

Gauging the Pressure You're Under

Part 2A

Introduction

Here's Part 2A of the Vacuum Gauges series. If you didn't read Part 1 (Lesker Tech Vol. 5 Iss. 1), please do. It discusses gas pressures and vapor pressures which, considering what we're trying to measure, has a certain—how shall I put it—relevance?

By the way, throughout this series when I used the word 'gauge' it means the sensor (the bit attached to the chamber) while 'controller' describes the box of electron-tricks or display.

In this issue, I'll recap the basic principles on which gauges work and look at the various mechanisms inside the first principle. Where possible I've noted the manufacturers' specifications, particularly accuracies, for particular gauge mechanisms.

But it's worth remembering, while the manufacturer once measured numbers close to the accuracies quoted:

- The exigencies of gauge production
- Less than 100% product testing
- Drift
- The hammering the gauge took while under your predecessor's TLC
- Mounting locations that are hot, or close to huge arc welders
- Oil vapor in the chamber that no-one wants to acknowledge
- Your less-than-enthusiastic interest in gauge calibration

and a variety of other effects have probably caused the gauge's accuracy value to expand/contract—always in the direction that makes the displayed pressure more flaky and further from reality. Such effects are so common someone has probably lumped them into a 'law' that bears his name. If not, I've just claimed it!

Using 'accuracy' as a segue, I was tempted to define words you might see, or wish to see, in a gauge's specifications. But it turned into the world's longest sidebar, so, I smartened up and made Part 2B the **Glossary**. Since it's already written, it should pop up in your email (editors willing!) within a week.

Meanwhile, back at Part 2A. . . I throw around indicated pressures (what you see on the display) and real pressure (what the pressure actually is) so often I've contracted them to **IP** and **RP** universally. But I'll wait until you've forgotten that before I use them. Any other words, names, or references I use that you don't recognize—open a browser and Google them.

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Recapitulation

Since you have just re-read Part 1, you'll know I claimed all pressure measurements are founded on three principles:

1. Directly measuring the **force** (actually kinetic energy) of gas atoms/molecules hitting a surface and relating that to pressure.
2. Using some physical **property** of a gas, such as viscosity or heat transfer characteristic, that is sensitive to the number of atoms/molecules and hence, pressure.
3. **Ionizing** the gas by collision with energetic electrons and measuring the resulting flow of positive ions.

Here, we're talking about the mechanisms and attributes of **force** gauges. No, I'm not going to suss out every mechanism hiding in the bushes. I'll just hit the more commonly used (or historically important, but I wouldn't dare mention that 'cos you'd all stop reading!)

'FORCE' GAUGES

Let's settle this 'surface' thing. As long as the gas molecules can hammer against it and the force imparted can be detected, the surface can be liquid or solid. I'll bet the first force gauge was a glass U-tube partly filled with water. Some medieval blowhard puffed into one side and recognized the water levels in the two arms changed. Then he 'sucked' and vacuum technology was born.

Of course, measuring a full range of pressures used in vacuum technology demands either a very long glass U-tube or a liquid denser than water. And, as everyone knows, mercury is such a liquid. So, ignoring Torricelli and his barometer, mercury filled U-tubes (mercury manometers) were the initial DIY vacuum gauges.

Bourdon Gauge

The first real force gauge was invented by Eugene Bourdon (1832). Basically, it is a bent metal tube with an oval cross-section, sealed at one end. If the open end is connected to a pressure



Bourdon Gauge

that isn't 'atmospheric', the tube bends a little more or less, depending on the sign of the pressure difference. The action is a bit like those party hooters—when you blow into them they unroll, sounding like an asthmatic duck.

This mechanism can not distinguish between pure gases, not-so-pure gases, totally mixed up gases, and vapors. It responds to the total pressure of them all, which is wonderful! Today, with a mechanical doodad to magnify the needle movement around the dial, these gauges show up on every gas cylinder regulator around the world.

For above-atmosphere pressures where you might need to know the difference between 138 bar and 131 bar (2000 - 1900 psi), this is a great gauge. But with a couple of exceptions, for vacuum measurements this mechanism's hysteresis and resolution (defined in the **Glossary** Part 2B) mean the Bourdon gauge's accuracy is only 'so-so'.

A typical Bourdon gauge for vacuum application is quoted as '3-2-3'. Near the top and bottom ends of its pressure range, the accuracy is $\pm 3\%$ while in the mid pressure range it is $\pm 2\%$. I take that to mean: when the **RP** is 25" Hg, the **IP** is between 25.75" Hg and 24.25" Hg (that is: $25 \pm 0.03 \times 25$). For a little more filthy lucre you can get a gauge with $\pm 1\%$ accuracy.

For 'inch-challenged' readers, the numbers are: when the **RP** is 0.863 kgf/cm², the **IP** is between 0.889 kgf/cm² and 0.837 kgf/cm². Just incidentally, if you need a good units convertor, check out www.members.optusnet.com.au/ncrick/converters/main.html. It's the work of a retired Australian aircraft maintenance engineer, Neil Ricketts. I only know that because I emailed him in January thanking him for his excellent website.

One of the exceptions to 'normal' accuracy gauges, noted above, is a precision Bourdon gauge made in Europe. One version has a big 8" or 10" diameter dial with a range 0 to 1060 mbar (0 to 795 Torr) and an accuracy of 0.7mbar. I interpret that to mean the accuracy is $\sim 0.07\%$ of full scale (since there's no \pm quoted). At a few tens of mbar up to 1060 mbar, that's great. If your working pressure is in this range and computer interfacing is not a question, this might be the gauge for you.

Bourdon Gauge Characteristics:

- The less accurate versions are pretty much 'dump-truck' rugged
- The accurate version is a good, non-electronic, minimum bells & whistles gauge
- Contamination is not a concern

- The construction materials may limit corrosive gas applications
- An immediately interpretable analog/visual display
- Cannot be interfaced with computers
- Unsuitable to pressure control feedback

Bourdon Gauge Applications:

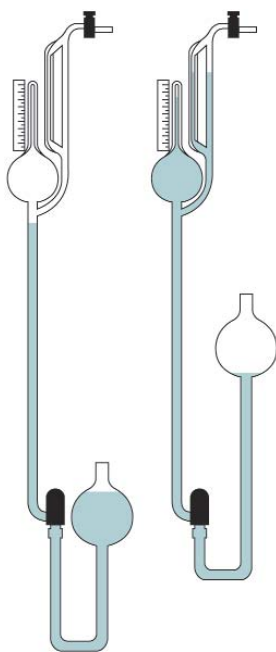
- Gas cylinder regulators
- Vacuum molding equipment
- Rough vacuum de-gassing
- Sub-atmospheric rough gas handling systems
- Central vacuum systems for the lab
- Chemical processes using rough vacuum

McLeod Gauge

The U-tube (manometer) mechanism was improved by H.G. McLeod in 1874. From the guy's initials, you can tell he used a mercury surface. In his version an empty, known glass volume is connected to the pressure of interest and mercury levels juggled to cut off that volume.

The Hg reservoir is raised and the trapped gas is compressed by the rising 'head' of mercury. When the volume reaches some known, small value (in a calibrated glass capillary, sealed at its top end), the reservoir is held still and the difference between the Hg's height in the small volume and the reservoir is measured with a cathetometer in mm Hg or Torr. (See? You just can't ignore Torricelli.)

From the known initial/final volumes and the final pressure, Boyle's Law gives the initial pressure. A McLeod gauge, correctly made, is accurate and precise at measuring pure gases and gas mixtures. Within its measurement range, ~1 Torr to 1×10^{-4} Torr, its accuracy (depending on manufacturing details, of course) is so good that measurement authorities use it as a calibration standard for other gauges.



McLeod Gauge

But vapors? VAPORS? **VAPORS!** Members of Clan McLeod are probably flapping their sporrans in disgust. Re-read Part 1 and you'll see that compressing vapors condenses them back to liquids, which puts the pressure measurement gods all atwitter!

Obviously, sloshing all this mercury around makes each measurement a royal pain. Back in the mid-last century (I've waited so long to use that expression!) I used a McLeod extensively—all that mercury vapor may account for certain personality disorders. Nowadays, OSHA would rightly have a hissy-fit with the apparatus I used, and modern versions are more spiffy. But always remember, using a McLeod (without an LN2 trap) fills your chamber with 1×10^{-3} Torr of mercury vapor (which is mercury's EVP at 20°C—and if you don't know what EVP means, you didn't re-read Part 1, did you!).

As close as I can time it, two decades ago mechanical pump manufacturers found the McLeod gauge and fell head-over-heels in love. Here was a gauge that ignored an oil's vapor pressure. What could be better in their never-ending squabble to prove, "My pump's better than your pump!"? It lets them quote 'ultimate pressures' at the inlet of two-stage rotary vane pumps in the low 10^{-5} Torr range. Unbelievable!

Oh sure, some manufacturers have the decency to state the ultimate pressure is, 'measured by McLeod' in small print while others coyly call it the 'ultimate partial pressure', whatever that means. The truth is, these subtleties zip right over the pump buyer's head who is then incensed (with the messenger!) when his/her chamber bottoms out in the mid 10^{-2} Torr range (not the mid 10^{-5} Torr when measured with regular gauge).

McLeod Gauge Characteristics:

- Hardly your "daily vacuum gauge"
- The ultimate in non-rugged construction
- Contaminates the system with mercury vapor
- Each measurement is a 'event' worthy of decorated floats and marching bands
- Pressure control feedback—are you joking?
- Only works for gases with close to ideal gas behavior
- Utterly incapable of measuring the pressure of vapors
- The word 'digital' means '1, 2, 3'.
- Interfacing a McLeod with a computer was a joke even in Babbage's day.

McLeod Gauge Applications:

- Primary calibration for other gauges
- Precise measurement in gas handling systems used in research labs (e.g. detecting He in meteorites)
- Used for measuring ultimate pressures in rough vacuum pumps (dammit!).

Diaphragm Gauges

The surface in these gauges is a thin flexible diaphragm of stainless steel, silicon, Inconel®, etc. One side of the diaphragm faces the vacuum while the other faces a fixed (often 'zero') pressure. When the vacuum-side pressure changes, the diaphragm's deflection is measured in some electrical, rather than mechanical, method.

Since the gas is not compressed and the diaphragm responds to the force of any atom or molecules hitting it, these gauges have the wonderful advantage of not distinguishing between pure gases, mixed gases, and vapors. But note, if the gauge is cooler than the chamber, vapors may condense in the gauge volume which can be a trifle confusing.

Diaphragm Manometer

For this gauge, the diaphragm can be stainless or silicon. Attached to the diaphragm's backside is a strain gauge that bends, converting the movement into an electrical signal. Since the diaphragm flexes in proportion to pressure and the strain gauge's output is proportional to degree of flex, then the output signal is proportional to pressure.

I'm not sure how strain gauges work, but I suspect they're cheap. At home, we have a posh kitchen scale that uses a strain gauge. It measures in ounces or grams, has a zero-out button, shows weights on an LCD, and the whole shebang cost less than \$18 from one of these artsy, upscale kitchen equipment stores (yeah, the pun was deliberate—just checking your melatonin level).

The diaphragm manometer works in the range 760 Torr to ~1 Torr with an accuracy of $\pm 1\%$ of reading or ± 1 Torr—whichever is worse. If the **IP** is high, 300 Torr, then the **RP** will be in the range determined by the 1% of reading [$300 \pm (300 \times 0.01)$], between 303 Torr and 297 Torr. However, if the **IP** is 1 Torr, then the **RP** is between 2 Torr and 0 Torr, using the ± 1 Torr accuracy value.



Diaphragm Manometer Characteristics:

- A good everyday gauge for its pressure range
- Largely unaffected by contaminants
- OK with any gas that does not attack SS or Si
- Measures the pressure of vapors but cannot be heated—meaning a vapor that condenses at room temperature may condense in a colder gauge
- Display is digital
- Can be interfaced with computers
- Some versions can be used for feedback control in higher pressure ranges

Diaphragm Manometer Applications:

- Sub-atmospheric gas handling systems
- Monitoring pump-down curves
- Often the high pressure part of a 'wide range' gauge assembly

Piezo Manometers

Ever wondered how your barbie's ignitor works? You pull a trigger or turn a switch until there's a 'snap' and the gas catches fire. It's all about piezoelectricity. A quartz crystal, when bent just slightly, develops a high voltage across the crystal's ends. A Wikipedia.com entry claims: a 1 cm quartz cube with 500 lbf (2 kN) applied to it, can produce 12,500 V. I'm guessing, but probably making the crystal thinner in one dimension means less force is needed to get the same voltage. Feed that to a small spark gap immersed in something combustible and snap: "*Houston, we have ignition.*" or, more likely these days, "*Xichang, the big firework's blue touch-paper is lit.*" [Come to think of it, the latter quote was more likely in ancient history too!]

Since the voltage is some function of the crystal's 'bentness', some clever folks mounted a quartz plate to a stainless steel diaphragm in a vacuum gauge. As with other diaphragm gauges, a pressure change deflects the diaphragm, which bends the quartz, which varies a voltage, which corresponds to the pressure, which is displayed on a screen, that sits in the house that Jack built.

This mechanism covers the range 760 Torr to ~1 Torr with an accuracy of



<1% reading and repeatability of $\pm 0.03\%$ FS. So, an **IP** of 460 Torr means the **RP** is between 464.6 Torr and 455.4 Torr (calculated as $460 \pm 0.01 \times 460$). But at low pressure it's not the accuracy that determines the inaccuracy (yeah, yeah!), it's the repeatability that gets ya! Say the **IP** is 3 Torr, then the **RP** using just accuracy error is 3.03 Torr to 2.97 Torr (calculated as $3 \pm 0.01 \times 3$). However, the repeatability confines the **RP** between 3.28 Torr and 2.76 Torr (calculated as $3 \pm 0.0003 \times 760$).

Piezo Manometer Characteristics:

- Like to the diaphragm manometer but more accurate
- Good everyday gauge for its pressure range
- Largely unaffected by contaminants
- OK with any gas that does not attack stainless steel
- Measures the pressure of vapor but cannot be heated—meaning a vapor that condenses at room temperature may condense in a colder gauge
- Display is digital and often in the user's choice of units
- Some versions have a digital output that directly interfaces with computers

Piezo Manometer Applications:

- Sub-atmospheric gas handling systems
- Monitoring pump-down curves
- Often the high pressure measuring part of a 'wide range' gauge assembly
- Some versions used for feedback control in higher pressure ranges

Capacitance Manometer

Perhaps the best known gauge in this group is the capacitance manometer. In this gauge, the metal diaphragm's movement is measured by detecting its (AC) electrical capacitance to some isolated electrodes close to its 'zero pressure' surface. To give you a feel for the 'precision' of this measurement, in Lafferty's *The Foundations of Vacuum Science and Technology*, Peacock noted that for a high accuracy capacitance manometer, the diaphragm's minimum resolvable deflection is about 3\AA or the diameter of an atom.

This is the most accurate practical pressure measurement device around for the range 1000 Torr to $\sim 1 \times 10^{-5}$ Torr.

A leading manufacturer (MKS Instruments) make gauges with a standard accuracy of 0.25% of reading. That is, at an **IP** of 720 Torr, the **RP** is between 721.8 Torr and 718.2 Torr (calculated from $720 \pm 0.0025 \times 720$). For an **IP** of 3×10^{-3} Torr the **RP** is between 2.9925×10^{-3} Torr and 3.0075×10^{-3} Torr (calculated from $3 \times 10^{-3} \pm 0.0025 \times 3 \times 10^{-3}$).

For the real nit-pickers out there, the same company makes a gauge with 0.08% accuracy.

Capacitance Manometer Characteristics:

- The most accurate diaphragm gauges, indeed, the most accurate gauge of any type that is suitable for everyday use
- OK with any gas that does not attack Inconel
- Can be heated and is often temperature stabilized above ambient
- Measures vapors just like gases
- Display is digital, in user's choice of units
- Can be interfaced with computers
- Used for feedback control throughout the pressure range of the specific sensor

Capacitance Manometer Applications:

- Sub-atmospheric gas handling systems
- Monitoring pump-down curves
- Specific models measure 100% vapor in CVD and ALD processes
- Accurate working pressure measurement for sputter deposition systems
- Feedback in precise pressure- or flow-control systems
- See sidebar (next page) about choosing gauges for 'reading' and 'controlling'



Watch for the **Glossary** (2B or not 2B) soon, and after that we'll continue with Property and Ionization Gauges

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Reading vs Controlling Pressures

Before you rush off and buy a capacitance manometer here are some points to ponder taken from MKS's literature:

1. The total operational pressure range (1000 Torr to 1×10^{-5} Torr) isn't covered by just one gauge. While sensors have full scale (F.S.) pressures of 0.02, 0.05, 0.1, 1, 2, 10, 100, and 1000 Torr, the dynamic range of any one sensor is $\sim 1:10^4$. To read any pressure within the full range you'll need (at least) two gauges.
2. If you're only **reading** a pressure, then the 0.02 Torr F.S. gauge is OK down to 1×10^{-5} Torr while the 1 Torr F.S. is OK down to 5×10^{-4} Torr.
3. If you're **controlling** a pressure, then the 0.02 Torr F.S. gauge is OK down to 1×10^{-4} Torr and 1 Torr F.S. is OK down to 5×10^{-3} .

So why the difference between **reading** and **controlling**? My local MKS engineer says, all gauges have output signals 0 - 10 VDC for zero to F.S. pressure. While a reading that's just a few millivolts is acceptable, attempting to control a process with just a few millivolts signal is daft.

The noise and ripple on that signal (induced from nearby electrical gear) will have the control electronics dancing like Drew or Stacy doing the jive. For control, get the output voltage above 50 mV where the influence of noise and ripple will be much less.

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Date	Event	Location	Booth
June 17	Canadian Light Source	Saskatoon, Canada	21
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June 28-29	Electronic Materials Conf.	University Park, PA	101
July 11-13	Semicon West	San Francisco, CA	2108/7330

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