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# ANALYSIS OF HIGH-SPEED GROWTH OF SILICON SHEET IN INCLINED-MENISCUS CONFIGURATION

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## Goals

USE TWO-DIMENSIONAL THERMAL-CAPILLARY MODEL TO IDENTIFY RATE AND PROCESSING LIMITS FOR GROWTH OF THIN SILICON SHEETS.

RESULTS FOR VERTICAL AND INCLINED DIE-DEFINED GROWTH SYSTEMS

## Important Results

1. MAXIMUM GROWTH RATE IN VERTICAL SYSTEM IS SET BY THERMAL-CAPILLARY LIMIT BEYOND WHICH STEADY GROWTH IS IMPOSSIBLE

   - LIMITS GROWTH RATE IN DIE-DEFINED SYSTEMS (EFG)
   - OF SECONDARY IMPORTANCE IN FREE-MENISCUS GEOMETRIES (DENDRITIC WEB,EDGE-SUPPORTED)

2. VERTICAL GROWTH IS QUALITATIVELY MODELLED BY ONE-DIMENSIONAL HEAT TRANSFER

   - LATERALLY UNIFORM TEMPERATURE
     ALMOST FLAT MELT/CRYSTAL INTERFACE

3. ONE-DIMENSIONAL MODEL IS VALID FOR A WIDE RANGE OF AMBIENT CONDITIONS

4. THERMAL-CAPILLARY LIMITS EXIST FOR INCLINED GROWTH SYSTEMS

## Thermal-Capillary Model, Heat Transfer
## $L^* = 0.025$ cm, $T^* = 1683°K$

CONDUCTION DOMINATED

$$K_1 \nabla^2 T = 0 \quad \text{(MELT)}$$

$$K_2 \nabla^2 T - Pe(\underline{V} \cdot \nabla T) = 0 \quad \text{(CRYSTAL)}$$

BOUNDARY CONDITIONS

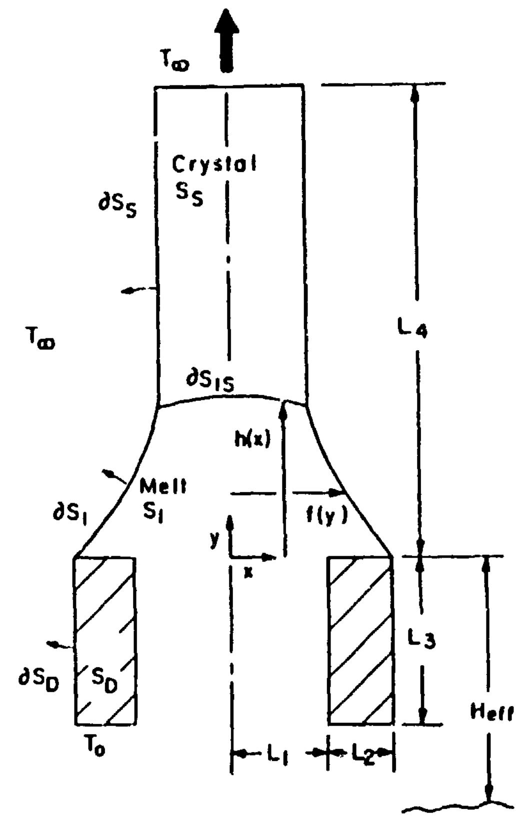
$$-\underline{N} \cdot K \nabla T = Bi(T - T_A) + R(T^4 - T_A{}^4)$$

$$T|_{Y=-L_3} = T_0$$

$$T|_{Y=H(X)} = 1.0$$

$$T|_{Y=\infty} = T_\infty$$

$$\underline{N} \cdot K_2 \nabla T - \underline{N} \cdot K_1 \nabla T = PeSt(\underline{N} \cdot \underline{V})|_{Y=H(X)}$$



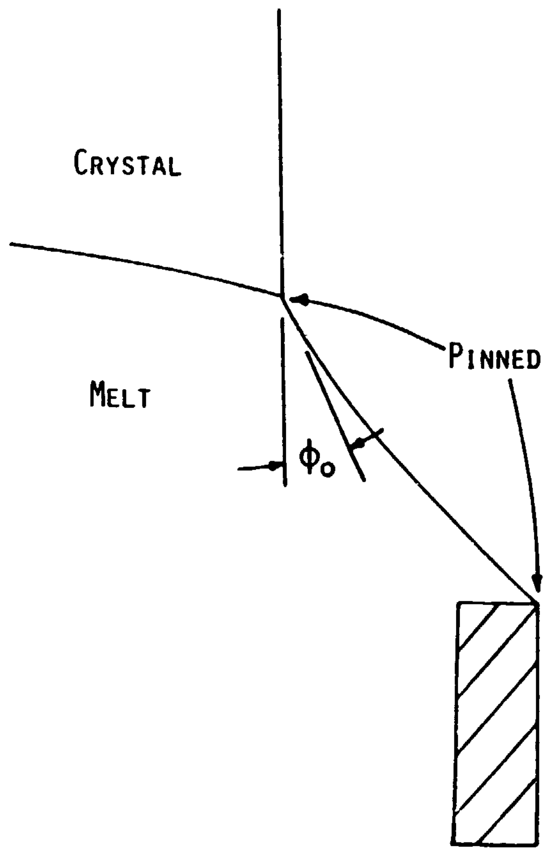
## Thermal-Capillary Model, Capillarity

MENISCI

$2\mathcal{H} = Bo(y + H_{EFF})$

BOUNDARY CONDITIONS

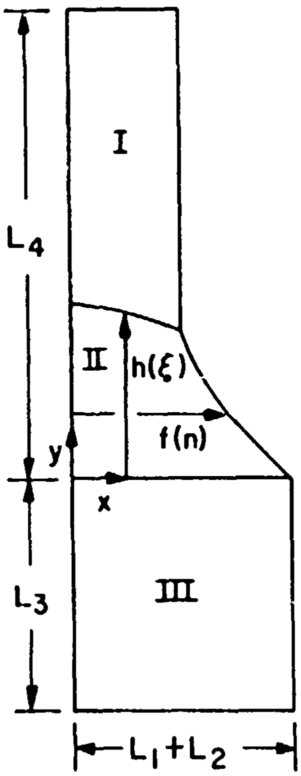
- PINNED AT DIE
- PINNED AT CRYSTAL
- STEADY STATE ANGLE, $\phi_o = 11^\circ$ USED TO DETERMINE THE CRYSTAL THICKNESS




## Characteristics of Isotherm/Newton Method

- GALERKIN/FINITE-ELEMENT APPROXIMATIONS TO
  - TEMPERATURE FIELD IN EACH PHASE
  - MELT/CRYSTAL INTERFACE SHAPE
  - MELT/GAS MENISCII
- SIMULTANEOUS CONVERGENCE IN ALL VARIABLES

## Mapping from Real Coordinates to a Unit Domain




**MAPPING**

I)

$X = \xi f(1)$

$Y = h(\xi) - (n-1)[L_4 - h(\xi)]$

II)

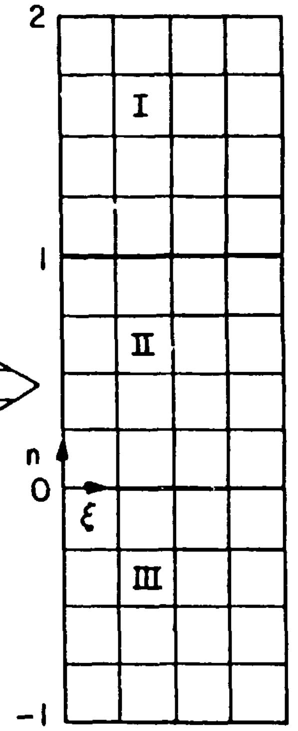
$X = \xi f(n)$

$Y = n h(\xi)$

III)

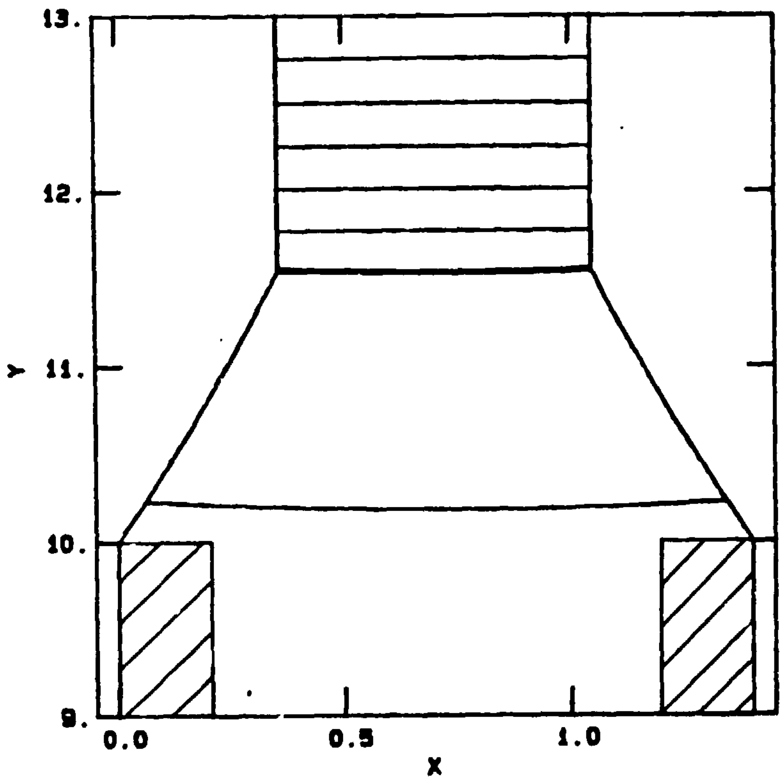
$X = \xi (L_1 + L_2)$

$Y = n L_3$



## Sample Result for Die-Defined System

V = 1.5 CM/MIN
UNIFORM AMBIENT , $T_{\infty} = 0.2$ (340°K)
ISOTHERMS 5° APART




- UNIFORM ISOTHERMS POINT TO 1D TEMPERATURE FIELD

One-dimensional model is based on:

- LATERALLY AVERAGED TEMPERATURE

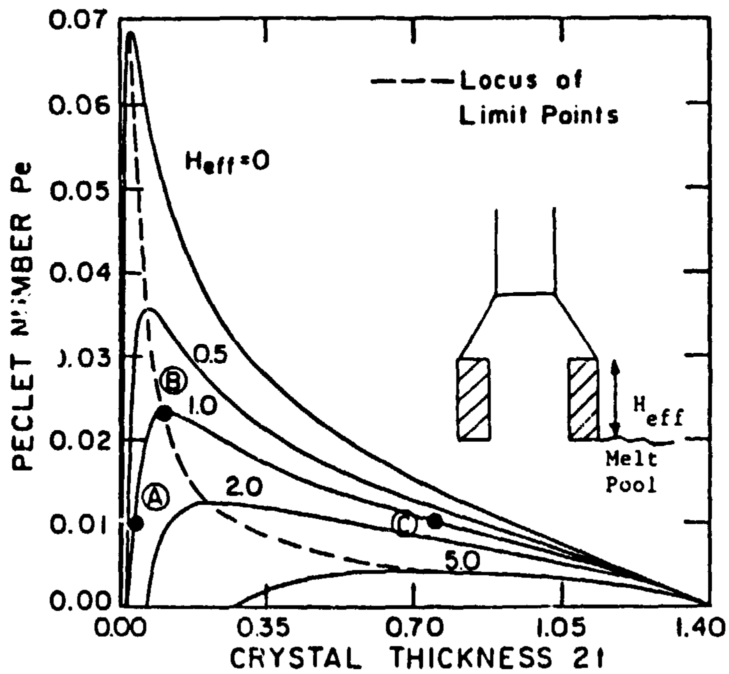
$$\hat{T}(y) = T(x,y) \quad \text{at } x = t$$

- CONDUCTION DOMINATES OVER RADIATION

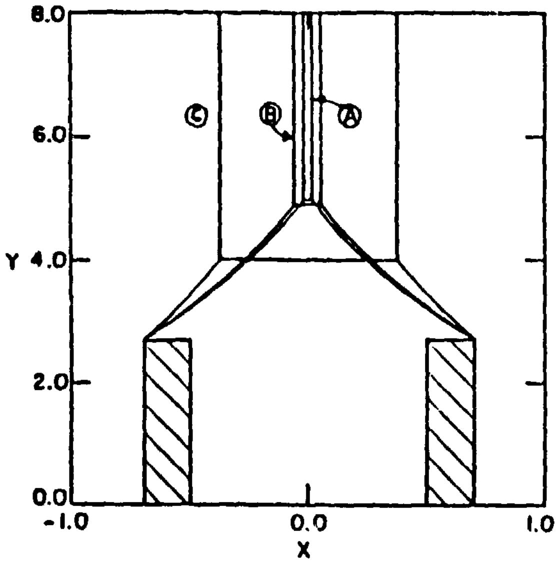
$$\frac{h\,t}{k} \ll 1$$

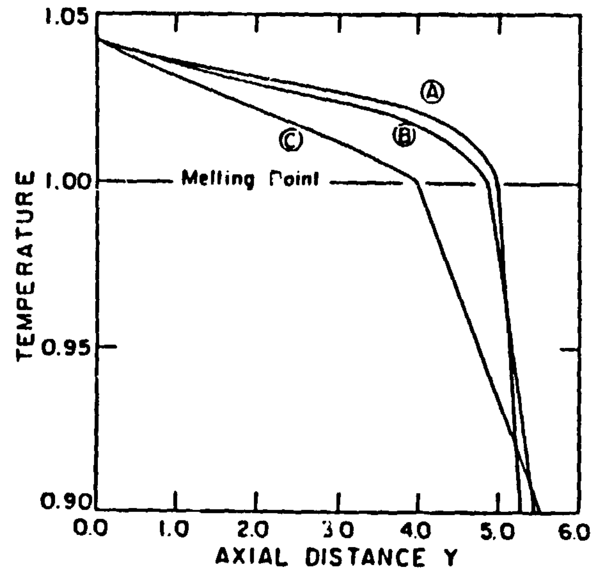
h = EFFECTIVE HEAT TRANSFER COEFFICIENT

Maximum Growth Rate in Die-Defined System is Determined by Limit Points

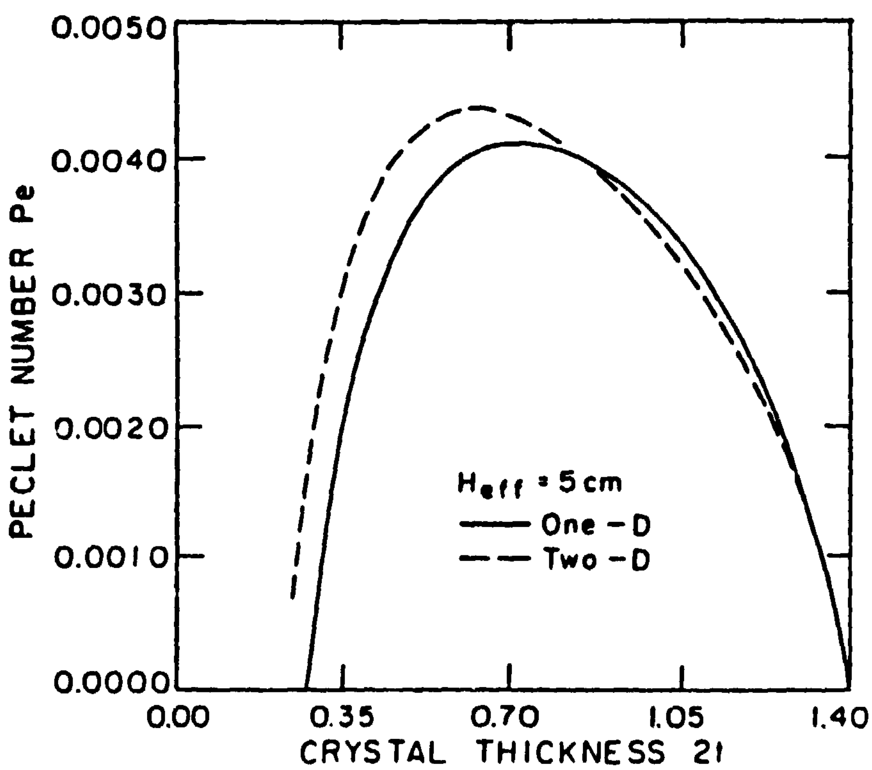


## At the Limit Point, the Sensible Heat Cannot be Funneled Quickly Enough from the Melt into the Crystal

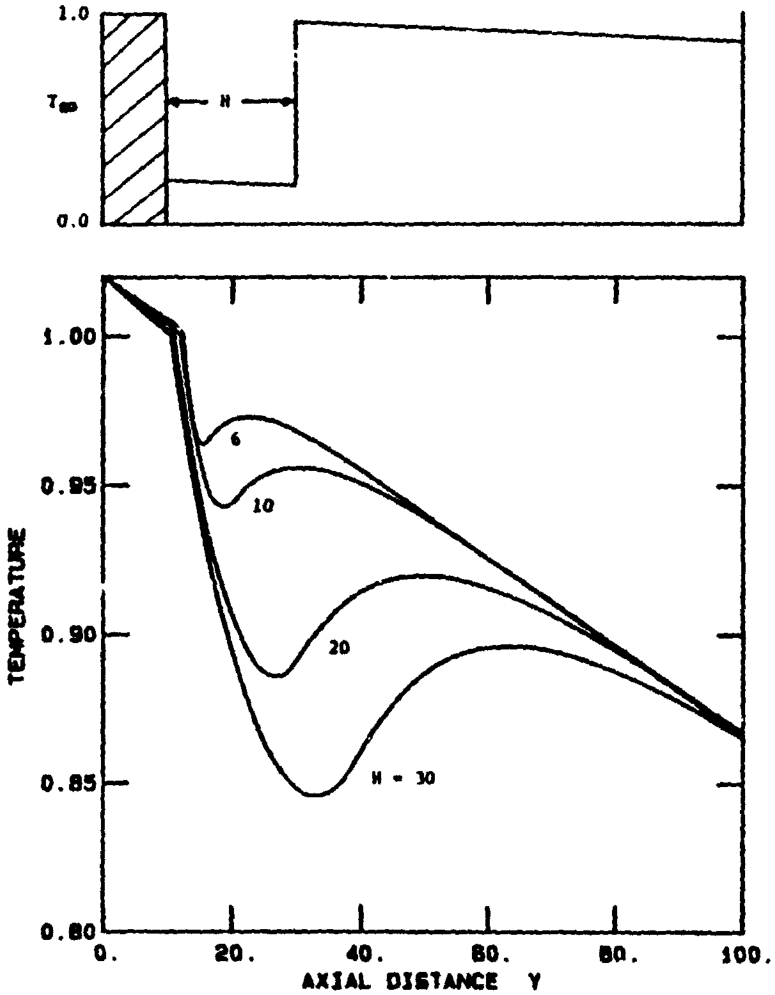


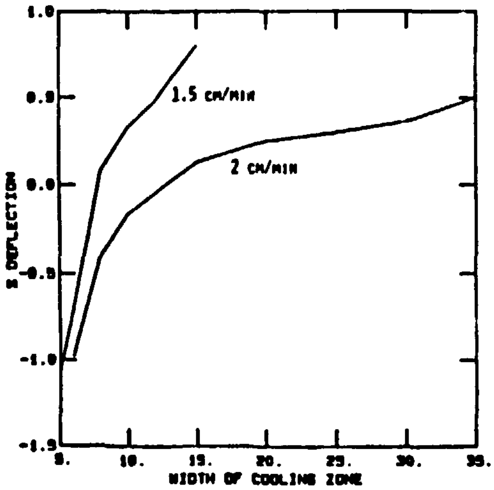

## Results of One- and Two-Dimensional Models are Qualitatively Similar

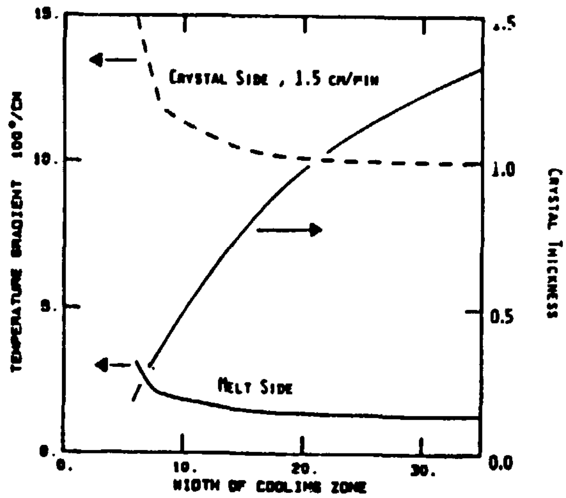


## How Important is the Ambient Temperature Profile?



## Deflection of Mel/Crystal Interface is Small (Temperature Gradient Almost Constant Except at Small Thicknesses)



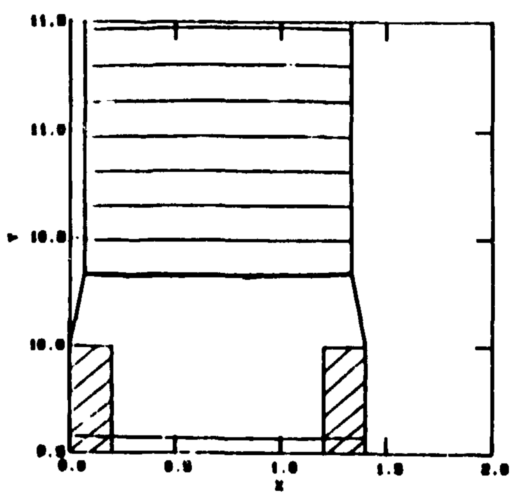




## Inclined Growth for Uniform Ambient

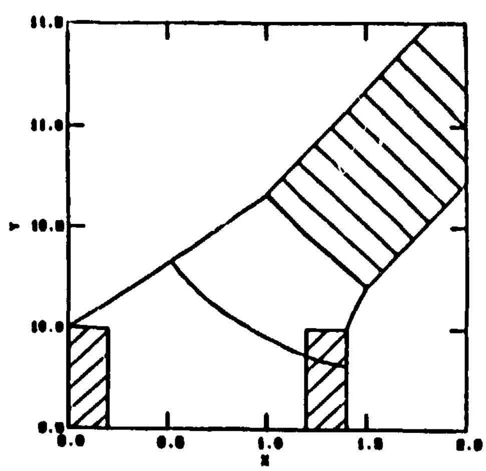
T = 5°K FOR ISOTHERMS

V = 1.5 CM/MIN

- ISOTHERMS ARE PERPENDICULAR TO DIRECTION OF GROWTH

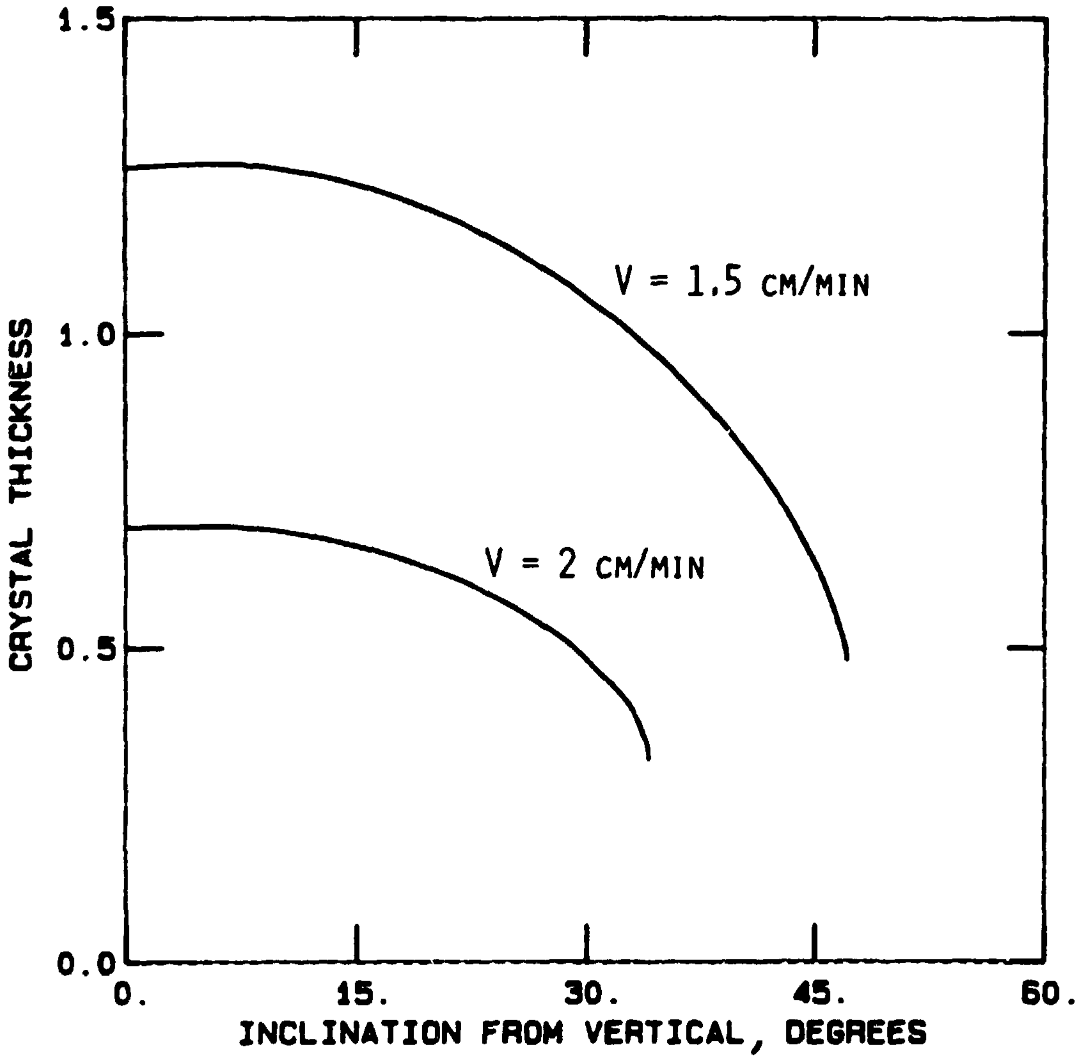


θ = 0°



θ = 45°

## Effect of Inclination on the Crystal Thickness




## Summary

- Maximum Growth Rate in Vertical and Inclined Systems is set by Thermal-Capillary Limits
- Melt/Crystal Interface is Flat
- Vertical Growth is Qualitatively Modelled by One-Dimensional Heat Transfer