

VACUUM TECHNIQUES and THERMIONIC EMISSION

The **aims** of this project are two-fold: participants should firstly gain a good basic understanding of vacuum technology, both from a theoretical and practical point of view, and secondly, gain an understanding of the emission characteristics of a thermionic diode.

READ THIS ENTIRE HANDOUT *BEFORE* COMMENCING.

- **The lab report is an integral part of this project.** If you are unsure of the correct layout and style in which to prepare your report, refer to Kirkup, Methods of Experimental Physics. You should include enough information so readers will know exactly what you've done without having prior knowledge of the experiment. **Don't present pages of unexplained or poorly annotated graphs in your report.** If necessary attach your collection of well-described and properly annotated graphs as an Appendix.
- This manual contains a brief description of vacuum theory that includes some short calculations that *must* be completed and handed in as part of the lab report.
- The thermionic diode experiment is not difficult but can take some time and patience. You may need to repeat readings and calculate average values (including standard deviations) to present in your report. Data analysis is best done using Mathematica or Excel.

BEWARE!!

- **NEVER** assume, **ALWAYS** double check.
- You will be using high current and high voltage power supplies. Turn power supplies **OFF** before handling potentially live wiring.
- **ALWAYS** wear safety glasses when handling liquid nitrogen – it burns. Wear covered shoes for the same reason.
- **ENSURE** cooling water is running at all times when diffusion pump is hot.
- **NEVER** apply voltages greater than 200V, *under any circumstances.*
- **NEVER SWITCH OFF THE MACINTOSH COMPUTER.**

CONTACTS:

Lab. Demonstrator: David Waterhouse rm 3.55 x2745 dkw@physics.uwa.edu.au
Lab. Technician : Lance Meschmidt

VACUUM TECHNOLOGY:

A good way to learn about vacuum technology is to get your hands dirty and use it, but not before some of the fundamental physics is understood. This section will outline some of the basic rules of vacuum technology. The original notes for this experiment were prepared by A/Prof. John Robins and this version was prepared by Dr David Waterhouse at the University of Western Australia. You could check <http://www.vacgen.com/vacgen/catalogue.htm> for further information about pumps, liquid nitrogen cold traps, and pressure measurement devices. Another useful site can be found at <http://photon.physics.ucf.edu/XRAY/Courses/Phy904/Vacuum/Vacuum.htm>

REASONS FOR VACUUM:

- To increase mean-free paths to reduce scattering
- Minimise chemical attack by removing gas atoms/molecules
- Reduce contamination by reducing particle impacts and adsorption/absorption.

PRESSURE:

Defined 'ideally' as the force per unit area exerted on a surface bounding a gas by repeated collision of particles with the surface. The particles have random motion with kinetic energy related to their temperature. Other more relevant and related ideas might include (i) the number of particles per unit volume (ii) the mean free path (iii) the time to form a monolayer of particles on an existing surface.

UNITS: 760 Torr = 760mm Hg = 1 atm = 101.3 kPa.

EQUATIONS:

Gas Law: everyone should know $PV = nRT$ and its variations.

Avogadro's Number: 6.023×10^{23} particles in **1 mole** of any gas.

Loschmidt's Number: 2.637×10^{19} gas particles in 1cm^3 at 760 Torr and 273 K

STP standard temperature and pressure: 273 K and 760 Torr

Partial Pressure: pressure exerted by any one component of a mixture of gases if it were the only gas in that volume.

Mean free path: $\lambda = 1/(2^{1/2}\pi n d^2) = kT/(2^{1/2}\pi P d^2)$

where n = no. particles per unit volume, d = particle diameter, P = pressure (in Pa),
 k = Boltzmann's constant, T = temperature. For air at STP, $\lambda = 6 \times 10^{-6}$ cm.

Boundary impact frequency: $\nu = 3.5 \times 10^{22} P/(MT)^{1/2}$

where P is the pressure in Torr and M is the molecular weight of the gas.

For nitrogen at 20 °C : 760 Torr, $\nu = 3 \times 10^{23} \text{ cm}^{-2}\text{sec}^{-1}$, 10 Torr $\nu = 4 \times 10^{14} \text{ cm}^{-2}\text{sec}^{-1}$

Monolayer coverage time: $\tau_m = n_0/(\alpha \nu)$

n_0 is particles/cm² ($\approx 10^{15}$) and α is the accommodation coefficient (usually $\alpha = 1$)

For nitrogen at 20 °C: 760 Torr $\tau_m = 3 \times 10^{-9}$ sec, 10^{-6} Torr $\tau_m = 2.5$ sec

GAS FLOW: Can be expressed in a number of ways, some are more preferable than others:

Volumetric flow rate: S (litres per second) only useful if the pressure (a measure of particle density) is quoted at the same time.

Mass flow rate: (particles per second).

Throughput: Q (Torr litre per second, Torr ls⁻¹) is the mass flow rate of gas past any point in a vacuum system. At equilibrium the throughput is the same for all points in the system.

$$Q = SP + V(dP/dt) \quad \text{-- at equilibrium } dP/dt = 0$$

Example: Volumetric flow rate 1000 ls⁻¹ at pressure 10⁻³ Torr.

Throughput $Q = \text{Speed} \times \text{Pressure} = 1000 \times 10^{-3} = 1.0 \text{ Torr ls}^{-1}$

Mass flow rate = $2.6 \times 10^{19} (1000/1) (1/760) (273/293)$ particles/sec (from Loschmidt's number)
= 3.2×10^{19} particles/sec
= $(3.2 \times 10^{19} / 6.023 \times 10^{23}) 29$ grams/sec (assume molecular weight of air ≈ 29)
= $1.5 \times 10^{-3} \text{ gs}^{-1}$

TYPES OF GAS FLOW: Three flow types can be distinguished by the relative mean free path λ of particles and the transverse dimension d of the vacuum system:

Viscous flow - at moderate pressures and moderate pressure gradients, $\lambda < 0.01d$. The flow rate is proportional to the pressure gradient, viscosity, molecular weight, temperature and pressure. Collisions with other particles are more common than collisions with the chamber walls. This type of flow is common in rotary backing pumps.

Molecular flow - at high vacuum $\lambda > d/3$. The flow rate is proportional to the pressure difference across the component and the inverse of the square root of molecular weight and temperature. Collisions with the chamber walls are more common than collisions with other particles. This type of flow is common in high vacuum pumps like diffusion or turbo-molecular pumps.

Transitional (Knudsen) flow - occurs when part of the gas flow is viscous and part is molecular.

PUMPING SPEED, S.

The speed S of a vacuum pump is defined as the volumetric rate of flow into the pump (ls⁻¹) where the volume is measured at the pressure at the pump inlet (Torr).

A perfect pump could be thought of as a one-way opening of area $A \text{ cm}^2$ in the wall of a chamber, with every particle impinging on the opening passing through it and out of the chamber, but none enter or re-enter through it. The throughput would then be the rate of impact of particles on area A and is directly proportional to pressure. Of course in the real world particles re-enter the vacuum chamber via the opening and a perfect pump is hard to find.

Most of the commonly used vacuum pumps have constant pumping speeds over a large fraction of their operating pressure range. Each pump will usually have different pumping speeds (also called efficiency) for the selective pumping of different gases. Usually workers refer to rates as ls⁻¹ for vacuum pumps and lmin⁻¹ for slower rotary (or backing) pumps.

PUMP-DOWN TIME:

Consider a volume of gas in a chamber being evacuated by a pump. The pressure in the chamber falls as the pump removes particles and the rate of removal is the **throughput** of the pump. For a given volume V , how long does it take to reduce the pressure from P_0 to P with a pump of speed S ?

$$Q = d(PV)/dt = -V(dP/dt), \text{ but } Q = SP \text{ so by substitution } dP/dt = -SP/V \text{ and then } P = P_0 e^{-(S/V)t}$$

$$t = 2.3(V/S)\log(P_0/P) \text{ seconds.}$$

Clearly the pressure (and hence the pump throughput) falls exponentially with time. For constant throughput pumps the time taken to reduce the pressure to P is roughly:

$$t = [V/S_m][\log(P_0/P) - 1] \quad (\text{power series expansion of } \ln \text{ term above})$$

CONDUCTANCE:

For steady state flow conditions the throughput of gas between two points is proportional to the pressure difference between these points so:

$$Q = C(P_2 - P_1)$$

where C is the *conductance* measured in ls^{-1} and is a constant that depends upon the geometry of the system and the nature and temperature of the gas for molecular flow, and containing a pressure term if the flow is viscous. Conductance can be thought of as the vacuum equivalent of capacitance, so when calculating the overall conductance of several vacuum components:

$$\text{connected in series: } 1/C_s = 1/C_1 + 1/C_2 + 1/C_3 + \dots$$

$$\text{connected in parallel: } C_s = C_1 + C_2 + C_3 + \dots$$

CONDUCTANCE OF TUBES FOR MOLECULAR FLOW CONDITIONS

Assume a cylindrical tube with dimensions in cm, diameter D , radius R and length L :

$$\text{If } D \approx L \text{ then } C_{\text{short tube}} = 12D^3(L + 1.33D)^{-1} \text{ ls}^{-1} \text{ for air at } 20^\circ\text{C}$$

$$\text{If } D < L \text{ then } C_{\text{long tube}} = 100R^3/L \text{ ls}^{-1} \text{ for air at } 20^\circ\text{C}$$

Clearly large diameter is more important than short length. Conductance formulae for other geometries or for viscous flow conditions can be found in various vacuum text books.

EFFECTIVE PUMPING SPEEDS:

Usually a length of tube is necessary to join a pump to a chamber. The effective pumping speed S_e at the chamber will be less than the pumping speed S of the pump due to the impedance (the reciprocal of conductance) of the connecting tube.

$$\text{For the pump } Q = SP = S_e P_c \text{ and for the tube } Q = C(P_c - P), \text{ where } P_c = P_{\text{chamber}} \text{ and } P = P_{\text{pump}}$$

$$\text{Solving for } S_e \text{ gives } 1/S_e = 1/S + 1/C. \text{ which can be written } S_e = S/(1 + S/C)$$

Clearly S_e can never be greater than S or C . This observation highlights the importance of making the conductance of the connecting tube as large as possible. That is, use tubes that have the largest diameter and shortest length possible.

The effective pumping speed **never** exceeds the value of the minimum conductance (or pumping speed) of the individual parts that are stacked together.

Example: Suppose a 1500 ls^{-1} oil diffusion pump with a 300mm entrance opening is connected to a chamber via a tube 300mm long and the diameters listed below. Using the expression for conductance $C = 100R^3/L$:

$$\begin{aligned} 50 \text{ mm} : C &\approx 52 \text{ ls}^{-1} \text{ and } S_e \approx 50 \text{ ls}^{-1} && \text{BAD design!!} \\ 150 \text{ mm} : C &\approx 1400 \text{ ls}^{-1} \text{ and } S_e \approx 730 \text{ ls}^{-1} \end{aligned}$$

For a 300 mm tube we should use $C_{\text{short tube}}$ and then $C = 4600 \text{ ls}^{-1}$ and $S_e \approx 1150 \text{ ls}^{-1}$.

LOCATION OF PRESSURE GAUGE:

It is a good idea to place a vacuum pressure gauge in a position that has the most constricted access to the pump so that it measures P_c and not P .

In the example above with a 150mm diameter tube, by placing the gauge at the pump entrance the pressure measured is P , not P_c . From $Q = SP = S_e P_c$ we can write $P/P_c = S_e/S = 730/1500 \approx 1/2$. The indicated pressure is thus half the actual pressure in the chamber.

VACUUM SYSTEMS:

The ultimate or base pressure that can be attained in any vacuum system depends not only on the speed of the pump but also on the rate $L \text{ Torr ls}^{-1}$ at which gas leaks into the system. There are many ways gas can enter a system:

Real leaks are holes in the walls of the system. They may be due to poorly fitted flanges, cracked ceramic or glass on electrical feedthroughs, or may have been accidentally made during construction. The size at which a hole becomes troublesome depends upon the final pressure required. A cracked weld may be no problem at 10^{-6} Torr , but can be serious at 10^{-10} Torr .

Virtual leaks are cracks, restricted pumping tubes like teflon sleeves threaded over electrical conductors, blind holes or confined spaces that fill with gas when the system is open to atmosphere. The trapped gas can only escape slowly when the system is pumped and thus represents a gas leak, even though there is no actual hole in the chamber wall. Usually it is the result of poor design or neglect, such as welding butt joints on the outside of a flange rather than the inside.

Backstreaming from pump: If oil vapours from an oil diffusion pump diffuse back into the work chamber then the ultimate pressure is limited by the vapour pressure of the oil. As well, the oil vapour forms a troublesome and highly undesirable coating on surfaces within the chamber. Traps and baffles are usually mounted above the pumps and cooled with water or liquid nitrogen to preferentially condense the oil vapours onto them and so minimise contamination. The traps and baffles have the disadvantage that they reduce the effective pumping speed of the pump.

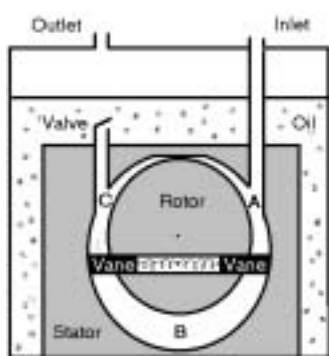
Vapour pressure of components: The ultimate pressure in a vacuum chamber is limited by the vapour pressure of materials contained within. For example, it is preferable not to use solder inside a vacuum chamber. If rubber or viton O-rings are used their vapour pressure limits the ultimate pressure to about $2 \times 10^{-8} \text{ Torr}$

Outgassing of components: Gases adsorb onto and diffuse into all materials, with the final concentration being in equilibrium with the adjacent gas pressure (eg atmosphere). When the pressure is reduced the gases desorb and diffuse back out of the materials, creating a significant 'leak' into the system. Note that some materials are for example hygroscopic and 'suck up' water vapour that then leaks slowly into the vacuum chamber. Outgassing rates are typically around 10^{-6} Torr $\text{ls}^{-1}\text{cm}^{-2}$ for polymers and plastics, and around 10^{-8} Torr $\text{ls}^{-1}\text{cm}^{-2}$ for metals. The diffusion rates can be accelerated by applying heat in a process known as baking and for metals this can reduce the outgassing rate to as low as 10^{-12} Torr $\text{ls}^{-1}\text{cm}^{-2}$. Below about 10^{-10} Torr the finger grease left on components if they are not cleaned after handling can be a serious problem.

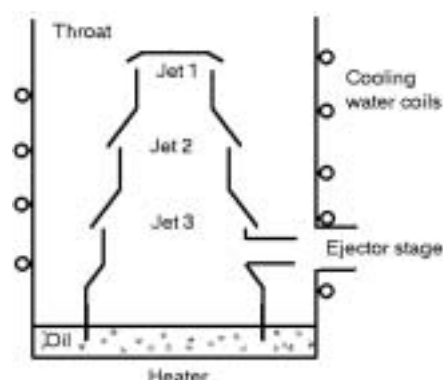
Permeation through walls: metal chambers generally have low permeability for most gases at moderate temperatures.

TYPES OF PUMPS USED IN THIS EXPERIMENT:

Two pumps are used in a standard series configuration in this experiment: A high-vacuum oil diffusion pump is pumped in turn by a small rotary or backing pump. The rotary pump pumps away all of the gas expelled by the diffusion pump and maintains the diffusion pump outlet pressure below the critical backing pressure. The rotary pump is also used to evacuate the work chamber so the initial gas load on the diffusion pump is below 10^{-2} Torr.



ROTARY PUMP



DIFFUSION PUMP

Rotary Pump: A rotor rotates on an off-centre axis, with sliding vanes maintaining contact with the inner walls of the stator to divide the space between into regions A, B and C. The whole rotor/stator assembly is immersed in oil which acts as a sealant and a lubricant. Gas enters region A via the inlet and is pushed through an intermediate stage B and is compressed into the final stage C. When the gas pressure in C is sufficiently high the valve is forced open and gas escapes.

Diffusion pump: Gas from the system enters the throat by molecular flow (usually). At each jet a stream of heavy oil molecules is directed downwards and outwards where oil vapour hits the cooler pump walls and condenses to trickle back to the boiler at the bottom of the pump. Gas molecules gain downward momentum in collisions with the oil molecules and regions of higher pressure are created in the bottom of the pump. As the oil jets can only maintain small pressure differentials a diffusion pump must have an outlet pressure below a certain value known as the critical backing pressure, of the order 0.3 Torr. Gas is usually removed from the diffusion pump by another pump (the rotary pump) mounted in series.

PRACTICAL CONSIDERATIONS:

Diffusion pumps:

- Must be hot to operate. Heating takes about 20 minutes.
- Must be cooled using chilled or tap water when operating.
- Close the gate valve above the diff. pump to enable rapid cycling of the work chamber without having to turn the diff. pump off.
- Ensure the liquid nitrogen cold trap remains cold whenever the diff. pump is turned on and the gate valve is open.
- Diff. pump oils must not be exposed to atmospheric pressure when hot as the low vapour pressure large molecules 'crack' into small higher vapour pressure components. Cleaning out cracked oil is time-consuming, dirty and expensive - the oil costs about \$1 per millilitre so *take care. If the oil burns, it's your job to clean it up.*
- A holding or ballast volume should be used in the backing line for times when the rotary pump is diverted. The volume should be large enough that the integrated throughput of the diff. pump does not raise the pressure in the ballast above the critical backing pressure of the pump.

Rotary pumps:

- Respond instantly, so be wary of oil suck-back out of the rotary pump into the diff. pump when the rotary pump is switched off.
- The rotary pump can be used to 'back' the work chamber, but if this is done then always ensure the diff. pump is isolated from the rotary pump by (i) closing the gate valve and (ii) closing the backing line valve.

VACUUM GAUGES:

There are many different types of vacuum gauge available. We use two on this experiment.

Pirani: based on the cooling of an electrically heated wire. The heating is increasingly pressure dependent below 1 Torr. The readings from this type of gauge are dependent of the type of gas in the system, but are good to about 10^{-3} Torr

Penning: a low pressure electrical discharge is enhanced by the field of an external permanent magnet. The discharge current decreases as the pressure falls and depends on the type of gas in the system. Penning gauges are useful below about 10^{-3} Torr.

A third and very common type is an **Ion gauge**. It works by using a hot filament to emit electrons which ionise surrounding gas atoms. The ionised atoms are attracted by a high potential towards a thin wire collection anode. The current collected on the anode wire is proportional to the gas pressure. These gauges are effective from 10^{-4} to lower than 10^{-12} Torr.

NOTE FOR THIS SYSTEM:

HV valve has poor seal. Do not attempt to let chamber up to atmosphere with diff. pump still operating. Close HV, let liquid nitrogen evaporate then turn off diff pump.

CALCULATION EXAMPLE:

A metal chamber contains several pieces of experimental apparatus and has a total surface area of 5000 cm^2 . If the materials have an outgassing rate of $1 \times 10^{-8} \text{ Torr ls}^{-1} \text{ cm}^{-2}$ then what effective pumping speed is required to attain a base pressure of $1 \times 10^{-6} \text{ Torr}$? If the leak rate drops to $1 \times 10^{-9} \text{ Torr ls}^{-1} \text{ cm}^{-2}$ after baking what is the ultimate base pressure using this pump?

The effective leak rate is $5000 \times 10^{-8} = 5 \times 10^{-5} \text{ Torr ls}^{-1}$.

The effective pumping speed required (from $P = L/S$) is $S = L/P = 5 \times 10^{-5} / 10^{-6} = 50 \text{ ls}^{-1}$

The ultimate base pressure with this pump is $P = 5000 \times 10^{-9} / 50 = 10^{-7} \text{ Torr}$.

QUESTIONS:

Answers to these questions must be included in your laboratory report (you must also include a suitably labelled sketch and your working):

Consider the vacuum apparatus that you are using in this lab. Estimate the inside diameters of connecting tubes and the dimensions of the work chamber. As a guide assume the wall thickness of the pipework is 2mm. The nominal pump speeds are 150 ls^{-1} the diff. pump, and 3 ls^{-1} the backing pump.

1. Calculate the *effective* pumping speed of the diffusion pump at the entrance into the large chamber. Assume that a 90° bend in a pipe is equivalent to a straight section with length equal to three times the bend radius. Also assume that the baffle above the diffusion pump acts like a short tube with diameter and length equal to $\frac{2}{3}$ the diameter of the pump throat. Include in your answer the conductance of the baffle and the conductance of the tube.
2. If the outgassing rate of material in the chamber and the chamber walls is $10^{-8} \text{ Torr ls}^{-1} \text{ cm}^{-2}$, determine the ultimate base pressure that can be maintained in the work chamber.
3. Calculate the effective pumping speed of the rotary pump at the entrance to the diffusion pump. Include in your answer the conductance of the tube, assuming that it is straight and unrestricted.
4. How long it will take to reduce the pressure in the chamber from atmosphere to 10^{-2} Torr using only the rotary pump? You will need to determine the effective pumping speed of the rotary pump at the chamber entrance.
5. How long will it take to obtain the base pressure calculated in Qu.2 using the diffusion pump, if the initial pressure is 0.01 Torr ?
6. If a typical particle within a vacuum chamber has diameter $d = 3 \text{ angstrom}$, what is the mean free path of electrons emitted from a filament at 1000K in a vacuum chamber with $P = 10^{-6} \text{ Torr}$? Is this pressure sufficiently low for this experiment?

Compare each answer (except 6) with your experimental observations – how similar are the calculated and observed values? Why might they be different?

VACUUM OPERATION:

Initial pump-down with diff pump cold and chamber at atmospheric pressure:

1. Close HV, CRV, DRV and VENT valves and switch BP on. Switch Pirani 2 on. The pressure should fall quickly to less than 0.1 Torr.
2. Open DRV to pump diff pump. When pressure reaches 0.05 Torr **turn the cooling water on** and switch on the diff pump. Leave the diff pump to heat up for about 20 minutes.
3. Fill the cold trap with liquid nitrogen and wait another 15 minutes.
4. Pump the chamber to a pressure of about 0.1 Torr or better (measured on Pirani 1) through the bypass valve by closing DRV and opening CRV.
5. Close CRV, open DRV and open HV to pump chamber via the diffusion pump.
6. Wait 5-10 mins, then switch on the Penning gauge. The pressure should go down to the lower end of the $10^{-5} - 10^{-4}$ range before you commence experiments with the filament in the chamber.

Intermediate access to the chamber:

1. Switch off the Penning gauge.
2. Close HV, turn off the diff. pump.
3. Wait about 20 mins for pump to cool.
4. Open VENT valve
5. No effect should be observed on Pirani 2. An increased reading indicates air leakage through the HV valve. If this occurs close the vent valve and if necessary follow the steps for initial pump down.

Final shut-down

The aim is to isolate the diff pump and the chamber separately, but both under vacuum.

1. Switch off the Penning gauge
2. Close HV
3. Switch off the diff pump heater. Wait 20 minutes for pump to cool.
4. Close DRV
5. Turn off pirani gauges
6. Switch off rotary pump.
7. Turn off cooling water.

THERMIONIC DIODE

A thermionic diode consists of a current-carrying emitter (cathode) and a current collector (anode). The temperature of the cathode rises by resistive heating as the driving current is increased and thermally excited electrons may gain enough energy to overcome the potential barrier (work function) W of the material and are emitted from the cathode. Varying the potential difference between the anode and cathode controls the amount of current collected on the anode, thus defining the diode characteristic of the device. In this experiment the cathode is a thin tungsten wire and we use a set of 3 cylindrical anodes threaded over the cathode. Typical characteristics of a thermionic diode are as shown in figure 1:

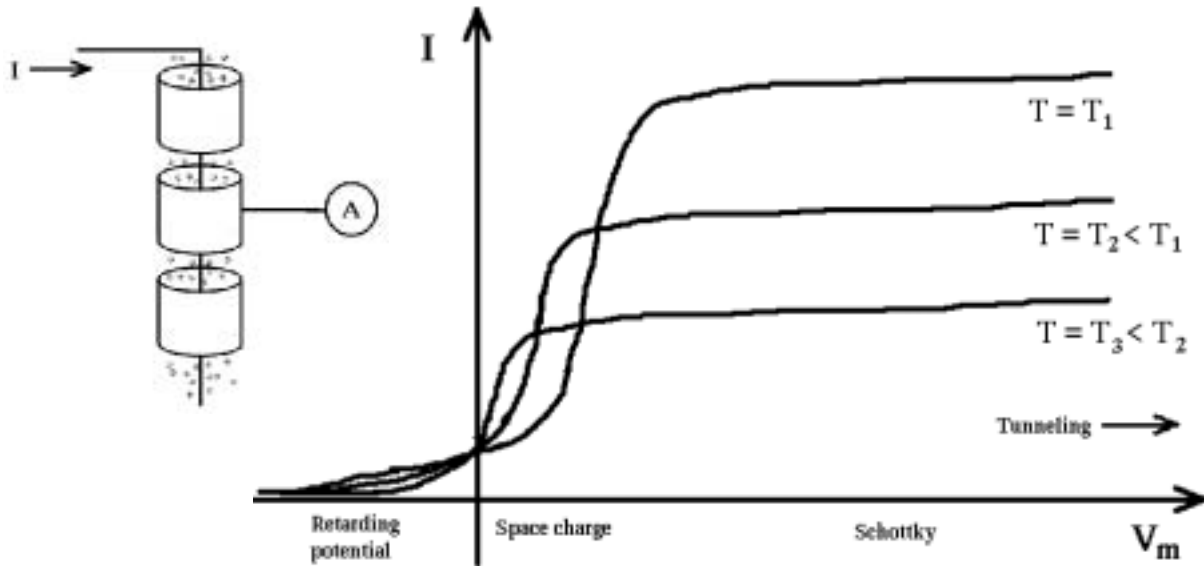


Figure 1: thermionic diode and characteristic response curves.

Why does the current collected on the anode vary this way? A good way to investigate is to consider the potential seen by each electron within the metal cathode: Figure 2 shows the simplest potential model we can use (cathode side). It assumes electrons at the Fermi level E_F only require sufficient energy E to overcome the attraction of unbalanced nuclear charges at or near the surface of the material. This energy is called the work function W of the material and $E = E_F + W$. The maximum current occurs when all available electrons are collected (we can ensure this is so by applying a large positive potential to the anode relative to the cathode).

For large enough potential the maximum current depends only upon the temperature of the material since it is thermal excitation that provides electrons with sufficient energy to overcome the work function. If this is so then the maximum current that can be collected is 'temperature limited' and is quantified using the Richardson-Dushman equation:

$$I = AT^2 \exp(-W/kT) \quad (1)$$

where W is the work function of the cathode, k is Boltzmann's constant, and $A = 4\pi me^2 k^2/h^3$ (120 Amperes/cm² K⁻²). The theoretical value of A is larger than the experimental value; the discrepancy is explained by surface reflection of electrons back into the cathode and by the presence of different crystal faces, each with its own work function. **For pure tungsten, the value of A is actually about 60.** The derivation of the Richardson-Dushman equation is given in the appendix. The R-D equation is a reasonable approximation for the maximum current that will be collected on the anode but it doesn't describe the voltage-dependent behaviour of the diode.

What if the potential applied between the cathode and the anode is removed? The measured current then is due only to electrons ejected from the cathode that have sufficient energy to overcome (i) the potential barrier at the cathode surface given by the work function W , and (ii) the potential difference between the electrodes. The latter is not zero and is not simply the measured voltage V_m which represents the energy difference between the Fermi levels of the two electrodes, because the contact potential difference (the difference in work functions) must be taken into account when the electrodes are made from different metals. This is shown graphically in figure 2:

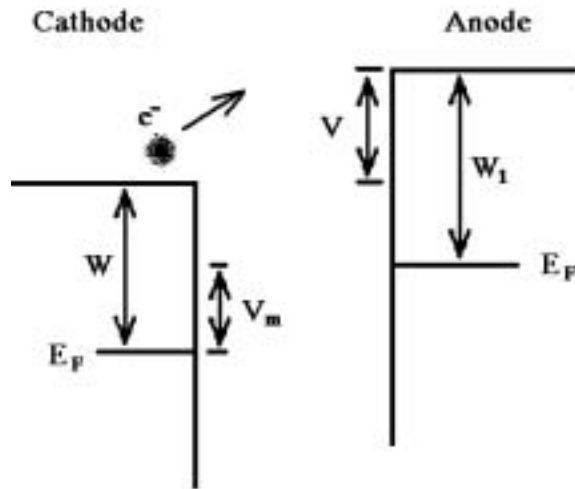


Figure 2: Energy level diagram for thermionic diode. Note that $E_{F \text{ cathode}} \neq E_{F \text{ anode}}$

The only electrons that leave the cathode and reach the anode are those with $E > E_F + W + eV$ where V is the potential difference between a point just outside the cathode and a point just outside the anode. Reference to figure 2 shows this energy E must be at least $E_F + W_1 + eV_m$ where W_1 is the work function of the anode and V_m is the difference in the Fermi levels of the electrodes as before. Thus we can write $eV = eV_m + (W_1 - W)$, and from this expression it is clear that only when the work functions are equal is V the same as V_m . Strictly speaking we should write the work functions in terms of potentials ϕ and ϕ_1 for the cathode and anode, then $(W_1 - W) = e(\phi_1 - \phi)$ where $(\phi_1 - \phi)$ is the 'contact potential difference'. This shows that even when the measured potential difference is zero there can still be a field between the electrodes and $V = \phi_1 - \phi$.

In the general case, the current to the anode is obtained using the Richardson-Dushman equation by changing W to $W + eV$ or to $eV_m + W_1$. Hence in terms of the measured potential difference V_m the current is given by

$$I_{RD} = AT^2 \exp[-(eV_m + W_1) / kT] \quad (2)$$

This expression shows a clear difference from the first version because it indicates the maximum current that can be collected on the anode depends upon the measured potential difference between the anode and the cathode.

Space Charge Effect

The expression above holds only if all electrons leaving the cathode can reach the anode. If electrons accumulate between the anode and the cathode because the potential difference slows the more energetic electrons, the negative space charge of electrons in transit between the electrodes acts like a potential barrier (see figure 3c), retarding the transmission of electrons from the cathode

to the anode. The height of the 'space charge' potential barrier increases the minimum energy necessary for electrons to escape the metal, hence effectively increasing the work function. One way to avoid space charge effects is to apply a large potential between the anode and cathode to drag electrons to the anode as quickly as they are emitted from the cathode. Another option is to increase the current flowing through the cathode, which will increase the average kinetic energy of emitted electrons so they move towards the anode more quickly. For low driving currents and low applied potentials the space charge potential barrier increases as the number of electrons in transit increases and the current collected on the anode may even decrease, becoming 'space charge limited' with

$$I \propto V^{3/2} \tag{3}$$

This is the Langmuir-Child Law or 'three-halves' power law. The effect of space-charge can be seen in the steeper sections of each curve at small voltages in figure 1. As well, figure 1 indicates that finite current will be measured on the anode with zero applied voltage. This is due to the finite kinetic energy of the electrons that have left the surface of the cathode and in part due to the contact potential difference between the anode and the cathode. It is also apparent that the collected current falls exponentially with increasing negative (retarding) potential. Unfortunately we cannot observe the negative voltage characteristics of the diode due to experimental constraints.

The Schottky Effect

It will be noticed in figure 1 that the diode characteristics up to 200 V do not level out to a perfectly horizontal 'temperature limited' plateau. This is because we have neglected the effect of the externally applied electric field at the surface of the metal. A moderate field of a few thousand volts per cm will lower the potential energy barrier seen by the electrons and so will decrease the effective work function to W_{eff} as **shown in figure 3b** below

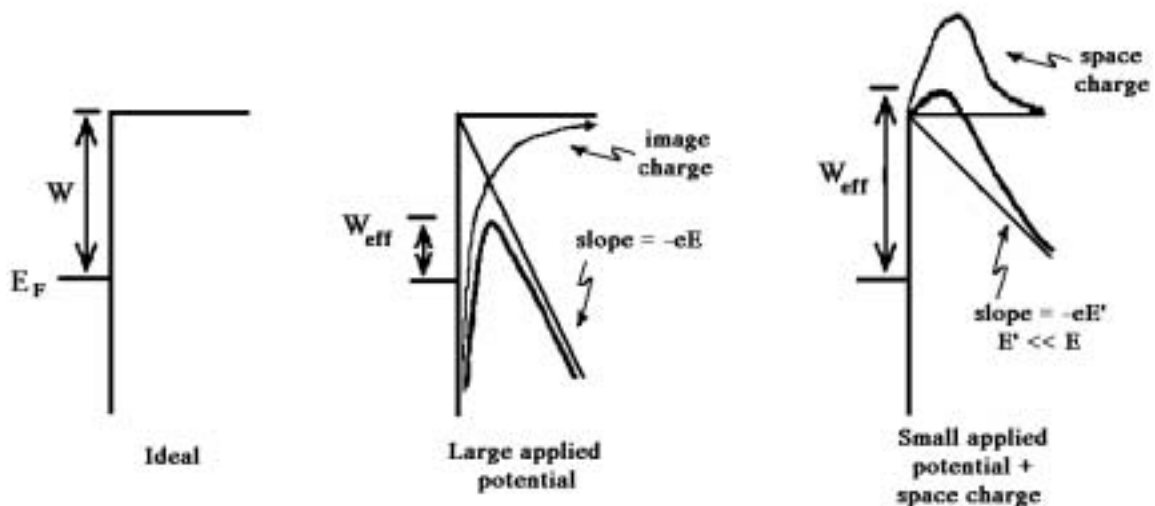


Figure 3: Effect of space charge and applied potential.

In figure 3b where the influence of large applied potential is indicated, the effect of the image charge theorem is also included. This theorem asserts that the forces on an electron above a homogeneous conducting plane (the surface of the metal) can be modelled by an equivalent positive charge on the opposite side of the plane.

Lowering the work function to W_{eff} by applying a large potential difference between the anode and cathode increases the current from the cathode. This increase is known as the **Schottky Effect**. The

magnitude of the Schottky increased current from the cathode I_S can be expressed as a fraction of the theoretical Richardson-Dushman saturation current I_{RD} by

$$I_S/I_{RD} = \exp(0.44E^{1/2}/T) \quad (4)$$

where E is the field strength in Vm^{-1} at the surface. A simplified discussion of this effect may be found in Hemenway, Henry and Caulton, "Physical Electronics", Chap. 4.

CONSIDERATIONS IN THIS EXPERIMENT

This experiment uses a thin tungsten wire as the cathode and cylindrical anodes to collect the emitted current. With a circular cross-section wire cathode the electric field strength E at the surface of the wire increases as the diameter is reduced. The Schottky effect is thus enhanced with a fine wire cathode as used in this experiment. With very strong fields of the order of 10^8Vm^{-1} , much higher than are obtainable here, the width of the potential barrier in figure 3b becomes small enough for quantum mechanical tunnelling to occur, thus causing 'high field' or 'cold cathode' emission even at room temperature. Assuming that the external field is not distorted by space charge, in a cylindrical diode with filament radius 'a' and anode radius 'b',

$$E = (V_m + \phi_1 - \phi)/[a \log (b/a)]$$

where V_m is the measured voltage between the electrodes. At large values of V the contact potential difference ($\phi_1 - \phi$) may be neglected and approximately $E = V_m / [a \log (b/a)]$, so from eqn (4);

$$\ln I_S = \ln I_{RD} + 0.44[T\sqrt{a \log b/a}]^{-1} \sqrt{V_m}$$

Thus plotting $\ln I_S$ vs $\sqrt{V_m}$ should yield straight line in the Schottky effect region, with an intercept at $V_m = 0$ equal to $\ln I_{RD}$ for the particular temperature. The temperature of the wire may be determined from the filament current and the wire diameter using the data for tungsten attached as an appendix. Note $T \approx 10^3 \text{K}$ is a ballpark figure.

YOUR TASK:

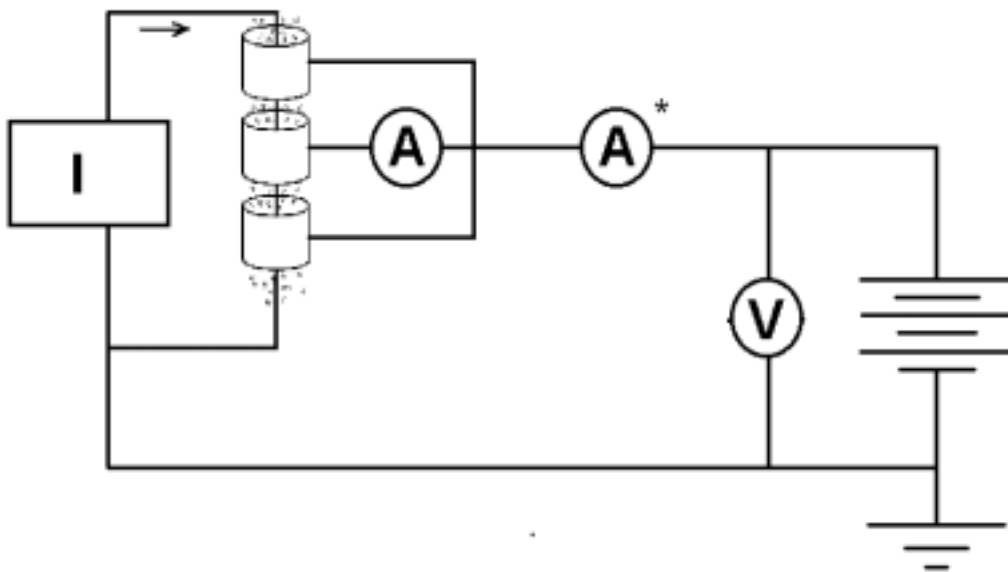
1. Build a suitable circuit to test the thermionic diode. See notes later in this handout for points to consider. **CHECK WITH YOUR SUPERVISOR BEFORE USING THE CIRCUIT.**
2. Plot I_{anode} vs V_m for at least three different I_{cathode} driving currents.
3. Points to note:
 - (a) take more readings when the slope is changing rapidly.
 - (b) allow time for the system to equilibrate before taking each reading.
 - (c) repeat readings for each driving current 3-4 times and average your data.
 - (d) **DO NOT** apply anode voltages greater than 200V
4. Test the linearity of the resulting data in the space-charge-limited region for low +ve V_m . Plotting your data as I vs $V^{3/2}$ may be helpful, and the regression coefficient of the resulting plot is a useful indicator of the validity of the Langmiur-Child Law.
5. For each data set plot $\ln I_S$ vs $\sqrt{V_m}$ and hence determine I_{RD} for each driving current I_{cathode} . Note I_{RD} should be of the order 10^{-6}A .
6. Once you have determined I_{RD} for each driving current (temperature), plot $\ln[I_{RD}/T^2]$ vs $1/T$. This should be a straight line. Determine the work function ϕ of tungsten from the slope of the line (don't forget Boltzmann's constant). **Compare with the accepted value. Discuss.**

You must include error analysis and discuss your observations in each task.

EXPERIMENTAL METHODOLOGY:

You are provided with the following equipment:

- Vacuum chamber, diffusion pump (100ls^{-1}), rotary pump (3ls^{-1}) and liquid nitrogen cold trap.
Access to cooling water for diffusion pump
Liquid nitrogen can be obtained from basement Cryogenic workshop.
Vacuum grease for rubber O-ring seal should be used sparingly.
- Thin tungsten wire to make diode filaments
- Current supply 0-3A 0-30V
- High DC voltage high current power supply 0-25mA, 0-3000V (**DO NOT** use above 200V)
- Ammeters (0 – 200 μA) and voltmeters (0 – 200 V), equipped with RS232 port
- Assorted connectors and wiring to construct circuit
- Mac computer with Igor Pro data acquisition program written by Frank van Kaan.



* = optional ammeter placement

CONNECTING THE METERS:

Each meter must be set to ALWAYS ON (shown at top right hand end of LED panel), and ensure that RS232 communication is enabled (RS232 is lit up at the left end of the LED screen). Ensure RS232 cables are securely plugged into the Mac.

QUESTIONS:

- Why is it important that the ammeter is not inserted between the voltmeter and the power supply? Hint: consider the finite resistance of the meter.
- Explain why you measure the current collected only on the central anode cylinder. What is the role of the two outer cylinders?
- Do you need to consider the finite resistance of the tungsten filament wire? Explain your reasoning. Hint: check the voltage output of the current supply.
- Why does the voltage supply need to be capable of handling large currents?

TUNGSTEN FILAMENT DATA

The data that follows is based upon (a) Emissivity, σ_T : American Inst. Physics Handbook (p.6-79)
 (b) Resistivity, ρ_T : Phys. Lab. Handbook by Angerer & Ebert.

Temp °K	σ_T	$\rho_T(\Omega.M)$	$\left(\frac{\sigma_T}{\rho_T}\right)$	$\left(\frac{\sigma_T}{\rho_T}\right)T^4$
300	.032	7.5×10^{-8}	4.27×10^5	0.346×10^{16}
400	.042	9.4	4.46	1.142
500	.053	11.6	4.57	2.856
600	.064	13.8	4.64	6.013
700	.076	16.5	4.61	11.069
800	.088	19.2	4.58	18.760
900	.101	22.3	4.53	27.721
1000	.114	25.5	4.47	44.700
1100	.128	28.5	4.49	65.738
1200	.143	31.9	4.48	92.897
1300	.158	35.2	4.49	128.239
1400	.175	38.6	4.53	174.024
1500	.192	41.8	4.59	232.369
1600	.207	45.2	4.58	300.155
1700	.222	48.5	4.58	382.526
1800	.236	51.7	4.56	478.690
1900	.249	55.1	4.52	589.051
2000	.260	58.5	4.44	710.400
2100	.270	61.7	4.38	851.827
2200	.279	65.0	4.29	1004.958
2300	.288	68.4	4.21	1178.131
2400	.296	71.7	4.13	1370.235
2500	.303	75.0	4.04	1578.125
2600	.311	78.4	3.97	1814.195
2700	.318	81.7	3.89	2067.305
2800	.323	85.0	3.80	2335.693

The electrically dissipated power = net energy loss by radiation exchange with surroundings,

$$I^2 \rho_T (l/\pi r^2) = 2\pi r \sigma_T \sigma_s (T^4 - T_0^4)$$

In the above expressions σ_s is Stefan's constant, l and r are the length and radius of the wire respectively, T is the wire temperature and T_0 is the temperature of surroundings. When $T = 800$ and $T_0 = 300$ °K, the second term in $(T^4 - T_0^4)$ is 2% of the first and for $T > 1000$ K the equilibrium equation is:

$$I^2 \rho_T = 2\pi^2 r^3 \sigma_T \sigma_s T^4$$

$$\text{or} \quad I^2 \left(\frac{\ell}{2\pi^2 r^3 \sigma_s} \right) = \left(\frac{\sigma_T}{\rho_T} \right) T^4 \quad \text{eqn A}$$

Using the above table and appropriate values for ρ and σ_s the temperature T corresponding to a given driving current I may be calculated. **The data can be approximated using a power-law fit, given by $T = 0.0346 x^{0.253}$** , where $x = (\sigma_T/\rho_T)T^4$ calculated from parameters in **eqn A**.

Rate of emission of electrons from a metal surface as a function of T

The maximum energy that electrons may have inside a metal crystal at $T = 0$ K is the Fermi energy, E_F . The least amount by which the energy of an electron must exceed E_F in order to escape from the crystal is the work function W . Thus for escape, the electron energy must be $E > E_F + W$.

Let the surface of the metal be parallel to the 0_{xy} plane of the crystal. The minimum velocity v_z of an electron that can escape from inside the crystal is $\frac{1}{2}mv_z^2 = E_F + W$. In terms of momentum this is simply written $p_z^2/2m = E_F + W$. To calculate the total number of electrons per unit area per second that will leave the metal we assume zero reflection of electrons at the surface and apply Fermi-Dirac statistics to electrons in the metal.

According to Fermi-Dirac statistics the electrons are treated as indistinguishable particles subject to Heisenberg's uncertainty principle. The latter imposes a lower limit to the dimensions of the elementary cells into which phase space may be divided: $dx dy dz p_x dp_y dp_z = d\tau = h^3$. Then taking spin into account only two electrons may occupy such a cell. Allocating electrons at random to the available cells, the equilibrium distribution at a given temperature is that which can be achieved in the greatest possible number of ways i.e. the state of maximum probability. In this state the number of electrons in the cell of volume $d\tau$ is

$$2 \frac{dt}{h^3} \left[e^{(E-E_F)/kT} + 1 \right]^{-1} \text{ where } [\quad]^{-1} \text{ is the Fermi factor}$$

Consider electrons in the momentum range $dp_x dp_y dp_z$. Assume that within the metal is a region of uniform potential so there is no field of force within the metal. The number of electrons reaching a surface element A in time dt is the number of electrons in an oblique cylinder of height $v_z dt$ and base area A . That is, $N = Av_z dt$ or in terms of momentum $N = A(p_z/m)dt$. Then the number per unit area per unit time is (p_z/m) . These electrons and this volume, together, correspond to a volume of phase space $d\tau = (p_z/m)dp_x dp_y dp_z$.

The number of electrons in this cell will be

$$\frac{2}{h^3} dp_x dp_y dp_z \frac{p_z}{m} \left[e^{(E-E_F)/kT} + 1 \right]^{-1}$$

where the electron energy $E = (p_x^2 + p_y^2 + p_z^2)/2m$.

The electrons that escape from the surface are those with $p_z^2/2m > E_F + W$. The number of electrons, or the *emission current* per unit area will be

$$I = e \frac{2}{h^3} \frac{1}{m} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{p_z}^{\infty} \left[e^{(E-E_F)/kT} + 1 \right]^{-1} p_z dp_x dp_y dp_z$$

where $p_z^! = \sqrt{2m(E_F + W)}$.

This integral may be simplified by noting that the work functions of metals lie between 1 and 5 eV. Since $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ and $k = 1.38 \times 10^{-23} \text{ J.deg}^{-1}$, for a typical operating temperature of 2000 K and a work function of 4.5 eV (tungsten), $(E - E_F)/kT = 26$ for an electron which just escapes with zero kinetic energy. For more energetic escaping electrons the factor is greater. Hence for the *emitted* electrons the +1 term in $[\quad]^{-1}$ may be ignored and the velocity distribution is Maxwellian.

Taking the constant term $\exp(E_F/kT)$ outside the integral and evaluating,

$$I = \frac{2e}{mh^3} e^{E_F/kT} \exp\left(-\frac{p_x^2 + p_y^2 + p_z^2}{2mkT}\right) p_z dp_x dp_y dp_z$$

Using the standard integral the above integral reduces to

$$\begin{aligned} I &= \frac{2e}{mh^3} e^{E_F/kT} (\pi 2mkT) \int_{p_z} \exp\left(-\frac{p_z^2}{2mkT}\right) p_z dp_z \\ &= \frac{4pmek^2}{h^3} T^2 e^{E_F/kT} \exp\left(-\frac{p_z^2}{2mkT}\right) \end{aligned}$$

But for escaping electrons $p_z^2/2m = E_F + W$

Hence $I = \frac{4\pi mek^2}{h^3} T^2 e^{-W/kT}$ - this is the Richardson-Dushman equation.

Reference: Physical Electronics: Hemenway, Henry and Caulton, Chapter 4.