An Analytical Analysis of the Fluid Mechanics Involved In PCB Plating

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Abstract
It has been the conventional wisdom of the industry that the predominate board parameter associated with through hole plating is the aspect ratio of the through hole. While this is intuitively understandable, very little has been done to analytically verify the assertion. This paper will explore this hypothesis by developing a first principles flow model using the Navier-Stokes analog for viscous fluids. The first concern is to define the proper flow regime, laminar or turbulent based on the Reynolds Number associated with the process. Once this is established, a proper mathematical model can then be identified. At that point, the governing equations are parameterized and the crucial parameters identified. Faraday's Law will then be folded into the model to define an algebraic model for electrolytic plating. Finally, an order of magnitude analysis is presented to determine the relative importance of the critical parameters.

Introduction

The theory of the through hole plating has evolved primarily from anecdotal and empirical evidence as well as hear say. Very little has been forthcoming to present a defendable mathematical analysis of the process. To do so will require combing the physics of fluid mechanics and electrochemistry. The importance of such an analog is to both identify the parameters that govern the process as well as the degree to which a particular variable impacts the process. For instance it is well accepted that the aspect ratio of the through hole plays an important role in the process, but it is not understood if the impact is linear, sub-linear of super linear. This analysis will provide this insight.

First the flow regime, turbulent or laminar, will be determined followed by a development of the governing equations describing the fluid mechanics of the plating process. This will then be coupled with the governing laws of electroplating (Faraday's second law) to complete the analog.

Flow Regime

The flow regime is determined by the Reynolds Number. For the case at hand, a good and well developed analogy is the flow in a linear pipe. This type of flow is referred to as Hagen-Poiseuille Flow and the Reynolds Number is given by:

$$R = \frac{u_0}{\upsilon} d \qquad (1)$$

Where and for our purposes

u_0 is the mean velocity of the fluid in the hole (we will use 10ft/min to maximize the Reynolds Number)
d is the diameter (we will use 30 mils to again maximize the Reynolds Number)
υ is the kinematic viscosity (for most acids 0.00016 ft^2/sec)

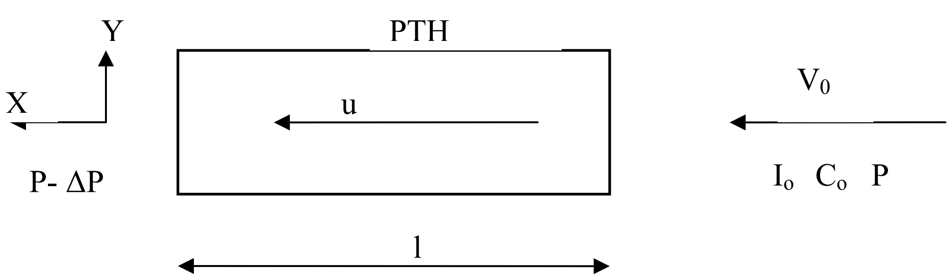
The numerical value of the Reynolds Number in this case is

R=2.6

It is generally accepted that the flow will be laminar, as opposed to turbulent, for a Reynolds Number less than 2300. Keep in mind that the Reynolds Number is a point function and the flow can vary between laminar and turbulent over a very small distance.

The Governing Equations of Fluid Mechanics

In this case depicted below, plating fluid passing through a through hole:



The governing equations are the so called Navier-Stokes equations. When adapted to the case at hand the result is (see Ref 1):

$$u = -\frac{1}{4\mu}\frac{dp}{dx}(r^2 - y^2) \quad (2)$$

The mean velocity (u_0) which will become of great importance in the next section on electroplating is

$$u_0 = \frac{r^2}{8\mu}(-\frac{dP}{dx}) \quad (3)$$

Where μ is the viscosity

and

$$\frac{dP}{dx} = \frac{\Delta P}{l} = \frac{1/2\rho V^2}{l} \quad (4)$$

V is the speed of the plating fluid relative to the surface being plated and ρ the density. The numerator is often referred to as the dynamic pressure and is the pressure component associated with a moving fluid.

The volume flow rate is

$$Q = \frac{\pi r^4 u_0}{\mu}(-\frac{dP}{dx}) \quad (5)$$

or

$$Q = \frac{\pi}{16}\frac{D^3 V^2}{A\upsilon} \quad (6)$$

Where A is the aspect ratio of the hole.
It is desirable to maximize the volume flow rate. The conventional wisdom has been that the volume flow rate is inversely proportional to the aspect ratio which is in agreement with the analysis; but even more important is the hole diameter which has a super linear impact on the volume flow rate and explains why small holes are difficult to plate. It is also seen that the relative velocity or agitation speed also plays a super linear role. These effects are shown in the Figureures below.

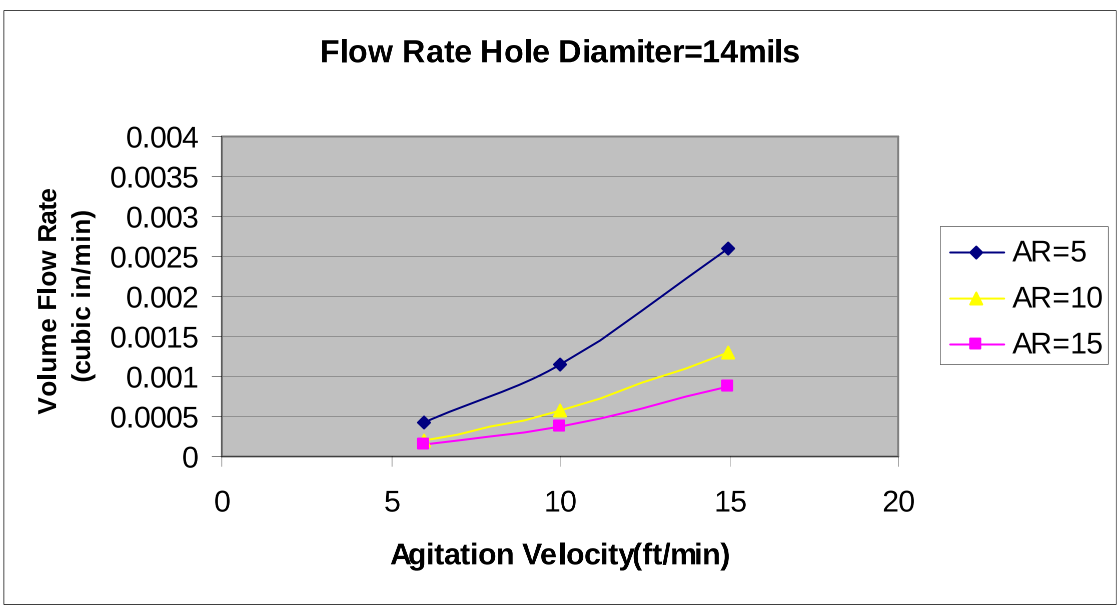


Figure 2

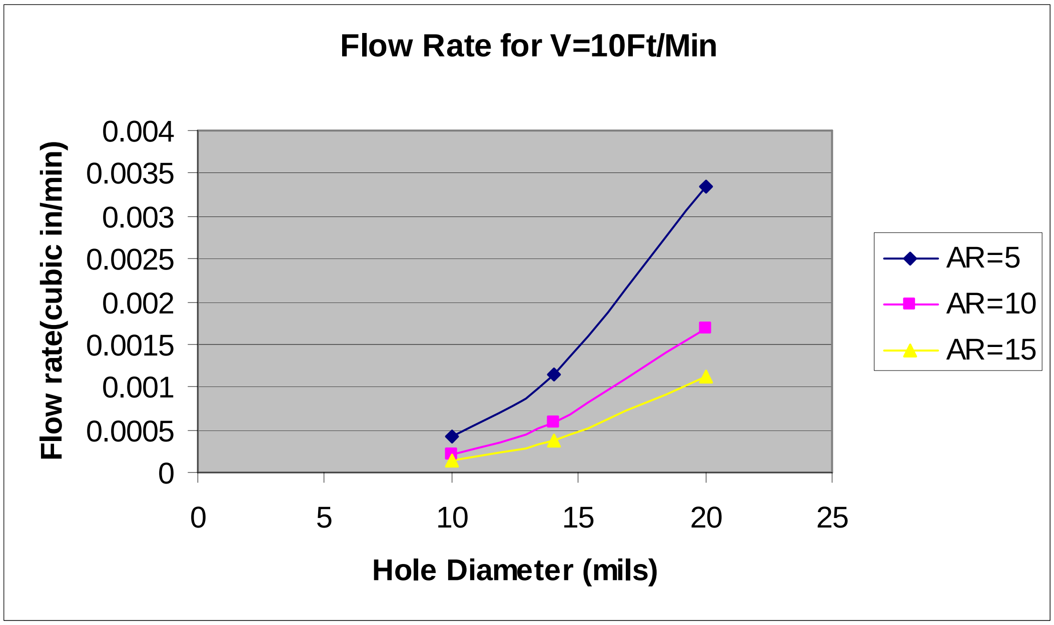


Figure 3

In summary, while the aspect ratio is a very important parameter in through hole plating, both the hole diameter and the agitation speed are even more critical variables.

Electroplating Issues

The next step in this analysis is to combine the laws of electrochemistry into the above analysis. The electro plating mechanism was first developed by Faraday.
According to Faraday's Law the number of moles of material plated at a cathode is proportional to the number of moles of electrons transferred at that electrode (see Reference 2) or:

$$w = GIt$$

The rate of deposition is then

$$\dot{w} = GI \quad (7)$$

Where w is the amount of material plated, G is a constant, I is the effective current and t is time.

The effective current is primarily a function of the concentration of the plating solution. Normally, the concentration of the bulk bath is very near the maximum level and the plating process is said to be 100% efficient, but as the concentration decreases the effective current becomes (see Ref 3):

$$I = I_o(1 - \exp[-k\frac{c}{c_0}]) \quad (8)$$

Where
I_0 is the total current supplied to the plating bath
k is a constant
c is the local concentration
c_0 is the maximum concentration (concentration of the bath)

Since the plating bath is usually very large compared to the cathode the bulk concentration of the bath will be assumed to be constant at c_0. The concentration of the plating solution in the through hole however decreases as the plating fluid transverses the hole. The analysis requires an algebraic expression for this mechanism.

Plated Through Hole Dynamics

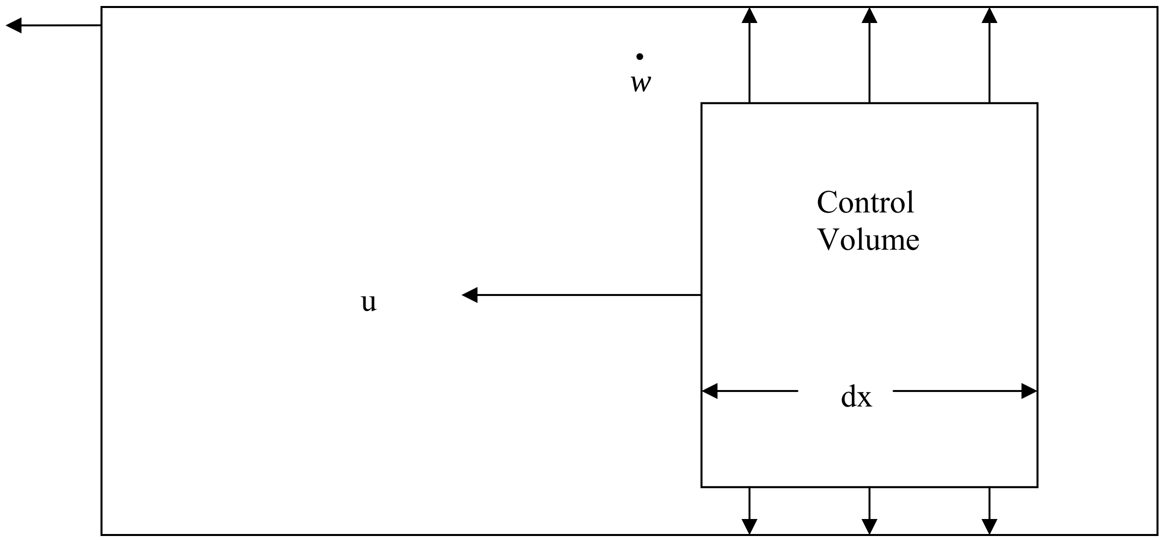


Figure 4

In Figure 4 a control volume of plating fluid is shown moving through the PTH at a speed of u and plating the surface of the barrel at a local rate $\dot{w}$. To an observer attached to the control volume, the rate of change of the concentration in the control volume ($\dot{c}$) is

$$\dot{c} = \frac{dc}{dx}u = -\frac{GI}{V} \quad (9)$$

where V is volume of the control volume.

Combining equations (7), (8) and (9) and then integrating using the identity that $c=c_0$ at $x=0$ the result is a relationship between the concentration and the position in the barrel.

$$x = -\frac{uV}{(\dot{w})_s}\{(c - c_0) + \frac{c_0}{k}\ln(\frac{1-\exp(-\frac{kc}{c_0})}{1-\exp(-k)})\} \quad (10)$$

where $(\dot{w})_s$ is the plating rate at the surface of the cathode.

The velocity (u) of the control volume is given by (3)

Also it is pointed out in Reference (3) that the plating efficient of a copper bath is approximately 10% when the concentration is 2.86 g/ft^3.
In that case, the value of k is

$k=0.0367c_0$

The relationship between the position in the barrel (x/l) and the concentration becomes

$$\frac{x}{l} = -\frac{\pi}{256}(\frac{D}{A})^2\frac{(V_0)^2}{\upsilon}\frac{c_0}{(\dot{w})_s}[\frac{c}{c_0} - 1 + k\ln(\frac{1-\exp(-kc/c_0)}{1-\exp(-k)})] \quad (11)$$

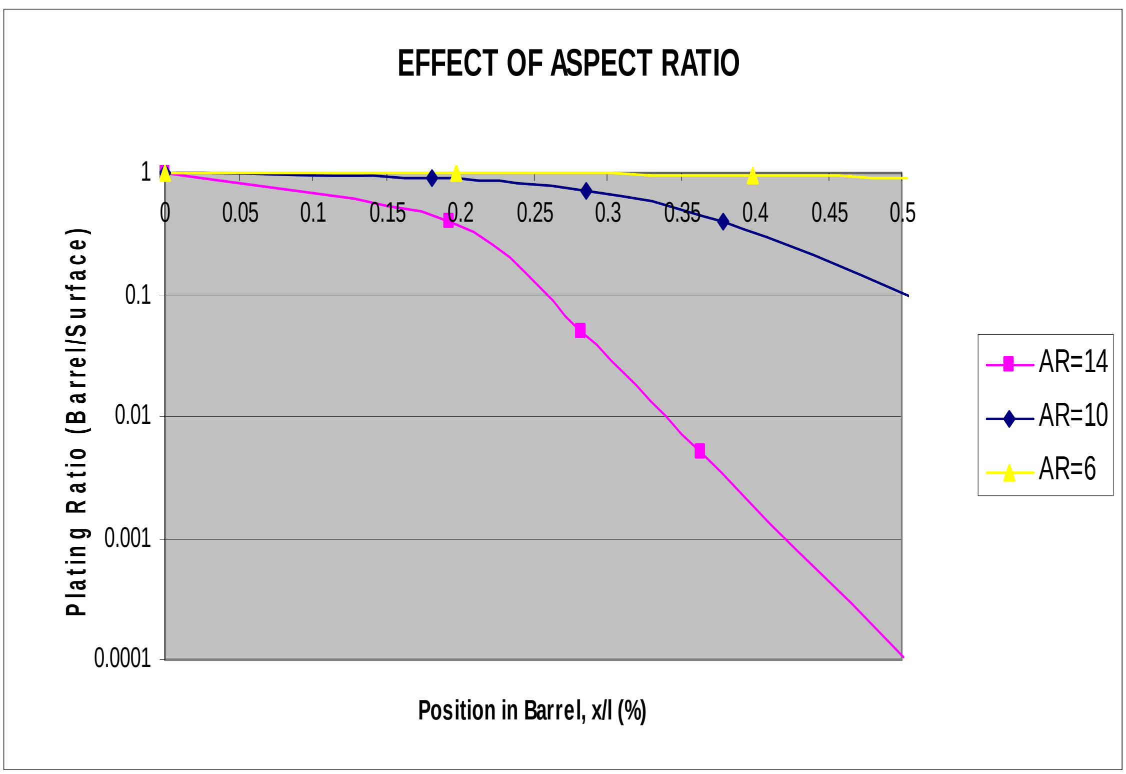
Equation (11) defines the concentration along the barrel of the PTH.

With the concentration defined, the plating efficient follows (see 8). Then using Faraday's Law (7), it is now possible to calculate the theoretical plating thickness anywhere in the barrel. It will be noticed in (11) the controlling parameters are: (D/A), V_0, c_0, and $\dot{w})_s$

It has long been empirically realized that the plating becomes more difficult with increasing hole aspect ratio, but (11) shows that the hole diameter plays an equally important role separate and apart from the aspect ratio. It is also common knowledge that the through hole plating is improved with agitation, (11) in fact finds the agitation speed plays a super linear role. The concentration of the bath is also important as is the plating rate at the surface. The surface plating rate is principally a function of the applied current I_0, which demonstrates that low amperage plating will improve the uniformity of PTH side wall which has recently been the observation of several leading edge PCB shops. The plating profiles are shown below as a function of these variables. This will accomplished by using variations from the "Based Line Parameters" shown in the table below.

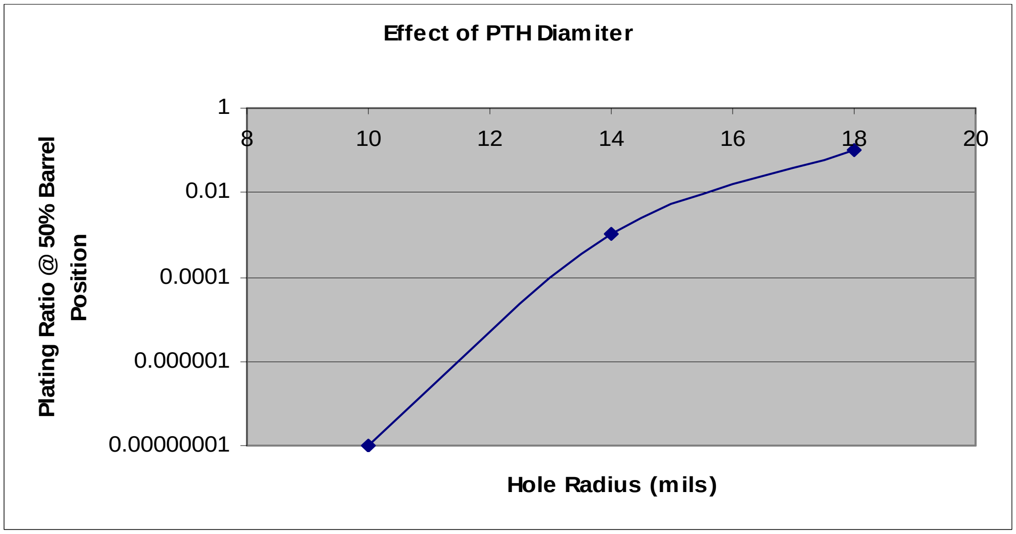
Base Line Parameters
A=10
Hole diameter =18 mils
c_0 = 140 g/ft^3
V_0= 8 ft/min
$\dot{w})_s = 0.0001 g/\sec$

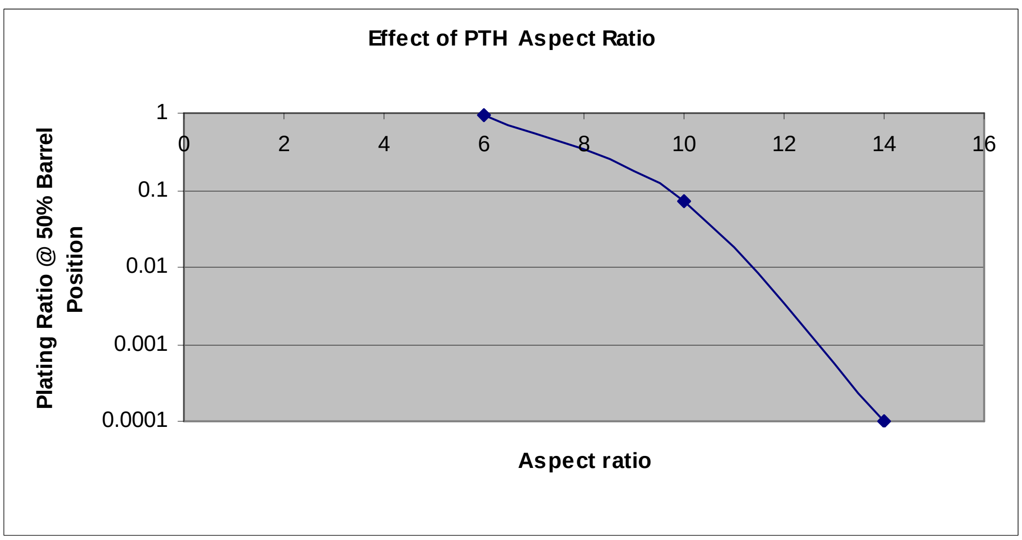
The first variation is shown below for aspect ratio and hole diameter.



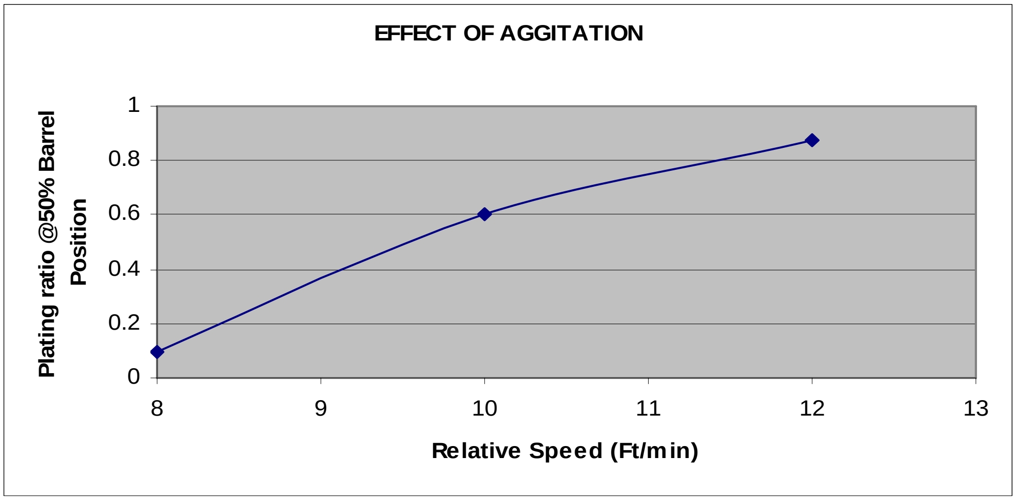
It will be noticed that as the aspect ratio is increased, the plating thickness along the hole wall is reduced in a nonlinear manner. It is also noticed that as the hole diameter decreases, the plating thickness quickly subsides causing a substantial nonlinear variation in the thickness of copper along the barrel. For instance at an aspect ratio of 6, the impact of the hole diameter is minor, but at an aspect ratio of 14 the impact is severe.

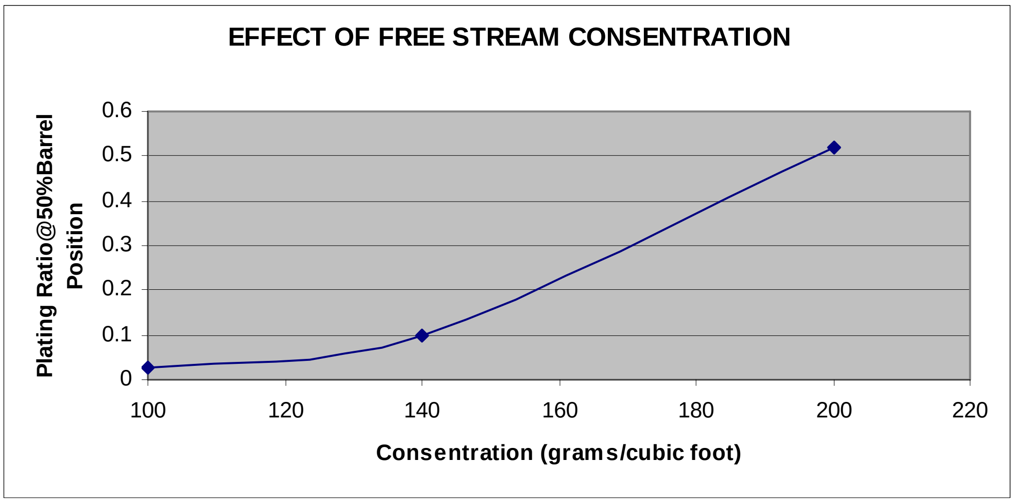
This information is now summarized by viewing the minimal through hole plating thickness which occurs half way through the barrel after being normalized to the surface plating rate. The effect of the hole diameter at the 50% barrel position is shown below followed by a similar graph for the aspect ratio:

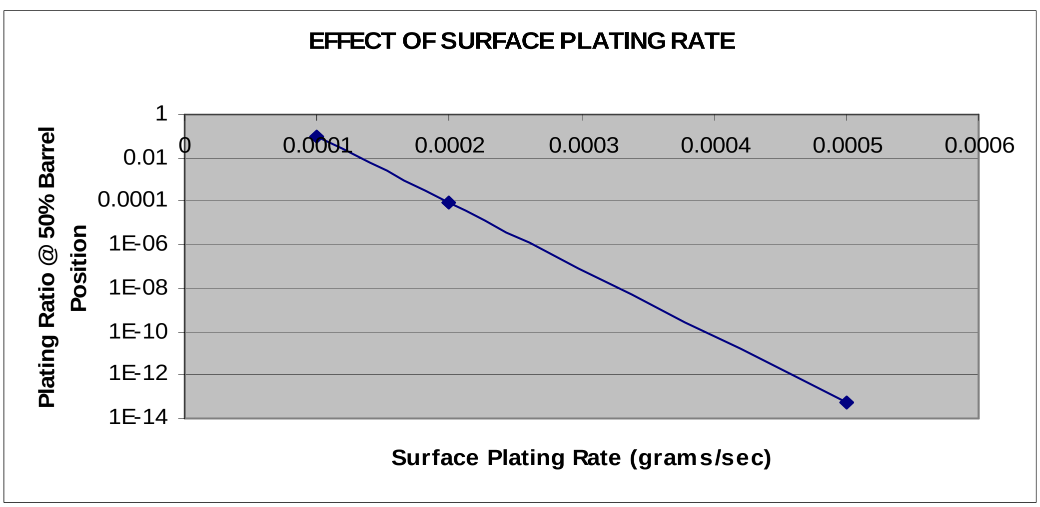




The predicted effect of the other parameters on the minimal plating thickness is shown below:







Summary

The analysis concludes that the conventional wisdom concerning the variables that drive an electroplating through hole process is correct, but incomplete. This analysis finds that in addition to the aspect ratio, there are several other variables of equal importance which are listed below:

Variable	Magnitude of Influence
Aspect Ratio	Square
Hole Diameter	Square
Agitation Speed	Square
Bulk Concentration	Super Linear
Surface Plating Rate (Current Density)	Linear

References

(1) Schlichting, Herman, Boundary Layer Theory, McGraw Hill Book Company
(2) Faraday's Law, The Columbia Encyclopedia, Sixth Edition
(3) National Metals Finishing Resource, Bluebook , Pollution Prevention and Control Technologies for Plating Operations

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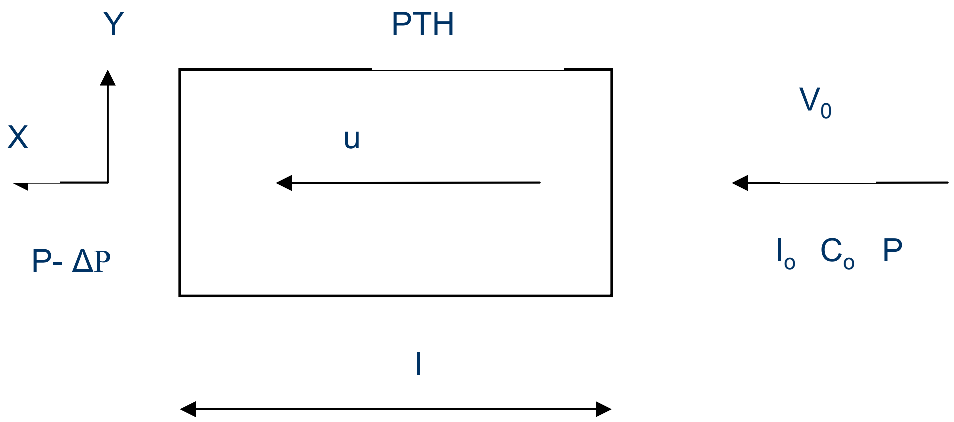
Agenda

- Develop the governing equations
  - For flow in a PCB barrel
  - The electroplating process
  - Combine the governing equations
- Identify and quantify the controlling parameters
- Examine how perturbations of the controlling parameters effect the “throwing power” of the plating bath

Fluid Mechanics

Model of the Mechanics of Fluid Flow in a PCB Through Hole



Flow Regime
Laminar or Turbulent ?

- Flow regime is determine by the Reynolds number (dimensionless)

$$R = \frac{V_0 D}{\nu}$$

- Where
  - V_0 is the free stream velocity
  - D is the diameter of the hole
  - v is the dynamic viscosity
- The transition from laminar to turbulent is
  - ≈ 2300
- For this application
  - R ≈ 3.0
  - Flow in the barrel is laminar

Governing Equation for Fluid Flow in the Barrel

$$u = -\frac{1}{4\mu}\frac{dp}{dx}(r^2 - y^2)$$

- Where
  - μ is the viscosity

$$\frac{dp}{dx} = \frac{\Delta p}{l}$$

  - r is the radius of the barrel
  - y is the radial coordinate
  - u is local velocity

$$\Delta p = 1/2\rho V_0^2$$

Governing Equation for Fluid Flow in the Barrel

It follows that the volume flow rate is

$$Q = \frac{\pi D^3 V_0^2}{16 A \upsilon}$$

- A is the aspect ratio
- D is the hole diameter

- And the mean velocity is

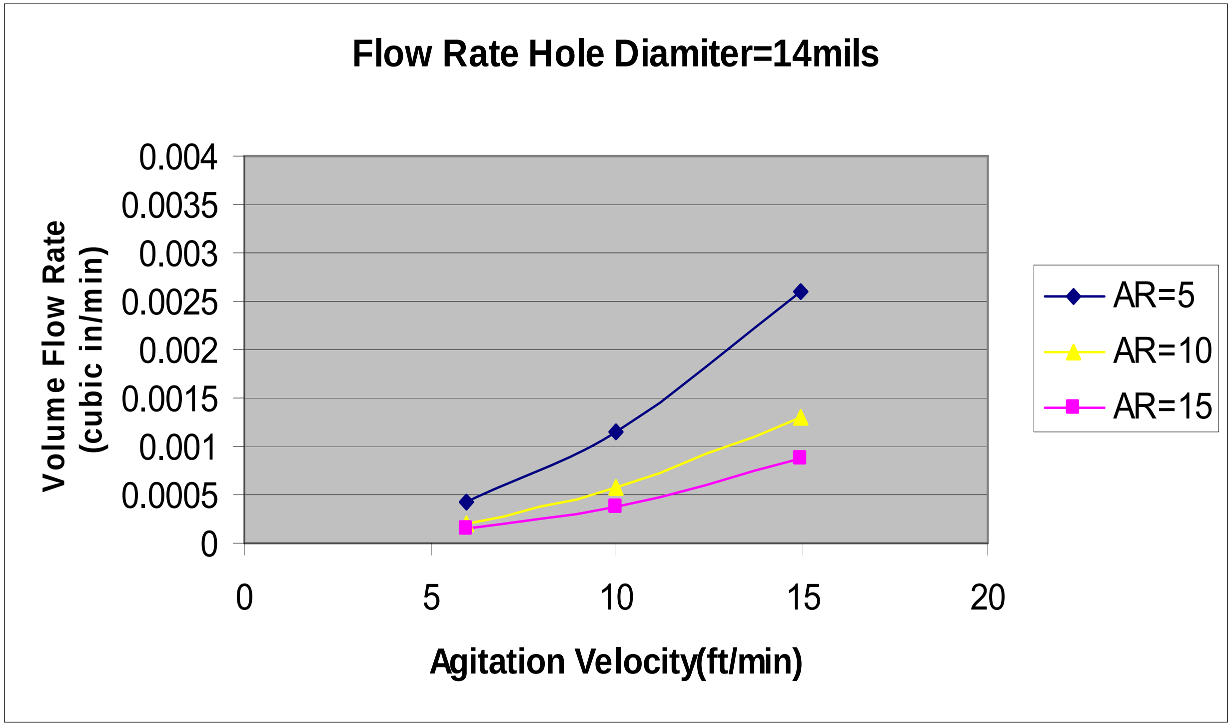
$$u_0 = \frac{r^2}{8\mu} \frac{\Delta p}{l}$$

  - μ is the viscosity

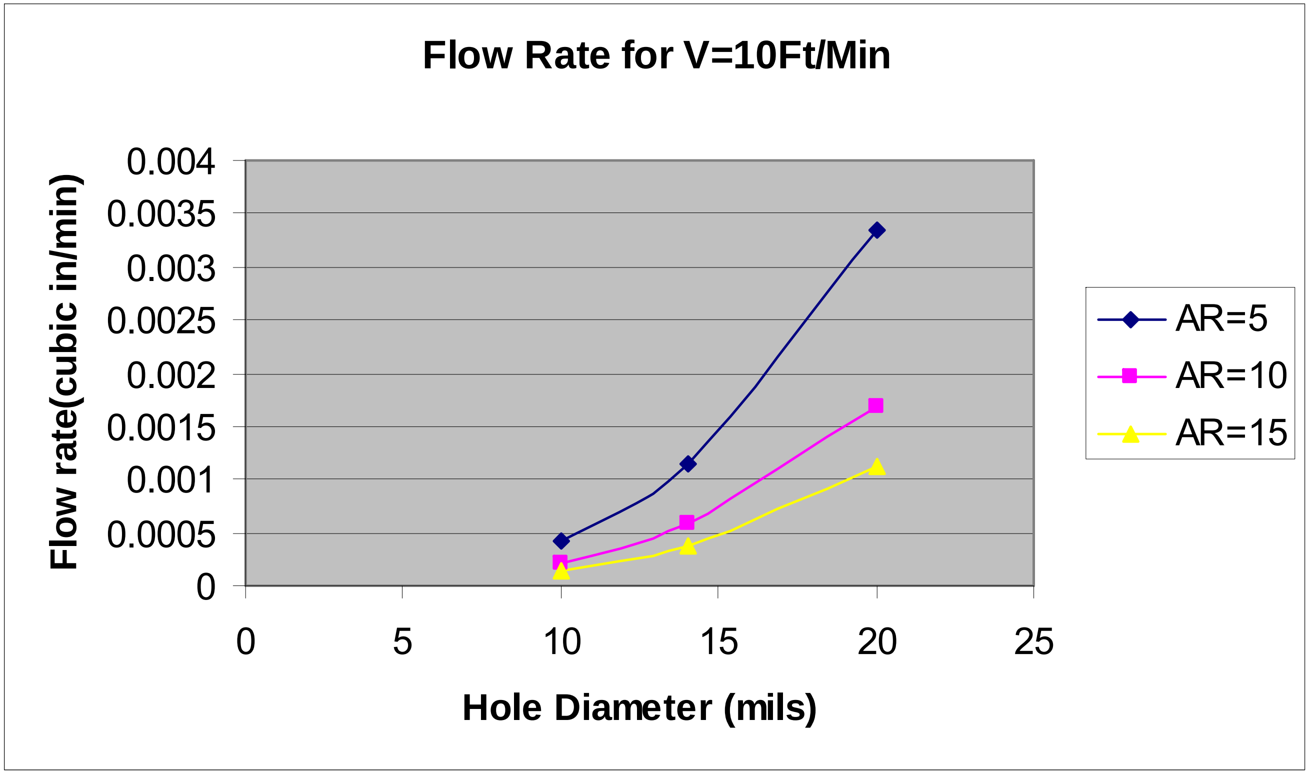
Fluid Flow in a PTH Conventional Wisdom *vis a vis* Analysis

- Conventional wisdom:
  - The volume flow is proportional to
    - aspect ratio
    - agitation speed
- Analysis
  - The volume flow is proportional to
    - aspect ratio
    - the square of the agitation speed
    - third power of the hole diameter

The Impact of Aspect Ratio and Agitation Speed on Flow Rate



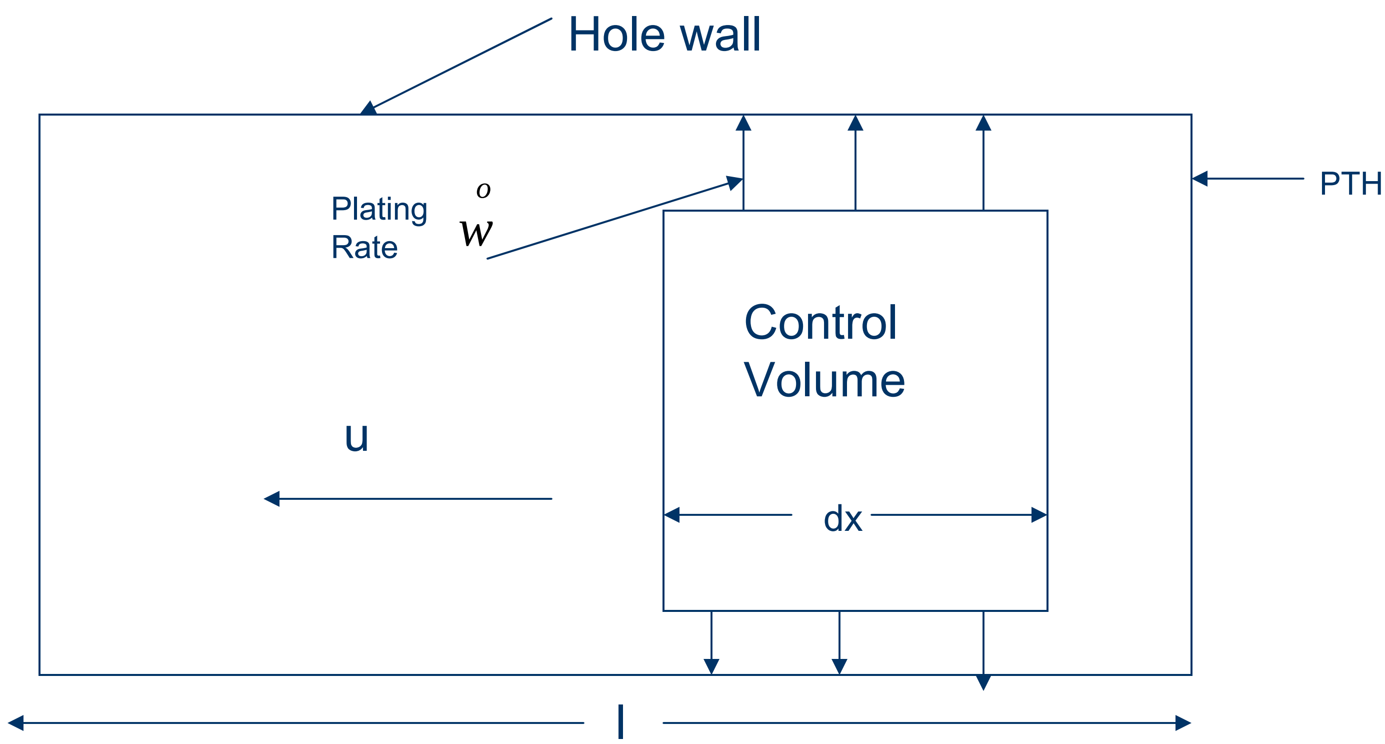
Impact of Hole Diameter and Aspect Ratio on Flow Rate



Electrolytic Plating Dynamics

$\dot{w}$

Electrolytic Plating Model for a PTH



Assessment

- The fluid mechanics have already been develop
- An analytical description of the plating rate is now required, i.e. $\overset{o}{w}$
- Faraday's Law

Faraday's Law

- According to Faraday's law the plating rate in a through hole is

$$w = GIt$$

- And

$$\overset{o}{w} = GI$$

- Where:
  - w is the plated mass
  - G a constant
  - t is time
  - I is the effective amperage, i.e. the portion of the current used by the plating process as opposed to formation of gases etc.

Effective Amperage

- The effective amperage is (see Ref 3)

$$I = I_o(1 - \exp[-k\frac{c}{c_0}])$$

- Where
  - c is the concentration
  - c_0 is the maximum concentration
  - I_0 is the effective amperage at the maximum concentration (normally the induced current)
  - k is a constant

Concentration Variation in PTH

- To an observer attached to the control volume the concentration will vary as

$$\dot{c} = \frac{dc}{dx}u = -\frac{GI}{V}$$

- Where V is the control volume
- The effective amperage I is already defined

Concentration Along the Barrel of the PTH

- Setting
  - $c=c_0$ @ $x=0$
  - Defining the surface plating rate as

$$\overset{o}{w}_s$$

  - And integrating the above system of equations
  - Produces the implicit relationship between the concentration and hole wall position

$$\frac{x}{l}=-\frac{\pi}{256}\left(\frac{D}{A}\right)^2\frac{(V_0)^2}{\upsilon}\frac{c_0}{(\dot{w})_s}\left[\frac{c}{c_0}-1+k\ln\left(\frac{1-\exp(-kc/c_0)}{1-\exp(-k)}\right)\right]$$

Normalized Plating Thickness

- The concentration ratio c/c_0 now can be determined along the barrel
- The concentration ratio defines the amperage ratio I/I_0
- From Faraday's law the plated mass ratio
- $w/w_s = I/I_0$
- The relative plated mass can now be calculated as a function of barrel position
- It remains to define the plating constant k

Bath Plating Index

- Define the bath plating index as
- $\chi = -\dfrac{1}{c}\ln\left(1 - \dfrac{I}{I_0}\right)$
- Ref 3 found that when the concentration of a Cu bath is reduced to 2.86 g/ft^3 the plating efficiency (I/I_0) is approximately 10%
- Then χ=0.0367 and k=0.0367c_0
- The value of χ can be heavily influenced by plating additives.

Analysis

Variables Effecting Plating Dynamics

- The analysis finds that the variables controlling the plating process are
  - Bath concentration c_0
  - Agitation speed V_0
  - Surface plating rate (i.e. current density), $\overset{o}{w}_s$
  - Aspect ratio
  - Hole diameter
  - Plating bath index

Parametric Analysis of the Control Variables

- The influence of each of the controlling variables will be evaluated by:
  - Defining a set of base line values for the control variables
  - Perturb each variable while holding the others fixed

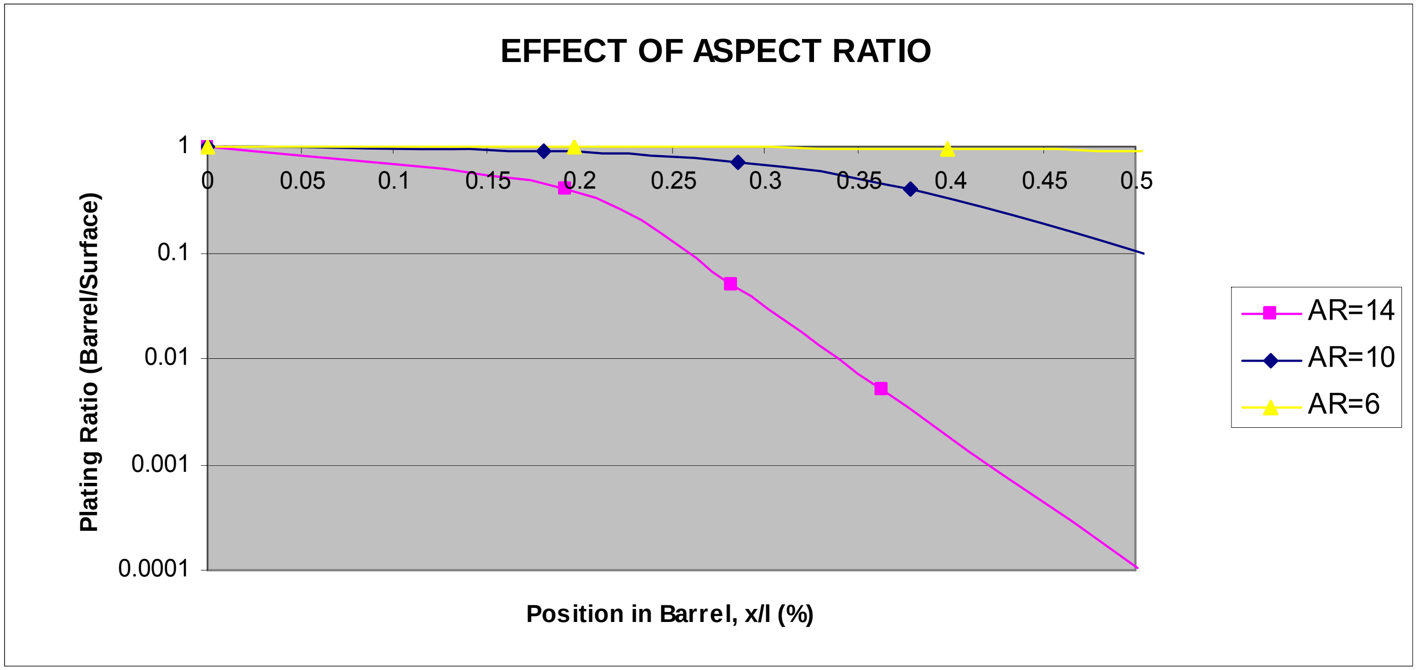
Base Line Parameters

A=10
Hole diameter =18 mils
c_0 = 140 g/ft^3
V_0= 8 ft/min

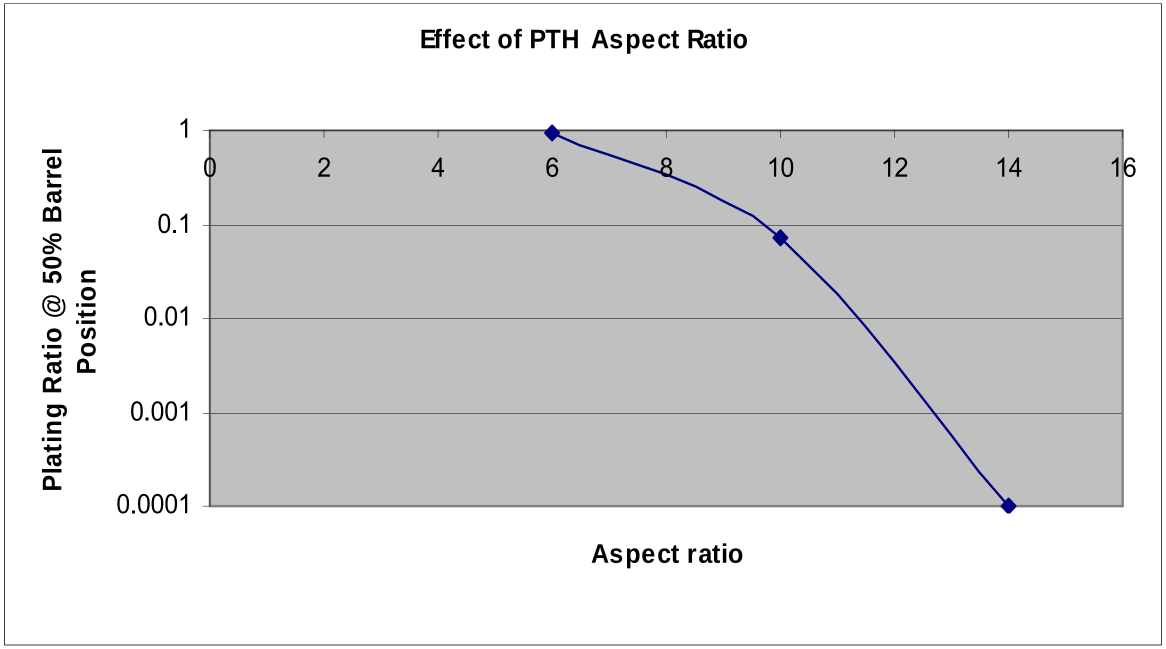
χ=0.0367ft^3/g

$\dot{w})_s = 0.0001 g/\sec$

Effect of Aspect Ratio



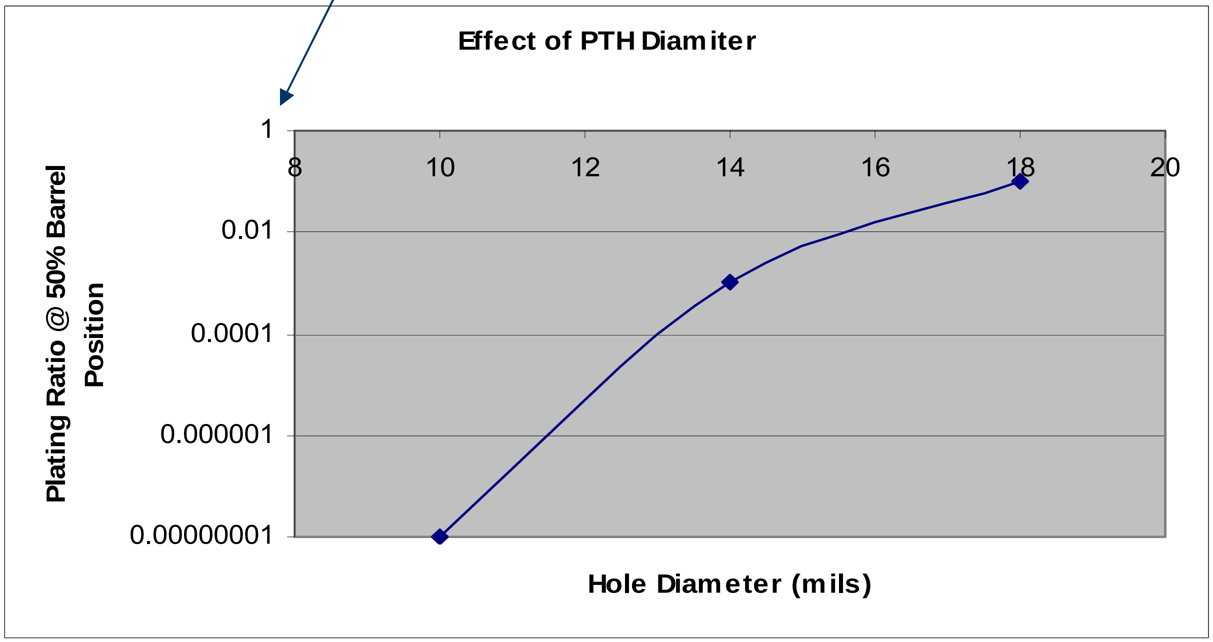
Effect of Aspect Ratio on Minimal Thickness x/l=50%



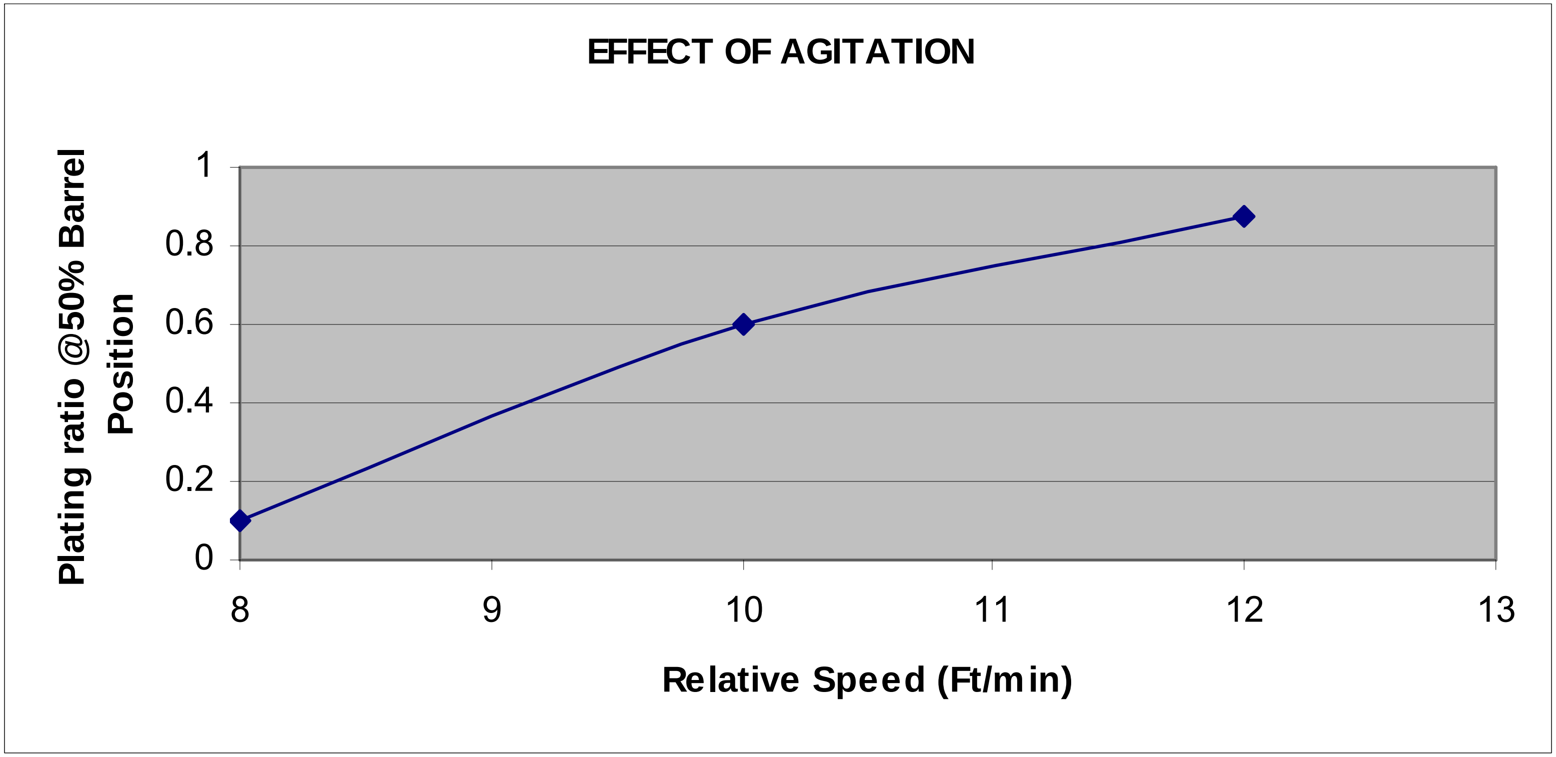
For the Other Variables Only the Minimal Thickness (*Center of Barrel*) Will be Examined

Effect of Hole Diameter

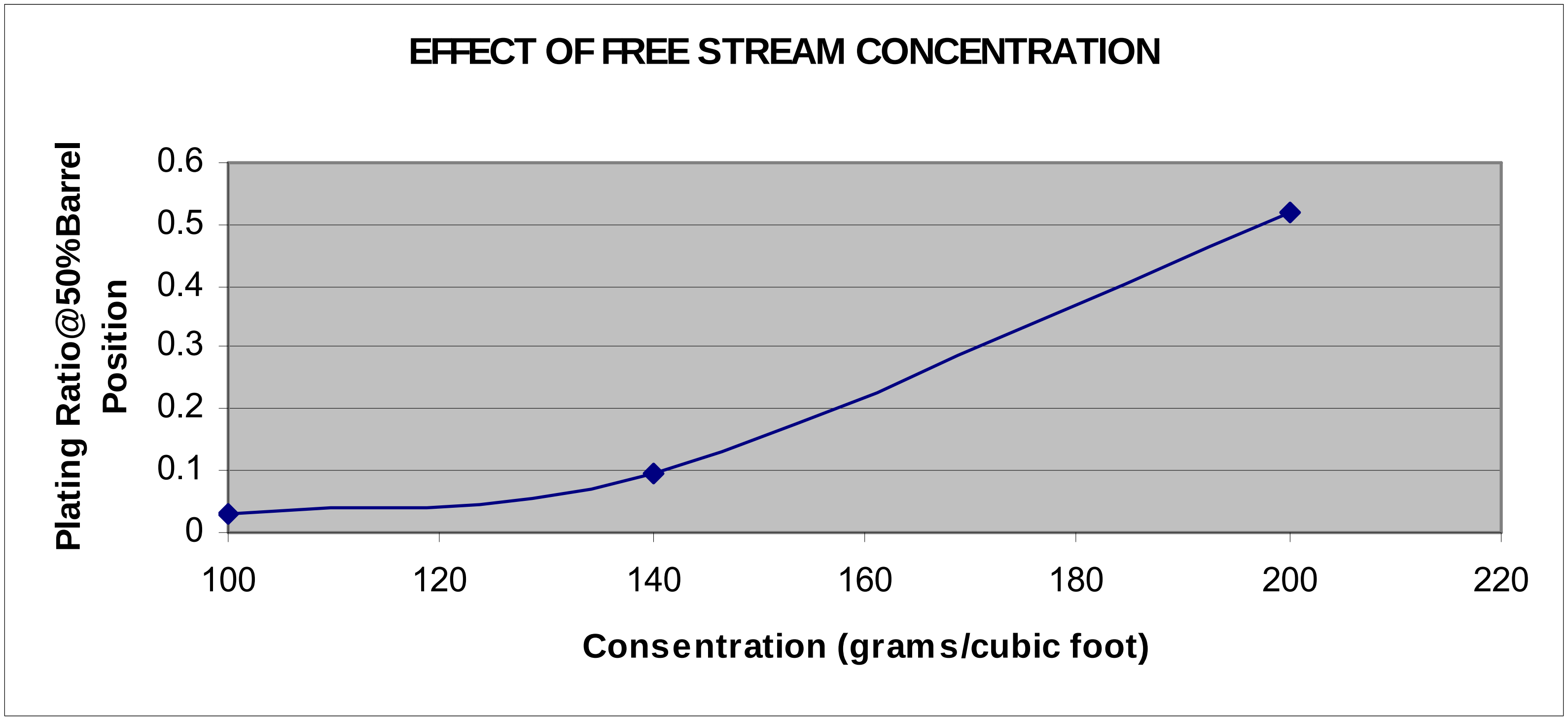
A ratio of 1.0 indicates uniform plating
In the barrel



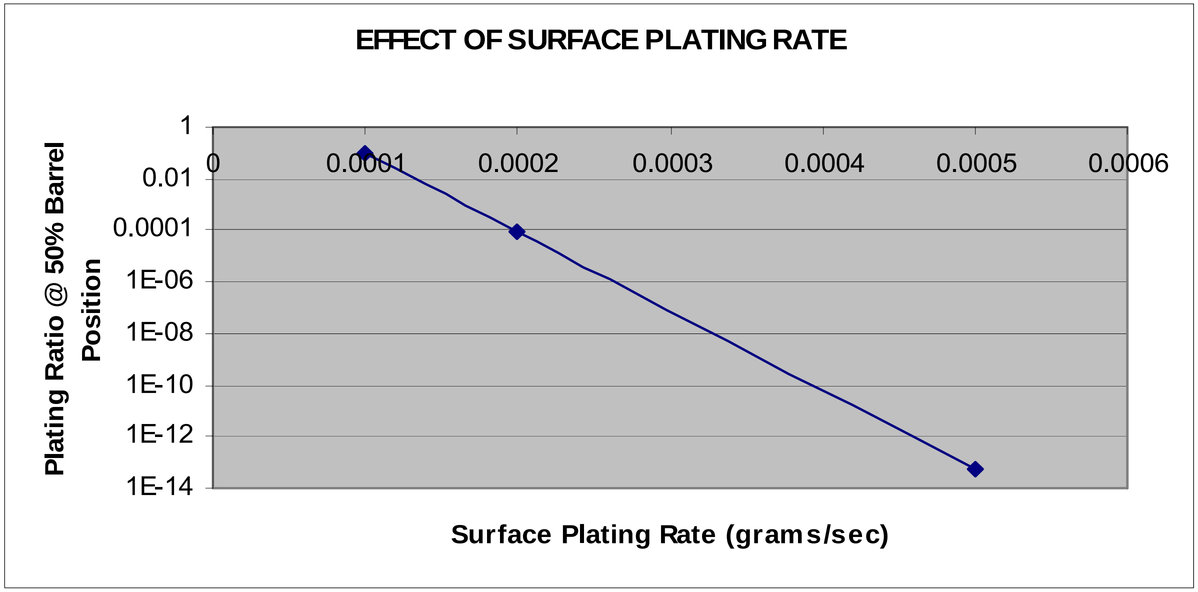
Effect of Agitation



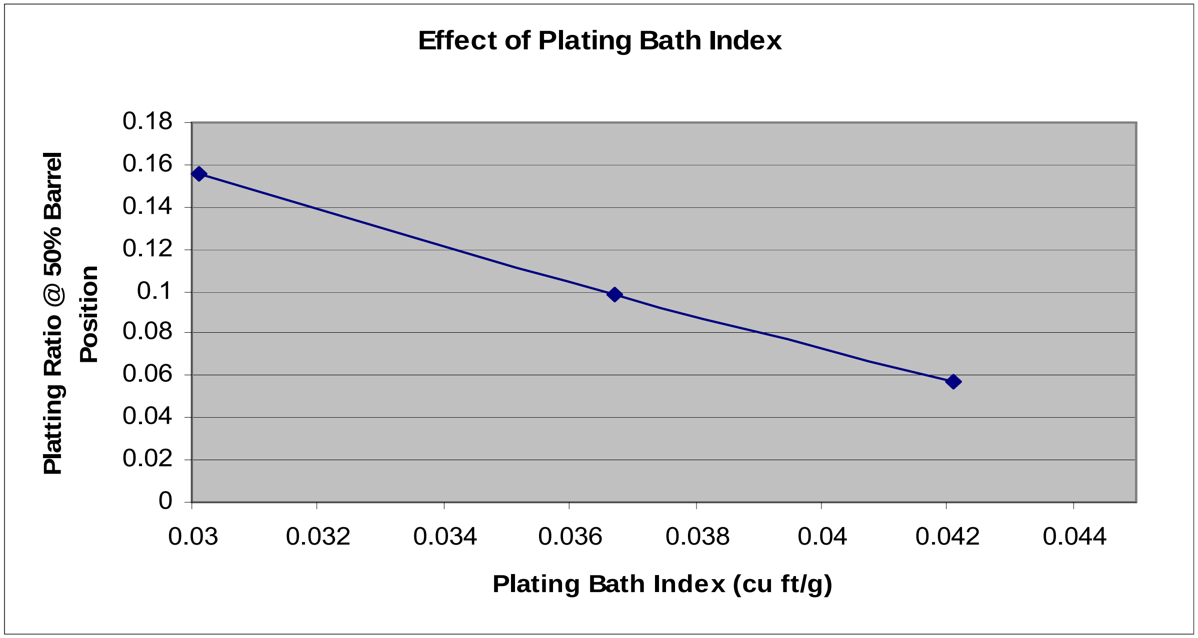
Effect of Bulk (Free Stream) Concentration
c_0



Effect of Surface Plating Rate i.e. Current Density



Effect of Plating Bath Index



Summary
Order of Magnitude Analysis

Variable	Magnitude of Influence
Aspect Ratio	Square
Hole Diameter	Square
Agitation Speed	Square
Bulk Concentration	Super Linear
Surface Plating Rate (Current Density)	Linear
Plating Bath Index	Linear

Thank You