Capillary Fill Time & Meniscus Shape:

A non-symmetric, non-equal contact angle, coplanar cavity study

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Surface Phenomena Project

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Problems:

- What is the shape of the meniscus as it traverses a *wavy* cavity?
- How does the fluid properties and the system geometry affect the fill time?

Motivation:

- Nanoimprint lithography techniques under development at UT, Harvard, Princeton require a fluid to fill a cavity that is not planar.
- Production speeds require a fill time of ~1 second.

What is the surface tension contribution?

- How does the fluid affect is?
  - Rate of Fill $\propto 1/\mu$
  - Rate of Fill $\propto \gamma$
- How does the “wavy” surface affect it?
  - Requires more insight into the geometry!!!

Fill Time Prediction:

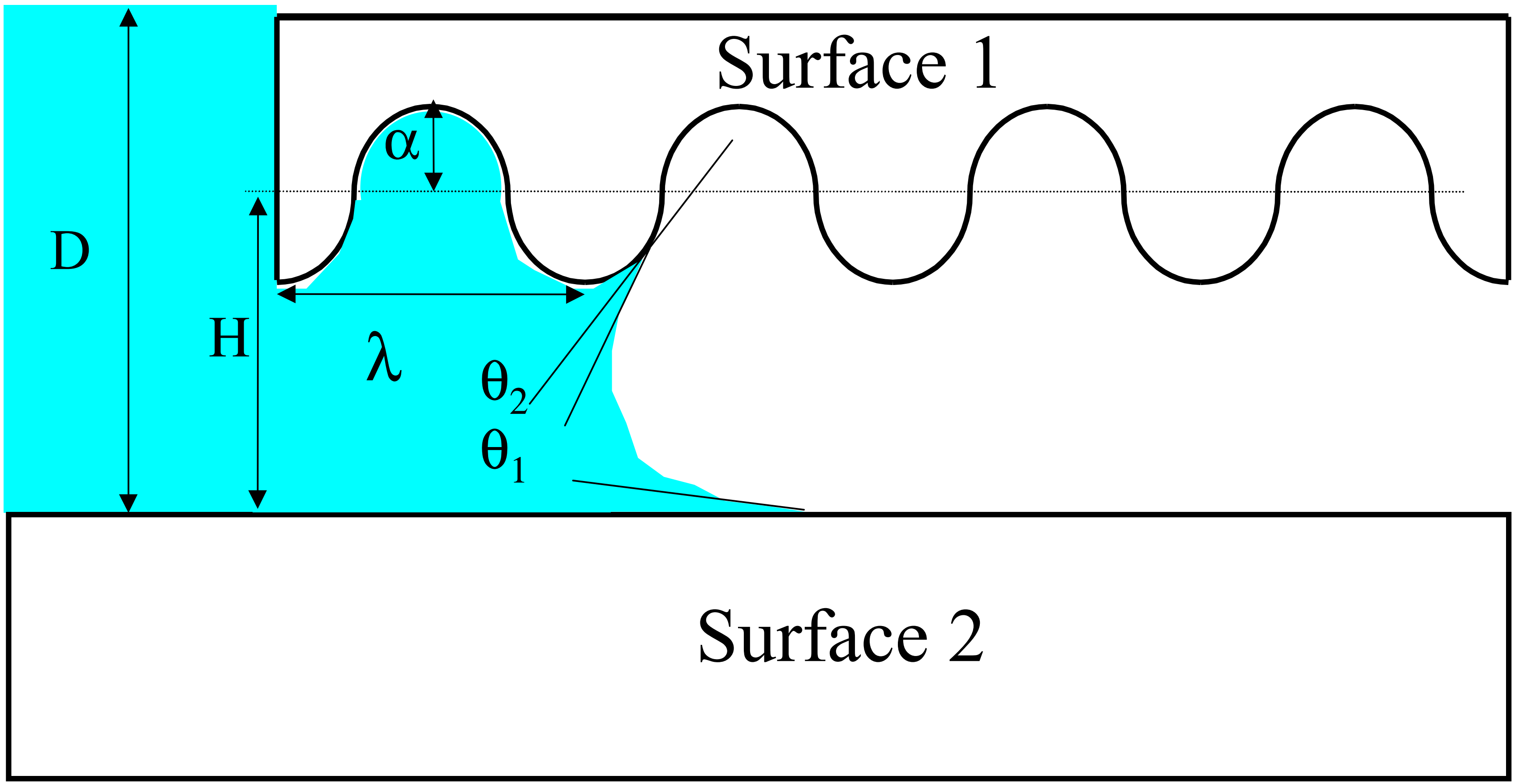
- Washburn Equation for Cylindrical Capillary

$$\frac{dx}{dt} = \frac{2\pi R\gamma\cos\theta + \pi R^2 P}{8\pi\mu x}$$

- Washburn Equation for Planar Cavity

$$\frac{dx}{dt} = \frac{(\gamma / R)}{(24 \mu x) / H^2}$$

Model System:



Fluid Properties: μ, θ_1, θ_2, γ

Model Assumptions:

- Constant Contact Angles
- Newtonian Fluid
- Constant Density
- Pressure at Inlet $\propto$ Height of Feed
- Height of Feed $\propto$ Volume of Cavity

Assumptions Con't:

Experimental System	Model
1:1:1 solvent: monomer: polymer	Newtonian Fluid of constant viscosity and density
Top plate has anisotropic etched pattern of depth, 2_{α}, and period, λ.	Sinusoidal pattern of amplitude, α, and wavelength, λ.
Plates are 1 square inch.	Plates of length (L), 2.5 cm. Neglect Edge effects.
Slightly non-coplanar plates	Coplanar plates
$0^{o} < \theta_1 < 30^{o}$ $50^{o} < \theta_2 < 90^{o}$	$\theta_1 = 30^{o}$ $\theta_2 = 60^{o}$
Fluid feed by a convex drop of radius R' on one edge.	Fluid feed with fluid height, D. Initially D= L*H/ 1 microns

Defined Surfaces:

Upper Surface

$$s(t) = t\vec{i} + (H + \alpha \sin(\frac{2\pi x}{\lambda}))\vec{j}$$

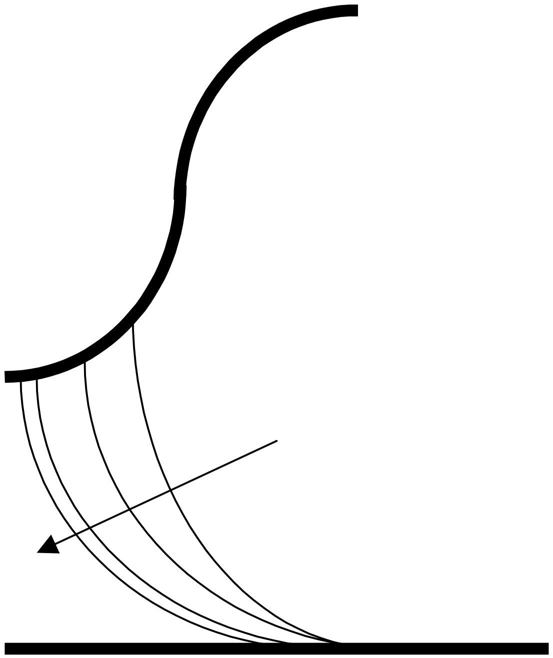
Lower Surface

$$g(\gamma) = \gamma\vec{i}$$

Meniscus

$$\eta(\beta,\gamma) = (x_c(\gamma) + R\cos(\beta))\vec{i} + (y_c(\gamma) + R\sin(\beta))\vec{j}$$

Model Method: *A Shooting Approach*



- Increase radius until the meniscus and the upper surface touch.
- Calculate the dot product and check constraint is met.

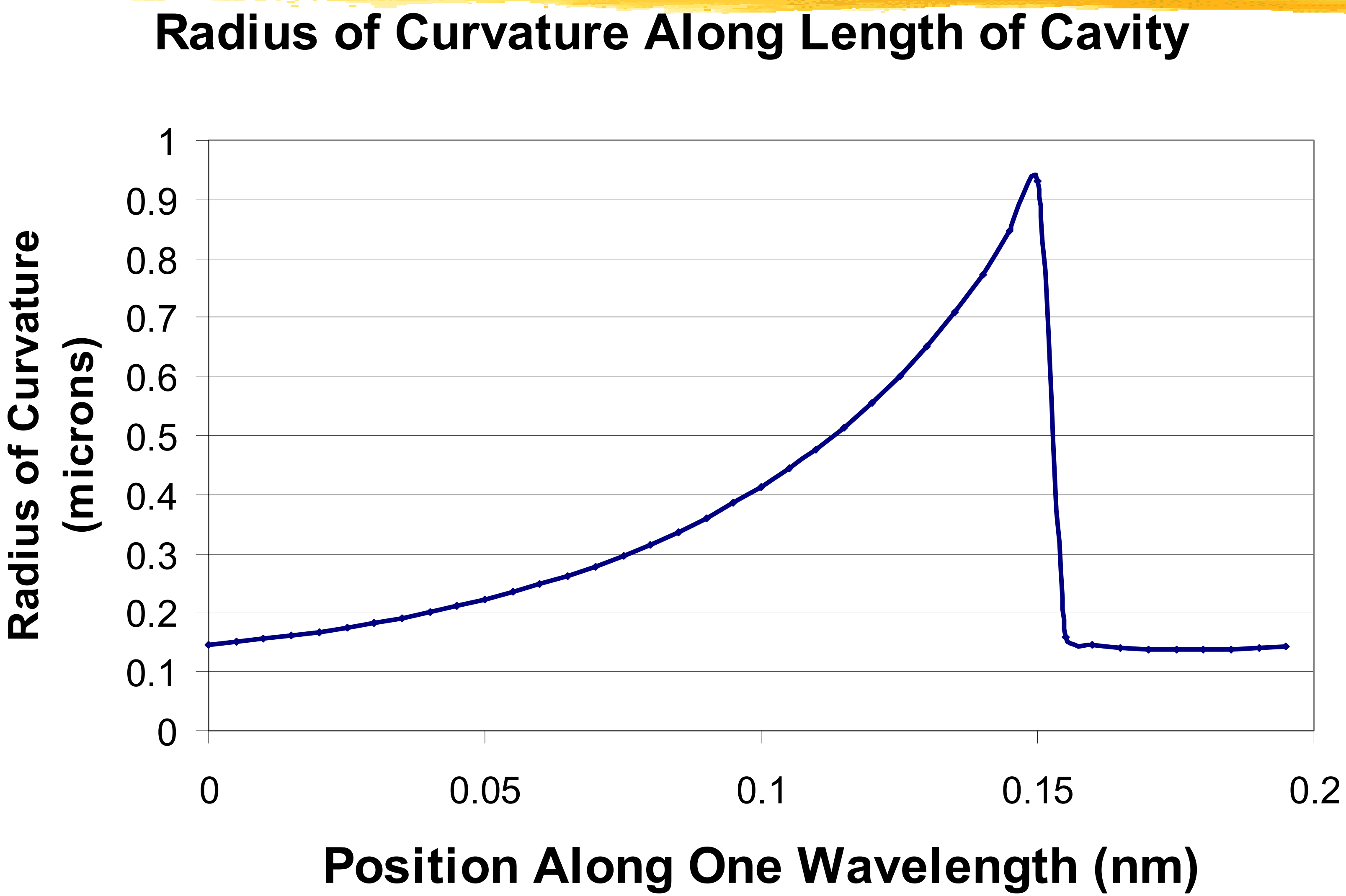
Model Constraints:

- Contact Angles, θ_1 & θ_2 must be met.

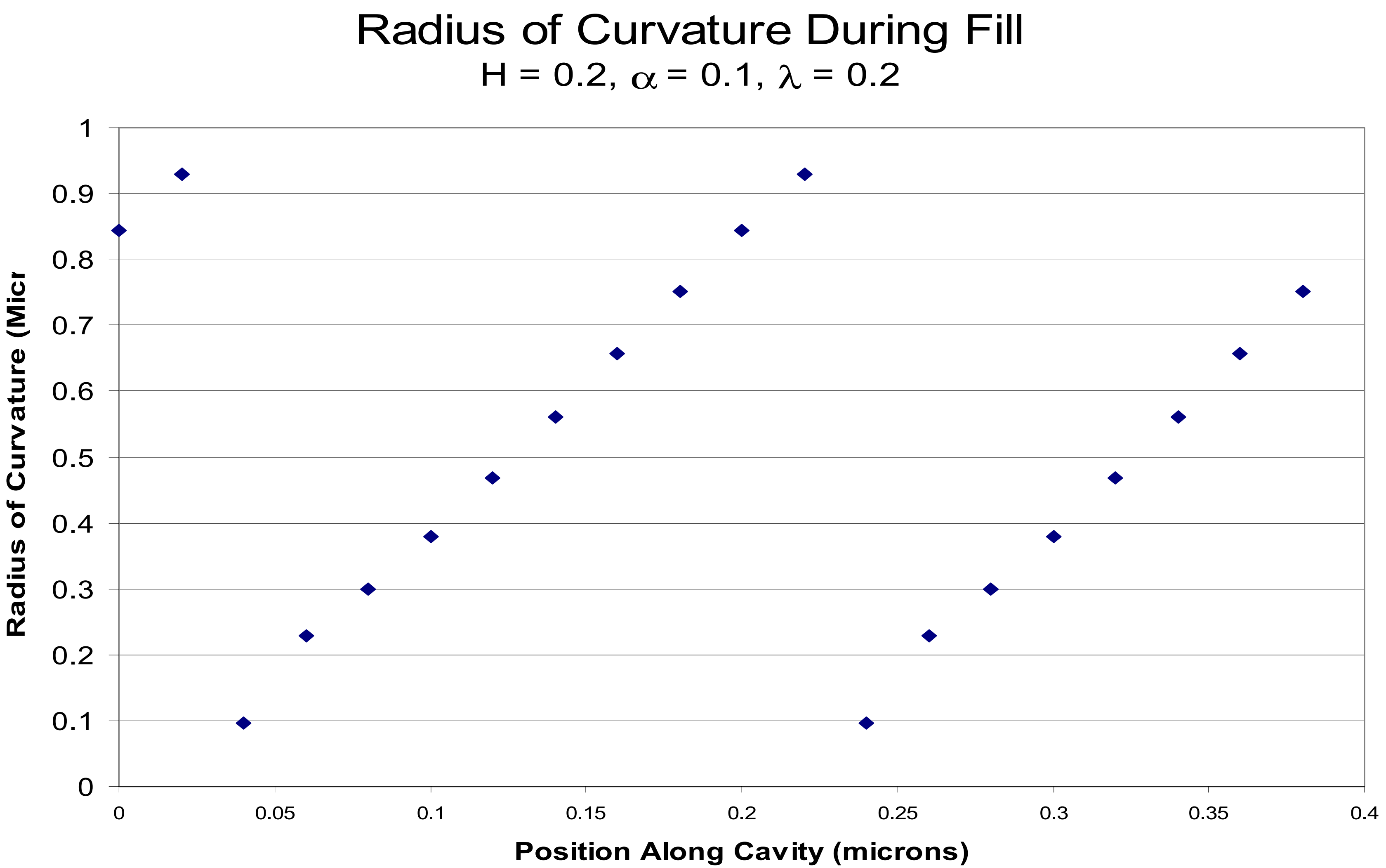
$$\cos\theta_2 = -\frac{\left[(2\pi \boldsymbol{A}/\lambda)\cos\beta_{\boldsymbol{s}}\cos(\frac{2\pi \boldsymbol{t}}{\lambda}) - \sin\beta_{\boldsymbol{s}}\right]}{\left[1+((^{2\pi \boldsymbol{A}}\!/_{\lambda})\cos(^{2\pi \boldsymbol{t}}\!/_{\lambda}))^2\right]^{1/2}}$$

$$\cos(\theta_1) = -\sin(\beta_1)$$

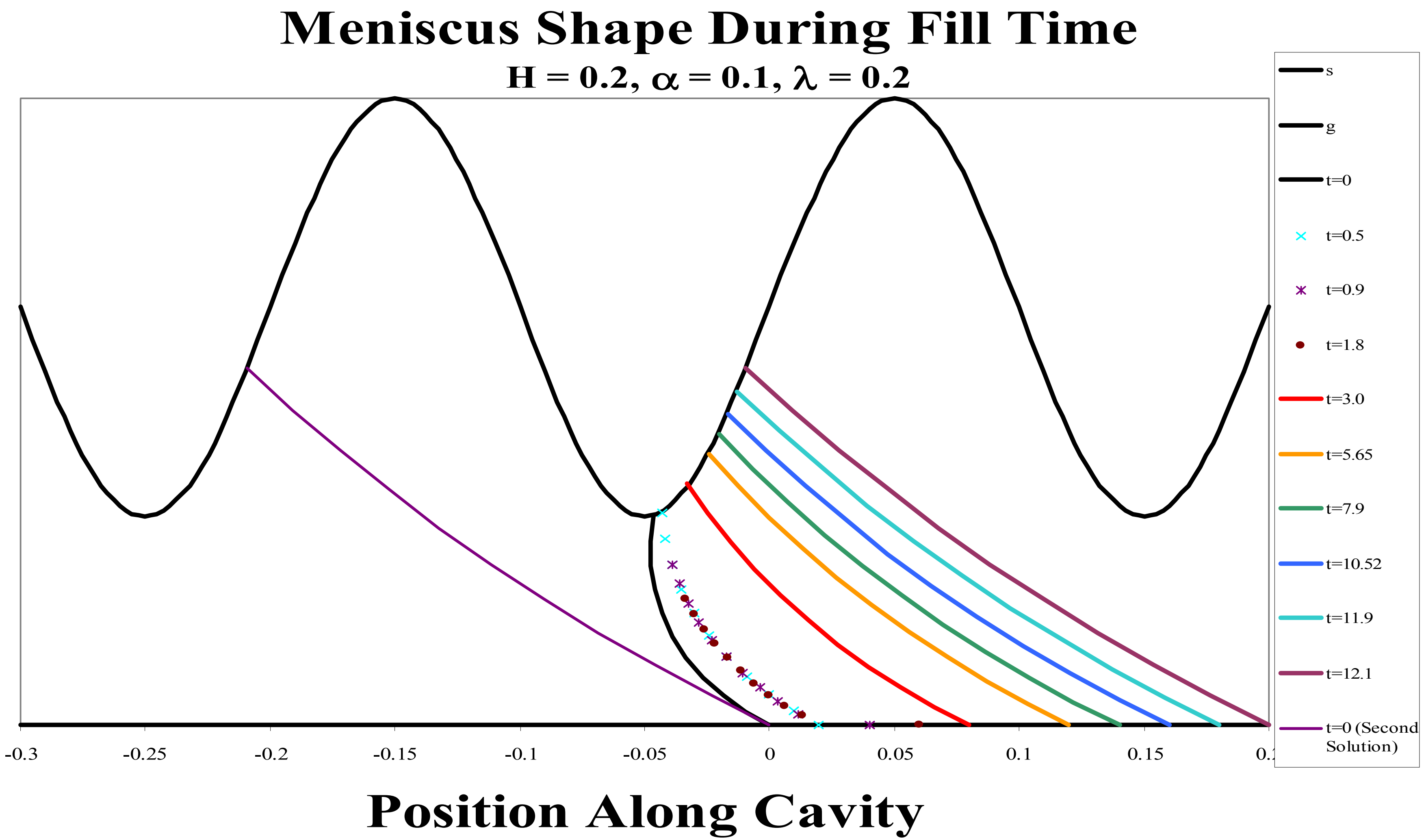
Radius Along Path II:



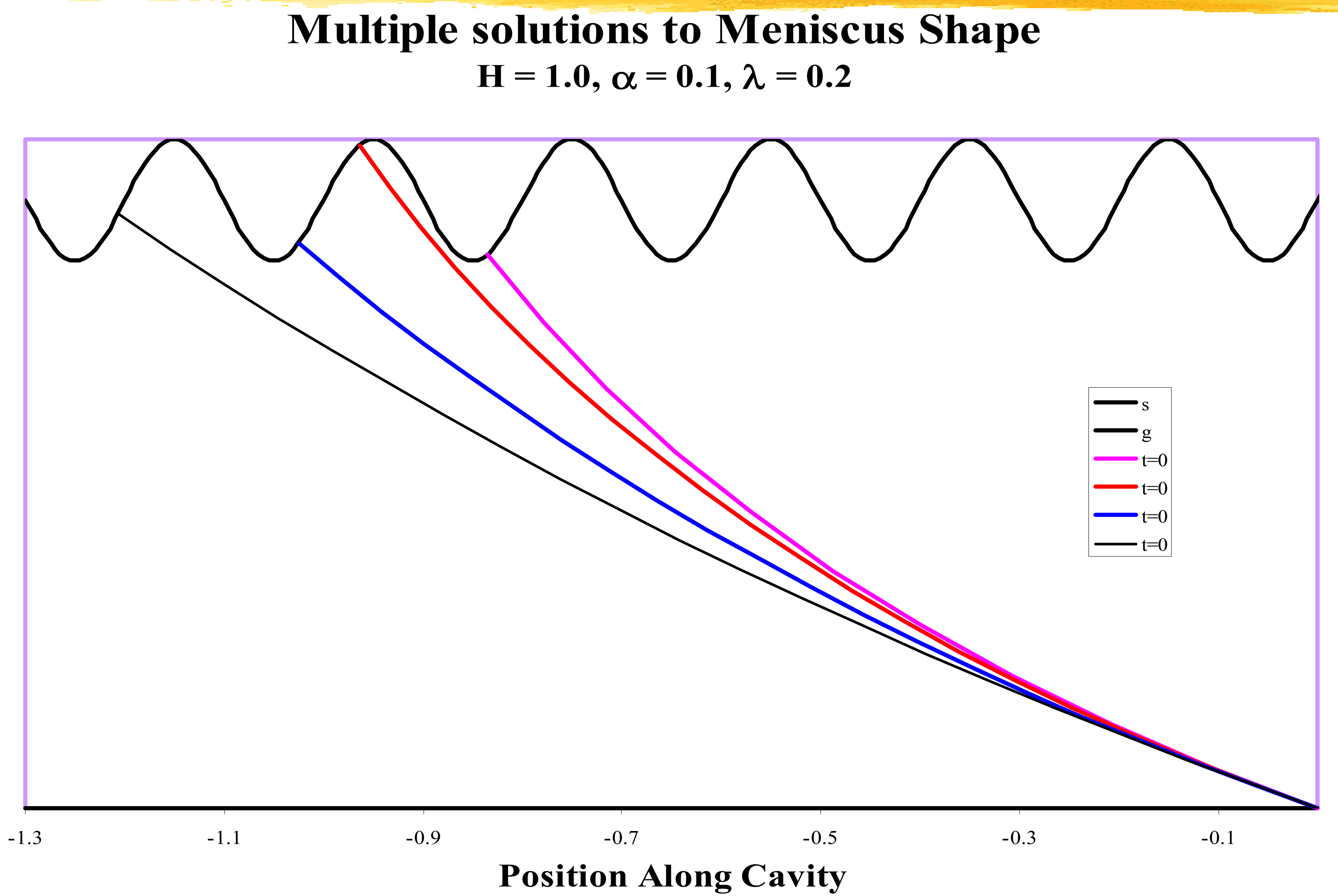
Radius Along Path:



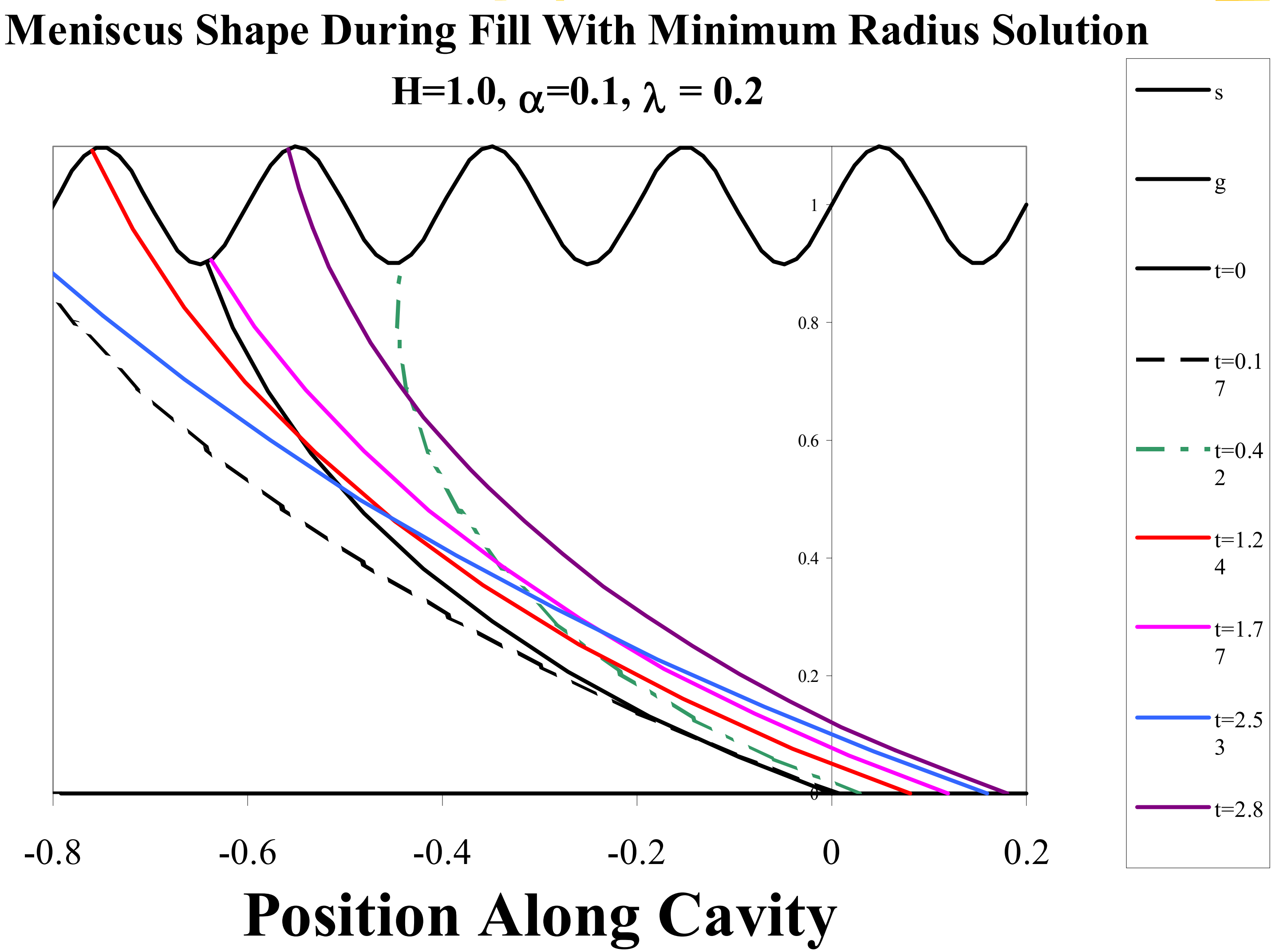
Meniscus Shape During Fill:



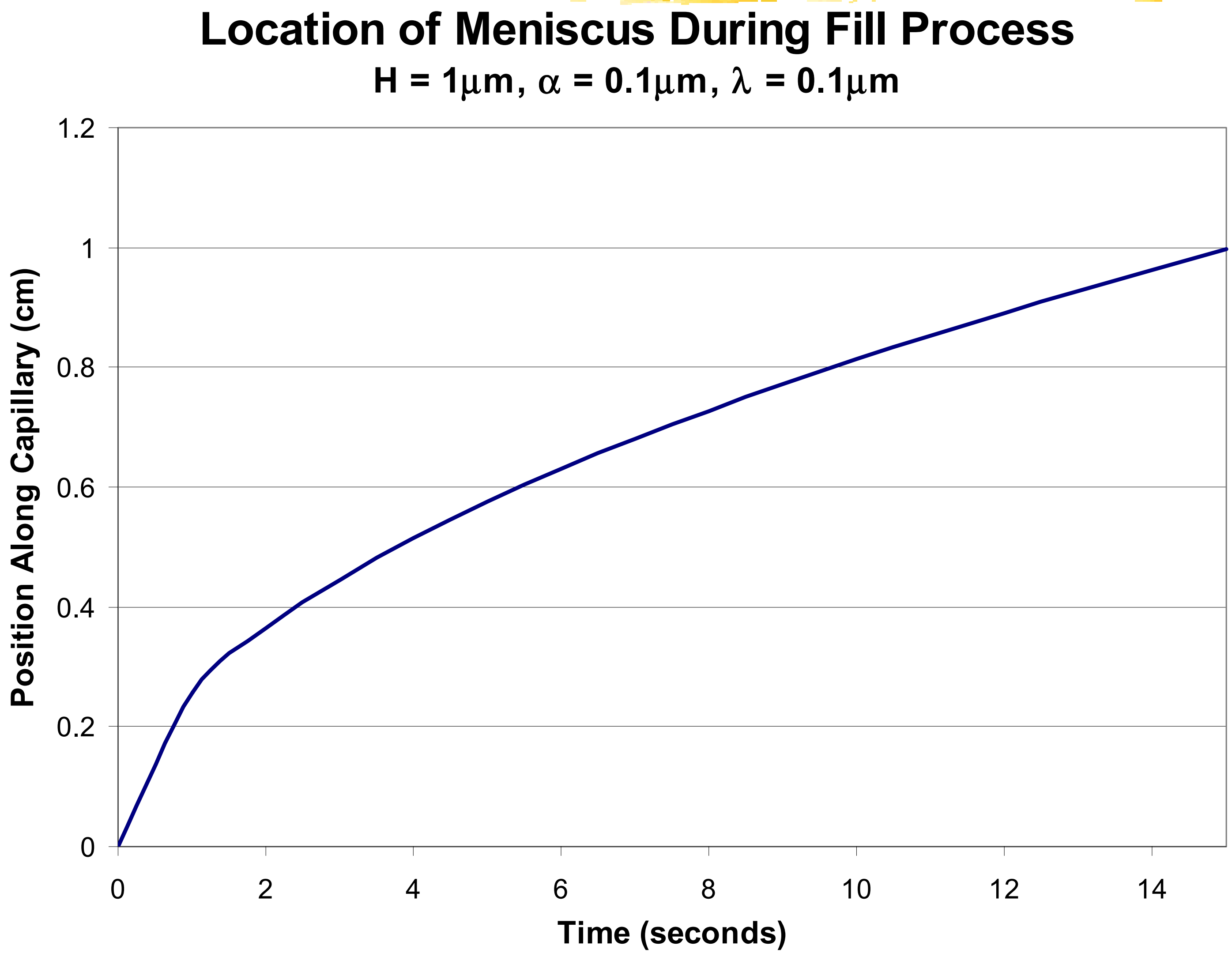
Added Complexity: *Multiple Solutions*



Minimum Radius Solution:



Meniscus Location During Fill



Fill Time For Different Viscosities & Surface Tensions:

Fill times (seconds)

Viscosity (P)	H=1, α=0.1, λ = 0.2	H=1, α=0.1, λ = 0.1	H=0.2, α=0.1, λ = 0.2	H=0.2, α=0.1, λ = 0.1
0.001	28.56	15.12	112	56
0.01	285.6	151.2	1120	560
0.1	2856	1512	11200	5600
1	28560	15120	112000	56000

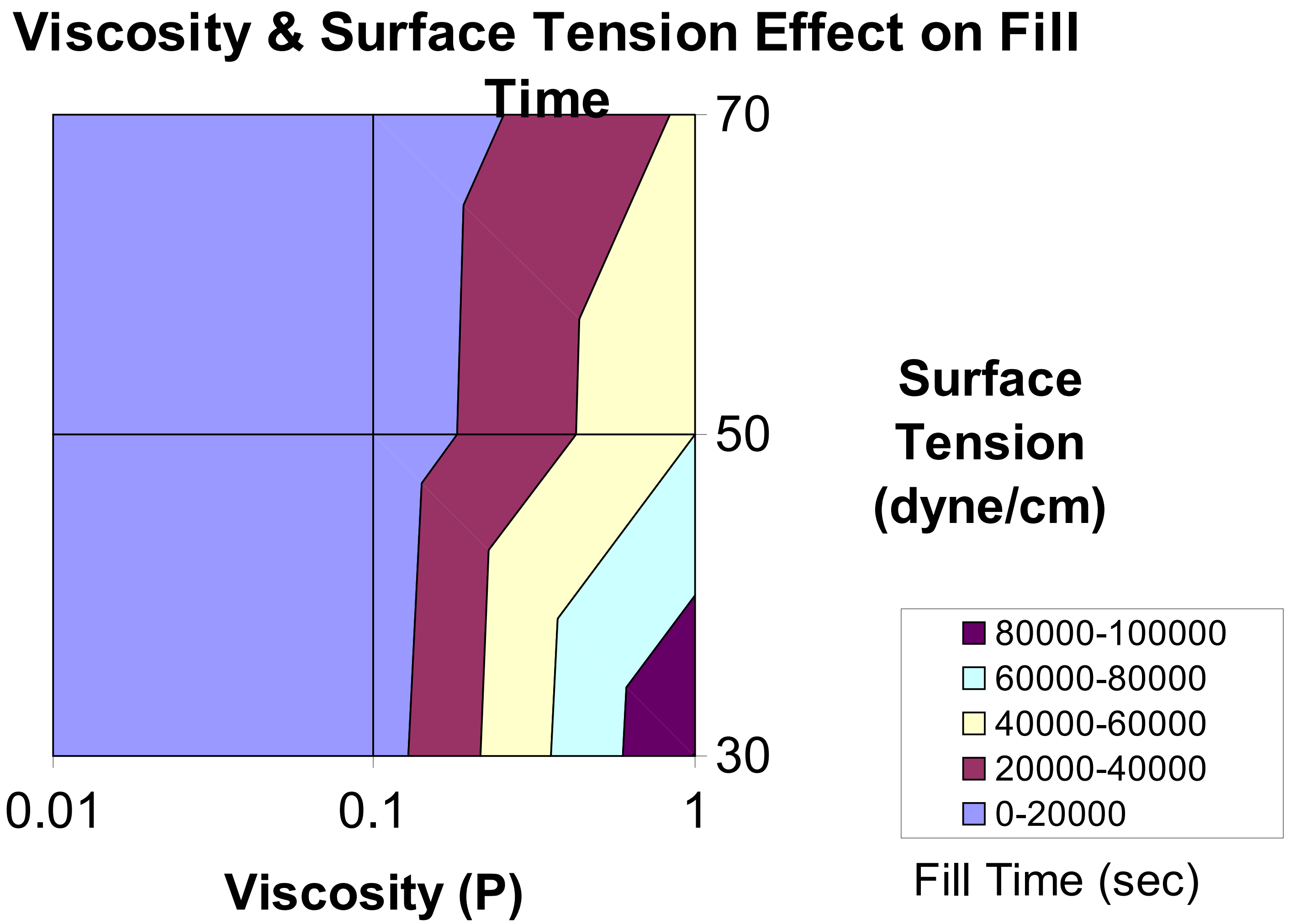
Fill times (seconds)

Viscosity	γ = 30 dynes/cm	γ = 50 dynes/cm	γ = 70 dynes/cm
0.01	8	4.8	3.4
0.1	80	48	34.3
1	800	480	342.9

Lower μ, higher γ, small λ provides fastest fill time.

Unsatisfactory for production photolithography rates.

Fill Time:


Viscosity & Surface Tension Effect on Fill Time
70
50
30
0.01
0.1
1
Viscosity (P)
Surface Tension (dyne/cm)
80000-100000
60000-80000
40000-60000
20000-40000
0-20000
Fill Time (sec)

Conclusions:

- Smaller wavelengths fill faster than longer wavelengths due to affects on radius of curvature.
- Higher surface tension and lower viscosity improve fill times.
- Considering only capillary action, fill times are too slow for production use.

Future Improvements:

- Improve computational time.
- Eliminate contact angle dependence, use specific surface energies of different surfaces to predict performance.
- Look at free energy of entire system as it traverses the cavity.
- Add non-uniformity of surface energy along treated *wavy* surface.