa (1 x 10^{-3} Torr).
  - Above this altitude pressure, temperature, and composition vary greatly due to space weather.

- However, the atmospheric density within the first few hundred kilometers above the Kármán line is still sufficient to produce significant drag on satellites.
  - At sea level there are 10^{19} molecules per cm^3.
  - At the Kármán line there are 10^{14} molecules per cm^3.

Safety

- Pressure of 14.7 psi x 100 sq. in. = 1,470 pounds of force on a 10 inch x 10 inch surface.
- Implosion and rebound
- Glass vessels (CRT’s)

Effects of Vacuum

- No atmospheric drag or pressure.
- No interference with desired electron or ion beams, evaporated or sputtered metals, or desirable charged particles.
- Purity and economy: only the desired substrate and reactant(s). (Example: metallization of telescope mirrors with aluminum.)
    - Uniform, angstroms-thick coatings
    - Unique chemistries are possible
        - SiO_2 deposition on Aluminum
    - No unwanted reaction(s) with atmospheric gasses and contaminants. (O_2, N_2, H_2O, CO_2, NO, SO_2, NH_3 etc.)
- However, vacuum facilitates OUTGASSING.

Effects cont'd

- Isolation from ambient surroundings / control of hazardous byproducts (with scrubbed exhaust, treated exhaust, or dilution).

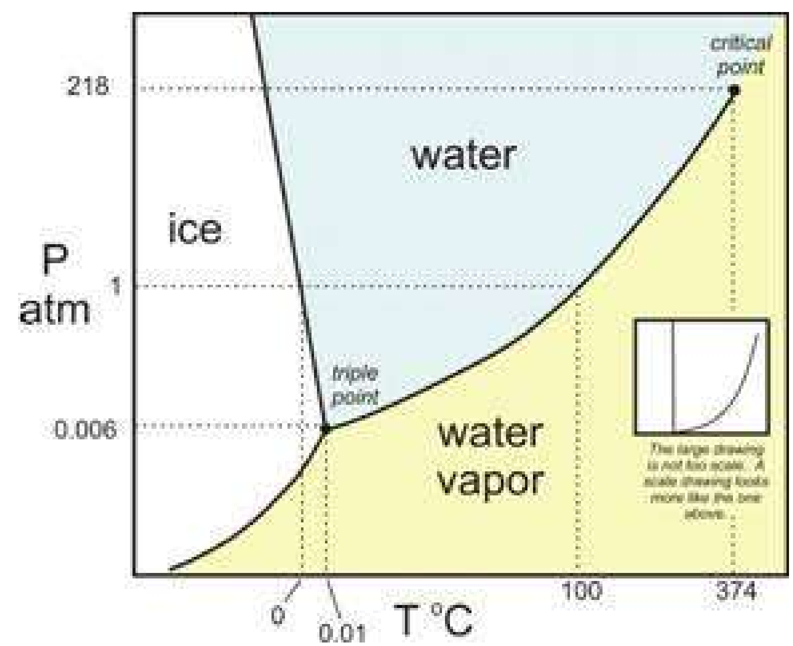
  Examples: hazardous substances used in vacuum equipment in semiconductor manufacturing--

  - Arsenic (solid or Arsine gas) (deadly poisons)
  - Phosphorous (solid or Phosphine gas) (deadly poisons)
  - Boron (di-Borane or Boron tri-fluoride gases) (deadly poisons)
  - Silane (SiH_4) (pyrophoric gas)
  - Hydrogen Fluoride gas (deadly poison)

- Phases (solid-liquid-gas) change at different temperatures as pressure decreases.

Water Phase Diagram

- 1 atm = 760 mm Hg (760 Torr)
- .006 atm x 760 Torr / atm = 4.56 Torr. This vacuum can be achieved with a mechanical (piston or rotary vane) roughing pump. Below this pressure foods can be “freeze-dried” by sublimation.



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.

Vapor Pressure

- **Vapor pressure** or **equilibrium vapor pressure** is the pressure of a vapor in thermodynamic equilibrium with its condensed phases in a closed system. All liquids have a tendency to evaporate, and some solids can sublimate into a gaseous form. Vice versa, all gases have a tendency to condense back to their liquid form, or deposit back to solid form.
- The equilibrium vapor pressure is an indication of a liquid's evaporation rate. It relates to the tendency of particles to escape from the liquid (or a solid). A substance with a high vapor pressure at normal temperatures is often referred to as *volatile*.
- The vapor pressure of any substance increases non-linearly with temperature according to the Clausius–Clapeyron relation. The atmospheric pressure boiling point of a liquid (also known as the normal boiling point) is the temperature at which the vapor pressure equals the ambient atmospheric pressure. With any incremental increase in that temperature, the vapor pressure becomes sufficient to overcome atmospheric pressure and lift the liquid to form vapor bubbles inside the bulk of the substance. Bubble formation deeper in the liquid requires a higher pressure, and therefore higher temperature, because the fluid pressure increases above the atmospheric pressure as the depth increases.
- The vapor pressure that a single component in a mixture contributes to the total pressure in the system is called partial vapor pressure. For example, air at sea level, saturated with water vapor at 20 ℃ has a partial pressures of 24 mbar of water, and about 780 mbar of nitrogen, 210 mbar of oxygen and 9 mbar of argon.

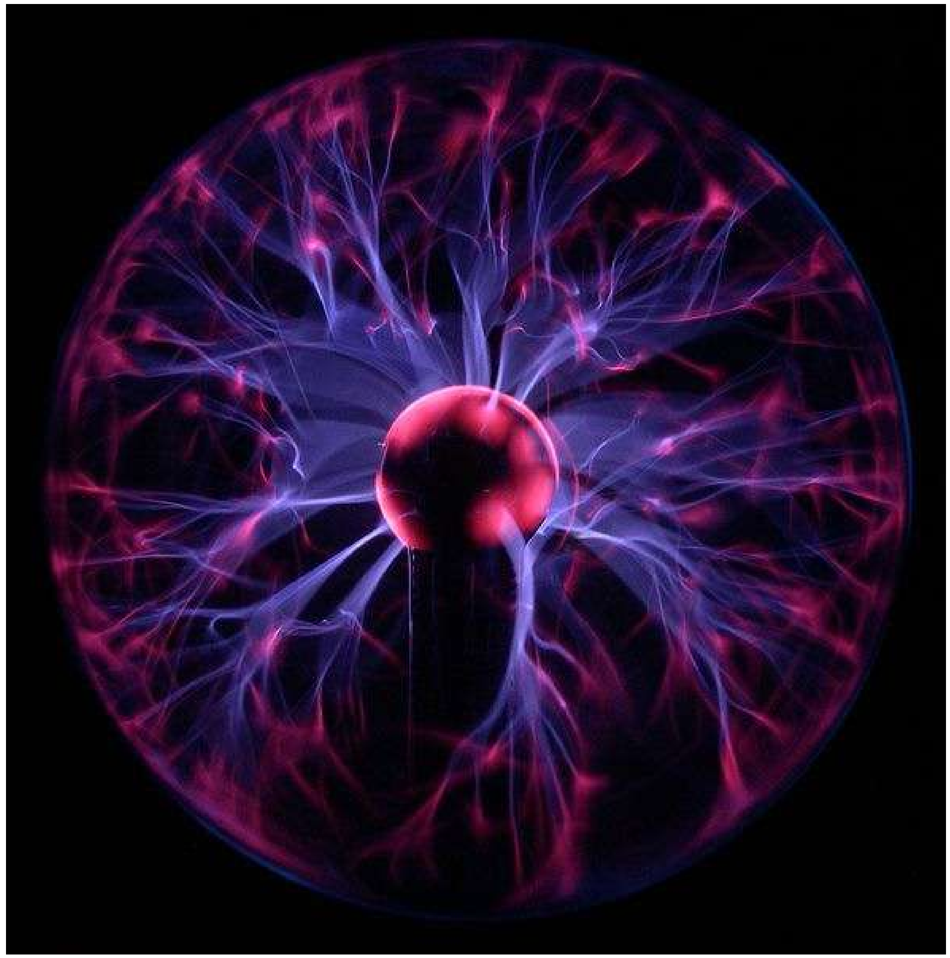
Low vapor pressure greases for use in vacuum environments:

Excellent for o-rings!

KF flange o-ring seal for rough and high vacuums.

- Copper conflat flange metal-to-metal seal for high and ultra-high (“research-grade”) vacuums.

Plasma



And Plasma: the fourth state of matter

- Low pressure facilitates the creation of gas plasmas = ionized gas = gas with free electrons in order to:

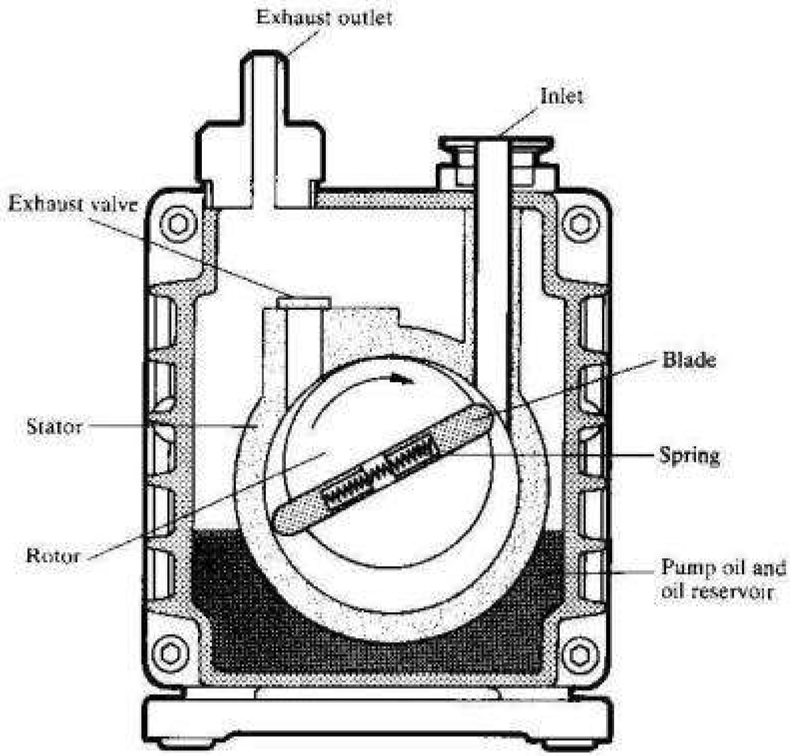
  - Enhance chemical reactions:
    - RF plasma etching
    - Ashing (rapid oxidization)

  - Sputtering:
    - high voltage accelerates an ionized heavy gas molecule
      - » like Argon, AMU 40, into a target material
      - » like Aluminum, AMU 27
    - resulting in momentum transfer, which deposits
    - atomic aluminum AT ROOM TEMPERATURE
    - on almost anything!

Space thermal simulation vacuum chamber (high vacuum)

- Cryopump →
- Rotary Vane roughing pump →

Rotary vane roughing pump (low vacuum)

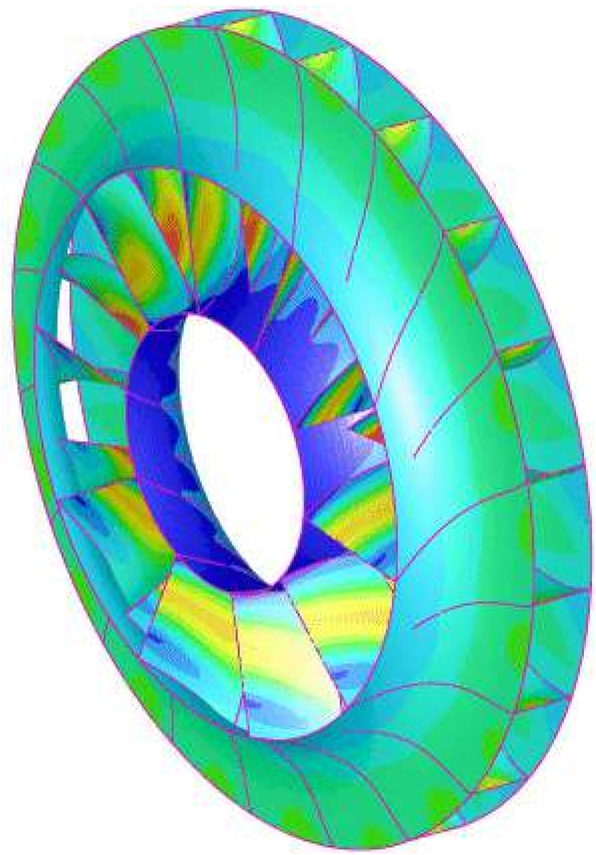


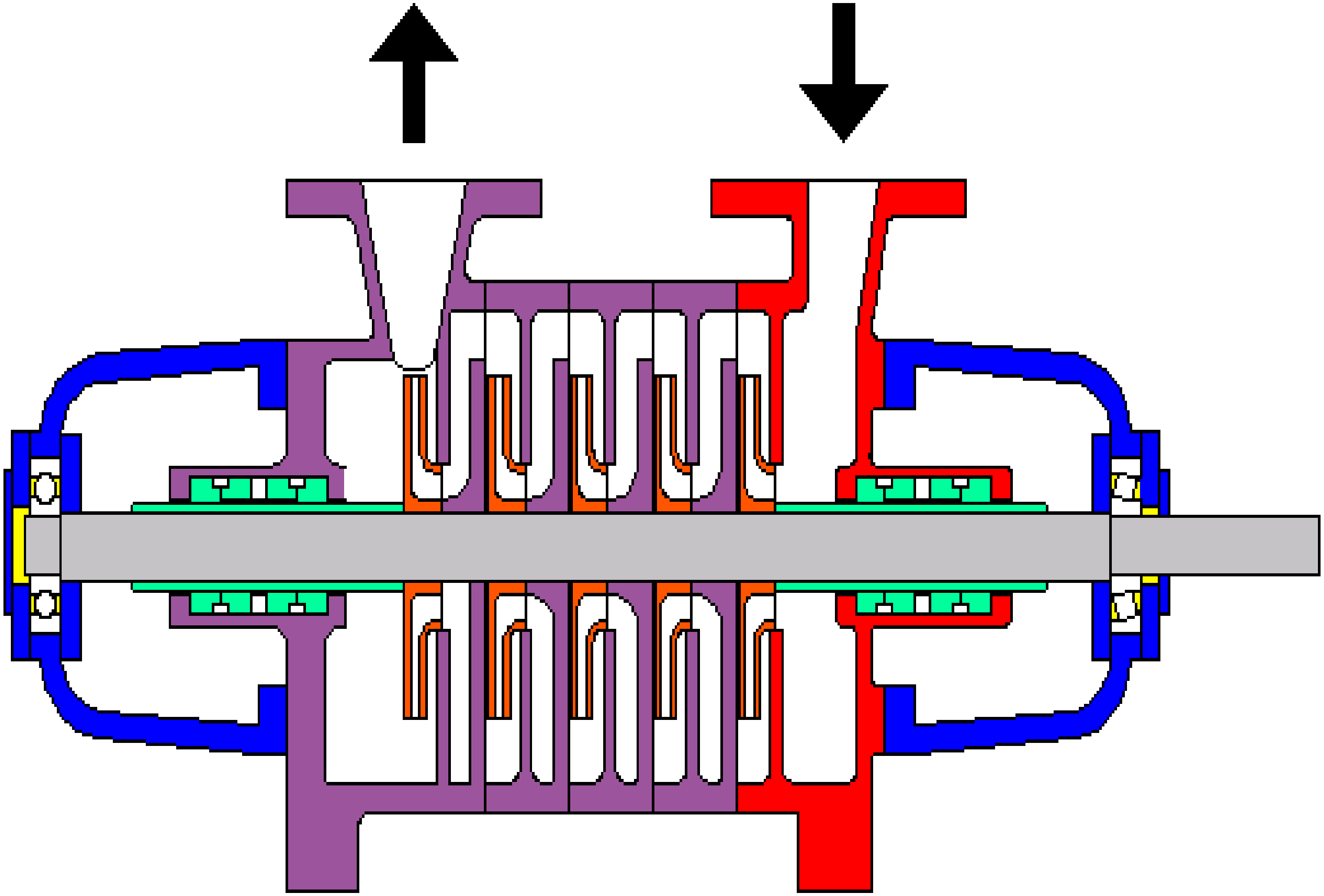
2XZ-2

Massaponax (car wash next to WAWA)

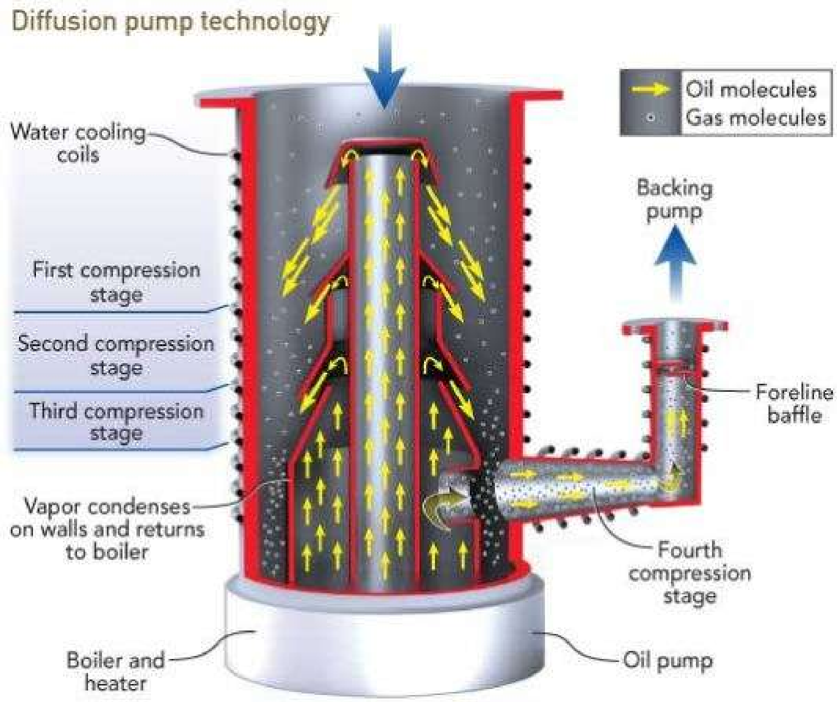
- Car Wash vacuum system:
  - 20 hp, 3 phase, continuous duty electric motors
  - pump / compressor
    - air-cooled
    - multi-stage turbine
    - with cast-aluminum ½ in turbine heads
    - and backward curved impellers
    - 350 Torr (guestimated)
  - 12-gauge steel separators

Radial flow turbine with curved impellers





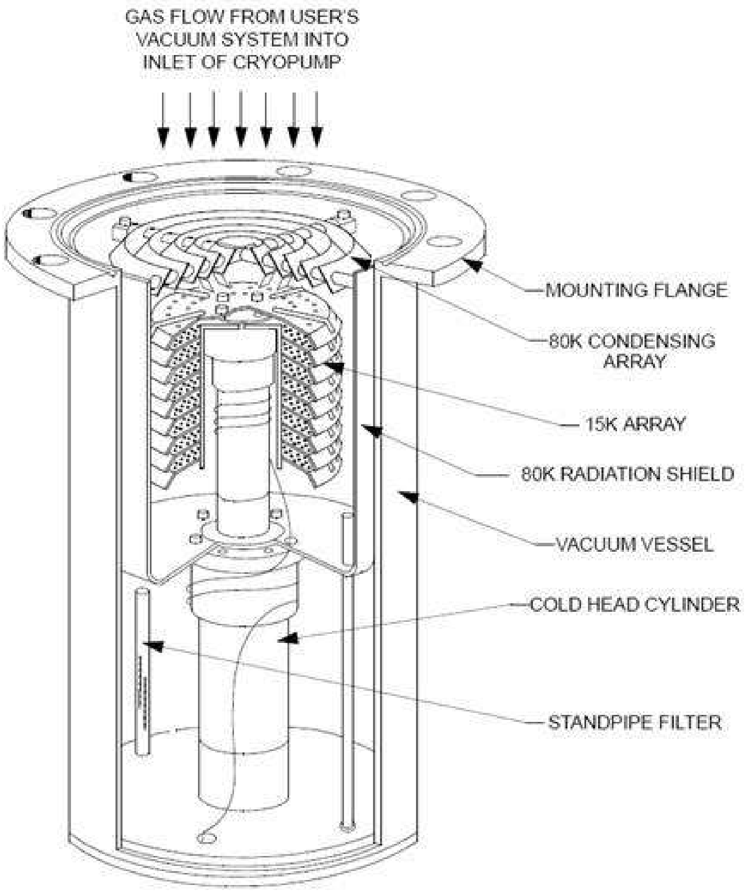
Diffusion pump (high vacuum)



Turbomolecular pump (high vacuum)

- Vacuum chamber flange →
- Turbine blades →
- Roughing port → (for hose to roughing pump)

Cryopump (high vacuum)



Telescope Mirrors

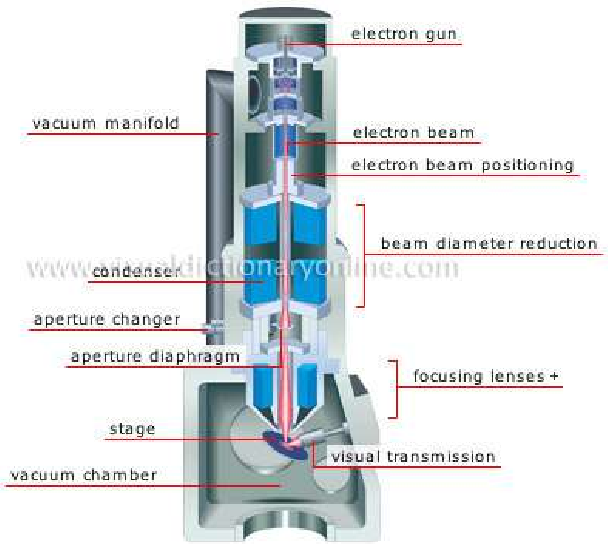
- *Front silvered* or first surface mirrors eliminate the additional reflection from the air / glass interface.
- Aluminium is more reflective than silver at short wavelengths.
- Aluminum reflects 90% to 95% of the incident light when new.
- Applied by vacuum deposition.
- A very thin SiO_2 (quartz) overcoat is usually applied before the mirror is removed from the vacuum to retard corrosion from oxygen and humidity in the air.

E-Beam Evaporator (high vacuum)

- **CHA SEC-1000-RAPDescription:** Dual Gun E-Beam Evaporator.
  Two single pocket e-guns with individual power and sweep control.
  Inficon IC4 Plus deposition rate monitor.
  Temescal CV-8 E-beam power supply.
  Auto-Tech II valve controller.
  Single substrate carrier with rotation control. 25.5 in. diameter water cooled stainless steel bell jar.
  CTI cryopump with compressor and roughing pump.**Inventory Number: 55643Price:$75,000**

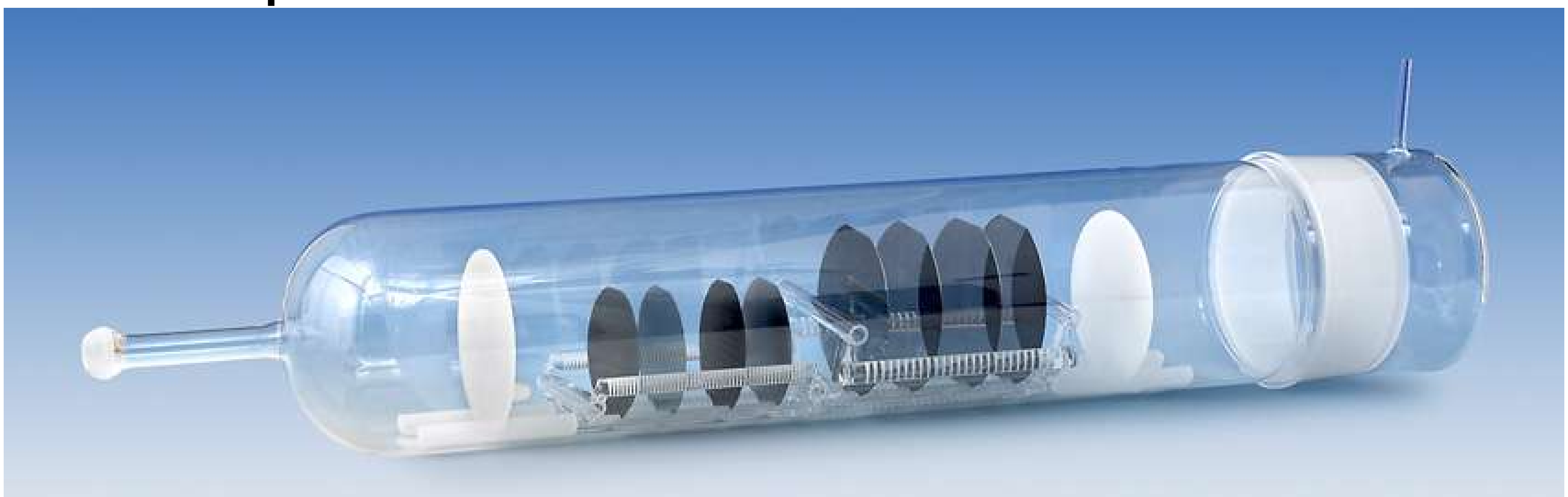
Ion Implanter (high vacuum)

Electron Microscope (high vacuum)



Diffusion Furnace Quartz Tube (Vacuum Chamber) with Si Wafers

- And quartz “baffle wafers” at both ends.



World's Largest Vacuum Chamber

- The Space Power Facility at NASA Glenn Research Center's Plum Brook Station in Sandusky, Ohio, houses the world's largest vacuum chamber. It measures 100 feet in diameter and is a towering 122 feet tall.

NASA Space Power Facility
Sandusky, Ohio

World’s largest vacuum chamber

VLA Receiver
Helium Cryopump Cold Head

VLA S-Band Detector Assembly

VLA Detector Vacuum Manifold with flange o-ring seal, manual vent valve, solenoid roughing valve, thermocouple vacuum gauge, and KF flange connection to roughing line.