# INTRODUCTION TO VACUUM TECHNOLOGY

DAVID M. HATA, ELENA V. BREWER, NANCY J. LOUWAGIE

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# ABOUT THIS BOOK

Vacuum systems are critical to many industries. They are vital to establishing required process pressures, establishing a clean process environment, and removing reaction by-products from the process chamber. Often vacuum systems are taken for granted until there is a malfunction that changes the process environment, resulting in unplanned personnel time fixing equipment, improperly processed products, and ultimately, a loss of revenue for the company.

Technicians with the knowledge and skills to maintain, troubleshoot, and repair vacuum systems are highly-valued in manufacturing and research organizations. These technicians are vital to keeping an organization's vacuum equipment up and running. But vacuum equipment/systems and their operations pose unique challenges to maintain and support. Author David Hata's *Introduction to Vacuum Technology,* published in 2008, was a textbook written specifically for individuals preparing to maintain and troubleshoot vacuum equipment systems. Hata's book was a great companion textbook for any vacuum course included in a two-year technical program-of-study.

As of 2019, publisher Pearson Prentice Hall decided to discontinue printing copies of the *Introduction to Vacuum Technology* textbook. The publisher reverted the copyright for the book back to the author David Hata. The author, Dr. Elena Brewer from Erie Community College (Williamsville, NY), and Nancy Louwagie from Normandale Community College (Bloomington, MN) submitted a proposal to the National Science Foundation Advanced Technological Education (NSF-ATE) program in consideration of a project which would convert Hata's textbook to an e-book version. The updated textbook resource would be made easily accessible via on-line platforms and incorporate resources in the textbook design to promote active learning styles for the benefit of today's student population. The NSF awarded funding in support of the project (DUE #2000454).

The first four chapters of *Introduction to Vacuum Technology* is an open e-book version of Hata's textbook. Like the previous version, this textbook addresses basic topics in vacuum technology and is written for individuals who are tasked with maintaining vacuum systems. It is also written for instructors, especially those who teach technician-level courses at community colleges who are looking for materials to support vacuum technology instruction. For these instructors, a laboratory manual and accompanying instructor's guide have also been developed to support the delivery of lecture-laboratory courses.

Most vacuum books approach the subject topically. That is, separate chapters are devoted to rough vacuum pumps, high vacuum pumps, pressure gauges, vacuum materials, and other topics. This organization is appropriate for a reference book but not for a teaching text.

This book approaches vacuum systems from a pressure regime viewpoint. That is, after covering some basic vacuum science, the first pressure regime covered is the rough vacuum regime. Within the study of rough vacuum systems, the following topics are covered: gas load, pumping mechanisms, pressure measurement, vacuum system construction, and basic troubleshooting concepts. The discussion of rough vacuum is then followed by the study of high vacuum systems. The same topics are revisited, but this time from a high vacuum perspective. Once both rough vacuum and high vacuum systems are covered, then the topics of leak detection and residual gas analysis are introduced.

This pedagogical approach lends itself to laboratory experimentation. During the review of gas laws from chemistry, experiments and demonstrations can be performed to reinforce basic laws and concepts. Then, during the study of rough vacuum systems, pump-down times can be calculated and pump-down operations performed in the laboratory. Likewise, during the study of high vacuum systems, pump-down operations as well as other lab exercises, such as leak detection and residual gas analysis, can be performed.

Our intent was not to create an exhaustive treatment on vacuum science nor cover all the various vacuum technology components. Some topics have been consciously omitted, such as ultrahigh vacuum systems and the pumps that are used to create these very low pressures. The questions driving decisions to include or exclude material in the book focused on the needs of technicians in a production environment and the types of vacuum systems used.

This book is the result of years of teaching vacuum at the community college level. Many thanks go to the former students for challenging the authors to learn more about vacuum science, the variety of vacuum system designs and how these systems work. It was rewarding to work with them in the vacuum laboratory and experience their joy of discovery while making the connections between the science and the technology. The satisfaction in observing people putting these pieces together is the biggest motivation to write this book.

Please complete a short survey (surveymonkey.com/r/2P5693M) if you: want to provide feedback, found any mistakes and/or typos, or would like to add problems or activities. Your feedback will greatly help us to maintain and improve this E-book which was developed under National Science Foundation grant #2000454. Your time and expertise are greatly appreciated. Click on this link to access the survey: surveymonkey.com/r/2P5693M.

This work is supported by the National Science Foundation under grant number 2000454. Any opinions, findings, and conclusions or recommendations expressed in this e-book are those of the authors and do not necessarily reflect the views of the National Science Foundation.

# ABOUT THE AUTHORS

**David M. Hata** received his B.S. in Electrical Engineering from Washington State University and M.S. in Electrical Engineering from University of Washington. He has 32 years of experience teaching Electronic Engineering Technology and Microelectronics Technology at Portland Community College (PCC) in Oregon. He has taught technician-level courses on vacuum and plasma technology, authored *Introduction to Vacuum Technology*, published by Pearson Prentice Hall in 2008, and implemented a vacuum/plasma teaching laboratory at PCC. Although he is retired from teaching, he continues to impact technician education as a consultant and external evaluator for NSF ATE projects at community colleges around the country.

**Elena V. Brewer** received her B.S. in Physics from Irkutsk State University and PhD in Physics from the University at Buffalo. She has over 20 years of experience teaching Electrical Engineering Technology, Nanotechnology, Renewable Energy and Physics courses at SUNY Erie Community College (SUNY ECC), as well as Physics at the University at Buffalo. She has substantial experience in program/course development at SUNY ECC and was instrumental in starting the Nanotechnology program at this institution.

**Nancy J. Louwagie** received her B.S. in Electrical and Electronics Engineering from North Dakota State University and M.S. in Electrical Engineering from the University of Minnesota. She has 18 years of industry experience and over 15 years of teaching Engineering Technology and Vacuum Technology courses at Normandale Community College. She is currently the Chair of the Engineering Technology Programs Department at Normandale. She served as the co-Principal Investigator (co-PI) on the NSF-ATE DUE #1400406 project and subsequently as the PI on NSF-ATE DUE #1700624 project. These projects focused on revisions to the core vacuum technology courses in Normandale's Vacuum and Thin Film Technology program so that vacuum technology classes could be delivered in a telepresence classroom venue and offered to students who attend and participate in these classes at remote locations.

This work is supported by the National Science Foundation under grant number 2000454. Any opinions, findings, and conclusions or recommendations expressed in this e-book are those of the authors and do not necessarily reflect the views of the National Science Foundation.

# INDUSTRY TESTIMONIALS

*“Demand for products made using vacuum-enhanced processes is growing +10% per year. Applications including semiconductors, solid-state lighting, and space simulation continue to apply pressure on manufacturers, like the Lesker Company, who are capacity-limited because of the deficit in our vacuum-skilled workforce. The availability of modern, interactive teaching materials will help streamline the process to build a capable labor supply to meet growing demands and maintain our country’s competitive advantage in vacuum technology.”*

J.R. Gaines, Technical Director of Education, The Kurt J. Lesker Company

*“The importance of vacuum science as general industrial skill set cannot be overstated. A program that trains future technicians, engineers, and scientists on this vital subject provides a solid career foundation with ample room for growth. Vacuum technology is widely deployed in many critical areas – such as medical, analytical metrology, reliability, food sciences, semiconductors, and optics, to name a few. As the technical needs in different professions grow, so will the application of vacuum science.”*

Jeff Salzmann, Senior Research Engineer, Advanced Materials Technology Group

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# ACKNOWLEDGEMENTS

Although this textbook addresses how to create vacuum, an important acknowledgement is that writing and publishing a textbook does NOT occur in a vacuum! Producing a textbook requires access to many resources. It especially takes many people with a variety of talents committed to making it come together in a final product. We would like to express our appreciation and thanks to all who provided the resources and played a part in publishing this textbook.

We are very grateful for the support received from the National Science Foundation (NSF) under the new-to-ATE grant project award DUE # 2000454. The NSF's support makes it possible to undertake projects like this one that can generate valuable resources to improve technician education.

We thank author David Hata who owns the copyright for the original print *Introduction to Vacuum Technology* textbook for granting permission to use his materials in this e-book version of the textbook.

We thank Allison Brown from the Digital Publishing Services Office at SUNY Geneseo for help in navigating the Milne Open Textbooks publishing platform. Allison's on-going support was essential to make use of this platform's editing, graphics, and other on-line book production features.

We also thank all the individuals who helped secure permissions to use figures, videos and animations from their company publications: J.R. Gaines from Kurt J. Lesker Company, Jake Young from Busch Vacuum Solutions, and Brian Hillegass from Leybold USA Inc. Special thanks to Gigi Bocek for creating and updating numerous graphics and animations for this e-book.

And many thanks to all the individuals who reviewed the book and provided feedback. These individuals represent faculty, students, technicians, and other practitioners whose invaluable perspectives helped to make the content addressed in this book much more relevant.

This work is supported by the National Science Foundation under grant number 2000454. Any opinions, findings, and conclusions or recommendations expressed in this e-book are those of the authors and do not necessarily reflect the views of the National Science Foundation.

# CHAPTER 1: VACUUM: AN ENABLING TECHNOLOGY

Learning Objectives

Chapter 1 introduces the concept of vacuum and why it is important to be able to create a vacuum condition in a controlled space. After you read this chapter, you will be able to:

- Identify a variety of everyday items that are manufactured using vacuum technology.
- Define the meaning of the word "vacuum" as it will be used in this text.
- Describe some common processes enabled using vacuum technology.
- Explain reasons why a vacuum condition is beneficial in manufacturing and research processes.
- Describe different ways to create a vacuum condition.
- Identify other resources that provide information on vacuum technology.

# A Brief Vignette

> *The impact of* ***vacuum technology*** *on today's world is extensive. But like the air that surrounds us, the use of vacuum technology is mostly invisible to us, so we don't necessarily appreciate that it exists despite how much it influences our everyday lives.*
>
> *You look out the* ***window*** *and it's raining outside. You've been studying awhile on the* ***computer*** *and are ready for a break. You turn on the* ***lights*** *in the kitchen, pour a glass of water from the* ***faucet*** *and open a* ***bag*** *of pre-popped popcorn. You decide to watch a show on* ***television*** *this evening. You use the* ***remote control*** *to turn on the TV. As you scan through the viewing options, you see an advertisement for a pair of* ***sunglasses*** *you want to buy. Out of the corner of your eye, you notice that one of the* ***framed pictures*** *hanging on the wall next to the TV is crooked. Your hand moves to straighten the picture, but you brush across a spider web. Ugh! Need a* ***vacuum cleaner*** *to get rid of that! Then your* ***cell phone*** *goes off. Well, so much for your TV time!*

For many of the products mentioned in our vignette, vacuum technology played an important, if not critical role, in its manufacture. In the case of the window, faucet, bag, sunglasses, and framed pictures, it is one or more thin material coatings on the surface which enhance the function of each product. In the case of the computer, television, remote control, and cell phone, vacuum plays a critical role in the manufacture of the integrated circuits that determine their function. And, the kitchen lights, if incandescent or fluorescent, would not work if the air inside the bulb were not removed. Without vacuum, none of these products would exist in their present form.

## 1.1 Introduction

Vacuum technology is an "enabling technology" that makes it possible to achieve other goals. This concept was expressed by Lars Montelius, President of the International Union for Vacuum Science, Technique, and Applications (IUVSTA) when he shared his view on the creative nature of vacuum science and how vacuum has enabled innovations that help to build a more sustainable society. Here is a quote from an article in the publication *2018 Physics World Focus on Instruments and Vacuum*:

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=27#oembed-1*

Video 1.1. Vacuum as an enabling technology in industry. Source: Busch Vacuum Solutions, www.buschusa.com

> "Vacuum systems are used in all kinds of equipment, and not only in the sciences. There is a long history of using vacuum for industrial machines and processes. Within the sciences, vacuum is important if you want to understand materials at a very small scale, because to do that you need very clean and stable conditions. In industry, one of the major applications is in industrial machines. For instance, vacuum is used to lift, position, and move objects. Simply speaking, without vacuum many industries would not exist. An example is the semiconductor industry. Once upon a time, the electronics industry ran on vacuum tubes: vacuum was an essential requirement for switching electrical currents. Although these switches have been replaced by solid-state electronics, manufacturing the electronics and circuits still requires vacuum conditions. I think vacuum is one of the most important elements of modern society, but it's a paradox because vacuum itself is maybe not so important – it's what you do with it that's important. Vacuum is an enabler." (1)

## 1.2 What is "Vacuum"?

You probably have a notion of the meaning of the term "vacuum." As a noun, it can refer to a "vacuum cleaner" or some other contraption that picks up objects. In another sense, one might say that when someone leaves a group, their departure creates a "vacuum" in the group. So, with multiple definitions, and uses, for the term, it makes sense for us to define how we intend to use it in our discussions ahead.

**… a vacuum is created when gas molecules are removed so that the density of gas molecules in an enclosed space is less than the density of molecules in the surrounding environment.**

In the ideal sense, a ***vacuum*** is a space that contains absolutely nothing, a space totally devoid of matter. However, in actual practice, such a perfect vacuum does not exist, even for the best vacuum systems. Under the best of vacuum conditions, a ***chamber*** still contains hundreds of thousands of gas molecules per cubic centimeter. A variety of useful processes are accomplished under very different levels of vacuum. So, in this sense, a vacuum is created when gas molecules are removed so that the density of gas molecules in an enclosed space is less than the density of molecules in the surrounding environment.

The definition of ***vacuum*** for the purposes of this text is a space partially emptied (to the degree necessary to support a process) by artificial means (using a ***vacuum pump***). This results in a volume containing far fewer gas molecules than the same volume in the surrounding atmosphere, that is, a degree of ***rarefaction*** below ***atmospheric pressure***. If the surrounding atmosphere is at normal atmospheric pressure, then a vacuum exists if the density of the gas molecules in the chamber is less than the density of gas molecules outside the chamber in the ambient atmosphere.

Section 1.2 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=27#h5p-3*

# 1.3 Vacuum as an "Enabler"

In this section, we will examine examples of how vacuum "enables" various processes that benefit our lives today. We will examine how vacuum is used in food preservation, in thermal insulation, in surface coating materials, and in manufacturing processes used to manufacture integrated circuits.

## 1.3.1 Food Preservation

There are three things that cause food to deteriorate: heat, water, and oxygen. Vacuum sealing, freeze-drying and proper packaging overcome all three of those factors to allow long term food storage, up to 15 to 25 years in some cases. Furthermore, freeze-drying food causes little damage to the nutritional value of the food being preserved compared to other methods that use higher process temperatures, like canning and dehydration.

Vacuum sealing removes air from the package containing the food prior to sealing. The intent of vacuum sealing is to remove oxygen from the package to extend the shelf life of foods, thereby limiting the growth of aerobic bacteria or fungi. Vacuum sealing can also reduce "freezer burn" which occurs when the surface of the food dehydrates while it is frozen leading to a dried, leathery appearance and a change in flavor and texture. Figure 1.1 shows a vacuum sealer that can be used at home.

Figure 1.1. Vacuum sealer used for food preservation. Photo provided by Nancy Louwagie, Normandale Community College.

One example of a freeze-dried food item is astronaut ice cream, a slab of ready-to-eat dehydrated ice cream like the one shown in Figure 1.2. Unlike regular ice cream, astronaut ice cream can be kept at room temperature without melting. It was first developed by Whirlpool Corporation under contract to NASA for the Apollo mission, but it was never actually used on any Apollo missions. Other freeze-dried foods were developed to reduce the weight of food by removing its water and oxygen content. Lighter-weight foods packaged for a longer shelf life could be sent on long-duration spaceflights.

Freeze-drying, also known as lyophilization, is a dehydration process that removes water from a frozen food. To make astronaut ice cream, the ice cream is placed in a ***vacuum chamber*** and frozen until the water crystallizes. Air is then evacuated from the chamber to create a partial vacuum. The crystallized water then begins to sublimate, that is, change from a solid to gas. Heat can be applied to speed up the ***sublimation*** process. And finally, a ***freezing*** coil captures the vaporized water. This process continues for hours and eventually results in a freeze-dried slice of ice cream.

Figure 1.2. Freeze-dried Neapolitan ice cream. Freeze-dried neapolitan ice cream by Evan-Amos, Public Domain.

**Vacuum technology enables food preservation through vacuum sealing and freeze-drying.**

## 1.3.2 Thermal Insulation

Vacuum enables “thermal insulation”. Thermal insulation ***retards***, or slows down the flow of thermal energy. Consider a simple vacuum flask. You might commonly refer to it as a “thermos bottle.” It can be used to keep cold drinks cold, and warm drinks warm. Thermos bottles come in a variety of designs, but each design’s construction is essentially the same. As shown in Figure 1.3, a thermos bottle is basically two chambers, historically glass, but now typically metal, one inside the other with a partial vacuum between the two chambers.

What happens when the contents of the flask are surrounded by air at atmospheric pressure? The contents within the flask might be cold with warm or hot air outside the flask, or the opposite, hot inside and cooler or very cold air on the outside. In either case, a temperature difference exists between the surrounding air and the contents of the vacuum flask. Heat transfer occurs when molecules collide

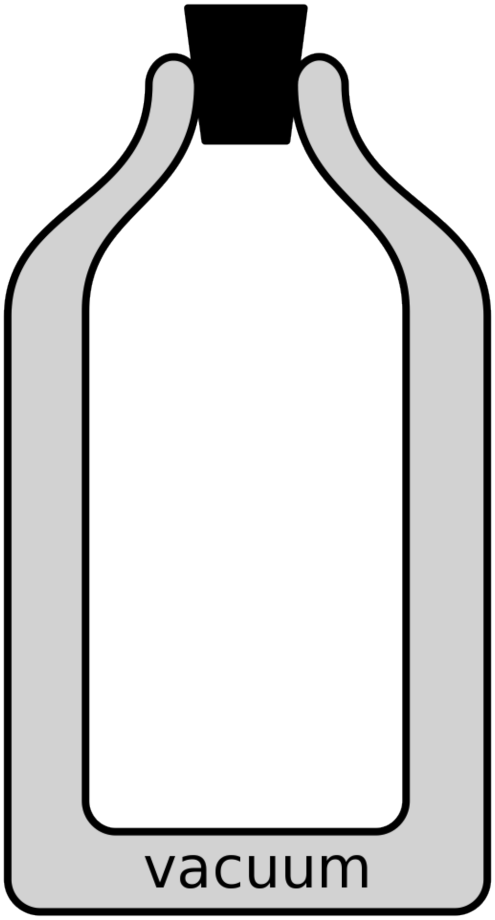

Figure 1.3. Diagram of a vacuum flask. Vacuum Dewar Flask by Acdx, Creative Commons Attribution-Share Alike 3.0 Unported.

with each other and transfer energy. Heat flows from the warmer region to the colder region. A space in which more molecules are present supports a higher rate of heat transfer than the same space with fewer molecules. Different gas molecules have different energies, so the type of gas molecules present in the space also affects the rate of heat transfer.

How does a vacuum condition impede heat transfer? Suppose we have filled the thermos bottle with a cold liquid. Between the inner and outer surfaces, most of the air is removed to create a vacuum. If we remove enough of the air molecules, the air molecules will be able to travel between the inner and outer surfaces without colliding with another air molecule. So, an air molecule hits the warmer outer surface and picks up some energy. After rebounding off the outer surface, the air molecule then travels toward the inner surface where another collision results in a transfer of energy from the air molecule to the inner surface, providing energy to warm the cold liquid. The goal is to minimize the number of gas molecules transferring heat energy from the outer surface to the inner surface. The fewer the air molecules in the vacuum space, the slower the heat transfer to our cold liquid, and the longer our cold liquid will remain cold.

**Vacuum technology can create insulating layers to slow down the transfer of heat energy.**

## 1.3.3 Vacuum Gripping

Vacuum gripping is useful in lifting, moving, or holding objects in place. Consider a simple suction cup. Air is removed by pressing a flexible membrane against a surface. Then the membrane is pulled away from the surface, expanding the volume that is captured underneath the membrane. The ***pressure*** in the volume between the flexible membrane and the surface is lower than the pressure exerted on the opposite side of the surface keeping the membrane in place.

For example, the cell phone holder pictured in Figure 1.4 uses a suction cup at its base to adhere to a smooth surface. The cell phone holder consists of a flexible base with a moveable diaphragm, a lever attached to the diaphragm, a ball joint to allow positioning of the holder, and the cell phone holder. When the cell phone holder is placed on a non-porous surface and the lever is moved down, it mechanically pulles the diaphragm away from the surface creating a vacuum by expanding the space with trapped air molecules. The atmospheric pressure of 14.7 ***psi*** now provides the holding force for the cell phone holder. To release the holder, the lever is moved up, or away from the base of the holder, and the space created by the deformed diaphragm shrinks so that the holder can be moved, or re-positioned.

Glass handles operate in a manner similar to the cell phone holder. They allow a person to hang onto a large sheet of glass, for example, a large storm window. The glass handle is positioned on the pane of glass and a lever lifts the diaphragm creating a void next to the glass. Again, atmospheric pressure applies pressure to the glass handle, keeping it securely attached to the glass. Figure 1.5 shows a glass handle with the diaphragm base.

A vacuum chuck is another example of vacuum gripping and is primarily used on non-ferrous materials, for example, glass, plastic, copper, aluminum, and even wood. In a vacuum chuck, air is pumped from a cavity behind the workpiece and again atmospheric pressure provides the holding force. In Figure 1.6, vacuum chucks are placed under a wooden workpiece and the vacuum holds the workpiece while it is milled. Vacuum clamping is a technique to prevent marring or damage to a workpiece that might occur if it was otherwise mechanically clamped in place. Vacuum gripping can also allow greater access to the work piece being machined.

Figure 1.4. Photo of Cell Phone Holder with diaphragm base. Photo provided by David Hata.

Figure 1.5. Photo of a glass handle. Photo provided by David Hata.

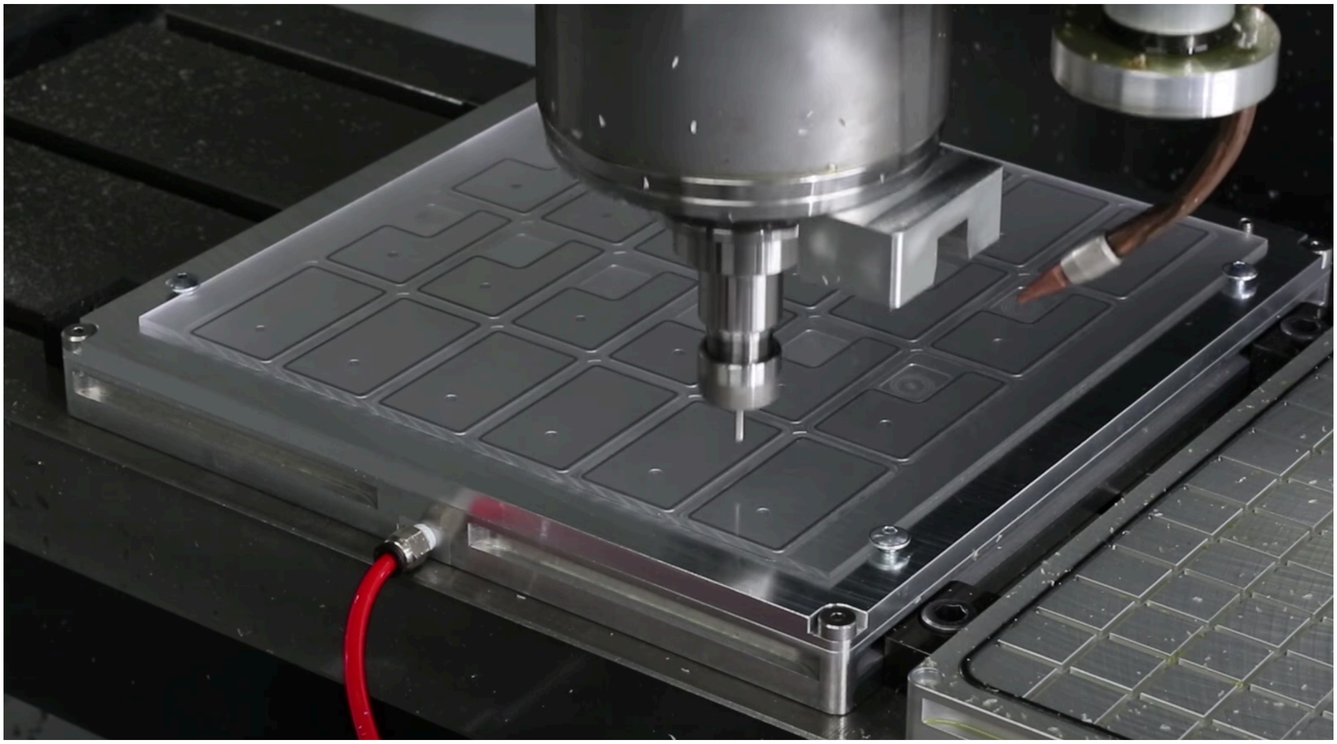

Figure 1.6. A work piece is held in place with vacuum chucks while it is being milled. Source: Pierson Workholding website, https://piersonworkholding.com/media/..

**Creating a partial vacuum underneath a flexible membrane enables the gripping function to adhere to a smooth surface.**

## 1.3.4 Thin Film Deposition by Metal Evaporation

Vacuum systems are used to establish conditions necessary to carry out manufacturing processes. Consider metal ***evaporation***. In this manufacturing process, the goal is to coat a surface with a thin metal layer. In semiconductor manufacturing this metal layer can be patterned to form the interconnects between various points on a silicon wafer.

The basic evaporation process involves two steps: (1) in a crucible, a hot metal source evaporates creating a vapor of metal atoms and (2) the metal atoms travel to the substrate and condense on the substrate's surface. However, before this two-step process is performed, the chamber is put under vacuum. A vacuum condition ensures that metal atoms, once vaporized can travel to the substrate without being impeded by other gaseous atoms or molecules, or colliding with foreign particles that may react with them. When evaporation is performed in a poor vacuum, or close to atmospheric pressure,

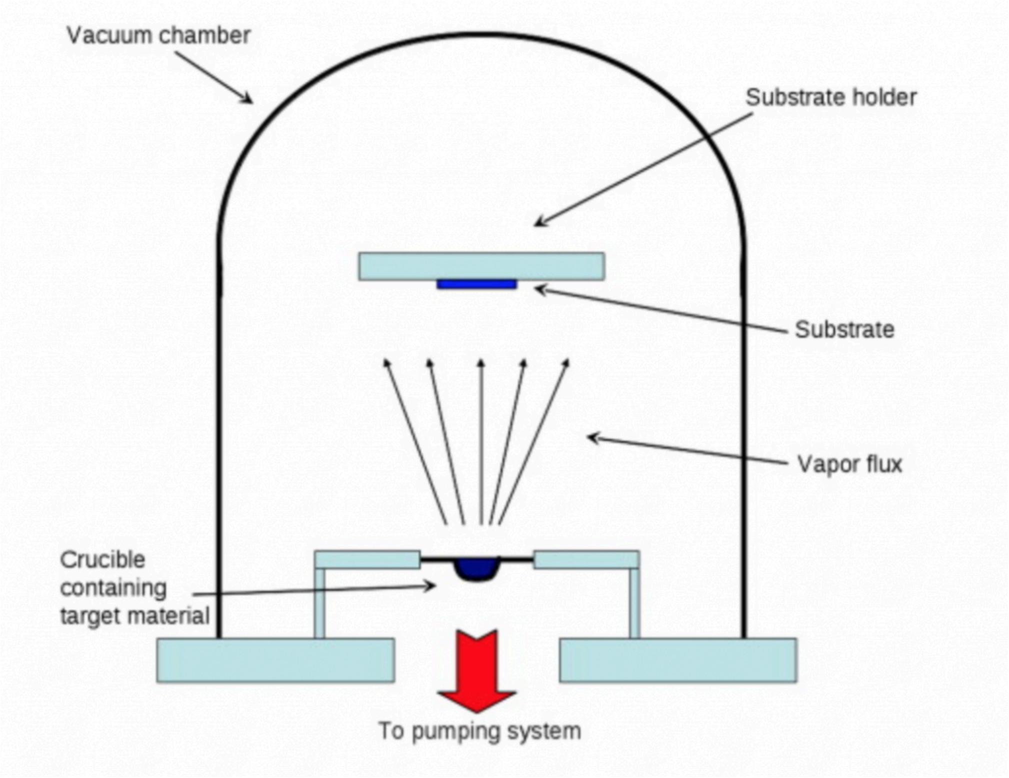

Figure 1.7. Diagram of a metal evaporator.
Public domain, generated by CNEU staff for free use.

the resulting layer of metal is generally non-uniform both in thickness of the deposition and quality of the material deposited. Figure 1.7 shows a typical diagram of metal evaporator used for such processes.

One advantage of metal evaporation is that multiple substrates can be processed at the same time, but it does pose a challenge. Because the metal vapor originates at a point source, the evaporated metal atoms attack the substrate surface from a single direction. Protruding features can block the metal atoms and "shadowing" can occur. To limit this problem, a different thin film deposition process called "sputtering" can be used.

**Before metal evaporation can be done, the chamber must be placed under vacuum.**

## 1.3.5 Other Examples

The examples of vacuum as an "enabler" described in Section 1.3.1 through 1.3.4 are just a few of the many processes where vacuum is used. Table 1.1 lists other processes carried out in each of three pressure regimes. This is by no means an exhaustive list, but it does give you a view of the breadth of applications where vacuum is used.

Table 1.1. Processes that use vacuum.

| **Rough Vacuum** | **High Vacuum** | **Ultrahigh Vacuum** |
|---|---|---|
| Food Processing/Packaging | Heat Treating | Materials Research |
| Freeze Drying | Vapor Deposition | Metallurgy |
| Gas Lasers and Neon Signs | Ion Implantation | Surface Analysis |
| Sputtering | Surface Coating | Molecular Beam Epitaxy |
| Distillation | Thermal Insulation | Physics Research |
| Electric Conduction | Chemistry Research | Space Research |

In many applications that require pressures in the high vacuum and ultrahigh vacuum pressure regimes, specialized tools and instruments are needed. For example, in the semiconductor industry, complex manufacturing tools are needed for chemical vapor deposition and ion implantation. These tools are composed of multiple subsystems, one of which is the vacuum subsystem. In other applications, specialized tools such as electron microscopes utilize vacuum to establish the operating environment in which measurements can be made. Vacuum technology and the application of vacuum is so pervasive in our world today that without vacuum technology, we would not have many of the products we use on a daily basis.

**Vacuum technology is used to manufacture a wide range of products in today's world and to support scientific research.**

Section 1.3 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=27#h5p-4*

# 1.4 Benefits of Creating a "Vacuum"

We have described the types of applications enabled by vacuum technology such as food preservation, freeze-drying, thermal insulation and metal evaporation. Now, let's examine why one would want to create a vacuum in a semiconductor manufacturing process, for example, chemical vapor deposition, sputtering, or ion implantation.

Removing gas molecules from an enclosure or process chamber achieves several objectives. First, it results in a cleaner process environment by removing potential contaminants. Contaminants can be particles as well as unwanted gases that, if allowed to remain in the chamber, can participate in the chemical reactions taking place in the chamber and ultimately, produce unwanted by-products. For example, if two gases are to react in a process chamber to deposit a coating on a silicon wafer, you don't want the oxygen and nitrogen present in air to combine with the reactant gases. Therefore, before introducing the reactant gases into the process chamber, the air in the chamber is first removed from the chamber to reduce the amount of oxygen and nitrogen molecules present. After the desired chemical reaction has taken place, the unused reactant gases must be pumped out of the chamber before the chamber pressure can be brought back to atmospheric pressure and the wafer removed.

Second, creating a vacuum in a process chamber increases the ***mean free path*** (λ) of the gas molecules. The mean free path of a ***gas molecule*** is the average distance the gas molecule will travel before colliding with another gas molecule. As the chamber pressure is reduced, fewer gas molecules occupy the volume. When the number of gas molecules in the space is reduced, the molecules remaining in the space collide with each other less frequently as shown in Figure 1.8. This is important in manufacturing processes such as sputtering, evaporation, and ion implantation. In these examples, a high ***molecular density*** of gas molecules would impede particles from reaching the substrate, for example, a wafer.

Third, creating a vacuum in a process chamber is a way of controlling the number of collisions of molecules against a surface, for example, a wafer. This is important when sputtering metal layers or in controlling the rate of film growth in chemical vapor deposition.

Fourth, creating a vacuum lowers the molecular density. Consider the case of the ordinary incandescent light bulb. If the inside of the light bulb were not first evacuated to remove air, any oxygen molecules left in the bulb when the filament is heated would react with the metal and the metal filament would burn up.

Fifth, creating a vacuum can result in a force that is useful in many manufacturing processes. For example, a force can be created to secure a wafer to a vacuum wand when the wafer has to be moved from one place to another, or to a chuck so that the wafer cannot move during a manufacturing process.

Sixth, creating a vacuum reduces the rate of heat flow. A reduction in pressure decreases the molecular density and hence, a reduction in the number of molecule-to-molecule and molecule-to-surface collisions. Fewer collisions result in less heat transfer.

Seventh, creating a vacuum can increase vaporization. ***Vaporization*** occurs when liquid molecules leave a surface and do not return. It works like this: if the chamber containing a liquid is evacuated, fewer molecules

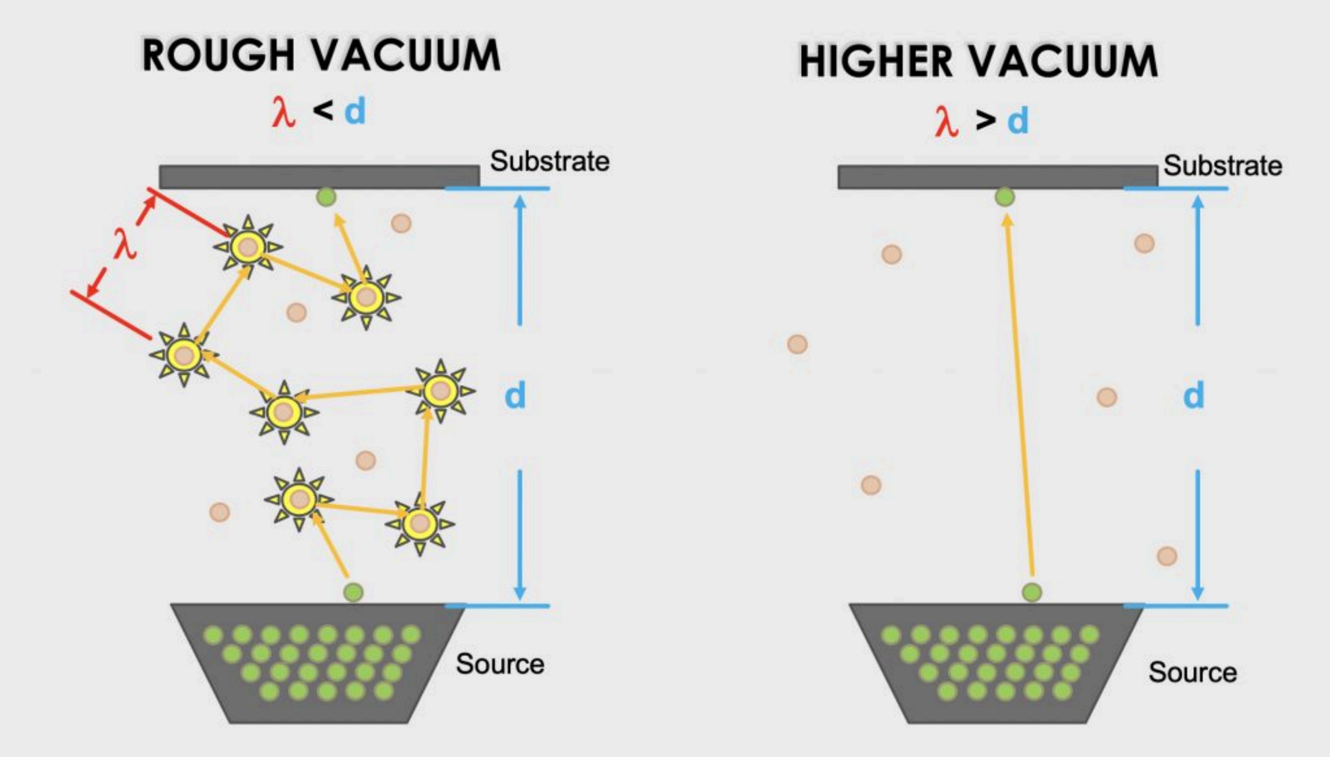

Figure 1.8. Effects of vacuum on mean free path. (Courtesy of Nancy Louwagie, Normandale Community College)

will be above the liquid surface. Thus, a molecule that evaporates from the surface of the liquid is less likely to collide with another gas molecule because there are fewer molecules in the space adjacent to the liquid surface. With fewer molecules present for collisions, vaporizing molecules travel enough distance from the liquid surface so that they cannot readily return to the liquid surface.

Finally, creating a vacuum can protect materials from reacting with air. To accomplish this, the chamber is first evacuated and then backfilled with an inert gas in order to remove as many reactive gas molecules as the process dictates.

Table 1.2. Benefits of a vacuum.

| **Benefits of a Vacuum** |
|---|
| Produces a cleaner process environment |
| Increases mean free path |
| Controls the number of surface collisions |
| Lowers molecular density |
| Creates a force |
| Reduces heat flow |
| Increases vaporization |
| Protects materials |

Section 1.4 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=27#h5p-5*

## 1.5 How to Create a "Vacuum"

In our discussion in this chapter describing how vacuum is an enabling technology, we have described several ways to create a vacuum. The simplest way to create a vacuum is to mechanically increase the volume of the enclosed space. The cell phone holder and glass handles are examples. Deforming a flexible diaphragm and pulling it away from a non-porous surface creates a space underneath the diaphragm with a gas density much lower than the atmospheric conditions above the diagram. However, for this to work, the seal at the edge of the diaphragm must be airtight.

Ways to Create Vacuum:

- mechanically increase the volume of the enclosed space
- lower the temperature of the gas in the enclosed volume
- change from a gas to a solid when molecules strike a cold surface and become immobilized
- change gas to a solid using chemically reactive material.
- remove gas molecules from the chamber

Another way to create a vacuum is to lower the temperature of the gas in the enclosed volume. As the temperature is lowered, the gas molecules travel slower. When they hit the walls of the enclosed space, the force they exert will be smaller and there will be less pressure inside the closed space.

Now consider this, if the temperature is low enough and the gas molecules are able to ***freeze***, that is, the molecules change directly from the gas state to a solid state, there will be fewer gas molecules in the gaseous state and they will be traveling slower, hence reducing the pressure. Consider a freezer in your home. Have you ever noticed that when you try to open the freezer door immediately after closing it, it often takes a little more force to open the door? This occurs because room air enters the freezer while the door is open. When you close the door, the room air is cooled by the cooling coils in the freezer and some of the water ***vapor*** may adsorb on the coils. This effectively reduces the pressure inside the freezer and the atmospheric pressure condition external to the freezer door, which remains constant, tends to hold the freezer door closed.

Another method to create a vacuum without lowering the temperature is accomplished by reacting the gas molecules with a chemically-reactive material to create a solid material. For example, within a closed chamber, the oxygen gas molecules in air will react with titanium to form titanium oxide, a solid compound that sticks to the chamber walls. By permanently removing oxygen from the gaseous state, the pressure level within the chamber is lowered to create a vacuum.

A more common and more efficient way of creating a vacuum is to displace, and remove, gas molecules from the chamber. There are many ways to accomplish this result using a variety of pumps of different sizes and designs. If the chamber pressure is near atmospheric pressure, ***mechanical pumps*** like rotary vane pumps, ***diaphragm pumps***, and scroll pumps are used. As the gas density is reduced, these mechanical pumps become less effective in removing air from the chamber. To further reduce the chamber pressure, turbomolecular pumps, ***cryo pumps***, and sublimation pumps are used. We will describe some of these pumps in more detail as we study various vacuum pressure regimes.

**There are several ways to create vacuum including mechanical, chemical, and thermal mechanisms. All of them require an understanding of gas behaviors which will be discussed in Chapter 2.**

Section 1.5 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=27#h5p-14*

## 1.6 Sources for Information on Vacuum Technology

The material presented in these chapters is not intended to be an exhaustive treatment of vacuum and vacuum systems. Instead, it is intended to provide a fundamental understanding of vacuum systems for technicians and others who will be working with vacuum systems on a regular basis. Nevertheless, there will be times when you will want to research topics in vacuum technology in more depth.

### 1.6.1 Professional Societies

There are two major professional societies in the United States that focus on vacuum technology and its applications. They are the AVS and the Society of Vacuum Coaters (SVC).

AVS (formerly known as the American Vacuum Society): From the avs.org website,

> *As an interdisciplinary, professional society, AVS supports networking among academic, industrial, government, and consulting professionals involved in a variety of disciplines – chemistry, physics, biology, mathematics, all engineering disciplines, business, sales, etc. through common interests related to the basic science, technology development, and commercialization of* ***materials, interfacing and processing area.***
>
> *Founded in 1953, AVS is organized into technical divisions and technical groups that encompass a range of established as well as emerging science and technology areas. There are also regional chapters, international chapters and affiliates, and student chapters that promote communication and networking for professionals and students within a geographical region. AVS is comprised of approximately* ***4,500 members worldwide.***

Society of Vacuum Coaters (SVC): From the svc.org website:

> *SVC is a non-profit, international, professional organization primarily devoted to coating and surface finishing using vacuum processes. Our organization consists of industry, academia and members from national research laboratories. Our industry membership includes coating companies, materials suppliers, process designers, equipment manufacturers. Our industry applies coatings and treatments to a wide variety of consumer and industrial products in all business sectors.*

As with most professional societies, both AVS and SVC provide resources on their website that can be accessed for free.

### 1.6.2 Publications

*Vacuum Technology & Coating* is a readable monthly magazine on vacuum instrumentation, plasma processing, and thin film deposition. Each month, the magazine has feature articles on "Vacuum Technology," "Photonics and Microelectronics," "Thin Films and Materials," "Nanotechnology," and "Biotechnology." Website: www.vtcmag.com

### 1.6.3 Vacuum Equipment Manufacturers

There are a number of companies that make and sell ***vacuum components***, instrumentation, and related products. These companies include Pfeiffer Vacuum, Leybold Vacuum, MKS, Inc., Edwards Vacuum, Agilent, and Kurt J. Lesker Company. There is a wealth of information on vacuum on these websites. Here is a list of their websites:

- Pfeiffer Vacuum: Pfeiffer-vacuum.com
- Leybold Vacuum: leybold.com
- MKS: mksinst.com
- Edwards Vacuum: edwardsvacuum.com
- Agilent: agilent.com
- Kurt J. Lesker Company: lesker.com

## 1.7 Looking Ahead

Our study of vacuum systems will begin with a review of the behavior of gases. You may have studied gas laws in another class, for example, chemistry, so the material in Chapter 2 may be familiar. For a more in-depth treatment, a general chemistry text would be a good reference on this topic.

Chapter 3 will introduce vacuum systems and the components used to construct them. The presentation by design will be general. Chapters 4 and 5 will then provide a more detailed discussion of vacuum systems used in the ***rough vacuum regime*** and then the high vacuum regime. The discussion will follow a specific pattern and answer the following questions:

Looking Ahead

- Chapter 2 – Behavior of gases
- Chapters 3 and 4 – Rough vacuum systems
- Chapter 5 – High vacuum
- Chapters 6, 7, 8, 9 – Leak detection and other advanced topics

- What is the "***gas load***"? What gases must be pumped out of the chamber?
- How will the gas be removed from the chamber? What type of pump will best serve the need?
- How will the chamber pressure be measured? What type(s) of ***pressure gauges*** will be needed?
- How should the system be constructed? What types of fittings, valves, and other vacuum components will be needed?
- Are there other types of measurement and diagnostic equipment that will be needed, for example, residual gas analyzers and leak detectors?

Chapter 6 will describe an instrument called the residual gas analyzer. Unlike pressure gauges that require you to know what gas that is being pumped, the residual gas analyzer measures the ***partial pressure*** of each gas being pumped.

Chapter 7 will describe vacuum leak detectors. Unfortunately, leaks do occur, and leak detectors are used to find leaks in a vacuum system. In the case of vacuum systems, we will be looking at the ways that unwanted gas gets into the vacuum system.

Chapter 8 will provide a brief introduction to gas delivery and pressure control. The mass flow controller will be described along with several pressure control strategies.

Finally, Chapter 9 will conclude our discussion of vacuum systems with an overview of the safety issues related to vacuum systems.

# Summary

**Vacuum Technology is an "enabling" technology for a wide range of manufacturing processes.**

Vacuum technology is an "enabling" technology making possible a wide range of manufacturing applications. Examples are food preservation, thermal insulation, vacuum gripping, metal evaporation and other semiconductor manufacturing processes. A vacuum environment is beneficial, and in many cases necessary, to produce certain products. Using vacuum allows us to control contamination, aid in material deposition processes, reduce heat flow, produce large forces, increase vaporization, and protect materials from reactions with air. There are several viable ways to create vacuum by using mechanical, chemical and thermal processes. These processes and corresponding technological solutions will be discussed in the following chapters.

# Chapter 1 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=27#h5p-26*

# References

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Montelis, Lars. *Vacuum the Enabling Technology*, 12 Aug. 2018: http://www.physicsworld.com.

Quirk, Michael, and Julian Serda. *Semiconductor Manufacturing Technology*. Prentice-Hall, Upper Saddle River, NJ, 2001.

Tompkins, Harland G. *The Fundamentals of Vacuum Technology*. 3rd ed. AVS Monograph Press, New York, NY, 1997.

# Questions and Problems

1. How do you define vacuum? Draw an image that illustrates vacuum.

2. Explain how a vacuum condition enables the food canning process. How do you recognize the can is sealed? How is the presence of a vacuum condition confirmed?

3. Many food products are vacuum sealed. Provide two or more reasons or advantages for vacuum sealing food products.

4. What's another product where a vacuum condition usefully serves to slow heat transfer? Explain in general terms how slowing the rate of heat transfer benefits the product.

5. Consider a pot of boiling water on a stove top. You pass a plate above the rising steam. Describe what happens and why.

6. Pick one of the "Other Examples of Vacuum Processes" listed in 1.3.5. Explain the process in general terms. Roughly, what is the amount of pressure required for that process?

7. Go to the latest edition of vtcmag.com. Identify a new product enabled by vacuum.

8. Go to the website of one of the vacuum manufacturers listed. Identify some of the vacuum related products they sell.

9. The following individuals are recognized to have made significant contributions to the development of vacuum science and vacuum technology. Use online resources to describe their work related to vacuum science/technology:
   a. Torricelli, Evangelista
   b. Pascal, Blaise
   c. Boyle, Robert
   d. Von Guerike, Otto
   e. Amontons, Guillaume
   f. Gay-Lussac, Joseph Louis
   g. Charles, Jacques
   h. Dalton, John
   i. Clausius, Rudolf
   j. Maxwell, James Clerk
   k. Boltzmann, Ludwig
   l. Sprengel, Hermann
   m. McLeod, Herbert
   n. Swan, Joseph
   o. Edison, Thomas
   p. Pirani, Marcello
   q. Gaede, Wolfgang

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# CHAPTER 2: THE BEHAVIOR OF GASES

Learning Objectives

Chapter 2 provides an overview of the behaviors of gases that are key to understanding the operation of vacuum systems. After you read this chapter, you will be able to:

- Identify the states of matter and describe characteristics of the underlying molecular behaviors in each state.
- Convert pressure measurements from one unit of measure to another.
- Describe the underlying assumptions related to the kinetic theory of gases.
- Explain the relationship between molecular density and pressure.
- Explain the effect of temperature on the shape of speed distribution for gas molecules.
- Apply Boyle's law, Charles's law, Gay-Lussac's and the ideal gas law to solve for unknown system parameters.
- Apply Dalton's law to relate partial pressures of gas constituents and the total pressure.
- Define the term *mean free path* and explain how it changes as the pressure decreases.
- Describe the processes of adsorption, desorption, diffusion and permeation.
- Describe the differences in the thermal conductivities of air, argon and helium.
- Explain the processes associated with vapor pressure and how changes in temperature impact vapor pressure.

## 2.1 Introduction

The key to understanding the operation of vacuum systems is the ability to visualize how gases behave. This is where our discussion of vacuum systems begins. Some of this information will be familiar to you, because living on Earth teaches us many things about the behavior of gases. For example, we have observed objects being scattered on a windy day and enjoyed the cool breeze from an electric fan on a hot day. We have seen steam rising from a lake in the early morning. Each of these situations occurs because of gas molecules in motion.

We also observe varying effects due to different gases. A helium-filled balloon, for instance, rises into the air, whereas balloons filled with room air fall to the floor. Dry ice, the common name for carbon dioxide in solid form, when placed in water sublimes readily from solid to gas to create a dramatic fog effect. We know that air is a life sustaining gas. But other gases, like carbon monoxide, are toxic.

**This chapter overviews the laws of chemistry and physics that govern the behavior of gases.**

We have used pumps to concentrate gas in a confined space, as when we pump up the tires of a bicycle or car. We have enjoyed the benefits of a reduction in gas molecules between the walls of a Thermos bottle that slows the movement of heat and keeps liquid refreshments hot or cold. We have observed the results of matter changing from the gaseous state to the liquid state (***condensation***), or from the solid state to the gaseous state (***sublimation***). These are only a few examples, and you can probably think of many more.

The goal of this chapter is to review the laws of chemistry and physics that govern the behavior of gases. The material in this chapter will help you develop a mental picture, or model, of the behavior of gases so that you will be able to visualize what is actually happening inside a vacuum system.

## 2.2 States of Matter

Before we begin our study of gases, let's briefly review concepts related to the states of matter. Matter exists in one of four states: a *solid*, a *liquid*, a *gas*, and a *plasma*. Water, plain old $H_2O$, serves as a familiar example to address the first three states.

In its lowest energy state, water exists as ice at temperatures below 0°C at ***standard atmospheric pressure*** at sea level (1 atmosphere). The water molecules are held in a rigid structure that gives ice shape, forming a solid material. When a piece of ice is placed in a container, the ice will partially fill the container but will not take the shape of the container. The surface of the ice behaves as an interface between the molecules held in solid ice form and the air that surrounds the ice. At the ice-air interface, water molecules, if they have enough energy, can cross the solid-gas boundary. The process of a water molecule escaping from the solid structure at the ice-air interface and entering into the air is called ***sublimation***. The process in which a water molecule in the air strikes a very cold surface and becomes frost, a solid form, is called ***adsorption***.

**Matter can exist in one of four states: a solid, a liquid, a gas, and a plasma.**

When the ambient temperature is increased above the ***freezing*** point, water begins to change from the solid state to the liquid state. Water exists as a liquid between the temperatures of 0°C and 100°C at standard atmospheric pressure. As a liquid, water molecules can now move, and the water can conform to the shape of the container into which it has been placed. For example, water placed in a pitcher conforms to the pitcher's shape. The surface of water behaves as an *interface* between the water below and the air above. At this water-air interface, water molecules, if they have enough energy, can cross the liquid-gas boundary. If the movement of the water molecules is from the liquid state to the ***vapor state***, then the process is called ***evaporation***. Conversely, water molecules can move from the vapor phase to the liquid phase. We know this process as ***condensation***.

At 100°C and standard atmospheric pressure, the boiling point of water is reached. As more energy is added, the temperature of the water will remain at the boiling point until all the water is converted to a ***vapor***. When in the gaseous state, the water vapor (steam) can now fill the entire enclosed space above the boiling water. In the gaseous state, water molecules are able to move independently. It is the behaviors of water vapor and other gases that we will study in the chapters to follow.

In the last state of matter, *plasma*, the gas molecules are ionized, forming a mixture of particles. There are *electrons*, *ions*, *radicals*, *neutrals*, and other energetic particles. Plasmas hold the promise of energy generation through fusion and are used in a variety of manufacturing processes that produce products we use every day. Plasma is a fascinating state of matter and one that is the basis for important vacuum-based processes.

**Gas is one of the four basic states of matter.**

Looking at the periodic table of elements, illustrated in Figure 2.1, we find elements that exist naturally in one of three states of matter, that is, solid, liquid, or gas. A majority of the elements exist as solids at the normal temperature and pressure (NTP) condition, that is defined as 20°C and 1 atmosphere (101,325 Pa): copper, iron, and silicon are examples. Only two elements, mercury and bromine, exist at room temperature as a liquid. The remaining elements exist as gases at room temperature, for example nitrogen, oxygen, and argon.

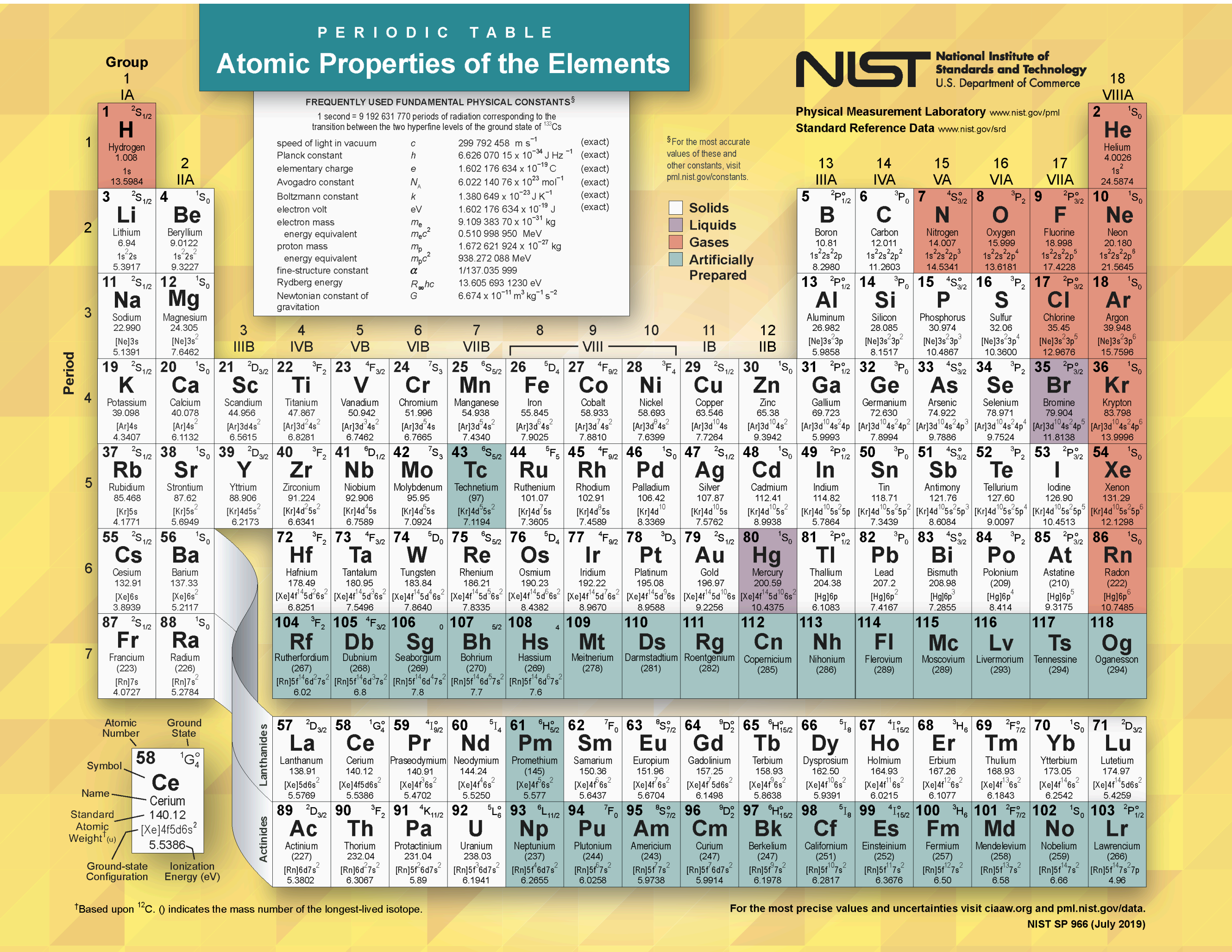
With this brief review of the states of matter, let's begin our study of gases. We will start with an explanation of gas pressure as a physical property and the units of measure used to express gas pressure quantitatively. We will focus on units of measure used to express pressures in the vacuum regime.

Section 2.2 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-15*

## 2.3 Gas Pressure

A gas is made up of many gas molecules in rapid motion. Inside a closed ***chamber***, the gas molecules collide with each other and with the chamber walls. Each collision with the chamber wall exerts a small force on the



PERIODIC TABLE

**Atomic Properties of the Elements**

FREQUENTLY USED FUNDAMENTAL PHYSICAL CONSTANTS§

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of $^{133}$Cs

| | | | |
|---|---|---|---|
| speed of light in vacuum | $c$ | 299 792 458 m $s^{-1}$ | (exact) |
| Planck constant | $h$ | $6.626\ 070\ 15 \times 10^{-34}$ J $Hz^{-1}$ | (exact) |
| elementary charge | $e$ | $1.602\ 176\ 634 \times 10^{-19}$ C | (exact) |
| Avogadro constant | $N_A$ | $6.022\ 140\ 76 \times 10^{23}$ $mol^{-1}$ | (exact) |
| Boltzmann constant | $k$ | $1.380\ 649 \times 10^{-23}$ J $K^{-1}$ | (exact) |
| electron volt | eV | $1.602\ 176\ 634 \times 10^{-19}$ J | (exact) |
| electron mass | $m_e$ | $9.109\ 383\ 70 \times 10^{-31}$ kg | |
| energy equivalent | $m_ec^2$ | 0.510 998 950 MeV | |
| proton mass | $m_p$ | $1.672\ 621\ 924 \times 10^{-27}$ kg | |
| energy equivalent | $m_pc^2$ | 938.272 088 MeV | |
| fine-structure constant | $\alpha$ | 1/137.035 999 | |
| Rydberg energy | $R_\infty hc$ | 13.605 693 1230 eV | |
| Newtonian constant of gravitation | $G$ | $6.674 \times 10^{-11}$ $m^3$ $kg^{-1}$ $s^{-2}$ | |

§For the most accurate values of these and other constants, visit pml.nist.gov/constants.

- ☐ Solids
- ▨ Liquids
- 🟥 Gases
- 🟩 Artificially Prepared

NIST National Institute of Standards and Technology U.S. Department of Commerce

Physical Measurement Laboratory www.nist.gov/pml

Standard Reference Data www.nist.gov/srd

†Based upon $^{12}$C. () indicates the mass number of the longest-lived isotope.

For the most precise values and uncertainties visit ciaaw.org and pml.nist.gov/data.

NIST SP 966 (July 2019)

Figure 2.1. Periodic Table of Elements.

chamber wall as shown in Figure 2.2. The cumulative effect of all the molecules-wall collisions can be expressed as a force per unit area, or ***pressure***, such as pounds-per-square-inch, or ***psi***:

$$Pressure = \frac{force\ exerted\ by\ gas\ molecules}{unit\ area\ of\ surface}$$

**Gage pressure is a pressure measured in reference to the atmospheric pressure.**

**Absolute pressure is referenced to the ideal state of zero pressure.**

There are a great many units of measure used to specify the pressure of a gas. In the United States, the most familiar units are pounds per square inch (***psi***) and inches of mercury (in Hg). For example, the air pressure in car tires is specified in psi. Tire pressure is also what is called ***gage pressure*** or pressure measured in reference to the atmospheric pres-

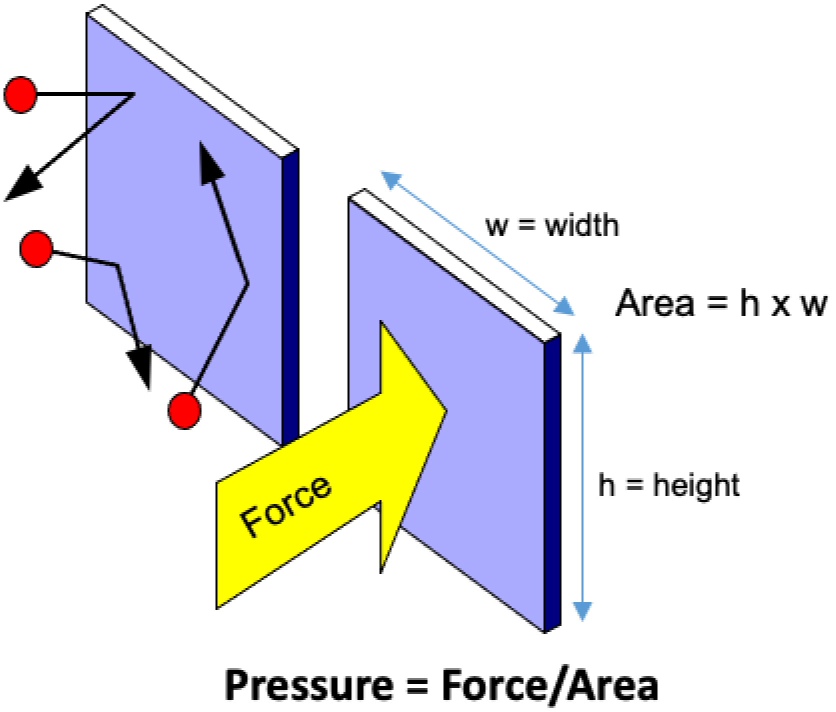


Figure 2.2. Gas molecules within a chamber. Graphics is provided by MATEC.

sure. This means that a tire pressure of 30 psi (or 30 psig), for example, is 30 psi higher than the local atmospheric pressure.

In contrast, ***absolute pressure*** is measured with reference to ideal zero pressure. ***Absolute pressure*** can be measured in units of atmospheres, ***torr***, ***bar***, ***mbar***, and ***pascal***. The pressure unit, torr, is often used in the United States and is the standard unit of pressure used in this textbook. In other parts of the world that have adopted the *Systeme international des unites* (***SI***), the standard unit of pressure is newton per square meter (N/m$^2$) or ***pascal (Pa)***, although ***millibar*** (mbar) is used as well.

It is important for you to be able to convert from one system of units to another. The following pressures are equal to 1 atm of pressure:

1 atm = 760 Torr
= 101,325 Pa (N/m$^2$)
= 101.325 kPa
= 1.01325 bar
= 1013.25 mbar
1 mmHg = 1.0000004 Torr (approximately 1 Torr)

**There are many units used for pressure. Some of the examples are mmHg, torr, pascal, kilopascal, bar, and mbar.**

Some books on vacuum technology give conversion tables for equating a pressure value in one system of units to an equivalent pressure value in another. This is helpful when you happen to have the table with you or have committed the table to memory. It is also useful to understand how to convert units of measurement. Unit conversion is based on the mathematical fact that multiplying the original pressure by the number 1 does not change the value of the original pressure. The ratio of 1 atm/760 Torr is exactly equal to 1, and the ratio of 760 Torr/1 atm also equals 1. The trick is to find the right form of the number 1. The form of 1 that should be used has 1 atm expressed in the new unit of pressure in the numerator and 1 atm expressed in the original unit of pressure in the denominator. The original pressure is then multiplied by this ratio. Mathematically, it can be expressed as follows:

$$P_{new} = P_{original}\frac{(1atm)_{new}}{(1atm)_{original}}$$

The following example illustrates how using the method adapted from dimensional analysis works. Note that the original units should cancel, leaving only the new unit of pressure.

**Example 2.1**

Convert 100 Torr to pascals.

**Solution:**

To convert pressure in torr to an equivalent pressure in pascals, we need to know, from memory or a table, the number of each unit in one atm.

$$1atm = 760\,Torr$$

$$1atm = 101,325\,Pa$$

The pressure unit torr (Torr) is our original pressure and the pressure unit pascal (Pa) is our new pressure unit. Hence

$$P_{new} = P_{original} \frac{(1atm)_{new}}{(1atm)_{original}}$$

$$P_{new} = 100\,Torr \left( \frac{101,325\,Pa}{760\,Torr} \right)$$

$$P_{new} = 13,300\,Pa$$

Despite the myriad of pressure units, one would think that measuring pressure in a chamber would be no more complicated than measuring temperature. One would reasonably expect that just like thermometers which are used for a variety of purposes and to measure different temperature ranges, ***pressure gauges*** are also available in a variety of types. However, as we will see, accurately measuring the pressure of a gas is not a trivial task, and is certainly more complex than measuring temperature.

In the ***rough vacuum regime*** (760 Torr to 1 millitorr), there are basically two types of pressure gauges: direct reading gauges and indirect reading pressure gauges.

**Direct reading gauges measure the force exerted on a surface by the gas molecules.**

***Direct reading gauges*** measure the force exerted on a surface by the gas molecules. One example of a direct reading gauge is a Bourdon gauge. A ***Bourdon gauge*** is a purely mechanical gauge that uses a curved copper tube which deflects in response to the difference between atmospheric pressure on the outside and the chamber pressure on the inside. Another type of direct reading gauge is a capacitance ***diaphragm gauge***, also known as a capacitance manometer. In a capacitance diaphragm gauge, a thin diaphragm is deformed by the force exerted by the gas molecules. This deformation changes the capacitance between the diaphragm and a reference electrode. The gauge controller electronics converts this change in capacitance into a pressure reading.

**Indirect reading gauges are based on the heat conduction or ease of ionization properties of gases to infer the corresponding pressure condition.**

One type of ***indirect reading gauge*** uses the heat conduction property of gases to determine the density of the gas which infers the pressure in the chamber. The more gas molecules, the greater the rate of heat transfer, and thus the higher the pressure. Thermocouple and Pirani pressure gauges are examples of indirect reading pressure gauges.

In the high vacuum regime (pressures less than 1 millitorr), neither mechanical force nor the heat transfer mechanism can be used to measure pressure. To measure pressure in the high vacuum regime, gas molecules are converted from neutral atoms and molecules to ions. The ions are then collected, and the resulting electrical current is measured. The amount of current is converted to a pressure reading. A decrease in the current corresponds to a decrease in pressure.

The heat-conduction properties and the ease of ionization of gases differ based on the type of gas. Therefore, the pressure reading obtained will have to be adjusted depending on the gas or gas mixture. This makes accurate pressure measurement more complex than just reading a number on the pressure readout or display. We will talk more about this later in the book.

Section 2.3 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-7*

In the next section, we will start developing a mental picture of how gases behave. Our mental picture will be based on the kinetic theory of gases.

## 2.4 Kinetic Theory of Gases

The kinetic theory of gases attempts to explain the physical behavior of gases. As is typical of theories in science, it is based on a set of assumptions. In the case of the kinetic theory of gases, the underlying assumptions include the following:

- Gases are composed of a very large number of separate, independent atoms or molecules that are in constant, straight-line motion. These molecules are so widely spaced that, on the average, the total volume of the molecules is very small compared to the volume of the space those molecules are contained within.
- In the absence of collisions, the gas atoms and molecules display no attraction, or repulsion, toward one another.
- The straight-line motion of the gas molecules may be interrupted by collisions with other gas molecules or with the walls of the chamber enclosing the gas. The collisions are assumed to be completely elastic, resulting in no energy being converted to heat or another form of energy or a change in the atoms, or molecules, involved in the collision.
- Because gas molecules are in constant motion, they possess a certain amount of kinetic energy. Since the gas molecules can have different velocities, each ***gas molecule*** can have a different kinetic energy. The total kinetic energy possessed by the gas is proportional to the temperature of the gas in units of Kelvin (K) and is a function of the combined molecular velocities of all the gas atoms, or molecules, in the

chamber. The underlying speeds of the gas molecules also vary by molecule type at any given temperature. Heavier molecules move on average more slowly than lighter molecules at the same temperature.

Sometimes it is helpful to draw a picture to help visualize this concept. First, draw an enclosed space of any shape that we will call the "chamber." Inside this chamber, draw small circles to represent the gas molecules. Since the gas molecules are not static but in motion, we can represent this motion with arrows to represent the direction of travel and the speed at which it is traveling (length of the arrow) as shown in Figure 2.3. Some of the gas molecules will collide with each other, and some will collide with the walls of the chamber.

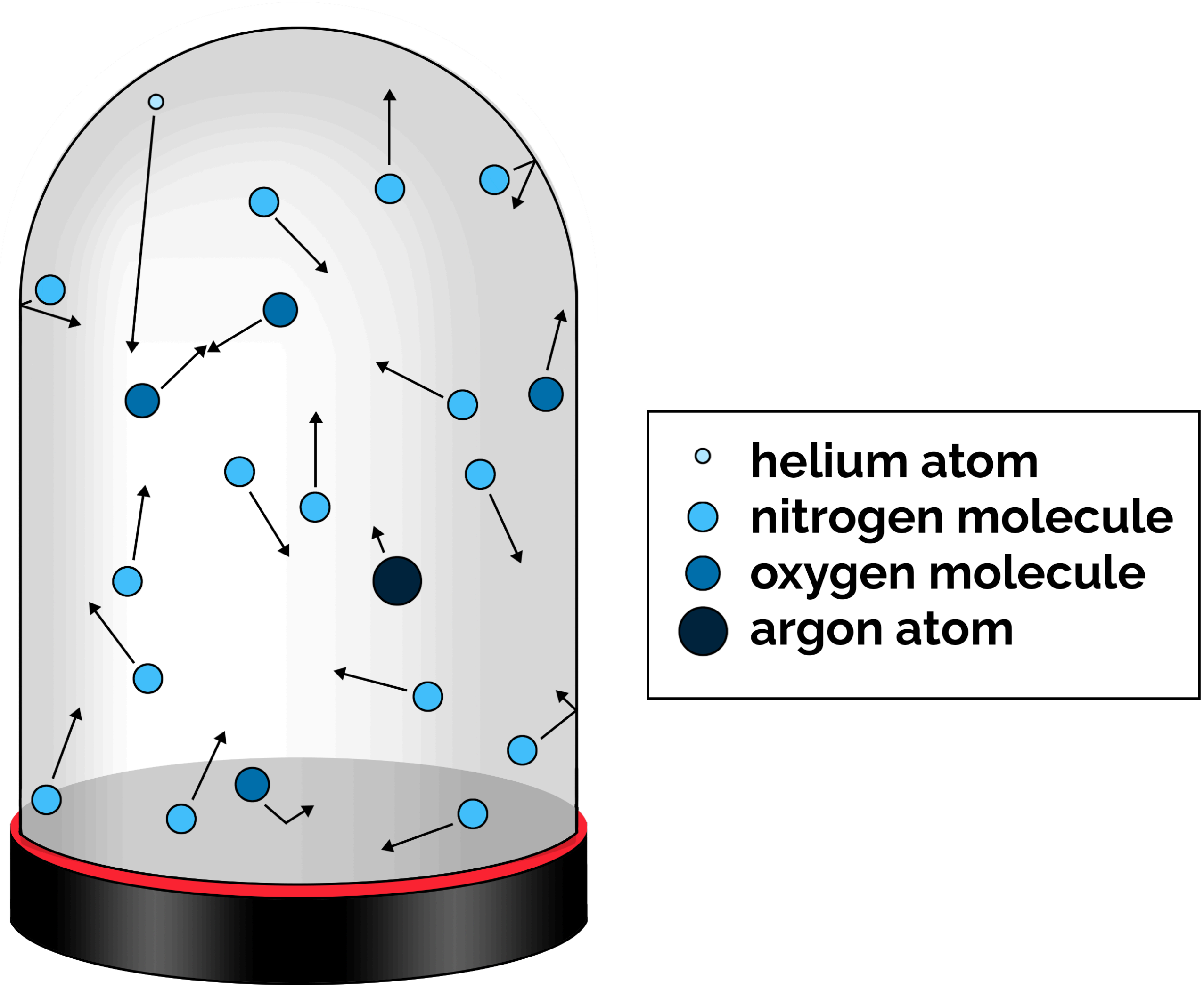


Figure 2.3. Gas molecules within a chamber. Graphics provided by Gigi Bocek, Normandale Community College.

The kinetic theory of gases can be used to explain the following properties of gases:

- Gases fill a chamber completely, irrespective of pressure and the shape of the chamber.

- Gases are compressible (relates to Boyle's Law).
- Gases expand/contract with changes in temperature (relates to Charles's Law).
- Gases of equal volume and pressure have an equal number of molecules (Avogadro's Law).
- The total pressure of a mixture of gases is equal to the sum of the ***partial pressures*** of each gas in the mixture (Dalton's Law).

**The kinetic theory of gases attempts to explain the behavior of gases on the microscopic level.**

## 2.4.1 Distribution of Gas Molecules in an Enclosed Volume

When a certain amount of gas is placed within an enclosed volume or chamber, the gas fills the entire volume and the population density of gas molecules is uniform throughout the chamber. If this were not true, there would be areas of greater concentration of gas molecules and areas of lesser concentration. This concentration difference would produce a flux that would cause the gas molecules to move from areas of higher concentration to areas of lesser concentration. This movement of gas molecules would continue until the concentration difference and the flux are reduced to zero. Hence, the density of gas molecules must be uniform throughout the entire enclosed volume.

The density of gas molecules varies with pressure. The relationship between pressure and ***molecular density*** is shown in Table 2.1.

Table 2.1. Molecular density as a function of absolute pressure.

| **Pressure (Torr)** | **# of Molecules Per Cubic Centimeter** |
|---|---|
| 760 | $3 \times 10^{19}$ |
| 1 | $4 \times 10^{16}$ |
| $1 \times 10^{-3}$ | $4 \times 10^{13}$ |
| $1 \times 10^{-6}$ | $4 \times 10^{10}$ |
| $1 \times 10^{-9}$ | $4 \times 10^{7}$ |

At 760 Torr, there are approximately $3 \times 10^{19}$ air molecules per cubic centimeter, about 30 million trillion molecules. That is a lot of gas molecules and they are constantly in motion and are bumping into each other as well as nearby surfaces. In fact, they are so close together that, on average, each molecule travels only $6 \times 10^{-5}$ millimeters before colliding with another molecule. When a chamber is sealed with air at atmospheric pressure, the molecular collisions occurring within the chamber volume are overwhelmingly gas molecules running into each other compared to gas molecules striking the interior walls of the chamber.

If we reduce the pressure by six orders of magnitude to a pressure of one millitorr, the number of gas molecules per cubic centimeter is approximately $4 \times 10^{13}$, or 40 trillion. That still seems like a lot of gas molecules, but at this pressure, the distance traveled by gas molecules between collisions approaches 2 inches, or approximately 5 centimeters. In large chambers, the number of gas molecules to gas molecule collisions dominates, whereas there are proportionately fewer collisions against chamber walls.

**As pressure in the chamber is reduced, the average distance a molecule travels before colliding with another molecule increases.**

If the pressure is further reduced to $1 \times 10^{-9}$ Torr, another reduction of six orders of magnitude, the number of gas molecules per cubic centimeter is now $4 \times 10^{7}$, or 40 million. That is still a lot of gas molecules in a small space, but now the distance that gas molecules travel between collisions with each other is 31 miles (50 kilometers), a distance much greater than the dimensions of almost any chamber. At these pressures, the collisions between gas molecules and the chamber walls dominate. This change from majority of gas molecule to gas molecule collisions at atmospheric pressure to majority of gas molecule to chamber wall collisions at very low pressures is important in processes carried out at these very low pressures.

## 2.4.2 Compressibility of Gases

One of the qualities that distinguishes gases from solids and liquids is ***compressibility***. From our life experiences, we know this to be true. For example, we have probably experienced the compressing of air when pumping up a bicycle or car tire.

**One of the qualities that distinguishes gases from solids and liquids is compressibility.**

The compressibility of gases can be explained quite easily using the kinetic theory of gases. Gas molecules are seen as very small molecules separated by great distances compared to their size. Reducing the volume enclosing the gas molecules crowds them together. As the gas molecules move within a smaller volume, the number of collisions between them increases, as does the number of collisions between the gas molecules and the chamber walls. The cumulative effect of all the collisions between the gas molecules and the wall of the chamber creates a greater force on the chamber wall, or chamber pressure, as shown in Figure 2.4.

The relationship between the volume of gas and the absolute pressure exerted by a constant amount of gas is stated in Boyle’s Law. ***Boyle's law*** states that if the temperature and the amount of gas are held constant, the volume of gas is inversely proportional to the pressure exerted by the gas. The relationship can be expressed in equation form as

$$V \sim \frac{1}{P} \qquad (temperature\ is\ held\ constant) \qquad (2.1)$$

The proportionality can be changed to an equality by inserting a proportionality constant, $k$. Hence,

$$V = k \times \frac{1}{P} \qquad (temperature\ is\ held\ constant) \qquad (2.2)$$

If a fixed volume of gas at a constant temperature is compressed or expanded, then

$$P_i \times V_i = k$$

where $P_i$ and $V_i$ is the initial or first condition, and

$$P_f \times V_f = k$$

where $P_f$ and $V_f$ is the final or second condition.

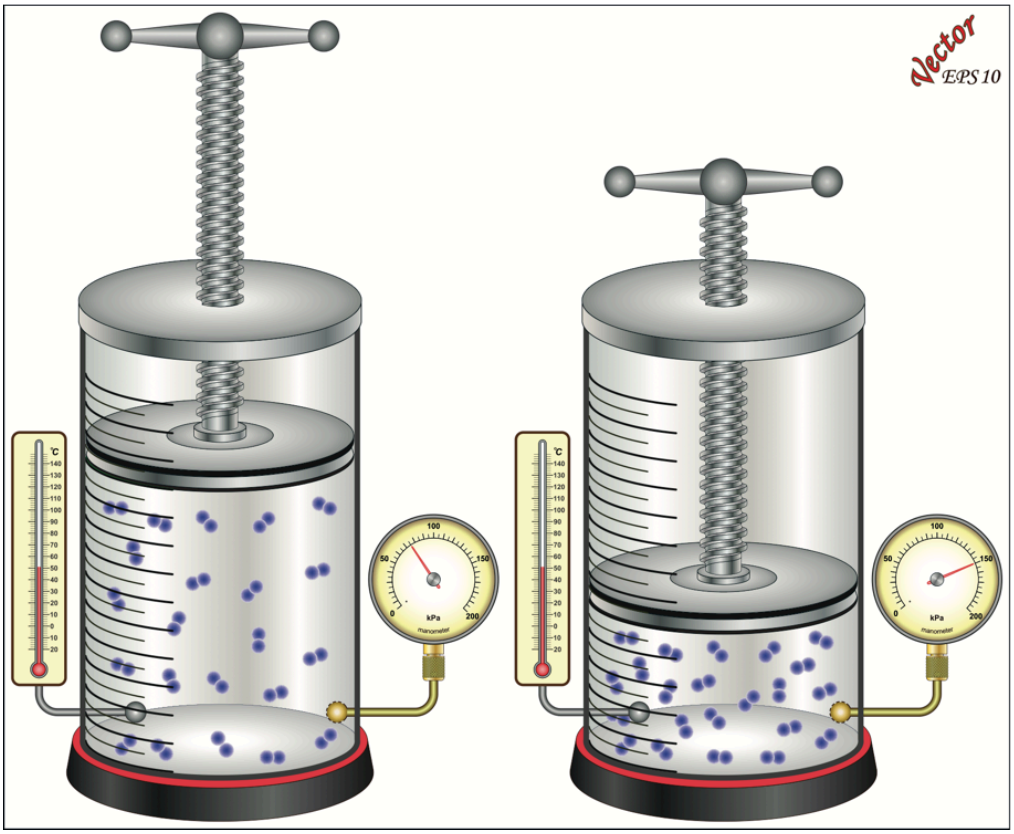


Figure 2.4. Pressure-volume relationship. Photo provided by Fouad A. Saad/ Shutterstock.com.

Since the two equations equal the same constant, we can set an equals sign between them. This yields,

$$P_i \times V_i = P_f \times V_f. \qquad (2.3)$$

This is the mathematical statement of Boyle's law.

If the amount of gas and the temperature are constant, we can use Boyle's law to solve for the missing parameter if the other three parameters are known. For example, if we know the initial absolute pressure and volume and the final volume, we can solve Equation 2.3 for $P_f$. This yields,

$$P_f = \frac{P_i \times V_i}{V_f}. \qquad (2.4)$$

It is important to note that $P_i$ and $P_f$ represent absolute pressure in equation 2.4.

Before doing numerical examples, let's first see how an ideal gas behaves when the temperature is held constant and the volume of the gas changes. We are going to use the embedded "Introduction to Gases" Simulation 2.1 below. When you open the simulation, choose the "Laws" option at the bottom of the simulation. Introduce a small number of gas molecules into the chamber by using the simulated pump. One "pump" of gas is enough. Choose the option to hold temperature constant and increase the volume to the maximum value allowed. Note the pressure indicated on the pressure gauge. Then reduce the volume to half of the original volume and note how the pressure in the chamber changes. You should be able to see that cutting the volume in half results in doubling the pressure if temperature is held constant. This is consistent with Equation 2.4.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36*

*Simulation 2.1. Introduction to Gases Simulation. PhET Interactive Simulations, University of Colorado Boulder, https://phet.colorado.edu.*

It is important to note that a gage pressure value must be converted to an absolute pressure value when performing a calculation using Boyle's law.

**Example 2.2**

A gas is compressed at a constant temperature from an initial volume of 1.5 liters to 1.0 liter. If the initial pressure is 800 Torr, what is the final pressure in torr?

**Solution:**

Using Equation 2.4,

$$P_f = \frac{P_i \times V_i}{V_f}$$

$$P_f = \frac{(800\, Torr) \times (1.5\, liters)}{(1.0\, liter)}$$

$$P_f = 1200\, Torr$$

**Example 2.3**

How does Boyle's law help explain why a bag of potato chips seems to have more air in it while in flight than on the ground at the boarding gate.

**Solution:**

Consider the situation of purchasing a bag of potato chips at the airport in Miami, a location that is very near sea level. The pressure within the bag when it is completely sealed and you are standing at the boarding gate should be near 1 atm. The temperature within the bag can be assumed to be the same as the temperature inside the terminal which may be close to 20°C.

After the plane takes off and reaches cruising altitude, the cabin is pressurized to approximately 0.7 to 0.8 atm in order to maintain a suitable level of oxygen for passengers. The temperature in the plane's cabin will likely be close to 20°C.

A potato chip bag is a relatively flexible material. Since the temperature in the terminal and the temperature in the plane's cabin is the same, we can use Boyle's law to understand what should happen to the sealed bag.

$P_i$ = 1 atm within the sealed potato chip bag when you're at the boarding gate in the terminal

$P_f$ = 0.8 atm within the sealed potato chip bag when the plane is at cruising altitude

$V_i$ = volume of the sealed potato chip bag at the boarding gate

$V_f$ = volume of the sealed potato chip bag at cruising altitude

$$V_f = \frac{P_i \times V_i}{P_f}$$

$$V_f = \frac{(1\,atm \times V_i)}{(0.8\,atm)}$$

$$V_f = 1.25 \times V_i$$

Boyle's law predicts that the volume of the bag will be 1.25 times larger when the plane is at cruising altitude than its volume when you were standing at the boarding gate. An important point here is that even though the volume of the sealed bag is expanded and looks like it contains more air during an airplane flight, it still contains practically the same number of gas molecules as it did when you were standing at the boarding gate!

## 2.4.3 Effects of Temperature

Since gas molecules are in constant motion, each gas molecule has a certain amount of kinetic energy. The kinetic energy of a gas molecule is equal to

$$KE = \frac{1}{2}mv^2 \qquad (2.5)$$

where $m$ is the mass of the gas molecule and $v$ is the velocity magnitude or speed of the gas molecule. The gas molecules in the chamber do not all have the same velocity or speed. The distribution of the velocities of gas molecules follows a curve known as the *Maxwell-Boltzmann distribution*. Different gas types will have slightly different *Maxwell-Boltzmann* distributions.

Figure 2.5 shows the velocity distribution for four gases at the same temperature. Examining the graph, we see that the number of gas molecules with zero speed is essentially zero because few, if any, gas molecules are standing still at any instant. Moving to the right along the horizontal axis represents the increasing speeds of individual gas molecules at a given temperature. The vertical axis represents the probability that a molecule has a particular speed. In other words, for a given speed, out of all the gas molecules present, a certain number of them, not all of them, are moving at that speed. The graph peaks at a point that represents the most probable speed – that is the speed at which the largest number of molecules out of all the gas molecules present are moving. Moving right from the most probably speed, the numbers of molecules present that are moving at higher speeds decreases and approaches zero. The average speed of the gas molecules is higher than the most probably speed because the curve is not symmetric.

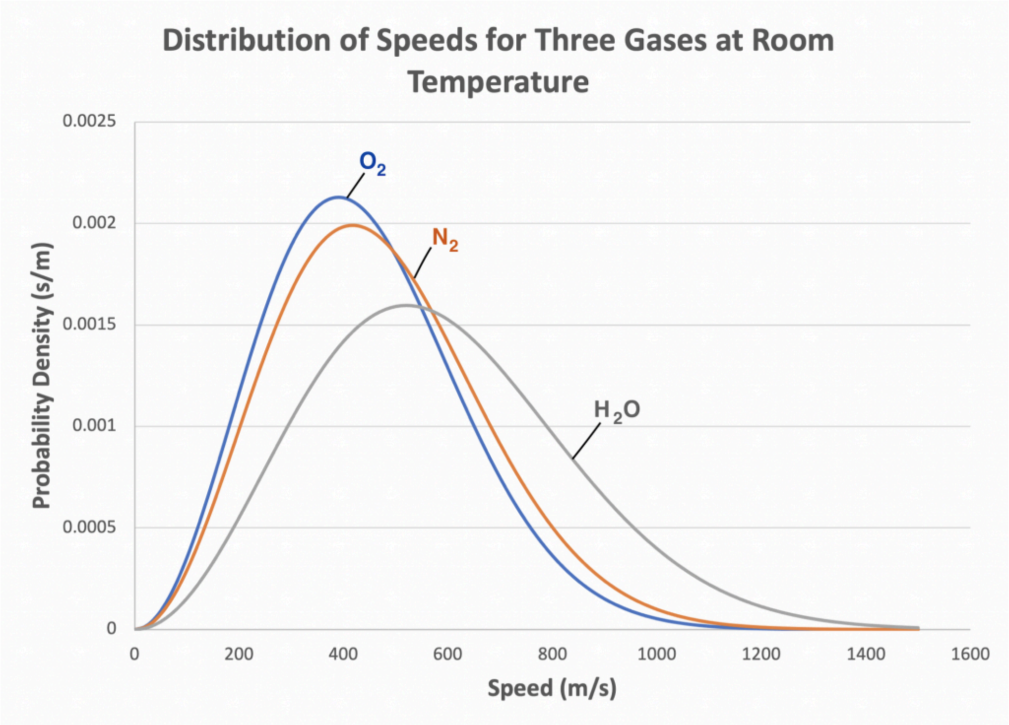


Figure 2.5. Distribution of speeds for four gases at the same temperature. Graph provided by E. Brewer at SUNY Erie Community College.

**Speed distribution of the molecules at higher temperature is wider resulting in larger percentage of molecules at higher speeds.**

When the temperature of a gas changes, the shape of the curve described by the Maxwell-Boltzmann distribution changes. For example, if the temperature of a gas is increased, the kinetic energy of the gas molecules increases corresponding to increased molecule speeds. The shape of the curve flattens out, and more gas molecules exhibit higher speeds. Corresponding increases are seen in both the most probable speed and the average speed. Figure 2.6 shows the effect of increasing or decreasing temperatures on the speed distribution for a gas.

The “Gas Properties” Simulation 2.2 below also shows the effects of temperature change on the speed distribution of molecules in a gas. To run the simulation, open the “Energy” tab and introduce gas into the system by using the bicycle pump. Note the current temperature, average speed and real-time speed distribution graph. Now, increase the temperature by heating the bucket and observe what happens to the temperature, average speed and the shape of the speed distribution. As temperature increases, you should be able to see that the average speed increases and the distribution of the speeds becomes wider, as a larger number of molecules have higher speeds.

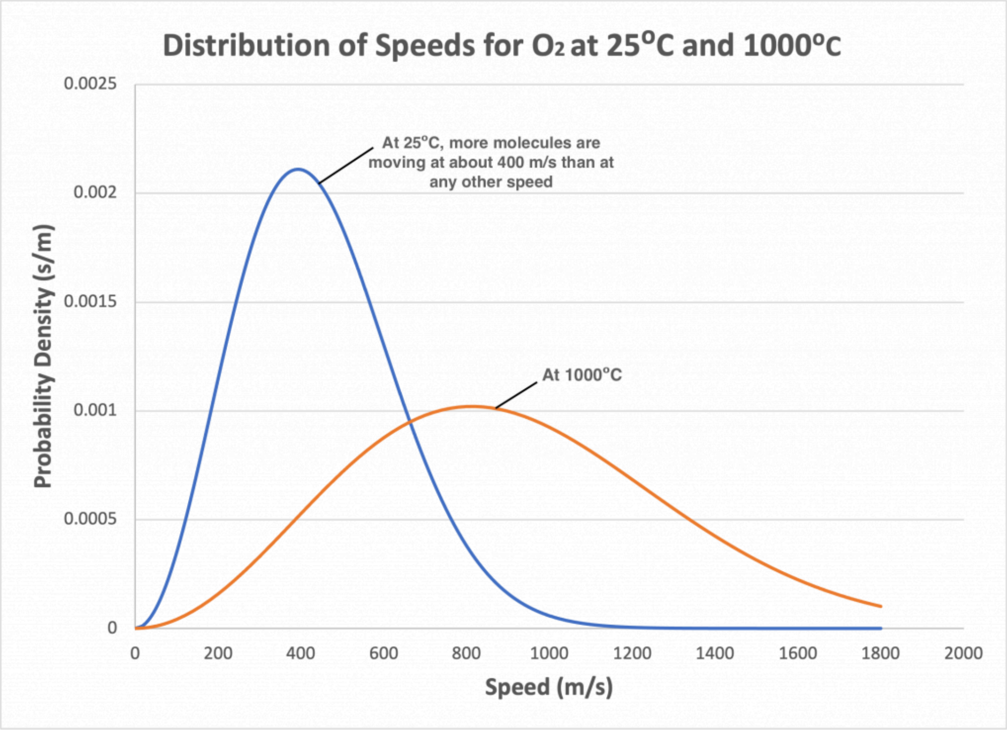


Figure 2.6. Speed distribution for the same gas at different temperatures. Graph provided by E. Brewer at SUNY Erie Community College.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36*

*Simulation 2.2. Gas Properties Simulation. PhET Interactive Simulations, University of Colorado Boulder, https://phet.colorado.edu.*

The relationship between volume and temperature, at a constant pressure is given by Charles's law, which is named after the eighteenth-century French chemist Jacques Alexander Charles. ***Charles's law*** states that the volume of a gas is directly proportional to the absolute temperature at a constant pressure. Mathematically, Charles's law can be expressed as

$$V \sim T \qquad (at\, a\, constant\, pressure) \qquad (2.6)$$

where $V$ is the volume of the gas and $T$ is the absolute temperature. Charles's law can also be expressed as an equality:

$$\frac{V}{T} = k = constant \qquad (2.7)$$

If gas is kept at a constant pressure while its volume and temperature change, then

$$\frac{V_i}{T_i} = k$$

where $V_i$ and $T_i$ is the initial or first condition, and

$$\frac{V_f}{T_f} = k$$

where $V_f$ and $T_f$ is the final or second condition.

Since the two equations equal the same constant, we can set the equal sign between them. This yields,

$$\frac{V_i}{T_i} = \frac{V_f}{T_f} \qquad (2.8)$$

This is the mathematical statement of Charles's law.

If the amount of gas and the pressure are constant, we can use Charles's law to solve for the missing parameter if the other three parameters are known. For example, if we know the initial volume and temperature and the final temperature, we can solve Equation 2.8 for final volume $V_f$. This yields,

$$V_f = \frac{V_f}{T_f} \times T_f. \qquad (2.9)$$

It is important to note that when using the equation for Charles's law, temperatures must be in units of Kelvin. That is, temperature given in Celsius or Fahrenheit must be first converted to Kelvin in order to perform the calculation using Charles's law.

**Example 2.4**

A certain amount of gas occupies a volume of 3.0 liters at a temperature of 30°C and a pressure of 1 atm (atmosphere). How many liters will it occupy at a temperature of 75°C and an absolute pressure of 1 atm? Assume the pressure remains constant.

**Solution:**

From the data given, the pressure remains constant, while volume and temperature change. According to Charles's law given by Equation 2.8,

$$\frac{V_i}{T_i} = \frac{V_f}{T_f}$$

Solving for $V_f$,

$$V_f = V_i \left( \frac{T_f}{T_i} \right)$$

Before this calculation can be performed, all temperatures must be converted from degrees Celsius to Kelvin:

$$T_i = (30 + 273\,K) = 303\,K$$

$$T_f = (75 + 273\,K) = 348\,K$$

Then,

$$V_f = (3.0\,liters) \left( \frac{348K}{303K} \right)$$

$$V_f = 3.45\,liters$$

## Example 2.5

Use Charles's law to explain why an empty plastic water bottle collapses when it remains in a space that cools off.

**Solution:**

Consider a situation in which you are traveling in a car and drinking water from a plastic bottle. When you are finished drinking the water, you screw the cap on the bottle. The temperature inside the car is 20°C. The atmospheric pressure experienced inside the car is nearly identical to the pressure outside the car.

You happen to be traveling in Minnesota during January, and it is very cold outside. The car is parked, turned off and left to sit outside overnight. The capped bottle is left in the car while the temperature inside the car drops to -25°C.

A plastic water bottle can be a relatively flexible material. Since the atmospheric pressure experienced inside and outside the car is nearly identical, we can use Charles's law to understand what should happen to the water bottle as the temperature in the car cools.

$T_i$ = 20°C within the capped water bottle when the car is turned off

$T_i$ = 20°C = 20 +273K = 293K

$T_f$ = -25°C within the capped water bottle after the car sits outside overnight

$T_f$ = -25°C = -25 +273K = 248K

$V_i$ = volume of the capped water bottle when the car is turned off

$V_f$ = volume of the capped water bottle after the car sits outside overnight

$$V_f = \frac{(V_i \times T_f)}{T_i}$$

$$V_f = \frac{(V_i \times 248K)}{293K}$$

$$V_f = 0.85 \times V_i$$

Charles's law predicts that the volume of the water bottle will be 15 percent smaller after sitting in the cold car overnight. An important point here is that even though the bottle's volume shrinks and looks like it contains less air, it contains roughly the same amount of molecules as it did before the car started cooling.

And finally, ***Gay-Lussac's law*** , also known as *Amonton's law*, describes how the absolute pressure of a gas depends on its temperature while the volume of the gas is held constant. According to this law, the absolute pressure of a gas at a constant volume is directly proportional to the absolute temperature. Stated in equation form,

$$P \sim T \qquad (at\ a\ constant\ volume) \qquad (2.10)$$

or using a proportionality constant,

$$\frac{P}{T} = k = constant. \qquad (2.11)$$

If gas is kept at constant volume, while its pressure and temperature change, then

$$\frac{P_i}{T_i} = k$$

where $P_i$ and $T_i$ is the initial or first condition, and

$$\frac{P_f}{T_f} = k$$

where $P_f$ and $T_f$ is the final or second condition.

Since the two equations equal the same constant, we can set an equals sign between them. This yields,

$$\frac{P_i}{T_i} = \frac{P_f}{T_f}. \qquad (2.12)$$

This is the mathematical statement of Gay-Lussac's law.

If the amount of gas and the volume are constant, we can use Gay-Lussac's law to solve for the missing parameter if the other three parameters are known. For example, if we know the initial absolute pressure and temperature and the final temperature, we can solve Equation 2.12 for final absolute pressure $P_f$. This yields,

$$P_i = \frac{P_f}{T_f} \times T_i. \qquad (2.13)$$

This can be illustrated by using the "Introduction to Gases" Simulation 2.3 below. When you open the simulation, choose the "Laws" option at the bottom of the simulation. Introduce a small number of gas molecules into the chamber by using the simulated pump. One "pump" of gas is enough. Choose the option to hold volume constant. Take a note of the current pressure and temperature values. Use the bucket control below the chamber to increase the temperature. You should be able to see that as temperature increases, pressure is also rising.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36*

*Simulation 2.3. Introduction to Gases Simulation. PhET Interactive Simulations, University of Colorado Boulder, https://phet.colorado.edu.*

### Example 2.6

A gas exerts a pressure of 500 Torr at 25°C. What pressure in torr will the gas exert if the temperature is raised to 40°C? Assume the volume remains constant.

**Solution:**

From Gay-Lussac's law given, as by Equation 2.12,

$$\frac{P_i}{T_i} = \frac{P_f}{T_f}$$

Solving for $P_f$,

$$P_f = P_i \frac{T_f}{T_i}$$

The temperatures, given in Celsius, must be converted to absolute temperatures in degrees Kelvin.

$$T_i = 25^{\circ}C = 25 + 273K = 298K$$

$$T_i = 40^{\circ}C = 40 + 273K = 313K$$

Substituting for $P_i$, $T_i$, and $T_f$ in the $P_f$ equation,

$$P_f = (500\, Torr)\, \frac{313K}{298K}$$

$$P_f = 525\, Torr$$

### Example 2.7

Use Gay Lussac's law to calculate the pressure inside of a glass bottle that sat in a cold car overnight. Assume the cap is secured to the bottle just before the bottle is transferred to a warmer environment.

**Solution:**

Since glass is a much more rigid material than plastics, a glass bottle capped off will behave like a constant volume. Assume that the glass bottle that sits in the cold car overnight gets to a temperature of -25°C. Let's assume that the atmospheric pressure is 740 Torr, which is the nominal atmospheric pressure experienced in much of Minnesota. 740 Torr can be assumed to be the pressure inside the cold glass bottle when you secure the cap on the bottle. You bring the bottle into a building where the temperature is 20°C and allow the bottle and the air inside of it to warm up.

Use Gay-Lussac's law to calculate the pressure inside of the glass bottle when the air inside of it warms up to 20°C.

$$T_i = -25^{\circ}C\, within\, the\, capped\, water\, bottle\, just\, before\, taking\, it\, indoors$$
$$T_i = -25^{\circ}C = -25 + 273K = 248\, K$$
$$T_f = 20^{\circ}C\, within\, the\, capped\, water\, bottle\, after\, it\, warms\, up$$
$$T_f = 20^{\circ}C = 20 + 273K = 293\, K$$
$$P_i = 740\, Torr\, = pressure\, within\, the\, capped\, water\, bottle\, just\, before\, taking\, it\, indoors$$
$$P_f = \; pressure\, within\, the\, capped\, water\, bottle\, after\, it\, warms\, up$$

$$P_f = \frac{P_i}{T_i} \times T_f$$

$$P_f = \frac{740\, Torr}{248\, K} \times 293\, K$$

$$P_f = 874\, Torr$$

Gay-Lussac's law predicts that the pressure inside the capped glass water bottle will increase after it is transferred from a cold environment to a warm environment. Unlike the previous two examples, there won't be a visual cue of the bottle changing shape that let's you know that the pressure increased inside the bottle. You may be able to release the cap in a manner that allows you to visualize that a change has occurred, for example, into a balloon. As with the previous two examples, even though the air within the bottle is under a higher pressure after the air inside the bottle warms up, the bottle still contains roughly the same amount of molecules as it did at the point the cold bottle was capped.

## 2.4.4 Gases of Equal Volume and Pressure

Amedeo Avogadro proposed *Avogadro's law*, which states that equal volumes of gases at the same temperature and pressure contain equal numbers of gas molecules. Avogadro's law was subsequently used to show that gases such as hydrogen, oxygen, and chlorine must be *diatomic* in structure.

If we examine one mole, that is, an amount of $6.02\times10^{23}$ atoms or molecules, of a gas at a temperature of 0°C, or 273 K, and a pressure of one standard atmosphere, or 760 Torr, we can measure the molar volume at conditions defined as Standard Temperature and Pressure (***STP***). Table 2.2 gives the molar volume for some common gases. From the results of these measurements plus measurements for other gases, the average volume occupied by one mole of gas at STP is 22.4 liters, and this value is therefore taken to be the molar volume of an ideal gas at STP.

Table 2.2. Molar volumes for some common gases.

| **Gas, symbol** | **Molar Volume in liters** |
|---|---|
| Argon, Ar | 22.397 |
| Carbon Dioxide, $CO_2$ | 22.260 |
| Helium, He | 22.434 |
| Hydrogen, $H_2$ | 22.433 |
| Nitrogen, $N_2$ | 22.402 |
| Oxygen, $O_2$ | 22.397 |

(Source: Adapted from Brady, *General Chemistry*, Table 11.1, p. 343.)

## 2.4.5 Mixture of Gases

When two or more gases that do not react chemically are placed in the same confined space, the pressure exerted by *each gas* in the mixture is the same as it would be if it were the *only gas* in the confined space. The pressure exerted by each gas in a mixture is called its ***partial pressure***. The total pressure is equal to the sum of the partial pressures of each gas in the mixture. This statement is called ***Dalton's law*** of partial pressure. Mathematically, it can be expressed as,

$$P_{total} = P_{gas\ A} + P_{gas\ B} + P_{gas\ C} + \ldots \qquad (2.14)$$

where

$P_{total}$ = the total pressure of the gas mixture,
$P_{gas\ A}$ = the partial pressure of gas A,
$P_{gas\ B}$ = the partial pressure of gas B,
and so on.

Consider the composition of our atmosphere at STP. Table 2.3 lists the gases that make up our atmosphere, the percentage by volume, and the partial pressure of each constituent gas. If we add all the partial pressures for the constituent gases that make up air, the sum of the partial pressures is approximately 760 Torr.

Table 2.3. Gas composition of air at STP.

| **Gas** | **Symbol** | **Percent by Volume** | **Partial Pressure (Torr)** |
|---|---|---|---|
| Nitrogen | $N_2$ | 78 | 593 |
| Oxygen | $O_2$ | 21 | 158 |
| Argon | Ar | 0.94 | 7.1 |
| Carbon Dioxide | $CO_2$ | 0.03 | 0.25 |
| Helium | He | 0.0005 | $4 \times 10^{-3}$ |
| Hydrogen | $H_2$ | 0.00005 | $4 \times 10^{-4}$ |
| Water | $H_2O$ | 0 – 2.3 | 0 – 17.5<br>based on relative humidity |

### Example 2.8

Predict the partial pressures of the gases making up the atmosphere in the cabin of an airplane at cruising altitude. Assume that the percent by volume occupied by the gases is unchanged in the airplane's cabin. Ignore the partial pressure of water.

**Solution:**

A plane's cabin pressure at cruising altitude is approximately 0.8 atm.

We could show the partial pressures of each of the gases in units of atmospheres. In order to compare the results to the ones listed in Table 2.4, we will convert units of atmospheres to units of torr.

Convert the plane's cabin pressure at cruising altitude from atmospheres to torr.

- 1 atm = 760 Torr
- 1 atm / 760 Torr = 760 Torr / 1 atm = 1

Any value multiplied by 1 is itself.

- 0.8 atm x 1 = 0.8 atm * (760 Torr / 1 atm) = 608 Torr

The plane's cabin pressure at cruising altitude is 608 Torr. Multiply the percent volume of each gas in the composition of air by the cabin pressure at cruising altitude.

Table 2.4. Gas Composition of air in plane at cruising altitude.

| Gas | Symbol | Percent by Volume | Partial Pressure (Torr) |
|---|---|---|---|
| Nitrogen | $N_2$ | 78 | 474.2 |
| Oxygen | $O_2$ | 21 | 127.7 |
| Argon | Ar | 0.94 | 5.7 |
| Carbon Dioxide | $CO_2$ | 0.03 | 0.2 |
| Helium | He | 0.0005 | $3 \text{ x } 10^{-3}$ |
| Hydrogen | $H_2$ | 0.00005 | $3 \text{ x } 10^{-4}$ |

The sum of these partial pressures adds up to the total pressure in the cabin at cruising altitude:

$$P_{air,cabin\ pressure} = P_{N_2} + P_{O_2} + P_{Ar} + P_{CO_2} + P_{He} + P_{H_2}$$

$$P_{air,cabin\ pressure} = (474.2 + 127.7 + 5.7 + 0.2 + 3 \times 10^{-3} + 3 \times 10^{-4})\,Torr$$

$$P_{air,cabin\ pressure} = 607.8\,Torr$$

Section 2.4 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-6*

# 2.5 Ideal Gas Law

The three gas laws explained in Section 2.3 can be combined into one law known as the *combined gas law*. The combined gas law can be expressed as

$$\frac{P \times V}{T} = constant$$

As with Boyle's law, Charles's law, and Gay-Lussac's law, the amount of gas is assumed to be constant. The combined gas law allows us to analyze situations where two of the three parameters change at the same time. Equation 2.15 below represents the combined gas law:

$$\frac{P_i \times V_i}{T_i} = \frac{P_f \times V_f}{T_f} \qquad (2.15)$$

where $P_i$ and $P_f$ are initial and final absolute pressure, and $T_i$ and $T_f$ are initial and final temperature in Kelvin (K). The following example illustrates the use of the combined gas law.

**Example 2.9**

A sample of gas, stored in a 0.5-liter container at 25°C, exerts a pressure of 750 Torr. What would be the pressure of the gas if the gas sample were transferred to a 1-liter container at 50°C?

**Solution**

Let us begin by organizing the given information in tabular form as shown below.

| | **Initial Conditions** | **Final Conditions** |
|---|---|---|
| Pressure, P | 750 Torr | ? |
| Volume, V | 0.5 liter | 1.0 liter |
| Temperature, T | 25 + 273 K | 50 + 273 K |

Solving the combined gas law equation (Equation 2.15) for the final pressure, $P_f$, yields

$$P_f = P_i\left(\frac{V_i}{V_f}\right)\left(\frac{T_f}{T_i}\right)$$

$$P_f = (750\,Torr)\left(\frac{0.5\,liter}{1.0\,liter}\right)\left(\frac{323\,K}{298\,K}\right)$$

$$P_f = 406\,Torr$$

If we allow the amount of gas to vary, then the constant (*PV/T*) in the combined gas law will also vary. For example, if the number of moles of gas is doubled, the value of the constant will double. If the number of moles of gas is reduced by one half, the value of the constant in the combined gas law will likewise be reduced by one half.

If *n* represents the number of moles of gas, then the combined gas law can be written as

$$\frac{PV}{T} = n \times (another\ constant)$$

Many chemistry textbooks use the letter *R* to represent this other constant and they name it the ***universal gas constant***. Hence, this relationship can be written as

$$PV = nRT \qquad (2.16)$$

Equation 2.16 is also known as the *ideal gas law*. Using the ideal gas law, if three of the variables are known, the fourth can be found.

The value of the universal gas constant, *R*, can be found experimentally by finding the volume of one mole of gas under a known condition. As was stated in Section 2.4.4, one condition that can be used is STP. Although the volume that one mole of gas occupies at STP varies somewhat for different gases, the average molar volume is 22.4 liters.

From the ideal gas law,

$$R = \left(\frac{PV}{nT}\right)$$

$$R = 0.0821\ \left(\frac{liter \cdot atm}{mol \cdot K}\right)$$

The universal gas constant can be expressed using other units, for example, milliliters, torr, moles, and K. This conversion can be performed as follows,

$$R = \left(0.0821 \frac{liter \cdot atm}{mol \cdot K}\right) \times \left(1000 \frac{mL}{liter}\right) \times \left(760 \frac{Torr}{atm}\right)$$

$$R = 6.24 \times 10^4 \frac{mL \cdot Torr}{mol \cdot K}$$

**Example 2.10**

What volume will 24.0 g of nitrogen ($N_2$) occupy at 20°C and a pressure of 0.755 atm?

**Solution:**

Algebraically solving the ideal gas law for volume, *V*, yields

$$V = \frac{n\,R\,T}{P}$$

Since pressure is given in atmospheres, we can use the gas law constant 0.0821 (liter·atm)/(mol·K) and convert the given data to the units used in this constant. Hence,

$$n = 24\,g\,of\,N_2 \times \frac{1mol\,of\,N_2}{28g\,of\,N_2} = 0.86mol\,of\,N_2$$

$$T = 20^\circ C = 20 + 273K = 293K$$

Substituting these values into the equation for volume yields,

$$V = \frac{(0.86mol)\left(0.0821\frac{liter \cdot atm}{mol \cdot K}\right)(293K)}{0.755atm}$$

$$V = 27.4\,liters$$

Section 2.5 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-16*

## 2.6 Mean Free Path

In a process chamber at atmospheric pressure, the gas molecules are constantly colliding with one another and with the walls of the chamber. The distance traveled by a given gas molecule before colliding with another gas molecule is called the *free path*. The distance a gas molecule travels and the direction of travel are randomly distributed. Hence, the ***mean free path*** is the average of the free paths traveled by the gas molecules in the chamber. According to kinetic theory, this can be represented mathematically as

$$\lambda = \frac{1}{\left(\sqrt{2}\right)\pi d_0^2 n} \qquad (2.17)$$

where $\lambda$ is the mean of the free paths, $d_0$ is the molecular diameter in meters, and $n$ is the gas density in molecules per cubic meter.

**Example 2.11**

Use the equation for $\boldsymbol{\lambda}$ to estimate the mean free path of air molecules at 760 Torr and 0°C.

**Solution:**

From a table of physical properties of gases, the molecular diameter of air molecules is 0.372 nm at $T$ = 0°C. The density of air at 760 Torr is approximately $3 \times 10^{25}$ molecules per cubic meter. Hence,

$$\lambda = \frac{1}{\left(\sqrt{2}\right)\pi(0.372 \times 10^{-9}\ m)^2 \left(3 \times 10^{25}\ \frac{molecules}{m^3}\right)}$$

$$\lambda = 5.42 \times 10^{-8}\ m$$

$$\lambda = 5.42 \times 10^{-6}\ cm$$

**The average distance traveled by gas molecules between molecule-to-molecule collisions is called the *mean free path*.**

The mean free path of gas molecules is related to gas density and thus to the pressure of the gas within the chamber. The lower the pressure, the lower the density and the greater the spacing between gas molecules. In this case, because the gas molecules are more widely spaced, a gas molecule will travel a greater distance before colliding with another gas molecule. Conversely, a higher pressure means a greater density of gas molecules and a shorter distance between collisions, that is, a shorter mean free path.

If the temperature is relatively constant at 20°C, a rule-of-thumb relationship between mean free path and air pressure can be described mathematically as

$$\lambda = \frac{5 \times 10^{-3} Torr \cdot cm}{P} \qquad (2.18)$$

where $\lambda$ is in centimeters and $P$ is in torr.

### Example 2.12

Use equation 2.18 to find the approximate mean free path of air at 760 Torr.

**Solution:**

Substituting 760 Torr into Equation 2.18 yields,

$$\lambda = \frac{5 \times 10^{-3}\, Torr \cdot cm}{760\, Torr}$$

$$\lambda = 6.58 \times 10^{-6}\, cm$$

Note that the result obtained using Equation 2.18 is close, but not exactly equal, to the value obtained earlier using Equation 2.17. That is OK. The important idea here is the relationship between mean free path and pressure. The mean free path and the pressure are inversely related. As the pressure goes down, the mean free path goes up, and conversely, as pressure goes up, the mean free path goes down.

Why is the mean free path of atoms and molecules an important parameter in manufacturing processes? As we described in the metal evaporation process in Chapter 1, in order to create a thin film of pure metal material on a substrate surface, the metal vapor must travel from the crucible to the substrate surface without being impeded or reacting with another element along the way. Lower pressure conditions correspond to a longer mean free path as shown in Table 2.5. So lower pressure conditions enable molecules to travel longer distances without colliding with other molecules.

**The mean free path is important in thin films deposition manufacturing processes. A rule-of-thumb relationship between mean free path and gas pressure at temperatures near 20°C is given by Equation 2.18.**

Table 2.5. Relationship between pressure and mean free path.

| Pressure | Mean Free Path |
|---|---|
| 760 Torr | 6.6 x $10^{-6}$ cm |
| 1 Torr | 5 x $10^{-3}$ cm |
| 1 x $10^{-1}$ Torr | 5 x $10^{-2}$ cm |
| 1 x $10^{-3}$ Torr | 5 cm |
| 1 x $10^{-6}$ Torr | 50 m |
| 1 x $10^{-9}$ Torr | 50 km |

Section 2.6 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-8*

# 2.7 Adsorption and Desorption

**_Adsorption_ is a process whereby atoms and molecules stick to the surface of something else.**

***Adsorption*** and ***desorption*** are processes that occur at surfaces. *Adsorption* is a process whereby ***gas phase*** atoms and molecules stick to the surface of something else. The “surface” is all of the interior surface of the process chamber including the surface of the wafer, or other substrate material, being processed in the chamber. In a vacuum system, the molecules that stick to a surface are usually water vapor, because water vapor, in the form of humidity, is always found in air.

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Animation 2.1. Adsorption Animation. Animation provided by Gigi Bocek.

Since gas molecules are in constant motion, water molecules in the gas phase strike the surfaces in the chamber at a steady frequency. When the water molecules hit the surface, some of them will attach to the surface and are said to be *adsorbed* on the surface. The attachment occurs because there are stable positions for the water molecule to form a bond on the surface. In addition, the impinging atoms or molecules must give up enough of their kinetic energy to adsorb on the surface. Sometimes, the impinging atoms or molecules do not lose the required amount of kinetic energy and are quickly reflected from the surface. The likelihood that a molecule will stick to a surface varies with the gas and the surface material.

The polar nature of water molecules does not simply cause them to adhere to the chamber surfaces; they also adhere to each other in ever-weakening bonds as the layers of adsorbed molecules become thicker and thicker and more disordered. Over time, the adsorbed water molecules can form many monolayers of water molecules on surfaces. Figure 2.7 and Animation 2.1 show the ***hydrogen bonding*** between water molecules.

Any material exposed to air for any length of time will come to *equilibrium* with the surrounding water vapor – that is, a point where the number of water molecules attaching to the surface will equal the number of water molecules leaving the surface. At this point, the surface is said to be *saturated*.

As a pump-down cycle proceeds to reduce pressure in the chamber, the adsorbed water molecules begin to *desorb*, that is, leave the surface to which they have bonded. In fact, water vapor becomes the dominant gas source and determines the ***gas load*** for the vacuum system. The weakly held outer layers will desorb quickly, and the more tightly held layers will take longer to desorb, as shown in Animation 2.2.

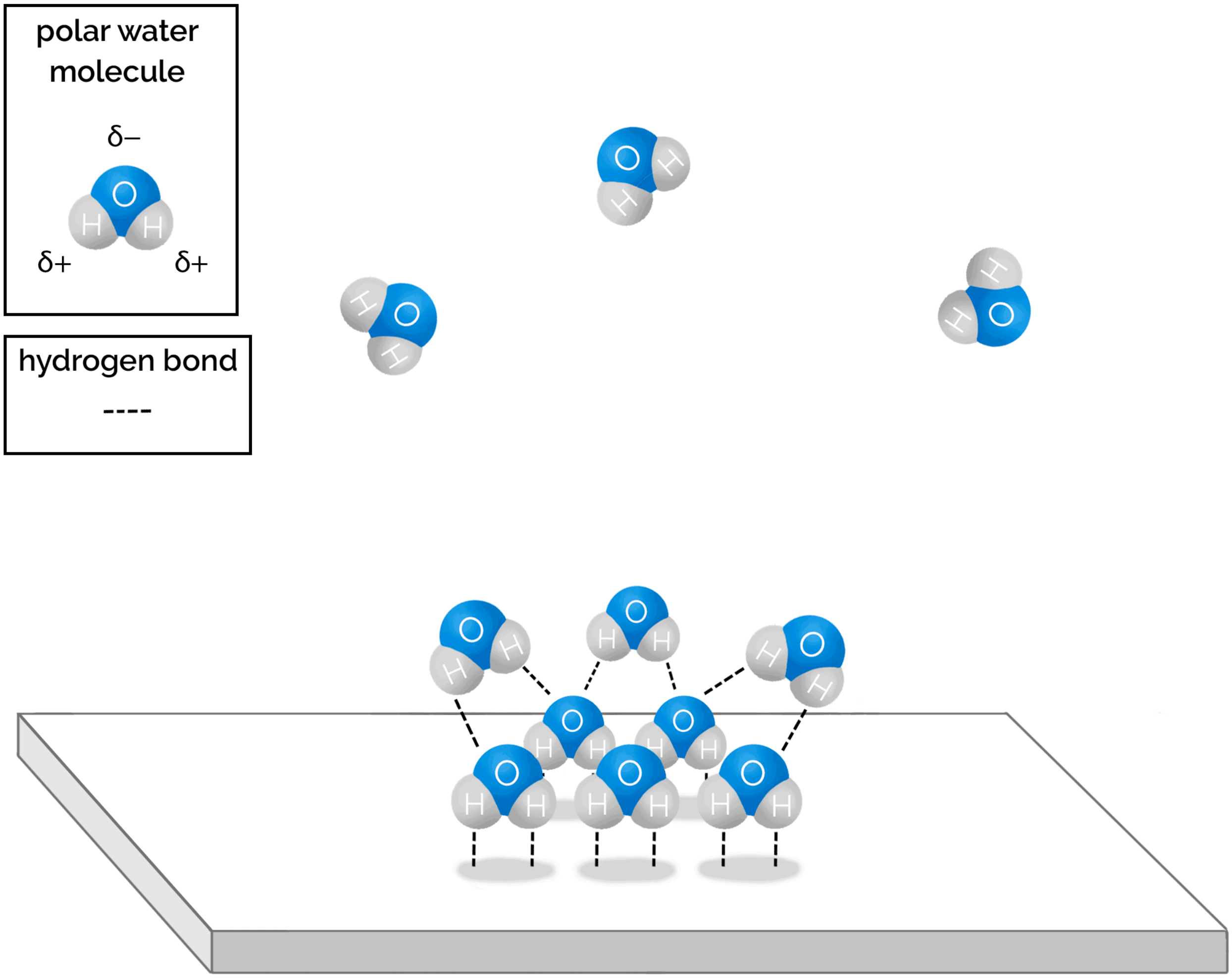

Figure 2.7. Hydrogen bonding between water molecules.
Graphics provided by Gigi Bocek, Normandale Community College.

*Desorption* of water from a surface can be sped up by adding energy to the surface and the water molecules. One method is to heat the vacuum-exposed surfaces with a radiant energy source such as a heat lamp. Energy from the heat source provides the energy needed for water molecules to break the ***hydrogen bonds*** that hold them to each other. Another method is to put ***vacuum components*** into an oven or wrap their surfaces on the outside of the vacuum chamber in heating tape to thermally drive the water molecules from the vacuum-exposed surfaces. This method is called *bake out*.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#oembed-2*

Animation 2.2. Desorption Animation. Animation provided by Gigi Bocek.

Purging the chamber with a dry gas will also remove water adhering to the interior surface of the chamber.

A gas often used for this purpose is dry nitrogen. The nitrogen gas molecules strike the surface and dislodge water molecules.

Section 2.7 Quiz

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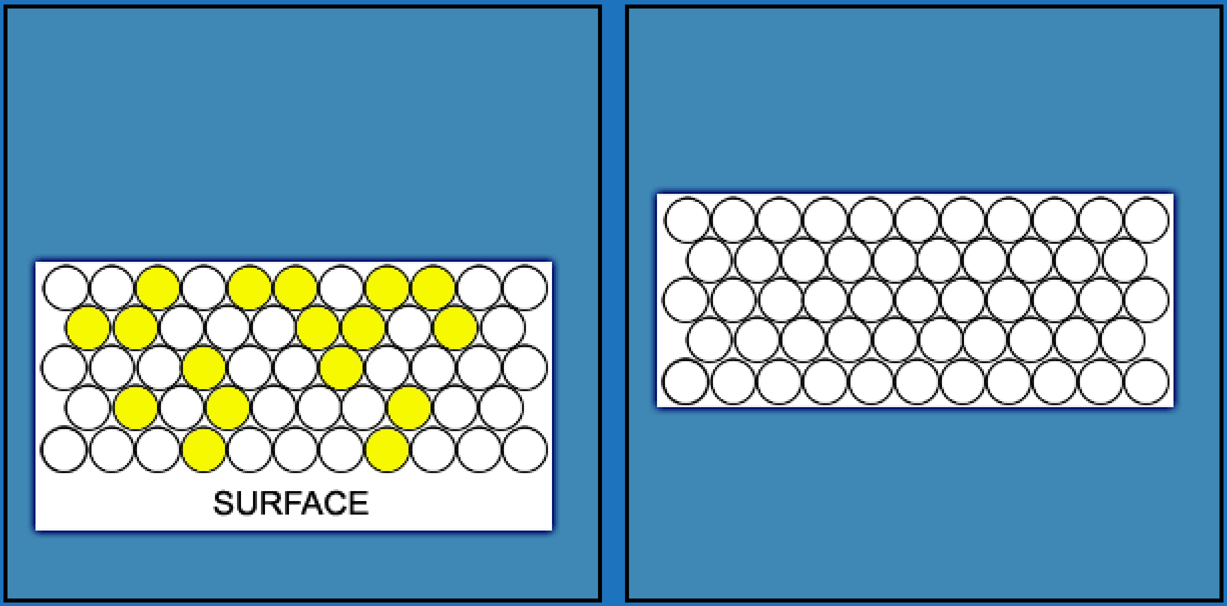
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-17*

## 2.8 Diffusion and Permeation

***Diffusion*** and ***permeation*** are often confused. Let's review these phenomena and differentiate between these two terms. Both, diffusion, and permeation are shown in Animation 2.3 below.

*Animation 2.3. Diffusion and Permeation Animations*



Diffusion Animation. Source: Kurt J. Lesker, Company, www.Lesker.com

Permeation Animation. Source: Kurt J. Lesker, Company, www.Lesker.com

*Diffusion* is the movement of molecules within a material, whether it be a solid, liquid, or gas. Diffusion is the process by which atoms or molecules move from an area of high concentration to an area of low concentration within the material. We are familiar with some every day examples of diffusion. Perfume diffuses in the air in the room. A drop of ink diffuses when dropped into a beaker of water.

*Permeation*, on the other hand, is a three-step process whereby a gas molecule passes through a material, typically a solid. First, a gas molecule adsorbs onto an outer surface. Then, it is taken in, that is, absorbed, by the bulk material. Next, the molecule diffuses through the bulk material. Finally, this gas molecule ***desorbs*** from a location on the inner surface and enters the gas load. In a vacuum system, steady-state permeation acts like a constant leak.

***Permeation* is a three-step process that includes sorption (both adsorption and absorption), diffusion, and desorption.**

Section 2.8 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=36#h5p-9*

## 2.9 Thermal Conductivity

The ability of a gas to conduct heat is not the same for all gases. Using the data found in Appendix B.2 of *A User's Guide to Vacuum Technology*, 3rd Ed. by John F. O'Hanlon, the thermal conductivity of air which is made up of primarily nitrogen and oxygen is 24.0 mJ/(s K), while argon has a thermal conductivity of 16.6 mJ/(s K). This says that air is a much better conductor of heat than argon. On the other hand, the thermal conductivity of helium is 142.0 mJ/(s K), a value about six times greater than the thermal conductivity of air.

The thermal conductivity of gases and their ability to transfer heat varies predictably from approximately 1 Torr down to 0.001 Torr (1 milliTorr or 1mTorr). As the pressure falls below 0.001 Torr, *radiation* becomes the dominant mode of heat transfer. We will return to this gas parameter when we discuss pressure gauges that rely on the thermal conductivity of gases for their operation.

## 2.10 Vapor Pressure

When a liquid is placed in a closed container or chamber, molecules in the liquid that possess high kinetic energies (see section 2.3.3, Maxwell-Boltzmann distribution) and are located right at the surface may escape the liquid surface and accumulate as part of the total gas load in the chamber volume. Once these molecules transition from the liquid phase into a gas phase, commonly referred to as vapor phase, they exert a pressure, just like other gas molecules in the chamber. The pressure will rise initially and then gradually become constant, having reached an ***equilibrium vapor pressure***.

This behavior of vapor pressure can be visualized in the following manner. Upon introduction of a liquid into the chamber, molecules at the surface with high kinetic energies begin to evaporate, moving from the liquid phase to the vapor phase. Once in the vapor phase, the evaporated molecules begin to exert a pressure against the walls of the chamber. As time passes, more and more molecules escape from the liquid phase to the vapor phase. At the same time, some of these molecules collide with the liquid surface where they transfer some of their energy back to the molecules in the liquid. Lacking enough energy to return to the vapor phase, these molecules once again transition back into the liquid phase. This is the process of ***condensation***. Hence, there are two opposing processes working at the same time, evaporation of molecules from the surface to the vapor phase and condensation of molecules back to the liquid phase. When the two opposing processes are equal, the equilibrium vapor pressure has been reached, as depicted in Figure 2.8.

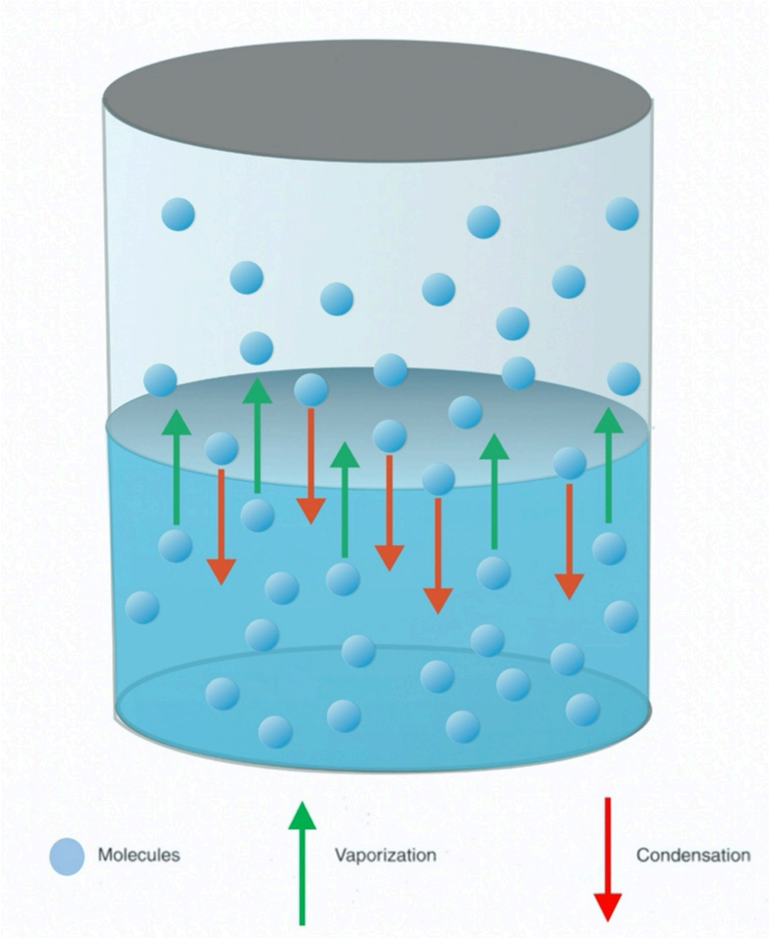


Figure 2.8. Equilibrium is reached in the chamber. Rates of evaporation (vaporization) and condensation are equal. Photo provided by tersetki/Shutterstock.com.

Vapor pressure is a function of temperature. The relationship between vapor pressure and temperature can be described by the following mathematical equation:

$$\log_{10} P_{vp} = A - \frac{B}{T}$$

where

$P_{vp}$ is the vapor pressure in torr,
$A$ and $B$ are constants for a specific gas, and
$T$ is the temperature in Kelvin.

**The boiling point of water is the temperature at which the vapor pressure of the water equals the pressure surrounding water in its liquid state.**

If temperature were to increase, then the negative term in the equation becomes smaller and the right-hand side of the equation becomes a larger number. Hence, the logarithm of the vapor pressure becomes larger, and the vapor pressure becomes greater as can be seen in Figure 2.9. On the other hand, if the temperature decreases, the negative term increases, and when subtracted from A makes the value of the right side of equation smaller. If the logarithm of the vapor pressure is smaller, then the vapor pressure must decrease.

What happens when the vapor pressure of the liquid equals the pressure of the gas volume above the liquid? We have all observed what happens in cooking food. When water in a pan is heated to a high-enough temperature, it boils. Raising the temperature of the water increases the vapor pressure of the water. The boiling point is therefore the temperature at which the vapor pressure of the water equals the atmospheric pressure. At 760 Torr, water boils at 100$^{\circ}$C, and this temperature is referred to as the *normal boiling point* of water. At higher than atmospheric pressures, the boiling point of water will be higher than 100$^{\circ}$C, and conversely, at lower than atmospheric pressures, the boiling point will be lower than 100$^{\circ}$C as shown in Figure 2.10.

What happens if the temperature of a liquid is increased? The highest temperature at which a distinct liquid phase can exist is called the *critical temperature*, and the associated vapor pressure is called the *critical pressure*. These are the temperature and pressure at the *Critical Point* shown in Figure 2.10.

**Solids can also evaporate just like liquids. However, in the case of solids, the process is called *sublimation*.**

Solids can also evaporate just like liquids. However, in the case of solids, the process is called *sublimation*. The solid form of carbon dioxide, more commonly known as dry ice, is a familiar example. In dry ice, a crystalline solid, the molecules vibrate about their equilibrium position and undergo collisions with their nearest neighbors. This gives rise to a distribution of energies, similar to a liquid. At the surface of the solid, some of the molecules possess kinetic energies large enough to enable them to break away from the surface and enter the vapor phase. If this process

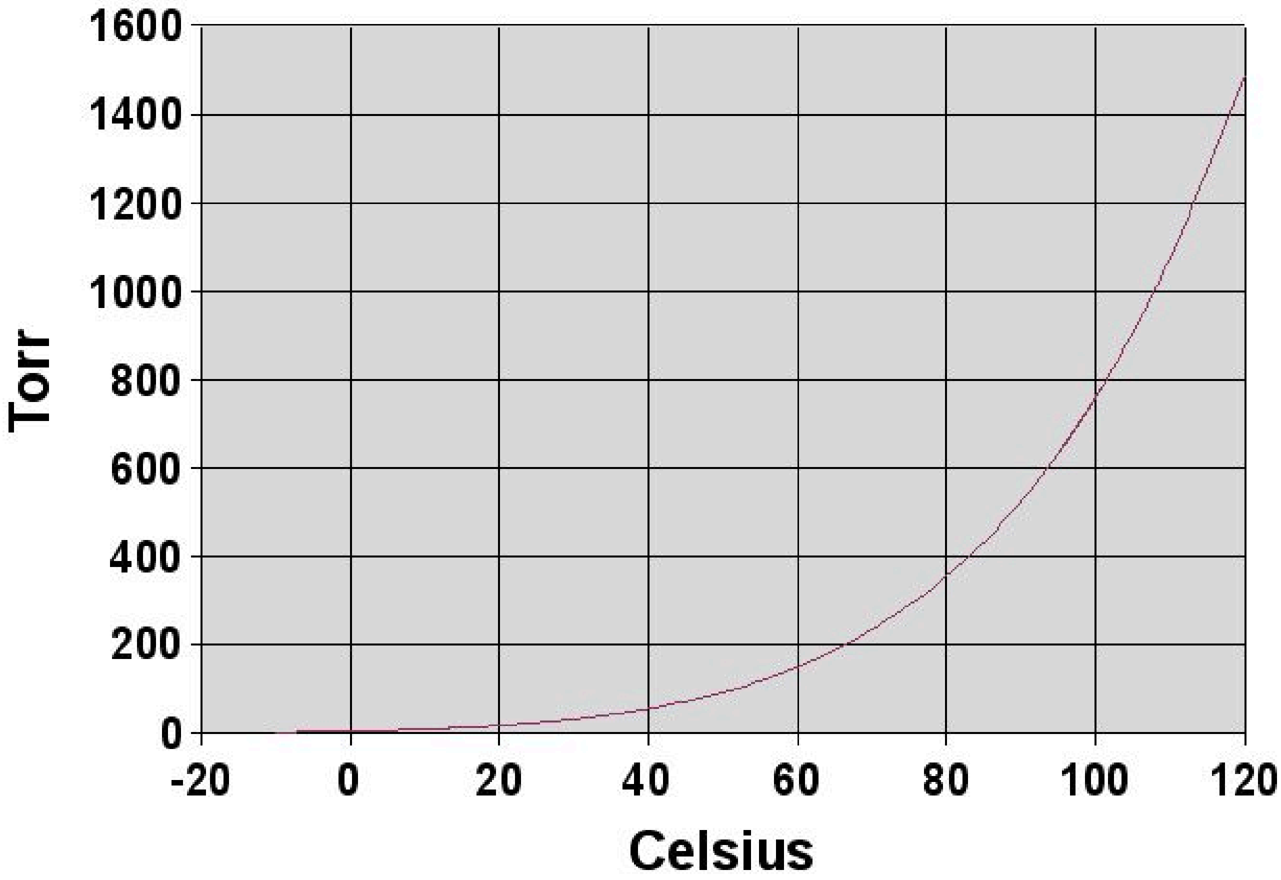


Figure 2.9. Graph of water vapor pressure versus temperature. At the normal boiling point of 100°C, it equals the standard atmospheric pressure of 760 Torr. Water vapor pressure graph by Yannick Trottier, Creative Commons Attribution-Share Alike 3.0 Unported.

occurs in a closed chamber, an equilibrium condition will occur when the rate at which molecules leave the solid equals the rate at which they return to the solid. The pressure exerted by the vapor is the *equilibrium vapor pressure* of the solid.

A commercial example that uses sublimation is freeze-drying. Freeze-dried instant coffee begins as a batch of brewed coffee. The brewed coffee is then frozen and the ice (water) component is removed under vacuum. In this way, the delicate heat-sensitive molecules are preserved and the flavor is retained.

Section 2.10 Quiz

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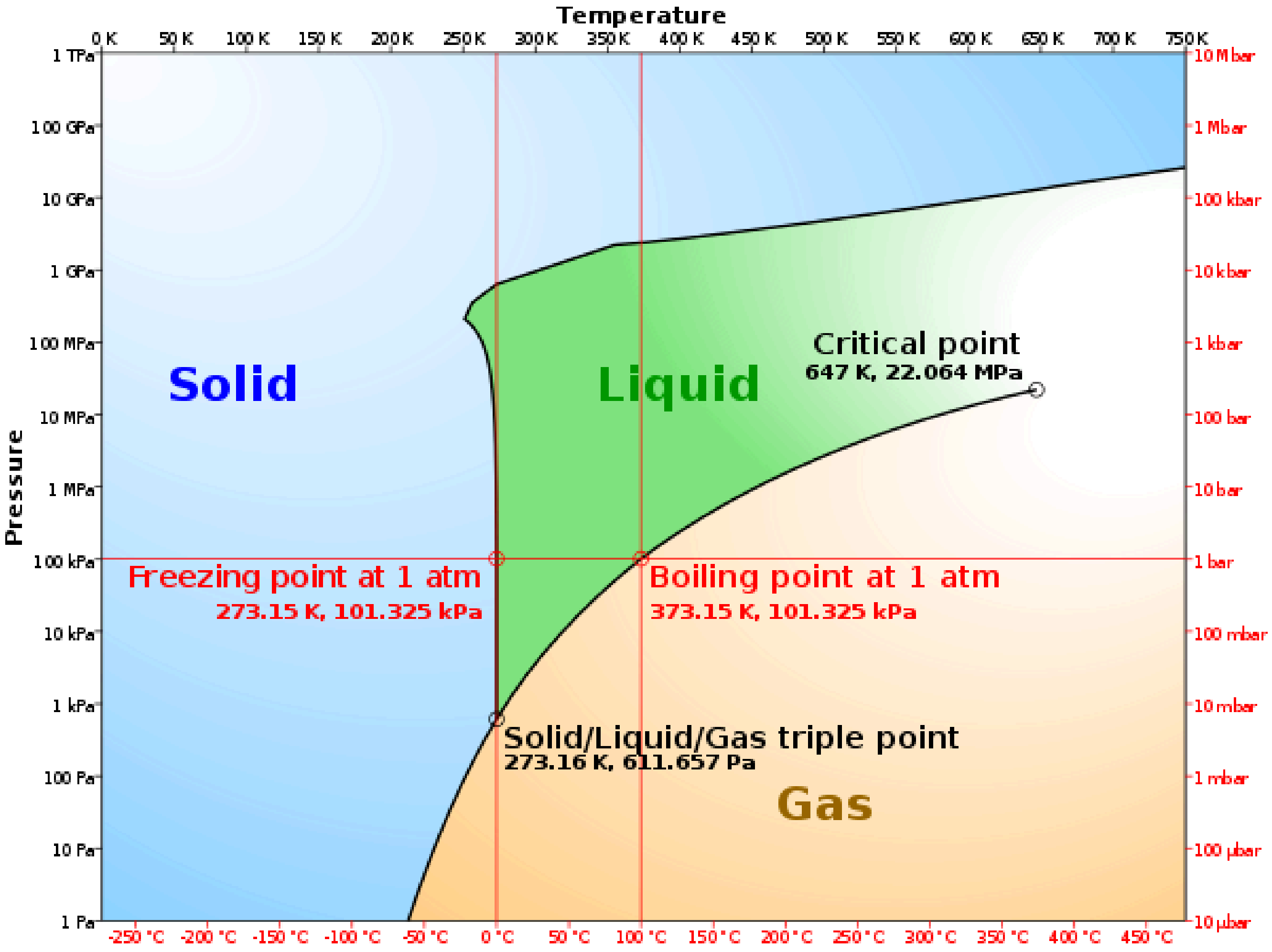

Figure 2.10. Simplified pressure/temperature phase change diagram for water. Simplified temperature/pressure phase change diagram for water by Cmglee, Creative Commons Attribution-Share Alike 3.0 Unported.

## Summary

Knowledge of the behavior of gases is useful in understanding the operation of vacuum systems. The kinetic theory of gases is an important model that describes the physical behavior of gases. Based on the assumption of this theory, we can predict and account for the following physical phenomena associated with gas behaviors:

- Gases will expand to uniformly fill the enclosure in which they are confined.
- Gases are compressible.
- Gases captured in a volume with elastic boundaries will cause the volume to expand/contract in response to temperature changes.
- Gases of equal volume and pressure have an equal number of molecules.
- The total pressure of a mixture of gases is equal to the sum of the partial pressures of each gas in the mix-

ture.

Four physical variables define a gaseous system: pressure, temperature, volume, and the number of moles of gas. The ideal gas law is a mathematical model that relates these four parameters. We use this model to predict a physical state of the system if we can measure the other physical states.

There are other important physical phenomenon attributed to gases. Gases can move via the processes of diffusion and permeation. Gases can adsorb onto, absorb into, and desorb from surfaces. Gases can conduct thermal energy.

Molecules with enough energy can escape from the solid (sublimation) or liquid (evaporation) state as a vapor and enter into the gas load adjacent to the interface. These molecules that escape into the gas load contribute to the total gas pressure. The maximum amount of molecules that can escape into the gas load is determined by the vapor pressure of the solid or liquid. Vapor pressure is a function of temperature.

Gas pressure can be expressed with different units of measure. The vacuum regime includes gas pressures that are less than atmospheric pressure. Different gauge types are used to measure the pressure in a vacuum system. Absolute pressure values must be used to solve problems based on applications of the ideal gas law.

## Chapter 2 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
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## Questions and Problems

1. Using the concepts presented in this chapter, explain why:

   a. It is more difficult to open the freezer door just after you have opened and closed it a few moments before.
   b. A balloon filled with helium is buoyant one day, but it has less "lift" the next day.
   c. It is difficult to separate two plastic cups when one is stacked inside the other for more compact storage.
   d. A plastic water bottle emptied and capped off at cruising altitude during flight, collapses during the landing especially at a destination located at sea level.

2. In our local newspaper the other day, the barometric pressure was given as 29.93 and falling. In what units is this barometric pressure reading given?

3. A gas is compressed form a volume of 0.60 liter to 0.35 liter. If the initial pressure was 500 Torr, what is the final pressure? Assume that the temperature of the gas remains constant.

4. At a temperature of 25°C and a pressure of 1 atm, a gas occupies a volume of 1.25 liters. If the temperature is increased to 75°C and the pressure remains constant at 1 atm, what is the new volume that the gas occupies?

5. A bicycle pump has a barrel 65 cm long. On the up-stroke, air is drawn into the pump at a pressure of 1 atm. On the down-stroke, air in the barrel is compressed. How long must the down-stroke be to increase the pressure of the air in the barrel to 4 atm? Assume that the temperature of the air remains constant during the compression process.

6. Calculate the number of liters occupied at STP by 0.35 moles of nitrogen gas ($N_2$).

7. A 2.0-liter mixture of gases is produced from 2.0 liters of $O_2$ at 300 Torr, 2.0 liters of $N_2$ at 500 Torr, and 2.0 liters of Ar at 100 Torr. What is the pressure of the mixture of gases in torr?

8. Two chambers are connected by a U-shaped manometer. The manometer is filled with oil having a density of 0.910 g/mL. The pressure of the gas in Chamber A is 550 torr, and the oil in the arm of the manometer connected to Chamber A is 85 cm higher than the oil in the arm of the manometer connected to Chamber B. What is the pressure in Chamber B?

9. You have been assigned the task of decorating a ballroom with 250 helium-filled balloons. A 25-liter helium tank filled with helium at a pressure of 25.0 atm and three 100-balloon packages have been delivered to the ballroom. If each balloon, when filled, holds 2.4 liters of helium at a pressure of 1.09 atm, will you be able to fill all 250 balloons? Assume the gas temperature stays constant as the balloons are filled.

10. (a) What is the volume occupied by 2.00 mol of air at standard test conditions (1 atm and 0°C)? Treat air

as ideal gas. (b) What is the number of molecules per cubic cm?

11. 1000 $cm^3$ of air at 40°C and pressure of 752 Torr expands until its volume is 1500 $cm^3$ and its pressure is 644 Torr.
    a. Find the number of moles of air present.
    b. Find the final temperature of the sample in degrees Celsius.

12. The best laboratory vacuum has a pressure of $1.00 \times 10^{-18}$ atm. If the temperature in the room is 25°C, how many gas molecules are there per cubic centimeter?

13. From *Chemistry: Connections to our Changing World* by H. Eugene LeMay, Jr., p. 430:

> The Scene: The local county fair. A magician has just announced to a crowd of people at the fair that he can tell one gas apart from another just by feeling the gases. “You can’t feel a gas,” came a voice from the crowd. “Well,” said the magician, “for the price of my show, which happens to be one dollar, I’ll demonstrate that I can identify a gas by the way it feels. If I can do it successfully, I get to keep the money. But if I fail, you will get a refund. How’s that?
>
> Their curiosity aroused, people quickly paid the money and within a very short time, the magician’s tent was full of eager spectators. They could not imagine how the magician would be able to tell two gases apart just by feel, without relying on color or odor. The magician stepped from behind a curtain holding two stoppered bottles. “Fill one bottle with xenon and the other with helium. Make sure you keep track of which gas is in which bottle.”
>
> A volunteer from the crown filled the bottles from the compressed gas tanks that were conveniently secured to the stage. She identified each bottle with a secret mark and then gave the bottles to the magician.
>
> The magician examined each bottle, took each stopper off briefly and stuck his finger into the bottles. “This is helium and this is xenon,” he said. He was right! He performed the trick several times and never failed. How did he do it?

14. A recent advertisement appeared in a local newspaper about a local tire store filling car tires with pure nitrogen gas instead of atmospheric air. The advertisement claimed that tires filled with pure nitrogen gas leaked slower than tires filled with atmospheric air. Is this claim valid? Give a supporting argument or reason for your answer.

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# CHAPTER 3: AN INTRODUCTION TO VACUUM SYSTEMS

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Learning Objectives

Chapter 3 describes the general operating conditions associated with the function of a vacuum system and the types of components used in the design of these systems. After you read this chapter, you will be able to:

- Identify the sources that contribute to gas load in rough and high vacuum regimes.
- Calculate the gas load of the bulk gas present in a vacuum chamber before initiating a system pumpdown.
- Describe the terms “throughput”, “pumping speed” and “conductance” and explain the relationship between these terms.
- Calculate the net pumping speed at the outlet of a vacuum chamber given the pumping speed and conductance.
- Identify the main components present in a vacuum system.
- Calculate an estimated gas load associated with the outgassing of the vacuum chamber material given the outgassing rate of the chamber material and the dimensions of the chamber.
- Identify and classify the types of vacuum pumps suitable for use in the rough vacuum and high vacuum regimes.
- Identify and classify the types of gauges suitable for use in the rough vacuum and high vacuum regimes.
- List and describe other components used in the design of vacuum systems.
- Draw a schematic diagram of a basic vacuum system using symbols commonly used to represent vacuum system components.

## 3.1 Introduction

In Chapter 1, we learned that vacuum technology is used to intentionally create a volume with a lower density of gas molecules than the atmospheric conditions surrounding it. Vacuum pressure conditions enable a variety of processes. In other words, a sub-atmospheric operating condition makes it possible to create and manufacture useful products or do scientific research. Different processes require different levels of vacuum. In Chapter 1, Table 1.1 listed examples of different processes that depend on vacuum and sorted them according to the vacuum regime in which they take place.

In Chapter 2, we reviewed some of the science that explains the behavior of gases. The kinetic theory of gases is the foundation for understanding properties of gases, including the ideal gas law and the special cases that arise from it. The kinetic theory of gases also addresses characteristics of molecular motion. We discussed how as the pressure is decreased below ***atmospheric pressure***, the distance a molecule travels before colliding with another molecule, its free path, increases. The ***mean free path***, the average of the distances between molecule-to-molecule collisions, is related to the pressure. Processes designed to be carried out under vacuum focus on controlling the types and amounts of gas molecules present to achieve a suitable mean free path.

With this background, we can begin to address the foundations of vacuum system installation, operation, maintenance, and troubleshooting. This chapter begins with a discussion of ***gas load***, that is, the amount of gas that has to be removed from the ***chamber***. Contributions to the gas load in a vacuum system come from many different sources. In each pressure regime, certain sources of gas molecules play a bigger role in contributing to the gas load than others. The design of a vacuum system is tailored to the process it supports including how to address the gas load.

Next, we will look at ways to describe, quantitatively and physically, how a vacuum system functions. In its simplest form, a vacuum system consists of a volume, the chamber, connected to a vacuum pump. The ***vacuum pump*** is the active mechanism used to remove gases from the chamber. Ideally, vacuum system design would be a simple activity with the only consideration being what vacuum pump will most quickly remove gases from the chamber. The reality of functional vacuum system design is much more complex. The issue that drives the level of complexity is the changing composition of the gas load and the underlying motion of the gas molecules, especially as the ***molecular density*** decreases within the vacuum system. We will introduce the interrelated concepts of ***throughput***, ***pumping speed*** and ***conductance***. Throughput, pumping speed and conductance are quantities used to represent the ability of the vacuum system to remove gas molecules from the system.

We will introduce and provide an overview of the various components found in vacuum systems. Component selection is tied to what operating pressure is required by the process and the conditions necessary to achieve that operating pressure. Individual components and the condition of those components can significantly impact a vacuum system's performance. Individuals who install components, troubleshoot, or perform routine maintenance activities on a vacuum system need to be aware of and anticipate component-related issues as they perform these activities. We conclude this chapter with a description of a very simple vacuum system including a schematic drawing used to represent this simple vacuum system.

The purpose of this chapter is to set the stage for Chapters 4 and 5. As we study the rough and high-vacuum pressure regimes, we will approach each regime in the same manner. First, the gas load in the given pressure regime will be described. Then the different pumping mechanisms that can be used to remove gas molecules from the chamber and appropriate pressure gauges will be presented. A short discussion of valves and fittings will follow, and the chapter will close with system characterization and troubleshooting. So, let's begin.

## 3.2 Gas Loads

A vacuum system functions to first remove gas from the chamber environment and then to maintain a certain pressure to support a desired process. The vacuum system has to deal with a gas load that changes as pressure in the system decreases. Gas load is defined as the rate at which gas molecules from various sources enter into the vacuum system. At any point in time, the total gas load reflects the sum of all these rates from the contributing gas sources. The composition of the gas load in a vacuum system is not only the volume gas in the chamber but also depends on the types of components and associated materials used to construct the system, the presence and relative amount of water vapor, and the constituents and by-products of the process being performed. Although vacuum systems can be designed to achieve extremely low-pressure conditions, it is impossible to eliminate the gas load entirely.

Let us consider some of these contributing gas sources (see Figure 3.1). In the rough-vacuum regime, the major contributor to gas load is the ***volume gas***, also called the ***bulk gas***. The bulk gas is the gas that originally fills the chamber. Using the ideal gas law, we can predict the amount of bulk gas present by multiplying the pressure in the chamber by the chamber volume. Therefore, the larger the chamber, the greater the amount of bulk gas that needs to be removed from the chamber. Every vacuum system, if it has been opened to the atmosphere, begins at approximately 1 atmosphere (atm), or 760 Torr pressure at sea level. The gas load at this point predominantly consists of air as the bulk gas. So, if the chamber volume is 10 liters and the pressure is 760 Torr, the gas load in the chamber due to the bulk gas is 760 Torr x 10 liters, or 7600 Torr-liters.

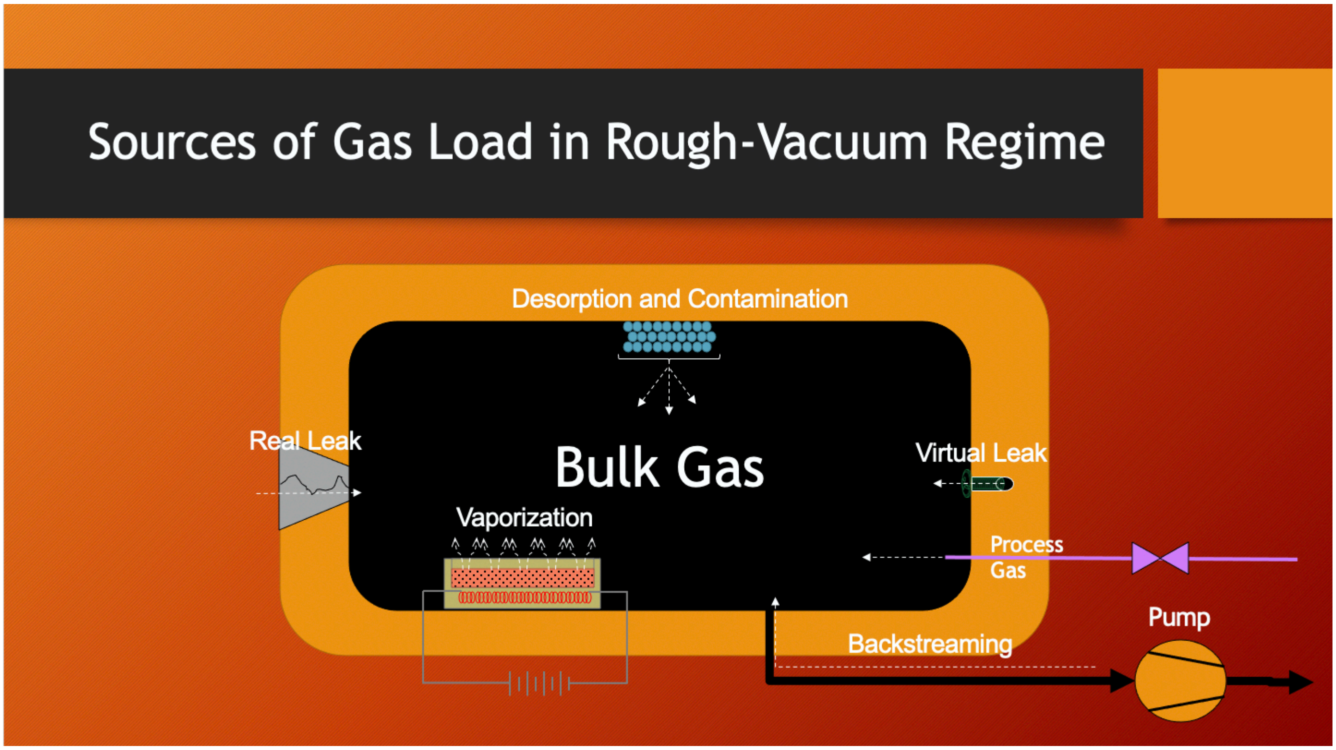

Figure 3.1. Sources that contribute to gas load in the rough-vacuum regime. Figure provided by John Laswell, Normandale Community College.

### Example 3.1

For a cylindrical chamber with an inner diameter of 170 mm and a height of 230 mm, calculate the approximate gas load in a chamber due to the bulk gas. Assume this chamber is located in Salt Lake City, Utah.

**Solution:**

The initial contribution of the bulk gas to the gas load is the volume of the chamber multiplied by atmospheric pressure.

In this particular example, it is important to recognize that location, specifically the location's altitude, affects the level of atmospheric pressure to assume. Salt Lake City, Utah is at an altitude much greater than sea level. The nominal atmospheric pressure condition in Salt Lake City is approximately 640 Torr.

Calculate the volume of this chamber.

$$V = \pi r^2 \times h = \pi \left(\frac{d}{2}\right)^2 \times h \qquad (Volume\,of\,a\,cylinder)$$

Substituting 170 mm for *d* and 230 mm for *h*,

$$V = \pi \left(\frac{170mm}{2}\right)^2 \times 230mm = 5.2 \times 10^6 mm^3$$

Convert units of $mm^3$ to units of $cm^3$,

$$5.2 \times 10^6 mm^3 \times \left(\frac{1cm}{10mm}\right)^3 = 5.2 \times 10^6 mm^3 \times \left(\frac{1cm^3}{1,000mm^3}\right) = 5.2 \times 10^3 cm^3$$

One $cm^3$ is equal to 1 milliliter (ml). One liter is equal to 1,000 ml.

$$V = 5.2 \times 10^3 cm^3 \times \left(\frac{1ml}{1cm^3}\right) \times \left(\frac{1liter}{1,000ml}\right) = 5.2\, liters$$

So, if the volume of the chamber is 5.2 liters and the pressure is 640 Torr, the gas load due to the bulk gas is 640 Torr times 5.2 liters, or 3,328 Torr-liters.

As the chamber is pumped down and most of the bulk gas is removed, the pressure drops reflecting the decreasing gas load in the fixed volume of the chamber. At the low end of the rough-vacuum regime, the bulk gas no longer is the major contributor to gas load and other gas (vapor) sources now take greater significance. For example, water vapor ***desorbing*** from the chamber walls now becomes a significant contributor.

In the high-vacuum regime, other sources of gas become noticeable since the dominant gas sources that contributed to gas load in the rough-vacuum regime have been removed (see Figure 3.2). Outgassing and permeation now become significant contributors to gas load. ***Outgassing*** refers to the escape of gas molecules that are condensed onto and within solid materials, for example, the chamber wall material and any other solids placed in the chamber, and enter into the gas load within the chamber. ***Permeation*** is a process in which gas molecules pass through materials used in the construction of vacuum systems, such as the elastomer ***O-ring*** seals in the flanges that connect vacuum components.

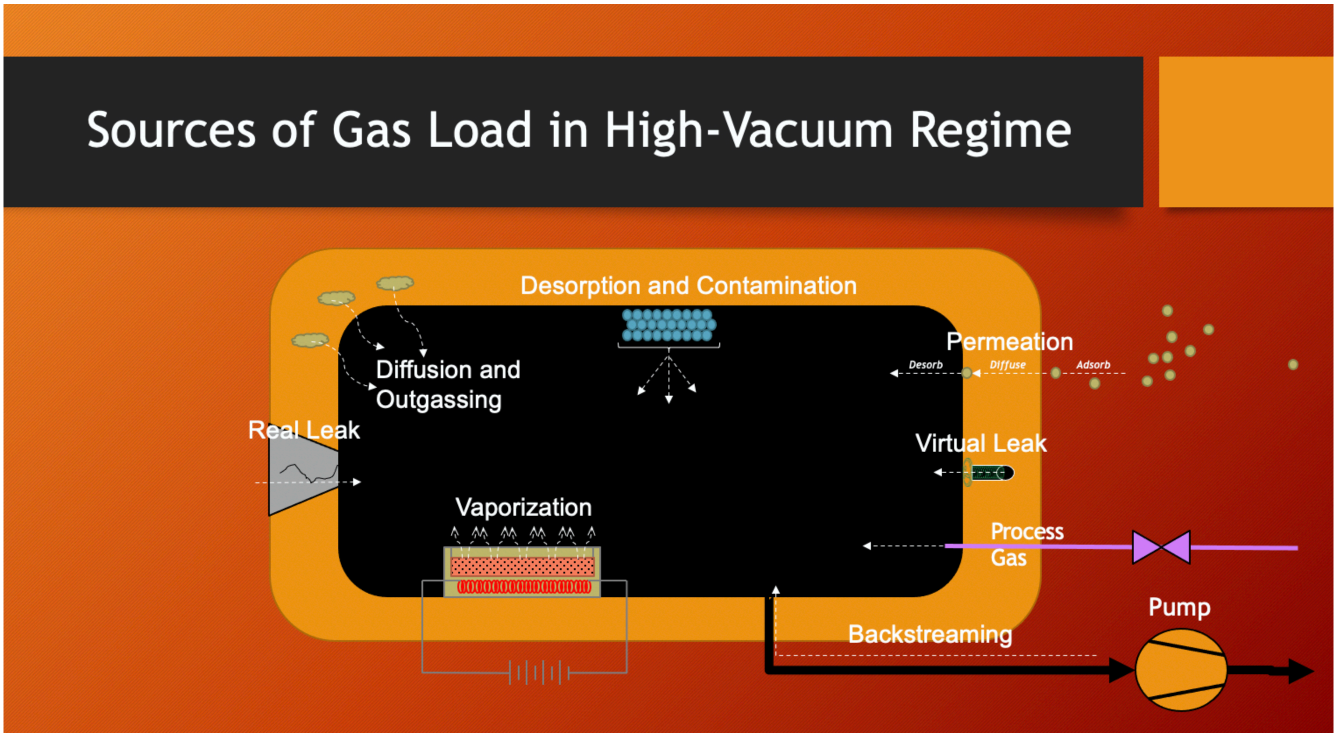

Figure 3.2. Contributors to gas load in the high-vacuum regime. Figure provided by John Laswell, Normandale Community College.

Contributions to gas load due to leaks can be caused by real leaks or virtual leaks. Leaks can occur in any of the vacuum regimes. In life, we have all experienced real leaks, except the gas is usually flowing from inside to outside, like a bicycle tire that has a puncture. In a vacuum system, a ***real leak*** provides a path for air molecules to travel from outside the chamber to inside the chamber through a space in the chamber wall or through a faulty connection in the vacuum system. In contrast, virtual leaks are not true leaks, but they act in a similar manner, adding to the gas load. ***Virtual leaks*** are amounts of trapped gas molecules that escape slowly as pressure decreases in the chamber. An example might be the gas trapped between the threads of a screw in the interior of the chamber.

And finally, when a process is being run, the process chamber is first pumped down to the desired pressure, and process gases are fed into the chamber at a specific flow rate. Some of the process gases react in the chamber, producing not only the desired material but also reaction by-products. Reaction by-products and any unreacted process gas molecules add to the gas load and must be removed from the chamber.

We will examine gas loads in more detail in the following chapters when we take a closer look at each pressure regime. Knowing the sources that contribute to gas load is important to effectively operate, maintain and troubleshoot vacuum systems.

Section 3.2 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=53#h5p-11*

## 3.3 Throughput, Pumping Speed and Conductance

All vacuum systems are not created equal. Some are more efficient at removing gas from a ***vacuum chamber*** and are able to achieve a desired operating pressure in a shorter length of time. Some vacuum systems are small and have a minimal footprint while others are large and require more space. Some systems require only 120-volt, single-phase power to operate while others use three-phase power at higher voltages. Vacuum components can be very expensive, and therefore, financial considerations may limit the choice of components available to the overall system design. We will defer the discussion of vacuum system space, size, power, cost, and other factors for now. In this section, we will focus on a vacuum system's ability to transfer gas out of the process chamber through interconnecting piping and valves and into the vacuum pump where the gas is ultimately removed from the vacuum system.

Vacuum systems are used to create an environment with a molecular density lower than that of the prevailing atmosphere in order to carry out a specific process. As stated at the beginning of this chapter, the vacuum pump is the component in a vacuum system which actively removes gas molecules from the chamber. The vacuum pump isolates the molecules that enter into the pump from the rest of the system and then subsequently expels the molecules or renders them immobile. The result is fewer molecules left to move about freely in the system.

***Throughput***, represented by $Q$, is a quantitative term used to express a rate at which a quantity of molecules is moving in a vacuum system. Throughput is derived from the ideal gas law ($PV = nRT$). For the purpose of this discussion, we'll over-simplify the mathematics involved and express throughput as $nRT/t$, where $t$ represents some period of time. The quantity and associated unit of measure for $nRT/t$ reflects the energy per unit time required to move a number of molecules across a plane. Although throughput is a function of temperature ($T$), $T$ is generally specified as a constant typically at room temperature, that is, 293K (20°C). When the temperature is specified as such, throughput reflects a mass flow rate, that is, a rate at which a quantity of molecules passes across a plane. By extension of the ideal gas law, $nRT/t$ is equal to $PV/t$. Hence, the expression used for calculating throughput in a vacuum system can be written as,

$$Q = \frac{PV}{t} \qquad (3.1)$$

The quantity *V/t* is called the ***volume flow rate***, or ***pumping speed***, and is represented by the variable *S*. So the form of expression for calculating throughput is most often shown as

$$Q = P \times S \qquad (3.2)$$

The units of measure commonly used to express throughput are standard atmosphere-cubic centimeter per minute (sccm), Torr-liter per second (Torr-l/sec) or ***mbar***-liter per second (mbar-l/sec).

One important concept related to throughput is that at any point in time, the throughput must be the same at all points along the gas flow path. If this were not the case, gas molecules would accumulate at some point in the system, and the pressure would increase with time at that point in the system. However pressure and volume flow rates can be different along the length of the gas flow path, but at any given point in time, the product, *PxS,* is the same for all points along the flow path as shown in Figure 3.3. Throughput decreases as the pressure level decreases in the vacuum system. The lowest pressure achievable in the vacuum chamber is the point at which the throughput generated by the vacuum pumping system can no longer overcome the rate at which molecules add to the system's gas load.

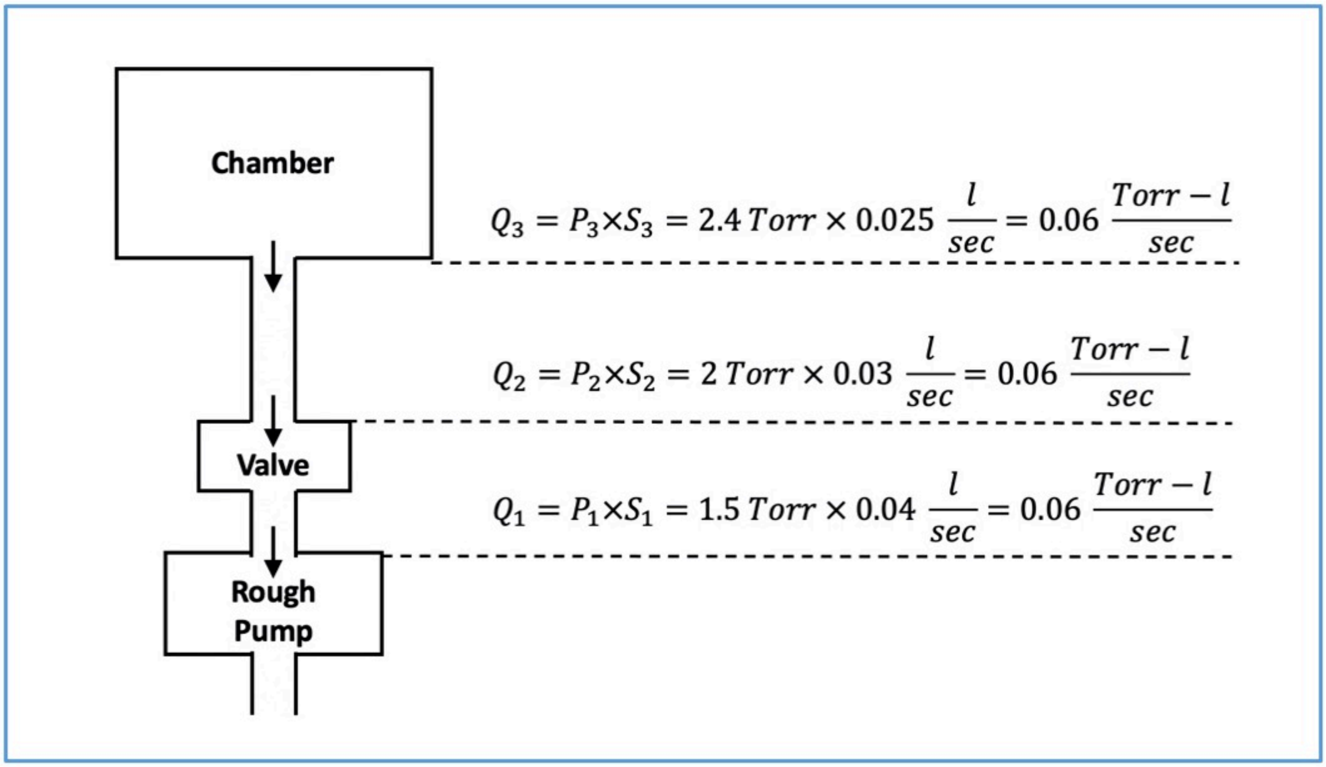

Figure 3.3. Gas Flow Path Diagram illustrating a constant throughput along the gas flow path. Diagram provided by Nancy Louwagie, Normandale Community College.

There are two terms used in combination that quantitatively describe a vacuum system's ability to support gas volume flow in the system: ***pumping speed*** (*S*) and ***conductance*** (*C*). Pumping speed and conductance are both expressed as a quantitative value with a unit of measure that represents the rate that a volume of gas moves in a given time period. The units of measure commonly used to express both pumping speed and conductance are liters per second (liter/sec), cubic feet per minute ($ft^3$/min or cfm) or cubic meters per hour ($m^3$/h).

Vacuum pumps, the active component in a vacuum system, are designed to achieve certain levels of pumping speed performance. As we will discuss shortly, each vacuum pump has a limited operating pressure range. Different styles of vacuum pumps operate in different pressure ranges of the vacuum regime. The pipeline and valves used to connect the vacuum pump to the chamber, though passive in nature, also impact the ability of the gas to flow through the system. The impact the pipeline and valves have on the vacuum system is quantitatively defined as conductance. The amount of conductance the pipeline and valves contribute is a function of the part's geometry and the governing pressure conditions. The pumping speed of the vacuum pump in combination with the conductance of the system establishes the ***net pumping speed***. The net pumping speed is always a quantity that is less than the pumping speed of the vacuum pump. It is the system's net pumping speed that determines the throughput performance for the chamber.

How is this net pumping speed calculated? When the pump and piping are placed in series, the net pumping speed, $S_{net}$, is determined using the following equation

$$\frac{1}{S_{net}} = \frac{1}{S_{pump}} + \frac{1}{C_{piping}} \qquad (3.3)$$

where $C_{Piping}$ is the conductance of the piping and $S_{Pump}$ is the pumping speed of the pump.

This mathematical relationship tells us that when the pump and piping are placed in series, the net pumping speed, $S_{net}$, will be less than either $S_{pump}$ or $C_{piping}$. We also note from the form of this equation that if conductance of the piping is much larger than the pumping speed of the pump, then the net pumping speed is approximately equal to the pumping speed of the pump. This design is preferable. Otherwise, a situation is created where the piping impedes the pump's function and negatively affects the overall vacuum system performance.

How fast can gas be removed from the vacuum chamber? The answer depends upon on what level of vacuum in the chamber is required, and after that, how well the vacuum system's design facilitates reducing the gas load to achieve the desired level of vacuum. The term "***pump down***" is used to describe the action of removing gas from a vacuum chamber. Let's consider a vacuum system with a ***rough vacuum pump***. The manufacturer provides a specification for the pumping speed performance of the rough vacuum pump. For our discussion, let's assume that the pump's pumping speed is 5 cfm (cubic feet per minute) at atmospheric pressure. When a system starts to pump down, the pumping speed should be close to 5 cfm. The pressure falling is an indication that the gas load is decreasing. Note that if the volume is constant and the same unit of time is used, then $Q \propto P$. As the pressure falls and the throughput decreases, the rough vacuum pump loses its ability to maintain the initial pumping speed. The pumping speed of the pump falls off and eventually reaches zero. Often manufacturers will provide pumping speed versus pressure graphs to show the change in pumping speed as pressure decreases. So, the first important consideration with respect to achieving a certain ***pump-down time*** is selecting a pump that is capable of achieving a pressure level less than the pressure level required in the chamber. The next consideration is to be aware of how quickly the pump's pumping speed decreases. The time it takes the system to achieve lower and lower pressure levels in the chamber lengthens as the pump's pumping speed decreases.

As stated previously, the piping that interconnects the chamber to the vacuum pump reduces conductance of the system. This conductance is in series with the pump. The conductance of the piping depends on the physical characteristics of the piping, that is, its diameter and length, as well as the pressure differential between the two ends. Common experience tells us that if we were drinking a liquid through a straw, the larger the diameter of the straw, the easier it is to draw liquid through the straw. If we double, triple, or quadruple the length of the straw, we would not be surprised if it were harder to draw liquid through the straw. Or, if we were to increase the pressure difference between the two ends of the straw, we could draw more liquid through the straw. This suggests that as the pressure decreases in the chamber, the conductance of the piping will decrease. The piping in series with the vacuum pump reduces the net pumping speed of the system and as a result, acts to increase the pump-down time to reach the target pressure level in the chamber. The system should be designed to minimize the impact of the piping's conductance on the system's pump-down time. Generally, the pipeline design should be one with short tubes and large cross sections to achieve the maximum conductance possible.

We will return to throughput, pumping speed, conductance and their impact on a vacuum system's pump-down characteristics in later chapters. We will look at how to use information provided by vacuum pump manufacturers to determine the pump's pumping speed. For each pressure regime, conductances will be calculated using mathematical equations specific to the regime and underlying gas flow condition. An estimated net pumping speed of the vacuum system can be calculated based on the pump's pumping speed and the system conductance. The net pumping speed will help us determine what base level of pressure is achievable based on the gas load present.

**Example 3.2**

Consider the simple vacuum system shown in Figure 3.4. Suppose the conductance of the pipeline between the chamber and the pump is 400 liters/second (liters/sec) when the isolation valve is fully open. The pumping speed of the vacuum pump is 100 liters/sec. What is the net pumping speed at that moment in the chamber?

**Solution:**

Using Equation 3.3, we can calculate the net pumping speed:

$$\frac{1}{S_{net}} = \frac{1}{S_{pump}} + \frac{1}{C_{piping}}$$

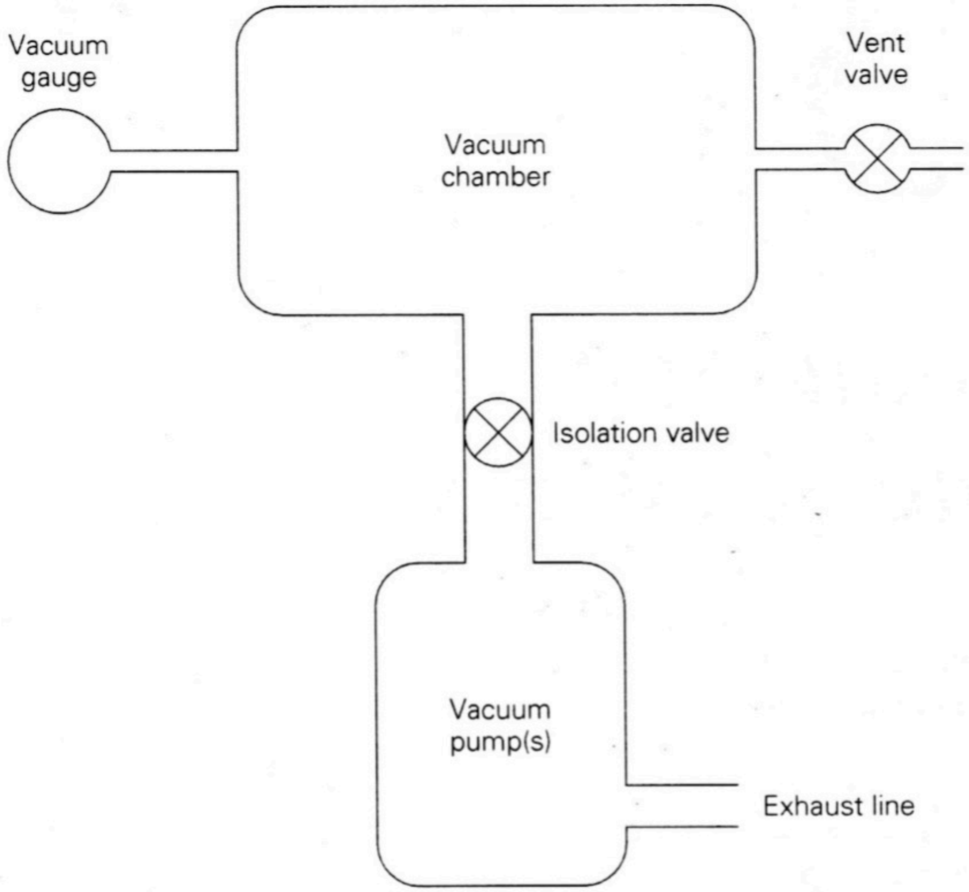

Figure 3.4. A simplified block diagram of a vacuum system. Diagram provided by David Hata.

Substituting the known values for the pipeline conductance and the pumping speed of the vacuum pump yields:

$$\frac{1}{S_{net}} = \frac{1}{100\frac{liters}{sec}} + \frac{1}{400\frac{liters}{sec}}$$

Solving for $S_{net}$,

$$\frac{1}{S_{net}} = \left(0.01\frac{liters}{sec}\right)^{-1} + \left(0.0025\frac{liters}{sec}\right)^{-1}$$

$$\frac{1}{S_{net}} = \left(0.0125\frac{liters}{sec}\right)^{-1}$$

$$S_{net} = \frac{1}{\left(\frac{1}{S_{net}}\right)} = \frac{1}{\left(0.0125\frac{liters}{sec}\right)^{-1}} = 80\frac{liters}{sec}$$

## Example 3.3

What is the throughput in the system when the inlet pressure at the pump is 1.5 Torr and the pumping speed of the pump is 0.5 liter/sec? Assume the gas temperature is 20°C.

**Solution:**

Using Equation 3.2, we can calculate throughput:

$$Q = P \times S$$

Substituting the known values for pressure and pumping speed and solving for *Q*,

$$Q = \left(1.5\, Torr \times 0.5 \frac{liter}{sec}\right) = 0.75 \frac{Torr - liter}{sec}$$

## Example 3.4

When a vacuum system's net pumping speed for the chamber is 50 liters/sec and the gas load at the chamber is 2 x $10^{-4}$ Torr-liters/sec, what is the expected base pressure in the chamber?

**Solution:**

The gas load at this point in time is assumed to be equal to the throughput. Using Equation 3.2, we can calculate the base pressure in the chamber:

$$P = \frac{Q}{S}$$

Substituting the known values for the pumping speed and gas load and solving for *P*,

$$P = \frac{2 \times 10^{-4} \frac{Torr-liters}{sec}}{50 \frac{liters}{sec}} = 4 \times 10^{-6}\, Torr$$

Section 3.3 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=53#h5p-12*

## 3.4 Vacuum Systems – an Overview

Again, consider a simple vacuum system represented by the block diagram shown in Figure 3.4. The vacuum system consists of a vacuum chamber that is connected to a vacuum pump with an ***exhaust line***. Between the chamber and the vacuum pump is an ***isolation valve*** to provide control when gas is being removed and when it is not. Connected to the chamber is a vacuum gauge that allows us to monitor the gas pressure in the chamber. A ***vent valve*** is also attached to the chamber so that when the isolation value is closed, the chamber can be "vented," allowing room air to enter the chamber and return the pressure to the ambient pressure outside the chamber.

### 3.4.1 Vacuum Chamber

The ***vacuum chamber*** is usually the focal point in a process system. This is also true in vacuum system design. The walls of the chamber must be made thick enough to withstand the forces exerted by the atmosphere. In some cases, the chamber may be strengthened by adding additional supports, either internally or externally.

Chambers can be constructed of metal, glass, ceramic, or plastic components. Since all of these materials outgas at different rates and subsequently add to the total gas load, material selection is critical. Materials that do not bond well with water molecules and have a low vapor pressure to reduce outgassing are ideal. Plastic materials have higher vapor pressures than metals and glass. So vacuum chambers constructed from plastics cannot be used in high- and ultra-high-vacuum applications. Metals such as stainless steel and aluminum have low outgassing rates in the range of $10^{-6}$ to $10^{-9}$ Torr-liter/sec-cm$^2$. Figure 3.5.a and Figure 3.5.b show examples of combination stainless-steel and aluminum chambers. Glass, or Pyrex, also has low outgassing rates, but these materials are not as mechanically strong as stainless steel or aluminum and need to be thicker and protected from scratching to withstand forces from the atmosphere and normal use. An example of a Pyrex chamber with protecting metal guard is shown in Figure 3.5.c. For most applications in the high-vacuum regime, permeation through the chamber walls can be considered negligible.

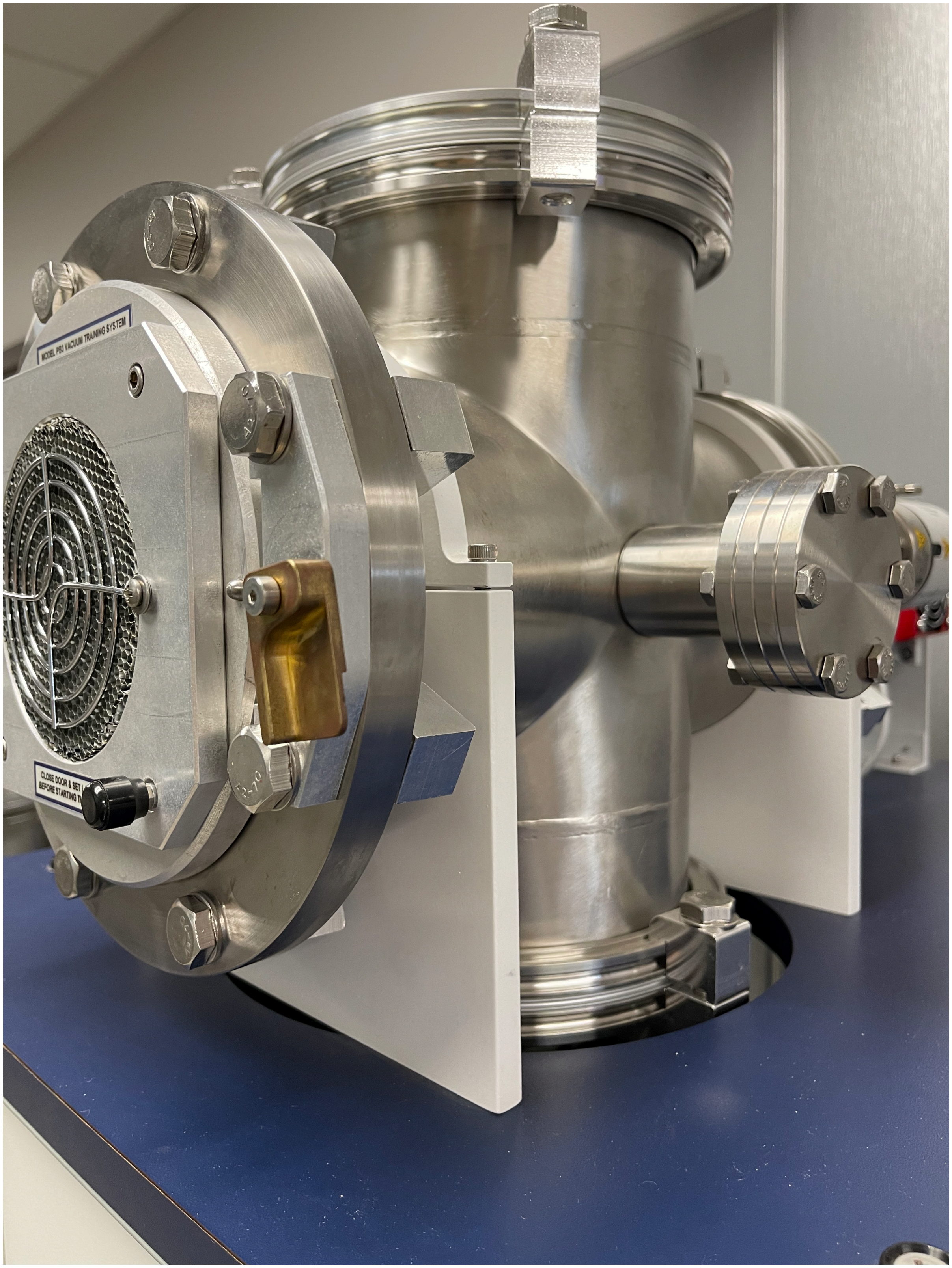

Figure 3.5.a. Stainless-steel chamber. Photo provided by Elena Brewer, SUNY Erie Community College.

Figure 3.5.b. Stainless-steel chamber. Photo provided by Elena Brewer, SUNY Erie Community College.

Figure 3.5.c. Pyrex chamber with metal guard. Photo is used with permission of Kurt J. Lesker Co., www.lesker.com.

**Example 3.5**

Estimate the gas load due to outgassing from a cylindrical chamber made of stainless steel. The chamber's dimensions are 7.75 inches in diameter and 10 inches in height. Assume that the outgassing rate for the stainless steel is $5 \times 10^{-8}$ Torr-liters/sec-cm$^2$.

**Solution:**

To determine the gas load based on the outgassing rate of the stainless steel, we begin by calculating the interior surface of the chamber.

The area of the two ends of the chamber can be found as follows:

$$Area_{ends\ of\ chamber} = 2\pi r^2$$

$$Area_{ends\ of\ chamber} = 2\pi\left(\frac{7.75\, inches}{2}\right)^2$$

$$Area_{ends\ of\ chamber} = 94.3\, in^2$$

The surface area of the body of the cylindrical chamber can be found as follows:

$$Area_{body\ of\ chamber} = 2\pi rh$$

$$Area_{body\ of\ chamber} = 2\pi\left(\frac{7.75\, inches}{2}\right)(10\, inches)$$

$$Area_{body\ of\ chamber} = 243.5\, in^2$$

Adding the surface areas together yields the total interior surface area of the stainless-steel chamber.

$$Area_{Total} = Area_{ends\ of\ chamber} + Area_{body\ of\ chamber}$$

$$Area_{Total} = 94.3\, in^2 + 243.5\, in^2$$

$$Area_{Total} = 337.8\, in^2$$

Using the total surface area and the given outgassing rate for stainless steel, we can calculate the total gas load due to outgassing by the stainless-steel chamber:

$$Gas\ Load = Area_{Total} \times Outgassing\ Rate$$

$$Gas\ Load = \left(337.8\, in^2\right) \times \left(2.54\frac{cm}{in}\right)^2 \times \left(5 \times 10^{-8}\frac{Torr - liters}{sec - cm^2}\right)$$

$$Gas\ Load = \left(337.8\, in^2\right) \times \left(2.54^2\frac{cm^2}{in^2}\right) \times \left(5 \times 10^{-8}\frac{Torr - liters}{sec - cm^2}\right)$$

$$Gas\ Load = \left(337.8\, \cancel{in^2}\right) \times \left(2.54^2\frac{\cancel{cm^2}}{\cancel{in^2}}\right) \times \left(5 \times 10^{-8}\frac{Torr - liters}{sec - \cancel{cm^2}}\right)$$

$$Gas\ Load = 1.1 \times 10^{-5}\frac{Torr - liters}{sec}$$

## Example 3.6

For the gas load calculated in the previous example, approximately what net pumping speed would be necessary to maintain a pressure in the chamber of 1 x $10^{-6}$ Torr?

**Solution:**

We will assume that the throughput in the system equals the gas load due to the outgassing of the chamber material. Using Equation 3.2, we calculate the net pumping speed needed to maintain a certain pressure as follows:

$$Q = P \times S_{net}$$

$$S_{net} = \frac{Q}{P}$$

$$S_{net} = \frac{1.1 \times 10^{-4}\,\frac{Torr-liters}{sec}}{1 \times 10^{-6}\,Torr}$$

$$S_{net} = 110\frac{liters}{sec}$$

This value represents the net effect of the vacuum pump's pumping speed combined with the system conductance.

## Example 3.7

Calculate the system's conductance if the net pumping speed experienced at the outlet of the chamber is 110 liters/sec and the pumping speed of the vacuum pump is 150 liters/sec.

**Solution:**

Using equation 3.3, we can calculate conductance of the system:

$$\frac{1}{S_{net}} = \frac{1}{S_{Pump}} + \frac{1}{C_{Piping}}$$

$$\frac{1}{110\frac{liters}{sec}} = \frac{1}{150\frac{liters}{sec}} + \frac{1}{C_{Piping}}$$

$$\frac{1}{C_{Piping}} = \frac{1}{110\frac{liters}{sec}} - \frac{1}{150\frac{liters}{sec}}$$

$$\frac{1}{C_{Piping}} = 0.00242\left(\frac{liters}{sec}\right)^{-1}$$

To determine $C_{Piping}$, take the inverse of both sides of the equation as follows:

$$\left(\frac{1}{C_{Piping}}\right)^{-1} = \left(0.00242\left(\frac{liters}{sec}\right)^{-1}\right)^{-1}$$

$$C_{Piping} = 412.5\frac{liters}{sec}$$

So the conductance of the tubing which connects to a vacuum pump with a pumping speed of 150 liters/sec should be 412.5 liters/sec in order to achieve a net pumping speed of 110 liters/sec at the outlet of the chamber.

Another important consideration is the sealing material used to construct the chamber joints. If the vacuum chamber is a glass or plastic bell jar, a rubber gasket placed between the chamber and a baseplate is used to create the airtight seal. Metal vacuum chambers usually are designed with one or more ports welded to the chamber. Special welding techniques are used to insure that ports attached to the chamber do not leak. These ports are fitted with ***KF (Klein Flansche)*** or ***CF (ConFlat) fittings*** of industry-standard sizes. For KF fittings, the sealing material is an elastomer ***O-ring***. Figure 3.6 shows an example of KF fitting and an elastomer O-ring. For CF fittings, the sealing material is a copper gasket as shown in Figure 3.7. Elastomer seals are used on joints that are intended to be demountable. The drawback to elastomer materials is that they have high vapor pressures and are much more permeable than metals. Thus, use of elastometer materials adds molecules to the gas load due to outgassing and permeation. Conversely, a metal seal, like the ***CF flange***, has a lower outgassing rate and is not as prone to permeation. Metal seal also allows for bake out at reasonably high temperatures (> 150°C) to increase desorption rate. However, the CF flanges are more costly and difficult to attach and detach, and so they are intended for joints that will rarely be disconnected.

## 3.4.2 Vacuum Pumps

Vacuum pumps come in a variety of types and styles, and pump selection depends heavily on the application in which the pump is used. Figure 3.8 depicts a family tree of vacuum pumps. Although not a complete family tree, it does show the variety of vacuum pumps available. There is no one vacuum

Figure 3.6. KF fitting, centering ring with elastomer O-ring (left), and clamp (right). Photo provided by Elena Brewer, SUNY Erie Community College.

pump that alone and by itself is capable of removing gas molecules to the extent of achieving pressures across the entire vacuum regime.

Vacuum pumps can be classified as either “gas transfer” pumps, or “capture” pumps. ***Gas transfer pumps*** remove gas from the process chamber and expel the gas into an exhaust system in the building. Gas molecules pass through a transfer pump from an inlet to the outlet. In contrast, gas molecules taken in by a ***capture pump*** are “captured” within the pump. Capture involves changing the gas molecules in the ***gas phase*** to a solid by “freezing” them or chemically reacting them with a chemically-reactive material such as titanium to form a solid compound that can stick to the interior surface of the pump. In either case, gas molecules are made immobile, so they are no longer part of the gas load.

Gas transfer pumps fall into two classifications: positive displacement vacuum pumps and kinetic vacuum pumps, also known as momentum transfer pumps. ***Positive displacement pumps*** expand the effective volume of the chamber, seal off the expanded volume, thus trapping and often compressing the trapped gas, and then exhaust the trapped gas. There are two main types of positive displacement vacuum pumps: ***reciprocating*** and ***rotary***. ***Diaphragm pumps*** and ***piston pumps*** are

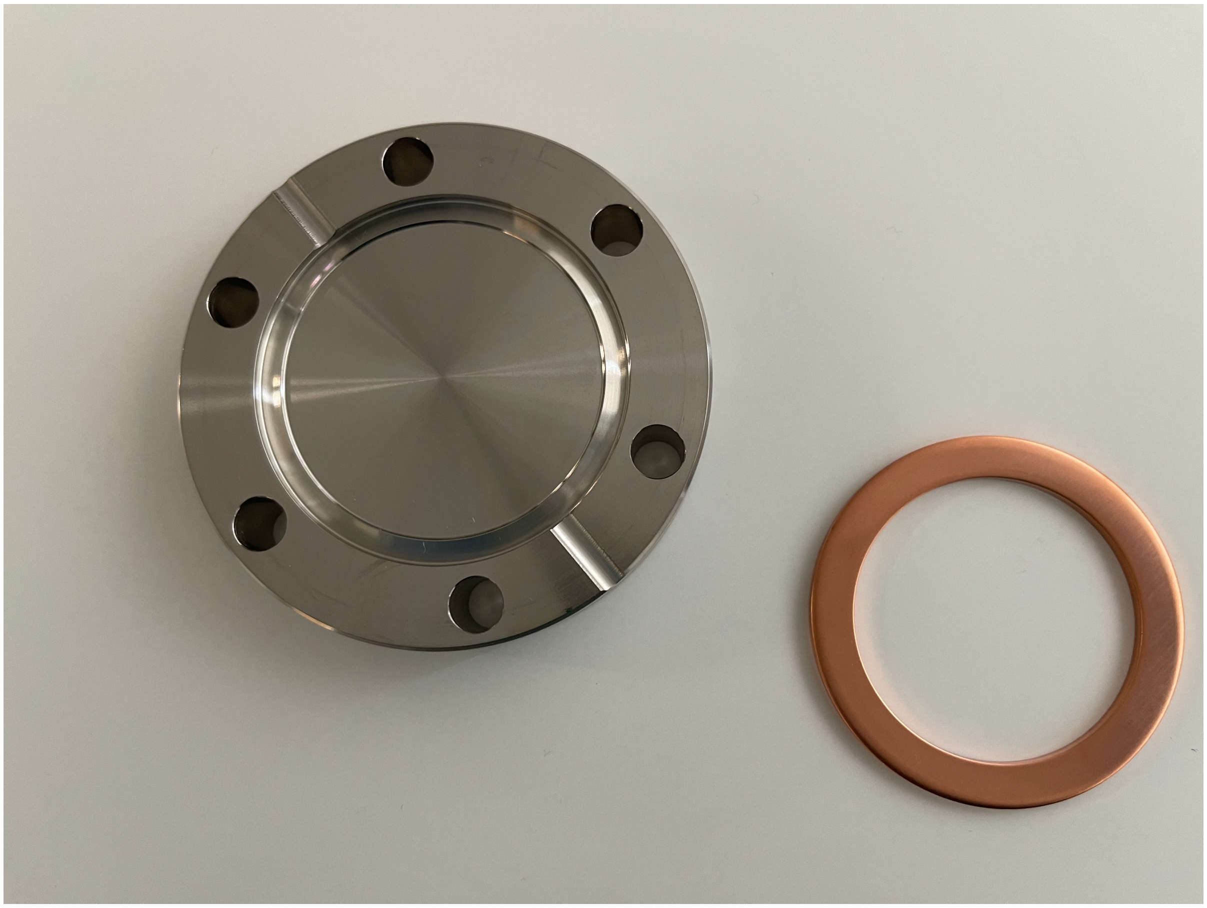

Figure 3.7.a. CF fitting with copper gasket. Photo provided by Elena Brewer, SUNY Erie Community College.

examples of reciprocating pumps, whereas rotary pumps include ***rotary vane pumps***, ***rotary piston pumps***, and ***Roots pumps***.

***Kinetic vacuum pumps*** include ***diffusion pumps*** and turbomolecular pumps, or turbo pumps. A diffusion pump heats a special oil with a low vapor pressure and then forces the oil vapor at high speeds through directional nozzles. Those high-speed molecules collide with other molecules in the space. In those collisions, the high-speed oil molecules transfer their momentum to the gas molecules they strike and impart a velocity to the gas molecules, so they move in a direction away from the chamber and are expelled from the pump. Turbo pumps use high-speed turbine blades to also transfer their momentum to gas molecules and move them through the pump. Both diffusion pumps and turbo pumps require a ***roughing pump*** to expel the gas molecules from the pump and subsequently to the building's exhaust system.

Capture pumping methods create a vacuum by condensing or freezing gas-phase molecules. ***Cryo pumps*** use this technique. Cryo pumps use very cold surfaces to freeze the gas molecules, entrapping them on the inner surfaces of the pump. Physical ***absorption*** is a technique used in cryogenic techniques. This technique uses highly porous materials, such as activated charcoal, activated alumina, and

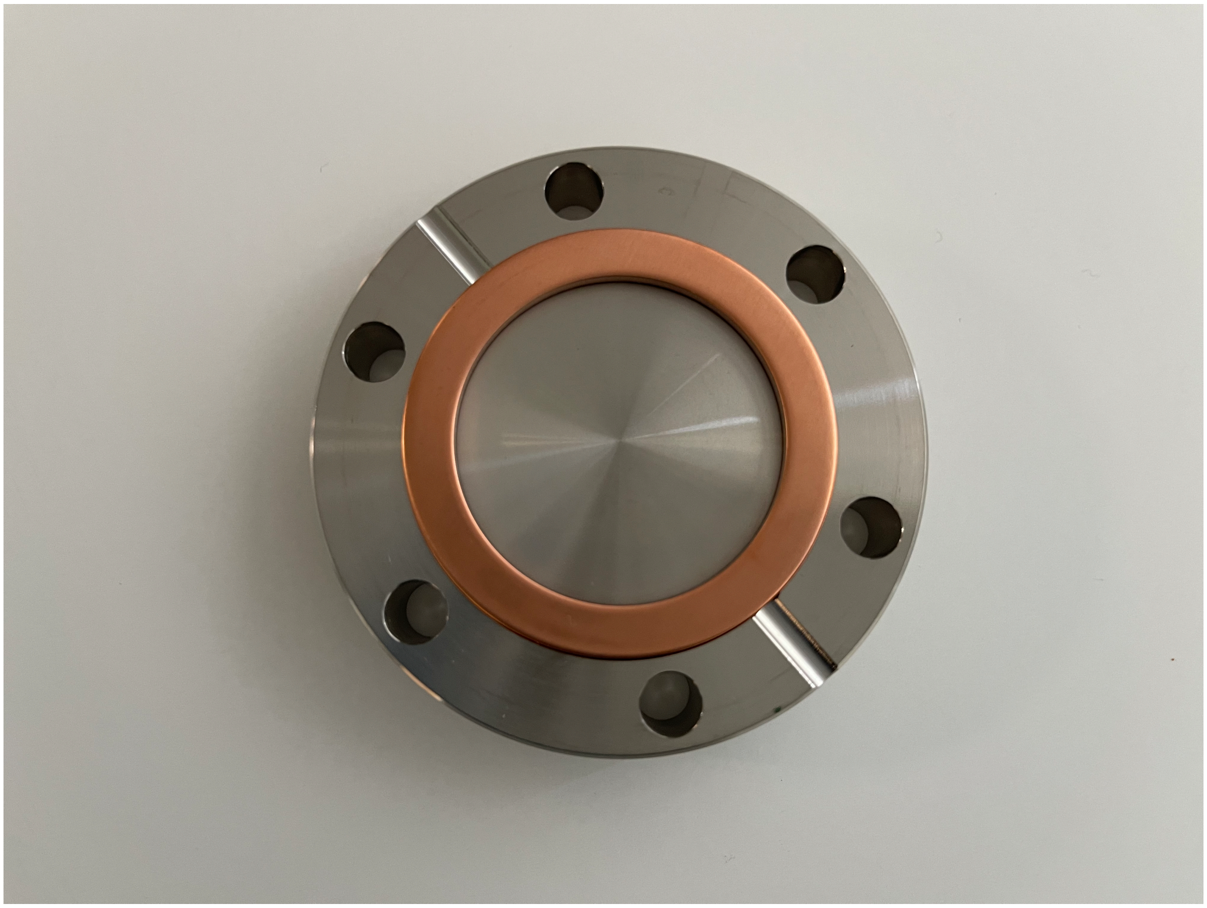

Figure 3.7.b. CF fitting with copper gasket partially assembled. Photo provided by Elena Brewer, SUNY Erie Community College.

materials called zeolites, as gas sponges. The gas molecules travel into the porous structure of the material and are entrapped within the pump.

Another capture pumping technique used to create vacuum removes gas molecules from the gas load through chemical reactions. This technique is used to accomplish ultra-high vacuum conditions. For example, getter pumps use very reactive materials, such as titanium, to form solid materials from the gas molecules. These solid materials stick to the inner surfaces of the pump which effectively removes gas molecules from the gas load in the chamber as shown in Animation 3.1 and Animation 3.2.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=53#oembed-1*

Animation 3.1. How ion pumps work. Animation provided by Gamma Vacuum, licensed under SPDX-License-Identifier: Apache-2.0, www.gammavacuum.com.

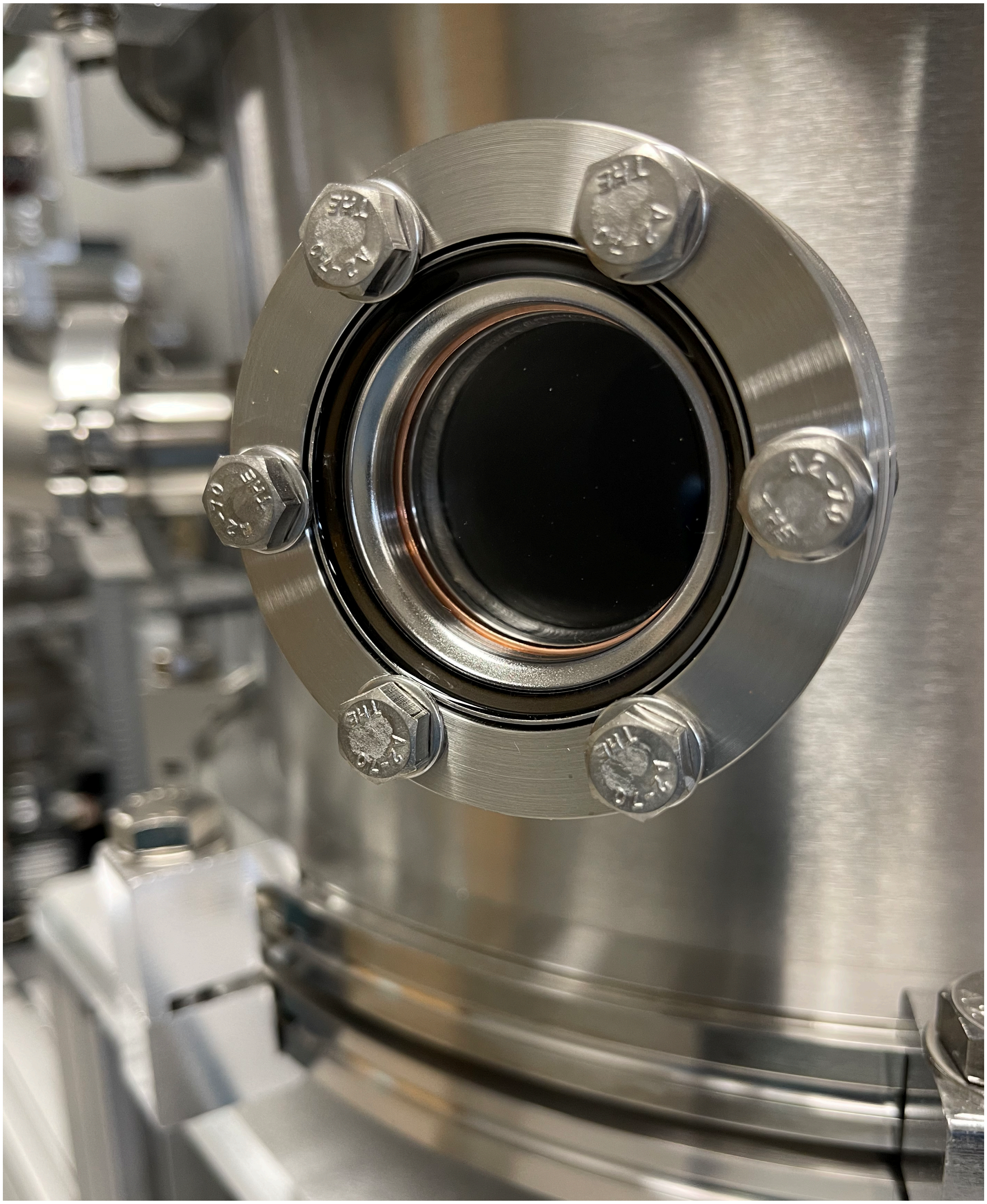

Figure 3.7.c. CF fitting with copper gasket completely assembled and shown as part of vacuum system. Photo provided by Elena Brewer, SUNY Erie Community College.

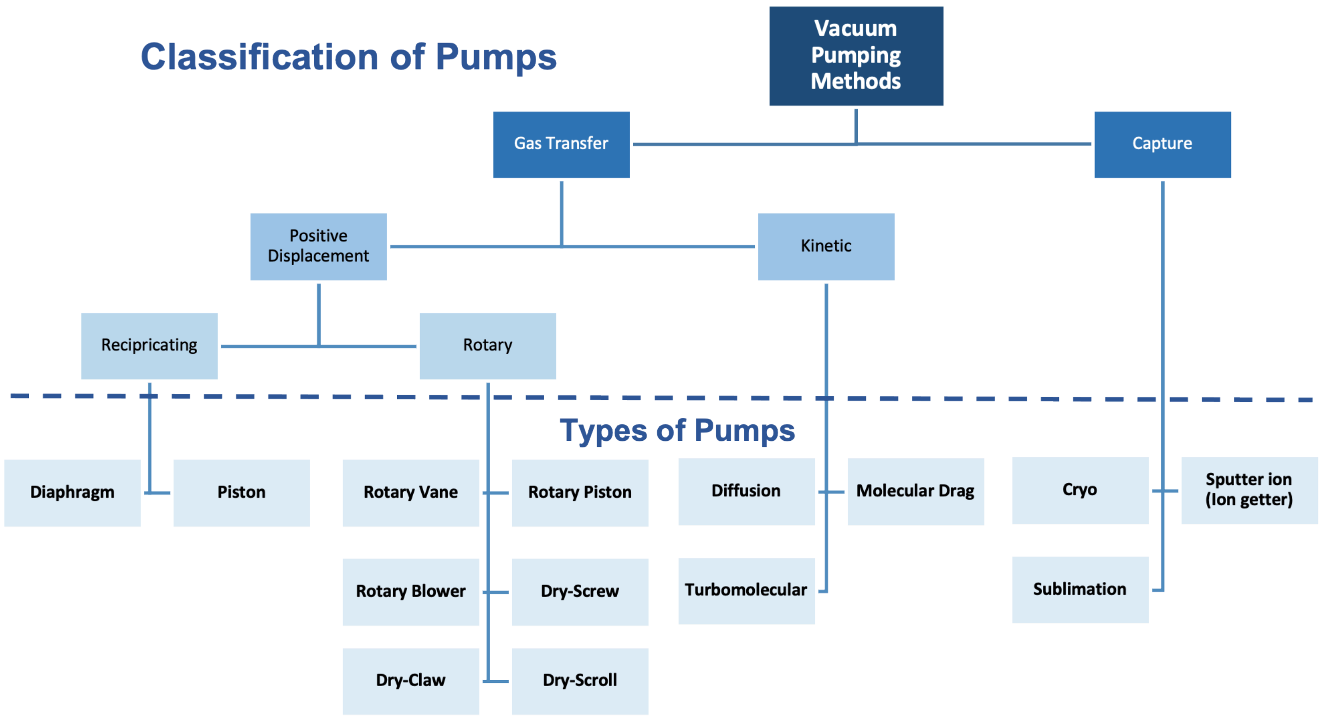

Figure 3.8. Family tree of vacuum pumps. Diagram provided by Nancy Louwagie, Normandale Community College.

Vacuum pumps are designed to operate over specific pressure ranges. Figure 3.9 illustrates the operating pressure ranges for different types of vacuum pumps. If the desired operating range of a vacuum system spans a wider pressure range than can be provided by one type of vacuum pump, multiple pumps can be used together and operated in a specific sequence to span the entire pressure range that is required. For example, if the operating pressure range is in the rough vacuum pressure regime from atmosphere to say, 1 Torr, ***mechanical pumps*** may be the appropriate choice as shown in Figure 3.9. But, if the desired operating pressure range extends into the high vacuum regime, a ***rough vacuum pump*** will have to be used in combination with a high-vacuum pump such as a diffusion pump or turbomolecular pump to reach an operating pressure in the high vacuum regime. In this case, the rough vacuum pump reduces the pressure to the upper operating range of the high-vacuum pump, and then the high-vacuum pump is enabled to further reduce the pressure until the desired operating

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Animation 3.2. Ion pump element styles. Animation provided by Gamma Vacuum, licensed under SPDX-License-Identifier: Apache-2.0.

pressure is reached. To reach pressures in the ultrahigh vacuum regime, three or more pumps will often have to be used.

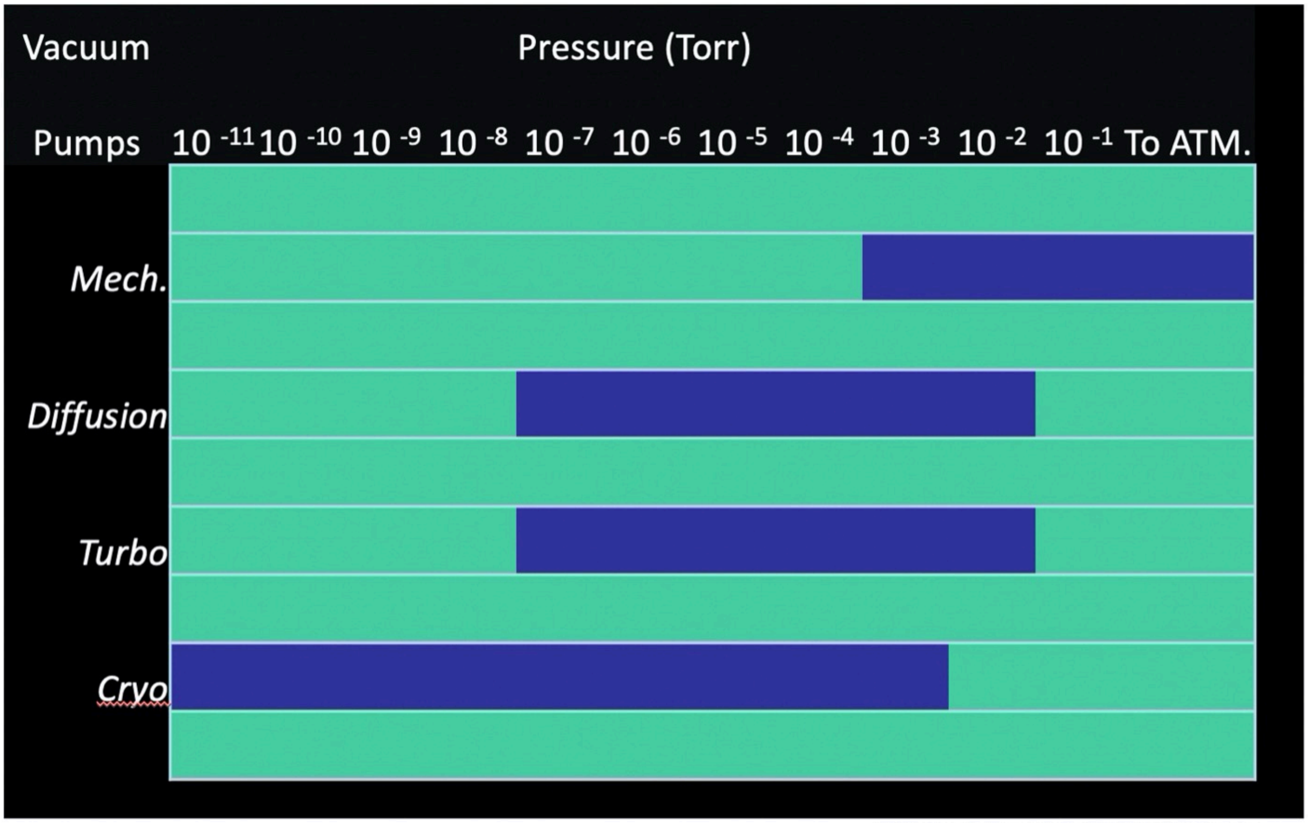

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Figure 3.9. Operating pressure ranges for various types of vacuum pumps. CNEU, Public Domain.

Given the myriad of vacuum pumps on the market today, selecting the “best” vacuum pump for a specific application can be a daunting task. In many situations, there will probably be no single pump that will satisfy all process requirements. Here are some useful considerations when selecting a vacuum pump:

- What base pressure must be reached to support the process? Does the pumping speed versus pressure curve fit the process requirements?
- What is the anticipated gas load? Are there any problems associated with the gas load, for example, use of corrosive gases?
- Can the pump be installed in the intended space and with the desired orientation? Are there other considerations, such as vibration and noise that might affect its installation?
- What are the pump’s power requirements?
- Will the pump require a ***backing pump*** or other components such as valves?
- Can the pump be easily maintained? How often will the pump(s) require maintenance?

- What cleanliness level is required? Is an oil-free pump required?
- Will the process chamber be opened frequently? Is the external environment typically dry or humid? Is the external environment impacted by seasonal changes?
- What will be the cost of ownership over the period of use, not just the original purchase price?
- What is the reliability and reputation of the vendor?

This is by no means a comprehensive list of questions. Each application will have its own set of questions to consider in order to address all the issues associated with the process. The questions in this list, however, will give you a starting point in your selection process, or elimination process, as the case may be.

## 3.4.3 Vacuum Gauges

Measuring pressure in each regime requires converting a parameter associated with the gas molecules' behavior which is subsequently converted into a pressure readout. There is no one gauge that alone and by itself is capable of measuring all pressures across the entire vacuum regime. ***Vacuum pressure gauges*** differ with respect to their operating pressure range, accuracy, and cost. With the exceptions of the ***McLeod gauge*** and the ***Bourdon gauge***, all other vacuum pressure measurement devices include a transducer and the electronics to perform the conversion process and provide the pressure readout. A vacuum gauge is classified as a ***direct reading gauge*** if its measurement is based on the actual force exerted by the gas. A vacuum gauge is classified as an ***indirect reading gauge*** if the pressure is inferred from another process. Figure 3.10 shows a family tree of common pressure gauges used on vacuum systems.

In the ***rough vacuum regime*** where the gas is relatively dense, two parameters are commonly used, the force exerted by the gas on a surface and the thermal conductivity of the gas. The McLeod gauge and the Bourdon gauge are two purely mechanical type vacuum gauges that measure pressure based directly on the force of the gas molecules present. The McLeod gauge with a design similar to a mercury manometer is capable of accurately measuring pressures of non-condensable gases as low as $10^{-6}$ Torr. The Bourdon gauge has a tube which flexes in response to pressure changes. The flexing motion actuates the mechanical movement of a needle indicator. Since the McLeod gauge and Bourdon gauge lack the electronics needed to interface to automated process systems, they are not used extensively in vacuum systems.

The ***capacitance diaphragm gauge*** is also a type of rough vacuum gauge that uses the force of the gas on a surface. There is a thin diaphragm inside the capacitance manometer. On one side of the diaphragm is a reference pressure, and on the other side is the gas in the chamber. A pressure differential causes the diaphragm to deform. The diaphragm effects the capacitance between the two electrodes on a one-sided capacitor. Since

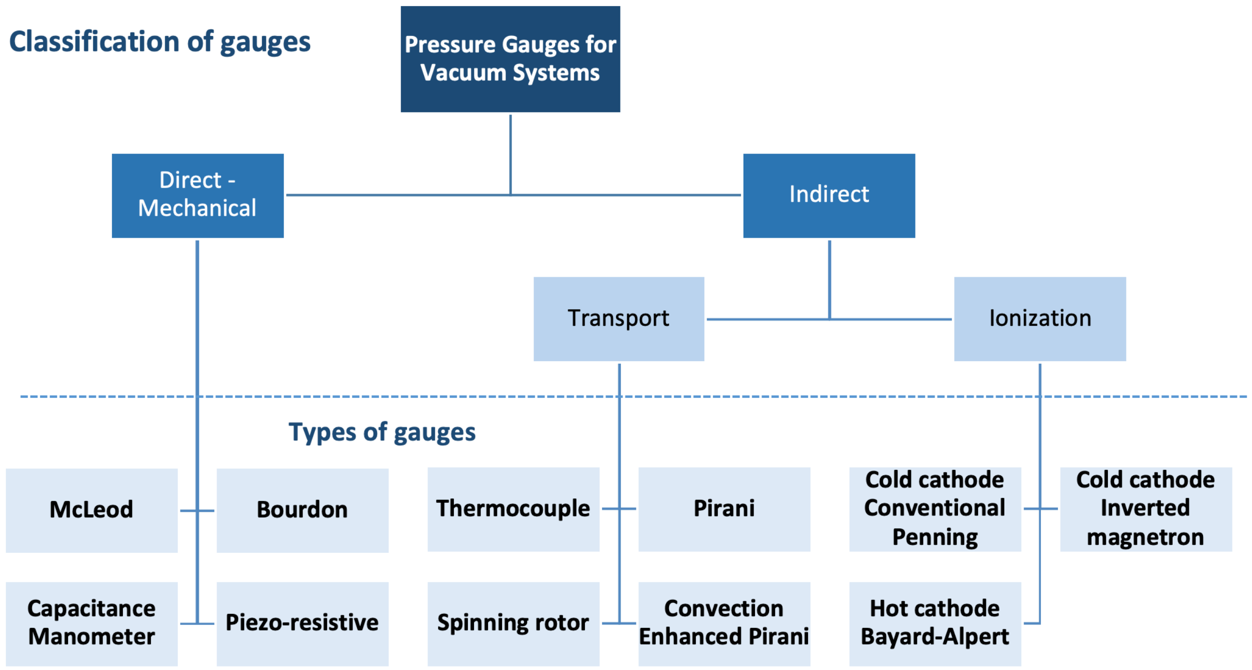


Figure 3.10. Family tree of vacuum pressure gauges. Diagram provided by Nancy Louwagie, Normandale Community College.

$$C = \varepsilon \frac{A}{d}$$

where $C$ is the capacitance, $\varepsilon$ is the permittivity of the dielectric, $A$ relates to the plate area, and $d$ is the separation between plates, then any change in the separation caused by deformation of the diaphragm results in a change in the capacitance. The gauge controller converts this change in capacitance into an electrical signal and a pressure readout.

Similar to the capacitance diaphragm gauge, the strain gauge uses the force of the gas on a surface. This gauge is built using an insulating flexible diaphragm which supports a metallic foil pattern. On one side of the insulating diaphragm with foil is a reference pressure, and on the other side is the gas in the chamber. The difference in pressure causes the diaphragm and foil to deform. As the metallic pattern on the foil deforms, it's electrical resistance changes. This change in electrical resistance is measured and the amount of induced stress and corresponding pressure differential can be inferred.

Examples of rough vacuum gauges that rely on the *thermal conductivity* of the gas are the ***thermocouple gauge***, the ***Pirani gauge***, and the convection enhanced Pirani gauge. The transduction process involves the transfer of heat from a filament in the gauge as the gas molecules strike the filament. Recalling the example of the Thermos in Chapter 1, as the pressure in a vacuum system decreases, heat is not transferred as readily across the space. In a *thermocouple gauge* operating at a constant filament power, the temperature of the filament provides an indication of the environment's changing ability to transfer heat. This temperature change in the filament is sensed and converted to an electrical signal by a thermocouple. In the case of the *Pirani gauge*, the change in temperature of the filament results in a resistance change, and this resistance change is converted to an electrical signal. In a modern ***convection-enhanced Pirani gauge***, temperature variations of the gauge surface are carefully accounted for, resulting in a gauge design that is more thermally stable, and therefore, can produce a pressure indication over a wider range.

In the high-vacuum regime, the gas is too rarefied to rely on force or thermal conductivity to measure the gas pressure. High-vacuum gauges such as the ***Bayard-Alpert gauge*** sample the pressure by ionizing gas molecules within the gauge. At the high-pressure, that is, lower vacuum, end of the operating range, a large number of ionizations occurs and results in a large current in the collector terminal of the gauge. At the low-pressure end of the operating range, fewer ionizations occur, and the resulting current in the collector is smaller. The gauge controller converts the current in the collector into a pressure readout.

Figure 3.11 shows the typical operating ranges for common vacuum gauges. In the rough vacuum regime, convection, strain, and capacitance manometers can be used to measure pressures from atmosphere into the rough vacuum regime. However, these gauges have a lower pressure limit below which they cannot accurately measure the chamber pressure. To measure pressures into the high-vacuum regime, high-vacuum gauges must be used. When the chamber pressure decreases to the upper operating limit of the high-vacuum gauge, then the high-vacuum gauge can be turned on to measure the chamber pressure. A vacuum system which uses three gauges such as capacitance manometer, thermocouple, and ***hot-cathode ionization gauges*** to monitor chamber pressure provides a measurement of the pressure condition from atmosphere into the $10^{-9}$ Torr pressure range.

Unfortunately, measuring pressure is not merely as simple as connecting the gauge to the chamber and the gauge to the controller. A direct reading gauge yields a pressure measurement that reflects the forces exerted by the mixture of gas molecules without needing to know the underlying types of gas molecules present. However, when using ***indirect reading gauges***, it is important to remember that gases differ in their thermal conductivity and ease of ionization. As a result, at lower pressure levels where only indirect reading gauges can be used, the readout depends on the gas composition in the chamber. Correction tables for different gases are used to correct the pressure reading presented on the readouts of gauge controllers.

Like the selection of vacuum pumps for your application, you will have a number of choices for vacuum gauges. Vacuum gauge design has come a long way in the last 20 years and new designs add convenience to pressure measurement. Here are some considerations when selecting vacuum gauges.

- Over what range must pressure be measured?
- Can the gauge accurately and safely measure the pressure of the gases in the vacuum system?
- Will the gauge require calibration and re-calibration?

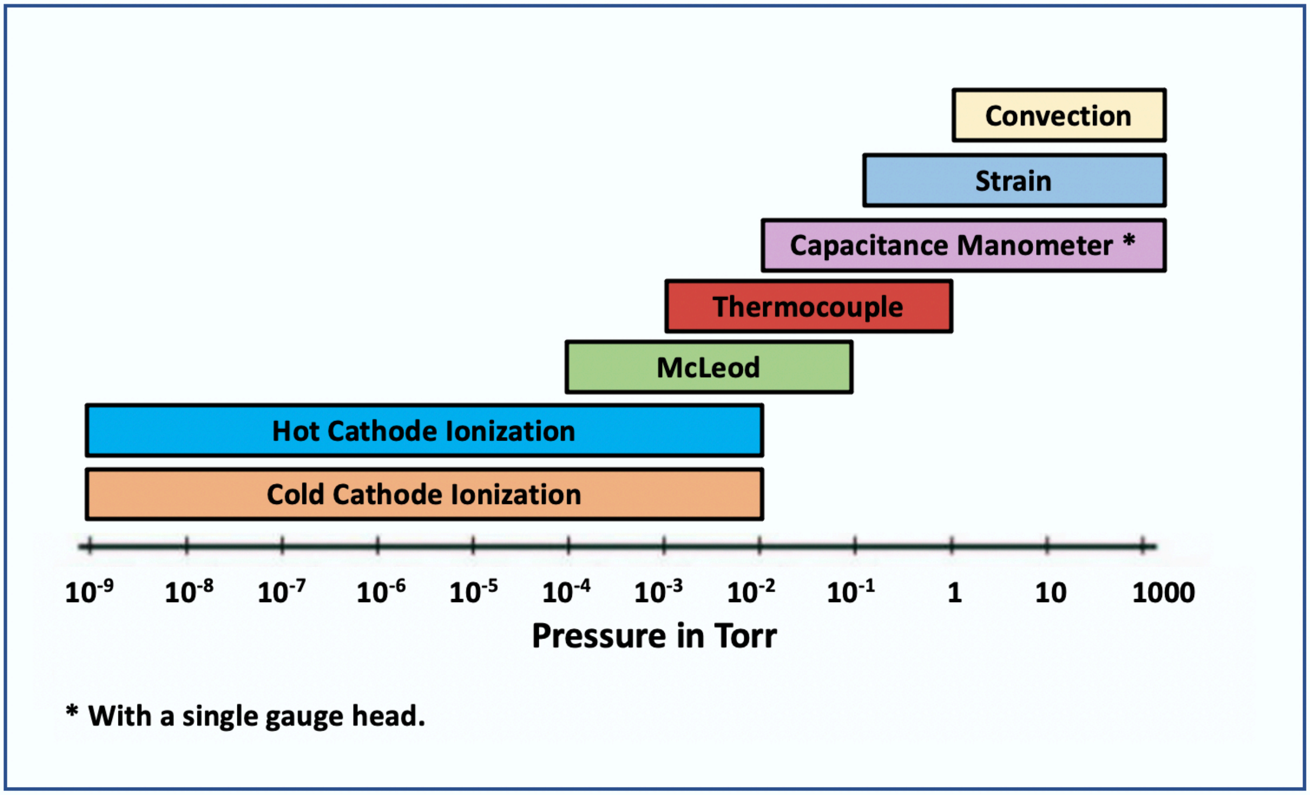


Figure 3.11. Operating pressure range for common types of vacuum pressure gauges. Diagram provided by Nancy Louwagie, Normandale Community College.

- Where will the gauge be physically positioned in the vacuum system? Should the gauge include a local display?
- What is the accuracy and repeatability of the vacuum gauge?
- What is the cost of the vacuum gauge? Is it a self-contained unit, or does the transducer require a separate gauge controller?

## 3.4.4 Vacuum System Components

A vacuum system rarely consists of only a chamber, a pump, and a pressure gauge. Other components are needed to connect these three system components and to provide control in its operation. These additional ***vacuum piping components*** include control valves, nipples, elbows, tees, reducers, crosses, couplings, seals, flanges, and ***feedthroughs***.

For example, a variety of valves provide vacuum systems with isolation, control, and venting capabilities. ***Isolation valves*** allow parts of the system to be isolated from other parts of the system. An isolation valve can be placed between the chamber and the vacuum pump so that the chamber can be isolated and vented to atmospheric pressure without turning off the pump. Butterfly valves and ***throt-***

***tling valves*** provide a way to control conductance and thus, the flow of gas molecules in order to adjust the pressure level in the process chamber. Air admittance valves provide a way to vent the chamber or admit gas into the process chamber.

What should you consider when selecting a valve? The main factors to be aware of when selecting a valve are its operating pressure, leak-tightness, impact on conductance, and underlying outgassing rates from the materials used in the construction of the valve. Of course, there is the initial purchase price, but the functional design considerations affect the cost of ownership over the long-term operation of the vacuum system. For example, the internal geometry of the valve, depending on its placement in the vacuum system, may add to the internal surface area of the chamber. Additional surface area means more opportunity for ***desorption*** and outgassing in the vacuum system. Also, internal valve mechanisms are a source of particles and thus, contamination.

Another consideration when selecting a valve will be the materials used to manufacture it. Valve bodies are made of brass, cast aluminum, machined aluminum, or stainless steel. Brass as a material has temperature limitations, porosity and outgassing characteristics which do not support high- and ulta-high vacuum conditions. Brass components are limited to use in the ***foreline*** and ***roughing line*** of a vacuum system and to applications that do not use corrosive gases. Components constructed of aluminum and stainless steel are used in a wide variety of pressure ranges. Stainless steel has the advantage of resisting many corrosive gases.

Three common types of valves are gate, poppet, and butterfly valves. Gate values, configured with either circular or rectangular openings, provide the highest conductance. They feature a straight-through aperture. ***Poppet valves***, also called block valves, have a seating component that is lowered into the cylindrical body to seal against a seat inside the valve. Because of their simple design, poppet valves have a long life. Poppet valves have a lower conductance than ***gate valves*** because they force the gas to make turns as the gas moves through the valve. Butterfly valves, along with throttling gate valves, are variable conductance valves that can provide a means of controlling pressure in a system.

Other vacuum system components provide the plumbing to interconnect the system. These components include pipeline components (see Figure 3.12), such as nipples, elbows, tees, crosses, couplings, reducers, and adapters, and come in industry-standard sizes. The connections between these components also come in a variety of styles. The most common are the ***ConFlat flange*** (CF), the KF flange, and the ***ISO flange***. The ***CF flange*** uses a copper gasket to form the seal, and the components to be joined are bolted together. The KF flange, on the other hand, uses an ***elastomer O-ring*** to form the seal, and when a KF clamp is used to connect two components, the elastomer O-ring is compressed in the flange. ISO flanges are used for tubing requirements that generally exceed 2-inches in outside diameter. ISO flanges are similar to KF flanges that use a centering ring with an elastomer O-ring, and use a set of single- or double-claw clamps to hold the components together.

Vacuum systems are often used to create the pressure condition necessary to carry out certain processes. In order to carry out those processes, additional energy or matter may need to be introduced

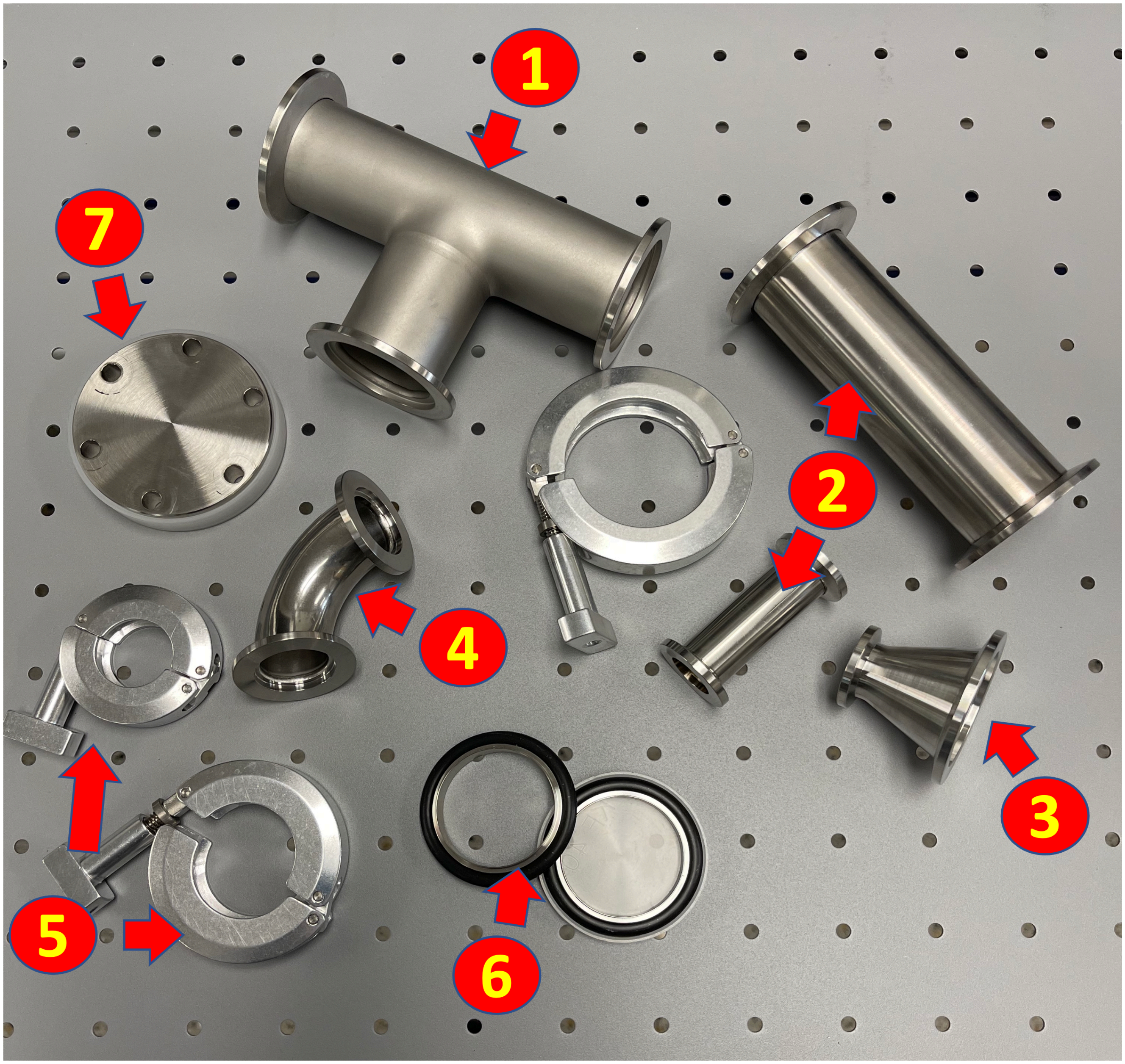


Figure 3.12. Vacuum flange fittings: 1 – tee, 2 – nipple, 3 – reducer, 4 – elbow, 5 – KF clamp, 6 – centering ring with fitted O-ring, 7 – CF pipe end fitting. Photo provided by Elena Brewer, SUNY Erie Community College.

into the vacuum system. Feedthroughs are leak-tight components that allow for energy or matter to be delivered into the vacuum system. For example, electrical feedthroughs deliver high voltage or high current inside the chamber space. Other feedthroughs allow liquids and gases to be introduced into the chamber space.

Section 3.4 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=53#h5p-13*

## 3.5 Schematic Symbols and Diagrams

Technical schematics are important documents in a manufacturing workplace. Technical schematics are a graphical representation of a complex system in a concise form that can be more easily interpreted by the reader. A technical schematic does not show the elements of a system to their actual size or scale but instead uses symbols often paired with quantitative information, like distances and electrical power, to describe the system's configuration.

Leybold GmbH is an international manufacturer of vacuum equipment and components. Leybold compiled a listing of schematic symbols for ***vacuum components*** that can be used to create diagrams of vacuum systems. The schematic symbols fall into categories that include, but are not limited to, vacuum pumps, isolating devices such as valves, vacuum gauges, and connections and piping. Examples of schematic symbols are shown for vacuum pumps in Figure 3.13, isolating devices in Figure 3.14 (a), valve actuation in Figure 3.14 (b), vacuum gauges in Figure 3.15, and connections and piping in Figure 3.16.

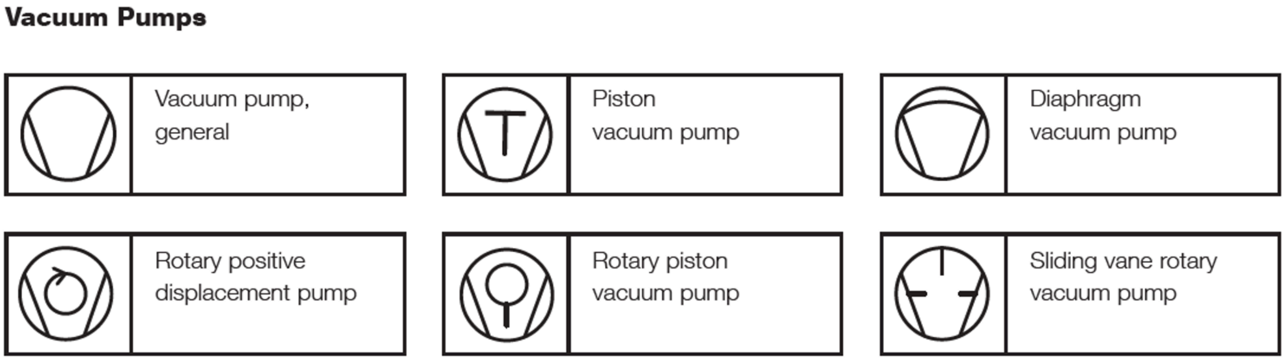


Figure 3.13. Schematic symbols for vacuum pumps. Leybold Full Line Catalog 2021, page 14.

## 3.6 A Simple Rough Vacuum System

In this section, the simple rough vacuum system, shown in Figure 3.17, will be described. The system's vacuum chamber is a Pyrex bell jar that sits on a metal base plate. In Figure 3.17, the Pyrex chamber is shown without the protective shield/guard, whereas Figure 3.18 shows the same chamber surrounded by the protective metal guard used during operation. Gas is removed from the chamber using a rough vacuum pump, in this case a

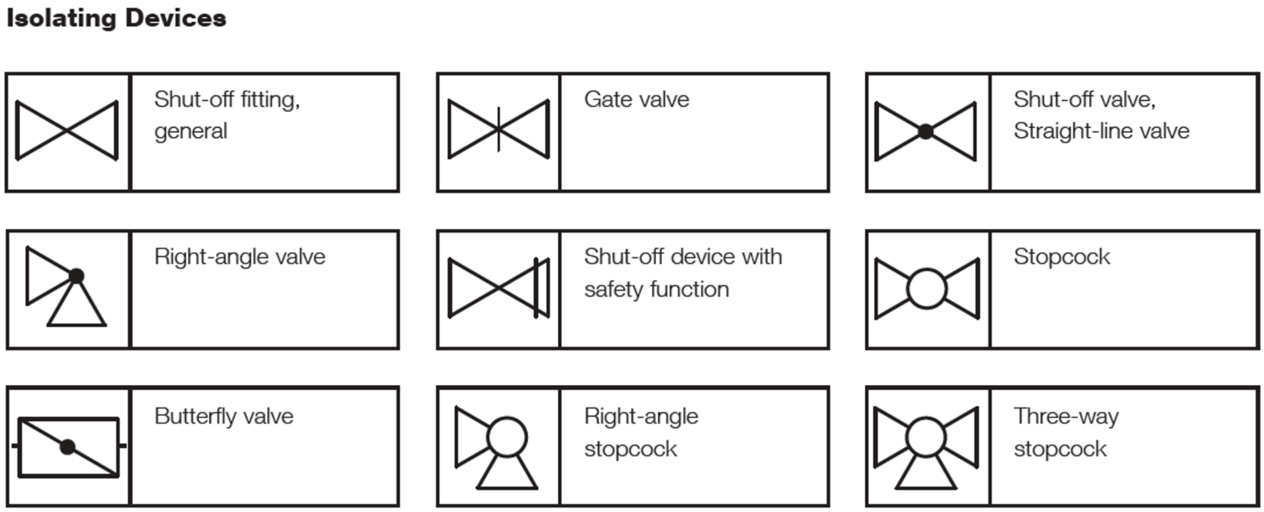


Figure 3.14. (a) Schematic symbols for isolating devices. Leybold Full Line Catalog 2021, page 15-16.

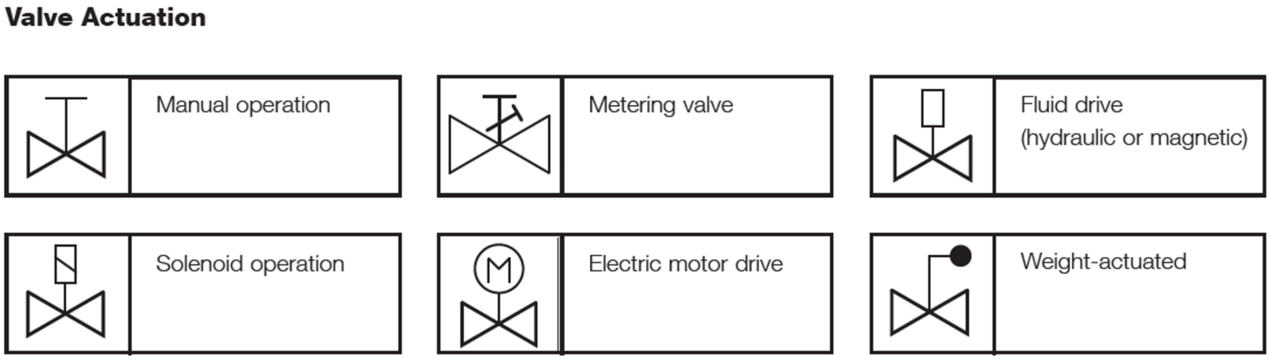
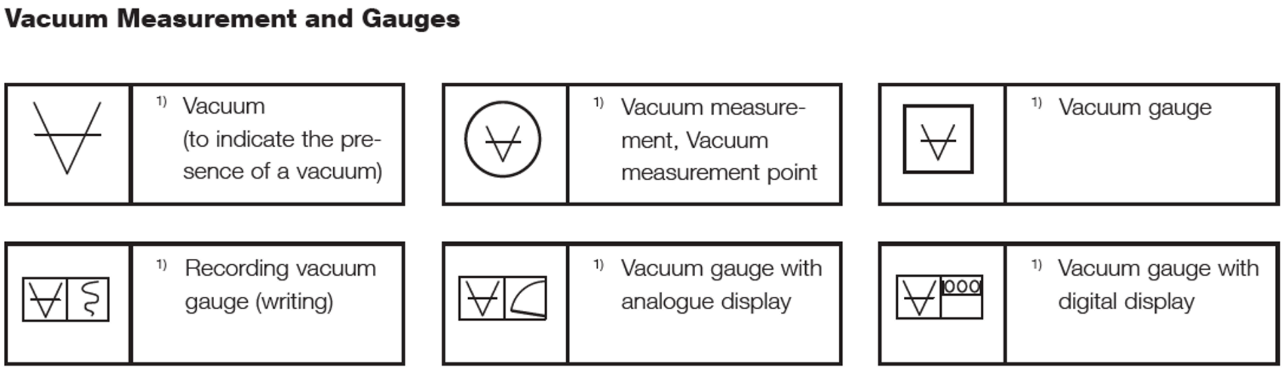


Figure 3.14. (b) Schematic symbols for valve actuation. Leybold Full Line Catalog 2021, page 15-16.

***scroll pump***. The pump is connected to the bell jar through piping that includes a KF40 to KF16 adaptor to change the size of the piping. A manually-actuated ***butterfly valve*** is placed in the gas flow pipeline to isolate the bell jar from the vacuum pump, or to change the conductance in the roughing line. Pressure in the system is measured by a rough vacuum gauge (Convection Enhanced Pirani gauge). Finally, a vent valve provides a means to return the bell jar to atmospheric pressure. Video 3.1. provides the detailed overview of this rough vacuum system.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=53#oembed-3*



**Vacuum Measurement and Gauges**

1) Vacuum (to indicate the presence of a vacuum)

1) Vacuum measurement, Vacuum measurement point

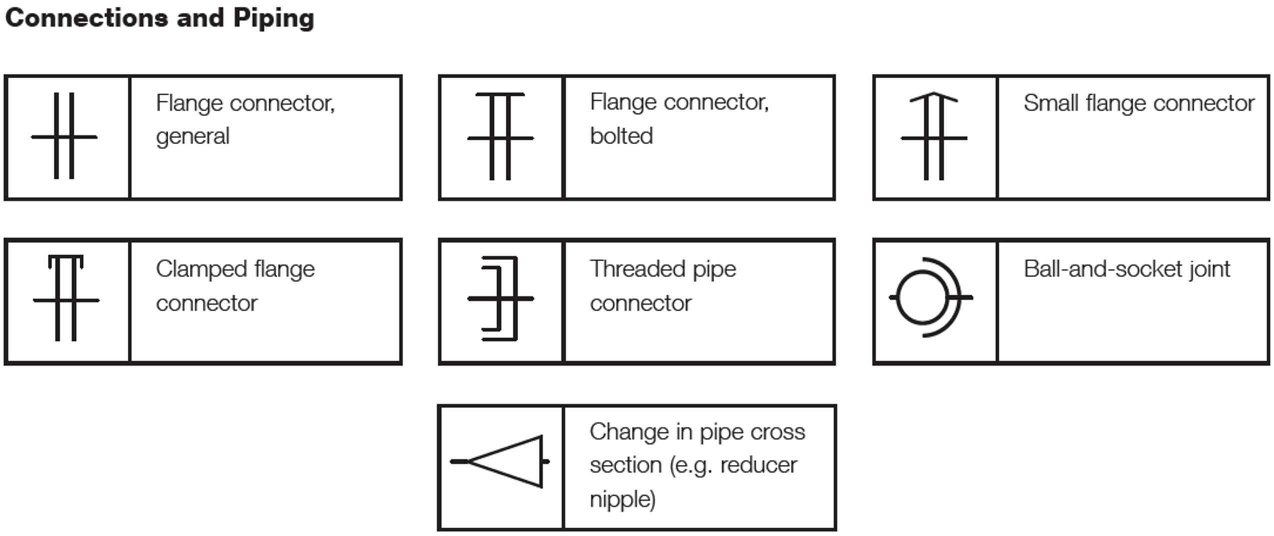
1) Vacuum gauge

1) Recording vacuum gauge (writing)

1) Vacuum gauge with analogue display

1) Vacuum gauge with digital display

Figure 3.15. Schematic symbols for vacuum measurement and gauges. Leybold Full Line Catalog 2021, page 17.



**Connections and Piping**

Flange connector, general

Flange connector, bolted

Small flange connector

Clamped flange connector

Threaded pipe connector

Ball-and-socket joint

Change in pipe cross section (e.g. reducer nipple)

Figure 3.16. Schematic symbols for connections and piping. Leybold Full Line Catalog 2021, page 16.

Video 3.1. Description of SUNY Erie's rough vacuum system. Video prepared by Richard Hill and Anthony Klejna, SUNY Erie Community College.

Figure 3.19 shows the location of various components in the vacuum system and the vacuum symbol that can be used to present each system component. On the left side of the figure are the main components of the rough vacuum system and the associated schematic symbol. On the right is a picture of the rough vacuum system with letters and arrows to show the location of each system component.

Using Leybold's vacuum component symbols, we can then create a schematic diagram that represents the

Figure 3.17. A simple rough-vacuum pumping system. Photo provided by Richard Hill, SUNY Erie Community College.

physical, rough-vacuum system shown in Figure 3.20. The schematic shows the connections between the components used to construct the rough-vacuum system and conveys the function of each vacuum component. Using the schematic diagram, you can trace the conductive pathway from the bell jar to the pump, identify the gauge used to measure pressure, and determine where valves are located to control the flow of gas in the system.

## 3.7 Characterizing Vacuum Systems

Knowing your vacuum system is the first step in detecting and addressing problems that occur in vacuum systems. Qualitatively, this can be as simple as hearing unusual sounds from your system, just as you might hear odd noises in your car when you start it or drive it. Unfortunately, problems in vacuum systems cannot always be detected by listening.

Another method is to keep records of vacuum system performance. For example, a system log might include the time-to-pressure or pump-down times along with base pressures recorded at establish the system's baseline performance. This offers simple tracking data that will indicate when system performance has changed, such as when the system seems to be pumping down slower than usual or is not pumping down quite as far as it used to.

Figure 3.18. A Pyrex bell jar chamber from Figure 3.17 covered by the metal protective shield/guard. Photo provided by Richard Hill, SUNY Erie Community College.

Phil Danielson, in an October 1998 article entitled "The Value of Pumpdown Curves," describes the industry practice of using ***pump-down curves*** to characterize vacuum systems and to diagnose problems. A pump-down curve is a graph of pressure versus time that shows the performance of a vacuum system as the system is pumped down from initial pressure to base pressure. If you acquire data to create pump-down curves that correspond to optimal system operation, future pump-down curves can be compared to the optimum curve to monitor system performance. If the two curves are identical or very similar, chances are that the system is operating normally, and there is no problem. On the other hand, if the two curves differ, this can indicate that a change, and possibly a new problem, has occurred in the system and corrective action should be taken.

We will return to the use of pump-down curves and address other system diagnostic practices in later chapters.

## Summary

Chapter 3 describes the general components needed to construct a rough vacuum system: a vacuum

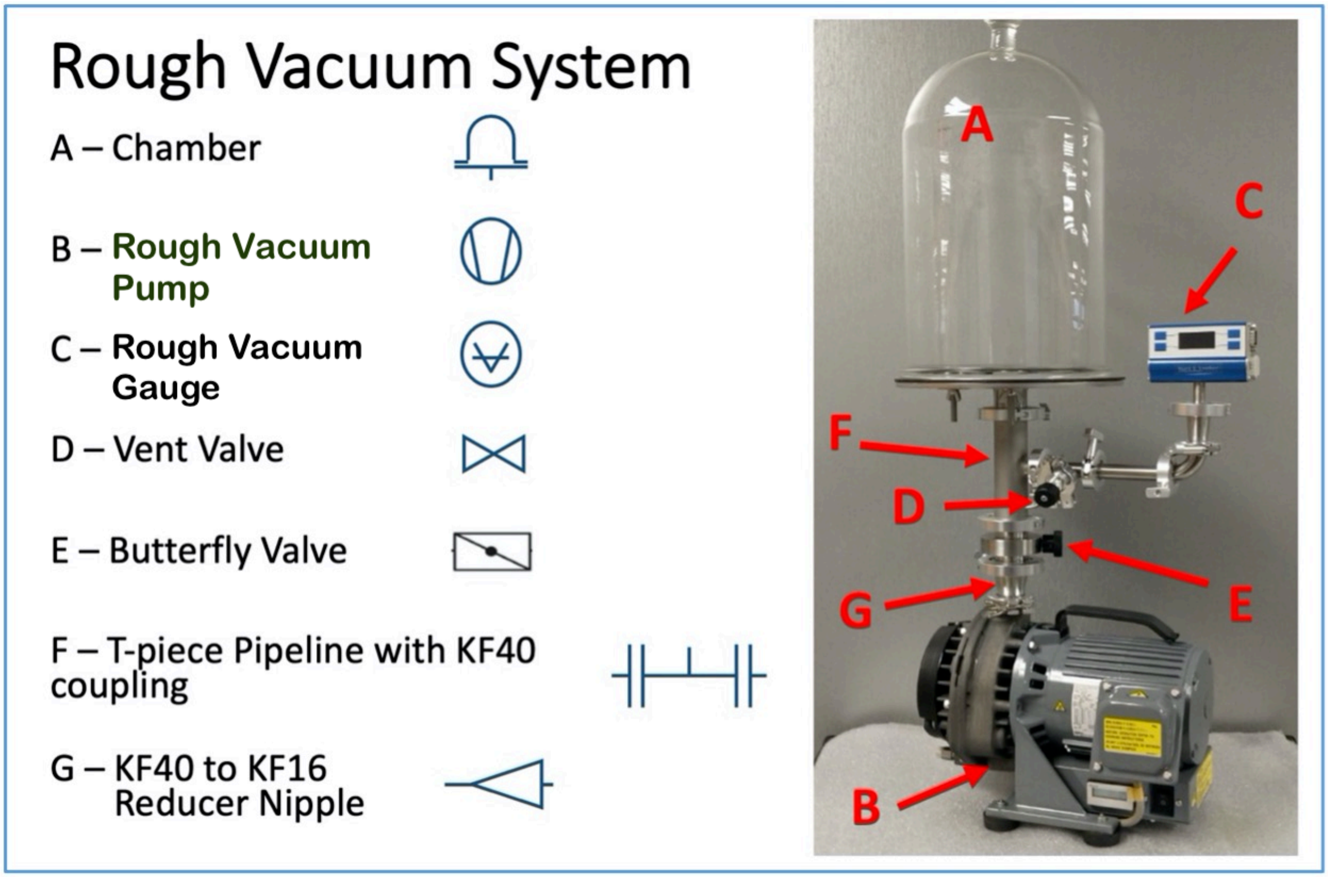


Figure 3.19. Rough vacuum system with component identification and associated schematic symbols. Diagram provided by Elena Brewer, SUNY Erie Community College.

chamber, vacuum pump, vacuum gauge(s), valve(s), and fittings. The amount of gas from all sources to be removed from the system is defined as the gas load. These sources of gas include the bulk gas in the vacuum chamber, desorption of surface gas, outgassing, permeation, contamination, leaks, and ***backstreaming***.

Vacuum pumps are used to remove gas from the chamber. Vacuum pumps come in a variety of designs and work over a limited range of gas pressures. Rough vacuum pumps are typically positive displacement pumps that trap a volume of gas, compress it, and then exhaust it from the system. High-vacuum pumps are either kinetic-type pumps, such as turbomolecular pumps, or ***capture pumps***, such as cryogenic or cryopumps.

Vacuum gauges also come in a variety of designs. In the rough vacuum regime, gauges operate either through the force exerted by a gas on a solid wall or by sensing the loss of energy from a filament via thermal conduction by the gas molecules. In the high-vacuum regime, pressure gauges operate by ionizing gas molecules.

Parts that connect the chamber to pumps and gauges also come in a myriad of designs. Fittings include KF, CF, and ISO designs, and piping in the form of tubes, elbows, tees, and other forms. The

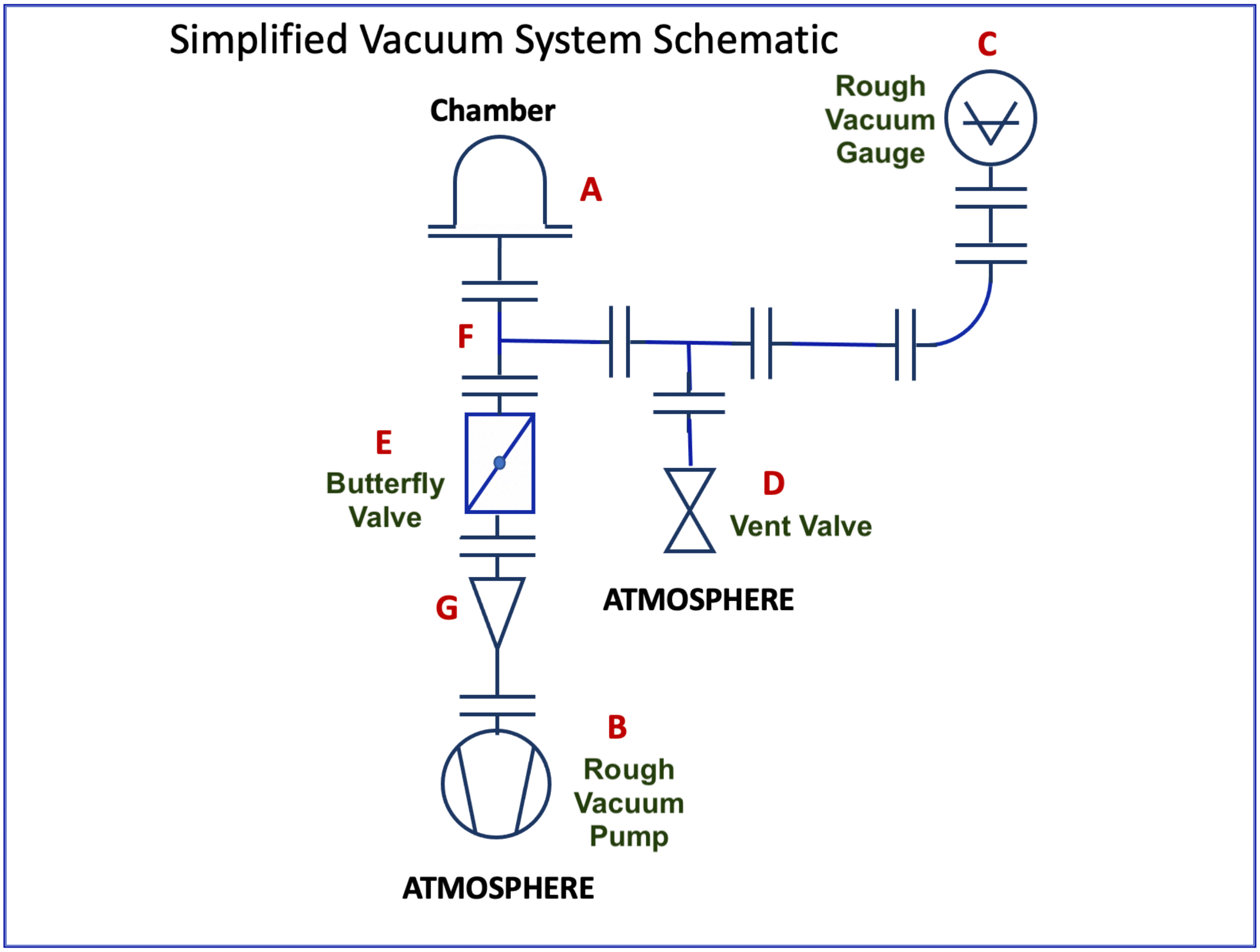


Figure 3.20. A schematic diagram for the rough-vacuum system shown in Figure 3.14. Schematic is provided by Elena Brewer, SUNY Erie Community College.

valves used in the rough vacuum regime are typically block valves, whereas high-vacuum valves may be of the linear gate variety.

The terms "conductance" and "throughput" were introduced to describe the flow of gas through the system. Conductance is a volumetric measure of gas flow given in units of volume per unit time. Throughput describes the amount of gas moving through the pumping system and is measured in units such as Torr-liters per second.

The chapter concluded with a simple example of a rough vacuum system. On the picture of this physical system, various vacuum system components were identified using arrows and letters. Finally, a system schematic representation, using industry-accepted symbols, was created to show the interconnection of vacuum components in the rough vacuum system.

Now that we have a general sense of what makes up a vacuum system, we will turn to examining in more detail rough vacuum systems, that is, vacuum systems that reduce the chamber pressure from atmospheric pressure to approximately 1 millitorr. We will examine rough vacuum systems in terms of gas load, pumps, gauges, and system components. The next chapter will describe how to analyze rough vacuum systems and how to characterize their operation.

## Chapter 3 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=53#h5p-2*

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## Questions and Problems

1. When referring to a vacuum system,
    a. Define the term "gas load."
    b. In the rough vacuum regime, identify the major contributors to gas load.
    c. In the high-vacuum regime, identify the major contributors to gas load.

2. For a rectangular chamber (25 cm long, 25 cm wide, and 40 cm high) located in Boulder, Colorado, calculate the gas load due to bulk gas. Assume that atmospheric pressure is 840 mbar at that location.

3. What is the net pumping speed of a simple vacuum system in which the conductance of the piping is 300 liters/sec and the pumping speed of the pump is 600 liters/sec?

4. What would be the effect of changing the pump in Problem 3 from a 600 liters/sec pump to a

much larger pump having a pumping speed of 1,800 liters/sec? What percentage improvement can be achieved?

5. Consider a simple system consisting of a chamber, a rough vacuum pump and a piping. If the pumping speed of the pump is 1200 liters/sec, what is the minimum conductance the piping can have to maintain the net conductance of the system at 1000 liters/sec or higher?

6. Pump-down curves are used as a diagnostic tool in maintaining vacuum systems.
   a. What information do pump-down curves provide?
   b. Give an example of a problem that could be diagnosed using a pump-down curve.

7. If conductance of the piping is much larger than the pumping speed of the pump, then the net pumping speed is ______ the pumping speed of the pump.
   a. much larger than
   b. larger than
   c. approximately equal to
   d. much smaller than

8. Convert the pump's pumping speed of 10 cfm to units of:
   a. liters/sec
   b. liters/min

9. If the desired process pressure in the chamber is $50 \times 10^{-5}$ Torr, what should the net pumping speed be to maintain the throughput of $4.0 \times 10^{-4}$ Torr-liters/sec?

10. List at least 4 components of the rough vacuum system.

11. Consider outgassing rates of the following materials given in Table 3.1:

Table 3.1. Outgassing rates.

| **Material** | **Average Outgassing Rate (torr-liters/sec/cm$^2$)** |
|---|---|
| High density ceramic | $3.0 \times 10^{-9}$ |
| Stainless steel | $6.0 \times 10^{-9}$ |
| Pyrex | $8 \times 10^{-9}$ |
| Copper | $1.7 \times 10^{-8}$ |
| Aluminum | $2.3 \times 10^{-7}$ |
| Mild steel | $4.7 \times 10^{-7}$ |
| PVC | $2.4 \times 10^{-6}$ |
| Brass | $4.0 \times 10^{-6}$ |
| Neoprene | $3.0 \times 10^{-5}$ |

Based on these values of outgassing rates, which one of the listed materials is the least desirable for the high vacuum system? Explain.

12. Calculate the gas load due to outgassing from a spherical chamber made of Pyrex. The inside radius of the chamber is 5.00 inches. Use the outgassing rate for Pyrex as $8 \times 10^{-9}$ torr-liters/sec/cm$^2$.

13. What will happen to the gas load in Problem 12 if Pyrex chamber is replaced with mild steel chamber of equal size? Explain.

14. To maintain the same throughput as in Problem 13, what should be the length of Pyrex chamber if its inside diameter is 10.0 inches?

15. In-class group exercise: Draw schematic of the rough vacuum system shown in Figure 3.21 below.

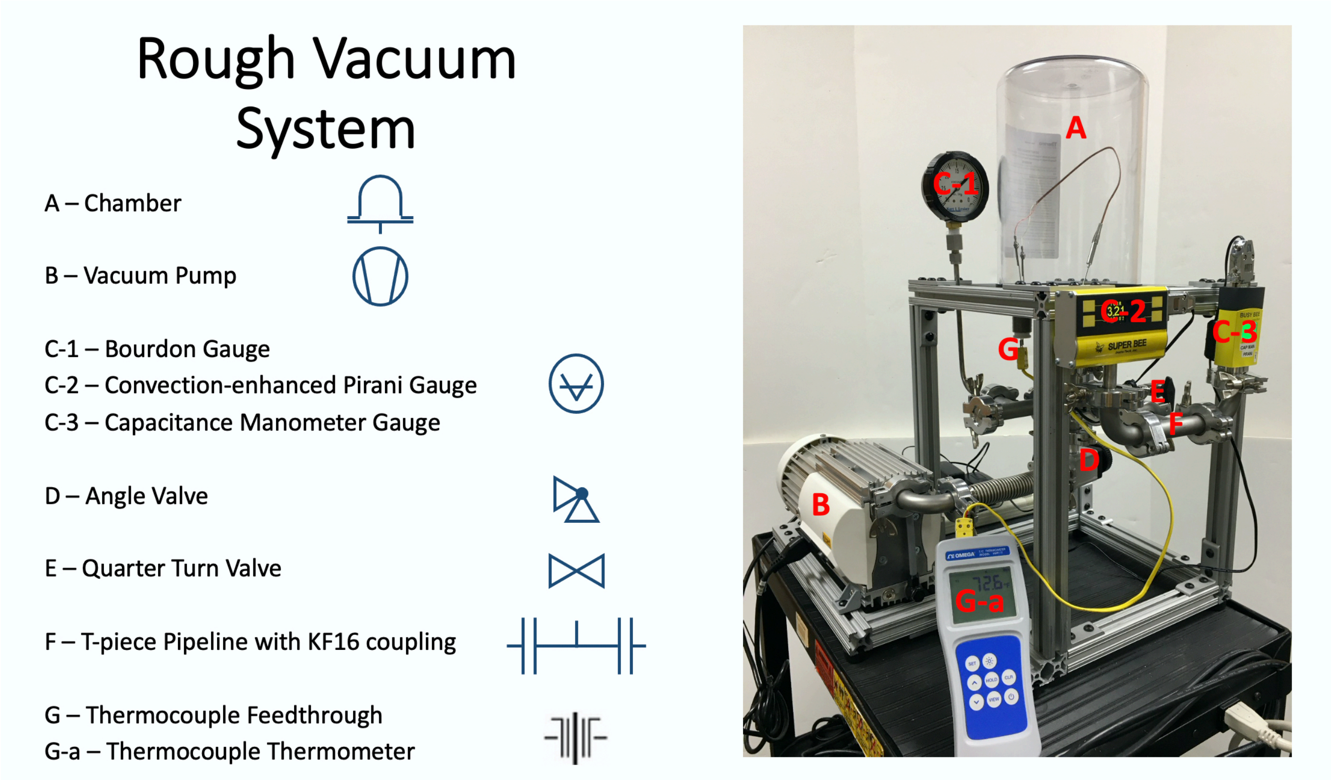

Figure 3.21. Example of rough-vacuum pumping system.
Photo and schematics provided by Nancy Louwagie, Normandale Community College.

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# CHAPTER 4: ROUGH VACUUM REGIME

Learning Objectives

Chapter 4 provides a detailed description of rough vacuum systems and how they function. After you read this chapter, you will be able to:

- Identify the main components present in a rough vacuum system and explain how these components support the function of the system.
- Explain the types of sources that contribute to the gas load in the rough vacuum regime.
- Starting at a specified chamber pressure, calculate intermediate pressures using Boyle's Law and graph the pump-down curve for a chamber connected to a positive displacement pump based on the respective volumes of the chamber and the pump.
- Describe the principle of operation, applications, maintenance, advantages and limitations of various rough vacuum pumps.
- Describe the principle of operation, applications, maintenance, advantages and limitations of various rough vacuum gauges.
- Calculate the absolute pressure that corresponds to a Bourdon gauge pressure measurement given the atmospheric pressure condition.
- Identify the various types of valves and fittings that are needed to configure a vacuum system.
- Calculate the approximate amount of conductance associated with a cylindrical tube of a specified diameter and length given the gas molecules are moving through it under viscous, laminar flow conditions.
- Calculate an estimated pump-down time for a vacuum system given the volume of the vacuum chamber, the pumping speed of the vacuum pump and the conductance associate with the vacuum piping.
- Explain common vacuum system problems and approaches to troubleshooting these problems.

## 4.1 Introduction

In the previous chapter, we introduced how a vacuum system functions along with the various underlying components needed to support those functions. In this chapter, we will examine more closely the roughing function, that is, the initial phase of vacuum system operation. During this phase, the vacuum system starts removing the ***gas load*** from the chamber. The decreasing pressure level indicates to what extent the gas load is reduced. The starting point for every vacuum system is ***atmospheric pressure***.

Any vacuum system that has been opened to the atmosphere will have a chamber pressure that is equal to the local air pressure conditions. The atmospheric pressure depends upon the elevation and current weather conditions at that specific location. Nominally at sea level, atmospheric pressure is 1 atm, or 760 Torr. When pumped down, the first pressure regime the chamber pressure will pass through is the rough vacuum pressure regime. Sometimes the rough vacuum pressure regime is described as covering a range of pressures from atmosphere to approximately 1 Torr, and the pressure range between 1 Torr to 1 millitorr is called medium vacuum. However, for our discussion, we will define the ***rough vacuum regime*** as pressures ranging from 759 Torr to 1 millitorr, about six orders of magnitude for pressure. Over this range, the ***molecular density*** of the gas molecules changes from a high of $3 \times 10^{19}$ molecules per cubic centimeter ($cm^3$) at 759 Torr to a low of $4 \times 10^{13}$ molecules per $cm^3$ at 1 millitorr. Over the same pressure range, the ***mean free path*** of the air molecules increases from $2.5 \times 10^{-5}$ mm at 759 Torr to 5.1 cm at 1 millitorr.

This chapter begins with a discussion of the gas load sources starting at the atmospheric pressure condition and through the rough vacuum regime. In the roughing regime, a vacuum system removes the ***bulk gas***, and the pressure in the system drops quickly, provided no ***gross leaks*** are present. For vacuum systems operating in a 20°C environment, water vapor present in the gas load can become problematic once the system reaches approximately 20 Torr and poses a challenge for every vacuum system. Good system design, assembly and operating practices lead to more predictable vacuum system performance through the roughing regime.

If a vacuum system is free from gross leaks, the ***pump-down curve*** through the roughing regime should be predictable. An estimate of a vacuum system's pump-down curve through the rough regime can be determined based on the type of mechanical roughing pump selected. A variety of mechanical roughing pumps are available for use in vacuum systems. Each ***vacuum pump*** has its advantages and limitations. It is important to understand these differences to properly maintain and service vacuum systems.

A vacuum system needs one or more pressure measurement devices that provide information about how the system is performing. Pressure measurements are taken at regular time intervals after the vacuum system starts its roughing process to generate a pump-down curve. The pump-down curve provides useful diagnostic information to determine the condition of the vacuum system. A variety of pressure measurement devices are available for use in vacuum systems. Just like vacuum pumps, each measurement device has its advantages and limitations. Since the pressure measurement device is often the first indicator checked to assess the operating state of the system, it is important to understand any limitations of the device so the measurement readings are interpreted correctly.

Other hardware components used in a vacuum system impact the vacuum system ***pump-down time*** through the roughing regime. Chamber size is important. Increasing the chamber volume and internal surface area increases gas load sources. The tubing and valves used to interconnect the chamber to the vacuum pump should be selected carefully. The conductance that occurs due to the tubing and valves present in the system should not unduly compromise the system's pump-down performance. And a vacuum system must include a valve that allows at least a part of the system, frequently the chamber, to return to atmospheric pressure conditions so items can be placed in or removed from the system.

After considering the various vacuum system components, we will address the operation of a complete rough vacuum system. This chapter concludes with a short section on troubleshooting rough vacuum systems.

## 4.2 Overview of a Rough Vacuum System

The components of a rough vacuum system are shown in Figure 4.1. The *mechanical roughing pump* is capable of reducing the chamber pressure from 760 Torr down to an ***ultimate pressure*** near to that specified by the pump manufacturer. A nominal pumping speed in either liters per minute or cubic feet per minute will indicate the rate at which the bulk gas can be evacuated from the chamber. The inlet of the roughing pump is connected to the chamber by tubing or piping. A *roughing (isolation) valve* is typically placed in the ***roughing line*** to provide means of isolating the pump from the chamber by blocking the pathway for the gas to flow between the chamber and the pump. The outlet of the ***roughing pump*** is usually connected to the ***house exhaust system***, or if the chamber contains only room air, the exhaust can be left open to the room. The pump should include some type of filter to prevent exhausting particles into the work environment. For example, if an oil-sealed pump is exhausted into a room, then a mist-extractor filter is often attached to the pump's exhaust fitting.

Two other features are needed to complete the rough vacuum system. First, there must be a way of measuring the chamber pressure. This is accomplished by connecting a rough ***vacuum gauge*** to the chamber or to the roughing line. The rough vacuum gauge measures the chamber pressure and displays the pressure reading.

Second, there must be a way of returning the chamber to atmospheric pressure from a lower operating pressure so that the chamber can be opened and its interior space accessed. To provide this capability, a vent (air admittance) valve is connected directly to the chamber. When the ***vent valve*** is opened, room air at atmospheric pressure (or often dry nitrogen) flows into the chamber and the chamber returns to room pressure.

Section 4.2 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#h5p-18*

## 4.3 Gas Load in the Rough Vacuum Regime

An important concept when working with vacuum systems is gas load. We will define gas load as the amount of gas that has to be removed from the chamber. Contributors, or sources of gas load, vary as the pressure varies and different contributors to gas load do not all equally contribute to the total gas load. Contributors to the gas

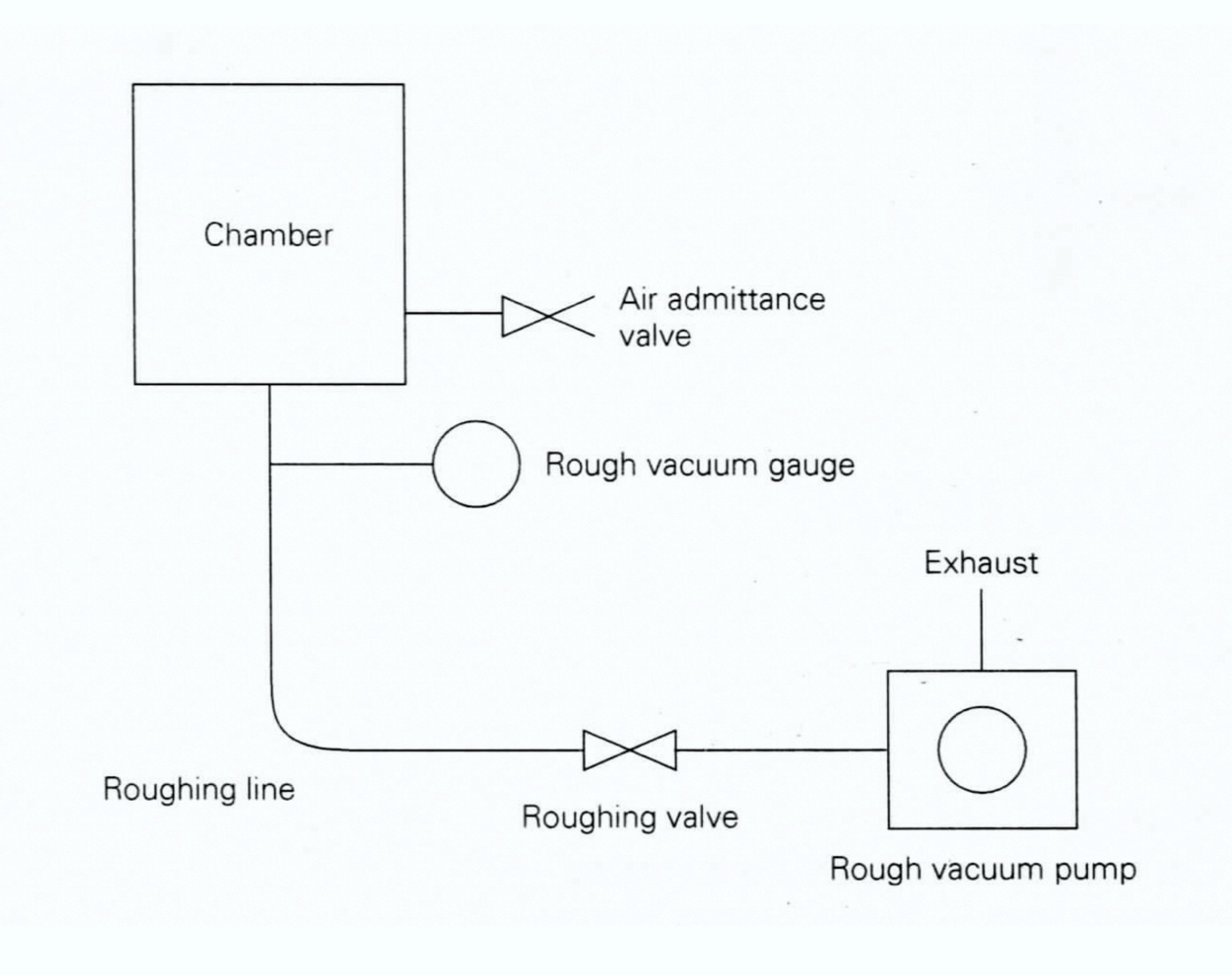

Figure 4.1. Rough vacuum system. Diagram provided by David Hata.

load will also depend on the types of materials used in the vacuum system design and how the vacuum system is constructed and assembled.

The major contributors to gas load in the rough vacuum regime are the bulk gas, ***desorption*** of gas from surfaces, and ***virtual*** and ***real leaks*** (see Figure 4.2). For the time being, we will assume that there are no real leaks in the system. We will also assume that the system was built without creating sources of virtual leaks. That leaves the bulk gas and desorption of surface gas, mainly water in most cases, as the major contributors to gas load. Other gas load sources, namely bulk ***outgassing***, ***diffusion***, ***permeation***, and ***backstreaming***, contribute negligible amounts in the rough regime, so we will not address them in this chapter.

The bulk gas can be determined by multiplying the chamber pressure by the volume of the chamber plus any other volumes interconnected and open to the chamber. The amount of gas is measured in torr-liters, or an alternative volume-pressure product. For example, a 5-liter chamber at atmospheric pressure (760 Torr) has a bulk gas contribution to gas load of 5-liters multiplied by 760 Torr, or 3,800 Torr-liters of gas. In Chapter 3,

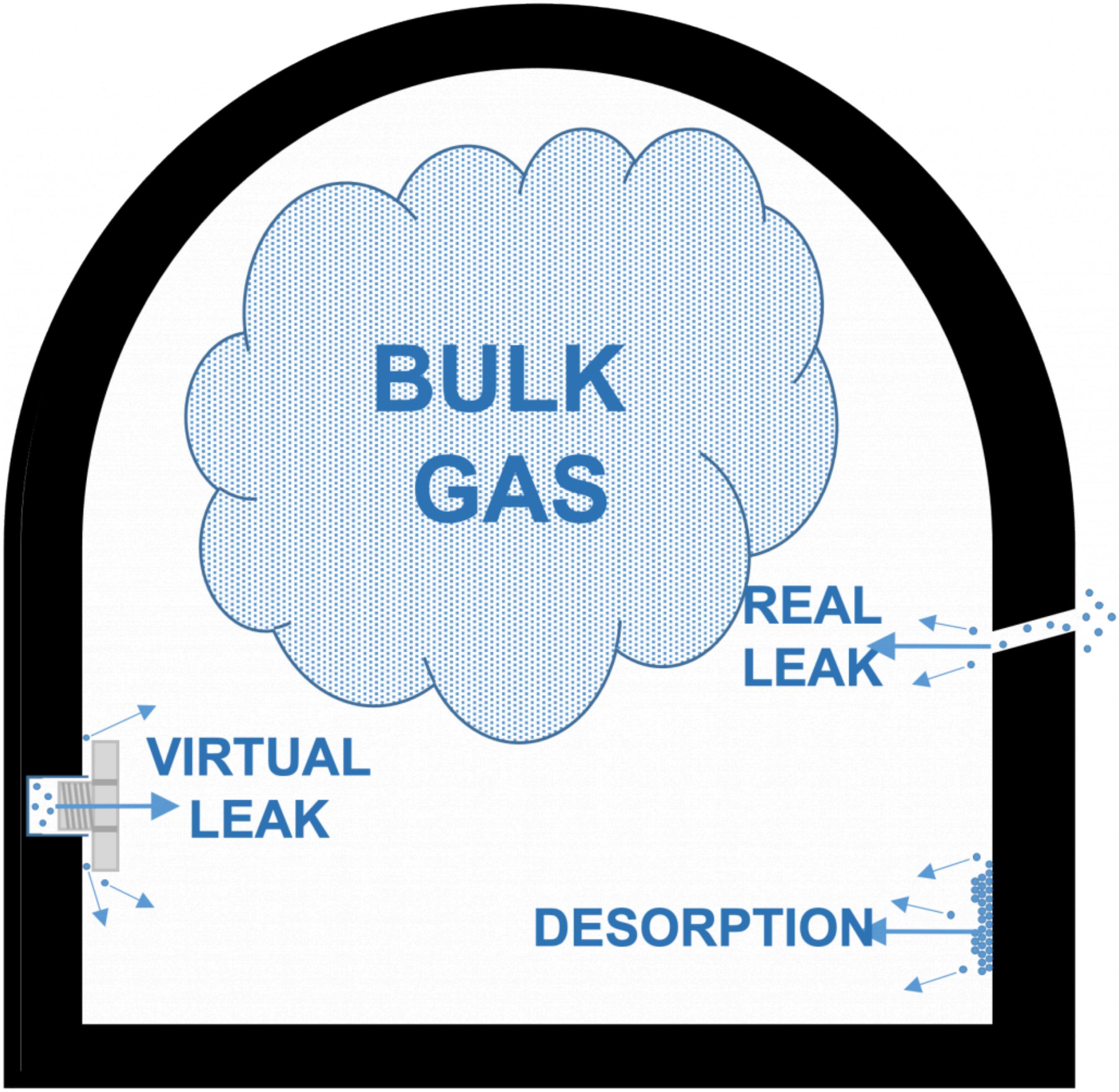

Figure 4.2. Gas load in the rough vacuum regime.
Figure provided by Nancy Louwagie, Normandale Community College.

Example 3.1 shows how to calculate a volume and use the local atmospheric pressure condition to determine the gas load due to the bulk gas present.

The contribution of surface gas to gas load is harder to quantify. This contribution depends on the surface area, the humidity of the air allowed into the chamber, and the length of time the chamber is exposed to the atmosphere. We may have little control over these variables. Nevertheless, if the system has been vented to the atmosphere, water vapor from the air has coated the inner surface of the chamber, piping, and other system components. As the chamber is pumped down, the water on the inner surface of the chamber will begin to ***desorb*** from the surface and enter the gas phase. The bonds between water molecules in the layers nearest the chamber's surface can take a very long to break. Heating, or baking, the chamber speeds up desorption of water from the inner surfaces of the chamber. Once in the gas phase, those water molecules can be pumped out of the chamber.

Section 4.3 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
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## 4.4 Rough Vacuum Pumps

***Rough vacuum pumps*** are called positive displacement vacuum pumps. The operation of a ***positive displacement pump*** is based on Boyle's law applied over many repetitive cycles. Positive displacement pumps repeatedly expand the volume, isolate it, compress the trapped gas, and then expel the trapped gas as shown in the Figure 4.3.

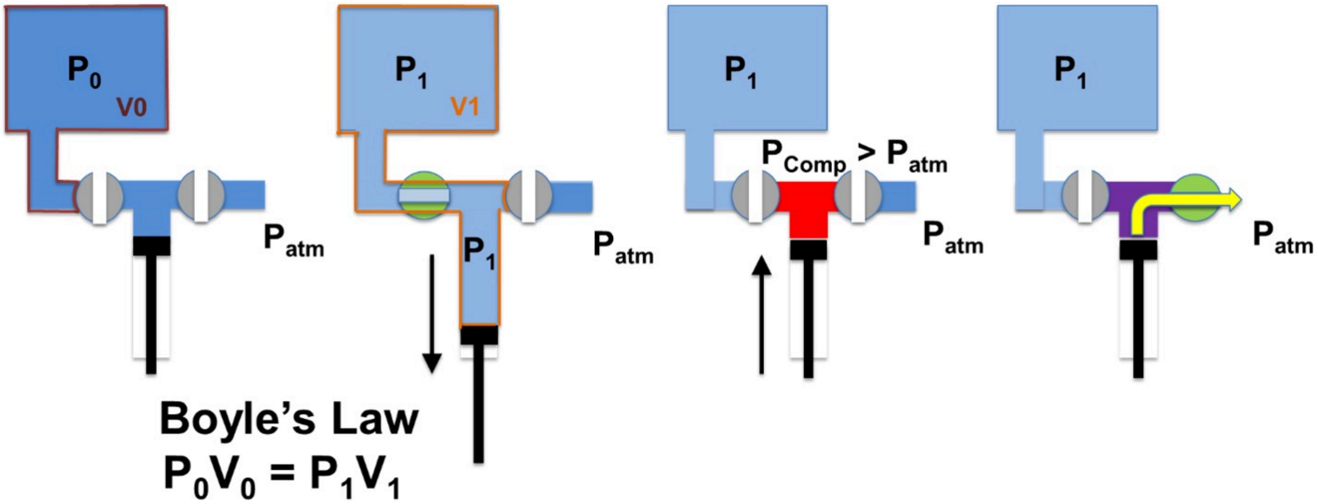

Figure 4.3. Positive displacement pump cycle.
Diagram provided by Nancy Louwagie, Normandale Community College.

## Example 4.1

To illustrate this process, consider the system shown in Figure 4.4. A ***piston-type pump*** is connected to a 10-liter chamber. A pressure gauge and a vent valve are attached to the chamber. The volume within the piston pump is 1-liter. What will the chamber pressure be after five strokes of the piston pump?

**Solution:**

Initially, the chamber pressure is nominally at 1 atm, or 760 Torr. The piston pump is pushed in so that the interior volume of the pump is zero. The pressure gauge displays a pressure reading of 760 Torr.

We will apply Boyle's law to determine what happens to the chamber pressure, one stroke of the piston pump at a time.

**Stroke 1.** When the piston and handle of the pump is drawn back, the pump's exhaust valve is closed, and the inlet valve of the pump is opened allowing gas from the chamber to flow into the pump. This essentially expands the chamber volume to 11 liters (10-liters in the chamber plus 1-liter in the pump). By applying Boyle's law, we calculate the pressure in the chamber according to:

$$P_{after\,1\,stroke} \times V_{after\,1\,stroke} = P_{initial} \times V_{initial}$$

Where,

$$\begin{aligned} P_{initial} &= 760\,Torr \\ V_{initial} &= 10\,liters\,in\,the\,chamber \\ V_{after\,1\,stroke} &= 10\,liters\,in\,the\,chamber + 1\,liter\,in\,the\,piston = 11\,liters \end{aligned}$$

Hence,

$$\begin{aligned} P_{after\,1\,stroke} &= \frac{10\,liters}{11\,liters}(760\,Torr) \\ P_{after\,1\,stroke} &= 690.0\,Torr \end{aligned}$$

When the piston is pushed forward, the pump's inlet valve closes, and the pump's outlet valve opens. The gas within the pump is compressed and expelled to atmosphere. When the handle returns to its original position, the volume within the pump is again zero. The first stroke cycle is complete, and fewer gas molecules remain in the chamber volume.

**Stroke 2.** When the piston is drawn back out again, the outlet valve closes, and the inlet valve opens so the system volume again expands by an additional 1-liter to a total volume

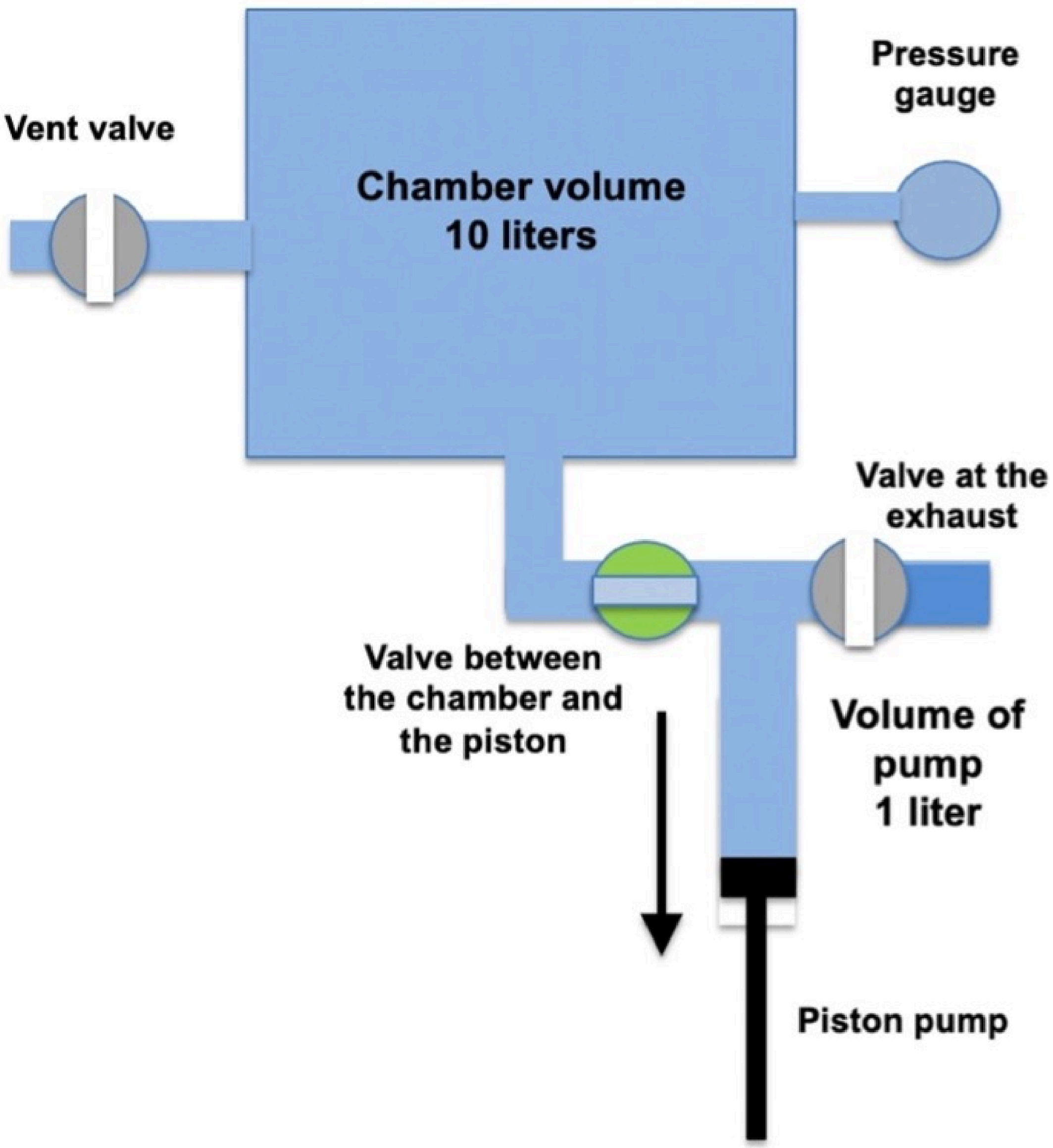

Figure 4.4. A 1-liter piston pump connected to a 10-liter chamber. Diagram provided by Nancy Louwagie, Normandale Community College.

of 11-liters. The gas flows from the chamber into the pump volume and the pressure decreases. Again, we apply Boyle's law to determine the new pressure level using *P (after 1 stroke)* as the initial pressure. The *P (after 2 strokes)* is calculated by:

$$\begin{aligned} P_{after\,2\,strokes} &= \frac{10\,liters}{11\,liters}(690.9\,Torr) \\ P_{after\,2\,strokes} &= 628.1\,Torr \end{aligned}$$

As before, the liter of gas in the pump is isolated. Then, as the piston is returned to its original position, the trapped gas in the pump is compressed and exhausted from the pump. The second stroke cycle is complete, and even fewer gas molecules remain in the chamber.

**Stroke 3.** When the piston is drawn back a third time, the gas volume again expands to 11-liters. The new pressure is:

$$\begin{aligned} P_{after\,3\,strokes} &= \frac{10\,liters}{11\,liters}(628.1\,Torr) \\ P_{after\,3\,strokes} &= 571.0\,Torr \end{aligned}$$

Again, the gas cycle (isolation, compression, and exhaust) is repeated. The third stroke cycle is complete.

**Stroke 4.** When the piston is drawn back a fourth time, the gas volume again expands to 11-liters. The new pressure is:

$$\begin{aligned} P_{after\,4\,strokes} &= \frac{10\,liters}{11\,liters}(571.0\,Torr) \\ P_{after\,4\,strokes} &= 519.1\,Torr \end{aligned}$$

The fourth stroke cycle is complete.

**Stroke 5.** Again, the piston is drawn back a fifth time, expanding the gas volume. The new pressure is:

$$\begin{aligned} P_{after\,5\,strokes} &= \frac{10\,liters}{11\,liters}(519.1\,Torr) \\ P_{after\,5\,strokes} &= 471.9\,Torr \end{aligned}$$

And finally, the liter of gas in the pump is again isolated, compressed, and exhausted. The fifth stroke cycle is complete. Hence, the pressure in the chamber after five strokes of the piston pump is approximately 472 Torr. See the animation below that takes you through this process step-by-step.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-1*

Animation 4.1. Piston Pump Example. Animation provided by Elena Brewer, SUNY Erie Community College.

If this example is continued for twenty strokes and a pressure versus strokes graph is plotted, a graph as shown in Figure 4.5 would be obtained. The graph shows an exponential decrease in pressure. This graph is called a ***pump-down curve***. The curve shown in Figure 4.5 asymptotically approaches zero pressure as the number of strokes increases. In practice, it is not possible to achieve ***absolute zero*** pressure. The positive displacement pump has a pressure limit below which the Boyle's law model does not apply due to change in the gas flow characteristics. The actual lowest pressure achieved by a positive displacement pump is called its *ultimate pressure*.

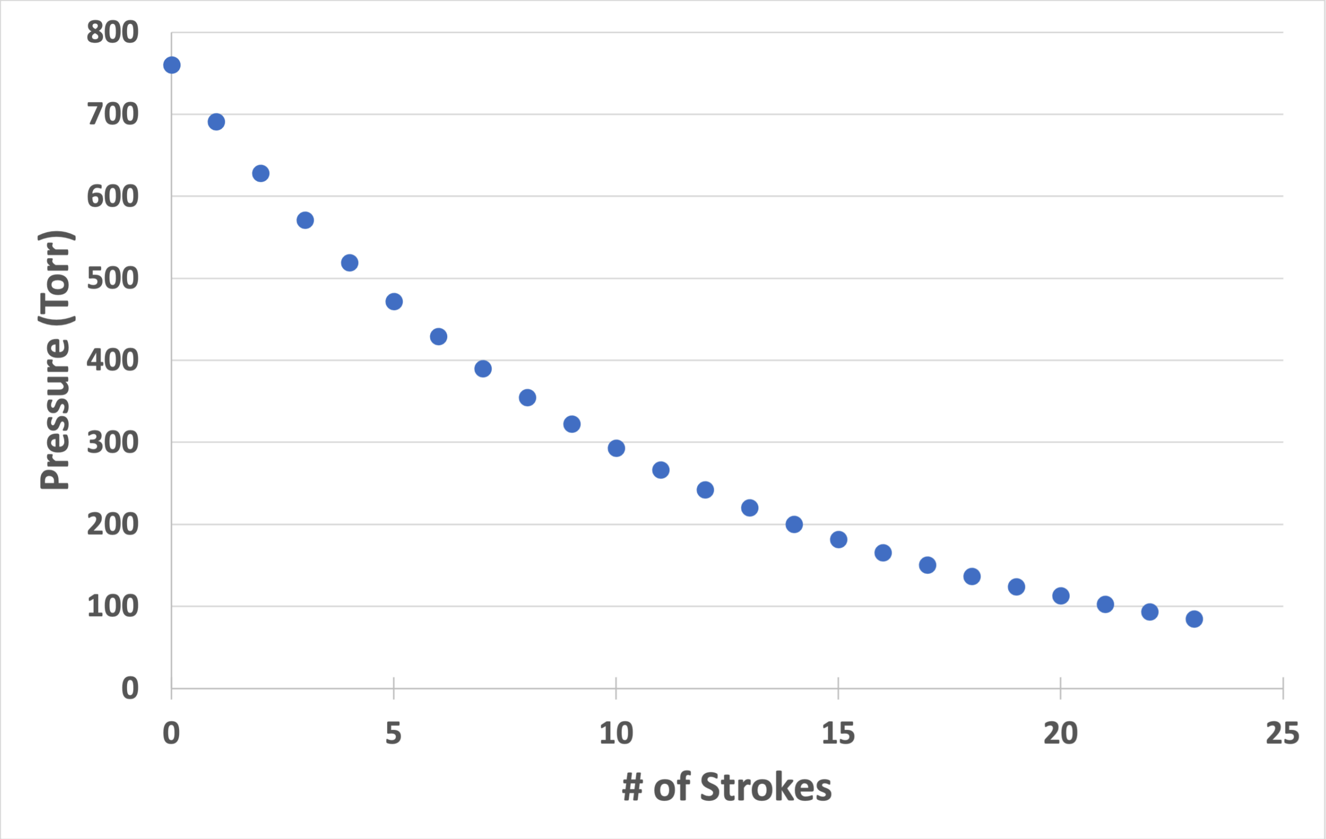

Figure 4.5. Sample piston pump pump-down curve. Graph provided by Elena Brewer, SUNY Erie Community College.

All positive displacement vacuum pumps use this expansion, isolation, compression, and exhaust cycle to move gas from the pump's inlet to the pump's outlet. Let us examine the pumping action of four types of rough vacuum pumps: diaphragm pumps, scroll pumps, rotary vane pumps, and Roots pumps.

## 4.4.1 Diaphragm Pumps

***Diaphragm pumps*** are one of the basic types of positive displacement pumps. They are simple in design, reliable and relatively low-cost.

When we breathe, our lungs behave like a diaphragm pump. As the diaphragm at the bottom of the chest cavity is pulled down, expanding the volume of the chest cavity, air flows into our lungs. When the diaphragm is pushed up, the volume of the chest cavity decreases, the air in our lungs is compressed, and we exhale. We repeat this pumping cycle over and over again throughout our life.

Figure 4.6 shows the pumping mechanism for a diaphragm pump and the corresponding flow of gas through the pump. A diaphragm made of a flexible material forms one wall of a small chamber. The flexible diaphragm is attached to a piston, which is attached to an eccentric cam driven by an electric motor. As the cam rotates, the piston rod moves up and down which acts to push and pull on the flexible diaphragm. When the diaphragm is pulled down, the volume within the pump's small chamber increases. When the diaphragm is pushed upward, this volume decreases. Animation 4.2 shows the flow of gas through the pump during each pumping cycle.

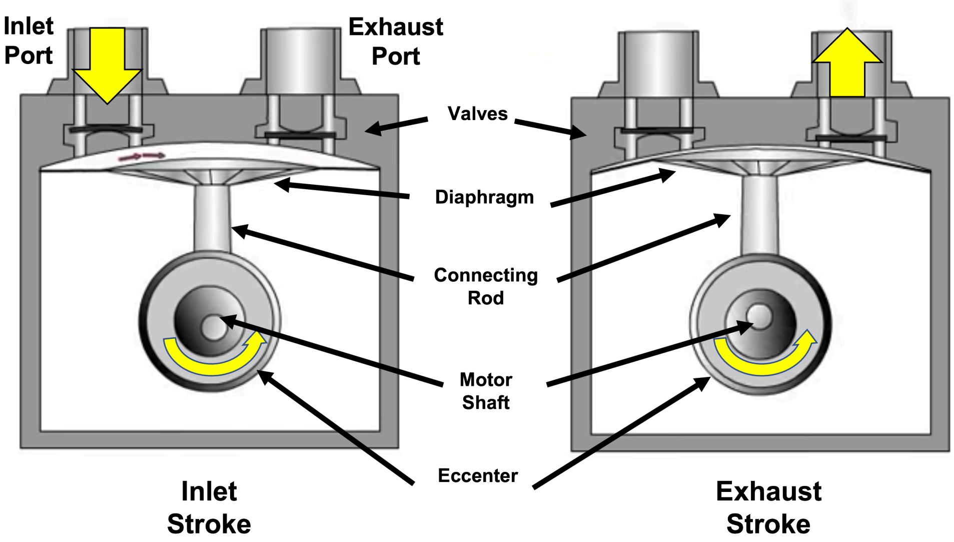

Figure 4.6. Pumping mechanism of a diaphragm pump. Graphics provided by MATEC, edited by E. Brewer.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-2*

Animation 4.2. Diaphragm Pump Example. Animation provided by MATEC.

The pumping cycle consists of two phases. During the gas capture phase of operation, the cam rotates, and the piston rod is pulled down. The piston pulls on the diaphragm, the diaphragm stretches which causes the volume within the pump chamber to increase. As the volume within the pump increases, the corresponding pressure in that space decreases. This causes the inlet valve to open, and gas from the chamber flows through the inlet port and into this expanded space within the pump. The second phase begins when the rotation of the cam causes the piston rod to change direction and begin moving upward. This upward motion of the piston pushes the diaphragm up and reduces the volume of the small chamber. The trapped gas gets compressed, and the pressure in the small chamber increases. This causes the inlet valve to close and the exhaust port to open, and the gas is expelled from the chamber. This completes one pumping cycle.

A single stage diaphragm pump is capable of reducing the pressure level to approximately 50 Torr. The lowest pressure a vacuum pump can achieve is defined as its ultimate pressure. Diaphragm pumps may be made with multiple chambers to improve pumping performance. Up to four chambers can be combined in a single pump. A four-stage pump can achieve an ultimate pump pressure of approximately 0.5 Torr. Pumping speeds range from 10 to 60 liters per minute. Most diaphragm pumps operate at either 120 V / 60 Hz or 220 V / 50 Hz.

Diaphragm pumps are best suited for applications that do not require removal of large volumes of gas. One significant functional advantage to using diaphragm pumps is that they are a type of ***dry pump***. A dry pump does not use oil to create airtight seals during operation. Use of dry pumps eliminates back streaming of oil vapor as a gas load source in a vacuum system. Diaphragm pumps are commonly utilized in small analytical systems or as the ***backing pump*** for a turbo pump. These systems are used in clean operating environments. Another important consideration in vacuum pump selection is the cost of the pump. Diaphragm pumps tend to be relatively inexpensive compared to other positive displacement pumps. Diaphragm pumps are also attractive because they are ambient air-cooled, rather than water-cooled.

Maintenance tasks associated with a diaphragm pump are easy to perform. The diaphragm should be replaced routinely to maintain optimal pump performance. Generally, the replacement period for a diaphragm is after every 10,000 hours of operation. Replacing the diaphragm is not difficult. Sub-components associated with the pump's inlet and outlet valves, like gaskets, may also need to be replaced. If the diaphragm pump starts exhibiting an increase in its ultimate pressure, the condition of the diaphragm and possibly the valve components should be checked and/or replaced.

Drawbacks to using diaphragm pumps are their inherently low pumping speed and high ultimate pressure. Because of these two limitations, diaphragm pumps are not used as the primary roughing pump in large-scale manufacturing applications.

Diaphragm Pump Key Takeaways:

| Diaphragm Pump Advantages | Diaphragm Pump Limitations |
|---|---|
| • Dry: no backstreaming oil<br>• Reliable<br>• Low noise level<br>• Cost-effective<br>• Simple design and maintenance | • Low pumping speed (0.2-2.8 liters/sec) that decreases uniformly with pressure drop<br>• High ultimate pressure (0.5 – 50 Torr)<br>• Should not be used to pump abrasive/corrosive gases<br>• Should not be used to pump condensable gases/vapors<br>• Frequent maintenance (diaphragm replacement) |

## 4.4.2 Scroll Pumps

Another type of positive displacement pump is a ***scroll pump***. The scroll pump, like the diaphragm pump, is a type of dry pump. Oil-free scroll pumps like the one shown in Figure 4.7 provide clean operating environments with no sealant or lubricant required in the vacuum-exposed region. They are ambient air-cooled and do not require cooling water. Scroll pumps are capable of much higher pumping speeds than diaphragm pumps and can achieve a lower ultimate pressure. Scroll pumps are used extensively in systems that support manufacturing processes conducted in very clean environments like semiconductor manufacturing.

Scroll pumps use two scrolls, or plates, shaped into a spiral called an involute curve. The two scrolls fit inside one another. The edge of the scroll is covered by a tip seal. One scroll is fixed in place and remains stationary during operation. The other scroll moves with an orbital motion around the stationary scroll. The scroll pump design does not include an inlet valve component like the diaphragm pump design. Instead, the orbiting motion of the movable scroll continually traps pockets of gas and compresses each pocket to the point at which the gas is expelled from the pump.

The motion of the scroll pump creates a crescent shaped volume that repeatedly opens to the vacuum system and serves to expand the system volume. The pressure in the vacuum chamber decreases as the gas flows out of the chamber through the system and into the pump. After gas flows into the crescent shaped pocket, the one scroll plate continues its orbital motion, and the gas pocket seals (see Figure 4.8 and Animation 4.3). The crescent shaped pocket shrinks as the movable scroll continues in

Figure 4.7. Scroll pump. Photo provided by Kurt J. Lesker Company, https://www.lesker.com.

its orbital trajectory, and the trapped gas is compressed. The trapped gas moves along the scroll toward the center of the scroll. When the pocket of gas reaches the center, it is expelled through the pump's outlet. The sequence of gas capture, gas compression, and gas exhaust is performed over and over again as the movable scroll moves in this orbital trajectory.

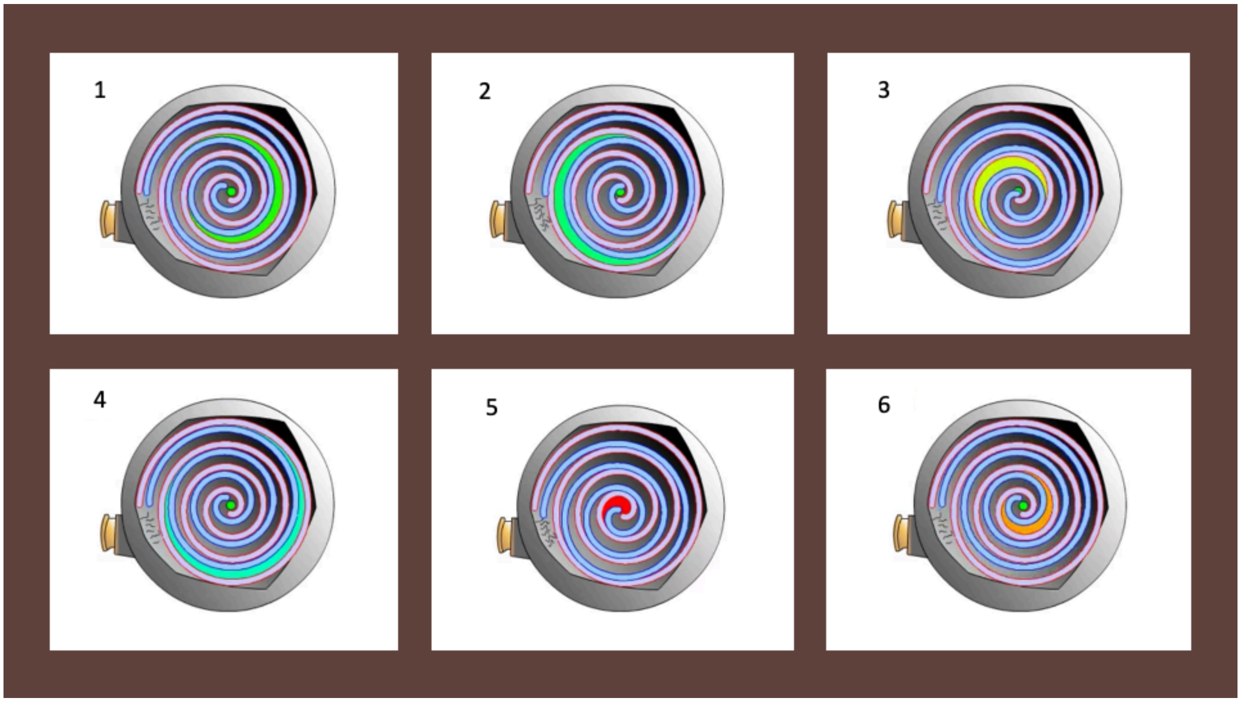

Figure 4.8. Pumping mechanism of a scroll pump. Graphics provided by MATEC, edited by E. Brewer.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-3*

Animation 4.3. Dry Scroll Pump Mechanism Animation. Animation provided by MATEC.

Scroll pumps offer several functional advantages. Scroll pumps are dry, have high pumping speeds, and achieve low ultimate pressures. Using a scroll pump eliminates the risk of oil contamination and the need for oil traps and eliminators. Pumping speeds range from 300 to 600 liters per minute. Scroll pumps can reach ultimate pressures from 0.01 ($10^{-2}$) Torr to 0.001 ($10^{-3}$) Torr. Scroll pumps can also be configured for either single-phase or three-phase operation at 50 Hz or 60 Hz.

Routine maintenance tasks associated with a scroll pump are relatively easy to perform. The tip seal should be replaced regularly to maintain optimal pump performance. Service intervals are specified by the vendor and often are around 10,000 hours of continuous operation. The process of replacing the tip seal is not difficult. If the scroll pump starts exhibiting an increase in its ultimate pressure during operation, the tip seal should be replaced. The tip seal should also be replaced if the pump emits excessive particulate during operation. However, if a scroll pump is emitting excessive amounts of particulate, this may be an indication that a scroll pump is not suitable for the process being run or there is a problem with the underlying process.

Scroll pumps are intended for use in clean environments to support clean, dry processes. Any particulate or liquid state matter present in the gas load can damage the scroll pump. A gas ballast may be included on a scroll pump to help prevent certain vapors from condensing as they are compressed by the pump. The ballast function will be explained in more detail in the section addressing the rotary vane pump. A drawback to scroll pumps is that the pump itself can be the source of particle generation as the tip seal wears out. Scroll pumps as an initial investment are also moderately expensive compared to some other rough pump types.

Scroll Pump Key Takeaways:

| **Scroll Pump Advantages** | **Scroll Pump Limitations** |
|---|---|
| • Very high pumping speeds (300 – 600 liters/min)<br>• Low ultimate pressure (~$1\times10^{-2}$ Torr)<br>• Can pump from atmospheric pressure<br>• Dry: no backstreaming oil<br>• Reliable<br>• Low noise level (except for the first few seconds)<br>• Simple design and maintenance | • Should not be used to pump abrasive/corrosive gases<br>• Should not be used to pump condensable gases/vapors and particulates<br>• More expensive than rotary vane and diaphragm pumps<br>• Pump can be a source of particulates generation |

## 4.4.3 Rotary Vane Pumps

One of the very first mechanical vacuum pumps was a piston type as described in Section 4.4. A successor to the piston pump was a mechanical, mercury-sealed rotary pump. Today the ***rotary vane pump*** is one of the most commonly used vacuum pumps. A rotary vane pump is shown in Figure 4.9. The rotary vane pump works on the same principle as the diaphragm pump and the scroll pump. As the pump cycles, volumes of gas are repeatedly expanded, trapped, and expelled. The pressure in a chamber connected to the pump decreases over successive cycles of pump operation. Unlike the diaphragm pump and scroll pump, the function of the rotary vane pump requires the use of oil. The oil serves important functions in rotary vane pump operation. First, oil lubricates moving parts in the pump to reduce frictional wear. Second, the oil equilibrates and dissipates heat generated during the pump's operation. And finally, the oil makes a seal which traps each volume of gas that is subsequently compressed and expelled.

The pumping mechanism in a rotary vane pump is enclosed by a stator as shown in Figure 4.10 (a). Inside the stator is an offset rotor that is mechanically coupled to a drive motor. The drive motor turns the offset rotor that contains spring-loaded vanes. A small amount of oil in Figure 4.10 (b) forms the seal between the end of the sliding vanes and the inner surface of the stator. As the rotor turns, a sealed space within the pump is created.

Let's examine the operation of a rotary vane pump in more detail. Again, a cross-sectional view of

Figure 4.9. Rotary vane pump. Photo provided by Kurt J. Lesker Company, https://www.lesker.com.

a rotary vane pump is shown in Figure 4.10(a). As the sliding vane passes by the opening to the inlet port, gas molecules begin to flow into the space behind the sliding vane. As the space behind the sliding vane increases, more gas molecules flow into this space. Eventually, the other end of the vane passes the inlet opening and seals off the volume of gas molecules that have moved into the pump.

As the rotor continues to rotate, the trapped volume of gas is gradually compressed and the pressure of the trapped gas increases. The compressed gas is then opened to the exhaust port. If the pressure of the trapped gas is greater than the pressure on the other side of the discharge valve, the discharge valve opens, the trapped gas escapes into the ***exhaust line*** and exits through the exhaust port. This process repeats twice for each rotation of the sliding vane if a two-vane pump is used as shown in Figure 4.10 (c). However, if the pressure of the trapped gas is insufficient to open the gas discharge valve, then the gas stays in the pump and no gas is exhausted from the pump. Figure 4.10(c) shows snapshots in time illustrating the movement of gas through the pump.

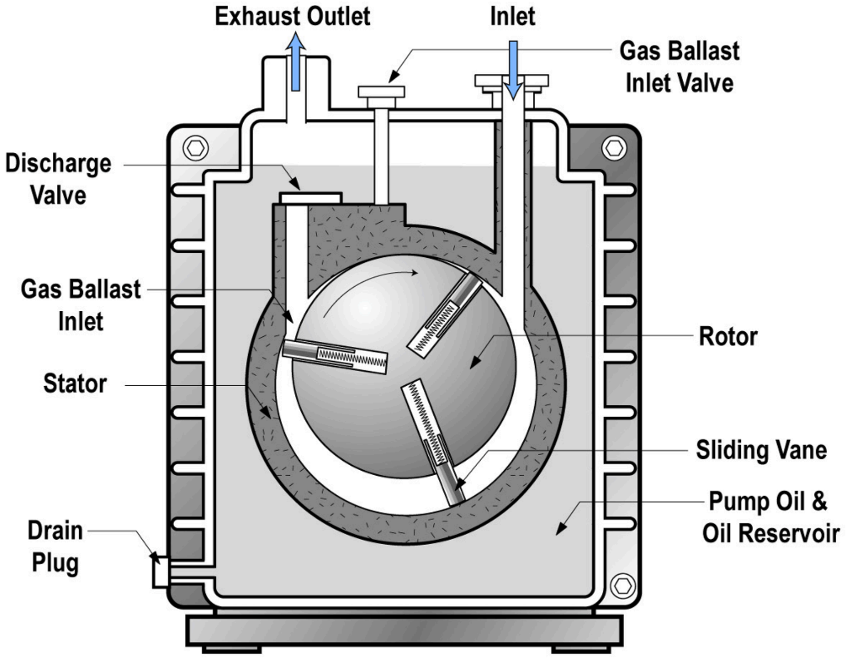

Figure 4.10 (a). Cross-section of a rotary vane pump. Graphics is used with permission of Maricopa Advanced Technology Education Center (MATEC).

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Animation 4.4. Rotary vane pump. Animation used with permission of MATEC.

If the discharge valve does not open, there is a risk of vapor ***condensation*** and contamination of the pump oil. If the oil becomes contaminated with water or other impurities, these contaminants will increase the vapor pressure and make it impossible, or at least more difficult, to reach satisfactory base pressures.

A gas ballast feature is often used to ensure that the discharge valve opens during every cycle. The ballast valve opens during each cycle, allowing a quantity of air, or an inert gas, to be admitted during the compression cycle. This extra gas ensures that the pressure of the compressed gas is great enough to open the discharge valve, allowing condensable vapors to exit the pump before they condense inside the pump. Without the extra gas admitted through the gas ballast mechanism, some of the vapors present will condense inside the pump if the gas reaches its ***saturation vapor pressure*** during the compression phase. The downside of the ballast function is an increase in the ultimate pressure of the pump.

When oil-sealed ***mechanical pumps*** are operated at low pressures, they tend to backstream oil vapor back into the roughing line and process chamber. This may affect the process being run. Oil

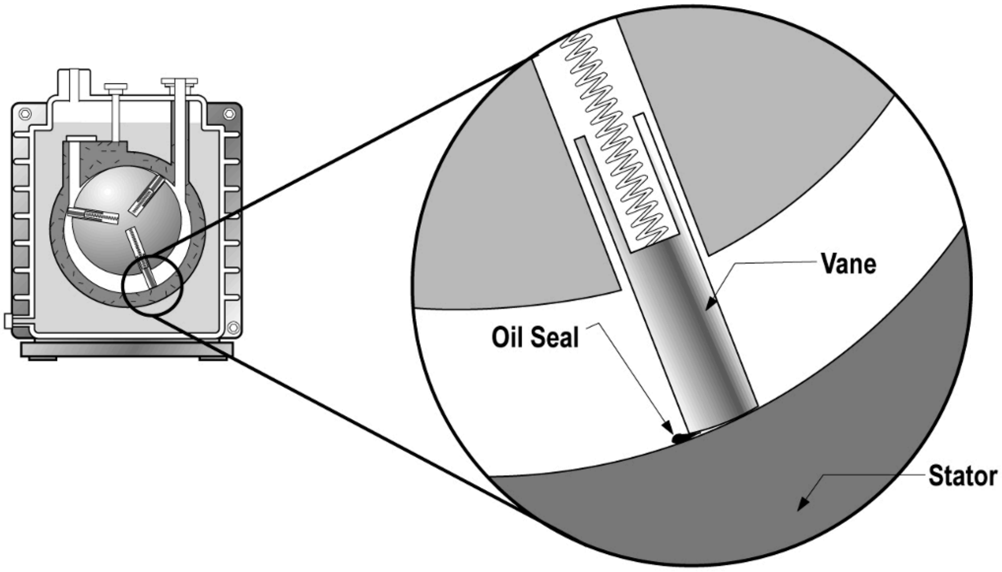

Figure 4.10 (b). Low-vapor pressure oil acting as a sealing medium. Graphics is used with permission of Maricopa Advanced Technology Education Center (MATEC).

migration can be controlled by inserting traps, such as molecular sieve traps, in the roughing line. Another solution is to use oil-free mechanical pumps, such as diaphragm pumps and scroll pumps.

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Animation 4.5. Rotary vane vacuum pumps. Animation is used with permission of Busch Vacuum Solutions, www.buschusa.com.

Rotary vane pumps are very popular pumps and used in many applications. This type of rough vacuum pump offers several functional advantages. Rotary vane pumps can achieve high pumping speeds and low ultimate pressures, are relatively easy to use, and if maintained properly, are rugged and durable. These pumps come in a variety of sizes and support different levels of pumping capabilities. They also come in a wide range of pumping speeds spanning from approximately 10 liters per minute up to 20,000 liters per minute. Rotary vane pumps can reach ultimate pressures as low as 0.001 ($10^{-3}$) Torr without a ballast. When the gas ballast is used, a rotary vane pump's ultimate pressure increases by approximately a factor of 10. Rotary vane pumps are available as one-stage or two-stage pumps. Some two-stage pumps are capable of higher pumping

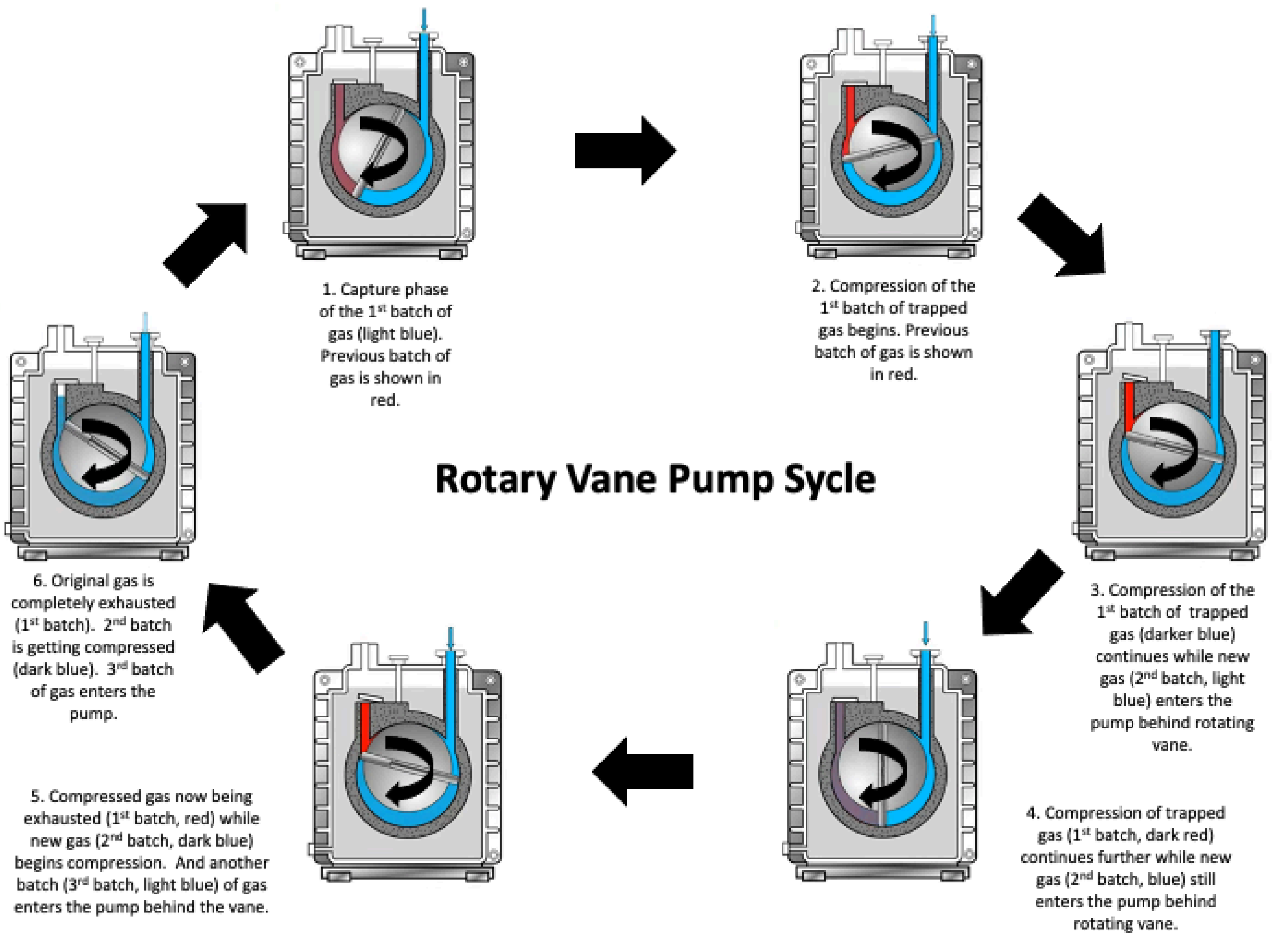

Figure 4.10 (c). Pumping sequence of a rotary vane pump. Graphics is used with permission of Maricopa Advanced Technology Education Center (MATEC), adapted by E. Brewer.

speeds and lower ultimate pressures than one-stage pumps. These pumps can be selected for either 120 VAC / 60 Hz or 220 VAC / 50 Hz operation.

It is important to maintain a rotary vane pump properly to ensure its optimum performance. Maintenance tasks associated with a rotary vane pump are relatively easy to perform. The pump's oil should be inspected routinely and changed regularly. It is important to use the right type of oil with this pump. The oil used with a rotary vane pump should have a low vapor pressure, for example, as low as 0.075 milliTorr at room temperature. If the oil looks like it is chemically reacting (often with water) such that it is acquiring a milky green appearance, it should be changed immediately. Other mechanical parts and accessories like the springs, blades, rotor, stator, valves, seals, filters, and traps on the pump can be replaced if they malfunction or wear out.

Rotary vane pumps are versatile and used in a variety of manufacturing environments. These pumps, when maintained properly, provide dependable performance for a long time. The major drawback to rotary vane pumps is the presence of the oil which can vaporize and cause problems for certain processes. Rotary vane pumps are typically the least expensive of the rough pump options, but the price of this pump can vary greatly. The low vapor pressure oil used with these pumps can be expensive. This represents an on-going operating expense that needs to be considered when selecting this type of pump.

Rotary Vane Pump Key Takeaways:

| **Rotary Vane Pump Advantages** | **Rotary Vane Pump Limitations** |
|---|---|
| • High pumping speeds (300 liters/sec)<br>• Low ultimate pressure ($\sim 1\times10^{-2}$ Torr for one-stage pumps, $\sim 1\times10^{-3}$ Torr for two-stage pumps)<br>• Can pump from atmospheric pressure<br>• Reliable<br>• Low cost (some are <$1,000) | • Oil used as lubricant, coolant, and gas sealant for vanes: oil backstreaming<br>• High noise level and low frequency vibration<br>• Should not be used to pump abrasive/corrosive gases<br>• Should not be used to pump condensable gases/vapors and particulates<br>• Frequent maintenance: changing and disposing of pump oil |

## 4.4.4 Roots Vacuum Pumps

One rough vacuum pump that operates differently from the pumps previously described is the mechanical booster pump. This positive displacement pump is better known as a ***lobe blower*** or the ***Roots pump***. Like previous rough pumps, a volume within the Roots pump expands allowing gas molecules from the chamber to move into the pump, the pump's motion traps the gas molecules and transfers the gas to the pump's exhaust. The Roots pump differs from the previous pumps because this pump does not include valves at its inlet and outlet. The Roots pump functions to transport gas molecules from the inlet to the outlet very rapidly.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: [https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-6](https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-6)*

Animation 4.6. Roots blower vacuum pump. Animation provided by Gigi Bocek.

The Roots pump accomplishes the pumping function through the rotation of a meshed lobed rotor mechanism with impellers mounted on parallel shafts and rotating in opposite directions. Figure 4.11 shows a cross-section of a mechanical booster pump with two-lobe rotors. The arrows show the direction of rotation by the rotors and the resulting flow of the gas molecules within the pump. The rotors do not touch each other as they rotate, nor do they make contact with the surrounding walls (stator). The clearances between the rotor faces and other surfaces are generally less than 0.5 mm. The rotors spin at speeds between 1,400 and 4,000 revolutions per minute. The high rotational speeds are possible because the speed of the lobes is not reduced by friction with the stator.

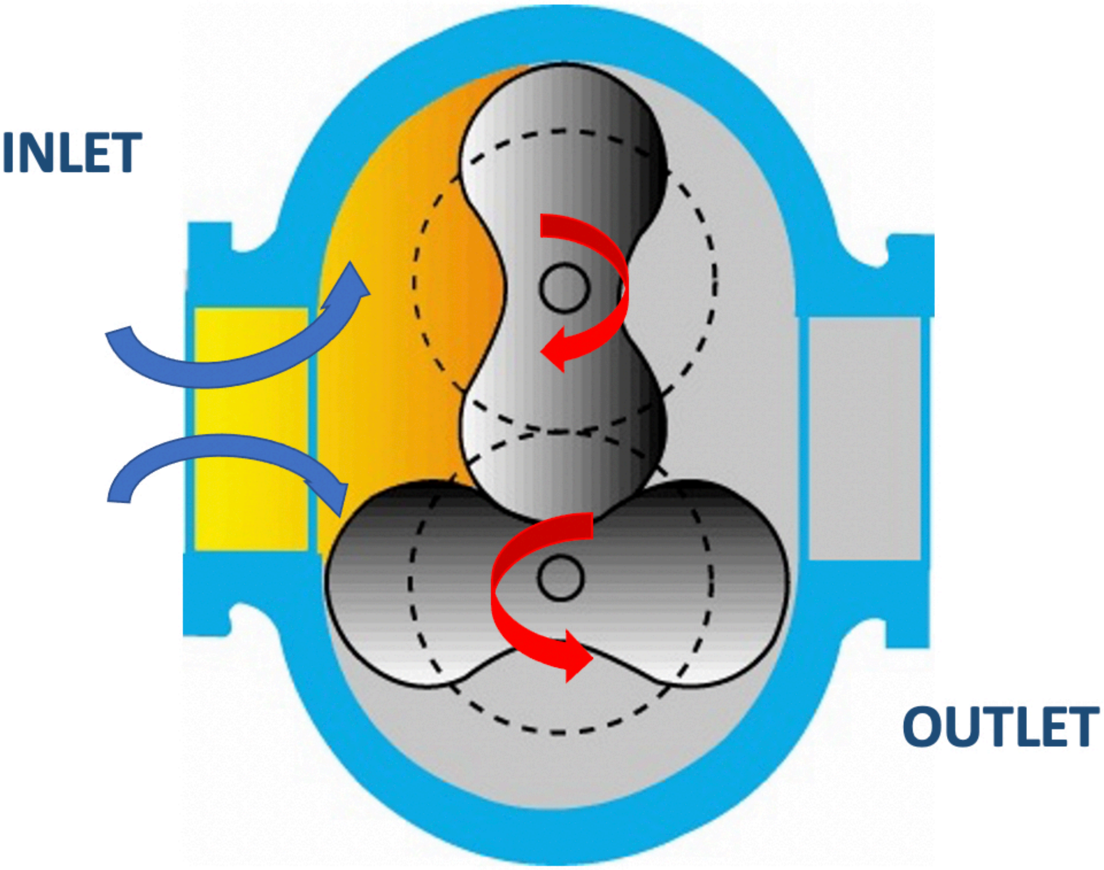

Figure 4.11. Roots vacuum pump cross-section. Figure provided by Kurt J. Lesker Company, [https://www.lesker.com](https://www.lesker.com).

The Roots pump is frequently operated in combination with another type of positive displacement pump. Since the rotor faces within a Roots pump do not completely seal during their pumping motion, gas molecules from a single-stage Roots blower can easily leak from the pump outlet back toward the chamber. The result is that a Roots pump operating by itself achieves a very low pumping speed when it exhausts the trapped gas to atmosphere.

A Roots pump rapidly passes the gas through the pump without compressing the gas appreciably. Therefore, a single Roots pump cannot exhaust directly to atmosphere. The outlet of a Roots pump is connected to the inlet of another positive displacement pump which serves as a backing pump. The backing pump compresses and exhausts the gases to atmosphere. In some systems, the Roots pump is not energized as the system starts pumping down from atmosphere. Instead, the backing pump does the initial work to start the pump-down process from atmosphere. During the initial stage of the pump-down process, the Roots pump impellers rotate freely allowing gas to flow through the Roots pump. When the inlet pressure to the backing pump reaches a pressure of approximately one to ten Torr, the Roots pump is energized so the impellers become actively driven. After this point in the system pump-down process, the Roots pump will increasingly function to enhance the pumping speed of the system as the system continues to pump down through the pressure range of one Torr to $1 \times 10^{-3}$ Torr.

The Roots pump is susceptible to generating high levels of heat. As stated previously, the Roots pump design does not function to support high compression ratios. Attempting to operate the Roots pump starting at atmosphere can overload the pump motor and cause the pump to overheat. The backwards movement of molecules through the Roots pump, especially smaller molecules like hydrogen and helium, compounds the heat generation problem.

Making a few careful considerations in the design and operation of a vacuum system with a Roots pump will help to avoid excessive heat generation by the Roots pump. It is important to pair a Roots pump with an appropriate backing pump. The pumping speed of the Roots pump should be limited to no more than a factor of two to eight times greater than the pumping speed of the backing pump. During its operation, the pressure difference between the outlet of the Roots pump and its inlet should not exceed the manufacturer-specified limit. Some Roots pumps are designed with a bypass line and relief valve that help to limit the pressure difference between the outlet and the inlet of the pump. Other Roots pump models include gas coolers in their design that allow the pump to tolerate larger pressure differences between the outlet and the inlet during operation. And some Roots pump models automatically slow down at high pressures to avoid generating excessive heat or overloading the motor.

Since Roots pumps are effective at pumping on large volumes and achieving low system base pressures, they are used in a variety of manufacturing and research environments. Roots pumps in combination with an appropriate backing pump achieve the highest pumping speeds through the medium vacuum range at up to 50,000 liters per minute. Vacuum systems with a Roots pump can achieve ultimate pressures below one milliTorr. Compared to other positive displacement pumps, the Roots pump is typically more expensive due to the complexity of the pump design. Multi-stage Roots pumps models are also available. Like the other positive displacement type pumps, Roots pumps can be selected for either 120 VAC / 60 Hz or 220 VAC / 50 Hz operation.

When properly operated and maintained, these pumps are very durable and provide dependable performance for long periods of time. The Roots pump, like the diaphragm and scroll pump, is a type of dry pump that can help limit backstreaming from an oil-sealed rotary vane pump. Although oil is used to lubricate the gears and bearings in a Roots pump, no oil is present in the gas flow space. It is important to maintain an oil fill level in the pump that properly lubricates the inner gear teeth that drive the impellers. Lubricants and oils should provide the right level of viscosity over the range of pump operating temperature.

Roots Pump Key Takeaways:

| **Roots Pump Advantages** | **Roots Pump Limitations** |
|---|---|
| • Very high pumping speeds (up to 50,000 liters/min)<br>• Low ultimate pressure (~$1 \times 10^{-4}$ Torr with $10^{-3}$ Torr backing pump)<br>• Dry: no backstreaming oil<br>• Reliable<br>• Can be used to pump abrasive/corrosive gases and some particulates<br>• Minimal maintenance – maintain oil level for gear teeth | • Does not start from atmospheric pressure. Operating pressure range is 20 Torr – $10^{-4}$ Torr<br>• Should not be used to pump condensable gases/vapors<br>• Expensive<br>• Usually requires backing pump<br>• Generates high level of heat and requires cooling |

## 4.4.5 Other Rough Vacuum Pumps

There are other types of commonly used rough vacuum pumps. These pumps include ***rotary piston pumps***, ***claw pumps***, and ***screw pumps***. Each pump implements the gas capture, compression, and gas exhaust cycles using different geometries. A very brief description for each of these pumps is provided in this section. See the references for additional information about the design and operation of each of these pumps.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-7*

Animation 4.7. Dry claw vacuum pump. Animation used with permission of Busch Vacuum Solutions, www.buschusa.com.

Rotary piston pumps are similar to rotary vane pumps. The eccentric cam drives a piston that draws a volume of gas into the pump, isolates the volume, compresses it, and exhausts it. Pumps of this kind are typically used as roughing pumps on large vacuum systems either alone or in combination with a Roots pump. They are rugged and mechanically simple, providing high pumping speeds.

Claw pumps use two claws rotating in opposite directions, like the Roots pump, to capture, compress, and exhaust the gas. Claw pumps can be used to effectively pump corrosive and abrasive gases. They are often combined with Roots pumps to achieve high pumping speeds and pressures in the millitorr range.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-8*

Animation 4.8. Dry screw vacuum pump. Animation used with permission of Busch Vacuum Solutions, www.buschusa.com.

Screw pumps are also used to pump corrosive and abrasive gases. These pumps find application in backing turbomolecular pumps in reactive-ion etching and chemical vapor deposition systems. The screw pump uses a pair of large rotating screws to move the gas from the inlet end of the pump to the exhaust end. Like claw pumps, screw pumps have high pumping speeds and ultimate pressures in the millitorr range.

Table 4.1 summarizes vacuum pumps that were discussed in Section 4.5 and compares their main characteristics: pumping speed, ultimate pressure, backstreaming oil, reliability, noise/vibration level, ability to handle corrosive/abrasive gases and condensable gases/vapors, and cost.

Table 4.1. Rough vacuum pumps summary.

| Characteristics: | Diaphragm Pump | Scroll Pump | Rotary Vane Pump | Roots Pump |
|---|---|---|---|---|
| **Typical Pumping Speeds (liters/min)** | **12 – 167** | **300 – 600** | **17 – 16,000+** | **Up to 50,000** |
| **Typical Ultimate Pressure (Torr)** | **1 -38** | **$10^{-2} – 10^{-3}$** | **$10^{-1} – 10^{-3}$** | **$10^{-2} – 10^{-4}$** |
| **Dry vs Wet** | **Dry** | **Dry** | **Wet** | **Dry** |
| **Oil Backstreaming** | **No** | **No** | **Yes** | **Possible – Use Dependent** |
| **Typical Noise Level (dB(A))** | **50 – 55** | **47 – 65** | **48 – 80** | **Various** |
| **Can be used to pump abrasive and corrosive gases** | **Somewhat – With Care** | **Somewhat – With Care** | **Somewhat – With Care** | **Somewhat – With Care** |
| **Can be used to pump condensable gases/vapors** | **No** | **No** | **No** | **No** |
| **Cost** | **Low** | **High** | **Low** | **High** |

Section 4.4 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#h5p-20*

## 4.5 Rough Vacuum Gauges

The vacuum pump functions to create the lower pressure condition within a system and specifically within the vacuum chamber. A vacuum gauge measures the level of vacuum present in the vacuum chamber and at other points in the system. Measurements of pressure help us understand and respond to a vacuum system's performance. There are different types of vacuum gauges available to measure pressure. Each type of gauge has certain features that are useful in a working vacuum system. Each gauge also presents with some limitations for its use. It is important to understand how the different types of gauges function in order to appropriately utilize the measurement data they generate.

As we discussed in Chapter 3, vacuum gauges are classified as either direct reading or indirect reading. ***Direct reading vacuum gauges*** measure pressure in the rough vacuum regime. This gauge type measures pressure based on the force exerted by the gas on an area. At pressures between atmosphere down to $1\times10^{-3}$ Torr, the molecular density of the gas is high enough to exert forces that can be detected mechanically. On the other hand, ***indirect reading vacuum gauges*** infer the pressure based on measuring another property of the gas that changes predictably as the gas density changes. Vacuum gauges that measure pressure based on heat transfer principles also provide a reliable indication of rough vacuum pressures. At pressures below $1\times10^{-4}$ Torr, other indirect measurement techniques are required.

How well will the vacuum gauge measure the pressure in the chamber? This question is a very important one to consider. All measurement devices are inaccurate to some extent. The accuracy of a measurement device is determined by the device's capability to display a reading that falls within a band defined as an upper limit and lower limit of what is thought to be the true value. The closer the upper limit and lower limit values are to one another, the more accurate the measurement. Vacuum gauges can often be calibrated by the manufacturer or the user to improve their accuracy.

The following sections will describe the behavior of four types of rough vacuum gauge technologies: Bourdon, capacitance diaphragm, thermocouple, and Pirani gauges. There are also measurement devices that combine two different gauge type technologies, like the capacitance diaphragm and Pirani, into a single package. This kind of vacuum gauge is called a combination gauge.

### 4.5.1 Bourdon Gauges

A ***Bourdon pressure gauge*** was patented by Eugene Bourdon in France in 1849. Two years later, Bernard Schaeffer patented a successful diaphragm pressure gauge. Together, the two pressure gauges revolutionized pressure measurement in industry. They were widely adopted for their superior sensitivity, linearity, and accuracy at that time. These low-cost gauges are still used today to measure pressure levels above 1 Torr.

A commercially-available Bourdon pressure gauge is shown in Figure 4.12. This is a direct reading gauge. It operates on the principle that a curved, flattened tube often of non-circular cross-section will straighten when pressure inside the tube increases or will curl when the pressure decreases. To magnify the effect of the pressure change, the tube is formed into a C-shape, or even a helix, so that the entire tube tends to straighten out or uncoil elastically as it is pressurized and will coil when the pressure decreases.

Figure 4.12. Commercially available Bourdon gauge. Photo is provided by Kurt J. Lesker Company, https://www.lesker.com.

Figure 4.13 shows the internal structure of a Bourdon pressure gauge. The C-shaped Bourdon tube is open at one end and sealed at the other end. As the tube responds to changes in pressure, the movement of the tip is transmitted mechanically through an adjustable link to a segmented lever. The segmented lever rotates around a pivot point and the sector gear end meshes with a pinion gear. As the pinion gear rotates, it moves the attached needle. As the needle moves over the scale, the needle tip indicates the pressure reading. Animation 4.9 demonstrated operation of a Bourdon pressure gauge.

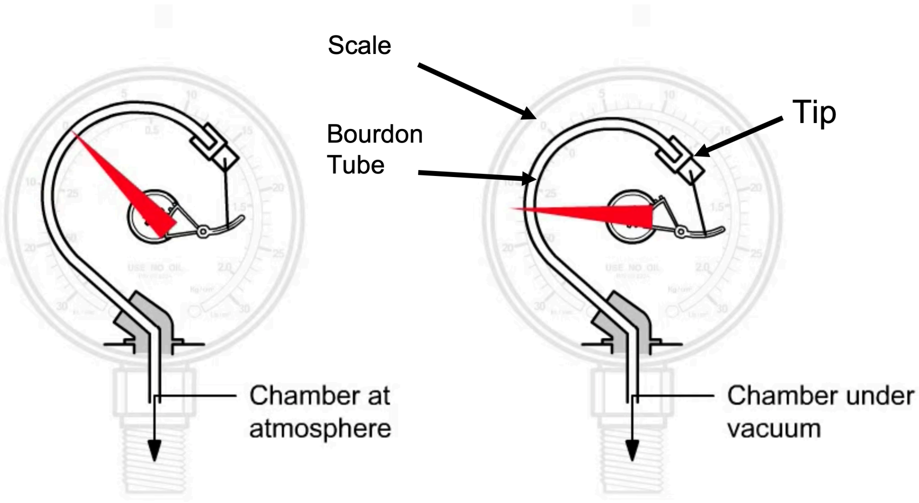

Figure 4.13. Internal Structure of the Bourdon gauge. Graphics provided by MATEC, edited by E. Brewer.

*One or more interactive elements has been excluded from this version of the text. You can view them online here: https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#oembed-9*

Animation 4.9. Bourdon Pressure Gauge Animation. Animation provided by MATEC.

A Bourdon pressure gauge measures pressure relative to ambient atmospheric pressure, as opposed to absolute pressure. A reading of zero on most Bourdon gauges indicates atmospheric pressure. As the pressure detected by the Bourdon gauge decreases to levels less than atmospheric pressure, the internal coil retracts, and the needle moves to indicate a non-zero value.

***Gage pressure*** is related to absolute pressure and atmospheric pressure by the equation,

$$P_{gage} = P_{absolute} - P_{atmospheric} \qquad (4.1)$$

### Example 4.2

If a Bourdon gauge displays the pressure in a vacuum chamber as 5.50 in Hg vacuum, what is the approximate absolute pressure within the chamber?

**Solution:**

If the chamber's specific location is not provided, assume that $P_{atmospheric}$ is equal to standard atmospheric pressure, that is, 29.92 in Hg for Earth at sea level.

The known values are:

$$P_{gage} = 5.50\, in\, Hg\, vacuum = -5.50\, in\, Hg,\ and$$
$$P_{atmospheric} = 29.92\, in\, Hg$$

Substituting these values in Equation 4.1 gives,

$$P_{gage} = P_{absolute} - P_{atmospheric}$$
$$P_{absolute} = P_{gage} + P_{atmospheric}$$
$$P_{absolute} = -5.50\, in\, Hg + 29.92\, in\, Hg$$
$$P_{absolute} = 24.42\, in\, Hg$$

## Example 4.3

For the same pressure measurement in the previous example, what is the absolute pressure within the chamber in units of inches of Hg if the system is located in Denver, Colorado?

**Solution:**

Denver, Colorado is located at an altitude of roughly 1 mile above sea level. The atmospheric pressure decreases as you move to higher altitudes and get farther away from sea level. At sea level the atmospheric pressure is nominally 760 mm Hg, or 760 Torr. Assume that the typical atmospheric pressure in Denver, Colorado is 615 mm Hg.

The known values are:

$$\begin{aligned} P_{gage} &= 5.50\, in\, Hg\, vacuum \;=\; -5.50\, in\, Hg,\ and \\ P_{atmospheric} &= 615\, mm\, Hg \end{aligned}$$

We use,

$$\begin{aligned} P_{gage} &= P_{absolute} \;-\; P_{atmospheric} \\ P_{absolute} &= P_{gage} \;+\; P_{atmospheric} \end{aligned}$$

In order to solve for $P_{absolute}$ in Equation 4.1, the values of $P_{gage}$ and $P_{atmospheric}$ must be of the same unit of measure, that is, inches of Hg *(in Hg)*.

We will convert the value $P_{atmospheric}$ from units of mm Hg to in Hg:

$$\begin{aligned} P_{atmospheric} &= 615\, \cancel{mm}\, Hg \times \frac{1\, in}{25.4\, \cancel{mm}} \\ P_{atmospheric} &= 24.21 in\, Hg \end{aligned}$$

Substituting the converted $P_{atmospheric}$ value:

$$\begin{aligned} P_{absolute} &= -5.50\, in\, Hg \;+\; 24.21\, in\, Hg \\ P_{absolute} &= 18.71\, in\, Hg \end{aligned}$$

## Example 4.4

The Bourdon gauge in Figure 4.14.a displays a measurement of the pressure within a vacuum chamber. What is the absolute pressure within the chamber in units of mbar?

Figure 4.14.b displays the barometric pressure condition in the room in which the vacuum chamber is located.

Figure 4.14.a. Bourdon gauge measurement of pressure inside a vacuum chamber. Photo provided by Nancy Louwagie, Normandale Community College.

Figure 4.14.b. Barometric pressure measurement in the room. Photo provided by Nancy Louwagie, Normandale Community College.

**Solution:**

The known values are:

$$P_{gage} = 20.00\, in\, Hg\, vacuum = -20.00\, in\, Hg,\ and$$
$$P_{atmospheric} = 980.5\, mbar$$

We use,

$$P_{gage} = P_{absolute} - P_{atmospheric}$$
$$P_{absolute} = P_{gage} + P_{atmospheric}$$

In order to solve for $P_{absolute}$ in Equation 4.1, the values of $P_{gage}$ and $P_{atmospheric}$ must be of the same unit of measure, that is, mbar.

We will convert the value $P_{gage}$ from units of in Hg to mbar:

$$P_{gage} = -20.00\ \cancel{in\,Hg} \times \frac{1013.25\,mbar}{29.92\ \cancel{in\,Hg}}$$

$$P_{gage} = -677.3\,mbar$$

Substituting the converted $P_{gage}$ value:

$$P_{absolute} = -677.3\,mbar + 980.5\,mbar$$

$$P_{absolute} = 303.2\,mbar$$

## Example 4.5

A second gauge measuring the pressure within the vacuum chamber displays the reading shown in Figure 4.14.c when the Bourdon gauge reads 20.00 in Hg vacuum. How do the measurements from the two gauges compare?

Figure 4.14.c. Capacitance manometer / Pirani gauge measurement. Photo provided by Nancy Louwagie, Normandale Community College. Photo edited by Gigi Bocek.

**Solution:**

Since the unit of measure displayed on the gauge in Figure 4.14.c is in torr, we know the measurement displayed by the gauge reflects an absolute pressure.

Convert the value displayed on the gauge in Figure 4.14.c from units of torr to mbar:

$$P_{absolute} = 2.19 \times 10^{2}\ \cancel{Torr} \times \frac{1013.25\,mbar}{760\ \cancel{Torr}}$$

$$P_{absolute} = 292\,mbar$$

The percent difference between the value calculated for the Bourdon gauge measurement and the measurement on the second gauge shown in Figure 4.14.c is:

$$\%_{difference} = \left[\frac{(303.2\,mbar\ - 292\,mbar)}{((303.2\,mbar\ + 292\,mbar)\ \div\ 2)}\right] \times 100\%$$

$$\%_{difference} = 3.76\,\%$$

## Example 4.6

If the pressure within a vacuum chamber is 488 Torr, what measurement value will a Bourdon gauge display as the pressure in units of in Hg vacuum? The atmospheric pressure is 734 Torr.

**Solution:**

The known values are:

$$P_{absolute} = 488\,Torr,\ and$$
$$P_{atmospheric} = 734\,Torr$$

We use,

$$P_{gage} = P_{absolute}\ - P_{atmospheric}$$
$$P_{gage} = 488\,Torr\ - 734\,Torr$$
$$P_{gage} = -246\,Torr$$

This result implies that the measured pressure is 246 Torr less than the prevailing atmospheric pressure.

We will convert the value *P<sub>gage</sub>* from units of torr to in Hg:

$$P_{gage} = -246\ \cancel{Torr} \times \frac{29.92\,in\,Hg}{760\ \cancel{Torr}}$$

$$P_{gage} = -9.68\,in\,Hg,\ or\ 9.68\,in\,Hg\,vacuum$$

The Bourdon gauge is a purely mechanical device. No electrical power is required to operate a Bourdon gauge. Thus, one advantage of using a Bourdon gauge is it will continue to display the pressure condition within a vacuum system if the system loses power. Another advantage of the Bourdon gauge is its fast response time. The disadvantage of a purely mechanical device is that without electronics, a system operator must directly observe and interpret, and, if necessary, hand record the measurement value right at the gauge. Another limitation of the Bourdon gauge is that it does not measure very accurately. A Bourdon gauge provides just a general indication of the vacuum level present. The rate at which the needle moves on the Bourdon gauge provides an idea of how fast a vacuum system is pumping down. When a Bourdon gauge needle stays at zero after a ***pump down*** sequence has been initiated, most likely a gross leak is present in the system.

## 4.5.2 Capacitance Diaphragm Gauges

A capacitance diaphragm gauge, or capacitance manometer, is also a direct reading gauge. It senses the deflection of a flexible metal diaphragm in the gauge produced by the collective force of many gas molecules striking the diaphragm. The metal diaphragm functions as a boundary that separates two spaces. One space is evacuated and permanently sealed. This space provides a vacuum reference pressure. The space on the opposite side of the diaphragm is open to the gases present in the vacuum system. The metal diaphragm forms part of a capacitance circuit. Since,

$$C = \epsilon \frac{A}{d}$$

where C is the capacitance in farads, ε is the permittivity of the dielectric material, A is the plate area, and d is the plate separation, capacitance is inversely proportional to the distance between the two plates forming the capacitor. Note, plate area and the dielectric material do not change. The electronic circuitry in the gauge controller converts this change in capacitance to a corresponding frequency and then to a pressure readout. Figure 4.15 shows a capacitance manometer gauge.

Capacitance manometers are used as process-control monitors because they are gas species independent and can be very accurate. They can provide highly accurate measurements over almost seven decades of pressure from 1,000 Torr to approximately $1.0 \times 10^{-4}$ Torr. However, it may be necessary to use two or three capacitance manometer gauges if you want to make accurate measurements over this full range of pressures. Capacitance manometers are calibrated to take accurate readings within a smaller range of pressures. The measurement range of any one capacitance manometer is typically limited to two or three decades of pressure, for example from 10 Torr to 1,000 Torr for two decades or 0.01 Torr to 10 Torr for three decades. They are very fast, with response times on the order of 1 millisecond or less and have an accuracy of ± 0.25%, or less, of full scale. The downside of using capacitance manometers is that they are more expensive than other gauges within the same pressure range, such as thermocouple and Pirani gauges.

Figure 4.15. Capacitance manometer gauge. Source: www.lesker.com.

## 4.5.3 Thermal Conductivity Gauges

A gas has the ability to carry away heat. Conduction is a form of heat transfer in which individual molecules transfer heat from hotter to colder regions. After an air molecule collides with and rebounds from a heated surface, it carries away some of the surface heat energy. An increase or decrease in the number of air molecules present to collide with a heated surface causes a corresponding increase or decrease in the rate at which heat is carried away from the surface. We are familiar with thermos bottles. As was described in Chapter 1, the thermos bottle design consists of a smaller flask inserted within a larger flask. Air is removed from the sealed space to create a vacuum condition. By reducing the molecular density in the space between the inner flask and the exterior wall of the thermos bottle, the rate of heat transfer to or from the liquid inside the thermos bottle is reduced. In this way, we can keep cold liquids cold and hot liquids hot.

***Thermal conductivity gauges*** are a type of indirect-reading pressure measurement gauge. The term *indirect reading* implies that the gauge does not measure pressure directly, but instead measures some other parameter associated with the gas and then converts it to a pressure reading. The operating principle employed by a thermal conductivity gauge is based on the ability of a gas to conduct heat. As the name implies, a thermal conductivity gauge measures temperature and then translates or converts the temperature to a pressure reading.

Thermal conductivity gauges operate by measuring how much heat is lost from a heated surface as the molecular density surrounding the surface changes. The heated surface in a thermal conductivity gauge is created by passing electric current through a very thin filament wire. Heat is lost from the surface of the wire every time a gas molecule hits it and rebounds back into the chamber, taking some heat energy from the wire's surface. Higher pressures mean more collisions between gas molecules and the heated filament surface which results in a high rate of heat loss. Conversely, lower pressures mean fewer collisions between gas molecules and the surface, and consequently a lower rate of heat loss. The amount of heat loss can be measured using either Fahrenheit, Celsius, or Kelvin temperature scales. Thermal conductivity gauges are effective at measuring pressures in the lower range of the rough vacuum regime, that is, pressures between 0.001 and 10 Torr.

### 4.5.3.1 Thermocouple Gauges

A ***thermocouple gauge*** is one type of thermal conductivity vacuum gauge. The function of this gauge is enabled by a thermocouple sensing element. A thermocouple consists of two different metals joined together. The joining of two dissimilar metals produces a small electrical voltage. Heating or cooling the thermocouple causes corresponding changes in the junction voltage. Thus, a thermocouple behaves like an electric thermometer.

Figure 4.16 (a) shows the construction of a thermocouple gauge. The gauge controller applies a set voltage to the filament to heat it up to its operating temperature. As the pressure decreases around the filament, fewer gas molecules are available to carry away the filament's heat energy. As a result, the filament gets hotter as shown in Figure 4.16 (b). A thermocouple is attached to the filament to sense the temperature of the filament. The gauge controller monitors the voltage produced by the thermocouple and produces a pressure reading that corresponds to the magnitude of the voltage.

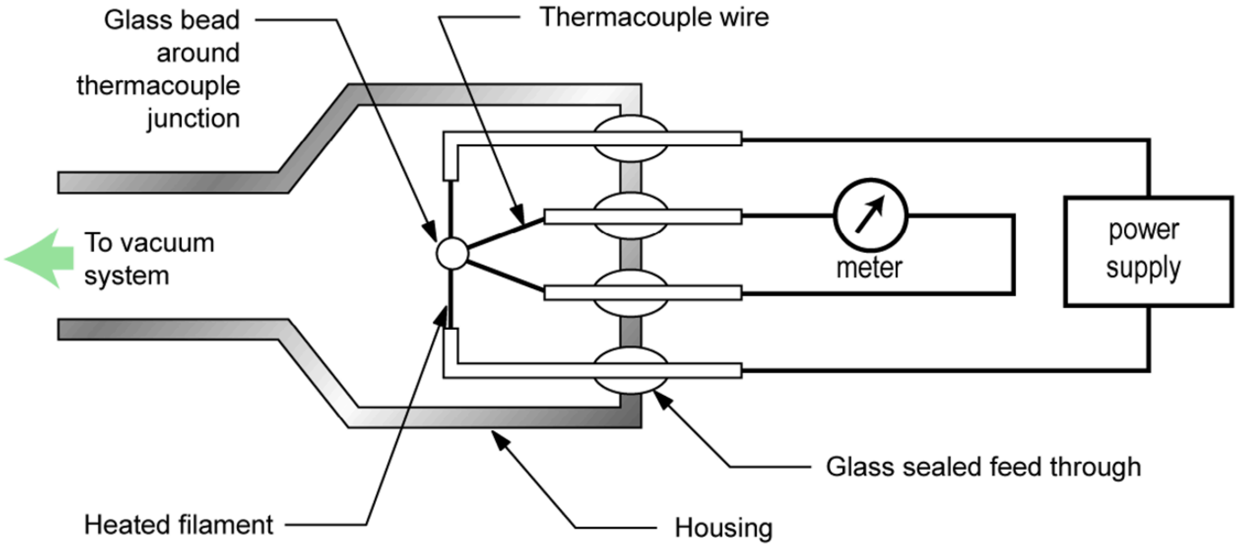

Figure 4.16 (a). Thermocouple gauge diagram. Diagram is used with permission of Maricopa Advanced Technology Education Center (MATEC).

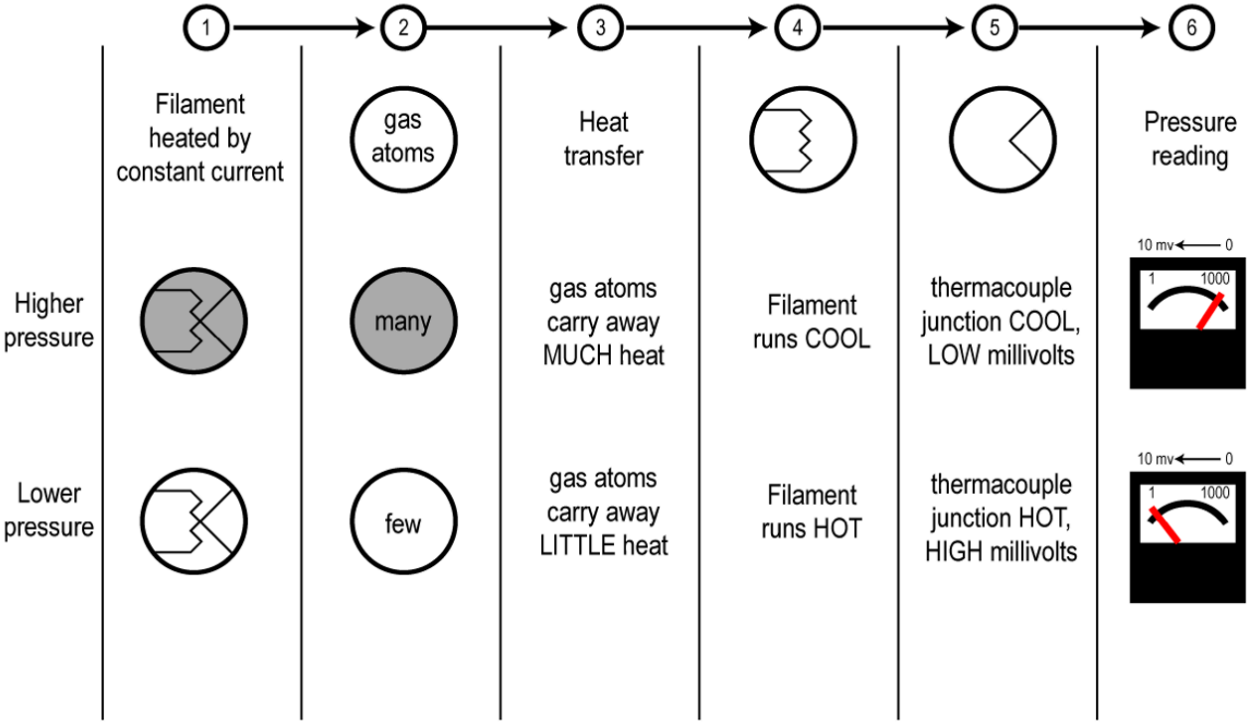

Figure 4.16 (b). Thermocouple gauge response. Diagram is used with permission of Maricopa Advanced Technology Education Center (MATEC).

The useful measurement range of a thermocouple gauge is approximately between 0.01 and 1 Torr. Some thermocouple gauge designs include enhancements which expand the measurement range slightly. The measurement accuracy of a properly calibrated thermocouple gauge for a specified gas type is approximately ±15%. Some of these gauges can be calibrated at the lower end of the measurement range by adjusting the temperature of the heating filament. Thermocouple gauges are relatively inexpensive.

## 4.5.3.2 Pirani Gauges

A ***Pirani gauge***, shown in Figure 4.17 is also a type of thermal conductivity gauge. A Pirani gauge consists of a length of thin filament wire that is heated and passed through a metal cylindrical tube. The filament is incorporated in the gauge as one of the resistive arms in a Wheatstone Bridge. A Wheatstone Bridge in its simplest form consists of four resistances arranged in a square, or diamond, shape, like a baseball diamond. Using the baseball analogy, a meter is placed between first base and third base, and a power supply is connected between home plate and second base. As the pressure changes, the Pirani gauge detects a change in an electrical property due to changes in the resistance of the heated filament.

Figure 4.17. Commercially available Pirani and Enhanced Pirani gauges. Photos provided by Kurt J. Lesker Company, [www.lesker.com](http://www.lesker.com).

The circuit, shown in Figure 4.18 (a) operates in the following manner. If the bridge is balanced, the voltage at first base equals the voltage at third base, and there is no voltage potential across the meter. No voltage means no current flows through the meter and the meter reads zero. If one of the resistances changes, the bridge will become unbalanced. For example, when pressure in the chamber decreases, the filament within the Pirani transducer heats up, which in turn causes an increase in the filament's resistance. Then, the voltage at first base and third base will no longer be equal, and the potential difference across the meter will cause an electrical current to flow through the meter. The magnitude of the electrical current will be proportional to the new pressure in the vacuum chamber.

There are two primary Pirani gauge hot-filament designs. One design is based on supplying a constant voltage across the bridge. The pressure is determined by measuring changes in the bridge current caused by changes in the resistance of the filament wire. The constant voltage Pirani gauge design supports pressure measurements in a range of approximately 0.001 to 1 Torr. The second design is based on maintaining a constant filament temperature by adjusting the bridge voltage. The pressure is determined by measuring the changes in power supplied to maintain the constant filament temperature. The constant temperature gauge design supports a measurement range of approximately 0.001 to 100 Torr.

Two other types of Pirani gauge designs are commonly used in vacuum systems. One of them is called the convection-enhanced or convection Pirani gauge. The core design of a ***convection-enhanced Pirani gauge*** is the same as the constant filament temperature design.

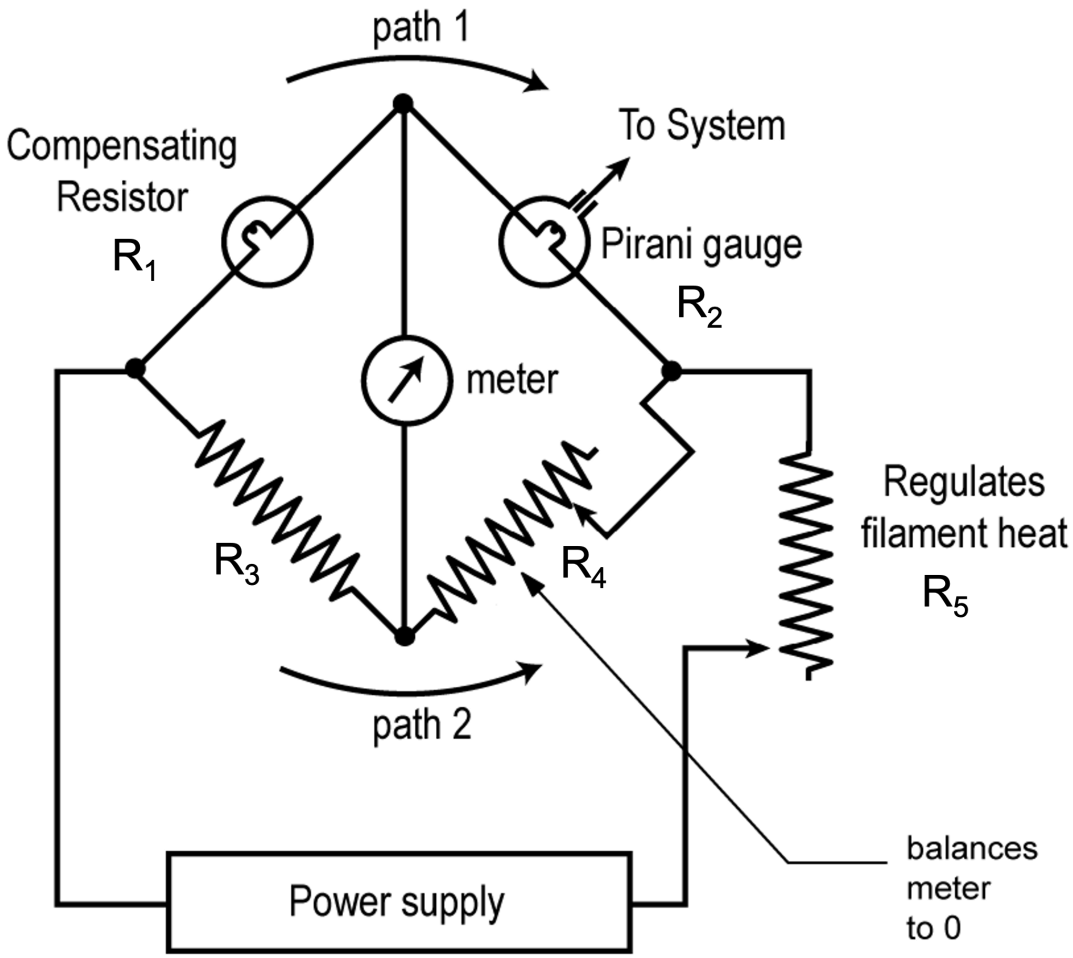

Figure 4.18 (a). Circuit diagram of a bridge circuit for a Pirani gauge. Diagram is used with permission of Maricopa Advanced Technology Education Center (MATEC).

This gauge design is enhanced to provide pressure measurements higher than 100 Torr by utilizing the convection currents around the filament. Figure 4.18 (b) shows that convection becomes the primary heat transfer mechanism for pressures above 10 Torr. The orientation of a convection-enhanced Pirani gauge is critical to its operation. The heated filament must be oriented in a horizontal position. When the gas molecules within the metal tube are in ***viscous flow***, that is, at pressures greater than 10 Torr, convection currents will draw heat from the filament making higher pressure measurements possible. A convection-enhanced Pirani gauge supports a measurement range of approximately 0.001 to 1000 Torr.

The second Pirani gauge design is a significant departure from the heated filament design. This Pirani gauge design is called a MEMS (microelectromechanical systems) Pirani. A ***MEMS Pirani gauge*** incorporates the same elements present in the heated filament-based design, but all the elements are fabricated on a silicon substrate as part of a MEMS sensor unit. The func-

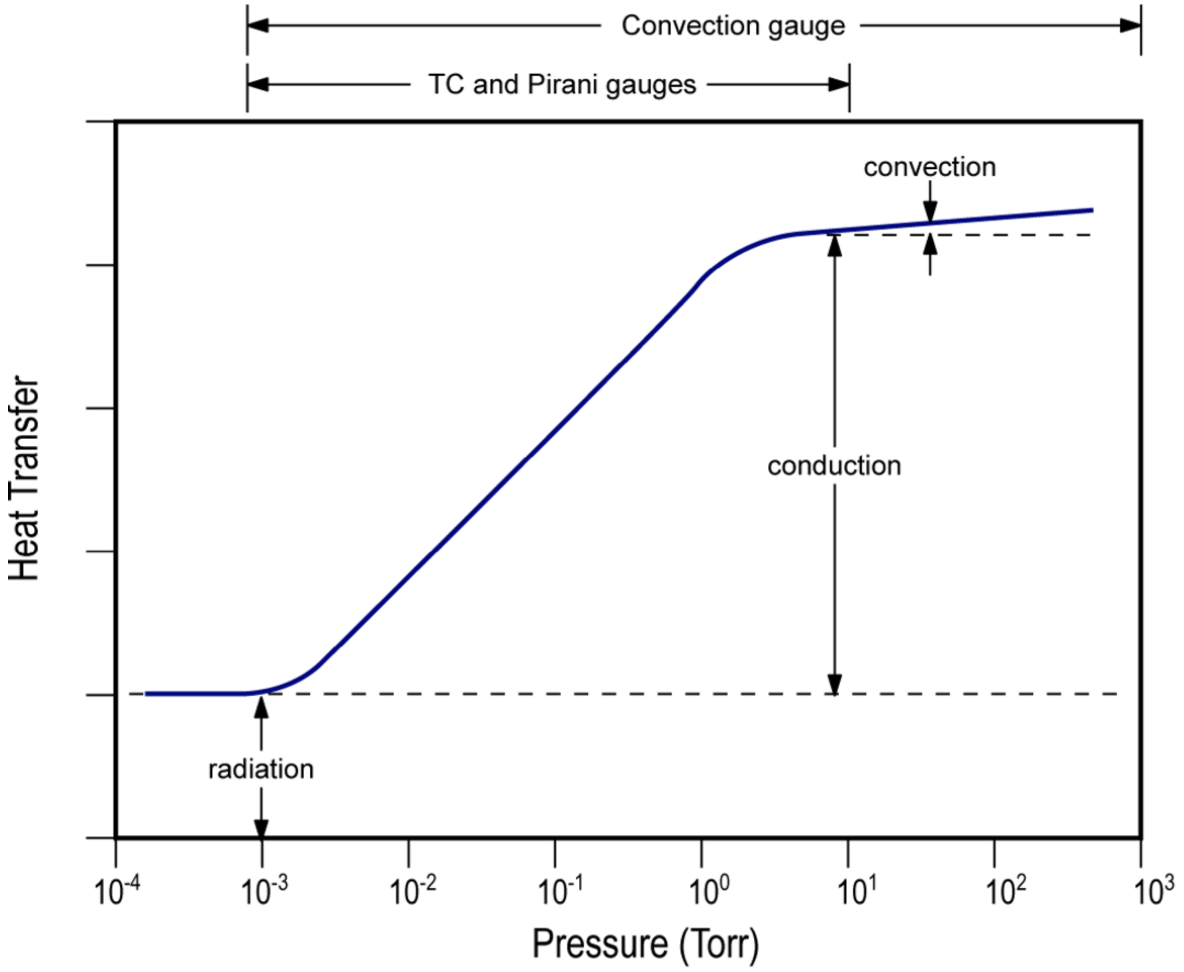

Figure 4.18 (b). Predominant heat transfer mechanism (radiation, conduction, or convection) as a function of pressure. Diagram is used with permission of Maricopa Advanced Technology Education Center (MATEC).

tion of the heated filament is accomplished by a thin serpentine configuration of nickel metal fabricated on the MEMS sensor. The nickel metal on the MEMS sensor serves as the heated element. The MEMS Pirani gauge supports an extended pressure measurement range from 1 x $10^{-5}$ to 1000 Torr, as shown in Figure 4.18 (c), due to the miniaturized MEMS sensor design.

Measurement accuracy of a specified gas in a properly calibrated hot-filament Pirani gauge is approximately ±10% over the measurement range of 0.001 to 10 Torr. In contrast, properly calibrated convection-enhanced Pirani gauges have a measurement accuracy of ±10% below 10 Torr and ±5% for pressure measurements above 10 Torr. A MEMS Pirani gauge has varying measurement accuracies across its measurement range. At the lowest end, that is, at pressures between 1 x $10^{-5}$ to 1 x $10^{-3}$ Torr, the measurement accuracy of a MEMS Pirani gauge is ±10%. For pressure measurements between 1 x $10^{-3}$ to 100 Torr, the measurement accuracy of a MEMS Pirani gauge is ±5%. For pressure measurements above 100 Torr, the MEMS Pirani

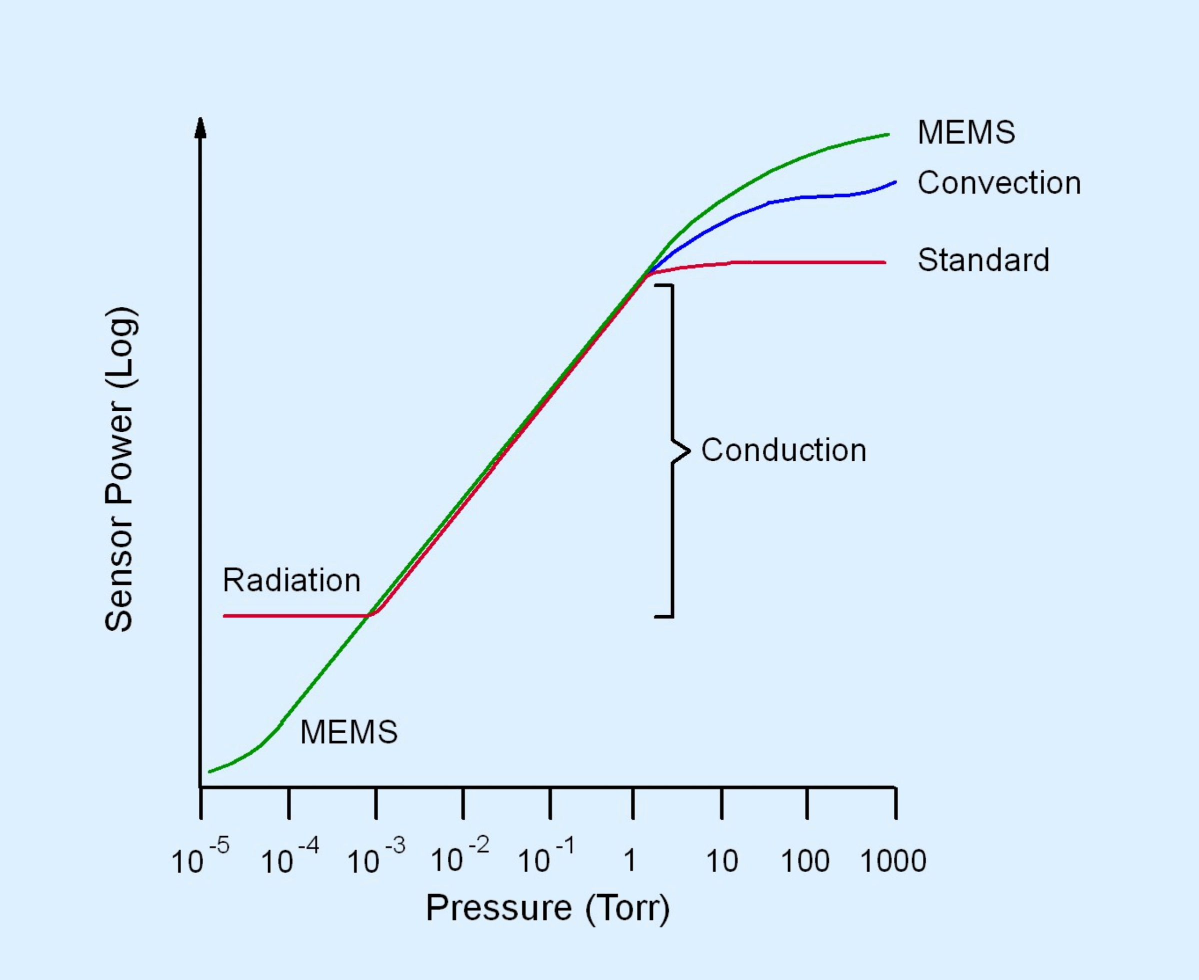

Figure 4.18 (c). MEMS Pirani gauge sensor profile. Diagram is used with permission of Steve Hansen.

gauge has a measurement accuracy of ±25%. Pirani gauges can be calibrated at both ends of the measurement range. Pirani gauges provide better measurement accuracy than thermocouple gauges but are not as accurate as capacitance manometer gauges. A convection-enhanced Pirani or a MEMS Pirani gauge will support a much wider measurement range than a capacitance manometer. Pirani gauges are more expensive than thermocouple gauges but much less expensive than a capacitance manometer.

### 4.5.3.3 Thermal Conductivity Gauges and Gas Species Dependencies

Using a thermal conductivity gauge is not as simple as hooking up the gauge to the vacuum chamber or lines in a vacuum system and reading the numbers off the gauge controller. Since the thermal conductivity of different gases varies, the number representing the pressure may have to be adjusted if the gas composition is different from the gas composition for which the gauge was calibrated. Table 4.2 gives the thermal conductivity of common gases.

Table 4.2. Thermal conductivity of common gases.

| Gas | Thermal conductivity MJ/(s · m · K) |
|---|---|
| Air | 24.0 |
| Argon | 16.6 |
| Carbon Dioxide | 14.58 |
| Helium | 142.0 |
| Hydrogen | 173.0 |
| Methane | 30.6 |
| Neon | 45.5 |
| Nitrogen | 24.0 |
| Oxygen | 24.5 |
| Water Vapor | 24.1 |
| Xenon | 4.50 |

What Table 4.2 tells us is that the amount of heat lost from the filament in a thermal conductivity gauge depends on the gas(es) in the system. For example, if the chamber is filled with helium as opposed to nitrogen, the helium, having a higher thermal conductivity, will carry more heat away from the filament than nitrogen, and thus an equivalent amount of helium will cool the filament to a greater extent than nitrogen. Argon, on the other hand, with a lower thermal conductivity, will not cool the filament as fast as nitrogen. Figure 4.19 (a) shows heat transfer characteristics of helium, nitrogen and argon depending on pressure. So with any gas other than nitrogen, you should not take the observed pressure reading at face value.

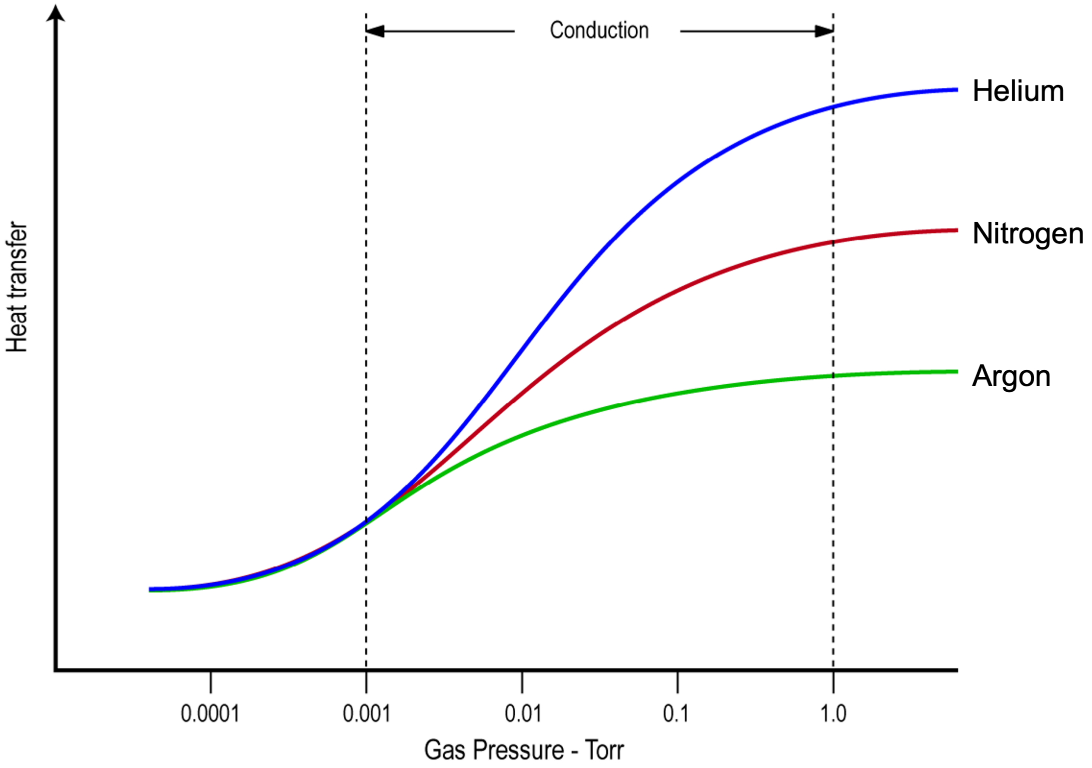

Figure 4.19 (a). Heat transfer characteristics of various gases as a function of pressure. Graph is used with permission of Maricopa Advanced Technology Education Center (MATEC). Adapted by E. Brewer.

Let's use the Model PG 105 Convection-Enhanced Pirani gauge produced by Stanford Research Systems (SRS) as an example. All PG 105 gauges are factory-calibrated and temperature-compensated for nitrogen (essentially air). The response of the gauge is very well characterized, and with proper calibration data, it is possible to obtain accurate pressure measurements for other gases as well. For user convenience, nitrogen- and argon-specific calibration curves are loaded into SRS's Model IGC 100 Gauge Controller, making direct measurements possible for these gases. For other gases, gas-correction curves are provided for the PG 105 gauge (see Figure 4.19 (b) and Figure 4.19 (c)). However, for gases, or mixtures of gases, not included in the gauge data sheet, users will have to generate their own conversion curves.

For the PG 105 convection-enhanced Pirani gauge, the actual pressure is equal to the nitrogen-equivalent reading from the gauge controller times the gas-correction factor. For pressures below 1 Torr, the gas correction factor for argon is given as 1.59 in the data sheet. Hence, if the pressure reading on the controller display is 0.50 Torr (the nitrogen equivalent reading), then the actual pressure is equal to 0.50 Torr x 1.59, or approximately 0.80 Torr. When properly configured, controllers such as the Model IGC 100 can perform this calculation for you

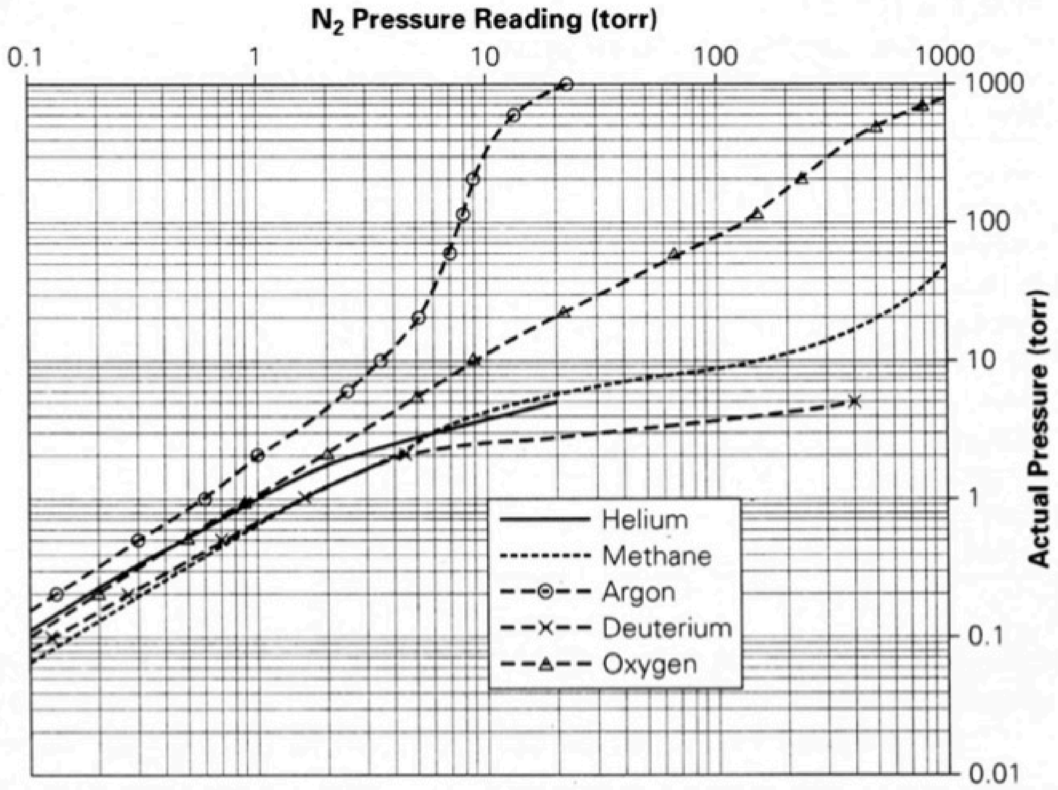

Figure 4.19 (b). Typical gauge indicated pressure ($N_2$ equivalent) vs actual pressure curve for pressures above 0.1 Torr (100 mTorr).

and display the actual argon pressure on the controller readout. Care should be taken if a thermal conduction gauge calibrated for $N_2$ is present when a vacuum system is vented with argon. The thermal conduction gauge will indicate a lower pressure value than the actual system pressure. The risk would be creating an over-pressure condition if the pressure within the chamber is unknowingly allowed to exceed atmospheric pressure.

On the other hand, if the vacuum chamber is filled with methane and the observed pressure reading on the gauge controller is 0.50 Torr, we can use the given gas-correction figure for methane to determine the actual pressure. From the sensitivity correction data sheet provided with the Model IGC 100 Controller, the gas-correction factor for methane is 0.63. Multiplying the gas-correction factor, 0.63, times the gauge pressure reading, 0.50 Torr, we obtain 0.32 Torr, the actual pressure for methane in the chamber.

It is important to read the operating instructions and data sheet for the pressure gauge you are using. In some cases, you may be instructed to divide (not multiply) the observed reading by the gas-correction factor.

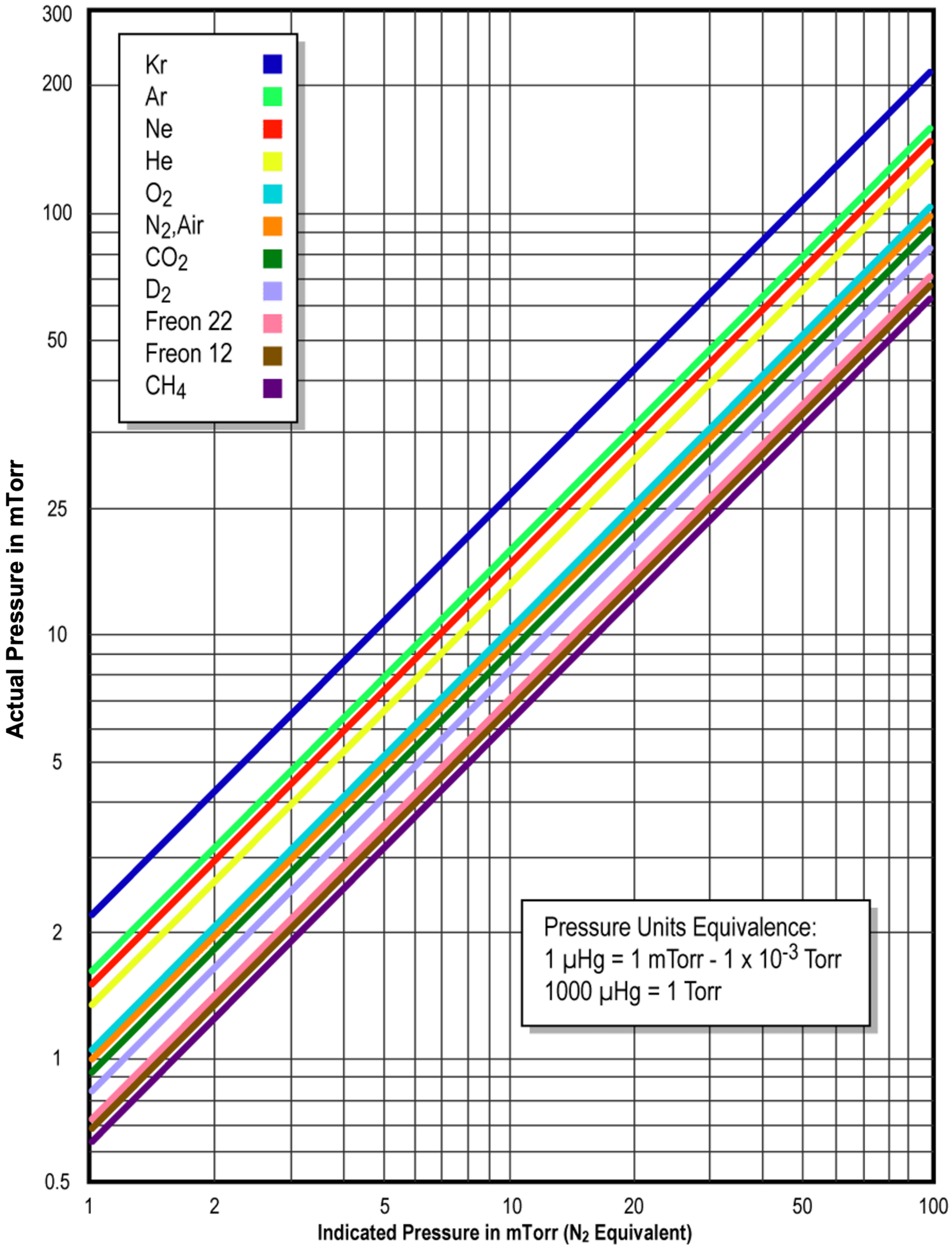

Figure 4.19 (c). Typical gauge indicated pressure ($N_2$ equivalent) vs actual pressure curve for pressures below 0.1 Torr (100 mTorr). Graph is used with permission of Maricopa Advanced Technology Education Center (MATEC). Adapted by E. Brewer.

### 4.5.4 Other Rough Vacuum Gauges

Two other vacuum measurement gauges are worth mentioning. The first one, the ***piezoelectric vacuum gauge***, is another type of direct pressure measurement device. ***Piezoelectricity*** is a phenomenon in which electric charge builds up in certain materials as a direct response to a mechanical stress applied to the material. A piezoelectric vacuum gauge includes a piezoelectric sensing unit. This gauge detects changes in an electrical property, for example, resistance, due to material deformation as a response to changes in pressure. A measurement based on the changing electrical property is converted to a pressure reading. Piezoelectric vacuum gauges support a measurement range of 0.1 to 1000 Torr. The measurement accuracy of a piezoelectric vacuum gauge varies over its range of measurement. The accuracy of the measurement is generally 1% or better for pressures of 10 Torr and higher. At pressures below 10 Torr, this device becomes increasingly less accurate.

The other vacuum measurement gauge we will address here is the combination gauge. As the name suggests, this gauge is the combination of two different measurement technologies within a single package. The underlying technologies combined in one unit are the capacitance manometer and Pirani technologies or the piezoelectric and Pirani technologies. A combination gauge can support a measurement range of $1\times10^{-5}$ to 1000 Torr. The accuracy of the measurement varies over the device's measurement range and corresponds to the accuracy of the underlying technology. For the range in which the capacitance manometer or piezoelectric technology applies, the measurement accuracy is better than 1%. For the range in which the Pirani technology applies, the measurement accuracy is 5-10%. The advantage of using a combination gauge is the ability to measure the system pressure over the entire rough vacuum regime using a single device.

Table 4.3. Summary of rough vacuum gauges.

| **Gauge Technology** | **Accuracy** | **Pressure Range** | **Direct vs Indirect** | **Response Time** |
|---|---|---|---|---|
| **Bourdon** | ± 10% | 1 Torr to 760 Torr | Direct | Fast (immediate) |
| **Capacitance Diaphragm** | ± 0.25% | Approximately $1.0\times10^{-4}$ Torr to 1,000 Torr | Direct | Fast (msec) |
| **Thermocouple** | ± 15% | Approximately 0.01 Torr to 1 Torr | Indirect | |
| **Pirani (hot filament)** | ± 10% | 0.001 Torr to 1 Torr (constant voltage); 0.001 Torr to 100 Torr (constant temperature) | Indirect | 1 – 2 sec for constant voltage; <50msec for constant temperature |
| **Convection-enhanced Pirani** | ± 10% below 10 Torr; ± 5% above 10 Torr | 0.001 Torr to 1,000 Torr | Indirect | <50msec in conduction regime; slower in convection regime |
| **MEMs Pirani** | ± 10% between $1\times10^{-5}$ Torr and $1\times10^{-3}$ Torr; ± 5% between $1\times10^{-3}$ Torr and 100 Torr; ± 25% above 100 Torr | $1.0\times10^{-5}$ Torr to 1,000 Torr | Indirect | |

Section 4.5 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#h5p-21*

# 4.6 Piping, Valves and Fittings

Other components are needed to configure a suitable and operational vacuum system. The selection of an appropriately sized ***vacuum chamber*** is the first consideration. Piping hardware connects the pump to the chamber. A valve is typically inserted in the piping line between the chamber and the pump, so the chamber can be isolated from the pump. Another valve is present and used for venting the chamber to atmosphere. One or more pressure gauges may be connected to the vacuum system to monitor the pressure at critical locations within the system.

At pressures above 10 milliTorr, gas molecules act much like a fluid. We can use our familiarity with the flow of liquids to help us visualize how gas flows in a vacuum system in the rough vacuum regime. Flow in this pressure regime is known as viscous flow. The term "viscous" implies that the gas molecules are "thick", which also suggests that the number of gas molecules present is very, very large. In viscous flow, the gas molecules are constantly bumping into each other and the walls of the chamber. In fact, the molecules are so closely packed that when some of them are pumped out of the chamber, other gas molecules will rush to fill the empty space and distribute themselves within the chamber. Molecular movement is very predictable in the rough vacuum regime when the flow of the molecules is viscous. Because of this predictability, smaller-diameter hoses and pipes can be used when large quantities of molecules per unit time move from one place in the system to another.

In the rough vacuum regime, a variety of options are available for the piping that connects the system components. In a vacuum system with a base pressure of 10 milliTorr or higher, it is reasonable to use piping made of materials such as plastics and ***elastomers***. For example, flexible polyvinyl chloride (PVC) cord-reinforced vacuum hose is a very suitable piping for connecting a positive displacement vacuum pump to a chamber. Gaskets made out of elastomer materials have elastic qualities making them reusable. Elastomer gaskets are used at demountable junctions in vacuum systems. However, plastics and elastomers are not suitable materials to use in vacuum chambers and piping that are required to establish and maintain high vacuum conditions. Plastic and elastomer type materials have relatively high vapor pressures and high permeability rates. These materials adversely contribute to the gas load in a vacuum system through outgassing and permeation. The presence of elastomer chamber materials will make it difficult or impossible for a system to attain a base pressure in high vacuum. In a manufacturing setting and for vacuum systems with base pressures in the high vacuum regime, the piping is usually made of stainless steel or aluminum.

***Klein Flansche flanges (KF flanges)*** are common classes of vacuum flanges and fittings used in the rough vacuum regime. As shown in Figure 4.20, KF flanges use a centering ring with an elastomer O-ring as the seal. The O-rings are made of either Buna-N or Viton. These particular elastomer materials have low outgassing rates. The O-ring is placed within a centering ring which is then positioned between the two components to be joined. A clamp is then used to hold the two components together and compress the elastomer O-ring to form a good seal. Flanges come in standard sizes ranging from KF10, the smallest, to KF50, the largest size. The KF10 is used to connect a tube of 10 mm inside diameter (ID), while the KF50 connects to a tube of 50 mm ID.

When using KF flanges to make a connection, it is important to ensure that the groove and mating surface are clean and dry. Check the sealing surfaces for scratches that cross the sealing area. If O-rings are reused, visually inspect them to make sure they do not have small crosswise cracks or nicks that might leak. Since elastomer

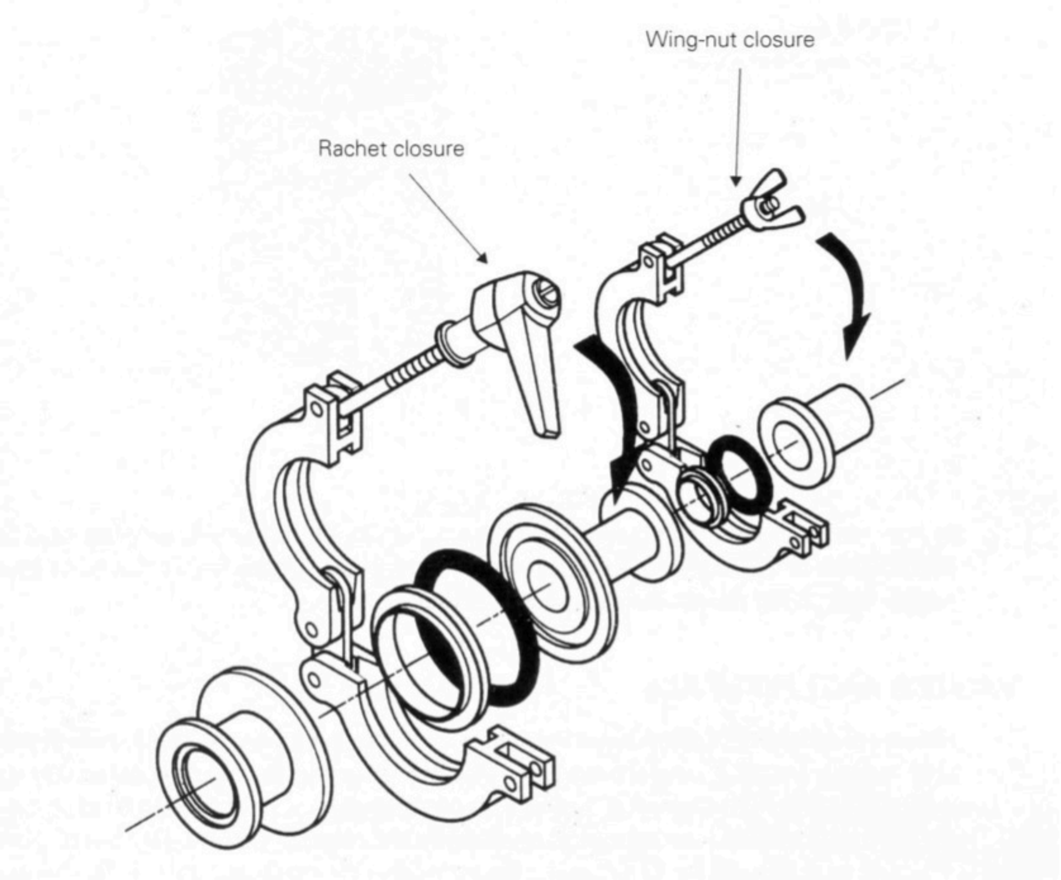

Figure 4.20. KF flanges. Source: Varian Vacuum Products, Basic Vacuum Practice, 3rd Edition, p. 159.

material is very permeable, greases and solvents should be used on elastomer seals in a vacuum system sparingly or not at all. Greases and solvents that permeate into the elastomer O-ring will outgas into the vacuum system. When grease is applied to an O-ring, it should be one with a low vapor pressure. If an O-ring has been exposed to solvents or excessive heat that has caused it to swell or deform, do not reuse it. Replace it with a new one.

Valves are used to provide isolation between vacuum components. The block valve is commonly used for this purpose in the rough vacuum regime. Block valves are made of aluminum, stainless steel, or brass. They can either be hand-operated, pneumatically (air)-operated, or activated electromagnetically. Flange options include KF flanges as well as others. They can be either in-line or right-angle. Figure 4.21 shows some examples of various metal valves with KF flanges.

KF fittings include nipples, elbows, tees, and reducers, to name a few. Figure 4.22 shows some of these KF fittings.

And finally, we need a valve that we can use to vent the system back to atmospheric pressure. Metal sealed or elastomer-sealed valves can be used for this purpose. They can also be used as gas inlets for process gases to the process chamber.

Figure 4.21. Various metal valves with KF flanges. Source: Kurt J. Lesker Company, www.lesker.com.

Figure 4.22. KF fittings. Photo provided by Rich Hill, SUNY Erie Community College.

Section 4.6 Quiz

*An interactive H5P element has been excluded from this version of the text. You can view it online here:*
*https://milnepublishing.geneseo.edu/introtovacuumtech/?p=698#h5p-22*

## 4.7 Rough Vacuum Pump-Down Process

To ***pump down*** the vacuum chamber in our simple rough vacuum system shown in Figure 4.1, the following procedure can be used. Let's assume that the vent valve and roughing valve are both closed and the chamber is filled with air at atmospheric pressure. If we are operating a system at a location near sea level, the rough vacuum gauge will be calibrated to display a reading very close to 760 Torr.

Prior to beginning the pump-down process, the rough vacuum pump is started and the roughing line between the pump and the rough vacuum valve pumps down. If this volume between the pump and the roughing valve is small, the ***pump-down time*** should be very short. To start the chamber pump-down process, the roughing valve is opened. The vacuum pump repetitively captures volumes of air from within the system including the chamber and expels those trapped gas molecules to the surrounding atmosphere. The molecular density within the chamber decreases as the quantity of molecules present within the chamber volume decreases. The pressure gauge will sense the decreasing molecular density condition in the chamber and will indicate a decreasing pressure reading on the pressure display. It should be noted that a convection-enhanced Pirani gauge may initially show an increase in pressure before it shows the pressure starting to decrease. The pressure in a small chamber will drop quickly and then gradually level off at the base pressure of the system. The pump-down time for the system will depend on the size of the gas load and the ***net pumping speed*** of the rough vacuum system. Figure 4.23 shows the general shape of the pressure versus time graph for a rough vacuum system.

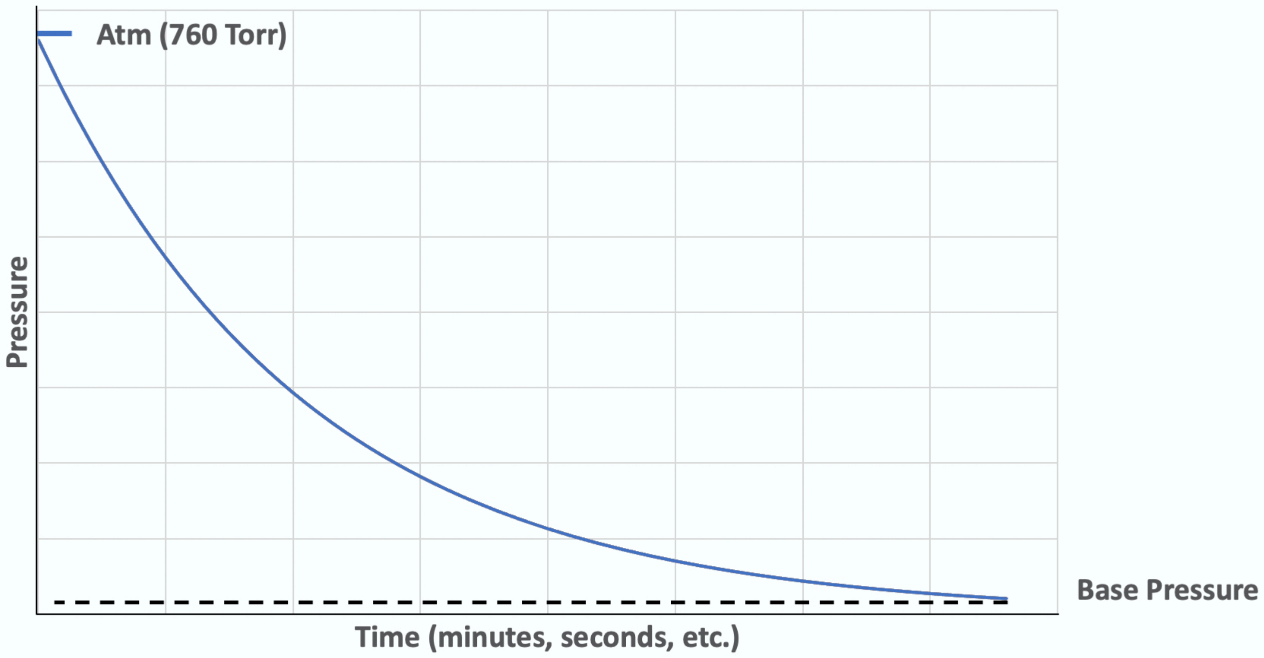

Figure 4.23. Rough vacuum pump-down curve. Graph provided by Elena Brewer, SUNY Erie Community College.

For pressures above 0.01 Torr (10 mTorr), the volume of the chamber and pumping speed are the determining factors when calculating pump-down times. Let's assume that we have a chamber of volume $V$ with a pump connected directly to the chamber that achieves an ***effective pumping speed*** $S_{eff}$. The ultimate pressure of the pump is specified as $P_{ult}$. At time $t = 0$, the initial pressure shall be $P_i$ . The pump-down time from $P_i$ to some final pressure $P_f$ ($P_f > P_{ult}$) can be estimated by

$$t = \frac{V}{S_{eff}} \, ln \left( \frac{P_i - P_{ult}}{P_f - P_{ult}} \right) \tag{4.2}$$

Equation 4.2 assumes that the chamber is clean and does not have any leaks. It also assumes that the conductance of the connection between the pump and the chamber is much greater than the effective pumping speed of the pump.

Equation 4.3 implies that the pressure versus time curve follows an exponential decay of the form,

$$p(t) = (P_i - P_{ult}) \, e^{\left(-\frac{S_{eff}}{V} t\right)} + P_{ult} \tag{4.3}$$

In Equation 4.3, $P_f$ of Equation 4.2 is replaced with the more general term *p(t)*, where *p(t)* means pressure as a function of time.

Example 4.7

A rotary vane pump with a nominal pumping speed of 193 liters per minute is used to pump down a 300-liter chamber. How long will it take to pump down the chamber from atmosphere to 1 Torr? Assume the pump connects directly to the chamber and the conductance of the connection between the pump and the chamber is much greater than the effective pumping speed of the pump. Assume that from the data sheet, the pump's ultimate vacuum pressure, $P_{ult}$, is 0.003 Torr.

**Solution:**

From the problem statement, we are given the volume of the chamber, *V*, as 300 liters, the effective pumping speed, $S_{eff}$, as 193 liters per minute, the starting pressure, $P_i$, as atmospheric pressure, which is assumed to be 760 Torr, and the final pressure, $P_f$, is 1 Torr.

Substituting this information into Equation 4.2 yields

$$t = \frac{300 \, liters}{193 \, liters/min} \, ln \left( \frac{760 \, Torr - 0.003 \, Torr}{1 \, Torr - 0.003 \, Torr} \right)$$

Since 0.003 Torr is much smaller than 1 Torr, the equation simplifies to

$$t = \frac{300 \, liters}{193 \, liters/min} \, ln \left( \frac{760 \, Torr}{1 \, Torr} \right)$$

$$t = (1.55 \, min) \, ln \, (760)$$

$$t = 10.31\, min.$$

Example 4.8

A mechanical diaphragm pump with a nominal pumping speed of 40 liters/min is used to evacuate the same 300-liter chamber as in Example 4.7. The pump's ultimate pressure is 3.8 Torr. How long will it take this pump to reduce the pressure in the chamber from atmosphere to 10 Torr? Assume the pump connects directly to the chamber and the conductance of the connection between the pump and the chamber is much greater than the effective pumping speed of the pump.

**Solution:**

From the problem statement, the volume of the chamber, *V*, is 300 liters, the initial pressure, $P_i$, is atmospheric pressure and assumed to be 760 Torr, and the final pressure, $P_f$, is 10 Torr. The nominal pumping speed is 40 liters per minute, and the ultimate vacuum pressure, $P_{ult}$, is 3.8 Torr.

Substituting this information into Equation 4.2 yields

$$t = \frac{300\, liters}{40\, liters/min}\, ln\left(\frac{760\, Torr - 3.8\, Torr}{10\, Torr - 3.8\, Torr}\right)$$

Performing the computations yields

$$t = (7.5\, min)\, ln(122)$$
$$t = 36\, min.$$

Note: In this case the vacuum pump's ultimate pressure is significant. If the ultimate pressure value is assumed to be negligible, the pump-down calculation yields 32 minutes, about a 10% difference.

Example 4.9

Calculate the pump-down time for the Anest Iwata ISP-90 Oil-Free Scroll Mechanical Vacuum

Pump to reduce the pressure in a 13.0-liter chamber from atmosphere ($10^5$ Pa) to 10 Pa. Use the pump speed curve for the ISP-90 shown in Figure 4.24.a. Assume the pump connects directly to the chamber and the conductance of the connection between the pump and the chamber is much greater than the effective pumping speed of the pump.

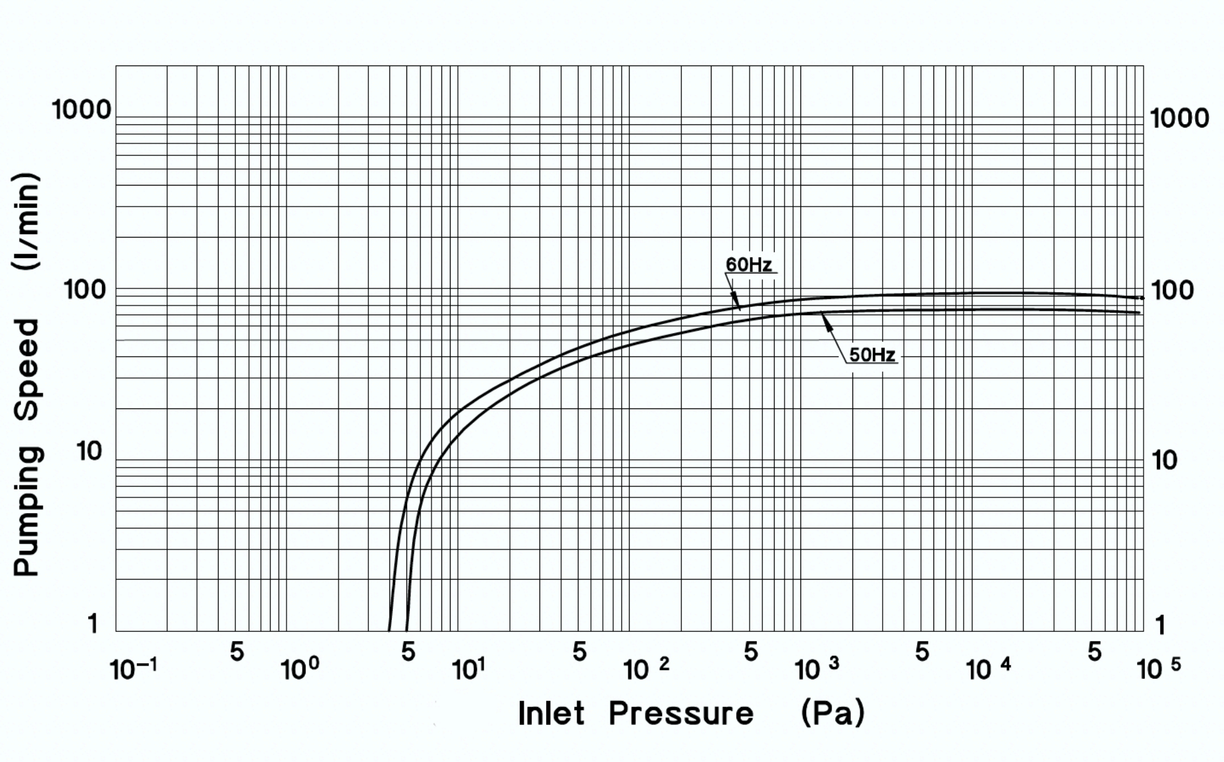

Figure 4.24.a. Anest Iwata ISP-90 oil-free scroll mechanical pump speed curve.

**Solution:**

From the ISP-90 ***pumping speed curve***, we observe that the pumping speed is approximately 93 liters/min from atmosphere to about 1000 Pa. Below 1000 Pa, the pumping speed rolls off with a slope of 3.6 liters/min per decade of pressure. If we assume that the pumping speed is constant at 93 liters/min over the entire pressure range from atmosphere to 10 Pa, our calculated pump-down time will be shorter than the actual pump-down time. Therefore, we need a better method for calculating the pump-down time.

One alternative method is to use a piece-wise linear approximation for the pumping speed curve. To implement this method, let us divide the pressure range into two segments. To do this, we need to plot two lines on the pump speed curve. The first line will be horizontal and tangent to the speed curve for pressures above 1000 Pa. The second line will be tangent to the sloped curve somewhere between 10 Pa and 1000 Pa depending on how conservative we want to approximate the pump-down time. The point where these two lines cross (as shown in Figure 4.24.b) will determine the pressure (300 Pa) separating the two pressure segments. Thus, the first pressure segment is from atmosphere ($10^5$ Pa) to 300 Pa, where the pumping speed is a constant 93 liters/min as read from the graph. And the second range is from 300 Pa to 10 Pa, where the pumping speed decreases from 93 liters/min to approximately 20 liters/min at 10 Pa. We can find an average pumping speed in the 300 Pa to 10 Pa range by adding 93 liters/min and 20 liters/min and dividing by 2 (essentially finding the average pumping speed over this pressure range). This yields an average pumping speed over this range of 56.5 liters/min. Now we can calculate the pump-down time for each pressure segment and then add both time segments to find the total pump-down time.

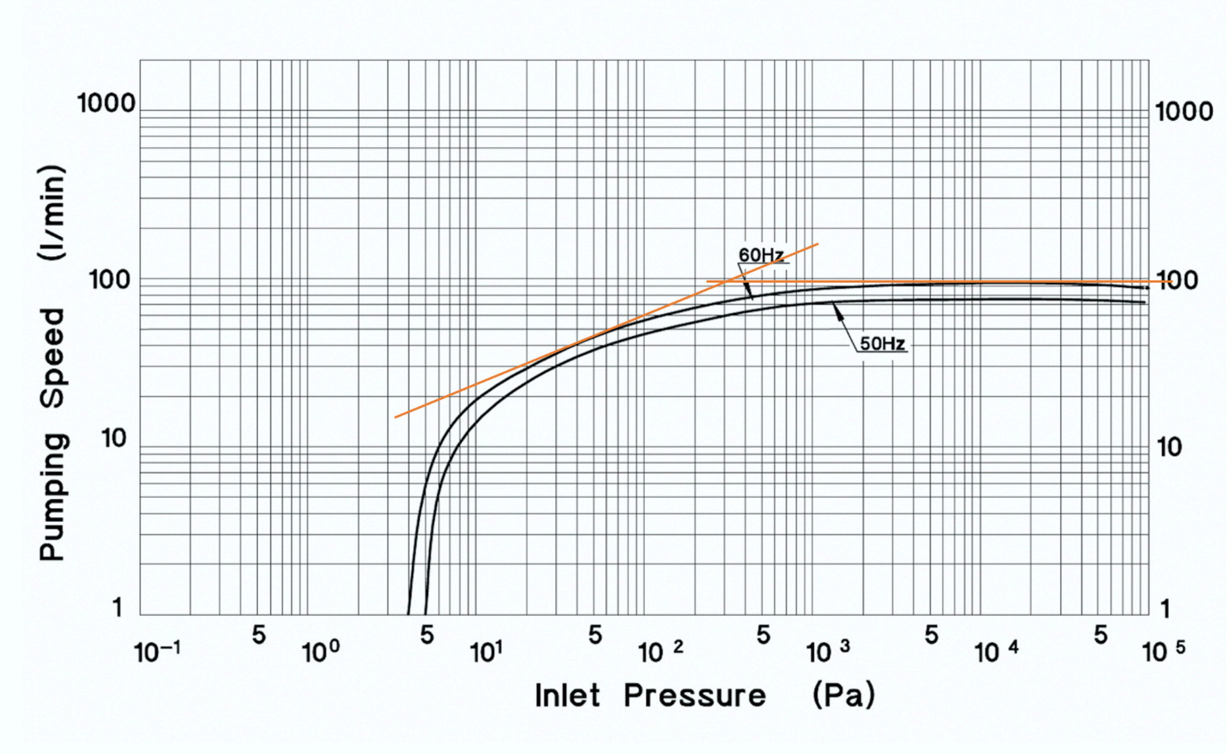

Figure 4.24.b. Determining pressure ranges for pumping time calculation using ISP-90 oil-free scroll mechanical pump speed curve.

$$t_{pd1} = \frac{13\,liters}{93\,liters/min}\,ln\left(\frac{100,000\,Pa - 4\,Pa}{300\,Pa - 4\,Pa}\right) = 0.81\,min.$$

$$t_{pd2} = \frac{13\,liters}{56.5\,liters/min}\,ln\left(\frac{300\,Pa - 4\,Pa}{10\,Pa - 4\,Pa}\right) = 0.90\,min.$$

$$t_{pd} = t_{pd1} + t_{pd2} = 0.81\,min. + 0.90\,min.$$

$$t_{pd} = 1.71\,min. = 1\,min.\ 43\,sec.$$

How does this compare to the pump-down time using the assumption that the pumping speed is a constant 93 liters/min over the entire pressure range? The pump-down calculation using the constant 93 liters/min pumping speed yields a pump-down time of 1.36 minutes, a difference of 0.35 minutes or 20.5%. Is this significant? It depends on the application. Purely from a time perspective, a 20.5% difference can seem substantial. But for this particular result, the pump-down time is so short that it may not make much of a noticeable difference when operating the system.

Section 4.7 Quiz

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## 4.8 Conductance

But wait a minute. What about the effect of the piping if the rough pump has to be placed at some distance from the vacuum chamber? Wouldn't it affect the pump's ability to remove gas from the chamber? The answer is, "It depends."

From our experience in daily life, we know that pipes, or tubes, of varying lengths and cross-sections can conduct gases and liquids with different degrees of difficulty. Say, you are drinking a soft drink through a straw. Drawing the liquid through a regular 8-inch straw poses no great difficulty. Now, imagine that the straw is 30 inches long. It would take more effort to drink the liquid if one had to draw it along the entire length of the straw. Or imagine that an 8-inch straw of one-tenth the diameter is used. It would again require more effort to draw the liquid through the narrower straw.

The ease with which a gas or liquid is drawn through a pathway of given geometry is quantified by a property called ***conductance***. Conductance values depend not only on the pressure and the nature of the gas flow, but also on the shape of the conducting element. Other factors are the conducting element's length and whether it is straight or curved. The result is a large set of equations that take into account various combinations of these elements that affect conductance.

For example, the conductance of a straight pipe, or tube, $C_t$, shown in Figure 4.25, of length $L$ and with a circular cross-section of diameter $d$, operating in the ***laminar flow*** range, is given by

$$C_t = 180 \frac{liters}{cm^3\,Torr\,sec} \frac{d^4}{L}(p_{ave}) \qquad (4.4)$$

where

$C_t$ is the conductance in liters per second,

$d$ is the cross-sectional diameter of the pipe in centimeters,

$L$ is the length of the pipe in centimeters, and

$p_{ave}$ is the average pressure in the pipe in torr,

$$p_{ave} = \frac{p_1 + p_2}{2}$$

where $p_1$ is the pressure at the start of the pipe (along the direction of flow) and $p_2$ is the pressure at the end of the pipe.

### Example 4.10

What is the conductance of a 15-inch long pipe with an inside diameter (ID) of 0.5 inches if the pressure is 20 Torr at the start of the pipe and 1 Torr at the end of the pipe? Assume that the gas flow within the pipe is viscous laminar.

**Solution:**

We are given the following information:

$$L = 15\,inches = 15\,inches \times 2.54\frac{cm}{inch} = 38.1\,cm$$

$$d = 0.5\,inches = 0.5\,inches \times 2.54\frac{cm}{inch} = 1.27\,cm$$

$p_{ave}$ can be calculated from the pressures at the ends of the pipe:

$$p_{ave} = \frac{20\,Torr + 1\,Torr}{2} = 10.5\,Torr$$

Substituting these value into Equation 4.4 yields,

$$C_t = 180\frac{liters}{cm^3\,Torr\,sec} \times \frac{(1.27\,cm)^4}{38.1\,cm} \times (10.5\,Torr)$$

$$C_t = 129\,\frac{liters}{sec}$$

We now ask a follow-up question: Is there a conductance at the aperture where the gas enters the pipe from the chamber? (See Figure 4.26.) There certainly seems to be some congestion occurring here, much like the masses of people leaving a football stadium at the end of the game.

For viscous flow, the conductance of the aperture can be calculated using the following equation,

$$C_a = 20\frac{liters}{cm^2\,sec}\frac{A}{1 - \delta} \qquad (4.5)$$

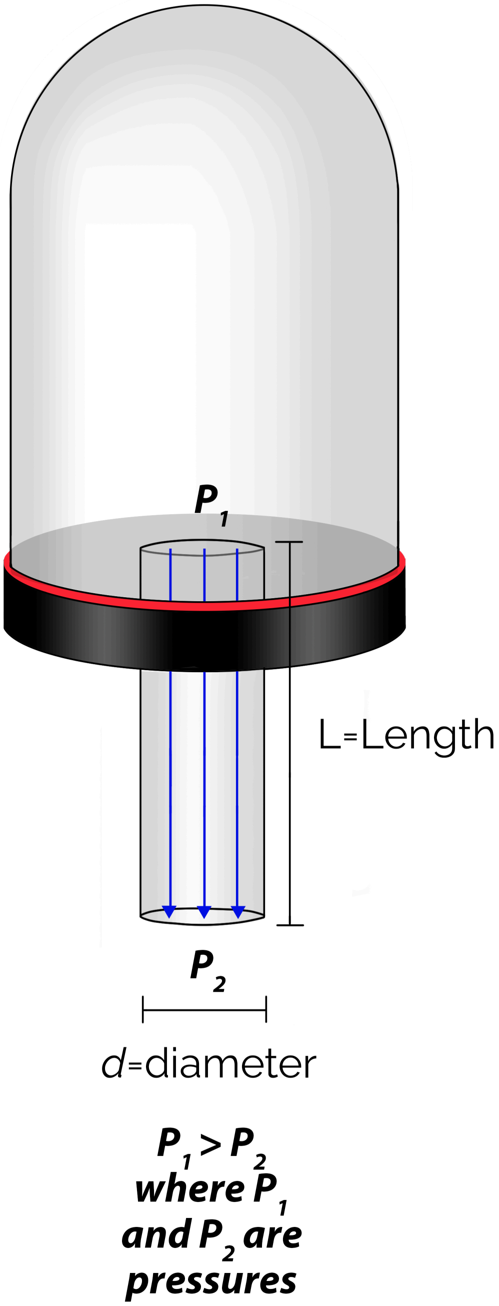

Figure 4.25. Cross-sectional view of pipe carrying gas in laminar flow. Figure created by Gigi Bocek.

where

$C_a$ is the conductance of the aperture in liter per second,

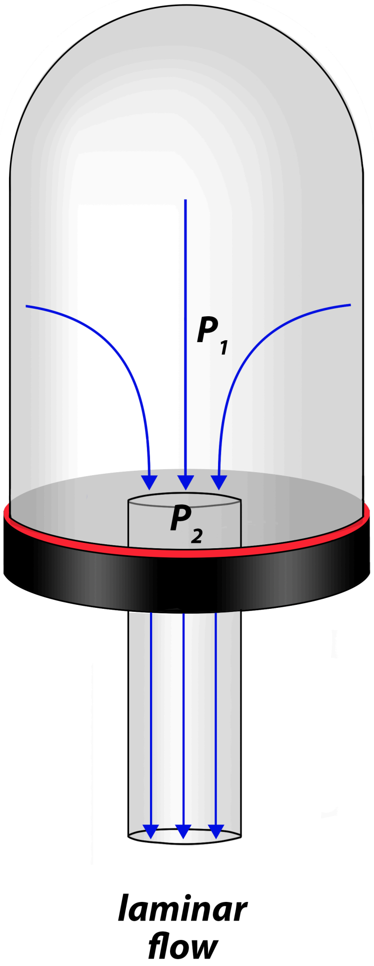

Figure 4.26. Cross-sectional view of chamber, aperture, and tube. Figure created by Gigi Bocek.

$A$ is the cross-sectional area of the aperture in $\text{cm}^2$, and

$\delta$ is the ratio of $P_2$ to $P_1$ where $P_2$ is the pressure in the pipe and $P_1$ is the pressure in the chamber (for the gas to flow out of the chamber and through the pipe to the pump in the system, $P_1$ must be greater than $P_2$).

But, are we in viscous flow? The following condition, based on the ultimate pressure, $P_u$, and the cross-sectional diameter, $d$, of the circular pipe, can be used,

$$P_u \cdot d > 5 \times 10^{-1} \, Torr \cdot cm.$$

For the preceding example, the ultimate pressure was 1 Torr and the diameter of the pipe was 1.27 cm. Applying the test for viscous flow,

$$P_u \cdot d = 1 \, Torr \cdot 1.27 \, cm = 1.27 \, Torr \cdot cm > 5 \times 10^{-1} \, Torr \cdot cm.$$

Thus, the condition for viscous flow is met, and Equation 4.5 can be used.

Note that in the viscous flow, $\delta$ is usually very small and Equation 4.5 reduces to

$$C_a = 20\frac{liters}{cm^2\ sec} \cdot A. \qquad (4.6)$$

As a result, in the viscous flow range, the conductance is not a function of pressure, but only depends on the geometry of the aperture.

Returning to our Example 4.10, we can determine the conductance of an aperture of diameter 0.5 inches, or 1.27 cm. Using Equation 4.6 yields,

$$C_a = 20\frac{liters}{cm^2\ sec} \cdot \left(\pi \cdot \left(\frac{1.27\,cm}{2}\right)^2\right).$$

$$C_a = 25.3\,\frac{liters}{sec}.$$

Since the conductance of the tube and the conductance of the aperture act as series elements, the two conductances can be combined as follows:

$$\frac{1}{C_{net}} = \frac{1}{C_t} + \frac{1}{C_a} \qquad (4.7)$$

or

$$C_{net} = \frac{C_t \cdot C_a}{C_t + C_a}. \qquad (4.8)$$

Substituting our values for our 15-inch long pipe with 0.5-inch diameter yields a net conductance of

$$C_{net} = \frac{129\frac{liters}{sec} \cdot 25.3\frac{liters}{sec}}{129\frac{liters}{sec} + 25.3\frac{liters}{sec}}$$

$$C_{net} = 21.2\,\frac{liters}{sec}.$$

The final step is to calculate the net pumping speed by combining the net conductance of the piping and the pump's speed in series. This has the same form as Equation 3.3.

$$\frac{1}{S_{net}} = \frac{1}{C_{net}} + \frac{1}{S_p} \qquad (4.9)$$

where

$S_{net}$ is the net conductance or pumping speed of the pump plus the piping,

$C_{net}$ is the net conductance of the piping, and

$S_p$ is the pumping speed of the vacuum pump.

Equation 4.9 can be rearranged and an equation for $S_{net}$ can be written,

$$S_{net} = \frac{C_{net} \cdot S_p}{C_{net} + S_p}. \qquad (4.10)$$

Example 4.11

What is the net pumping speed at the outlet of the vacuum chamber if a 90-liter-per-minute mechanical pump is connected to piping in Example 4.10? Give the net pumping speed in liters per second. Assume that viscous flow conditions apply.

**Solution:**

Since the net pumping speed is to be specified in liters per second, the pumping speed of the mechanical pump should be converted to liters per second.

$$S_p = 90\,\frac{liters}{min} \times \frac{1\,min}{60\,sec} = 1.5\,\frac{liters}{sec}.$$

Substituting the given values for $C_{net}$ and $S_p$ into Equation 4.10 yields,

$$S_{net} = \frac{21.2\frac{liters}{sec} \cdot 1.5\frac{liters}{sec}}{21.2\frac{liters}{sec} + 1.5\frac{liters}{sec}}$$

$$S_{net} = 1.40\,\frac{liters}{sec}.$$

In this example, we note that the conductance of the piping is much greater than the pumping speed of the pump. Therefore, the factor limiting the net pumping speed is the pumping speed of the mechanical pump, not the size of the piping. However, this is not always the case.

Section 4.8 Quiz

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## 4.9 Troubleshooting Rough Vacuum Systems

There are a number of things that can go wrong with rough vacuum systems. Knowing the optimal behavior of your vacuum system when it is functioning properly helps in detecting and troubleshooting system problems when they occur. This section discusses some common problems and how to fix them.

## 4.9.1 No Start-Up

Failure to start up is one of the simpler things to diagnose and possibly to fix. The observed symptom is the failure of the mechanical pump to start when the power is turned on. The cause may be that power is not getting to the pump. Corrective action begins with checking the electrical system. This includes checking the power switch to see if it is actually in the ON position, checking the circuit breaker, which may have been switched OFF. Another possibility is an open circuit in the power line running to the pump. A voltmeter can be used to measure the voltage at the pump.

Another possibility is that the pump has frozen or seized up. In this case, the observed symptom may be a whining or buzzing noise indicating that the motor is trying to turn but cannot do so for some reason. If this condition persists, overheating may be detected by a burning odor.

## 4.9.2 Pump is running, but no vacuum is detected

If the pump is operating normally, but the system pressure does not decrease, there are several possible causes. If the mechanical pump uses a belt drive, it is possible that the belt has broken or slipped off the pulley(s). Another possibility is that the rough valve has not been opened. A third possibility is that the vent valve has not been closed and is in the open position. Another possibility is another very large leak to atmosphere exists somewhere in the system.

It is also possible that an accurate pressure reading is not being displayed. If a multi-gauge controller is being used, it may be displaying a reading from the wrong gauge, a gauge in another part of the vacuum system that is looking at atmospheric pressure.

## 4.9.3 Deviation from standard pump-down curve

A deviation from the standard pump-down curve can be caused by an increase in the gas load or a change in the characteristics of the pressure gauge. Increases in the gas load can be caused by leaks in the system or the presence of one or more contaminants in the system or in the vacuum pump, such as condensed water vapor, solvents, or gases in the pump oil.

Pressure readings that are too high, or too low, can be caused by a dirty or contaminated sensor.

## 4.9.4 Cannot reach base pressure

Failure to reach base pressure can be caused by an increase in gas load or a problem within the pump. Increased gas load often results from a leak, but this is not the only cause. Contamination can also increase the gas load significantly and adversely impact the system's ability to achieve base pressure. The most significant contaminant to be mindful of in rough vacuum as well as high vacuum is water vapor.

A drift in the performance of the pressure gauge can also be the cause of a perceived change in the base pressure level attained by the system. In addition, if system's chamber originally contains gas other than air (for example, argon), then direct-reading gauges and indirect-reading gauges will display different values.

Section 4.9 Quiz

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# Summary

Rough vacuum systems are relatively simple and minimally consist of a single mechanical pump, chamber, and pressure gauge, one or more valves, and piping. The types of mechanical pumps used include rotary vane and piston pumps, diaphragm pumps, and scroll pumps. These pumps operate by expanding the volume, trapping a volume of gas, compressing the gas, and finally exhausting the gas from the pump. Pump selection will depend on the application, cost, pumping speed requirements, and space, among other factors.

Vacuum gauges used in rough vacuum systems can be either direct-reading pressure gauges like capacitance manometers or indirect-reading pressure gauges like thermocouple and Pirani gauges. Pressure gauge selection will be influenced by such factors as cost, pressure range, and response time. It is important to remember that thermal conductivity gauges are sensitive to gas type. They are calibrated for nitrogen, but gauge readings for other gases require correction using the correction factors supplied with the pressure gauge. Direct-reading pressure gauge readings do not require correction for gas type.

A wide variety of fittings can be used in rough vacuum systems. KF fittings are the most common ones used in rough vacuum regime. Piping can be made of flexible plastic materials or metals. Again, it depends on the application, cost constraints, and other factors relevant to your application.

Graphing the rough vacuum pump-down curves for your vacuum system will help characterize and establish the nominal performance of your rough vacuum system. By comparing present pump-down curves to past pump-down curves, you can detect changes in system performance and take corrective action, if necessary.

Maintaining rough vacuum systems is relatively easy. Mechanical vacuum pumps require regular maintenance to replace seals and diaphragms and change pump oil. Chambers may require periodic cleaning, depending on what is being pumped.

Troubleshooting rough vacuum systems usually focuses on leaks and worn-out system components. Failure of the vacuum system to pump down to base pressure can be caused by leaks, failure to open the roughing valve, failure to close a manual vent valve, failure of an automatic vent valve to close, or an error with the gauge operation. It can also be caused by wear on system components and may indicate the need for system maintenance to replace worn-out components.

## Chapter 4 Quiz

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## Questions and Problems

1. A 0.50-liter piston pump is connected to a 5-liter chamber. Assume that the pressure in the chamber is

atmospheric pressure (1 atm). What will be the pressure in the chamber after eight strokes of the piston pump?

2. A 0.25-liter piston pump is connected to a 20-liter chamber. How many strokes of the piston pump will be needed to reduce the pressure in the chamber from one atmosphere to 0.75 atmospheres?

3. A diaphragm pump is connected to a cylindrical chamber 15-inches in diameter and 12 inches in length. How long will it take the pump to reduce the pressure in the chamber from atmosphere to 10 Torr? Assume the nominal pumping speed of the pump is 30 liters per minute, the ultimate vacuum pressure, $P_{ult}$, is 1.2 Torr, and the piping from the pump to the chamber is not a limiting factor.

4. A Varian SD-451 mechanical pump is connected to a 200-liter chamber. Assuming that the conductance of the connecting pipe is not a limiting factor, how long will it take to pump down the chamber from atmosphere to 0.5 Torr? Show all calculation and list all assumptions made. Use the following pump specs for your calculations if necessary: nominal pumping speed 14.6 cfm, ultimate pressure $1.5 \times 10^{-3}$ Torr.

5. Calculate the pump-down time for an IDP-7 Dry Scroll Mechanical Vacuum Pump to reduce the pressure in a 450.0-liter chamber from atmosphere to 1 Torr. Use the pump speed curve for the IDP-7 shown in Figure 4.27. Assume that pump connects directly to the chamber and the conductance of the connection between the pump and the chamber is much greater than the effective pumping speed of the pump.

6. Three identical thermal conductivity gauges are used to measure the gas pressure in three identical tanks of equal volume. Each tank contains the same number of moles of gas. Tank 1 contains dry nitrogen gas, Tank 2 contains argon gas, and Tank 3 contains helium gas. Which gauge will read the highest pressure, and why? Which tank will read the lowest pressure and why?

7. Determine the net conductance of a circular pipe 25 cm long and 3.0 cm in diameter if the pressure at one end of the pipe is 30 Torr and at the other end is 4 Torr.

8. Determine the smallest inside diameter (ID) of the aperture between the chamber and the circular pipe necessary to maintain viscous flow. Assume that system uses the IDP-7 dry scroll pump (Figure 4.27). Then calculate the net conductance of the circular aperture with this ID.

9. A 150-liter-per-minute mechanical pump is connected to a 20-inch circular pipe with inside diameter (ID) of 2.0 inches. The pressure in the chamber (and at the start of the pipe) is 80 Torr and 3 Torr at the other end of the pipe. The ultimate pressure of the pump is 0.5 Torr.
    a. Check if viscous flow condition is met.

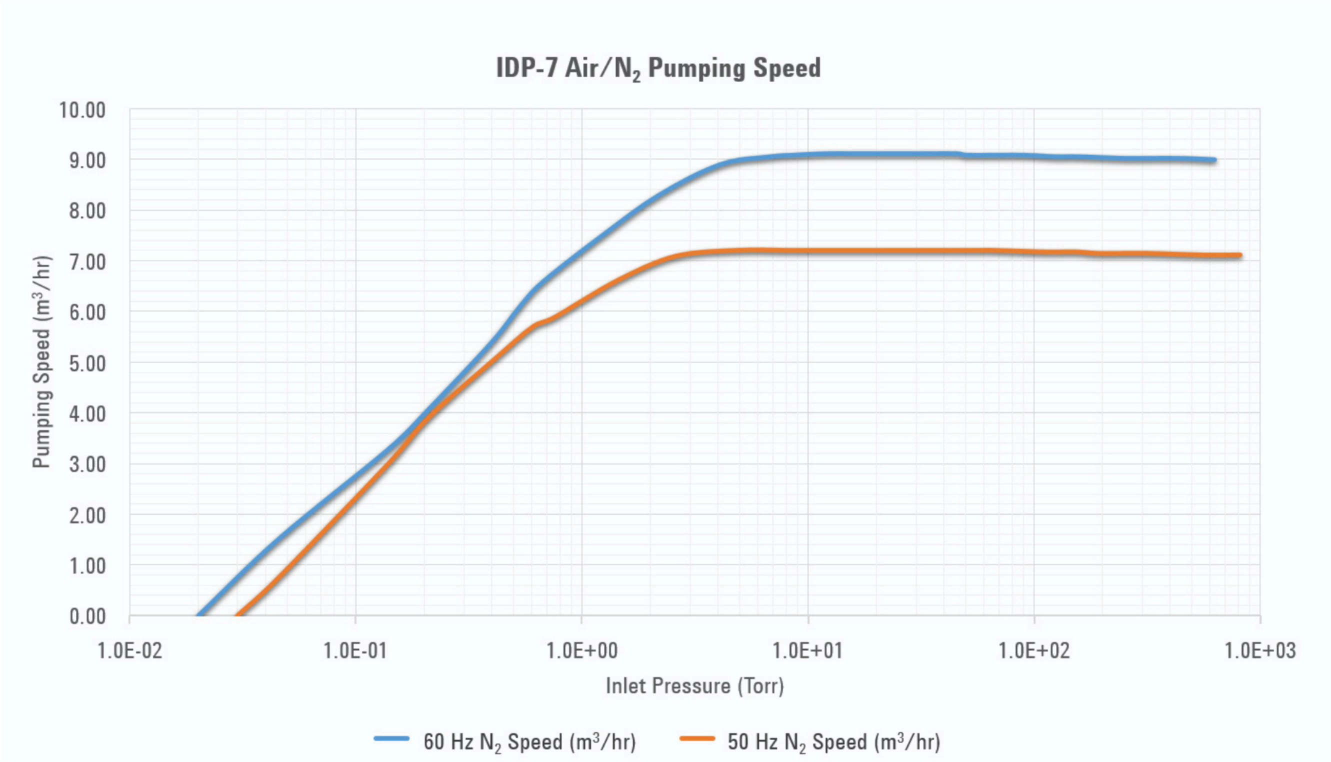

Figure 4.27. Pumping speed curve for IDP-7 dry scroll vacuum pump. Source: Kurt J. Lesker Company, https://www.lesker.com/newweb/vacuum_pumps/pdf/manuals/agilentvarian-idp7-manual.pdf.

b. Calculate the conductance of the given circular pipe.
c. Calculate the conductance of the given circular aperture.
d. Calculate the net pumping speed at the outlet of the vacuum chamber in liters per minute. In liters per second. In m$^3$/hr.

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# GLOSSARY

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***absolute pressure***

The total pressure measured with reference to absolute zero pressure, that is, the condition of perfect vacuum. The following values correspond to absolute zero pressure: 0 Pa = 0 Torr = 0 mbar.

***absolute zero***

The temperature at which gas-phase molecules have zero kinetic energy. This value is known as zero degrees Kelvin (0 K) which is approximately -273.15 $^{o}$C.

***absorption (absorb)***

The taking up of a gas or vapor by a solid or liquid due to physical forces in which the gas diffuses into the bulk of the solid or liquid.

***adsorption (adsorb)***

The taking up of a gas or vapor by a solid or liquid due to physical forces in which the gas is retained at the surface of the solid or the liquid. Adsorbed gases are not bound to a surface permanently.

***atmospheric pressure***

The pressure exerted typically by the Earth's atmosphere. Also see ***standard atmospheric pressure*** and ***standard temperature and pressure (STP)***.

***Avogadro's number***

The number of molecules of an ideal gas that would be contained in 22.4 liters at standard atmospheric pressure and temperature (1 atm, 0 $^{o}$C). This quantity is about 6 x $10^{23}$.

***backing pump***

See ***pump, backing***.

***backstreaming (oil)***

When unwanted gases like oil vapor or particles flow from downstream pumping or other components toward the vacuum chamber or process components, that is, in a direction opposite to the direction of the desired gas flow.

***bar and millibar***

The bar is a metric unit of pressure but is not part of the International System of Units (SI). One bar is exactly equal to 100,000 Pa. The millibar (mbar) is a unit of pressure typically used to express vacuum pressures. One mbar is exactly equal to 100 Pa.

***Bayard Alpert (hot cathode) ion gauge***

See ***gauge, Bayard Alpert (hot cathode) ion***.

***Bourdon gauge***

See ***gauge, Bourdon***.

***Boyle's law***

Gas law that states that if the temperature and the amount of gas are held constant, the volume of gas is inversely proportional to the pressure exerted by the gas.

***bulk gas***

The volume of gas trapped within the chamber and vacuum piping components prior to initiating a pump-down cycle. Also called *volume gas.*

***butterfly valve***

A type of high-vacuum valve with a movable circular plate that is mechanically adjusted to allow varying levels of gas flow through the valve's orifice or block gas flow altogether.

***capacitance diaphragm gauge***

See ***gauge, capacitance diaphragm***.

***capture pumps***

See ***pumps, capture***.

***conflat-type (CF) flange***

A type of de-mountable metal-sealed joint used in vacuum technology that supports ultra-high vacuum operation. Also known as conflat-type (CF) fitting.

***chamber***

The sealed part(s) of pressure-controlled research or production apparatus where vacuum and/or other processes occur.

***Charles's law***

Gas law that states that the volume of a gas is directly proportional to the absolute temperature at a constant pressure. Also known as *the law of volumes*.

***compressibility***

A measure of the instantaneous relative volume change of a fluid or solid as a response to a pressure change.

***condensation***

Generally referring to the condition when gas-phase molecules have adsorbed onto a surface or coalesced within a volume to an extent that this can be visually observed.

***conductance***

A parameter used to represent the ease of a molecule's flow through an obstacle based on the pressure difference on either side of the obstacle.

***convection-enhanced Pirani (thermal) gauge***

See ***gauge, convection-enhanced Pirani (thermal)***.

***cryogenic (cryo) pump***

See ***pump, cryogenic (cryo)***.

***Dalton's law***

The total pressure is equal to the sum of the partial pressures of each gas in the mixture.

***degassing***

The deliberate desorption of gas from a material.

***desorption (desorb)***

The liberation of gases and vapors sorbed (adsorbed and absorbed) by a material.

***diaphragm gauge***

See ***gauge, diaphragm***.

***diaphragm pump***

See ***pump, diaphragm***.

***diffusion***

A process in which atoms or molecules move through a solid, liquid or gas.

***diffusion pump***

See ***pump, diffusion***.

***direct reading (pressure) gauges (manometers)***

See ***gauges, direct reading (pressure) gauges (manometers)***.

***dry pumps***

See ***pumps, dry***.

***effective pumping speed***

The pumping speed that a vacuum pump can provide when it is limited by conductance of a tube and/or an orifice.

***elastomer***

A natural or synthetic polymeric material that demonstrates elastic properties.

***equilibrium vapor pressure***

The pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature in a closed system.

***evaporation***

A process where surface-bound molecules are thermally desorbed from a solid or liquid surface to become part of the gas phase. Evaporation typically takes place below the boiling temperature.

***exhaust line***

A tube that connects the gas outlet from a vacuum system to a building exhaust system.

***feedthrough***

A vacuum component that transfers motion, electrical charge, water, light, heat, etc. into and/or out of a vacuum chamber while maintaining vacuum.

***fluid sealed vacuum pump (wet pump)***

See ***pumps, wet***.

***foreline***

The vacuum tube that connects the output of a high-vacuum diffusion, turbomolecular, and/or drag pump to a rough-vacuum mechanical backing pump.

***freeze, freezing***

The transition of a liquid to a solid by the removal of heat, i.e. lowering the temperature of the liquid. An example is water, a liquid at room temperature, when it turns to ice as the temperature is lowered below its freezing point.

***gage pressure***

The difference between absolute pressure and atmospheric pressure.

***gas ballast pump***

See ***pump, gas ballast***.

***gas load***

The amount of gas that must be removed from the chamber in a vacuum system by the vacuum pump(s). It is typically measured in torr-liters per second, cubic feet per minute, or cubic meters per hour.

***gas molecule***

An individual particle in a vacuum that has neither a defined volume or shape. A gas molecule can be a single atom (e.g., a noble gas such as Argon, Ar) or a number of atoms bonded together to form a compound (e.g., such as water, $H_2O$).

***gas phase***

A structural state of matter in which the thermal motion of the respective molecule species near room temperature is sufficient to exceed any cohesive forces, and permit their free motion. Contrast with term vapor phase.

***gas transfer pumps***

See ***pumps, gas transfer***.

***gate valve***

A large diameter valve usually placed between the vacuum chamber and the vacuum pumps to isolate the vacuum chamber from the pumps when it is necessary to work on something in the chamber.

***gauge, Bayard-Alpert (hot cathode) ion***

A type of indirect reading vacuum gauge in which a heated filament supplies free electrons at a constant controlled rate due to thermionic emission. The number of resulting ions collected in this gauge type is an indication of the total pressure present. The Bayard Alpert ion gauge is the most typical hot-filament ion gauge used.

***gauge, Bourdon***

A type of direct reading vacuum gauge with a thin-walled metal tube bent into a circular arc that will straighten if pressure is applied to the inside of the tube. The movement of the metal tube is used to indicate pressure. Bourdon gauge was invented by Eugene Bourdon (1808-1884), a brilliant French watchmaker and engineer, in 1849.

***gauge, capacitance diaphragm***

A type of direct reading vacuum gauge where a measurement of electrical capacitance of the diaphragm position is used to indicate pressure. Also known as capacitive gauge.

***gauge, convection-enhanced Pirani (thermal)***

A Pirani gauge that incorporates a secondary heated wire, a compensator, which surrounds the primary heated sensor wire. Incorporating the resistance of the compensator wire serves to counteract temperature variations of the gauge body. A convection-enhanced Pirani gauge measures pressures up to atmospheric pressure and thus has a wider pressure measurement range than a basic Pirani gauge.

***gauge, diaphragm***

A manometer-type and direct reading rough vacuum gauge that measures the displacement of a thin solid membrane caused by pressure difference on opposite sides of the membrane.

***gauge, hot-cathode ionization***

An ionization vacuum gauge in which the gas is ionized by electrons emitted from a heated cathode. Also see *ionization vacuum gauges (gauges, ionization). Also can be called hot-filament ionization gauge or hot-filament gauge.*

***gauge, McLeod***

A type of direct reading vacuum gauge which is used to measure very low pressures, down to $10^{-6}$ Torr (1.33 mPa). It was invented in 1874 by Herbert McLeod.

***gauge, MEMS Pirani***

A MEMS Pirani vacuum sensor, gauge or transducer is a device for measuring vacuum gas pressure by measurement of the pressure dependent heat-loss from a heated resistive element deposited on a suspended micro-machined diaphragm. The MEMS Pirani vacuum transducer can measure vacuum gas pressure over a span of 9 decades from atmospheric pressure down to $7.5 \times 10^{-7}$ Torr).

***gauge, piezo-resistive (vacuum)***

Piezoelectricity is the charge created across certain materials when a mechanical stress is applied. Piezoelectric pressure sensors exploit this effect by measuring the voltage across a piezoelectric element generated by the applied pressure. They are very robust and are used in a wide range of industrial applications.

***gauge, piezoelectric (vacuum)***

See ***gauge, piezo-resistive (vacuum)***.

***gauge, Pirani***

A thermal conductivity pressure gauge containing a heated filament having a large temperature coefficient of resistance as an element of a resistive bridge. Because heat dissipation from the filament is a function of the gas pressure in a certain pressure range, filament resistance or power required to maintain a constant filament resistance can be correlated with gas pressure. Invented by German Physicist, Marcello Pirani (1880-1968) in 1906.

***gauge, thermocouple***

A specific type of thermal vacuum gauge where the temperature of the wire sensor is measured with a thermocouple to estimate pressure within the gauge.

***gauges, direct reading (pressure) gauges (manometers)***

Pressure gauges that operate by sensing deflection of a solid or liquid surface caused by momentum transfer to that surface from energetic gas molecules. Direct reading gauges are largely insensitive to gas type.

***gauges, indirect reading (pressure)***

Pressure gauges that measure a property related to gas pressure and then convert that measurement into a gas pressure reading.

***gauges, ionization vacuum***

Vacuum gauges in which the molecular density is determined by measuring the ion current produced in the gas by ionization under controlled conditions. The ion current is directly related to gas density, and hence, is proportional to the gas pressure.

***gauges, pressure***

See ***gauges, vacuum (pressure)***.

***gauges, thermal (conductivity)***

Any one of several vacuum gauges where the temperature of an internal heated wire sensor is measured to estimate pressure.

***gauges, vacuum (pressure)***

One of several types of electrical or mechanical devices used to measure pressure and/or gas density at various locations of a vacuum system.

***Gay-Lussac's law***

Gas law that describes how the absolute pressure of a gas depends on its temperature while the volume of the gas is held constant. Also known as *Amonton's law*.

***hot-cathode ionization gauge***

See ***gauge, hot-cathode ionization***.

***house exhaust system***

A centralized system within a building to remove exhaust gases from pumps and pumping systems.

***hydrogen bond***

Molecules that have a hydrogen bonded to nitrogen, oxygen, or fluorine have unusually strong dipole-dipole attractions called hydrogen bonds.

***ideal gas constant***

The proportionality constant (R) used in the Ideal Gas Law that relates the product of gas pressure (P) in a give volume (V) to the gas temperature (T) and number of molecules (n) present in the volume (i.e., PV = nRT). For P in Torr, V in Liters, and T in Kelvin, the gas constant is approximately $1 \times 10^{-22}$ Torr-Liter /(Molecule-Kelvin).

***indirect reading (pressure) gauges***

See ***gauges, indirect reading (pressure)***.

***ionization vacuum gauges***

See ***gauges, ionization vacuum***.

***ISO flange***

A high vacuum flange that uses a metal O-ring to seal the connection between two components using either clamps or bolts.

***isolation valve***

A valve placed between two components, or parts of a vacuum system, that blocks the flow of gas between the two parts.

***KF (Klein Flansche) flange***

Quick-release flange couplings in sizes DN 16 to DN 40, suitable for low (rough), medium and high vacuum. Elastomer gaskets and metal gaskets can alternatively be used for sealing. KF (Klein Flansche) flange is also known as KF (Klein Flansche fitting).

***kinetic vacuum pumps***

See ***pumps, kinetic vacuum***.

***Knudsen number***

The ratio of the mean-free path of a molecule in a vacuum environment to a characteristic size of that particular vacuum environment.

***laminar flow***

A type of viscous gas flow where particles travel smoothly in regular paths, and the particle velocity is generally much slower near stationary objects in the flow path. No turbulent mixing occurs in viscous gas flow.

***leaks, gross (real)***

A crack, hole, or other pathway that allows gases to pass through from outside the vacuum system to inside the vacuum system. Also known as gross leaks.

***leaks, virtual***

A volume of trapped gas that enters the vacuum system when the system is pumped down.

***lobe blower pump***

See ***pump, Roots (blower)***.

***mBar***

See ***bar and millibar***.

***McLeod gauge***

See ***gauge, McLeod***.

***mean free path (MFP)***

The average distance which a molecule travels between two successive collisions with other molecules of the gas.

***mechanical pumps, mechanical roughing pumps***

See ***pumps, mechanical (roughing)***.

***MEMS Pirani gauge***

See ***gauge, MEMS Pirani***.

***molecular density***

The number of molecules per unit volume of gas.

***molecular flow***

Gas flow in which molecules interact primarily with surfaces in or along the flow path rather than with other molecules. Contrast with ***viscous flow***.

***momentum transfer pump***

See ***pumps, momentum transfer***.

***net pumping speed***

The mean volume flow through the cross section of the inlet port of a vacuum pump after the effect of all conductances have been accounted for.

***O-ring***

A mechanical gasket in a circular shape made of an elastomer with a round cross section or metal such as copper. O-ring is sandwiched between two components and blocks a path which may otherwise allow gas to escape. Essentially, they help to prevents leaks when two components are joined together.

***outgassing***

The process of gas molecules that are weakly bound to a surface, bound to pores or cracks in a material, or diffused into the bulk leaving the surface to become gas-phase molecules. Also known as surface desorption.

***partial pressure***

The pressure exerted by a particular species of gas molecules. According to Dalton's law, the sum of the partial pressures of all the component species in a mixture is equal to the total pressure.

***pascal (Pa) and kilo-pascal (kPa)***

The SI unit of pressure equal to one newton per square meter. There are 101,325 pascals in one standard atmosphere. There are 1,000 Pa in 1 kPa. Named after French mathematician and philosopher, Blaise Pascal (1623-1662).

***permeation (permeability)***

The process of molecular penetration of gases, vapors, or fluids completely through a material.

***piezo-resistive gauge***

See ***gauge, piezo-resistive (vacuum)***.

***piezoelectric vacuum gauge***

*See* ***gauge, piezo-resistive (vacuum)***.

***piezoelectricity***

The ability of certain materials to change resistance or generate an electric charge in response to applied mechanical stress, and vice versa.

***Pirani gauge***

See ***gauge, Pirani***.

***piston (vacuum) pump***

See ***pump, piston (vacuum)***.

***poppet valve***

A valve typically used to control the timing and quantity of gas flow.

***positive displacement pump***

See ***pumps, positive displacement***.

***pressure***

A way of measuring how much force is acting over an area or the perpendicular force per unit area.

***pressure gauges***

See ***gauges, vacuum (pressure)***.

***psi (psig)***

A pressure unit defined as Pounds per Square Inch (of Gas).

***pump, backing***

A rough vacuum pump used in a vacuum system with the inlet of the rough vacuum pump connected to the outlet of a momentum transfer type-high vacuum pump. The rough vacuum pump operates to maintain an effective pressure in the foreline (also called backing line) for the expected throughput.

***pump, claw***

Claw pumps use two claws rotating in opposite directions, like the Roots pump, to capture, compress, and exhaust the gas. Claw pumps can be used to effectively pump corrosive and abrasive gases. They are often combined with Roots pumps to achieve high pumping speeds and pressures in the millitorr range.

***pump, cryogenic (cryo)***

A type of high vacuum pump that uses cold surfaces to remove gas-phase molecules by cryocondensation and/or cryosorption. Often used to refer to a vacuum pump operated with closed-cycle helium refrigeration system. Cryopump technology is based on Gifford-McMahon cryocooler which was first used to make a vacuum pump by Helix Technology Corporation in 1976.

***pump, diaphragm***

A type of dry mechanical, rough vacuum pump that utilizes a movable diaphragm element to displace and compress a volume of gas from an inlet to an outlet region.

***pump, diffusion***

A high vacuum pump that uses a directed stream of heavy vapor molecules to flow gas molecules toward increasing higher pressure regions in the pump. Diffusion pump was invented in 1915 by Wolfgang Gaede.

***pump, gas ballast***

A positive-displacement pump in which a controlled quantity of a suitable non-condensable gas is admitted during the compression part of the cycle so as to reduce the extent of condensation within the pump. This technology was originally developed by Wolfgang Gaede in 1935.

***pump, lobe blower***

See ***pump, Roots (blower)***.

***pump, piston (vacuum)***

A type of positive displacement pump where the high-pressure seal reciprocates with the piston. Also called rotary piston (vacuum) pump.

***pump, reciprocating (vacuum)***

A vacuum pump that draws air by periodically changing the working volume of the pump.

***pump, Roots (blower)***

A rotary plunger type pump where two symmetrically shaped impellors rotate in opposite directions inside the pump housing. Roots pumps are used where great volumes have to be pumped. Also known as *lobe blower pump*.

***pump, rotary vane***

A positive-displacement pump that consists of vanes mounted to a rotor that rotates inside a cavity. Invented by Charles C. Barnes in 1874.

***pump, screw***

A dry mechanical pump that contains two screw rotors which rotate inside a cylinder. The gas is trapped between cylinder and screw chambers and carried to the gas exhaust.

***pump, scroll***

A dry mechanical vacuum pump design that utilizes two intermeshed spirals (i.e., scrolls) to displace and compress a crescent-shaped volume of gas from an inlet to an outlet region.

***pump, vacuum***

A vacuum component that moves gas molecules from a low-pressure region to a higher-pressure region. Vacuum-pump design is typically specific to its operating-pressure region, with the three main pressure regions being low vacuum (i.e., atmospheric pressure to ~$10^{-3}$ Torr), high vacuum (i.e., $10^{-3}$-$10^{-9}$ Torr), and ultra-high vacuum (i.e., less than $10^{-9}$ Torr).

***pumps, capture***

A classification for high vacuum pumps that operate by adsorbing gas-phase molecules onto a surface or into a bulk material.

***pumps, dry***

Vacuum pumps that use no fluids for sealing or momentum transfer.

***pumps, gas transfer***

Vacuum pumps that remove gas from the vacuum chamber, move it through the pump, and then exhaust the gas to the building exhaust system or into the environment.

***pumps, kinetic vacuum***

Kinetic vacuum pumps use various mechanisms to transfer momentum to gas molecules in order to move them toward the outlet port of the pump. Diffusion pumps use oil jets to impart momentum to gas molecules while turbomolecular pumps use high-speed turbine blades.

***pumps, mechanical (roughing)***

In vacuum systems, mechanical pumps are motor-driven pumps that move gas from the inlet port to outlet port using a mechanical mechanism, e.g. rotary vanes, scrolls, pistons, and diaphragms among others.

***pumps, momentum transfer***

A classification of pump where one part of the pump (either a solid component or molecular vapor) imparts preferred momentum to gas-phase molecules.

***pumps, positive displacement***

A classification of pump that captures a volume of gas near the inlet and mechanically displaces it to the outlet. Often compression of the captured volume occurs between the inlet and the outlet.

***pumps, rotary (vacuum)***

Mechanical pump that utilizes rotary motion to drive pumping mechanism. Examples of rotary pumps are *screw pump, lobe blower pump*, and *rotary vane pump*.

***pumps, rough (vacuum)***

See ***pumps, mechanical (roughing)***.

***pumps, roughing (vacuum)***

See ***pumps, mechanical (roughing)***.

***pumps, wet***

A vacuum pump that uses a fluid or vapor for sealing or momentum-transfer. Also known as fluid sealed vacuum pump.

***pump down***

Commonly used term for evacuation of a vacuum chamber from atmospheric pressure to a pre-defined base pressure.

***pump-down curve***

Graph describing a time-dependent pressure drop in a vacuum system; popular control instrument when designing and operating a vacuum system.

***pump-down time***

Time required to evacuate a chamber from atmospheric to a predefined base pressure.

***pumping speed***

The volume of gas that will flow past a given plane in a gas flow path in a given amount of time. Units are in volume per time (e.g., Liters per second). See also ***Volumetric Flow Rate***.

***pumping speed curve***

A graphical representation of the pumping speed performance of a pump as a function of the pressure of the gas being pumped.

***rarefaction***

Decrease in density of gas.

***real leak***

See ***leaks, gross (real)***.

***reciprocating (vacuum) pump***

See ***pump, reciprocating (vacuum)***.

***retard***

Delay in time.

***Roots (blower) pump***

See ***pump, Roots (blower)***.

***rotary piston (vacuum) pump***

See ***pump, piston (vacuum)***.

***rotary (vacuum) pump***

See ***pumps, rotary (vacuum)***.

***rotary vane pump***

See ***pump, rotary vane***.

***rough (vacuum) pump***

See ***pumps, mechanical (roughing)***.

***rough vacuum (pressure) regime***

Vacuum pressure regime with pressures between 760 Torr and 1 X $10^{-3}$ Torr.

***roughing, roughing line***

Roughing a vacuum chamber indicates that it is being evacuated with a low-vacuum pump through a roughing line from atmospheric pressure to a pressure that is sufficiently low to allow a high vacuum pump to be engaged.

***roughing pump***

*See* ***pumps, mechanical (roughing)***.

***saturation***

The state or process that occurs when no more of something can be absorbed, combined with, or added.

***saturation vapor pressure***

*The pressure exerted by a vapor which is in thermodynamic equilibrium with one of its condensed phases at the prevailing temperature.*

***screw pump***

See ***pump, screw***.

***scroll pump***

See ***pump, scroll***.

***series conductance***

When various vacuum components, each with different values of conductance, are arranged in a single flow path, therefore requiring each gas molecule to transit through each vacuum component.

***SI***

International System of Units (Abbreviation of French: *Systeme International d'unites*). The only system of measurement with official status in nearly every country in the world.

***standard atmospheric pressure***

Pressure defined in 1925 by the National Advisory Committee for Aeronautics as 760 Torr (101,325 Pascal, or 1013.25 mBar, or 29.9213 inches of Hg) for a "normal" day at 0°C and at sea level.

***standard temperature and pressure (STP)***

In vacuum technology, defined as a temperature of 273 K (0º C, 32º F) and an absolute pressure of exactly one standard atmosphere (1 atm, 760 Torr, or 101.325 kPa at sea level). Since 1982, Defined by IUPAC (International Union of Pure and Applied Chemistry) as a temperature of 273 K (0º C, 32ºF) and an absolute pressure of exactly 105 Pa (100 kPa, 1 bar).

***sublimation***

Transition of a substance directly from a solid state/phase to a gas state/phase.

***surface outgassing***

The release of surface-bound molecules to the gas phase. For most vacuum systems, the main species of surface-bound molecule is water. Measured as a mass flow rate (e.g., in Torr-Liters/sec).

***thermal (conductivity) gauges***

See ***gauges, thermal (conductivity)***.

***thermocouple gauge***

See ***gauge, thermocouple***.

***throttle valve (throttling valve)***

A vacuum valve that can be controlled by the operator to be only partially open (or partially closed). Allows to control pumping speed by decreasing conductance (to throttle) between a vacuum chamber and a vacuum pump.

***throughput***

Term used to indicate molecular flow rate or mass flow rate. Identifies number of molecules flowing past a plane in a flow path. Units are in Pressure x Volume / Time (e.g., Torr-Liter/Sec).

***torr***

Widely used (but non-SI) pressure unit in vacuum technology, equal to 1 mm of mercury in a historic barometer, and named after Italian physicist Evangelista Torricelli (1608-1647). Torr is still widely used in the US, and is therefore the pressure unit primarily used in this e-book.

***ultimate pressure***

Lowest attainable pressure in a vacuum system. In a vacuum pump, the lowest pressure that can be attained with that pump. Ultimate pressure is limited by the pumping speed of the vacuum pump and the vapor pressure of the sealing fluid, among other factors.

***universal gas constant***

See ***ideal gas constant***.

***vacuum***

A "prefect vacuum" is defined as a space that is entirely devoid of any gas molecules. However, in vacuum technology, the more useful definition is a space in which the density of gas molecules is significantly reduced below that of atmospheric pressure, or where the mean-free-path is sufficient to conduct the desired vacuum process.

***vacuum chamber***

See ***chamber***.

***vacuum component***

Any one of the many parts that are required to construct a functioning vacuum system, or parts required to undertake and control a vacuum process.

***vacuum fluid***

Generally, an organic or inorganic fluid that has a sufficiently low vapor pressure, as well as chemical and thermal stability to enable effective use as a lubricant and/or sealant in certain vacuum systems or processes.

***vacuum (pressure) gauges***

See ***gauges, vacuum (pressure)***.

***vacuum grease***

A two-part mixture comprised of vacuum-fluid molecules (i.e., base gel) and much larger molecules or particles (i.e., thickener). The components of the mixture are selected to demonstrate desirable mechanical, thermal, and other properties, and also demonstrate sufficiently low vapor pressure to allow its use as a lubricant and/or sealant in a certain vacuum systems or processes.

***vacuum piping components***

Vacuum piping components provide pathway for the gas to flow within a vacuum system. Examples of vacuum piping components are tees, nipples, elbows, crosses, reducers, and flanges or fittings.

***vacuum pump***

See ***pump, vacuum***.

***vacuum technology***

A body of knowledge and related skills required to undertake processes and measurements under conditions of sub-atmospheric pressure.

***vapor, vapor state***

The term “vapor” is often used when a material may be present in several phases within a vacuum chamber at a given pressure. For example, during thermal evaporation of a metal, metal generally exists as a solid source, then as a pool of liquid metal as the temperature increases, and finally as a metal vapor evaporating from the surface of the liquid. The evaporated metal vapor will re-condense into a solid when it adsorbs onto any relatively cool surface (i.e., a substrate).

***vaporization***

Conversion of a substance from the liquid state/phase to the gas (vapor) state/phase.

***vent valve***

Part of a vacuum system that controls the flow of outside air (or gas) into the vacuum chamber.

***virtual leak***

See ***leaks, virtual***.

***viscous flow***

Gas flow in which molecules interact primarily with other molecules, rather than with surfaces in or along the flow path. Contrast with ***molecular flow***.

***volume flow rate (volumetric flow rate)***

The volume of gas that will flow past a given plane in a gas flow path in a given amount of time. Units are in volume per time (e.g., Liters per second). See also ***pumping speed***.

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