

ACCELERATOR VACUUM 101, MADE EASY???*

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Abstract

This paper, FERMILAB-CONF-06-568-AD and MSDN – ME – 000069, has been formatted for presentation as background material for the BIW08 tutorial on vacuum issues. The original paper is used as a vacuum primer for engineers and technicians at Fermilab's Accelerator Division, Mechanical Support Department. This version is without the appendix, which has specific examples to illustrate how this material is used. The full document can be obtained from the Fermilab, AD/MS Department.

INTRODUCTION

This paper presents a condensed, simplified, and practical discussion of the principles, procedures, and operating parameters of particle accelerator vacuum systems as practiced at Fermilab. It is intended to provide a basis for designers, builders, and operators of accelerator systems to communicate with each other about the needs and impact of the vacuum system. Rigorous analytical development of the equations and concepts are not given. It is assumed that the reader has some limited understanding of the subject. Practical examples of real world experiences are used to illustrate the concepts outlined. Examples of how to use this material is given in appendix 1 and references for further study are given in appendix 2. The following advice is given for people who design, build, or operate accelerator vacuum systems:

- A) Keep it simple.
- B) Keep it clean.
- C) Establish guidelines and standard practices; then follow them.
- D) Always stop and think about what the outcome will be before you do something to the system.
- E) Test and certify everything you can before it goes in the system.
- F) Despite the abundance of "hot air" around physics laboratories, air is not the only gas we need to think about.
- G) There is no vacuum gauge on this planet that, in and of itself, gives you the real picture.

Vacuum can be a complicated subject, but on a base level it does not need to be. Some may view this discussion as over simplified, but they should realize others don't have their level of understanding. Others may find it complicated and they should realize that they need to have a base understanding in order to meet operational goals.

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All need to realize that they need to communicate with each other on some base level. Most of the problems that arise in vacuum practice are a result of a lack of knowledge or communication. Complicated technical issues can be addressed by physicists and experts. Practical issues are usually addressed by engineers and technicians. Having a base understanding by all involved is essential to ensure a successful outcome for the projects they work on.

WHY VACUUM?

Most all vacuum texts start out with a discussion on the ideal gas law ($PV = nRT$). For this discussion it would be nice to avoid this, but it is simply too fundamental to ignore. In particle accelerators the purpose of the vacuum system is to remove gas molecules from the path of the beam. So, for accelerators it is more appropriate to think of the ideal gas law in terms of the number of moles in a volume. Pressure is nothing more than a measure of the number of molecules that can interfere or interact with the beam.

$$n = P V / R T \quad (1)$$

Where: n = Number of Moles
 P = Pressure (Torr)
 V = Volume (L)
 R = Universal Gas Constant (62.3632 Torr-L/K-mol)
 T = Temperature (K)

THE VACUUM WORLD ACCELERATORS LIVE IN

Figure 1, below, is a graphic representation of the vacuum bounds associated with accelerator vacuum systems. The information depicted is intended to be a guide or a starting point when thinking about accelerator vacuum systems. Given a pressure range that a system needs to operate in, the chart gives a reasonable estimate of the out-gassing rate needed, the time scale that will be needed to achieve a given pressure, and the likely pump types that will be needed.

The chart shows $1(10)^{-3}$ Torr as the transition point between the viscous and molecular flow regimes. This is not strictly the case, though. Molecular flow can exist above $1(10)^{-3}$ Torr and there is the transition flow regime between viscous and molecular. For all practical purpose in accelerator vacuum systems $1(10)^{-3}$ Torr is a good place to start thinking about molecular flow.

For the systems encountered in accelerators the range between atmosphere and $1(10)^{-3}$ Torr is not of a lot of concern. The roughing pumps and turbo molecular

Elastomers will permeate water and helium and have a significant out-gassing rate. Helium permeation will interfere with leak checking by lowering the sensitivity and slowing clean-up time.

BASIC EQUATIONS FOR VACUUM

Equations 2 through 5 constitute the basic equations for most all vacuum work. Knowing these relationships and how to apply them is essential for understanding what is happening with regard to any vacuum systems. In most cases accelerator vacuum work can be simplified to this level. References [1] & [2] in appendix 2 are excellent sources for learning how to apply and understand these relationships. In these sources, additional formulas for calculating the conductance based on an assortment of geometries and gasses are presented. Figure 2 illustrates the effect of geometry on the conductance for round tube.

For molecular flow the following apply:

$Q = S P$ (Eq. 2) (Relationship between Flow, Pump Speed, & Pressure at the Pump)

$Q = C \Delta P$ (Eq. 3) (Relationship between Flow, Conductance, & Pressure Drop)

$C = k A \alpha$ (Eq. 4) (Relationship between Conductance, Gas Species, & Geometry)

$1/S_{eff} = 1/S + 1/C$ (Eq. 5) (Relationship between Effective Pump Speed, Rated Pump Speed, & Conductance)

- where:
- Q = Gas Flow (Torr-L/s)
 - S = Pump Speed (L/s)
 - P = Pressure (Torr)
 - C = Conductance (L/s)
 - k = Flow Constant for Specific Gas (L/s-cm²)
 - A = Cross-Sectional Aperture Area (cm²)
 - α = Transmission Probability
 - S_{eff} = Effective Pumping Speed (L/s)

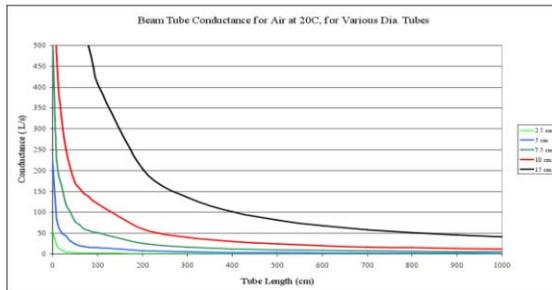


Figure 2. Conductance for round tube. Multiply by $(29/M_m)^{0.5}$ to adjust for other gasses, where M_m = molar mass (g/mol) of gas.

SYSTEM DESIGN

At this point in the discussion it is useful to outline the basic design parameters used in designing accelerator vacuum systems. Figure 3 shows the basic layout for most accelerators. In general there is some vacuum space (generally a stainless steel tube) with pumps connected to it at some defined spacing (L_p). The spacing is often dictated by the length of the magnets used for steering the beam. The aperture of the tube can be round, elliptical, or rectangular and is mostly dictated by the beam size and the magnet pole tip spacing. The vacuum levels required are dictated by the beam and operational reliability. Equations 6 through 8 [1] are the governing relationships for the system design.

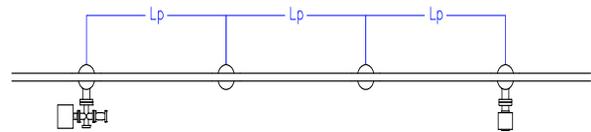


Figure 3. Basic accelerator vacuum system layout.

$P_m = P_p + \Delta P$ (Eq. 6) (Pressure between pumps)

$P_p = q_D B L_p / S$ (Eq. 7) (Pressure at the pump)

$\Delta P = q_D B L_p / (4C)$ (Eq. 8) (Pressure drop in a beam tube from midpoint to pump)

- Where:
- P_m = Midpoint Pressure (Torr)
 - P_p = Pump Pressure (Torr)
 - q_D = Specific Outgassing Rate (Torr-L/s-cm²)
 - B = Inside Tube Perimeter (cm)
 - L_p = Pump Spacing (cm)
 - C = Conductance Over Length $L_p/2$ (L/s)

Although the beam size and magnet geometry dominate the geometry for the vacuum system, vacuum considerations must be taken into account early in the magnet and tube size selection. This is necessary to make sure the vacuum system will perform as needed. To illustrate this, example 1 is given in appendix 1.

COMPONENT AND DEVICE DESIGN

This brings us to the point in the discussion where we need to address components and devices that get placed where magnets aren't. For the purpose of this discussion, components are any part of the vacuum system that is not the beam tube. Components would include bellows, fittings, flanges, valves, and any other parts whose primary function is as part of the vacuum system. Devices are components whose primary function is beam related. Examples would be RF cavities, separators, collimators, Lambertsons, and instruments such as BPM's, IPM's, flying wires, etc.

Given that there is a basic system design, a system will have some gas load per unit length. If $Q = S P$, then $S P / L_p$ equals the gas load/cm for the system. Any component or device to be installed has to have a gas load, per unit length, equal to or less than the above load. If the gas load is larger, additional pumping must be supplied. In general the pressure at any additional device or component has to have a pressure equal to or less than the average in the system. Devices and components installed in accelerators tend to have very large internal surface areas relative to their length. In addition, the materials used are not always the best choice for use in vacuum systems. Therefore, very high gas loads can be expected. Examples 2 and 3 are given in appendix 1 to illustrate these basic concepts.

Someone knowledgeable in vacuum practice should always be involved in the design, manufacture, and assembly phases of these components and devices. The best way to assure that these are built so that they will do no harm to the vacuum system that they will reside in is to test the components before they go into the assembly and certify the assemblies before they go in the system. If components and devices are installed without certification there is a very real risk that the entire system can become contaminated.

Figure 4 is a sketch of a test chamber for testing parts that will be used in devices. The set-up would be the same for certifying an assembly, with the assembly replacing the chamber. With a set-up like this, one can test for out-gassing rates, total gas load from a part, identify contaminants, and determine the gas composition in the assemblies. Tables 1 & 2 are

examples of the results obtained from tests done with this set-up.

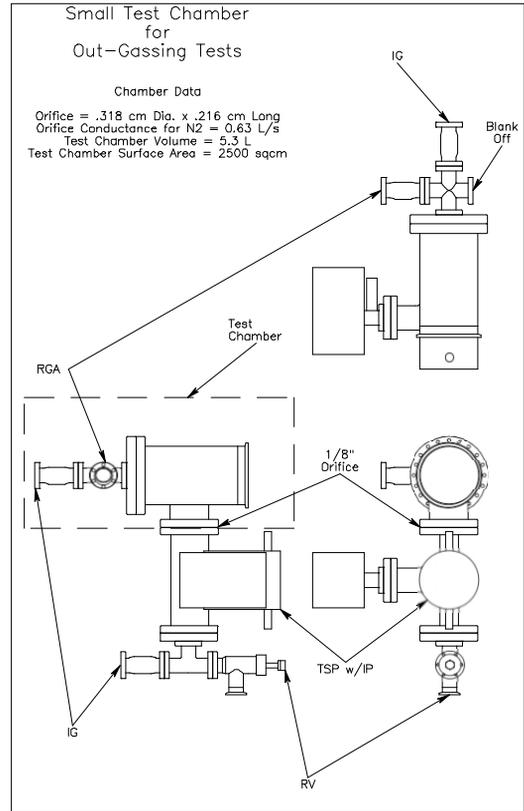


Figure 4. Vacuum test chamber set-up.

Table 1: Out-gassing Rates (Torr-L/s-cm²) of Various Materials

Material	Totals	H ₂	CH ₄ Methane	H ₂ O	CO / N ₂	C ₂ H ₆ Ethane	Ethyl Alcohol	O ₂	Ar	C ₃ H ₈ Cyclo - propane	CO ₂
Stainless Steel (unbaked)	1.0E-10	5.0E-11	2.0E-13	5.0E-11	1.0E-12	5.1E-14		3.0E-16		1.0E-14	1.0E-13
Stainless Steel (baked, no degas)	5.1E-11	5.0E-11	2.0E-13	8.0E-14	2.0E-13	5.1E-14		3.0E-16		1.0E-14	8.0E-14
Stainless Steel (baked & degassed)	6.7E-13	6.2E-13	1.0E-14	1.3E-14	1.3E-14	5.4E-15		1.7E-16	4.8E-16		5.7E-15
Torlon (baked)	3.1E-08	4.2E-09	6.2E-11	2.5E-08	6.7E-10	9.6E-11		8.2E-11	2.6E-12	7.5E-12	9.1E-10
Armalon (baked) (Glass filled Teflon)	3.1E-10	3.0E-10	2.0E-12	6.0E-12	4.0E-12	3.0E-13	3.0E-14	2.0E-15	1.0E-14	4.0E-13	2.0E-12
Rulon (baked)	6.7E-11	6.1E-11	1.7E-13	4.2E-12	1.4E-12			1.4E-15			1.3E-13
MF190 (baked)	6.5E-11	4.0E-11	2.5E-13	1.1E-11	6.0E-12	1.1E-12		3.8E-14	3.3E-15	5.7E-14	6.2E-12

Table 2: Out-gassing Rates (Torr-L/s) of Various TeV IPM Flex Circuit Components

Sample Material	Total	H ₂	CH ₄ Methane	H ₂ O	CO / N ₂	C ₂ H ₆ Ethane	Ethyl Alcohol	O ₂	Ar	C ₃ H ₈ Cyclo - propane	CO ₂
Test Chamber Baseline	2.3E-08	2.2E-08	1.2E-10	2.2E-11	6.8E-10	1.2E-11			5.3E-13	3.7E-13	3.6E-11
Flex Circuit Sample 1	1.0E-07	8.7E-08	6.9E-11	1.9E-09	1.3E-08	5.0E-10	1.2E-10	4.9E-12	3.1E-11	1.3E-10	6.2E-10
Flex Wires	2.3E-08	2.2E-08	1.7E-10	1.5E-11	9.9E-10	2.5E-12					3.9E-11
Flex Circuit Sample 2	1.7E-08	1.6E-08	7.1E-11	4.0E-11	9.7E-10	2.1E-12	1.2E-11				3.4E-11
Flex Circuit Sample 3	3.9E-08	3.1E-08	4.6E-10	7.0E-10	5.6E-09	5.4E-11		3.9E-11			5.6E-10
Peek Connector, before bake	1.3E-04	3.6E-05	1.1E-07	8.5E-05	2.0E-06	2.2E-07		6.4E-06	6.4E-08	1.1E-09	3.3E-06
Peek Connector, after bake	7.2E-07	4.0E-07	1.4E-09	2.7E-07	2.4E-08			8.1E-09			1.7E-08

A CAUTIONARY TALE

Earlier the potential for contamination was mentioned, Figure 5 is a residual gas analyzer (RGA) scan of a device (Flying Wire) that was installed in Fermilab’s Recycler. The black peaks are from a scan taken before installation. This device was not properly certified prior to installation. There was no low temperature bake done to get an accurate picture of the assembly and the RGA was only on for a couple of hours. RGA’s need to be on for many hours to days before reasonable scans can be taken. The scan seen here (black peaks) is typical of an RGA being on for only a few hours. The clusters of peaks that repeat about every 12 to 14 mass units are hydrocarbons.

If there is no contamination they are the result of the RGA filament heating up and degassing. On a clean system, with a clean RGA, this can be seen to clean up over several hours. On this particular device these

Other measurements and diagnostics systems

clusters were observed to be decreasing over a period of a couple hours.

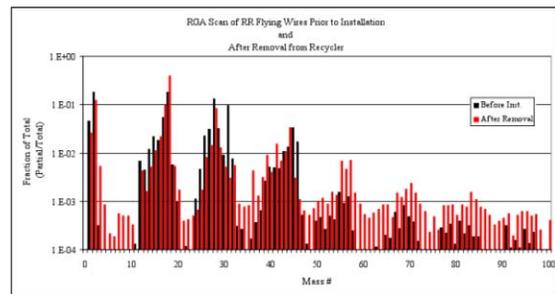


Figure 5. RGA scan of recycler flying wire.

There was a push to install this device during a shutdown and the decision was made to go ahead with the installation without a proper certification. The

device was subsequently installed and baked in-situ at 150° C. The bake appeared to go well and the system came down to 1(10)⁻⁹ Torr after the bake. After the shutdown was over and the machines started running it was noticed that the vacuum was degrading in this sector. Over the course of a week the pressure degraded to 1(10)⁻⁸ Torr and stabilized. Another access was made and the TSP's were reactivated and the pressure again was 1(10)⁻⁹ Torr. Within a week the pressure was again 1(10)⁻⁸ Torr and stabilized. This went on for several months with periodic accesses to leak check and other attempts to find the problem. Eventually an RGA was installed on the system and the scan showed something very similar to the red peaks in Figure 5.

It turned out that a bearing in the rotary feedthrough on the device had a grease lubricant with a high vapor pressure. The original bearings specified for the feedthrough were dry, but the supplier had sent some that had grease. To make matters worse, the initial 150° C bake had spread the contamination through the entire sector and the change in tunnel temperature while running (about 15° C) would accelerate the out-gassing by an order of magnitude. The TSP's would spoil in about a week. Figure 6 shows the effect of the small temperature rise. Ultimately the entire sector had to be replaced.

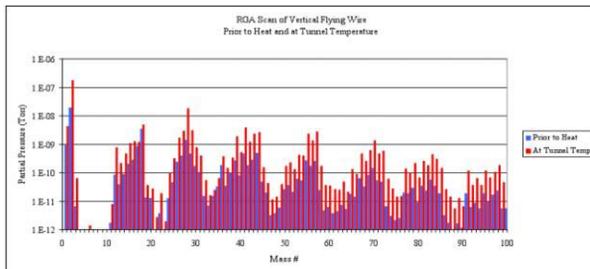


Figure 6. Change in out-gassing due to small temperature rise.

This tale is told to illustrate several points that have been made in this discussion:

- 1) Establish guidelines and standard practices, then follow them.
- 2) Always stop and think about what the outcome will be before you do something to the system.
- 3) Don't guess – test and certify everything you can before it goes in the system.
- 4) Someone knowledgeable in vacuum practice should always be involved in the design, manufacture, and assembly phases of components and devices that will reside in the vacuum system.

KEEP IT CLEAN

If I have learned anything in my 18 years at Fermilab, it is that everything that goes in the vacuum system needs to be clean. In my opinion, this is the

single most important factor affecting the quality of a vacuum system. The equipment will run better, last longer, and be more reliable if the system is clean. The gas composition will be more acceptable to the beam and the desired pressure levels will be achievable. I have this sign on my office wall (Figure 7) and it is the single most important guiding principle when I look at vacuum systems.

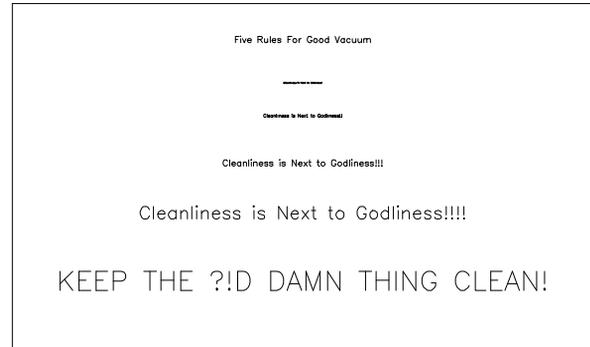


Figure 7. Terry's five rules for good vacuum.

The obvious next question is; what constitutes a clean vacuum system? And, the answer is; that depends. The better question is; what is a contaminant? And, that answer is easy. Any gas in the system that does not need to be there, that interferes with the beam, or prevents the system from reaching the required ultimate pressure is a contaminant. Figure 8 is an RGA scan of a very clean system. H₂ is over 95% of the gas composition with the next highest component being CO at about 1%. N₂ is slightly less than CO and CH₄, H₂O, C₂H₆, and CO₂ are all some fraction of 1%. These are all contaminants, but it may not be possible to do any better. If the pumping is sufficient the system should be able to reach a desired ultimate pressure and at that pressure the beam/gas interaction should be acceptable.

Figure 9 is an RGA scan of a dirty system, and is the one discussed earlier with the grease in the bearing. The hydrocarbons in that system did not need to be there, they interfered with the beam (caused large losses and short life times), and they prevented the system from reaching the required ultimate pressure.

It is always asked what the best cleaning procedure is? The best cleaning procedure is the one that works best for a given application. There are any number of procedures that work, so be flexible when specifying cleaning procedures. An understanding of the processing that a part has been through is a prerequisite for determining the proper cleaning procedure. Specify the vacuum performance you want, and then choose the cleaning procedure that works. Once a part or device is clean, great care should be taken to keep it clean. Clean assemblies should always be vented with dry N₂ and clean parts should always be stored under vacuum or in hermetically sealed UHV grade containers, back-filled with dry N₂. Clean parts should always be

handled with clean latex (or equivalent) gloves. Transfer of solvents, grease, and dirt by handling is the number one way a system is contaminated.

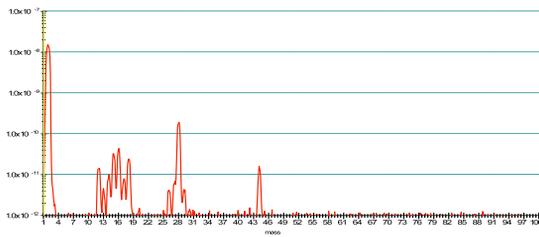


Figure 8. What a very clean system looks like.

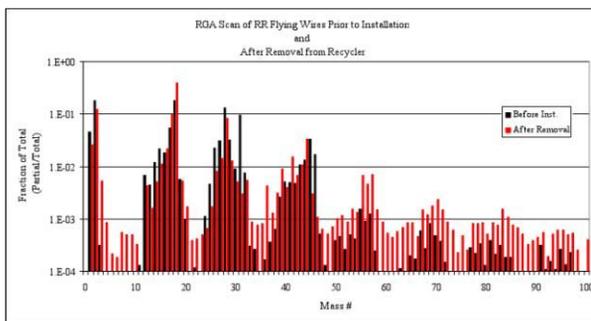


Figure 9. What a dirty system looks like.

The most common procedure used is ultrasonic cleaning with an acid or alkaline based detergent. This is followed by several thorough clean water rinses (usually distilled or de-ionized water). If it is a metal part and needs to be cleaner than the above procedure can achieve, follow it with a vacuum bake at 400 to 500° C, and that will be about as good as it gets.

VACUUM QUALITY AND OPERATION

To this point the discussion has centered on how a system is designed and a little bit about how that design is achieved. But ultimately, what really matters is how the system performs and how easy it is to maintain and operate. The only performance that really matters is the interaction (or lack of) with beam. This goes back to how much gas and of what species is in the vacuum space. Two different gasses (say H₂ and H₂O) at the same pressure can have dramatically different effects on the beam. It basically comes down to the size of the molecules; larger molecules present a bigger target for the beam to hit. Physicists use a number, Z_{eff} (Eq. 9), as a measure of the molecular size of the gas mixture that the beam encounters. This is really nothing more than the effective atomic number of the gas mixture. Higher values for Z_{eff} present a greater potential for beam/gas interactions than smaller values, thereby increasing losses and decreasing beam lifetimes.

$$Z_{\text{eff}} = \Sigma(x_n n_i Z_i / n_n) \quad (\text{Eq. 9})$$

where n_i = The number of atoms of the ith species in the molecule.

Z_i = The atomic number of the ith atom in the molecule.

x_n = The fractional concentration of the nth gas.

n_n = The number of atoms of the nth molecule.

So, when one talks about accelerator vacuum quality, it is really the combination of the system pressure (a measure of the number of molecules in the space) and the species of the gasses remaining in the system.

Operationally this means that there is some standard (quantitative and qualitative) that has to be maintained for any given system. Most of this is addressed in the design and building phase of a system through proper selection of materials, processing methods, and careful construction. But, at some point the system has to operate and invariably will need modifications. Additions and modifications to a system must follow the same rules that were used to design and build it.

Maintaining the system operationally requires an understanding of what was done before and what will happen in the future if something is done now. More precisely this means that the people responsible for maintaining the system need to know what the system design parameters are, what the vacuum quality (both quantitative and qualitative) needs to be, and what has been done over the course of time that could have changed the vacuum quality. At a basic level this means good record keeping.

They also need to know what the effect will be if something is done that changes the system's equilibrium temporarily or permanently. An example of this is the simple act of letting-up a system to atmospheric pressures. Figure 10 is a plot of a system that was first baked at 200° C, and then vented by two different methods. The first method was venting with clean dry N₂ and then pumping back down without a bake. The second method was to vent to outside air and remain exposed for two hours, then pumping back down without a bake.

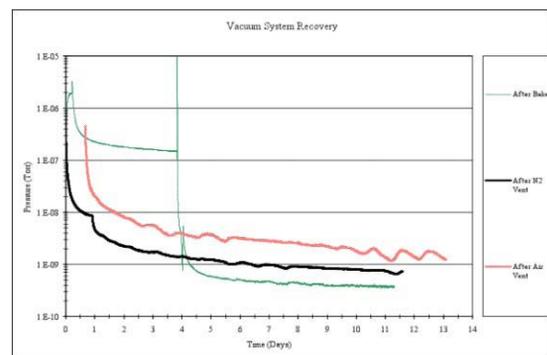


Figure 10. What happens when a system is vented?

It can be seen that there is a difference in both total pressure and the time taken to reach any given pressure. Zero time in all cases is the start of initial pump down. The bake was approximately 4 days, but could have been as short as two days with about the same results. As far as total pressure goes, there is about a factor of two between the subsequent processes. From a strictly pressure point of view this is not very significant. But, if the gas mixture composition is looked at (Figure 11) the difference is significant.

There is a significant increase in the carbon containing molecules (CH₄, CO, C₂H₆, and CO₂), H₂O, and N₂. The increase in the carbon compounds is probably driven by the hot filaments on the ion gauge and RGA. This will probably clean up in time and has a large affect because the vessel is small relative to the number of filaments. What is significant though, is the increase in H₂O and N₂. For the system vented with air there is an increase in the level of H₂O of almost two orders of magnitude. This is due to mono-layers of H₂O accumulating on the surfaces from the moisture in the air. Without a bake this will take a very long time (months to years) to pump away. There is also an increase in the H₂O level as a result of venting with clean dry N₂. This is because the vent line and exterior of the system valve had all been exposed to air for a very long time. Additionally, there is always a slug of air in the vent line; unless it is permanently connected to the system, purged of air, and baked to remove the H₂O. The N₂ level has increased in both cases and will continue to remain high for some time, but will eventually pump away. Below the chart are values for Z_{eff} in the three cases.

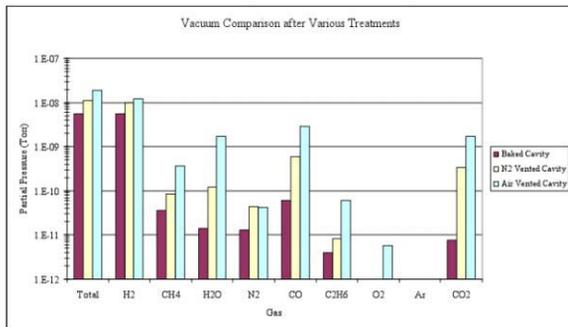


Figure 11. Vacuum quality after venting, Z_{eff} for baked system = 1.1, Z_{eff} for N₂ Vented System = 1.57, Z_{eff} for Air Vented System = 2.75

GAUGES

To this point, the discussion has really said nothing about gauges except a statement in the introduction that; there is no vacuum gauge on this planet that, in and of itself, gives you the real picture. We could probably leave it at that and go on with life in blissful ignorance. But, if you really want to understand what a vacuum system is doing an understanding of this is

required. In practice, gauges are the only indicator of a system's health. And, that is all they are; indicators. Almost all gauges used in the vacuum regimes that are of interest to accelerators are calibrated for N₂ as the only gas in the system. As was shown earlier this is almost never the case. In addition, most of the gauges used (primarily ion gauge and cold cathode) are total pressure gauges. So they treat all the gas species as one gas. The relationship between the gauge pressure and actual pressure for a specific gas for a Bayard-Alpert type ion gauge is given in equation 10.

$$P_{\text{gasX}} = (P_{\text{ind}} / r_{\text{gasX}})(K_{\text{N2, cont}} / K_{\text{N2, gauge}}) \tag{10}$$

- Where P_{gasX} = The pressure of gas X.
- P_{ind} = The N₂ equivalent pressure indicated by the gauge.
- r_{gasX} = Gas sensitivity for gas X.
- K_{N2, cont} = Controller sensitivity for N₂.
- K_{N2, gauge} = Gauge sensitivity for N₂.

Values for K_{N2, gauge}, K_{N2, cont}, and r_{gasX} can be found in the literature and manufacturers' catalogs. K_{N2, gauge} is typically between 10 and 25 /Torr. If the controller and gauge are calibrated the same the K terms drop out. Typical sensitivity values for some gasses are listed in Table 3.

Table 3: Gas Sensitivity Table

Gas	H ₂	CH ₄	H ₂ O	CO	N ₂	C ₂ H ₆	O ₂	Ar	C ₃ H ₆	CO ₂
Sens., r	0.46	1.4	1.12	1.05	1.0	2.6	1.01	1.29	3.6	1.4

To get a better picture, a gauge that differentiates between the various gasses is needed. At first glance an RGA would seem to do this, but there are also calibration issues there. An RGA differentiates between the masses of the various gasses, but thinks everything is still N₂ when it comes to the magnitude of the pressure. In addition, there is always a question of how well any gauge (ion gauge, cold cathode, or RGA) is calibrated for N₂. As a general rule, I treat all high or ultra-high vacuum gauges as only being accurate to within a factor of two. Most RGA's are moved from system to system as needed. This is mostly because they cost so much. Even when they are permanently installed on a device or system, it is usually only the analyzer that is installed and the head and electronics are moved from analyzer to analyzer. In this case calibration becomes a real slippery slope, and can be off by orders of magnitude.

To combat all these inaccuracies and uncertainties I try to only use an RGA in conjunction with an ion gauge. The RGA is used only to get a qualitative measure of the gasses in the system and a sense of the relative concentrations of the gasses. An ion gauge is then used as the total pressure measurement and the RGA data is normalized to that. As an example

assume that the RGA scan in Figure 8 indicates the relative partial pressures of the gasses as shown in Table 4. The ion gauge on the system near the RGA shows a total pressure of $2.7(10)^{-9}$ Torr. The fractional contribution of each gas to the total is also shown in the table. Setting both K's in Equation 9 equal to 1 and making use of the fact that the sum of the partial pressures is equal to the total pressure an equation can be written to correct for the gauge calibration.

$$P_{Tact} = P_{TIG} / \sum((P_i / P_{TRGA}) r_i) \tag{11}$$

where P_{Tact} = Actual total pressure (Torr).

- P_{TIG} = Indicated ion gauge pressure (Torr).
- P_{TRGA} = Total indicated RGA pressure (Torr).
- P_i = Partial pressure of the i^{th} gas (Torr).
- r_i = Gas specific sensitivity for the i^{th} gas.

It can be seen that the actual total pressure is 5.6×10^{-9} Torr, which is about two times the indicated 2.7×10^{-9} Torr. The individual partial pressures are then the fractional contributions of each gas times P_{Tact} .

Table 4: RGA Analysis Normalized to an Ion Gauge

	Totals	H ₂	CH ₄	H ₂ O	N ₂	CO	C ₂ H ₆	CO ₂
RGA Partial Pressure (Torr)	1.54E-08	1.50E-08	1.00E-10	3.90E-11	3.50E-11	1.70E-10	1.10E-11	2.10E-11
Fractional Contribution to Total	1.00	0.976	0.007	0.003	0.002	0.011	0.001	0.001
Gas Specific Sensitivity (r)		0.46	1.40	1.10	1.05	1.05	2.60	1.40
Adjusted Partial Pressure (Torr)	5.64E-09	5.51E-09	3.67E-11	1.43E-11	1.28E-11	6.24E-11	4.04E-12	7.71E-12

CONCLUSION

The topics discussed here are by no means complete. Anyone needing an in-depth knowledge of the subject is encouraged to pursue further study with the references suggested. This discussion does, however, provide a core of knowledge for those working with accelerator vacuum systems. The intention was to condense and simplify the basic concepts, design, and operating parameters that are encountered in most accelerator vacuum systems. This discussion should be of particular use to those that design and build components and devices that reside in the vacuum system, but who typically have no involvement in the design, building, or operation of the vacuum system itself. For those that are actively involved in the design, building, and operation of a vacuum system, this discussion provides a base point to build on. The primary purpose of this discussion is to give all those that are in some way contributors to the vacuum system, whether directly or ancillary, a common means to communicate with each other.

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