The US Particle Accelerator School
Vacuum Testing and Leak Detection

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Measuring the speed of a pump

There are four common methods of measuring the speed of pumps:

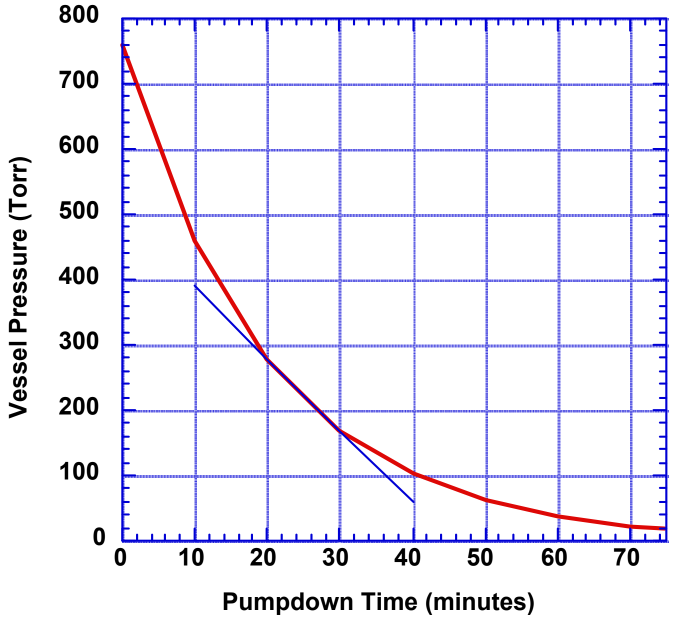
1. Rate of Pumpdown method
2. Single Gauge Dome method
3. Three Gauge Dome method
4. Fischer - Mommsen Dome method

Rate of Pumpdown Method

- Measure the rate in which a pump evacuates a vessel
- This method is normally used to measure the speed of roughing pumps

$$Q = \frac{d(VP)}{dt} = P\frac{dV}{dt} = V\frac{dP(t)}{dt}$$

$$Q = V\frac{dP(t)}{dt}$$



Rate of Pumpdown Method (continued)

Since $C_t >> S$, $P \sim P_{pump}$:

$$Q_v \sim SP(t)$$

$$S = S_{max}\left(1 - \frac{P_B}{P}\right)$$

$$S_{max}\left(1 - \frac{P_B}{P}\right)P(t) = V\,\frac{dP(t)}{dt}$$

Solving for P(t),

$$P(t) = P_B + P_o e^{-\left(\frac{S}{V}\right)t}$$

Single Gauge Dome Method

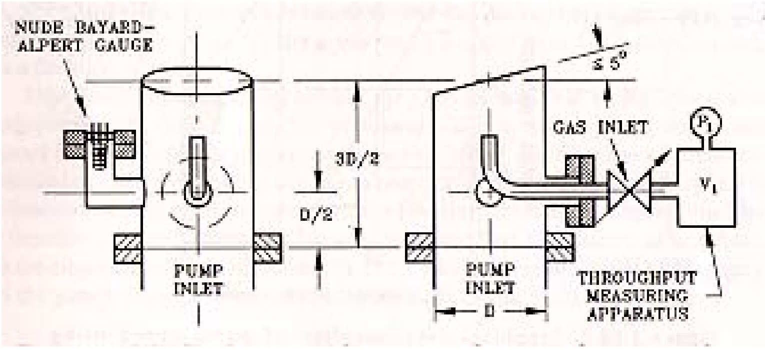
- Used for many years to measure diffusion pump speeds
- Pump throughput is determined by measuring dP/ dt of a known volume

$$Q_d = \left(\frac{dP}{dt}\right)V$$

- Pump speed is determined by assuming the chamber pressure is the same as the pump pressure

$$S = \frac{V_d}{P_d} \times \frac{dP}{dt}$$

- Requirements for this test method
  - —gauges calibrated for test gas
  - —known volume



Three Gage Method

- Pump throughput is determined by measuring the pressure difference along a tube of known conductance

$$Q_p = C_1 (P_1 - P_2)$$

- We can either assume that the pressure of the pump is equal to P_3 or we can calculate the conductance between the pump and P_3

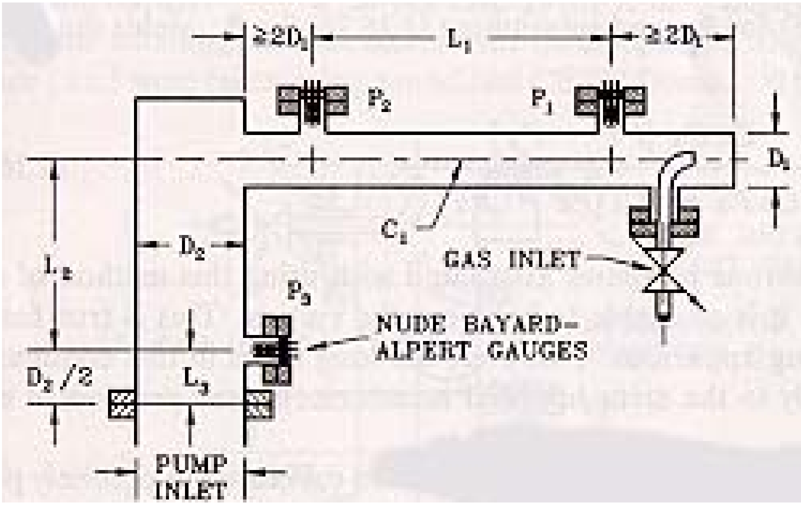
$$C_3 = 12.1 \frac{(D_2)^3}{L_3}$$

$$Q_p = C_3(P_3 - P_p) = C_1(P_1 - P_2)$$

$$P_p = P_3 - \frac{C_1}{C_3}(P_1 - P_2)$$

- The pump speed is ultimately determine by the equation:

$$S_p = \frac{C_3 C_1 (P_1 - P_2)}{C_3 P_3 - C_1 (P_1 - P_2)}$$



Problems with the Three Gage Method

- Calculated conductances introduce errors
- The three pressure gages must be "normalized" with respect to each other

Typically,

$$P_{abs} \neq P_{1i} + P_{2i} + P_{3i}$$

Normalized,

$$P_{1i} = k_2 P_{2i} + k_3 P_{3i}$$

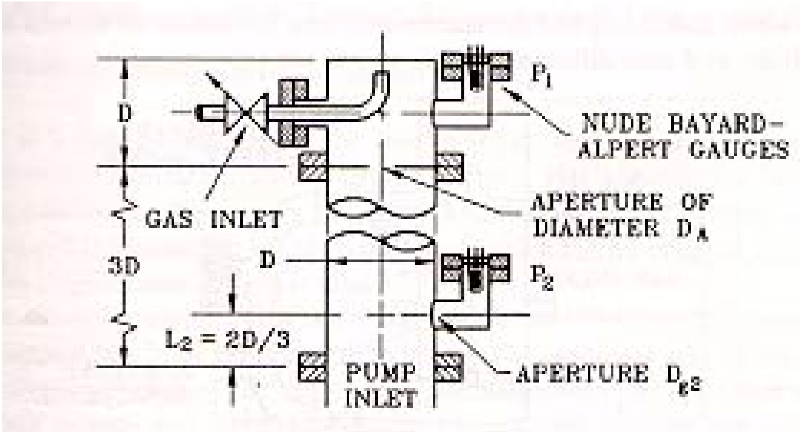
Fischer - Mommsen Dome Method

- Also known as the CERN method
- The aperture diameter is sized to maintain a minimum pressure differential. This requires some knowledge of the pump speed.

$$Q_p = C_a(P_1 - P_2)$$

$$P_p \sim P_2$$

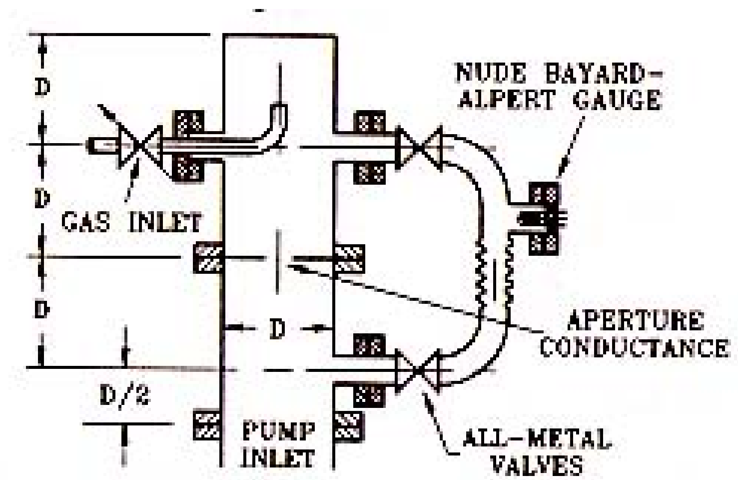
$$S_p = C_a \frac{(P_1 - P_2)}{P_2}$$



- Pressure gages need to be "normalized" to each other.

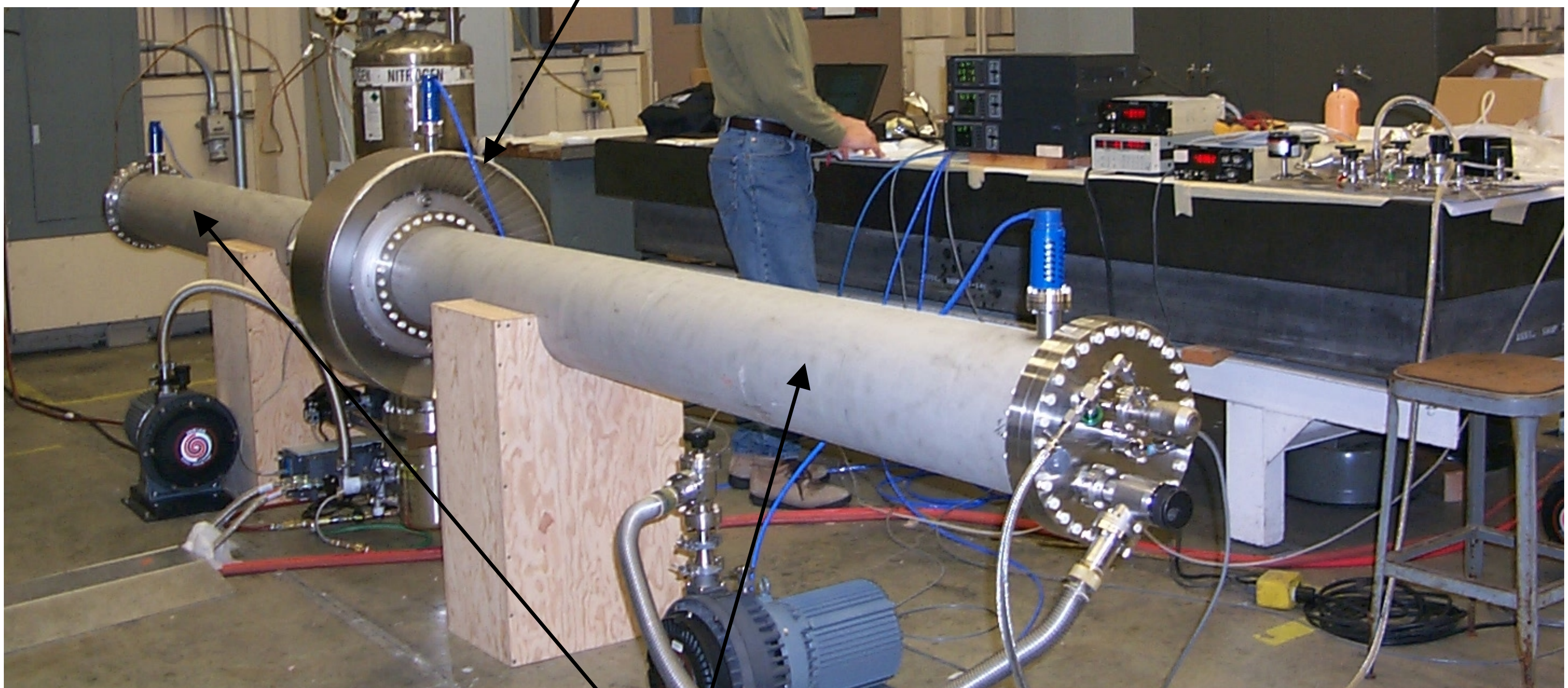
Modified CERN Method

- Utilizes a single gauge.
- By opening and closing the isolation valves, both P_1 and P_2 can be determined with the single gauge.
- Gauge normalization is eliminated (assuming gauge linearity with pressure).



DARHT II Accelerator Intercell Pump Speed Test

Intercell Pump Station



Tubes mock-up the Accelerator Bore

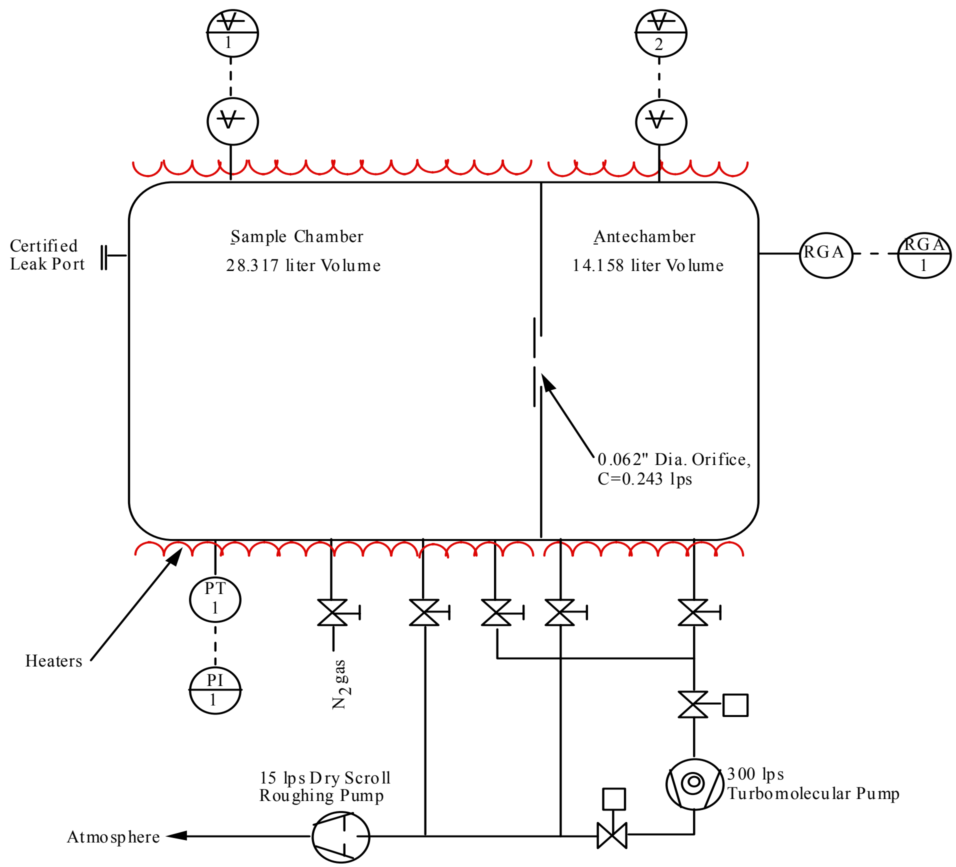
Desorption (outgassing) Tests

There are two approaches to conducting outgassing tests:

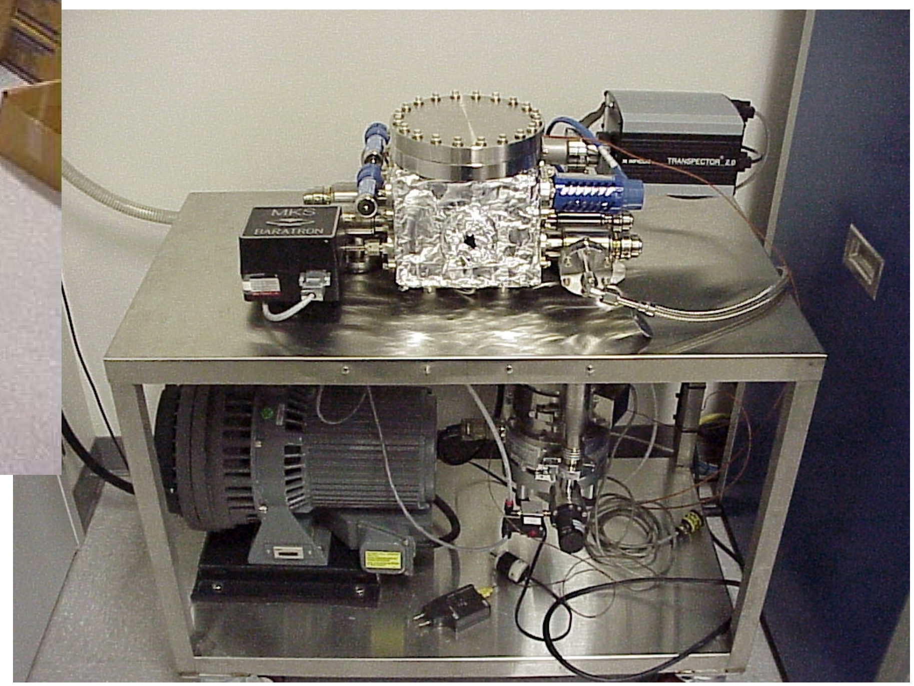
1. **Measure rates of representative material samples within a test stand (such as an AVS dome).**

2. **Measure rates of actual vacuum system components (such as whole beam pipes, collimators, beam dumps, etc.).**

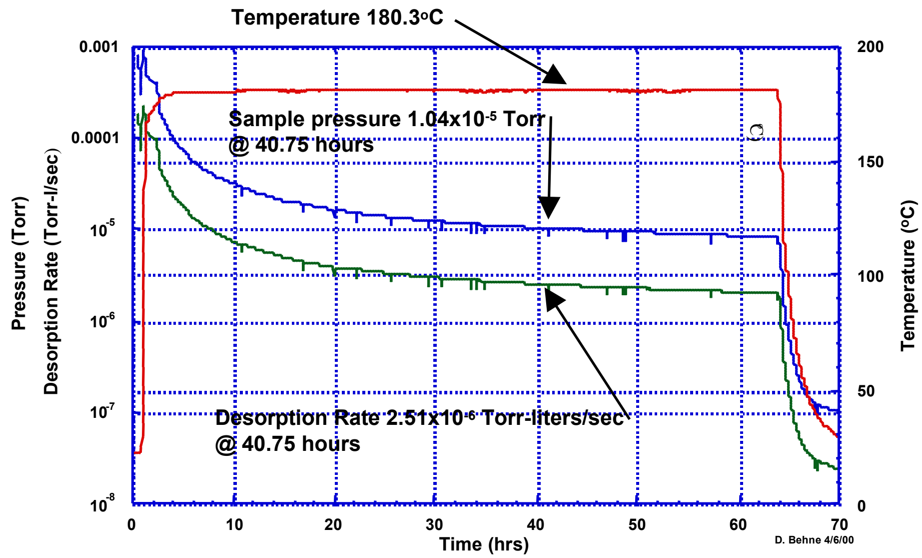
LLNL Outgassing Station Schematic

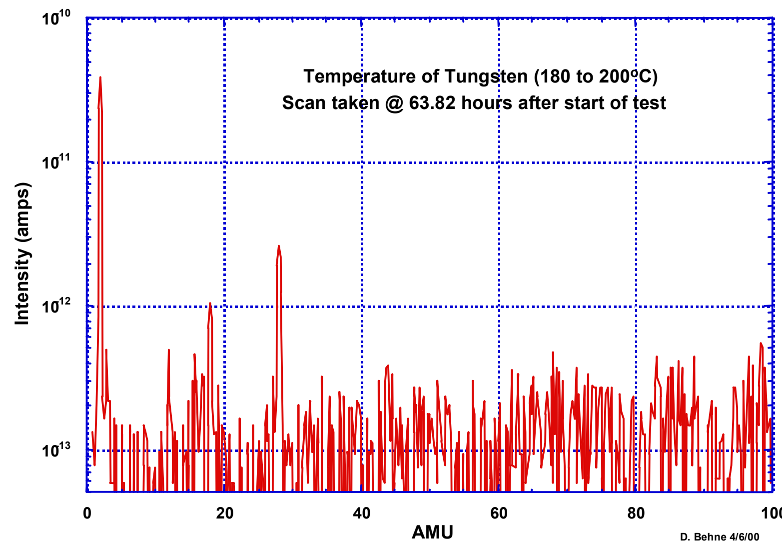


Photos of LLNL Outgassing Stations

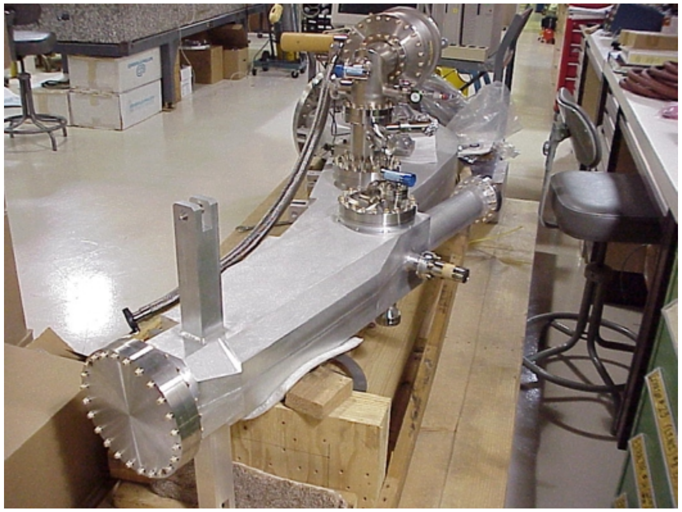


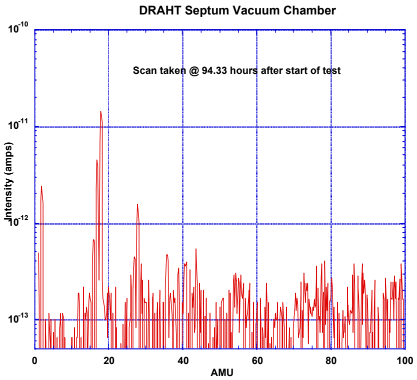
Sample Results from an Outgassing Test

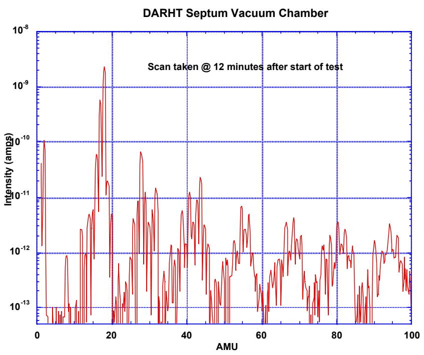


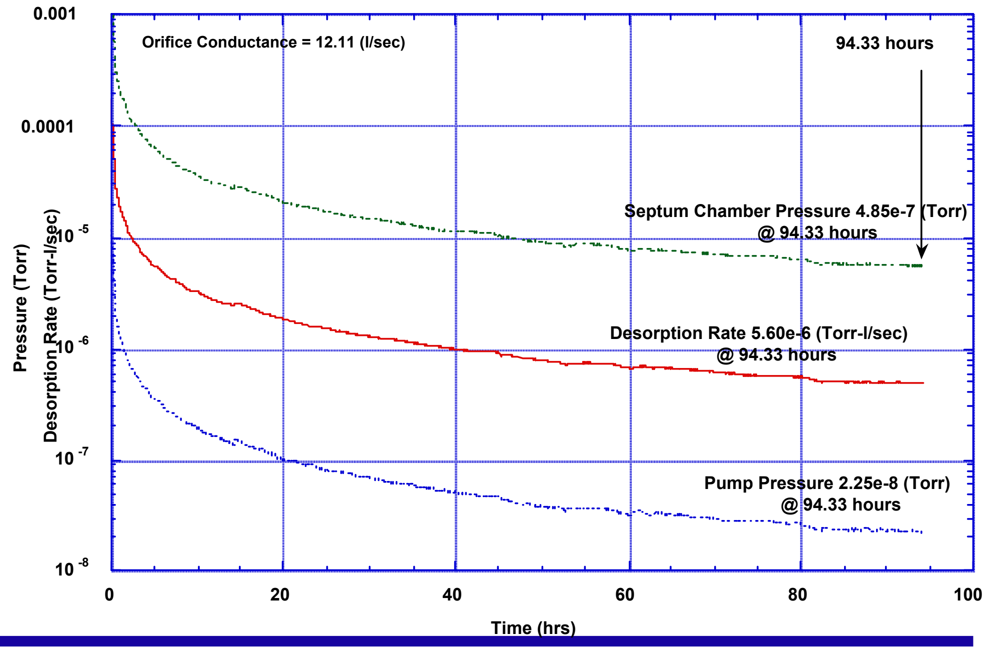


DARHT II Septum Chamber Test Results

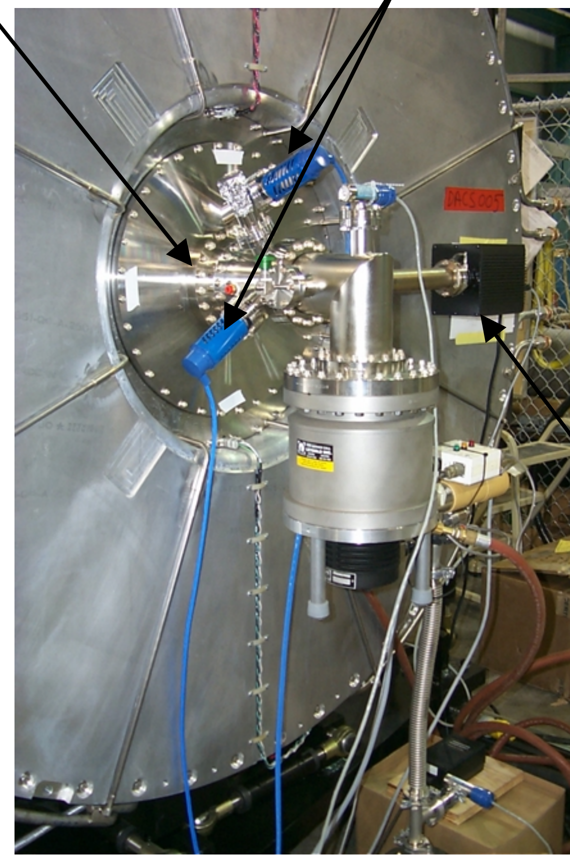




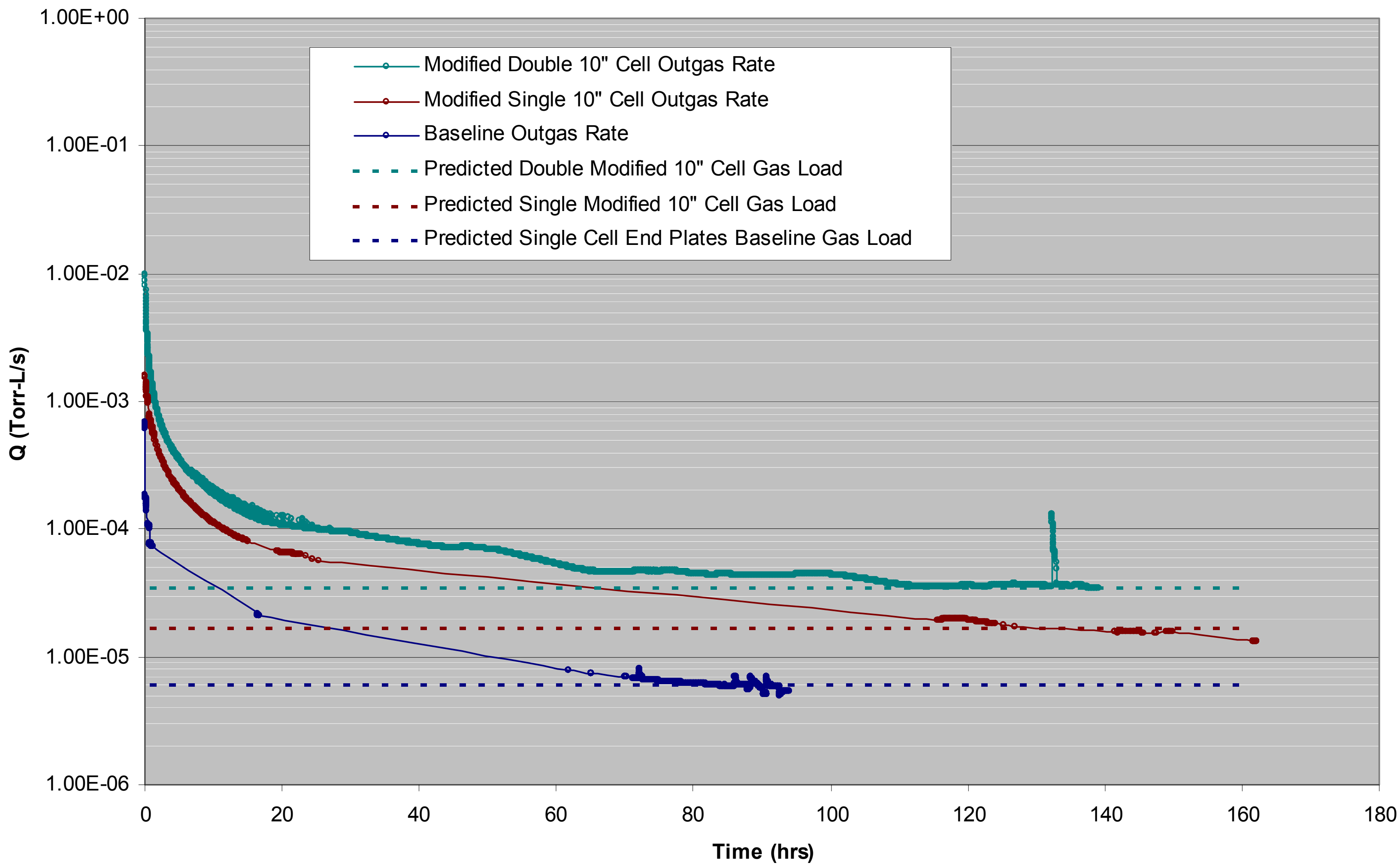




DARHT II Accelerator Cell Outgassing Tests



Data from DARHT II Accelerator Cell Outgassing Tests



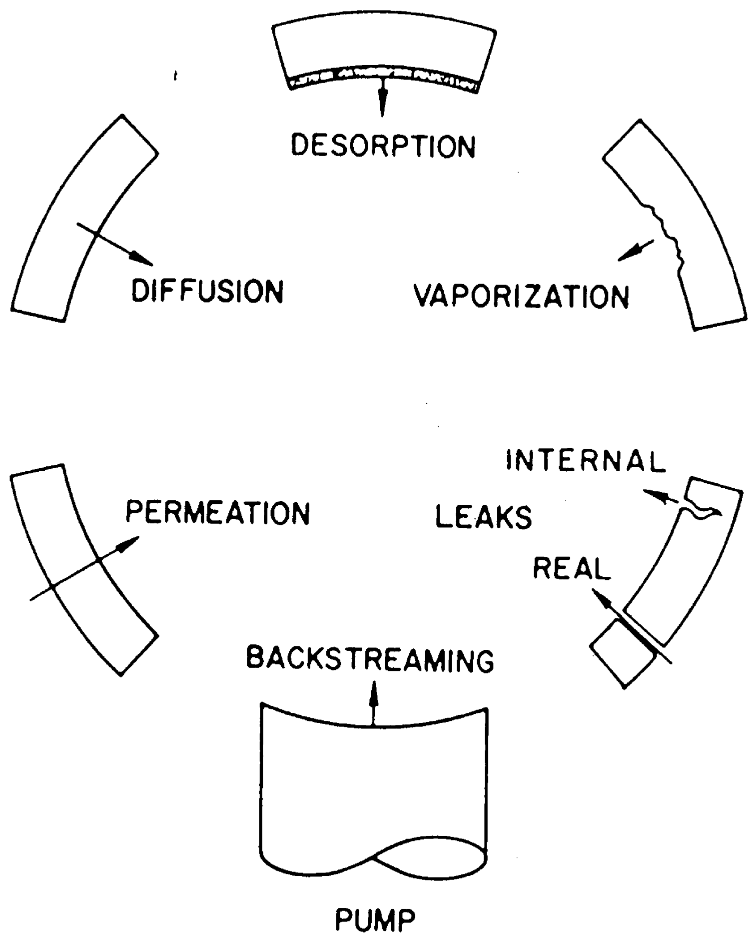
Fundamentals of Vacuum Leak Detection

- The Mike Benapfl "motherhood" statement.
  "Leak Detection is an art. <u>Not everyone is an artist!"</u>

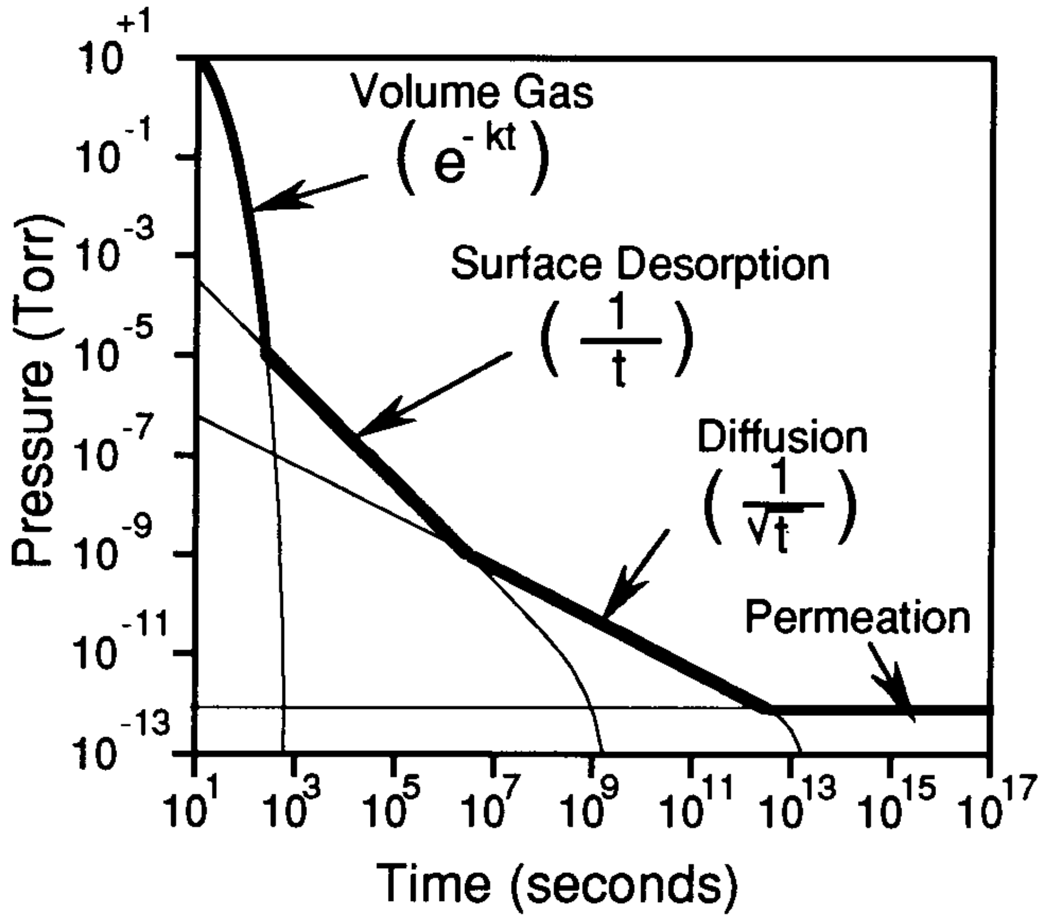
- Leak Detection should be performed in accordance with some ASTM Standard.
  - ASTM E493-94
  - ASTM E498-94
  - ASTM E499-97

- Leak Detection should be performed in a series of logical steps.

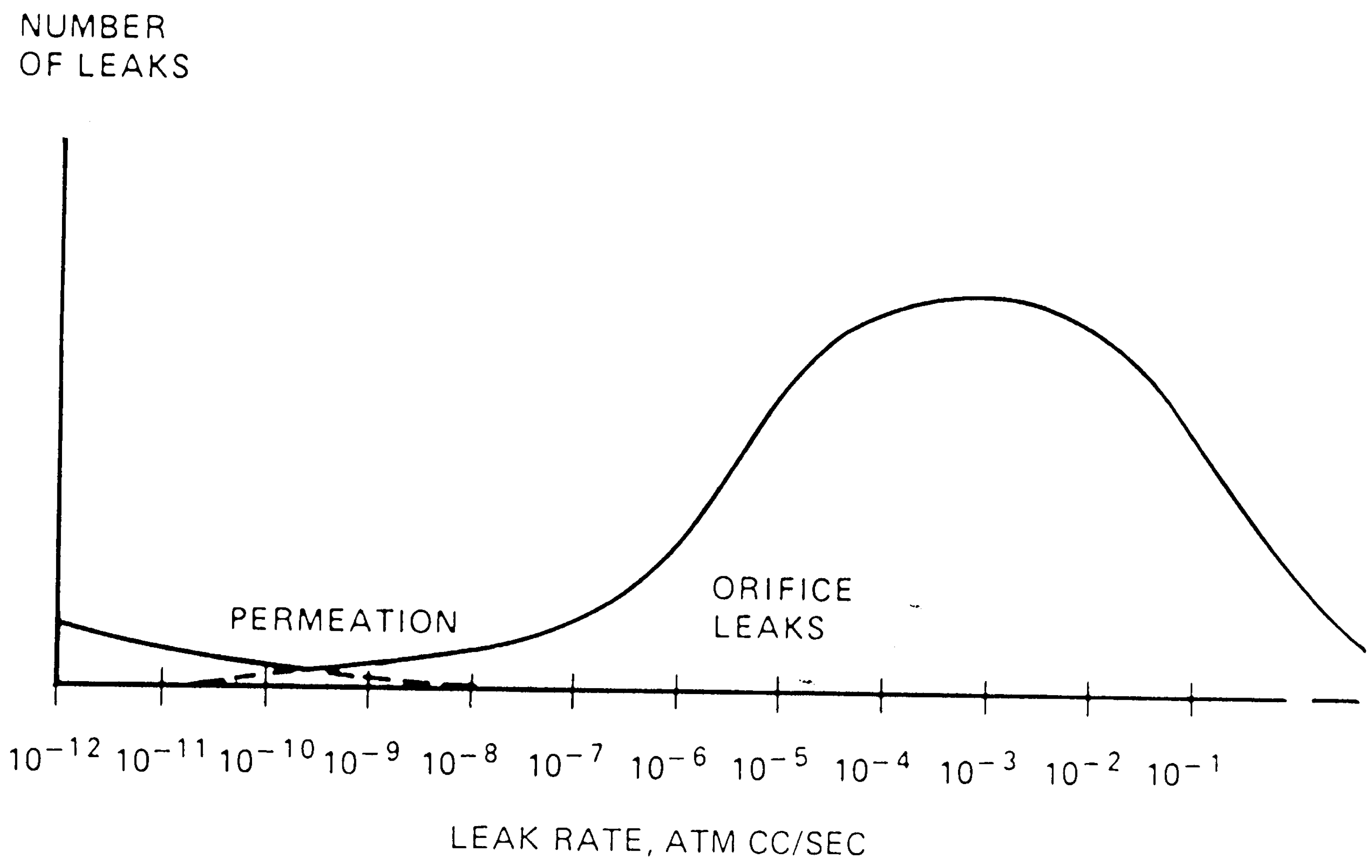
Sources of Gases in a Vacuum System



Evacuation of a Vacuum System



Distribution of Leaks



How do Leaks Affect Us Economically?

- Is a process being compromised by the current system performance?
  - poor adhesion or bonding, short filament life
  - reaction of process with gas (air)
- Determine base and optimal system pressures.
- Choosing the appropriate method of leak detection.
  - pressure gauges, mass spectrometers, *Snoop, acoustical*

Leaks into vacuum systems can present some problems

Gases leaked into the vessel or system must be removed to maintain a defined pressure. In which case, the pumping speed for the in-leaking gas must be increased.

$$Q_t = S_n \times P_t$$

Gases leaking into the vessel create a change in the vacuum environment. This may change in-chamber chemistry. The result could be a change in coating stoichiometry, adhesion, and possible increases in partial pressures. (Since most vacuum pumps pump gases somewhat selectively, a change in the partial pressures of the internal gases may occur).

What is the Significance of a Leak?

Change in chemical composition within the vacuum vessel

Change in the process

Increase in pump speed required to maintain the desired pressure

EXAMPLE:

A 1000-division leak will require a calculatable pumping speed to maintain a pressure (assuming the pump can handle the gas species).

Using the relationship $Q = S \times P$ and the calibration data, we can determine the speed required.

$$Q = 2 \times 10^{-10} \frac{\text{atm - cm}^3}{\text{sec - division}} \times 1000 \text{ divisions} = 2 \times 10^{-7} \frac{\text{Torr - liters}}{\text{sec}}$$

$$S = \frac{Q}{P} = \frac{2 \times 10^{-7} \frac{\text{Torr - liters}}{\text{sec}}}{1 \times 10^{-7} \text{ Torr}} = 2 \frac{\text{liters}}{\text{sec}}$$

Methods of Leak Detection

- Acoustical
- Bubble testing
- Dye penetrant
- Vacuum decay ("rate of rise" test)
- Pressure decay
- Thermocouple gauges
- Ion gauges and ion pumps
- Halogen leak detectors
- Partial pressure analyzer (PPA)
- He Mass Spectrometer Leak Detector (HMSLD)

The Rate of Pressure Rise in a Vacuum Vessel is a Useful Inspection Technique

- This procedure integrates the accumulation of gases in the vessel from all sources; outgassing, permeation, inleakage, etc.

- The procedure is to evacuate the vessel to a pre-determined pressure, isolate it from the pump(s) and measure the rate of pressure increase.

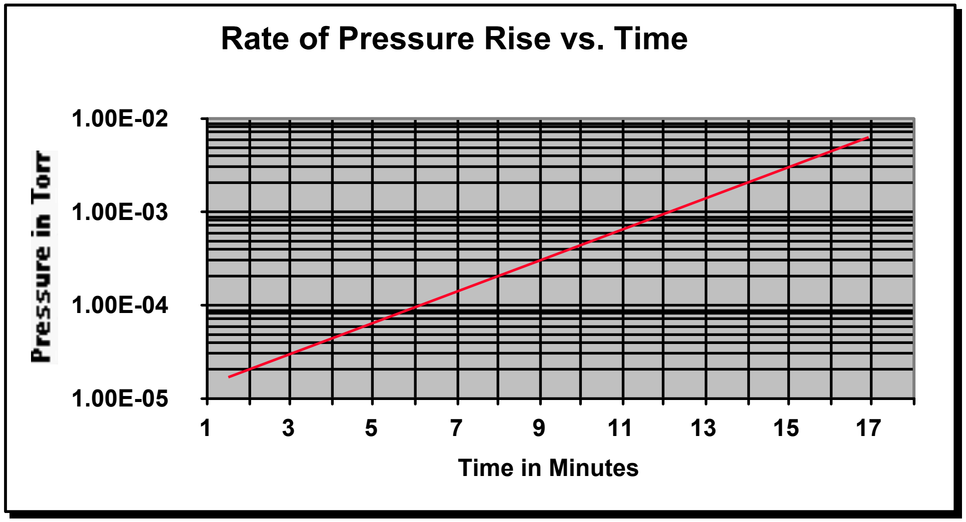
$$Q = V \frac{P_2 - P_1}{t_2 - t_1}$$

- What is measured is "Q", gas load in Torr-liters/sec, assuming the vessel volume is known or approximated.

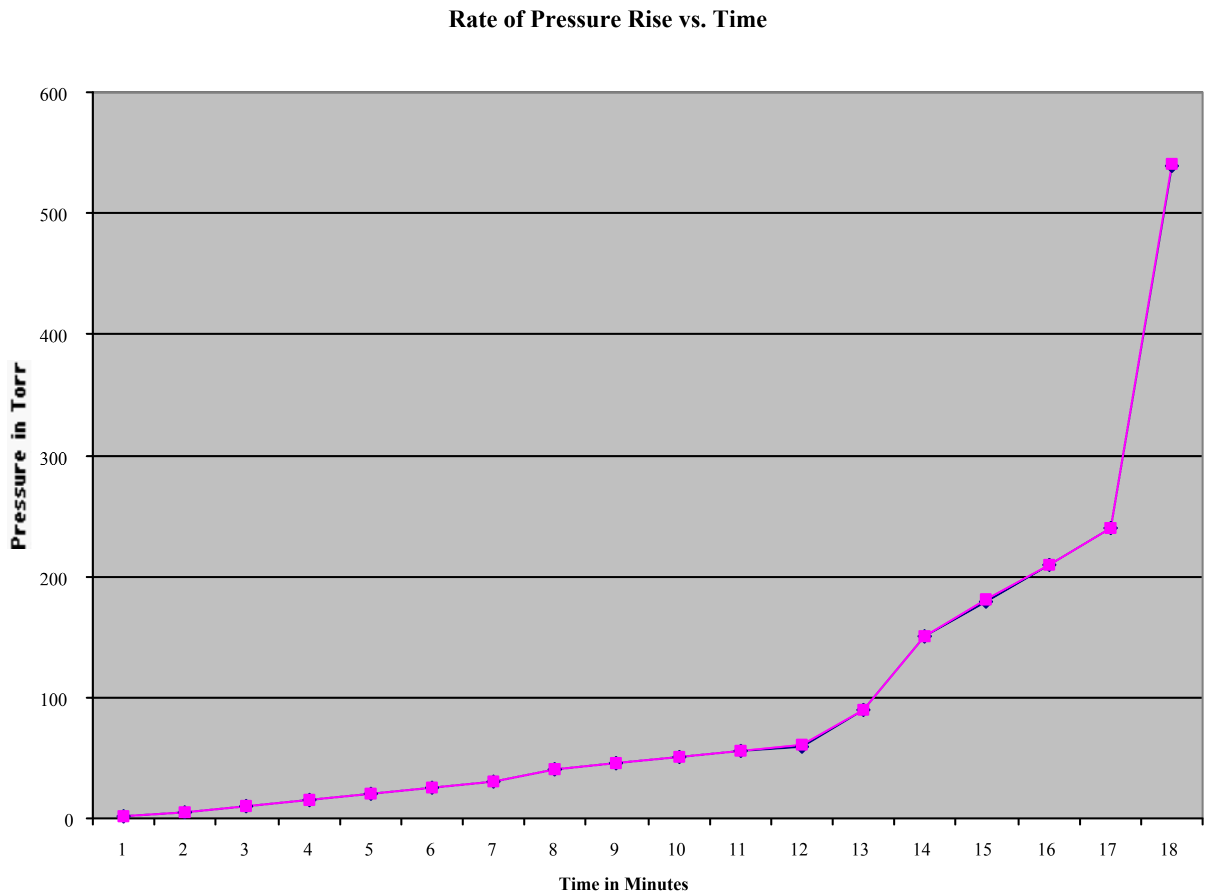
- The slope of the resulting curve can be used to determine the integrity of the vessel regarding leaks and surface cleanliness, and as a proof-test to verify that the vessel will achieve the desired pressure when placed in operation.

A Rate of Pressure Rise Test can be used to Your Advantage in Several Ways

- The rate of pressure rise can be used to determine inleakage, permeation, and outgassing in a system or vessel.
- As an aid to the designing of new systems, rate of pressure rise data can be used to "model" the gas loads of existing systems or process.
- The pumping speed delivered to the vessel can be determined by using the rate of pressure rise data and the known pressure at the start of the test.

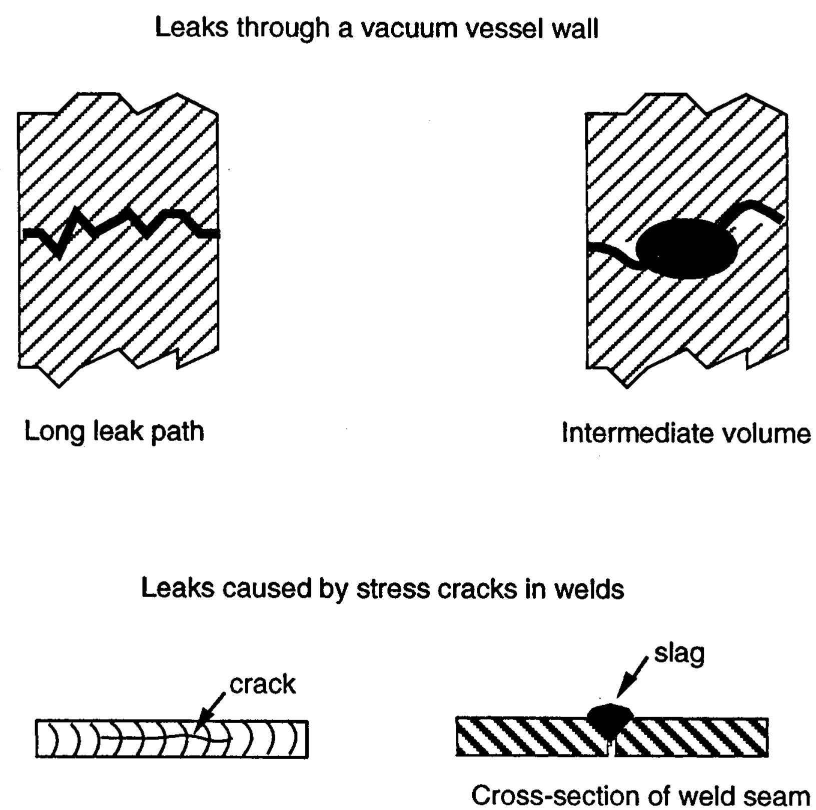


Rate of Pressure Rise--plotted data



Types of Leaks--Real Leaks

Real leak – physical hole or crack in vessel wall allowing gas to enter the vessel



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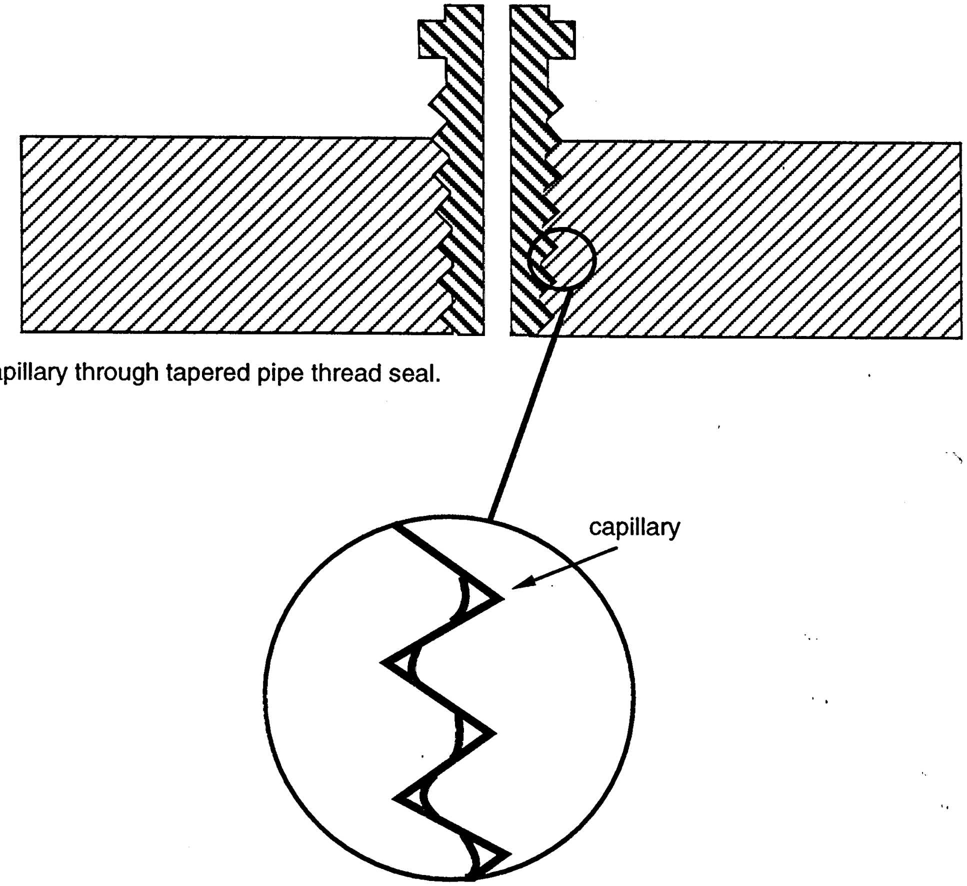
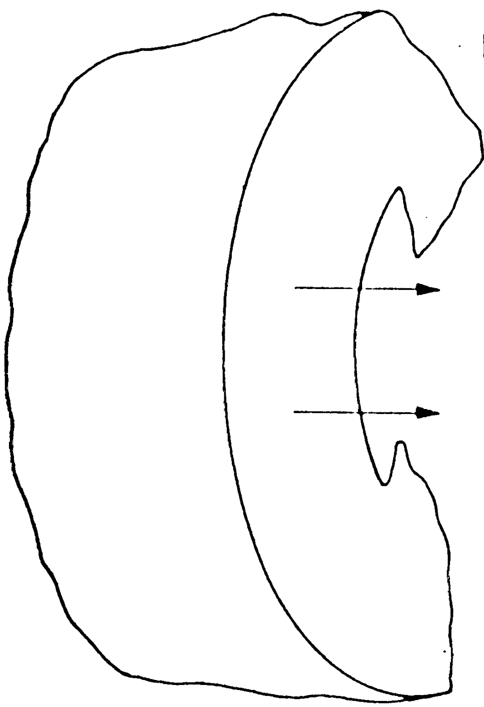


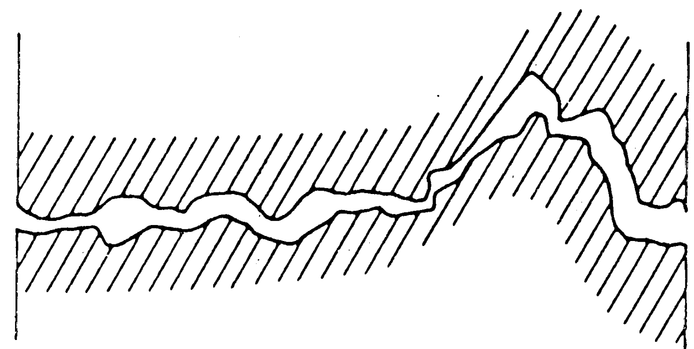
Capillary through tapered pipe thread seal.

Vacuum Leak Detection

For Hole With Diameter At Least 10 X Length



Void



Tortuous Path Whose Length is Greater Than Cross-Section:

Helium Rate May be Equal to Air Rate for Large Leak or Many Times Larger for Small Leak

Molecular Flow Through Circular Aperture:

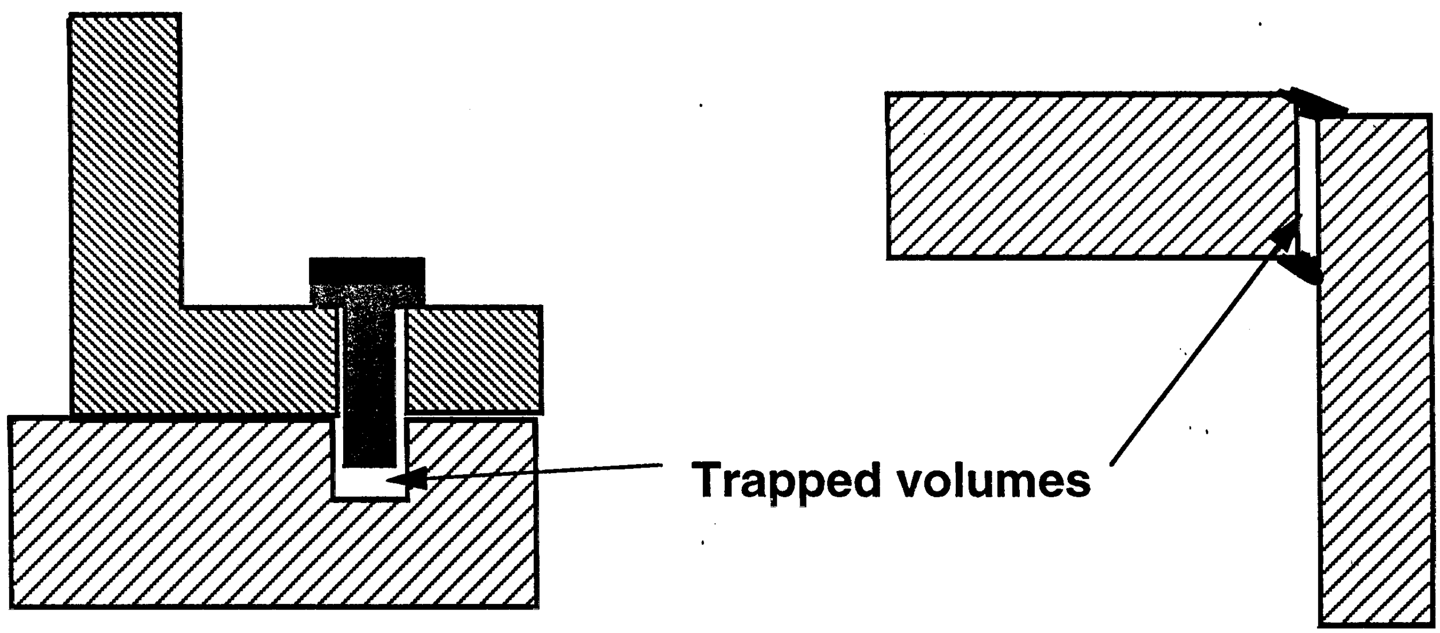
Helium Rate = 2.7 x Air Rate

Most Leaks

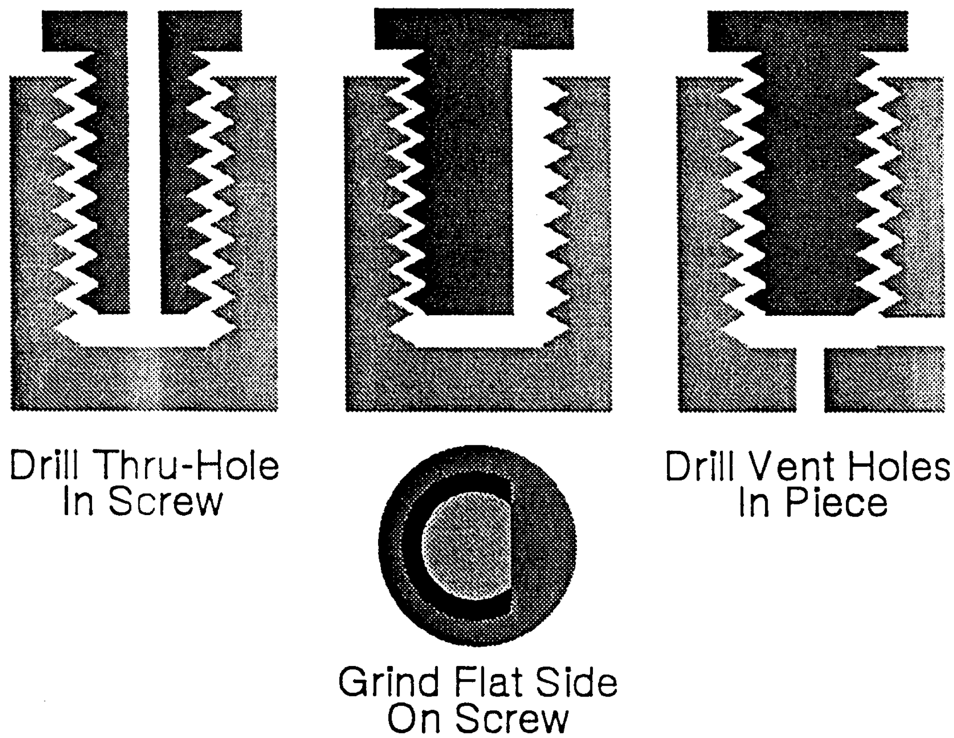
Kinetic Theory

Virtual Leaks

A virtual leak is a volume of trapped atmospheric gas that leaks into the vacuum vessel through holes or cracks that do not go all the way through the vessel wall.

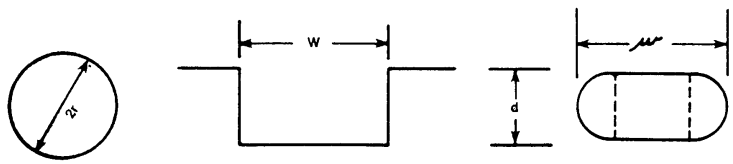


Virtual Leaks - blind tapped holes



Thread and blind hole venting techniques

Virtual Leaks - O-ring grooves



2r	d	W	w	W - w
.100/.106	.074/.080	.171/.123	.115/.135	-.018/+.008
.135/.143	.101/.107	.157/.163	.157/.181	-.024/+.006
.205/.215	.152/.162	.247/.253	.239/.271	-.024/+.014
.269/.281	.201/.211	.322/.327	.315 .352	-.030/+.012

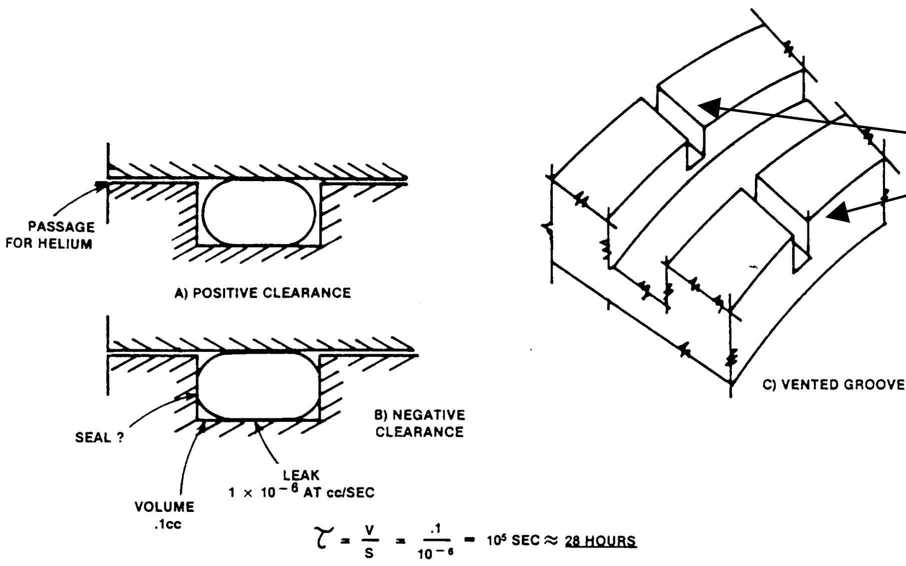


FIG. 3. O-ring seal.

Slot in O-ring groove helps to reduce chance of virtual leak

Real Leaks vs. Virtual Leaks

Real Leaks	Virtual Leaks
external	internal
constant flow	decreasing flow
constant pressure	decreasing pressure

Types of Leakage

Gas passes through holes or cracks in the vessel wall. Flow is a function of the size of the flaw.

Permeative gas diffuses through a material having no holes large enough to allow passage of more than a few molecules of gas per unit time.
(polymeric materials such as rubber gaskets, O-rings diaphragms, etc.)

Vacuum Leak Detection

Leakage and Outgassing

In general, unless leaks are large, the effects of outgassing will overwhelm the effects of the leaks.

Technique:

1. Pump from ~100 mtorr to 1 mTorr, and record time.
2. Isolate pumps, allow the pressure to rise to 100 mTorr.
3. Repeat step 1 and compare pumping times.

If $T_1 = T_2$, then a leak is suspected.
If $T_2 < T_1$, then outgassing may be the culprit.

Average Composition of Dry Air

Gas	Partial Pressure (Torr)	Volume %
Nitrogen	593	78.1
Oxygen	159	20.9
Argon	7.1	0.934
Carbon dioxide	0.25	0.033
Neon	1.4×10^{-2}	0.0018
Helium	4.0×10^{-3}	0.00053
Methane	1.5×10^{-3}	0.0002
Krypton	8.6×10^{-4}	0.00013
Hydrogen	3.8×10^{-4}	0.00005
Nitrous Oxide	3.8×10^{-4}	0.00005
Xenon	6.6×10^{-5}	0.0000087

Average Molecular Size of Some Gas Molecules

Gas molecules must "fit" through real leaks to be a problem. Molecules Are not discrete spherical particles, however….molecular diameter can be Calculated from gas viscosity.

Hydrogen	2.75 Angstroms
Helium	2.18
Argon	3.67
Oxygen	3.64
Nitrogen	3.64
"Air"	3.74

A 10^{-10} atm-cc/sec air leak @ 20° C in a 0.25" plate will have a diameter of 10^{-5} cm, or 10^{3} Angstroms, or about 300 times the size of an air molecule.

Helium is the most common gas used as a "tracer" in locating leaks

When compared to other gases, helium has certain advantages as a tracer:

- Low molecular weight (4)
- High intrinsic velocity
- Small molecular size
- Chemically inert
- Non-flammable
- Readily available
- Inexpensive
- Low partial pressure in the atmosphere

Some disadvantages are:

- Is not well pumped by ion or chemical combination pumps
- Is not well pumped by cryogenic pumps

Molecular Velocities

Molecules in the gas phase have a distribution of velocities, the average velocity (v):

$$v = 14{,}551 \left(\frac{T}{M}\right)^{1/2} \quad \text{cm/s}$$

M = molecular weight

For N_2 at room temperature (20 °C) :

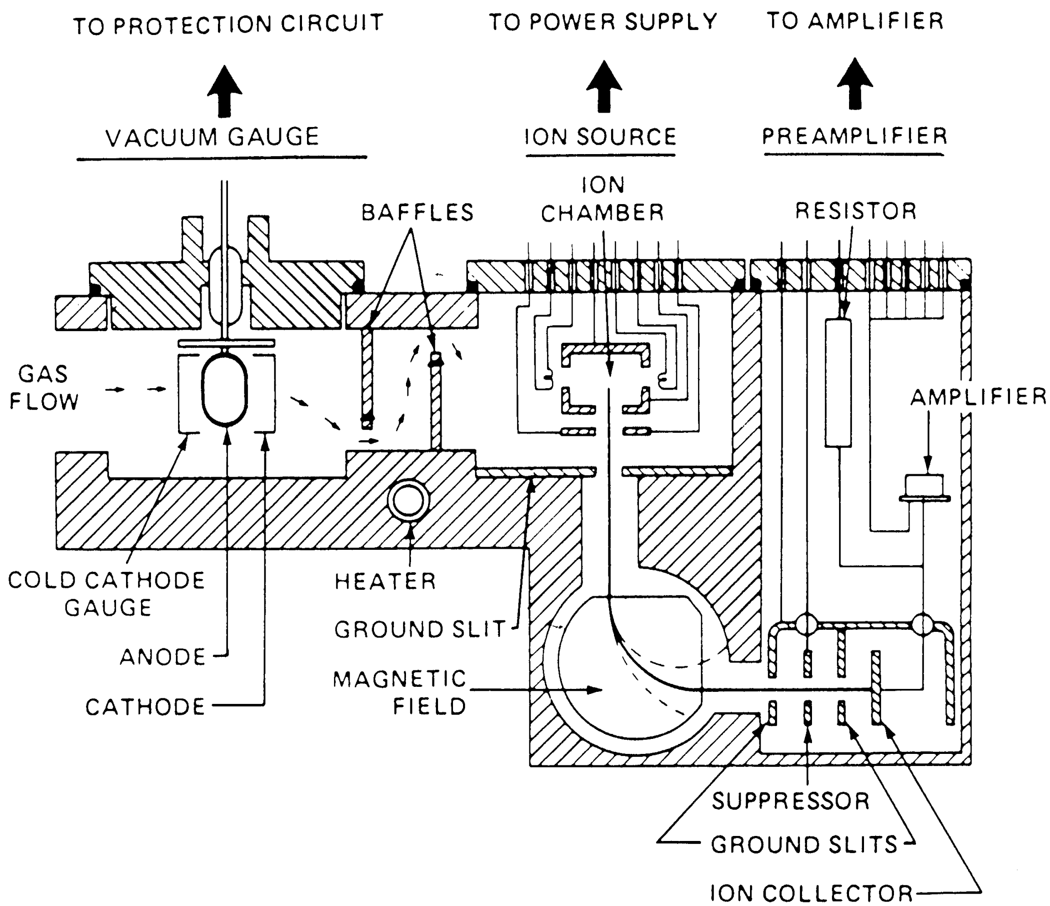
$$v = 14{,}551\left(\frac{293}{28}\right)^{1/2} = 4.71x10^4 = 1054 \quad \text{mph}$$

Note that v is independent of pressure

What is a Helium Mass Spectrometer Leak Detector?

- It is a Helium-specific partial pressure analyzer
- It detects Helium applied as a tracer or probe gas
- It consists of:
  - the mass spectrometer tube
  - it's own vacuum system capable of 10^{-5} Torr in the spectrometer tube
  - a sensitive and stable amplifier
  - valves, and auxiliary pumps for interfacing to vacuum system
  - a display for monitoring leak rate
  - normal-flow vs. counter-flow configurations

Cross-section of a Typical Spectrometer Tube



Calibration calculation

Calibration of a leak detector is accomplished by attaching the leak standard, allowing the leak to flow into the detector, and reading the output from the spectrometer tube on the leak rate meter. A straight forward calculation is made and the calibration of the meter is understood. It must be noted that variations in temperature, detector pumping speed, electronic "drift" and background noise can influence the stability of the calibration.

$$\text{Calibration} = \frac{\text{Standard Leak Rate}}{\text{Change inLeak Rate Meter}}$$

$$\textit{Calibration} = \frac{\text{atm - cm}^3}{\text{sec - division}} = \frac{2 \times 10^{-7}}{1000} = 2 \times 10^{-10} \frac{atm - cm^3}{sec - division}$$

Vacuum Method of Leak Detection

Most common (and desirable method): The HMSLD is connected to the system, and a helium tracer gas is applied to the exterior of the system under test in a controlled manner. ASTM E-498-94

Connection configurations:

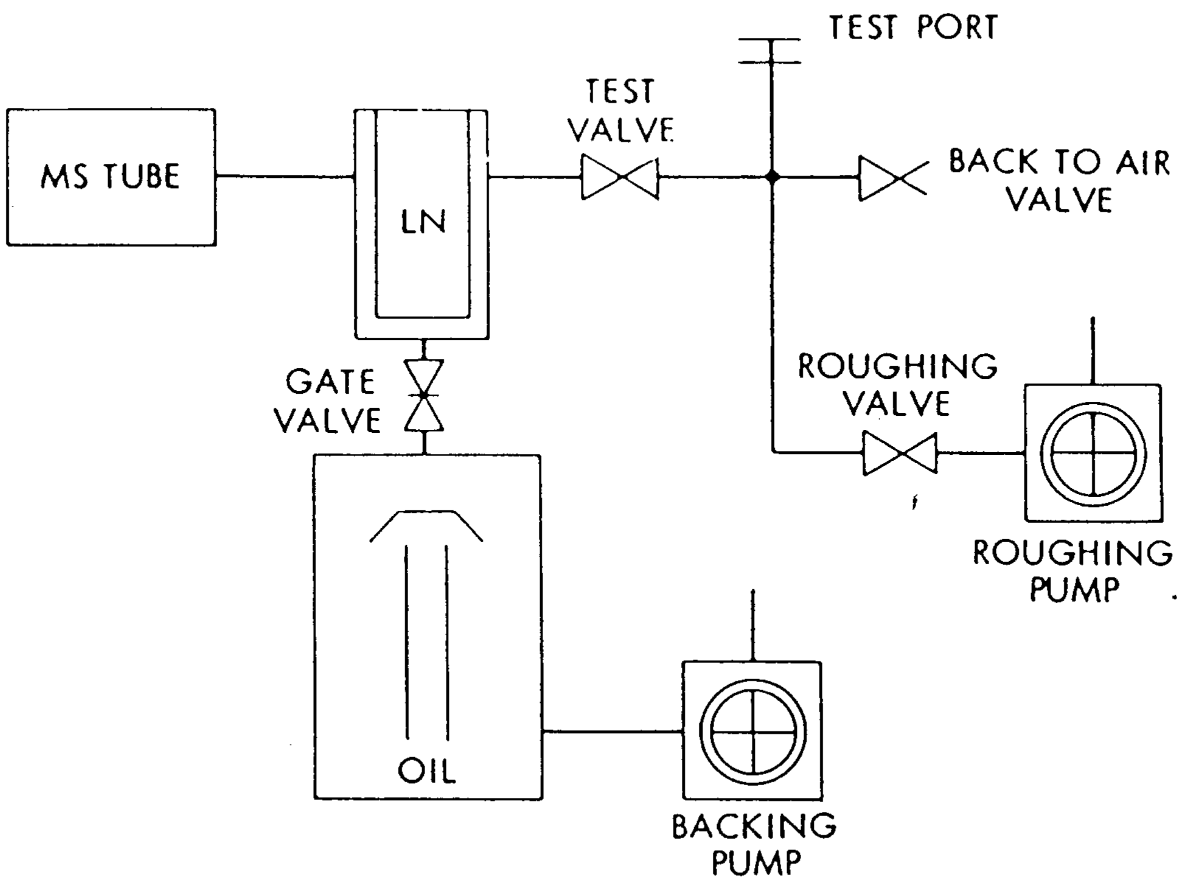
1. Directly to the component or system
2. In parallel with other pumps on the system
3. In series, backing another pump connected to the system

Vacuum Method of Leak Detection

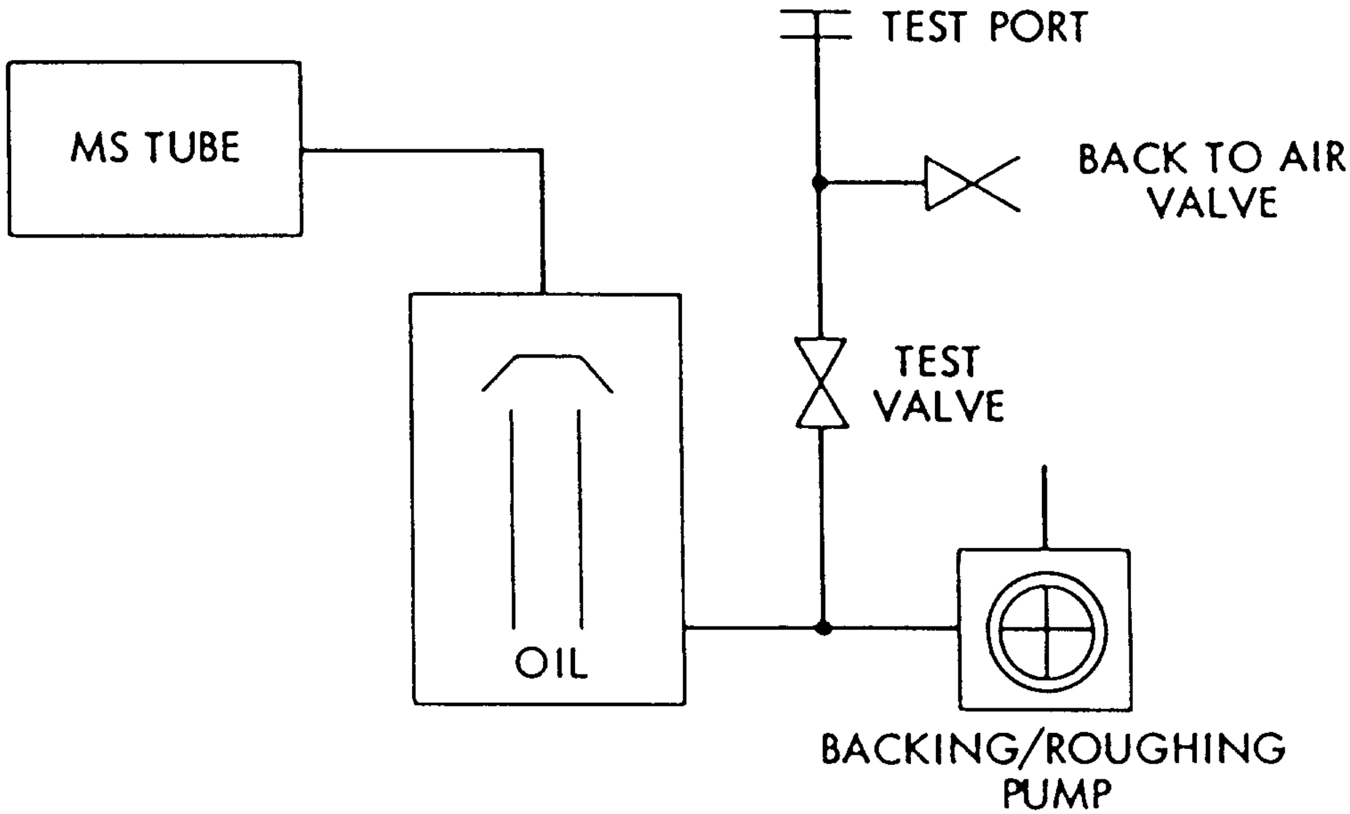
Most helium leak detectors have two test modes; normal-flow and contra-flow. You, as the operator, can decide which mode you should be operating in.

Either mode has distinct advantages and disadvantages!

Schematic of "Normal Flow" Configuration



Schematic of Contra-flow Configuration



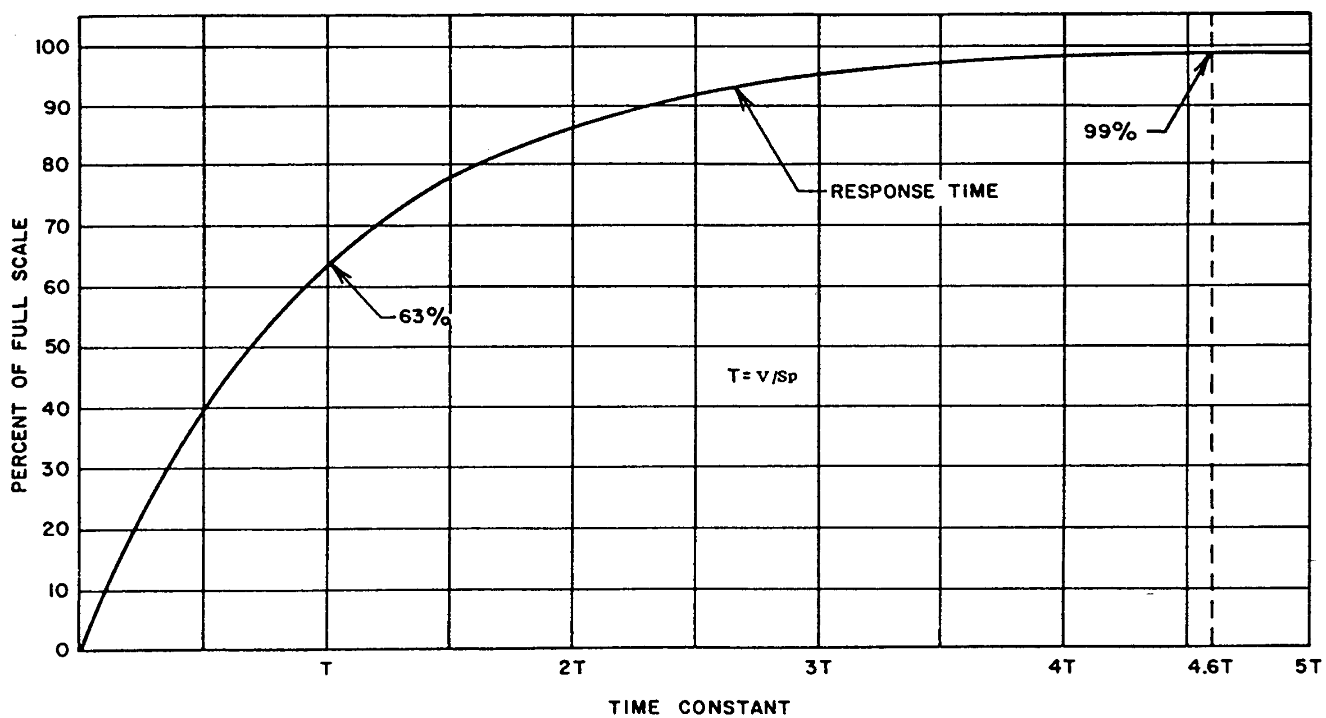
HMSLD Response Time

Response time is often defined as the time it takes a HMSLD to indicate a rise in signal (63%) after the application of a tracer gas.

- Sensitivity of the instrument
- Tracer gas leak rate
- Volume of the system under test
- Pumping speed for helium of the HMSLD
- Pumping speed of any additional pumps

Time Constant and Response Time

Ideal Response Time



Manifolding Cells Together for Leak Testing of Spatial Filter Vacuum Vessel (Ranor)

10” vacuum lines connect to 2000 l/s turbo pump

Calibrated Leak Mounted to 100,000 liter Vessel

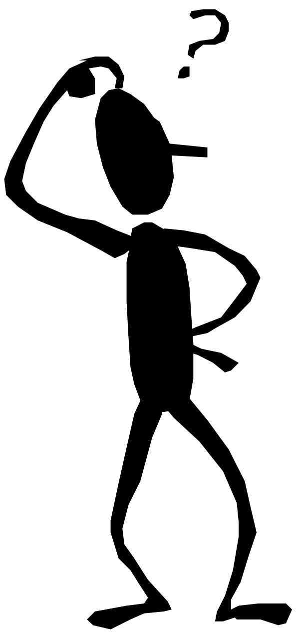
Leak was attached at the most remote port on the vessel.

Response time was incredibly rapid, about 8 seconds!

Spatial Filter Being "Bagged" for Total Integrated Helium Leak Test

Major Leak Testing Problems

- Background (outgassing)
- Large Volumes, slow pumping speed for Helium
- Helium permeation
- Leak "plugging"
- Detector maintenance
- Operator training

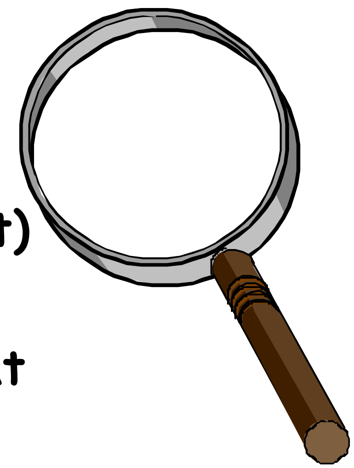


Leak Detection, Tips & Tricks

- Pipe threads (and the use of *Teflon* tape)
- Use of “Accu-pucky”, vacuum sealants and sprays
- Helium dissolves in most vacuum greases
- Isolate O-rings to prevent permeative “masking” of real leaks
- Always test the connecting lines first!
- When introducing helium, start at top and work down (Tracer probe)

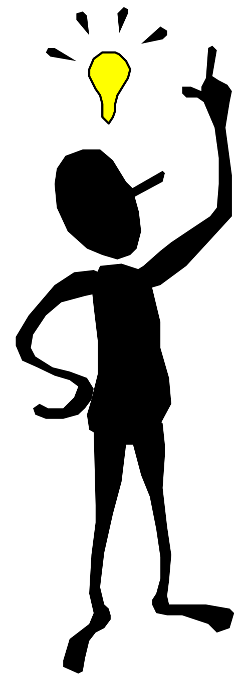
Tips & Tricks, Cont'd.

- Mount a calibrated leak to the system under test (response time)
- Calibrate the HMSLD before, and after, each use
- Minimal use of the tracer gas (adjust in water or solvent)
- Operate diffusion-pumped systems properly, especially at start-up and shutdown
- Don't use your leak detector as a portable pumping station!



Techniques for Detecting Small Leaks

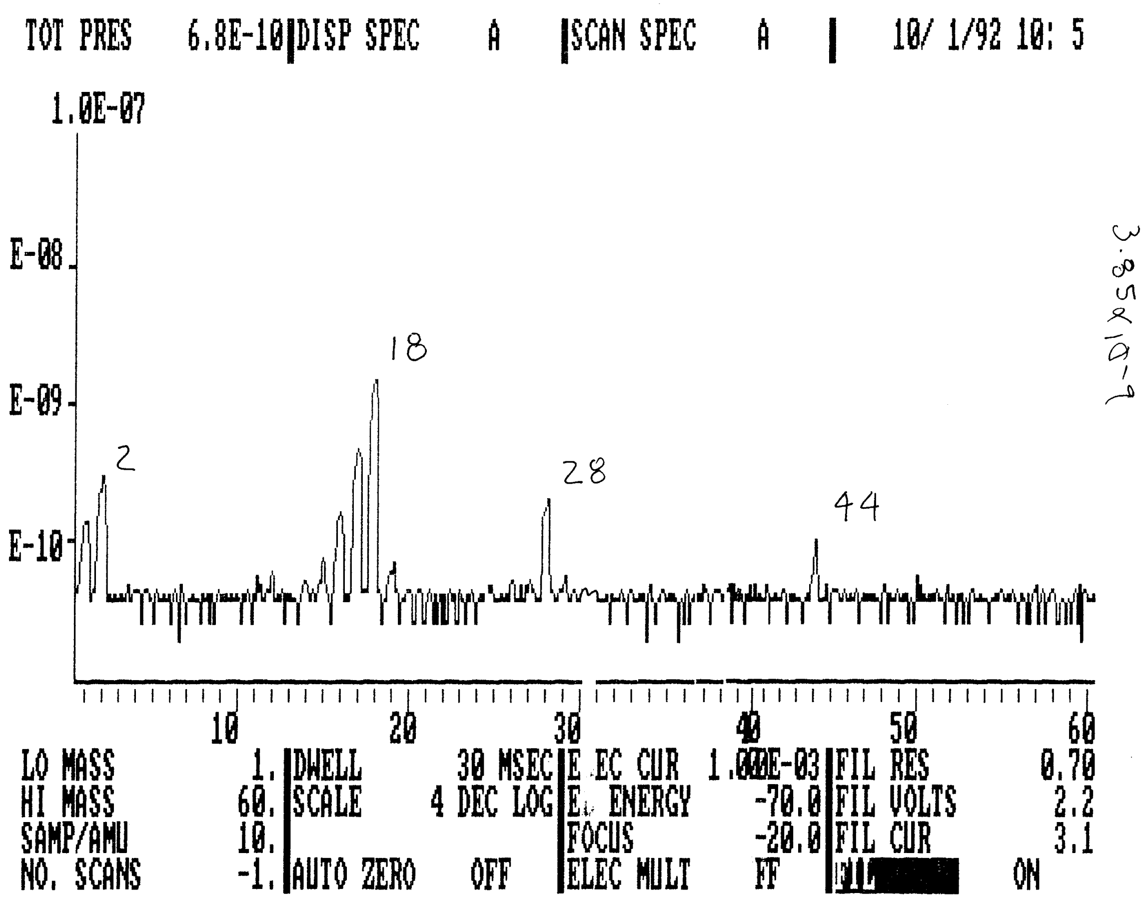
- Check the sensitivity of the leak detector
- Calibrate the HMSLD using an external standard
- Flow all pumped gases through the HMSLD, if possible
- Use low-flow tracer probe technique
- Keep Helium away from permeable materials (elastomers)
- Make use of “bagging” and “taping” techniques



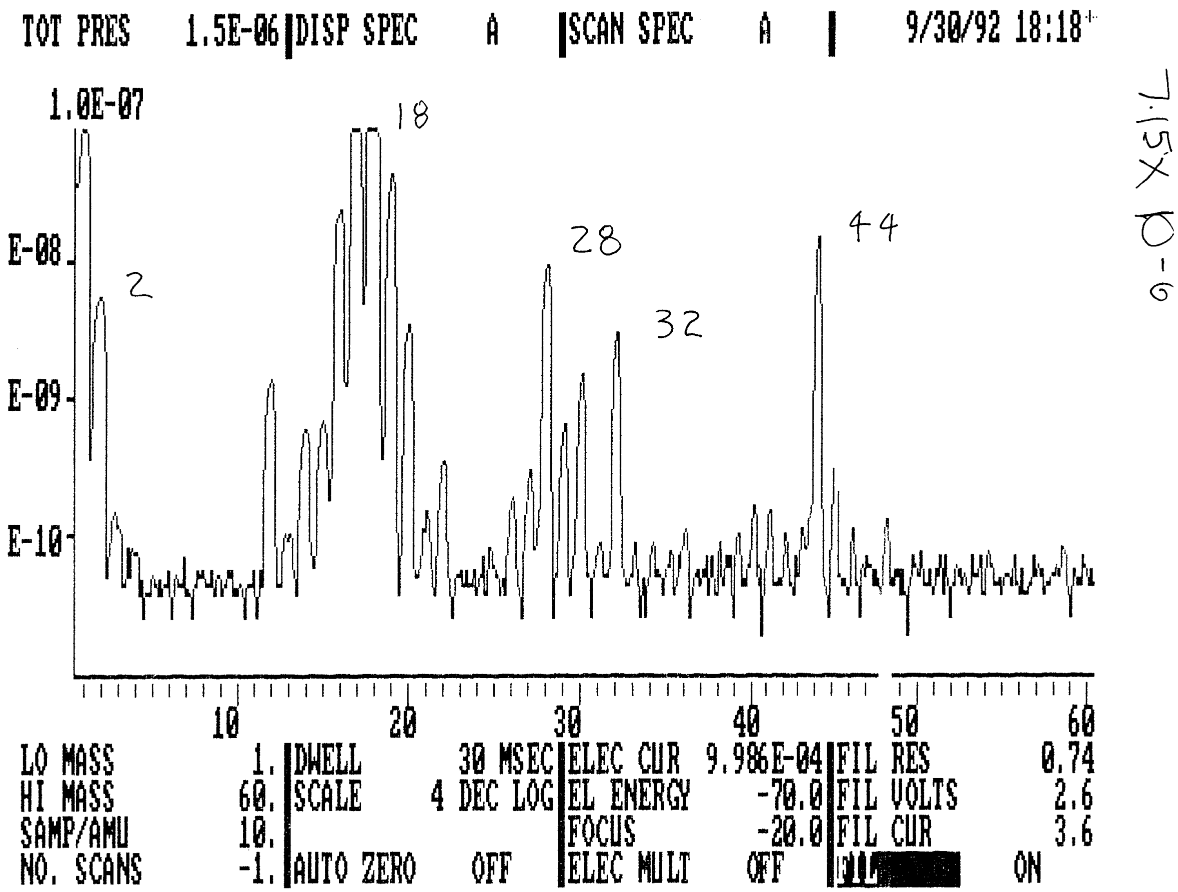
Partial Pressure Analyzers (RGA's) are often used in the leak testing of vacuum systems

- When calibrated, they can provide quantitative as well as qualitative data regarding the vacuum environment.
- RGA's have the ability to measure real-time environment changes.
- Gas Analyzers can be calibrated for various gas species.
- Gas Analyzers are often mounted permanently on a vacuum vessel or process equipment, utilizing the equipment's own pumping system.

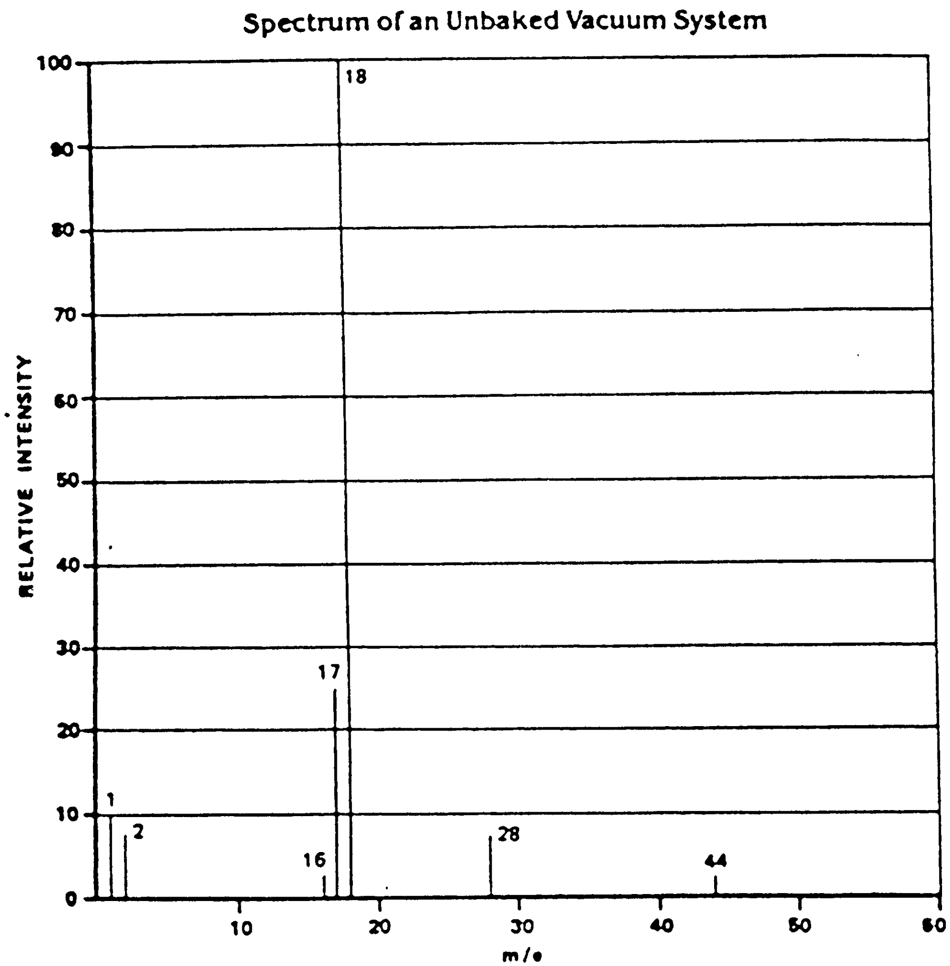
Clean System Spectrum



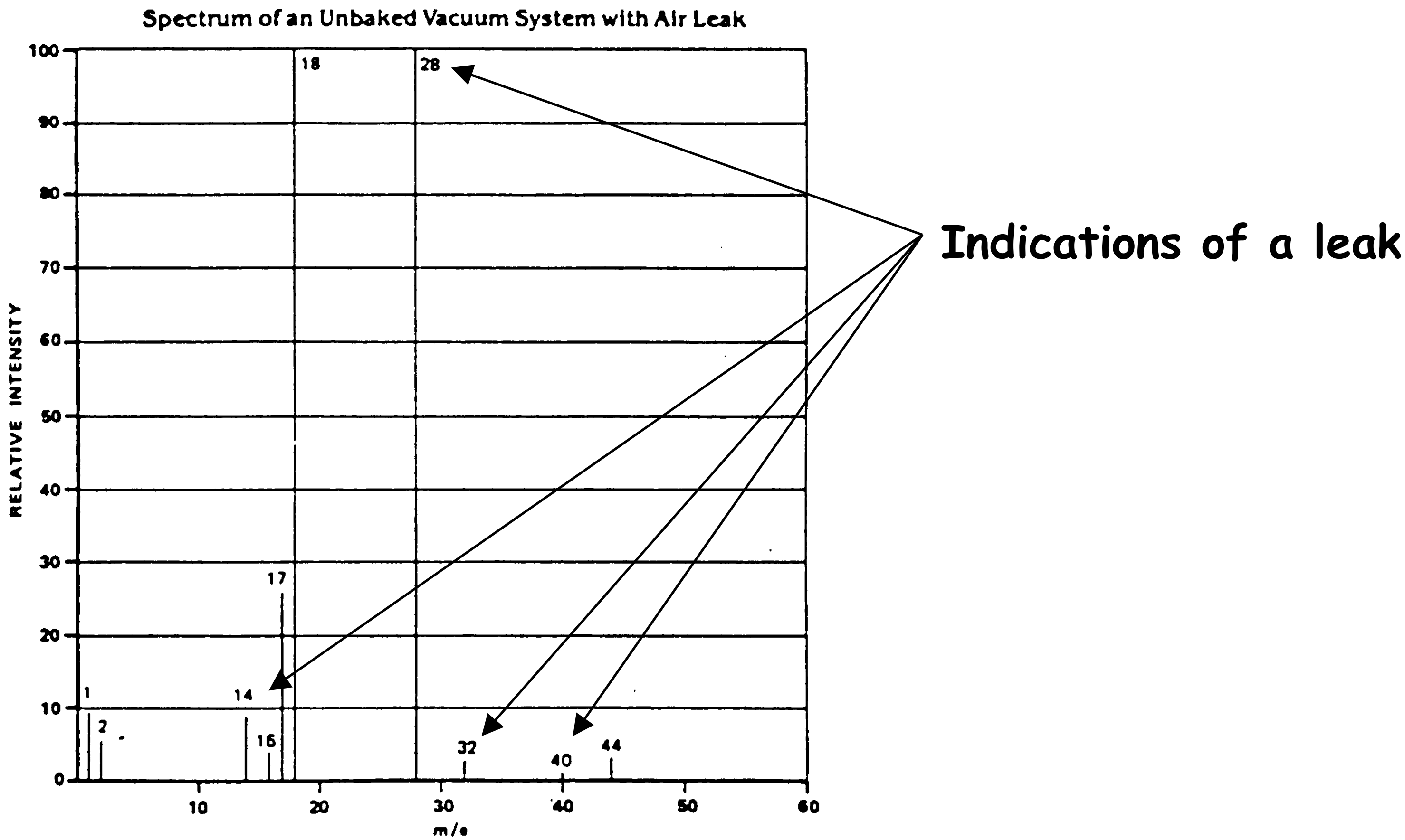
Less-than-clean System Spectrum



Spectrum of an Unbaked Vacuum System



Spectrum of a System With an Air Leak



Equipment-related Factors that Influence Residual Gases in the Vacuum Environment

Backstreaming
(system design)

Selection of pumping action
(capture vs. momentum transfer)

Vaporization of materials
(low vapor pressure materials)

Desorption
(surface condition of vessel walls)

Permeation
(elastomers)

Leakage
(real leaks)
(virtual leaks)

Operator-related Factors that Influence Residual Gases in the Vacuum Environment

- Handling procedures
  - grease, oil, salt
- Cleaning procedures
  - solvents (alcohol, acetone, MEK)
- Fabrication Techniques
  - machining coolants and lubricants
  - voids and occlusions
- Operation Procedures
  - use of traps
  - venting system to room air
  - backstreaming

Specifying Leak Rate and Detection Procedures

- Specification can include:
  - Maximum allowable leak size
  - Total maximum leakage rate (infers bagging)
  - Component pressure during leak detection
  - Type and sensitivity of the leak detector (e.g. MSLD with a sensitivity of 2×10^{-10} atm-cc of He/s
  - Use of certified standard leak immediately before and after testing
- ASTM standards E432, E479, E493, E498, E499, and F97
- If application is critical, witness the testing, or do it yourself
- Avoid phrases like; leak tight, vacuum tight, good to 10^{-8} Torr, good for ultrahigh vacuum, etc.