INTERNATIONAL ATOMIC ENERGY AGENCY
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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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WORKSHOP ON SPACE PHYSICS:
"Materials in Micorgravity"
27 February - 17 March 1989

"Unidirectional Solidification"

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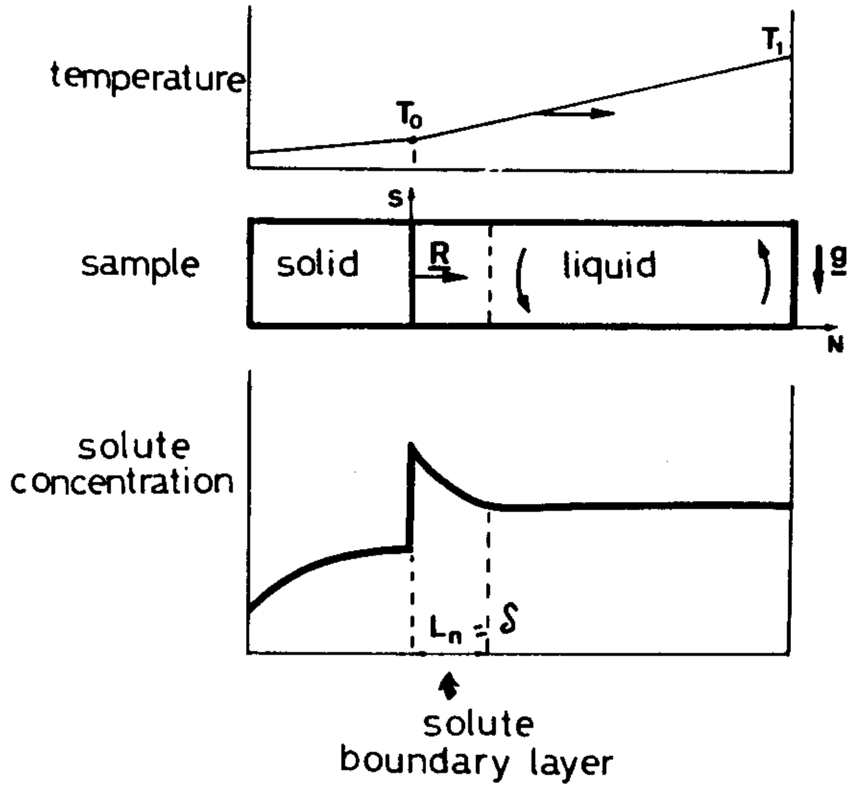
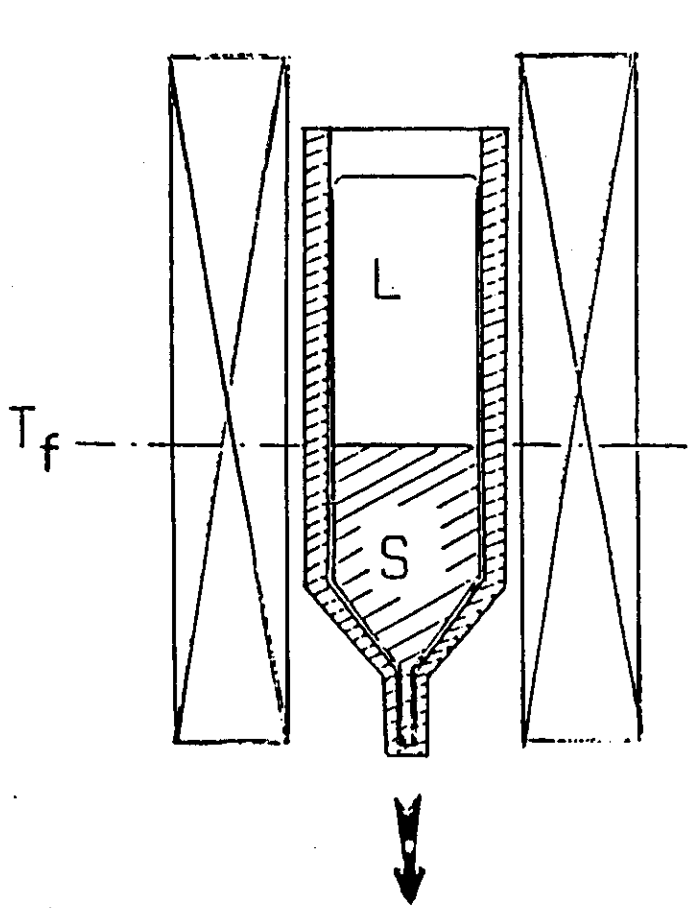
Please note: These are preliminary notes intended for internal distribution only.

UNIDIRECTIONAL SOLIDIFICATION

SOLIDIFICATION TYPE	INFLUENCE OF MICROGRAVITY
PLANAR FRONT $\frac{G_L}{R} > \frac{M_L C_0 (1 - K) K'}{K D_L}$	• LONGITUDINAL MACROSEGREGATION REDUCED IN MICROGRAVITY • SHIFT OF THE LIMIT OF THE MORPHOLOGICAL STABILITY TOWARDS HIGHER G_L/R RATIO
CELLULAR SOLIDIFICATION	• CELL SIZE LARGER • MORE REGULAR STRUCTURE } IN MICROGRAVITY THAN 1G
DENDRITIC SOLIDIFICATION	• DENDRITE SIZE LARGER • MORE REGULAR STRUCTURE } IN MICROGRAVITY THAN 1G
EUTECTIC SOLIDIFICATION (LAMELLAR, FIBER-LIKE, IRREGULAR EUTECTICS)	NO SIGNIFICATIVE INFLUENCE OF MICROGRAVITY EXCEPT FOR OFF-EUTECTICS
IMMISCIBLE ALLOYS ARTIFICAL COMPOSITES	INFLUENCE OF MICROGRAVITY ON SEDIMENTATION BECOMES NEGLECTIBLE BUT OTHER LIMITATING PARAMETERS CAN PREVENT THE FORMATION OF A FINE AND HOMOGENEOUS DISPERSION



PROCEDE : BRIDGMAN



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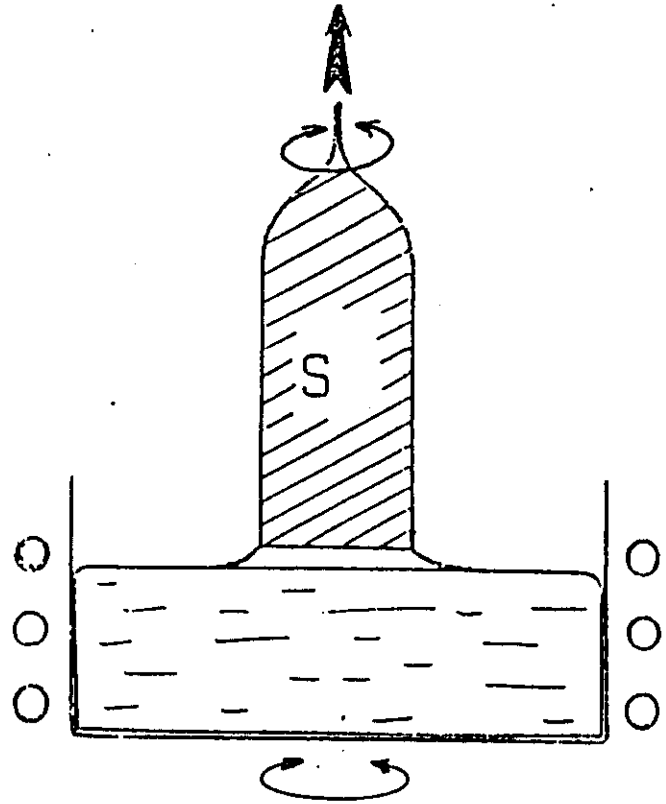
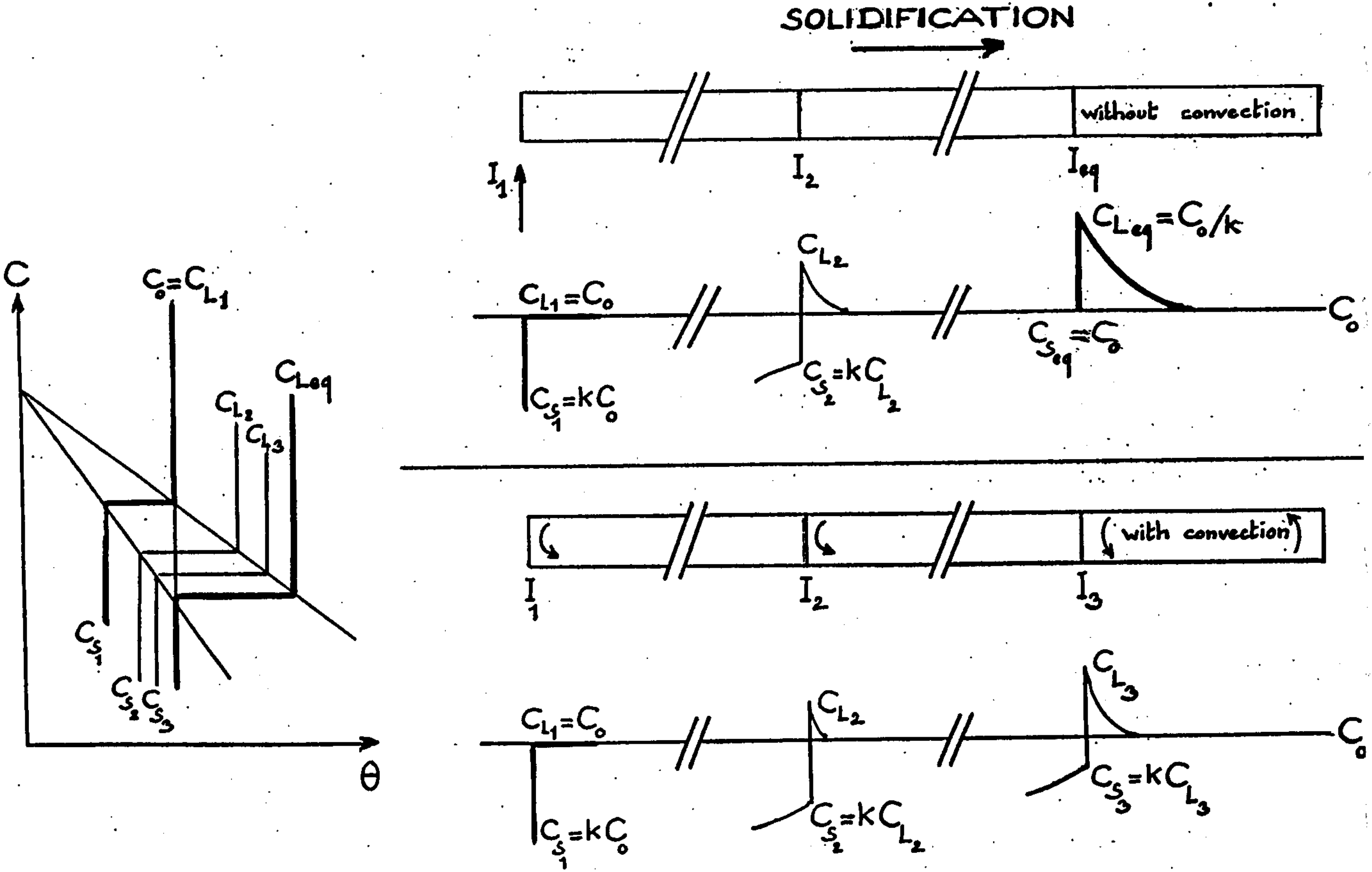
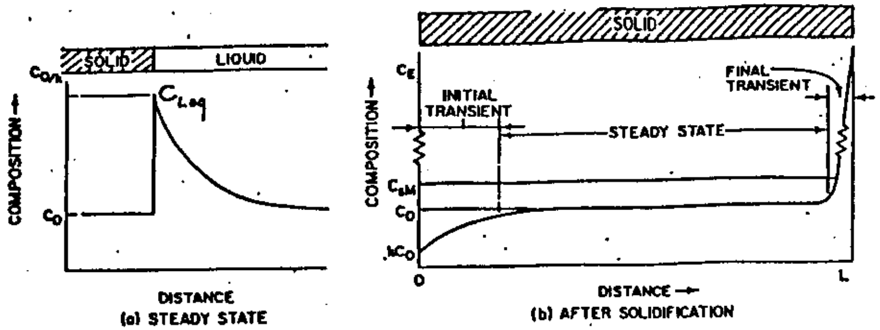


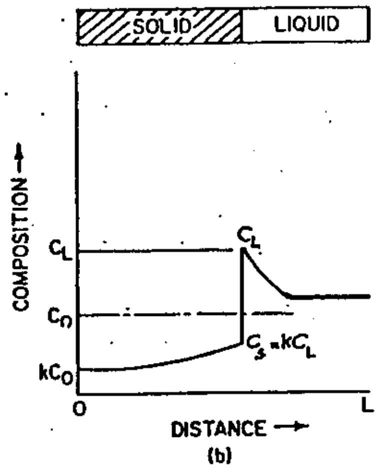
CZOCHRALSKI

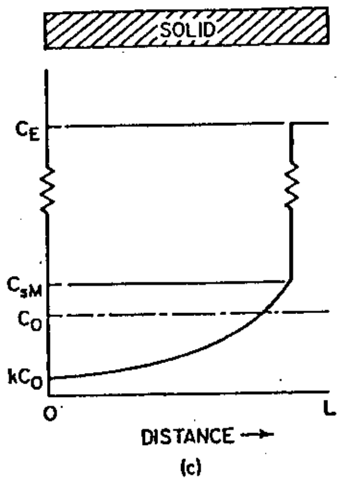


SOLIDIFICATION
without convection
I_1
I_2
I_{eq}
$C_{L_{eq}} = C_0/k$
C_{L_2}
$C_{L_1} = C_0$
C_0
$C_{S_{eq}} = C_0$
$C_{S_2} = kC_{L_2}$
$C_{S_1} = kC_0$
with convection
I_1
I_2
I_3
C_{L_3}
C_{L_2}
$C_{L_1} = C_0$
C_0
$C_{S_3} = kC_{L_3}$
$C_{S_2} = kC_{L_2}$
$C_{S_1} = kC_0$
C
$C_0 = C_{L_1}$
$C_{L_{eq}}$
C_{L_2}
C_{L_3}
C_{S_1}
C_{S_2}
C_{S_3}
θ



DIFFUSIVE REGIME





partition ratio:

$$k = \frac{C_s}{C_L}$$

effective partition ratio:

$$k' = \frac{k}{k + (1-k)e^{-(R\delta/D_L)}}$$

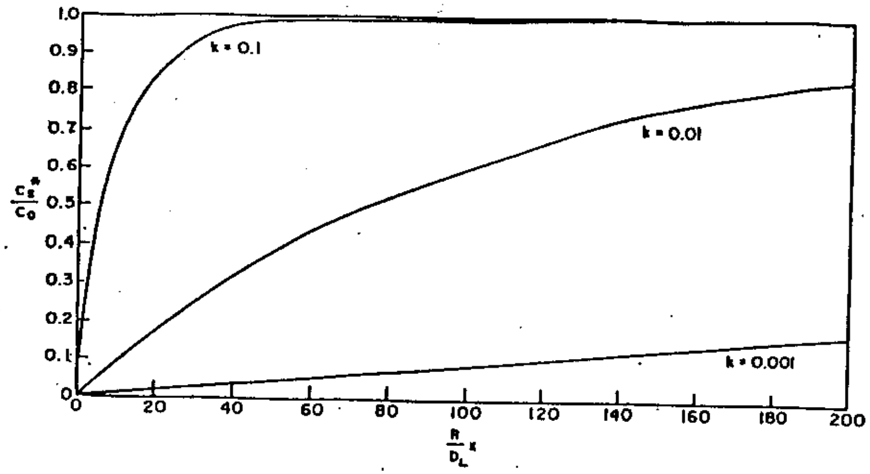
$k' = 1$ diffusive regime

$k' = k$ convective regime

Scheil law:

$$C_s = k' C_0 \left(1 - f_s\right)^{k'-1}$$

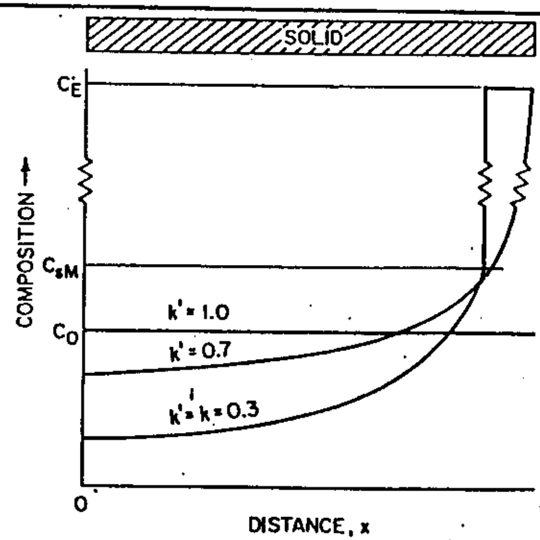
CONVECTIVE REGIME



Solute distribution in initial transient.

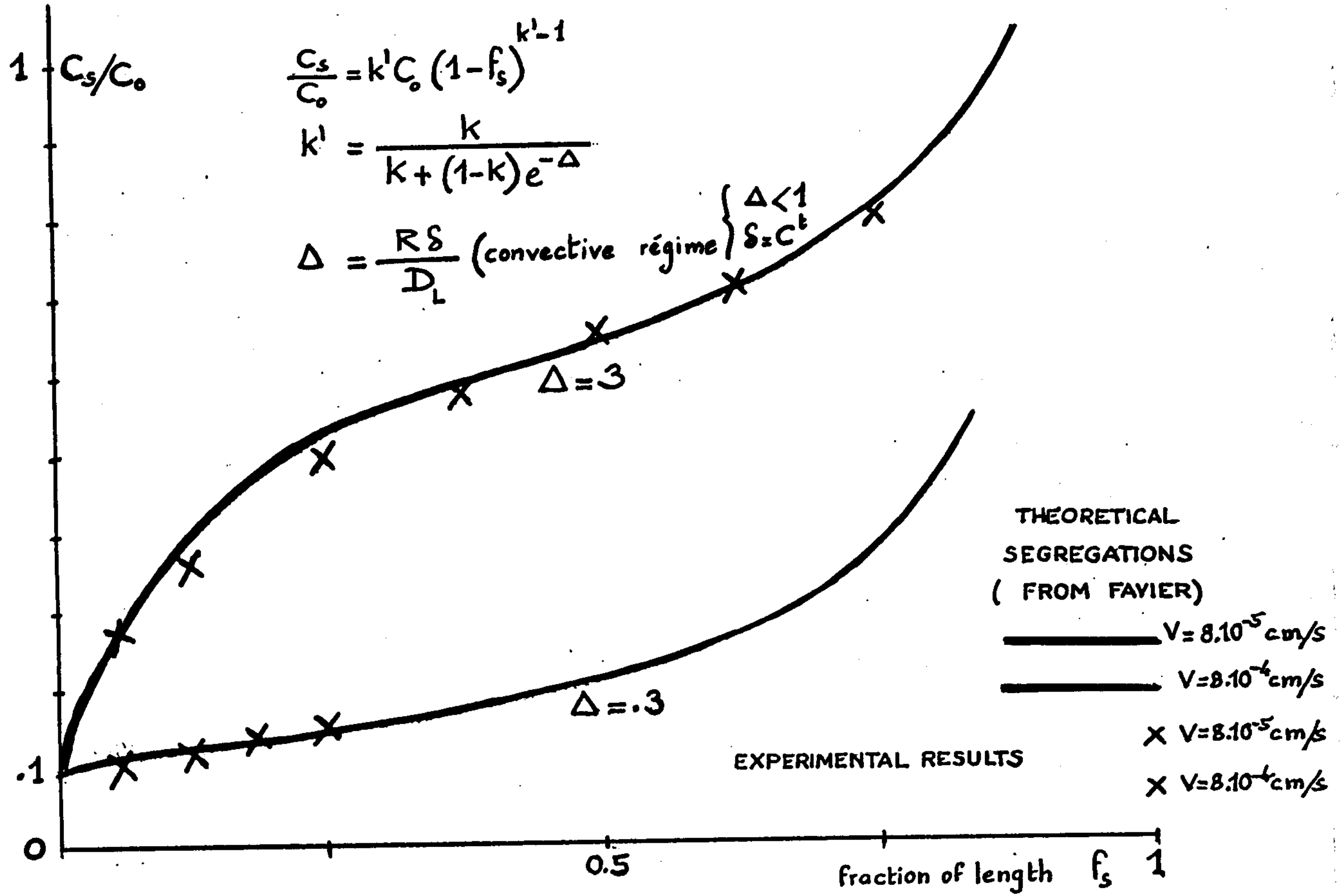
Characteristic length of the transient $\frac{D}{kR}$

DIFFUSIVE REGIME

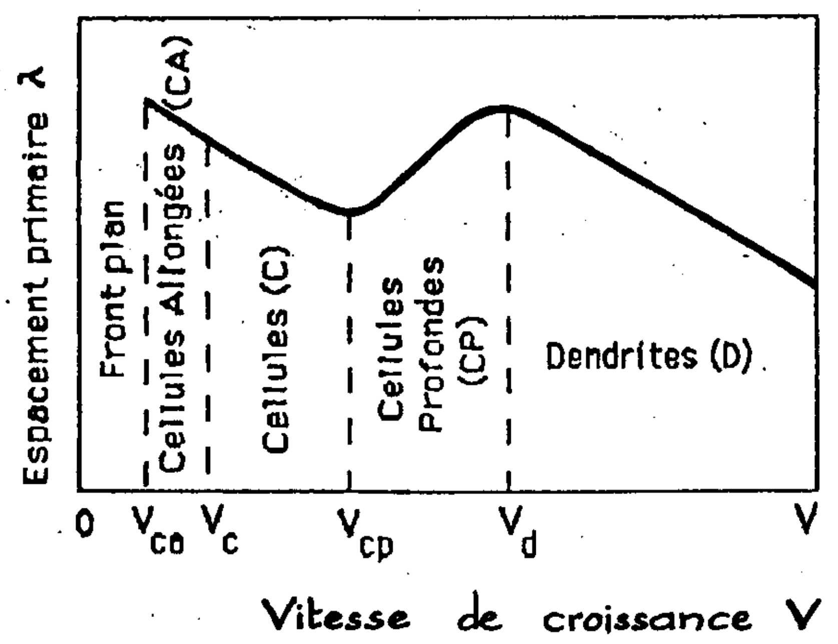


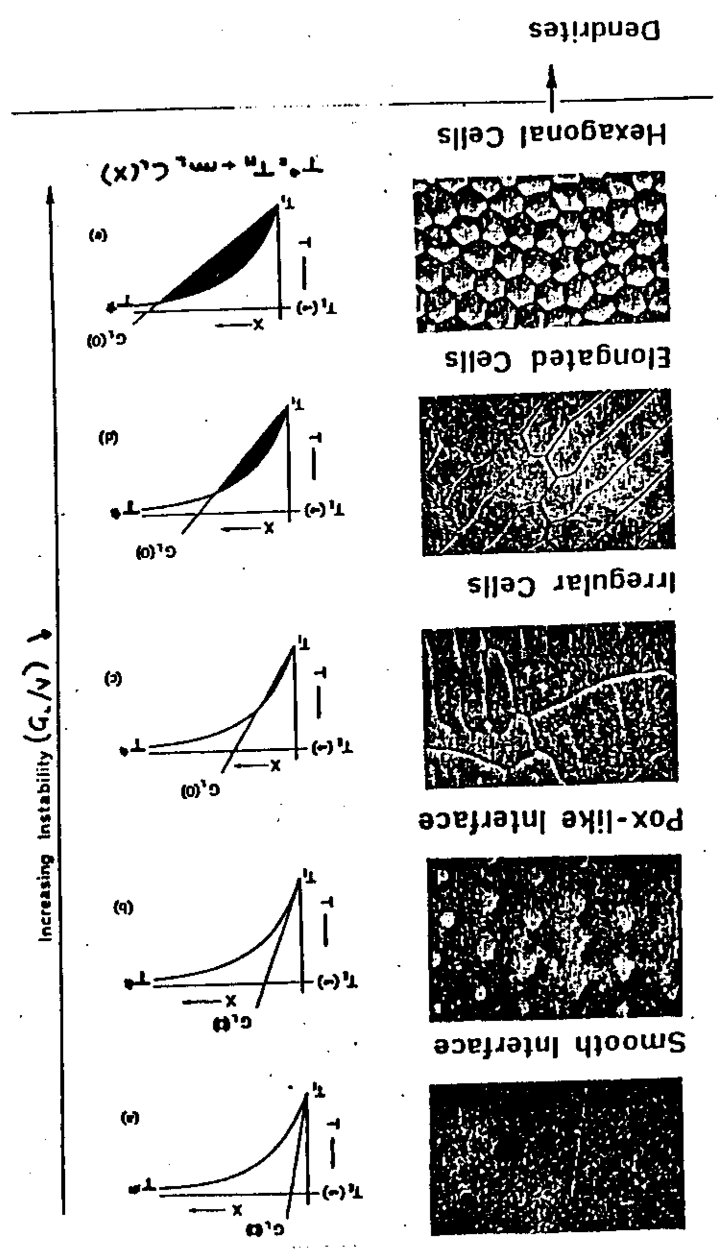
Final solute distributions for solidification with limited liquid diffusion and different amounts of convection.

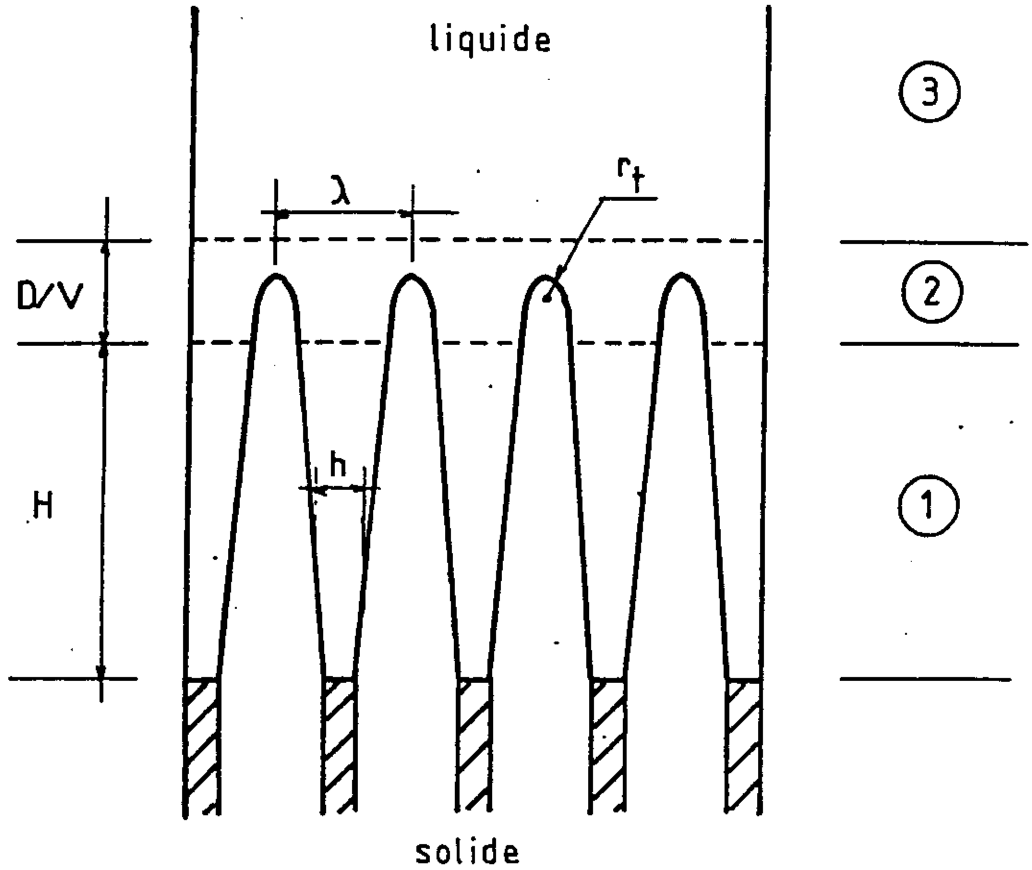
CONVECTIVE REGIME



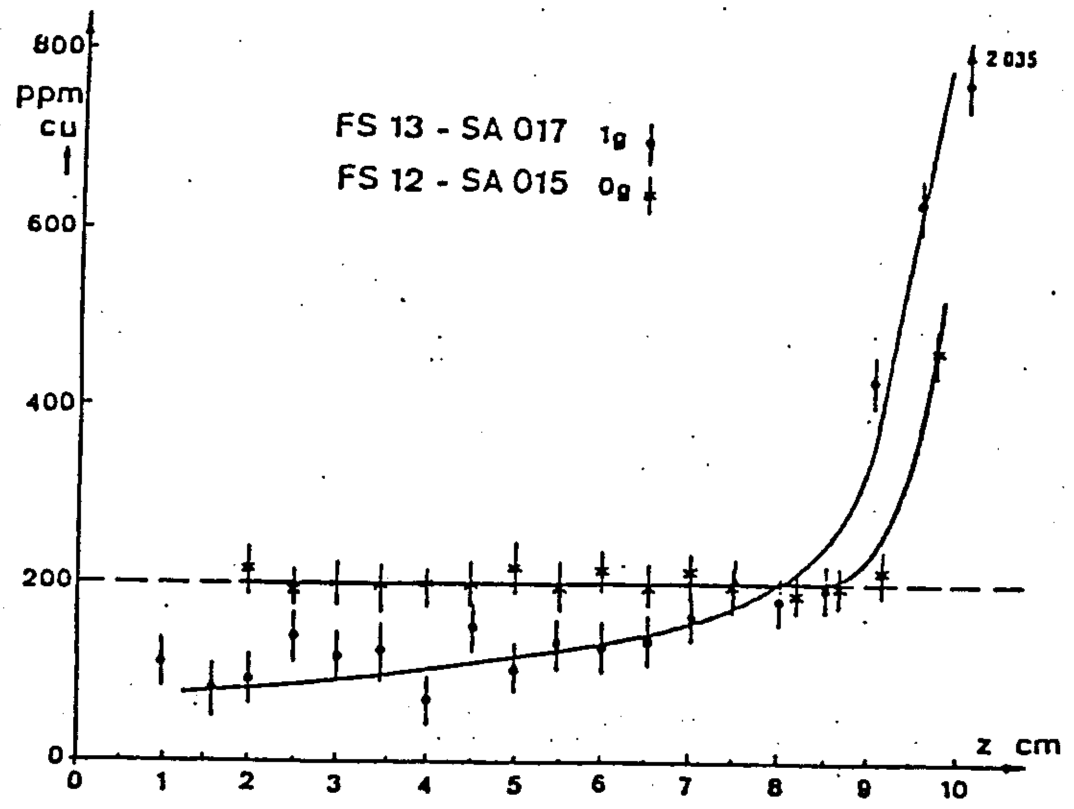
$\frac{C_s}{C_o} = k' C_o (1-f_s)^{k'-1}$
$k' = \frac{k}{k+(1-k)e^{-\Delta}}$
$\Delta = \frac{R\delta}{D_L}$ (convective régime) $\Delta<1$, $\delta = C^t$
C_s/C_o
1
.1
0
0.5
1
fraction of length f_s
$\Delta = 3$
$\Delta = .3$
THEORETICAL SEGREGATIONS (FROM FAVIER)
$V = 8.10^{-5}$ cm/s
$V = 8.10^{-4}$ cm/s
EXPERIMENTAL RESULTS
× $V = 8.10^{-5}$ cm/s
× $V = 8.10^{-4}$ cm/s


Espacement primaire λ
Front plan
Cellules Allongées (CA)
Cellules (C)
Cellules Profondes (CP)
Dendrites (D)
0
V_{ca}
V_c
V_{cp}
V_d
V
Vitesse de croissance V

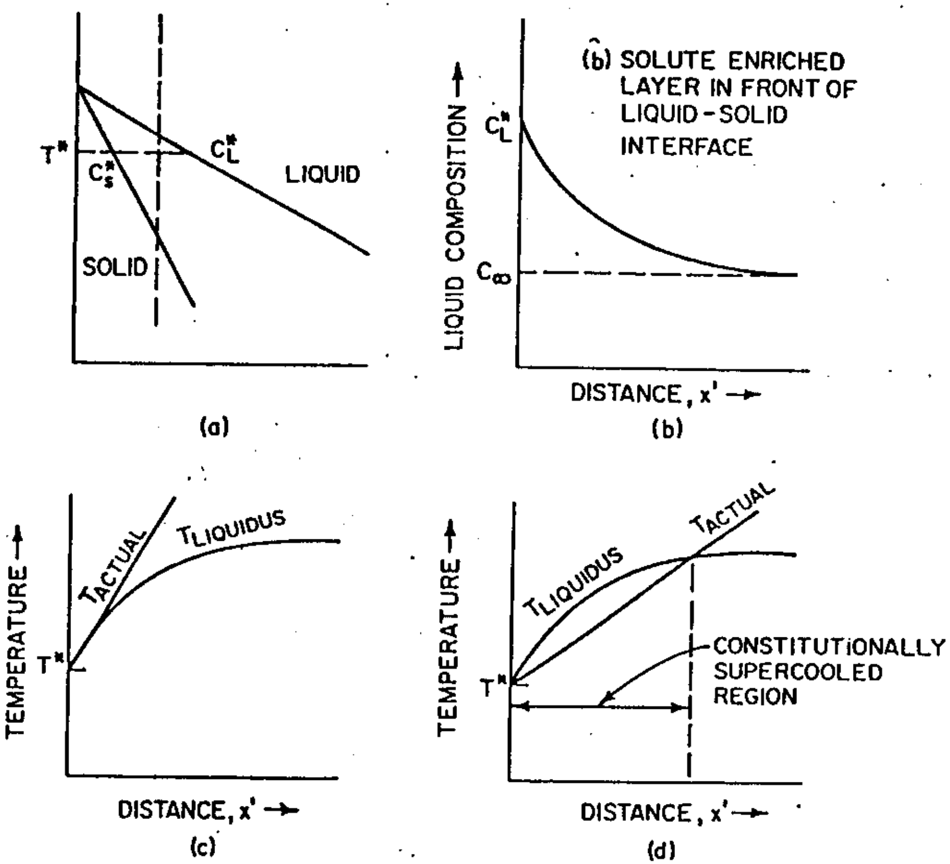

Smooth Interface
Pox-like Interface
Irregular Cells
Elongated Cells
Hexagonal Cells
Dendrites
Increasing Instability (G_L/V)
$T^* = T_M + m_L C_L(x)$



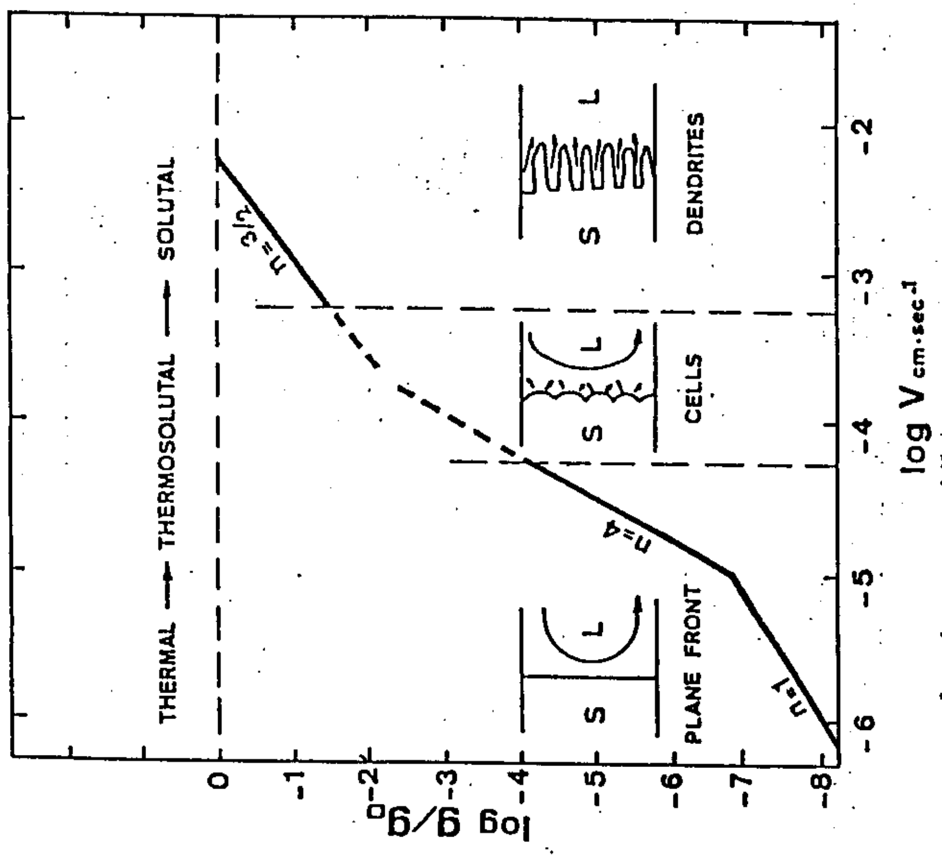
<u>Fig. 1:</u> Schematic representation of the dendritic solidification front.



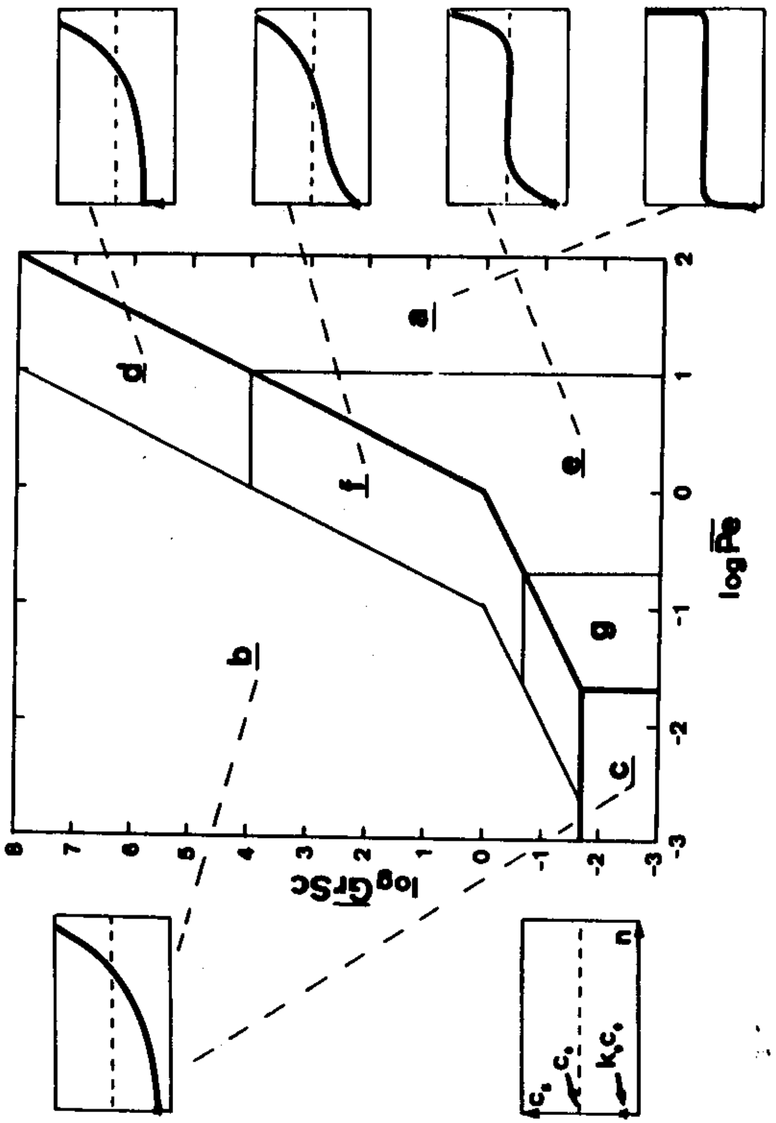
Longitudinal segregation profiles of copper in aluminium in the case of horizontal growth on earth (*FS* 13) exhibiting macrosegregation and in space (*FS* 12) showing an homogeneous concentration profile a part from the final transient



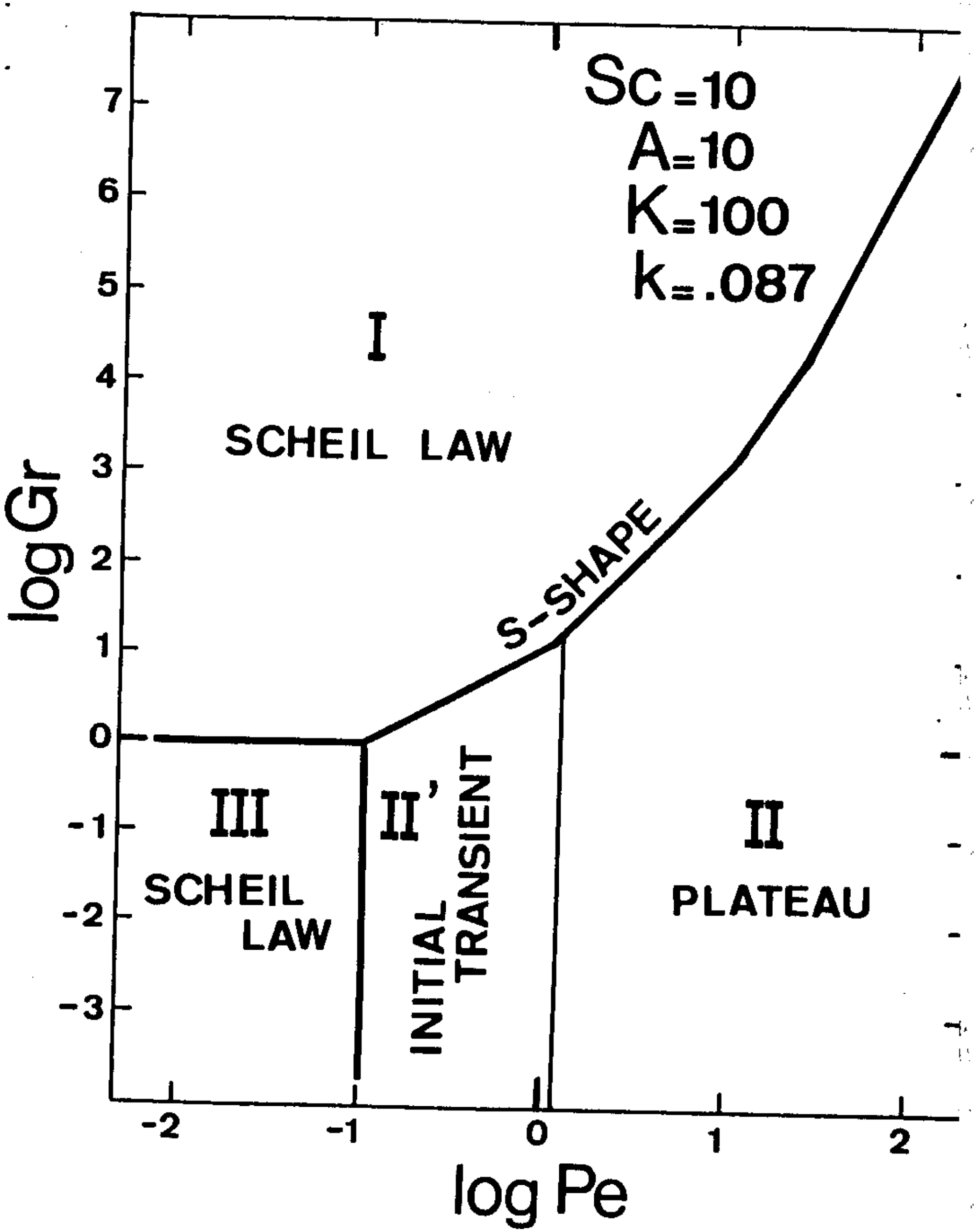
onstitutional supercooling in alloy solidification. (*a*) Phase diagram; (*b*) solute-ıriched layer in front of liquid-solid interface; (*c*) stable interface; (*d*) unstable terface.



Maximum allowed stationary *g*-level to get convection free solidification in the range of solidification rates covering planar, cellular and dendritic fronts. The dominant driving force for convection is mentioned above (Al-Cu, $G=25\ K\cdot cm^{-1}$, $C=20\ \%Cu$)



a
b
c
d
e
f
g
log Pe
log GrSc



Sc=10
A=10
K=100
k=.087
I
SCHEIL LAW
S-SHAPE
III
SCHEIL LAW
II'
INITIAL TRANSIENT
II
PLATEAU
log Gr
log Pe

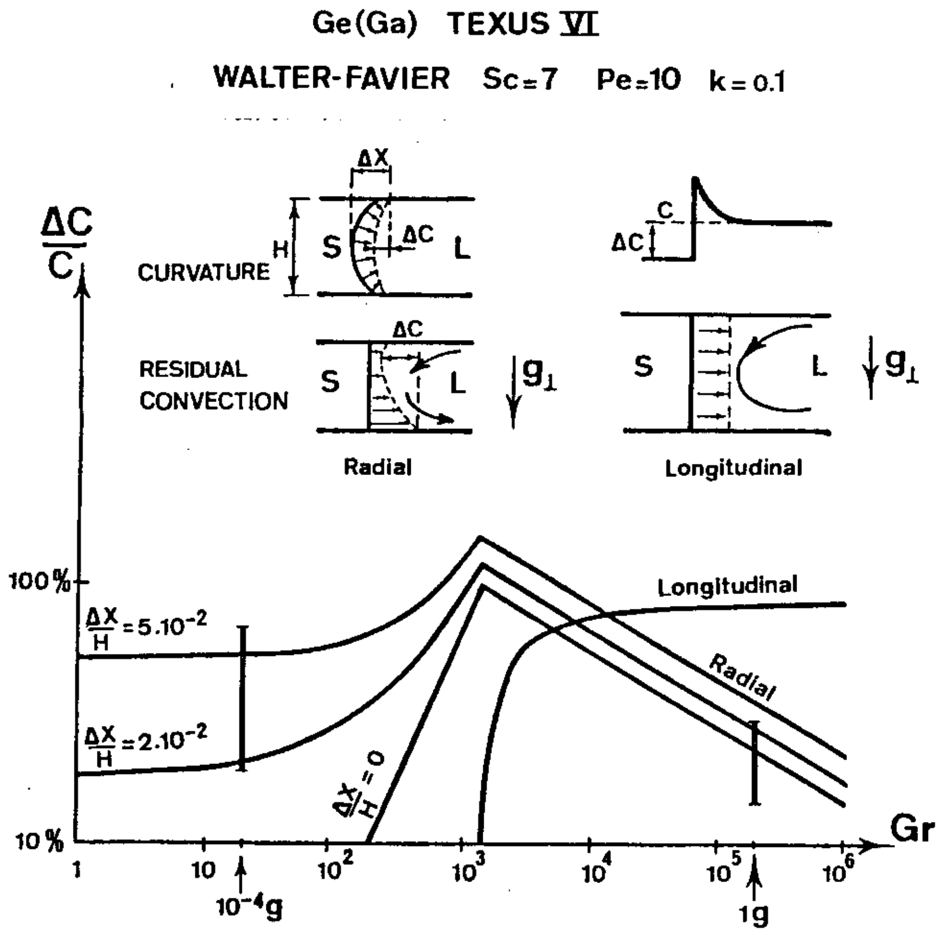
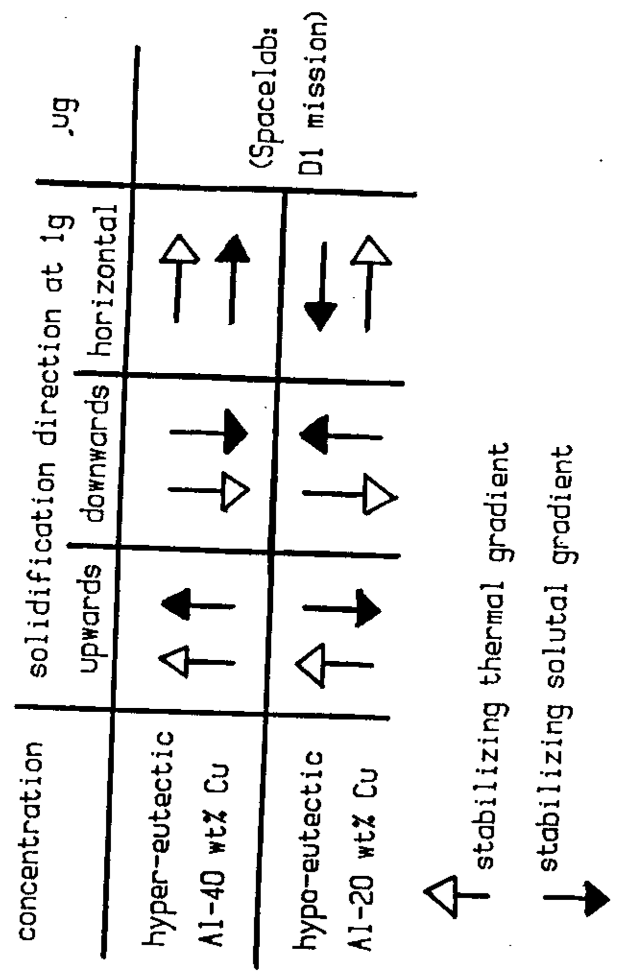


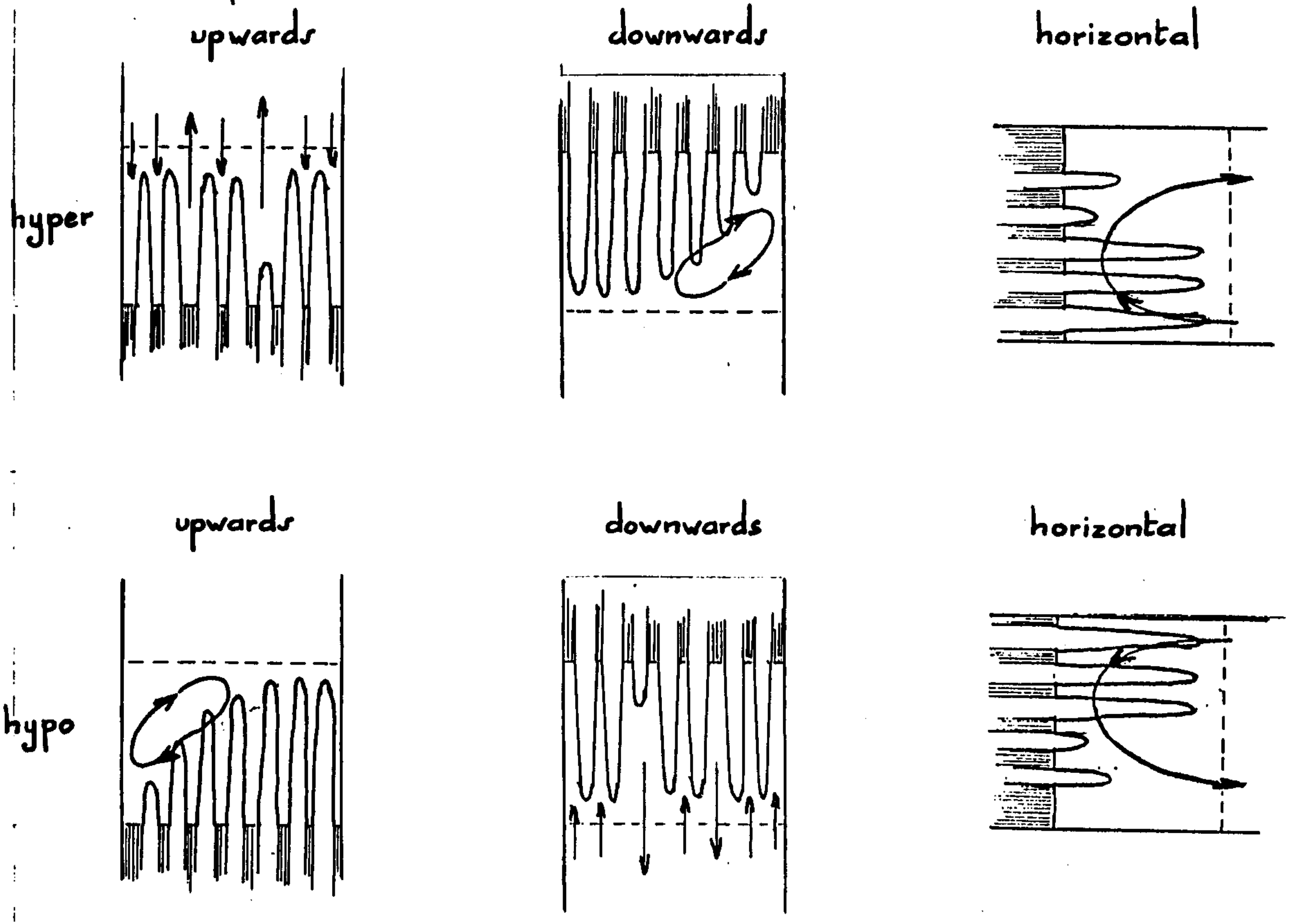
Fig.4.7.: Effect of g-level and interface curvature on radial segregation: case of Favier's experiment [24].

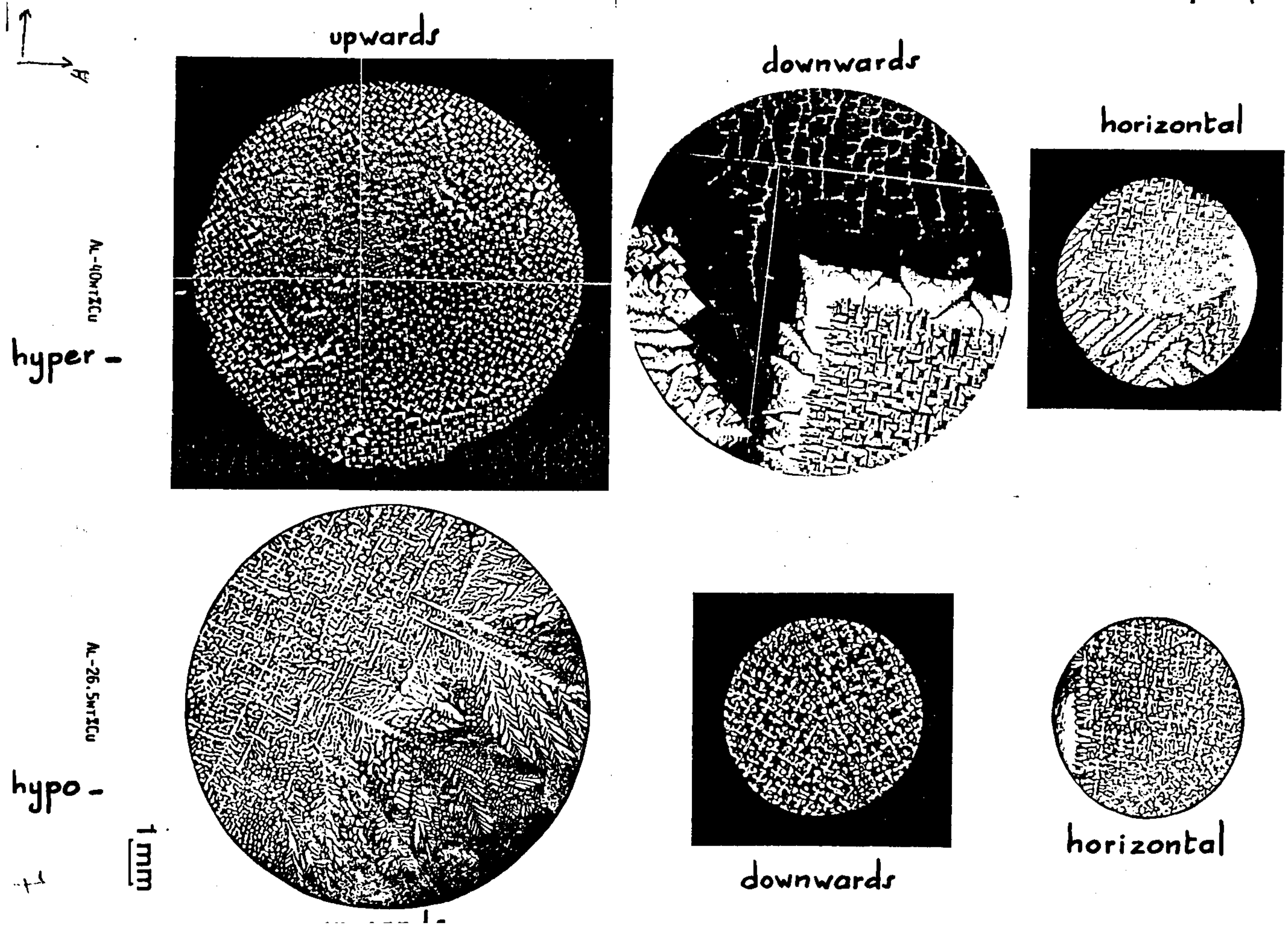
EXPERIMENTAL PARAMETERS

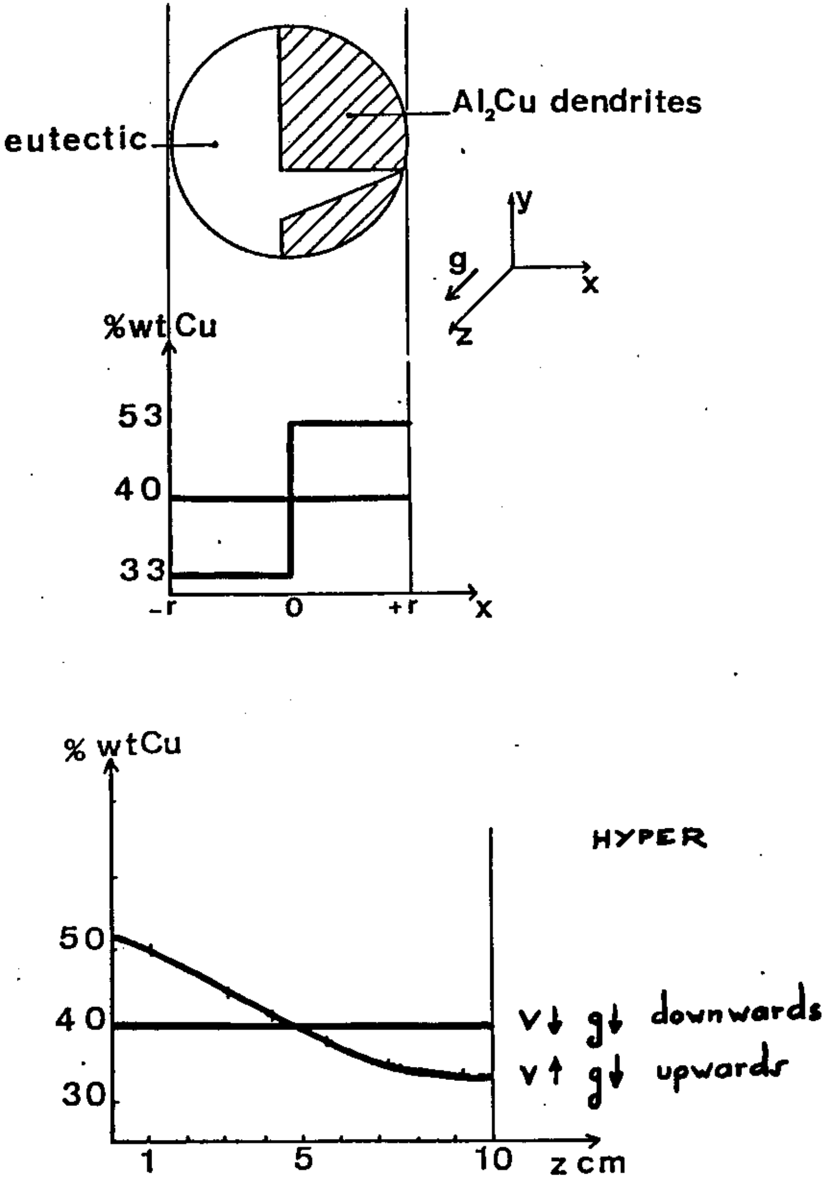
- solidification parameters: V=1.5 cm/h G=25 K/cm
- convection parameters



flow patterns :




upwards
downwards
horizontal
Al-40wt%Cu
hyper -
Al-26.5wt%Cu
hypo -
1 mm
downwards
horizontal



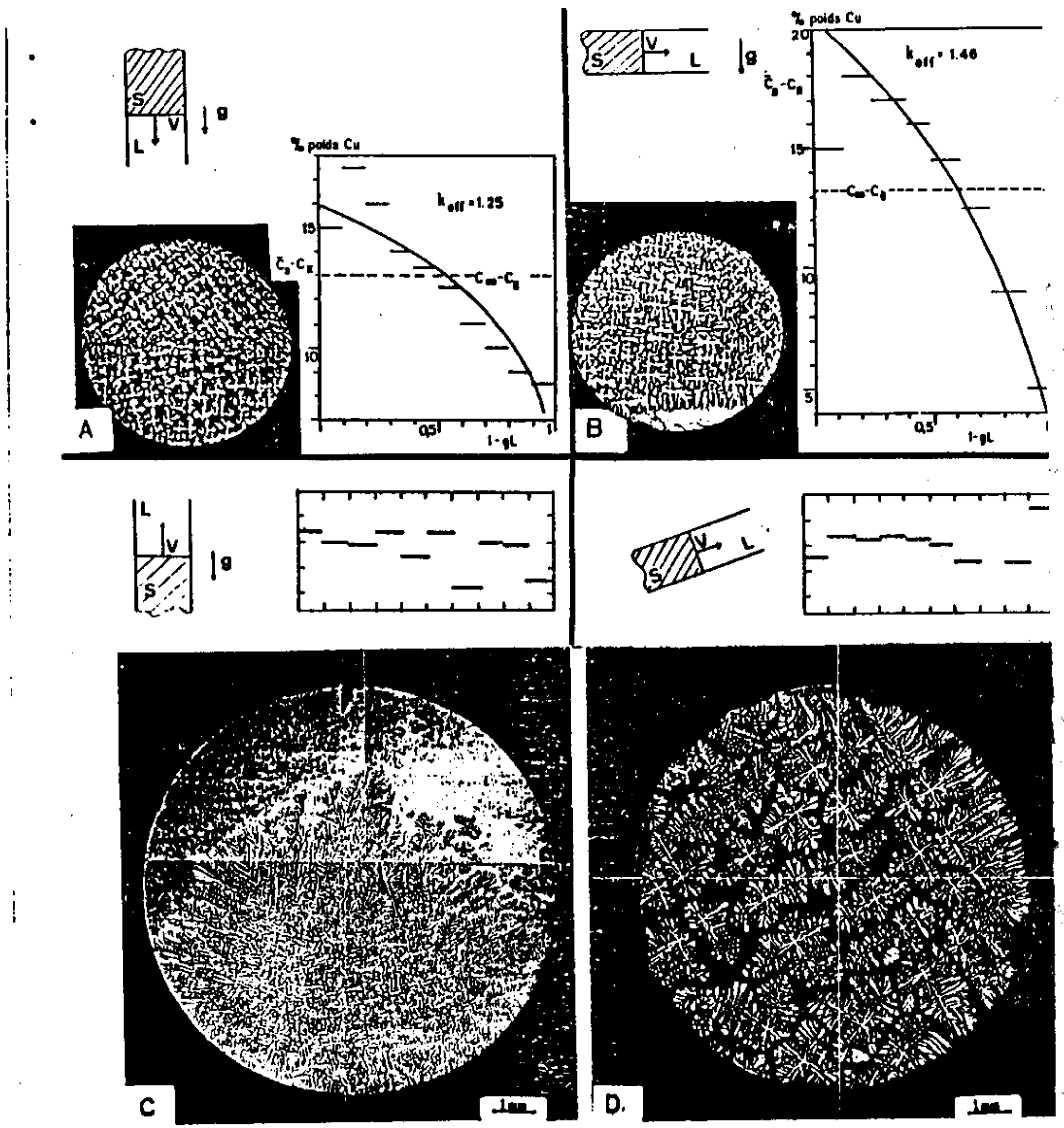
- Fig. 2

Schematic representation of the segregation in the hyper-

eutectic sample solidified

upwards (—— · ——— · ——) and downwards (——)

a/ radial segregation



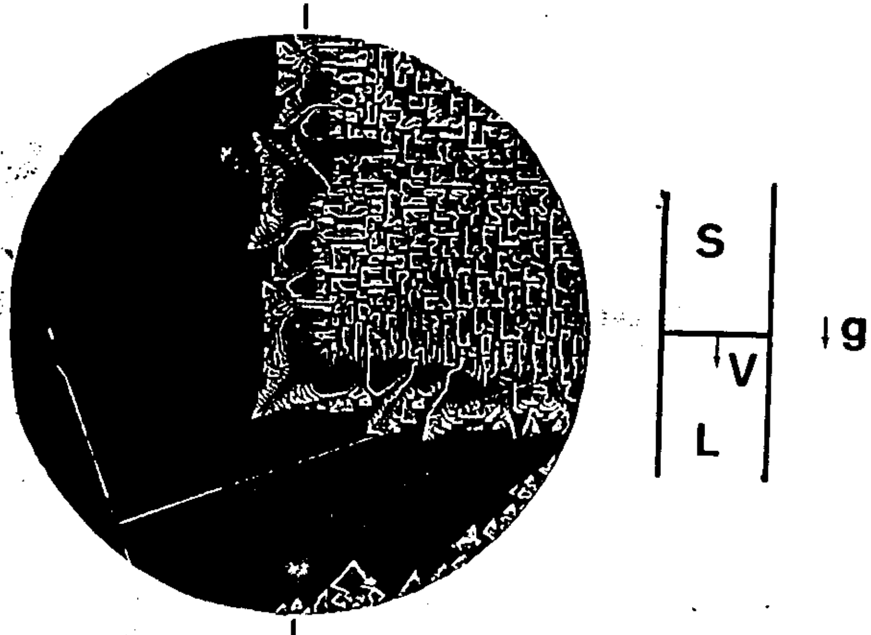
Longitudinal segregations and metallographies of transverse sections observed on an Al-26 wt% Cu alloy solidified in different orientations at 1-g and under microgravity

($R = 4.10^{-4}$ cm/s, $G = 30$ K/cm).

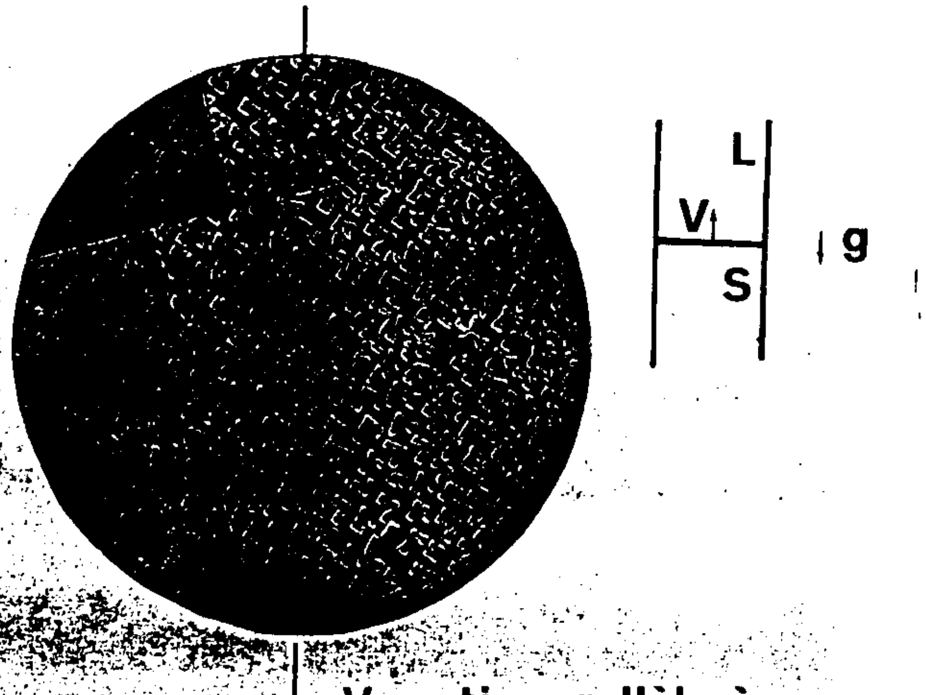
D-1 MISSION : EXPERIMENT WL-GHF-04

G.R.A.M.M.E.

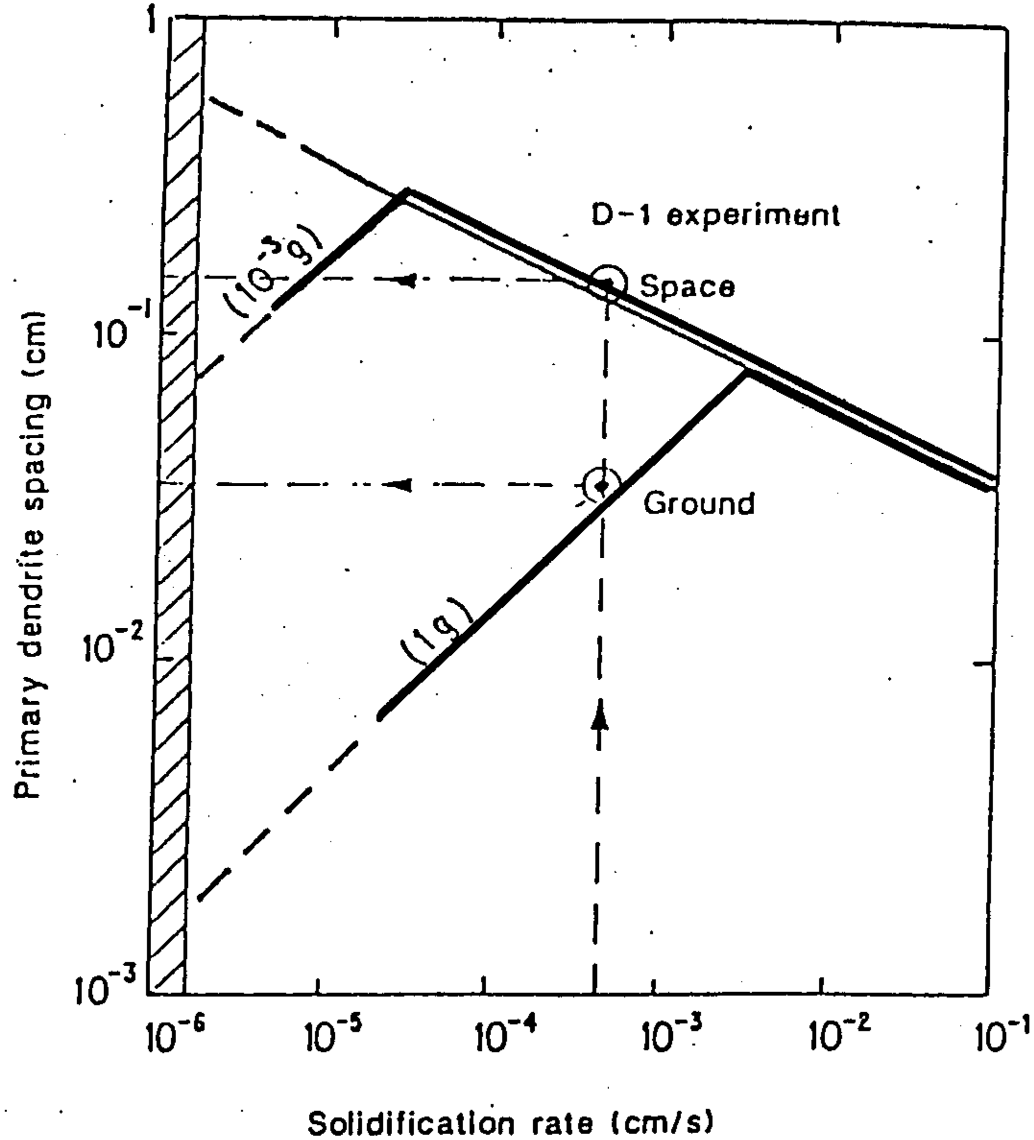
C.E.A. C.N.E



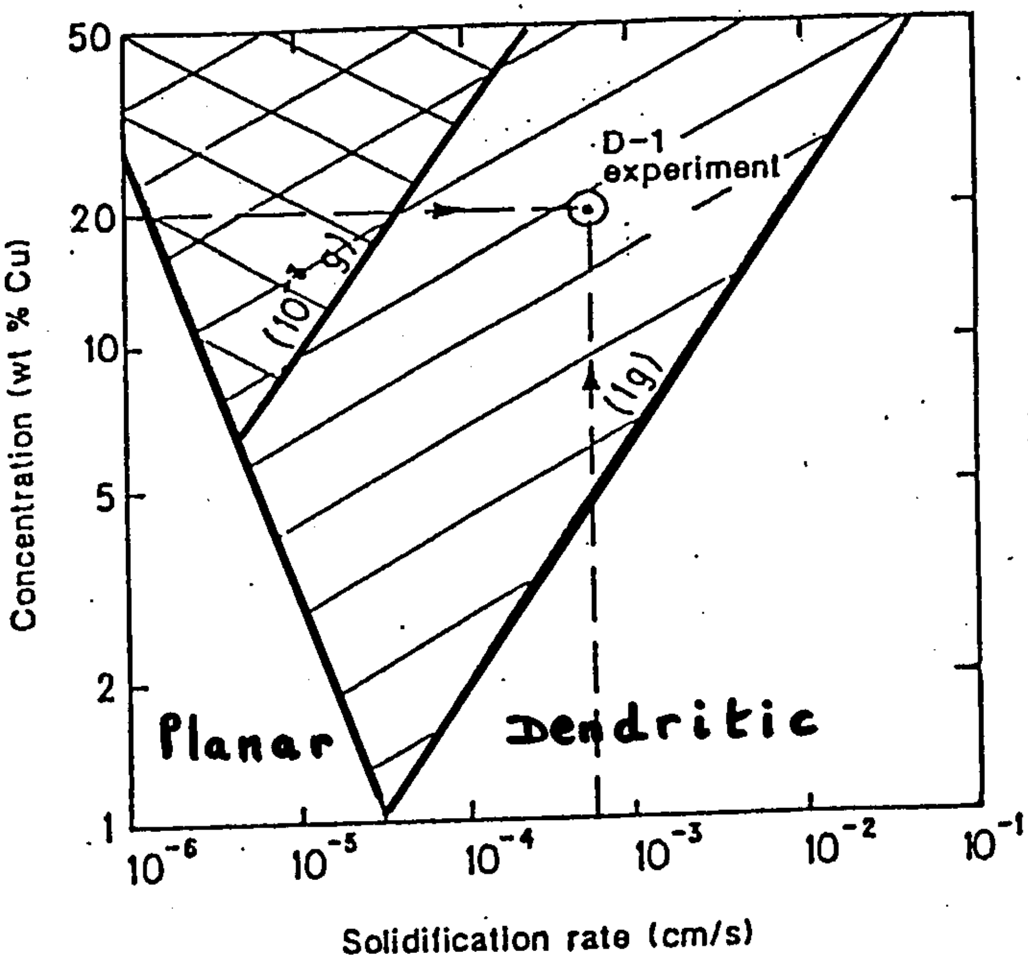
1mm V parallèle à g



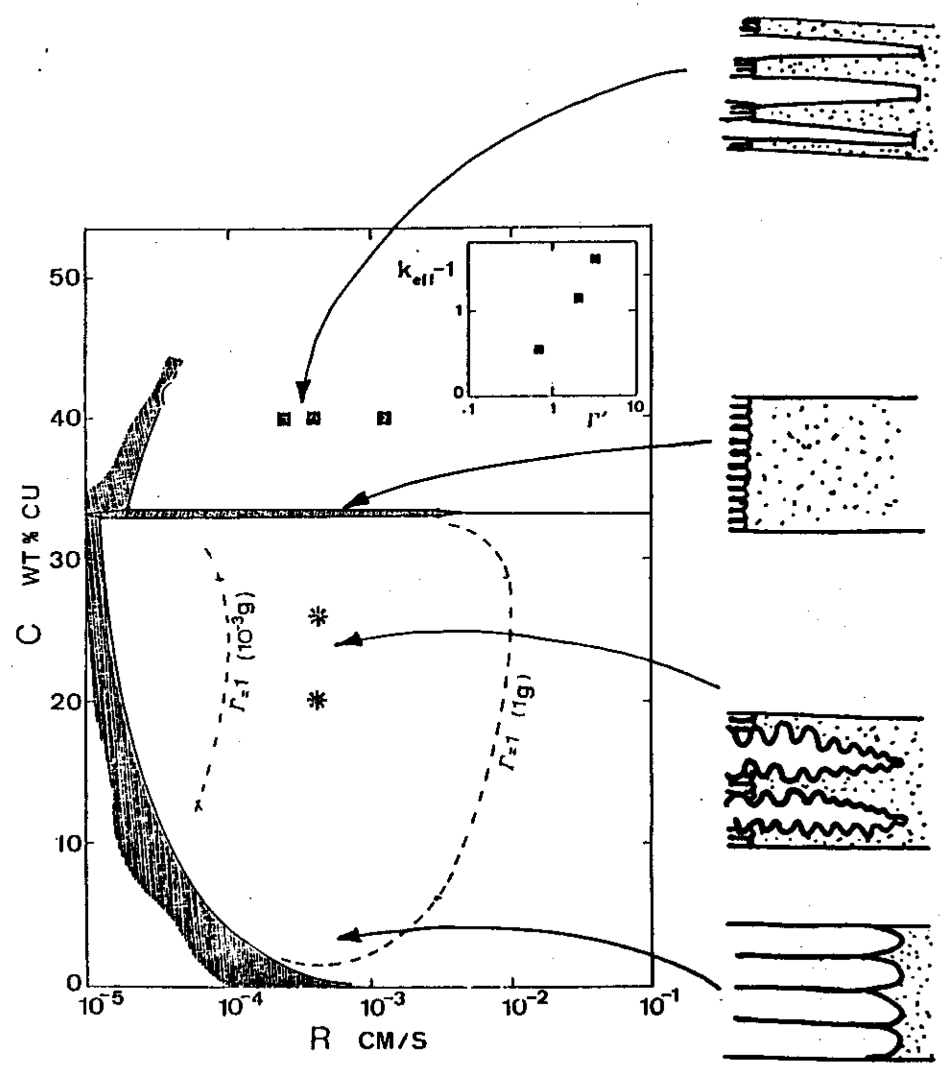
V anti-parallèle à g



Primary interdendritic spacing versus growth rate: (*solid line*) theoretical, (•) ground and D-1 experi-



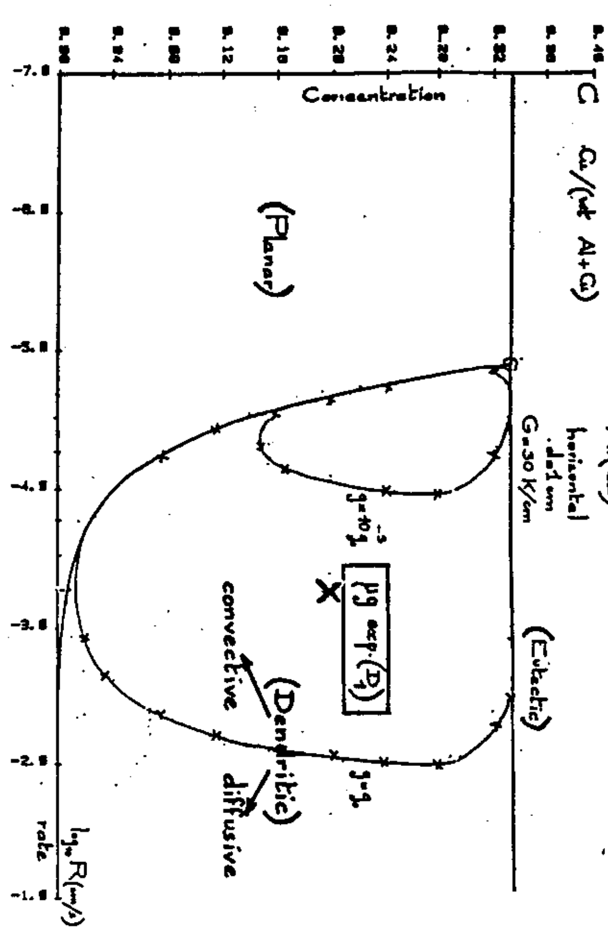
Transition between convecto diffusive regime (*dashed* area) and pure diffusive regime in <u>dendritic</u> solidification. The transient is represented for 1 g and 10^{-3} g The D-1 experiment is also plotted

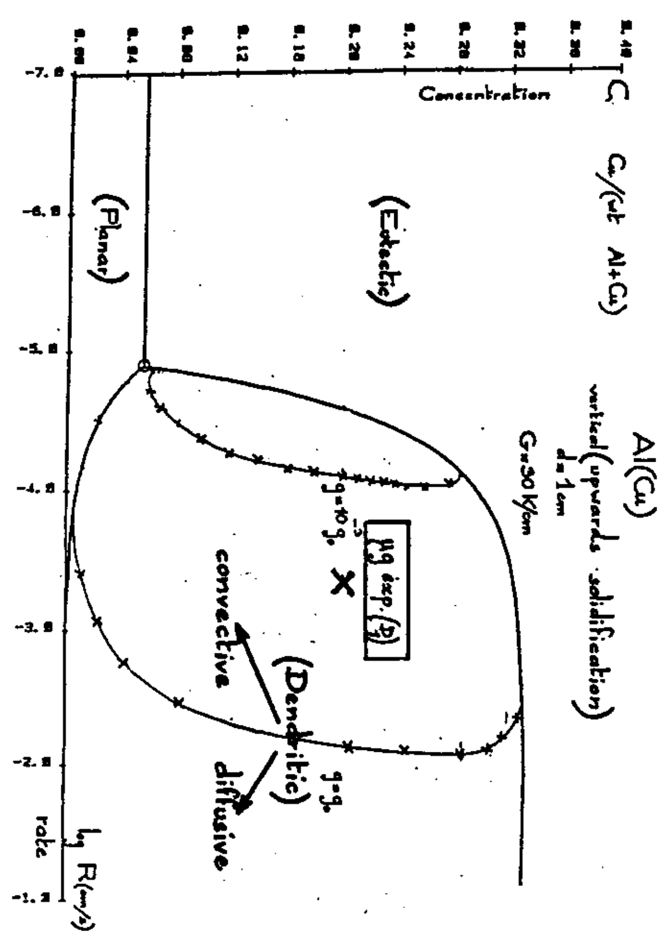


– transition cellule-dendrite (D2 _ IML2)

– solidification dendritique

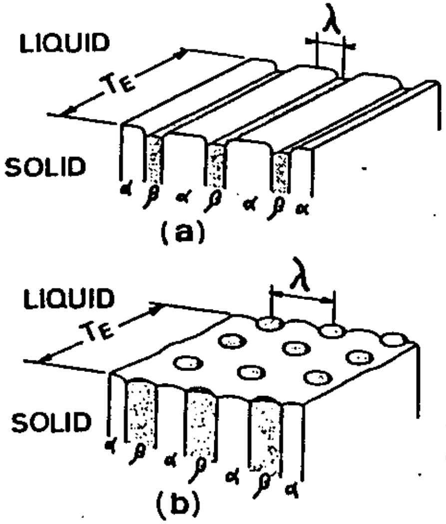
– eutectiques irréguliers





1. *In situ* composites: minority component formed by a physico-chemical reaction from a homogeneous liquid, which results in a composite structure during solidification.
2. *Artificial* composites: minority component formed by artificially mixing the different constituents and stabilizing their distribution in the melt and after solidification.

Sketch of regular eutectic structures:
a) Lamellar eutectic



Volume fraction > 20%

b) Fiberlike eutectic

The spacing is in the range of 1-10μm.

Volume fraction < 20%

MECHANISM OF COMPONENT SEPARATION OCCURS

3λ AHEAD INTERFACE → 3λ ~ 10 μm

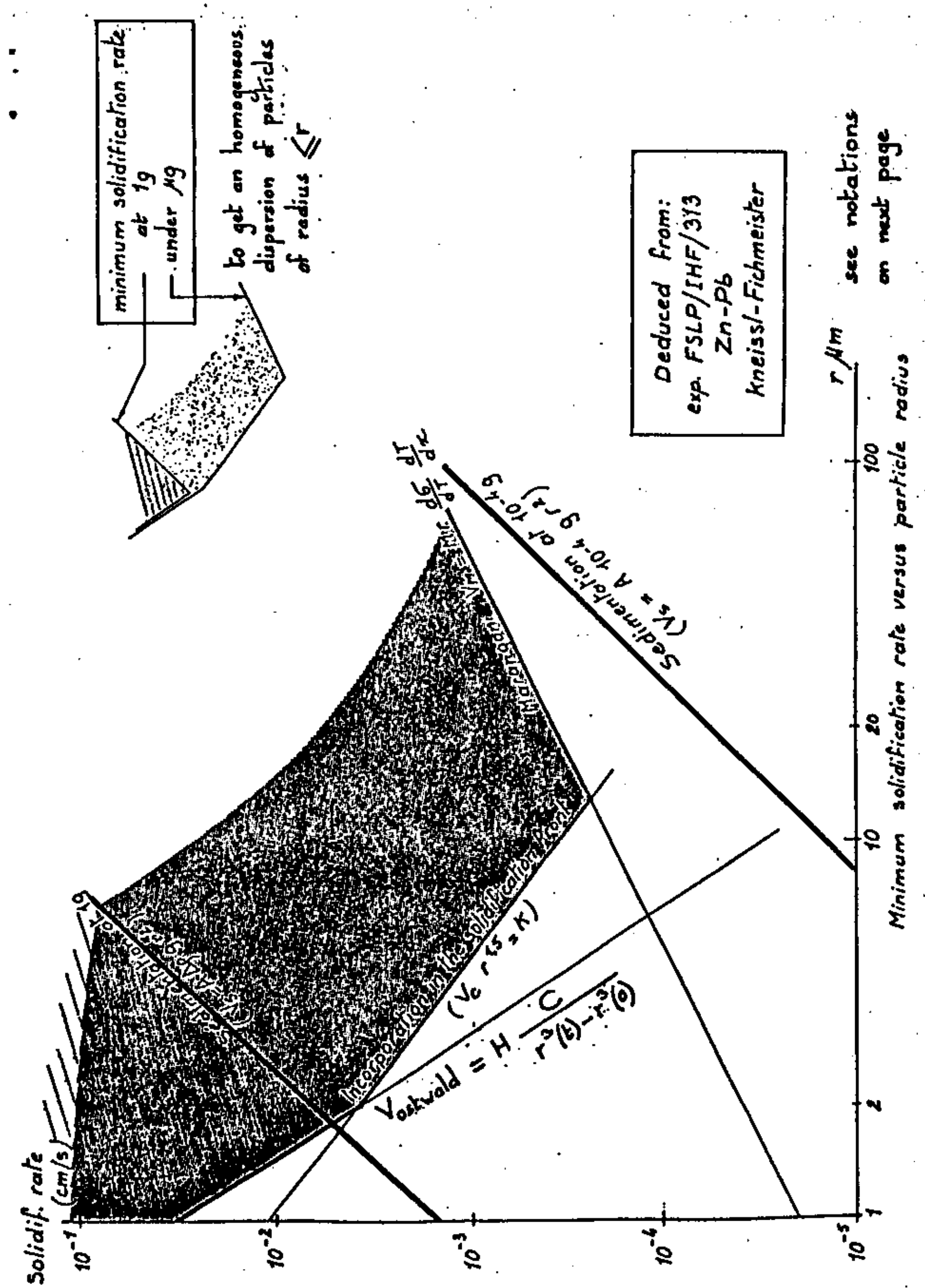
DIFFUSIVE BOUNDARY LAYER THICKNESS IS

$\delta = \frac{D}{R}$ FOR $D = 5 \times 10^{-5}$ cm²/s AND

10^{-4} cm/s $< R < 5 \times 10^{-3}$ cm/s

$100\ \mu m < \delta < 5000\ \mu m$

- **NO INFLUENCE OF MICROGRAVITY ON EUTECTIC GROWTH AT EUTECTIC COMPOSITION.**
- **INFLUENCE OF MICROGRAVITY ONLY FOR <u>OFF-EUTECTIC COMPOSITION</u>.**



and Solidification of Dispersions

- ⊠ Nucleation and growth
- ⊠ Spinodal decomposition
- o Coalescence/agglomeration
- o Capillarity phenomena
- o Flow induced by shape changes or volume changes
- ⊠ Marangoni convection $V_M = M r \frac{d\sigma}{dT} \cdot \frac{dT}{dx}$
- ⊠ Ostwald ripening $r^3(t) - r^3(0) = C \cdot t$
- o Interaction with solidification front $V_c \, r^{1,5} = K$

⊠ Do not applied to solid dispersions

Mechanisms virtually eliminated under Microgravity:

- o Gravity-driven convection
- o Sedimentation/buoyancy $V_s = A \, \Delta\rho \, g \, r^2$

To get an homogeneous dispersion the solidification rate must be higher than the most limitating speed.

In 1g as well as in µg conditions, to get $r < 2\ \mu m$, the limitating phenomena is the Ostwald rifening.

Between 2µm to 100µm the sedimentation is no more the limitating parameter, others parameters (incorporation in the solidification front, Marangoni motion) impose a minimum cooling rate.

This example shows that microgravity conditions are not sufficient to get a fine enough dispersion and may explain the conclusion of Walter

// Clearly, dispersions as desired for technological applications cannot be produced by simply cooling through the miscibility gap even under microgravity conditions. //

Directional Solidification		
		Material
Basic Research	Monophase (macrosegregation) Morphological stability	Sn, Al
	Cellular/dendritic solidification at low velocity (part of MEPHISTO program)	
Preindustrial Developpement	Reference samples (for properties measurements) Turbine blades Magnetic alloys	Superalloys (Ni base) MnBi, GdMg

Artificial Composites		
		Material
Basic Research	Dispersion of particles or short fibers; dispersion of bubbles	Mg, Al, Ag, Cu
Preindustrial Developpement	Mechanical hardening Whiskers dispersion Electrical properties Superconducting materials (type II)	Mg, Al, Ag, Cu Ag, Cu Ex: Pb, Ag, BaO

In Situ Composites		
		Material
Basic Research	Eutectics: lamellar, fiberlike, irregular Off-eutectics Immiscibles: monotectics, hypermonotectics	Sn-base, Al base
Preindustrial Developpement	Light alloys Superalloys Casting Magnetic alloys Superconducting materials	Al-base (Al-Li, Al-Mg) Ni-base+ Co, W, Ta Cast iron Fe-In, Fe-Mg Cu-Nb