

Gauging the Pressure You're Under

Part 3

Introduction

This is part 3 of the Gauges Quartet, so let's first review parts 1, 2A, and 2B (yeah, it's one of those quartets).

Part 1 introduced the three 'principles' on which pressure measurements are made:

- The **force** exerted by gas atoms/molecules on a surface
- Using a gas's **physical** property that is pressure dependent
- Ionizing the gas and detecting the **positive** ion current

Part 2A looked at some of the **force** gauges commercially available and noted their applications. Part 2B gave a **glossary** of terms used to describe a gauge's characteristics. This issue is about **physical** property gauges and in writing it, I refer so often to two excellent books that I've given them shorter names:

"*Founds*" - *Foundations of Vacuum Science and Technology*,
1998 ed JM Lafferty

"*Totes*" - *Total Pressure Measurements in Vacuum Technology*,
1985 by A Berman

Yet again I'm using **IP** (indicated pressure) for what you read on the display and **RP** (real pressure) for the force per unit area the gas exerts on the walls. As always, any other words, names, asides, or references you don't recognize—open Google and search.

Physical Properties of Gases

Introduction

Right out of the starting gate, these gauges raise naming issues. Modern authors divide them into Energy Transfer or Momentum Transfer types. But in common vernacular they are called, *Thermal Conductivity* (i.e. energy transfer) and *Viscosity* (i.e. momentum transfer)—names adopted before the vacuum industry reached the age of enlightenment! Alas, despite a better understanding of what's going on, the 'industry' names have stuck.

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The problem is, *thermal conductivity* and *viscosity*, while valid gas properties, aren't necessarily the properties these gauges use. So, before venturing into explaining the gauge mechanisms, let's kick the tires on those gas properties.

Thermal Conductivity

Open Google and type *define: thermal conductivity*. Up pops many definitions all stating something like: "*Thermal conductivity measures the transfer of heat through a material*" which, as a definition, is like Philip Glass's music.

Go to hyperphysics.phy-astr.gsu.edu/hbase/hframe.html and drill down into Thermodynamics looking for 'thermal conductivity, You'll find "*Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole*" which, when discussing gases, stretches the bounds of credibility just a tad!

Home.worldonline.dk/jsrsw/Tcondvspressure.html makes a logical derivation that shows ". . . *thermal conduction is independent of pressure*" (original author's emphasis). In addition, chapter 1 of *Founds* states, ". . . *the thermal conductivity of a gas is independent of pressure, which is valid as long as the pressure is higher than the range in which molecular flow occurs.*"

So, we're about to measure pressure using a gas's thermal conductivity that doesn't vary with pressure!

But work with me here. When you stick a spoon into your steaming potato soup, Clausius's version of the Second Law of *Thermodynamics* (I just shuddered!) states, heat only flows from the hot pot to the cool tool. So, we probably need something hot if we expect to use thermal conductivity to measure pressure.

Let's make a wire hot by passing an electric current through it. Let's put that wire in an cylindrical 'case', surround it with gas, and then decide how it loses energy. The list of effects that contribute to energy loss is surprisingly short!

1. Thermal radiation to the case
2. Thermal conduction through the power leads
3. Thermal conduction by the gas to the case
4. Convection in the gas to the case

Figure 1 (from data shown in *Founds* for one particular gauge) shows the relationship between pressure (x-axis) and some function of the wire's temperature (y-axis).

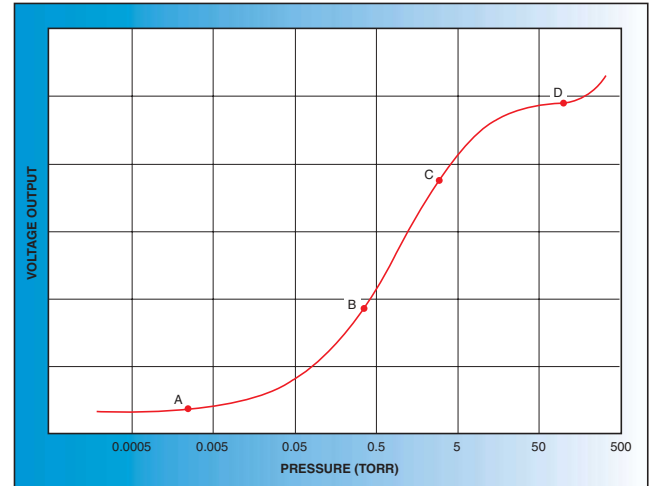


Fig. 1

Below point A on the graph, effects 1 and 2 dominate. Between A and B effects 1 and 2 have a decreasing influence on effect 3. The straight line from B to C may show that effect 3 dominates. From C to D effect 3 is petering out. Above D effect 4 gets into top gear. Indeed, devices that measure pressures near one atmosphere are deliberately constructed to enhance effect 4.

Since *Figure 1* shows that the wire's temperature does vary with pressure, albeit in a very non-linear way and only partly using thermal conductivity, what we need is a way to measure a wire's temperature and we have a pressure gauge. Two methods are commonly used:

- *Thermocouple* (See Sidebar) for **thermocouple** gauges
- *Wheatstone bridge* (See Sidebar pg. 3) for **Pirani** and **convection** gauges

Thermocouples Explained

Do you have dental cavities drilled and filled with dental 'amalgam'? According to www.cdc.gov/oralhealth/factsheets/amalgam.html amalgam is roughly equal amounts of liquid Hg and an alloy powder of Ag, Sn, and Cu, sometimes with a little Zn, Pd, or In.

Have you ever jabbed a filling with a stainless steel fork or chewed on aluminum foil? Did you leap over the nearest tall building? If so, you know all about thermocouples—and may just be Clark Kent. That Kryptonite blast was an electric current running through your tooth's nerve.

Cont. on pg. 3

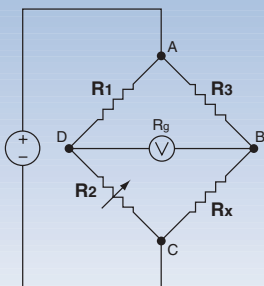
An electric current? Yup! And here's an easy, non-painful demonstration. Grab a length of copper wire from any old cable in your garage. Ask your local florist for a few wires used to support flower arrangements (they're usually iron). Take one Cu and one Fe wire and scrape all four ends to remove insulation and corrosion. Twist together one pair of ends, connect the other ends to a DC microvoltmeter, and a voltage appears—a voltage large enough to drive a current through your tooth's nerve.

A thermocouple is the junction between two dissimilar metals that gives stable, repeatable *Seebeck Effect* voltage for a fixed junction temperature. Change temperatures and the voltage changes—that's how thermocouples indicate temperature.

So, back to the wire kept hot by a current flowing through it. Weld a tiny thermocouple junction to the wire's mid-point; Connect the output to a circuit that automatically converts temperature to pressure; and *ta-daa!* we have a **thermocouple** pressure gauge.

Wheatstone Bridge Un-Explained

While Wheatstone was a talented guy, he didn't invent this bridge. That credit goes to Sam Christie—son of Christie's auction house founder. Wheatstone got the honors by improving and popularizing the bridge as a method of accurately measuring resistance.



The 'bridge' consists of four resistors; **R_x** is unknown; **R₁** & **R₃** are known and fixed; **R₂** is known and variable. By fooling with the variable resistor till the meter reads zero, then using a little mathematical jiggery-pokery with resistance ratios, you can accurately measure **R_x**'s value. Alternatively, you can fix **R₂** too, and then (avoiding Star Wars jokes) the meter reading depends on **R_x**'s value.

Now, if **R_x** is a wire with a repeatable *resistance vs temperature* curve, and if the wire's kept hot by a current flowing through it, and if its resistance is automatically measured by the bridge, and if a circuit automatically converts this resistance to temperature, and if another automatically converts this temperature to pressure, then *sapristi nabolis!* all those 'ifs' have produced a **Pirani** pressure gauge.

Thermal Conductivities of Different Gases

However, before celebrating "We got gauges!", let's sneak a peek at the thermal conductivity of various gases (these values are taken from *Found's*.)

Gas	Thermal Conductivity (W/cm.K)
H ₂	17.30
He	14.36
N ₂	2.38
O ₂	2.44
Ar	1.60
CO ₂	1.44

If thermal conductivity has any part in the heat transfer from wire to envelope, shouldn't we be bothered by these values?

Let's say you have a closed volume filled with pure CO₂ at a known **RP**. You note the **IP**. You then replace the CO₂ with exactly the same **RP** of pure H₂. Will the new **IP** be: the same? a little different? on another planet? My guess . . . ? Oh, I'm already donning my space suit.

Look at it a different way—let's consider a gas we'll call Mixture 1. What if the first molecule to hit the wire is CO₂, the next is H₂, and the next is Ar? Won't the energy transferred during each collision be different? And won't the total heat transfer depend on the heat transfer 'properties' of each separate atom/molecule?

And if the gas composition changes a bit to something we'll call Mixture 2, so that the 'hits' are Ar, H₂, H₂ won't that change the total heat transfer? My answer is . . . you betcha!

And if you change the total heat transfer, won't the wire's temperature change? Again . . . you betcha!

And if the wire's temperature changes won't that change the **IP** even if the **RP** of Mixture 1 is exactly the same as the **RP** of Mixture 2? One more time . . . you betcha!

Viscosity

Open Google and type *define: viscosity*. You'll get over 25 hits crafted in such exquisite prose— "*Duh, like its rezitants to flo*"—you'll wonder what Flo did to deserve it. Wikipedia almost saves the day by mentioning '*shear stress*' and '*fluids*' but it's clearly biased towards liquids. Not one hit discusses gas viscosity, so, the first question is, do gases exhibit viscosity?

And here I'm stumped. I can't think of one simple test to show viscosity is a gas property. (Yes, there's a complicated test involving gas chromatography, constant gas pressure, and temperature programming—but I'm not sure we're ready to handle all those "unsubscribe" emails.)

All I can say is, gases do exhibit viscosity and here are two factoids with which you can astound your friends (and guarantee they'll avoid you in future).

Factoid 1: As its temperature goes up, every gas's viscosity *increases*.

Factoid 2: A gas's viscosity is largely *independent* of pressure.

Dayton, writing in *Foundations*, claims the confirmation of these factoids, ". . . has been justly regarded as one of the most signal triumphs of the kinetic theory of gases."

Given what increasing temperature does to your car's oil, road tar, molasses, or even that potato soup you stole from the refrigerator, factoid 1 is a real kick in the head. But don't dwell on that. . . look at factoid 2. We're headed, yet again, for another rip-roaring failure by measuring pressure using a gas property that doesn't change with pressure.

Writing in *Foundations* Peacock states, "Viscosity gauges utilize the drag effect observed when gas molecules act upon a moving object or surface."

In *Totes* Berman writes, "The *viscous damp* or *drag effect* due to changes in a gas viscosity is determined by measuring either the *damping* effect on a vibrating surface. . . or the *drag* exerted on a rotating surface." (The emphasis is Berman's.)

Both mention viscosity but in subsequent paragraphs neither points a finger anywhere near ". . . a measure of the resistance of a fluid to deformation under shear stress" which is how www.wikipedia.com defines *viscosity*.

Interactive Viscosity

Here is a game for an idle moment. Go to <http://bpesoft.com/s/wleizero/xhac/?M=v> and play about. It's an html 'form' that calculates various atmospheric parameters vs. altitude. I made a table of a few (rounded) results:

Altitude (m)	Pressure (kPa)	Viscosity (kg/m.s)	Temperature (°C)
0	101.5	1.789e-05	15.0
100	100.3	1.786e-05	14.4
1000	90.0	1.758e-05	8.6
10000	26.5	1.458e-05	-49.9
30000	1.2	1.503e-05	-41.5

For the "kPa-challenged" the pressure in the first line is roughly one atmosphere and in the last line is ~8.6 Torr.

Look at the viscosity column. As the altitude increases (and the pressure decreases), viscosity drops a bit. But then at the lowest pressure, viscosity pops back up. What's happening? Well, look at the temperature column and recall factoid 1. Gaia sneakily increases the atmosphere's temperature between 10000m and 30000m.

Considering how the temperature drops from 0m to 10,000m, you might suspect that viscosity variations are more about temperature change than pressure change. And you'd be right.

High Pressure Viscosity

What about the 'other end' of the pressure scale, where vacuumists fear to tread? Does viscosity rocket up when gas pressure is above 14.7 psia (760 Torr or 0.1013 MPa)?

I looked at the viscosity of CO₂ at 305K (~90°F), first in the Handbook of Chemistry and Physics and then in a Wikipedia entry (on supercritical fluids) at the same temperature:

Pressure 0.1 Mpa viscosity 0.0148 cp

Pressure 7.38 Mpa viscosity 0.02 - 0.1 cp

That is, carbon dioxide's viscosity increases ~5x for a pressure increase of ~70x

As proof that *viscosity* increases rapidly with *pressure*, that doesn't exactly blow my door handles off. Talking of door handles, that 5:70 ratio roughly describes how my ancient XJ6's speed varies with its petrol consumption.

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Viscosities of Different Gases

Our experience with the thermal conductivities of different gases suggests we'd better look at the viscosities of different gases too. I've tabulated a few data from a 1958-1959 edition of the CRC's *Handbook of Chemistry and Physics*. (Like wines, I like my data—mature.) These are the values listed for atmospheric pressure and 20°C (or close there-to), except water vapor which is given for 100°C.

Gas/Vapor	Mol Wt	Viscosity (micropoise)
H ₂	2	87.6
He	4	194.1
H ₂ O	18	125.5
Ne	20	311.1
N ₂	28	178.1
O ₂	32	201.8
Ar	40	221.7
CO ₂	44	148.0

How'd you like them apples, sports fans? See any rhyme or reason in those numbers? But it gets even more staggering if you compare the viscosities of slick helium atoms and clunky hydrocarbon vapor molecules like n-nonane when both are at ~200°C.

Helium 267.2 micropoise

n-Nonane 78.1 micropoise

It's like: "So, *viscosity* gauges don't use viscosity as the measurement property? Well, hot diggity, ain't that a relief!"

Physical Property Gauges

As should be obvious by now, the response of a *gas property* gauge depends on:

- The gas's pressure
- (Dare I say it?) the gas's properties

And one of those properties is composition! Any small changes in the gas composition can, and often will, make large changes in the *IP*. And, regrettably, this is one area where calibration does squat. If you're measuring a gas's pressure and you don't know its composition, how can you possibly calibrate a gauge with an identical gas mixture?

So, in most applications, these gauges have terrible and unpredictable accuracy—not because they are bad gauges but from that d*** gas composition problem.

Thermoconductivity Gauges

If you read the gas properties stuff above, it's no surprise there are three common gauges in this 'energy transfer' group—*Pirani*, *thermocouple*, and the *convection*. Table 1 gives each gauge's approximate pressure ranges.

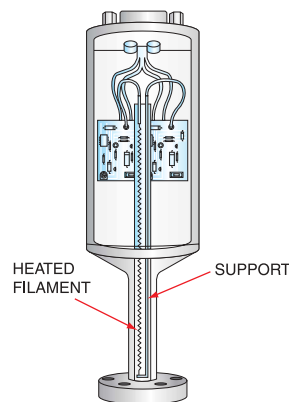
Name	Pressure Range
Pirani	10 ¹ – 10 ⁻⁴ Torr
Thermocouple	1 – 10 ⁻⁴ Torr
Convection	10 ³ – 10 ⁻¹ Torr

Peacock, writing in *Foundations*, says the combination of *Pirani* and *convection* mechanisms into an 'enhanced Pirani' gauge that covers the range 1000 Torr to 10⁻⁴ Torr was sorted out in 1957. But they've only been commercially implemented in the past decade or so.

Pirani Gauges

Marcello von Pirani invented this gauge in 1909 right after he patented a electron beam source for vacuum melting and refining tantalum and other high melting point metals. Vacuum-wise, this was one multi-talented guy!

How the Pirani gauge does its hot wire thing is described in the *Wheatstone Bridge* (See Sidebar pg. 3). But there are interesting wrinkles since the wire can be heated in: constant-current; constant-voltage; or constant-temperature modes. The last is the most sensitive and accurate since the thermal radiation (effect 1) and thermal conduction through the power leads (effect 2) are both constant in this mode.



Trouble is, the bridge must be 'balanced' before every pressure measurement and the circuitry to automate that is more expensive than 'constant-current' or 'constant-voltage' circuits. So, take note: not all gauges with the same name are created exactly equal.

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Different manufacturers quote accuracies as:

- (a) < 5% of value or ± 3 mTorr, whichever is larger
- (b) $\pm 5\%$ F.S. from 7.5×10^{-4} to 0.75 Torr
- (c) $\pm 15\%$ of reading between 5×10^{-3} and 1×10^2 mbar.

It's possible the better accuracies are constant-temperature gauges; I can't tell from the information given. But I have to believe these numbers completely ignore all that 'gas composition' stuff I ranted about earlier.

Characteristics:

- A pretty rugged 'everyday' gauge for its pressure range
- Measures the pressure of vapors too
- Inaccurate—due to gas composition errors
- Digital displays
- Can be interfaced with computers
- Some versions can be used for feedback control in higher pressure ranges

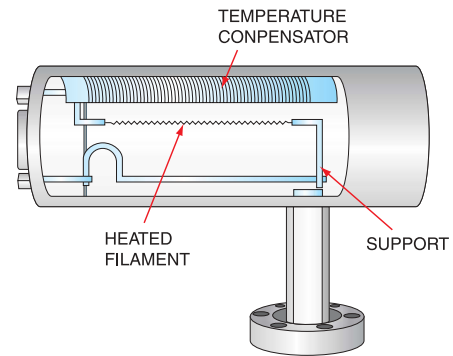
Applications:

- Cross-over pressures (rough pump to high vacuum pumps)
- Rough vacuum de-gassing
- Backfill to rough vacuum pressure
- Chemical processes using rough vacuum

Convection Gauges

Basically, the convection gauge is a Pirani gauge turned on its side. With a horizontal hot wire, convection transfers heat to the surface vertically above it. If that surface is the gauge's vacuum envelope, ambient temperature variations will affect the heat transfer rate. So convection gauges have an additional surface inside the envelope outfitted with temperature compensation coils.

And that's about all manufacturers will tell you. My suspicion is, the coils simply heat the surface to something above normal ambient. Heat transfer is always between a hot wire at $X^{\circ}\text{C}$ and a surface at $Y^{\circ}\text{C}$ where X and Y are fixed above room temperature.



Trying to pin down accuracies for convection gauges is like chasing a will o' the wisp. One manufacturer of an enhanced Pirani quotes $\pm 15\%$ accuracy around midrange but states '*accuracy is reduced at the limits of the measuring range*'. Another company truly claims its convection gauge's accuracy is '*exceptionally good*'. Exceptionally good compared to what . . . Primanti Brothers sandwiches as a weight-loss diet?

Characteristics:

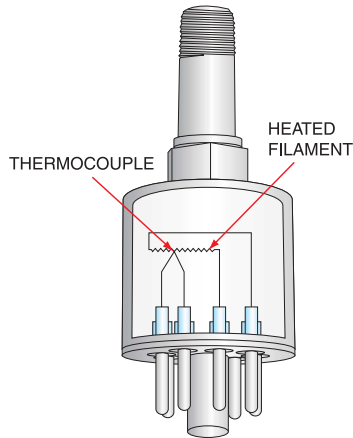
- The enhanced Pirani covers the range 1000 Torr to 10^{-4} Torr in one gauge
- Measures the pressure of vapors
- Accuracy is for the birds (**plus d***** gas composition)
- Gauge axis must be horizontal or everything is screwed
- Digital display and computer interfaces

Applications:

- A pacifier ('dummy' in British English) to relieve the "What's happening?" angst during long rough-downs from atmosphere
- Cross-over pressures (particularly for rough pumps to roots blowers).
- Central vacuum systems
- Vacuum molding equipment
- Course vacuum de-gassing
- Sub-atmospheric rough gas handling systems

Thermocouple Gauges

Invented in 1906 by Voege, the thermocouple (T/C) gauge's mechanism is described in *Thermocouples Explained* (See Sidebar pg. 2).



T/C gauge accuracies vary with manufacturer and pressure range. Examples from different manufacturers are:

- (a) ± 1 mTorr 1-20 mTorr, $< 5\%$ reading 20-1000 mTorr
- (b) $< \pm 2$ mTorr 1-20 mTorr, $< 5\%$ 20-2000 mTorr
- (c) ± 1 micron 0-10 microns, 10% reading 10-100 microns, 20% reading 100-1000 microns

Characteristics:

- A rugged everyday gauge for its pressure range
- Measures the pressure of vapors
- Inaccurate—(need I write 'gas composition' again?)
- Filament is hotter than the Pirani's and is said to contaminate easier
- Low cost analog display versions available but you can get swish digital displays too
- Some models give a DC output voltage and I'll bet there are some with RS 232

Applications:

- Monitoring cross-over pressures (particularly rough pump to high vacuum)
- Low pressure gas backfill supplies
- Double o-ring differential pressure measurement
- Degassing pressure measurement

Viscosity Gauges

While kicking viscosity's tires above, I was quickly convinced the mechanism of *viscosity gauges* has nothing to do with viscosity. In *Totes* index, under 'Viscosity Gauge', Berman refers to a slew of other gauge names: Decrement, Radiometer, Resonance, and Rotating. Reading through Berman's short descriptions, however, all seem to be different ways of measuring momentum transfer.

I think only two 'commercial embodiments' (as the toilers at the patent office say) of these momentum gauges have existed long enough to be called products. And while I'll never own up to such bias, I'm all for crass commercialism and if you can't buy it, you won't hear about it here!

The two broad groups of commercial momentum transfer gauges are 'waggers' and 'rollers' or, to express that with more linguistic precision, *quartz crystal oscillators* and *spinning rotor devices*. But the mechanism is the same for both: the gas's pressure directly affects the rate at which the atoms/molecules hit the wagger or roller, which affects the momentum transfer rate and causes some detectable effect on the wagging and rolling.

With viscosity out the window as a mechanism, viscosity differences between specific gases is unimportant. However, momentum transfer effects are also gas-specific so we're far from out of the woods if we want to use such a device to measure the pressure of anything but a pure gas.

Quartz-Crystal Oscillator

A variety of quartz crystal oscillators have been used including: fibers and vanes; single- and double-ended tuning forks (literally like those found in Seiko wrist watches in some cases); and discs suspended on torsional wands. To visualize what a torsional wand might be, Europeans or Anzacs should imagine a Jowett Jupiter's suspension; North Americans should think anti-sway bar. (I apologize to readers in other continents for not having appropriate analogies.)

All these devices depend on gas molecules hitting some oscillating part and either:

- Reducing its resonant frequency (and measuring the power needed to maintain the oscillator's amplitude)
- Slowing the oscillator (and timing the rate of 'slowth')

The trade magazine *Solid State Technology* in June 2004 stated: "*Modern quartz-crystal oscillator gauges use tuning fork designs and have a pressure measurement range from*

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10^{-4} mbar to atmosphere." Using umpteen keywords, I've searched high and wide but can't find one commercial source of such gauges. One Japanese company apparently offered one in 1997 but when I checked its website . . . bupkis! My guess is, the mechanism is just a little too delicate and measurements a little too long-winded to make good practical, everyday gauges.

Spinning Rotor Gauge

The only commercially available momentum gauge I have found is MKS Instruments' spinning rotor gauge (SRG). Interestingly, the SRG's brochure states: "*Collisions of the gas molecules with the surface of the ball impart a drag which decelerates the ball. Pick up coils measure the deceleration.*" Doesn't sound like MKS believes in the *shear stress* of *viscosity* either.

Adding to my skepticism, the SRG has 'guaranteed precision' in the molecular flow regime from 5×10^{-7} Torr to 1×10^{-2} Torr. Expressed differently, put this gauge in transitional/continuum flow, you might expect *shear stress* in the gas to make a difference, and all bets are off. Yes, it will measure pressures up to 1 Torr but the 'guaranteed precision' pressure range quits two decades lower.

At the heart of any SRG is a ~5 mm diameter ball that's electrostatically or magnetically levitated and spun at 400-800 rpm. Once at speed, the spin power supply is disabled so the ball spins freely. Collisions with gas molecules decelerate it and pick-up coils measure the deceleration rate. Using the sampling time and the gas's physical parameters, an accurate pressure reading is determined.

And how accurate is *accurate*? For the MKS SRG in its 'guaranteed precision' range the accuracy is "1% of the measured value $\pm 3 \times 10^{-8}$ Torr. . ."

I interpret this as: if the **RP** is 3.4×10^{-4} Torr, the **IP**'s value will be in the range 3.383×10^{-4} to 3.417×10^{-4} Torr (that is, the **IP** is within $\pm 0.5\%$ of the **RP**).

I think the $\pm 3 \times 10^{-8}$ Torr bit is one of those 'whichever is the greater error' indications (although it would be nice for MKS to confirm this in the specs). If correct, the $\pm 3 \times 10^{-8}$ Torr accuracy only kicks in when the **RP** is lower than 6×10^{-6} Torr (since $\pm 0.5\%$ of 6×10^{-6} is $\pm 3 \times 10^{-8}$). As an example, say the **RP** is 8×10^{-7} Torr, then the **IP** will be between 7.7×10^{-7} and 8.3×10^{-7} Torr.

If all these accuracy numbers sound pretty good, they are! MKS's SRG is used as a stable *transfer standard* meaning it

is calibrated to some traceable standard before shipping and used to calibrate other gauges.

Characteristics:

- Accurate as all get out—providing it's a pure gas that's being measured
- Not an everyday pressure gauge, nor is it intended to be
- Measures the pressure of vapors (but why would you?)
- MKS Instrument's version has DKD traceable calibration (NIST optional)
- Suggested re-calibration cycle, 1-2 years
- No filaments and no ionization
- Digital display and RS 232 interfacing
- Even back in 2002 a complete gauge cost ~\$11,000

Applications:

- Calibrating other gauges that overlap the pressure range 5×10^{-7} to 1×10^{-2} Torr for example: capacitance manometers, ionization gauges, and RGAs
- Monitoring semiconductor tools with critical pressure requirements

Conclusions

Gas property gauges certainly have: a place, a pressure, and a price in which they are the best deals around. If you're into mostly pure gases (or vapors), then the repeatability is good and calibration with that pure gas can make the accuracy reasonable too.

But as stated many times, when measuring the pressure of mixtures such as the residual gases that vary in composition, implicitly trusting the value you read off the gauge controller is a bit naive.

At the top end of the measurement hierarchy, the spinning rotor gauge is the bee's knees for accuracy and repeatability. It is used to calibrate other gauges.

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