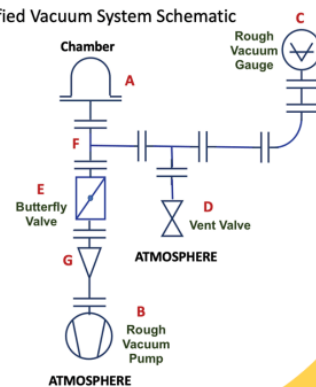


INTRODUCTION TO VACUUM TECHNOLOGY

STUDENT LABORATORY MANUAL



Simplified Vacuum System Schematic



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

Introduction to Vacuum Technology

INTRODUCTION TO VACUUM TECHNOLOGY

Student Laboratory Manual

DAVID M. HATA; ELENA V. BREWER; AND NANCY J. LOUWAGIE



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ABOUT THIS BOOK

Vacuum systems are critical to many industries and technicians with the knowledge and skills to maintain, troubleshoot, and repair vacuum systems are essential in manufacturing and research settings. This Laboratory Manual contains a sequence of hands-on, experiential-learning activities that will help you develop the knowledge and skills needed to be a vacuum equipment technician. These activities can be performed using a simple Rough Vacuum Equipment Training (RVET) System.

The sequence of learning activities is designed and organized to be used with the e-book entitled Introduction to Vacuum Technology-E-book by David Hata, Elena Brewer, and Nancy Louwagie. The first set of learning activities focuses on fundamental gas laws. These activities are followed by learning activities that focus on using the RVET system to practice system operation, system characterization, and system diagnosis and troubleshooting. This lab manual is the result of years of teaching vacuum technology at the community college level and have been classroom-tested at Normandale Community College and Erie Community College. Many thanks go to our former students for challenging the authors to learn more about vacuum science, the variety of system designs, and how these systems work and don't work, at times. We hope that you will experience the same joy of discovery as you develop your knowledge and skills needed by vacuum technicians.



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

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ROUGH VACUUM EQUIPMENT TRAINING (RVET) SYSTEM

A simple Rough Vacuum Equipment Training (RVET) system, at a minimum, consists of an interconnection of a rough vacuum pump, chamber, vacuum gauge for measuring pressure, two valves, and piping to interconnect the main components. These system components can be arranged in different geometries. One version of a RVET system, used at SUNY Erie Community College, is shown in Figure 1.

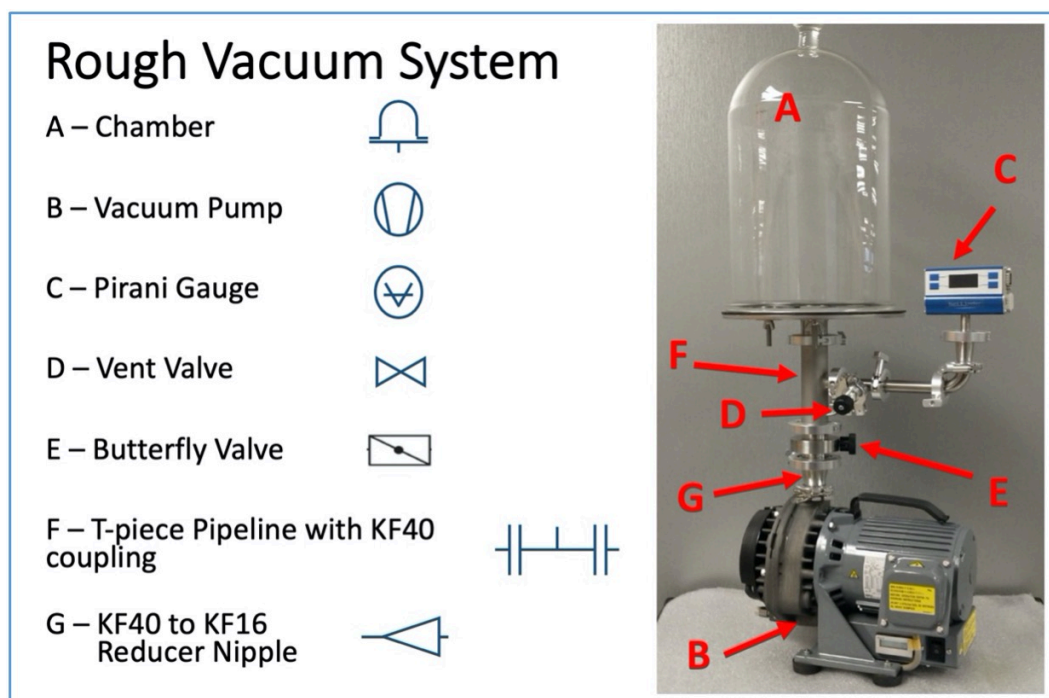


Figure 1. Rough Vacuum Equipment Training (RVET) System. Photo supplied by E. Brewer, SUNY Erie Community College.

Using the RVET shown in Figure 1, most of the learning activities in this lab manual can be performed.



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Learning Activity 1.1: Marshmallow Preparation - Measurements and Calculations

[Summary of Learning Activity](#)

[Student Learning Objectives](#)

[Suggested Pre-lab Assignment](#)

[Theoretical Background](#)

[Equipment and Materials](#)

[Procedure](#)

Summary of Learning Activity

- Measuring the dimensions and mass of a cylindrically-shaped object, such as marshmallow.
- Making calculations of surface area, volume, and density of the cylindrically-shaped object.

Student Learning Objectives

1. Measure linear dimensions and the mass of a cylindrical object using proper techniques.

2. Calculate surface area and volume of a cylindrical object.
3. Calculate density of an object.
4. Report final calculated results with the correct number of significant digits.

Suggested Pre-lab Assignment

1. Find 3 measuring instruments at your home or workplace and identify units of measurement and the smallest division of the measurement. Examples: bathroom scale, kitchen scale, tape measure, measuring cup, timer, etc.

Instrument	Unit	Smallest Division

Report the following results with the appropriate number of significant figures.

2. Convert 45.3 mm (millimeters) to units of cm (centimeters).
3. Convert 45.3 mm to units of meters.
4. Calculate the volume of a cube that is 2.0 cm x 2.0 cm x 2.0 cm.
5. Calculate the surface area of a cube that is 2.0 cm x 2.0 cm x 2.0 cm.

Theoretical Background

Figure 1.1 shows a cylindrically-shaped object with its diameter D and height H indicated on the figure.

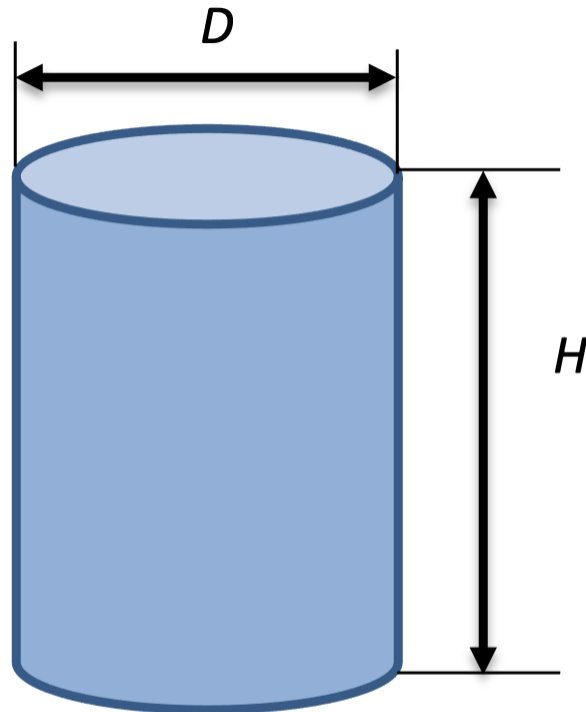


Figure 1.1. Dimensions of a cylindrical object.

The surface area of the flat top or bottom part of the cylinder can be calculated using Equation 1.1:

$$A_{circle} = \frac{\pi D^2}{4} \quad (Eq. 1.1)$$

It can also be calculated using radius $R = D/2$:

$$A_{circle} = \pi R^2$$

The surface area of the wall (tube) can be calculated using Equation 1.2:

$$A_{tube} = \pi DH \quad (Eq. 1.2)$$

or, alternatively, using radius instead of diameter as:

$$A_{tube} = 2\pi RH$$

Then the total surface area (Figure 1.2) can be determined by adding the areas of both the top and bottom circle and the surface area of the tube as shown in Equation 1.3:

$$A_{surface} = 2A_{circle} + A_{tube} \quad (Eq. 1.3)$$

Surface area of the tube is equal to the area of the rectangle as shown in Figure 1.2.

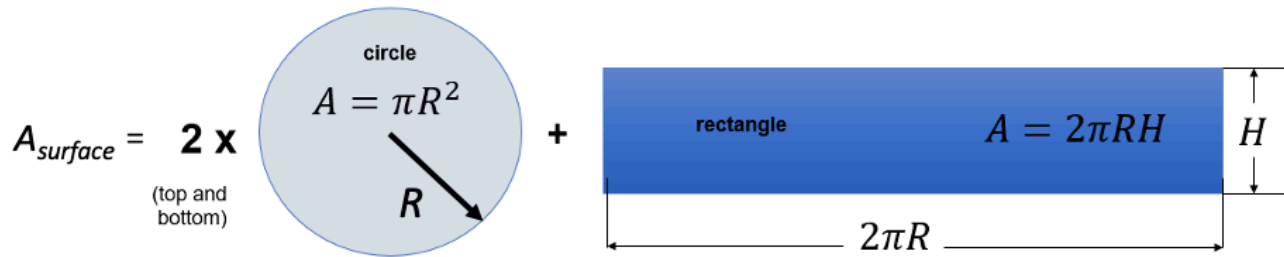


Figure 1.2. Surface areas of a cylindrical object.

Then, volume of the cylinder can be determined using Equation 1.4:

$$V = A_{circle} H = \left(\frac{\pi D^2}{4} \right) H \quad (\text{Eq. 1.4})$$

When measuring the height or diameter of the cylinder, different measuring tools can be used. The resolution of the measuring tool dictates the number of significant digits for the measured quantity. If the measured values for the diameter and height have different numbers of significant digits, then how many significant digits should be present in the final answer for a calculated value, such as volume? The final answer should contain the same number of significant digits as the measured quantity with the least number of significant digits used in the calculation, for example, the diameter or height parameter.

As an example, if $H = 15.0$ cm and $D = 2.0$ cm, then the height value has 3 significant digits while the diameter value has only 2 significant digits. This means that the calculated value for volume should be rounded to 2 significant digits:

$$V = \left(\frac{\pi(2.0\text{cm})^2}{4} \right) (15.0\text{cm}) = 47.12389 \text{ cm}^3.$$

So, the calculated result yields a value of 47.12389 cm^3 . When the rules of significant figures are applied, the final result will be reported as 47 cm^3 . If the third digit had been greater than or equal to 5, for example 47.62389 , then the second digit would be rounded up to an 8 for a final result of 48 cm^3 . Note that only the final answer reported should be rounded to the correct number of significant digits. If you are using the calculated volume to calculate another quantity, you should include the resolution of the calculated value, that is, 47.12389 cm^3 to reduce rounding error.

Another useful quantity which can be determined for any object is its volume density or density. Density ρ is determined by dividing the mass of the object M by its volume V as shown in Equation 1.5:

$$\rho = \frac{M}{V} \quad (\text{Eq. 1.5})$$

with units being unit of mass divided by unit of volume. If mass is measured in grams (g) and volume is calculated in cm^3 , then the density will have units of g/cm^3 . Note, when the object expands, it will occupy a larger volume. Dividing the same mass by a larger volume yields a smaller density. Alternatively, when the volume becomes smaller, the density increases.

Equipment and Materials

- 1 Ruler with units of measure in millimeters (mm)
- 1 Mass Scale or Mass Balance with units of measure in grams (g)
- Sharpie pen
- 2 Marshmallows (Jumbo size if available)
- Plastic Ziploc bag to store marshmallows for another Learning Activity

Procedure

1. Use a sharpie or felt tip pen to mark one marshmallow with a 1 and the other marshmallow with a 2.
2. Identify measurement tools and measurement resolution:

<p>Tool 1</p> <p>Tool 1 unit of measure</p> <p>Tool 1 resolution</p>	
<p>Tool 2</p> <p>Tool 2 unit of measure</p> <p>Tool 2 resolution</p>	

3. Use a ruler displaying units of measure in millimeters (mm) and centimeters (cm) to measure the diameter and height of Marshmallow “1”. If the flat surface face of the marshmallow has an obvious oval shape rather than a near circle shape, measure the long diameter and the short diameter and calculate the average of the two diameters.

Diameter D (centimeters, cm)	
Height H (centimeters, cm)	

4. Calculate volume V (cubic centimeters (cc or cm^3)):
5. Calculate surface area of the flat bottom (circle) (square centimeters (cm^2)):
6. Calculate surface area of the wall (tube) (square centimeters (cm^2)):
7. Calculate total surface area (square centimeters (cm^2)):
8. Use a scale that displays units of measure in grams (g) to measure the mass M of the marshmallow:

Mass M (grams, g)	
---------------------------------------	--

9. Calculate density ρ (gram/cubic centimeter, g/cm^3 , or g/cc):
10. Significant Figures: report all calculated values with the appropriate significant figures:

Volume	
Surface area of the bottom face (circle)	
Surface area of the wall (tube)	
Total surface area	
Density	

11. Take measurements for the second marshmallow and record all relevant quantities below:

Diameter D (centimeters, cm)	
Height H (centimeters, cm)	
Mass M (grams, g)	

12. Place Marshmallow “1” and Marshmallow “2” in Ziploc bag and seal it tightly. Write your group member’s name on the bag. We will use the marshmallows for the next week’s activity with the Rough Vacuum Equipment Trainer.
13. After class, repeat the calculations we did in class, but this time for Marshmallow “2”.
- Calculate the volume V of marshmallow “2” in units of cm^3 and report with appropriate significant figures:

- Calculate the surface area for the flat bottom (circle) in units of cm^2 and report with appropriate significant figures:
- Calculate the surface area for the wall (tube) in units of cm^2 and report with appropriate significant figures:
- Calculate the total surface area in units of cm^2 and report with appropriate significant figures:
- Calculate the density of Marshmallow “2” in units of g/cm^3 (or g/cc, or gram/cubic centimeter) and report with appropriate significant figures:

- Report all calculated values with the appropriate significant figures:

Volume	
Surface area of the bottom face (circle)	
Surface area of the wall (tube)	
Total surface area	
Density	



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Learning Activities 2.1 – 2.4: Marshmallow Measurements, Pressure Calculation, Components of the Rough Vacuum Trainer System, and Gas Flow Paths

[**Summary of Learning Activities**](#)

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Learning Activity 2.1: Pressure Exerted by the Marshmallow on a Table Top**](#)

[**Learning Activity 2.2: Components of the Rough Vacuum Equipment Trainer System**](#)

[**Learning Activity 2.3: Gas Flow Paths**](#)

[**Learning Activity 2.4: Expanding a Marshmallow under Vacuum**](#)

Summary of Learning Activities

- Measuring the dimensions of a cylindrically-shaped object (marshmallow) to calculate force and pressure of the object when it comes in contact with a flat surface.
- Calculating pressures exerted by the marshmallow on the table top before expanding the marshmallow under vacuum and after compressing it when the system is vented.
- Identifying system components of the rough vacuum equipment trainer system and gas flow paths.

Student Learning Objectives

1. Practice measuring linear dimensions of the cylindrical object.
2. Calculate the surface area of the object in contact with the table top.
3. Calculate the force and pressure the object exerts on the table top.
4. Present the final calculated pressure value in correct units of Pascal with the proper number of significant digits.
5. Demonstrate how pressure exerted by an object on a tabletop changes when the object expands or contracts.
6. Identify the components of a rough vacuum equipment training system.
7. Identify gas flow paths and states of valves for each flow path.

Suggested Pre-lab Assignment

1. Read Section 3.4 of the E-book and list 5 components of the rough vacuum system with short description of their functionality.
2. Read Section 3.5 of the E-book and draw a symbol for each vacuum system component from Question 1.

Theoretical Background

Figure 2.2 shows cylindrically-shaped object with diameter D and height H .

Surface area of the flat bottom part of the cylinder is calculated using Equation 2.1:

$$A_{bottom} = \frac{\pi D^2}{4} \quad (Eq. 2.1)$$

Then, force exerted by this object on the flat surface is calculated as shown in Equation 2.2:

$$F_g = mg \quad (Eq.2.2)$$

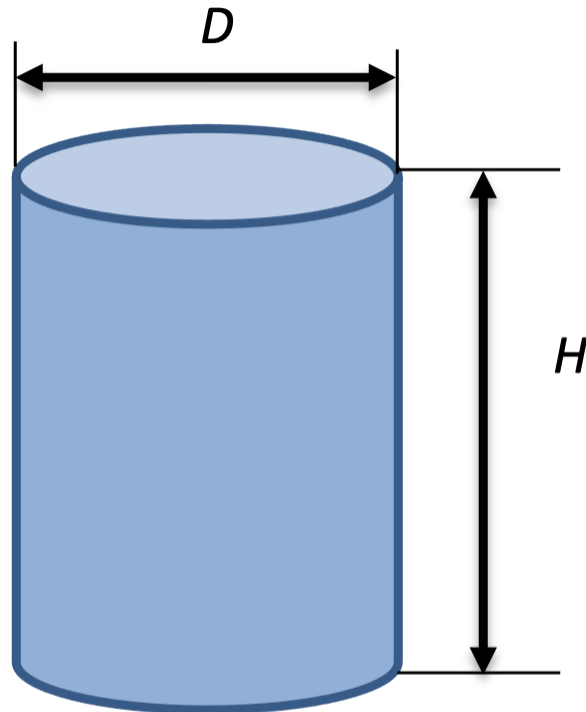


Figure 2.2 Dimensions of a cylindrical object.

where F_g is the force of gravity or weight of the object in units of Newton (N), m is the mass in units of kilograms (kg), and $g = 9.81 \text{ m/s}^2$ is the acceleration due to gravity.

Finally, pressure is calculated using Equation 2.3:

$$P = \frac{F_g}{A_{bottom}} = \frac{F_g}{\pi D^2 / 4} = \frac{4F_g}{\pi D^2} \quad (\text{Eq. 2.3})$$

where P is the pressure in units of Pascal, F_g is the weight of the object in Newtons, and D is the diameter of the cylindrical object in meters.

For example, let's calculate the pressure exerted by the cylindrical object with a diameter of 4.5 cm and mass of 54.0 g on a flat surface.

First, convert a measurement in units of grams (g) to kilograms (kg) as follows:

$$1 = \frac{0.001 \text{ kg}}{1 \text{ g}} = \frac{1 \text{ kg}}{1,000 \text{ g}}$$

or, simply divide the mass in grams by 1,000 g/kg as indicated below:

$$m = 54.0g = \frac{54.0g}{1,000g/kg} = 0.0540kg = 5.40 \times 10^{-2}kg$$

Note that the answer above is given in scientific notation with three significant digits.

Next, calculate the weight of the object as:

$$F_g = (0.0540kg) \times (9.81m/s^2) = 0.529N$$

Before calculating the pressure, we need to convert diameter from centimeters to meters using the conversion factor 1 m = 100 cm or, simply, dividing the measurement in units of centimeters by 100 cm/m to obtain meters:

$$D = 4.5cm = \frac{4.5 \cancel{cm}}{100 \cancel{cm}/m} = 0.045m = 4.5 \times 10^{-2}m$$

Then calculate the area of the bottom part of the object that comes in contact with the flat surface using Equation 2.1:

$$A_{bottom} = \frac{\pi(0.045m)^2}{4} = 0.00159m^2 = 1.59 \times 10^{-3}m^2$$

And, finally, the pressure exerted by the cylindrical object in contact with the flat surface is calculated using Equation 2.3 to two significant digits:

$$P = \frac{0.529N}{0.00159m^2} = 330Pascal = 3.30 \times 10^2Pa$$

When the object expands as the pressure surrounding it decreases under vacuum conditions, its weight does not change, but A_{bottom} will get larger which will result in less pressure on the flat surface.

Equipment and Materials

1. 1 Ruler
2. 1 Mass Scale or Mass Balance
3. 1 Marshmallow
4. RVET (rough vacuum equipment trainer)

Procedure

Learning Activity 2.1: Pressure Exerted by the Marshmallow on a Table Top

You may use data obtained for the marshmallow measured during Learning Activity 1.1 or measure the mass and diameter of a new marshmallow using a mass scale/balance and ruler.

1. Calculate the pressure exerted by the face of the marshmallow in contact with a table top before expanding the marshmallow under vacuum.

a. Mass of the marshmallow in grams (g) and kilograms (kg):

b. Diameter of the marshmallow in centimeters (cm) and meters (m):

c. Force exerted by the bottom of the marshmallow on a flat surface in Newtons (N) (remember, $1 \text{ N} = 1 \text{ kg}\cdot\text{m}/\text{s}^2$ (kilogram-meter/second²)):

d. Pressure exerted by the bottom of the marshmallow on a flat surface in Pascals (Pa) (remember, $1 \text{ Pa} = 1 \text{ N/m}^2$ (Newton/meter²)):

Learning Activity 2.2: Components of the Rough Vacuum Equipment Trainer System

1. What are the components of the Rough Vacuum Equipment Trainer (RVET) system? You may watch Video 2.1 to answer this question.
 - a.
 - b.
 - c.
 - d.
 - e.



bed-1

One or more interactive elements has been excluded from this version of the text. You can view them online here: <https://milnepublishing.geneseo.edu/introtovacuumtechinstructor/?p=26#oem->

Video 2.1. Typical rough vacuum system components. Video produced by Elena Brewer and Richard Hill, SUNY Erie Community College.

Learning Activity 2.3: Gas Flow Paths

1. What states do the following components need to be in for the system to be pumping down? You may watch Video 2.2 to help answer this question.

a. Vacuum chamber:	open	closed	doesn't matter
b. Roughing valve:	open	closed	doesn't matter
c. Venting valve:	open	closed	doesn't matter
d. Roughing pump:	open	closed	doesn't matter



One or more interactive elements has been excluded from this version of the text. You can view them online here: <https://milnepublishing.geneseo.edu/introtovacuumtechinstructor/?p=26#oem-bed-2>

Video 2.2. Rough vacuum system pump-down procedure. Video produced by Elena Brewer and Richard Hill, SUNY Erie Community College.

2. What states do the following components need to be in for the system to be venting? You may watch Video 2.3 to help answer this question.

a. Vacuum chamber:	open	closed	doesn't matter
b. Roughing valve:	open	closed	doesn't matter
c. Venting valve:	open	closed	doesn't matter
d. Roughing pump:	open	closed	doesn't matter



One or more interactive elements has been excluded from this version of the text. You can view them online here: <https://milnepublishing.geneseo.edu/introtovacuumtechinstructor/?p=26#oem-bed-3>

Video 2.3. Rough vacuum system venting procedure. Video produced by Elena Brewer and Richard Hill, SUNY Erie Community College.

Learning Activity 2.4: Expanding a Marshmallow under Vacuum

1. What happened to the marshmallow in vacuum at pressures close to atmospheric pressure (just after pump-down process started)?
2. What happened to the marshmallow after the roughing valve was closed at lower pressures (higher vacuum)?
3. What happened to the marshmallow when the air was allowed to vent back into the system?

After-class Assignment

Write down which marshmallow your group used in Learning Activity 2.1 and use that same one for calculations below.

1. Calculate the pressure the face of the marshmallow will exert when it comes in contact with a table top after the marshmallow has shrunk.
 - a. Mass of the marshmallow in grams (g) and kilograms (kg):

 - b. Diameter of the marshmallow in centimeters (cm) and meters (m):

 - c. Force exerted by the bottom of the marshmallow on a flat surface in Newtons (N) (remember, $1\text{ N} = 1\text{ kg}\cdot\text{m}/\text{s}^2$ (kilogram-meter/second²)):

 - d. Pressure exerted by the bottom of the marshmallow on a flat surface in Pascals (Pa) (remember, $1\text{ Pa} = 1\text{ N}/\text{m}^2$ (Newton/meter²)):

2. Draw a simple schematic for the RVET system using the symbols shown in class. Label the different gauges and valves. Draw arrows to show the gas flow in the RVET system when it is being (a) pumped down and (b) vented.



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Learning Activities 3.1 - 3.4: Unit Conversion, Scientific Notation, Absolute and Gage Pressure, and Pressure Measurement

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[Learning Activity 3.1: Unit Conversion Practice](#)

[Learning Activity 3.2: Atmospheric Pressure in Scientific Notation](#)

[Learning Activity 3.3: Expected Atmospheric Pressure](#)

[Learning Activity 3.4: Pressure in Scientific Notation](#)

Summary of Learning Activities

- Measuring absolute and gage pressure.
- Performing pressure unit conversions.
- Expressing pressure in scientific notation.

Student Learning Objectives

1. Practice measuring absolute pressure and gage pressure using different pressure measurement devices.
2. Practice converting between different pressure units of measure.
3. Practice converting gage pressure measurements to an absolute pressure value.
4. Express pressure values in scientific notation.

Suggested Pre-lab Assignment

Calculate expected atmospheric pressure for your location using the fact that atmospheric pressure drops by about 1 inch of Mercury for every 1,000 ft of elevation above the sea level. Assume standard atmospheric pressure of 29.92 inches of Mercury (in Hg).

Theoretical Background

Table 3.1. Pressure unit conversion table.

To Convert	Multiply By						
From --- To	Pa	Torr	Atm	mbar	u	In Hg	psia
Pascal (Newtons/m ²)	1	7.5×10^{-3}	9.87×10^{-6}	1×10^{-2}	7.5	2.95×10^{-4}	1.45×10^{-4}
Torr (mm of Hg)	133	1	1.32×10^{-3}	1.33	1,000	3.94×10^{-2}	1.93×10^{-2}
Atm (atmosphere)	1.013×10^5	760	1	1,013	7.6×10^5	29.9	14.7

To Convert	Multiply By						
From — To	Pa	Torr	Atm	mbar	u	In Hg	psia
mbar (millibar)	100	0.75	9.87×10^{-4}	1	750.1	2.95×10^{-2}	1.45×10^{-2}
millitorr or u (micron)	0.133	1×10^{-3}	1.32×10^{-6}	1.33×10^{-3}	1	3.94×10^{-5}	1.93×10^{-5}
In Hg	3.39×10^3	25.4	3.34×10^{-2}	33.9	2.54×10^4	1	0.491
Psia (lbs/inch ² absolute)	6.90×10^3	51.7	6.80×10^{-2}	69.0	5.17×10^4	2.036	1

Table 3.1 provides multiplicative factors to convert pressure values from one unit of measure into another. For example, to convert a pressure of 132 Torr to the unit of mbar, locate the unit of torr in the 2nd row in Table 3.1 (highlighted). Since we are converting to the unit of mbar, we will use the 4th column in Table 3.1 (also highlighted). The multiplicative factor to convert from torr to mbar is located at the intersection of this row and column, and that value is 1.33. This means, we multiply the pressure in units of torr by the conversion factor 1.33, to obtain the pressure value in units of mbar:

$$132 \text{ Torr} = \left(132 \cancel{\text{ Torr}} \right) \times 1.33 \frac{\text{mbar}}{\cancel{\text{ Torr}}} = 176 \text{ mbar}.$$

Some pressure measurement devices (gauges) measure absolute pressure, while other gauges measure gage pressure or the amount of pressure above (or below) the atmospheric pressure. Equation 3.1 below shows the relationship between absolute, atmospheric, and gage pressures:

$$P_{\text{absolute}} = P_{\text{gage}} + P_{\text{atmospheric}} \quad (\text{Eq.3.1})$$

An example of a gage pressure measurement device is the Bourdon gauge. Some examples of absolute pressure measurement devices used with vacuum systems are the capacitance diaphragm, Pirani, convection-enhanced Pirani, and thermocouple gauges.

A Bourdon gauge is a confusing pressure measurement device for interpreting the measurement readings. Figure 3.1 below shows a Bourdon gauge at atmospheric pressure. The reading needle is at 0 in Hg Vacuum, indicating that the measured pressure is exactly at atmospheric pressure.



Figure 3.1. Bourdon gauge reading of atmospheric pressure. Photo is provided by Nancy Louwagie, Normandale Community College.

When measured pressure is below atmospheric pressure, that is, when a vacuum condition is present, a Bourdon gauge will indicate a value representing the amount of pressure below atmospheric pressure. For example, Figure 3.2 shows a Bourdon gauge reading of 7.6 in Hg Vacuum or 7.6 in Hg below atmospheric pressure (or -7.6 in Hg):

$$P_{gauge} = 7.6 \text{ in Hg Vacuum} = -7.6 \text{ in Hg}$$

Note that a below-atmospheric gage pressure value should be negative, $P_{gage} = -7.6$ in Hg, when performing absolute pressure calculations. To convert this value to the absolute pressure, we need to know atmospheric pressure at this location. If atmospheric pressure is $P_{atm} = 29.9$ in Hg, then:

$$P_{absolute} = -7.6 \text{ in Hg} + 29.9 \text{ in Hg} = 22.3 \text{ in Hg}$$

or 22.3 in Hg above absolute zero pressure. Some Bourdon gauges may show pressure values below atmosphere as negative pressure, instead of stating “Vacuum”. This will depend on the display design of the particular Bourdon gauge device.

If atmospheric pressure is measured in a unit of measure other than the unit used by the Bourdon gauge (for example, torr), then the Bourdon gauge reading needs to be converted to that other pressure unit before calcu-



Figure 3.2. Bourdon gauge reading of below-atmospheric pressure. Figure provided by Nancy Louwagie, Normandale Community College.

lating absolute pressure. If atmospheric pressure was measured as 760 Torr, we will need to convert $P_{gauge} = -7.6 \text{ in Hg}$ to Torr:

$$-7.6 \text{ in Hg} = \left(-7.6 \cancel{\text{ in Hg}} \right) \times 25.4 \frac{\text{Torr}}{\cancel{\text{ in Hg}}} = -193 \text{ Torr}$$

then, to calculate absolute pressure:

$$P_{absolute} = -193 \text{ Torr} + 760 \text{ Torr} = 567 \text{ Torr}.$$

Equipment and Materials

1. Rough Vacuum Equipment Trainer (RVET) system
2. Unit conversion table (Table 3.1)

Procedure

Learning Activity 3.1: Unit Conversion Practice

1. Refer to the marshmallow weight calculated in the after-class assignment of the Learning Activity 2.4. Using Table 3.1, convert the pressure due to the marshmallow's weight from:
 - a. Pascals (Pa) to atmospheres (atm),
 - b. Pascals (Pa) to Torr.

2. Using Table 3.1, convert the reading of the absolute pressure gauge (capacitance manometer, Pirani gauge, or other) to:
 - a. Pascals (Pa),
 - b. atmospheres (atm).

Absolute pressure gauge reading: _____ Unit: _____

3. What is the pressure exerted by each tire on a 1,400 kg pickup truck if each tire makes contact with 37 in^2 of the road surface? Write your answer in units of Pa, torr, and psia.

4. Tire pressure is about 35 psi. Is this absolute or gage pressure?

5. Convert 35.0 psig to Pa, atm, and torr, assuming standard atmospheric pressure of 14.7 psi.

Learning Activity 3.2: Atmospheric Pressure in Scientific Notation

Atmospheric pressure measurements.

1. Vent RVET to atmosphere.
2. Set absolute pressure reading gauge to reading in units of torr and in scientific notation.
3. **Read the absolute pressure reading gauge for a measurement of atmospheric pressure and record in the Table 3.2 below.**

- Repeat step 3 for a second measurement of atmospheric pressure. Record in Table 3.2.

Table 3.2. Pressure Data Table. Date data collected: _____

Location	Reading 1 from the absolute pressure reading gauge (Torr)	Reading 2 from the absolute pressure reading gauge (Torr)

- Convert these readings to decimal notation and record in Table 3.3.

Table 3.3. Pressure Data in Decimal Notation Table.

Date data collected: _____

Location	Reading 1 in Decimal Notation (Torr)	Reading 2 in Decimal Notation (Torr)

Learning Activity 3.3: Expected Atmospheric Pressure

- Use an internet search tool (e.g. Google) to look up the expected atmospheric pressure at the following locations. Record each value in the middle column of Table 3.4 with the units that were given. Then record this value in torr in the last column. You may need to do some unit conversions.

Table 3.4. Atmospheric Pressure Data Table.

Location	Expected Atmospheric Pressure with units	Expected atmospheric Pressure (Torr)
Location 1: <i>Your location</i>		
Location 2: <i>Denver, Co (altitude of 5,279 feet)</i>		
Location 3: <i>Miami, FL (altitude of 7 feet)</i>		
Location 4:		
Location 5:		

- For each location, are the pressures you found the same as the pressures that would be read from RVET at the instructional site? If they are not, list some reasons why they might be different.

Learning Activity 3.4: Pressure in Scientific Notation

- Record the value of atmospheric pressure from the Bourdon gauge for your location. Record in the Table 3.5 below.

Table 3.5. Bourdon Gauge Reading of Atmospheric Pressure Table.

Location	Reading from the Bourdon Gauge (in Hg Vacuum): Atmospheric Pressure

2. What should this value be?

3. Close the vacuum chamber and venting valve.
4. Turn on the pump.
5. Open the roughing valve.
6. Pump down for approximately 10 seconds, then close the roughing valve.
7. **Record the pressure measurement reading from the gage pressure measurement gauge as the value for Pressure 1 in Table 3.6.**
8. Open the roughing valve.
9. Pump down for approximately 10 seconds, then close the roughing valve.
10. **Record the pressure measurement reading from the gage pressure measurement gauge as the value for Pressure 2 in Table 3.6.**

Table 3.6. Gage Pressure Data Table.

Location	Pressure 1 from the Bourdon Gauge (in Hg Vacuum)	Pressure 2 from the Bourdon Gauge (in Hg Vacuum)

11. Convert these measurements to absolute pressure in torr and record in Table 3.7.

Table 3.7. Absolute Pressure Data Table.

Location	Absolute Pressure (Torr)	Absolute Pressure (Torr)

12. Measure the pressure measured by the absolute pressure reading gauge and record in Table 3.8.

Table 3.8. Absolute Pressure Data Table.

Location	Pressure 2 from Absolute Pressure Reading Gauge (Torr)

13. How does the measurement from the absolute pressure measurement gauge compare to the calculated absolute pressure from the gage measurement device? How should the two values compare?
14. What is the relationship between the measurement values obtained from the Bourdon gauge and the absolute pressure reading gauge (capacitance manometer or Pirani gauge)? What type of measurement does the capacitance diaphragm gauge make: absolute or gage? What type of measurement does the Bourdon gauge make: absolute or gage?



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- Figure 3.2. © Nancy Louwagie is licensed under a [CC BY-NC-SA \(Attribution NonCommercial ShareAlike\)](#) license

Learning Activities 4.1 - 4.4: Gas Laws Activities

Learning Activities 4.1: Demonstrations of the Boyle's Law Phenomena in Vacuum Systems

Summary of Learning Activities

Student Learning Objectives

Suggested Pre-lab Assignment

Theoretical Background

Equipment and Materials

Procedure

Learning Activity 4.1.a: Demonstration with Expanding Glove

Learning Activity 4.1.b: Demonstration with Plastic Wrap

Learning Activity 4.1.c: Demonstration with Marshmallows

Learning Activity 4.1.d: Demonstration with Slime

Learning Activity 4.1.e: Demonstration with Plastic Bottles

Learning Activity 4.1.f: Other Examples that Demonstrate the Expansion of a Volume under Vacuum Conditions

Learning Activities 4.2: Demonstrations of Various Physical Phenomena in Vacuum Systems

Summary of Learning Activities

Student Learning Objectives

Suggested Pre-lab Assignment

Theoretical Background

Equipment and Materials

Procedure

Learning Activity 4.2.a: Demonstration with Radio

Learning Activity 4.2.b: Demonstration with an Electric Fan

Learning Activities 4.3: Gas Pressure and Boyle's Gas Law

Summary of Learning Activities

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Procedure**](#)

[**Learning Activity 4.3.a: Boyle's Law for Expanding Marshmallow**](#)

[**Learning Activity 4.3.b: Boyle's Law for Expanding Shaving Cream**](#)

[**Learning Activities 4.4: Gas Pressure and Amontons' Gas Law**](#)

[**Summary of Learning Activities**](#)

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Procedure**](#)

[**Analysis of Results**](#)

Learning Activities 4.1: Demonstrations of the Boyle's Law Phenomena in Vacuum Systems

Summary of Learning Activities

- Qualitatively investigating the relationship between changes in gas pressure and the volume the gas occupies when the prevailing temperature condition of the system remains constant (Boyle's law).
- Utilizing a Rough Vacuum Equipment Trainer (RVET) system with a chamber to hold different objects in a space that experiences changes in pressure.

Student Learning Objectives

1. Explain the phenomenon that relates the changes in gas pressure to the changes in the volume of the gas for a fixed amount of gas at a constant temperature when the gas is contained within a volume possessing an elastic boundary.
2. Qualitatively explain the relationship between the change in gas pressure and the corresponding change of the gas volume during the RVET pump-down process (Boyle's law).

Suggested Pre-lab Assignment

None.

Theoretical Background

The relationship between the volume of gas and the absolute pressure exerted by a constant amount of gas when the temperature remains constant is stated in **Boyle's law**. Mathematically, Boyle's law can be expressed as:

$$P_1 V_1 = P_2 V_2,$$

where P_1 and V_1 are the initial pressure and volume of the system and P_2 and V_2 are the final pressure and volume of the system. So theoretically, as long as the amount of gas and temperature do not change, the product of pressure and volume should not change. In real life under these conditions, the products of pressure and volume may not be equal for two different states due to imperfect experimental conditions such as gas leaks and/or temperature fluctuations.

The phenomenon associated with Boyle's law can be readily observed by subjecting different objects that contain a volume of a gas within a flexible boundary to changing external air pressure conditions. As the pressure in the vacuum system decreases, the object expands (volume increases) to the point at which the pressure of the gas trapped inside the object is in equilibrium with the pressure in the chamber of the vacuum system. The learning activities described below provide different examples of how this phenomenon is demonstrated. All of these learning activities visibly demonstrate the inverse relationship between pres-

sure and volume. An inverse relationship is characterized quantitatively as a situation in which one value increases while another value simultaneously decreases. These activities also provide qualitative insights on the types of physical conditions that impact to what extent the Boyle's law model can be applied quantitatively in these situations.

Equipment and Materials

1. Rough Vacuum Equipment Trainer (RVET) system
2. Nitrile or Latex Gloves
3. Bubble wrap or plastic pocket packaging material
4. Marshmallows
5. Slime
6. Small beaker (100 ml)
7. Large beaker (1,000 ml)
8. Empty plastic bottle

Procedure

Learning Activity 4.1.a: Demonstration with Expanding Glove

1. Place a piece of metal mesh material over the opening in the vacuum system's baseplate to prevent the expanding glove(s) from blocking the outlet that allows gas from the chamber to flow to the pump.
2. Tie one end of a plastic glove to seal the glove volume. Place the glove in the chamber as shown in Figure 4.1.1.
3. Before starting the pump-down process, describe how you expect the glove to behave as the pressure in the vacuum chamber decreases.
4. Close the vent valve and roughing valve.
5. Start the roughing pump.
6. Open the roughing valve and pump the system down until the glove expands to a pre-determined volume or until the desired pressure is reached.

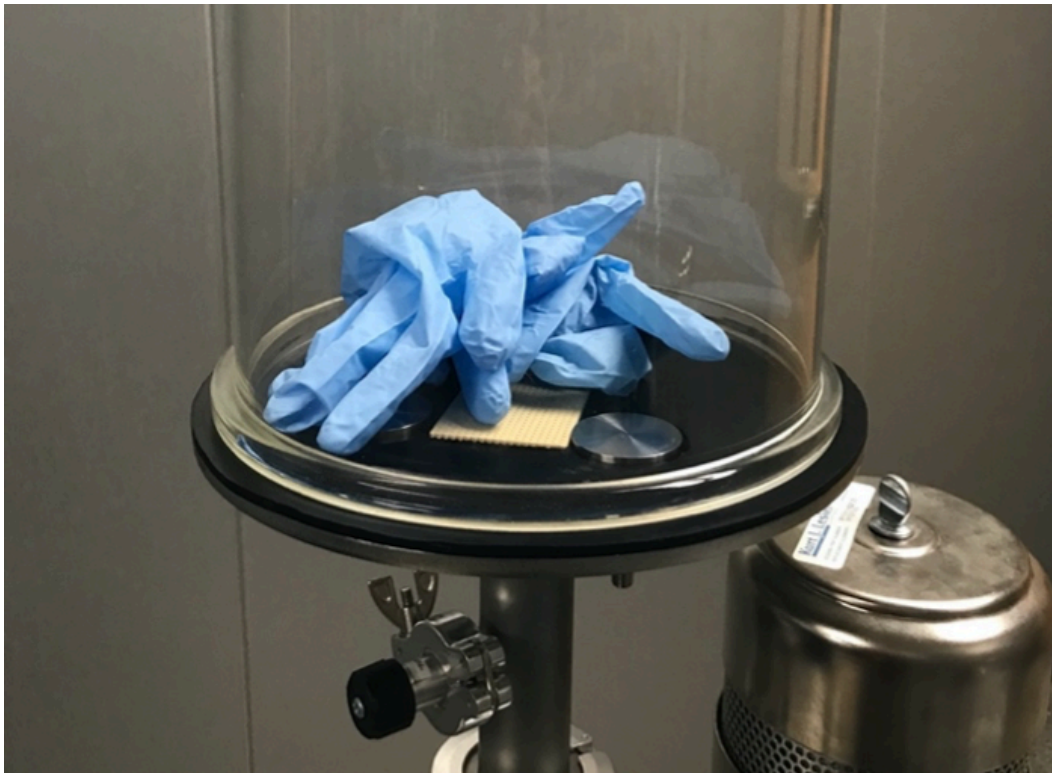


Figure 4.11. Glove Demonstration Set-up. Figure provided by E. Brewer, SUNY Erie Community College.

7. Close the roughing valve.
8. Why did the glove expand?
9. Which gas law can be used to explain the glove's expansion.
10. Observe the behavior of the glove for 1 or 2 minutes after the roughing valve is closed. Does the volume of the glove stay the same or change?
11. If the glove retains its expanded size, what does it mean for the vacuum system?
12. What conditions would cause the glove to stop expanding even if the pressure in the chamber continues to decrease.
13. If the glove is starting to contract, what potential problem(s) with this vacuum system might this indicate?
14. Open the vent valve and observe the behavior of the glove. Explain what happens to the glove.

15. Do you think that the expansion of the glove is appropriately modeled by Boyle's law? Explain why or why not.

Learning Activity 4.1.b: Demonstration with Plastic Wrap

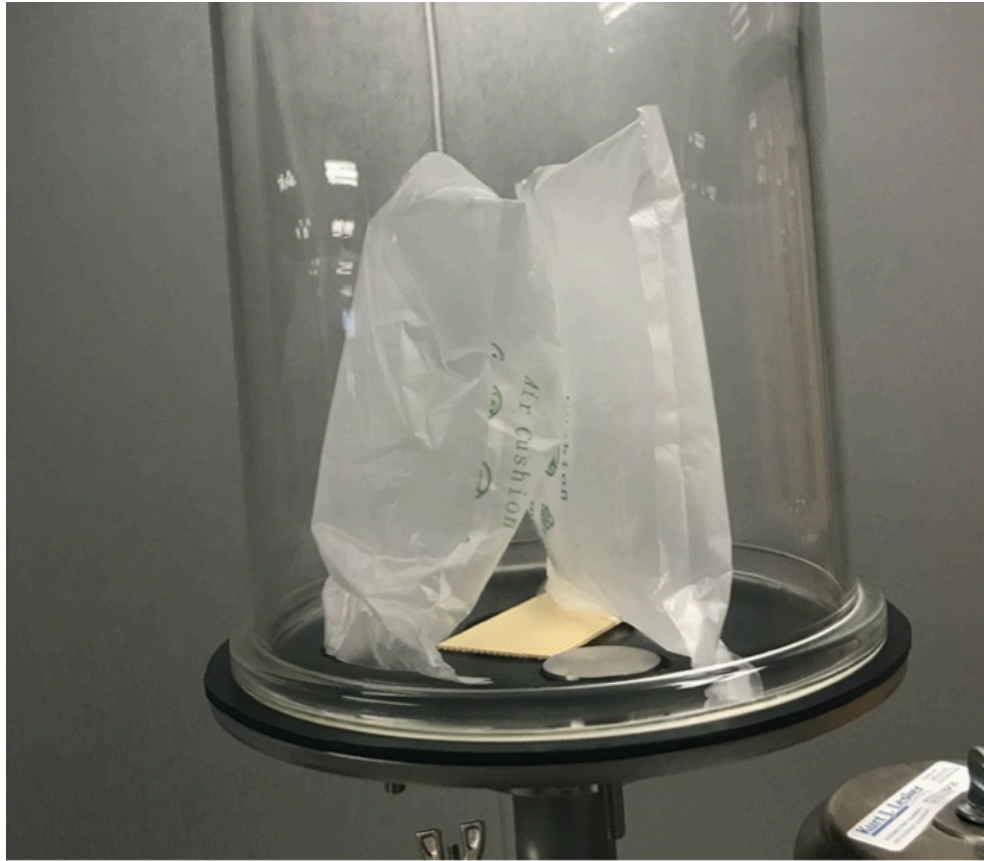


Figure 4.1.2. Plastic Wrap Demonstration Set-up. Figure is provided by E. Brewer, SUNY Erie Community College.

1. Vent the chamber.
2. Place a piece of metal mesh material over the opening in the vacuum system's baseplate to prevent the expanding object from blocking the outlet that allows gas from the chamber to flow to the pump.
3. Place the plastic bubble wrap in the chamber making sure it does not impede the gas flow to the pump as shown in Figure 4.1.2.
4. Before performing the pump-down procedure, describe how you expect the bubble wrap to behave as the pressure in the vacuum chamber decreases.

5. Close the vent valve and roughing valve.
6. Start the pump.
7. Open the roughing valve.
8. Pump the system down until you see visible changes in the state of the bubble wrap or pockets.
Describe your observations:
9. Why do the bubbles/air pockets expand during pump-down process? Deform? Burst?
10. Do you think that the expansion of the plastic packaging wrap material can be described by Boyle's law? Explain why or why not.

Learning Activity 4.1.c: Demonstration with Marshmallows



Figure 4.1.3. Marshmallows Demonstration Set-up. Picture is provided by E. Brewer, SUNY Erie Community College.

1. Vent the chamber.

2. Place a piece of metal mesh material over the opening in the vacuum system's baseplate to prevent blocking the path of gas flow to the pump.
3. Place the marshmallows in the chamber making sure they do not impede the gas flow to the pump (see Figure 4.1.3). A beaker can be used to hold the marshmallows.
4. Before performing the pump-down procedure, describe how you expect the marshmallows to behave as the pressure in the vacuum chamber decreases.
5. Close the vent valve and roughing valve.
6. Start the pump.
7. Open the roughing valve.
8. Pump the system down and observe what happens to the marshmallows. Describe your observations:
9. Explain the observed behavior of marshmallows.
10. Close the roughing valve.
11. Turn off the pump.
12. What do you expect will happen to the marshmallows when you vent the chamber?
13. Open the vent valve and observe what happens to the marshmallows. Record your observations:
14. Did the marshmallows return to their original shape when the chamber was vented? Explain why or why not.

Learning Activity 4.1.d: Demonstration with Slime

1. Vent the chamber.
2. Place a 1,000 ml beaker with slime in the chamber, making sure the beaker does not obstruct the opening in the vacuum system's baseplate preventing the flow of gas out of the chamber and to the pump. See Figure 4.1.4.

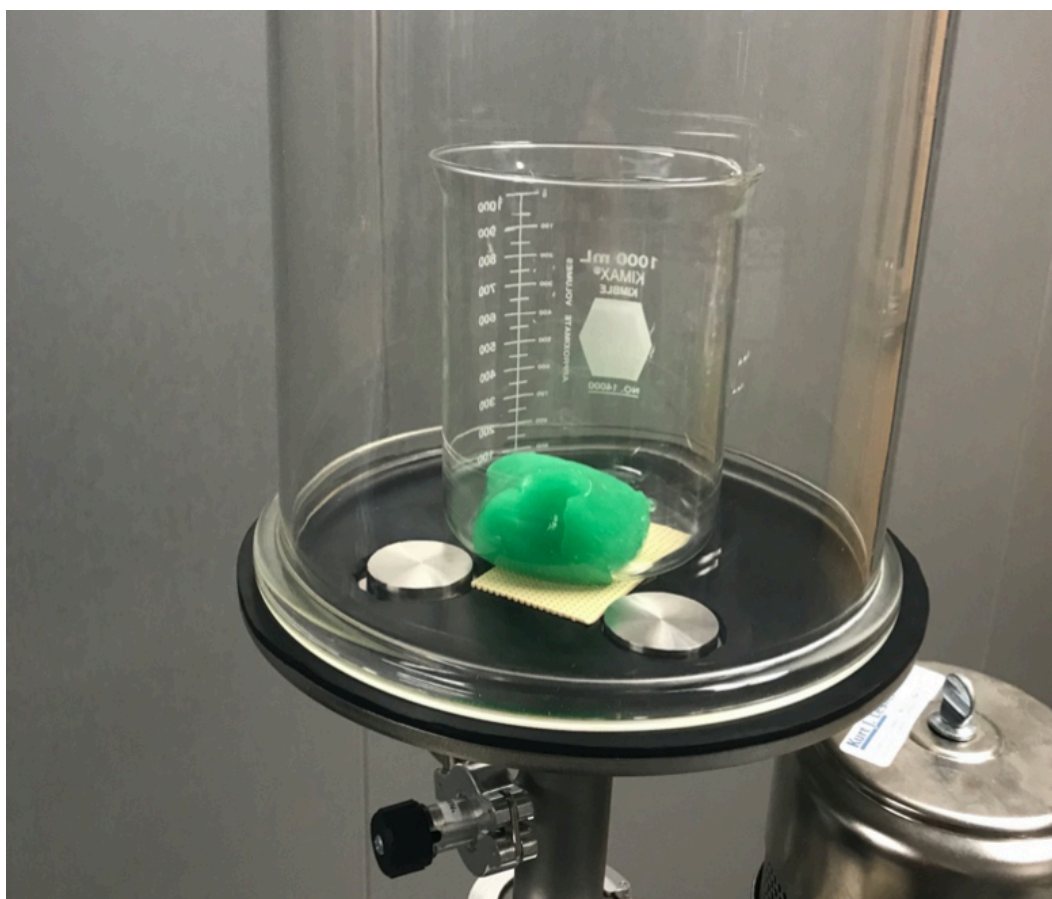


Figure 4.1.4. Slime Demonstration Set-up. Picture is provided by E. Brewer, SUNY Erie Community College.

3. Before performing the pump-down procedure, describe how you expect the slime to behave as the pressure in the vacuum chamber decreases.
4. Close the vent valve and roughing valve.
5. Start the pump.
6. Open the roughing valve.
7. Pump the system down and observe what happens to the slime. Note: close the roughing valve before the slime expands over the top of the beaker to avoid the slime material entering into the roughing pump.
8. Describe your observations:
9. Close the roughing valve.

10. Turn off the pump.
11. What do you think will happen when we vent the chamber?
12. Vent the chamber, observe the behavior of the slime, and record your observations.

Learning Activity 4.1.e: Demonstration with Plastic Bottles

1. What happens to the bottles when we pump the chamber down?
2. What happens to the bottles when we vent the chamber?
3. Explain the differences in the behavior of bottles and behavior of bubble wrap or slime?

Learning Activity 4.1.f: Other Examples that Demonstrate the Expansion of a Volume under Vacuum Conditions

1. Provide one or more examples of objects that could be used to demonstrate the expansion of a volume under vacuum conditions.
2. Describe how you would expect that object to behave if you could place it in a vacuum chamber and subject it to vacuum conditions. Explain why you would expect the behavior you describe.
3. Describe how you would expect that object to behave after subjecting it to vacuum conditions and then venting the system to atmosphere. Explain why you would expect the behavior you describe.
4. Look for a video example on the Internet of the object you selected being subjected to vacuum conditions. Did you observe outcomes that were consistent with what you anticipated?

Learning Activities 4.2: Demonstrations of Various Physical Phenomena in Vacuum Systems

Summary of Learning Activities

- Qualitatively investigating the effects of reduced pressure on propagation of sound.
- Qualitatively investigating the effects of reduced pressure on performance of mechanical systems such as a fan.

Student Learning Objectives

1. Qualitatively explain how vacuum conditions affect the propagation of sound waves.
2. Qualitatively explain the observed behavior of a fan operating at different pressure levels.

Suggested Pre-lab Assignment

None.

Theoretical Background

In a sound wave traveling in a gas, gas molecules vibrate back and forth parallel to the direction of the sound wave's travel. In places where molecules of gas momentarily move away from each other, low pressure areas are formed. And in places where molecules of gas move closer to each other, high pressure areas are formed. Such moving consecutive segments of high and low pressures form what we call a sound wave. The key point to understand is that a sound wave requires a medium (gas, liquid, or even solid) to be able to travel.

If the medium is removed, a sound wave will cease to exist. This means that sound cannot travel in an ideal vacuum. In a practical vacuum, the amount of gas molecules is reduced to the point that the intensity of the sound wave can drop below the audible level.

Another application that requires the motion of gas molecules is the operation of an electric fan. When a fan is operating at standard atmospheric pressure, it can move a substantial volume of air and produce a noticeable air flow. However, when a fan operates in a space under vacuum where enough gas molecules are removed, the fan cannot produce a noticeable air flow.

Equipment and Materials

1. Rough Vacuum Equipment Trainer (RVET) system
2. Nitrile or Latex Gloves
3. Small battery-powered radio.
4. Small battery-powered electric fan.

Procedure

Learning Activity 4.2.a: Demonstration with a Radio

1. Vent the chamber.
2. Place the radio (or other device) playing loud sound inside the chamber.
3. Do you hear sound from the radio inside of the chamber?
4. What is going to happen when we start pumping air out of the chamber?
5. What is going to happen after a lot of air has been pumped out of the chamber?
6. Close the vent valve and roughing valve.
7. Start the roughing pump.
8. Open the roughing valve.
9. Pump the system down and record your observations:

10. Close the roughing valve.
11. Turn off the pump.
12. Can sound travel in a vacuum and why?
13. Vent the system slowly and record your observations:

Learning Activity 4.2.b: Demonstration with an Electric Fan

1. Vent the chamber.
2. Place a working battery-operated electric fan with loose material strips inside the chamber. Do the blades of the fan move? Do the hanging strips of cloth or plastic move? Explain why.
3. Pump the system down and observe the behavior of the fan and hanging strips.
4. After the pump-down process is just started, do the fan blades still move? Do the strips move? Explain why.
5. After running the pump-down process for a while, do the fan blades still move? Do the strips still move? Explain why.
6. Close the roughing valve and turn off the pump when pump-down process is completed.
7. Vent the chamber.

Learning Activities 4.3: Gas Pressure and Boyle's Gas Law

Summary of Learning Activities

- Measuring the volume of two sample materials, shaving cream and marshmallows, at atmospheric pressure and a vacuum pressure level. Using pressure and volume data to verify Boyle's law.

Student Learning Objectives

1. Perform the pump-down sequence for the RVET system.
2. Collect pressure data points from the RVET system pressure gauges and volume data points for the sample materials.
3. Use scientific notation to represent numbers.
4. Apply rules of significant figures (digits) through unit conversion practice.
5. Calculate the percent difference between the initial and final PV products.
6. Verify Boyle's law.

Suggested Pre-lab Assignment

A sample of H_2 has a gage pressure of -120.3 Torr and a volume of 155 ml. If the sample was transferred to a 1 L volume, what would the pressure be? Apply rules of significant figures to calculations.

Theoretical Background

The relationship between the absolute pressure exerted by a constant amount of gas contained in a volume with an elastic boundary is stated in **Boyle's law**. Mathematically, Boyle's law can be expressed as:

$$P_1 V_1 = P_2 V_2$$

where P_1 and V_1 are the initial pressure and volume of an object with an elastic boundary and P_2 and V_2 are the final pressure and volume of that same object. Theoretically, as long as the amount of gas and temperature do not change, the product of pressure and volume should not change. In real life under these conditions, the product of pressure and volume may change slightly due to possible gas leaks from the object and/or sources of measurement error due to imperfect experiment conditions.

Equipment and Materials

1. RVET system outfitted with pressure measurement gauge.
2. Thermometer to measure the temperature within the chamber.
3. Shaving cream.
4. 2 each, jumbo marshmallows.
5. Ruler with units in mm.
6. 3 each, 200-milliliter (ml) beakers.
7. Dry wipes.

Procedure

Learning Activity 4.3.a: Boyle's Law for the Expanding Marshmallow

1. **Measure** the dimensions of two jumbo marshmallow: **height and diameter**. (*Note: if using marshmallows from the previous Learning Activity, use the volumes previously calculated.*)
2. Use a beaker with 50 ml graduated markings. Allow top of marshmallow to expand to the 200 ml level.
3. Place jumbo marshmallow in the beaker with a flat side down.
4. Make sure the roughing valve between the pump and the chamber is closed.

5. Vent vacuum chamber to atmosphere if needed. Remove the chamber.
6. Place beaker in the vacuum chamber. Place the chamber over the beaker.
7. **Record the temperature value T_i** from the thermometer sensing the temperature inside the chamber.
8. **Record the pressure value P_1** pressure measurement reading from the gauge.
9. Shut the vent valve. Start the rough pump.
10. Open the roughing valve to allow rough pump to remove air from the chamber.
11. Make sure the marshmallow is expanding to occupy the full volume of the beaker out to the sides of the beaker.
12. Close the roughing valve when the top of the marshmallow reaches the 200 ml marked level on the beaker.
13. **Record the pressure value P_2** pressure measurement reading from the pressure gauge.
14. Vent chamber to atmosphere.
15. Remove the beaker with marshmallow from the chamber.
16. Replace the marshmallow in the beaker with the second marshmallow.
17. Repeat steps 4 through 13.
18. **Record the temperature value T_f** from the thermometer sensing the temperature inside the chamber.
19. Vent chamber to atmosphere.
20. Remove the beaker with marshmallow from the chamber.
21. After removing items from the chamber, pump system to a vacuum pressure, close the roughing valve, turn off the pump and leave the system under vacuum and unpowered.

Table 4.3.2. Data Table for Learning Activity 4.3b.

Table 4.3.2. Date data recorded: _____

Data	Value and Unit of Measure
Starting height of the marshmallow b – Marshmallow 1	
Starting diameter of the marshmallow D – Marshmallow 1	
Initial volume of the marshmallow (V_1) – Marshmallow 1	
Starting height of the marshmallow b – Marshmallow 2	
Starting diameter of the marshmallow D – Marshmallow 2	
Initial volume of the marshmallow (V_1) – Marshmallow 2	
Initial chamber temperature (T_i)	
Starting chamber pressure – atmospheric pressure (P_1) – Marshmallow 1	
Chamber pressure when the marshmallow fills the beaker to the 200 ml mark level (P_2) – Marshmallow 1	
Pre-determined volume occupied by marshmallow	200 ml

Data	Value and Unit of Measure
(V_2) – Marshmallow 1	
Initial volume of the marshmallow (V_1) – Marshmallow 2	
Starting chamber pressure – atmospheric pressure (P_1) – Marshmallow 2	
Chamber pressure when the marshmallow fills the beaker to the 200 ml mark level (P_2) – Marshmallow 2	
Pre-determined volume occupied by marshmallow (V_2) – Marshmallow 2	200 ml
Final chamber temperature (T_f)	

Analysis: Verify Boyle's Law using the Pressure and Volume Measurements for Expanding Marshmallow

Does $P_1V_1 = P_2V_2$?

Calculate P_1V_1 and P_2V_2 . Apply rules of significant figures to the calculated results. Calculate the percent difference between P_1V_1 and P_2V_2 . Are the P_1V_1 and P_2V_2 results close enough to verify Boyle's law?

What are some reasons P_1V_1 and P_2V_2 might not be the same?

Why is the temperature measurement inside the chamber taken?

Did the different material types generate similar results? Comment on the similarities and the differences in the results.

Learning Activity 4.3.b: Boyle's Law for Expanding Shaving Cream

1. Apply power to the RVET system and the thermometer. Wait 30 minutes for electronic gauges to warm up.
2. **Record the temperature value T_i** from the thermometer sensing the temperature inside the chamber.
3. **Record the pressure value P_1** from the capacitance diaphragm gauge **at atmospheric pressure.**
4. Add approximately 50-ml of shaving cream to the 200-ml beaker. **Record the volume value V_1 of the shaving cream in the beaker.**
5. Place the beaker with shaving cream in the vacuum chamber.
6. Shut the vent valve. Make sure the roughing valve between the pump and the chamber is closed.
7. Turn on the pump. Open the roughing valve between the pump and the chamber.
8. Close the roughing valve when the shaving cream expands to 200 ml in the beaker.
9. **Record the volume value V_2 of the expanded shaving cream.**
10. **Record the pressure value P_2** from the capacitance diaphragm gauge.
11. Make sure the roughing valve between the pump and the chamber is closed. Turn off the pump.
12. Vent the RVET system.
13. Remove the beaker with shaving cream from the vacuum chamber.
14. Add approximately 50-ml of shaving cream to a second 200-ml beaker. **Record the volume value V_1 of the shaving cream in the beaker .**
15. Repeat steps 4-10.

16. **Record the temperature value T_f** from the thermometer sensing the temperature inside the chamber.
17. Make sure the roughing valve between the pump and the chamber is closed. Turn off the pump.
18. Vent the RVET system.
19. Remove the second beaker with shaving cream from the vacuum chamber.
20. Rinse the shaving cream from the beakers. Dry the beakers.

Table 4.3.1. Data Table for Learning Activity 4.3a.

Date data collected: _____

Data	Value and Unit of Measure
<p style="text-align: center;">Initial chamber temperature (T_i)</p>	
<p style="text-align: center;">Initial pressure (P_1) – 1st time</p>	
<p style="text-align: center;">Initial volume of shaving cream (V_1) – 1st time</p>	
<p style="text-align: center;">System pressure with shaving cream expanded (P_2) – 1st time</p>	
<p style="text-align: center;">Volume of expanded shaving cream (V_2) – 1st time</p>	
<p style="text-align: center;">Initial pressure (P_1) – 2nd time</p>	

Data	Value and Unit of Measure
<p style="text-align: center;">Initial volume of shaving cream $(V_1) - 2^{\text{nd}}$ time</p>	
<p style="text-align: center;">System pressure with shaving cream expanded $(P_2) - 2^{\text{nd}}$ time</p>	
<p style="text-align: center;">Volume of expanded shaving cream $(V_2) - 2^{\text{nd}}$ time</p>	
<p style="text-align: center;">Final chamber temperature (T_f)</p>	

Analysis: Verify Boyles' Law using the Pressure and Volume Measurements for Expanding Shaving Cream

Does $P_1V_1 = P_2V_2$?

Calculate P_1V_1 and P_2V_2 , then say if they are the same.

Calculate percent difference between P_1V_1 and P_2V_2 . Are they close enough to verify Boyle's law?

What are some reasons P_1V_1 and P_2V_2 might not be the same?

Learning Activities 4.4: Gas Pressure and Amontons' Gas Law

Summary of Learning Activities

- Measuring pressure of a gas at different temperatures to validate Amontons' law.

Student Learning Objectives

1. Collect pressure and temperature measurement data.
2. Verify Amontons' law.
3. Report calculated values with appropriate significant figures.

Suggested Pre-lab Assignment

Describe two everyday examples where Amontons' law applies.

Theoretical Background

The relationship between the temperature of gas and the absolute pressure exerted by a constant amount of gas is stated in **Amontons' law (Gay-Lussac's law)**. Mathematically, Amontons' law can be expressed as:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

where P_1 and T_1 are the initial pressure and absolute temperature of the system and P_2 and T_2 are final pressure and absolute temperature of the system. So theoretically, as long as the amount of gas and volume do not change, the ratio of pressure over temperature should not change. In real life under these conditions, the ratios of pressure over temperature will not be exactly equal for changing conditions due to possible gauge reading errors, limitations of the apparatus set up, or gas leaks.

Equipment and Materials

1. Closed metal vessel with a fixed volume.
2. Hot plate.
3. Pressure measurement gauge connected to the fixed volume vessel.
4. Thermocouple thermometer.

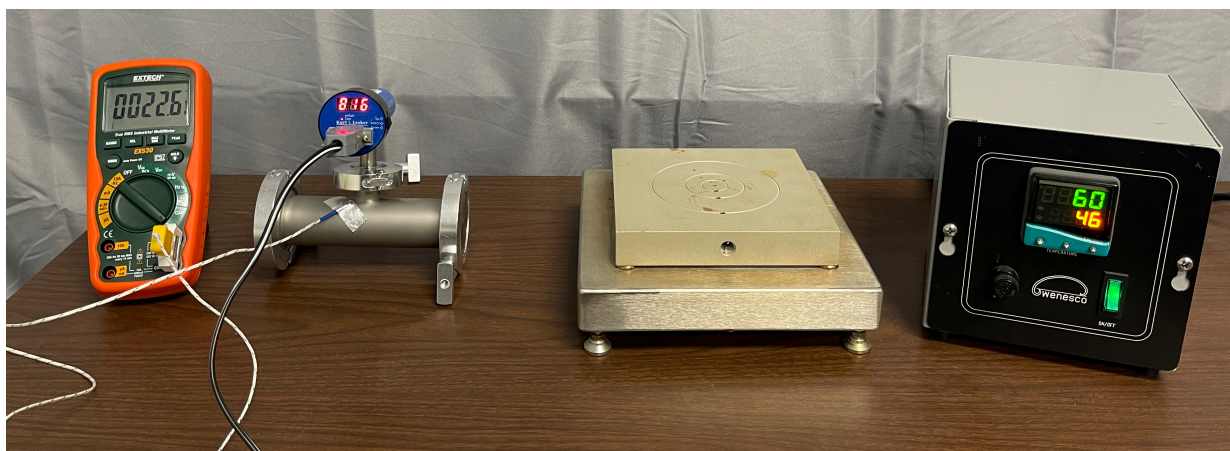


Figure 4.4.1. Sample system Setup 1 with hot plate. Photo provided by E. Brewer, SUNY Erie Community College.

Procedure

1. Preheat hot plate to up to 158°F (about 70°C).
2. Apply power to the pressure gauge.
3. Wait for the measurement value reflected on the pressure gauge to stabilize.
4. **In Table 4.4.1, record the pressure value in the closed metal vessel from the pressure measurement gauge.**
5. Connect the thermometer measuring unit. Wait for the measurement value reflected on the ther-

mometer to stabilize.

6. **In Table 4.4.1, record the temperature using the thermometer to reflect room temperature in the closed metal vessel.**
7. Place the closed metal vessel on a pre-heated hot plate.
8. Allow the temperature of the vessel to increase to a level of 90 – 115°F (32.2 – 46.1°C). You may want to change the orientation of the vessel on the hot plate periodically to insure more uniform heating. See Figure 4.4.2. Wait for the pressure and temperature measurement values reflected on the measuring devices to stabilize.

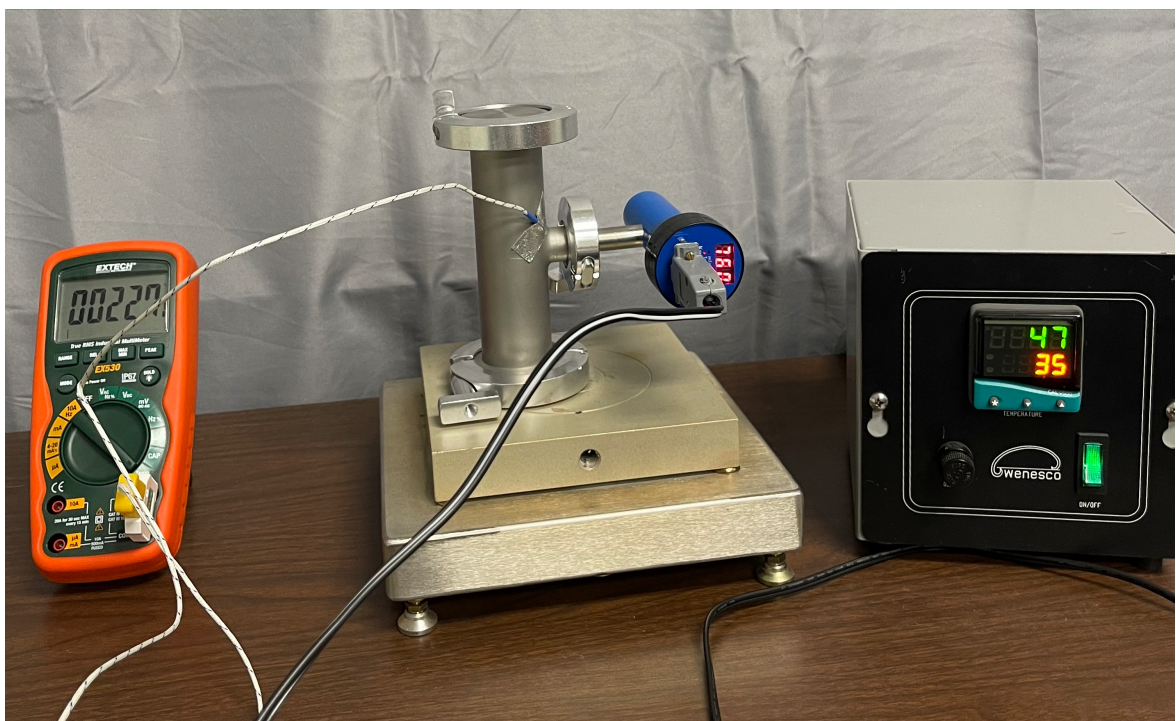


Figure 4.4.2. Different orientations of the vessel on the hot plate. Photo is provided by E. Brewer, SUNY Erie Community College.

9. **In Table 4.4.1, simultaneously record the pressure from the pressure gauge and temperature using the thermometer.**
10. Turn off the hot plate.
11. Let the temperature of the vessel drop approximately 5°F (2.8°C).
12. **In Table 4.4.1, simultaneously record the pressure from the pressure gauge and temperature using the thermometer when the temperature has decreased by 5°F (2.8°C).**

13. Remove power from the pressure gauge.

Name: _____ Date: _____

Table 4.4.1. Amonton's Law Data

Measurement	Pressure (Torr)	Temperature (°F)	Temperature (°C)
Initial P_1, T_1 (STEP 4 and STEP 6)			
Initial P_2, T_2 (STEP 9)			
Initial P_3, T_3 (STEP 12)			

Analysis of Results

1. Convert each measured temperature value to Kelvin and record in Table 4.4.2.
2. Calculate the ratio of P/T for the measurement values obtained in Steps 4 and 6. Be sure to use the temperature value reflecting units of Kelvin when calculating P/T . Report the calculated value with the appropriate number of significant figures. Record the result in Table 4.4.2.
3. Calculate the ratios of P/T for the measurement values obtained in Steps 9 and 12. Report the calculated values with the appropriate number of significant figures. Record the results in Table 4.4.2.
4. Calculate the percentage difference between the P/T ratios. Record the results in Table 4.4.2.

Table 4.4.2. Amonton's Law Calculations

Measurement	Pressure (Torr)	Temperature (K)	P/T (Torr/K)	% Difference (%)
Initial (STEP 4 and STEP 6)				N/A
Second (STEP 9)				
Third (STEP 12)				

5. How well does the measured data fit with the model of Amontons' law? Does $P_1/T_1 = P_2/T_2$? What could be some limitations to both sides of the equation being equal?



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Learning Activities 5.1 - 5.3: Equilibrium Vapor Pressure of Water

[**Summary of Learning Activities**](#)

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Learning Activity 5.1: Equilibrium Vapor Pressure of Water at Room Temperature**](#)

[**Learning Activity 5.2: Effects of Boiling Water on Pressure and Temperature in a Vacuum Chamber**](#)

[**Learning Activity 5.3: Effects of Water Temperature on Equilibrium Vapor Pressure**](#)

Summary of Learning Activities

- Measuring the equilibrium vapor pressure of water for different water temperatures.

Student Learning Objectives

1. Collect data to qualitatively assess water's changing equilibrium vapor pressure changes in

- the temperature of the liquid water.
2. Recognize that once the pressure at which the boiling point of water occurs, achieving lower pressures in the vacuum system corresponds to the decreasing temperature state of the water.
 3. Report calculated values with appropriate significant figures.

Suggested Pre-lab Assignment

1. Use an internet resource to determine the equilibrium vapor pressure of water at the following temperatures: 45°C, 20°C, 3°C. Suggested Sources:
 - [Wikipedia](#),
 - [CRC Handbook of Chemistry and Physics](#).
1. View Video 5.1 about boiling water inside the vacuum chamber:
https://youtu.be/h1YAP7XkzEc?si=zgkfgOjevciMc_C6Video 5.1. Boiling and Freezing Water in a Rough Vacuum System by Vacuum Demos, <https://youtu.be/h1YAP7XkzEc?si=q-iiZ0TItaJDOKeQ>.
2. Why did the water start boiling when pressure was reduced in the chamber?
3. What happens to the temperature of the water if the pump-down process is allowed to continue after boiling starts? What happens to the energy of the water molecules? Why?
4. Did you observe any phase transitions during the continuous pump-down process? If yes, explain why you think the water went through this phase transition.

Theoretical Background

There are two opposing processes working at the interface of liquid and gas at the same time, evaporation of molecules from the surface to the vapor phase and condensation of those molecules back to the liquid phase. When the two opposing processes are equal, the equilibrium vapor pressure of the substance has been reached. Equilibrium vapor pressure depends on the temperature of the substance and is described by the following expression:

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

where

P_{vp} is the vapor pressure in torr,

A and B are constants for a specific gas, and

T is the temperature of the substance in Kelvin

When the temperature of the substance increases, its equilibrium vapor pressure also increases. This relationship is shown in Figure 5.1. Conversely, as the temperature of the substance decreases, its equilibrium vapor pressure also decreases.

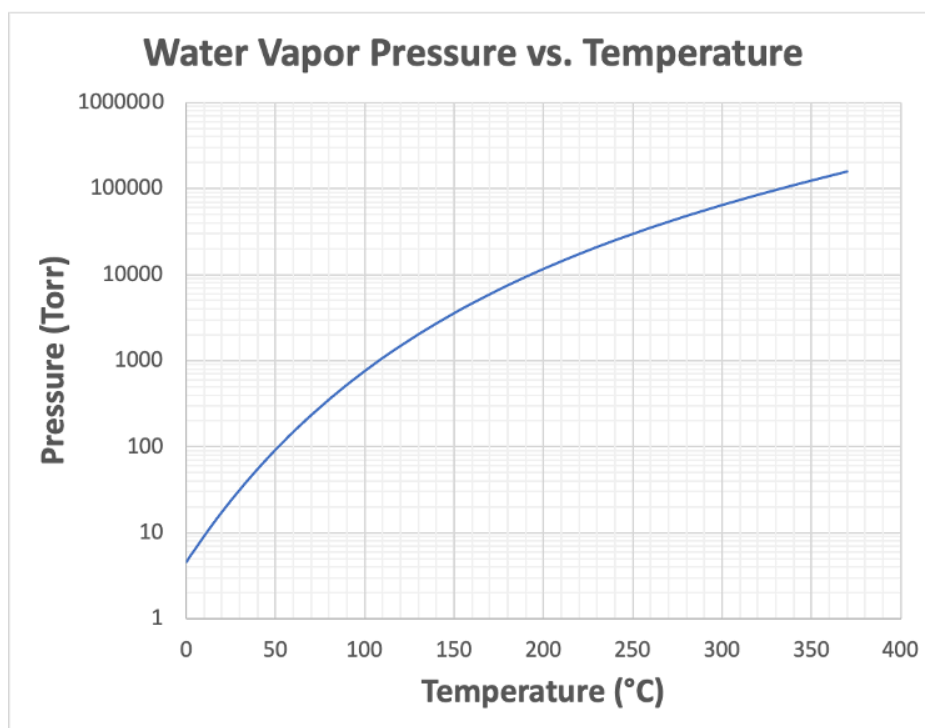


Figure 5.1. Graph of water vapor pressure versus temperature. At the normal boiling point of 100°C, it equals the standard atmospheric pressure of 760 Torr. Graph is provided by Elena Brewer, SUNY Erie Community College.

If a volume of liquid water is placed in a vacuum chamber and the pressure within the chamber is subsequently reduced, the liquid water will start to boil when the pressure in the chamber reaches the equilibrium vapor pressure of the water. Under a nominal atmospheric pressure condition of 1 atm, which is approximately 760 Torr, water boils at 100°C. This temperature is called the normal boiling point of water. As the air pressure decreases, the amount of energy needed by the water molecules for them to escape from the liquid state

decreases. Using a vacuum system to pump down to lower pressure conditions makes it possible for us to observe how the equilibrium vapor pressure changes with different water temperatures.

Equipment and Materials

1. Rough Vacuum Equipment Trainer (RVET)
2. Omega Thermometer HH911T (or similar device)
3. Device for heating water
4. 2 or 3 glass containers (one glass container must fit inside the RVET chamber and NOT completely block the outlet hole in the base plate)
5. Oven mitt to handle hot glass container
6. Water and ice

Procedure

Learning Activity 5.1: Equilibrium Vapor Pressure of Water at Room Temperature

1. Pour water into two glass containers, each approximately 1/4 full. Allow time for the water temperature in each container to reach approximately room temperature.
2. Put one of the glass containers with room temperature water into the RVET. If a thermocouple temperature measurement device is available, immerse the probe in the water. Apply power to the temperature recording device.
3. Place the bell jar over the glass container.
4. **Record the temperature of the water (T1) in Table 5.2.**
5. **Record the pressure value on the capacitance diaphragm gauge (P1_P) in Table 5.2.**
6. Make sure the RVET vent valve is closed.
7. Turn on the pump. Open the valve between the chamber and the pump.
8. When the water just starts splashing in a boil, close the valve between the chamber and the pump.

9. Record the temperature of the water (T_2) in Table 5.2.
10. Record the pressure value on the capacitance diaphragm gauge (P_2_P) in Table 5.2.
11. Vent the system.
12. Remove the glass container from the RVET.

Table 5.2. Vapor Pressure Data at Room Temperature Water.

Date data collected: _____

Temperature of the water (T_1)	
Chamber pressure (P_1_P)	
Temperature of the water (T_2)	
Chamber pressure (P_2_P)	

Question:

If you are/were able to stick your finger in the beaker to experience how hot or cold the water feels, do you expect it to be very hot? Remember, it was just boiling in the chamber. Explain your response.

Learning Activity 5.2: Effects of Boiling Water on Pressure and Temperature in a Vacuum Chamber

13. Place the second glass container containing room temperature water in the RVET.

14. Before pumping down, record the pressure from the capacitance diaphragm gauge and the temperature from the thermometer on the first row (initial conditions).
15. **Record the temperature of the water** when the water starts splashing in a boil **and record the pressure value on the capacitance diaphragm gauge in Table 5.3.**
16. Start a stopwatch.
17. Continue to pump the chamber.
18. After 15 seconds, **record the temperature of the water and record the pressure value on the capacitance diaphragm gauge in Table 5.3.**
19. Record temperature and pressure measurements every 15 seconds 11 more times for a total of three (3) additional minutes of pumping on the system after the water started boiling. NOTE: Does the water continue to boil?
20. Close the valve between the chamber and the pump.
21. Vent the system.

Table 5.3. Pumping on Room Temperature Water after it boils.

Date data collected: _____

	Site 1:		Site 2: Spring 2020, Wichita Falls, TX (continued to pump down)		Site 3: Spring 2023, Bloomington, MN (continued to pump down)	
Time (seconds)	Chamber Pressure (Torr)	Water Temp (°C)	Chamber Pressure (Torr)	Water Temp (°C)	Chamber Pressure (Torr)	Water Temp (°C)
Initial Conditions			744	19	719	21.9
0			17.5	17.3	19.0	21.7
15			17.1	16.9	18.4	21.6

	Site 1:		Site 2: Spring 2020, Wichita Falls, TX (continued to pump down)		Site 3: Spring 2023, Bloomington, MN (continued to pump down)	
Time (seconds)	Chamber Pressure (Torr)	Water Temp (°C)	Chamber Pressure (Torr)	Water Temp (°C)	Chamber Pressure (Torr)	Water Temp (°C)
30			16.9	16.5	18.3	21.3
45			16.6	16.1	18.3	21.3
60			16.3	15.7	18.3	21.2
75			16.1	15.5	18.3	21.2
90			15.8	15.1	18.3	21.2
105			15.4	14.8	18.2	21.2
120			15.2	14.6	18.3	21.2
135			15.0	14.2	18.2	21.2
150			14.9	14.0	18.2	21.2
165			14.5	13.7	18.0	21.2
180			14.3	13.5	18.3	21.1

Learning Activity 5.3: Effects of Water Temperature on Equilibrium Vapor Pressure

22. Remove the glass container from the RVET. Pour off some of the water in the glass container. Add ice. Let the ice water mix sit for two minutes.
23. Repeat Steps 2 – 11 using the container with ice water.
24. Remove the glass container from the RVET.
25. Use a device to heat some water to a temperature between 150 – 175°F. Pour the hot water into a glass container.
26. Repeat Steps 2 – 11 using the container with heated water. Use an oven mitt to transfer the glass container with hot water and place it in the RVET.
27. After the system is vented, use an oven mitt to remove the glass container from the RVET.

Table 5.4. Temperature Dependence on Vapor Pressure.

Date data collected: _____

Site: Normandale	Cold water	Room temperature water	Hot water
Temperature of the water (T1)			
Chamber pressure (P1_P)			
Temperature of the water (T2)			
Chamber pressure (P2_P)			

Activity Wrap Up:

- a. Make sure the beaker with water is removed from the RVET.

- b. Use a wipe to dry the inner surfaces of the chamber.
- c. Pump down the RVET until the pressure within the chamber is less than 10 Torr; pump on the empty RVET system for several minutes allowing the system to remove additional water vapor molecules.
- d. Close the valve between the pump and the chamber leaving the chamber under vacuum.
- e. Power off the RVET system.
- f. Power off the water heating device and discard remaining hot water.
- g. Discard the ice water.
- h. Dry and store glass containers.
- i. Put away other materials in designated locations.

Analysis of Results:

1. Create two separate graphs with data from all three sites included: one plotting the chamber pressure data versus time and the other plotting water temperature data versus time collected in Steps 13 – 21. The first point on both graphs should be the zero-time measurement (when the stopwatch was started).
2. How did the results for water vapor pressure of room temperature water compare from site to site?
3. How does the water vapor pressure data for different temperatures of water recorded during the in-class activity compare to expected values? You may use the table at the following link: https://en.wikipedia.org/wiki/Vapour_pressure_of_water.
4. Will the results for the equilibrium vapor pressure of water change if the atmospheric pressure condition is different?
5. What is the Boiling Point temperature of water in Salt Lake City, UT? What does this mean for processes like boiling food?
6. Which of the site locations is likely to experience a Boiling Point temperature of water closest to water's Normal Boiling Point Temperature and why?

7. What happens to the temperature of the water after it starts to boil and the pressure of the chamber continues to fall? Does the water appear to boil continuously after it starts boiling?



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Learning Activities 6.1 - 6.2: Building and Pumping Down a Rough Vacuum System

[**Summary of Learning Activities**](#)

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Learning Activity 6.1: Building Rough Vacuum System**](#)

[**Learning Activity 6.2: Pumping Down a Rough Vacuum System**](#)

Summary of Learning Activities

- Building a rough vacuum system from a vacuum system schematic.
- Applying appropriate cleanliness techniques when handling and assembling vacuum system components.
- Practicing proper pump-down procedures to operate a vacuum system.
- Evaluating the pump-down times for multiple cycles of vacuum system operation.
- Following proper procedures for storage of a vacuum system.

Student Learning Objectives

1. Follow vacuum cleanliness procedures when handling vacuum system components.
2. Identify vacuum system components.
3. Build a rough vacuum system from a system schematic.
4. Pump down a rough vacuum system.
5. Follow proper vacuum system storage procedures.

Suggested Pre-lab Assignment

1. Read Chapter 3 of the [Introduction to Vacuum Technology E-Book](#), Section 3.5, and draw schematic symbols for the following vacuum system components:
 - a. Diaphragm vacuum pump
 - b. Butterfly valve
 - c. Manual operation valve actuation
 - d. Vacuum gauge

Theoretical Background

A simple rough vacuum system used for this learning activity is described in Section 3.6 of the E-Book. Figure 1 below shows a rough vacuum system and symbols for its components. Figure 6.2 shows a system schematic for the rough vacuum system shown in Figure 6.1.

The video accessed from the link in Video 6.1 provides an overview of the rough vacuum system used for this learning activity.



One or more interactive elements has been excluded from this version of the text. You can view them online here: <https://milnepublishing.geneseo.edu/introtovacuumtechinstructor/?p=504#oembed-1>

Video 6.1. Description of a rough vacuum system used at SUNY Erie Community College. Video prepared by Richard Hill and Anthony Klejna, SUNY Erie Community College.

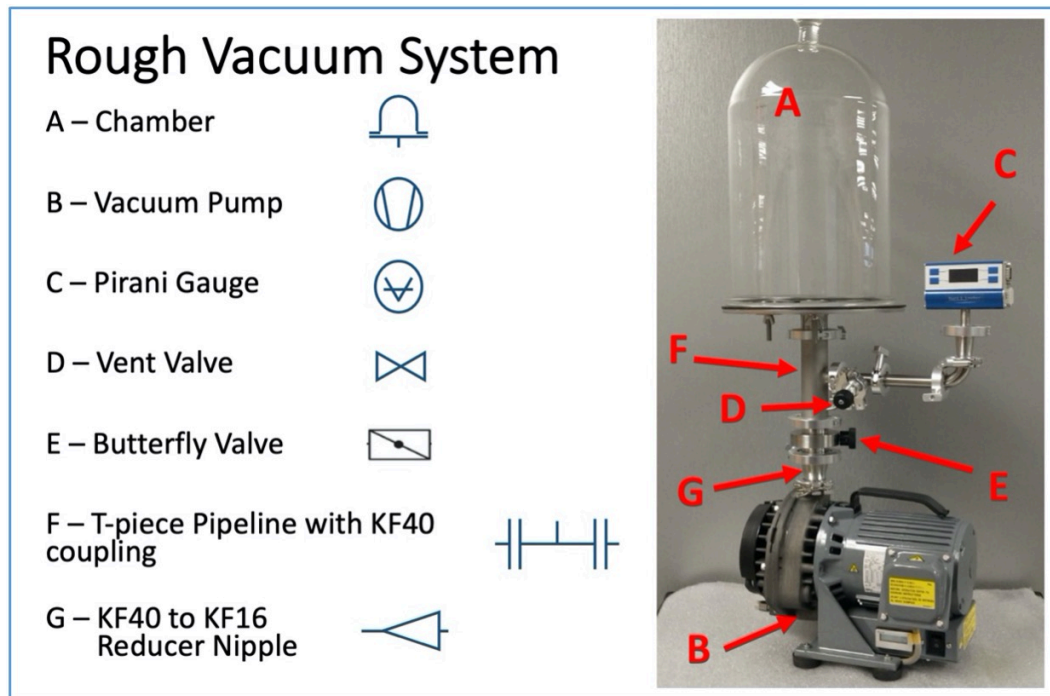


Figure 6.1. Rough vacuum system with component schematic symbols. Diagram is provided by E. Brewer, SUNY Erie Community College.

Equipment and Materials

1. Vacuum system consisting of: (one each)
 - a. Process chamber
 - b. Absolute pressure measurement device
 - c. Vent valve
 - d. Isolation/roughing valve
 - e. Vacuum piping
 - f. Rough vacuum pump
2. Nitrile Gloves (not powdered, not latex)
3. Masks
4. Isopropyl alcohol cleaning wipes
5. Timing device

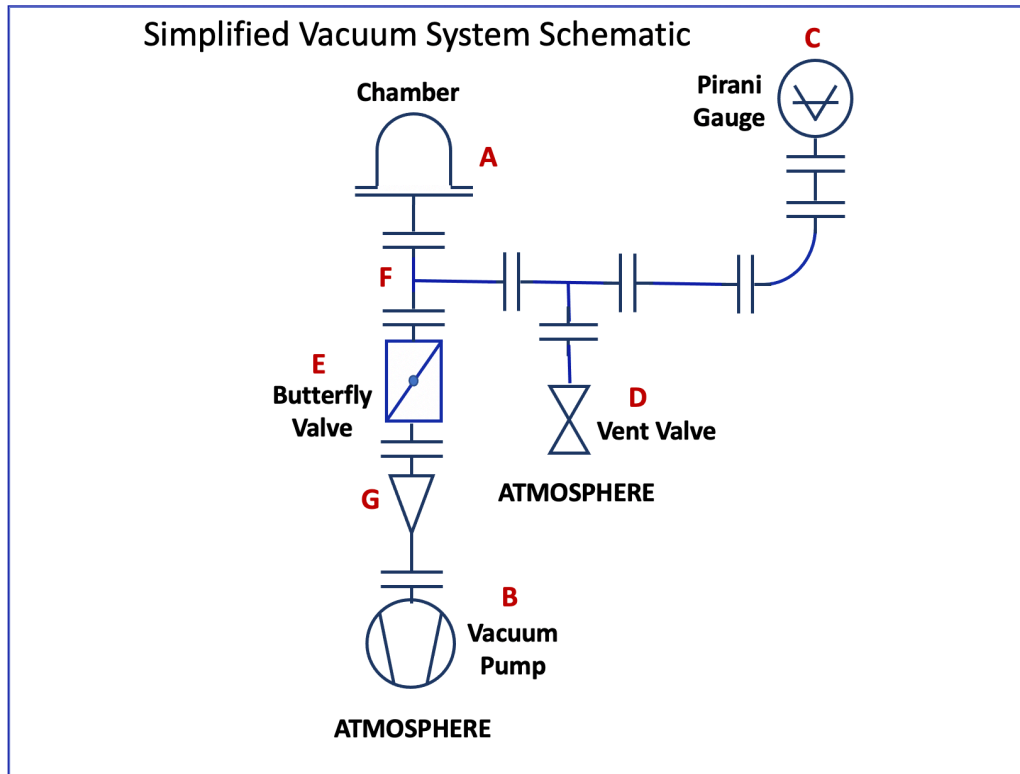


Figure 6.2. Schematic diagram for the rough vacuum system. Diagram is provided by E. Brewer, SUNY Erie Community College.

Procedure

Learning Activity 6.1: Building Rough Vacuum System

1. Put on gloves and mask, making sure that you touch only the opening of rim of each glove. No oil residue from your fingers should be left on the glove surface that will come in contact with vacuum system components.
2. Identify the following vacuum system components:

Pump:

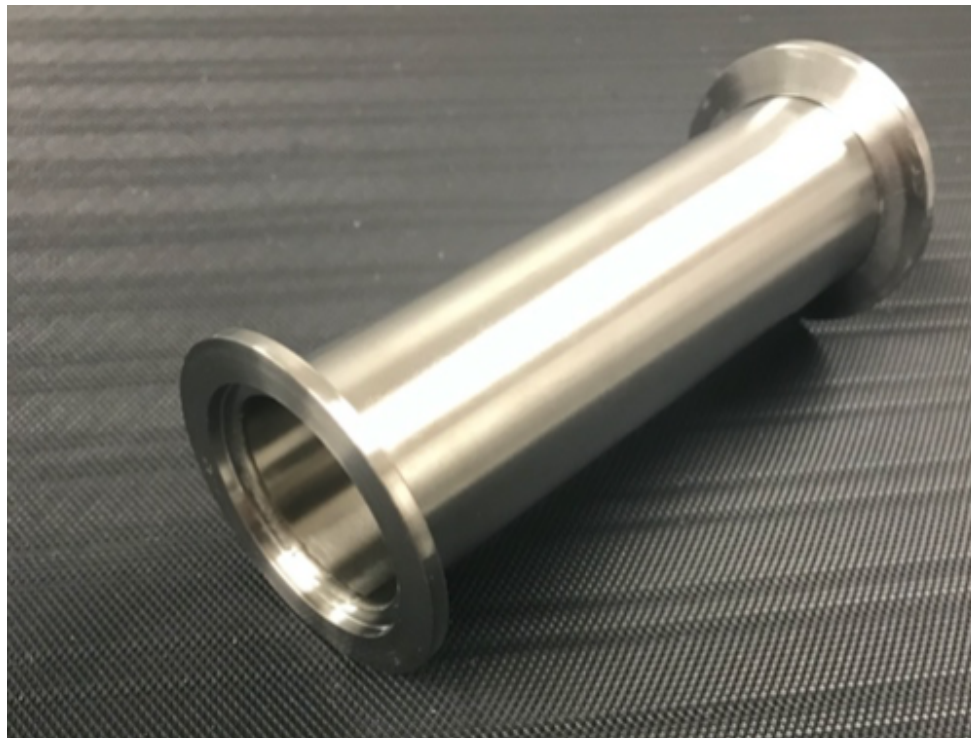


Note: The pump in Figure 6.1 is a scroll pump. The pump shown above is a rotary vane pump. Several types of rough pumps can be used in the rough vacuum system.

Tee:



Nipple:



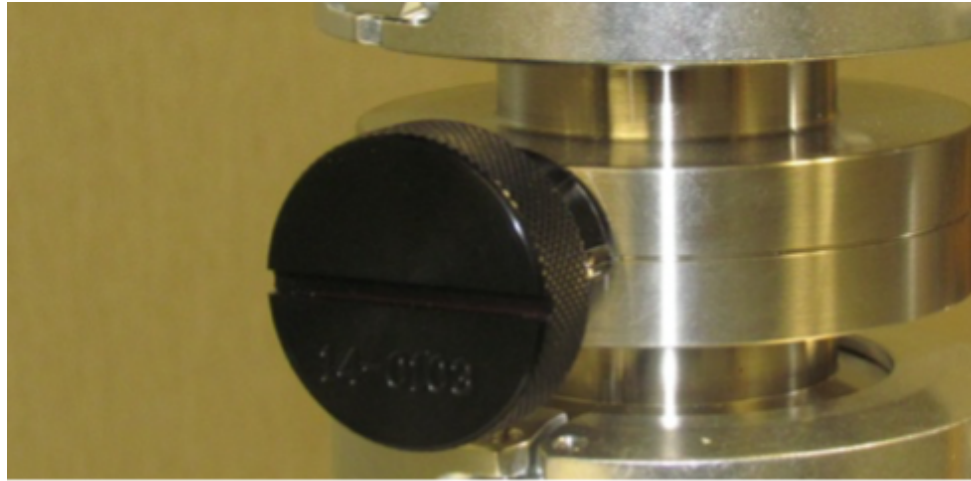
Elbow:



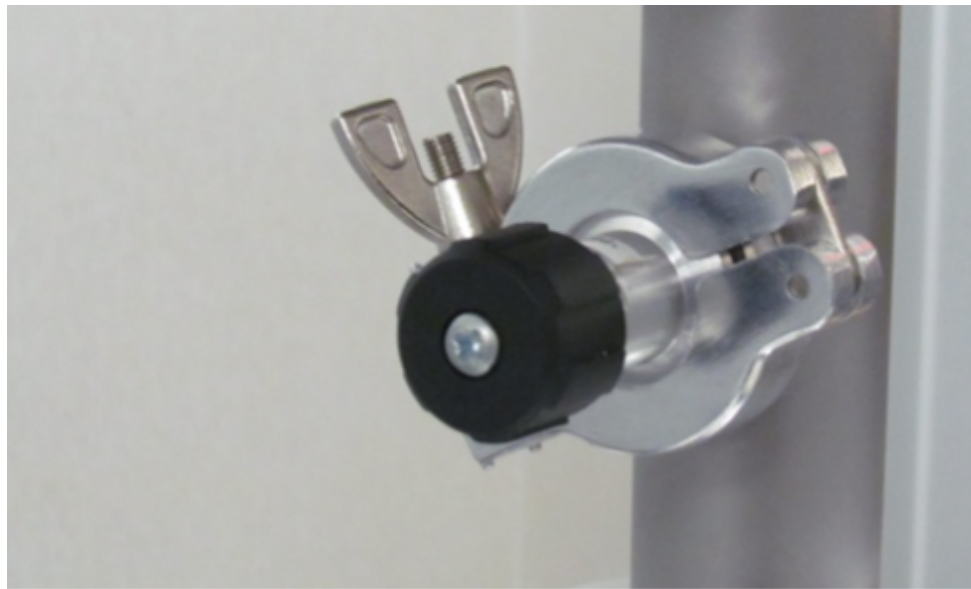
KF flange with O-ring:



Roughing (or Isolation) valve (butterfly valve is used here):



Vent valve:



Vacuum gauge:



Chamber base-plate:



Chamber:

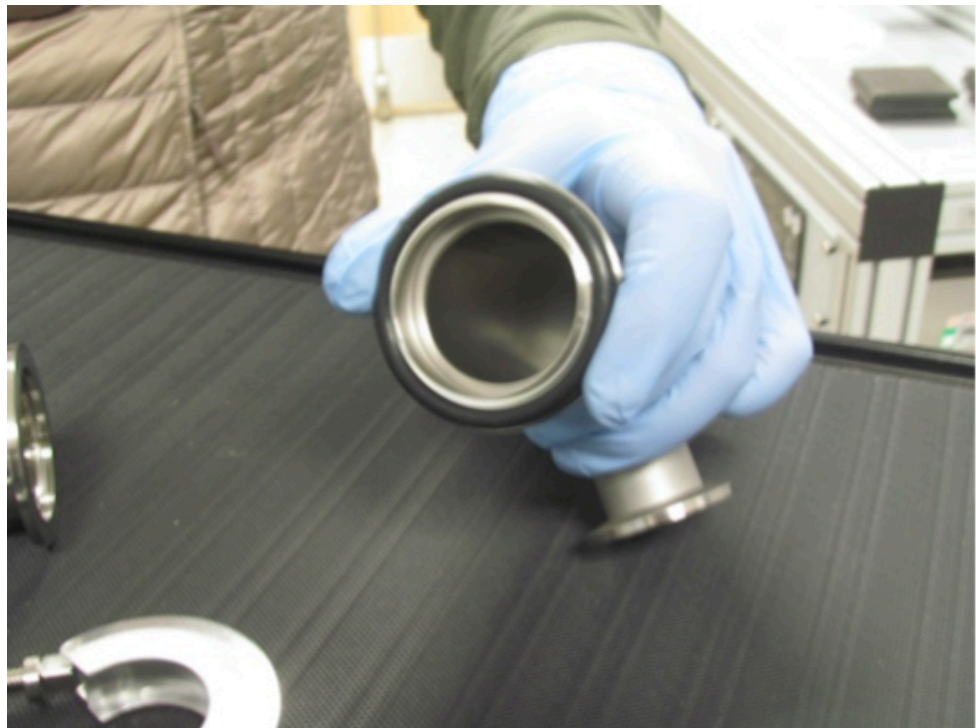
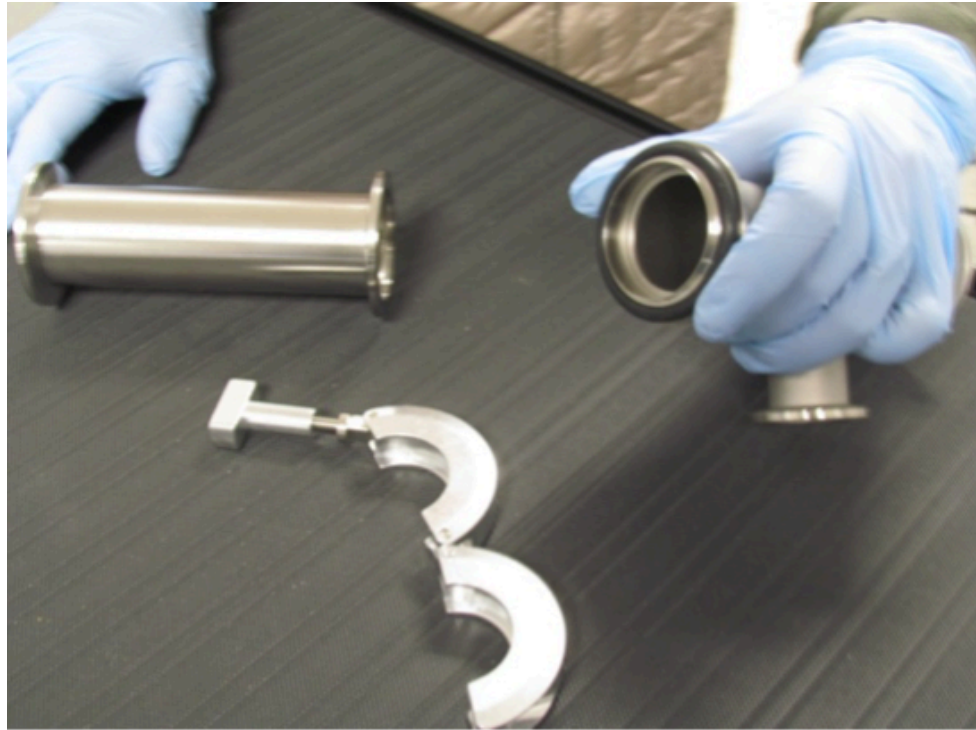


3. Practice assembling KF flanges with elastomer O-rings to properly connect vacuum components.

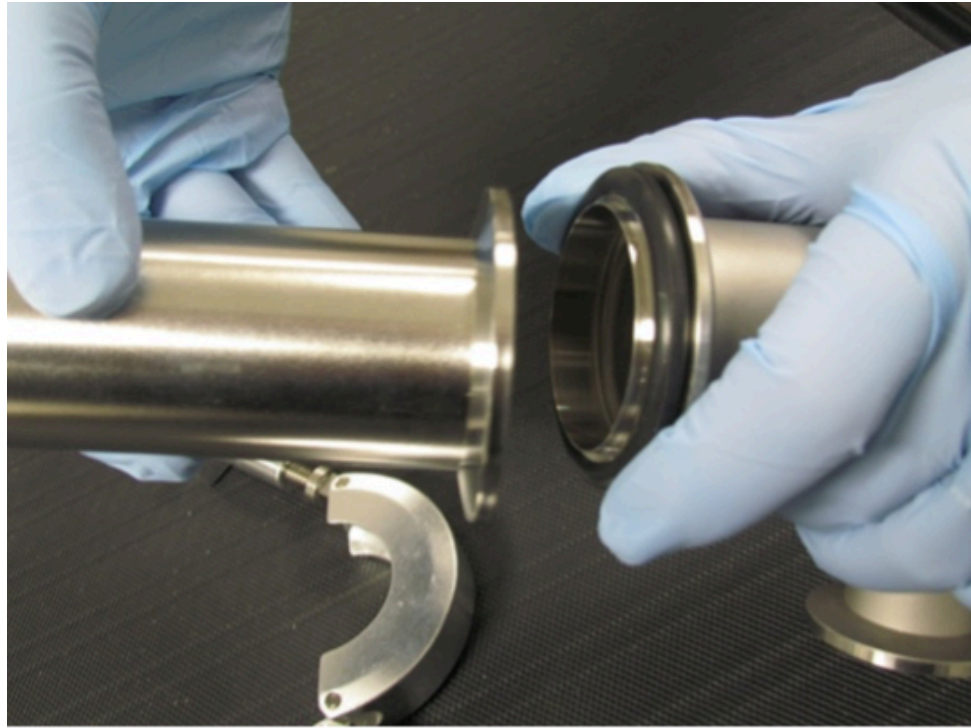
Start with two vacuum components (such as a tee and nipple), KF flange and O-ring. Wipe down the faces of the flanges and the O-ring with an isopropyl alcohol wipe.



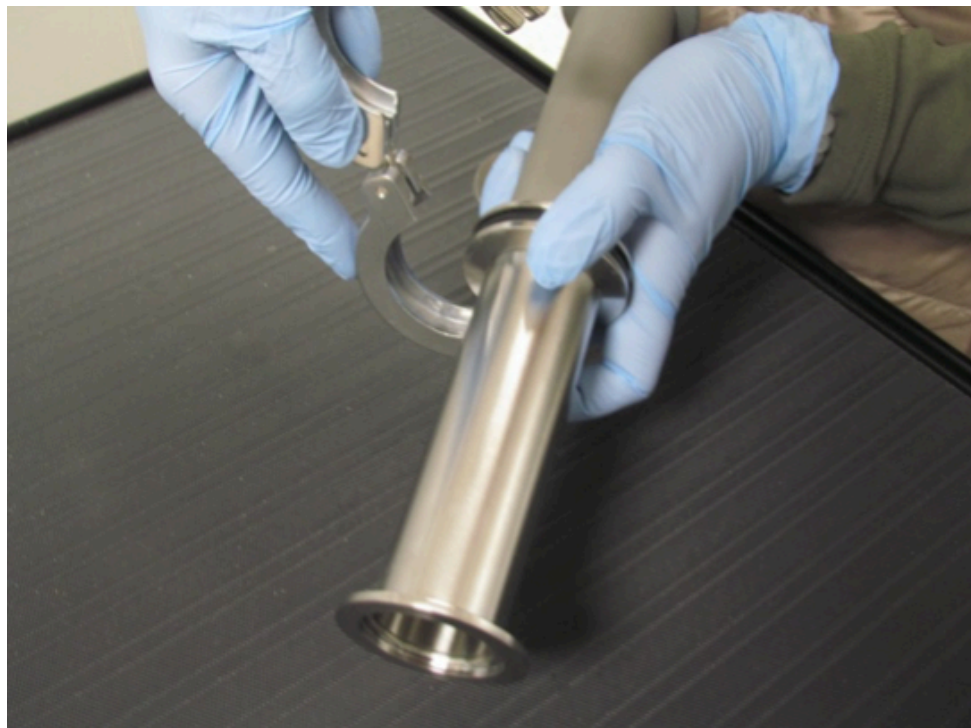
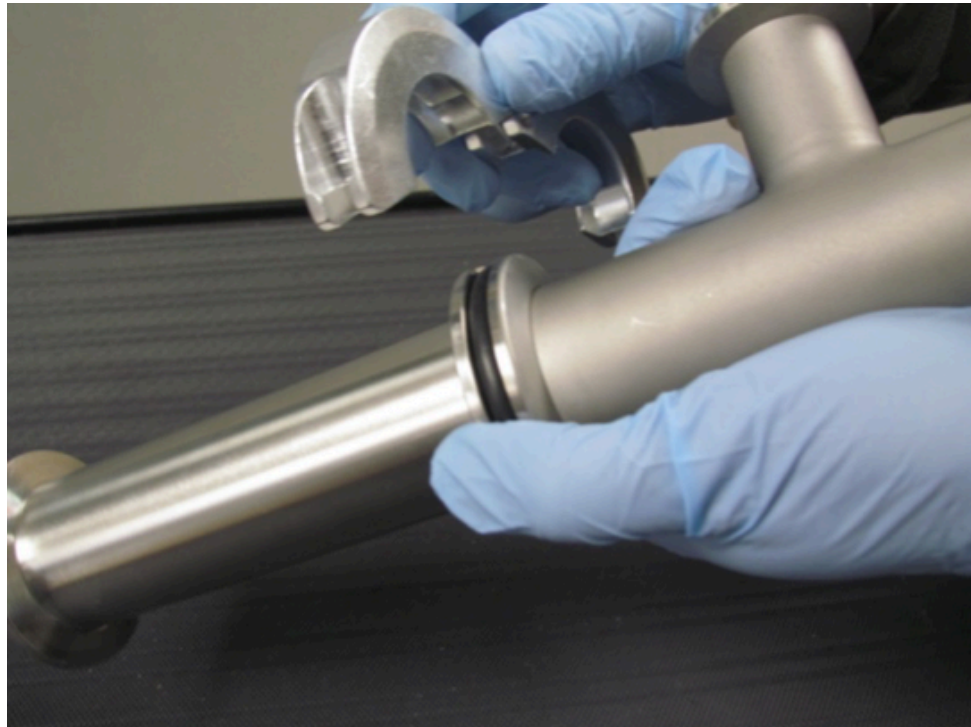
Using gloves, align the O-ring with one vacuum component and hold them with one hand:



Use your other hand to align the other vacuum component with the O-ring:



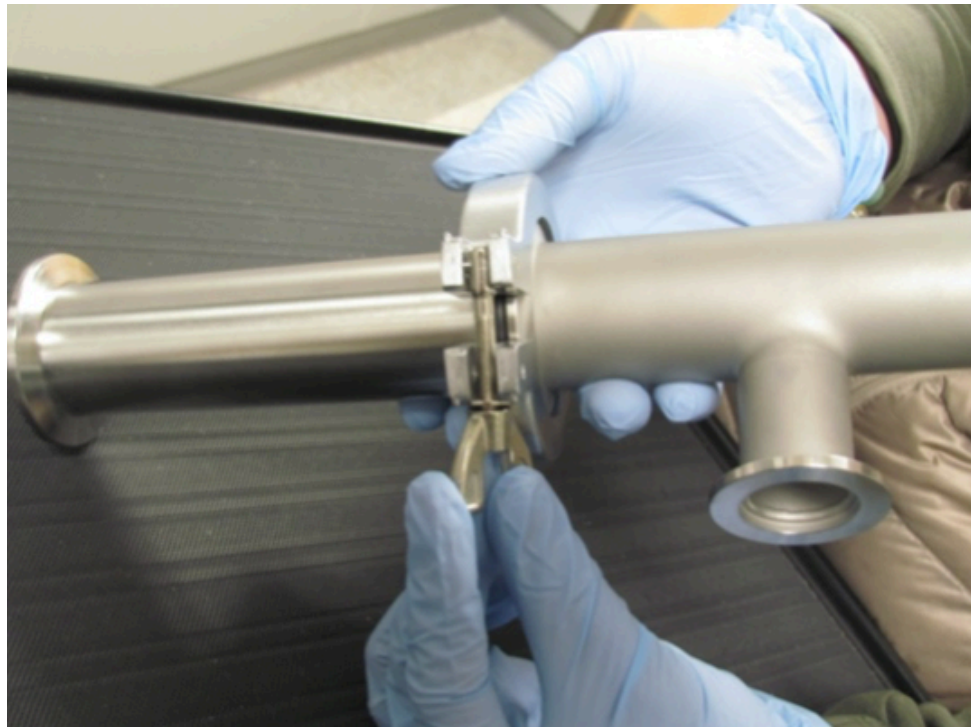
Make sure that the screw on the KF fitting is loose. With one hand hold both components aligned with the O-ring as shown in the picture and use your other hand to wrap the KF flange around the interface region.



Wrap the KF flange around the interface region and thread the bolt through the grooves:



Tighten the screw:



Now, the vacuum components are connected using a KF flange:



4. Check the ultimate pressure of the pump by connecting a pressure gauge directly to the pump and running the pump for several seconds. Compare the measured ultimate pressure to the ultimate pressure listed on the technical specifications sheet.
5. Continue this process, building the vacuum system based on the schematics provided. Start the assembly of connecting components at the pump and work towards the chamber.

Learning Activity 6.2: Pumping Down a Rough Vacuum System

6. Once, the rough vacuum system is fully assembled, close the vent valve and the roughing/isolation valve.
7. Turn on the vacuum gauge (if applicable).
8. Start the rough vacuum pump and allow it to run for several seconds to pump down the roughing line.
9. Open the roughing valve and start the timing device.

10. Run the vacuum pump until the desired pressure is reached (specified by the instructor); stop the timing device.
11. Close the roughing valve and then turn off the pump.
12. Record the pump-down time and the final pressure in Table 6.1.
13. Vent the system.
14. Repeat the pump-down procedure (Steps 7 through 12) two more times to reduce the amount of contamination present in the system. For each trial, record your data in Table 6.1.
15. Optional activity: remove one of the O-rings to demonstrate a real leak condition. Record data in Table 6.1.
16. Optional activity: add vacuum component contaminated inside (for example, a nipple contaminated with oil from food, such as pepperoni) and repeat the pump-down procedure. Record data in Table 6.1. Make sure you remove the contaminated component before the last step.
17. After the last pump-down process, pump on the empty system for several minutes to further reduce the contamination present in the system, then close the roughing valve when the system is under vacuum. Turn off the pump and the electronic pressure measurement device. Store the system under a vacuum condition.

Table 6.1. Data.

Date data collected: _____

Pump-down Trial	Final pressure after pump-ing system down	Unit of pressure	Pump-down time	Unit of time
1				
2				
3				

Pump-down Trial	Final pressure after pumping system down	Unit of pressure	Pump-down time	Unit of time
4 real leak (optional)				
5 virtual leak (optional)				

Observation Notes:

Describe how the pump-down time changed between the first, second and third pump-down trials. Why?

Analysis:

N/A

Interpretation:

How do you know if there is a gross leak present in the vacuum system?

Why were several pump-down trials required after system/components were exposed to atmospheric conditions?

What will happen if you handle an O-ring without gloves?

Why do we have to use dry, not powdered, gloves?



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Learning Activities 7.1 - 7.3: Vacuum Pump-down Curves and Vacuum Pump-down Time

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[Learning Activity 7.1: Baseline Vacuum Pump-Down Cycle](#)

[Learning Activity 7.2: Vacuum Pump-down With Dry Source of Outgassing](#)

[Learning Activity 7.3: Vacuum Pump-down With Water Vapor as a Source of Outgassing](#)

Summary of Learning Activities

- Obtaining pressure vs time pump-down curves during rough vacuum system operation.
- Determining a rough vacuum system's pump-down time from its pump-down curve.
- Obtaining pressure vs time pump-down curves during rough vacuum system operation when an outgassing source is present.
- Identifying differences in the system's pump-down behaviors by comparing the plots of pump-down curves.

Student Learning Objectives

1. Perform a rough vacuum system sequence of operations for pump-down and venting cycles.
2. Collect pressure measurement data at prescribed time intervals over a specified period of time.
3. Create pump-down curves using pressure vs time measurement data.
4. Determine the vacuum system's pump-down time from the pump-down curve.
5. Identify changes in the pump-down curve due to the presence of an outgassing source.
6. Identify changes in the pump-down time due to the presence of an outgassing source.

Suggested Pre-lab Assignment

1. Predict the pump-down time and the shape of the pump-down curve for the system assuming no outgassing sources are present.
2. Predict how the pump-down curve, envisioned in Question 1, will change with the addition of a ½" x ½" piece of dry paper towel as an added outgassing source in the chamber.
3. Predict how the pumpdown curve, envisioned in Question 2, will change with a small amount of water added to the piece of paper towel in Question 2.

Theoretical Background

As a rough vacuum pump removes gas from the chamber, the chamber pressure drops non-linearly as shown in the Figure 7.1 below. According to Boyle's law, the pressure in the chamber after each stroke/cycle of the rough vacuum pump can be calculated as:

$$P_{after\ 1\ stroke} = P_{initial} \frac{V_{initial}}{V_{after\ 1\ stroke}}$$

where

$P_{initial}$ = pressure before stroke,

$V_{initial}$ = volume of the process chamber, and

$V_{after\ 1\ stroke}$ = volume of the process chamber + vacuum pump's expansion volume.

The volume after 1 stroke is larger than the initial volume because the gas in the process chamber expands to occupy the volume of the process chamber plus the volume of the vacuum pump's expansion volume. As Boyle's law suggests, the gas pressure in the process chamber and throughout the expanded space decreases. At the end of the stroke, the pump isolates the expansion volume from the process chamber volume, compresses the trapped gas and exhausts it to atmosphere. However, the pressure in the chamber volume retains its lower pressure condition. At the beginning of the next stroke the initial pressure within the chamber starts from this lower pressure condition. In this way, each iteration of the pump's stroke cycle reduces the gas pressure within the process chamber.

Each consecutive pumping cycle achieves a smaller and smaller pressure reduction in the process chamber. After N strokes/cycles, this non-linear reduction in pressure over time can be estimated as:

$$P_{after\ N\ strokes} = P_{initial} \left(\frac{V_{initial}}{V_{after\ 1\ stroke}} \right)^N$$

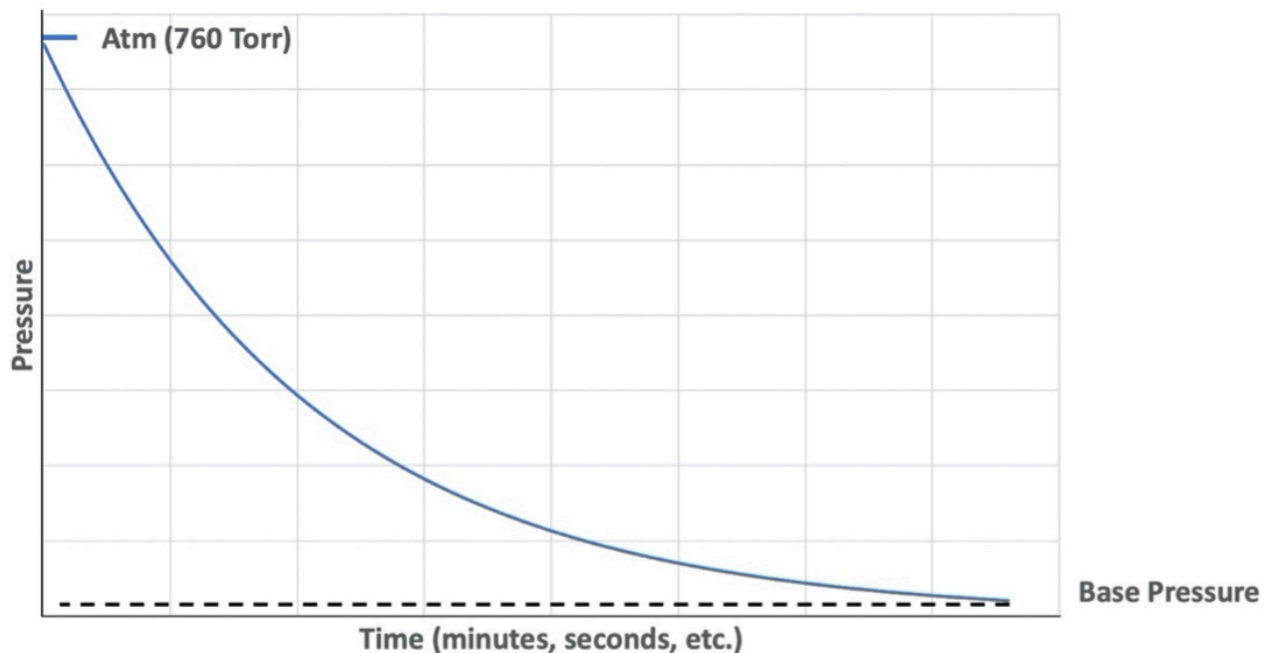


Figure 7.1. Pump-down Curve. Graph is provided by E. Brewer, SUNY Erie Community College.

When sources of outgassing are present in the vacuum system, those outgassing sources add to the gas load within the system. Since the vacuum system must also remove any gas molecules present associated with outgassing sources, the presence of outgassing sources in a vacuum system will affect the pump-down time and the shape of the pump-down curve. Generally, it takes longer to pump down to a target vacuum pressure when outgassing sources are present. If the gas load from outgassing is substantial, the vacuum system may not be able to reach the target pressure. This phenomenon can be observed on the pump-down curve as a pressure plateau that corresponds to the vapor pressure of the outgassing source. If the gas load generated from the outgassing source can be reduced by the system, the vacuum system should attain its standard operating pump-down time performance with a corresponding pump-down curve showing no indications of the outgassing source.

Equipment and Materials

1. Vacuum system consisting minimally of: (one each of the following components)
 1. Process chamber
 2. Absolute pressure measurement device(s)
 3. Vent valve
 4. Isolation/roughing valve
 5. Vacuum piping
 6. Rough vacuum pump
2. Timer
3. Barometer (not necessary if the vacuum system includes an absolute pressure measurement device with a measurement range that includes atmospheric pressure)
4. Manufacturer's specifications for the rough vacuum pump including the pump's ultimate pressure and the pumping speed chart
5. 2, $\frac{1}{2}$ " x $\frac{1}{2}$ " paper towel squares
6. Beaker
7. Water

Procedure

Learning Activity 7.1: Baseline Vacuum Pump-Down Cycle

1. Power the absolute pressure measurement gauge(s) (Pirani gauge, convection-enhanced Pirani gauge,

and/or capacitance diaphragm gauge). Allow the electronic gauge(s) to warm up.

2. Identify the ultimate pressure of the rough vacuum pump from the pump manufacturer's specifications.
3. Open the vent valve and vent the process chamber to atmosphere.
4. Identify and record current atmospheric pressure using a barometer or an absolute gauge on the vacuum system.
5. Close the vent valve and roughing valve.
6. Start the rough vacuum pump and run for few seconds.
7. Open the roughing valve and start the timer at the same time.
8. Record pressure measurements from the pressure measuring device every 5 to 10 seconds for 2 to 5 minutes in Table 7.1, until the pressure stops decreasing for more than 20 seconds or when pump's ultimate pressure is approached.
9. Close roughing valve.
10. Turn off the rough vacuum pump.

Learning Activity 7.2: Vacuum Pump-down With Dry Source of Outgassing

11. Vent the chamber. Place a $\frac{1}{2}$ ' x $\frac{1}{2}$ ' size piece of dry paper towel in a glass beaker. Place the beaker with the piece of dry paper towel in the chamber. This is a source of outgassing of air molecules that are trapped within the fabric of the paper towel.
12. Repeat steps 4 – 10, recording data in Table 7.2.

Learning Activity 7.3: Vacuum Pump-down With Water Vapor as a Source of Outgassing

13. Vent the chamber and remove the beaker with dry paper towel.

14. Drop 2-3 drops of water on another 1/2' x 1/2' piece of paper towel.
15. Place paper towel in the chamber.
16. Repeat steps 4 – 10, recording data in Table 7.3.

Preparing vacuum system for storage

17. Open the vent valve and vent the chamber.
18. Remove the beaker with the piece of wet paper.
19. Close the chamber, close the vent valve.
20. Start the pump and run it for few seconds.
21. Open the roughing valve.
22. Pump the system down to the lowest pressure obtained during the nominal system pump down.
23. Close the roughing valve.
24. Turn off the pump and leave the system under vacuum.
25. Power off the electronic vacuum gauge(s).

Data and Observations:

Table 7.1. Data for Basic Pump-down

Date data collected: _____

Atmospheric Pressure: _____

Time (sec- onds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (sec- onds)	Pressure from absolute pressure measurement device	Unit of pressure
0						

Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure

Observation Notes:

Describe how the pump-down process with an outgassing source compares to the baseline pump-down process.

Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure

Observation Notes:

Describe how the pump-down process with a source of water vapor outgassing compares to the pump-down process with dry outgassing source.

Analysis:

What is your absolute pressure measurement device (Pirani gauge, convection-enhanced Pirani, capacitance diaphragm, or other)?

What is the highest pressure measured by the absolute pressure measurement device?

Plot pressure vs time curves on the SAME linear scale graph and clearly label each curve. How do the curves differ?

Plot pressure vs time curves on the same semi-log y-axis scale graph and clearly label each curve. How do semi-log graphs differ from linear graphs? Why do we need to use semi-log graphs?

How does the semi-log graph for the baseline pump-down process differ from curves obtained when out-gassing sources were present?

Compare semi-log graphs for curves with dry outgassing and wet outgassing sources.

Determine the pump-down times from atmosphere to 3 Torr from the pump-down curves.

How do the pump-down times compare?

Interpretation:

Why is the use of the semi-log y-axis scale important when plotting pressure data for the pump-down curve?



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Learning Activities 8.1 – 8.5: Rough Vacuum System Pump-Down Time

[**Summary of Learning Activities**](#)

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Learning Activity 8.1: Determining Volume of Rough Vacuum System**](#)

[**Learning Activity 8.2: Determining Vacuum Pump's Parameters from Pump's Specs**](#)

[**Learning Activity 8.3: Determining Conductance of Rough Vacuum System**](#)

[**Learning Activity 8.4: Estimating the Pump-Down Time**](#)

[**Learning Activity 8.5: Experimentally Verifying the Pump-Down Time**](#)

Summary of Learning Activities

- Measuring physical parameters of the vacuum system to determine the volume of gas inside the chamber and vacuum piping.
- Using technical specification sheets to identify operational information for the rough vacuum pump such as its ultimate pressure and pumping speed curves.
- Calculating pump-down time using the pump's pumping speed.
- Calculating the series conductance of the vacuum piping components.
- Determining the effective pumping speed using the pump's pumping speed and the series conductance of vacuum piping components.
- Calculating pump-down time using effective pumping speed and experimentally verifying its

accuracy.

Student Learning Objectives

1. Use a vacuum pump's technical specification sheet to identify operational parameters.
2. Measure the dimensions of a rough vacuum system.
3. Estimate/calculate pump-down time for a rough vacuum system.
4. Practice unit conversion calculations.
5. Calculate the conductance of various vacuum piping components and their effect on the system's pumping speed.
6. Verify estimated pump-down times experimentally.
7. Practice organizing data and results using a table format.

Suggested Pre-lab Assignment

1. Review Examples 4.6, 4.7, 4.10 and 4.11 in Chapter 4.
2. Calculate the Knudsen number for a system operating at 10 Torr under room temperature conditions and with an internal pipe diameter of 4.0 cm. Use Equation 8.6 in the theoretical section. Determine whether the flow is viscous or molecular.
3. Calculate the Knudsen number for a system operating at 5×10^{-5} Torr under room temperature conditions and with an internal pipe diameter of 4.0 cm. Determine whether the flow is viscous or molecular.

Theoretical Background

For pressures above 10^{-2} Torr, the volume of the chamber and the effective pumping speed are the determining factors when calculating pump-down times. If a chamber with volume V is connected directly to a pump, then the effective pumping speed S_{eff} is essentially equal to the pump's pumping speed. The ultimate pressure of the pump is specified as P_{ult} and represents the lowest pressure attainable with this pump. At time $t = 0$, the initial pressure shall be given by P_i . The pump-down time from P_i to some final pressure P_f is given by the following equation, assuming that the chamber is clean and does not have any leaks:

$$t = \frac{V}{S_{eff}} \ln \frac{P_i - P_{ult}}{P_f - P_{ult}} \quad (\text{Eq. 8.1})$$

Vacuum chambers are typically shaped as cylinder, sphere, or some combination of both. Thus, the following expressions are useful to calculate the volume of the chamber. The volume of the cylinder is calculated using Equation 8.2:

$$V = \frac{1}{4} \pi D^2 L \quad (\text{Eq. 8.2})$$

where D is the inside diameter (ID) of the cylindrical chamber, and L is its length. The same expression can be used to calculate volume of cylindrically shaped vacuum piping components.

The volume of the sphere is calculated using Equation 8.3:

$$V = \frac{4}{3} \pi \left(\frac{D}{2} \right)^3 \quad (\text{Eq. 8.3})$$

where D is the inside diameter (ID) of the sphere.

See Example 4.9 in Chapter 4 of the EBook "Introduction to Vacuum Technology" for an example addressing the detailed calculations of the pump-down time.

Equation 8.1 above assumes that the conductance of the connection between the pump and the chamber is much greater than the pumping speed of the pump. When this is not the case, then the conductances of vacuum piping components need to be calculated and used to determine the effective pumping speed.

The conductance of a straight pipe, or tube operating in the viscous flow range, is given by:

$$C_t = 180 \left(\frac{\text{liters}}{\text{cm}^3 \text{Torr sec}} \right) \frac{D^4 p_{ave}}{L} \quad (\text{Eq. 8.4})$$

where

C_t is the conductance in liters per second,

D is the inside diameter of the pipe in centimeters,

L is the length of the pipe in centimeters, and

p_{ave} is the average pressure in the pipe in torr,

$$p_{ave} = \frac{p_1 + p_2}{2}$$

with p_1 being the pressure at the start of the pipe (along the direction of flow) and p_2 being the pressure at the end of the pipe.

The conductance of the aperture, where the gas enters the pipe from the chamber, also needs to be accounted for. For viscous flow, the conductance of the aperture can be calculated using Equation 8.5:

$$C_a = 20 \left(\frac{\text{liters}}{\text{cm}^2 \text{sec}} \right) \frac{A}{1 - \delta} \quad (\text{Eq. 8.5})$$

where

C_a is the conductance of the aperture in liters per second,

A is the cross-sectional area of the aperture in cm^2 , and

δ is the ratio of the pressure in the pipe divided by the pressure in the chamber (can be neglected for viscous flow when $P_{ult} \cdot D > 5 \times 10^{-1} \text{ Torr} \cdot \text{cm}$).

To verify that the system is operating in the viscous flow regime, Knudsen number should be less than 0.01. Knudsen number is calculated as shown in Equation 8.6:

$$K_n = \frac{MFP}{D} \quad (\text{Eq. 8.6})$$

where MFP is the mean free path in units of cm and D is the inside diameter of the piping in cm. If the temperature conditions are approximately 20°C , the rule of thumb calculation for MFP can be used: $\text{MFP} = 0.005 \text{ Torr} \cdot \text{cm}/P$ where P is the pressure in Torr.

Since the conductance of the tube and conductance of the aperture act as series elements, and they are in series with the pump, then the net conductance of the piping and the aperture in series is determined by the following expression:

$$\frac{1}{C_{net}} = \frac{1}{C_t} + \frac{1}{C_a} \quad (\text{Eq. 8.7})$$

where

C_{net} is the net conductance of the tube, and

C_t and C_a are conductances of the length of the tube and the tube's aperture respectively.

And finally, the effective pumping speed of the system or speed at which gas is removed from the chamber can be calculated using Equation 8.8:

$$\frac{1}{S_{eff}} = \frac{1}{C_{net}} + \frac{1}{S_{pump}} \quad (\text{Eq. 8.8})$$

where

S_{eff} is effective pumping speed,

C_{net} is the net conductance of all tubes and aperture, and

S_{pump} is the pumping speed of the pump.

Care should be taken to express all conductances and pumping speeds in the same units of measure. The unit of measure consistent with Equation 8.4 and Equation 8.5 is liters/sec.

Note that conductances of piping, as well as pump's pumping speed, change with changing pressure. Thus, pump-down time calculations will only produce an *estimate* for the system's pump-down time.

Equipment and Materials

1. Vacuum system consisting of: (one each of the following components)

1. Process chamber
 2. Absolute pressure measurement device(s)
 3. Vent valve
 4. Isolation/roughing valve
 5. Vacuum piping
 6. Rough vacuum pump
2. Timer
 3. Pumping speed chart for the rough vacuum pump (from pump's specs)
 4. Machinist's ruler and/or tape measure
 5. Vernier calipers (recommended)

Procedure

Learning Activity 8.1: Determining Volume of Rough Vacuum System

1. Measure dimensions of all vacuum components in centimeters (chamber, piping, apertures):
 - for cylindrical components, measure length L and inside diameter D ,
 - for spherical components, measure inside diameter D ,
 - for circular aperture, measure inside diameter D .

Use vernier caliper to measure inside diameter and the length of shorter pipes. Use ruler or tape measure for the rest of the measurements.

Note: If spare components of the same inside diameter are available, use them to make measurements instead of disconnecting components of the system. If you need to disconnect the system's components, make sure that you vent the rough vacuum system first and use gloves when working with the vacuum system.

2. Record measured data in Table 8.1.
3. Calculate the inside volume of each vacuum components. You may want to assign calculations for different components to different students in each lab group to speed up the process. Work as a team!
4. Record calculated volumes in Table 8.1.

5. Calculate total volume and record in units of cm^3/sec and liters/sec in Table 8.1.

Table 8.1. Volume Measurements and Calculation Results

Date data collected: _____

Component	Length (cm)	Inside Diameter (cm)	Radius (cm)	Volume (cm^3)	Volume (liters)
Chamber – cylindrical part					
Chamber – half sphere part					
Total Volume					

Learning Activity 8.2: Determining Vacuum Pump's Parameters from Pump's Specs

6. Identify pump's ultimate pressure, P_{ult} , and record in Table 8.2. Convert P_{ult} to units of torr and record in Table 8.2.
7. Identify pump's pumping speed, S_{pump} , and record in Table 8.2. You may need to use different estimates for pumping speed in different pressure ranges if pumping speed changes substantial between initial and final pressures. See EBook Example 4.9 for more details.
8. Express pumping speed in cm^3/sec and liters/sec and record in Table 8.2.

Table 8.2. Pump's Parameters

Date data collected: _____

P_{ult} with units	
----------------------	--

P_{ult} (Torr)	
S_{pump} with units	
S_{pump} (cm^3/sec)	
S_{pump} (liters/sec)	

Learning Activity 8.3: Determining Conductance of Rough Vacuum System

9. Verify the viscous flow regime by calculating Knudsen number (Equation 8.6).
10. Measure inside diameter (in cm) and the length (in cm) of every tubing component between the chamber and the rough vacuum pump. Calculate conductance of each tubing component, $C_{t\#}$, using Equation 8.4 and record in Table 8.3. Note: Divide conductance of each piping component by 2 for each 90 degree bend.
11. Measure the inside diameter of the piping component directly attached to the chamber. Calculate conductance of aperture, C_{ap} , using Equation 8.5 and record in Table 8.3.
12. Calculate net conductance of the system, C_{net} , using Equation 8.7, and record in Table 8.3.
13. Calculate effective pumping speed of the rough vacuum, S_{eff} , using Equation 8.8, and record in Table 8.3.

Table 8.3. Conductances – Data and Calculation Results

Date data collected: _____

Component	Inside Diameter (cm)	Length (cm)	Bend (Y or N)	Conductance (liters/sec)
Piping component 1 (C_{p1})				

Component	Inside Diameter (cm)	Length (cm)	Bend (Y or N)	Conductance (liters/sec)
Piping component 2 (C_{p2})				
Piping component 3 (C_{p3})				
Aperture (C_{ap})				
Net Conductance of Piping and Aperture (C_{net})				
Effective Pumping Speed of Rough Vacuum System (S_{eff})				

Learning Activity 8.4: Estimating the Pump-Down Time

14. Measure the initial pressure of the vented chamber, P_i , using an absolute pressure vacuum gauge, and record your measurements in Table 8.4 in units of torr.
15. Record the final pressure provided by the instructor, P_f , in Table 8.4 in units of torr.
16. Copy the ultimate pressure of the pump, P_{ult} , from Table 8.2 to Table 8.4.
17. Copy the total volume from Table 8.1 to Table 8.4.
18. Copy the S_{pump} and S_{eff} values from table 8.3 to Table 8.4.
19. Use Equation 8.1 to calculate the estimated pump-down time ($t_{pump\ only}$) using only the pump's pumping speed.
20. Use Equation 8.1 and S_{eff} to calculate the estimated pump-down time ($t_{pump\ and\ piping}$).
21. Calculate percent difference between pump-down times from step 17 and step 18 and record in Table 8.4.

Table 8.4. Pump-Down Time Estimation

Date data collected: _____

P_i (Torr)	
P_f (Torr)	
P_{ult} (Torr)	
V (liters)	
S_{pump} (liters/sec)	
S_{eff} (liters/sec)	
$t_{pump\ only}$ (sec)	
$t_{pump\ and\ piping}$ (sec)	
% Difference (%)	

Learning Activity 8.5: Experimentally Verifying the Pump-Down Time

22. Attach all components that you disconnected to take measurements.
23. Close the vent valve and the roughing valve.
24. Turn on the vacuum gauge, if applicable.
25. Start the rough vacuum pump and run for few seconds.
26. Open the roughing valve and start the timer at the same time.

27. Stop the timer when chamber pressure reaches the final pressure equal to the final pressure used in your calculations. Record the timer value as t_{exp} in Table 8.5.
28. Close the roughing valve.
29. Turn off the rough vacuum pump.
30. Turn off the vacuum gauge.
31. Note: You may want to repeat the pump-down because the first pump-down process may be affected by the outgassing of adsorbed water molecules.
32. Calculate the percent different between t_{exp} and $t_{pump\ only}$ and record in Table 8.5.
33. Calculate the percent different between t_{exp} and $t_{pump\ and\ piping}$ and record in Table 8.5.

Table 8.5. Experimental Data

Date data collected: _____

t_{exp} (sec)	
% Difference between t_{exp} and $t_{pump\ only}$ (%)	
% Difference between t_{exp} and $t_{pump\ and\ piping}$ (%)	

Observation Notes:

Describe how close are calculated and experimentally measured pump-down times.

Analysis:

Based on the percent difference between (t_{exp} and $t_{pump\ only}$) and between (t_{exp} and $t_{pump\ and\ piping}$), which calculated value is the closest to the experimentally measured one? Why?

Did you overestimate or underestimate the pump-down time? Explain what could be the possible reasons for this.

What are the effects of the conductance of the piping and the conductance of the aperture on the overall net series conductance and on the pump-down time?



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Learning Activities 9.1 – 9.2: Pressure Rate-of-Rise Curves

[**Summary of Learning Activities**](#)

[**Student Learning Objectives**](#)

[**Suggested Pre-lab Assignment**](#)

[**Theoretical Background**](#)

[**Equipment and Materials**](#)

[**Learning Activity 9.1: Taking Data**](#)

[**Learning Activity 9.2: Graphing Pressure Rate-of-Rise Curves**](#)

Summary of Learning Activities

- Collecting data and plotting pressure rate-of-rise curves for rough vacuum systems without leaks or outgassing sources present.
- Collecting data and plotting pressure rate-of-rise curves for rough vacuum systems with a real leak and/or an outgassing source present.
- Differentiating between the presence of a real leak or an outgassing source based on the pressure rate-of-rise curve plot.

Student Learning Objectives

1. Practice system pump down.
2. Collect data and plot pressure rate-of-rise curves.
3. Differentiate between the presence of a real leak and a source of outgassing present in the vacuum system based on the pressure rate-of-rise curve.

Suggested Pre-lab Assignment

None.

Theoretical Background

Vacuum pump-down curves and pressure rate-of-rise curves can be used to diagnose abnormal vacuum system performance. Figure 9.1 shows how a pump-down curve with a leak differs from the original pump down curve. Depending on the size of the leak, the final pressure may or may not be reached. If the leak is small, the system may be able to reach the desired final pressure, but it will take longer. With larger leaks, the target pressure may not even be achieved. Thus, a pump-down curve can help a technician identify that the vacuum system is operating abnormally, but it may not be very useful in differentiating between a real leak, a source of outgassing, or a virtual leak.

A real leak is present when gas can travel from the outside of a vacuum system to the inside. Real leaks can occur due to a broken gasket (O-ring), an improperly installed gasket, a bent centering ring, a hole in a weld, or from a malfunctioning pump. Outgassing originates from within the system, rather than from the atmosphere. Materials with high vapor pressures, contamination, residual water vapor, or backstreaming oil can cause outgassing within the vacuum system.

A disturbance present in the vacuum system and its type can be detected by performing a pressure rate-of-rise or “up-leak” test. First, the process chamber is pumped down to the desired base pressure. Then, the chamber is isolated from the vacuum pump and monitored for a rise in pressure over a period of time. The extent to which the pressure rises determines the type of disturbance present.

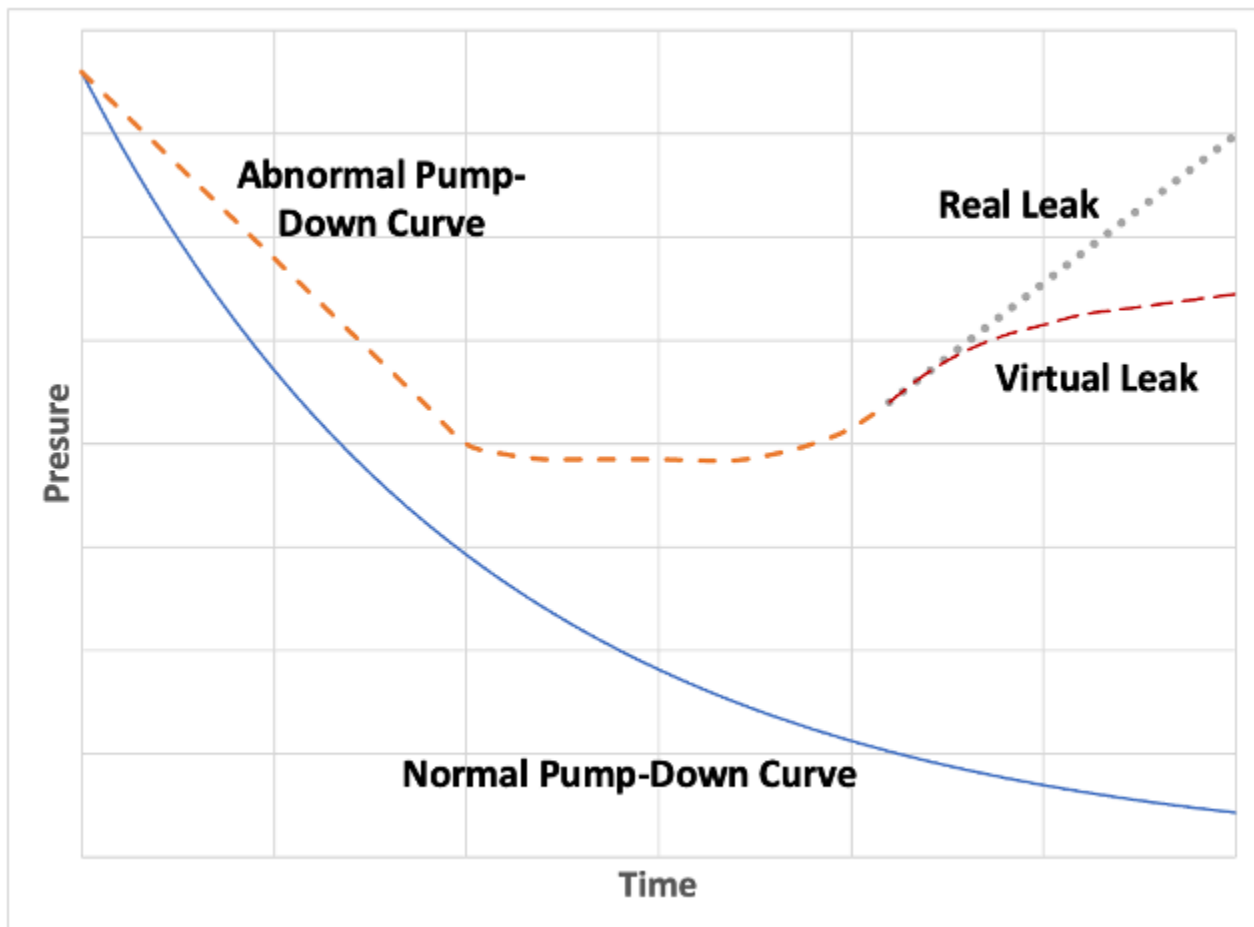


Figure 9.1. Leak detection scenarios. Figure provided by Elena Brewer, SUNY Erie Community College.

In Figure 9.1, a real leak is represented by linear rise in pressure after system is isolated from the pump. A virtual leak, on the other hand, slows down as pockets of gas, trapped in the system, are being exhausted. If there is no leak present, initially a very small increase in pressure will be detected, but it will be much smaller than in the system with real or virtual leak. The rise in the system pressure due to outgassing looks similar to the virtual leak.

Figure 9.2 show how the rate of rise of the pressure depends on the size of a real leak. The larger the leak, the steeper the slope of the plotted rate-of-rise curve.

Figure 9.3 shows a typical rate of pressure rise when outgassing is present in the system.

Figure 9.4 shows a possible rate-of-rise curve if a combination of real and virtual leaks is present.

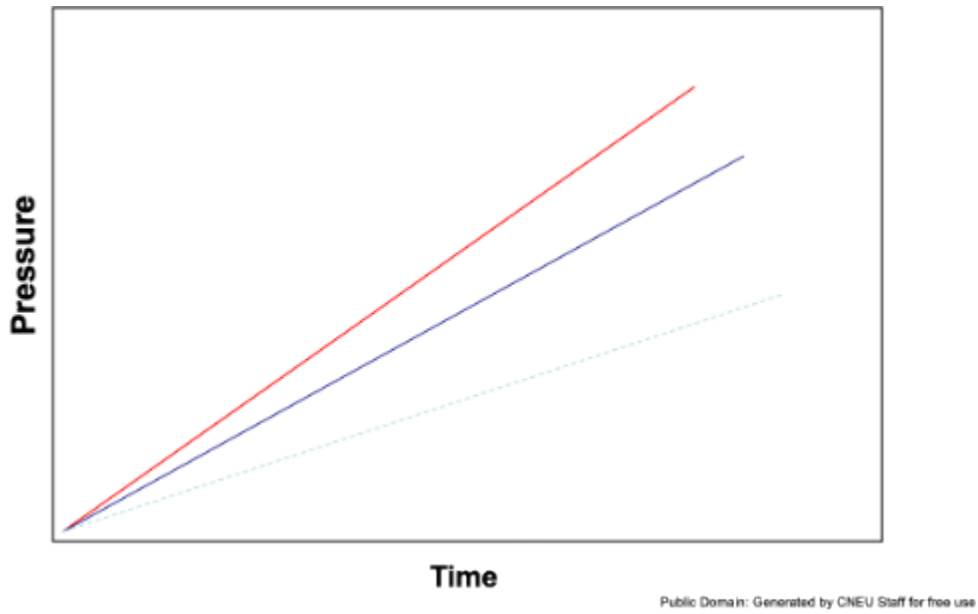


Figure 9.2. Rate-of-rise curves for real leaks. Public Domain: Generated by CNEU Staff for free use.

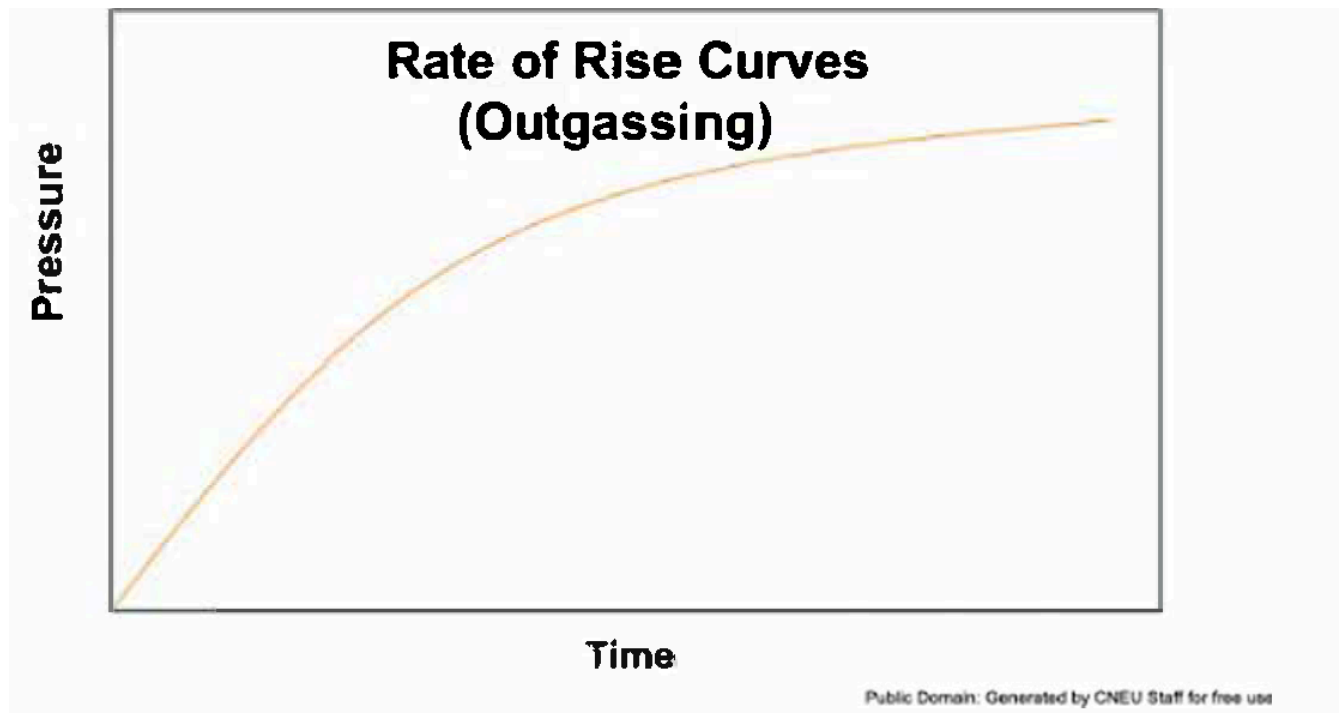
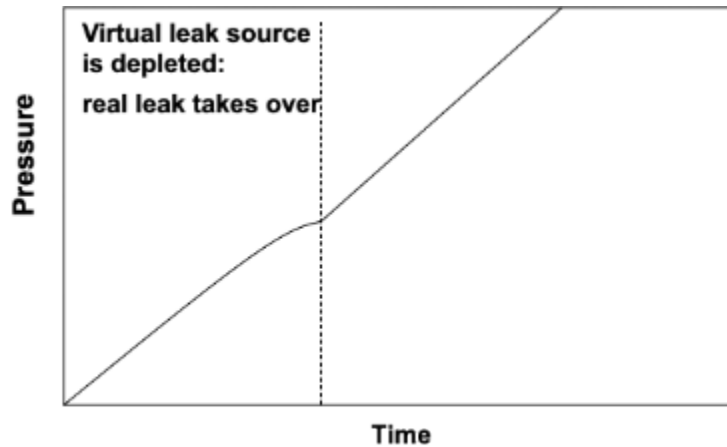


Figure 9.3. Rate-of-rise curve for a virtual leak. Public Domain: Generated by CNEU Staff for free use.

Equipment and Materials

1. Vacuum system consisting of: (one each)



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Figure 9.4. Combination of real and virtual leaks. Public Domain: Generated by CNEU Staff for free use.

- a. Process chamber
 - b. Absolute pressure measurement device
 - c. Gage pressure measurement device
 - d. Vent valve
 - e. Isolation/roughing valve
 - f. Vacuum piping
 - g. Rough vacuum pump
2. Timing device

Procedure

Learning Activity 9.1: Taking Data

1. Record the base pressure provided by the instructor.
2. Vent the chamber.
3. Pump down the rough vacuum system to the base pressure. Record the pump-down time. Note: if the base pressure state cannot be attained after a reasonable pump-down time, use the lowest pressure you can achieve.
4. Close the roughing valve and start the timer.

5. Take pressure measurements from the absolute pressure vacuum gauge every 5-10 sec for about 2-3 minutes and record them in Table 9.1.
6. Repeat steps 2 – 5 for the second rough vacuum system and record data in Table 9.2.
7. Repeat steps 2 – 5 for the third rough vacuum system and record data in Table 9.3.

Learning Activity 9.2: Graphing Pressure Rate-of-Rise Curves

8. Graph all three pressure rate-of-rise curves on the same graph using a linear scale.
9. Clearly label all three curves.
10. Based on the shape of each curve and one that achieved base pressure levels, identify which type of disturbance (if any) is present in each system.

Table 9.1. Rough Vacuum System 1

Date data recorded: _____

Base pressure: _____

Pump-down time: _____

Time (sec- onds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (sec- onds)	Pressure from absolute pressure measurement device	Unit of pressure
0						

Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure

Observation Notes:

Was the desired base pressure reached?

Table 9.3. Rough Vacuum System 3

Date data recorded: _____

Base pressure: _____

Pump-down time: _____

Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure
0						

Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure		Time (seconds)	Pressure from absolute pressure measurement device	Unit of pressure

Observation Notes:

Was the desired base pressure reached?

Analysis:

Based on the shape of pressure rise curves, which system did not contain any leaks? Why?

Rank the system performances based on the ability of the system to reach the desired base pressure.

Based on the shape of pressure rise curves, which system has a real leak? Why?

Based on the shape of pressure rise curves, which system has an outgassing source present? Why?



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

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Learning Activities 10.1 – 10.4: Thin Film Deposition Using Rough Vacuum Equipment Trainer

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Summary of Learning Activities

- Modifying a basic rough vacuum system for thin film deposition application.
- Depositing various thickness of an aluminum thin film.
- Characterizing the deposited thin film with microscope, profilometer, and/or micrometer.

Student Learning Objectives

1. Configure the rough vacuum equipment trainer as a thermal evaporator, based on schematics.
2. Practice vacuum cleanliness procedures when assembling and using the vacuum based system.
3. Perform the correct sequence of operations for thin film deposition.
4. Characterize the deposited thin film using a microscope, profilometer or micrometer.

Suggested Pre-lab Assignment

1. Calculate mean free path at the following chamber pressure levels:
a) 1 mTorr, b) 50 mTorr, c) 100 mTorr, d) 1 Torr, e) 760 Torr.
2. If the distance from the metal source to the substrate is 10 cm, what should be the maximum pressure allowing average particle to travel to the substrate without colliding with gas molecules?

Theoretical Background

The schematic of a basic rough vacuum system is shown in Figure 10.1.

A modified schematic for the conversion of the basic rough vacuum system into a thermal evaporator is shown in Figure 10.2.

A rough vacuum system ensures that thin film deposition is done in the reduced pressure environment to allow aluminum to reach the substrate (glass slide) and to reduce contamination. Ideally, the distance between the aluminum clips (or pellets) and the substrate should be smaller than mean free path where mean free path (MFP) can be calculated using Equation 10.1:

$$MFP = \frac{5 \times 10^{-3} \text{ Torr} \cdot \text{cm}}{P} \quad (\text{Eq. 10.1})$$

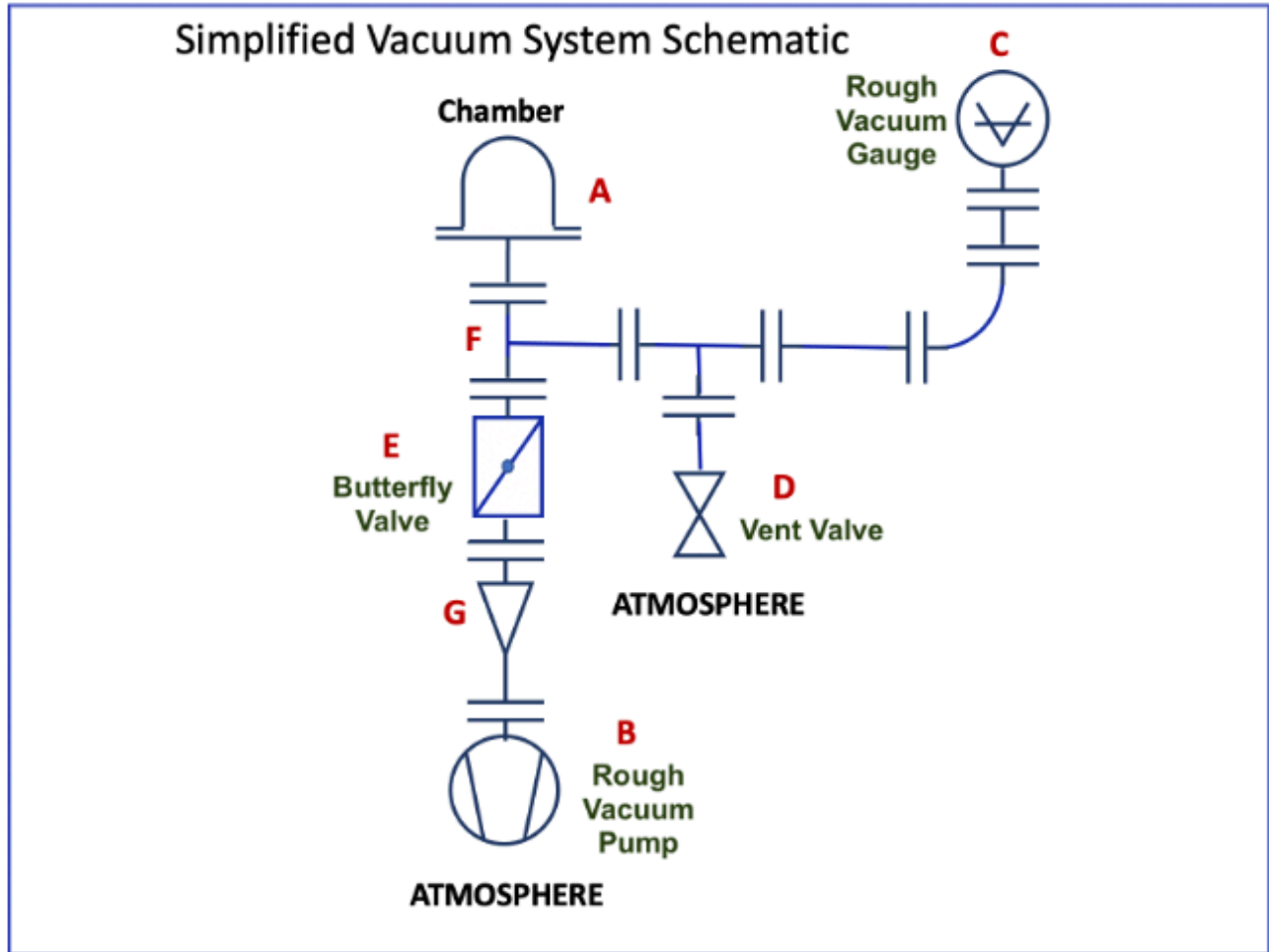


Figure 10.1. Schematic of a basic rough vacuum system. Figure is provided by E. Brewer, SUNY Erie Community College.

where P is the pressure in torr.

A variable transformer (variac) is used to adjust the voltage supplied to the fixed step-down transformer. The fixed step-down transformer decreases the voltage and increases the current supplied to the feedthrough electrodes.

Using transformer 266V6B as an example, if primary side of the transformer is rated at 117 V and 126 VA, then the current supplied to the primary side at full load is only:

$$I_{primary} = \frac{S}{V_{primary}} = \frac{126 \text{ VA}}{117 \text{ V}} = 1.08 \text{ A}$$

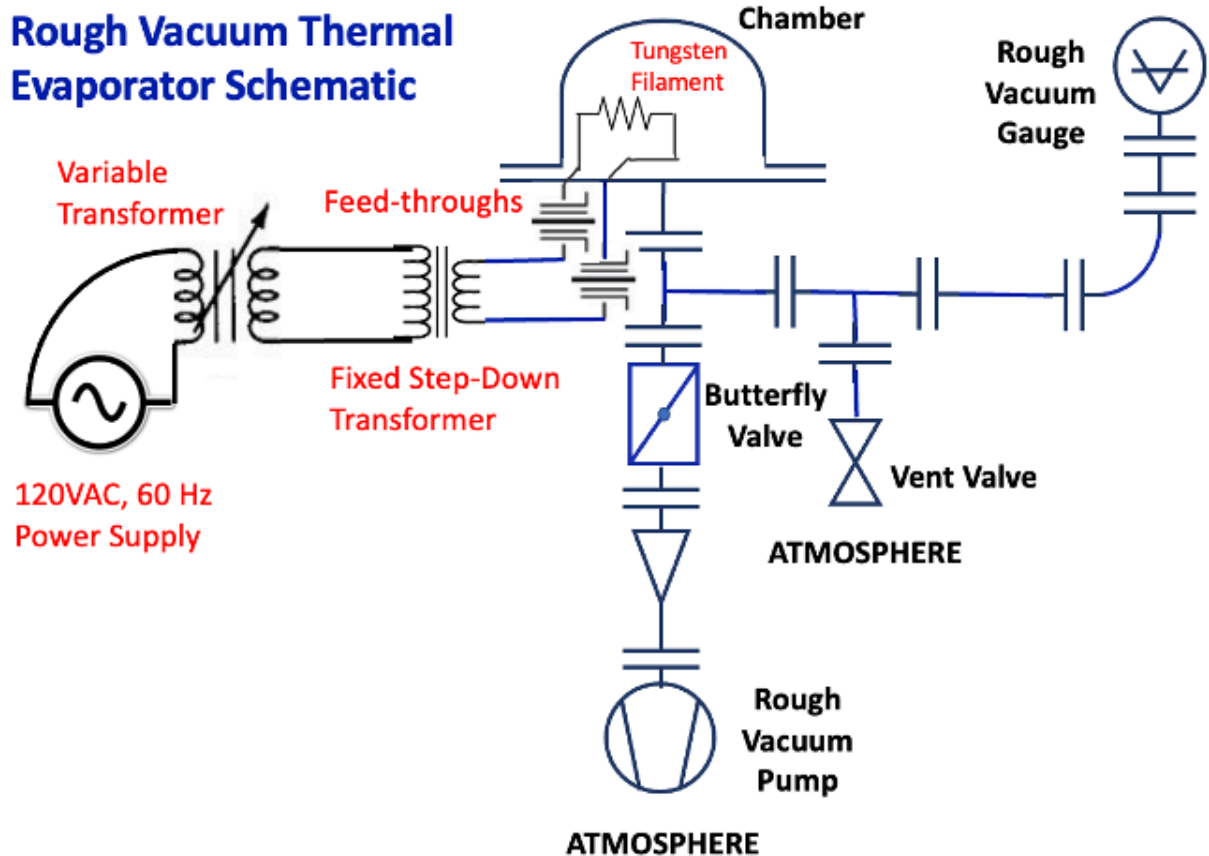


Figure 10.2. Schematic of a simple thermal evaporator. Figure is provided by E. Brewer, SUNY Erie Community College.

where I_{primary} is the current in amperes, V_{primary} is voltage in volts on the primary side of the transformer, and S is the source power in VA.

To heat and evaporate the aluminum, large currents on the order of 40-50A are required (smaller currents can be used if deposition is done at lower pressures). So, we need to increase the current on the secondary side.

For the ideal transformer, the amount of power transferred to the secondary side should be the same as the power on the primary side of the transformer:

$$I_{\text{primary}} V_{\text{primary}} = S = I_{\text{secondary}} V_{\text{secondary}}$$

If required current on the secondary side is 40A, then voltage on the secondary side should be:

$$V_{\text{secondary}} = \frac{I_{\text{primary}} V_{\text{primary}}}{I_{\text{secondary}}} = \frac{S}{I_{\text{secondary}}} = \frac{126 \text{ VA}}{40 \text{ A}} = 3.15 \text{ V}$$

The rated values for the 266V6B transformer are:

- RED-BLU: 3.15 V, 20A
- RED-YEL: 3.15 V, 20A

This means it has two secondary coils which can be connected either in series or in parallel. If the coils are connected in series, the resulting voltage and current will be 6.30V and 20A. If connected in parallel, the resulting voltage and current will be 3.15V and 40A. As 40A+ of current flows through the tungsten filament, it heats it up to the temperature sufficient to evaporate the aluminum clips placed on top of tungsten filament. Tungsten is used because its melting temperature is far above the temperature required to evaporate aluminum. However, the same amount of current will flow through the wires connecting fixed transformer to the feedthrough electrodes. Both, wires and electrodes, need to be rated for such high amount of current. For example, 8 AWG wire is required for currents between 40A and 50A. The currents on the primary side of the transformer (and the rest of the electrical circuit) are below 2A, so 16 AWG, or even 18 AWG, wires are sufficient.

Equipment and Materials

1. Rough Vacuum Equipment Trainer (RVET) with a baseplate with openings for feedthroughs
2. Two power feedthroughs rated at 50V and 400A
3. Tungsten filament with at least 4 coils
4. 1.4 KVA variable transformer (input 120V, output 0-140V)
5. 126 VA step-down transformer (primary 117V, 126VA rated; secondary 3.15V, 40A rated)
6. Clamp-on ammeter
7. Two digital multimeters (DMMs)
8. Micrometer
9. Profilometer (optional)
10. Microscope
11. 8 AWG wires for connecting to feedthrough electrodes
12. 18 AWG wires for the rest of the system
13. Glass slides
14. Timing device

Procedure

Learning Activity 10.1: Building Rough Vacuum Thermal

Evaporator

1. Connect the vacuum gauge to power. It needs 15 minutes to stabilize before accurate pressure readings can be achieved.
2. Use schematics shown in Figure 10.2 to add thermal evaporator components to the existing rough vacuum system shown in Figure 10.1
3. Connect primary side of the fixed transformer to the variable transformer output. Set dial on the variable transformer to 0. Keep the variable transformer powered down until the system is completely assembled.
4. Connect feedthroughs to the baseplate as shown in Figure 10.3. Make sure to use gloves when performing this task to reduce contamination.

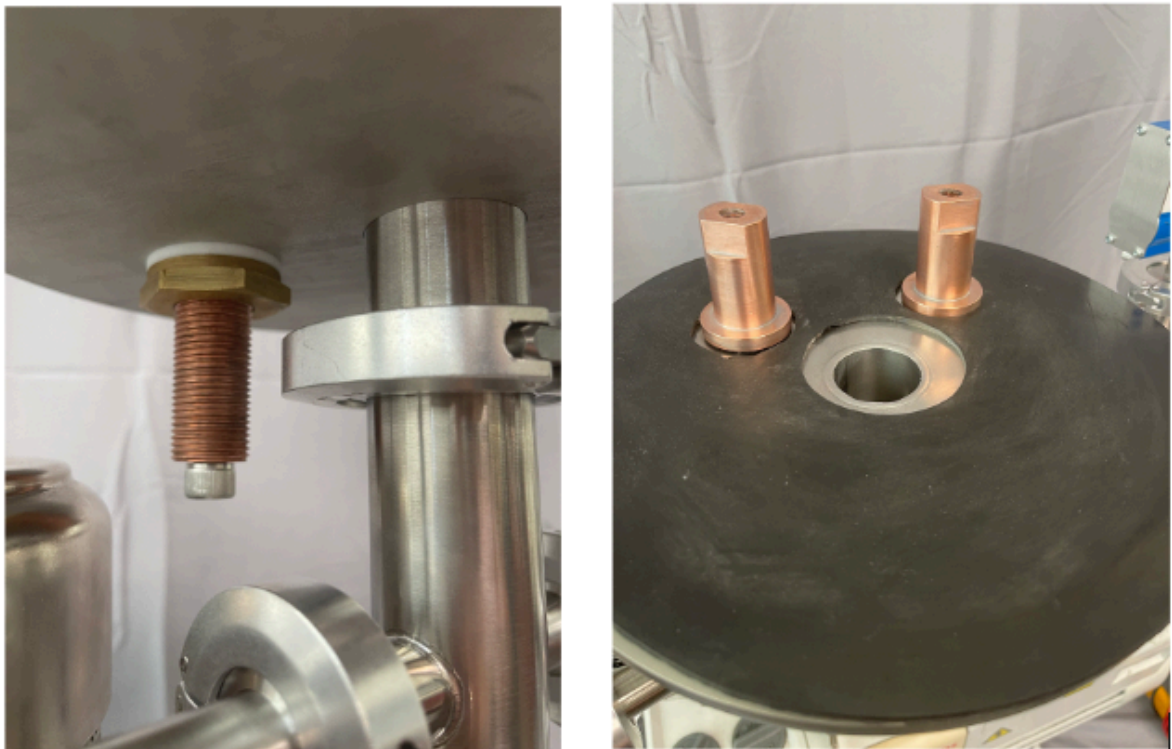


Figure 10.3. Connecting feedthroughs to the baseplate. Figure provided by E. Brewer, SUNY Erie Community College.

5. Connect both secondary coils of the fixed transformer in parallel and connect them to the bottom part of the feedthrough electrodes using the screws provided. Use screw terminals for the transformer wires. Make sure that 8 AWG wires are used to connect to feedthroughs.

6. Connect tungsten filament to the feedthroughs as shown in Figure 10.4.

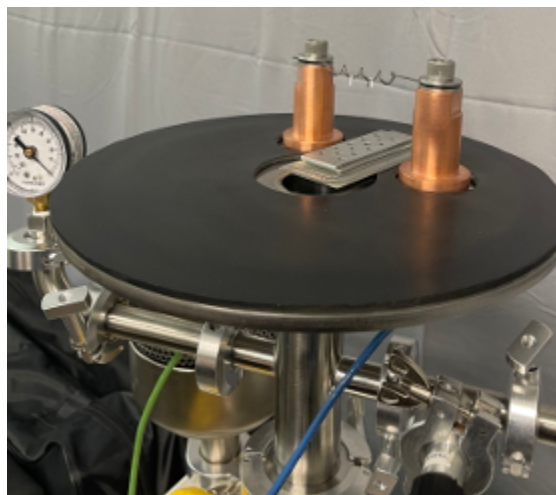


Figure 10.4. Connecting tungsten filament.
Figure provided by E. Brewer, SUNY Erie
Community College.

7. Place the clamps of the clamp-on ammeter around ONE of the wires leading to the feedthrough electrode as shown in Figure 10.5.
8. Connect DMMs to the primary and secondary sides of the fixed transformer to measure voltages V_{in} and V_{out} . Voltmeters are not shown on the circuit diagram in Figure 10.2.
9. Place glass slide with the shadow mask on top as shown in Figure 10.4 directly under the tungsten filament coil.
10. Place FOUR aluminum clips in the coils of the tungsten filament.
11. Close chamber.
12. Make sure that variac dial is set to 0 and connect it to a power source.
13. Perform one or two preliminary pump-down procedures (and venting procedures) to remove out-gassing sources from the chamber (such as contaminants on the feedthrough electrodes and water vapor molecules built up on the inside of the vacuum system while it was exposed to the atmosphere).

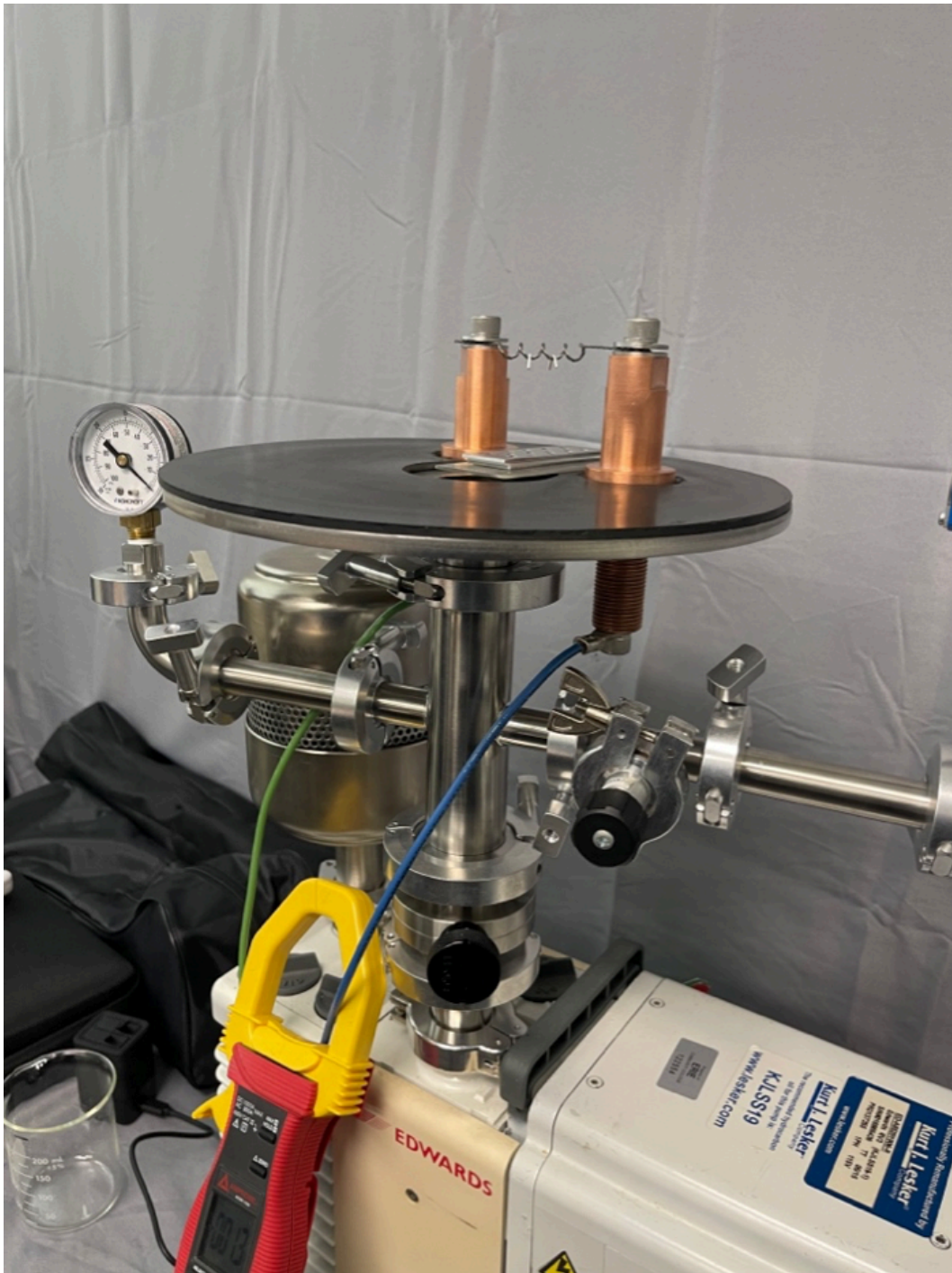


Figure 10.5. Placement of the clamp-on ammeter. Figure provided by E. Brewer, SUNY Erie Community College.

Learning Activity 10.2: Thin Film Deposition Procedure

14. Pump system down to 50 mTorr using a regular pump-down procedure.

15. Partially close the roughing valve so that pressure is maintained at roughly the same level. Keep the rough pump running. Note: if the roughing valve is completely closed, pressure will start rising. If roughing valve is completely open, the pressure will keep dropping unless the pressure is close to the pump's ultimate pressure.
16. Slowly adjust the dial on the variable transformer until the tungsten filament starts to glow. Record V_{in_glow} , V_{out_glow} , I_{glow} in Table 10.1.
17. Keep adjusting the variac dial until aluminum starts evaporating. Start the timer as soon as evaporation starts.
18. Keep the variac dial at the same level for 10-20 seconds or until no more material is being deposited on the wall of the chamber. One student should be responsible for recording deposition time in Table 10.1.
19. Another student should record values of voltages and currents during deposition in Table 10.1: $V_{in_deposition}$, $V_{out_deposition}$, $I_{deposition}$.
20. The third student should record pressure at the beginning of deposition and at the end of deposition. Then calculate and record the average pressure in Table 10.1.
21. Slowly turn the variac's dial back to 0 and turn the variac off.
22. Close the roughing valve and turn the pump off.
23. Slowly vent the chamber taking special care to not dislocate the glass slide.
24. Wait 2-3 minutes, then open the chamber and remove the sample. It is now ready to be characterized.

Table 10.1. Deposition Data.

Date data collected: _____

Trial #	1
# of aluminum clips	4

$V_{in_glow}(V)$	
$V_{out_glow}(V)$	
$I_{glow}(A)$	
$V_{in_deposition}(V)$	
$V_{out_deposition}(V)$	
$I_{deposition}(A)$	
P (mTorr)	
$T_{deposition}$ (sec)	

Learning Activity 10.3: Thin Film Characterization

25. Label the deposited circular areas as shown in the Figure 10.6. If a different shadow mask is used, the numbering will not be the same as shown in Figure 10.6. Use these number to keep track of all consecutive measurements.
26. Using a microscope in the bright-field setting and under 5X or 10X magnification, make and save images for 3 randomly selected features, for example, Features 7, 2 and 14. It is important to characterize deposited feature with a microscope first, because a profilometer and a micrometer both make destructive measurements.

What can you say about the deposition quality based on the microscope image?

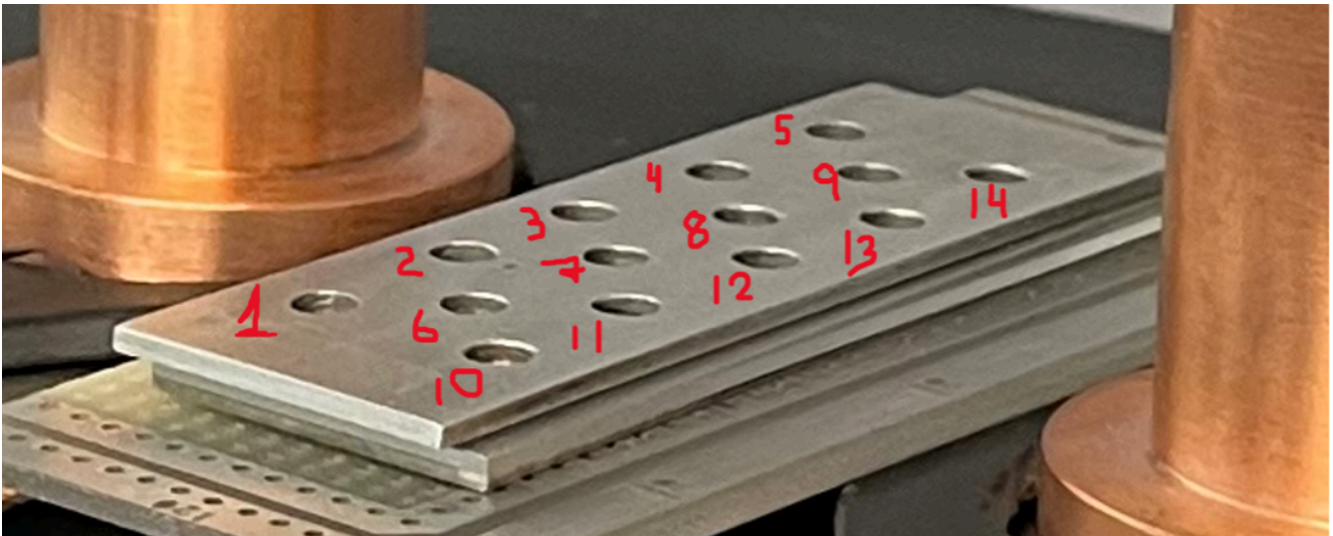


Figure 10.6. Numbering elements for the shadow mask. Figure is provided by E. Brewer, SUNY Erie Community College.

27. If microscope has dark-field capability, take images of the same 3 features in the dark-field mode.

What can you say about the uniformity of the thin film based on the dark-field images?

28. If the microscope has polarized light capability, take images of the same 3 features in polarized mode.

What can you say about the uniformity of the thin film based on the polarized light images?

29. Using profilometer, take measurements of the thicknesses of all numbered features and record them in Table 10.2. Note: Students must undergo training for the profilometer equipment prior to completing this lab.

Table 10.2. Profilometer Measurements.

Date data collected: _____

Feature #	Thin Film Thickness (μm)	Thin Film Thickness (nm)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		

Feature #	Thin Film Thickness (μm)	Thin Film Thickness (nm)
12		
13		
14		

Data Analysis:

1. Is the thickness of the thin film uniform? If not, where was more material deposited? Where was less material deposited?
 2. Based on the shape of the curve from the profilometer scans, what can you say about the smoothness of the deposited thin film?
30. Using micrometer, take measurements of the thicknesses of all numbered features and record them in Table 10.3.

Table 10.3. Micrometer Measurements.

Date data collected: _____

Feature #	Thin Film Thickness (μm)
1	

Feature #	Thin Film Thickness (μm)
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	

Data Analysis:

1. Is the thickness of the thin film uniform? If not, where was more material deposited? Where was less material deposited?
2. Compare thickness measurements obtained with profilometer and measurements obtained with micrometer.

NOTE: You will need at least 4 clips to get meaningful measurements using micrometer. The thicknesses measured are very close to the resolution limit of the micrometer, so the precision of the micrometer measurements will be low.

3. Take an image of one of the features under microscope after micrometer measurements have been taken. Discuss what changes happened to the thin film in this feature.

Learning Activity 10.4: Controlling Deposited Thickness of the Thin Film

31. Calculate average thickness of Features 7 and 8 from Table 10.2: _____
32. Divide the average thickness from the previous step by the deposition time from Table 10.1 to obtain the calculated deposition rate in micrometers per second: _____
33. Calculate the deposition time required to deposit a thin film with $2/3$ of the average thickness obtained in Step 31: _____ $2/3$ of the average thickness: _____

34. Repeat steps from learning activity 10.1 and record data in Table 10.4. Exception: use the deposition time calculated in Step 33.

Table 10.4. Deposition Data.

Date data collected: _____

Trial #	2
# of aluminum clips	4
$V_{in_glow}(V)$	
$V_{out_glow}(V)$	
$I_{glow}(A)$	
$V_{in_deposition}(V)$	
$V_{out_deposition}(V)$	
$I_{deposition}(A)$	
P (mTorr)	
$T_{deposition}(sec)$	

35. Using a profilometer (or microscope, if profilometer is not available), measure thickness of features 7 and 8, and record them in Table 10.5.

Table 10.5. Thickness Data.

Date data collected: _____

Feature #	Thin Film Thickness (μm)	Thin Film Thickness (nm)
7		
8		

Calculate average thickness: _____

36. Compare average thickness obtained in Step 35 to the 2/3 of average thickness obtained in Step 33 by calculating % difference: _____

Discuss the results:

37. Repeat Learning Activity 10.1 with different numbers of clips (2, 6, other) and record your data in Tables 10.6.A, 10.6.B, 10.6.C. Do measurements only for Features 7 and 8.

Table 10.6.A. Deposition Data.

Date data collected: _____

Trial #	3
# of aluminum clips	
$V_{\text{in_glow}}(\text{V})$	
$V_{\text{out_glow}}(\text{V})$	

$I_{\text{glow}}(\text{A})$	
$V_{\text{in_deposition}}(\text{V})$	
$V_{\text{out_deposition}}(\text{V})$	
$I_{\text{deposition}}(\text{A})$	
P (mTorr)	
$T_{\text{deposition}}(\text{sec})$	
Feature 7 thickness (μm)	
Feature 8 thickness (μm)	
Average thickness (μm)	

Table 10.6.B. Deposition Data.

Date data collected: _____

Trial #	4
# of aluminum clips	
$V_{\text{in_glow}}(\text{V})$	
$V_{\text{out_glow}}(\text{V})$	

$I_{\text{glow}}(\text{A})$	
$V_{\text{in_deposition}}(\text{V})$	
$V_{\text{out_deposition}}(\text{V})$	
$I_{\text{deposition}}(\text{A})$	
P (m Torr)	
$T_{\text{deposition}}(\text{sec})$	
Feature 7 thickness (μm)	
Feature 8 thickness (μm)	
Average thickness (μm)	

Table 10.6.C. Deposition Data.

Date data collected: _____

Trial #	5
# of aluminum clips	
$V_{\text{in_glow}}(\text{V})$	
$V_{\text{out_glow}}(\text{V})$	

$I_{\text{glow}}(\text{A})$	
$V_{\text{in_deposition}}(\text{V})$	
$V_{\text{out_deposition}}(\text{V})$	
$I_{\text{deposition}}(\text{A})$	
P (mTorr)	
$T_{\text{deposition}}$ (sec)	
Feature 7 thickness (μm)	
Feature 8 thickness (μm)	
Average thickness (μm)	

Discuss the results:

This work is supported by the National Science Foundation under grant numbers ATE DUE 2000454 and ATE DUE 1700630. Any opinions, findings, and conclusions or recommendations expressed in this e-book are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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