

COMPACT OSCILLATING HEAT PIPE AND DEVELOPMENT
OF FUZZY COPPER FOR WICKING STRUCTURES

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OF FUZZY COPPER FOR WICKING STRUCTURES

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This graduate thesis
is dedicated to my loving wife,
Amy, who supports and
encourages me in everything.

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Nomenclature

$\Delta P_{capillary}$ capillary pressure difference.

$\Delta P_{gravity}$ pressure drop due to the height difference between the evaporator and condenser.

ΔP_{liquid} pressure drop due to the liquid flow.

ΔP_{vapor} pressure drop due to the vapor flow.

ρ_l density, liquid

ρ_v density, vapor

σ surface tension

$Bo_{Critical}$ critical bond number

CPU Central Processing Unit of a computer

D_h Hydrolic Diameter

D_{max} Maxium hydraulic diameter

g gravity

OHP Oscilating Heat Pipe

$r_{c,eff}$ effective meniscus radius.

Abstract

A central processing units (CPU) calculation speed is limited by the heat it produces. As the number of transistors and the clock speed of CPUs increase they become more powerful, but they also generate more heat which must be removed or the chip will over heat and fail. CPUs in laptops and some desktop computers are currently cooled using heat pipe heat sinks. However, as CPUs increase in power, greater heat transfer capacity will be required, and the capabilities of current heat pipe designs will be exceeded. Thus it is necessary to develop an innovative cooling device that is capable removing a higher heat flux. Oscillating heat pipes (OHP) are a viable option, however, the current design is too large for incorporation into electronics packages. The compact OHP is proposed as a solution. The current investigation is designed to produce a compact OHP as a replacement of current cooling technologies. Electroforming was chosen as the method for fabricating the OHPs because of its cost effectiveness, and the maturity of the technology which lends itself well to prototyping. The electroforming technology was studied and an electroforming bath was constructed. In order to create an OHP in an electroforming bath, several techniques of masking the substrate for electroforming were studied and the preliminary process design of using photo lithography as a masking technique was completed. During testing of the electroforming system a new wicking structure was created, which is a form of dendritic growth. The wicking structure was analyzed using a light microscope and a three vapor chambers were fabricated and tested to characterize the capillary performance of the wick structure and heat transport capability.

Part I.

Compact Oscillating Heat Pipe

1. Introduction

1.1. Motivation

A central processing unit's (CPU's) calculation speed is limited by the heat it produces. To make computers more powerful the number of transistors and the clock speed of the CPUs must increase, however, increased number of transistors and clock speeds generate more heat which must be removed or the chip will fail due to over heating. CPU's in laptops and some desktop computers are currently cooled using heat pipe heat sinks. However, as CPU's increase in power, greater heat transfer capacity will be required, and the capabilities of current heat pipe designs will be exceeded. Oscillating heat pipes (OHP) have superior performance to traditional style heat pipe and are therefore the future of processor cooling. However, before they can be utilized effectively their limiting factors must be fully understood. Currently OHP's heat transfer capabilities are strongly affected by gravitational forces [2] which limit the application of OHPs. Creating a double planar OHP may help to eliminate gravitational dependence, and will increase the density of heat transfer media creating a highly efficient heat pipe. Currently OHP's can be used to transport heat with a higher heat flux, however, the current design cannot be readily incorporated into compact electronic equipment because of it's size. The size of the OHP's is limited by current construction methods, thus new methods of producing smaller OHP's is desired.

1.2. Objective

The objective is to create an oscillating heat pipe that has two planes of interconnected oscillating tubes. The OHP surface is a 3 inch square with a centrally located heat sources as shown in Figure 1.1. To minimize the pressure drop through the small tubes the square will be divided into 4 quadrants, each having one interconnected channel which is an independent OHP. The heat source is a 1 inch square. To cool the heat pipe a water-cooled block will be attached to the outer 0.5 inches of the square, as seen in Figure 1.1.

The channels will have a hydraulic diameter (D_h) less than 1 mm and will be formed in copper, which has a high thermal conductivity. The wall thickness between the oscillating channels will be minimized. An innovative feature of the heat pipes featured in this thesis is the construction method used to create them. The OHP's will be electroformed using an electroforming bath, as described below. To accomplish the construction of these new heat pipe designs a review on the background information was first conducted and then an experimental investigation was carried out by recreating current OHP designs on a smaller scale, finally, using the refined theoretical knowledge and tested experimental procedure a multi-plane compact OHP will be created.

1.3. Introduction to Oscillating Heat Pipes

The Oscillating Heat Pipe (OHP) was first invented and patented by Akachi, H in 1990 [1]. An OHP consists of a meandering tube that is heated and cooled at several points along its length. The diameter of the tube is such that the liquid creates a complete meniscus across the tube, the critical hydrolic diameter is related to the bond number, Bo, by Equation 1.1, where the bond number varies between 1.84 [14] and 2 [9].

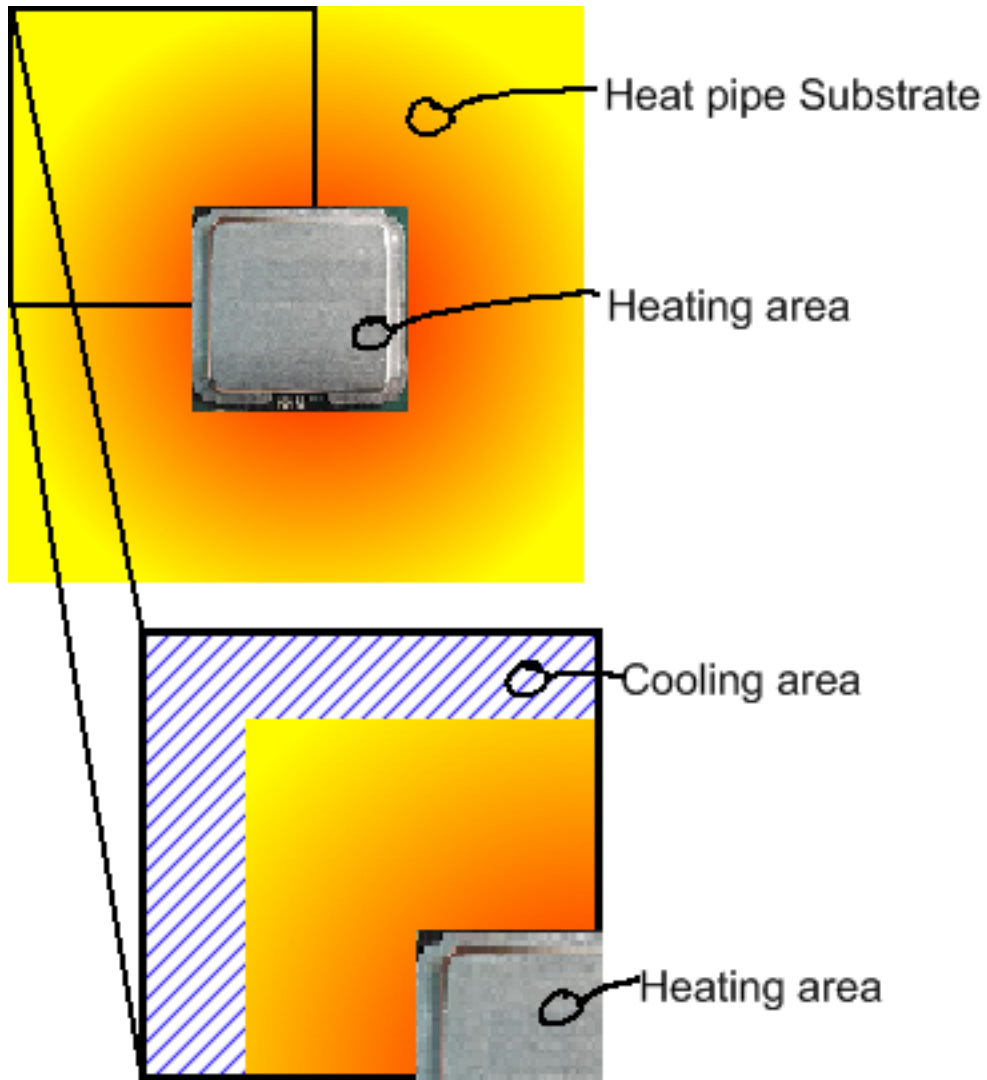


Figure 1.1.: The heat load pattern on a 3 x 3 inch area, divided into quaters with one heat pipe in each quadrant.

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$$D_{max} = \sqrt{\frac{Bo_{Critical}\sigma}{g(\rho_l - \rho_v)}} \quad (1.1)$$

The pipe is charged so that there is only a fluid and its vapor inside. Since the diameter of the pipe is designed to force the fluid to create a complete meniscus, the fluid forms liquid slugs separated by vapor bubbles, as seen in Figure 1.2. While the tube can be arranged in many ways a simple zig-zag structure, as seen in Figure 1.2 will be discussed in this paper as it is a simple design that has been used successfully in the past [2, 6, 17, 8, 18, 7, 13, 4]. When the aforementioned zig-zag structure is used, the heating and cooling are generally applied at either end across the turns. The heat causes the vapor to expand and the fluid to evaporate, creating high pressure in the heated regions of pipe. While the cooling sections cause the vapor to contract and condense creating low pressure in the cooled regions. This pressure gradient coupled with the random distribution of liquid vapor slugs result in uneven forces that cause the fluid within the pipe to move. The movement of the fluid transports heat from the heated area to the cooled area. The heat transfer is due to both latent heat and sensible heat.

There are two different types of OHPs, open and closed loop. A closed loop is similar to the OHP in Figure 1.2, where the tube is connected and if straightened would make a closed loop or circle. An open loop heat pipe has two ends, and if straightened would make a straight pipe, or open loop. The OHP's in this thesis are closed loop because open loop OHPs perform better [12].

1.4. Introduction to Vapor Chambers

A vapor chamber is essentially a 'chamber' that is filled so that it contains only a fluid and its 'vapor'. The fundamental mechanics are the same as a heat pipe, with the main difference between a vapor chamber and a heat pipe being the distance

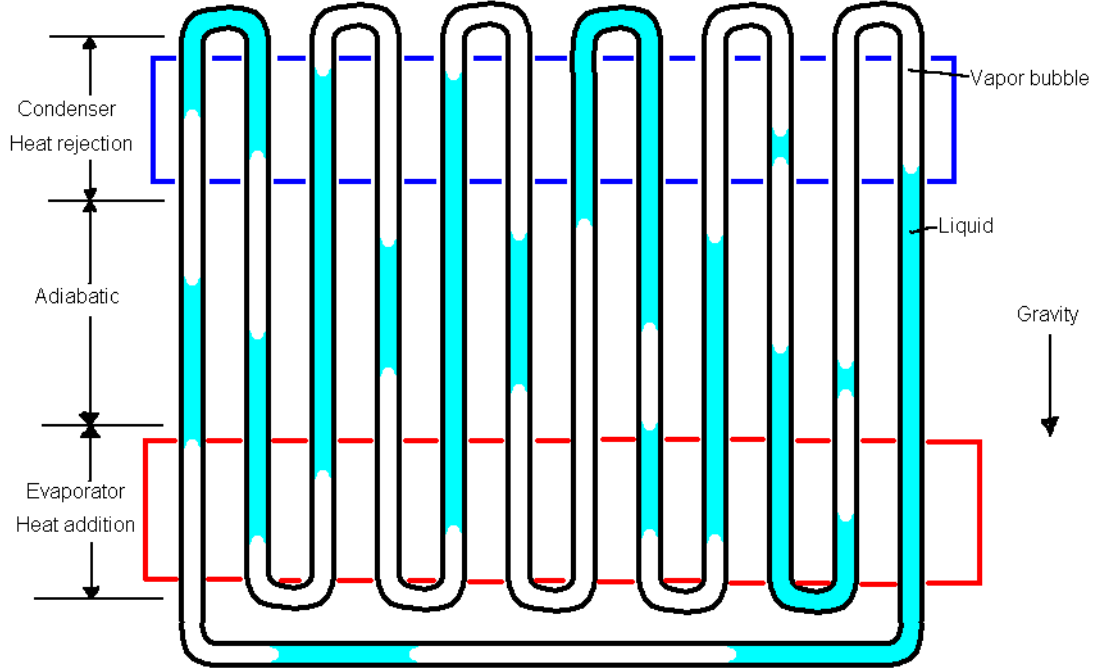


Figure 1.2.: Basic OHP. Heating at the bottom cooling at the top. Notice the liquid and vapor, slugs and plugs.

that the vapor travels after evaporating before condensing. In the case of a heat pipe the fluid generally evaporates at one end of the pipe and transverses the largest dimension of the chamber condensing at the opposite end of the pipe. Whereas in a vapor chamber when heat is applied to the bottom of the chamber the fluid evaporates, transverses a relatively short distance and condenses on the top plate of the vapor chamber. The aspect ratio, $\frac{L_A}{D}$ where L_A is the axial length and D is the diameter of the heat pipe, is a simple way of distinguishing a vapor chamber from a heat pipe. If the aspect ratio is less than one then it should be considered a vapor chamber. However, in practice the aspect ratio of vapor chambers are generally much less than one, as vapor chambers are primarily used to spread heat to reduce the heat flux. In this thesis the vapor chambers have an aspect ratio of approximately 0.13. Once the fluid condenses at the condenser it must return to the evaporator so that process can be repeated and additional heat can be transferred. The following is a

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more detailed look at the operation of a vapor chamber as well as the operational limits.

A vapor chamber operates in a two-phase closed loop system. There are no moving parts and the only energy used to operate the vapor chamber is the heat energy that is being transported. During operation the working fluid is in a saturated state, so long as the operating temperature is between the triple point and the critical state. When heat is added to the evaporator section of the vapor chamber the saturated fluid receives enough energy that it begins to vaporize. This vapor travels down to the condensing area of the vapor chamber and expels the latent heat of vaporization causing it to condense back into a liquid. This liquid is pumped by the capillary force back to the evaporator. The capillary wick is a structure with small interstitial spaces that create a capillary pumping force. This pumping force attempts to evenly spread the fluid throughout the wick, and will pump liquid from a more saturated area to a less saturated area. Thus as the fluid condenses in the condenser the capillary wick pumps it back to the condenser.

The distance that the capillary wick can pump the fluid depends on the sum of the pressure drops between the condenser and the evaporator. If the pressure created by the surface tension force is not greater than the sum of the pressure drops then the vapor chamber has reached the ‘*Capillary Limit*,’ and the vapor chamber evaporator will *dry out* because the working fluid can not be returned.

1.4.1. Surface Tension

The surface tension of a fluid is the force that occurs at the fluid boundary and holds the liquid together in a drop, and in the absence of gravity the surface tension of a fluid will cause the drop to create a perfect sphere. The force is oriented along the surface normal vector, pointing into the fluid. In non-polar fluid the force is created by molecular dispersion forces only. However, in water, a polar fluid, hydrogen bonding

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also influences the surface tension. As a result the surface tension of polar fluids is greater than that of non-polar fluids. In the case of metallic fluids, like mercury, metallic bonding forces increase the surface tension. Thus fluid metals have the greatest surface tension.

$$\sigma = \sigma_{dispersion} + \sigma_{hydrogen} + \sigma_{metallic} \quad (1.2)$$

The surface tension of a fluid is also related to its temperature, as the temperature of a fluid decreases the surface tension increases and visa versa. They are inversely related in a linear fashion, such that,

$$\sigma = C_1 - C_2(T), \quad (1.3)$$

where C_1 and C_2 are constants unique to the fluid. [3, 10]

1.4.2. Contact Angle

The contact angle, α , that a fluid makes with the wicking structure affects the capillary transport capability of the wick. The contact angle is the angle between the surface and the line tangent to the curvature of a drop of water where the drop meets the surface, as shown in Figure 1.3. The contact angle and the surface tension are related by:

$$\cos\alpha = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}} \quad (1.4)$$

where σ_{sv} is the surface tension between the surface and the vapor, σ_{sl} is the surface tension between the surface and the liquid, and σ_{lv} is the surface tension between the liquid and the vapor, as seen in Figure 1.4.

Since contact angle is related to surface tension it is also dependent on temperature.

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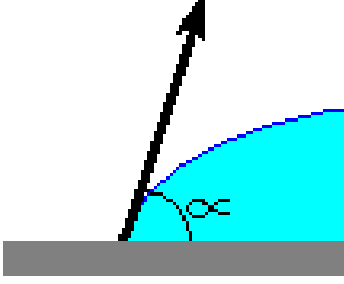


Figure 1.3.: Contact angle, α , of a fluid on a surface.

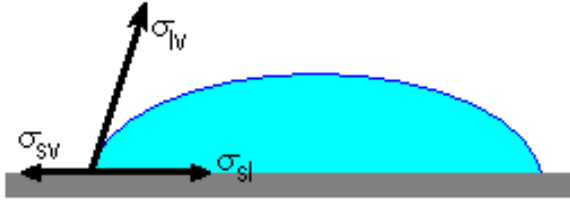


Figure 1.4.: Surface tension components.

As temperature increases, the contact angle decreases, and the fluid becomes more *wetting*. The wettability of a fluid describes the tendency of a fluid to spread out in a thin layer on a given surface. Wettability consists of two main categories, wetting and non-wetting. A wetting fluid has a contact angle between 0° and 90° , while a non-wetting fluid has a contact angle between 90° and 180° . At either extreme the fluid is considered either completely wetting or completely non-wetting. In most cases a contact angle less than 30° provides very good wetting characteristics.

The driving force behind the capillary fluid flow is the pressure difference that occurs at the fluid-vapor boundary. This pressure difference can be determined by observing the radius of the fluid curvature and using the Laplace-Young Equation,

$$P_1 - P_2 = \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right). \quad (1.5)$$

Where r_1 and r_2 are the radii of the liquid surface as seen in Figure 1.5, and where P_1 and P_2 are the pressures of the vapor and the liquid respectively (for a concave

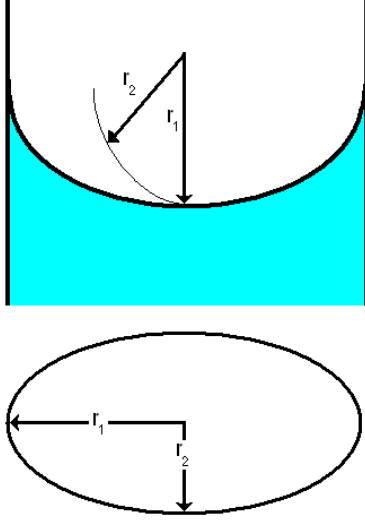


Figure 1.5.: Radii of fluid cavity(r_1 is on the plane of the page, r_2 is in the plane perpendicular to the page.)

liquid face). [3, 10]

1.4.3. Limiting conditions

1.4.3.1. Capillary Limit

The capillary wick can take many forms, but its function is always the same. It returns the working fluid to the evaporating section of the vapor chamber. A vapor chamber reaches the capillary limit when the wick can no longer supply the evaporator with fluid. When the pressure drops due to the liquid, vapor, and gravity exceed the capillary pressure the capillary limit is reached and the vapor chamber ‘dries out,’ which mathematically can be expressed as:

$$\Delta P_{capillary} \leq \Delta P_{liquid} + \Delta P_{vapor} + \Delta P_{gravity} \quad (1.6)$$

Capillary Pressure The capillary pressure is the pressure difference across the liquid vapor layer as described by the Laplace-Young Equation, equation 1.5. The pressure is related to the surface tension of the fluid and the meniscus radius. As the vapor

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chamber transfers heat, the fluid moves from the evaporator to the condenser. This causes the fluid level to drop in the evaporator and rise in the condenser resulting in a change in the meniscus radius in the evaporator and condenser. The meniscus radius decreases in the evaporator and increases in the condenser resulting in a pumping force from the condenser to the evaporator.

The maximum capillary pressure exists when the meniscus radius in the condenser approaches infinity (a level surface) and the meniscus radius in the evaporator is at a minimum. The Laplace-Young equation can be simplified for this case to:

$$\Delta P_{capillary_{max}} = \frac{\sigma}{r_{c,eff}}, \quad (1.7)$$

where $r_{c,eff}$ is the effective meniscus radius for the given channel geometry as described by Ma [10]. For rectangle capillary channels $r_{c,eff}$ can be determined by:

$$r_{c,eff} = \frac{w}{\cos\alpha}, \quad (1.8)$$

where w is the groove width and $\cos\alpha$ is the contact angle for the fluid surface system. The $r_{c,eff}$ for a sintered particle vapor chamber is found by:

$$r_{c,eff} = 0.41r_p \quad (1.9)$$

where r_p is the radius of the sintered particle.

Liquid pressure drop The pressure drop in the liquid is caused by the inertia of the liquid particles and the viscous forces. However, the flow rate in the wick is generally low and the inertial forces can be ignored. Thus the pressure drop is due only to the viscous forces, which are composed of the solid-liquid frictional forces and the interaction with the friction from the vapor-liquid flow. The change in pressure along

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the fluid flow path or the pressure gradient can be expressed as,

$$P_{liquid} = \left(\frac{\mu_{liquid}}{K A_w \rho_{liquid}} \right) \dot{m}_{liquid} \quad (1.10)$$

where K is the permeability of the wick structure,

$$K = \frac{2\varepsilon r_{l,h}^2}{f_l Re_l} \quad (1.11)$$

ε is the wick porosity, defined by $\varepsilon = \frac{Vol_{open}}{Vol_{total}}$; $r_{l,h}$ the hydraulic radius, calculated by $r = \frac{2A_{channel}}{Perimeter_{wetted}}$; f_l is the friction factor and Re_l is the Reynolds number. If laminar flow exists then $f_l Re_l$ is constant. However, it is affected by the vapor flow, and the channel angle and surface contact angle.

The pressure gradient can be integrated along the length of the fluid flow path to determine the total pressure drop, from the evaporator, $x=0$ to the condenser $x=L$,

$$\Delta P_{liquid} = - \int_0^L \frac{dP_{liquid}}{dx} dx \quad (1.12)$$

The total pressure drop can be determined from,

$$\Delta P_{liquid} = \left(\frac{\mu_l}{K A_w h_{fg} \rho_l} \right) L_{eff} q \quad (1.13)$$

where, $q = \dot{m}_l h_{fg}$, and L_{eff} is the fluid flow path, from the condenser to the evaporator.

Vapor pressure drop The vapor pressure drop is caused by the working fluid evaporating in the evaporator. The pressure drop created by this vaporization for one dimensional vapor flow can be approximated by:

$$\Delta P_{vapor} = \left(\frac{C f_v Re_v \mu_v}{2r_{v,h}^2 A_v h_{fg} \rho_v} \right) L_{eff} q \quad (1.14)$$

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C is a constant that is dependent on the Mach number and the product of the friction factor and the Reynolds number. Where the Mach number is,

$$Ma_v = \frac{q}{A_v \rho_v h_{fg} (R_v T_v \gamma_v)^{0.5}} \quad (1.15)$$

γ_v is dependent on the molecule type, monatomic ($\gamma_v = 1.67$), diatomic ($\gamma_v = 1.4$), and polyatomic ($\gamma_v = 1.33$).

$C = 1.0$ if $Re_v < 2300$ and $Ma_v < 0.2$ and $f_v Re_v$ is constant.

$C = 1.0$ if $Re_v > 2300$ and $Ma_v < 0.2$ and $f_v Re_v = 0.038 \left(\frac{2r_{v,h} q}{A_v \mu_v h_{fg}} \right)^{0.75}$.

$C = \left(1 + \frac{\gamma_v - 1}{2} Ma_v^2 \right)^{-0.5}$ if $Re_v < 2300$ and $Ma_v > 0.2$ and $f_v Re_v$ is constant.

[3, 10]

1.4.3.2. Boiling Limit

When boiling occurs in a vapor chamber, heat transfer is greatly limited because the boiling characteristics dominate the thin film evaporation and the bubbles formed during boiling increase the thermal resistance between the wall of the vapor chamber and the fluid. When the bubbles form, they form on the surface of the wall and create a vapor layer, separating the fluid from the wall. Since the thermal resistance of a fluid's vapor is much greater than the thermal resistance of the fluid, the vapor acts as an insulating layer. To prevent boiling the temperature difference between the wall and the fluid's saturation temperature must be less than the super heat required to cause the fluid to boil, given by the Clausius-Clapyeron equation,

$$T_l - T_{sat}(P_l) = \frac{2\sigma T_{sat}(P_l)_{sat}}{h_{fg} r_e} \left(\frac{1}{\rho_v} - \frac{1}{\rho_l} \right) \quad (1.16)$$

where r_e is the radius of the meniscus of the vapor bubble, which is related to the cavity size in the wick structure. If the vapor density is very small compared to the liquid density, this may be simplified as: [19] Since the temperature difference

1. Introduction

between the wall and the saturated liquid temperature must remain below the super heat temperature the maximum, or critical heat flux, can be determined:

$$q'' = k_{eff} [T_l - T_{sat}(P_l)] = \frac{k_{eff} 2\sigma T_{sat}(P_l)_{sat}}{h_{fg} r_e} \left(\frac{1}{\rho_v} - \frac{1}{\rho_l} \right) \quad (1.17)$$

[3, 10]

1.4.3.3. Viscous Limit

The viscous limit is reached when the vapor pressure drop is not great enough to overcome the vapor's viscous forces, as described by:

$$q_{vis} = \frac{4r_v^2 h_{fg} \rho_{v,evap} P_{v,evap} A_v}{f_v Re_v \mu_v L_{eff}} \quad (1.18)$$

where $\rho_{v,evap}$ is the density and $P_{v,evap}$ is the pressure in the end cap of the evaporator.

This equation assumes laminar flow, ideal gas, and zero pressure in the condenser.

[3, 10]

1.4.3.4. Sonic Limit

The vapor pressure increases as the heat transfer rate increases, as does the vapor velocity. When the vapor velocity reaches the speed of sound it cannot travel any faster, and the sonic limit of the vapor chamber is reached because the heat transfer will be limited by the flow velocity of the vapor. The sonic limit can occur at the exit to the evaporator, or at any point in the condenser where the flow geometry changes. Using the momentum equation and assuming negligible frictional force and ideal gas the sonic limit for one dimensional flow can be approximated by:

$$q_{sonic} = A_v \rho_v h_{fg} \left[\frac{\gamma_v R_v T_0}{2(\gamma_v + 1)} \right]^{0.5} \quad (1.19)$$

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where T_0 is the stagnation temperature and A_v and ρ_v are the cross sectional area and the vapor density where the sonic limit is reached. [3, 10]

2. Compact OHP

2.1. Background

Several different construction methods were considered to make the micro-channels for the OHP, including, machining, chemical etching, and electroforming. Initially the grooves were going to be machined out of a block of tellurium copper (copper alloy 145 - tellurium is added, enhancing the machinability of the copper at the cost of ~10% of copper's thermal conductivity). Tellurium copper can be machined very well, with exceptional tool life even at very high feed rates, however, the machining process is relatively slow and the channel size is limited by the size of available end mills. The feed rate and therefore the machining time is also directly related to the size of the channels - the smaller the channels the lower the feed rate and the longer the machining time.

Since the machining process is limited by the practical limit of tool size chemical etching of the copper substrate was considered as a possible alternative. When using a chemical etching process a mask is applied to the surface, in this case the mask would contain the pattern of channel walls that are desired. The masked copper is then placed into the etching solution, and allowed to etch until the desired depth of channel is reached. While the etching process allows the channels to be as small as it is possible to create a mask line, it creates channels with angled side walls, and if the masked copper plate is left in the etching solution for too long the etchant will

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begin to eat under the masked region. Since the etching process creates channels with angled sides the depth of the channel is limited by the width of the top of the channel, creating channels that have a triangular profile. Most importantly, the copper cannot be etched into a perfect channel.

With both the machining process and the chemical etching process open topped channels are created and to complete the fabrication of the channel surface into an OHP the channels must be covered with a top plate. The top plate covering poses the biggest challenge in both construction techniques. Due to the desire to minimize the overall size of the OHP a thin covering plate is ideal, however, the thinner the plate the more difficult it is to create a good seal with the channel walls. There are several complications with using a thin covering plate, namely creating a cover plate that is both thin and flat so that it matches well with the channeled plate - attaching the entire length of the top of the channel wall to the cover plate to prevent cross-channel flow, and constraining the flow to the desired channel path. One possible remedy to this issue is to use a brazing foil in an oven, creating a sandwich of the channeled plate, brazing foil, and cover plate. However, brazing the cover plate to the channeled plate creates other challenges, namely using enough braze filler material that the channel walls adhere uniformly to the cover plate but avoid filling the channel with braze material. As an alternative to brazing on a cover plate, electroforming the cover plate was considered.

Electroforming is similar to electroplating, however, the part is left in the electrolyte plating bath for much longer, allowing the plating to grow to a structurally significant thickness. Since electroforming is an additive fabrication process the cover plate literally grows off the channel plate, thus eliminating any possibility of inter channel flow due to improperly connected channel walls. To prevent the copper from growing in the channels they are coated with non-conductive ink, or filled with jewelers casting wax, which is later removed from the channels. Electroforming is not

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limited to growing a cover plate for a machined channel plate, it can be used to form the entire channel geometry. Since electroforming will deposit copper onto any conductive surface the entire OHP can be grown in any shape, by first creating the channel pattern using wax wire and then coating the wax with conductive ink. The other option is to mix powdered graphite and carbon into molten wax, to make it conductive, and then extrude it in the desired channel pattern.

Since brazing is used widely in industry and is particularly useful for mass production of parts this method was explored further by Scott Thompson[11], however, the focus of this thesis is on the use of electroforming to construct OHP's.

2.1.1. Electroforming Basics

An electroforming bath consist of 3 major sections, the bath container, the electrolyte and the electrical system. The bath container consists primarily of the container that is used to hold the electrolyte, but also includes the pumping system and the filter. Active circulation of the fluid is important for proper bath functioning, as it minimizes the ion depleted boundary layer (fluid immediately adjacent to the work piece). During operation the cupric ions that are deposited onto the work piece from the boundary layer of electrolyte depleted the boundary layer of ions, and the ions must diffuse. The pump also forces the electrolyte through the filter which removes any particulate contamination from the solution. If the particles are not removed from the fluid they may be electroplated onto the work piece creating defects. The electroforming bath was fitted with a 1 micron filter and the entire volume of the bath is filtered every few minutes.

2.1.1.1. The Electrolyte

The electrolyte consists of approximately 87% Distilled water, ~12 % sulfuric acid, >1 % hydrochloric acid, ~2% plating additive, and the dissolved cupric ions. The acids

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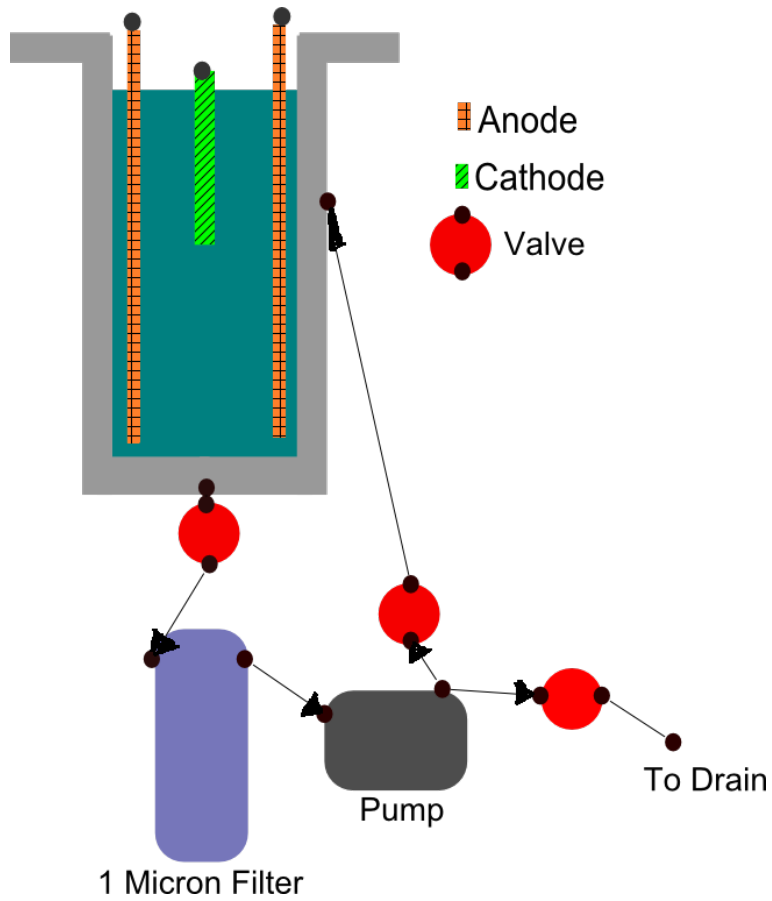


Figure 2.1.: Schematic of the fluid flow in the electroforming system.

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in the water are ions, and thus cause the distilled water to be electrically conductive allowing the plating process to occur. The acids also encourage the anode to dissolve by preventing the formation of an oxide layer. The plating additives consist of a carrier and a brightener that work to enhance the performance of the electroplating bath, but controlling the deposition of the cupric ions.

”In a well controlled plating bath, the carrier supports the formation of a black skin on the anode material which serves to regulate the diffusion of copper ions into the electrolyte. The material is also attracted to, but not co-deposited on the cathode (work piece) forming a layer (film layer) in close proximity to the surface that controls the rate of copper grain growth.

The brightener works within the film layer to control copper deposition on a microscopic level. It tends to be attracted to points of high electro-potential, temporarily packing the area and forcing copper to deposit elsewhere. As soon as the deposit levels, the local point of high potential disappears and the brightener drifts away. (i.e. brighteners inhibit the normal tendency of the plating bath to preferentially plate areas of high potential which would inevitably result in rough, dull plating) By continuously moving with the highest potential, brightener/levelers prevent the formation of large copper crystals, giving the highest possible packing density of small equilaxed crystals which resulting in smooth, glossy, high ductility copper deposition.[16]”

Lastly the electrolyte consists of the dissolved cupric ions, initially the bath is charged using cupric sulfate granules to 'jump start' the plating system. Technically plating can be done without having a sacrificial anode by replacing the sacrificial anode with one that will not dissolve into the solution and maintaining the cupric ions level by adding cupric sulfate as the ions get deposited onto the work piece. However, if a sacrificial anode is used the ion level will be self regulating, as the ions are deposited onto the work surface, they will be removed from the anode material.

2.1.1.2. The Electrical System

The electrical system is the driving force of the system, it consists of the power supply, the anode and the cathode (work piece). The power supply can be a DC rectifier or

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even a battery, so long as it can supply the required current. The current density controls the rate of deposition and generally ranges from 10 to 50 amps per square foot or plating surface - however this can be modified heavily depending the desired surface finish- during most plating in this thesis 20 amps per square foot was used. If the current density is too high the surface will be rough and non uniform. The positive terminal is connected to the anode and the negative terminal is connected to the cathode (work piece) - the anode supplies cupric ions which are deposited onto the cathode. When the system is running correctly the power supply delivers a current to the anode where the copper ionizes, loosing two electrons and forming Cu^{2+} . The Cu^{2+} cation is free in the solution and associates with sulfuric acid anion SO_4^{2-} . When the associated pair nears the cathode the Cu^{2+} cation is attracted to the negatively charge metal surface, where it binds to the copper metal matrix.

2.1.1.3. The Cathode - Workpiece

There is a variety of methods for producing electroformed parts; however, the basic concept is the same. A mandrel or mold is used to provide the conductive base and the form to produce the electroformed part. Depending on the resulting part, the mandrel can be either male or female and is often a flat plate with a pattern of either conductive or non-conductive inks. For example Lee, Chen, and Huang [15] produced a micro-featured flow field using nickle electroforming for use in a hydrogen fuel cell. Their process used a thick layer of photo resist to cover the parts of the plate that they did not want the channels to grow on. The thickness of the photo resist maintains the boundary of the channel walls, since electroformed material grows spherically from all conductive points, if there was not a vertical wall of photo resist to limit the growth of the nickel, the walls would grow wider and eventually they would join, completely covering the photo resist [15].

Electroforming can be used to make extremely small parts, and is essentially only

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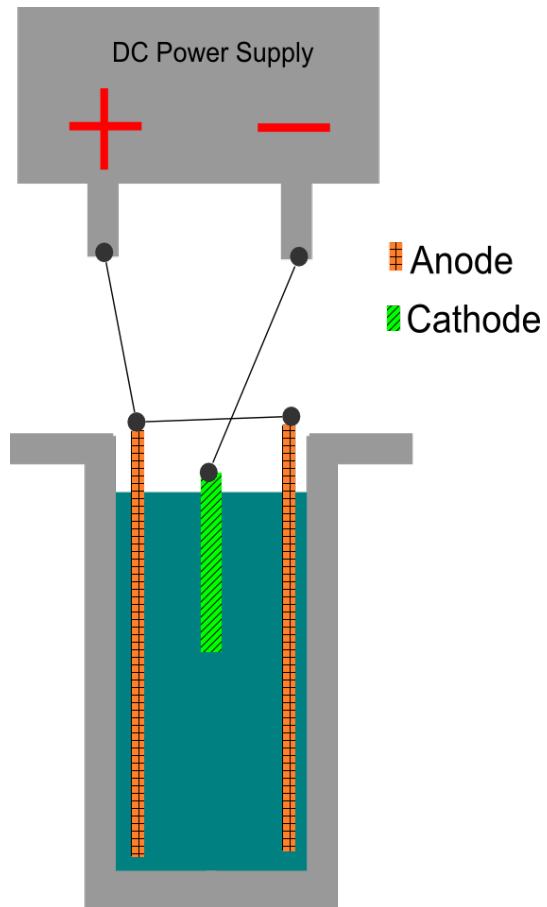


Figure 2.2.: Electroforming electrical system

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Figure 2.3.: Photo of one half of the anode bank, containing 3 anode tubes, with the electroforming bath in the background. (Anode bank consists of 1.5" PVC pipes with 1/3 removed from one side. Inside are phosphorized copper nuggets that are used as the sacrificial anode media. To maintain a conductive path there is a small copper tube inside the PVC tube that connects to the buss-rod. The buss rod connect one side of anode tubes and is connected to the positive side of the power supply.)

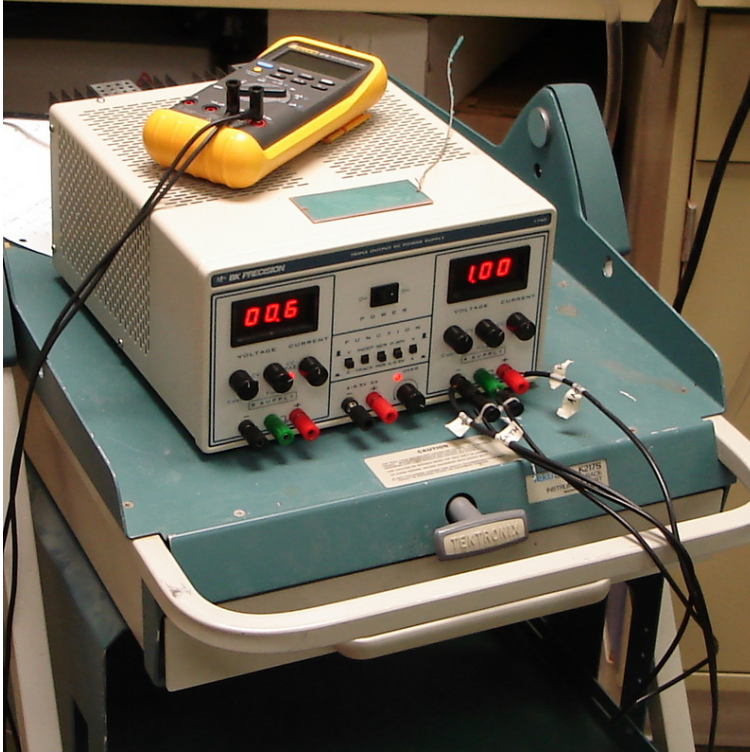


Figure 2.4.: Constant current DC power supply used to provide power to the electro-forming bath.

limited by the size of the metal atom, the resolution of the photo resist, and the required strength of the part produced.

Many different types of metals can be used to electroform including: nickle, copper, gold, chrome, and indium, however, nickle is the most common because it is the cheapest, and most structurally significant material. For the production of vapor chambers, however, an elctroforming process using copper was selected because of the superior thermal conductivity of copper. It is suggested that copper electroforming be used to ‘grow’ vapor chambers, a detailed proceedure will be created, exploring how to grow the entire vapor chamber. Starting with a piece of copper foil, the back and the sides will be painted or coated to prevent electroplating growth.

2.1.2. Masking techniques

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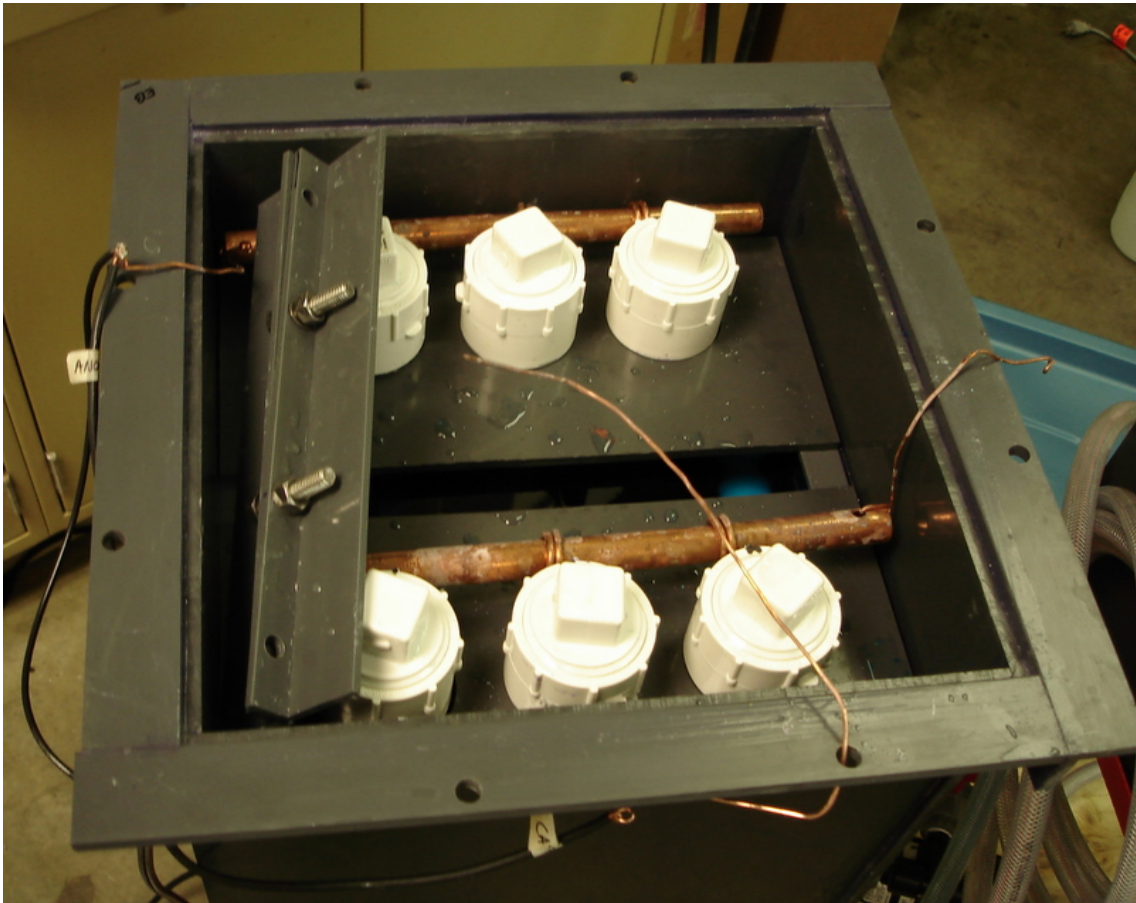


Figure 2.5.: Working area of the electroforming bath. (Notice the two anode banks, and the work piece holder on the left. The workpiece holder uses the two bolts to clamp onto the workpiece which is then suspended in the bath fluid.)

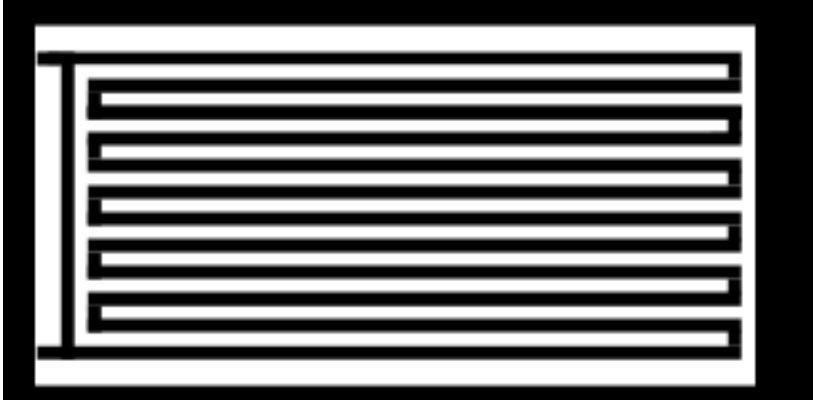


Figure 2.6.: Channel pattern drawn in a vector graphics package. The pattern will be transferred to a piece of copper.

2.1.2.1. Toner Transfer

Toner transfer is a common method used in the fabrication of custom circuit boards in very small quantities. The basic process consist of drawing the design on a computer, printing it with a laser printer onto paper, transferring the toner onto the new surface, and finally removing the paper from the toner leaving the toner on the new surface. Toner transfer is generally used as a way to mask the areas on a copper clad (copper coated) circuit board that one wishes to remain behind, as the board will be placed in an acid that will eat any exposed copper. However, in this case the toner was used to cover the copper where additional copper deposit is not desired. Thus the walls of the OHP are left white while the area that is to be the channels are colored black in the computer drawing, as seen in Figure 2.7.

Drawing the design is best done in a vector graphics program. Initially AutoCAD was used, however, it is more difficult to control the dimensions on the lines as an AutoCAD drawing is designed to be a reference and is not used to take measurements from. A vector graphic software on the other hand is designed to print exactly what is drawn to the correct scale, and it is easy to get the right line thicknesses. Inkscape¹ was chosen as the vector graphics editor because it is compatible with all commercial

¹Inkscape is a free, open source vector graphic editing software that is compatible with all major commercial vector graphic editors; <http://www.inkscape.org/>.

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vector graphic editors, it provides the required tools and it is free. To draw the design the 'box' drawing tool was used, along with the grid tool to aid with alignment. The areas that are supposed to be the channels were colored black while the channel walls and the surrounding area was left white. Once the design was drawn a page was design which contained 12 copies with a black background. The black background limits the area of copper that is available to be plated -thus saving plating resources.

2.1.2.2. Photo lithography

Photo lithography is the process of using a photo sensitive film and a patterned mask to form a pattern on the substrate material. Starting with a substrate, a photo sensitive film is deposited using a 'spin coater' which uses centrifugal forces to spread the film across the substrate and achieve a uniform thickness. The film is then heated to dry it. After drying the patterned mask is placed on top of the film. The patterning is done using clear and opaque material, the clear material will allow the photons from the near UV exposure light through to the photo sensitive film, while the opaque material will not. The UV light will cause the photo sensitive film to change chemically so that when it is heated in the post exposure bake (PEB) the exposed portions of the film will thermally interlink, changing their solubility. After the PEB the non-exposed film is removed during 'development', leaving behind a 3 dimensional copy of the pattern that was used as the photo mask. In this case the pattern will be a meandering channel that will be made into an OHP. The remaining photo sensitive film can be removed later using the removal chemicals.

There are three ways that the photo resist can be used to create an OHP. The first method is to make a mask where the opaque areas represent the wall of the OHP. Thus the walls will be electroformed and the photo resist will be removed and the OHP will be completely copper. This is probably the most useful method, because it will allow for maximum thermal conductivity throughout the OHP. It will also allow

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for thinner, stronger channel walls. The second method would be to design the mask so that the opaque areas of the mask represent the channels of the OHP. During processing of the photo resist the film must be cured (requires additional baking), then the entire surface will be coated with conductive ink and electroformed for a short period, forming a base layer. The channels would then be filled with wax and coated with conductive ink and the cover plate would be grown. This method would be faster because less thickness of copper must be formed, thus shorter plating times are required. The third method would be to use only the photo sensitive film for the construction of the OHP. To accomplish this a plate would be coated, exposed and PEBed as before, however before developing the plate a second film will be deposited over the first. The second film will be exposed entirely - cause the entire film to thermally interlink during the PEB, this would be the cover plate. Problems with the third method are;

1. During the development process extreme agitation will be required to remove the unexposed material from the first layer, to form the channels.
2. Timing of the exposure of the second layer is critical. The second layer must receive sufficient exposure so that it undergoes the required chemical changes, however, if the plate is exposed for too long the first layer will be re-exposed and the channels will be exposed. Exposing the channels will cause the film to thermally interlink and prevent the removal of the channel material - destroying the OHP.

Thus considering the advantages and limitations of each method it is suggested that the first method be utilized in the fabrication of the OHP's.

Fabrication Procedure Purpose: Create a 3" x 1.5" channeled flow field by applying removable photo resist compound to a conductive base. The base will be used as the

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cathod in an electroforming cell where more copper will be deposited into the space left by the removed photo resist. The remaining photo resist will then be stripped, leaving only the copper channel walls. The open channels will be filled with jewelers casting wax which will then be painted with a thin coat of conductive ink. The part will be placed back into the electroforming cell where the copper will deposit onto the conductive wax, forming a lid. The part will then be heated to remove wax, which will turn into a flammable vapor. Once the wax is removed the channeled part can be charged like a conventional heat pipe.

The following procedure is for forming a layer about $300\mu m$ thick photo resist on a 3 inch disk using SU-8 2075, for other applications refer to the reference material provided by Micro Chem.

Make glass based copper clad disk.

1. Clean the Glass disk using alcohol.
2. Cut 4 pieces of copper foil; approximately 10mm x 50mm.
3. Clean the foil strips using a Scotch-Britte pad.
4. Using cyanoacrylate glue (super glue), carefully adhere the a copper strip on the front of the glass at 90 degrees, 180 degrees, 270 degrees, 360 degrees - these are the conductive hang tags that are used to hang the plate in the electroforming bath.
5. Spin coat disk with OmniCoat
 - a) Dispense 3ml of OmniCoat into the center of the copper side of the copper clad disk(~ 1 ml of OmniCoat per 25mm (1 inch) of disk diameter).
 - b) Spin at 500 RPM for 5 seconds with the acceleration set to 100 RPM/*sec*.

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- c) Increase acceleration to 300 RPM/*sec* and spin at 3000 RPM for 30 seconds.
 - d) Remove disk from spin coater and place the disk on a 200°C hot plate and bake for 1 minute.
 - e) Remove disk from hot plate and allow to cool.
6. Spin coat disk with SU-8 2075:
- a) Dispense 3 ml of SU-8 2075 into the center of the disk (~1ml of OmniCoat per 25mm (1 inch) of disk diameter.)
 - b) Spin at 500 RPM for 5-10 seconds with the acceleration set to 100 RPM/*sec*².
 - c) Increase acceleration to 300 Rev/*sec*² and spin at 2000 RPM for 30 seconds (this will give a thickness of $\sim 110\mu\text{m}$).
 - d) *Soft bake*: A hot plate must be used for the soft bake process because if a convection oven is used a skin will form on the top of the photo resist, slowing the release of the solvent and increasing the bake time. If a hot plate is used, then the photo resist is heated from the bottom out, this aids removing the solvent from the photo resist that is next to the substrate. *Soft bake test*: to determine if soft baking is complete remove the disk from the heater and allow to cool, return the disk to the heater if the film wrinkles then allow it to continue heating for a few more minutes - repeat the wrinkle test until the disk no longer wrinkles when replaced on the heater.
 - i. Preheat the hot plate to 95°C
 - ii. Remove disk from spin coater.
 - iii. Place the disk on the 95°C hot plate and bake for 10-20 minutes.
 - iv. Remove from hot plate and allow to cool.

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- v. Perform soft bake test as described above.
 - vi. Repeat steps 3diii-3dv, until till the soft bake completion test is passed successfully.
 - e) Remove disk from hot plate and allow to cool.
7. Deposit 2ml conductive ink.
8. Spin the conductive ink at 500 RPM to create a thin uniform layer - insure that the conductive ink makes contact with the 4 copper foil hang tags. Do not touch the coat of conductive ink, because surface contamination will affect the plating.
9. Electroplate for approximately 7 hours to deposit a layer at least $100\mu m$ thick, rotating the plate to each hanging tab for $1/4$ of the cycle.
- a) Attach the plate to the hanging wire- insert approximately 1 inch of 20 gage wire though the hole in the top center of plate and bend in 180 degrees. Twist the wire together so that the wire is attached to the plate and the plate cannot be removed except by untwisting the wire.
 - b) Open electroforming bath lid. Remove cathode holder and loosen the bolts/nuts.
 - c) Place hanging wire though the cathode holder until the top of the plate is hanging ~ 2 inches below the lower surface of the cathode holder or lower to ensure that the top of the plat is approximately 1 inch below the surface of the liquid in the plating bath. Tighten the bolts/nuts, to secure the hanging wire in place.
 - d) Replace the cathode holder into electroforming bath - ensure that the workpiece is carefully inserted between the anode hanging plates (splash

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cover) and that the normal vector of the workpiece's plating surface is pointed towards one of the anode banks.

- e) Twist the hanging wire around the cathode lead.
 - f) Replace the lid on the electroforming bath.
 - g) Turn on the power and set the current to 20 amps per square foot (3 inch diameter + 10% = ~1.08 amps)
 - h) After 1/4 of the time has passed (1hr 45min) turn off the power, removed the lid, remove the cathode workpiece, untwist the 20 gage wire from the hanging tab and rotate the work piece 90 degrees and re-attache the 20 gage hanging wire to the next hanging tab.
 - i) Repeat step 1.j.vii at 1/2, and 3/4 time.
10. Remove the now copper clad glass from the electroforming bath, and rinse in the rinse bath. Finish rinsing in sink.
11. Use clean compressed air to remove water from top of disk to prevent rapid copper oxidation.

Make channel geometry

- 1. Place copper clad disk into spin coater.
- 2. Spin coat disk with OmniCoat
 - a) Dispense 3ml of OmniCoat into the center of the copper side of the copper clad disk(~1ml of OmniCoat per 25mm (1 inch) of disk diameter).
 - b) Spin at 500 RPM for 5 seconds with the acceleration set to 100 RPM/*sec*.
 - c) Increase acceleration to 300 RPM/*sec* and spin at 3000 RPM for 30 seconds.

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- d) Remove disk from spin coater and place the disk on a $200^{\circ}C$ hot plate and bake for 1 minute.
- e) Remove disk from hot plate and allow to cool.

3. Spin coat disk with SU-8 2075:

- a) Dispense 3 ml of SU-8 2075 into the center of the disk (~1ml of OmniCoat per 25mm (1 inch) of disk diameter.)
- b) Spin at 500 RPM for 5-10 seconds with the acceleration set to $100 \text{ RPM}/\text{sec}^2$.
- c) Increase acceleration to $300 \text{ Rev}/\text{sec}^2$ and spin at 2000 RPM for 30 seconds (this will give a thickness of $\sim 110\mu\text{m}$).
- d) *Soft bake*: A hot plate must be used for the soft bake process because if a convection oven is used a skin will form on the top of the photo resist, slowing the release of the solvent and increasing the bake time. If a hot plate is used, then the photo resist is heated from the bottom out, this aids removing the solvent from the photo resist that is next to the substrate.
Soft bake test: to determine if soft baking is complete remove the disk from the heater and allow to cool, return the disk to the heater if the film wrinkles then allow it to continue heating for a few more minutes - repeat the wrinkle test until the disk no longer wrinkles when replaced on the heater.
 - i. Preheat the hot plate to $95^{\circ}C$
 - ii. Remove disk from spin coater.
 - iii. Place the disk on the $95^{\circ}C$ hot plate and bake for 10-20 minutes.
 - iv. Remove from hot plate and allow to cool.
 - v. Perform soft bake test as described above.

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- vi. Repeat steps 3diii-v, until till the soft bake completion test is passed successfully.
 - e) Remove disk from hot plate and allow to cool.
 - f) Repeat steps 3a-e. Coating is now $220\mu m$
 - g) Repeat steps 3a-b.
 - h) Increase acceleration to $300 \text{ Rev}/\text{sec}^2$ and spin at 3000 RPM for 30 seconds (this will give a thickness of $\sim 75\mu m$).
 - i) Repeat steps 3d-e. The coating is now $295\mu m$ thick plus the thickness of the OmiCoat pushes the thickness a little over $300\mu m$
4. *Expose:* Exposure is the process during which the printed image on the mask is transferred to the photo resist using UV light. The wave length should ideally be 365 nm however, anything in the range of 350-400nm should work. Optimum exposure should give near vertical side walls, and precise transfer of the mask geometry to the photo resist. If the exposure energy is too high then 'T' topping will occur, where the top of the photo resist is exposed fully but the photo resist underneath is improperly exposed, thus when it is developed the photo resist will have 'T' shaped profile. If the exposure time is too great then the resolution of the transfer from the mask to the photo resist is limited, because the photo resist will be exposed underneath the dark area of the mask due to reflected UV light. Under exposure will cause the top layer of photo resist to harden, however the material underneath will not, thus when the disk is developed the entire layer of photo resist will be removed, leaving no channel pattern. Caution should be used when working with UV light as it will damage ones eyes. The following procedure should be used as a reference but it requires optimization.
- a) Draw channel design in a vector graphics software package, such as Inkscape and print onto a transparent film, over head projector plastic works well

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in combination with a laser printer. Set the printer to the highest possible ink transfer, to maximize the opacity of the ink on the transparency.

- b) Trim the mask so that it fits over the disk easily.
- c) Place the disk with the mask on top into the developing box.
- d) Expose the disk/mask to 365nm UV light at 630 mJ/cm^2 for 5 minutes.

5. *Post Exposure Bake (PEB)*: The post exposure bake continues the process of interlinking the photo resist molecules that was begun by exposure to UV light. If the exposure was successful then within 1-2 minutes of starting the PEB bake the exposed image should be visible, if no image is visible then either the exposure was not sufficient or the PEB bake temperature is not correct.

- a) Preheat hot plate to 95°C .
- b) Remove disk from exposure box
- c) Place on hot plate and bake for 22-24 minutes.
- d) Remove from hot plate and allow to cool

6. *Develop*: The development process removes the unwanted SU-8 compound leaving only the SU-8 that was thermally linked by exposing it to UV light and then PEB baking. If the SU-8 compound is not removed after prescribe soaking time, more agitation is required, an ultrasonic bath would be the ideal method of providing agitation to the development process

- a) Place disk in low walled dish, and coat with either diacetone alcohol or ethyl lactate or preferable Micro Chem's SU-8 developer.
- b) Allow the disk to soak for 10-20 minutes until the unwanted SU-8 is removed.
- c) If SU - 8 is not easily removed more agitation is required.

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7. Develop to remove the OmniCoat compound so that the conductive base is exposed. All of the OmniCoat must be removed, if any is left in the bottom of the channels it will prevent the copper from growing and ruin the plate.
 - a) Place disk in low walled dish, and coat with either MF319 - OminCoat developer.
 - b) Allow the disk to soak for 10-20 minutes until the exposed OminCoat is removed, leaving behind the conductive copper layer.
 - c) If the OmniCoat is not completely removed after the initial soak period more agitation is required.
8. Electroform the channel walls, ~ 20 hrs at 10 mA/cm^2 will produce approximately 0.27mm thick layer - depending on the throwing power of the bath, rotate disk 180 degrees at 5 hours, rotate 90 degrees at 10 hours and rotate 180 degrees at 15 hours.
 - a) Attach the plate to the hanging wire- insert approximately 1 inch of 20 gage wire though the hole in the top center of plate and bend in 180 degrees. Twist the wire together so that the wire is attached to the plate and the plate cannot be removed except by untwisting the wire.
 - b) Open electroforming bath lid. Remove cathode holder and loosen the bolts/nuts.
 - c) Place hanging wire though the cathode holder until the top of the plat is hanging ~ 2 inches below the lower surface of the cathode holder or lower to ensure that the top of the plat is approximately 1 inch below the surface of the liquid in the plating bath. Tighten the bolts/nuts, to secure the hanging wire in place.
 - d) Replace the cathode holder into electroforming bath - ensure that the workpiece is carefully inserted between the anode hanging plates (splash

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cover) and that the normal vector of the workpiece's plating surface it pointed towards one of the anode banks.

- e) Twist the hanging wire around the cathode lead.
 - f) Replace the lid on the electroforming bath.
 - g) Turn on the power and set the current to 20 amps per square foot (3 inch diameter + 10% = ~1.08 amps)
 - h) After 1/4 of the time has passed (1hr 45min) turn off the power, removed the lid, remove the cathode workpiece, untwist the 20 gage wire from the hanging tab and rotate the work piece 90 degrees and re-attache the 20 gage hanging wire to the next hanging tab.
 - i) Repeat step 1.j.vii at 1/2, and 3/4 time.
- 9. Remove the SU8 Compound via activating the OmniCoat's removal properties.
 - 10. Fill channels with wax, paint top of wax with conductive ink
 - 11. Remove conductive ink from top of channel walls
 - 12. Electroform the part at 10 mA/cm^2 for 6 hours, rotate 180 degrees at 3 hours
 - 13. Heat part to 300°C until all wax has vaporized.
 - 14. Seal and charge.

2.1.2.3. Wax.

The process of coating an object with wax on all sides is quite an art, and requires some basic knowledge on the interaction of the wax and copper and the wax and flame as well as a lot of practice applying the correct amount of heat with the blow torch. First the interaction of wax and copper will be discussed.

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When done properly the wax will coat the copper completely, creating a non conductive shell that is very good as a mask in the electroforming process, however, when done improperly the wax will not stick to the copper and a generally frustrating mess will result. When coating copper with wax one must first slowly heat the copper to the melting point of the wax, the goal is to keep it as close to the melting point as possible so that with the application of a little more heat the wax will melt, but when the heat is removed the wax will harden. If the copper is not preheated at all then the wax will not stick to it at all. One can get away with not preheating very thin copper parts (foil) as these heat up fast enough that as soon as heat is applied to melt the wax the thin copper is to temperature. With thicker parts, however, if the part is not preheated and wax is melted onto the copper it will appear that the wax is coating the copper, however, it is just sitting on top of the copper because it cools too fast to bond to the copper. Even if a blow torch is applied to the wax-copper the wax will not bond properly to the copper until the entire block of copper has reached the melting point of wax. When the copper is to the melting point of the wax, the wax will wet the copper very easily. After this initial wetting of the copper has been accomplished, additional wax can be added to the wax that is already on the copper without heating the entire block of copper back up to the melting point of the wax - this is key to coating all sides of a part. For further detail on the process of coating a part with wax refer to the procedure at the end of this sub subsection.

Flame control is also a very important skill, vital for getting a uniform coat of wax on a part. First one must start with the correct blow torch. The ideal torch is free standing but can also be held in the hand, and has an adjustable flame that does not require constant pressure on a switch to control. A small flame is all that is needed to heat the wax, however, the flame must be consistent. When using the flame to heat the wax care must be used, because the heat output of the flame is many time greater than the thermal conductivity of the wax, thus the wax's temperature can

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suddenly and rapidly increase. If the temperature of the wax exceeds its smoke point, the wax will begin to smoke, the smoke is vaporized wax and is flammable. Thus to avoid heating the wax too rapidly it is best to use either the side of the flame, or to move the torch rapidly over the wax, not allowing it to rest on any one point.

The following is the basic procedure to coat a copper cylinder that is approximately 3" diameter by 0.5 " thick, and that has a 2.25 " diameter area on the front face that is to be fuzzy plated.

1. Attach a 'metal loop' stand to a vertical chemistry rod stand, ensure that the loop is in the horizontal plane.
2. Place copper cylinder on top of the loop stand, with the front face upwards
3. Place a small piece of wax on top of the copper and heat the cylinder from under neath until the wax just begins to melt.
4. Remove the heat
5. Rub a large piece of wax over the exposed copper surface, coating it with a thin layer of wax. If the copper cools below the melting point of the wax reheating it until the wax melts again.
6. Allow the copper to cool until the wax is solid and it is cold enough to turn over.
7. Turn copper over and repeat steps 3-5.
8. Once the backside of the copper is coated with a thin film of wax use the flame to melt the large piece of wax above the surface of the cylinder, so that it drips the molten wax onto the backside of the copper cylinder. Drip wax until there appears to be enough to melt together to make a thick layer (2-3 mm). Make

2. Compact OHP

sure to uniformly distribute the drops of wax, as it will make it easier to make a uniform coating.

9. Heat the copper cylinder so that the dripped wax will melt and spread. This will cause the thin layer of wax on the front of the copper cylinder to melt and drip wax, so ensure that it is above a disposable or easily cleanable surface.
10. Once the backside of the cylinder is uniformly coated with a thick film of wax allow it to cool.
11. Remove the cylinder from the loop stand, and turn over, so that the front face is facing upwards. Allow to cool completely
12. Repeat step 8, until the front face is covered in droplets of wax.
13. Remove cylinder from loop stand and hold in hand.
14. Carefully, using a small flame heat the wax on the front of the cylinder. The goal is to melt only the wax, with out significantly heating the copper. Work on a small part at a time, heat briefly until the wax just begins to flow, then removed the heat and allow the wax to harden then repeat. If the flame is left on one spot for too long and the copper is heated to the melting point of the wax, the wax will melt off and the process must be restarted.
15. Repeat steps 12-14 until the entire cylinder is coated with a thick layer of wax.
16. To remove a select portion of the wax; heat the selected area gently until the wax becomes soft.
17. Using a scraping tool or a utility knife blade carefully remove the bulk of the wax so, reheat if needed.

2. Compact OHP

18. Once the bulk of the wax is removed use the blade without heat to remove as much as possible - the more that can be removed with a blade the faster the removal process will go.
19. Using a small piece of Scotch-Britte abrasive pad remove any remaining unwanted wax.
20. Clean the exposed copper surface in 50% mix of Dura Clean and water.
21. Place a small amount of water on the cleaned surface, if the water wet the surface evenly and easily then it is properly cleaned of wax, if not then repeat the wax cleaning process. A rinse in acetone can also help to remove contaminating oils from the surface, however, do not soak the part in acetone as the wax reacts with the acetone.

Subtractive Wax Wax also works well in a subtractive manner. That is a block or bulk form a wax is build to a roughly desired shape, and then parts are removed using tools such as blades and files until the final desired geometry is achieved. Subtractive techniques were used extensively in the production of the OHP as a way of producing the desired channel geometry

1. Cut out metal blank (4.2cm x 8 cm)
2. Scrub blank with 3M "Scotch-Britte, light duty hand pad (#6448)"
3. Clean the plate with a 50% solution of Dura Clean for 1 minute. Once the cleaning is performed do not touch the plating surface with fingers, as skin oil will be deposited which will interfere with the plating process.
4. Heat and coat with a thick layer of was on both sides of the plate.
5. Drill a hole in the top center - used to hand the plate on the hanging wire in the electroforming bath

2. Compact OHP

6. Remove any excess surrounding the hole that will interfere with the hanging wire making good contact with the plate, was with a razor and scotch Britte pad.
7. Using a razor blade for a utility knife and a small ruler draw a grid on the surface of the wax on the side that you wish to form into channels.
8. Once the grid is drawn lay out the channel pattern as seen in Figure 2.7
9. Using the razor blade cut into the wax until the underlying copper is reached, a metallic ruler is useful to maintain the linearity of longer lines. For thicker walls use a flat headed screw driver or similar tool to remove more wax, or use the razor to cut a double wall line, and remove the wax between the two cuts.
10. Once all of the wall-lines are cut double check that all the wax is removed from the groove, if any part of the copper in the groove is not properly exposed copper will not form that part of the wall and the entire plate will be scrap.
11. Repeat step 10, triple checking that all of the wax is removed from the wall lines. The final product should look like the plate in Figure 2.7.
12. Attach the plate to the hanging wire- insert approximately 1 inch of 20 gage wire though the hole in the top center of plate and bend in 180 degrees. Twist the wire together so that the wire is attached to the plate and the plate cannot be removed except by untwisting the wire.
13. Rinse with de-ionized or distilled water.
14. Clean plate in a 10% solution of Sulfuric acid for 1 minute.
15. Open electroforming bath lid. Remove cathode holder and loosen the bolts/nuts.
16. Place hanging wire though the cathode holder until the top of the plate is hanging ~ 2 inches below the lower surface of the cathode holder or lower to

2. Compact OHP

ensure that the top of the plat is approximately 1 inch below the surface of the liquid in the plating bath. Tighten the bolts/nuts, to secure the hanging wire in place.

17. Replace the cathode holder into electroforming bath - ensure that the workpiece is carefully inserted between the anode hanging plates (splash cover) and that the normal vector of the workpiece's plating surface it pointed towards one of the anode banks.
18. Twist the hanging wire around the cathode lead.
19. Replace the lid on the electroforming bath.
20. Turn on the power and set the current to 20 amps per square foot.
21. Plate for desired time ~10-20 hrs depending on the thickness of the wax and the amps per square foot - refer to electroplating instructions above for more detail.
22. Open electroforming bath lid and the rinse bath lid
23. Remover the cathode holder, take care that the workpiece does not snag on the splash guard.
24. Holding the top of the cathode holder swish the workpiece bath and forth in the rinse bath - removing the majority of acid and copper ions.
25. Take to sink and continue to rinse further using tap water
26. Remove the workpiece from the cathode holder and return the holder to the electroforming bath
27. Clean the plate with a 50% solution of Dura Clean for 1 minute.
28. Rinse with tap water, and allow to dry.

2. Compact OHP

29. Once dry, using a small paint brush apply the conductive ink only to the wax surface. Do not get ink on the top's of the channel walls as this will prevent a copper-copper bond and may allow separation of the cover from the channel walls.
30. Allow the ink to dry for several hours. Dry time is dependent on the thickness of ink coating
31. Once dry, clean the plate with a 50% solution of Dura Clean for 1 minute. Once the cleaning is performed do not touch the plating surface with fingers, as skin oil will be deposited which will interfere with the plating process.
32. Return the plate into the electroforming bath following steps 14-20. The power should be set to 20 amps per square foot ($4.2 \text{ cm} \times 8 \text{ cm} = \sim 0.85 \text{ amps}$).
33. Allow the workpiece to plate for 5-10 hours depending on the thickness of cover plate desired.
34. Follow steps 22-26 to remove the plate from the bath

2.1.2.4. Comparison of techniques

From the comparison in Table 2.1 it is easy to see that photo lithography is the ideal process for using in the 3D OHP project. Subtractive wax is useful for very basic work with the perfecting the growth of the channel wall, because it save the time of making an entire OHP plate using the photo lithography process only to have it fail in the electroforming process. Thus it is recommended that the subtractive wax technique be used for the initial optimization of the electroforming technique, but photo lithography should be used as the primary method of producing the 3D OHP's.

2. Compact OHP



Figure 2.7.: Wall channels cut through the thick wax layer on copper substrate

Table 2.1.: Comparison of the three masking techniques

	Pro's	Con's
Toner Transfer	Technology is universal and easily available.	Not 100% 'opaque' to electroplating. Which causes plate through.
	Very fast to prepare copper mask	High failure of trace transfer.
	Computer based pattern.	Requires iterative wax addition
Photo Lithography	Well developed technology.	High initial chemical cost
	Very high resolution.	
	Computer based pattern.	
	Consistent	
	Controllable	
Subtractive Wax	Low level technology	Limited accuracy Limited resolution
	Cheap and fast to produce mask	'Hands on' time intensive.

2.2. Process Experimentation

2.2.1. OHP single layer construction

As a proof of concept 2 OHP's were created. Their channel geometry consisted of a single planar layer, with 6-8 turns. The subtractive wax technique was used to make the mask for the electroforming bath because it is the easiest technique and allowed the concept to be tested quickly.

The first plate, TCV-1.6 was electroformed for 37 hours at 0.75 amps with the pump running at full power providing direct agitation to the cathode to produce the channel walls. The plate was then removed from the bath and rinsed and allowed to dry. Once dry the top of the wax was coated with conductive ink. The ink was applied using a small brush, taking care to not get the ink on the top of the electroformed copper walls. It was noticed that there was an area where the wax mask had not been removed completely, because of this the channel wall had a large gap in it. In an attempt to repair this the wax was removed properly, it was hoped that during the second plating session - to form the cover- the channel wall would grow. The plate was place back into the electroforming bath for 24 hours at 1.0 amps. This second time in the bath grew the top cover for the OHP. The channel wall hole was not completely repaired, so the plate was coated with wax covering all the copper except for the small region surrounding the hole. By masking the rest of the plate it would be possible to plate the OHP plate until it appeared that the hole had be sufficiently covered. After the hole repair was complete the wax was removed by heating the whole OHP with a blow torch.

The blow torch was used to slowly heat up the wax on the exterior of the OHP while holding it with a pair of pliers, causing it to melt and drip off. Once the bulk of the exterior wax was removed the OHP was place on a fire brick and heated up until the wax that was inside started coming out of the charging openings, however,

2. Compact OHP

it was also noticed that there were several holes randomly scattered around the OHP plate that were allowing wax and wax gas to escape. Additional heat was applied to burn the wax out. Once all the wax had been removed the plate was pressure tested with air and numerous leaks were found.

The second plate was produced in much the same way as the first plate, using the subtractive wax masking technique to pattern the channel wall geometry. TCV-2.0 was electroformed for 1.5 hours at 0.18 amps then for 19.5 hours at 0.07 amps and then for 25.5 hours at 0.7 amps to produce the channel walls. As with plate TCV-1.6 the conductive ink was used to make the wax conductive to grow a cover plate. The plate was electroformed for 18.5 hours at 0.85 amps. This second time in the bath grew the top cover for the OHP, which turned out to be the first piece of fuzzy copper created and will be discussed in detail in Part II.

2.2.2. Problems and Recommendations

There were two main problems with both plates that were created. Both TCV-1.6 and TCV-2.0 exhibited similar problems with the way that the copper walls grew, in that the tops of the walls were very lumpy and non uniform. Theoretically all of the wall should be the exact same height from the base material and since the channel walls were being grown on a flat substrate the tops should be even. However, instead of creating a smooth continuous piece of copper the electroforming bath was producing a rough, lumpy finish when left to plate for a long time. This lumpy surface, as seen in Figure 2.8, is indicative of dendrite growth, and the best method to prevent it is to use a pulse current.

The second problem with both plates is that the copper surface has though holes, this is also probably due to the dendritic growth leaving small holes between the lumps of copper, and in the case of plate 2 the fuzzy copper surface is permeable. This issue must be resolved before the electroforming bath will produce usable OHP's,



Figure 2.8.: TCV-2.0 after electroforming of the channel walls - notice the lumpy dendritic growth on the walls.

one possible solution is to use a pulse current, also known as pulse plating.

2.2.2.1. Pulse plating

Pulse plating is done by altering the dc power that is supplied to the electroplating bath so that it is pulsed at anywhere as slow as 10 Hz up to 1000 Hz or more. The ratio of the period on to the period off ($\frac{On}{Off}$) of the dc power is usually always less than 1 and is generally closer to 0.1, however as the ratio gets smaller the equipment required to produce the pulse gets more complex because the plating rate is based on the current average, so the smaller the ratio the larger the momentary peak current required to sustain the average current. During the pulse on period the electroplating cell operates normally, causing copper ions to adhere to the cathode. During the pulse off period the copper ions are allowed time to diffuse into the cathode boundary layer, thus when the power is again pulse on there will be a homogeneous distribution of ions within the fluid. Since there is always the maximum distribution of ions in the cathodic boundary layer the plating efficiency is increased.[5]

2. Compact OHP

Another benefit of the pulse system is that the pulsed power encourages the growth of new grains, so the resulting deposit has a finer more dense grain structure. Dendritic structures are eliminated and the overall plating is smoother and has fewer defects. Since pulse plating eliminates dendritic growth and encourages a more dense material structure it should eliminate any uneven plating and eliminate the permeability problems that plates TCV-1.6 and TCV-2.0 had.

Generally pulse plating consists of on-off pulses, however, to increase the leveling power of the pulse system the pulse can be designed so that the polarity of the cathode and the anode switch. This would turn the work piece into the source of ions. Since material is removed from areas of highest potential first and high spots on the work piece will be removed faster than the lower areas, thus leveling the surface. Extensive experimentation would be required to determine the optimum variation of regular current to reverse current.

Part II.

Fuzzy Copper as a Wicking Structure

3. Introduction - How it happened the first time

The system seemed to be working as expected, TCV-2.0 channel growth had just been completed and it had been coated with conductive ink and prepared to be returned to the bath. Before it was placed in the bath the fluid return nozzles were repositioned so that they were aimed to the center of the tank rather than about 1/4 down the tank to give better agitation to the parts. So using Fisherbrand powder coated latex gloves the nozzle spray direction was adjusted which required placing the fingers of the two gloved hands into the fluid. TCV-2.0 was placed back in the fluid and plated at 0.85 amps for 18.5 hours - very average values. However the resulting plating was drastically different from what had been produced thus far. TCV-2.0 was covered with a very fine but sharp 'copper fuzz'. The fuzz was uniform over the surface of the work piece and strongly attached. Figure 3.1 shows the 'fuzzy copper' growth after 18 hours in the bath.

Next a flat piece of copper was plated to see if it too would turn fuzzy, the following figures show, the results. This Figure 3.2 shows the two plates side by side, TCV-2.0 was done first TCV-2.1 was done second. The lines on TCV-2.0 are due to the underlying channel structure, TCV-2.1 is flat plate. As seen in Figure 3.2, TCV-2.1 grew a long tail spontaneously after ~24 hours in the plating bath.

3. Introduction - How it happened the first time

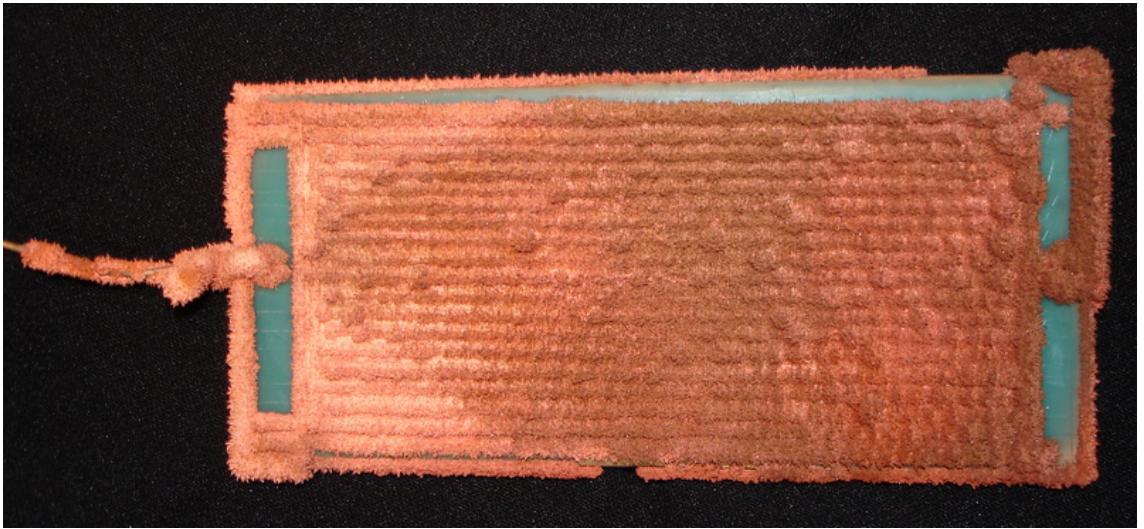


Figure 3.1.: TCV-2.0 with fuzzy copper cover growth

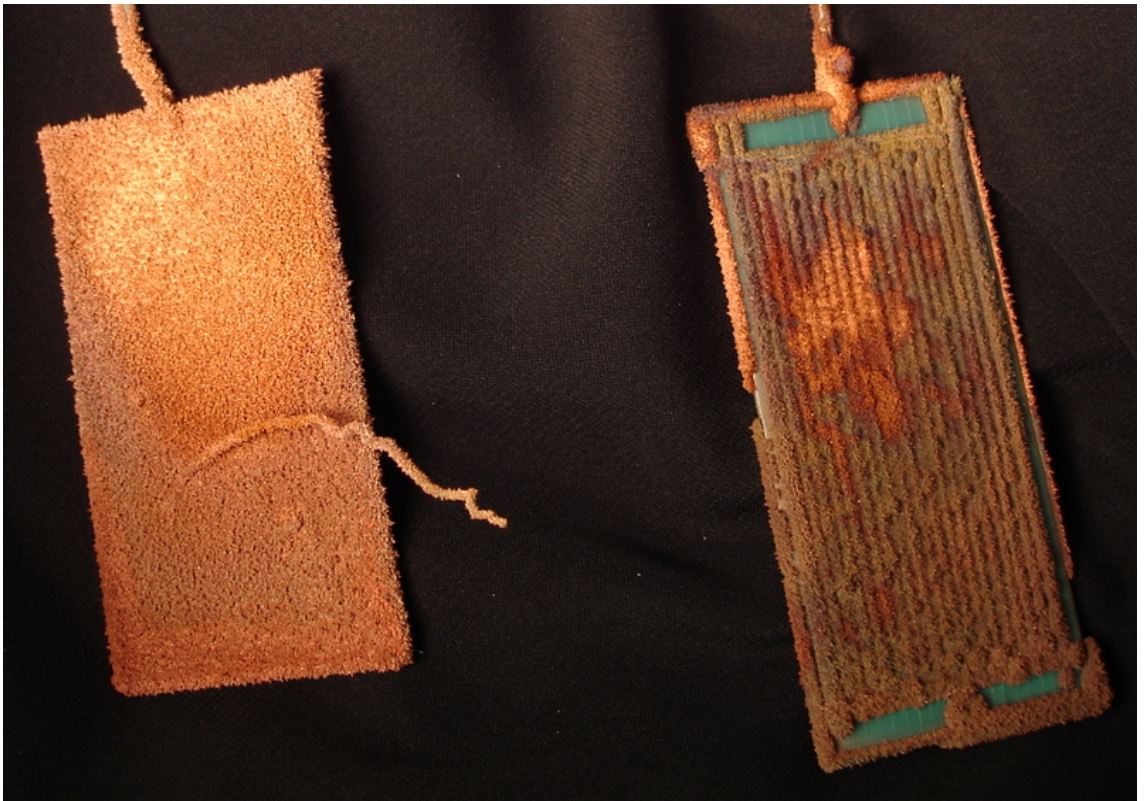


Figure 3.2.: TCV-2.1 is on the left, TCV-2.0 is on the right. The linear texture seen on TCV-2.0 is from the underlying channel walls that were electroformed before the cover was plated.

4. Introduction to the material structure

The fuzzy copper consists of dendritic copper structure, as seen in Figure 4.1, the copper clearly has the branching structure that is common to dendrite growth. Each growth has a main shaft from which branches extend and on each branch more branches extend. The branches tend to be close to perpendicular to the shaft from which they extend and theoretically should follow the path of least electrical resistance. Although their trajectory could be influenced by the agitation in the bath. The structure looks fragile but it is in fact quite tough and brittle - breaking instead of bending. All of the electrically exposed surface is covered with an even growth of the dendrite structure, with no apparent preference for the edges or corners of the plated part.

4.1. Light microscope results

A light microscope was used to take a closer look at the structure of the fuzzy copper material. TCV-2.1 was placed under the lens, while the results are interesting it is impossible to get a single picture with a complete view of the entire structure because it is too tall to focus on the whole thing at once. Thus the following figures are a series that were taken by first focusing the microscope at the bottom or root of the



Figure 4.1.: Edge of plate TCV-2.1. The green color is the wax used to mask the back of the copper plate and prevent the plating from growing on the back side. The fuzzy copper is clearly a crystalline dendritic structure.

structure, then moving the focus up the normal vector to the surface that was being observed. In this manner one can get an idea of the entire structure.

4.2. Light microscope results for original fuzzy copper specimen

Figure 4.2A is of the root of the structure. The scale is 1 unit equals $50\mu m$. Notice the round ball like structures in the root with a diameter of $\sim 50-75\mu m$, the roundness is indicative of traditional dendrites that form during an improperly prepared plating operation. The blurred areas are the portions of the plating that continue vertically, thus there is approximately 50% of the original plating area grows vertically, while the rest form a roughened channeled surface.

Figure 4.2B is of the mid section of the structure. Most of the structure is still rounded and appears to be several spherical parts joined together, however, the spherical diameter is larger than that found in the root. Also the size of each vertical structure is similar to what was seen in the first figure, thus the sides of the individual structures appear to be vertical. One can also see the first spike shaped protrusion in the bottom center of the figure - it is more visible in the next figure.

Figure 4.2C is of the top portion of the structure. Instead of rounded structure there are only spiked cone surfaces most of which have additional smaller spiked cones. The largest spike in the bottom middle is about $200\mu m$ long and $100\mu m$ wide at the base, which is significantly larger than the spheres seen in the root.

When ones finger is brushed over the surface it feels almost like Velcro, where the copper is attaching to the skin. The tactile sensation allow one to determine if the copper has formed very fine pointed branches or if it is still in it's knobby stage and consists of rounded features.

4. Introduction to the material structure

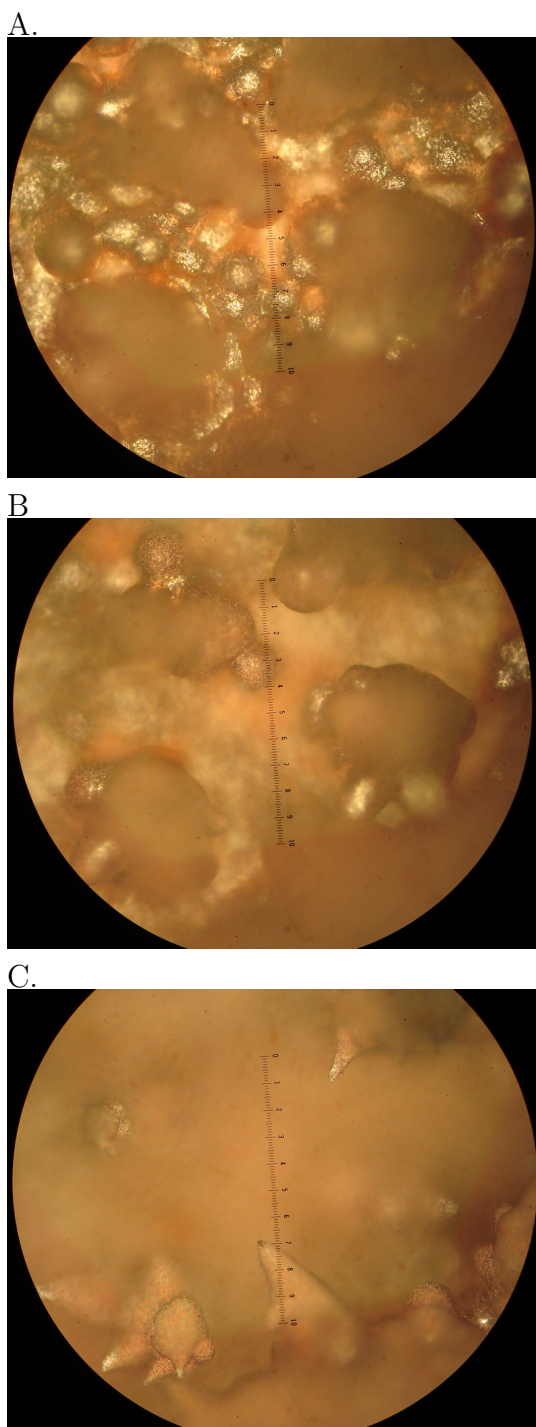


Figure 4.2.: A. - TCV-2.1 under the light microscope at 20x focused on the root of the structure. B. - TCV-2.1 under the light microscope at 20x focused on the mid section of the structure. C. - TCV-2.1 under the light microscope at 20x focused on the top portion of the structure.

4.2.1. Vapor chamber surface

Figure4.3A, shows the inside of the vapor chamber plating at 20x focused on the root or base of the plating. There are many similarities to Figure 4.2A, the surface is also covered with small structures, although they are flatter and less developed when compared with the root structure of TCV-2.1. There are also the blurry areas indicating vertical growth, they take up about 50% of the area in a similar manner to the above specimen.

Figure4.3B, shows the inside of the vapor chamber plating at 20x focused on the mid section of the plating. Unlike the in Figure 4.2B, the vertical growths have started growing pointed cones, seemingly with out an intermediate level of larger rounded growth. Another difference in the TCV-2.1 sample the growths in the vapor chamber plating seem to have non-vertical sides - where the cross section of the growth decreases as the distance in the z-axis is increased.

Figure4.3C, shows the inside of the vapor chamber plating at 20x focused on the top section of the plating. Like the in Figure 4.2C, spiked cones have developed, consisting of the main cone with smaller cones branching off.

The difference between the plating of the vapor chamber plating and the TCV-2.1 plate are probably due to the plating time which will be discussed more later, although could be due to subtle changes in the bath chemistry.

4.3. Fuzzy Copper Fabrication Procedure

The following procedure is to form a plate similar to TCV-2.1, although it could be used to plate any geometry provided that the size depended values are scaled accordingly.

1. Cut out copper blank (4.2cm x 8 cm).
2. Scrub blank with 3M "Scotch-Brite, light duty hand pad (#6448)".

4. Introduction to the material structure

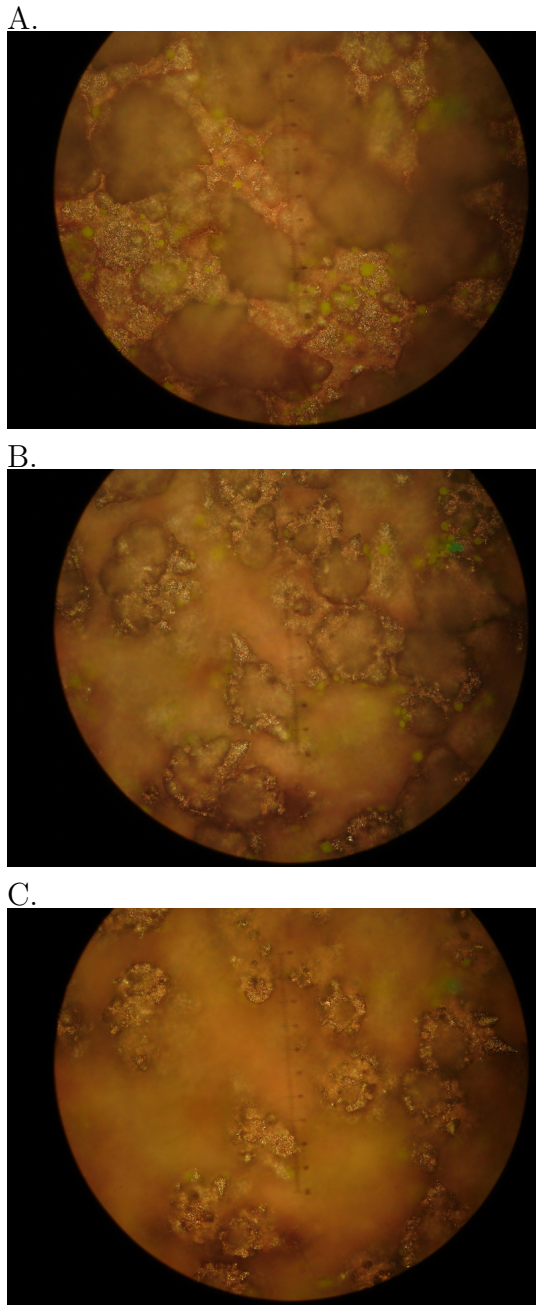


Figure 4.3.: Vapor Chamber inside plating 20x light microscope. A. Focused on the root. B. Focused on the mid section. C.Focused on the top portion.

4. Introduction to the material structure

3. Heat copper blank until surface is oxidized. The oxidation will aid in the later removal of the wax.
4. Heat and coat with a thick layer of wax on one side of the plate.
5. Drill a hole in the top center - used to hang the plate on the hanging wire in the electroforming bath
6. Remove any excess wax with a razor and scotch Britte pad.
7. Use a Scotch Britte pad to clean the oxidation off the copper surface that is to be plated. Clean it until the copper is showing though completely.
8. Attach the plate to the hanging wire- insert approximately 1 inch of 20 gage wire though the hole in the top center of plate and bend in 180 degrees. Twist the wire together so that the wire is attached to the plate and the plate cannot be removed except by untwisting the wire.
9. Clean the plate with a 50% solution of Dura Clean for 1 minute. Once the cleaning is performed do not touch the plating surface with fingers, as skin oil will be deposited which will interfere with the plating process.
10. Rinse with de-ionized or distilled water.
11. Clean plat in a 10% solution of Sulfuric acid for 1 minute.
12. Open electroforming bath lid. Remove cathode holder and loosen the bolts/nuts.
13. Place hanging wire though the cathode holder until the top of the plat is hanging ~ 2 inches below the lower surface of the cathode holder or lower to ensure that the top of the plat is approximately 1 inch below the surface of the liquid in the plating bath. Tighten the bolts/nuts, to secure the hanging wire in place.

4. Introduction to the material structure

14. Replace the cathode holder into electroforming bath - ensure that the workpiece is carefully inserted between the anode hanging plates (splash cover) and that the normal vector of the workpiece's plating surface it pointed towards one of the anode banks.
15. Twist the hanging wire around the cathode lead.
16. Replace the lid on the electroforming bath.
17. Turn on the power and set the current to 20 amps per square foot (4.2 cm x 8 cm = ~0.85 amps)
18. Allow to plate for desired time, do not disturb during the plating time

4.3.1. Time vs thickness

A test was conducted where seven piece of copper foil were attached to a copper wire, as seen in Figure 4.4 and placed in the electroforming bath at 20 amps per square foot. After one hour the copper wire with tabs attached was removed and the copper tab on the bottom was removed. This was repeated every hour until all seven tabs had been removed. Then the process was repeated, except that the it was allowed to electroform for 8 hours before the first tab was removed, then at two hour intervals the next tab was removed. Thus thickness data could be collected for 13 tabs at hourly and bi hourly intervals. The 14th tab on the second set was not used because when the 13th tab was removed it did not exhibit the expected dendrite structure and felt bumpy instead of sharp when rubbed with a finger. This may be because the last test tabs to be removed had been removed 6 times each - to remove the previous tabs. Thus the current was pulsed six times during the formation of the dendrite structure. According to pulse plating literature [5], pulse plating encourages the nucleation of new grains. Thus perhaps the very slow pulsing of the test tabs caused new grains to

4. Introduction to the material structure

nucleate creating a more rounded and less crystalline form of copper plate. Although the difference in seen in the last few test tab to be removed could also be because of the placement within the bath. Being higher in the bath, may have decreased the current density or agitation and thus decreased the plating rate.

The following table, Table 4.1, show the thickness of the grown structure compared to the time taken to grow. The times taken to grow the plating on the cover and the base plate are included. The plate thickness on the base of the vapor chamber parts is thinner than the plating thickness on the cover plates, this is because the base has a wall which will be at higher potential than the lower flat part of the base, and only the flat base of the base part was measured for thickness because the curvature of the wall would alter the thickness reading. Figure 4.5 is a graph of the data in Table 4.1, along with a best fit line for the copper test tab data. The best fit equation shows that the copper grows at 0.0048 inches, or 0.122 mm, per hour. The thickness data seems scattered, this may be because when the copper test tab were electroplated the tabs near the bottom of the bath might have had higher potential, thus plating faster. The plate rate is also dependent on the structure that is being plated. If the structure is highly porous then it will grow taller faster because the material being deposited is less dense.

4. Introduction to the material structure



Figure 4.4.: Copper tabs attached to a copper wire for the purpose to testing the growth rate of the electroforming bath.

Table 4.1.: Table of the thickness of the grown structure vs the time taken to grow.

Test Part Number	Plating Time (Hours)	Plating Thickness (Inches)
TCV-2.2.1	1.13	0.00760
TCV-2.2.2	2.13	0.01943
TCV-2.2.3	3.53	0.02860
TCV-2.2.4	4.20	0.02710
TCV-2.2.5	5.17	0.02957
TCV-2.2.6	6.13	0.03463
TCV-2.2.7	7.22	0.03777
TCV-2.2.8	7.98	0.06493
TCV-2.2.10	9.77	0.06740
TCV-2.2.12	12.13	0.07043
TCV-2.2.14	14.18	0.06683
TCV-2.2.16	15.97	0.06403
TCV-2.2.18	17.88	0.05767
TCV-VAP-1.4	12.59	0.04740
TCV-VAP-1.5	11.80	0.05510
TCV-VAP-1.6	11.23	0.05937
TCV-VAP-1.7	13.00	0.04552

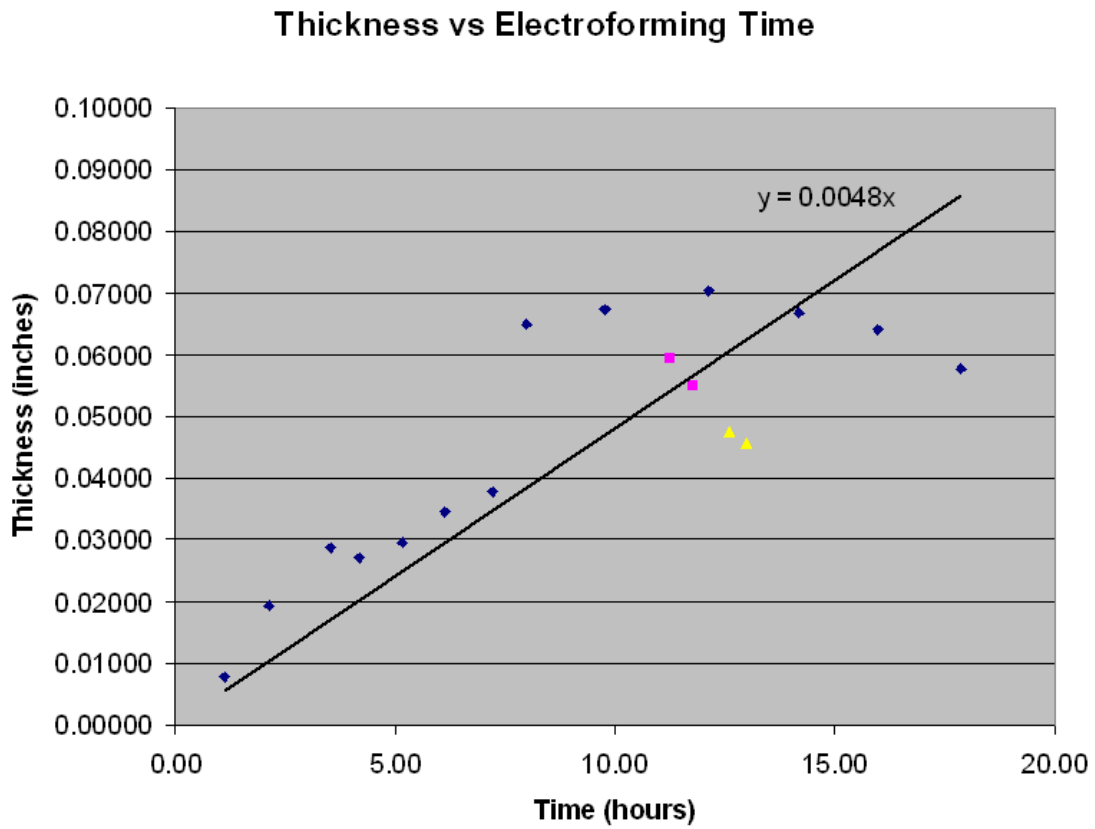


Figure 4.5.: Graph showing the thickness of the plating vs the process time.

5. Vapor Chamber Fabrication

Four vapor chambers were created to test the fuzzy copper as a wick structure. These four vapor chambers used the fuzzy wick structure as a capillary medium as well as capillary spring bridges and rolled mesh reservoirs. A fifth vapor chamber was made using no wicking structure so that it could be compared to the vapor chambers using the fuzzy copper. A solid block of copper of similar dimensions was also tested using the same setup.

5.1. Technologies Employed - Capillary Spring Bridges and Rolled Mesh reservoirs

Capillary spring bridge Capillary spring bridges and rolled mesh reservoirs were two of technologies that were using in the construction of the vapor chambers other than the fuzzy copper wick structure. The capillary spring bridges took two different forms, but the basic purpose was the same for both. The spring bridges connect the top wicking surface to the lower wicking surface of the vapor chamber with a wicking path that is shorter for the fluid to travel. Without capillary spring bridges the fluid, after evaporating from the lower capillary surface and condensing on the top surface, has to travel radially to the wall to return to the lower layer and evaporate again. The capillary bridges provide a link between the top and the bottom plate that is shorter, thus the fluid can complete the two phase cycle faster which allows

5. Vapor Chamber Fabrication

the vapor chamber to operate at higher heat flux without drying out. The first form of the capillary spring bridge was used in VAP 1 and can be seen in Figure 5.2, and consisted of a 10 mm wide strip of copper foil that had been electroplated with fuzzy copper solution for 2 hours. The strips were cut and bent into a 'V' shape, when the vapor chamber was sealed the two arms of the 'V' pressed on the top and bottom of the vapor chamber and the springiness in the copper foil ensured that the spring bridge remained in place.

The second generation capillary spring bridges were using on VAP 3 and VAP 4. The second generation bridges consisted of a copper spring that was soldered to the base plate of the vapor chamber. Then during the electroforming of the base plate the copper springs were coated with the fuzzy copper growth. Ideally a straight capillary bridge would be used because the distance required for the fluid to travel would be shorter, however, using straight bridges would require maintaining very tight tolerances on the size of the vapor chamber. The spring form of the copper wire was used so that when the vapor chamber was sealed the spring would be compressed, and the compression force in the spring would cause it to maintain good contact with the cover plate. Figure 5.1 shows the capillary spring bridges in VAP 3.

Rolled Mesh Reservoirs Since a thin layer of fuzzy copper was used at the capillary surface in the vapor chambers there was not much wick volume for liquid storage. So to provide additional fluid storage and prevent pool boiling a roll of copper mesh was place around the outer edge of the vapor chamber. The mesh reservoirs were made from a 1 inch wide strip of fine copper mesh that was rolled into a tube and then bent into place, as seen in Figure 5.1 and 5.2. The rolled mesh also increased the ability of the fluid to flow from the top to the bottom plate.

Table 5.1 has a list of what features were used in which vapor chambers.

5. Vapor Chamber Fabrication



Figure 5.1.: Capillary spring bridges in VAP 3

Table 5.1.: Table of the features that were used in each vapor chamber.

Vapor Chamber	Capillary Spring Bridge	Rolled Copper Mesh Reservoir
VAP1	First generation	Yes
VAP2	None	Yes
VAP3	Second generation	Yes
VAP4	High density of second generation	Yes

5.2. Vapor Chamber - VAP 1

The first VAP1 was machined out of a 3" cylinder of copper by first turning down the top side so that it would fit into the water cooling block. Next the bottom was bore out to make half of the chamber. The top was then slotted so that the portion of the copper that goes into the water block was finned to increase the heat transfer to the cooling water. The other half of the chamber, the cover plate, was made from a 1/8th inch thick copper sheet. Both the copper sheet and the machined part of the chamber were coated with jewelers wax to mask the areas that were not to be plated, and electroformed for 18.3 hours at 1.47 amps (~20 amps per square foot). After electroforming the wax was removed and two notches were made in the wall of the machined base, so that charging tube could be inserted. The two halves were assembled with the charging tubes in place, and a roll of copper mesh around the outer edge of the chamber. It was then placed on top of a fire brick and another fire brick was place on top, weighed down with scrap copper to force the two halve together. The charging tube were used to flood the chamber with nitrogen gas to prevent the copper surface from oxidizing. The halves were then soft soldered together using acid flux and soft solder, 50% lead 50% tin.

5.3. Vapor Chambers - VAP2, VAP3 and VAP4

Vapor chambers, VAP2, VAP3 and VAP4 were created in a very similar fashion. Instead of spending a week in the machine shop hollowing out a cylinder of copper a 3 inch copper pipe was cut into rings and soldered onto a plate. Starting with a 1/8th thick copper plate and a 3 inch ring of copper that was approximately 5 mm tall the base of the vapor chamber was made in a few minutes. The plate was placed on a fire brick, and the ring was placed on top and weighed down using another fire brick with weights on top. The ring was soldered into place using acid flux and

5. Vapor Chamber Fabrication



Figure 5.2.: Vapor chamber VAP 1, top and bottom plates and first generation spring bridges.

Table 5.2.: Table of the processing times and amperage's of vapor chambers VAP2, VAP3 and VAP4.

		Time (Hours)	Amperage (amps)
VAP2-Base	TCV-VAP-1.4	12.5888	1.30
VAP2-Cover	TCV-VAP-1.5	11.8	.98
VAP3-Cover	TCV-VAP-1.6	11.23	.98
VAP3-Base	TCV-VAP-1.7	13	1.36
VAP4-Base	TCV-VAP-1.8	27.6	.98
VAP4-Cover	TCV-VAP-1.9	27.2	1.50

soft solder. In the case of VAP 3 and VAP 4 the springs that were to become the capillary spring bridges were also soldered into place. The base the and cover plate were then electroformed to coat with fuzzy copper wicking structure, refer to Table 5.2 for the processing times and amperage's of the individual parts. As with VAP1; VAP2, VAP3 and VAP4 were coated with wax to mask the areas that were not to be plated.

After plating a hand held rotary tool was used to cut grooves in the chamber wall for the charging pipes. And a roll of copper mesh was installed around the outer edge of the vapor chamber. The two halves were place in Dura Clean for 1 minute to remove any oxide and then rinsed with water and then rinsed with acetone to speed surface drying and to remove an remaining residues. The vapor chamber was

5. Vapor Chamber Fabrication

assembled and flooded with a continuous flow of nitrogen gas to prevent the capillary surface from oxidizing. The assembled chamber was sandwiched between two fire bricks and sealed with acid flux and soft solder. Figure 5.3 shows VAP2, VAP3 and VAP4.

5.4. Charging the Vapor Chambers

The charging setup as seen in Figure 5.4 was used to charge the vapor chambers.

VAP3 3"tube – ‘spring bridges’ insides

Initial weight: 179.59g

Flooded with 14.4 g of water (~10ml) Rotated around slowly for 3 minutes to help distribute the water and fully wet the wick. Allowed to sit for 5 minutes Removed fluid until no more water slugs were seen leaving the Vap Chamber though the charging tube. The charging tube was crimped using phnematic plies, and then coated with solder.

Final weight: 187.38g

Water fill: 7.79g

VAP 5 3"tube – Mesh reservoir, no wicking structure

Initial weight : 150.34g

Flooded with 15.8 g of water (~15ml) Rotated around slowly for 3 minutes to help distribute the water and fully wet the reservoir. Allowed to sit for 5 minutes Removed fluid until no more water slugs were seen leaving the Vap Chamber though the charging tube. The charging tube was crimped using phnematic plies, and then coated with solder.

Final weight: 156.49 g

5. Vapor Chamber Fabrication

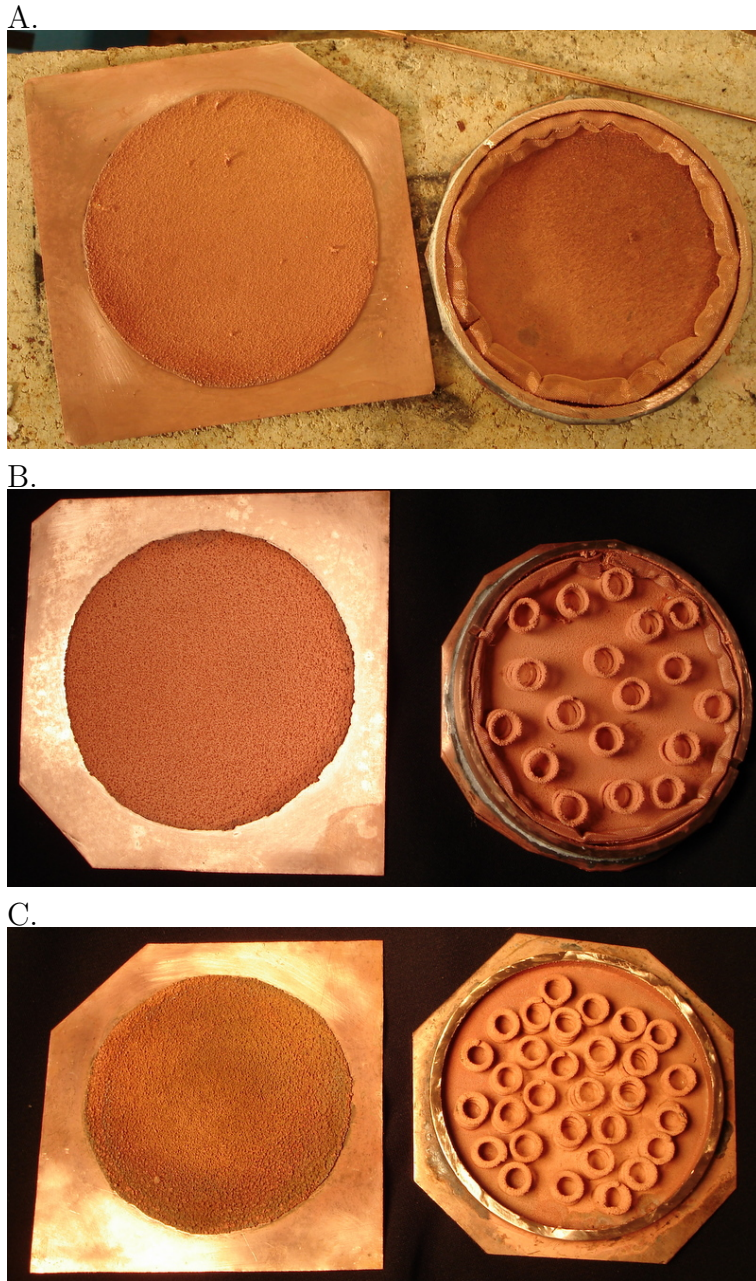


Figure 5.3.: A.VAP2, B. VAP3 and C. VAP4

5. Vapor Chamber Fabrication

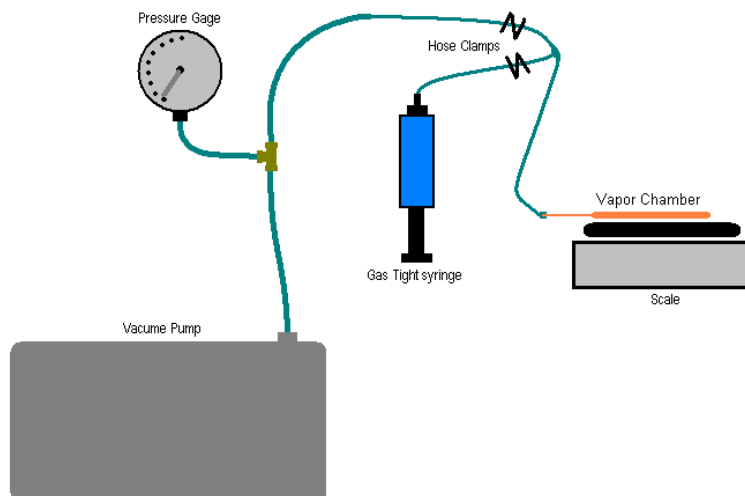


Figure 5.4.: Charging setup used to charge the vapor chambers.

Water fill: 6.15 g

Vap 3 – Charge 2 3”tube – ‘spring bridges’ insides

Initial weight: 179.59g

Attached to vacuum pump, vacuummed for ~45 min, shaking periodically until no more liquid water could be removed. The charging tube was crimped using pneumatic pliers, and then coated with solder.

Final weight: 183.92g

Water fill: 4.33g

6. Vapor Chamber Testing

6.1. Vapor Chamber Testing setup

6.1.1. Water block condenser

To provide cooling to the vapor chambers during testing a water block was made that would seal onto the top of the vapor chamber using a rubber O-ring. The cooling block is seen in Figure 6.1. In the top of the cooling block were the in and out water pipe barbs. Inside the water flow was forced close to the top surface of the vapor chamber by placing a piece of rubber hose across the flow, so that the bottom of the hose was just a few millimeters off the top surface of the vapor chamber. The rubber O-ring worked very well to seal the water block onto the tops of the vapor chambers and with proper clamping no leaks were experienced.

6.1.2. Thermocouple locations

Eight thermocouples were used to gather temperature data from the vapor chambers that were tested. After the thermocouples were welded and tested, and were functioning correctly the tip of the thermocouple was dipped in liquid electrical tape (liquid vinyl) allowed to dry and re dipped. The dipped end was then wrapped with a small piece of Teflon tape, tested again to ensure proper functionality and then installed onto the vapor chamber using a piece of aluminum tape to secure them in place.

6. Vapor Chamber Testing

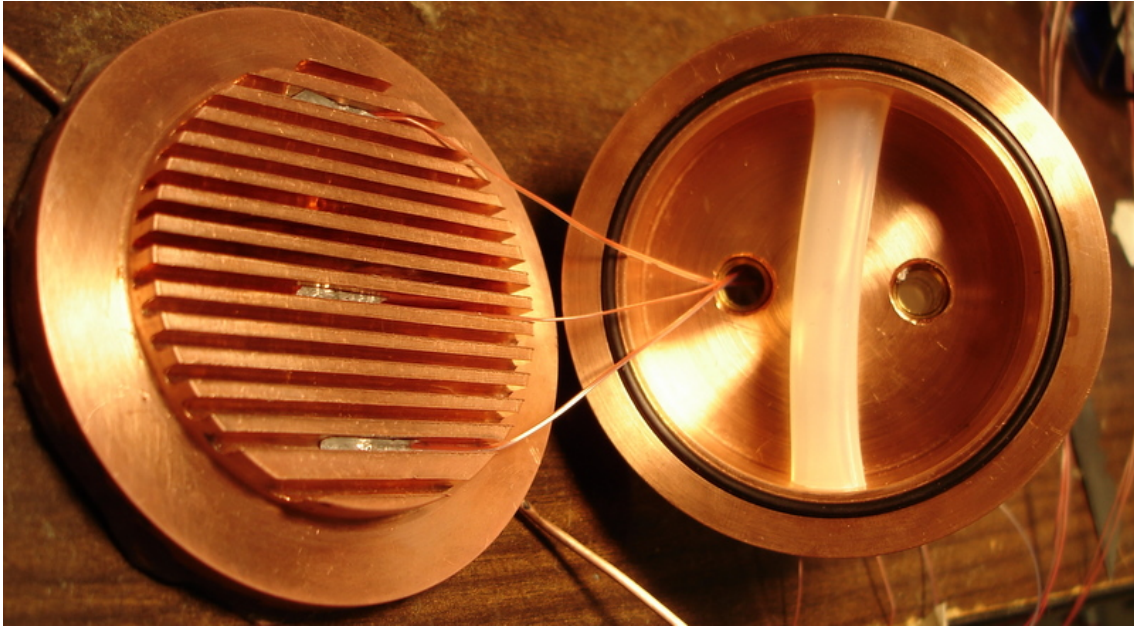


Figure 6.1.: On the right is the cooling block used to cool the vapor chambers, on the left is the top of VAP1 with thermocouples installed.

The thermocouple that was plugged into channel a1 was placed on the heater core - the piece of copper bar stock that the band heater was wrapped around. The bar stock provides the conductive path for the heat, from the heater to the vapor chamber. It also allows the contact surface area between the heater core and the bottom of the vapor chamber to be varied to simulate different heat loads. The thermocouple from channel a2, a3, and a4 were attached to the bottom of the vapor chamber as seen in Figure 6.3. A2 was placed 2.5 mm away from the edge of the heater core, A3 was placed 10 mm away and A4 was placed 17.5 mm away, along a straight radial line.

The thermocouples on the top of the vapor chamber had to be fed through the water inlet pipe. Initially the thermocouples were placed in the brass barb and the water hose was slid over the wires. This partially worked, except that the pipe-barb connection tended to leak around the wires and several times the thermocouple wires were broken due to the force that the hose applies to the wire as it is slid over the barb. To solve this issue, a wye-connection was added to the water inlet line, and on the second input into the wye a series of reducing tubes were connected that allowed

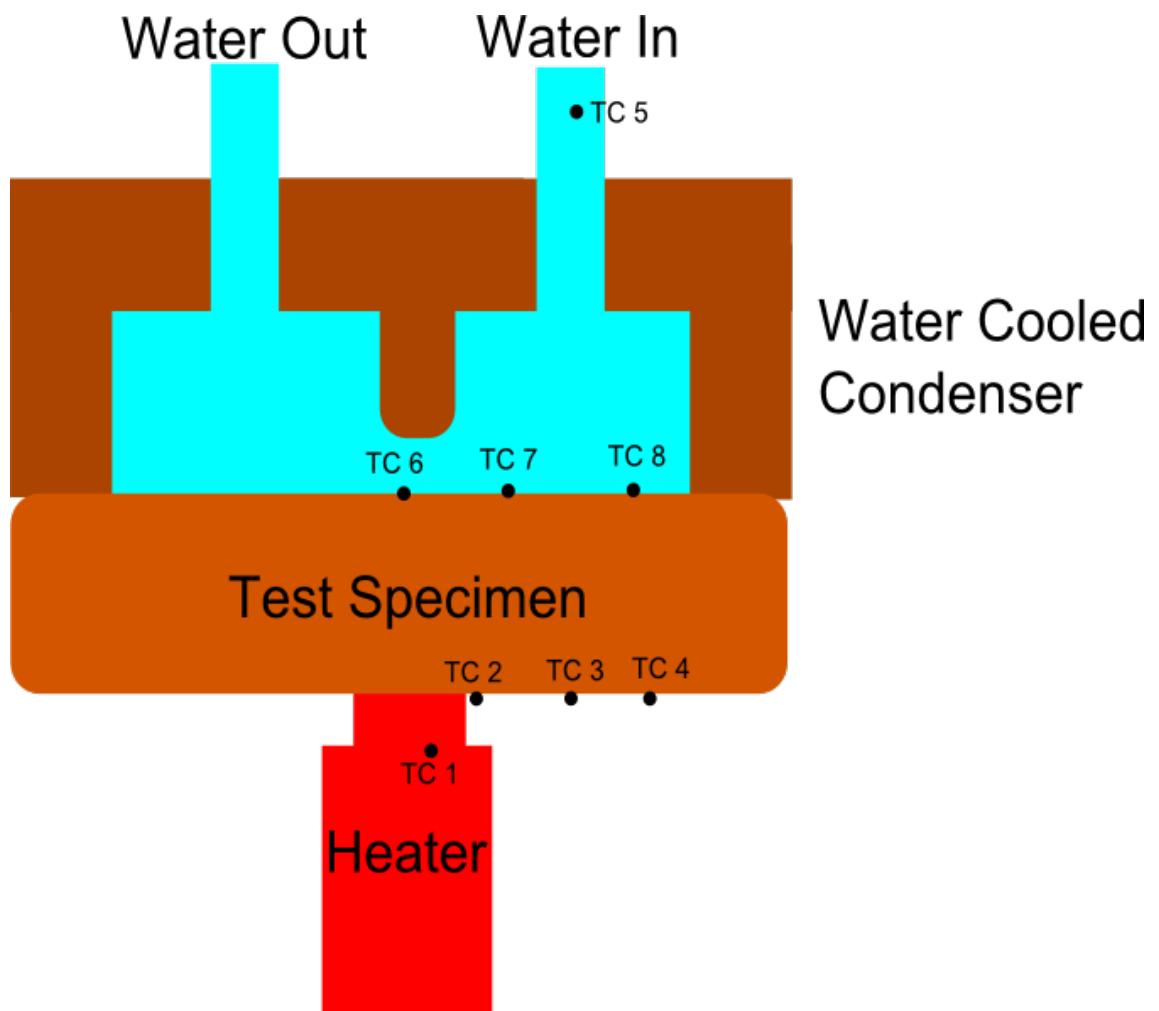


Figure 6.2.: Testing setup

6. Vapor Chamber Testing

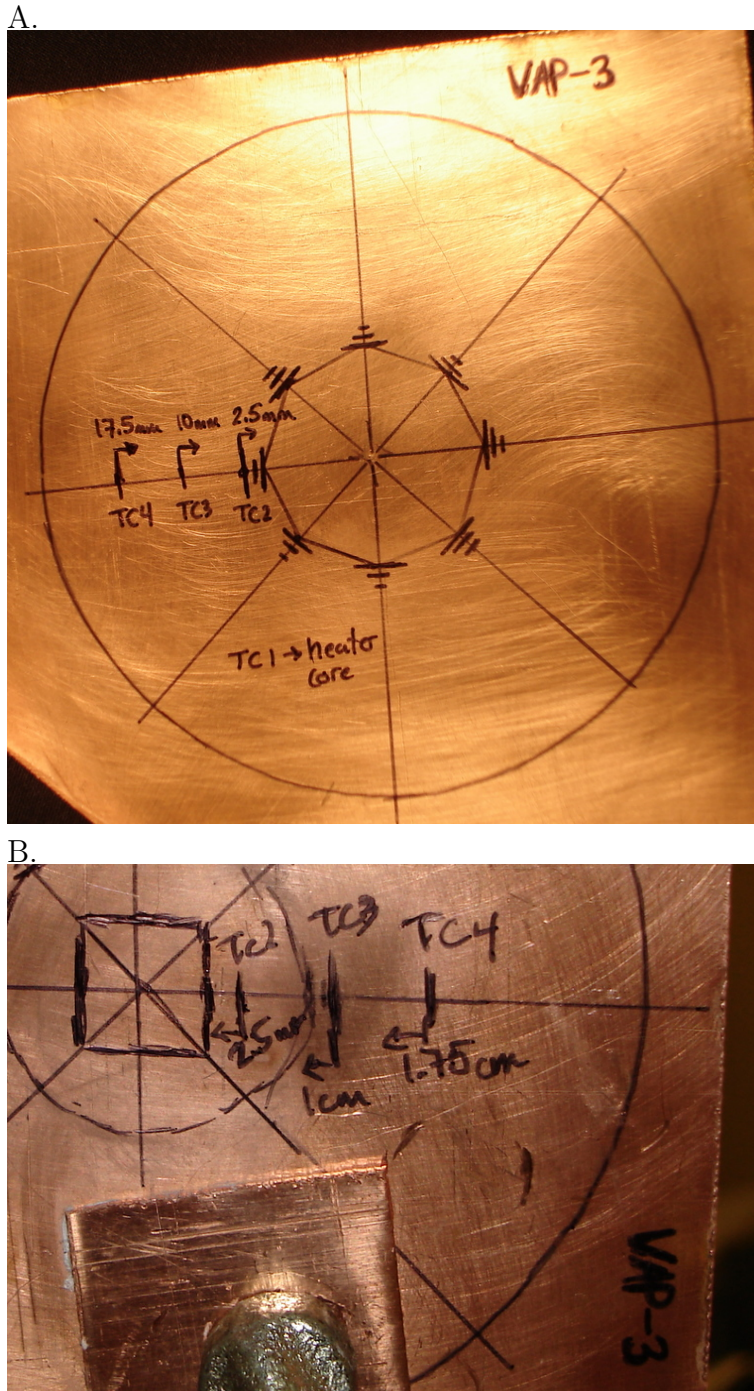


Figure 6.3.: Thermocouple placement on the bottom of the vapor chamber. Thermocouples include channels TC2, TC3, and TC4. A. Thermocouple placement for the 5 cm^2 surface area contact heater core. B. Thermocouple placement for the 1 cm^2 surface area contact heater core.

6. Vapor Chamber Testing

the thermocouples to be slid through and sealed in place, avoiding leaks and preventing extreme bending that encouraged the breaking of the wires. Once the thermocouples were fed through the wye into the water inlet hose they were fed into the condenser and attached to the top of the vapor chamber, as seen in Figure 6.4. Thermocouple connected to channel a6 was placed at the center of the top, a7 1cm away from the center and a8 2 cm away from the center, on a radial line. Thermocouple a5 was placed in the incoming water pipe to measure the temperature of the water coming into the condenser block. When the condenser block was placed on top of the vapor chamber it was situated so that the radial line which contained the three thermocouples was parallel to the fluid flow, with the thermocouples on the exiting side of the water block. So when the cool water entered the water block it would first flow over the first half of the vapor chamber and then flow over the second half containing the thermocouples.

6.1.3. Testing setup

To secure the water block to the top of the vapor chamber a two small C-clamps were used. To hold the heater onto the bottom of the vapor chamber the entire system was clamped in a large C-clamp, as seen in Figure 6.5. Clamping the system together simplified the construction of the individual parts, making them much faster and easier to produce. However, due to the thin wall thickness of the bottom plate and the centrally located force of the heater some deflection did occur, although it was insufficient to cause the top and the bottom of the chamber to touch, it was probably enough to slightly affect the capillary return of fluid to the center of the vapor chamber.

After the system was clamped together it was insulated with several inches of fiber glass to prevent heat loss to the environment.

6. Vapor Chamber Testing

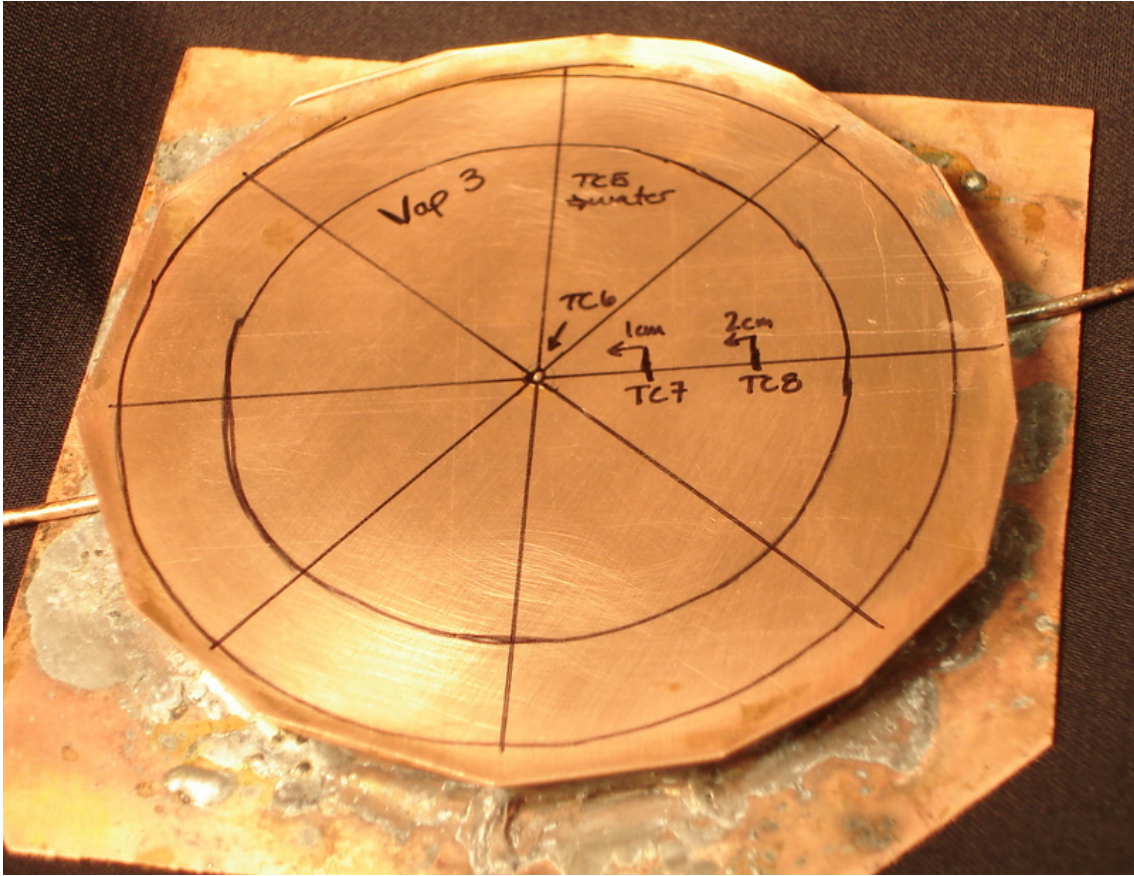


Figure 6.4.: Thermocouple placement on the top of the vapor chamber. Thermocouples include channels a6, a7, and a8. Channel a5 was placed in the water in pipe to record the temperature of the water entering the condenser.

6. Vapor Chamber Testing

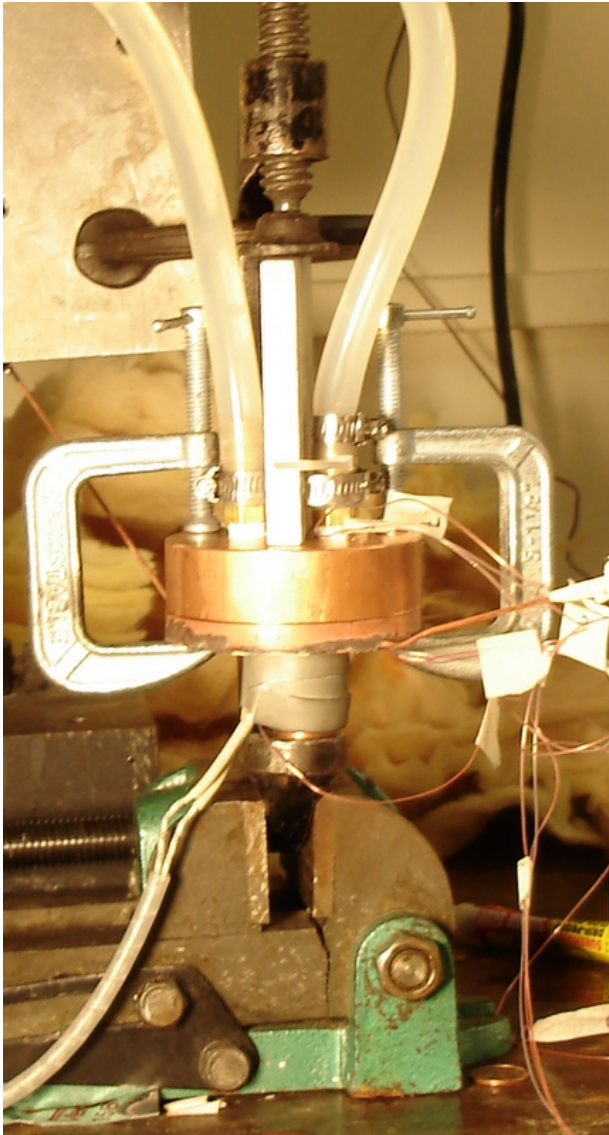


Figure 6.5.: Vapor chamber system set up and ready for testing. Notice how the system is clamped together.

6.1.4. Testing

VAP3 was charged with 7.79 g of high performance liquid chromatography (HPLC) grade water. It was tested for a heater contact cross section of both 5 cm^2 (1 inch round heater core) and 1 cm^2 (1cm x 1cm square). Test were using both heater cross sections at a condenser temperature of both 20°C and 60°C .

- Test 4 - 20°C - 5 cm^2 - VAP3 7.79 g of water
- Test 5 - 60°C - 5 cm^2 - VAP3 7.79 g of water
- Test 6 - 60°C - 1 cm^2 - VAP3 7.79 g of water
- Test 7 - 20°C - 1 cm^2 - VAP3 7.79 g of water

After running tests on VAP3 a copper disk of similar size, 3 inch diameter and ~8 mm thick was setup and tested in the same manner.

- Test 8 - 20°C - 1 cm^2 - Solid Copper

It was suspected that VAP3 in test 4-7 was over charged and that pool boiling was occurring so to test this VAP5 was fabricated. VAP5 had the same dimensions and a mesh reservoir, but no wicking structure on the walls, top or bottom plates. VAP 5 was tested using the same procedure

- Test 9 - 20°C - 5 cm^2 - VAP5 6.15 g of water

After seeing the results from VAP5, VAP3 was opened and a vacuum pump was used to remove any free fluid, 3.36 grams of water was removed, and VAP3 was retested.

- Test 10 - 20°C - 5 cm^2 - VAP3 4.33 g of water

6.1.5. Data Analysis

The temperatures on the vapor chambers were measured at 100 Hz, and the average test too about 15 minutes to reach steady state. Thus for each test there were approximately 720,000 piece of data, with 90,000 for each thermocouple. Initially Microsoft Excel was going to be used to analyze the data. However, Excel can only handle 65,000 rows of data and was truncating the remaining portion of the data. So instead code was written in Octave¹ to process the data.

Using Octave the raw data was averaged over five second intervals. Thus the 720,000 data points were reduced to 1440 with 180 data points for each thermocouple. The averaged data was plotted, an example can be seen in Figure 6.6 and visually inspected to ensure that the end of the data was at steady state. The last four averaged data points for each thermocouple were then averaged and taken as the steady state value for that thermocouple. The change in temperature was then calculated using the following equation.

$$\Delta T = \left(\frac{TC_2 + TC_3 + TC_4}{3} \right) - \left(\frac{TC_6 + TC_7 + TC_8}{3} \right) \quad (6.1)$$

The averaged differences in temperature across the vapor chamber can be seen in Table, 6.1 and plotted in Figure 6.14. Refer to the Appendix for the Octave code used.

6.2. Results

VAP1 and VAP2 were charged and tested, however, the data is not include here because VAP1 was charged with acetone and only tested once, while VAP2 was charged with acetone as well but was destroyed before testing could be completed. Thus the data for VAP1 and VAP2 is not repeated, and is therefore not considered reliable.

¹GNU Octave is a high level language that can be used for numerical modeling, or batch processing. It is provided free of charge. <http://www.gnu.org/software/octave/>

6. Vapor Chamber Testing

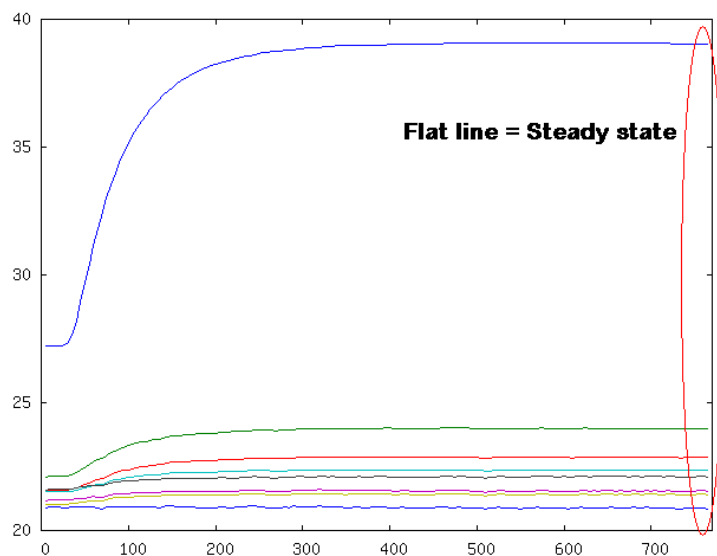


Figure 6.6.: Test 10-30watts; An example of the averaged transient data that was used to check that the data sequence ended with steady state values.

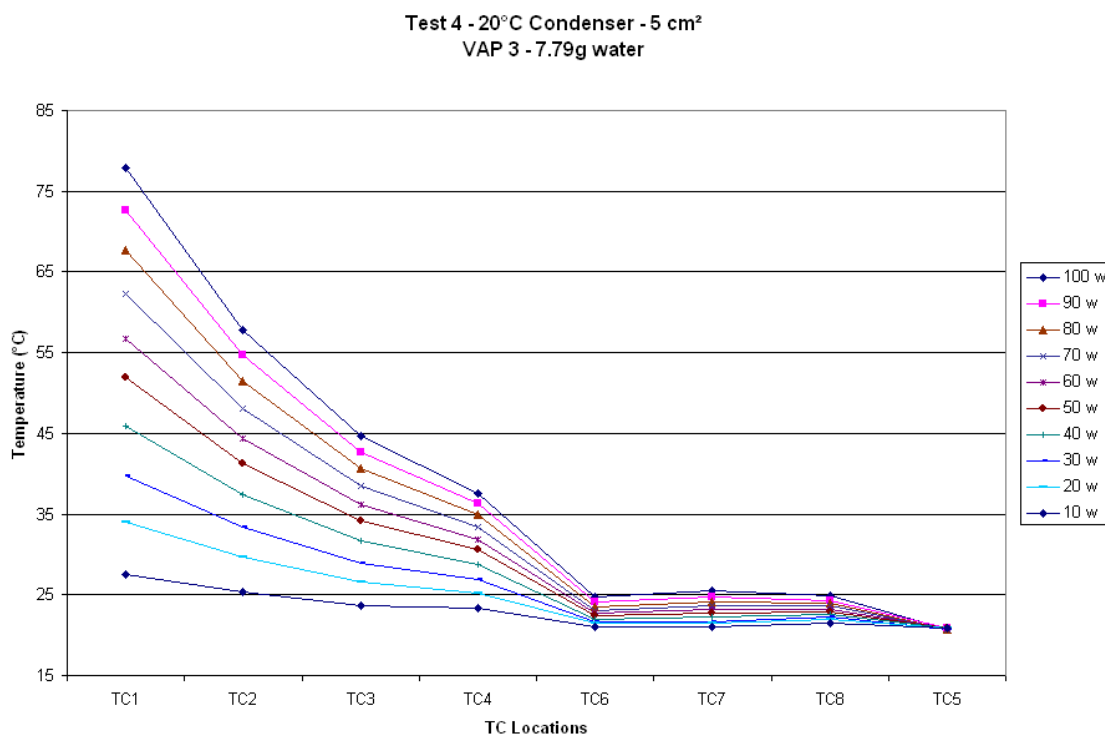


Figure 6.7.: Test 4 conducted on VAP3 charged with 7.79g of HPLC grade water, 20°C condenser 5 cm² heater core contact area.

6. Vapor Chamber Testing

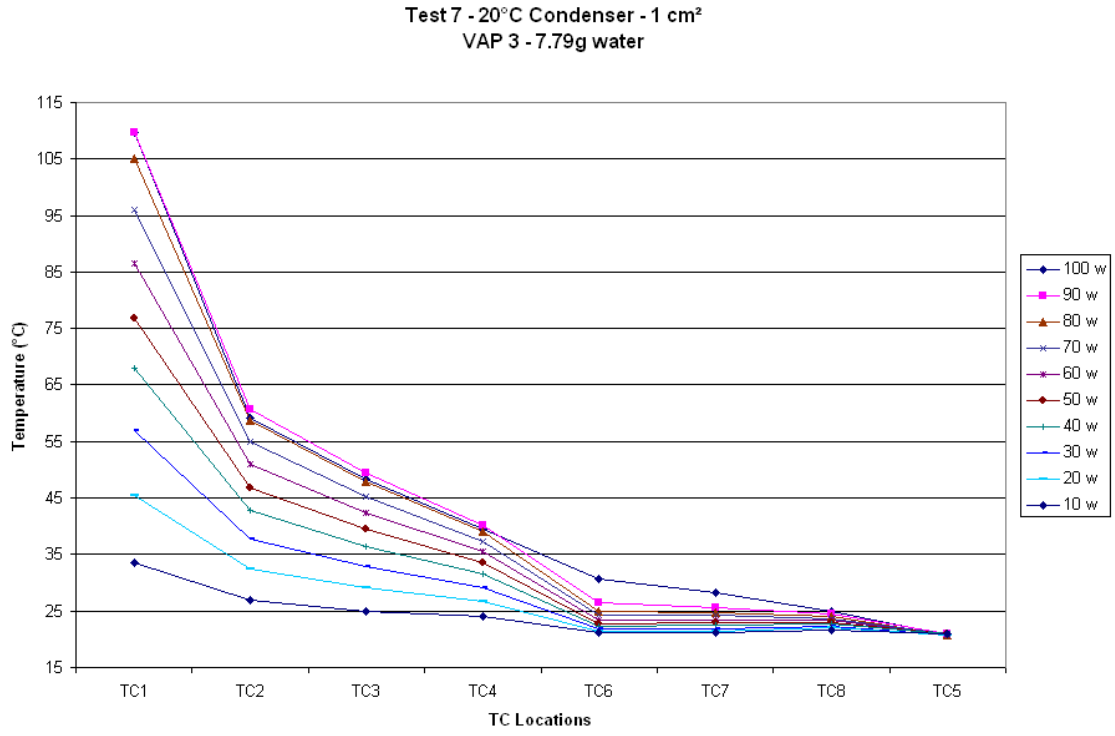


Figure 6.8.: Test 7 conducted on VAP3 charged with 7.79g of HPLC grade water, 20°C condenser 1 cm² heater core contact area.

6. Vapor Chamber Testing

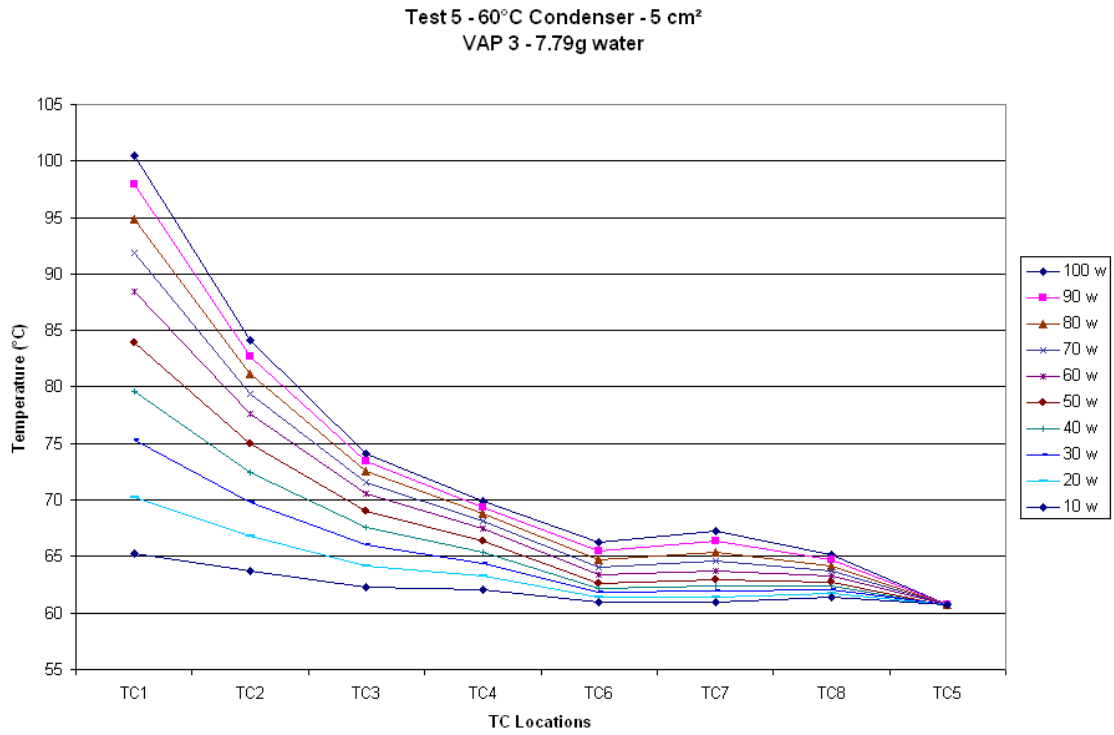


Figure 6.9.: Test 5 conducted on VAP3 charged with 7.79g of HPLC grade water, 60°C condenser 5 cm² heater core contact area.

6. Vapor Chamber Testing

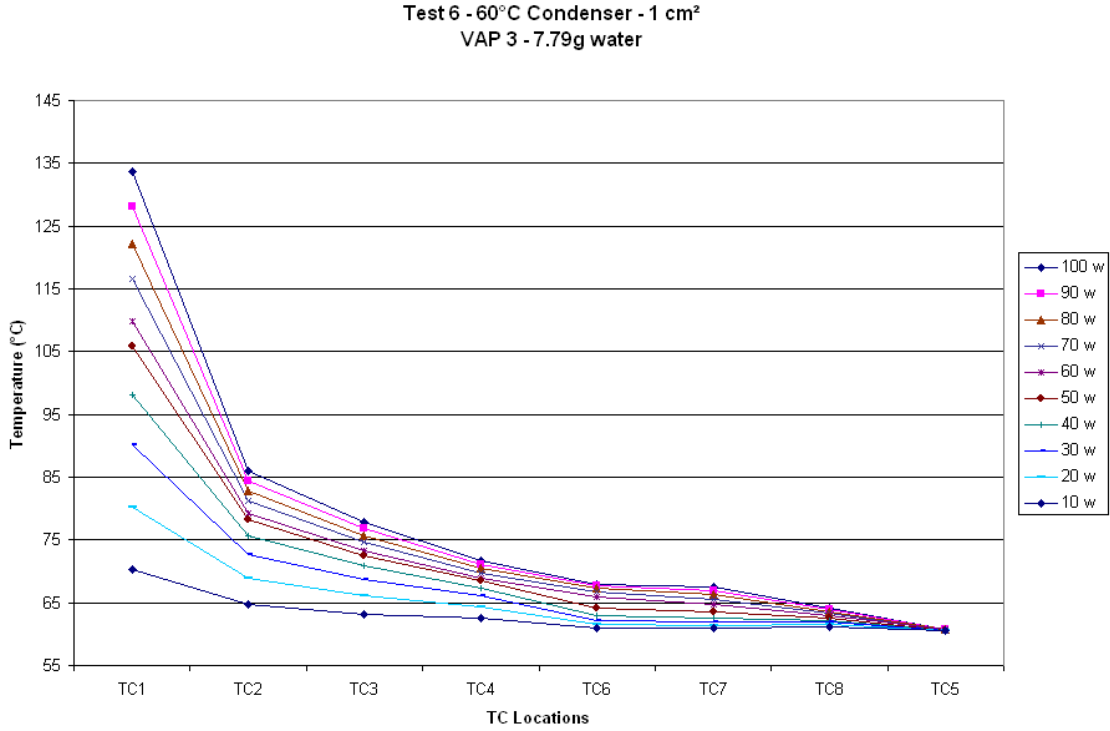


Figure 6.10.: Test 6 conducted on VAP3 charged with 7.79g of HPLC grade water, 60°C condenser 1 cm² heater core contact area.

Test 9 was testing VAP5 which did not have a wick structure thus pool boiling was the heat transport mechanism. As seen in Figure 6.14B the temperature differences for Test 4, 7, and 9 are close. Thus if pool boiling was occurring in Test 9, it was also occurring in Tests 4, 5, 6, and 7. Once the water volume was reduced in VAP3 the performance improved because thin film evaporation dominated the heat transfer instead of pool boiling. Test 8 tested a copper disc with similar dimensions to the vapor chambers that were tested. When comparing Test 8 to Test 10 it is noticed that the performance of the copper disc is just a little better than VAP3. This is in large part due to the design of the testing apparatus. The strength of the vapor chamber is that when heat is applied to a small area on the bottom of the vapor chamber the vapor that is formed at this point can very easily move to any point on the top

6. Vapor Chamber Testing

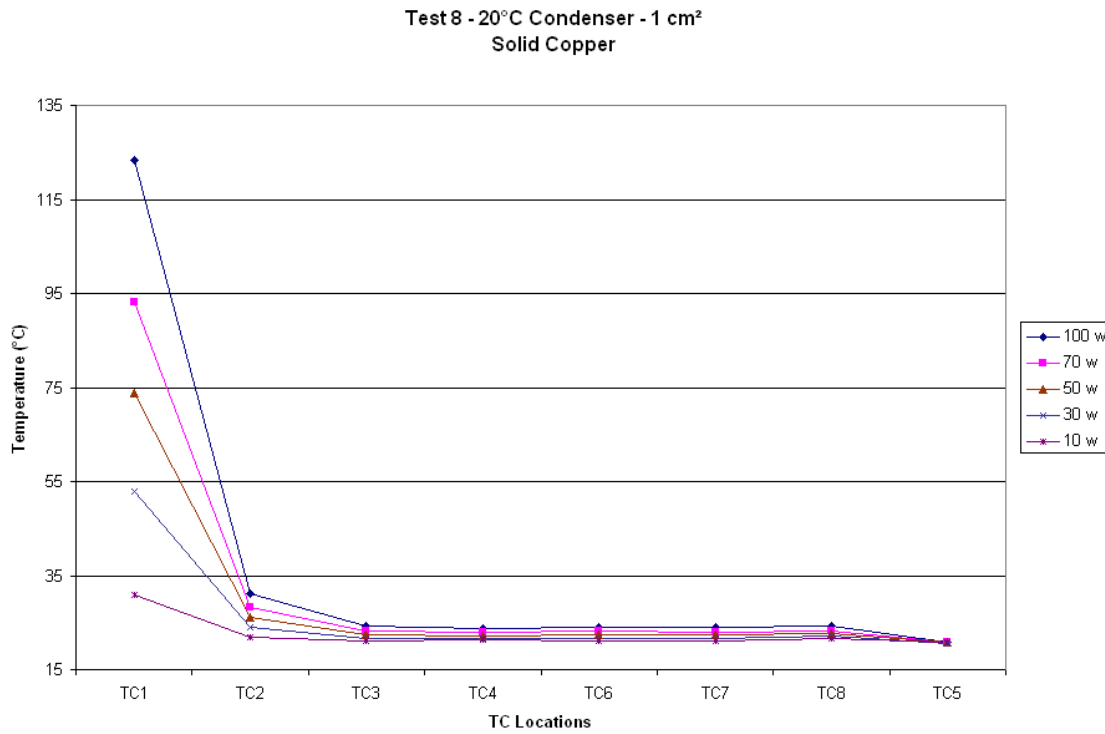


Figure 6.11.: Test 8 conducted on a solid copper disc, 20°C condenser 1 cm² heater core contact area.

Table 6.1.: Table of the averaged temperature differences in °C.

Watts	Test 4	Test 7	Test 5	Test 6	Test 8	Test 9	Test 10
100	21.65	20.99	9.86	11.93	2.34	29.06	3.95
90	20.19	24.63	9.62	11.27			
80	18.49	24.02	9.43	10.56			
70	16.53	21.80	8.87	9.97	1.58	25.94	3.03
60	14.47	19.56	8.43	9.25			
50	12.69	17.01	7.30	9.65	1.16	19.78	2.22
40	10.34	14.48	6.11	8.71			
30	7.88	11.23	4.78	7.15	0.70	12.02	1.38
20	5.53	7.75	3.23	4.90			
10	2.93	3.97	1.58	2.47	0.23	3.93	0.47

Test 4 - 20°C - 5 cm² - VAP3 7.79 g of water

Test 5 - 60°C - 5 cm² - VAP3 7.79 g of water

Test 6 - 60°C - 1 cm² - VAP3 7.79 g of water

Test 7 - 20°C - 1 cm² - VAP3 7.79 g of water

Test 8 - 20°C - 1 cm² - Solid Copper

Test 9 - 20°C - 5 cm² - VAP5 6.15 g of water

Test 10 - 20°C - 5 cm² - VAP3 4.33 g of water

6. Vapor Chamber Testing

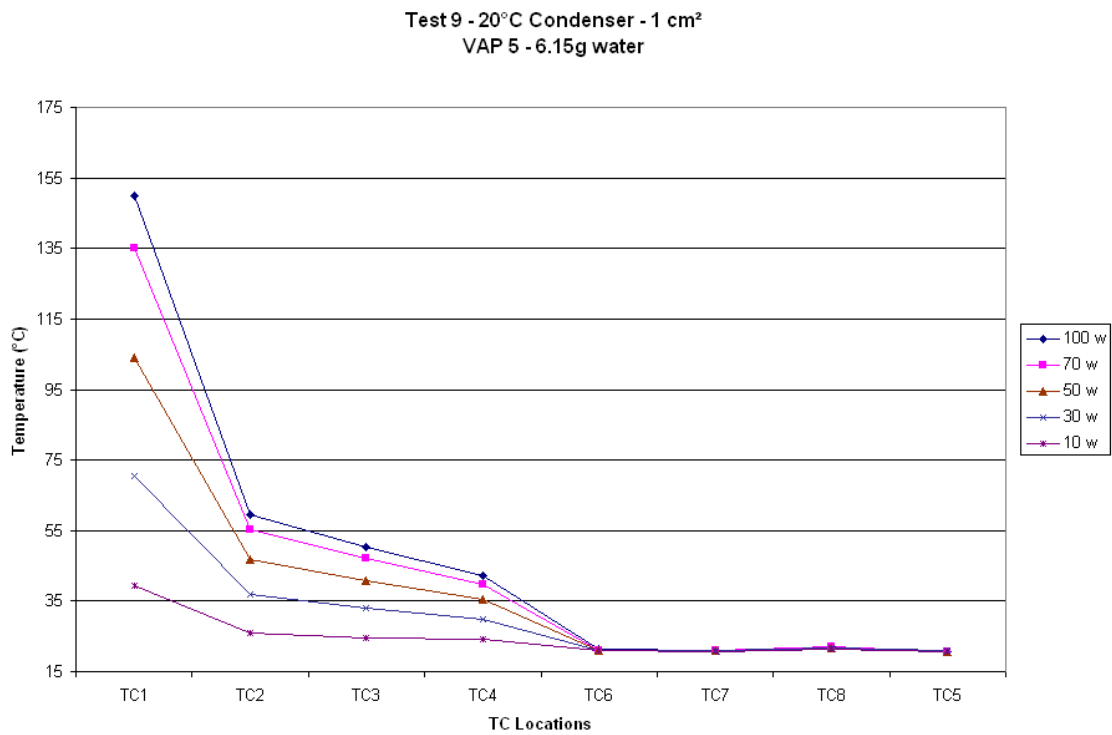


Figure 6.12.: Test 9 conducted on VAP5 charged with 6.15g of HPLC grade water, 20°C condenser 1 cm² heater core contact area.

6. Vapor Chamber Testing

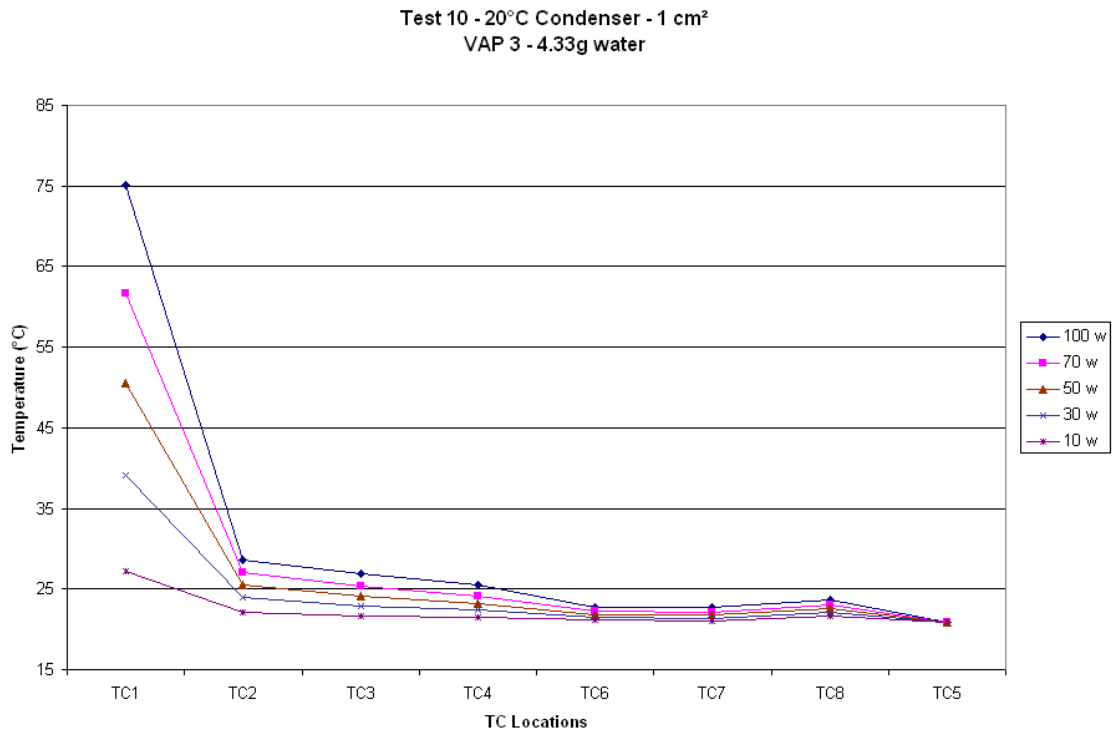
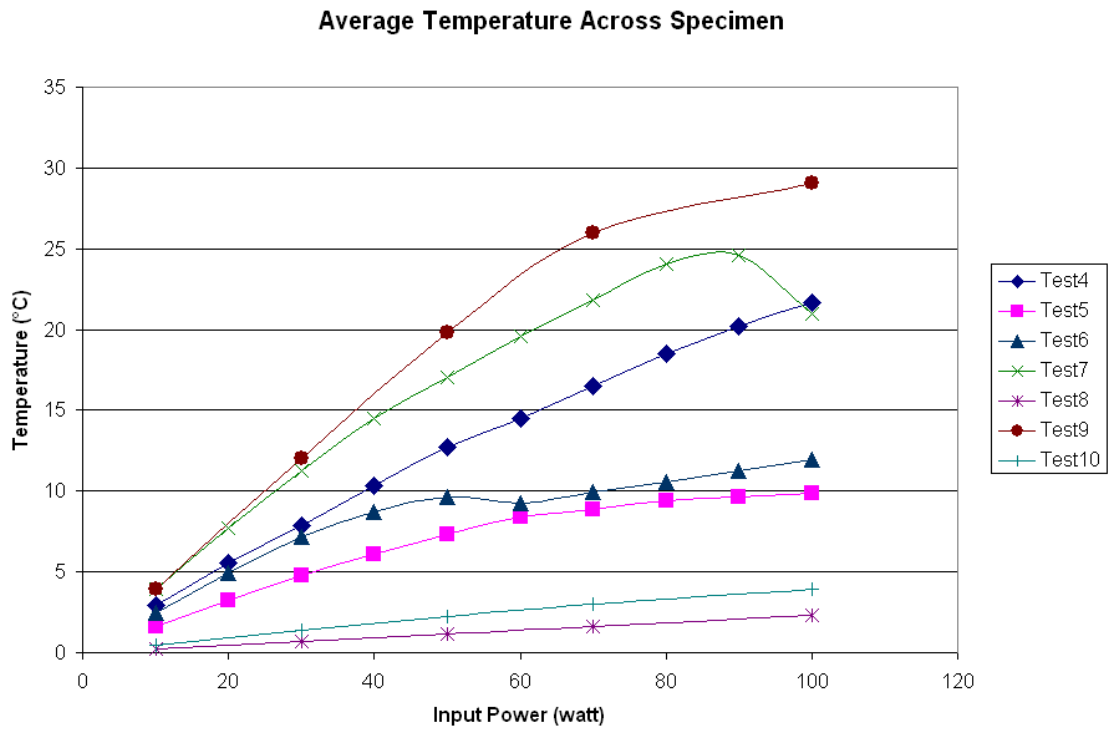


Figure 6.13.: Test 10 conducted on VAP3 charged with 4.33g of HPLC grade water, 20°C condenser 1 cm² heater core contact area.

6. Vapor Chamber Testing

A.



B.

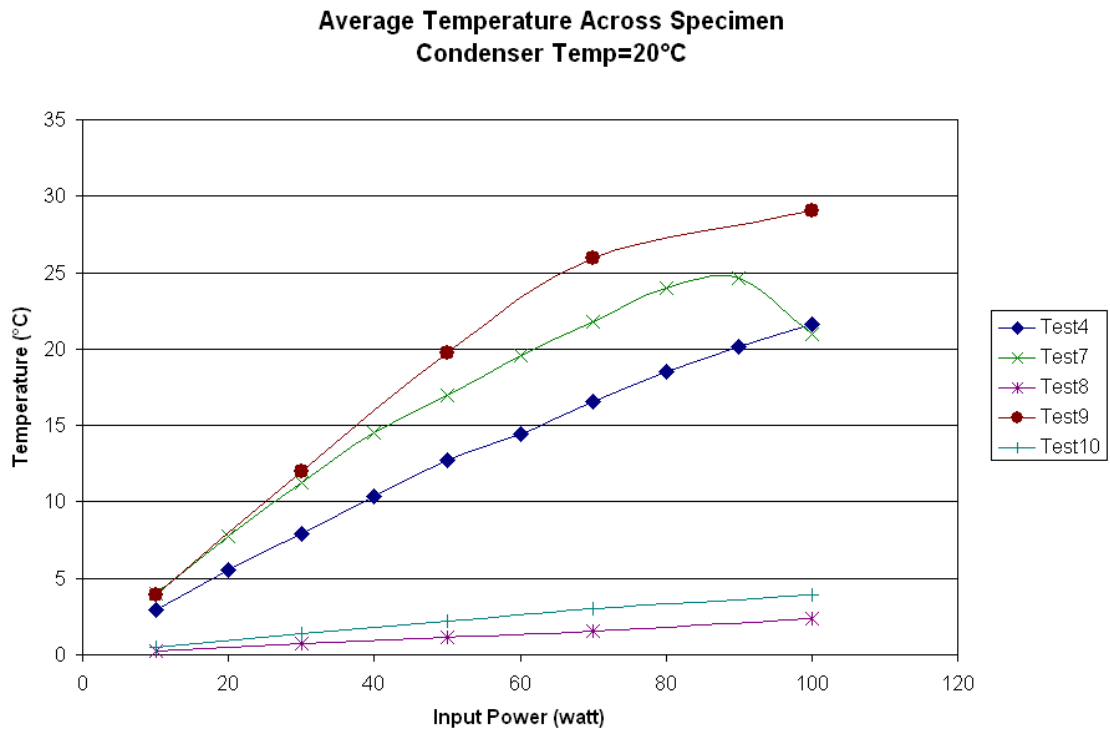


Figure 6.14.: A.) Graph of the averaged temperature differences. B.) Graph of the averaged temperature differences for tests using a 20°C condenser.

6. Vapor Chamber Testing

surface, in other words the conduction path from the heated point to any point on the top surface is approximately equal. Thus the vapor chamber can spread the heat applied to a small area on the base of the vapor chamber to the entire top surface. Where as in the case of the copper disc the conduction path from the heated spot to a point on the cooled top surface is dependent on the physical distance between the two points. Since conduction occurs on a log scale, a conduction path of 2 units is far worse than a conduction path of 1 unit. However, since the top side is water cooled it can support a high heat flux which maintains a short conduction path. Thus, since there is a short conduction path the copper disc out performs the vapor chamber.

In hind sight it would have been better to use air cooling, since air cooling cannot support a high heat flux, compared with water. With the lower heat transfer capability of air cooling the ability of the vapor chamber to spread the heat flux evenly across the entire top surface would make its performance superior to the copper disk.

From the results for VAP3 it is determined that the fuzzy copper wick structure is very good, compared to pool boiling. It would be ideal to test the vapor chamber until it dried out, as this would give a complete view of the capillary power of the structure.

The fuzzy copper wick structure is better than the currently used wick structures because it is easy to form on almost any surface

and has superior physical structure than sintered particles. Sintered particle are hard to use because it is hard to accurately deposit a thin layer evenly on a surface. If the layer of sintered particles is not thin enough the wick will have problems with trapping vapor in the root of the wick which will cause the thermal conductivity of the wick to fall and temperatures will increase. Also since sintered particles are considered and amorphous media and have relatively low thermal conductivity, compared with the material that they are made from, the sintered particle layer acts as an insulating layer. Fuzzy copper on the other hand is more similar to a finned surface where each

6. Vapor Chamber Testing

fin is finned - creating massive surface area. The massive surface area provides for a very large meniscus surface and there for a very large thin film evaporatory region, which is important because the majority of two phase heat transfer occurs though the thin film region. The finned structure resists trapping vapor, because all the cavities open directly to the surface of the wick. Also since each spiked cone in the fuzzy copper is connect via a solid metal connection to the base plate there is good thermal conductivity from the base to the thin film evaporation region. The fuzzy copper wick structure will be very useful in the creation of heat pipes and heat transfer surfaces capable of higher heat flux.

7. Conclusions

Compact OHP A background study was conducted on the using electroforming technology to produce compact OHP's. Several masking techniques including toner transfer, photo lithography, and subtractive wax carving were considered and tested, Toner transfer was a very fast technique to transfer the computer image to the copper work pieces. However, pin holes in the toner transfer allowed the electroforming bath to plate through the toner. A possible solution is to use a printer that deposits more toner. The benefits of the toner transfer method is that it is computer based, so the pattern is easily replicated, and the technology is very mature, easily available and cheap. Subtractive wax carving was tested as a masking technique. Since it is a hand based pattern a large amount of work is required to reproduce a pattern, but due to the very low technology level it is useful for testing. A procedure for using photo lithography to make the electroplating mandrel was also considered and found to be the optimal method because very complex designs can be created, and the technology is widely used for making micro channels.

A proof of concept test was done concerning the validity of using the electroforming bath to make compact OHP's. Two flat plate OHP's were created with 6-8 turns using the subtractive wax masking technique. The results were promising, although the OHP's were porous. It was suggested that pulse plating be used as a remedy to the plating problem as pulse plating encourages finer grain growth which makes a more dense and level deposit with homogeneous material properties.

7. Conclusions

Fuzzy Copper as a Wick Structure During the electroforming of the proof of concept OHP's the second OHP was plated with a fuzzy dendritic coating. The fuzzy copper was tested as a capillary surface and was determined to be very promising. So four vapor chambers, VAP1, VAP2, VAP3, VAP4 were fabricated using the fuzzy copper as the capillary medium in the vapor chambers. Also capillary spring bridges were designed to connect the top condensing surface of the vapor chamber to the bottom evaporating surface. The capillary bridges shorten the return path for the working fluid flow, by allowing the fluid to transverse the gap from the top to the bottom in the middle of the vapor chamber instead of around the perimeter. Rolled copper mesh was also installed along the outer edge of the vapor chambers as a fluid reservoir. Testing was conducted on vapor chamber VAP3 using four different sets of test parameters, including condenser temperatures of 20°C and 60°C and using a surface contact area between the heater core-vapor chamber of 5 cm^2 and 1 cm^2 . It was found the vapor chamber was over filled with fluid and pool boiling was occurring instead of thin film evaporation. VAP5 was created to test the pool boiling theory. VAP5 had no capillary structure, thus any heat transfer would be via pool boiling. The performance of VAP5 and the first four tests of VAP3 were very similar, proving that VAP3 was over charged. After removing fluid from VAP3 it was retested and perform with stellar results. A copper disc of similar dimensions was also tested to provide a reference. The experimental results confirmed that the fuzzy copper can be used as a wick structure which has a very good capillary performance.

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Appendix

```

clear all

Test=8;           %set to the number of the test that that you wish to compute.
test="8";

Short=1; %set to 1 if you want to just average the raw data - will proceed to findi
ng SS values after averaging the data,
           %set to 2 if you ONLY find SS values AND the averaged data has been
           compiled.

avgcalc=0;
sscalc=0;

switch Test
case (11)
    Name=["11_250w";"11_200w";"11_150w";"11_100w";"11_50w";];
case (10)
    Name=["10_100w";"10_70w";"10_50w";"10_30w";"10_10w";];
case (9)
    Name=["9_100w";"9_70w";"9_50w";"9_30w";"9_10w";];
case (8)
    Name=["8_100w";"8_70w";"8_50w";"8_30w";"8_10w";];
case (7)
    Name=["7_10";"7_9";"7_8";"7_7";"7_6";"7_5";"7_4";"7_3";"7_2";"7_1"];
case (6)
    Name=["6_10";"6_9";"6_8";"6_7";"6_6";"6_5";"6_4";"6_3";"6_2";"6_1"];
case (5)
    Name=["5_10";"5_9";"5_8";"5_7";"5_6";"5_5";"5_4";"5_3";"5_2";"5_1"];
case (4)
    Name=["4_10";"4_9";"4_8";"4_7";"4_6";"4_5";"4_4";"4_3";"4_2";"4_1"];
case(1)
    Name=["1-1"];
endswitch

RN=(rows(Name));
CN=(columns(Name));

for ff=Short:2
    calculation=ff;

    for ii=1:RN
        clear N;
        for i=1:CN
            %removes the empty space from the end of the 'N
AME' so that the file can be found.
            if Name(ii,i)==" "
                break
            else
                N(1,i)=Name(ii,i);
            endif
        endfor

        fn=["Test", N, ".txt"];
        ma=["T", N, "a.mat"];
        pn=["T", N, "a.png"];

        switch calculation
            case (1) %Converts the raw data to data that is averaged over the set tim

```

```

e step
    DTL=load (fn);
    DR=1/0.01; sm=5; %'DR' sets the data rate('DR' is in HZ), 'sm' sets t
he smoothing interval ('sm' is in seconds)
    [avgtestdata, aL, Ntc, time]=avgdata(DTL,DR,sm);
    save ("-ascii" ,ma, "avgtestdata")

    plot (time, avgtestdata)
    print (pn) %saves the plot to the file

    Test=N;
    duration_sec=aL*5;
    duration_min=aL*5/60;
    data_rate_hz=DR;
    averaged_time_sec=sm;
    testinfo(:,ii)=[duration_sec;duration_min;data_rate_hz;averaged_time_
sec];

    avgcalc=1;

    # aaa=["Test ", aba,]
    # aab=["Test duration ", abb, " sec || ", abc, " min"]
    # aad=["Test data taken at ", abd, "Hz"]
    # aae=["Test data averaged over ", abe, " sec"]
    # test_info=zeros(4,5)
    # test_info=["Test ", N," "," "," "];
    # "Test duration ", aab, " sec || ", aac, " min";
    # "Test data taken at ", aad, "Hz"," "," ";
    # "Test data averaged over ", aae, " sec"," "," "
case (2) %gathers the steady state temps of each TC
    avgtestdata=load (ma);
    avt=avgtestdata;

    Ntc=columns(avgtestdata); %Number of tc's
    aL=rows(avgtestdata);
    TCSSa=zeros(1,Ntc);

    for i=1:4
        TCSSa(1,:)=TCSSa(1,:)+avt(aL-i,:);
    endfor
    TCSSa;
    TCSS(ii,:)=TCSSa./4;

    for bb=1:3
        TCLavg(ii,1)=(TCSS(ii,2)+TCSS(ii,3)+TCSS(ii,4))/3;
        TCHavg(ii,1)=(TCSS(ii,5)+TCSS(ii,6)+TCSS(ii,7))/3;
    endfor
    DeltaTmax(ii,1)=(TCSS(ii,2)-TCSS(ii,7));
    DeltaT=(TCLavg-TCHavg);
    TCLHavg=[TCLavg,TCHavg, DeltaT,DeltaTmax];
    sscalc=1;

endswitch

endfor
clc

endfor
if avgcalc==1
    fticc=["TInfo",test,".mat"];
    save ("-ascii" ,fticc, "testinfo")

```

```

disp("=====")
disp(" ")
disp("\Test Averaging Info\" saved to")
fticc
testinfo
endif

if sscal==1
fc=["T",test,"SS.mat"];
save ("-ascii" ,fc, "TCSS")

fcc=["T",test,"SS1.mat"];
save ("-text" ,fcc, "Name")

fdt=["T",test,"dt.mat"];
save ("-ascii" ,fdt, "TCLHavg")

disp("=====")
disp(" ")
disp("\TC S.S.\" saved to")
fc
TCSS

disp(" ")
disp("=====")
disp("\Test Names\" saved to")
fcc
Name
disp(" ")
disp("=====")

disp(" ")
disp("=====")
disp("\Temperature Avg\" saved to")
fdt
disp("TCLavg || TCHavg || DeltaT || DeltaTmax")
TCLHavg
disp(" ")
disp("=====")
endif

```



```

function [avt, aL, Ntc, time]=avgdata(testdataraw,datarate,sao)

format short

tlr=(rows(testdataraw));
%datarate=1/0.01; %time step dt , used to calculated the time step

testdata(:,1)=testdataraw(:,1);
testdata(:,2)=testdataraw(:,2);
testdata(:,3)=testdataraw(:,3);
testdata(:,4)=testdataraw(:,4); %Sets the data in order of temperature so tha
t the hottest temp is on the left and the coldest is on the right... making the plo
ts look better.
testdata(:,5)=testdataraw(:,6);
testdata(:,6)=testdataraw(:,7);
testdata(:,7)=testdataraw(:,8);
testdata(:,8)=testdataraw(:,5);

%sao=5; %sets the number of seconds to average the data over - curently set to 5 th
erefore the data will be averaged over 5 second intervals
pao=sao*datarate; %points to average over

Ntc=columns(testdata); %Number of tc's

tl=(rows(testdata));%testlength

%ensures that the testlength is an even number so that the math works out right...
evenoddremainder=mod(tl,2);
if (evenoddremainder==1)
    tl=(tl-1);
endif

%removes extra data that does not fit in a pao second block
testlength123=mod(tl,pao);
tl=tl-testlength123;

%averaging over 5 seconds of data
bnext=1;
bnextb=pao;
aL=tl/pao;
addx1=zeros(aL,Ntc);

for Ntci=1:Ntc
    for c=1:aL
        for b=bnext:bnextb
            addx1(c, Ntci)=addx1(c, Ntci)+testdata(b, Ntci);
        endfor
        avt(c,Ntci)=addx1(c, Ntci)/pao;
        bnext=bnext+pao;
        bnextb=bnextb+pao;
        if bnext>=tl
            bnext=1;
            bnextb=pao;
        endif
    endfor
endfor

```

```
ad=(rows(addx1));
av=(rows(avt));

y=avt(:,1);

t=[(1:aL).*(pao/datarate)];
time=t';

# avtT=avt;
# avtT(:,9)=time;
t1;
aL;

endfunction
```