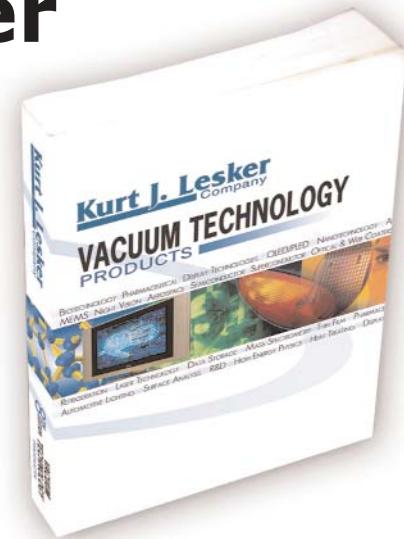


Gauging the Pressure You're Under

Part 1

First Things First

2006 is the **Year of the KJLC Catalog**—a designation as yet unlisted in the Chinese calendar*. This catalog is, without question, the best we've ever put out: 912 full-color pages, great photos and drawings, plus a super layout. Tom, the guy who muscled it through the 'process', has added many helpful features, selection guides, and a slew of new products. It should hit the streets early March 2006. If you haven't reserved your copy yet, go immediately to www.lesker.com, click on **Order Catalog**, and sign up.



Introduction

For *Lesker Tech*, 2005 was the year of the drought. There are good reasons but if I told you. . . well, you know that tired joke! With this issue, we're opening a series on **Vacuum Gauges**. There will probably be four issues organized as follows.

First, we have preliminaries to take care of. Before looking at measuring pressures, perhaps we'd better understand what pressure is. So, in this issue the. . . what? why? where? of *pressure* is explained. But, to quote Douglas Adams: Don't panic! Not once do I use that disgusting expression 'kinetic theory'. I follow that with a more detailed look at pressure differences/similarities of *gases* and *vapors*. Here, I'm trying to drive home several points (by way of *sidebars*) most folks know, sort of, but don't necessarily string together. I'll finish up this issue by introducing the three *principles* used for measuring pressures.

In the second issue I'll re-introduce these principles and start looking at the specific *mechanisms* inside each principle. Since each mechanism has a diagram or two, that takes space. This issue will only get through the first principle. It also jabs pump manufacturers who are, unfortunately, remarkably un-fazed by my jabs.

The third and fourth issues deal with the remaining measurement principles. In the fourth I'll also address the grand old gotcha: "*I bought two identical gauges from you guys. I put them in the same chamber and you screwed up. They're showing different pressures!*" I ask your prior indulgence if I get snippy in this segment. By the time we get there, you may see why that happens.

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* www.c-c-c.org/chineseculture/zodiac/zodiac.html

Pressure

Looking back through *Lesker Techs* I can't find one that explains *pressure*. Weird! OK, let's jump in at the deep end with a mess of numbers. To make them more exact, let's talk about a 1 meter cubed (1 m^3) box at 22°C filled with pure nitrogen at 760 Torr (1013 mbar).

Mass of one molecule	$4.65 \times 10^{-26} \text{ kg}$
Molecules in 1 m^3 box	$2.48 \times 10^{25} \text{ m}^{-3}$
Average molecular velocity	440 ms^{-1}
Molecules hitting $1 \text{ m}^2/\text{sec}$	$2.86 \times 10^{27} \text{ m}^{-2}\text{s}^{-1}$

And pressure is? . . . the combined force of these exceptionally tiny masses, whizzing about at ~ 900 mph, slamming into the box's walls, at the rate of ~ 3 gazillion per second.

But what if I'd used H₂ instead of N₂. All these numbers would change, right? Surprise! Only two would change:

Mass of one molecule	$3.347 \times 10^{-27} \text{ kg}$
Average molecular velocity	1670 m/s

The number of molecules in the 1 m^3 box at 1 atmosphere and 22°C and the number hitting each face of that box are exactly the same whether we're talking about nitrogen, hydrogen, carbon dioxide, argon, or any other ideal gas. Yeah, yeah! So I snuck in *ideal* and real gases aren't ideal. Just remember, all gases approach ideal behavior as their pressure decreases and I'm talking vacuum here!

And before you recover from the box shock, how about this? Do the old kinetic energy calculation (the equation is in the sidebar *Unitarianism*) for N₂, H₂ or any other gas and what do you get? Yes! the same value!

"Holy high speed zingers, Batman! Does that mean the force exerted by a zippy helium atom smacking into a surface is the same as that of a lumbering xenon atom?"

"'Fraid so, my excitable little companion."

But it gets even better. Suppose we have a mixture of helium and xenon (and it doesn't matter what percentage) that's at 760 Torr in the 1 m^3 box, what's the total atom count? You got it— 2.48×10^{25} !

(And I've just stolen all of Amadeo Avogadro's thunder, about any gas filling 22.4 L at atmospheric pressure containing 6.02×10^{23} molecules, without once mentioning him.)

Unitarianism

Do you recall your high school physics teacher droning on that the units (mass M, length L, time T) on both sides of an equation must agree? Well, life in the big city ain't any better 'cos I'm a unitarian too (note the lower case "u"). But here's the deal—stick with my droning and you'll see this units rubbish makes sense.

Kinetic Energy (KE): Go to Google and type in 'define: kinetic energy'. You'll get maybe 20 hits with the less sloppy ones saying—KE is the energy possessed by a moving body and its value is $\frac{1}{2}$ (mass x velocity squared) or $\frac{1}{2} \text{ MV}^2$. (As this discussion is only about units, I'm going to forget the number $\frac{1}{2}$ when it suits me).

Since we know molecules have mass and are rushing about at some velocity, they must have KE. Let's work out the M, L, T units for KE ($\frac{1}{2} \text{ MV}^2$) and see what happens.

Velocity is defined as the distance traveled per unit time. That is, velocity is length/time or LT⁻¹. But for KE, the velocity is squared so we must square the units too, making them L²T⁻². Multiplying those units by mass gives:

$$\text{KE's units } \text{M L}^2 \text{T}^{-2}$$

Pressure (P): Google (*v. trans.*) a definition for pressure and you'll find: force per unit area. Going deeper, force is defined as mass x acceleration. Ever deeper, acceleration is defined as the rate of change of velocity with time or VT⁻¹. But we've looked at velocity and found it was LT⁻¹. So acceleration is LT⁻¹ x T⁻¹ or LT⁻² and the units of force are MLT⁻²

Area is, of course, L x L or L². So, the units of P (force/unit area) are MLT⁻² ÷ L². Cross out L above/below the dividing line and

$$\text{P's units } \text{M L}^{-1} \text{T}^{-2}$$

Stare at these two expressions below for 3 seconds

$$\text{KE's units } \text{M L}^2 \text{T}^{-2} \quad \text{P's units } \text{M L}^{-1} \text{T}^{-2}$$

and without straining the old grey matter you can see:

$$\text{KE units } \text{x L}^{-3} = \text{P units.}$$

Oh, quit muttering! I'll tell you about L⁻³. We've already noted L² was area. So, what's L³? Obviously, volume! And what does that make L⁻³? How about *per volume*?

Hot diggity! Is it really that simple? The total kinetic energy of all the N₂ molecules in some volume equals the pressure in that volume (give or take a few numeric multipliers)? Yup, you've got it right and your physics teacher just swooned.

Vapor Pressure

The Scent of Chocolate

Pressure measurement newbies often ask, "I understand how gas molecules hitting surfaces and bouncing away cause pressure, but vapor molecules? . . . don't they just hit and stick?" Well, yes and no. Vapors exist because the original liquid or solid has something called an *equilibrium vapor pressure* (EVP). That is, if you put 'enough' material in an otherwise *empty* chamber at some fixed temperature, the chamber's pressure rises to some value, stops, and remains at that pressure. This stable value is the material's EVP at that temperature.

How do vapor molecules do that? Easy. . . they evaporate, maybe have a few gas phase bounces but eventually hit a surface and stick. They continue doing this until the entire chamber surface is coated with at least one layer of vapor molecules. The chamber reaches the material's EVP when the rate at which molecules hit a surface and stick exactly equals the rate at which they unstick from some other place to become vapor.

How long it takes to reach EVP depends on how high the material's EVP is. High EVP materials, like diethyl ether, take a much shorter time to reach their EVP than a relatively non-volatile silicone oil like DC705 or a chocolate bar. Huh? A chocolate bar has an EVP? Well, here's a simple olfactory test—can you smell it? If the answer is, yes, then it must have a vapor pressure. Your nose is reacting to something other than the Beach Boys 'good vibrations.' Me? Oh, I can smell a chocolate bar in a sealed wrapper at a 1000 paces.

Vapors and Gases

But there are other wrinkles to this story. Don't jump to the wrong conclusion when I say empty chamber. The conversion from the original liquid/solid to vapor still happens and the EVP is still reached, even when the chamber has another gas in it. The process just takes a whole lot longer than in an *empty* chamber (see bottom bar).

Let's extend that: let's put a beaker of water into a dry, empty chamber, backfill it with dry air at atmospheric pressure, blank off the system, set the temperature to 20°C, and wait. The initial pressure of 760 Torr slowly rises to 780 Torr.

What happened? Water's EVP at 20°C is 20 Torr. Some of the water evaporated from the beaker, coated the walls, and eventually reached its EVP, which simply added to the air's initial pressure. (To reassure any physical chemists out there, this has nothing to do with Raoult's Law—this is Dalton's Law of partial pressures in action.)

Squashing Vapor to Liquid

Extending it yet further: let's squash this chamber, at (760 + 20) Torr, to half its initial volume. Bobby Boyle's Law tells us halving the volume doubles the pressure. So, in the squashed chamber the pressure is

$$2 \times (760 + 20) = 1560 \text{ Torr}$$

right? . . . **Wrong!** The N₂ pressure (760 Torr) does indeed double to 1520 Torr. But at 20°C the water's equilibrium vapor pressure is 20 Torr no matter what the chamber's volume. So, squashing the chamber causes water vapor to condense until its vapor pressure is again 20 Torr. So, the total pressure is

$$2 \times (760) + 20 = 1540 \text{ Torr.}$$

EVP's Delay

Why does it take more time for a material to reach its EVP if another gas is present? My snooker-ball explanation probably violates every rule in quantum mechanics but here goes.

Imaging putting a glass cheese-cover (GCC) over a particularly smelly cheese wedge. Obviously, the GCC is filled with air and just as obviously, the cheese's surface has some smelly molecules (SMs) on it. And pressure being what it is, these SMs are continuously pounded by air 'molecules'.

Eventually an SM gains enough energy to break the surface's attractive forces and escapes. Let's say, given the SM's high mass and low velocity, it travels about its own diameter from the surface when—zap—it's hammered by an incoming air molecule. In

which direction will the momentum transfer knock the SM? Well, if it's close to the surface, sneaking an air molecule up behind the SM is tough. That is, it's less likely to get bumped into the gas phase than bonked back to the surface where re-sticking is always a possibility.

If this hand-waving picture is even partly true, it's pretty obvious why it takes time for the cheese to reach its EVP under the GCC. But when it does, and you lift the cover . . . phew! Gaseous diffusion (a rapid process) takes over. And writing 'phew' reminded me. Would you believe Cranfield University in Bedfordshire, UK has actually produced a scientific list of the Top 10 'World's Whiffiest Cheeses'? Who said the funds for serious academic research are in decline?

But don't go away thinking of vapors as whimpy clouds of nothingness that are only ever a small part of the total pressure picture. Imagine an empty 1 m³ boiler at 100°C into which 2 liters of water are injected. Some of the water turns into steam and what's its pressure? Yes, 760 Torr because that is water's EVP at 100°C.

And how many H₂O molecules are in the vapor phase of the 1 m³ chamber? Remember, for an atmosphere pressure of N₂ at 22°C there was 2.48 x 10²⁵. Water vapor at 100°C is also at atmospheric pressure but the higher temperature mean there are ~1.96 x 10²⁵ molecules. And why are there fewer in a hot box than a cold box at the same pressure? Well, read the *Unitarianism* sidebar. Pressure is all about kinetic energy... and kinetic energy has a velocity squared term... and higher temperature increases the average velocity... and... you take it from there.

As for the liquid volume remaining, it doesn't matter if it's a drop or a supertanker-load, as long as there's some in the 'reservoir' and it's at 100°C, then the chamber's pressure must be 760 Torr. And for you young whipper-snappers who don't know a Watt from a Newcomen, not long ago **steam ruled**.

Gauging Gauges

Vacuum technology applications that interest us fall in the range 760 Torr (1013 mbar) to perhaps 1 x 10⁻¹¹ Torr (1.33 x 10⁻¹¹ mbar). That's a dynamic range of 10¹⁴! For comparison, I've seen claims that the eye's dynamic range as 10⁵ or 10⁷ and a microbalance is 10⁷. But 10¹⁴ is way out past silly mid off** and going from atmosphere to UHV, measuring pressures all the way, requires three different gauge mechanisms.

Nowadays gauge manufacturers ease the pain of installing many gauges by making:

- One chassis that controls 2 gauges
- One chassis with customizable boards
- One sensor body with 2 mechanism. These are called *wide range* gauges and the pressure indication slides seamlessly through the mechanisms' cross-over pressure. For some combinations the dynamic range might be ~10¹².

However, I'm concentrating on the individual mechanisms and won't address combining them.

Measurement Principles

The three principles on which pressure measurements rely are summarized in phrases from a former era:

May the force be with you

(Obi-Wan Kenobi's hope for Luke Skywalker)

Let's get physical

(Kipner/Shaddick's plea to Olivia Newton-John?)

Accentuate the positive

(Johnny Mercer's message to the World)

EVP Anecdote

A customer's R&D department needed a big vacuum system for testing heavy equipment. They already had a chamber which, in a previous life, provided rough vacuum conditions for another department. R&D wanted to reach 1 x 10⁻⁶ Torr and asked us for a turbo pumping station.

We guessed the chamber's surfaces were less than pristine, so sized the turbo for a high outgassing rate. When tested before shipping, the pump package reached low in the 10⁻⁷ Torr range *stat*—as my medical mates say.

Two weeks later, an R&D engineer called. "No matter what we do, the chamber only reaches the 1 x 10⁻⁴ Torr and we can't find any leaks." Given our overestimation of the outgassing rate, 'no leaks' was tough to believe. We suggested a leak-back check—valve off the pumps, and just watch where the pressure goes.

The engineer called back, "The pressure rose quickly to 0.05 Torr and then stopped." This is classic! The pressure in a contaminated chamber rises to the EVP of the contaminant and quits. This chamber was contaminated with a capital C. We suggested he clean everything.

Three days later, he called back. He'd first shone a UV lamp in the chamber (something we'd never thought of) and a patch of chamber floor fluoresced like Las Vegas Boulevard at midnight. He talked to the original users and learned they'd had an anti-freeze spill. They wiped it up and, since their rough vacuum wasn't affected, forgot about it. So, he only solvent-cleaned the floor and, just before calling us, had seen 1 x 10⁻⁶ Torr on his gauge.

Look for ethylene glycol's vapor pressure on the web and you'll see 0.06 Torr quoted. Clearly, the chamber's pressure limit of 1 x 10⁻⁴ Torr when connected to a high speed turbo indicates that ethyl glycol's evaporation rate from this large patch was pretty d*** quick.

** I'm fed up with 'left field'. If you're American and need a giggle go to <http://www.abcofcricket.com/cfb1/cfb2/cfb3/cfb3.htm> and scroll down to 'fielding positions'. The game's inventors and players from other nations will be less amused.

To re-state those principles in less quotable ways:

1. Directly measuring the **force** of gas atoms/molecules hitting a surface includes the most woefully inaccurate and the most accurate methods of measuring modest vacuum pressures from 760 Torr to $\sim 1 \times 10^{-4}$ Torr.

2. Using some **physical** property of a gas, such as its thermal conductivity, or the drag the gas causes on a levitated ball spinning at high speed, gives moderate to highly accurate measurements from 760 Torr to $\sim 1 \times 10^{-4}$ Torr, but at a price. Only one pure single gas can be present and for (transfer standards) accuracy you'll need a spare \$25,000 in your pocket.

3. Once the pressure gets below $\sim 1 \times 10^{-4}$ Torr, however, you'd better be thinking about ionizing the gas, collecting **positive** ions, and measuring dinky ion currents if you want to measure pressures. As with physical property gauges, accuracy demands one pure gas and a gauge that was calibrated less than 20 minutes ago. In the real world? You'll see later!

In the next Lesker Tech issue we'll start by looking at gauges that respond to the force that gas, confined in a box, exerts on the walls.

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- RPT 100 Series** - Combination Piezo/Pirani style gas independent gauge (7.5×10^{-5} Torr to 900 Torr)
- HPT 100 Series** - Combination Pirani/Bayard-Alpert style gauge (3.75×10^{-9} Torr to 750 Torr)



Contact us at pressure@lesker.com or see our new 8th Edition Catalog available March 2006.

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Mar 13-16	Pittcon 2006	Orlando, FL	3538
Mar 13-15	APS	Baltimore, MD	901
Mar 21-23	Semicon China '06	Shanghai, China	3711

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