Design, and Construction of a High-Altitude Test Chamber

Clay Rumsey, Ian Cox, John E. Sohl, Weber State University, Department of Physics

Abstract:

Behavior of equipment when flown to the edge of space can vary dramatically from what is observed on the ground, so we set out to build a facility we could use to simulate the pressure extremes experienced in such a flight.

Our goals were to design and build a portable system with a large and easy-to-access chamber that could reach high vacuum pressure, using both a mechanical and diffusion pump. We wanted to use primarily surplus and hand-made parts, using as few purchased parts as possible. We also wanted to build a system that could obtain significantly higher vacuum levels than needed for flight testing so that it could also be used for semiconductor and other material science research.

There are a wide variety of issues that can cause problems in a system this highly sensitive. There are several strategies used to avoid, detect, and solve these problems. We successfully constructed a system that has been, and will continue to be, used in a wide variety of other student research projects.

Defining Vacuum

Class	Pressure (Torr)	Fraction of STP
Rough Vacuum	750 – .75	1/1,000
Medium Vacuum	.75 – 7.5×10^{-3}	1/100,000
High Vacuum	7.5×10^{-3} – 7.5×10^{-7}	1/100,000,000
Ultra High Vacuum	7.5×10^{-7} – 7.5×10^{-14}	1/10 quadrillionth

STP – 1.0 atm. = 1.01×10^{5} Pa = 1.01 bar = 760 Torr

Deep Space ranges between 10^{6} to 10^{17} Torr.
High-Altitude Research Balloons range between 760 to 0.8 Torr.

Particles in a Vacuum

- Air ≈ 78% Nitrogen, 21% Oxygen
  10^{19} molecules per cubic cm
- Rough Vacuum = 10^{2} to 10^{-2} Torr
  10^{15} molecules per cubic cm
- High Vacuum = 10^{-2} to 10^{-8} Torr
  10^{9} molecules per cubic cm

Chemical Makeup of Air

N_2	78.08 %
O_2	20.95 %
Ar	.93 %
CO_2	.033 %
Ne	1.8×10^{-3} %
He	5.24×10^{-4} %
CH_4	2.02×10^{-4} %
Kr	1.1×10^{-4} %
H_2	5.0×10^{-5} %
N_2O	5.0×10^{-5} %
Xe	8.7×10^{-5} %
O	7.0×10^{-6} %
H_2O	1.57 %

Note: If molecules were to stick to a surface, using kinetic theory of a gas, at10^{-6} Torr it takes 1 second to cover a surface with contaminating gas… it would take 100 seconds at 10^{-8} Torr.

Mean Free Path

$$\ell = \frac{1}{\sqrt{2}PN\,d^2}$$

When the mean free path is large, normal fluid dynamics breaks down. This changes the Pumping behavior of a gas.

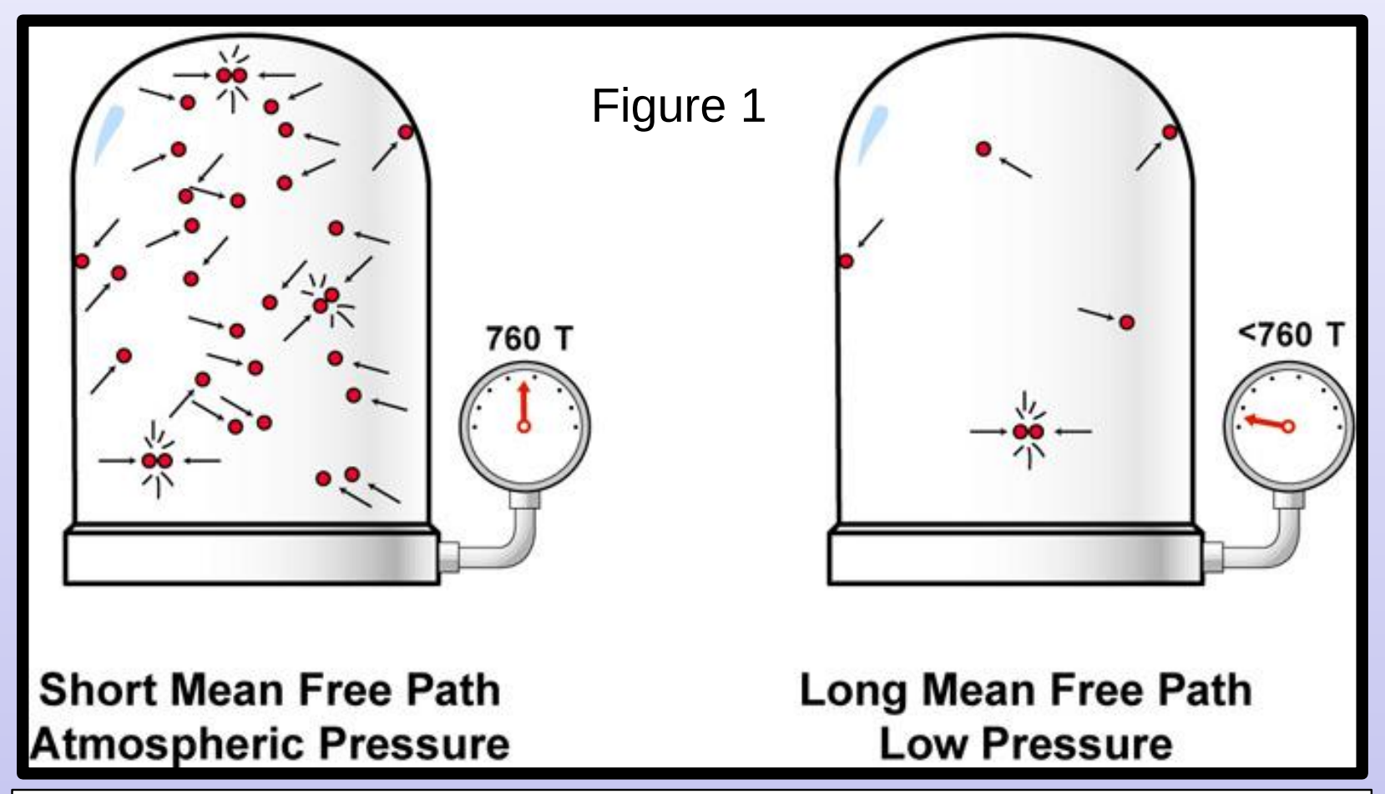


Figure 1

Figure 1. The mean free path is the average distance between collisions of one particle with another particle.

Ideal Gas Law

$$P = \frac{nRT}{V}$$

In a vacuum chamber, pressure change is a change in the number of particles in the system.

- Assume particles have no volume
- Assume no intermolecular forces

Kinetic Theory is another important concept in a vacuum chamber when mean-free-path is relatively long. Kinetic Theory of Gas assumes: Matter is made of particles of identical size, mass, and shape, the size of the particle is negligible, and the only interactions are collisions, which are perfectly elastic.

Figure 2

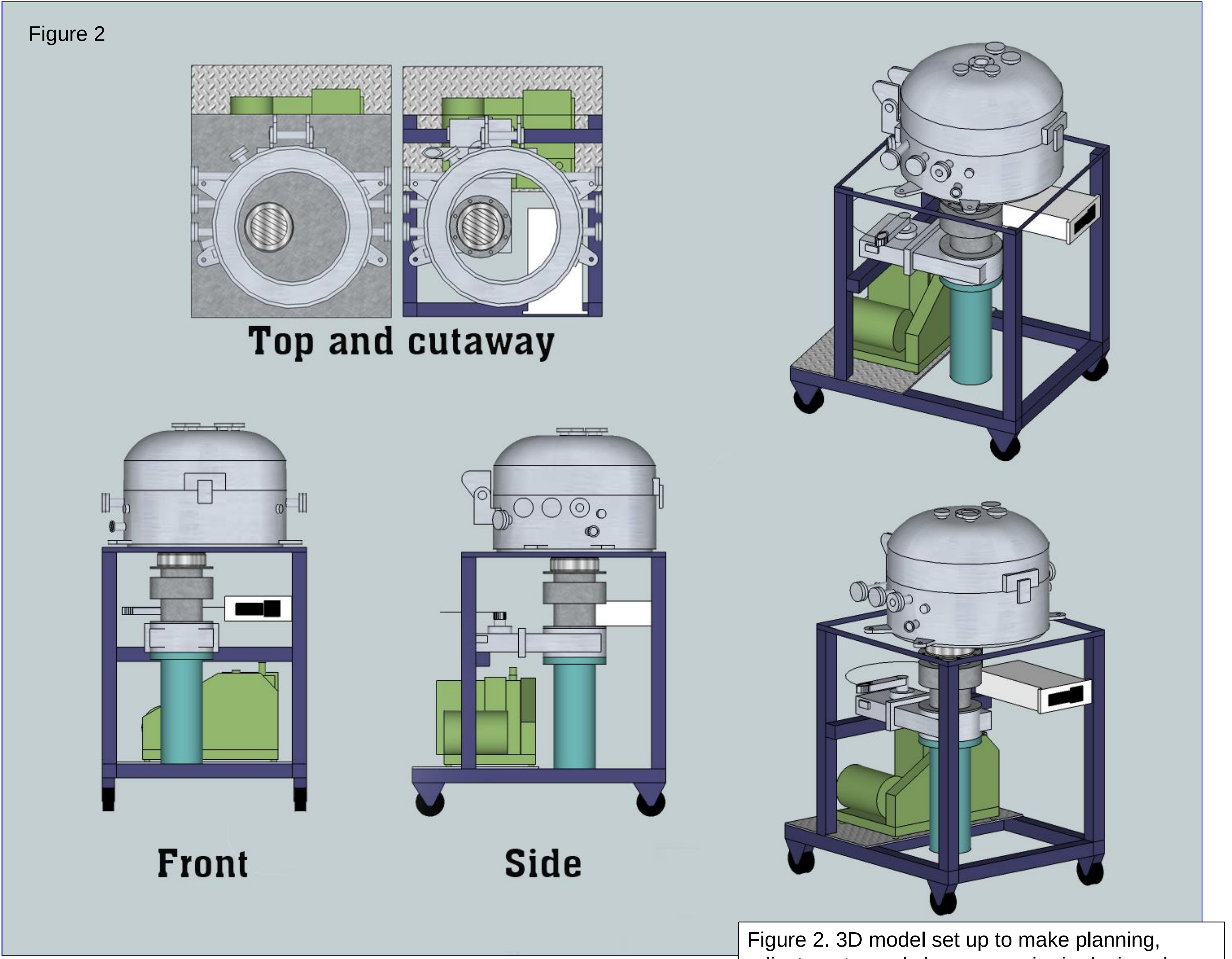


Figure 2. 3D model set up to make planning, adjustments, and changes easier in design phase.
Figure 3: finished vacuum system


Figure 3

System Mechanics

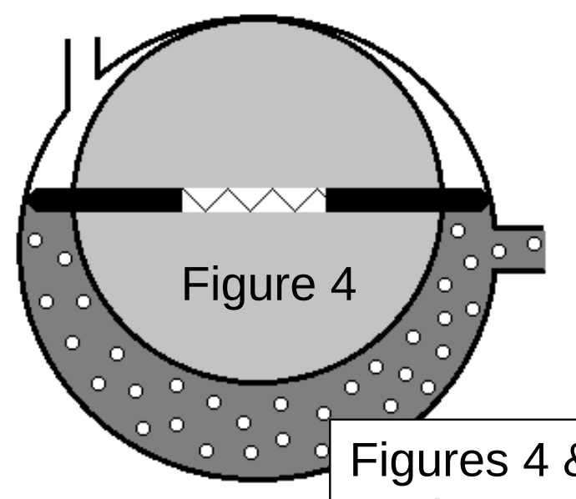


Figure 4

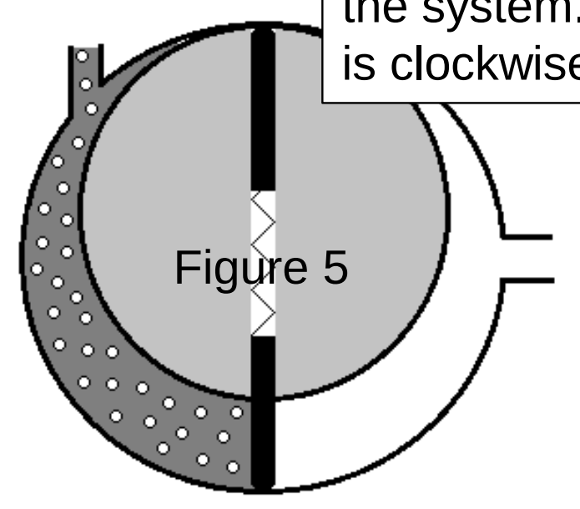


Figure 5

Figures 4 & 5. Vanes are in a constant state of pumping gas out of the system. (Rotation is clockwise.)

Rotary Vane Pump

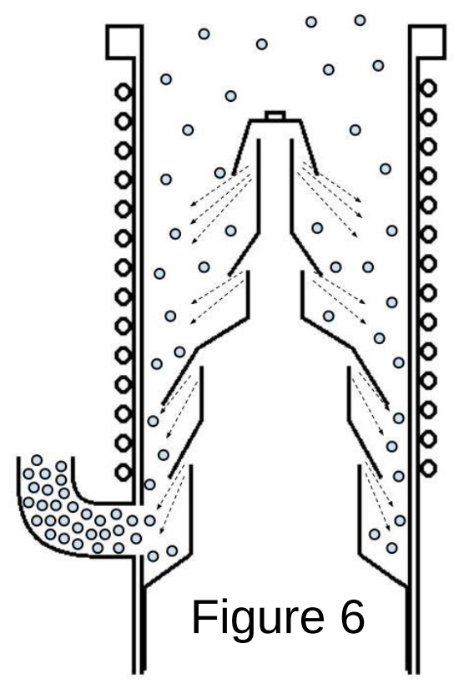


Figure 6

Diffusion Pump

Figure 6. A diffusion pump creates a pressure difference within the pump using vaporized oil to force gas particles to the bottom where they are drawn out by the mechanical roughing pump.

Diffusion Pump Oil

- The oil must have a high molecular weight, low reactivity, and low vapor pressure BP~230-270 degrees C.
- Oil Vapor droplets are moving at supersonic speed
- Back-stream into the system.


Figure 8

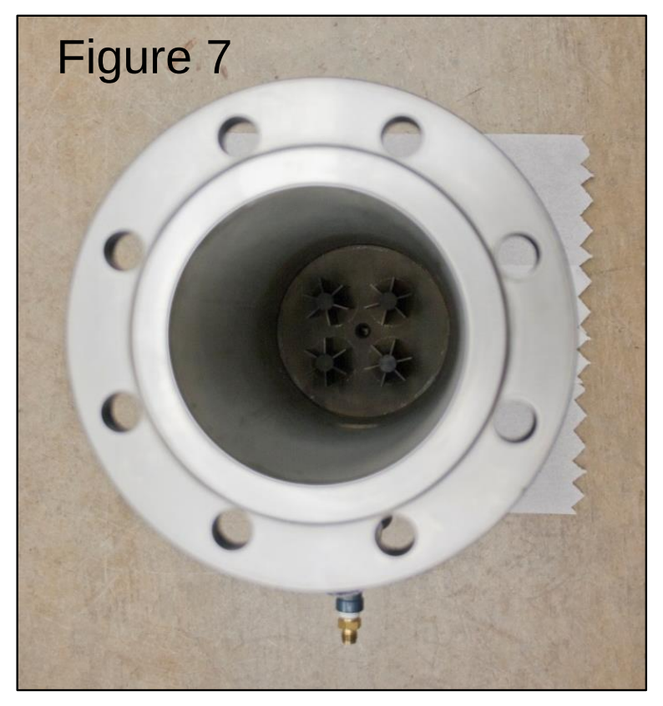


Figure 7

Figure 7. Diffusion pump with Christmas Tree removed.
Figure 8. Christmas Tree


Figure 9

Figure 9.Cold traps to prevent back-streaming of oil into the system.

Oil Comparisons

Motor oil - Vapor Pressure = 0.88 Torr
besides the VP, motor oil contains many contaminants hydrocarbons – alkanes, additives, corrosion control compounds, etc.)
$6 for 1 liter

Mechanical pump oil – VP = 10^{-6} Torr
$65 for 1 gallon

Our Diffusion pump oil
– VP = 6.65×10^{-8} Torr (max vacuum = 3.99×10^{-7})
$125 for 500cc

Diffusion pump oil – VP = 6.65×10^{-10} Torr
$890 for 500cc
$6,365 for 1 gallon

Virtual Leaks

A virtual leak behaves like a normal leak to the system, but there are no leaks to outside air. Virtual leaks can be very difficult to detect. Sources include:

- Bolt holes
- Finger prints
- Equipment outgassing
- Water vapor

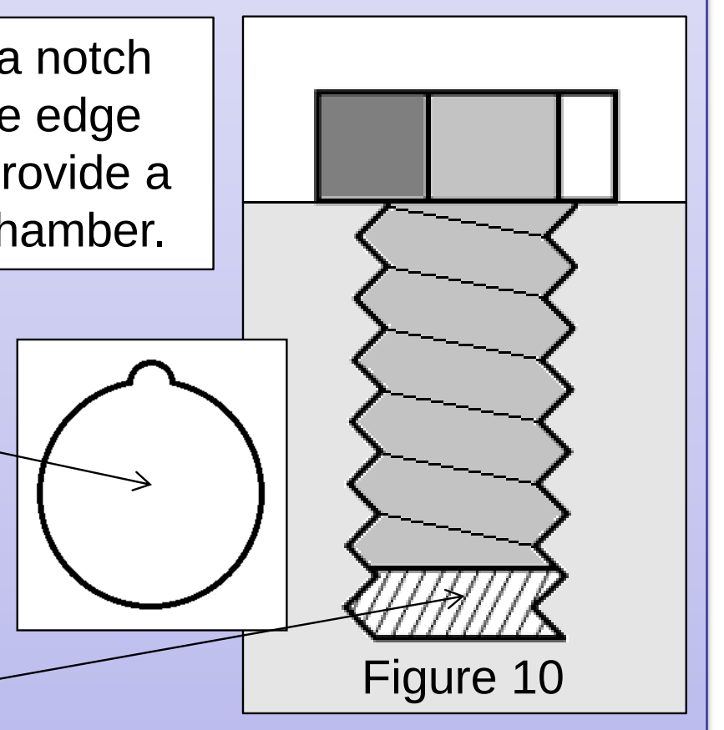


Figure 10. Showing a notch that was drilled at the edge of the bolt holes to provide a path for gas to the chamber.
Top view of bolt hole.
Trapped Air
Figure 10

A 1/16th inch gap in the bottom of a 1/4 inch hole contains ≈0.6 Torr·liters of gas (equivalent to 6×10^{-3} Torr in a 100 liter chamber).

A single fingerprint can outgas 10^{-5} Torr·liters/sec.

Measuring Vacuum

Analog Gauge

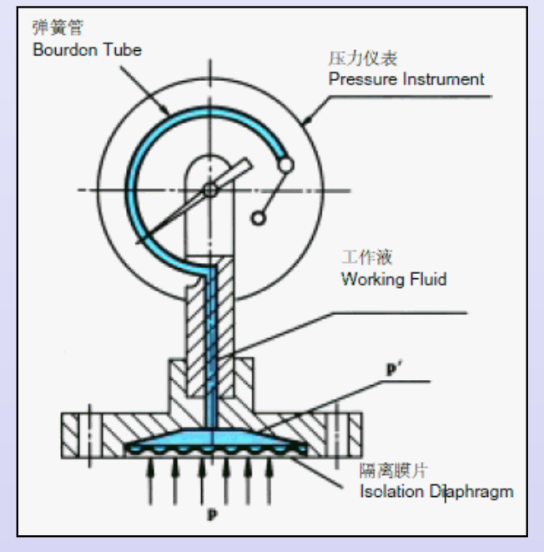
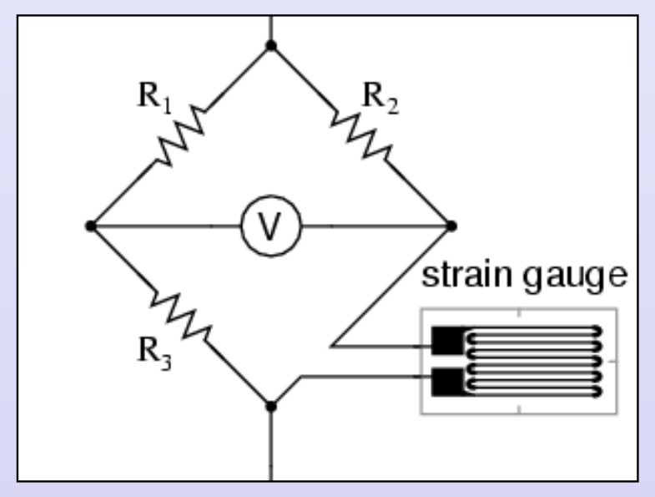


Figure 11. Analog pressure gauges (diaphragm) are sensitive to pressure which bows the material. They measure gauge pressure and work at rough vacuum ranges.

Strain Gauge



$$R = \rho\frac{L}{A}$$

$$V = IR$$

Figure 12. A strain gauge measures current through a set of resistors. When the material is stretched the length increases while the cross sectional area reduces. This increases the resistance of the material which will change the voltage drop across the center.

Thermocouple gauge

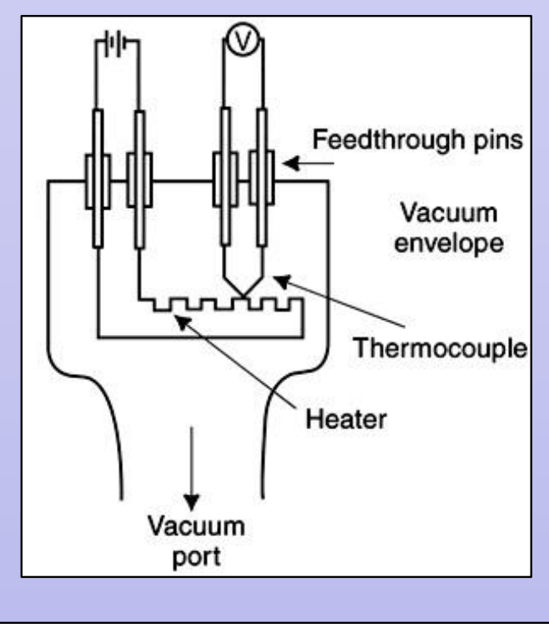


Figure 12. Thermocouple gauges operate on the principal of thermal conductivity. In lower pressures there are fewer molecules to absorb thermal energy. Temperature is measured and calibrated to read pressure as a product of molecular density. Thermocouple gauges operate in higher medium vacuum ranges.

Ion Gauge

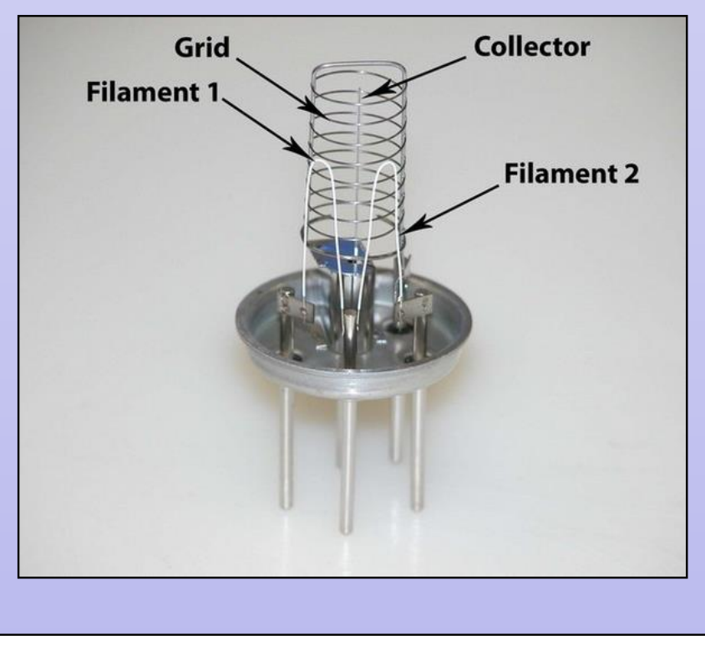


Figure 14. An ion gauge has a filament that gets hot enough to release electrons that ionize the gas molecules. The gas molecules are then attracted to the cathode where they become neutralized and create a current. The current will decrease as molecular density decreases. Ion gauges can measure high to ultra high vacuum ranges.

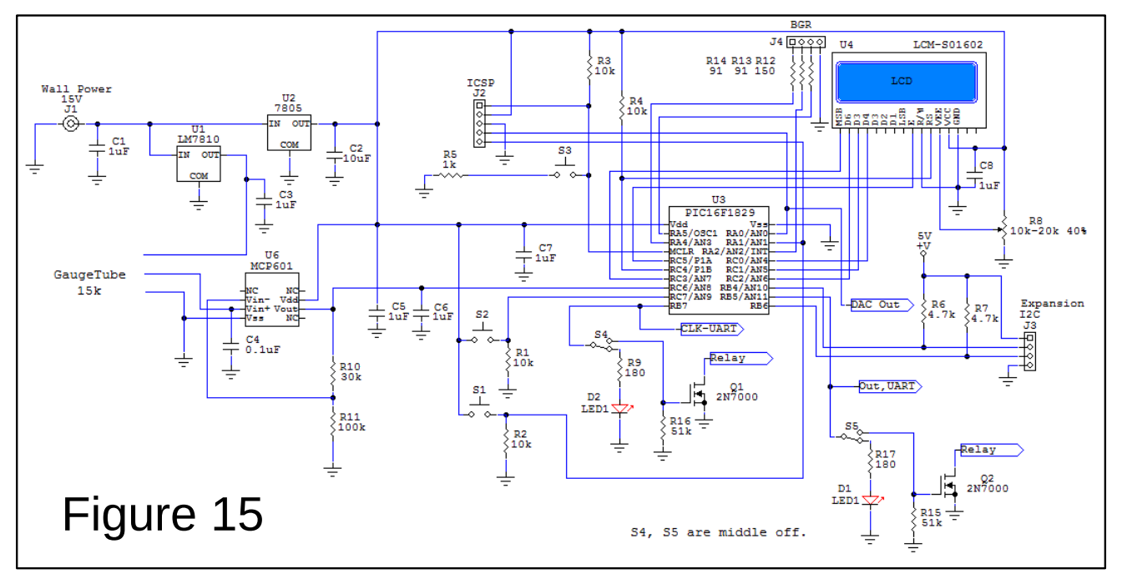


Figure 15

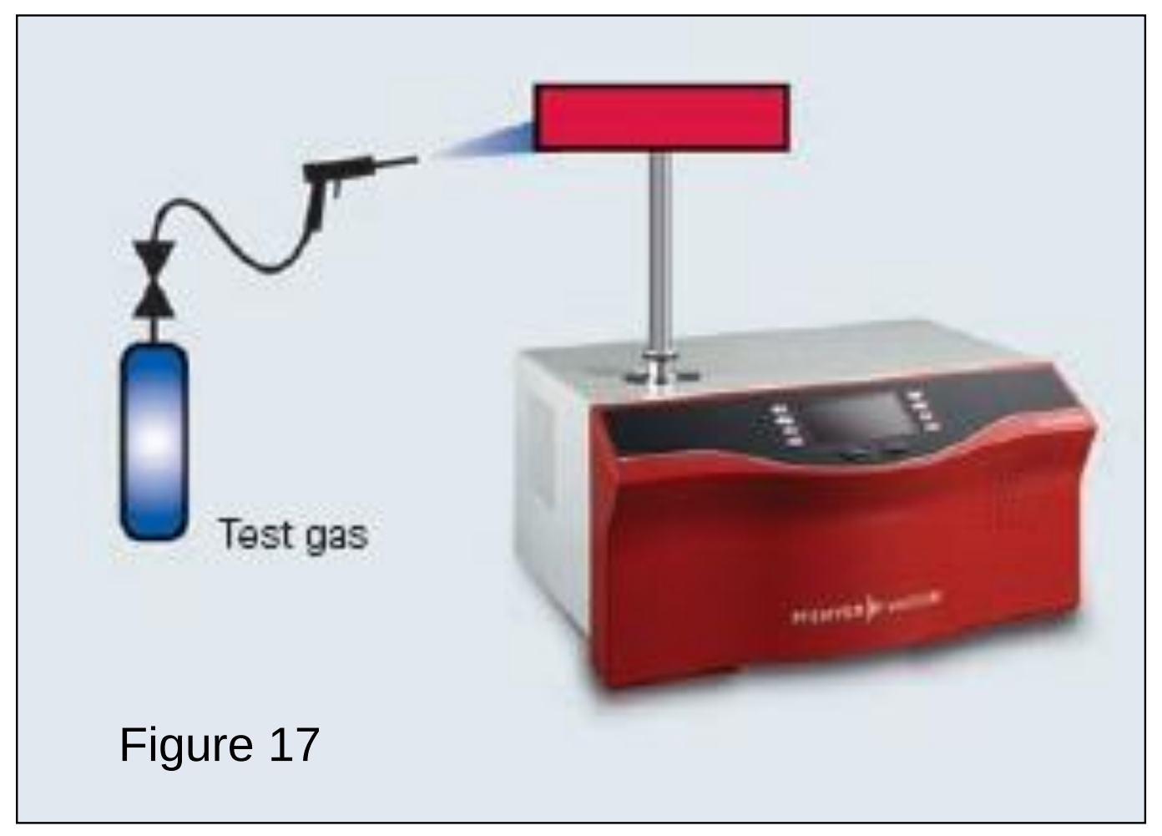


Figure 17

Figure 15. Circuit layout designed for building an electronic readout for calibrated strain gauge.
Figure 16. Calibration of strain-gauge at 10V.

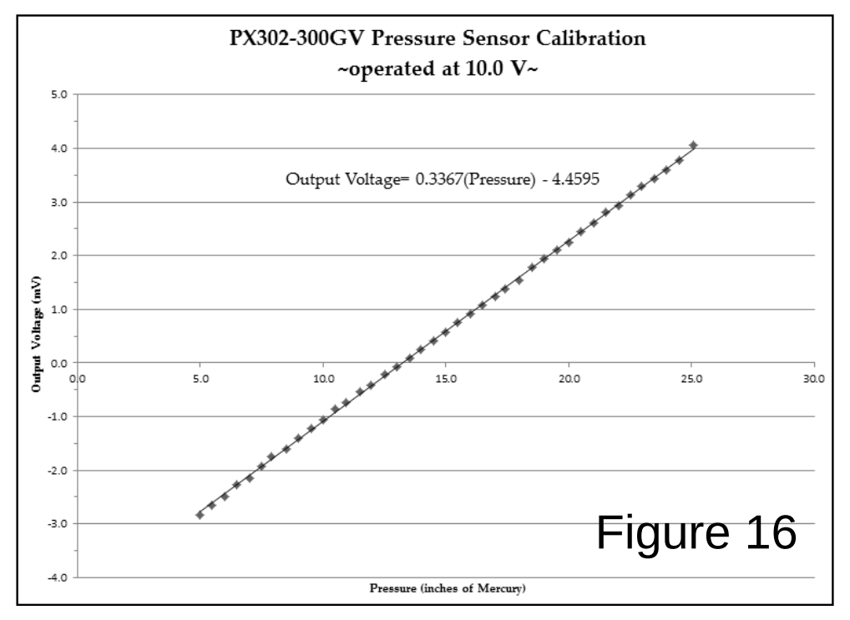


Figure 16

Figure 17. External leak detection is done by spraying helium on parts of the system where a leak is possible or suspected. A leak detector is a vacuum system equipped with a spectrometer that is capable of detecting trace amounts of helium.

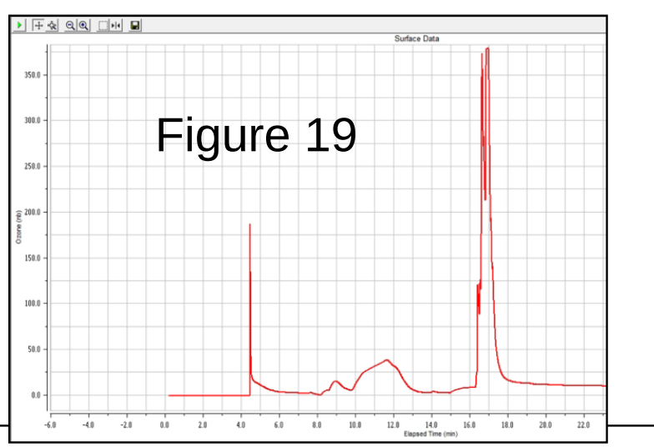


Figure 19

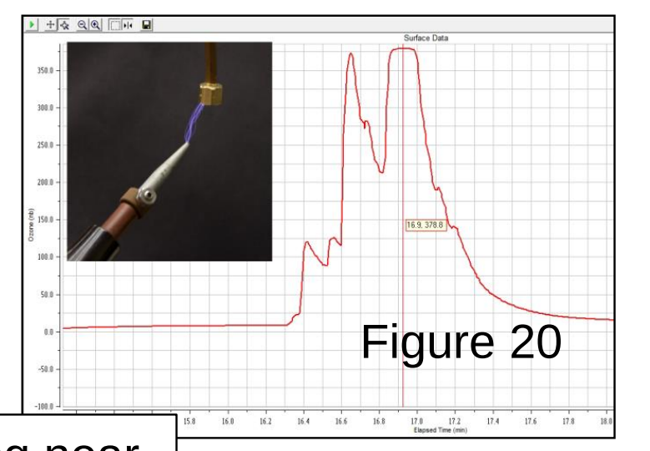


Figure 20

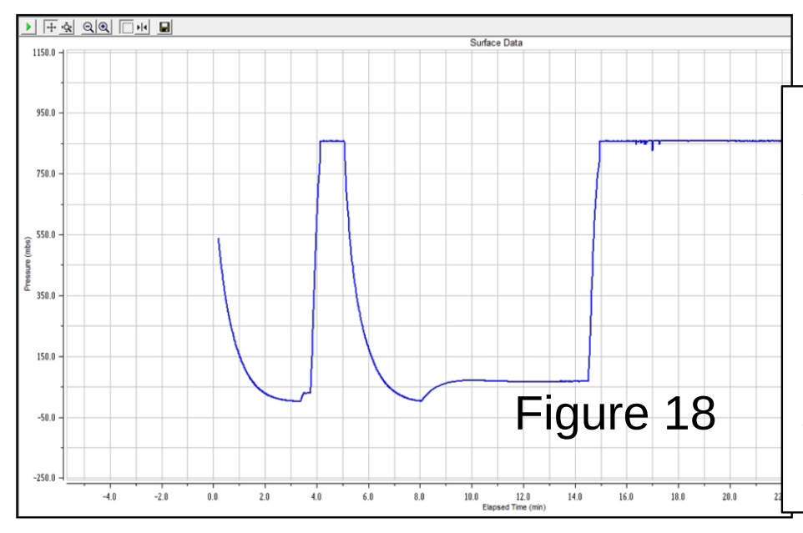


Figure 18

Figure 18. Graph of pressure during near-space flight test of ozonesonde in chamber.
Figures 19 & 20: Graph and zoom of ozone vs. time during test. Inset photo showing a Tesla coil used to generate O_3 near controlled leak valve.

Acknowledgements:
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