the Bell Jar
Vacuum Technique and Related Topics for the Educator & Amateur Investigator

Notes from the Vacuum Shack **No. 9 August 2020**

In this issue:

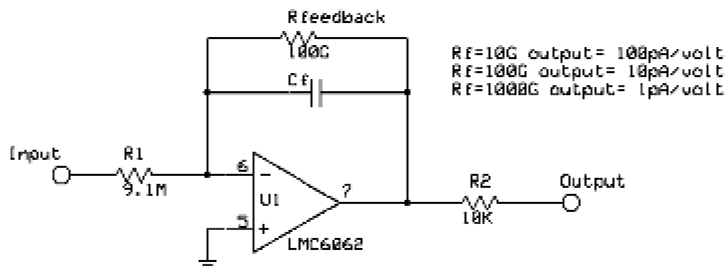
- Update on Chuck Sherwood's Alphatron gauge
- Making Use of Orifices
- The Vacuum Technology Education System (VTES)

Homebrew Alphatron Update

Chuck Sherwood (chuck1024@wowway.com) has continued to work on his Alphatron vacuum gauge. The June issue described his initial results. This article presents an update on the alpha gauge sensor and the electrometer. Readers should feel free to contact Chuck regarding his work.

The current version (2nd prototype) of the sensor assembly consists of 48 each ^{241}Am sources that were obtained via eBay. This seems to be the practical limit based on sensitivity in terms of current vs. pressure. The photos below show external and internal views of the assembly.

With regard to the electrometer, the Alphatron sensor generates an ion current proportional to the pressure. This current is only 5 pA per Torr in the first prototype and 7pA in the second prototype. This requires a sensitive electrometer to measure. Fortunately modern electronics makes this fairly easy with a simple current to voltage converter as shown here. The op-amps (LMC6062) are cheap but high value resistors are quite expensive. Surplus resistors are available but values will be off due to drift associated with age.



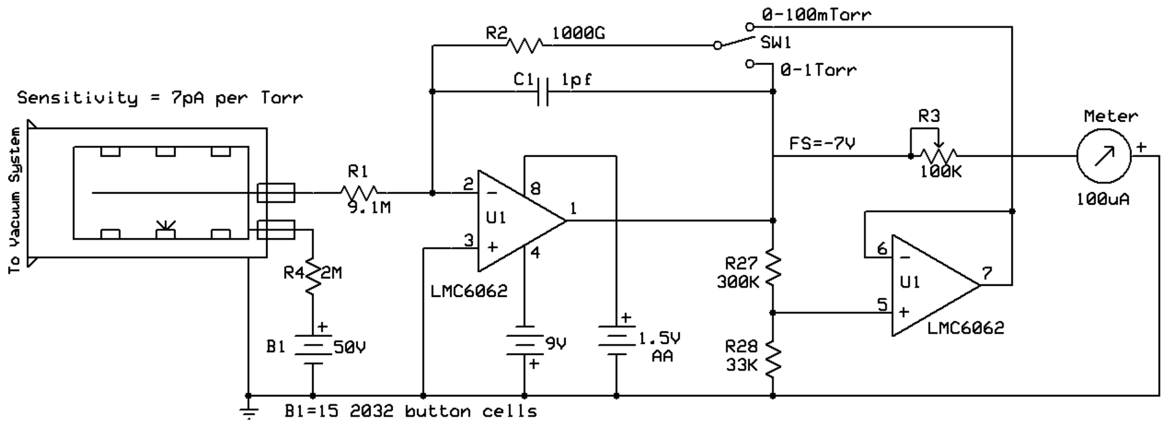
R1 is intended to limit input current spikes and has no effect on circuit operation. The input current flows into the op-amp and the op-amp adjusts the output voltage so the current through Rf matches and cancels the input. With a sensitivity of 7pA per Torr, the output with 1000 G feedback resistor is -7 volts at 1 Torr. By changing the feedback resistor in decades the output can be made to scale in decades producing -7V at 10 Torr with a 100 G resistor and -7V at 100 Torr with 10 G resistor. A few picofarads placed across the feedback resistor stabilizes the circuit. This capacitor needs to be a high quality low leakage part.

1000 G is the largest resistor I could find but it is possible to simulate a larger resistor by feeding back a percentage of the signal. I went through a couple of iterations to produce a final circuit with switchable ranges and readout.

This circuit feeds back 1/10 the output signal, emulating a 10 teraohm resistor providing a 100 mTorr range.

There are several issues associated with having multiple ranges. One is that switching signals at these levels is very difficult. The second is that the resistors have poor tolerances. I have found it necessary to use a gain stage for each range to compensate for the resistor variations and to set the output voltage to match the pressure.

The schematic on the next page shows the circuit with battery power. The 2 meg resistors are only to prevent destroying the batteries if the pickup wire is short circuited. The range switch selects between 0-100 mTorr and 0-1 Torr. I plan on adding 10 and 100 Torr ranges when I figure out a good switch arrangement. The unit works well and tracks well with commercial capacitance manometers.



Making Use of Orifices

Precision flow orifices represent a very versatile (and economical) tool for the vacuum experimenter. They can be used as simple mass flow control devices and for diagnostic purposes such as determining pumping speed.

I won't go into the characteristics of orifices or the basic flow and pressure calculations here. Two useful resources are my article in *Vacuum Technology & Coating* "The Orifice (not just another hole)" [1] and the video tutorial at http://www.belljar.net/video/orifice.html.

An important take away is that the flow through the orifice is directly proportional to the upstream pressure as long as the ratio of upstream to downstream pressures is >2:1. This is the choked (or sonic) flow condition. The choked flow condition is easy to achieve when flowing gas into a vacuum chamber.

I began using precision orifices on my home equipment sometime around 2003. This coincided with the exercises that I developed for the VPAL-A vacuum training system. The manual [2] has a couple of flow exercises that use orifices.

A few years later I built a "clean" passive high vacuum system using a molecular sieve trap (Kurt J. Lesker's "Micromaze", now discontinued) in combination with my Alcatel (now Adixen) rotary vane pump. The adsorption trap isn't really a pump in the normal sense – it simply cleans up the residual water vapor and blocks the backstreaming of oil – much like the action of any adsorption or cold trap. The system could pump a small volume to the mid 10^{-5} Torr range quite nicely. It performed well enough for small flash x-ray devices and the like and was more convenient to use for such small scale tasks than my old 2" Varian diffusion pump.

For some applications, I needed to raise the pressure into the low milliTorr range (just below where the "barefoot" mechanical pump would work) and introduce a working gas such as argon. Given the minuscule pumping speed of the system, the needed flow rates would be very small as well. For this I chose a 5 micron orifice.

Lenox Laser [3], besides offering a wide variety of flow orifices, has a very nice orifice flow calculator. (Registration is required but the use is free.) This works for a wide range of inlet and outlet pressures, gases and units. With a 1 atm. (760 Torr) input pressure, air and 17 degree C ambient, the calculated flow into vacuum was 0.22 sccm. When inserted into my system, the measured pressure was 3.5×10^{-3} Torr.

Using the relationship Q (Torr-l/s) = P (Torr) x S (l/s) my computed effective pumping speed was 0.8 liters per second which reasonably coincides with the manufacturer's pumping speed curve for this particular pump.

Next I checked the pressure with decreasing upstream pressures at the orifice while maintaining the choked flow condition where $Q = \mathrm{k}P$.

For example, at 3 psia (152 Torr) above the orifice (20% of atm. pressure), the calculated flow was 0.044 sccm, pressure was 7.5×10^{-4} Torr and effective pumping speed was again 0.8 l/s.

Needless to say, for pressures above 1 atm. at the orifice inlet the relationship follows.

For use with other gases flows will be higher (e.g. deuterium) or lower (e.g. argon) through a given orifice. The Lenox Laser calculator makes these calculations very simple.

Sub-atmospheric Pressure Regulators and Orifices

In the section above, I mention the use of an orifice with a sub-atmospheric upstream pressure. For this I use a sub-atmospheric pressure regulator on my gas line. If you are interested in using this type of device, there are several types of below-atmosphere regulator.

One type is commonly called a vacuum regulator. These are used to regulate the level of vacuum in a pumped chamber. In this type of application, the chamber is connected to a vacuum pump through the regulator. The regulator works by controlling the flow between the chamber and the pump. This type of regulator is also called a back pressure regulator since the pressure is controlled at the inlet port. A bleed into the chamber is required.

A second type is the vacuum relief, or vacuum break, regulator. These connect to the pumped chamber and admit ambient gas (generally air) to maintain the pressure.

The third type is the sub-atmospheric pressure regulator. This is inserted in the line between the gas source and the vacuum chamber and works exactly like a positive pressure regulator except that the outlet can be below 1 atm.

The regulator that I have is a CONCOA 412 series sub-atmospheric pressure regulator. The high pressure side is connected to a gas cylinder (typically an argon cylinder) and the outlet goes from -30 inHg (full vacuum, atmosphere referenced) to 30 psig.

One issue with very small aperture orifices is the purging of the line. First, assuming that the orifice is close to the chamber, the volume of the connecting line to the regular should be as short and small as possible. The line on my system is ¼" OD polyethylene tubing with a ⅛" ID and a length of about 4 ft. For very flow flows, I also have a purge line that goes to a supplemental vacuum pump. This effectively evacuates the line while the regulator is set to zero pressure (i.e. -30 inHg). The purge step also helps to ensure that the gas entering the chamber is as pure as possible from the outset.

Summary

Bottom line, I really like orifices for pressure control and diagnostics. They are easy to work with, very repeatable and low maintenance (just be sure to put a really good filter ahead of the finer orifices - I use a 0.5 micron filter).

In the next issue I'll have some practical pressure control examples using orifices.

References

1. Steve Hansen, "The Orifice (not just another hole)," *Vacuum Technology & Coating*, June 2009.
2. V*acuum Principles and Applications - Summary of VPAL Set Up Procedures and Exercises,* pp. 21-22. http://www.belljar.net/education/vpal_a_2007.pdf
3. https://lenoxlaser.com

The Vacuum Technology Education System (VTES)

Background

The first vacuum trainer that I designed was the MKS VTS-1B. This began as a prop for my on site vacuum training classes and was first used in late 1995. Shortly thereafter, the SEMATECH consortium launched a major effort to promote community college level programs for students who would enter the semiconductor industry as equipment and process technicians. Vacuum was one of the key elements in these programs. Seeing an opportunity, we launched the VTS-1B as a classroom training system for these programs. The layout and instrumentation of the system included standard industrial elements (fittings, flanges, gauges and controllers) arranged in a way that invited disassembly and reconfiguration while being quite resistant to damage from mishandling.

We sold quite a few to 2 and 4 year colleges (and even a high school) in the US, Singapore and the UK. Later on we offered a high vacuum add-on with a residual gas analyzer. A pressure reduction orifice was included so that gases in the medium vacuum side of the system could be monitored by the RGA.

Eventually, the call for plasma training resulted in the production of a separate RF trainer with a magnetron sputter gun and 100 watt 13.56 MHz generator and matching network.

When I retired in 2009, the product line was discontinued but the VTS-1B, in a simplified form, lived on in the VPAL-A that was manufactured and marketed by The Science Source in

Waldoboro, Maine. The full documentation for all of these systems is available on the *Vacuum Education* pages of my site.

The Science Source was sold in 2015. This ended the VPAL-A. The buyer had no interest in the vacuum trainer as the volume was relatively low and the support requirements were fairly high. Just before the sale, we were working on a more refined version of the VPAL-A which would also include an option for a high vacuum pump and an RGA. This would include some "real" vacuum hardware and the option to include functional elements such as mass flow controllers and even closed loop pressure control. With regard to these elements, one could go full-bore with heavy duty industrial grade equipment or go for less expensive options that have equivalent functionality. To save cost and lower unnecessary complexity, some minimal machine work is required.

I've gathered up my notes and the bits and pieces of prototype hardware with the intention to make all of this openly available. In this article I'll cover the general design goals with specifics on the medium vacuum base unit. I'll also mention a number of planned expansion options. These will be covered in later articles.

Overview

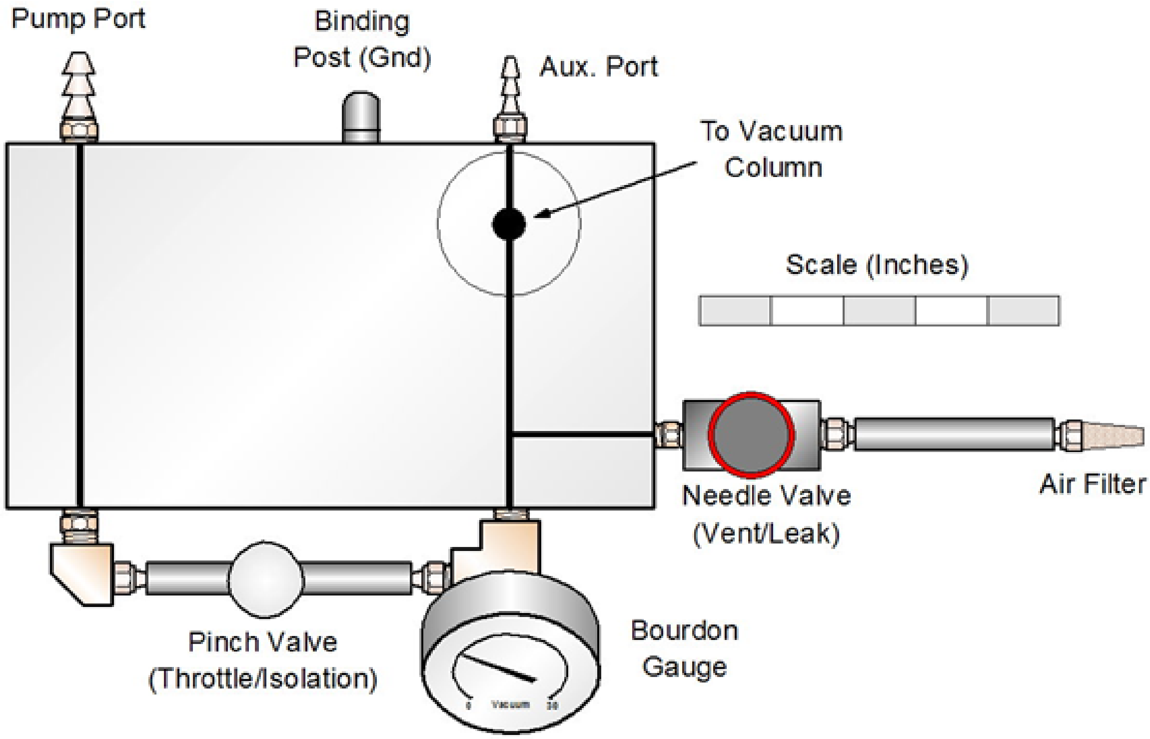
On the *Vacuum Educatio*n page are a couple of pictures of the 2012 training system prototype. The one on the left shows the aluminum base manifold with a plastic bell jar. The one on the right shows a configuration with a mass flow controller, microPirani gauge and a capacitance diaphragm gauge (all by MKS Instruments). The glass chamber (partially shown) is the same one used with the VPAL-A. Inside the chamber is a simple DC sputtering set up. This photo may be considered to be somewhat hypothetical. The remainder of this section will discuss the organization of the platform and some ways in which it may be configured for specific purposes.

The primary component is the base. It contains several flow passages that are connected together. The figure on the next page shows the layout of the base.

The base is fabricated from a 9 inch length of 5 inch x1.25 inch 6061 aluminum flat. I got it cut to length from Speedy Metals (http://www.speedymetals.com). The piece could be somewhat larger but the indicated dimensions accommodate all of the necessary components in a compact assembly.

Per the figure, drill two 7/16" holes from the front to the back at the indicated locations. These should be midway between the bottom and top. You will likely need to drill from each side due to the length of the hole. Then, using an R size drill, bore a hole from the right end to intersect the right fore and aft channel. Complete the flow channels by drilling a 7/16 inch hole from the top surface at the specified location to intersect with the right fore and aft channel. Drill this hole a little deep but definitely not through the plate.

Each of the fore and aft channels should now be tapped for ¼-NPT pipe. The side one is tapped for ⅛-NPT. The vertical hole in the top will be tapped for ¼-NPT.



I would suggest adding a tapped hole on the rear for a ground terminal. Now is also a good time to drill and tap holes on the bottom for rubber feet. I'd suggest feet that are ½ inch high.

At this point you may want to bore holes for mounting a flow controller, integrated pressure controller or proportioning valve. I drilled mounting holes for the "standard" MFC pattern, an MKS 640 pressure controller and an Enfield PFV-W12E01-P012C-0100 proportioning valve. Given my background, the choices of MFC and pressure controller as options would be obvious. I chose the Enfield valve as it has an integrated analog 0-10 volt valve driver which makes it compatible with a number of readily available PID controllers. It might also be easy to integrate with an Arduino microcontroller. More on this at a future date.

Now we can move on to attaching the various fittings.

The trickiest part of the assembly is the attachment of the KF40 to ¼-NPT female adapter. I used an aluminum MKS adapter part number 100312005 as it is easy to modify and is quite thick. There is not much thread in the attachment point in the base and I didn't want a gap between the adapter and the base. I ended up drilling a hole in the adapter large enough to clear a closed brass 1/4" nipple and deep enough so that the adapter with nipple could be screwed together without a gap. After drilling the clearance hole, tap the remaining hole. After dry fitting, put some fast setting epoxy on the nipple threads (level the epoxy with the top of the thread) and then assemble.

The figure shows the remaining fittings and their locations. The vent port serves a dual function. One, obviously, is for a vent valve. The other is for simple pressure control. For the valve I originally used a simple hardware store brass needle valve. More recently I have been using an

ARO 104104-F01 flow control needle valve. This valve has a composite body with metal inserts. It provides a much finer degree of control than is possible with the cheap hardware store valves. This valve should be installed with the valve seat on the vacuum side.

The photo below shows the details for the Bourdon gauge attachment. It is angled at 45 degrees for ease of viewing. The gauge shown is a 2-1/2" Weksler gauge with oil fill. It is marked in inHg and kPa.

The flow path is from the manifold that is attached to the KF40 flange then to the front where the Bourdon gauge is located. Here there is a tee that goes to a short length of ¼" ID x 7/16" OD Norprene tubing (available from McMaster-Carr https://mcmaster.com). A pinch clamp is mounted on this tube. This is used to control the pumping speed. I used a Flow-Rite PV-4W. These valves fit snugly on the tubing and work smoothly. The other end of the tube passes through the base to the rear where there is a ½" hose barb for the pump line. A ¼ inch hose barb is at the opposite end of the channel. This may be used as an extra attachment point but generally will be closed off with a short length of Norprene tubing and a pinch clamp.

The Manifold Assembly

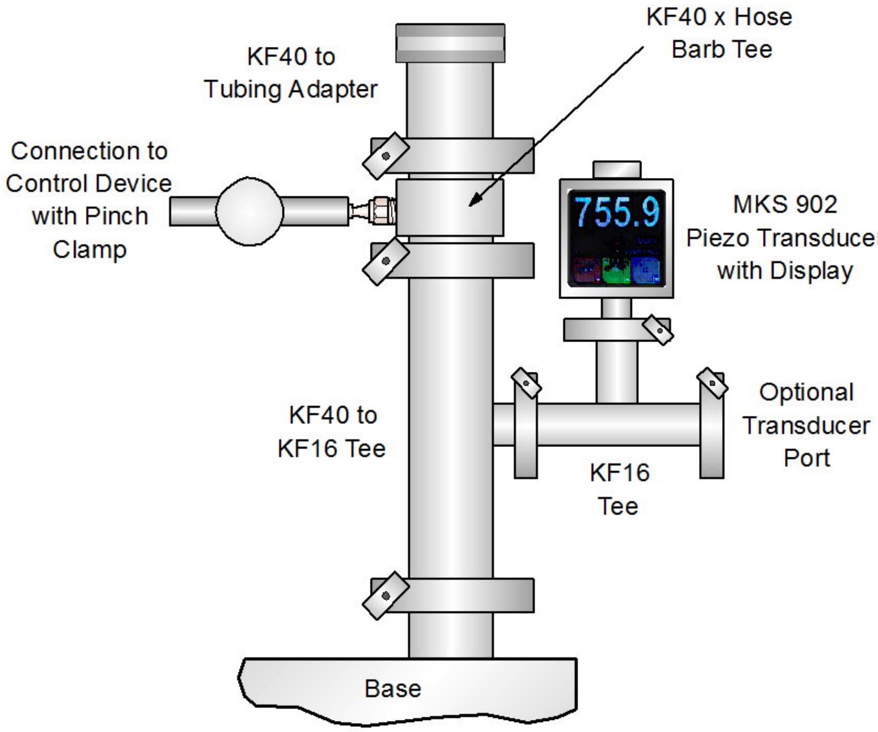
The manifold itself is fairly simple, consisting of several standard vacuum components. The illustration on the next page shows the components.

A 40 to KF16 tee is mounted on the KF40 flange on the base. Connecting to the side port is a KF16 tee. The illustration shows an MKS absolute piezo gauge, model 902, with integral touch screen display. This provides a complete gauge with readout and controls in a nice package that only requires DC power. I have the analog/RS232 output version of the gauge, the same configuration and pinout as the 925 microPirani gauge. For data logging, I use both the MKS software (available at https://mksinst.com/vtsw) as well as Vernier's Logger *Pro* 3 program. Information on interface cabling, software and set up are available on the *Vacuum Education* page.

The 902 measures from 0.1 to 1000 Torr. This is a narrower range than that of the 925 (10^{-5} to 1000 Torr) but the upper couple of decades are more accurate and the 902 is gas type insensitive. The default scaling is linear, 0-10 volts.

The extra port on the tee can be used for a second gauge. Here is where a microPirani gauge or even a capacitance diaphragm gauge (CDG) could be attached. For example, the output of a microPirani could be compared to the piezo (or CDG) gauge with different gases. The microPirani would be useful to extend the low range of the equipment to below 0.1 Torr.

Please note that the 925 is now available with an integral display.



Above the KF40 tee is a KF40 to ¼-NPT tee. This has a ¼ inch hose barb that can be used to attach the upper part of the column to any of a variety of flow or pressure control devices. The simplest device would be a precision orifice (see the related article in this issue). Other options would include the aforementioned MFC, pressure control or proportioning valves. A pulse valve e.g. fuel injector (see the July 2020 issue) could also be attached here.

Above this tee is a KF to tubing adapter. The VTS-1B used a 1-½ inch stainless steel adapter. The VPAL-A used a 1-1/4 inch brass fitting soldered to a brass KF40 flange. This is no longer an option as brass fittings have disappeared. If starting from scratch, I'd suggest a 1-⅛ inch adapter as they seem to be more readily available.

On the next page is a photograph of the system as described above along with the Enfield proportioning valve. The valve, as shown, is configured with a 5 micron inlet filter.

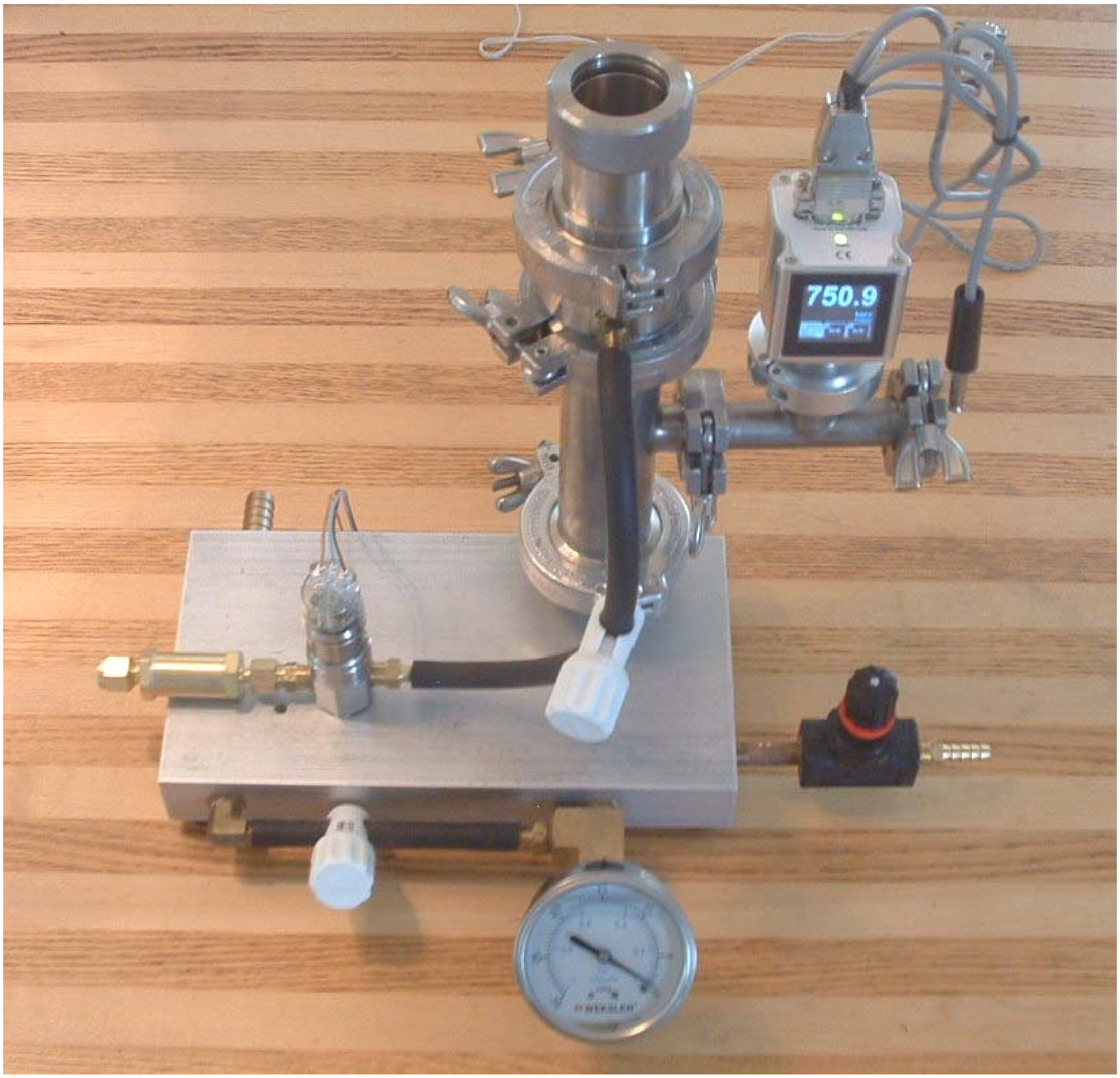
Conclusion

As a training tool, the VTES, as described, can be used to perform all of the exercises that are in the VPAL-A manual. With the exception of the closed-loop pressure control exercises, all of the exercises in the VTS manual can be performed. The system can also be used as a platform for other vacuum projects.

Some planned enhancements include:

- A more flexible sputtering chamber that can also be used for plasma etching. This would also include an electron gun with deflection plates.
- A Penning chamber for optical emission spectroscopy (OES)
- Closed loop pressure control.

Stay tuned.



Articles of Possible Interest in *Vacuum Technology & Coating* Magazine

July 2010
Traps: If you think you can't be baffled, you might fall into a trap
This article looks at the three common forms of trapping mechanisms: absorption, adsorption and condensation. We also looked at several practical applications of traps, including the prevention of backstreaming, water condensation and the control of condensable process effluents.

August 2010
Traps Gone Wild: When Traps become Pumps
Examines how the mechanisms that are used in traps can also be used to make practical vacuum pumps..

Articles may be accessed at http://vtcmag.com/. Scroll to the bottom of the page to the back issue selection box. Look for my columns and you can probably find other articles of interest in each issue.

That's it for this month.

Steve