

Determination of Filament Work Function in Vacuum

by

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Objective:

The objective of this experiment is to experimentally determine the work function (ϕ) of a filament. This experiment will also demonstrate that work function is a property of the surface of the sample and has very little to do with the bulk of the sample. In this process, students will use data to determine an equation that models the relationship between temperature and resistance of a filament. Students will also construct a system for conducting research in vacuum.

A Review of Work Function and Thermionic Emission:

The energy required to remove an electron from the Fermi-level of a metal and free it from the influence of that metal is a property of the metal itself. This property is known as the metal's work function (ϕ) (Oxford Paperback Reference, 1990).

Before the advent of transistors, vacuum tubes were used to amplify signals. It requires less energy to remove an electron from a vacuum tube's filament if the work function of the filament is low. As current flows through a circuit of two dissimilar metals heat is absorbed at one junction and given up at the other. It has recently been discovered that if the metals used have low work functions this process (known as the Peltier Effect) can occur at an efficiency of 70-80%. This process shows promise for uses ranging from cooling electronics to more industrial cooling processes. How well electrons can be removed from a heated filament depends on that filaments work function. Electrons that are removed from a heated filament can bombard gas particles in a vacuum. The gas particles become ions as a result of this collision and are pulled to a biased plate. The resulting flow of electrons can be calibrated to determine the level of vacuum obtained. This piece of equipment is referred to as either an ionization gauge tube, or a Bayard-Alpert gauge tube.

There are multiple methods available to remove electrons: Field emission uses strong fields to remove electrons from cold surfaces. Secondary emission is the result of high-energy electrons or ions colliding with a surface, essentially knocking electrons off of the surface. Photoelectric emission involves the use of high-energy light waves that supply energy to knock electrons from the surface of a metal. The method this experiment uses is thermionic emission. Thermionic emission occurs when a metal is heated to a point that electrons are shaken from the surface of the metal. The common factor among all methods is that energy is given to the electrons of the metal in hopes of removing them from the metal (Spangenberg, 1948).

For this experiment, a filament is heated to the extent that electrons are emitted from the surface of the sample. These electrons must have energy greater than the work function (ϕ) of the emitting surface. If the emitted electrons are not removed from the region around the emitting surface, a cloud of negatively charged electrons develops. This is referred to as a space charge (Reich, 1939). This space charge may limit the free electrons produced.

Fortunately, it is possible to reduce and perhaps eliminate the effect of space charges. A positively biased plate near the emitting surface should pull the electrons away from the surface reduce the number of electrons available to cause a space charge. This creates an emission current flow between the emitting surface and the biased plate. The emission current density was first described by Richardson and was modified by Dushman. This paper will refer to the relationship as the Richardson-Dushman equation (equation 1) (Eastman, 1941).

$$J = AT^2 e^{-\frac{\phi/k}{T}} \quad (1)$$

Where:

- J = emission, amps/cm² of hot emitting surface.
- A = a constant for metals.
- T = temperature of hot surface, in Kelvin.
- ϕ = work function, measured in electron volts or eV.
- k = Boltzmann's constant (1.371×10^{-23} Joule/Kelvin).

Current density can be determined by using a digital multimeter to record current traveling from a filament of known surface area to the bias plate. The relationship between the resistance and the temperature of tungsten can be used to determine the temperature of a tungsten filament. Rearranging the Richardson-Dushman equation for thermionic emission yields the following:

$$\log(J/T^2) = \log(A) - \frac{\phi/k}{T} \quad (2)$$

The line produced by plotting $\log(J/T^2)$ vs $1/T$ will have a slope of ϕ/k . This allows us to determine the work function of the filament.

Experimental Procedure to determine work function via thermionic emission:

The experimental set up requires a filament and bias plate to be in vacuum. This necessitates the use of electrical feedthroughs from atmosphere to vacuum. This experiment used an eight port electrical feedthrough. This allows for the connections necessary plus additional electrical ports in the event a thermocouple is used to determine temperature. The filament assembly is a 0.0127 cm diameter thoriated-tungsten wire spot welded to a tungsten filament designed for UHV gauges. The filament assembly is then screwed to two electrical feedthroughs (one positive electrical feedthrough and one negative).

A sheet of tungsten is wrapped into a cylinder approximately 7 cm tall by 2cm in diameter and spot welded together. This cylinder will be used as the bias plate. The plate will be positioned to surround the filament and will be attached to two electrical feedthroughs. One of the electrical feedthroughs will be used to positively bias the plate. The second feedthrough is used for additional physical support.

The vacuum chamber need only be large enough to contain the bias plate as the filament is situated within the plate. A three-way-cross is used as the chamber. One end of the cross is connected to the electrical feedthrough holding the filament and plate. The opposite end of the cross is closed with a viewport. The final end of the cross connects to a shut-off valve and to the vacuum pump. A complete list of equipment and suppliers along with some possible alternatives for equipment is in appendix a.

When the general assembly is complete the bias plate, filament and chamber wall are checked to ensure there are no electrical contacts between them. Once this is accomplished, the chamber is evacuated. The quality of data increases as the pressure drops. However, for this experiment, equipment limits vacuum to the order of 1×10^{-3} Torr. A DC power supply is used to pass a current between 1.0 – 2.5 amps at potentials from 5 to 11 volts through the filament. A second DC power supply is used to positively bias the plate surrounding the filament. The bias voltage for this experiment was +100 Volts. Lower voltages do not sufficiently reduce space charges while higher voltages pose too great of a hazard.

A resistor of 0.10 ohms was placed in series between the filament and the filament's DC power supply. Measuring the voltage drop across the resistor allows the experimenter to calculate the current flowing through the resistor (using Ohm's Law equation 3 below) and therefore the current flowing through the filament.

$$I_{\text{resistor}} = \frac{V_{\text{resistor}}}{R_{\text{resistor}}} \quad (3)$$

An ammeter is placed in series between the bias plate to the bias plate's DC power supply. This ammeter allows the collection of emission current data. If the two power supplies do not satisfactorily display their voltages, it may be necessary to connect a voltmeter across each power supply. The experimental set up is shown below in figure 1.

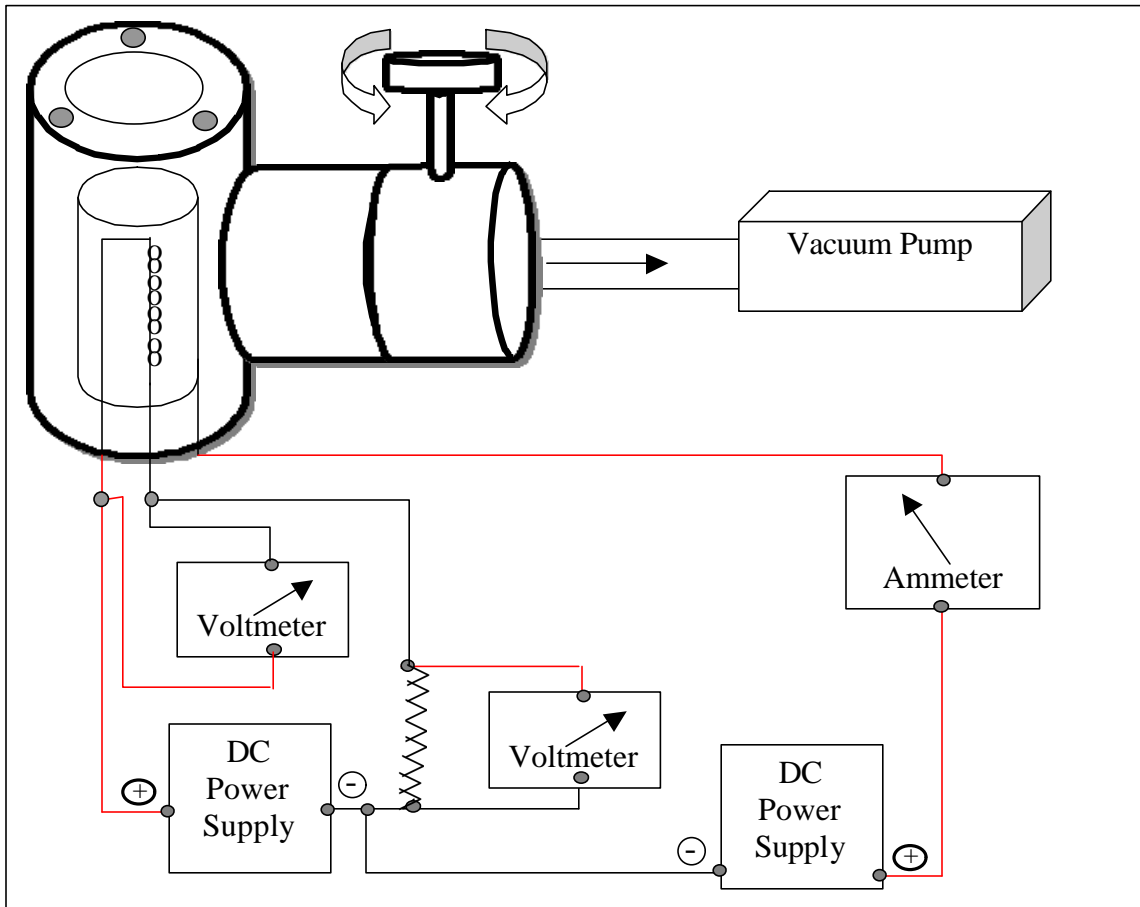


Figure 1: Diagram of Experimental Set Up

The temperature of the emitting filament must be known to use the Richardson-Dushman equation. This lab uses the resistivity (ρ) of the filament to determine the temperature. The ARIES program (ARIES online) collected data on the relationship between resistivity and the temperature of tungsten. Ohm's Law (equation 4 below) is used to determine the resistance of the filament. The voltage across the filament is known from the DC power supply. The current running through the filament was calculated by using Ohm's Law (equation 3 above). Resistivity is then calculated (equation 5 below). The ARIES data allows us to determine a general equation to determine the temperature of the filament from its resistivity (equation 6 below). During data collection, temperatures will range from 1700 K to 2300 K. Electrical resistance and resistivities are dependent on the bulk properties of the material. The filaments used in this experiment are 1% Thoriated Tungsten. It is assumed that the relationship between resistivity and temperature for tungsten will also apply for 1% thoriated tungsten.

$$R_{\text{filament}} = \frac{V_{\text{filament}}}{I_{\text{filament}}} \quad (4)$$

$$\rho_{\text{filament}} = \frac{R_{\text{filament}} A_{\text{filament}}}{L_{\text{filament}}} \quad (5)$$

$$T_{\text{filament}} = -7 \times 10^{-7} \rho^5 + 0.0002 \rho^4 - 0.0216 \rho^3 + 0.8199 \rho^2 + 24.055 \rho + 132.32 \quad (6)$$

Filaments heated to temperatures between 2100 and 2300K for 15 to 30 minutes allow the thorium present to diffuse to the surface of the filament. However, as the temperature rises the thorium will diffuse to the surface and evaporate (Spangenberg, 1948). For this experiment, the filament was first heated to a temperature of 2100 K for approximately 15 minutes.

With the bias voltage set at +100 volts, the filament voltage and current (and therefore temperature) is adjusted. At each new filament temperature the emission current is recorded. Acceptable regions of operation exist when the emission current continues to increase with increases in filament temperature. Space charges, and therefore unacceptable regions of operation, exist when increases in filament temperature result in little or no change in emission current. See figure 2 below for an example of emission current density and temperature data collected in the absence of space charges.

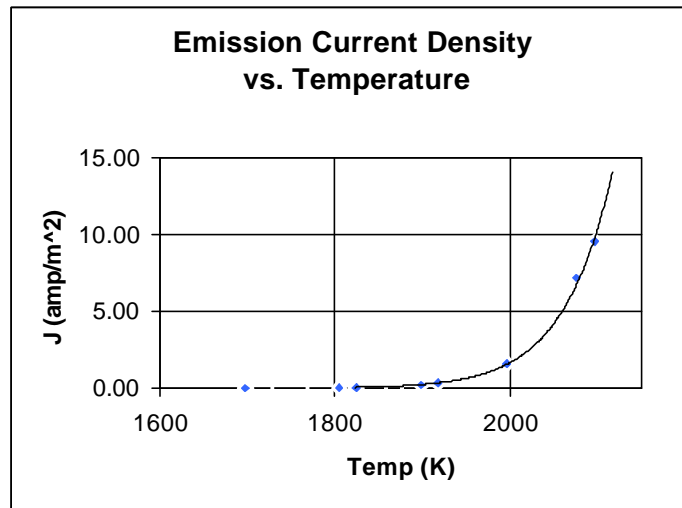


Figure 2: Typical Emission Current vs. Temperature plot when space charges are absent.

Once acceptable data has been determined, a plot is made of $\log(J/T^2)$ vs $1/T$. A trendline is drawn along the data. The slope of the trendline equals $-\phi/k$. The work function (ϕ) is then calculated by multiplying the slope by Boltzmann's constant and converted to electron-Volts by dividing by 1.6×10^{-19} (eV/J).

Experimental Results:

Once the experimental equipment was set up, several trials were run on thoriated tungsten filaments. Table 1 below shows a sample of data. Figure 3 shows that samples emission current density plotted against the temperature of the emitting surface. Figure 4 shows the plot of $\log(J/T^2)$ vs. $(1/T)$ along with the equation for a trendline run through the data.

Thoriated Tungsten 8-24-01, Run C Pressure = 22mTorr						
Area fil (m ²)	Length fil (cm)	diamter fil (cm)	radius fil (cm)	V _{bias} = +100V		
1.52E-05	3.800	0.0127	0.006			
V _{filament} (V)	I _{filament} (amp)	I _{emission} (amp)	J (amp/m ²)	R _{filament} (ohm)	r (ohm cm)	Temp (K)
3.014	1.73	6.00E-06	0.396	1.742	5.80E-05	1921.81
2.913	1.69	3.70E-06	0.244	1.724	5.74E-05	1905.30
2.904	1.69	3.60E-06	0.238	1.718	5.73E-05	1900.55
2.870	1.68	3.10E-06	0.205	1.708	5.69E-05	1891.63
2.855	1.67	2.90E-06	0.191	1.710	5.70E-05	1892.75
2.821	1.66	2.60E-06	0.172	1.699	5.66E-05	1883.67
2.752	1.64	2.00E-06	0.132	1.678	5.59E-05	1864.65
2.690	1.62	1.50E-06	0.099	1.660	5.53E-05	1849.00
2.624	1.60	1.10E-06	0.073	1.640	5.46E-05	1830.74
2.526	1.56	6.00E-07	0.040	1.619	5.40E-05	1812.23
2.494	1.55	5.00E-07	0.033	1.609	5.36E-05	1803.14
2.396	1.52	3.00E-07	0.020	1.576	5.25E-05	1773.99
2.330	1.50	2.00E-07	0.013	1.553	5.18E-05	1753.51

Table 1: Sample data collected at a pressure of 2.2×10^{-2} Torr.

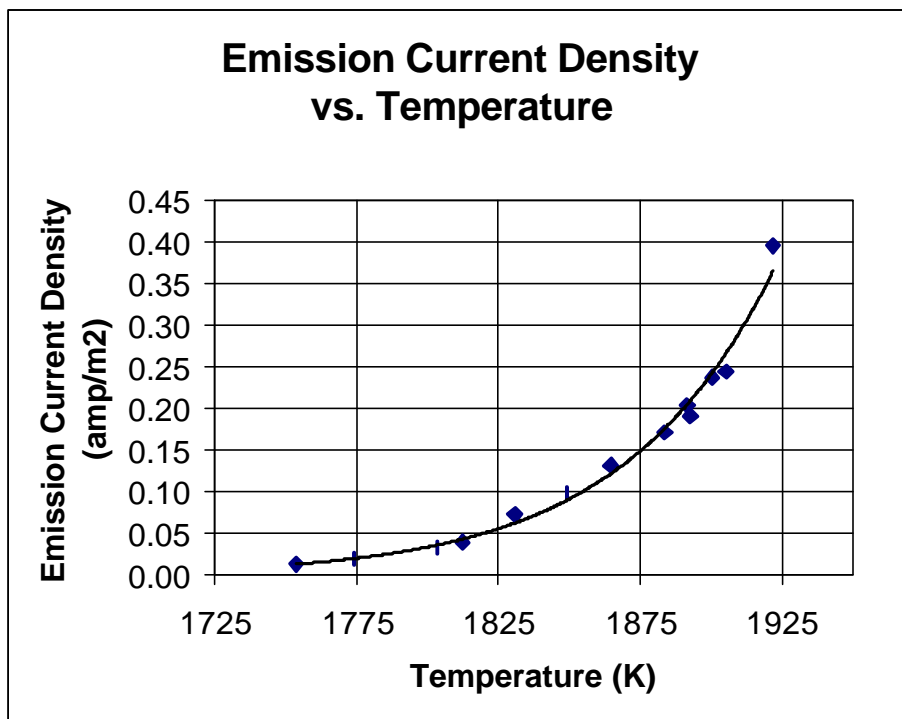


Figure 3: Emission current density vs. temperature for data in table 1.

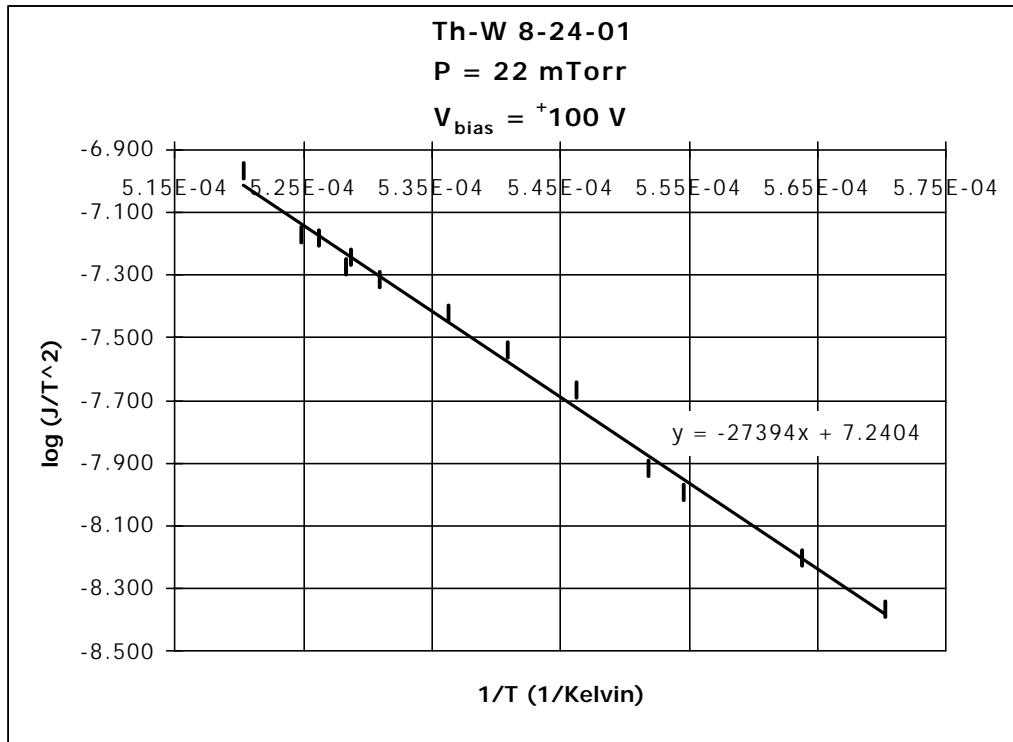


Figure 4: Final plot of table 1 sample data. Plot of $\log(J/T^2)$ vs $(1/T)$ with equation for trendline.

The slope of the trendline is $-\phi/k$. This allows us to determine the work function. Equations 7 through 13 below show a sample of determining the work function from the slope of the above trendline.

$$J = AT^2 \epsilon^{-\frac{\phi/k}{T}} \quad (7)$$

$$\log(J/T^2) = \log(A) - \frac{\phi/k}{T} \quad (8)$$

$$m_{\text{slope}} = -\phi/k \quad (9)$$

$$\phi = -m_{\text{slope}} \cdot k \quad (10)$$

$$\phi = -(27394 \text{ Kelvin}) \cdot (1.371 \times 10^{-23} \text{ Joule/Kelvin}) \quad (11)$$

$$\phi = \frac{3.756 \times 10^{-19} \text{ Joules}}{1.602 \times 10^{-19} \text{ Joules/eV}} \quad (12)$$

$$\phi_{\text{experimental}} = 2.34 \text{ eV} \quad (13)$$

Thoriated tungsten's work function data from multiple trials is stated in table 2 below. The accepted value of thoriated tungsten is 2.6 eV for a filament that has a 100% monolayer covering of thorium (Spangenberg, 1948).

Pressure (Torr)	V_{bias} (+volts)	Work Function (electron-Volts)
1.4 x 10 ⁻²	100	2.52
2.2 x 10 ⁻²	100	2.36
1.4 x 10 ⁻⁹	100	2.25
3.2 x 10 ⁻⁹	100	2.71
2.4 x 10 ⁻⁹	150	2.45
	ϕ_{average}	2.46
	ϕ_{accepted}	2.6
	Percent Error	5.38%

Table 2: Work function data for multiple trials on thoriated tungsten filaments.

The data in table 2 demonstrates a high level of agreement between the experimental values for thoriated tungsten's work function and the accepted value. While conducting this experiment there exist several potential sources of error.

Used filaments may tend to burn off oxides. These oxides may cause short. In this case, the filament and plate assembly must be removed and cleaned to ensure proper electrical contact.

Short, straight filaments produce emission currents of small magnitude. A digital multimeter with a resolution on the order of microamps is necessary. Longer filaments will increase emission currents. Filaments are typically made larger by coiling the filament so the larger length of wire fits within the same dimensions. In this lab, the longer filament length that resulted in higher emission currents required a higher bias voltage to reduce the space charges. These higher bias voltages pose serious hazards. As a result, the shorter filament lengths were tested and found to be quite suitable.

To obtain a sufficient vacuum the experimenter is encouraged to thoroughly clean all seals and components with methanol (isopropyl alcohol may damage some rubber seals). This will not only help obtain a good vacuum, this cleans the chamber and reduces the effect these particles might have on experimental data. It is possible for dirt on the inside of the chamber to result in varying wall charges which could influence the emission current (Spangenberg, 1948).

When this experiment is conducted at pressures in the milli Torr range (which is likely the lowest range possible in the educational setting) the filament may lose heat by conduction with gases in the chamber. This can be determined by calculating the average distance a gas particle travels before collision, referred to as the mean free path (equation 14 below) of the gas particles in the chamber. If the mean free path is larger than the dimensions of

the chamber it may be assumed that the particles are not significantly interacting with the filament.

$$\lambda = \frac{kT}{4\pi(2)^{1/2}r^2P} \quad (14)$$

Where:

λ = Mean Free Path (in meters)

k = Boltzman Constant (1.371×10^{-23} Joule/Kelvin)

T = Temperature (Kelvin)

R = Radius of Molecule (in meters)

P = Pressure of Gas (in Pascal or J/m^3 or N/m^2)

Before these calculations are made, we must determine some standard characteristics for this experiment. The temperature will range between 1700 K and 2300 K. For the purposes of this calculation, we will use the lower temperature range, 1700 K. To determine the radius of the molecules present, we will assume that the average molecule will fall inbetween that of a nitrogen molecule and an oxygen molecule. Using a weighted average of the two molecules (80 percent nitrogen and 20 percent oxygen to approximate the atmosphere) the average radius of a molecule present would be 1.49Å (Slye, 1999). The vacuum that is attainable in the student lab is approximately 1 Pascal. Inserting these values into equation 14 we get:

$$\lambda = \frac{(1.371 \times 10^{-23} \text{ (Joule/Kelvin)}) \cdot 1700 \text{ (Kelvin)}}{(17.77) (1.49 \times 10^{-10} \text{ m})^2 \cdot (1\text{Pa})} \quad (15)$$

$$\lambda = 5.91 \text{ cm}$$

This mean free path is on the same order of magnitude as some dimensions of the chamber (if the higher temperature range of 2300 Kelvin is used, the mean free path increases to only 8.00 cm). Because of this, the filament may lose heat by conduction with gas phase particles.

Summary:

Thermionic emission and the Richardson-Dushman equation do allow the determination of thoriated tungsten's work function when chamber pressure is in the milliTorr range and the bias voltage is set to +100 volts. The average value obtained in this experiment is $\phi_{\text{thoriated tungsten}} = 2.46 \text{ eV}$ while the accepted value is 2.6 eV (Spangenberg, 1948). There exists a 5.38% difference between the average experimental work function value and the accepted value.

This lab will be used as a possible student project to earn an honors credit for their work in the high school physics classroom. As it stands, this project will have students analyze data from other sources to determine a model for resistivity and temperature for tungsten filaments. Students will be responsible for constructing the filament assembly, the bias

plate system and maintaining the chamber. Students will be able to collect and analyze data to determine the work function of thoriated tungsten.

Additional tests may be possible. Students should be able to test a few additional filament materials such as tungsten wire (non-thoriated), Yttrium coated tungsten, and perhaps tantalum. It may be possible to place a negatively biased grid between the filament and the bias plate. This makes it possible to analyze the distribution of electron energies at varying temperatures.

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Appendices:

Equipment	Supplier	Cost	Alternative	Supplier
T(SS) for chamber	MDC	\$70.00	T – PVC	MDC *
Electrical Feedthrough	MDC	\$150.00	Sparkplugs	Automotive Store
Twin Tungsten Filament Holder	MDC	\$45.00	Nickle Wire	Alfa Aesar
Viewing Plate	MDC	\$100.00	¼inch Plexiglass	Hardware store
Shut-Off Valve	MDC	\$275.00	PVC Shut-Off Valve	Hardware Store
Titanium Sheet for Plate	Alfa Aesar	\$50.00	Copper Pipe	Hardware Store
Thoriated Tungsten Wire	Alfa Aesar	\$40.00		
3 – 4 Digital Multimeters	Omega	\$40.00 each		
Thermocouple Pressure Gauge	Duniway	\$62.00		
Thermocouple Gauge Controller	Duniway	\$210		
Variable DC power Supplies	Sargent-Welch	\$670		
Vacuum Pump	Boc Edwards	\$1200.00		

Note:

Not all of this equipment was purchased from these suppliers. Some equipment was donated from local universities and industries.

* MDC manufactures PVC tubing and fittings for use in a vacuum environment rated to 5×10^{-3} Torr. It may be tempting to check hardware stores, but the author of this paper is not aware of the safety of commonly available PVC tubing.

** As with any experiment done in vacuum, proper safety precautions should be made. Implosion will result if the chamber is not able to withstand the level of vacuum obtained. The experimenter is encouraged to use eye protection and to ensure that the chamber will be strong enough to support the desired vacuum level.