

**LOW PRESSURE EXPERIMENTS
AND
MODELING
FOR
HIGH SCHOOL SCIENCE CURRICULA**



Science and Technology
of
Materials, Interfaces and
Processing

**A STEM WORKSHOP CONDUCTED BY
THE EDUCATION COMMITTEE
AVS SCIENCE & TECHNOLOGY OF
MATERIALS, INTERFACES AND PROCESSING
SOCIETY**

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PREFACE

The AVS Science and Technology Society is a nonprofit organization which promotes communication, dissemination of knowledge, recommended practices, research, and education in technologies that require vacuum and other controlled environments. The Society publishes research in these topics and conducts various local and national educational programs for engineers, scientists, and technicians. The Society also recognizes the national need and impact of a technical workforce that keeps pace with the new technologies developed by its members. The AVS supports numerous outreach activities aimed at teacher enhancement and student science awareness and education. Through these various outreach programs, the Society is able to share the collective and individual expertise of its members with schools, teachers and students.

The two day professional development workshop associated with this workbook emphasizes the fundamentals of science, technology, engineering, and mathematics (STEM) and how they integrate into high school science curricula. Emphasis is made of the critical role high school teachers have in the influence of student's attitudes, interest, and fundamental perception of science and technology. Career opportunities in science, technology and engineering are also introduced.

This workshop is divided into three parts:

1. Lectures that underline the essential STEM concepts that relate the pressure, temperature, and volume to the theory, model, and observations presented.
2. Vacuum related demonstrations that reinforce the STEM topics discussed.
3. Ample time for participants to discuss and complete "hands-on" vacuum related experiences within small groups of science educators.

The workshop hands-on experiences are designed to relate vacuum technology with everyday phenomena, familiar to students; strengthen the mathematics connection to scientific observations; expand participant appreciation of STEM's role in student experimental activities. This workbook supplements and compliments the workshop activities. The book contains instructional and application-oriented materials to focus participant's interest on vacuum related engineering science concepts that can be developed or expanded for classroom use. This document is built from earlier contributions, edits, and arrangements by James Solomon.

Additional resource information is available at www.avs.org under "Education and Outreach"

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1. INTRODUCTION

There is a perception that science and engineering are distinctly different disciplines. Scientists wonder "why" and engineers "how". Perhaps this is the situation in a very broad stroke painting but, in fact, the thinking, problem solving, and expectations of technicians, scientists and engineers is more alike than different in the current technology driven world. This technology influence on research and product development is particularly the case when the situation under investigation requires a controlled pressure environment. For example, were Edison's efforts to improve vacuum pump technology driven by the desire to explore molecule behavior in low pressure environments or simply solve the inventor's problems associated with molecule behavior that caused light bulb filament failure? Is the international space station about science in a vacuum environment or knowledge and technology that will be of value just a few of miles below the station?

The focus of this workshop is to bring the attention of its participants to the different aspects of the natural and physical sciences as they relate to observations of different pressure environments generated with a vacuum system. Attention is directed to engineering perspectives of these phenomena and the impact that thought process has had, and continues to have, on our lives. The "hands on" format interspersed with lectures and group exercises provide a variety of learning experiences that always focus participants on the impact that pressure, volume, and temperature have on the theory, model and observation activities performed in this Workshop.

The overall Workshop goal is to present an integrating perspective of the interaction between science, engineering, and technology using mathematics as a tool to accomplish those interconnections. This Workshop relies on the premise that predictable events that occur when the pressure of an environment is manipulated are interesting to students. The Workshop begins with a review of popular demonstrations and exploration of new applications for vacuum in the high school science curriculum. This is followed by a general introduction to technologies that rely on a vacuum (low pressure) environment. The workshop concludes with a review of the operation, maintenance, and safety precautions related to the vacuum experiment station used in this workshop.

In summary, the Science Educators Workshop deals with the science and engineering aspects of the temperature and volume impact on systems at specified and controlled pressures. The pressure reflects the force applied to that system while the temperature and volume indicate the energy impact on the system. Changes in these parameters alter the system's thermodynamic properties and reflect a new state for the system that can spark an observer's curiosity. Our intent is to connect student observation curiosity to the STEM skills needed to really explore these curiosities.

2. CONTROLLED ENVIRONMENT EXPERIMENTS

Successful classroom demonstrations typically share a set of characteristics. First, the demonstration must be safe; easy to assimilate in a group situation; and free of embedded visual or audio impediments. Demonstrations must also assure: that the information registered by the observer's senses actually makes sense to the observer, provide the observer with insight into but not necessarily answers about the phenomena associated with the demonstration; and be inexpensive to operate, maintain, and repeat.

Some science demonstrations possess these three characteristics even for observers of different ages. Many vacuum based classroom demonstrations reflect this quality. A list of vacuum environment classroom demonstrations is provided below. The marshmallow demonstration is a classic that is suitable for all grades. The difference, of course, is the intent of the demonstration and the expectations of the observer. For the fifth grader, the initial expansion of the marshmallow provides both entertainment and an opportunity to explore the importance of normal but invisible atmospheric pressure. The tenth grader might be more focused on the reasons for the marshmallow's collapsed final state.

Classroom demonstrations and experiments that use vacuum

- Demonstrations and experiments included in this workshop
 - adiabatic expansion
 - pressure impact on:
 - marshmallows
 - vacuum plates (Magdeburg spheres)
 - pump speed
 - falling feather
 - gas laws -Boyle's law
 - latent heat
 - triple point of water
 - transmission of sound
- Other demonstrations and experiments
 - air resistance and gravity
 - Archimedes Principle
 - electron emission
 - heat transfer
 - index of refraction of air
 - ionization of gases
 - pressure effects on a pendulum
 - refractive index of air and other gases
 - sublimation of ice
 - thermionic effect - measuring pressure thin film growth
 - vapor pressure of water
 - speed of sound as a function of pressure

All of the demonstrations listed above meet the requirements of a good classroom demonstration. Many of them will work with a variety of age groups. None of them will be successful unless some attention is paid to the vacuum system that supports the demonstration. Vacuum systems are a safe and easy-to-use educational tool. The reluctance of some educators to use a vacuum system stems most often from our natural tendency to avoid using equipment that is unfamiliar to us. Vacuum systems, however, are quite durable and dependable with just a very little bit of TLC. The simple system illustrated in Figure 2.1 is actually a perfect match to the technology needed for most vacuum science demonstrations and experiments for all grades. The diagram shows a vacuum chamber that is connected to a pump. The pump is run by an electric motor. The pressure environment inside the vacuum chamber is monitored by a gauge. A valve is used to return the system to atmospheric pressure.

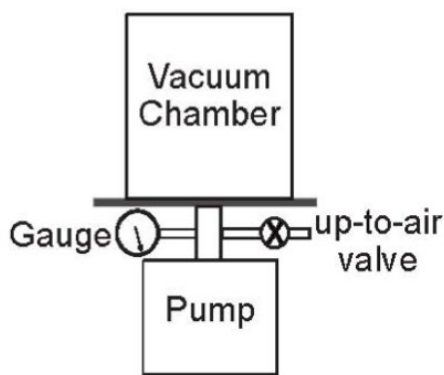


Figure 2.1. Schematic diagram of simple vacuum

In this workshop, different pumps, shown in Figure 2.2, are available to perform the various demonstrations and experiments. Although the connections between these pumps and vacuum jars may be different, the basic system configurations with these pumps are all similar to that shown in Figure 2.1.



Yellow Jacket SuperEvac
Ritchie Engineering Co., Inc.
www.yellowjacket.com



Robinair 15400 Cool Tech
Robinair / SPX Corporation
www.robinair.com



J/B DV-142N
J/B Industries
www.jbind.com

Figure 2.2. Vacuum pumps used in the workshop.

2.1 Expanding Balloon

The pressure inside a deflated balloon is about the same as the surrounding atmosphere. To inflate the balloon, the pressure inside is increased by forcing gas into it. The expansion of the balloon is opposed, partly by the material of which it is made and partly by the pressure of the atmosphere acting on the outside of the balloon. Thus, for a deflated sealed balloon, if the pressure of the atmosphere on the outside of the balloon is removed, the only requirement for expansion is the force needed to stretch the balloon material.

To demonstrate, tie off the neck of the balloon, leaving a little air at atmospheric pressure trapped inside. Place the balloon in the vacuum jar, as illustrated by the smallest circle in Figure 2.3, and evacuate the vacuum jar. As soon as the air removal begins, the balloon begins to expand since the pressure (force/ area of balloon surface) inside now exceeds that of the surrounding air. When the pump has removed all the air, the size of the balloon will depend on the volume of the air in it and the resilience of the balloon material.

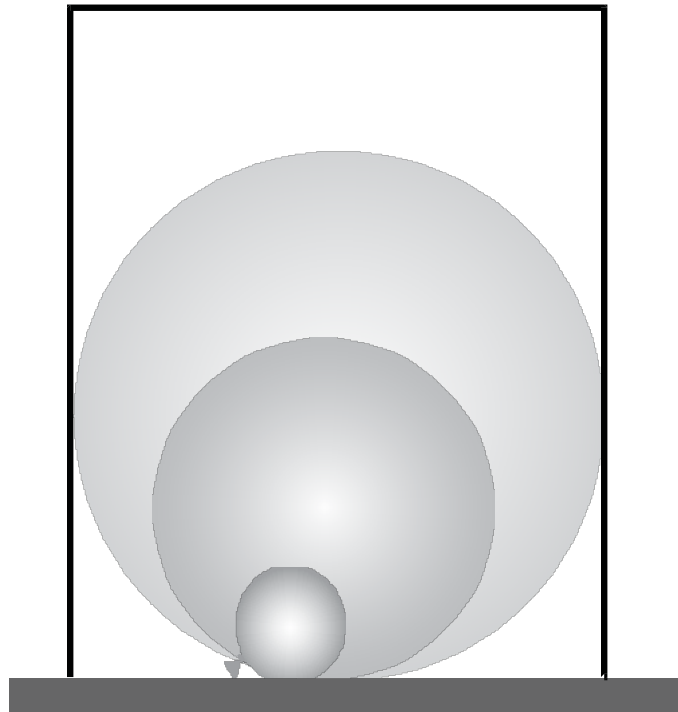


Figure 2.3. Expanding a balloon in a vacuum cham-

2.2 Falling Feather

The velocity of an object moving through air is impeded by the air resistance. At low velocities the resistance is normally insignificant; at high velocities the retarding force

can be important as in aerodynamics. All moving bodies feel a certain resistance as evidenced by watching a feather or a piece of paper fall to the ground. This effect can be demonstrated by observing an object falling a fixed distance in both atmosphere and vacuum. To demonstrate, a 'light' feather and a 'heavy' piece of metal are dropped simultaneously in the vacuum jar which is alternately at atmosphere and low pressure. The feather, being affected more by the air resistance will not fall as quickly as the piece of metal in air. However, in the evacuated vacuum jar, where the retarding force due to the presence of air is removed, the rate of fall will be the same for both the feather and the piece of metal.

Practical Points

- I. Use a piece of metal that is magnetic. Suspend it on the inner topside of the vacuum jar using a magnet as shown in Figure 2.4 with a feather partially sandwiched between the metal and the inner face of the vacuum jar.
- II. The feather should be extremely light to enhance the effect since the distance that the objects fall is not very great. Down feathers work best.
- III. Do not sandwich the feather completely between the metal and vacuum jar face - they might stick together nulling the effect. Remove the magnet quickly when demonstrating.

Discussion:

Discuss the effect of the mass of the falling body on its drop time. Distinguish between total force and force per unit area (why does a parachute work?). Check out the advanced experiments section at <http://www.avs.org/education.workshop> for an advanced experiment on the acceleration of gravity.

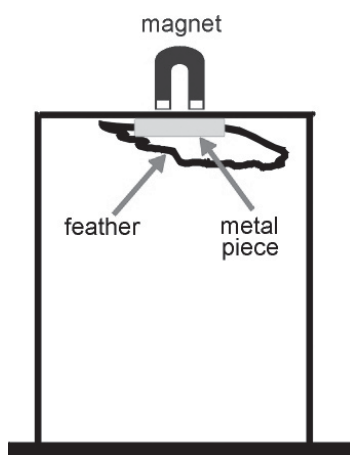


Figure 2.4. Setup for observing a falling feather in a vacuum chamber.

2.3 Transmission of Sound

Sound transmission requires a medium, such as a gas, liquid or solid. In air or any other gas, sound is transmitted by collisions between the molecules making up the gas. The molecules close to the source of the sound move in unison with its vibration. The movement of the molecules has the same amplitude and frequency as the source. This motion is transmitted by successive collisions between these molecules and other gas molecules, resulting in a wave-like transfer of vibrations outward from the source to a receiver, with a gradual decrease in the amplitude of the vibrations. This means that if no air or other gas is present, the sound will not be transmitted.

The effect of air pressure on sound transmission can be demonstrated with any number of sound producing devices, such as a mechanical alarm clock with external clapper, a radio, or a bursting balloon. Regardless of the device used, however, it is important to provide as much vibration dampening as possible between the sound source and the vacuum chamber since any solid-solid contact can also act as a transmission medium. A setup for demonstrating the absence of sound in vacuum is shown in Figure 2.5.

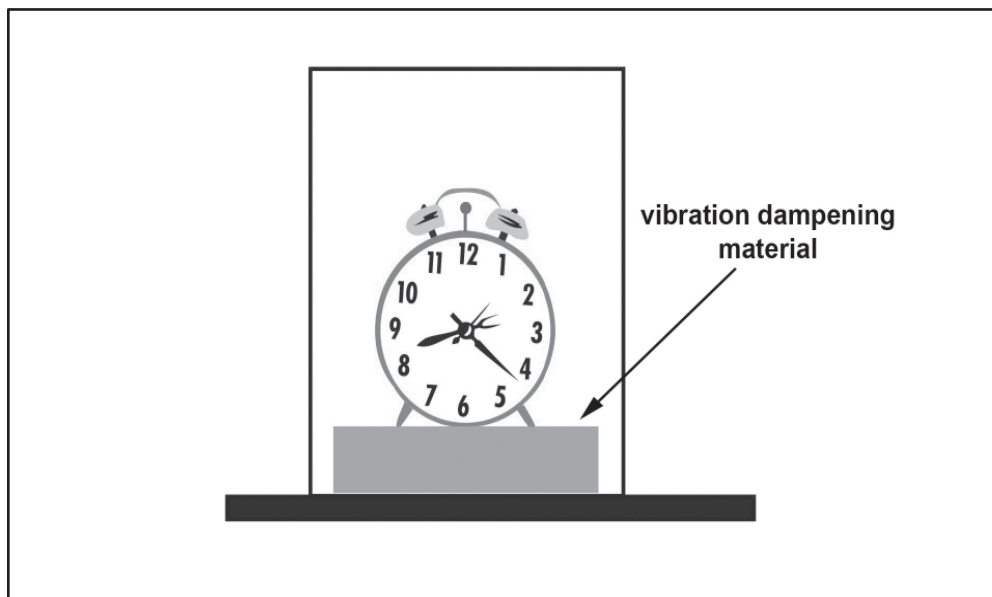


Figure 2.5. Setup for demonstrating the absence of sound in a vacuum.

Supplemental information. Sound emitting diode

A very effective device for demonstrating the difference between sound and electromagnetic radiation transmission is a battery powered photo sensitive device with light emitting diodes and a sound emitting piezo buzzer that can be controlled outside the vacuum chamber. With such a device the point can be made that while sound transmis-

sion is dependent on a gas, liquid or solid medium, electromagnetic radiation such as heat, light or radio waves require no medium for transmission. A schematic diagram for such a device is shown in Figure 2.6. With such a device, a demonstration could illustrate that sound transmission uses a gas or solid medium, electro-magnetic radiation (such as heat, light and radio waves) requires no medium for transmission.

The circuit is simple to build from parts available at electronic stores (Radio Shack part number are listed) and is easy to explain to students who have some knowledge of the voltage and current concept. It uses a 9 volt battery to supply operating energy to the photo cell, the light emitting diodes (LED's), and the piezo buzzer. The potentiometer that is serially connected between the photo cell and the battery terminal adjusts the voltage and current conditions at the base of the NPN transistor. The base input, in turn, determines if there is an adequate connection between the emitter and collector terminals of the transistor. If that connection is met, then the five LED's will light up since they will now be connected across the 9 volt battery. Naturally, the piezo buzzer will also vibrate since it is connected in parallel with the LED's. The vibrating buzzer will be easily heard at normal atmospheric pressure. The connection between the emitter and the collector of the transistor will support the current flow necessary to turn on the piezo buzzer when light is shown onto the photo cell.

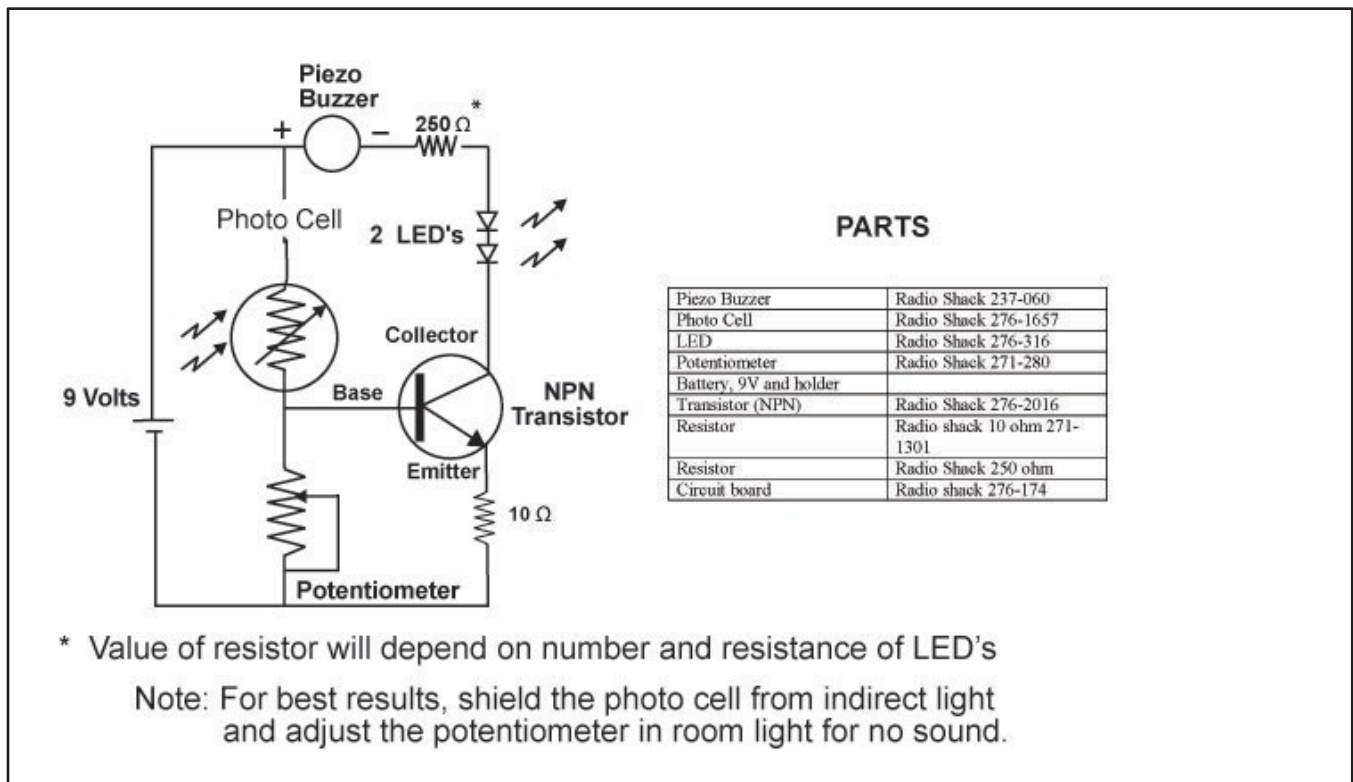


Figure 2.6. Schematic diagram for a sound emitting device controlled by a visible

2.4 Expanding Marshmallows

Marshmallows are colloids made with sugary polymers with gas or air trapped inside of the polymer. As we apply vacuum each one of the little bubbles filled with gas will expand as it happens with the case of the expanding balloon. When this happens we can see the marshmallows expanding/growing rapidly. The difference with the balloon is that in the marshmallow those bubbles reach a point of maximum expansion and burst. At this point the marshmallows shrink and collapse to a volume much smaller than the initial volume because the gas inside of the bubble was removed.

If the expansion before the bursting of the bubbles is stopped by reducing the vacuum inside the chamber the original size of the marshmallows can be restored when the pressure reaches the atmospheric pressure.

For the experiment put a few marshmallows inside the vacuum chamber as shown in Figure 2.7. Protect the exhaust port so no particles from the marshmallows reach the pump. Sugar from the marshmallows can produce damage to the oil vacuum pumps. After the experiment is done DO NOT allow anyone to eat the marshmallows since they are probably contaminated with pump oil.

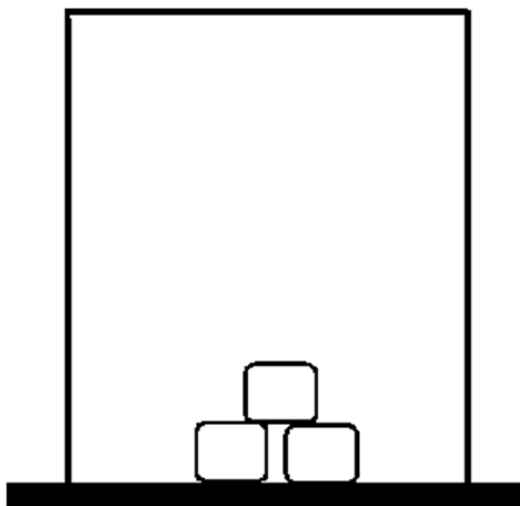


Figure 2.7. Expanding marshmallows experiment set up

3. WORKING WITH MODELS

The best quality of STEM as an education vehicle is the satisfactory feeling generated when a concept is completely understood in terms of the science, technology, engineering, and math involved in the concept. This kind of reinforcement is actually the result of a three component process in which all three parts are equal in value: theory, model, and observation. However, Figure 3.1 does illustrate the problem. When a physical phenomenon is completely understood it can be explained by a satisfactory theory, successfully described by a mathematical model and characterized by repeatable observations. The challenge is to recognize that the complete success (the ideal situation) is not the real situation. In actual situations, the puzzle pieces don't quite fit together. Fortunately, an ideal situation investigation is often close enough to the reality to make that an important exercise.

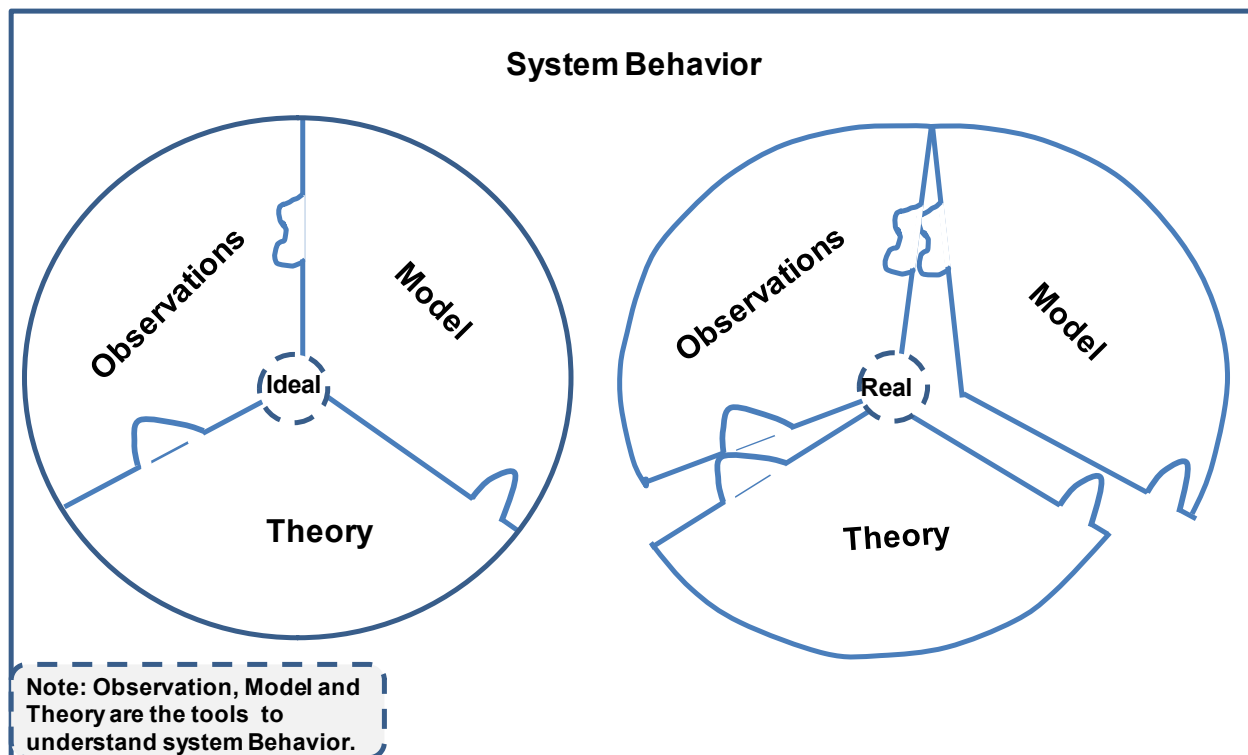


Figure 3.1. Ideal and Real Perspective for Understanding a System

Although an attempt to completely understand any concept in the natural or physical sciences requires success in all three of the puzzle component steps, usually it does not matter which of the three steps is attacked first. In fact, there are many important historical examples where each of the steps, theory, observation, or model were first in the development of the understanding of a scientific principle. There is, however, a recognized procedure after the process has begun. This process involves cycling and recycling through each of the three steps until there is a reliable recognized link between theory, the observation, and model for the phenomena in question.

For example, if the quest for new knowledge begins with the observation step it is common for many repeated observations to be made to confirm that initial observations are valid and precise. (Accuracy is not the focus since new knowledge pursuit usually does not include existing “truthful” measurable values.) The next phase is often to find a mathematical model that will describe the observations and perhaps facilitate predictions about additional experiments to confirm the observations. Finally, the third step in this case, is to develop a theory that complements the model and the observations. Once this process cycle has been completed and the conclusions are acceptable (based on the current state of knowledge about the subject), the theory, with or without some alterations, may be used to enter a new cycle for a different but related scientific phenomena that is subsequently characterized by experimental observations and ultimately described by accurate values determined from related mathematical models.

3.1 The Role of the Model

This workbook uses the term “model” to refer to the set of mathematical statements, equations, or functions that are intended to quantify a phenomenon of interest. By contrast, theory is a set of verbal generated images that facilitate the description of the phenomena to others. For example, the kinetic theory of gases is the description of molecular activity as it relates to energy and molecule motion. There are many excellent verbal descriptions and predictions of molecular behavior as proposed by the kinetic theory, and there is a specific set of mathematical relationships (equations) that quantify these descriptive statements.

The theory of ideal gas behavior is one subset of the kinetic theory of gases and comes with its own set of observations and models. Ideal gas behavior is centered on three assumptions: First, the molecules in the gas state are spherical in nature; Second, molecular collisions are completely elastic; Third, there are no chemical or electron interactions between different types of molecules when they share the same volumetric space. For this situation, a great model to use is the classic chemistry and physics mathematical equation, $PV = nRT$. This model translates the theories verbal and mental images into sets of tangible parameters (P, V, and T) that can be observed and measured. This workshop manual focuses on these three parameters as functions of time.

Granted, the distinction between theory and model provided above has an arbitrary tint to it. Most of the time, it is easy to mentally separate the theory from the model and proceed with the experimental exploration of the phenomena of interest. There are few times when the person(s) doing the investigation really has to stop and describe the actual three step process (theory, model, and observation) that is occurring. The only significant result is related to the success that the person has connecting the three steps. However, for students who are new to this way of thinking about scientific ideas, it is certainly helpful to separate the steps of the process so that they can recognize each phase of the puzzle-solving procedure.

Since working with any of the steps of this process is equally difficult to students, in the long run it does not make any difference which step is tackled first. However, when there are instructional time limitations there is a tendency to down play or even skip the model's role in the process. It is very important that students are exposed to all three aspects of this scientific method as well as their ultimate synergy if they are to successfully assimilate the complete process and make it their own. Ownership of this process provides the strong foundation for securing problem solving and troubleshooting skills.

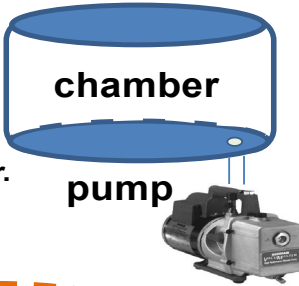
3.2 Skills Needed to Manipulate Some Common Models

The incredible contribution of the 19th century science, mathematics, and engineering community is based on the legacy from the study of engineering and science

Math: As STEM Tools

(i) Situation #1: Linear Model

$y = mx + b$



chamber

pump

Air is forced to enter chamber that already contains 7 liters of air.

A classic non-rhyming but important memory limerick.

$$\left(\frac{5 \text{ liter of air}}{15 \text{ seconds}}\right)(60 \text{ seconds}) + 7 \text{ liters of air} = \left[\left(\frac{5}{15}\right)(60) + 7\right] \text{ liters of air}$$

This model states a linear connection between the existing volume of gas in a container (7 liters of air) and the amount that will be in the container after 60 seconds.

$e^{-[1]}$ (The approximate value of this number is worth remembering!) $\leftrightarrow \frac{1}{e} = \frac{1}{2.718} = 0.37$

(ii) Situation #2: Exponential Model

This model states an exponential connection between remaining volume of gas in a container with the time pump pulls gas from that chamber.

$$y(a, b, t) = 7 \text{ liters of air } e^{-\left[\left(\frac{a}{b}\right)t\right]}$$

$y(9, 63, t) = (7 \text{ liters of air}) e^{-\left[\left(\frac{9}{72}\right)t\right]} = (7 \text{ liters of air})(0.37) = 2.59 \text{ liters of air}$

Chamber started with 7 liters of gas.

Pump is on for 8 units of time

$2.59 \text{ liters of air}$

Gas left in chamber

Figure 3.2. Fundamental Math Manipulations for Model Application

principles which lead to now perhaps mundane but then fantastic inventions and corresponding technologies that shape our world today and were best modeled with simple mathematical expressions. This is a mixed blessing for the 21st century STEM professionals because the habitual practice of using a linear, $y = mx + b$, model to describe a phenomena is ubiquitous. On one hand, such modeling is an excellent way to quantify a theory based on the expectations of a single variable's behavior when a value of m , a rate of change between x and y , and b , the value on the y axis, are known. On the other hand, phenomena under study in this century depend on the changing behavior of many variables simultaneously.

Actually, that popular high school line equation is now better portrayed as the model statement $y(m,b,x) = mx + b$. This version broadens the viewer's perspective and allows an inclusion of a "family" of lines that includes a collection of slope, m , and y -intercept, b , values as the descriptor of the linear system under investigation. Thus, $y(5,3,x)$ is still just $y(x) = 5x + 3$, but this notation indicates that other values of slope and y -intercept are involved in the modeling exercise. In any event, it is clear that students must understand the phenomena studied in the past if they are going to keep pace with the discoveries of the future. Thus, student ability to manipulate the basic algebra for solving the "equation of a straight line" is critical for the use of linear models to predict system behavior.

Figure 3.2 (i) illustrates a basic algebra manipulation example for a time dependent linear model used to predict a volume of air being transferred by a pump from a low pressure to a higher pressure environment. Filling a diver's scuba tank with compressed air might be a typical example situation. In this situation the basic frame of the model, $y(m,b,x) = mx + b$, is specifically $V(t) = (5/15)t + 7$ with $V(t)$ representing the predicted y value: the volume of gas transferred into the tank after 60 seconds of pumping.

In this example, the tank already contained 7 liters of air (the model's y -intercept value). The slope value, m , is the volumetric pumping speed (5 liters of air/15 seconds) and the y -intercept value, b , is 7 liters of air. The use of $(5/15)$ as the magnitude of the pumping speed is only to emphasize the need for students to improve their skill in manipulating fractions. For this example, it is hoped that a student would quickly see that the arithmetic $(5/15)(60)$ is also $(60/3)$ which leads to the quick conclusion that after 60 seconds $(20 + 7)$ liters of air are now resident in the tank.

The simple example in Figure 3.2(i) also provides an opportunity to introduce the observation component of this fill the tank exercise. Accepting that a linear model is the best choice, how do you determine that there are 27 liters of air in the tank? The two usual methods are the comparison of the tank's weight before and after the pumping or measuring the increase of pressure of the tank during the process. In either method, it is necessary to connect the theory behind gas behavior to interpret the results.

The late 18th, the 19th, and to some extent 20th century habit of making a theory fit a linear relationship is easy to understand. First, in many cases the linear model was the best choice. Second, without the aid of calculators and computers the linear model was the practical way to proceed. Third, most measurement devices avail-

able at the time of the original verifying experiments were crude compared to those available today.

Scientists and engineers become so enthralled with the success and simplicity of linear model manipulations, they often develop mathematical ways to transform nonlinear equations, typically exponential expressions, for presentations as linear representations. The natural log of an exponential expression is the classic example of this linearization process. The application of a Laplace transform is yet another. Although discussion of the latter is beyond the scope of this workbook, the former is not. In fact, the exponential equation is the model component of a great number of scientific theories.

The middle section of Figure 3.2 emphasizes an elementary property of exponential arithmetic. It may seem a bit unsettling to students because instead of the letter "e", it should show the number 2.718281828459045 raised to the -1 power. (Ask students to copy this number, Euler's number, ten times and they will quickly appreciate using the letter "e" instead). However, the point of the visual is to emphasize that e^{-1} is the same as $(1/e)$ and that value, approximately 0.37, turns out to be very useful when dealing with exponential models.

The bottom section of Figure 3.2 presents the exponential model in a general form. The story in Figure 3.2(ii) happens to reflect a different twist on a pump and tank situation. In this case, the pump will pull air from the chamber and there are 7 liters of air to be removed from the chamber. As was the case in Figure 3.2(i) the answer is represented by the letter "y" but instead of a slope, m , and a y -intercept the model uses two different scalars, a and b , in the exponent part of the model statement. The contrast between the situation shown in Figure 3.2(i) and Figure 3.2(ii) deals with the belief that, in Figure 3.2(i), there is a linear relationship between time and the rate gas is pumped into the dive tank. While in Figure 3.2(ii), there is an exponential expression that best connects time to the removal of gas from a vacuum chamber.

Fortunately, there are really only a few key mental images needed to transmit the essence of an exponential expression to students. Figure 3.3 provides illustrations of these ideas. First, for a model application, there is always a scalar value inserted in front of an exponential expression. Just because Figure 3.3(i) does not show it, it still must be present. In this case, since it is not a model statement the number 1 is actually present in front of the exponent. Second, the entire entity in the exponential bracket shown in Figure 3.3 (i) must be a number NOT a scalar. Thus, for the example shown in Figure 3.3 (i), the value of the answer, y , must be a number.

Math: To Remember

Any "formula" inserted in here must represent a number.

(i) $e^{-[\quad]} = y$ every answer for this calculation must be a number.
 (If you do not see anything printed here remember that the number 1 is still there. You just don't see it.)

(ii) $y(a, b, t) = (1) e^{-[(\frac{a}{b})t]} = \frac{(1)}{e^{+[(\frac{a}{b})t]}}$ every answer for this model equation is a number.

(iii) (If time (in seconds) is the "running" variable, then the fraction; $(\frac{a}{b})$ is in inverse seconds. (What ever that means!)) every answer for this model equation is a scalar. In this specific case: distance in feet.

(iv) $y(a, b, t) = (5 \text{ ft}) e^{-[(\frac{a}{b})t]} = \frac{(5 \text{ ft})}{e^{+[(\frac{a}{b})t]}}$

Note: What value for "t" will make the answer, $y(a,b,t)$, equal 1.85 ft?

Figure 3.3. Math Properties of Exponential Model statement

Figure 3.3 (iv) indicates the way to change an exponential expression into an exponential model. The value preceding the exponent term must be a scalar. $y(a,b,t)$ is the answer for "running" variable, time, values when a and b values are known and the scalar, 5 ft, is multiplied by the exponent term that has $(a/b)(t)$ as its bracket term. Since the exponential expression, $e^{-[(a/b)t]}$, is negative, the answer, $y(a,b,t)$, is the object's height in feet: 5 ft, when $t = 0$ ($(5 \text{ ft})e^{-[(a/b)(0)]} = (5 \text{ ft})e^0 = (5 \text{ ft})(1) = 5 \text{ ft}$); and $(5 \text{ ft})(0.37)$ when the bracket term $[(a/b)(t)] = 1$. Student complete understanding is demonstrated if they know that the bracket value is 1 when (b/a) is the time value when the model predicts 1.85 feet for an answer.

3.3 Applications of the Exponential Model

The exponential model is ubiquitous in the physical sciences and engineering as suggested in Table 3.1. A good way to bring this fact to the attention of students is to engage them with a scavenger hunt. Send them off to the library and/or the web to find such examples. In addition, ask them to determine the definitions and meaning of the terms in the exponent of the exponential expressions they find. For example, if a stu-

dent explores electrical engineering topics the exponential model will be quickly found. It is used to describe what happens to voltage as a function of time in a circuit that has a resistor and a capacitor in series. In this case, the "a" term is 1 and the "b" in the denominator of exponent term represents the product of the resistance and capacitance of the two series circuit components. The time value, t, which makes this exponent term, t/RC , equal to one is identified as the time constant for that circuit. This specific value of t corresponds to the time necessary for the voltage across the capacitor to decay from its maximum possible value to 0.37 of that value.

A discipline, Mechanical Engineering, listed in Table 3.1 deals with the characterization of pumps and other mechanical equipment. Vacuum pumps operation is a topic of this workshop and the exponential model for pump behavior is explored in depth. The exponential bracket, $[(a/b)t]$ for pumps defines the "a" term as the volumetric pumping speed, volume/time, and the "b" term as the volume of the gas being pumped. (Please confirm that $(a/b)(t)$ is a number even through (a/b) and (t) are scalars.)

Materials Science	Diffusion in Solids
Mechanical Engineering	Pumping Speeds for Gases
Environmental Engineering	First Order Reaction Rates
Electrical Engineering	Resistor / Capacitor Circuit Charging
Industrial Engineering	Statistical Distribution
Physics/Chemistry	Radioactive Decay
Biology/Ecology	Population Growth
Chemical Engineering -----	Vapor Pressure Behavior

Table 3.1. STEM Disciplines that use Exponential Models

Figure 3.4A and Figure 3.4B present a family of curves that were obtained from exponential model calculations. Figure 3.4A illustrates the results for an exponential growth model. The 4 plots show the visual difference when "b" equals 1 for each of the plots while 4 different values of "a" were used. When examining this group of curves, it is important to notice the slight shift in their shapes when the value of "a" is increased. For visual simplicity the value for "c" was also selected to be 1. What would this family of curves look like if the value of "c" equaled 6? Also remember that if "c" was 6 milliliters instead of the number 6, Figure 3.4A plots would be models of the change in volume as a function of time for different assigned values of "a".

One STEM example would be when cell biologists are studying the volume change in a cell system because of the change in the amount of nutrients initially given

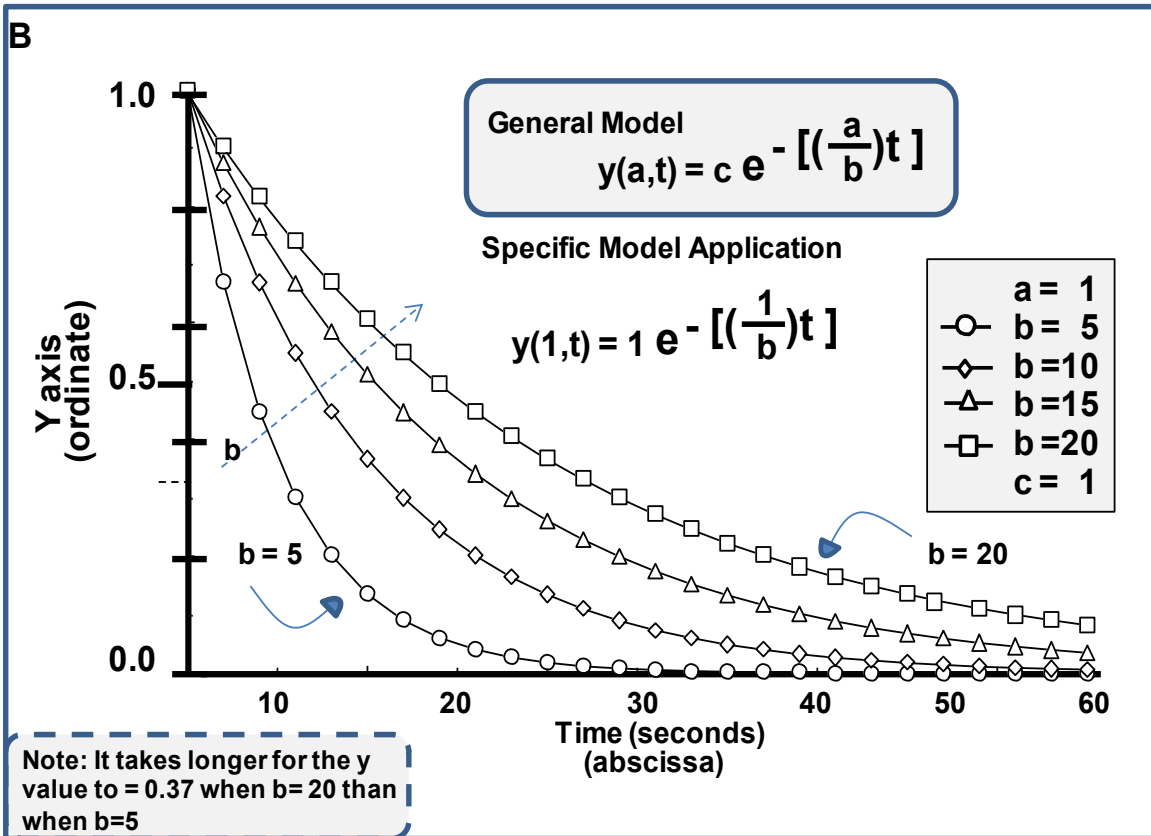
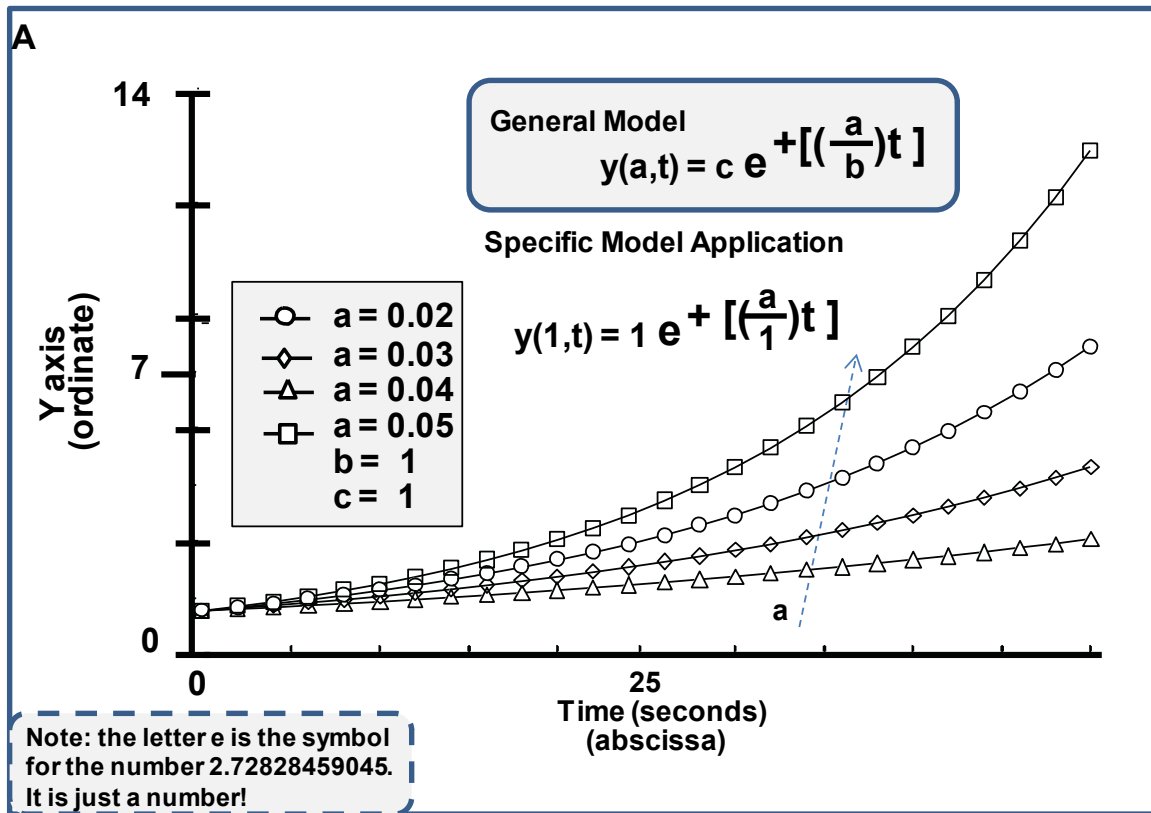


Figure 3.4. Examples of Exponential Growth and Decay Models

to the cell culture. The model indicates that a higher amount of nutrient results in a higher exponential increase in cell volume. Remember, returning to Figure 3.1, the final conclusion about nutrient amounts and cell volume is reached after the theory and observation steps have been completed and also support this model's suggestion.

Figure 3.4B presents a family of curves that illustrate an exponential decay model when "a" =1. Note the similar but reverse behavior of the 4 curves in Figure 3.4A. It should also be easy to see that the curve with "b" equal to 5 will reach the 0.37 mark on the ordinate sooner than the curve that was obtained from model calculations that used "b" = 20. This observation is driven by the time value needed for the exponential bracket term $[(1/20)t]$ to bring the total exponential term $e^{-[(1/b)t]}$ equal to e^{-1} and the fact that the number (2.718281828459045) raised to the -1 power is approximately equal to 0.37.

4. DEVELOPING MODELS

Since models are valuable for working with physical systems, it is useful to introduce students to the task of developing models. There are two general routes to model building. One of them is to develop the mathematical model from data that quantifies the observations of the phenomena under study. The other approach is to develop the model from the theory considerations.

4.1 Building a Model

4.1.1 Modeling Vacuum Pumpdown Characteristics

When designing a vacuum system, one of the most basic considerations is the time required to evacuate a vessel to a given pressure. This time typically ranges from a few minutes to hours but can, on occasion take a few days. The question that arises is:

“How long does it take to reduce the gas pressure inside the vacuum chamber from atmospheric pressure to a specific value below one atmosphere?”

If the pump is assumed to be operating at constant pumping speed and efficiency then the pressure vs. time behavior exhibited by a system is given by the following model:

$$P(s, V) = P_0 e^{-[(s/V)(t)]}$$

where P_0 is the initial absolute pressure at zero time t , P is the instantaneous absolute pressure at any time t greater than zero, V is the volume of the chamber (e.g. in liters), and s is the pumping speed of the pump (e.g. in liters/second). The quantity V/s is known as the time constant of the system and can be defined as the time it takes to pump the system to a pressure of P_0/e or 37% of its initial value.

The pumping speed of the pump and the time constant of the vacuum system can be obtained from pressure vs. time characteristics during the pumpdown cycle as illustrated in Figure 4.1. There are three main objectives of the following exercise: to experimentally determine the pumping speed of the pump and the time constant of the vacuum system, and to use these values to understand some of the problems inherent in the design of vacuum systems.

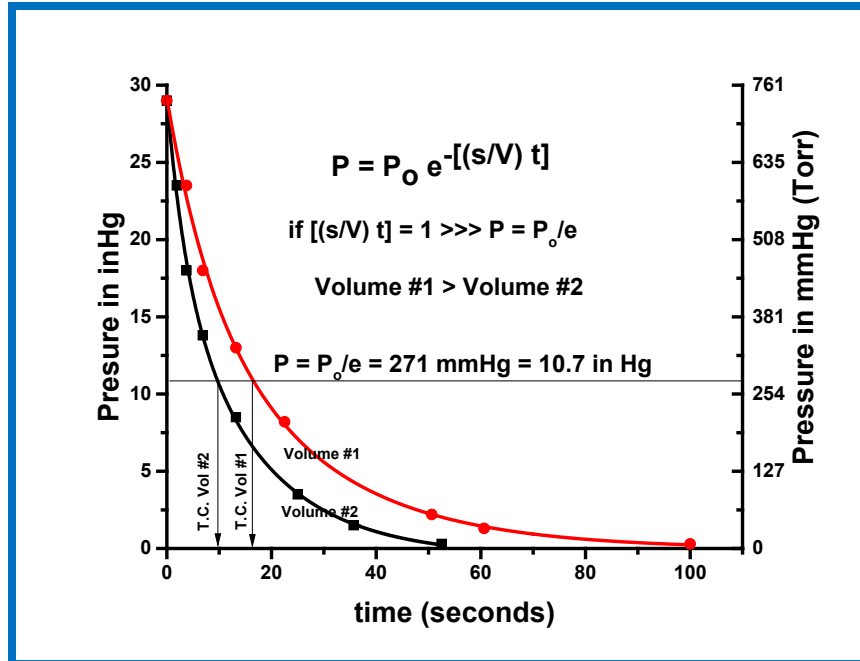


Figure 4.1. Pumpdown characteristics expressed as pressure vs time curves for two different volumes using a positive displacement mechanical vacuum pump.

Experiment. Pumpdown Exponential Model Verification

Measure the volume of the vacuum chamber and record the vacuum gauge value for atmospheric pressure. Start a pumpdown cycle for the properly assembled vacuum system by switching on the pump. Record the pressure every two or three seconds (or the time at predetermined pressures). Record data until the pressure is at the lower limit of the gauge. Allow the vacuum chamber to return to atmospheric pressure and repeat the pumpdown process again. Record the data for this second pumpdown as a separate set of data. Repeat the experiment yet one more if your data is not consistent in time.

Supplemental information: How do we collect the information?

P: is obtained with a device that measures gauge pressure in certain units. The gauge pressure needs to be converted to absolute pressure using the value of the atmospheric pressure when the experiment is performed.



P₀: initial system pressure in general atmospheric with same units as P, measured with an absolute gauge



V: volume of the system calculated measuring the size of the chamber



t: time measured with a stopwatch or similar



To minimize errors it is important to determine the best way to collect the data: is better to measure the pressure at fixed times or measure the time at fixed pressure values?

1. Plot the absolute pressure and time (in seconds) data pairs for the average of your experimental runs on the graph paper provided. Answer the following questions.
 - a) What is the value on the time axis when the pressure has fallen to 37% of its original value?
 - b) What is the value on the time axis when the pressure has fallen to 14% of its original value?
 - c) Does the pressure ever go to zero?
2. Plot $\ln(\text{Pressure})$ vs. t (time) for the same data on a different graph sheet, as illustrated in Figure 4.2.

If the vacuum system is following the exponential “decay” model and if you have not made any major errors in your data collection and plotting activity, the $\ln(P)$ vs. time plot should be a straight line, following this relationship:

$$\ln P = \ln P_0 - (s/V) t$$

$$y = b - mx$$

- a) What is the algebraic significance of the slope of your linear plot?
 - b) What is the algebraic significance of the pressure axis intercept of your linear plot?
 - c) What extra information is needed to determine the pumping speed, S , of the pump used in your experiment?
3. What is the pumping speed of the system?
 4. Change the volume of your vacuum system.
 - a) Plot the pressure readings vs. time in seconds for this new volume vacuum chamber on the same graph used in part 1 above.
 - b) Plot the $\ln(P)$ vs. time data on the same graph used for part 2 above.
 - c) What are the values on the time axis when the pressure has reached 37% and 14% of its original value?
 - d) What is the pumping speed for this new vacuum chamber? (Is it going to be a different value than the pumping speed calculated above in part 3?)

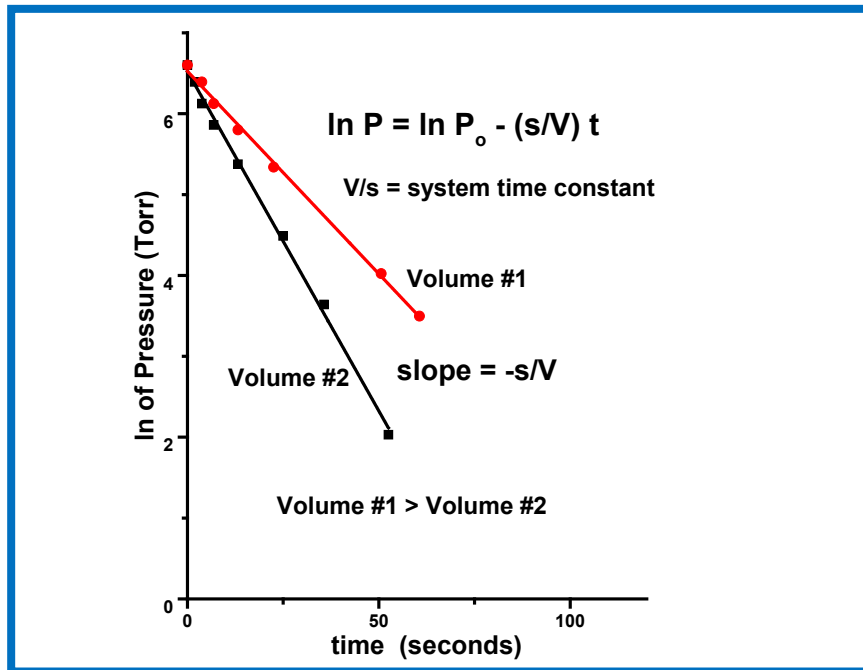


Figure 4.2. Pumpdown characteristics expressed as ln pressure vs time curves for two different volumes pumped with a positive displacement mechanical pump.

4.1.2 Modeling - Theory of Pumpdown Characteristics

A vacuum system consisting of a pump with chamber provides an excellent opportunity to have students test a model that was developed from a theory. In this case, ideal gas behavior as developed from the kinetic theory of gases will be used. In addition, students can test the model developed from this theory with a very simple experiment that addresses the question:

“How long does it take to reduce the gas pressure inside the vacuum chamber from atmospheric pressure to a specific value below one atmosphere?”

To begin, consider air to be an ideal gas and visualize its presence in the vacuum chamber at atmospheric pressure. Once the vacuum pump is turned on, this air begins to leave the vacuum chamber because it is being pulled into the pump and then pushed into the surrounding air outside the vacuum chamber and pump. Naturally, the number of gas molecules inside the vacuum chamber decreases as a function of time. The longer the pump keeps pumping the more gas is removed from the vacuum chamber. Thus, the question of interest really reflects how fast the pump can remove molecules from the vacuum chamber. The pump must be able to remove molecules from the chamber faster than molecules can return to the chamber via leaks. In other words, the pressure in the chamber will stop dropping once the number of molecules the pump is removing per unit of time is equal to the number of molecules per unit of time entering the chamber via leaks in the entire vacuum system.

The ability of a pump to remove molecules from the vacuum chamber is expressed by means of two parameters. One parameter is called throughput, Q , of the pump while the other is the pumping speed, s , of the pump. The throughput of a pump is a value that represents the number of molecules per unit time the pump can remove from the chamber. The pumping speed is the volumetric flow rate (volume per unit of time) the pump can maintain. To secure an answer to the question above, we can use a model that includes the pumping speed and expresses the current pressure inside the chamber as a function of time the pump has been running.

The theory behind pumping speed is based on maintaining a mass balance in a vacuum chamber. Making a mass balance in the vacuum chamber:

$$[Accumulation] = [Input] - [Output]$$

which can be written if there are no leaks into the vacuum chamber (Input =0) as:

$$\frac{dN}{dt} = -\dot{N}$$

where N is the number of moles in the vacuum chamber, at any time, and \dot{N} is the rate at which moles are leaving the chamber. Assuming ideal gas behavior:

$$N = \frac{PV}{RT}$$

$$\dot{N} = \frac{Ps}{RT}$$

where P is the absolute pressure, T is the absolute temperature, R is the ideal gas constant, V is the vacuum chamber volume and s is the pumping speed

Replacing in mass balance equation:

$$\frac{V}{RT} \frac{dP}{dt} = -\frac{Ps}{RT}$$

then at constant temperature and chamber volume:

$$\frac{dP}{P} = -\frac{s}{V} dt$$

Integrating over the initial pressure P_0 at time = 0 to the final pressure P at time t and assuming an effective pumping speed, s_{eff}

$$\ln \frac{P}{P_0} = -\frac{s_{\text{eff}}}{V} t$$

or:

$$P = P_0 e^{-[(s_{\text{eff}}/V)(t)]}$$

4.2 Student Homework Problems and Answers

4.2.1 Student Homework Problem: Pump Throughput

Develop an equation using the Ideal Gas Law from the kinetic theory that will relate a vacuum pump's throughput, Q , to the variables in the Ideal Gas Law, which is expressed as follows:

$$N = \frac{PV}{RT}$$

where N is the number of molecules, P , V , and T are the system pressure, volume, and temperature, respectively and R is the gas constant.

Answer:

If the only way molecules enter or leave the vacuum chamber is through the vacuum pump, and if no molecules enter the vacuum system while the pump is on, then the number of molecules, N , that exit the chamber and enter the vacuum pump per unit of time becomes N/t . In addition, the number of molecules in the vacuum pump at any instant of time can be calculated using the Ideal Gas Law with the system being the vacuum pump.

Therefore N/t , which is the definition of Q , becomes:

$$Q = N/t = (PV_{\text{pump}}/RT)/t = (P/RT)(V_{\text{pump}}/t)$$

Finally, defining the term that represents the volume of the pump divided by the time, V_{pump}/t , for the pump as the pumping speed, S , and recognizing that the term (V_{pump}/t) is also the volumetric flow rate for the pump, a general expression for vacuum pump throughput becomes:

$$Q = N/t = (P/RT)s$$

This model states that the number of molecules per unit of time that pass through the pump is equal to the (P/RT) multiplied by the pumping speed. If the situation for your vacuum chamber is such that the temperature is constant then R , the Ideal Gas Law constant, and T can be grouped with N/t to give:

$$\begin{aligned} (N/t)(RT) &= (P)s \\ (Q)(RT) &= (P)s \end{aligned}$$

Thus, the ideal gas throughput, Q , for a vacuum pump as related to a specific gas temperature, 0°C , is defined as the product of the pressure of the molecules entering the pump and the pumping speed of the pump in your vacuum system.

In practice, the throughput calculation uses two convenient short cuts. First, the value for RT is not calculated as long as the throughput value is always related to 0°C . Second, the numerical value for pressure used in the throughput equation is the pressure at the entrance of the pump, i.e. the pressure in the vacuum chamber. With these shortcuts in mind, the throughput equation becomes:

$$Q (\text{at } 0^\circ\text{C}) = (P)s$$

It is important to remember that the product of pressure, P , with pumping speed, s , only provides a numerical value that is proportional to the actual number of molecules that pass through the pump at any instant of time. However, it will still be true that a vacuum pump with large throughput value will pull more molecules out of a vacuum chamber per unit time than a vacuum pump with a lower throughput value.

4.2.2 AP Student Homework Problem: Pressure Prediction

Using the Ideal Gas Law from the kinetic theory develop a model which predicts the pressure in the vacuum chamber after the pump has been running a specific amount of time.

Answer:

As long as the pump is on, molecules from the vacuum chamber are pulled into the pump and then pushed out into the surrounding outside the chamber. Thus, the pressure in the vacuum chamber will decrease as the number of molecules in the chamber continues to decrease. It is straightforward to relate the number of molecules in the vacuum chamber at any instant of time to the volume of the chamber and the pressure in the chamber at the same instant of time.

$$N_{\text{chamber}} = (PV_{\text{chamber}}/RT) = [P/RT](V_{\text{chamber}})]$$

where P , T , and V_{chamber} correspond to the pressure, temperature and volume inside the vacuum chamber. It is also easy to use the gas law to express the change in the number of molecules inside the pump, $d(N_{\text{pump}})/dt$, to the pump's volumetric flow rate, i.e. pumping speed:

$$-d(N_{\text{pump}})/dt = (P/RT) (V_{\text{pump}}/t) = (P/RT)(s) = \{(P/RT)s\}$$

In this last equation the $d(N_{\text{pump}})/dt$ term on the left is a symbol that just transmits the idea that it is the change in the value of the expression inside the parenthesis, N_{pump} , not the actual value of that expression that is of interest. The V_{pump} value divided by time is the definition of pumping speed.

Unfortunately, these two expressions cannot be equated since the change in the number of molecules in the pump at any instant of time, the second expression, is never equal to the number of molecules in the vacuum chamber, the first expression, at that same instant of time. However, if we make the approximation that, for any instant of time the pump is on,

- a) molecules only leave the vacuum chamber by going through the pump, and,
- b) no molecules enter the vacuum chamber while the pump is running

then the change in the number of molecules in the vacuum chamber equals the change in the number molecules entering the pump. Mathematically, this is a differential equation that can be stated as:

$$- d(N_{\text{chamber}})/dt = d(N_{\text{pump}})/dt$$

Simple substitution with the appropriate equation above will produce:

$$- d[(P/RT)(V_{\text{chamber}})]/dt = \{(P/RT)s\}$$

moving the constant term, the RT term, and the chamber volume term on the left and outside the differential symbol, the differential equation becomes:

$$- (1/P) dP = (s/V_{\text{chamber}}) dt$$

Please note that the (s/V_{chamber}) term on the right involves the volume of the pump, as part of the "S" variable in the numerator, as well as the volume of the chamber in the denominator. These values are not equal since the pump volume in terms of the pumping speed, s, is much smaller than the chamber volume, V.

The solution to this differential equation model involves an integration of the differential terms on both sides of the equation. Fortunately this is easy to do. The integrals in question are found in any AP math textbook or first year calculus book. After integration the $(1/P) dP$ term becomes:

$$\ln (P/P_0)$$

while the $(s/V_{\text{chamber}}) dt$ term changes to:

$$(s/V_{\text{chamber}})(t-t_0)$$

Thus, the differential equation can now be expressed as an integral equation by substitution of the appropriate terms and the model for the problem statement now becomes:

$$-\ln(P/P_0) = (s/V_{\text{chamber}})(t-t_0)$$

Renaming the V_{chamber} term V, the antilog of both sides of the equation is taken and the general model becomes:

$$P = (P_0) e^{-[(s/V)(t-t_0)]}$$

If this model is applied to a vacuum system with an initial pressure, P_0 , equal to 1 atmosphere and the starting time for the vacuum pump, t_0 , is designated as 0 minutes (or seconds), then the model becomes:

$$P = (P_0) e^{-[(s/V)(t)]}$$

Thus, the value of P , the pressure inside the vacuum chamber, is now a function of the time the pump is operating. Actual values for pressure inside the vacuum chamber as a function of pump operation time can be calculated once the volume of the chamber, V , and the pumping speed, s , are known.

4.2.3 AP Student Homework Problem: Percent Pressure Drop

Use the general model that related the pressure in a vacuum chamber to the time in the vacuum pump to derive an equation that will express this decrease in pressure as a percent of the starting pressure value.

Answer:

The general model for pressure in a vacuum chamber with starting pressure P_0 is:

$$P = (P_0) e^{-[(s/V)(t-t_0)]}$$

in this equation the V term is the volume of the chamber, V_{chamber} . If the model always starts when the pump is turned on, $t = 0$, the expression becomes:

$$P = (P_0) e^{-[(s/V)(t)]}$$

and the equation that expresses pressure in the vacuum chamber as a percent of the starting pressure becomes,

$$\text{Percent of initial pressure} = P/P_0 \times 100 = e^{-[(s/V)(t)]} \times 100$$

where the 100 is used to get a % answer instead of a decimal value.

5. GAS PHASE MODELS

5.1 Ideal gas Model

An ideal gas is a concept defined as one in which all the molecules are spheres that do not react or interact with each other and all collisions are elastic. This is illustrated in Figure 5.1. Observations of the behavior of gases by Avogadro, Boyle, and Charles, led to the Ideal Gas Law in 1834 by Emil Clapeyron. The Ideal Gas Law is expressed as:

$$PV = NRT$$

where P = system pressure, V = system volume, T = system temperature, N = number of moles in the system, R = universal gas constant or an experimentally determined factor that makes the units of both sides of the equation consistent.

The ideal gas law arises from the Kinetic Theory of Gasses and is based on several assumptions:

1. Gasses are composed of a very large number of very small particles (molecules).
2. The molecules are always moving rapidly in straight lines.
3. The molecules are very small compared to the distance between them.
4. Molecules interact only by collision.

In Figure 5.1, we freeze all of the molecules except one and observe its motion as it collides with other molecules and the wall of the chamber. At atmospheric pressure there are many molecules in a volume and the molecules collide with one another much more often than with the walls of the chamber. As we reduce the pressure, the number of molecules in a volume decreases and molecules experience fewer collisions with one another. At very low pressures, collisions with the wall of the chamber become much more important than collisions between molecules.

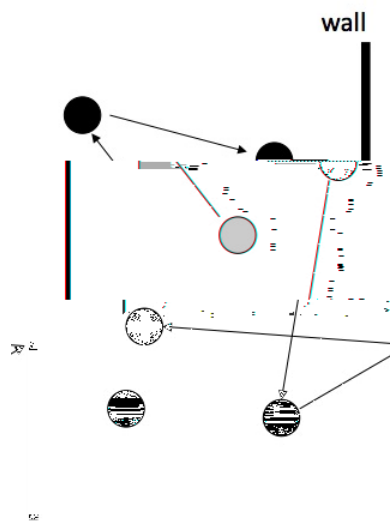


Figure 5.1. Motion of molecule (light color) in ideal gas law.

If some variables are held constant in the ideal gas law, simpler relationships have been identified. For instance, if P and N are constant, then volume is proportional to T (Charles' Law). Gasses expand when heated.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = \text{constant}$$

If T and N are constant, then P is inversely proportional to V (Boyle's Law). Compressing a gas increases the pressure.

$$P_1V_1 = P_2V_2 = \text{constant}$$

5.2 Boyle's law

For a system composed of a fixed quantity of an ideal gas at constant temperature, it is observed that the measured system pressure is inversely proportional to the volume occupied by the gas. This relationship is known as Boyle's Law and is named after the physicist Robert Boyle (1627-1691) who first stated it. In the ideal gas law, we are holding N and T as constants. This model can be expressed as

$$P \propto \frac{1}{V}$$

which can be graphed as the smooth line in Figure 5.2.

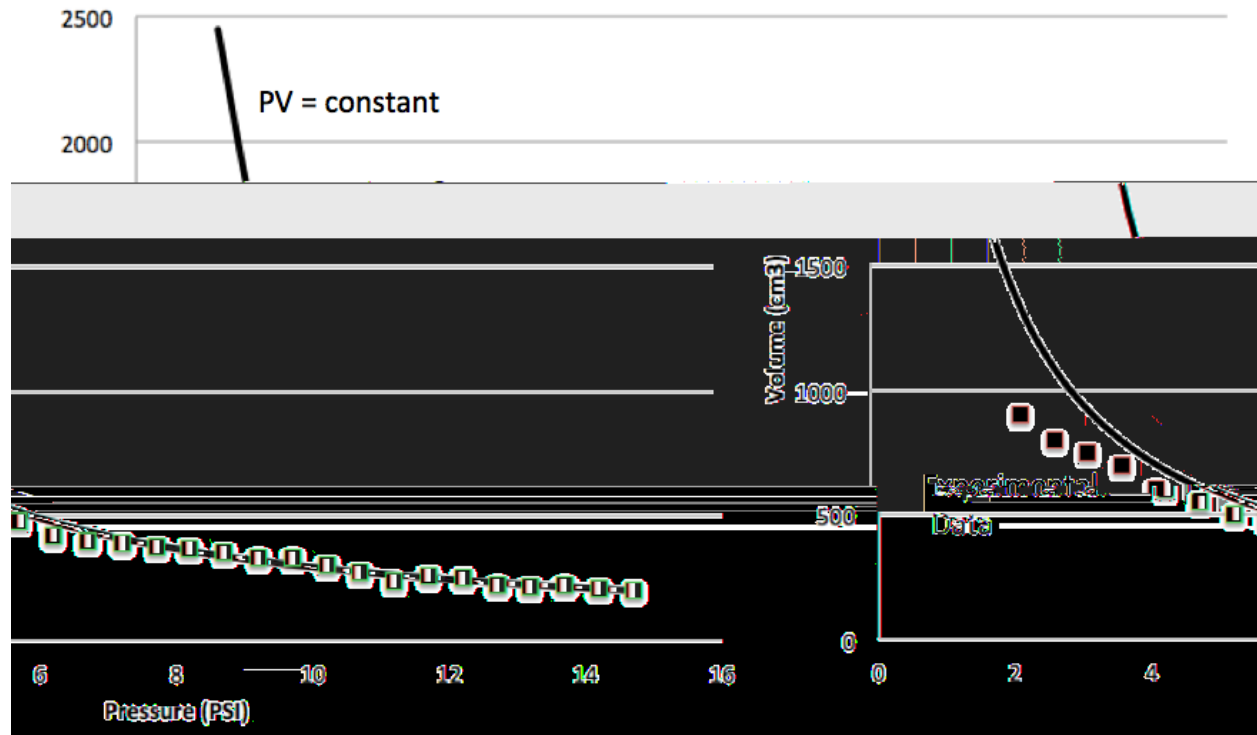


Figure 5.2. Experimental data (points) and model (line) for Boyle's Law.

Boyle's Law can be observed in any closed isothermal system in which the pressure or volume can be varied. A model for Boyle's Law can be developed providing

that these quantities can be measured. A good experimental setup for obtaining the pressure vs. volume data needed might be a closed vessel of known initial volume with a plunger at one end and a pressure gauge at the other. The pressure is read directly whereas the volume is proportional to the height of the plunger. If the cylinder is calibrated, then volume tic marks can be used.

Another useful but somewhat more challenging system is one demonstrated earlier in this workshop - the expanding balloon. The balloon represents a closed system whose volume and pressure is changed by varying the force of the surrounding air on its exterior surface. (See Demonstration #1: Expanding Balloon.) If an expanding balloon is to be used to observe Boyle's Law, there are two initial goals to the exercise. The first objective is to obtain pressure - volume data for a balloon at reduced pressures in a vacuum system. The second is to observe and characterize the difference between a model and experimental observations.

Experiment #2: Boyle's Law: Observation and Model

1. Partially inflate a balloon and determine the initial volume of the balloon.
2. Place the balloon in the vacuum chamber and begin the pumpdown. Since the balloon is expanding to equalize its internal pressure with the reduced external pressure of the vacuum jar, the pressure can be read directly from the gauge. Note that you can stop the pump for brief periods of time to take data points or you can pump until the balloon reaches maximum expansion, shut off the pump, and vent the system in controlled increments of pressure, taking pressure and volume readings as the pressure increases. (Be sure to take enough readings to develop the shape of the V vs. P plot.)
3. The only other measurement that is needed is that of the volume of the now nearly spherical expanding balloon in the vacuum jar. There are a number of ways to determine the volume. We will leave the approach to making this measurement up to you. Be creative but remember to be as accurate as you can!
4. Plot the experimental volume - pressure data pairs as volume vs. pressure, on the graph paper provided and draw a smooth curve to represent the data points.
5. Using the initial (atmospheric) PV product where the volume of the balloon is most accurately known, calculate a theoretical volume for each recorded pressure and plot this PV data on the same graph. This is the model curve. Your result will likely look something like Figure 5.2.
6. Compare the curves from the experimental results with the theoretical calculations. Discuss the likely sources of error. Aside from measurement errors how does the choice of the experimental setup play a role in the inaccuracies present in the data? (Hint: How does the balloon itself affect the volume measurements?).

5.3 Polytropic Process

A great number of situations of interest to chemical and mechanical engineers deal with the movement of a fluid. Specifically, the engineer is focused on any gain or

loss of energy a fluid experiences as it is transferred from one situation to another. Certainly, one reason for some energy losses as the fluid moves is due to friction. However, from any application perspective, the engineer's interest is related to fluid energy changes in the form of heat or work. Recall that work can be expressed as PV which ties us back to the Boyle's Law discussion.

The manipulation of a fluid, so that energy is expressed as heat or work, is easily done by devices within things (shuttle booster rockets, steam locomotives) that vary the temperature, pressure, or volume of the fluid as it moves through a particular device within that thing. As might be imagined, there are just as many variations of these three variables to generate energy changes in a moving fluid as there are different types of things that use these energy changes to function properly. How can anyone keep track of all of these various possibilities?

The trick is to define a vocabulary that is easy to use but allows anyone to clearly define the specific changes in the fluid's temperature, pressure, and volume of interest and also clearly indicate the amount of heat or work that resulted from those changes. Some example processes that use words in this heat/work vocabulary are isobaric process, isotropic process and isothermal process. Collectively we refer to these as polytropic processes.

A polytropic process is a generalized process that can be modeled such that the pressure times the volume raised to a power always equals a constant value, $PV^n = \text{constant}$. (This looks very similar to one statement of Boyle's Law, $PV = \text{constant}$.) Figure 5.3 illustrates several example curves of common polytropic processes. The curves are distinctive and easily identified by the specific values of n as shown. Isobaric (constant pressure) processes are represented by the vertical line that results when $n = 0$. This type of process occurs whenever a fluid passes through a device such that its temperature or volume (or both) change, while the pressure of the fluid remains the same as it was before it entered the device. Processes occurring on the earth's surface while exposed to the atmosphere are considered to be isobaric for most practical purposes. When $n = \text{infinity}$, we have an isochoric process where the volume does not change as the temperature and/or pressure change.

The other plots shown in Figure 5.3 are examples of polytropic processes: an isothermal process (Boyle's law describes an isothermal process when $n = 1$) and an isotropic process (where $n = k$ is a number other than 0 or 1). Isothermal processes are processes that occur because a fluid passes through a device such that the temperature remains constant while the pressure and/or volume change. An isotropic process is a process that occurs because a fluid passes through a device that changes the fluid's pressure, temperature and/or volume but does not change the general order (or disorder) of the fluid, i.e., there is no phase change in the moving fluid.

At this point, these terms might be new to you. To find an anchor for this expanding vocabulary, note that:

1. A process that follows Boyle's law is an isothermal process.

2. The isothermal process ($n = 1$) is a specific example of a polytropic process.

In summary, a polytropic process is a process that manipulates the temperature, pressure or volume of a fluid so that there is a predictable energy change as the fluid passes through a device in that process.

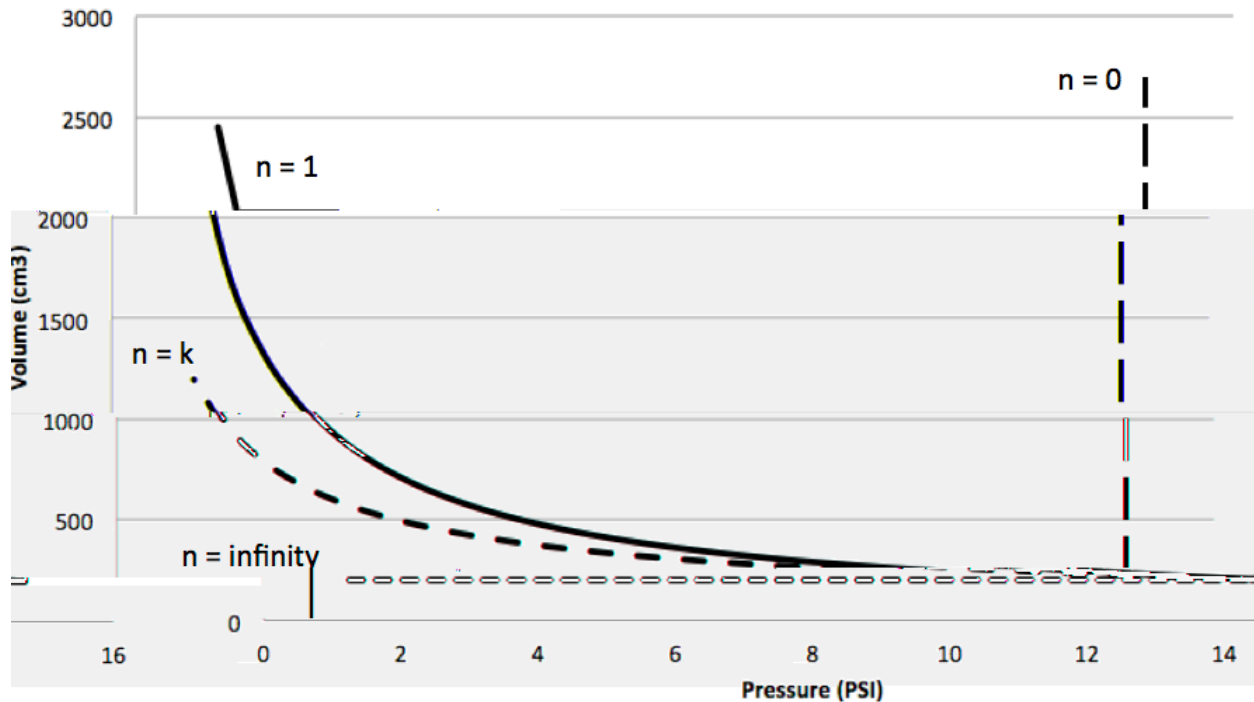


Figure 5.3. Plot of Volume vs. Pressure for four examples of polytropic processes.

5.4 Polytropic Perspective

Why not just use Boyle's and/or Charles' Law to describe pressure, volume and temperature relationships for gases? These are quick questions that come to mind, especially if polytropic sounds Greek to you. However, Boyle's and Charles' Laws are just specific cases of polytropic processes that apply to ideal gases and are very useful for gases that behave that way. Unfortunately, most gases in real applications do not behave as ideal gases. Therefore, the aim is to develop an understanding of gas behavior since any combination of changes of P, V, and/or T require a polytropic perspective.

This alternate way, the polytropic model, to describe P, V, T relationships was developed from applications that involved getting usable work from a moving fluid i.e., applied thermodynamics. Engineers and applied scientists have found polytropic models to be more useful when describing many applications such as steam engines and refrigeration cycles because these models are not restricted by the assumptions of ideal gases. Ideal gas assumptions are often inappropriate when dealing with supersaturated steam, pressurized coolants, and other fluids used in common engineering systems.

Additionally, for practical applications, it is more important to describe the behavior of the gases correctly (i.e., model their behavior) under their operating conditions rather than to know how they might behave if they were assumed to be ideal. The variable exponent k , in the polytropic equation allows such flexibility for dealing with ideal gases. Ultimately, the polytropic model allows for more accurate determination of energy requirements or production in terms of work or heat for engineered systems. Needless to say, accuracy determining the energy consumed or produced in a real operating process is very important. This is the case if all power production is used to produce electricity and/or heat for public consumption, or is converted to mechanical work to run factories, automobiles, etc.

As an exercise, you could go back to your experimental data from the Boyle's Law experiment and analyze it using $PV^k = \text{constant}$ rather than $PV = \text{constant}$. If you find the value of k then you have a polytropic model which describes your system.

6. STATES OF MATTER

When molecules in the liquid state start to boil, the molecules rapidly leave the liquid and enter the gas state. The amount of thermal energy, heat, required to accomplish that task will be determined by the heat required to reach the boiling point of the liquid plus the latent heat, hidden heat, of vaporization defined as “the quantity of heat required to change a unit mass of liquid into vapor at the boiling point”. This time dependent boiling process is illustrated in Figure 6.1 A by the second horizontal line from the left. The temperature is monitored as a function of time because the temperature of the molecules is an easier scalar to measure than the energy content (also a scalar) of those molecules. (The model calculation is an easier way to get that energy value.)

Normally, the thermal energy that must be supplied to reach and sustain boiling is supplied to the liquid from an external source. However, if the liquid is made to boil by reducing the pressure over the surface with no external heat provided, the process is reversed. The molecules leaving the liquid surface and entering the gas state still require their latent heat as before; but, since no heat is being supplied, the thermal energy is obtained from the molecules that remain in the liquid state. This will result in a reduction in the total energy of the remaining molecules of liquid. That decrease is reflected in a temperature drop remaining liquid.

As a subtle vocabulary point, the word "boiling" is reserved for the rapid vaporization when the pressure exerting its force per unit area on the liquid is 1 Atmosphere. At lower pressures, rapid vaporization is still observed. However, at pressures less than 1 Atmosphere, the temperature when rapid vaporization occurs is not "officially" called a boiling point. To be sure, people will say the liquid is boiling but hopefully anyone that does so also knows the actual definition of "boiling point". In addition, the amount of Latent Heat, the energy needed to take molecules from the liquid to the gas phase, is lower when the pressure is lower. Molecules need less energy to “escape” from the liquid into the gas phase when there is a lower number of molecules (lower pressure) pushing against the liquid surface.

Figure 6.1B provides additional model details when the water molecules are the subject of attention. The graphic indicates five different linear models with, looking from left to right, the first line indicating the temperature as a function of time while the solid water, ice, is accepting energy, heat, until it reaches water's melting point, T_2 . The second temperature vs time model predicts temperature as the solid water transitions to liquid water. This is an interesting plot of time versus temperature since the temperature, T_2 , is constant for the period of time, t_2 to t_3 , under investigation. The remaining three linear models simply replicate temperature approach and phase change at the next stage of the heating process with different values of specific and latent heats.

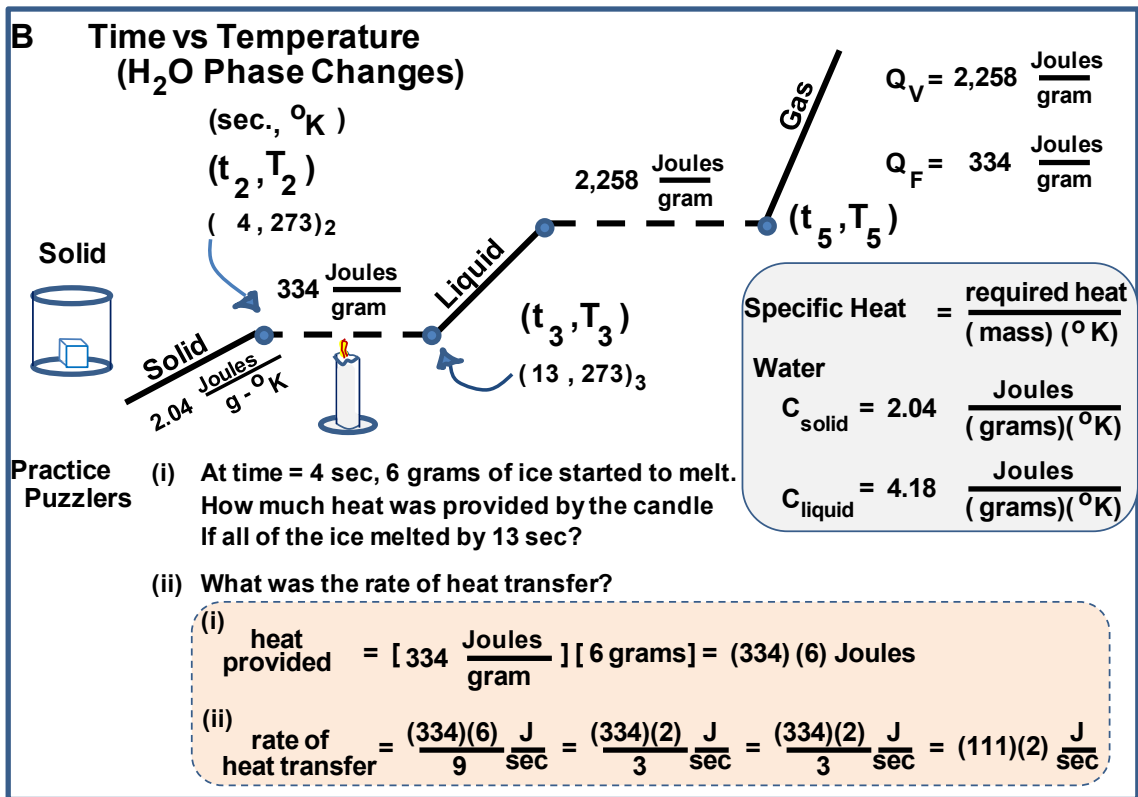
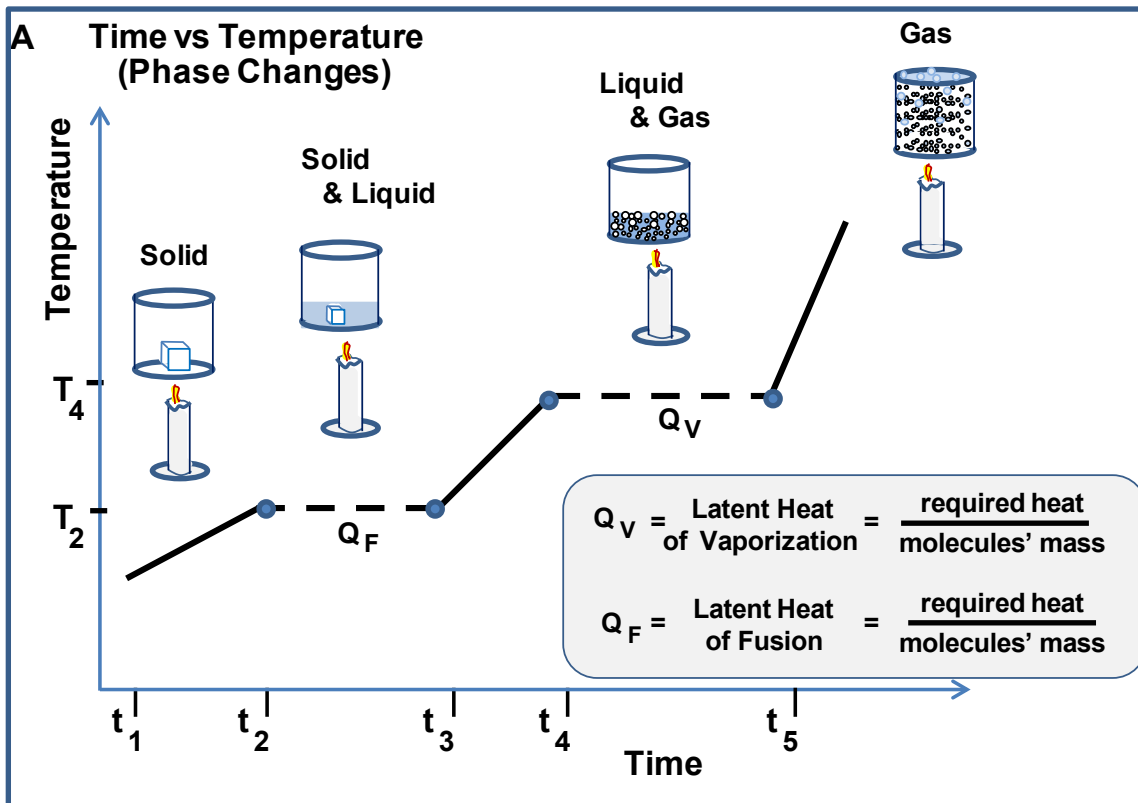


Figure 6.1. Temperature Observations during Phase Change of Water

The selection of the time model profiles in Figure 6.1B hint at the perspective difference the scientist and engineer might have when dealing with molecules and phase changes. The Chemist might be interested in determining the 3 different Specific Heat and two different Latent Heat values for a new material. Although this is vital information for the Chemical and/or Mechanical Engineer, their typical interest is the material's conductivity relative to the rate of heat transfer into or out of that material and how that affects the materials intended use. Figure 6.1B has a worked out example (Practice Puzzlers) of that energy and rate of energy transfer connection.

The complete appreciation of the heat transfer rate perspective reflected in the temperature versus time plots provided in Figure 6.1 requires an understanding of mathematical space that includes the various combinations of Pressure, Volume and Temperature (P,V,T) as illustrated in Figure 6.2. This three dimensional depiction is not the typical presentation in high school. Figure 6.3(i) is the most popular perspective of the PVT phase space presented to high school students. Hopefully, if visually guided, students will see the connection between Figure 6.2 and the two graphics in Figure 6.3

Examination of the shaded regions of Figure 6.2 indicates when to expect a two

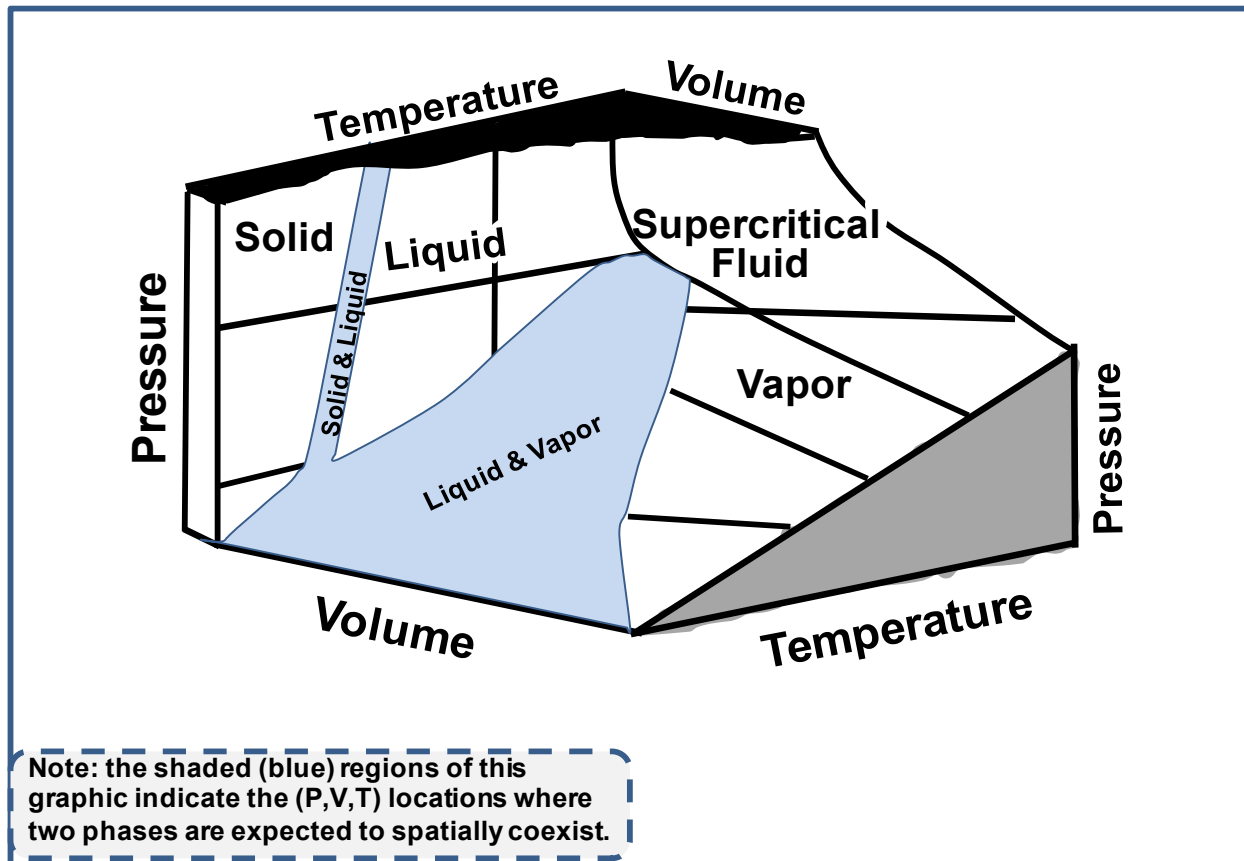


Figure 6.2. P,V,T Coordinate Space Relationships Illustrated in Phase Diagram 6.3.

phase region for specified values of pressure, volume, and temperature. A student will interpret the illustrated phase diagram properly if they notice that the two phase (solid

and liquid) region has limited values of volume and temperature values but a large range of pressure values. (This is a subtle visual observation and they may need help with it.)

Figure 6.3(i) shows the typical presentation of the water molecule phase behavior as a 2 dimensional space defined by temperature and pressure. The graphic shows three curves coming together as a single point. Each of the curves provides a demarcation between two phases. Most high school students are aware that the direction of the line showing the water phase change from ice to liquid is unusual. Perhaps these students also appreciate that a pair of temperature and pressure values that identify a specific location on that solid/liquid demarcation line indicate that the solid and liquid phase are present in an environment with those stated temperature and pressure values.

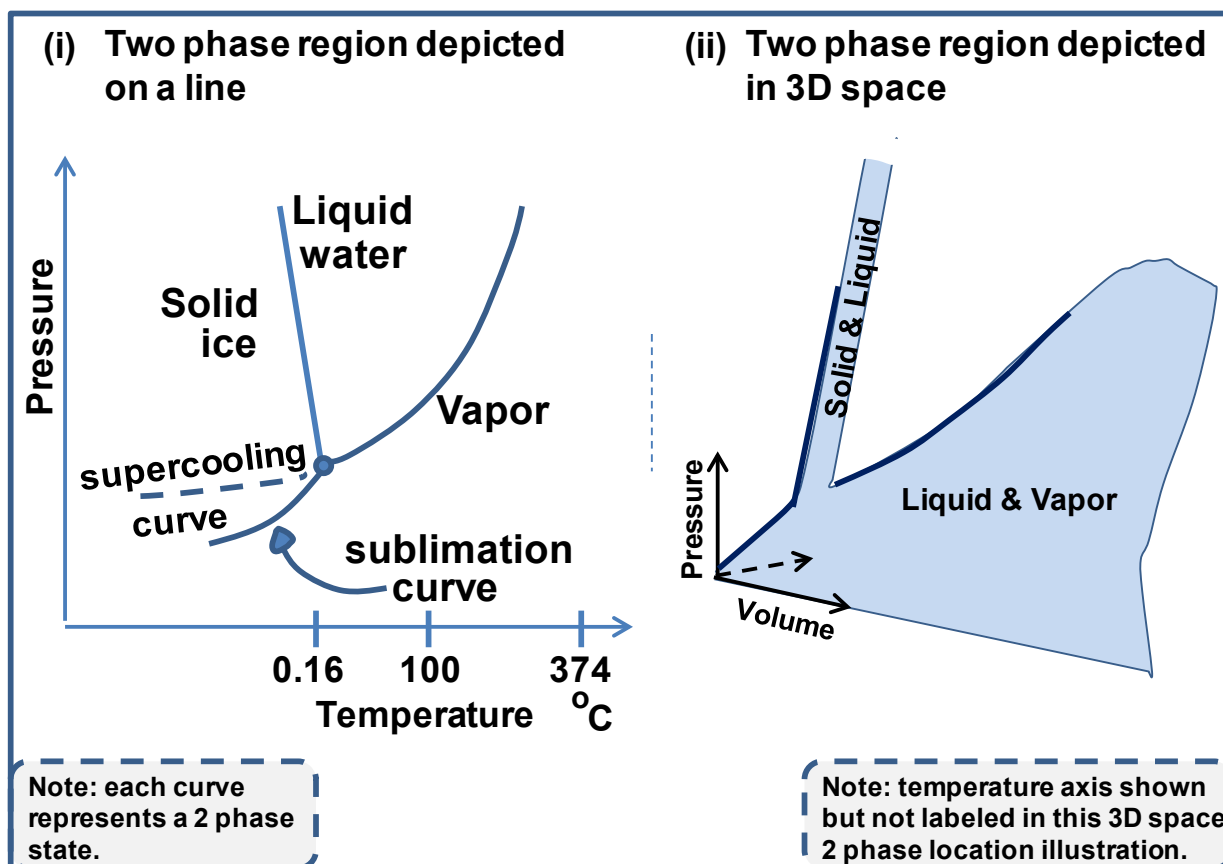


Figure 6.3. Two Presentation Perspectives for a Phase Diagram

Figure 6.3(ii) is a repeat of the typical (but not water) two phase region shown in Figure 6.2. This version does accent the forward edge of this region. The hope is that after a slight rotation of the student's viewing perspective of Figure 6.3 (ii), the accented edges (thicker lines) will resemble the curves in Figure 6.3 (i). If so, then the real distinction in water's unusual solid/liquid transition behavior will be obvious. In addition, it should be clear why the curves in the pressure / temperature plane of Figure 6.3 (i) do

not indicate the presence of two phases. That multiphase information is in the 3 dimensional (P,V,T) graphic. Thus, if the 3D graphic in Figure 6.3 (ii) is rotated so that the 2 dimensional (P,T) plane is flush on the paper, the volume coordinate is pointing outward (out of the paper) and Figure 6.3 (i) and (ii) project the same type of information. That information in Figure 6.3 (i) clearly indicates if the pressure on solid water at a specific temperature is increased, more liquid water will be made. By contrast, Figure 6.3 (ii) shows that when pressure on other types of molecules in the solid state at a fixed temperature is increased more solid is produced.

Figure 6.3 (i) also indicates the existence of a (P,T) order pair on the graph that predicts the existence of a three phase environment. When all three phases (solid, liquid and gas) are present and in equilibrium (pressure, temperature, and volume are constant) that graphic point is called the "triple point". For water molecules, the triple point situation will occur in a bell jar (constant volume) vacuum pump driven demonstration when the temperature is 0.16 °C and the pressure is 4.58 mm Hg.

Three important points to remember about a vacuum pump driven triple point demonstration: First, once the triple point has been obtained and the pump continues to remove gas from the bell jar the pressure continues to drop. As that happens, the "boiling" will stop and the liquid water will continue to change to solid water, ice. Second, although the vacuum created in the bell jar as the pressure is reduced lowers the rate of heat transfer from the room to the liquid water, heat will still enter the liquid. This means that the temperature is not constant. Fortunately for an experiment that uses a two stage pump, the rate of heat transfer is low enough that the liquid temperature does not prevent the initial observation of the triple point. (If it is practical, keep the bell jar in a refrigerator just before the experiment to lower the heat content of the jar and subsequent heat transfer to the liquid water in that vacuum chamber.) The third point's explanation is more convoluted. At the beginning of the experiment, there is air and liquid water in the bell jar. The air in the bell jar is at 1 Atmosphere (760 mm Hg, 760 Torr, 29.92 in Hg, 101,325 Pascal's, 14.6959 pounds per square inch). Since air also includes water in the gas state, those water molecules contribute to that 1 Atmosphere of total pressure and there is a little more water in the bell jar that cannot be seen. (The visible water is in the liquid state and the invisible water is in the gas state.). At 0 °C, the expected triple point temperature, (remember at 1 atmosphere water is in its solid state at 0 °C) there is still water in the gas state and those water molecules exert a pressure of 4.58 mm Hg on that ice.

A quick review of Figure 6.3 (i) indicates that for water molecules in the solid state at a specific temperature, increased pressure decreases the amount of ice and increases the amount of liquid. Thus, the temperature of the three phase mixture is raised a small amount when the "extra" liquid water changes back to water in the solid state. Once that transition has occurred, all of the water molecules in the vacuum chamber can exist at equilibrium as "boiling and "freezing" liquid water at the same time.

Finally, as closing thoughts for this discussion, a few comments about the vocabulary used when discussing water in its phases. First, everyone, with the possible

exception of residents very near the North Pole, connect the word water to an image of liquid. This is especially true of students. That is why the text above went to extremes to repeatedly use the words solid, liquid, and gas when water was the topic of discussion. The use of ice, liquid, and gas water phases works with students but one "fly in the ointment" is the usual use of the words water vapor instead of water gas. People simply do not appreciate that a material in its vapor phase is the same thing as the material in its gas phase. Perhaps the following classification conversation with students might help.

Consider water and nitrogen as conversation examples. At some location in this world nature provides a combination of pressure, temperature, and volume values that allow water to naturally exist in its solid (remember those folks that live near the North Pole) liquid, and gas phases. (Granted people living in Key West Florida will not see an ice berg float by but there is a lot of water in the gas phase (high humidity) and the rest is in the liquid phase.) Nitrogen on the other hand is very different. There are no naturally occurring locations where nitrogen exists in its liquid or solid phases. If you want liquid nitrogen you have to mechanically change the temperature and pressure of nitrogen molecules that are contained in a fixed volume metal container.

Historically, scientists and engineers reserve the word vapor for molecules in the gas phase when those molecules can also naturally exist in any of the three phases on Earth. Thus, nitrogen is not a vapor it is a gas. Water is a vapor it is not a gas. However, in both cases we are still just speaking about gas phase nitrogen and water.

The word humidity just muddies the water a bit. (Sorry for throwing that idem into the mix especially since mud is not a phase). High humidity simply means that there is a lot of water in its gas phase in the air. 100% humidity means that it is raining which really means that the water is in a two phase (liquid and vapor) situation with the amount of water as gas going down and the amount of liquid water going up.

Demonstration: Latent Heat of Vaporization

The classic way to demonstrate latent heat is to heat a substance such as water while observing the temperature. If the water begins in the liquid phase in a one atmosphere environment, the temperature rises with the input of heat until the boiling point is reached. As long as the water boils, the heat energy being put into the system is used for the phase change and does not increase the kinetic energy of the molecules, i.e., the temperature of the water does not increase until the phase change from liquid to vapor is complete. To demonstrate latent heat of water in a vacuum chamber, the process is carried out in reverse, as discussed earlier in this section.

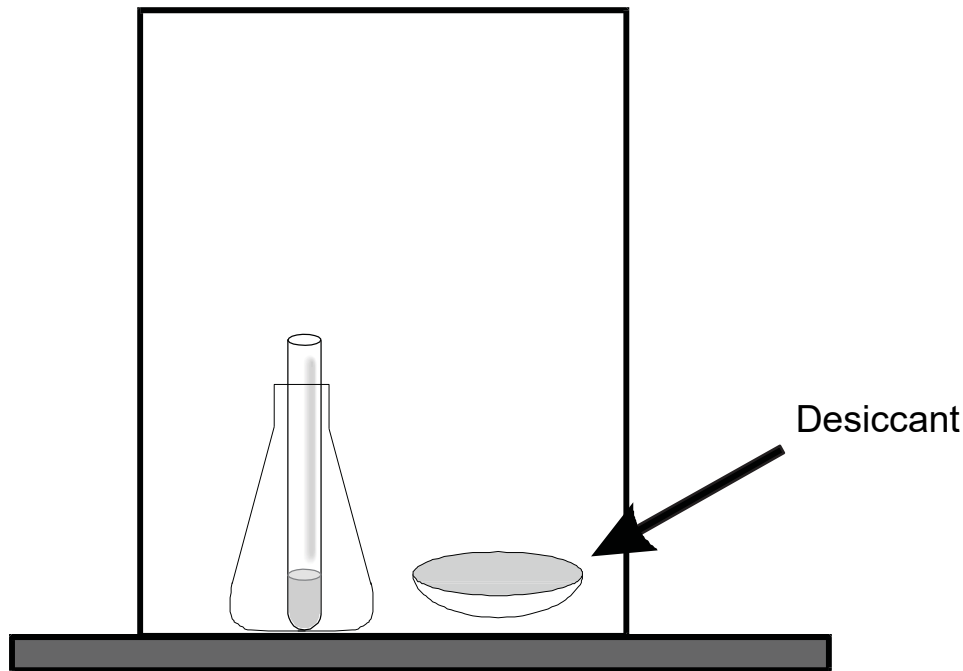


Figure 6.4. Setup for demonstration of the triple point of water in a vacuum chamber.

To demonstrate the effect, a test tube containing a small volume of water is placed in the vacuum enclosure, as shown in Figure 6.4. As the pressure in the vacuum enclosure is reduced, the air that is dissolved in the water will be released and observed as small bubbles. The release of this dissolved air is quickly followed by a more violent bubbling as the water begins to change from the liquid to the gas state. Figure 6.3(i) indicates, the pressure (the y axis values) temperature (the x axis values) combination needed to instigate this rapid evaporation. As the vacuum pump reduces the pressure above the liquid water, the temperature of the water decreases due to the evaporative cooling. If the pressure in the chamber continues to drop, the temperature will decrease to a value, $0.16\text{ }^{\circ}\text{C}$, at which point the liquid water is changed to solid water, ice, and a large amount of heat, the latent heat of fusion, is released. At this point, some of the liquid water is changed to ice while the released latent heat forces some of it to rapidly evaporate. This temperature and pressure combination is called the triple-point because, at this stage of the vacuum pumping process, all three forms of water- solid, liquid, and gas coexist and we can observe a curious occurrence, i.e., as some of the liquid water changes to ice while some of the water changes to gas.

The success of this demonstration depends on the complete removal of water vapor from the vacuum chamber as soon as it formed and thus the need of a vacuum pump with sufficient pumping speed. However, the pump's pumping speed is drastically reduced when the pump oil and pump cavities become saturated with water. To avoid this saturated condition, it is necessary to use a very small amount of water in the test tube for this demonstration. To further insure that you have sufficient pumping speed, you can add an additional non-mechanical "pump" by placing a small open container of dried desiccant.

cant (such as calcium carbonate or calcium sulfate) next to the water container in the vacuum chamber. The desiccant acts as a non-mechanical water pump, or, in this case, a chemical pump, because it removes some of the water vapor from the vacuum system by trapping it in its chemical structure, preventing it from contaminating the pump oil. Technically, it provides additional pumping capacity to reach the “triple point.” You may wish to run the experiment with the desiccant first, and then repeat it without the desiccant to demonstrate that the mechanical pump alone may not be able to reduce the pressure sufficiently to freeze the water.

Demonstration: Adiabatic Expansion of Moist Air

Adiabatic expansion of a gas can be demonstrated in two ways with a simple vacuum system. As shown in Figure 6.5, the first way is to simply place a thermometer in a vacuum system and observe the temperature as the system is evacuated. If the pumping speed of the system is rapid, the temperature will drop by several degrees; however, it will begin to rise again as the system comes to thermal equilibrium. The second way to demonstrate adiabatic expansion is to produce a cloud chamber by introducing water vapor into a chamber and then pump it out. As the temperature of the air decreases, any water vapor present condenses, since cooler air cannot hold as much moisture. If the expansion is great enough water droplets form on the gas molecules, producing a cloud. The clouding effect can be made more dramatic by dimming the room lights and shining a light through the chamber during pumpdown.

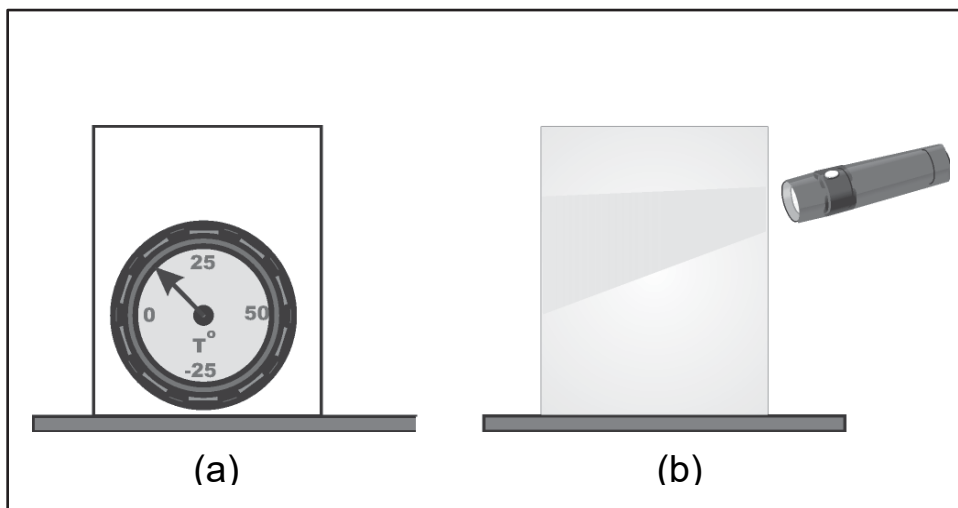


Figure 6.5. Demonstration of adiabatic expansion using (a) a thermometer and (b) a water vapor cloud.

Water can be introduced into the chamber by moistening the walls of the chamber before pumpdown or by introducing water vapor into an evacuated system. The latter can be achieved by placing a heavily moistened cloth over the up-to-air valve inlet for a few seconds when the system is partially evacuated and the pump turned off. Close the

valve, turn on the pump, quickly dim the room lights and observe the cloud formation with a bright flash light.

***Experiment:* Latent Heat of Vaporization and Adiabatic Expansion of Moist Air**

7. WORK & ENERGY ENGINEERING APPLICATIONS

Understanding and properly applying heat and work modeling principles is essential for the success of any dynamic engineering application. This fact was appreciated by Carnot (1824) as he developed an understanding of the optimal work cycle for steam engines that included James Watt's (1763) condenser innovation and the transfer of heat to and from the engine's system and surrounding. At that time, determining the best practice of heating a fluid from its liquid phase to its gas phase (the boiler for a steam engine) to allow that hot gas to push a piston and then to condense the "cold" gas back to the liquid phase to repeat this work cycle represented the technology edge for engine development. Today, the applications, air conditioning system for example, of a working fluid with all of its heat and work interactions are summarized with an elegant yet simple statement about any system of interest: "Heat + Work = Change in energy of the system".

Figure 7.1 illustrates a cylinder's moveable piston in two possible positions in its cycle. When the gas inside the cylinder is suddenly expanded, the molecules push the piston outward. This is described by saying that the expanding gas does work on its surroundings. In this illustration the work is demonstrated by the fact that the box has moved to a new position. There are options as to how the high pressure gas is initially obtained. (For a gasoline engine, a spark triggered explosion of the gasoline is the cause.) However, the point of the graphs is the fact that heat went into the system, the

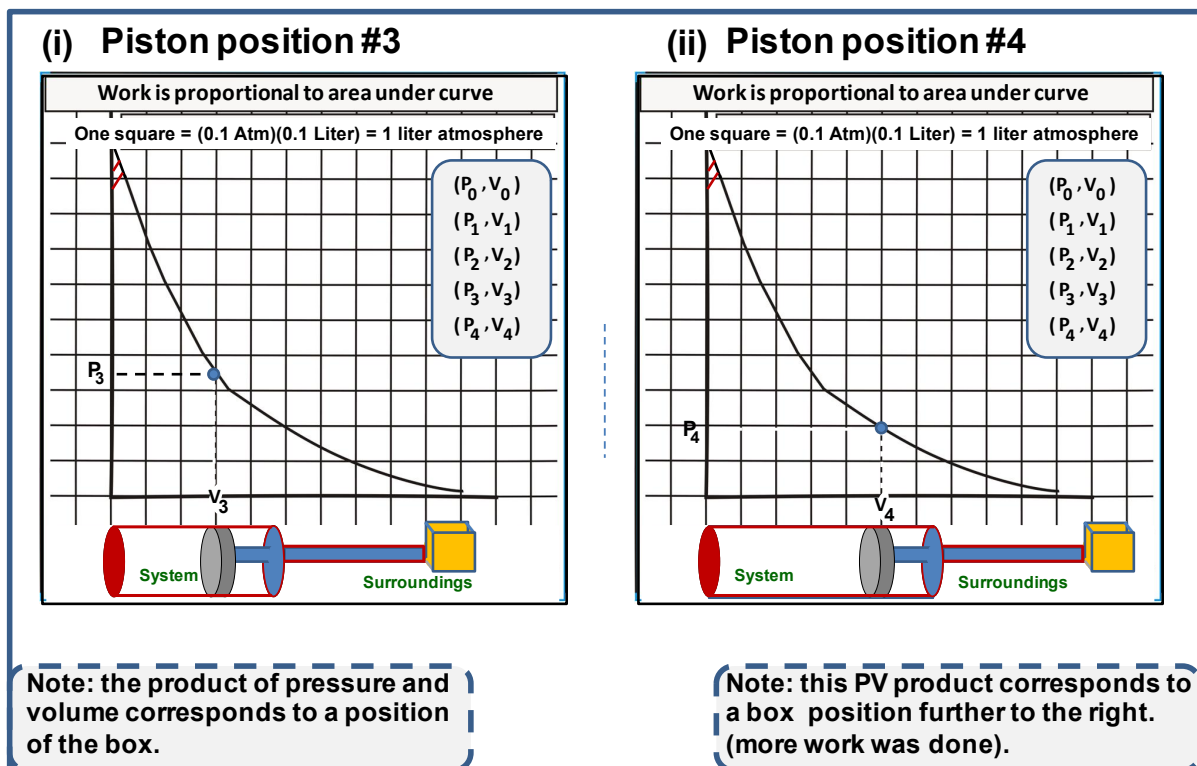


Figure 7.1. Two Possible Box Positions Because of Work Done by the Piston

cylinder with its movable piston, and work was done by that piston movement on the

surroundings (the box). The amount of work equals the force applied in the direction of the box multiplied by the distance the box moved. In this situation, that work is also directly proportional to the scalar value obtained by the product of the (P,V) ordered pair values identified by dots on the "PV" curve. If the ideal gas law model, $PV = nRT$, was used the model's PV pair products predict the work that is done. The work value for piston position #3, Figure 7.1 (i), is the area under the curve from V_0 to V_3 while the Figure 7.1 (ii) curve area from V_3 to V_4 represents the work done to move the piston and its attached box from position #3 to position #4.

Returning to the theme of Figure 3.1, if an experiment is conducted that provides the position connected box position to pressure and volume measures, that data (the real system) could be graphed and compared to the ideal system gas law model plot. If the two curves match, then the engineer can use $PV = nRT$, the ideal gas law, to predict the work related performance of the engine.

Students will demonstrate complete concept understanding of this PV example if they really appreciate that the amount of work the expanding gas performed is the sum of the work values needed to move the piston and the box. An impressive student understanding of this complete story happens when the work needed to compress the gas on the shaft side of the piston is included in the sum of work terms. This should also lead to the fact that the total PV gas expansion energy available is spent on work and the friction (heat) as the piston and box move.

7.1 Adiabatic Expansion

When a gas is suddenly expanded, molecules move outward. This action is summarized by saying that the expanding gas does work on its surroundings. As the work is accomplished, the temperature of the expanding gas drops and heat is transferred from the surroundings into the system. An adiabatic expansion is one in which there is no heat transfer between the surroundings and the system. In this situation, the decrease in temperature is still caused by energy loss from the molecules in the system but the lower temperature within the system will be permanent.

The adiabatic expansion of gas can be achieved in an insulated chamber as illustrated in Figure 7.2. As the piston moves the volume the gas can occupy increases and the temperature of the environment inside the cylinder decreases. Since heat is not easily transferred to the

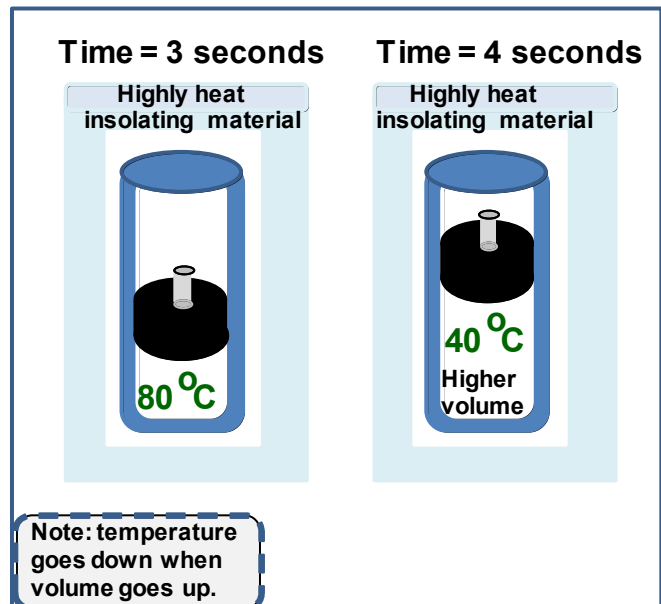


Figure 7.2 Adiabatic Gas Expansion

gas in the cylinder, the temperature of the gas in the cylinder cannot go back up. A vacuum chamber can be used to demonstrate the adiabatic expansion process. In this situation, the vacuum pump quickly starts to remove the gas in the chamber and the remaining molecules take up that space with the accompanying decrease in gas temperature. The vacuum space acts as a heat insulator to allow the temperature to remain at its lower value.

A specialized scientific application of the cooling produced by adiabatic expansion is the Cloud Chamber as perfected by C.T.R. Wilson in 1900. Today, this effect can be demonstrated with a two stage vacuum pump removing moist air (high humidity air) from a chamber. The rapid removal of molecules from the bell jar increases the volume, available space, for remaining air and water molecules in the container. This adiabatic expansion also lowers the temperature of all of the molecules still in the chamber. The water molecules respond to this new volume, temperature environment by a phase change, condensation. Water droplets form on various nuclei present, e.g., dust particles, and, if the expansion is rapid enough, a “cloud” appears inside the chamber.

7.2 Environmental Engineering Applications

7.2.1 Wastewater Treatment

Advanced Oxidation of Recalcitrant Organics in Wastewaters

The CAV_OX™ system is a commercial process for advanced oxidation of contaminated water with dissolved recalcitrant organic pollutants. The process, outlined below in Figure 7.3, is based on the premise that hydroxide free radicals can form from water molecules when cavitations occur in a pump. The hydroxide free radicals begin a chain reaction whereby the recalcitrant organic compounds are broken down to smaller and smaller fragments. The smaller organics may be oxidized all the way to carbon monoxide and water or become small enough that they are readily biodegradable. This initial free radical oxidation process is often used to remove halogens (chlorine, bromine, etc) from recalcitrant halogenated organic compounds.

Contaminated water is exposed to ultraviolet light radiation immediately after free radical generation in the cavitation chamber ensures complete hazardous organic compounds destruction. The ultraviolet light ensures propagation of the radical chain reactions for a designated time depending on the particular contaminant. Fluid flow is regulated by valves and a small portion of the effluent stream containing some free radicals is recycled to the beginning of the process to help propagate the chain reactions. The remaining portion is discharged for further treatment or reuse.

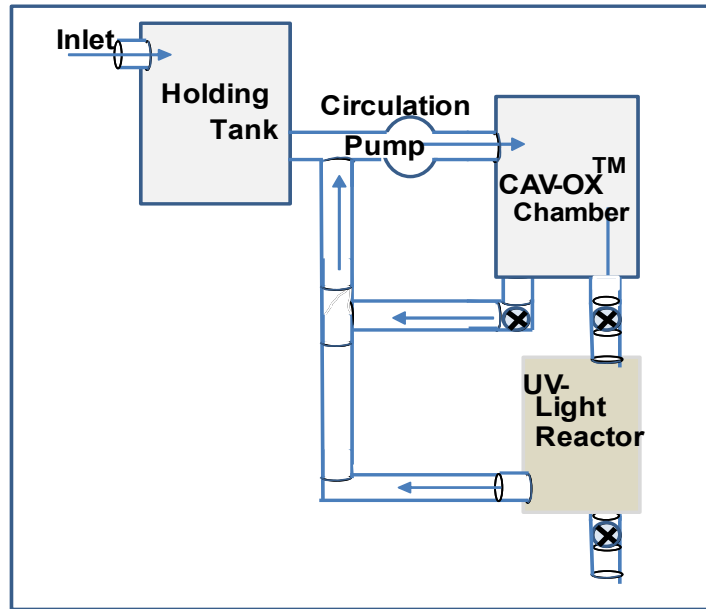


Figure 7.3. CAV_OX Advanced Oxidation Process for Water Treatment

Cavitation is a phenomena that occurs when a liquid is forced to pass through a restricted (smaller) orifice at a specific pressure and temperature, as shown in Figure 7.4. The velocity of the flowing liquid increases as it passes through the restriction. The increased velocity is accompanied by a decrease in pressure. If the pressure drops below the vapor pressure of the flowing liquid, some of the liquid vaporizes forming bubbles (cavities) of gas (water vapor, in the present case) in the liquid.

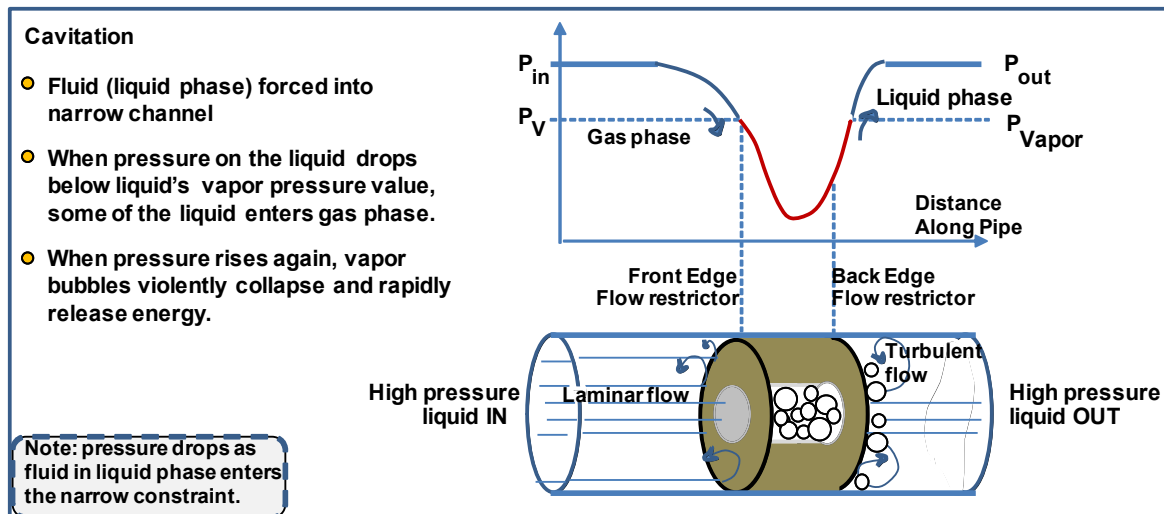


Figure 7.4. Cavitation Process in Pipe with Constrained Flow

As the fluid leaves the orifice, the velocity drops and the pressure increases. When the pressure rises above the vapor pressure of the liquid, the gas bubbles or cavities collapse back to the liquid state, releasing energy. The energy released is sufficient

to excite the water molecules. These excited water molecules can break apart into hydrogen and hydroxide-free radicals. In an effort to appease their unpaired electrons, the high energy hydroxide-free radicals begin a series of chain reactions with the nearby dissolved contaminant organic molecules in the wastewater that are the target of the destruction technology.

7.2.2 Subsurface Remediation

Soil Vapor Extraction

Below the surface of the earth, there are several distinct geologic soil zones that can be defined by their water content. There is a dry zone right under the surface that normally has no water (except immediately after rainfall events) in the pore space between the sand and soil grains. Some distance below the surface a water table exists, which is the elevation below which all the pore spaces between the sand and soil particles are filled with water.

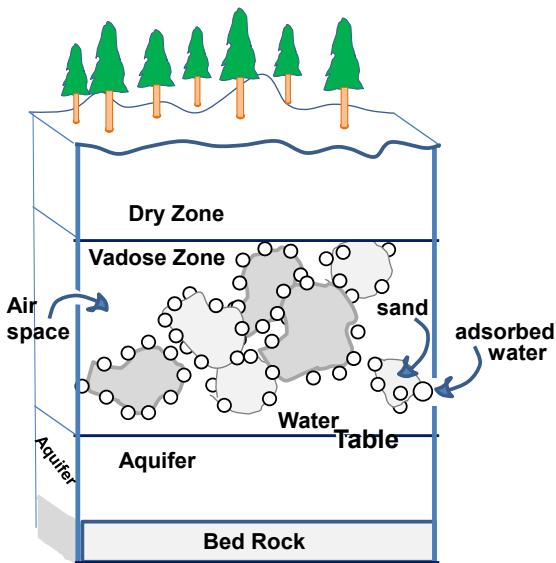


Figure 7.5. Subsurface Aquifer Zone Profiles

Immediately above the water table a zone exists where the soil void space is partially filled with water and partially filled with air. The water in this zone stays there via capillary action, pulling itself up the tiny spaces by means of surface tension in the small diameter pores. These subsurface zones are illustrated in Figure 7.5. Contamination in the subsurface may be found in any one or all of these three zones depending upon where the contaminant was released (such as a spill at the surface or a leaky underground storage tank). Different technologies must be used to remediate

contamination in these different zones due to the different environment of the undesirable chemical.

Soil Vapor Extraction (SVE) is a technology that can be used to remove contamination from the Vadose Zone. This zone is defined as the subsurface zone that extends from the ground surface down to the water table. Soil Vapor Extraction technology is most successfully used to remove organic contaminants that have low vapor pressures. Some organic compounds that can be removed by SVE are listed in the Table 7.1.

Volatiles	Semi-volatiles	Hydrocarbons
<u>toluene</u>	DCB (dichlorobenzene)	<u>jet fuels</u>
<u>ethylbenzene</u>	<u>chlorobenzene</u>	<u>diesel fuels</u>
<u>cyclohexane</u>	<u>methanol</u>	<u>kerosene</u>
PCE (<u>tetrachloroethylene</u>)	<u>pyridine</u>	<u>gasoline</u>
<u>acetone</u>	<u>dimethylfuran</u>	<u>heavy naphthas</u>
<u>carbon tetrachloride</u>		
TCA (<u>trichloroethane</u>)		
<u>benzene</u>		
<u>methylene chloride</u>		
TCE (<u>trichloroethylene</u>)		

Table 7.1. Molecule Removed by Soil Vapor Extraction

A schematic of the technology is illustrated in Figure 7.6. It includes an extraction well to pump up contaminated groundwater. At the surface, it is connected to one of the types of vacuum pump listed in Table 7.2. The pump reduces the local pressure in the vadose zone to a value below the vapor pressure of the contaminant to be removed. The extraction well draws from the soil pore spaces and is surrounded by an array of

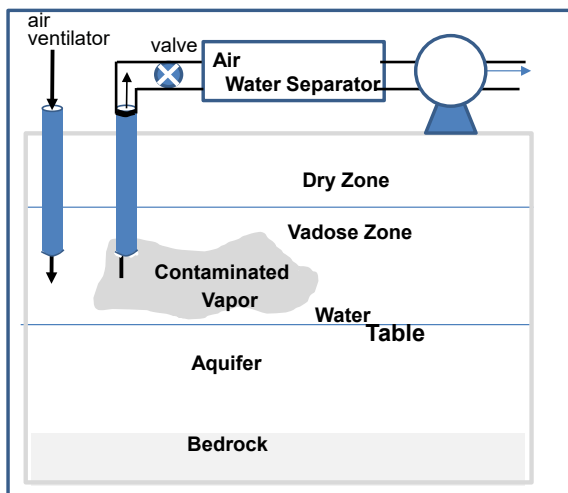


Figure 7.6. Soil vapor extraction process.

several air injection wells. The injection wells pump air down into the vadose zone to provide an adequate supply of air to the soil pore spaces from which the extraction well draws its air. Once extracted from the subsurface, any liquid water suctioned up with the vapors is separated from the contaminated air. Ultimately, both the gaseous and liquid discharges must be sent to treatment or be destroyed. Final remediation of the organic contaminant may be accomplished by subjecting the water and/or air streams to an above ground separation or destruction technology such as carbon adsorption or incineration.

Liquid Ring Pumps

0-29 inches Hg (760 Torr)

10-100 cubic feet per minute flow

used for remediation and permeability tests

high vacuum without wearing out rotor by compressing water

uses mechanical seal plus O-ring gasket for zero leaks

Rotary Vane Pumps

used for air permeability tests of soil strata and low volume flow applications

27 inches Hg minimum pressure

no oil required when carbon vanes/blades are used

Regenerative Blower Pumps

low to moderate vacuums at high flow rates (large volume)

used for large jobs

Table 7.2. Pump Options for Soil Vapor Extraction

7.2.3 Air Pollution Control

Landfill Gas Recovery

The process of biological decay can be either aerobic (with oxygen) or anaerobic (without oxygen). In sanitary landfills, the decay process is primarily anaerobic. The municipal solid wastes disposed of in the landfill are covered and compacted each day, which keeps air (and, therefore, oxygen) away from the decaying wastes. The end product of anaerobic decay include the gases methane and carbon dioxide and the mixture is sometimes referred to as "landfill gas". Since gases take up more volume than either

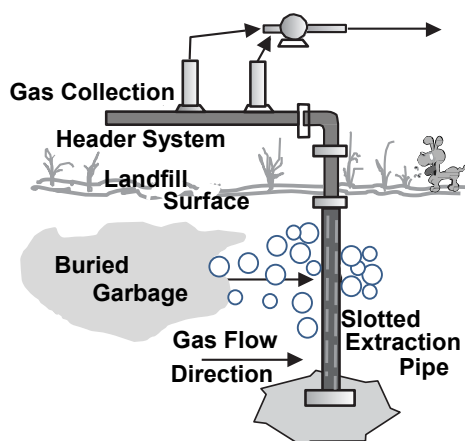


Figure 7.7. Landfill gas recovery well and collection system.

liquids or solids if they are allowed to accumulate in the compacted and covered landfill, they will build up pressure and may potentially cause the landfill to explode. To minimize the potential for such an explosion, it is necessary to remove the landfill gases. This is achieved by facilitating their migration through the buried garbage and soil layers and to vent them to the surface at the peripheral of the landfill. Methane gas has an unpleasant odor, and the combined carbon dioxide and methane mixture is combustible. Therefore, it is desirable to collect landfill gases and dispose of them or use them in a controlled manner.

The gas extraction process, as shown schematically shown in Figure 7.7, is similar to that used in soil vapor extraction, where venting wells are installed around the landfill. Each well is surrounded by several concentric layers of graded porous material (with increasing porosity toward the extraction pipe) so that the gases will migrate efficiently toward the wells. The wells are tied together above the surface with a header conduit system that is connected to a vacuum pump. The pump reduces the pressure in the wells to further enhance gas migration and collection. The collected landfill gas is either torched on site or collected and sold to local power utilities to be used as a fuel.

7.2.4 Waste Minimization

Dewatering Filter for Sledges

Sludge may be organic, inorganic, or biological (better known today as "biosolids") in nature. Generically, they are mixed waste solids that result from various water, wastewater and industrial water treatment processes. Most biosolids have solid contents that are 5% or less. This means that 95% or more is water. This high water content makes them unnecessarily expensive to dispose of because much of the disposal cost is related to transportation of the water bound in the biosolids. Transporting water mixed with the waste is just not economical or good use of water resources. The water can be separated, treated and recycled through a treatment facility. To reduce transportation costs most biosolids are dewatered at the processing plant before disposal.

There are several commercially available technologies currently used for dewatering various different types of sludge. These include centrifugation, floatation, compression settling and vacuum presses. One such device is a vacuum belt press as shown in Figure 7.8. Here, the wet sludge is spread out on a wide conveyor belt which passes over a suction plate under which a vacuum has been created. At the same time

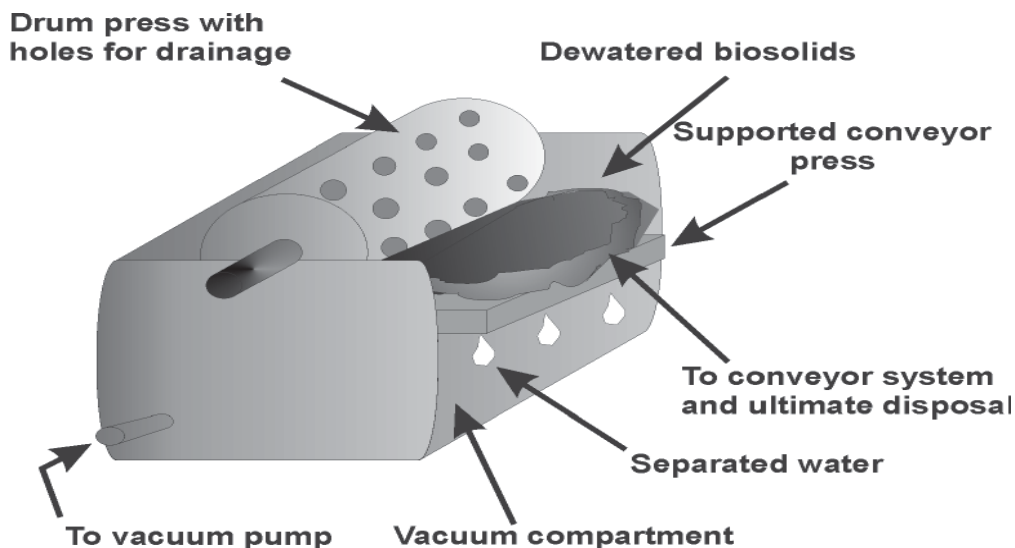


Figure 7.8. Schematic of vacuum dewatering system for biosolids.

that the biosolids are suctioned from below, they are compressed by another belt or a roller from above. This process uses the same principle as suction filtration processes often performed in chemistry labs with aspirators or vacuum pumps. Using one or more of these dewatering technologies in series, the solids content of sludges may be increased up to 20% solids. The economics of dewatering in most cases are more favorable than those of disposing of the original wet sludge.

7.2.5 Pollution Prevention

Spray Painting with Supercritical Fluids

One application of a supercritical fluid is solvents for paints that are applied with pressurized sprayers. Supercritical carbon dioxide can be used as a solvent for the paint that is to be applied by a pressurized spray device. Figure 7.9 shows a schematic of a basic supercritical fluid painting system. Carbon dioxide (or any other supercritical fluid carrier) is pressurized with an appropriate pump. The CO₂ reaches its supercritical phase in the pressurized delivery tube. As the fluid is pumped, small amounts of a paint pigment are metered into the line. After a sufficient mixing length, the "paint" is dispensed

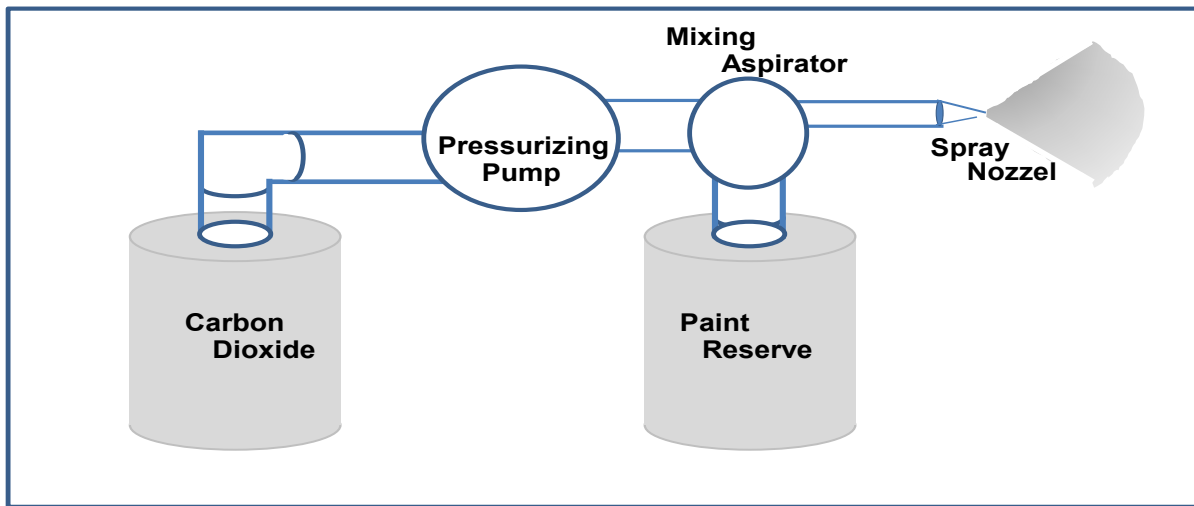


Figure 7.9. Illustration of Supercritical fluid Paint Spray Process

through a fine high pressure nozzle designed for the application. As shown in Figure 7.9, pressurized liquid carbon dioxide is brought above its critical temperature and pressure (1071 psi and 31 °C).

Organic solvents traditionally have been used as carrier solvents for paint pigments in these spray applications. However, the excess organic solvent becomes contaminated with paint pigment and must be collected for disposal, recycling, or reuse. Most organic solvents are somewhat harmful to human health. If it is a volatile liquid, it offers at least two exposure routes to humans: inhalation and adsorption through the skin during paint application. The use of supercritical carbon dioxide as the pigment carrier

fluid eliminates exposure to hazardous organic solvents in this application and reduces the amount of hazardous material that must be monitored and contained.

The environmental advantage of this technology is the fact that carbon dioxide returns to its vapor state when the paint/supercritical carbon dioxide mixture is vented through a nozzle as the paint is applied to the object desired. The amount of vented carbon dioxide gas in this process is generally considered to be nontoxic for humans and has minimal if any impact on the environment.

8. VACUUM PUMPS AND PRESSURE GAUGES

8.1 Some Historical Context on Vacuum Pumps

Among the first vacuum pumps were simple modifications of the barometer invented by Evangelista Torricelli in c.1643. As shown in Figure V8.1, the vacuum chamber was simply a glass bulb formed on the end of a glass tube, where the tube was at least 30 inches long. In operation, the tube and bulb were first filled with Hg, and then the entire apparatus was turned upside down while the open end of the tube was immersed in a tank of Hg. When the Hg flowed out of the bulb through the tube, the bulb would become evacuated. In this case, the “vacuum pump” was the liquid Hg flowing out of the tube, leaving a “vacuum chamber” containing primarily a dilute Hg vapor (Hg vapor pressure @ 25°C is $\sim 2 \times 10^{-3}$ Torr). During the next ~ 200 years, many different types of *Hg-based vacuum pumps* were developed, and later designs were used in the development and production of the first incandescent light bulbs at the end of the 1800’s.

Another noteworthy historical application of vacuum pumping technology shown in Figure 8.2 was developed for the construction of the US Transcontinental Railway (TCR) during the mid 1800’s. The engineering issue was, from the eastern starting point of the TCR (Omaha, Nebraska) to the Rocky Mountains, the only wood available for railway ties was from cottonwood trees. Unfortunately, the cottonwood railway ties lasted only ~ 1 year when in contact with damp ground, and it would take 3 years for the railway to reach the Rocky Mountains - where lumber from longer-lasting, conifer-based lumber could be readily acquired. The solution was to treat every cottonwood railroad tie using a large vacuum oven. The vacuum ovens were constructed of mild steel, and were 5-foot diameter and 100-foot long. They were fabricated on the eastern seaboard of the US, and brought by steamship around Florida and up the Missouri river to Omaha. Heating the ties in the oven at reduced pressure accelerated moisture evaporation from the lumber. Following this vacuum heat treatment, the chamber was backfilled with a zinc chloride vapor as it cooled, yielding “treated wood” ties that lasted the



Figure 8.1. c. 1700’s image of Torricellian Columns indicating identical Hg column heights independent of tube length. Note evacuated bulb on central column.



Figure 8.2. Burnettizer in operation c.1863. Vacuum chamber entrance is on left side. From: S.E. Ambrose, “Nothing Like it in the World - The Men Who Built the Transcontinental Railroad 1863-1869” (Touchstone Pub., New York, 2000).

needed 3 years. This early lumber treatment was called “Burnettizing,” and three Burnettizer vacuum systems were in operation 24/7 during the 6 years of the TCR construction. Although uncertain, it is likely the vacuum pumps used for the Burnettizers were *steam-driven aspirators* that would have produced a vacuum pressure on the order of ~100 Torr while pumping the large quantities of moisture removed from the lumber.

One final historic example demonstrating the importance of vacuum pumps relates to the US agricultural industry. This example also links vacuum technology to both the US Rural Electrification Association (REA) initiative of 1930’s, and US national security issues of the 1940’s. Figure 8.3 shows a small vacuum pumping system that would be used to produce the low pressure needed to operate automatic dairy milking machines. The vacuum pump used in this unit is very similar to the equipment used in this AVS workshop. This *rotary-vane vacuum pump* was patented in 1874, so by the 1920’s, the technology sufficiently advanced to meet the needs of the dairy industry. The problem was, in the 1920’s, very few farms in the US had electricity available to run the electric motor need for the vacuum-pumping system. Therefore, milking continued to be labor intensive - performed truly “by hand”. This changed in the mid 1930’s when the depression-era REA initiative began. These government programs sought to bring benefits of electricity to the rural US, thereby improving rural standard of living, and (more importantly) maintaining the US rural workforce needed to grow the food to feed a rapidly urbanizing country. Although the REAs were very successful in meeting these goals, an important and unforeseen benefit was realized in late of 1941 – at the start of WWII. Unlike other Allied countries, the US was able to quickly re-deploy a much larger portion of its agricultural-based workforce to military duties – while actually increasing agricultural output! This was largely because the human-labor requirements of US agriculture had been reduced through the benefits of rural electrification. Therefore, at least within the context of the US dairy industry, one might suggest the oil-sealed, rotary-vane vacuum pump was a contributing factor to the outcome of WWII.

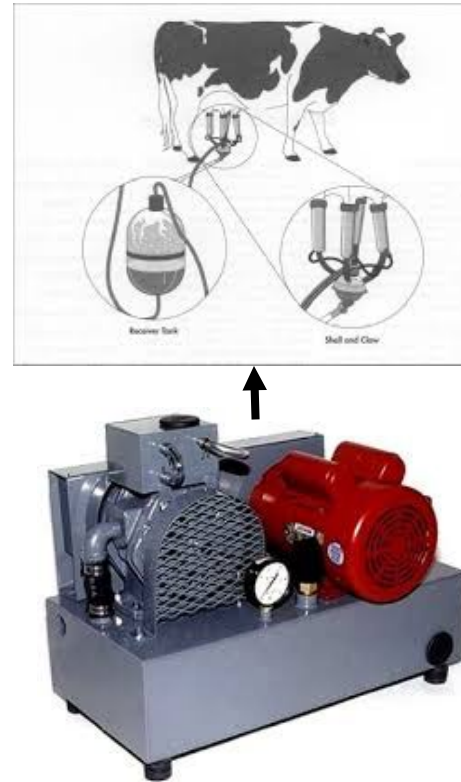


Figure 8.3. Vacuum-pumping system used in the dairy industry.

8.2 Modern Vacuum Pumps and Systems

Moving into “modern” uses of vacuum pumps, one can divide applications into categories of “simple,” vs. “moderately complex,” vs. “very complex” applications. One simple vacuum pump that many people have used or been exposed to is shown in Figure 8.4. Moving a bit forward in one’s age, likely the first moderately complex “vacuum-system” experience is shown in Figure 8.5. Although often the refrigerator is not considered a vacuum-pumped system, the pump used to transport refrigerant within the system is known as a *scroll pump* (to be described later), and is an important pump used in various vacuum industries. The combined compression of the refrigerant by the scroll pump, followed by heat-extraction by cooling radiators located on the back or bottom of the refrigerator, causes the gaseous refrigerant to transition first from a gas to a liquid phase, then later, from a liquid back to a gas phase (the second phase transition occurring within the refrigerated region). The Gas Laws presented earlier in this workshop describe the extent of temperature reduction during the latter phase change, and thus why “cooling” is produced (e.g., $P_1/P_2 = T_1/T_2$, see Amonton’s Law and/or Gay-Lussac Law). Although the operational pressure of modern refrigerants is generally higher than atmospheric pressure (e.g., the saturated vapor pressure of R22 refrigerant at 40°F is ~69 PSIG), assuring the plumbing circuit within the refrigerator is sufficiently clean prior to refrigerant addition is critically important in the refrigeration industry. Indeed, the primary use of the Yellow Jacket vacuum pump used in this workshop is for cleaning the refrigerant-circuit prior to refrigerant filling or re-filling (see Figure 8.6).

Other often observed (but under-appreciated) moderately complex uses of vacuum pumps can be seen in when visiting the drive-up window of your local bank. In this case, the pressure differential in the pneumatic tube (that drives the shuttle to bring you your cash!) is typically provided by a vacuum pump. Another moderately complex example, seen in many high-school classrooms, is the *water driven aspirator vacuum pump* as shown in Figure 8.7. Although very effective and educational for simple vacuum filtration experiments, most local ordinances now limit the use



Figure 8.4. One of the first vacuum-pumps used by many.



Figure 8.5. Likely our 2nd vacuum-pump enabled experience.



Figure 8.6. Vacuum pump used in this workshop configured for its primary use in refrigeration-circuit cleaning.

because chemicals used in the classroom can enter the municipal drain/waste-treatment system.

A related example to the water aspirator “vacuum pump” is the wing of the aircraft that brought most of you to this workshop. Although science teachers generally know the



Figure 8.7. Water-driven aspirator vacuum pump - historically used in high-school chemistry classes.

Bernoulli principle of air flow on the top of the wing produces a lower pressure than air flow on the bottom of the wing (the resulting pressure difference manifesting in the “lift” force), we generally don’t think of the wing as a vacuum pump. However, the Venturi-effect that describes the water aspirator vacuum pump - can be viewed as

a multiple-sided airfoil (see Figure 8.8).

Moving from moderately complex to highly complex vacuum pumps, we enter the world including scientific research, electronic products, and aerospace simulations. In this area again, vacuum pumps are separated into various categories that can relate to parameters such as their size, ability to pump various types of gas, their minimum pressure, and their cost.

Considering the size of the vacuum pump, Figure 8.9 shows one of the smallest pumps - presently being developed to pump Micro-Electro-Mechanical Systems (MEMS). In this case, the “vacuum chamber” to be pumped would be smaller than a grain of sand - and fabricated entirely onto an integrated-circuit microchip. Although the prototype pump indicated in Figure 8.9 can presently achieve vacuum pressures of only ~1 Torr, the design goals of the project are to eventually attain pressures 1×10^{-6} Torr, and be at least 100X smaller in size

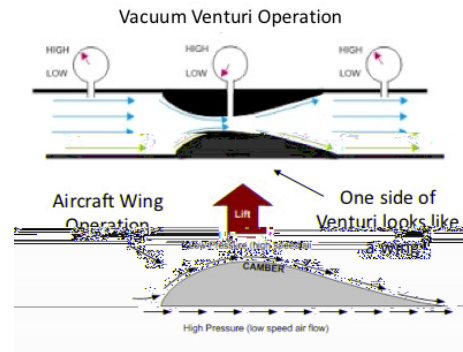


Figure 8.8. Illustration that Venturi operation to produce vacuum is essentially the same as Bernoulli airfoil lift.

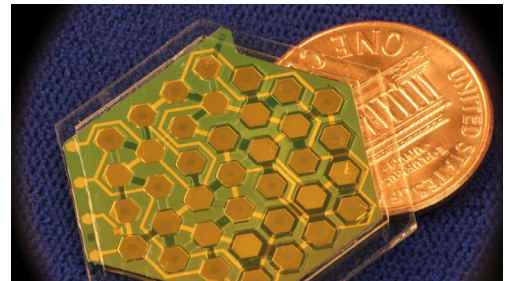


Figure 8.9. DARA-developed, prototype MEMS-based vacuum pump

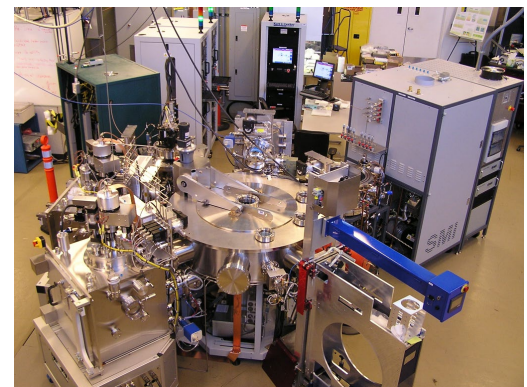


Figure 8.10. 7-chamber cluster tool at the National Renewable Energy Laboratory (NREL) designed for advanced contact metallization research related to thin-film PV solar cells.

Increasing in size, and reducing in pressure, Figure 8.10 shows a research “cluster tool” incorporating 7 chambers. Although each chamber is configured with a vacuum pump to address specific process requirements, the chambers are collectively designed to produce a vacuum base pressure of $\leq 5 \times 10^{-8}$ Torr. This cluster tool was designed to perform advanced research for development of electrical contacting strategies that would be used to produce future thin-film photovoltaic (PV) solar cell modules demonstrating decreased cost and/or increased long-term reliability/durability. Recent research directions included developing contacts that would remain stable during 50-100 years of PV module deployment in harsh conditions.

Increasing still further in vacuum chamber size, and still lower in attainable chamber base pressure, Figure 8.11 shows the main target chamber installed at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. During operation, the chamber is designed to expose a “target” of hydrogen isotopes to a focused beam of 192 high-power lasers. The goal of the research is to better understand nuclear fusion processes. The chamber has a reported design base pressure $\sim 5 \times 10^{-6}$ Torr, but is also indicated to attain pressures of $\sim 3 \times 10^{-10}$ Torr in critical regions of the chamber. Attaining these pressure levels, within a ~ 30 -foot diameter vacuum chamber, requires many different types of vacuum pumps – each designed for specific procedures during the operation of the NIF. For example, in addition to low vacuum base pressure, the pumps used on the NIF chamber must also consider issues such as vibration, long-term operation, and sensitivity to radiation by-products.



Figure 8.11. ~ 30 -foot diameter NIF main target chamber being position into facility. During operation, 192 high-power lasers focus on a target the size of a BB projectile to simulate and understand issues of nuclear fusion.

8.3 Vacuum Pumps and Pumping Mechanisms

The above review indicates that not all vacuum processes require the same performance from the vacuum pump. It is further implied that parameters such as pump performance, reliability, and ease of operation, has continually improved since the inception of vacuum pumps in the mid 1600's. Figure 8.12 illustrates many of the pumps that have been developed and used since about 1900. The figure provides not only the operating pressure range for each pump, but an indication of the time during major pump development activities, and the major societal influence at the time of development.

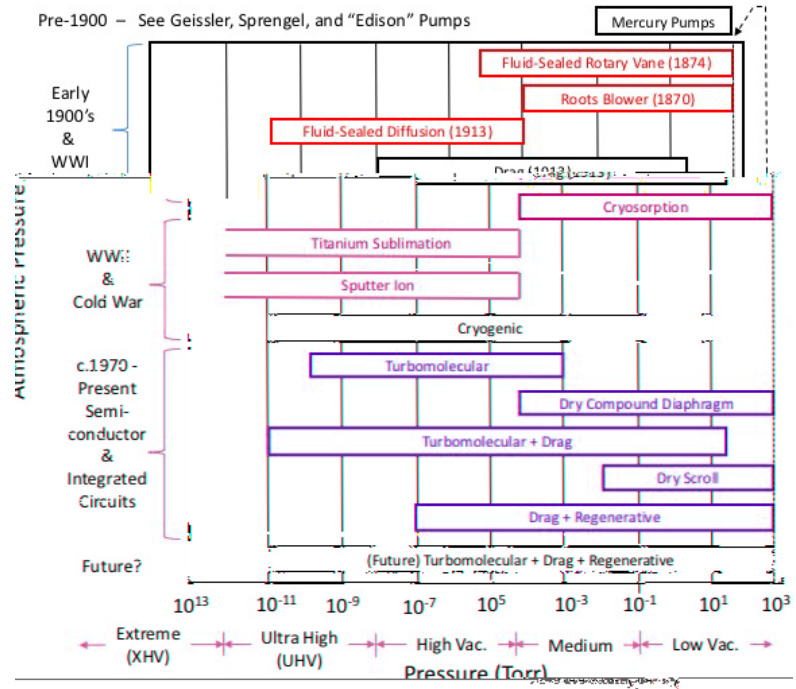


Figure 8.12. Illustration of many of the various pumps used today in various sectors of vacuum technology. The different colors of pumps suggest which specific pumps are often used together on a single vacuum system, or are used together for certain types of processes. Modern pumps continue to expand their pressure range.

All of the pumps indicated in Figure 8.12 can be divided into three basic categories that describe the main functionality of the pump. The three pumping categories are:

- (1) Positive Displacement
- (2) Momentum Transfer
- (3) Capture

Positive Displacement Pumps (PDP) were the first types of pumps developed. PDPs in Figure 8.12 include the Hg-based, fluid-sealed rotary-vane, roots blower, diaphragm, and scroll pumps. The pumping mechanism of a PDP can be viewed as a volume of gas that is allowed to expand into the pump inlet, and this entire trapped gas volume is moved through the pump and exhausted. The oil-sealed rotary vane pump used for this workshop is a PDP, and will be discussed in detail later.

In contrast to PDP, a Momentum Transfer Pump (MTP) operates at a sufficiently low pressure so that the mean free path of the gas molecules within the pump is longer than the distance between the moving parts within the pump. At this low pressure (recall

at $\sim 5 \times 10^{-3}$ Torr, the mean free path is ~ 1 cm), moving parts within the pump can strike individual gas particles more-or-less one at a time, knocking them in a preferred direction (i.e., toward the exhaust of the pump). MTPs in Figure 8.12 include fluid-sealed diffusion pumps, drag pumps, and turbomolecular pumps.

Finally, and differing from both PDPs or MTPs, are Capture Pumps (CPs). In a CP, gas-phase molecules are encouraged to “stick” to a surface within the pump. This encouragement can take advantage of either chemical activity (i.e., ionic or covalent bonding), dipole bonding (i.e., Van Der Waal forces), or low temperature induced condensation. CPs in Figure 8.12 include Cryosorption, Ti-Sublimation, Sputter-Ion, and Cryogenic pumps.

8.4 Modern Vacuum Pumps and their Pumping Mechanisms

Positive Displacement Pumps:

The most well-known type of PDP is the oil-sealed, rotary-vane pump. This is the type of pump used in this workshop. Figure 8.13 presents a schematic cross section of this pump, showing a central “rotor” containing “vanes” that move in such a way to maintain contact with an outer “stator” assembly. The entire stator is surrounded by a fluid that acts to remove the heat of compression generated by the pump, and also serves to lubricate and seal the surfaces between the rotor and the vanes, and the vanes and the stator. Details of the operation of this pump will be discussed in a later section, but the key points for now is that the fluid-sealing, that allows the pump to function up to atmospheric pressure, also can cause some fluid vapor to “backstream” into the vacuum chamber, leading to contamination concerns.

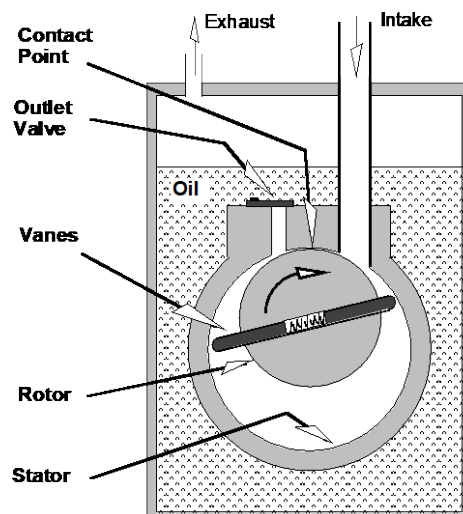


Figure 8.13. Cross-Section of fluid-sealed, rotary vane pump showing main components.

Another well know PDP is the diaphragm pump shown in Figure 8.14. Diaphragm pumps are available with various performance attributes, and low-cost options in typical science-supply catalogues/websites may have performance consistent with the needs of many high-school science projects. However, unlike the oil-sealed rotary-vane pump, a low-cost diaphragm pump will not achieve a pressure much less than 100 mTorr (i.e., 100X time higher than the fluid-sealed rotary vane pump used in workshop), so it may not work for some experiments - like the triple point of water. However, the diaphragm pump does not require the use of vacuum-pump fluid, and so it can be a much cleaner option for some experiments - such as those involving investigating the effect of atmospheric force.

One final PDP pump for classroom consideration is the modern *scroll pump* shown in Figure 8.15. As mentioned earlier, the scroll pump mechanism is the same as that used in most household refrigerators and/or air conditioning systems. However, for vacuum service, air is being pumped rather than a self-sealing/lubricating refrigerant. Therefore, flexible “tip seals” must be used within the pump to yield an acceptable base pressure - presently on the order ~ 10 mTorr (i.e., $\sim 10X$ higher than the fluid-sealed, rotary vane pump). Present tip seal materials have a useful life of about 1 year of continuous operation. Therefore, for a classroom pump that is only used for ≥ 100 hrs a year, the tip seal could be expected to last for ~ 100 years! Unfortunately, present scroll-type vacuum pumps are more expensive (and generally larger) than the fluid-sealed rotary vane pump used for this workshop. However, as price and available sizes of vacuum scroll pumps decreases, and reliability improves, they could become an option for high-school, science-class uses.

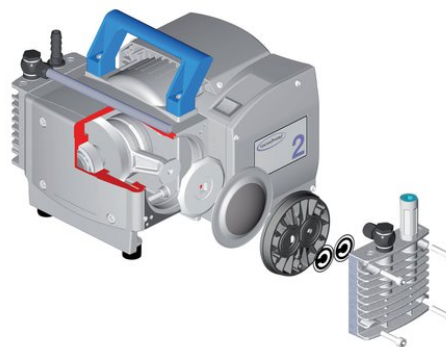


Figure 8.14. Exploded view of two-stage diaphragm pump meeting needs of some education projects.

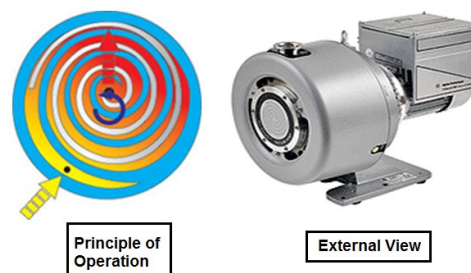


Figure 8.15. Illustration of scroll pumping mechanism, and external image of scroll pump.

Momentum Transfer Pumps:

The two most often used types of momentum transfer pumps (MTPs) are the fluid sealed diffusion pump and the turbomolecular+drag pump. As the name implies, the fluid-sealed diffusion pump uses a fluid to affect its pumping mechanism. This pumping mechanism is shown in Figure 8.16, where hot, heavy oil molecules (thermal velocity ~ 500 m/sec) are ejected from the “jets” surrounding the side of a series of concentric chimneys within the pump. The use of the concentric chimneys is to maintain pump performance as hydrocarbon or silicone-based fluids fractionate (become smaller) when heated to high temperature for long periods of time. Major advantages of the diffusion pump include relatively low purchase cost, availability with very large pumping speed, and significant tolerance to items being dropped into the pump (because there are no moving parts within the pump – except diffusion pump fluid!). However, major disadvantages include the potential fluid “backstreaming” into the chamber, and changes in pump performance because the diffusion fluid can become mixed with fluid from a connected fluid-sealed “backing” pump.

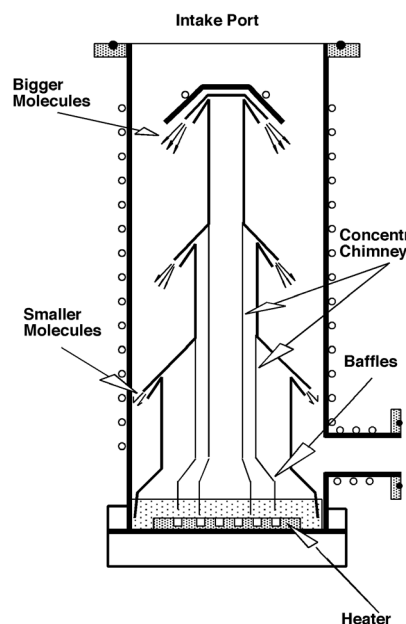


Figure 8.16. Cross-section of jet operation in a diffusion pump.

In contrast, the turbomolecular+drag pump (also called a turbodrag pump, see Figure 8.17) does not rely on fluid to transfer momentum to gas molecules. Instead, the turbodrag pump contains a series of rapidly spinning (50K-80K RPM) blades that selectively impart momentum and direction to gas molecules, moving them preferentially toward the exhaust port. The “drag” stages (shown as flat plates below the “turbo fins” in Figure 8.17) of the turbodrag pump provides additional pumping speed in the pressure region between ~10 mTorr and ~30 Torr. This enhanced performance at higher pressures eliminates the need for an oil-sealed backing pump, allowing instead the use of a (dry) diaphragm or scroll pump for backing. Advantages of the pump include the potential to produce very clean vacuum environments, one-button operation, and access for computer monitoring to optimize performance and maintenance. Disadvantages include high purchase cost, intolerance to mechanical shock or parts being dropped into pump, and limited time between failure (especially for smaller pumps).



Figure 8.17. Cut away showing both turbomolecular and drag stages within a turbodrag vacuum pump.

Capture Pumps:

The final pumping mechanism is capture pumping (CP). There are three main types of CPs used presently in the vacuum-technology industry: Sputter-ion pumps (SIPs); Ti-sublimation pumps (TSPs); and Cryogenic pumps. Of these three, SIPs and TSPs are often incorporated together within a single chamber; especially for research and analysis systems where process gases are not used. SIPs were initially developed during the “Cold War” era of the 1950’s for use to evacuate radar tubes (then known as Klystron Tubes), and can achieve pressures within a vacuum chamber of $<1 \times 10^{-10}$ Torr - if the chamber is properly designed and operated. Figure 8.18 illustrates the main functional components of a SIP. The components include two grounded Ti cathodes and an anode that operates 2000-5000 Volts relative to ground potential. A magnetic field is also required, and this is typically produced using a large permanent magnet located on the outside of the chamber. Advantages of an SIP include that the pump has no moving parts (except for ions and electrons), it can be operated nominally in any orientation, has a potential to achieve pressures significantly $<10^{-10}$ Torr, and has very low power consumption. The main disadvantages include intolerance to even small gas loads, poor pumping speed for inert gases (e.g., Ar and He), sensitivity to magnetic fields, and

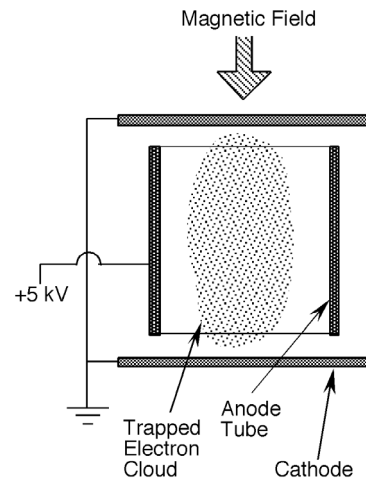


Figure 8.18. Functional components of a single cell in a sputter-ion pump.

high initial cost. TSPs are typically configured with an SIPs because the TSP can significantly increase overall pumping speed for N₂, O₂ and H₂ (See Figure 8.19).

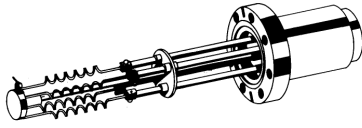


Figure 8.19. Illustration of wire-type Ti-sublimation pump.

portion” (i.e., cooling portion) of a He closed-cycle cryogenic pump. The major components are a surface maintained at ~80K that will pump water and organics, a 15K stage that will pump N₂, O, and Ar, and a 15K stage with a sieve material attached (activated charcoal) to pump H₂, He, and Ne. Advantages of the cryogenic pump include high pumping speed for typical gases, sufficient low base pressure (~1x10⁻¹¹ Torr) for many UHV processes, and a cost that is generally lower than the turbodrag pump. Disadvantages of cryogenic include the need for warming the pump occasionally to release condensed gas, the tendency of the pump to produce charcoal particles when operated upside down, and the fact that the pump could contain condensed toxic or explosive gases (i.e., the ozone that can be produced during sputtering oxides).

Cryogenic pumps are likely the most rapidly expanding type of CP pump. Although the cryogenic pump cannot attain base pressures as low as the SIP+TSP combination, it can readily pump very large gas loads, especially N₂, O₂, and/or Ar (i.e., the three most abundant gas species in earth’s atmosphere), and uses no pump fluid. For these reasons, cryogenic pumps have found key applications in semiconductor process applications. Figure 8.20 shows a schematic cross section of the “expander

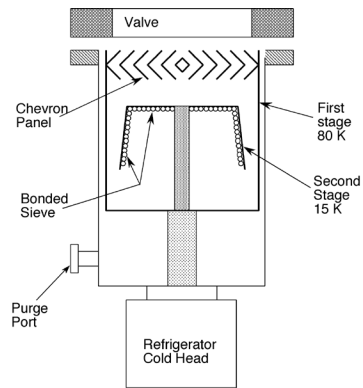


Figure 8.20. Functional components within a cryogenic pump expander.

8.5 Parts, Operation and Maintenance of the Yellow Jacket Vacuum Pump

The Yellow Jacket pump used in this workshop is a typical, multi-stage, fluid-sealed, rotary-vane pump. With the main operational components already described (see Figure 8.13 and related discussion), Figure 8.21 further illustrates how gas will progress through the pump during a single revolution of the rotor. Because the entire stator assembly is submerged below the pump fluid, during the final compression (Panel D of Figure 8.21), the pumped gas will produce bubbles as the gas escapes through the “flapper valve”. This explains why, when the pump initially begins pumping on the chamber, the sound of bubbling through a liquid will be heard.

The pumping sequence discussed so far would be accurate if a pump had only one stage. This “single-stage” pump would be expected to achieve a base pressure of ~10-100 mTorr. To achieve lower pressure (~0.1-1 mTorr), the exhaust of the “first stage” of the pump can be attached to a “second stage” as shown in Figure 8.22. One should note that because the rotary-vane pump is a continuous throughput pump (i.e., for every gas molecule that goes in, one molecule must come out), the 2nd stage of the pump will be smaller than the first stage (i.e., if Pressure x Volume is constant, Volume must decrease in the 2nd stage because Pressure is higher). Nearly all rotary-vane pumps today are 2-stage pumps.

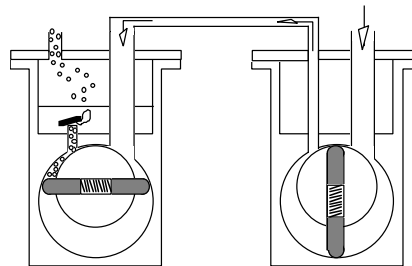


Figure 8.22. Schematic illustration of a 2-stage rotary-vane pump. Note that 1st and 2nd stage rotors will be attached to same shaft, and thus rotate at same speed, and that 2nd stage will be smaller than 1st stage.

One final important comment on the operation of the fluid-sealed, rotary-vane pump, relates to the moisture-laden gases. When this happens, moisture can be incorporated into the pump fluid, limiting pump performance and causing internal corrosion during pump storage. Pump fluid containing moisture can be noted by the pump fluid becoming milky white/brown, and remaining so even if the input valve is closed with the pump running. To remove moisture from the fluid, the inlet valve is closed and the “gas ballast” port is opened for ~30-60 min. The “ballasting” allows relatively dry air into the pump just before gas compression (Panel C of Figure 8.21). In this situation, the water vapor cannot attain its “dew-point” concentration, so it cannot condense into liquid-water droplets. Because the pump will also run hotter with the gas ballast open (because compressing more gas yields more heat!), the dew-point “temperature spread” is increased, further assisting the water vapor to maintain its vapor state, and be exhausted from the pump. The location of the gas ballast plug/screw is shown in Figure 8.23.

pumps operation when pumping



Figure 8.23. Yellow Jacket pump showing location of gas ballast port.

One important consideration of the fluid-sealed, rotary-vane pump is the composition and durability of the actual sealing fluid. In the early days of vacuum technology, the typical sealing fluid was Hg (i.e., liquid mercury). Although expensive, Hg was known to be a relatively heavy molecule that had relatively low vapor pressure, and was believed (at the time!) to be relatively safe. However, as vacuum technology advanced into the 1920's, researchers had begun to experiment with other heavy, low vapor pressure liquids. Among the available alternatives were large hydrocarbon molecules. These hydrocarbon-based fluids were being distilled for other applications, such as lubricants and fuels. The chemical structure of these natural hydrocarbon molecules were largely mixtures of paraffins (single bonds between carbon atoms), olefins (double bonds be-

tween carbon atoms), and phenyls (the most common being 6 carbons in a benzene ring, with alternating single and double bonds between the carbon atoms). Some examples of these molecules are shown in Figure 8.24. Careful distilling of these natural hydrocarbons from “crude oil” wells eventually lead to commercial production of hydrocarbon fluids with well-controlled viscosity, molecular weight, and vapor pressure. However, it was noticed that these natural hydrocarbon fluids would eventually break down (i.e., fractionate into smaller hydrocarbon molecules) when subjected to either corrosive gases (e.g., high oxygen concentrations) or high temperatures for long duration. The fractionated fluids would generally be darker than the new fluids, because the smaller fractionated molecules would absorb light more readily.

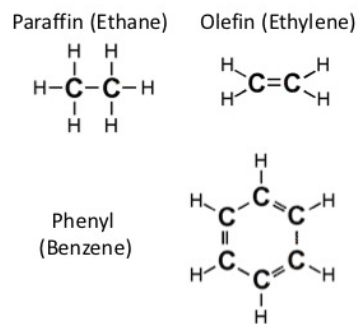


Figure 8.24. Simple examples of low molecular weight hydrocarbon molecules.

The pump fluid supplied with the Yellow Jacket pumps (produced by Ritchie Engineering Corp., Bloomington, NM) is a natural hydrocarbon mineral oil that has a trade name of SuperEvac (See Figure 8.25). The term “mineral oil” is used for a paraffin mixture that is distilled from crude oil - a product of long-term decomposition of carbon-based plant matter over millions of years (compared to similar paraffin mixtures from recently grown vegetable or animal sources). The SuperEvac fluid is a product that is intended for vacuum evacuation of refrigeration lines. Ritchie Corp. recommends that the fluid be drained from the pump after every refrigeration-line service, because contamination from the refrigeration lines will reduce the fluids operational performance. Because of this expectation for frequent fluid replacement, the quality (and thus cost) of the fluid is can be lowered. Because the reduced quality manifests in a wider range of molecular weights, lighter-weight molecules can impart a “petroleum scent” to even the as-received fluid. Further, although the envisioned classroom use for the Yellow Jacket pumps does not anticipate evacuating refrigeration lines, it remains likely that long-term contact of the fluid with residual moisture can cause degradation, turning it darker, and increasing its “petroleum scent.” For these reasons, it is recommended to outgas the fluid after every use by gas ballasting, and replace the fluid if it become visually darker or acquires a stronger smell.



Figure 8.25. Vacuum-pump fluid with trade name “SuperEvac” from Yellow Jacket/Ritchie Corp.

Supplemental Information for Effective Operation of the Yellow Jacket Pump

Following are some tips for effective use of the Yellow Jacket rotary-vane pump. They are intended to help make experiments easier to run and limit problems during pumpdown and venting. Additional information can be found in the literature that is delivered with the pump, while other information (including some YouTube Videos) can be found on associated websites.

1. Make sure to fill you pump with vacuum-pump fluid and check fluid level frequently. Nearly all fluid-sealed mechanical pumps have a “sight glass” that shows both the fluid level and color of the fluid (See Figure 8.26) Follow manufacturer’s instructions regarding proper fluid level. See also previous discussion on gas ballasting and frequency of fluid replacement. Similar to your car, drain the pump fluid (using the Drain Port, See Figure 8.26) when the fluid is hot to suspend contamination within the fluid.

2. Make sure that the sealing/shipping cap on the exhaust port of the pump is removed before operating the pump (See Figure 8.26). If the cap is not removed, pressure will build in the pump that could damage the sight glass or other parts of the pump.

3. When constructing custom vacuum apparatus, avoid long vacuum lines, sharp turns, and constrictions, especially if achieving minimum pressure in a short time is desired. If flexible vacuum hose is used, use as short of a hose as practical, and use hose clamps at the barbed or tapered fitting to ensure a proper seal. A thin coating of vacuum grease can allow easier attachment and detachment from a barbed fitting (e.g., Dow Corning High Vacuum Grease, available in classroom scientific supply catalogues, See Figure 8.27), while Teflon tape can assist sealing pipe threads.

4. Experience with the Yellow Jacket pump has indicated, for a small chamber, pump-down time to the systems base pressure (~30” Hg) is on the order of ~ 1 min. If pump-down time to this vacuum level is significantly longer, or if the pump is making strange or labored sounds, switch off the pump,

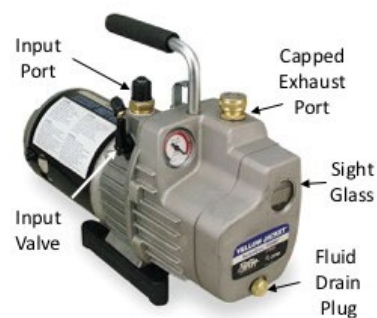


Figure 8.26. Yellow Jacket pump showing location of fluid sight glass and exhaust cap used for shipping.



Figure 8.27. Vacuum grease example.



Figure 8.28. Yellow Jacket pump configured with exhaust-mist filter.

vent the chamber and pump, and check the system for obvious leaks (improper positioning of the plastic bell jar on the base plate gasket is a common location for a leak). If no leaks are found, be sure to check that the input valve is fully open (See Figure 8.26), the input port is unobstructed, the KF flange clamp is sufficiently tight, the KF flange contains an O-ring seal, and that the gas ballast valve is fully closed (See Figure 8.23).

- When the pump is operating, and especially when it is pumping large amounts of gas (e.g., initial evacuation of the classroom chamber), it is normal for gas bubbling through the pump fluid to form an “exhaust mist” which exits through the exhaust port. This mist is composed of small droplets of vacuum fluid, and will eventually coat surfaces near the pump making them slippery and providing a surface for dust and dirt to collect. To limit this problem, an exhaust filter can be purchased from the pump manufacturer (See Figure 8.28). Alternatively, a short length of garden hose can be used as an exhaust line to direct the exhaust mist outside the building. Note that the exhaust port of the Yellow Jacket pump is delivered with a connection that attaches directly to a standard garden-hose fitting.

- Even if the exhaust is directed out of the building, if the pump is operated for extended periods of time, it is normal for the pump to generate a stronger “petroleum scent”. This is typically due to some traces of pump fluid coating the outside of the pump becoming sufficiently warm to evaporate. The scent can be limited by cleaning the outside of the pump with a cloth soaked in a warm solution of laboratory detergent (e.g., 5% Alconox in water) followed by thorough water rinsing. Do not immerse the pump/motor unit in the cleaning solution.

- If the pump suddenly begins to make a loud metallic clanking noise, switch it off. Although the noise could originate from the inside the pump (i.e., rotors and vanes) or the electric motor, it is more likely that the motor-to-pump *coupler fitting* may have become loose and/or the elastic coupler element has deteriorated, allowing the two metal shaft coupler fittings to

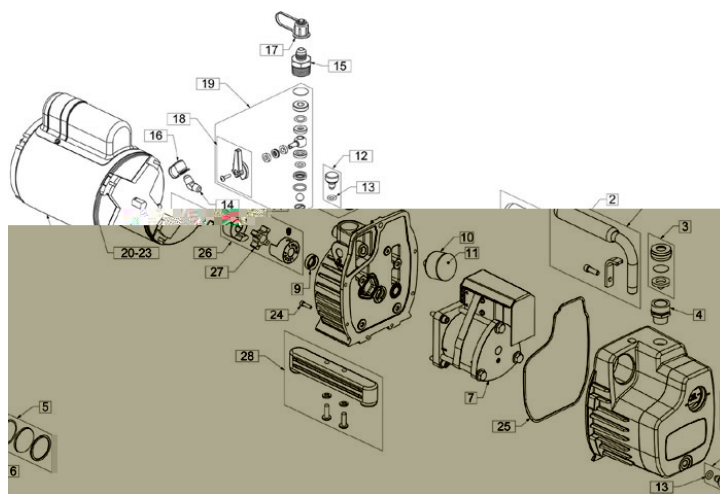


Figure 8.29. Schematic of Yellow Jacket pump. The two shaft couplers are shown as component #26, and elastic coupler element is shown as component #27. The 4 long screws that attached the electric motor to the pump housing are not shown.

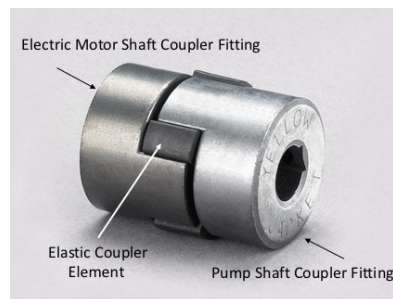


Figure 8.30. Motor-to-pump coupler fitting.

interact (See Figures 8.29 and 8.30). Check this coupler by first disconnecting the pump electric motor from the power source, and then loosening the 4 long (~8-inch) screws that attach the electric motor to the pump housing. Once the screws are loosened, the motor and pump will easily separate, and the shaft coupler fittings, and the elastic coupler element, can be checked. In this configuration, both the pump and electric motor can be rotated manually to check for proper operation.

8.6 Pressure Gauges

Comments on Accuracy and Precision of Vacuum-Pressure Gauges

As discussed earlier in the workshop, the first vacuum pressure gauge was the barometer invented by Evangelista Torricelli in c.1643. Based on existing reproductions (See Figure 8.31), it might be assumed that this instrument may have demonstrated an “optimum accuracy” of $\sim \pm 10$ Torr (i.e., ± 10 mm Hg) for pressures $> \sim 10$ Torr. The accuracy would have depended on the purity and distilling capability of the liquid Hg, and the ability to measure the Hg column height *above* the liquid level in the lower reservoir. However, the “precision” of the instrument (the ability of the same instrument to repeat a measurement on the same system) was likely much greater (possibly ± 0.5 Torr), and limited only by the user’s ability to draw a set of thin lines, and then visually aligning the top of the Hg column to these lines when they were firmly positioned near the top of the column.



Figure 8.31. Top portion of a historic Torricelli barometer indicating a

Understanding this difference between “accuracy” and “precision” remains central to understanding the functionality and limits of modern vacuum-pressure gauges. For example, in a classroom situation, the accuracy of a pressure measurement is seldom of significant importance. The more important thing is to know that the pressure in a chamber has “changed” by a certain amount. Further, if the same experiment is repeated next year, and the change in pressure is the same as last year, the expectation is that the results of the experiment this year will be similar to last year. This situation requires some reasonable amount of “precision,” and some amount of long-term reliability of the vacuum-pressure gauge. However, it does not require gauge “accuracy.”

Surprisingly, for many important research projects, the situation is similar to that described above for a high-school classroom. Specifically, for a given vacuum system, the researcher often wants to know how a controlled *change* in pressure will affect the quality of a vacuum-process and/or vacuum-processed material. For example, if a “precise” vacuum gauge for today’s experiment indicates an Argon (Ar) pressure 20 mTorr,

the researcher will be reasonably sure that the Ar pressure today is ~5 mTorr greater than during a similar experiment done yesterday when the indicated pressure was 15 mTorr (using the same precise gauge). Further, the pressure today will be 5 mTorr less than the experiment planned for tomorrow - at 25 mTorr. In this example, although the researcher might be assured that the three data points assessed at the three pressures are 10 mTorr apart, the accuracy of the pressure measurement may be completely unknown (i.e., the *actual* Ar pressure change may be from ~70 mTorr to 80 mTorr, rather than from ~15 to 25 mTorr). However, if the change in pressure leads to an important observation or result, the researcher can be reasonably assured that the *trend* is accurate. At that point, if the researcher wants to publish the work in a reputable scientific journal, the researcher will often have to spend significant money to purchase a gauge with greater *accuracy*, or they will have to state clearly in the publication the limits of accuracy of the vacuum pressure gauge used. Another likely situation would be if the researcher wanted (or needed) to repeat the result - using another system - with a different vacuum gauge. This often happens if a “research result” has to be transferred to a commercial-production entity - who may be ultimately funding the research! The take-home lesson is, it is important to know if your vacuum gauge is “precise” or if it is “accurate” (or if it is neither), and also when each of these attributes are needed.

Review of Typical Vacuum Pressure Gauges

There are three main types of vacuum-pressure gauges. They are: (1) Manometers Gauges; (2) Thermal Transfer Gauges; and (3) Ion Gauges. Figure 8.32 indicates many of these gauges, with the gauges shown in bold being the ones that will be reviewed in this workshop. The table also is constructed such that the gauges developed earlier are nearer the top of the table, while the more recently developed gauges are nearer the bottom. Although the table does not indicate the accuracy or precision of the individual gauge types, the table does indicate that gauge development has generally sought to establish an ability to measure increasing lower vacuum pressures. In general, if a gauge can measure to lower pressure, the gauging mechanism can often provide reasonable precision - at least within its operative range.

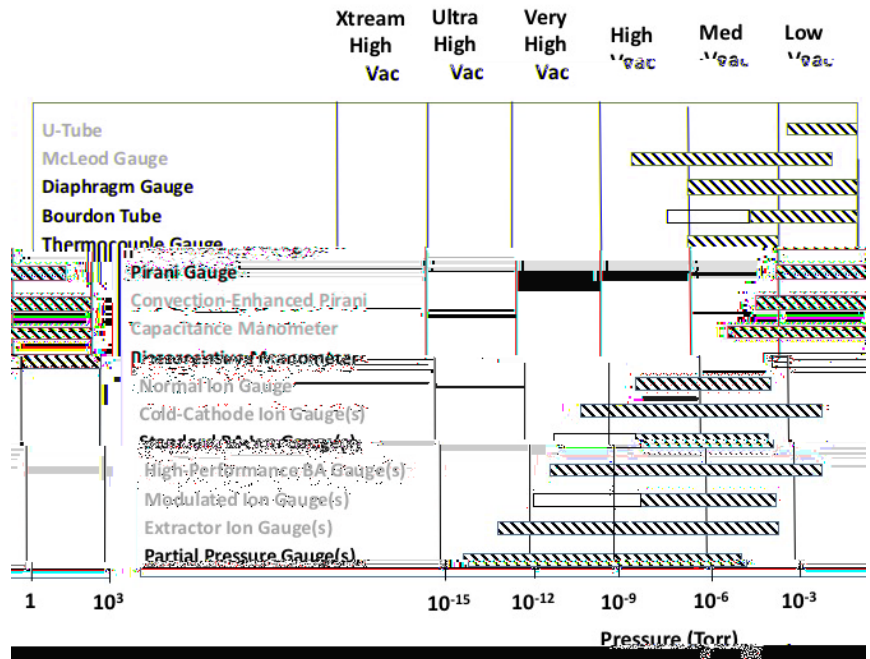


Figure 8.32. Table showing many of the vacuum-pressure gauges used in the vacuum technology. The gauge types shown in bold will be briefly reviewed in this workshop.

Manometers:

Manometers are pressure gauges that can measure a deflection of a part of the gauge that is caused by gas molecules exerting a differential force on that part. The simplest of these is shown in Figure 8.33 and is known as a diaphragm gauge. For a diaphragm gauge to operate, the pressure to be measured must be present on the *external* surfaces of

the diaphragm elements (which are sometimes called an aneroid). As the pressure on the outside of the aneroid decreases, the residual pressure on the inside of the aneroid causes it to expand. The distance of expansion can be connected to a mechanical arm that can use a precision mechanical movement to turn a dial indicator. Although diaphragm gauges can measure from atmospheric pressure to about 1 mTorr, the fact that the pressure must be exerted on the outside surface of the aneroid is a concern in vacuum technology. This is because even weakly corrosive vacuum process can alter the precision mechanical linkages connected to the aneroid, and also because the lubricants present on the mechanical linkages can contaminate the vacuum environment. Regarding accuracy and precision, diaphragm gauges can be relatively accurate near atmospheric pressure, if the actual atmospheric pressure is known at the time of calibration. Regarding precision, because of thermal expansion of the aneroid and other moving parts, the gauge can be sensitive to temperature changes that may occur during an experiment. Vacuum diaphragm gauges are more commonly used for educational rather than commercial vacuum technology purposes. However, an aneroid gauge is widely used to measure re-

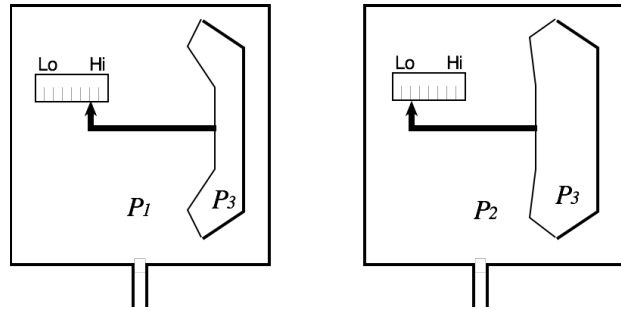


Figure 8.33. Cross-sectional of functional elements of a vacuum diaphragm gauge.

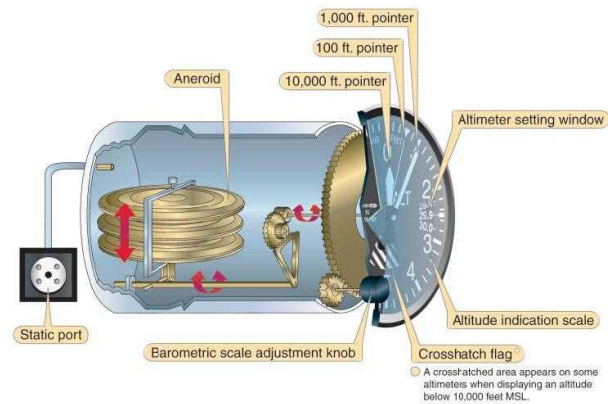


Figure 8.34. Aircraft altimeter showing aneroid (i.e., diaphragm elements).

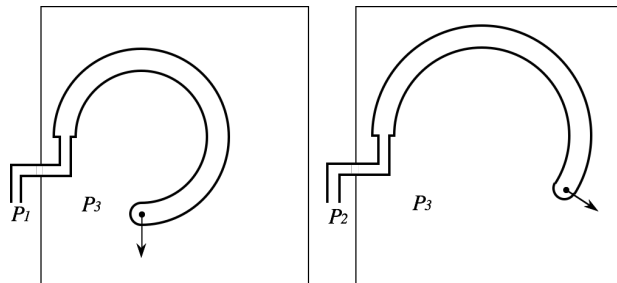


Figure 8.35. Bourdon tube at low internal pressure (P_1 , left) and higher internal pressure (P_2 , right).

duced pressure environments experienced as an aircraft ascends in altitude, and are called altimeters (See Figure 8.34).

The concerns of having the outside surface of the diaphragm element exposed to the vacuum environment can be limited by a gauge design called a Bourdon tube (See Figure 8.35). The Bourdon tube responds to changes in pressure exerted on its internal surfaces. The response is to uncurl the tube if the inside pressure is greater than the pressure on the outside surface, and to curl the tube more tightly if the inside pressure on the inside is less than the pressure on the outside surface. Like the diaphragm gauge, the small movement of the Bourdon tube is generally enhanced by using a precision mechanical movement to rotate a dial indicator. Because the pressure to be measured is only on the inside of the Bourdon tube, the vacuum environment will not effect the precision mechanical movement, while the lubricants on the mechanical movement will not be in contact with the vacuum environment. The accuracy and precision of the Bourdon tube have limitations similar to the diaphragm gauge.

The final manometer that will be discussed is the piezoresistive manometer. This gauge is somewhat similar to a diaphragm gauge, except that instead of using a precision mechanical mechanism to measure the deflection of a diaphragm, a piezoresistive material is carefully affixed to the diaphragm element. A piezoresistive material is a material that either can respond mechanically (e.g., a deflection) when a voltage is applied to the material, or (vise-versa), will yield a voltage that is induced by a mechanical deflection of the material. In the piezoresistive manometer, it is this second attribute that is utilized. Figure 8.36 shows a schematic cross section of a piezoresistive manometer, that is also configured with a thermal gauge to provide lower pressure indication (thermal gauges will be discussed later). This combined gauge type is generally known as a piezoresistive-bridge manometer, because the electrical circuit that reads the thermal gauge uses a sensitive Wheatstone Bridge to provide an added degree of precision. Regarding overall accuracy of the gauge, if properly calibrated, and temperature compensated (i.e., the gauge is enclosed in a box that is maintained typically at 60°C), the gauge can be relatively accurate in the pressure range from atmospheric pressure to about 1 Torr (i.e., the range where the manometer is operational). Below ~1 Torr (i.e., where the thermal gauge is operational), accuracy will be less certain, and depend on the gas species present.

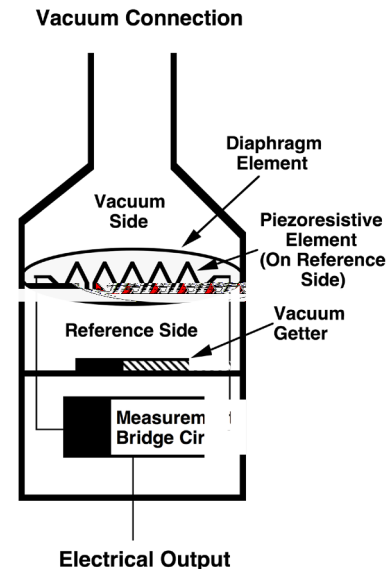


Figure 8.36. Schematic cross-section of a piezoresistive bridge manometer.

Thermal Gauges:

There are two main thermal vacuum gauges used in the vacuum industry, and both can be cost effective and sufficiently simple to operate for consideration in classroom use. The general idea behind a thermal vacuum gauge is as follows: If a heated

wire (~100-200°C) is present in a vacuum chamber at a pressure $> \sim 1$ mTorr, the wire will lose heat through interactions with the gas-phase molecules. If the “vacuum chamber” is a small gauge, the heat lost from the wire will be transferred to the gauge, and then transferred to the atmospheric-pressure air surrounding the gauge. Therefore, if the wire is heated at constant power, measuring the temperature of the wire can provide an indication of the pressure inside the gauge. This is the basic idea of a thermocouple (or TC) gauge schematically illustrated in Figure 8.37. Although the TC gauge can provide pressure indications from ~ 1 mTorr to atmospheric pressure, because of heat lost through the 4 electrical connections (i.e., 2 connections for the heated wire, and 2 connections for the thermocouple), and uncontrolled thermal “convection” currents, the pressure range that is most “precise” is ~ 1 mTorr to ~ 1 Torr. Regarding accuracy, because different molecules transfer heat from the wire differently, the TC gauge is not considered a highly accurate gauge.

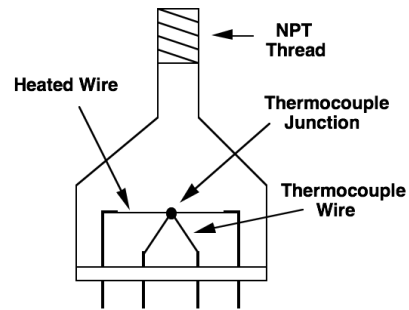


Figure 8.37. Schematic cross section of a thermocouple vacuum gauge.

To extend the operational range of the thermal vacuum gauge, one can also measure the power (i.e., the voltage and the current) being supplied to the heated wire. Because metal wires have a well-known change in electrical resistivity with temperature, knowing the power being delivered to a wire (with a known resistivity vs. temperature coefficient) can provide a very accurate indication of the wire temperature – without the need to attached a thermocouple - and thus avoiding the heat-sinking associated with the thermocouple leads. This type of gauge is known as a Pirani gauge (after the 1909 inventor, M. Von Pirani). It has a wider pressure-measurement window compared to the TC gauge of ~ 1 mTorr to 100 Torr. The basic gauge is shown schematically in Figure 8.38. Although it is difficult now to purchase a simple Pirani gauge as shown in Figure 8.38, in the mid 1970’s, a convection-enhanced Pirani gauge was introduced (See Figure 8.39). This gauge was designed to account for outside temperature variations of the gauge surface, and can provide higher precision and accuracy (when properly calibrated) from 0.1 mTorr to atmospheric pressure. Because of its wide pressure window and cost effectiveness, the convection-enhanced Pirani gauge (Trade Name “Convectron”) and its

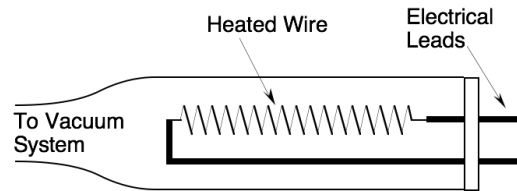


Figure 8.38. Cross-section of Pirani-type thermal vacuum gauge.

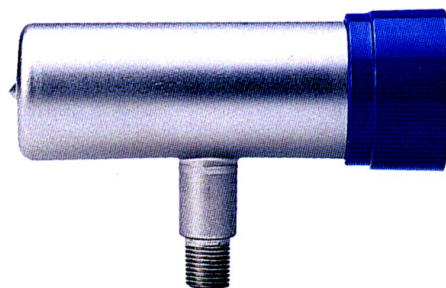


Figure 8.39. Image of “Convectron Gauge” developed by Granville-Phillips Corp.

predecessors, are presently one of the most widely used gauges in the vacuum-technology industry.

Ion Gauges:

The gauges discussed so far can measure pressures down to ~ 0.1 mTorr. For classroom use, this is the lowest pressure that an oil-sealed, rotary-vane mechanical can attain. However, as discussed in the section on vacuum pumps, many vacuum systems operate at pressures much less than 0.1 mTorr. At these lower pressure, there is an insufficient number of gas-phase molecules to exert a measureable mechanical force on a surface (so a manometer type gauge will not work), and there are also too few molecules to measure the “heat” removed from a heated wire (so a thermal-type gauge will not work). However, in this low-pressure range, it remains possible to ionize some of the gas molecules (i.e., remove an electron from an electrically neutral molecule), collect some of these ionized molecules, and correlate the number of collected ions to the total gas pressure. These types of gauges are called Ion Gauges, and the most typical type of ion gauge used to today is known as the hot-filament Bayard-Alpert gauge (also known as a Standard BA Ion Gauges that is indicated in the Table shown in Figure 8.32).

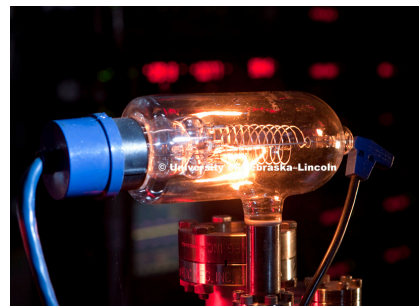


Figure 8.40. Image of a standard-design BA gauge in operation.

Figure 8.40 shows a typical BA gauge in operation. Many of gauge components very similar to a standard incandescent light bulb. It is a glass bulb that contains a tungsten filament that glows. Because the filament is very hot, it emits electrons, that are accelerated toward a positively charged counter electrode. Some of these electrons acquire sufficient energy to interact with neutral gas-phase molecules, and knock an electron off of them, thereby producing a gas-phase ion. Some of these ions are then collected by a third electrode, measured with a sensitive ammeter, and a correlation to the gas pressure is made. Figure 8.41 shows schematically the various electrodes within the standard BA ion gauge.

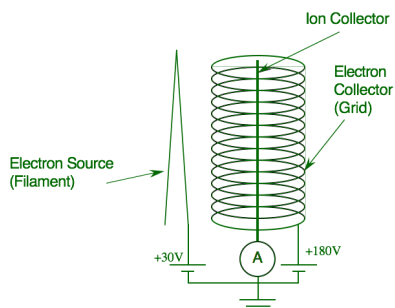


Figure 8.41. Schematic illustration of a BA ion gauge, showing the three electrodes of the gauge.

Regarding accuracy, all ion gauges have a limitation similar to thermal gauges. In this case, different gas molecules have a different likelihood that an electron impact will create an ion. Therefore, the pressure indication will be different - depending on the gas that is present in the chamber. However, if the type of gas within the chamber is well known, calibrated ion gauges are available that can measure economically (in research terms) pressures to values as low as 1×10^{-11} Torr.

Partial Pressure Gauges:

All of the gauges discussed so far are total-pressure gauges, meaning that they provide an indication of the total number of gas molecules present in a vacuum chamber. However, pressure gauges are available that can measure not only the number of molecules present, but the proportion of different gas types within the vacuum chamber. These gauges are called either Partial Pressure Analyzers (PPAs) or Residual Gas Analyzers (RGAs). Figure 8.42 shows some typical output of an RGA for a vacuum system that has an air leak (known because of the amount and ratio of N_2 and O_2 present). Of the gauges discussed, PPAs and RGAs will be among the most expensive. They are usually used to determine what contamination may exist within a vacuum system, and/or control beneficial residual gases.

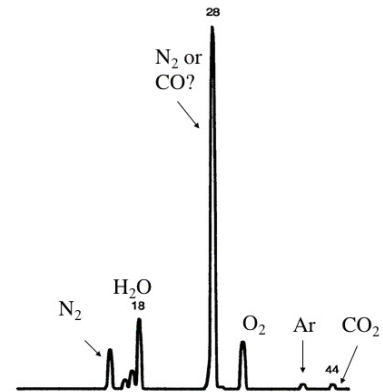


Figure 8.42. RGA spectra of a turbo-pumped system that has an air leak. Noted by large peaks for N_2 and O_2 .