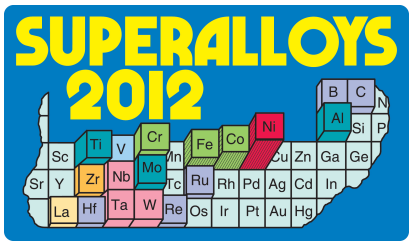
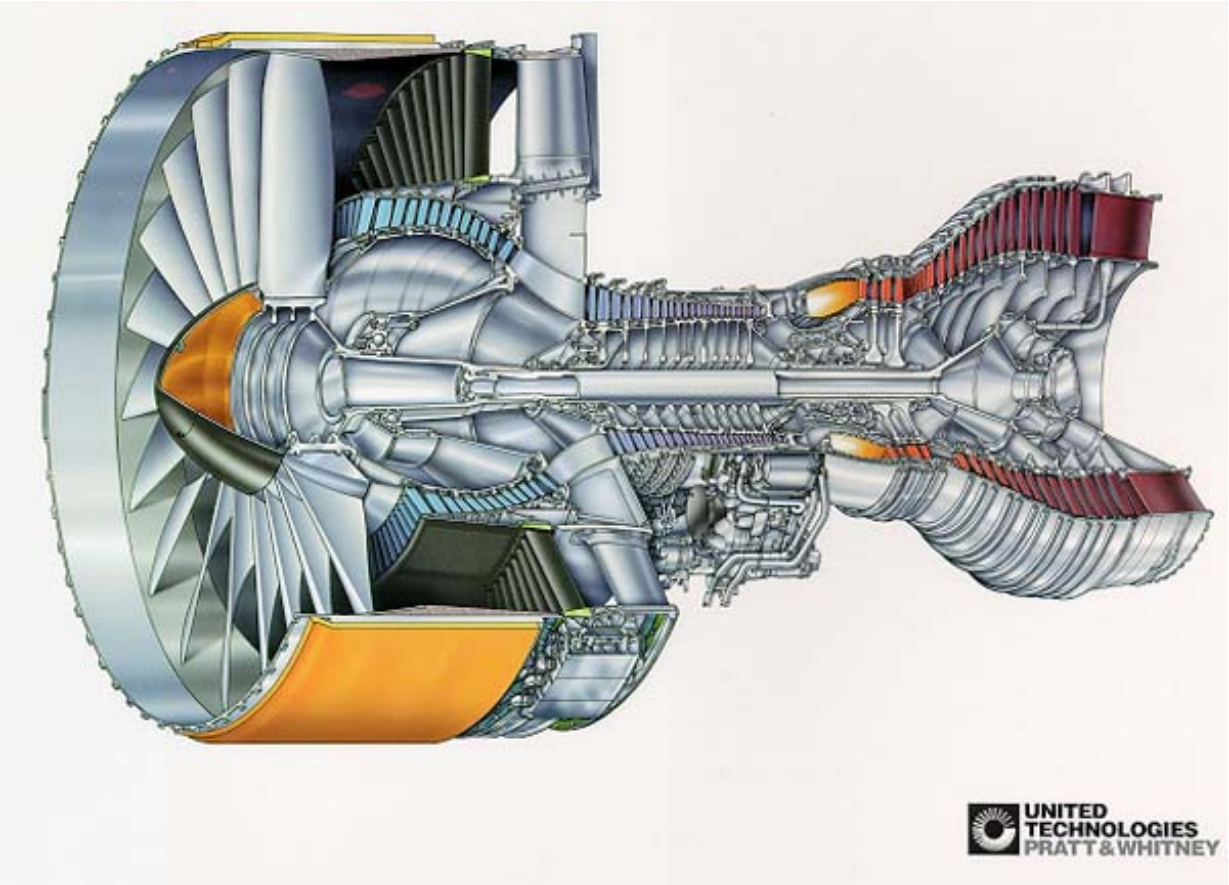


The Development of Single Crystal Superalloys

Anthony Giamei

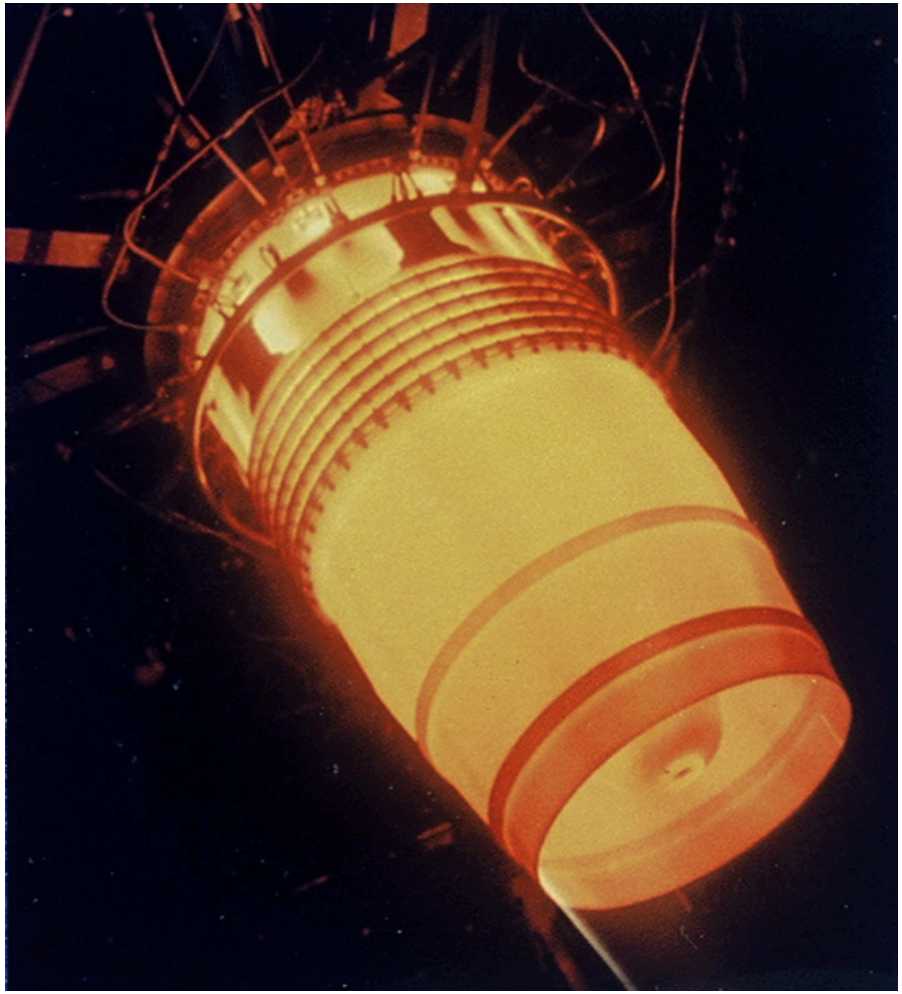
Conference Dedicatee

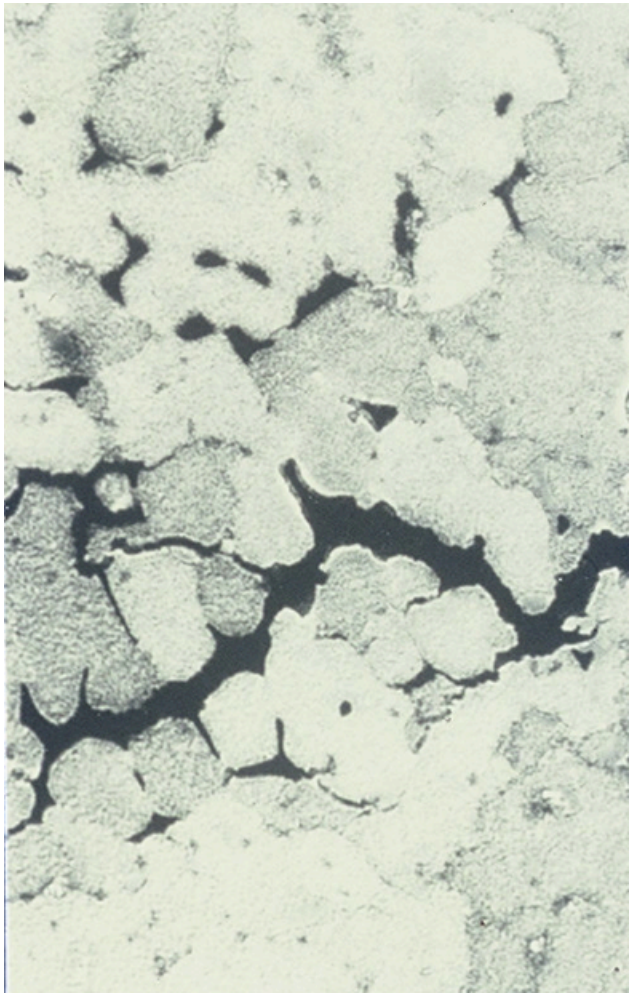
September 9-13, 2012 – Seven Springs, Pennsylvania



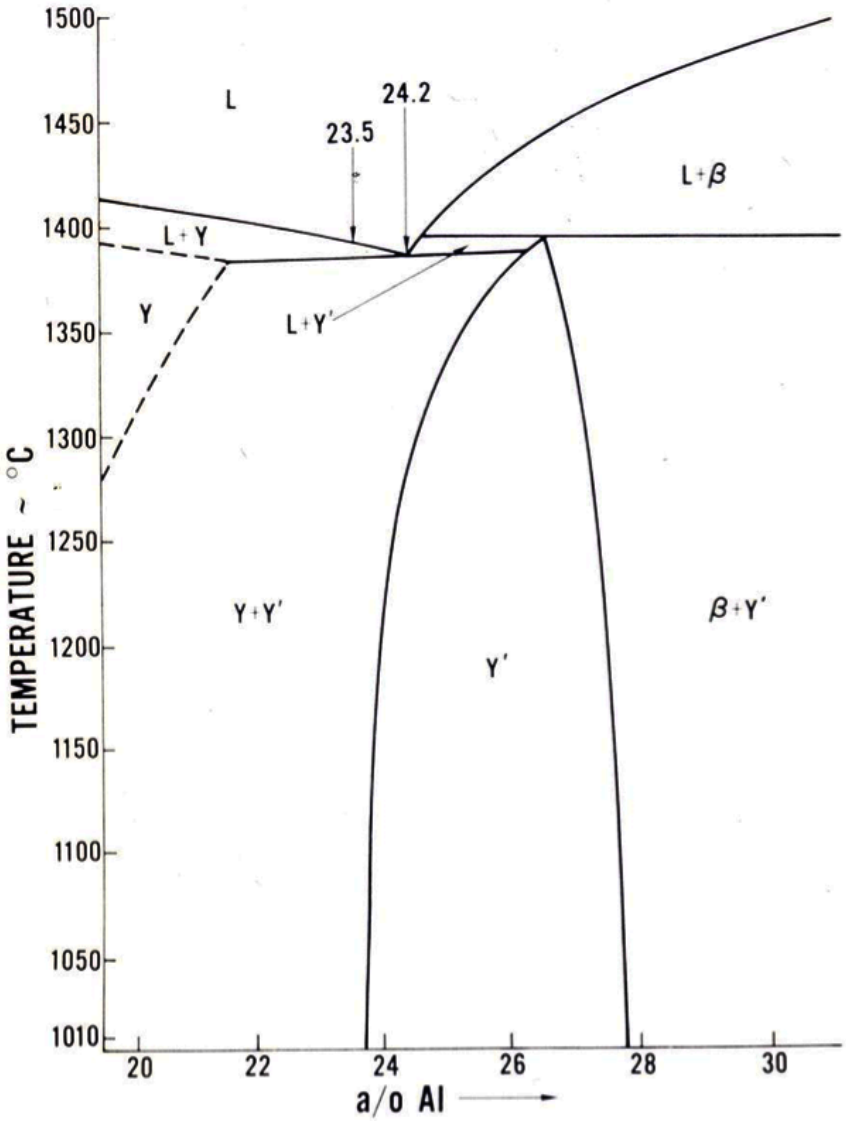
PWA 4098 GAS TURBINE ENGINE

Failure occurs at grain boundaries





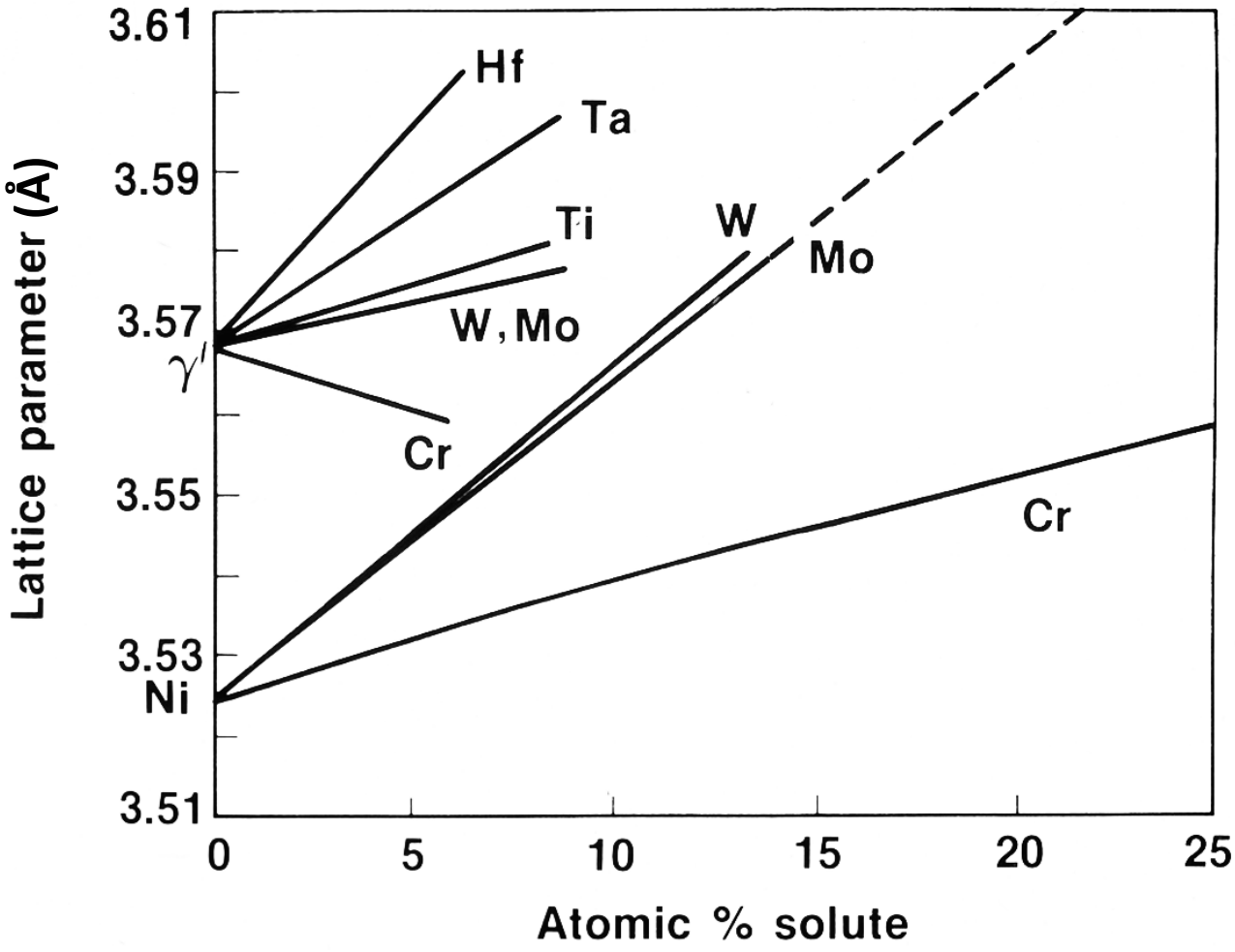
Ni-Al phase diagram



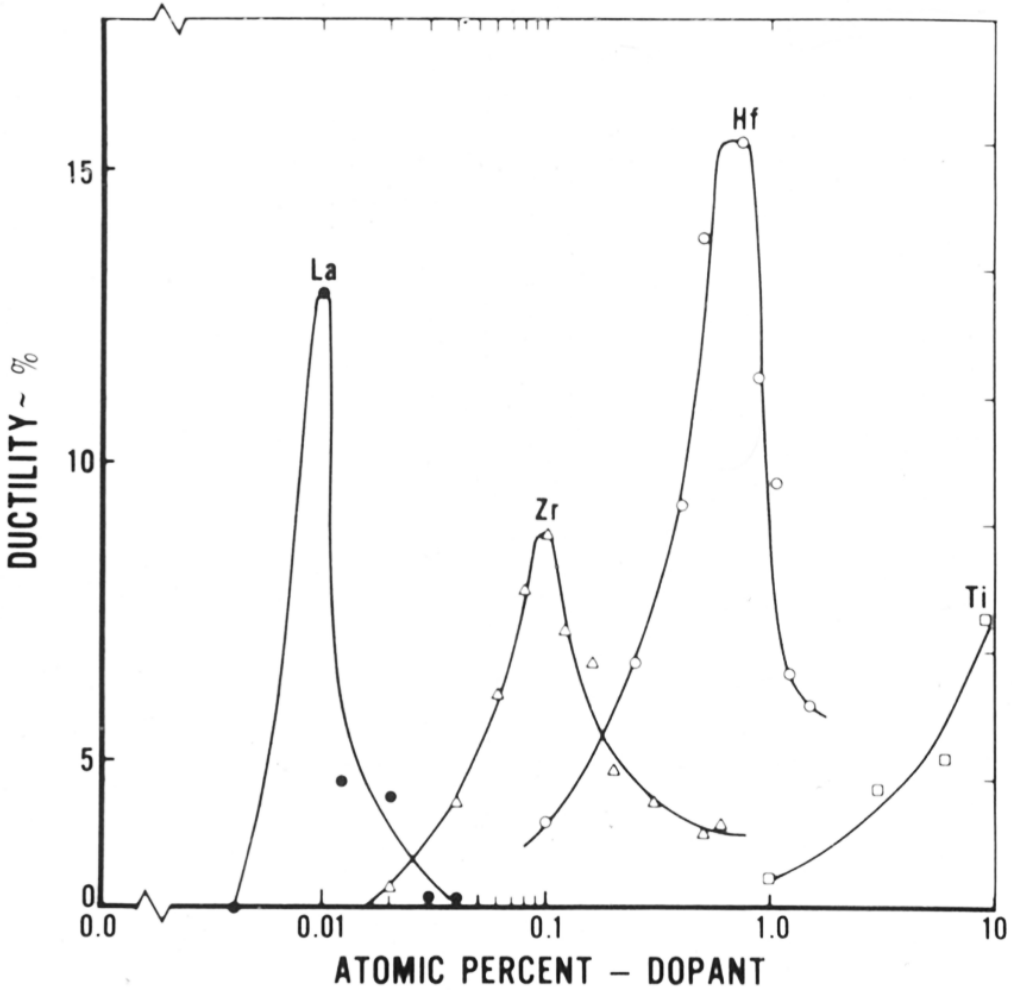
Nominal compositions (wt.%) for some nickel base superalloys

Alloy (wt.%)	Cr	Co	W	Ti	Al	C	B	Zr	Nb	Hf	Mo	Ta	V
Mar-M200+Hf	9.0	10.0	12.5	2.0	5.0	0.15	0.015	0.05	1.0	2.0	---	---	---
B-1900+Hf	8.0	10.0	---	1.0	6.0	0.11	0.015	0.08	---	1.2	6.0	4.3	---
IN-100	9.5	15.0	---	4.8	5.5	0.18	0.015	0.06	---	---	3.0	---	1.0

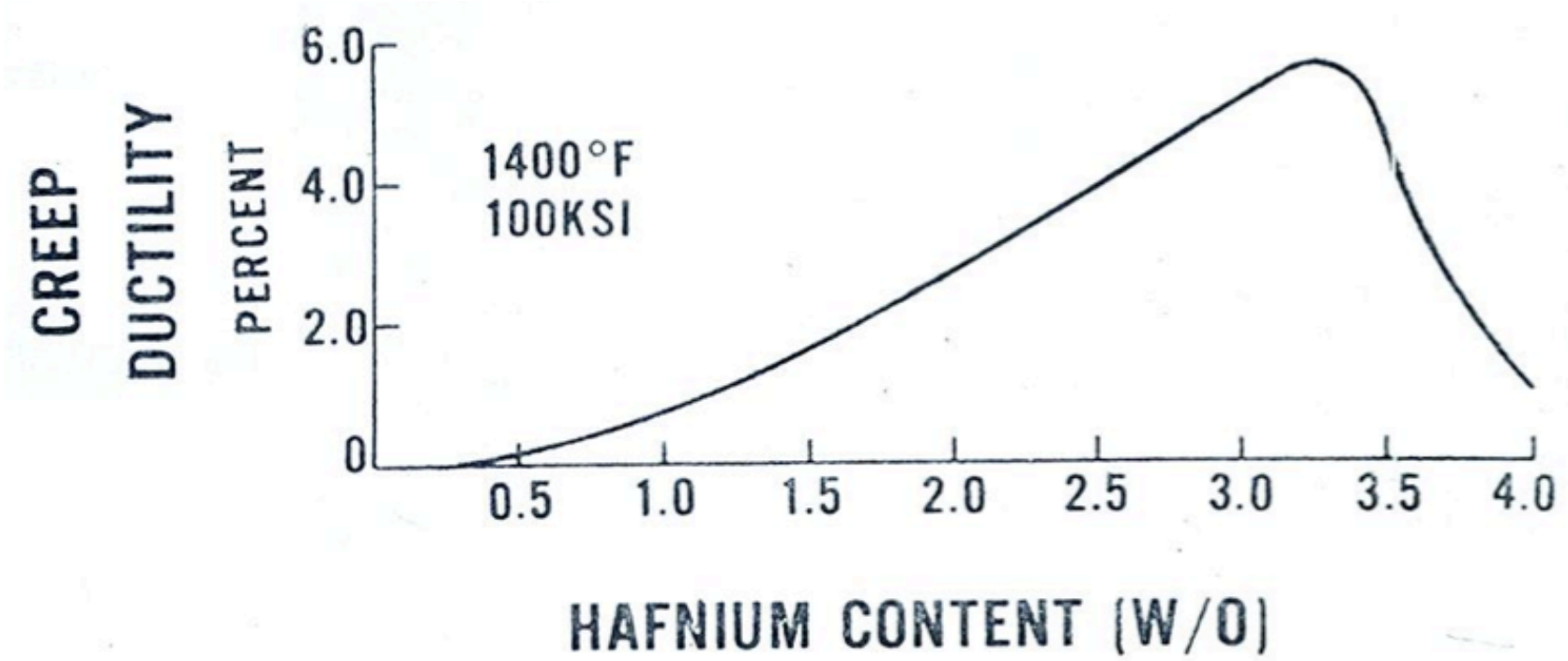
Solute effects on lattice parameters [Å]



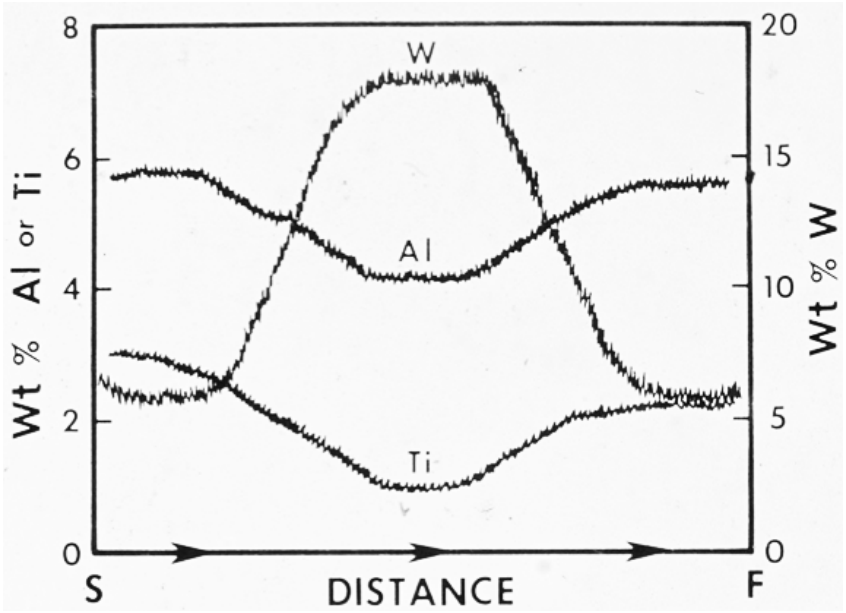
Grain boundary strengthening for Ni

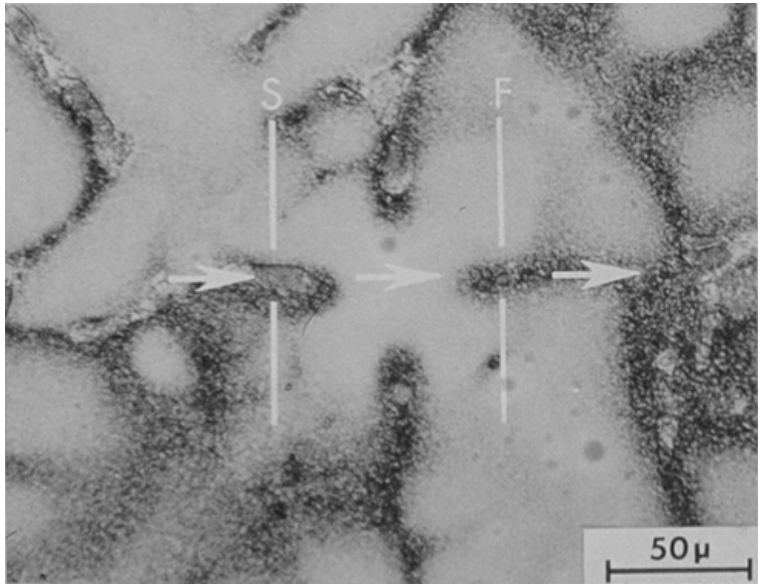


Effect of Hf additions to Mar-M200

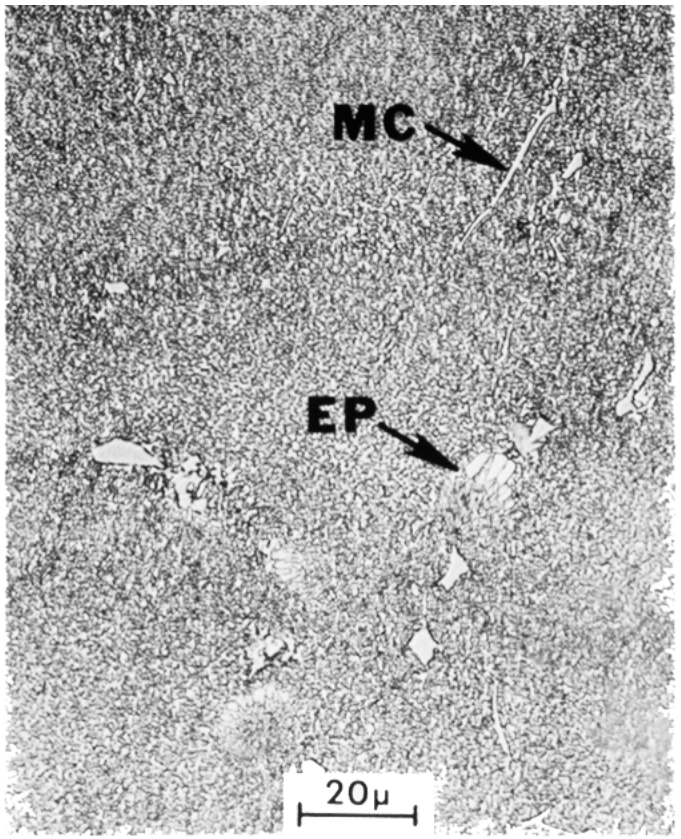


Micro-segregation in Mar-M200

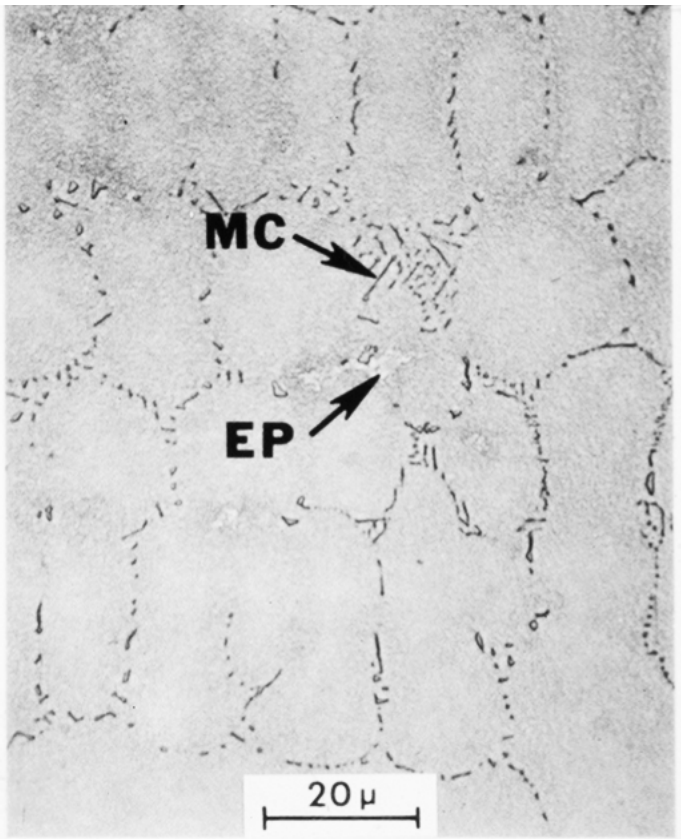




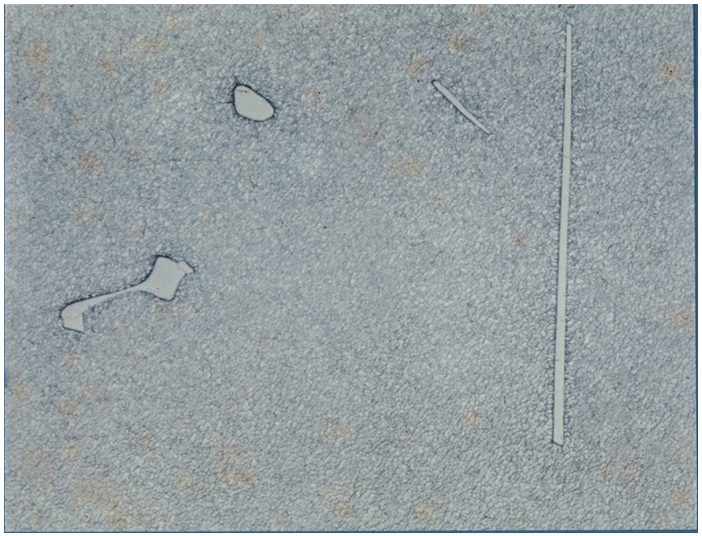
Refining MC carbides



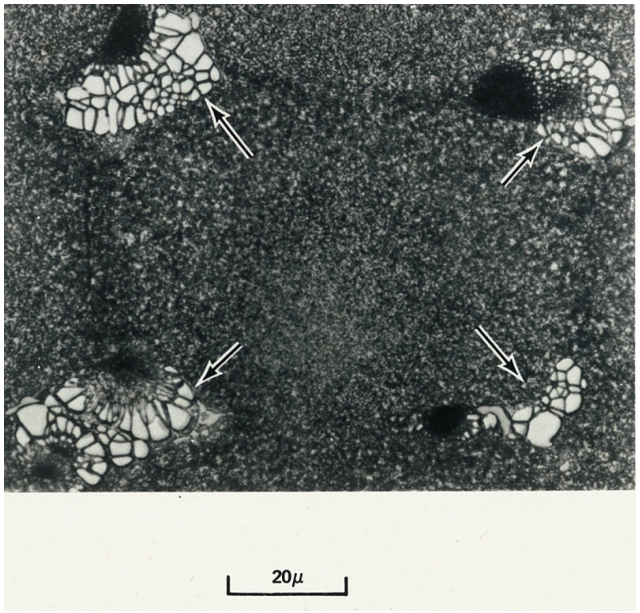
LMC at 1.7×10^{-2} cm/sec



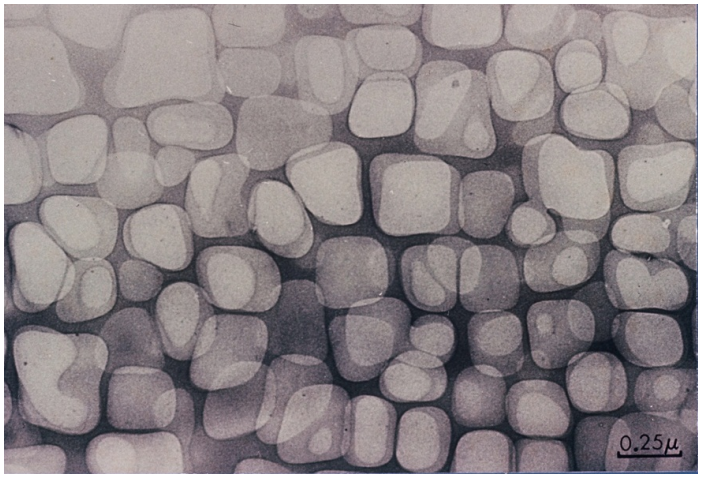
LMC at 2.1×10^{-1} cm/sec



MC platelets can initiate fatigue cracks

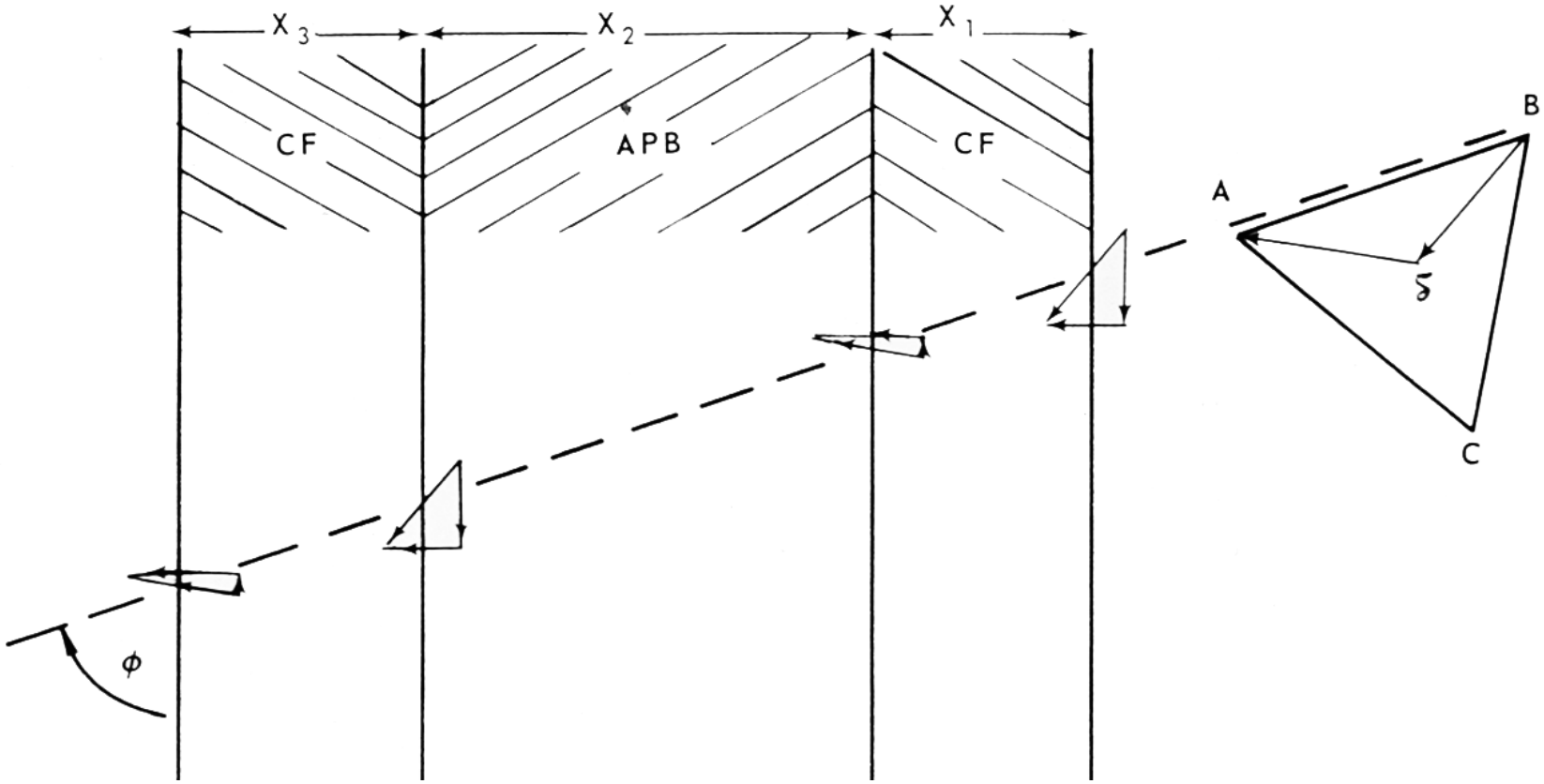


Close-up of eutectic microconstituent

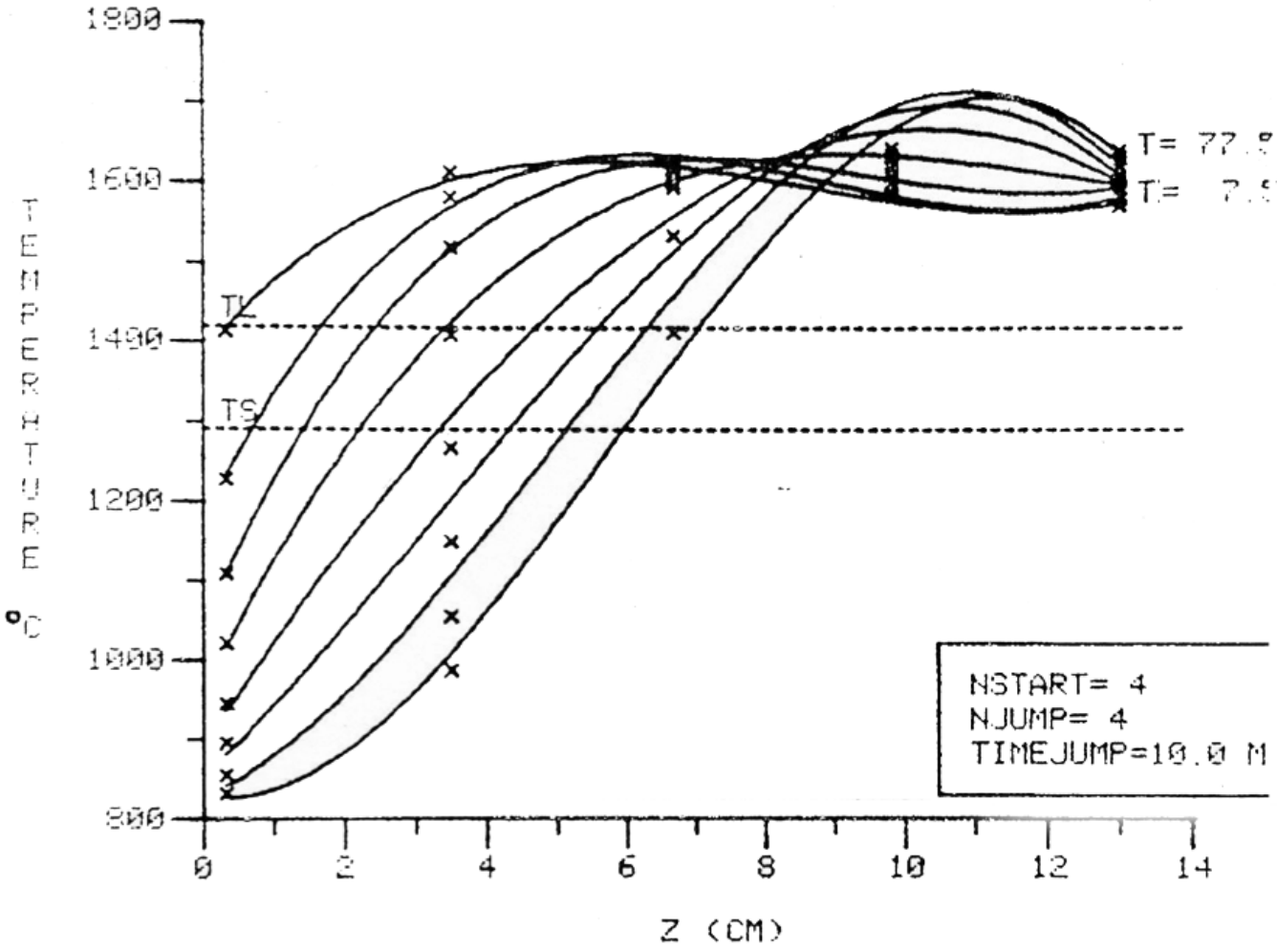


TEM micrograph of gamma prime particles

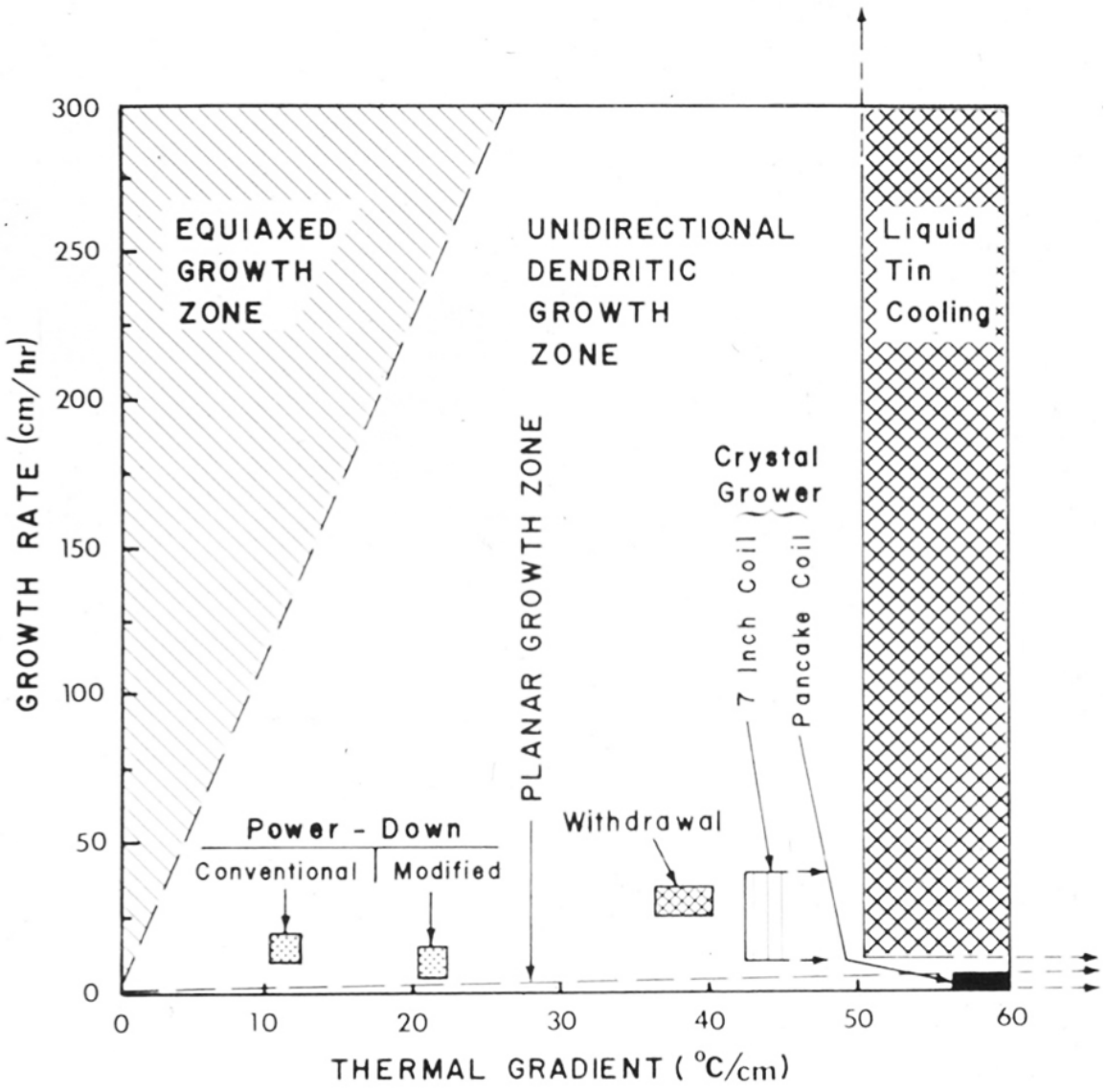
Fault configuration in the γ' phase

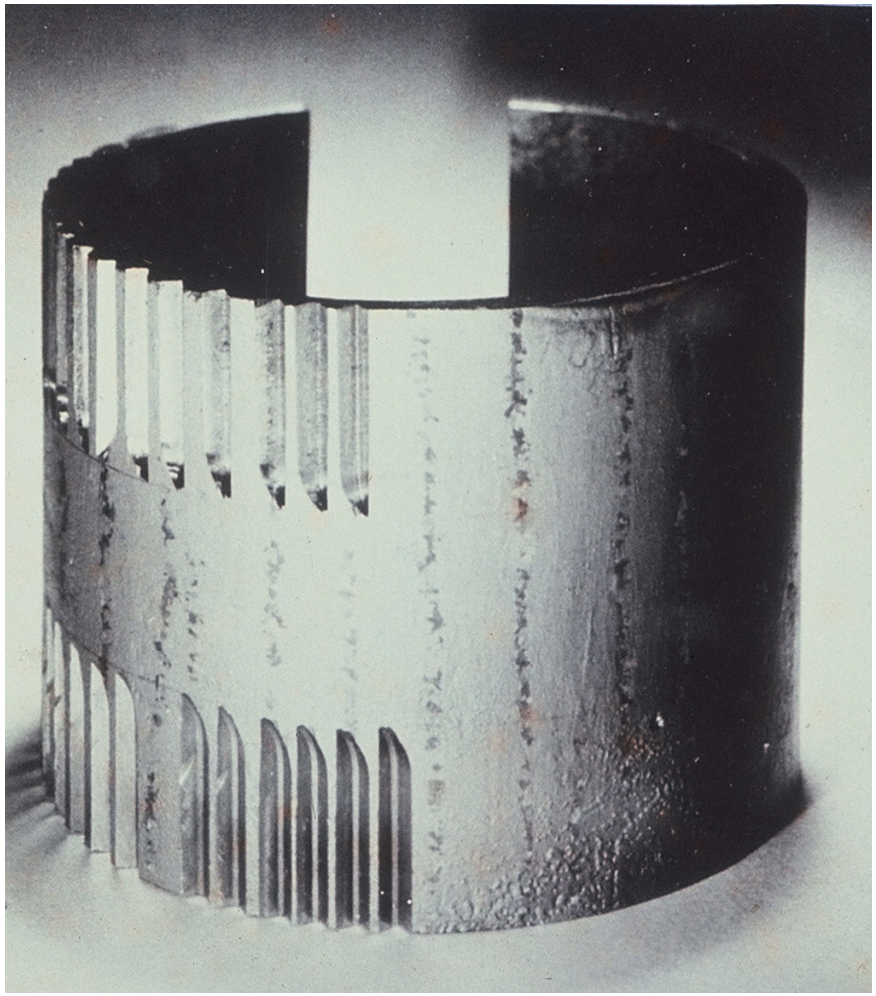


Thermal profiles during solidification



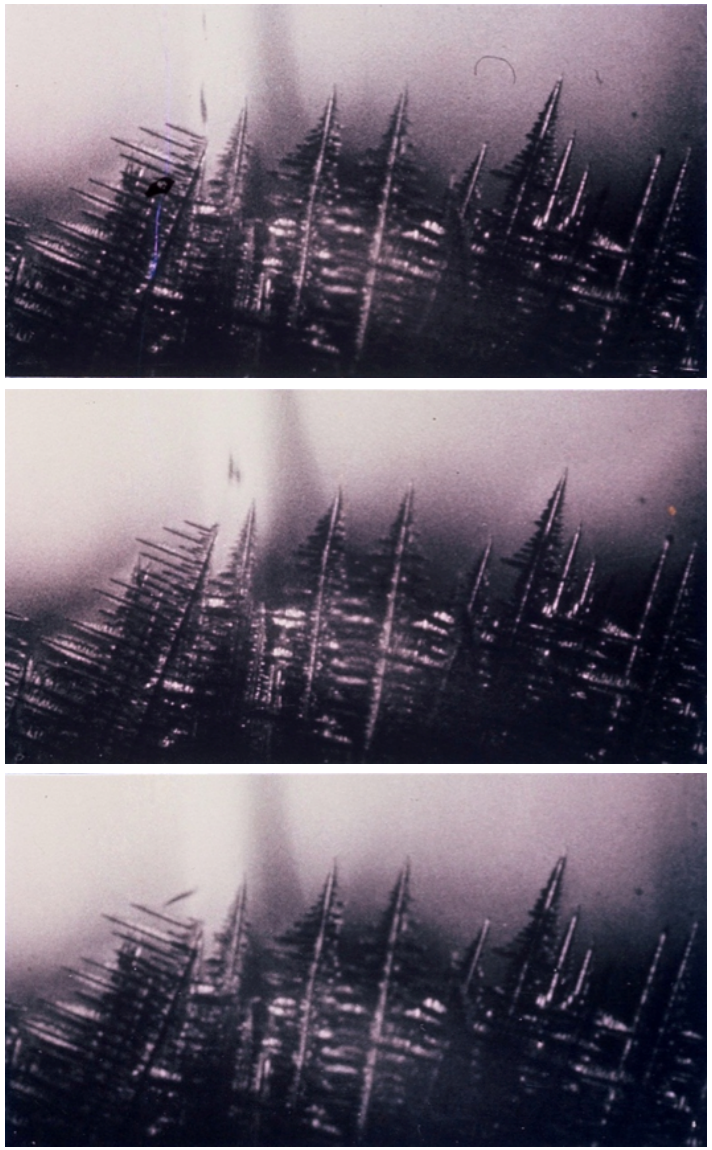
Parameters associated with various DS processes



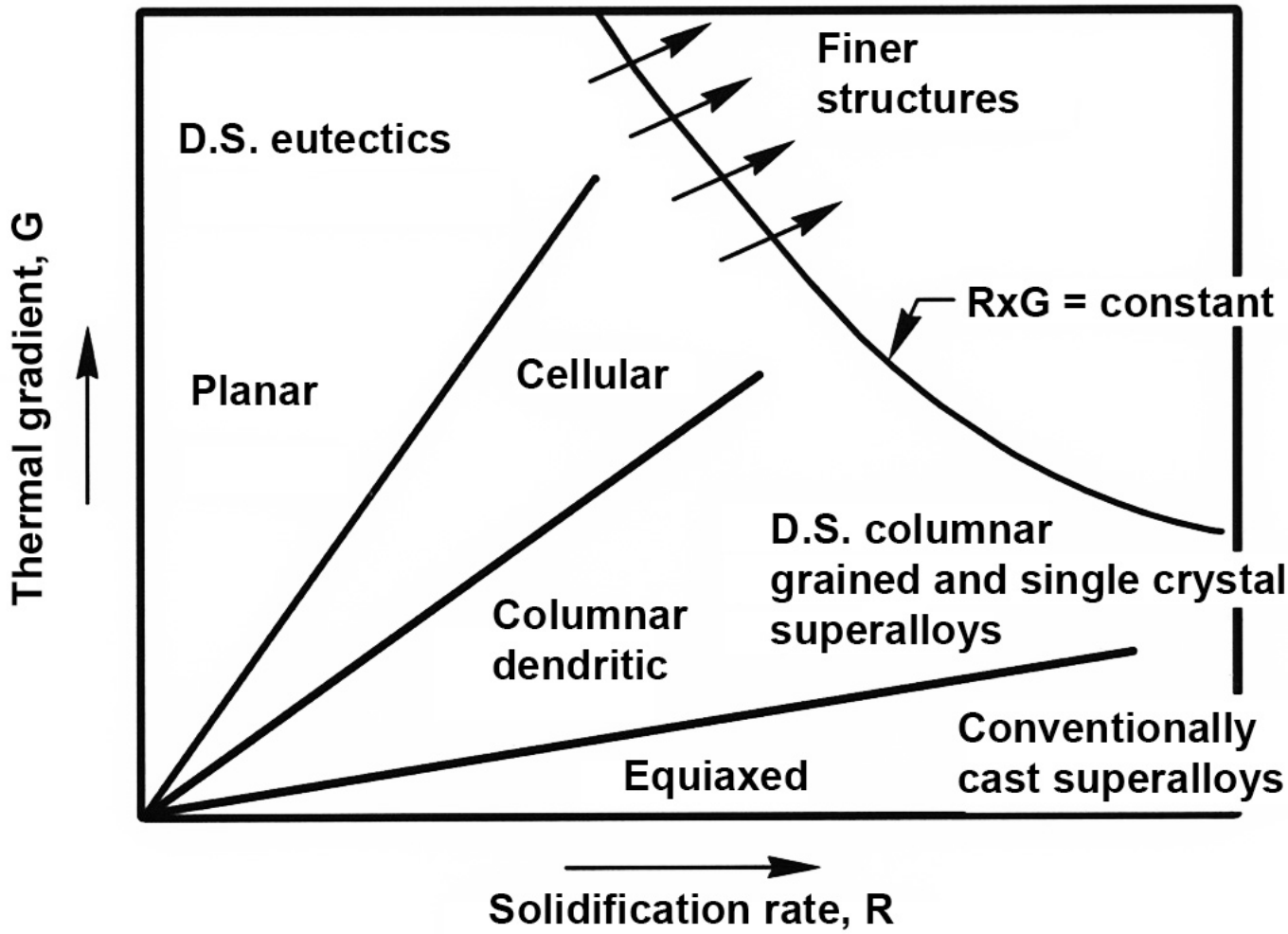


Trepanned single crystal ingot showing “freckle” trails

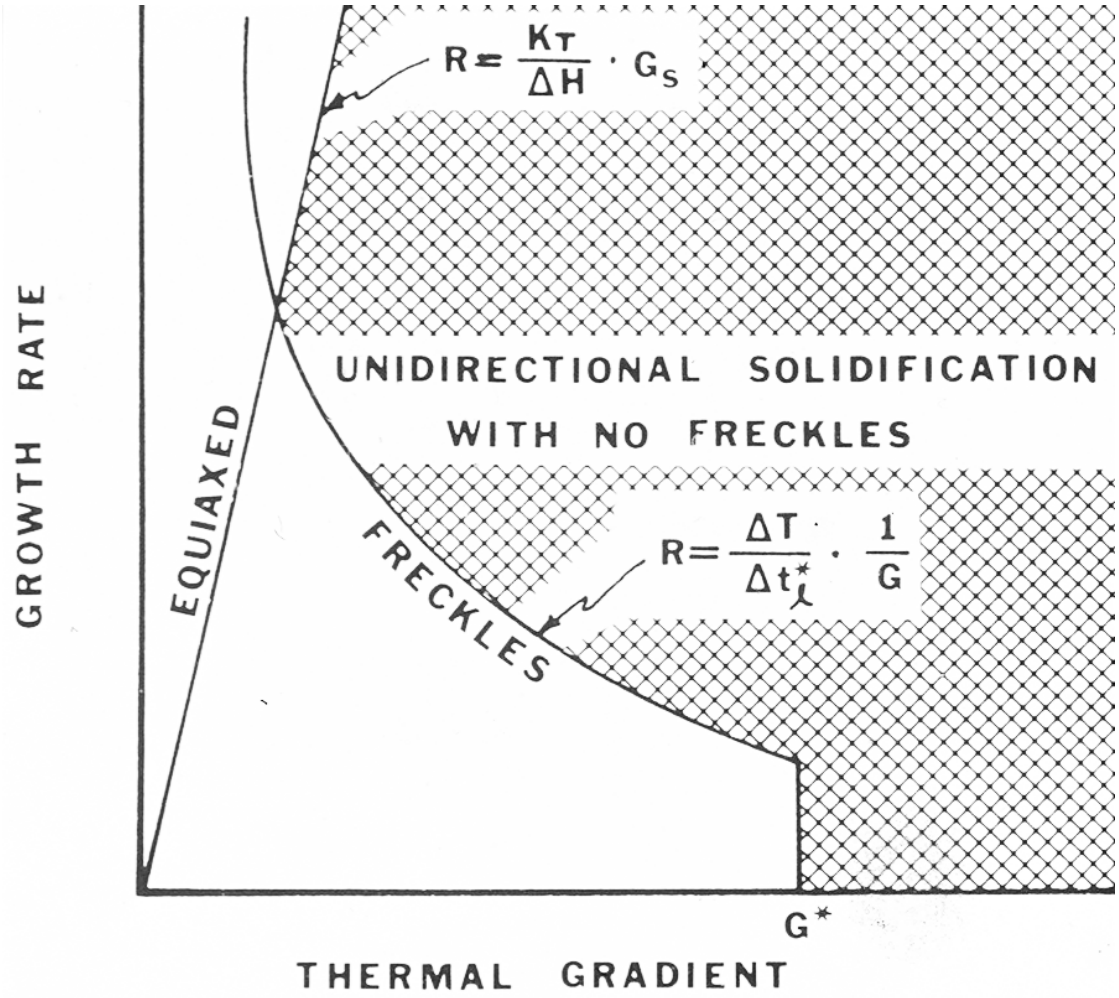
$NH_4C\ell$ dendrites, convection plume and fragmentation



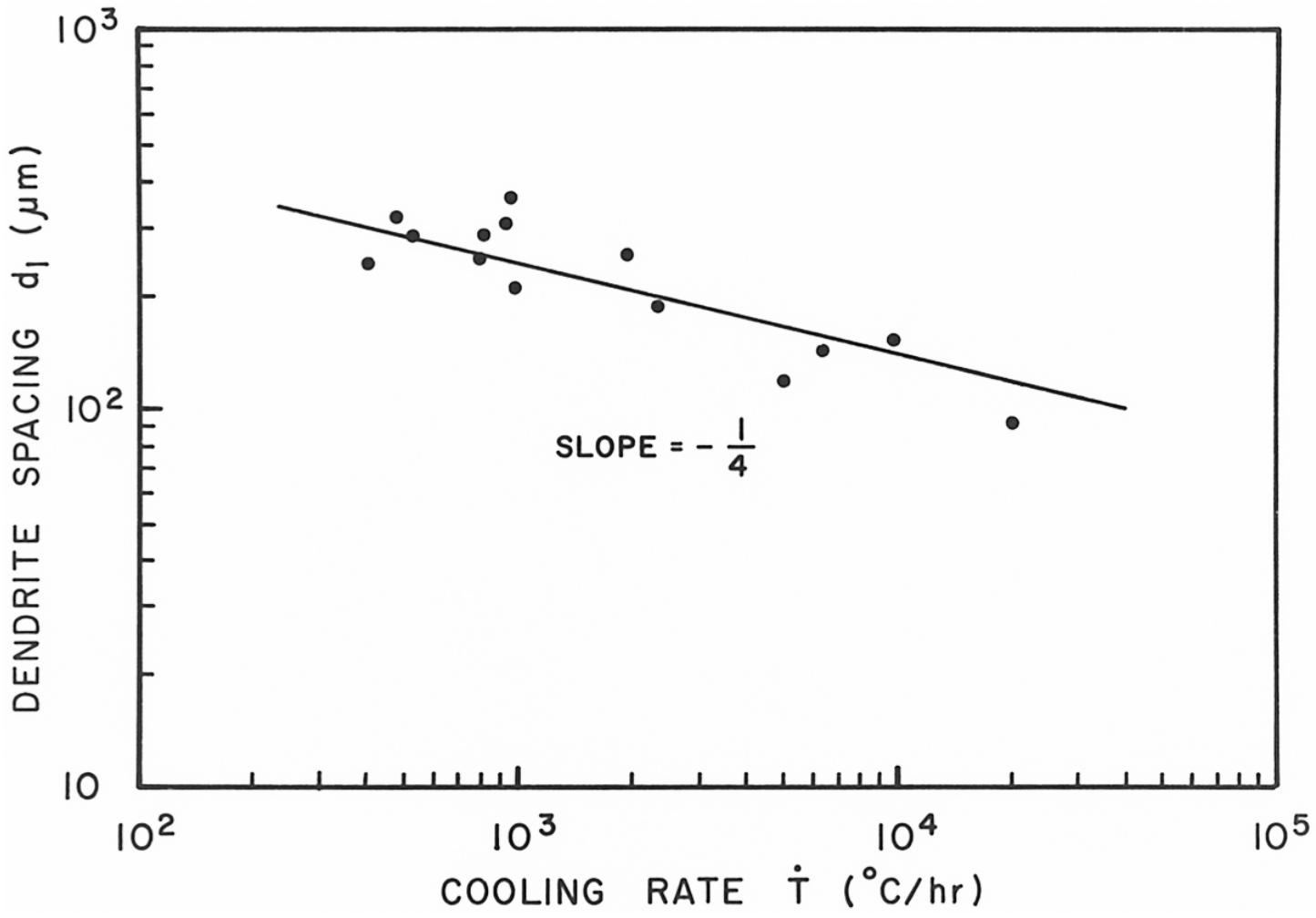
Solidification modes



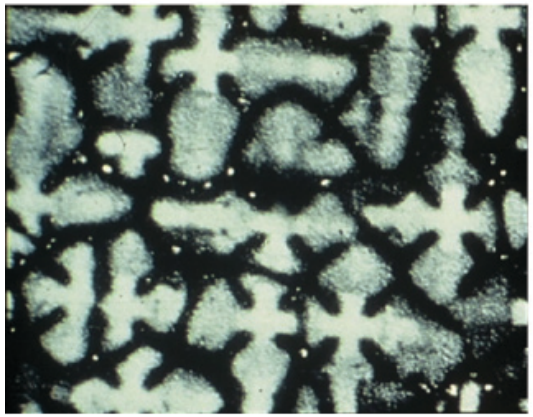
Conditions for freckles



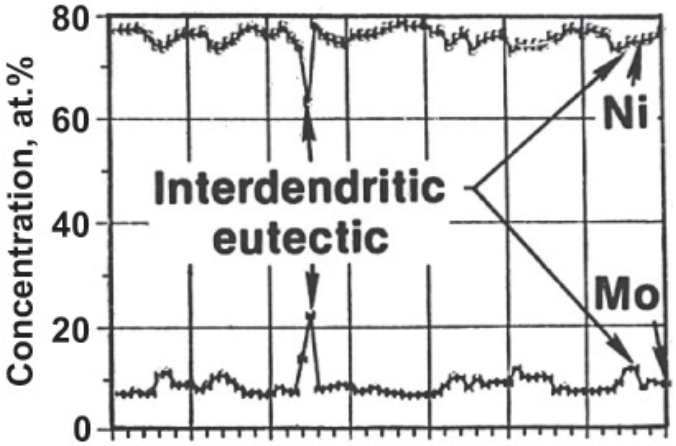
Dendrite arm spacing data

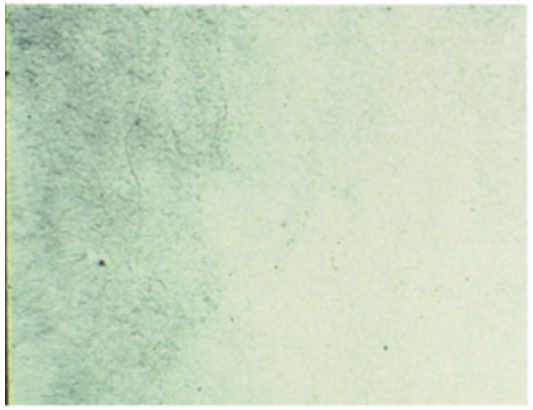


Homogenization of single crystals

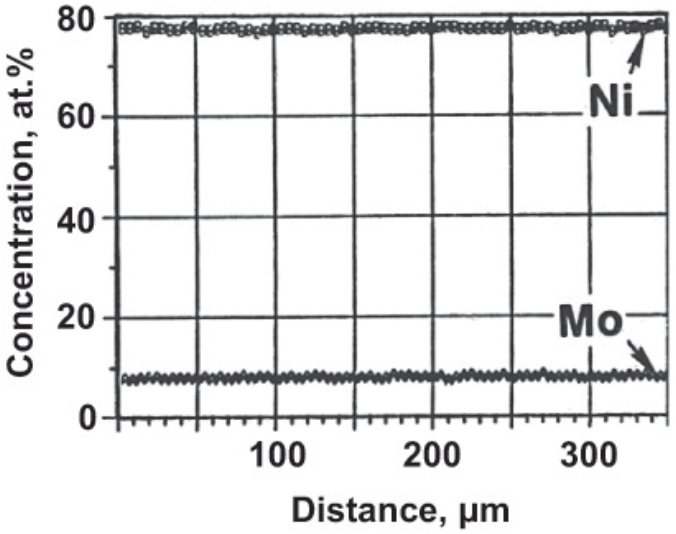


AS CAST

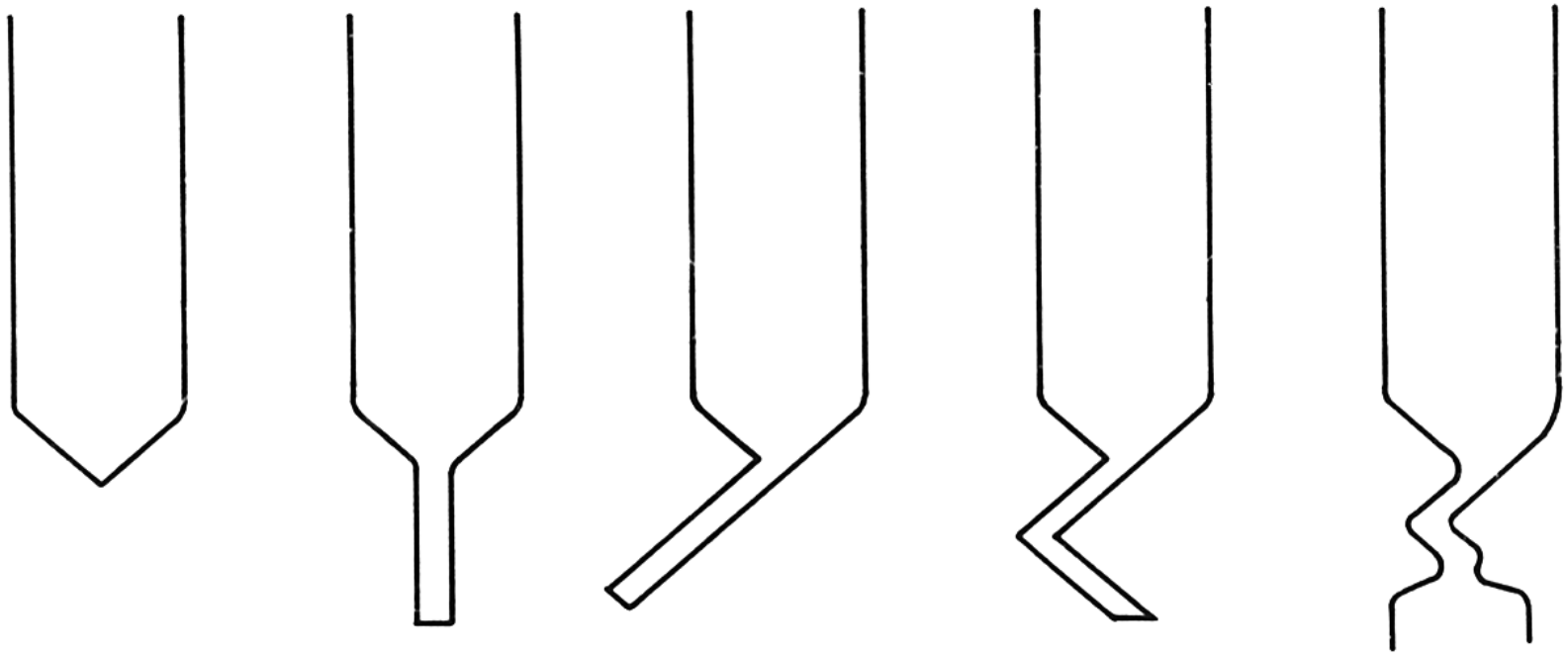




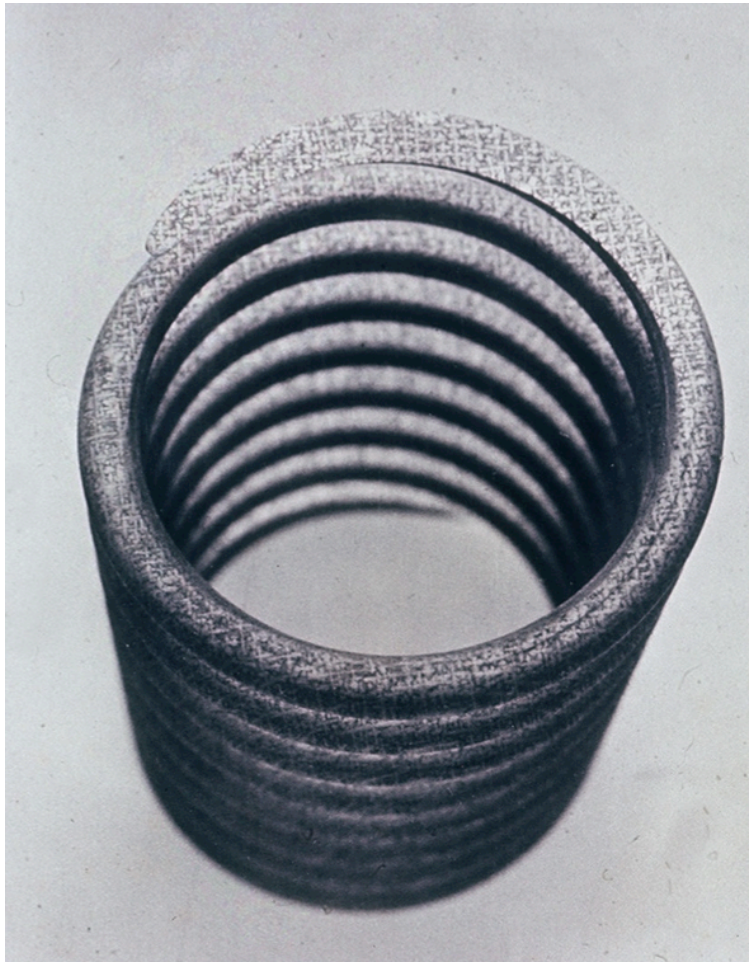
HOMOGENIZED
1593 K
16 hrs

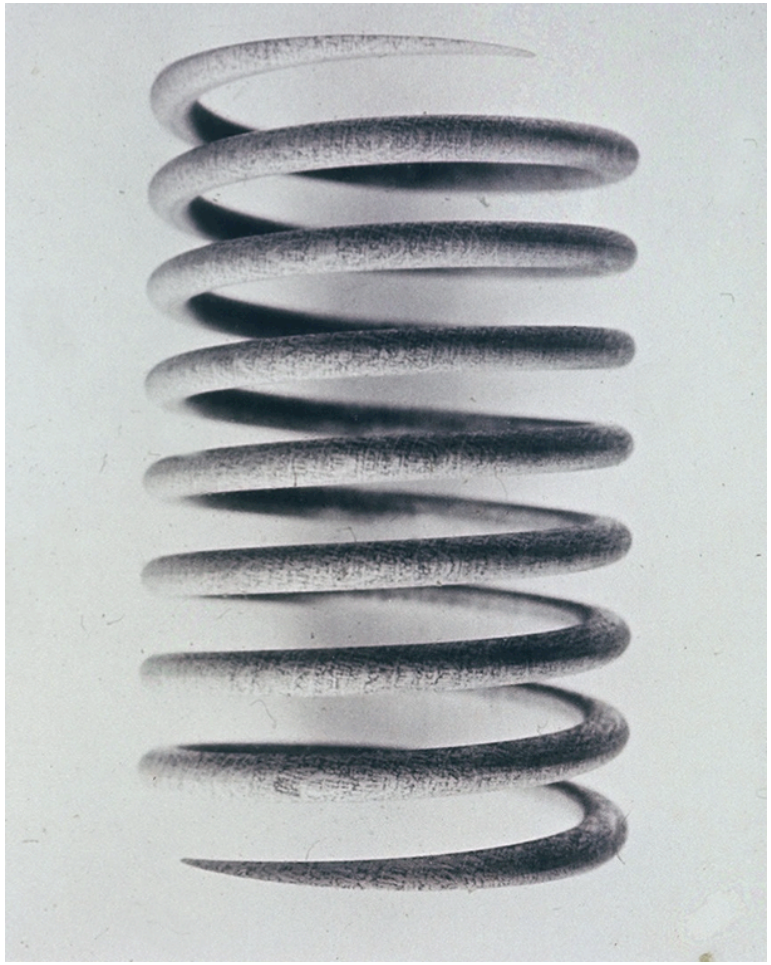


Single crystal grain selectors

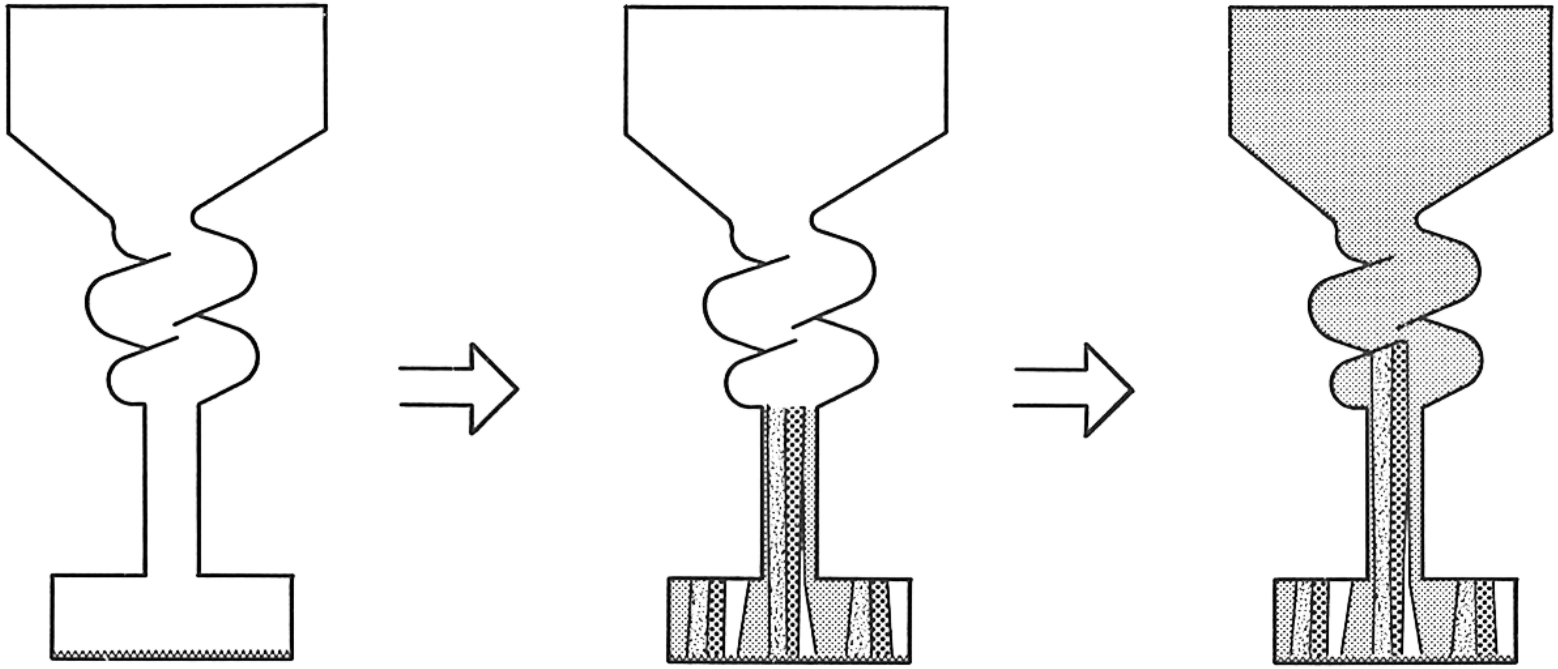


Cast single crystal spring





Formation of single crystal

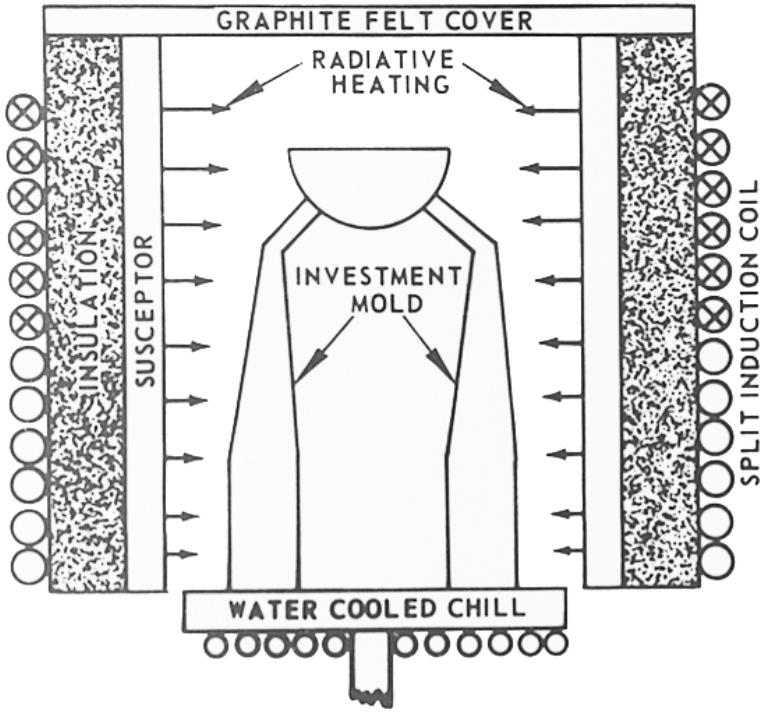


Grain nucleation

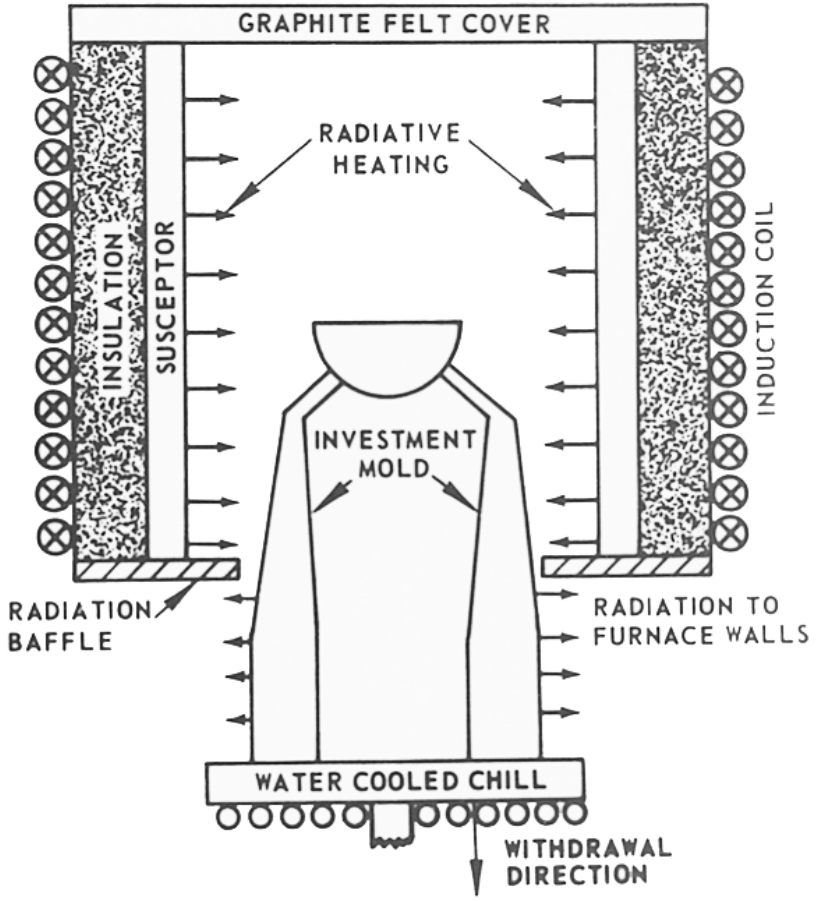
Competitive grain growth

Grain selection and growth

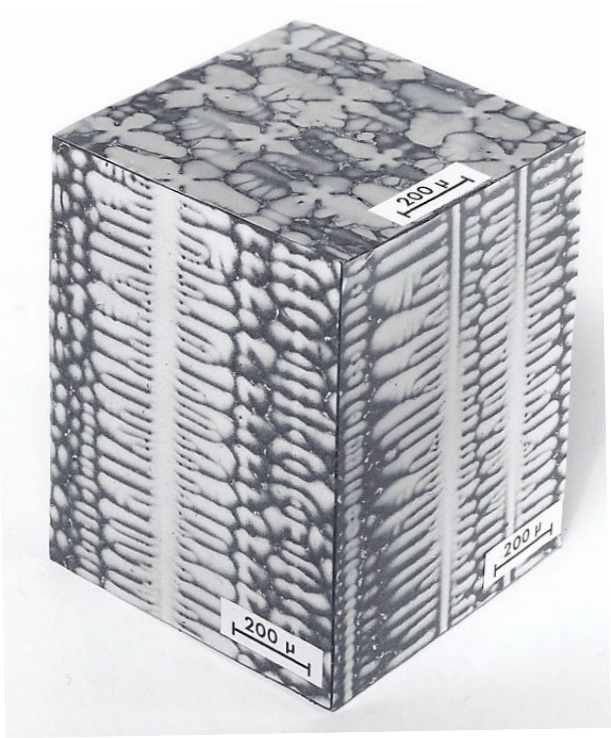
Withdrawal process



(a)

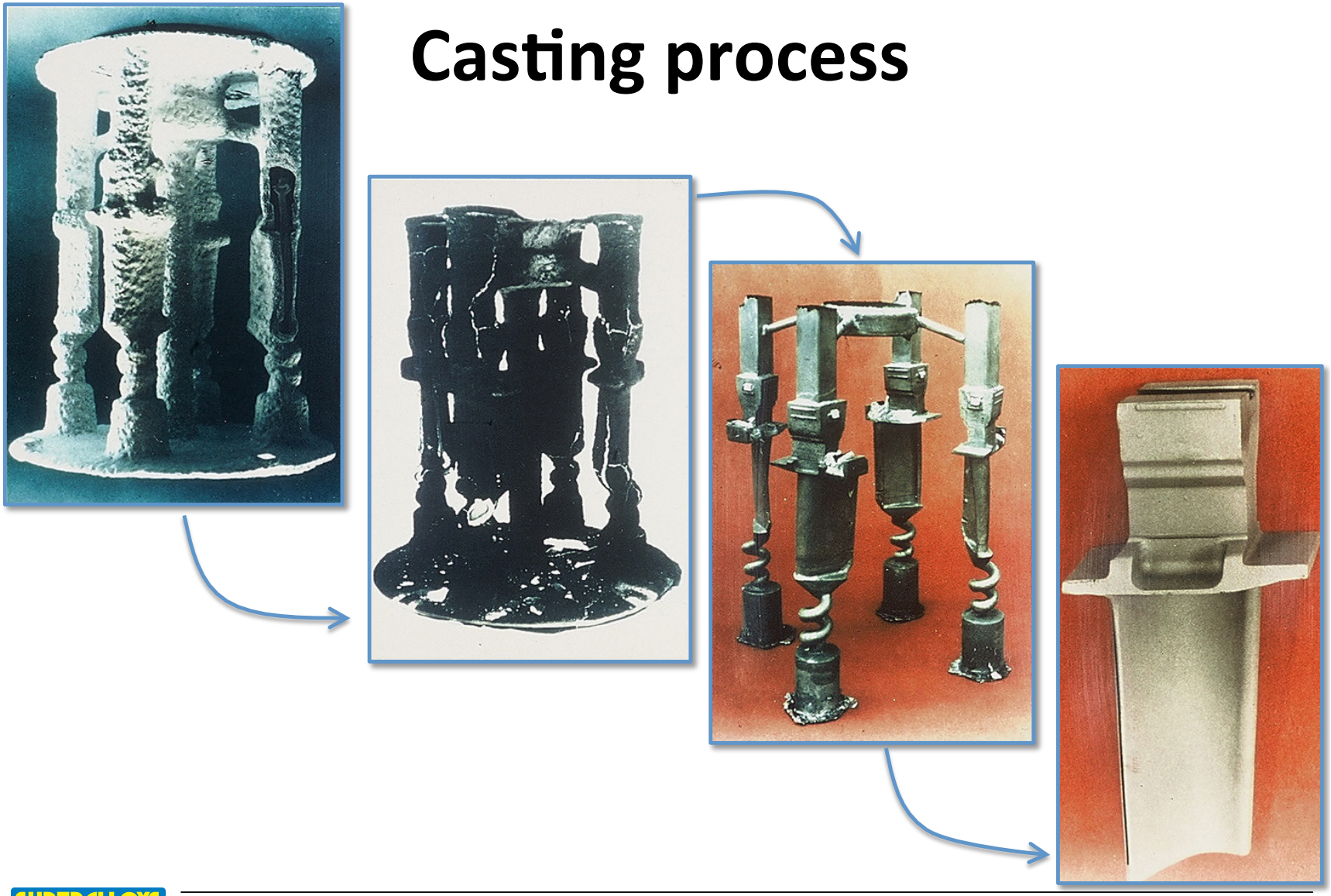


(b)



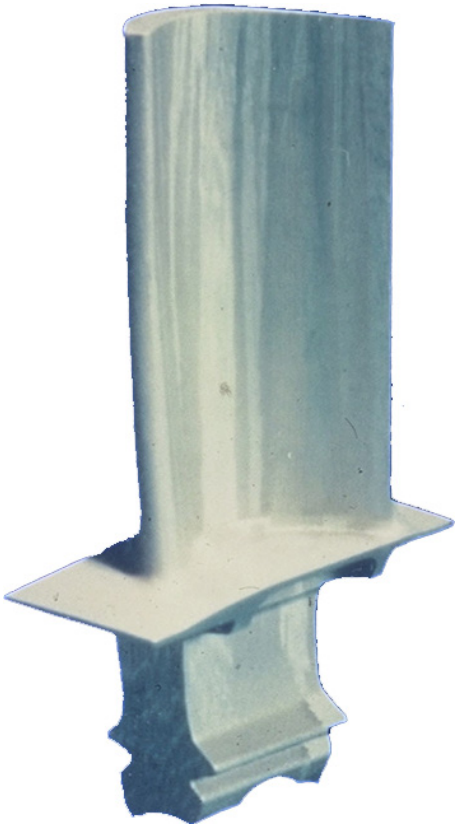
3D SUPERALLOY DENDRITE FIELD

Casting process



Advances in blade materials

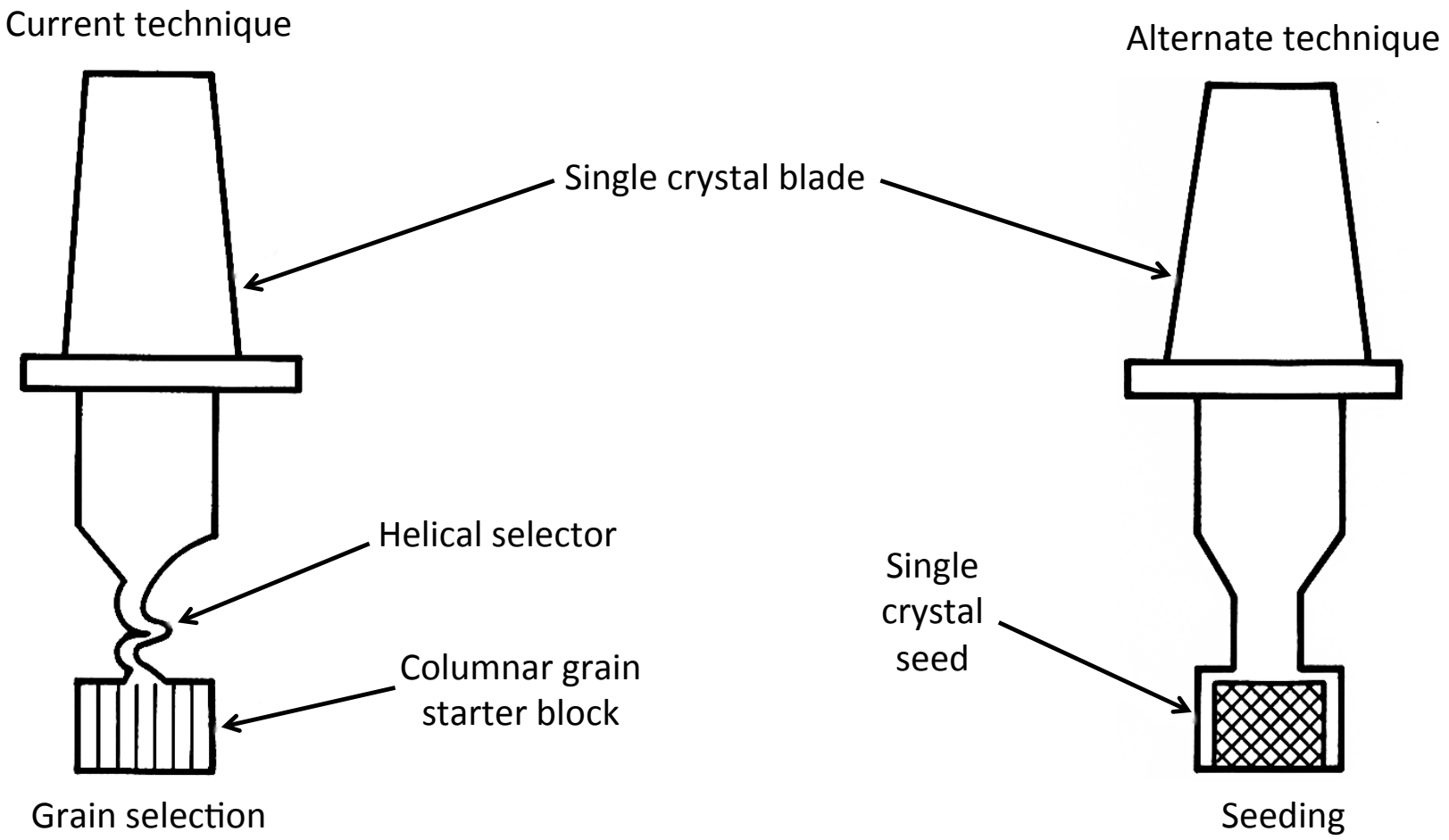
Conventional casting



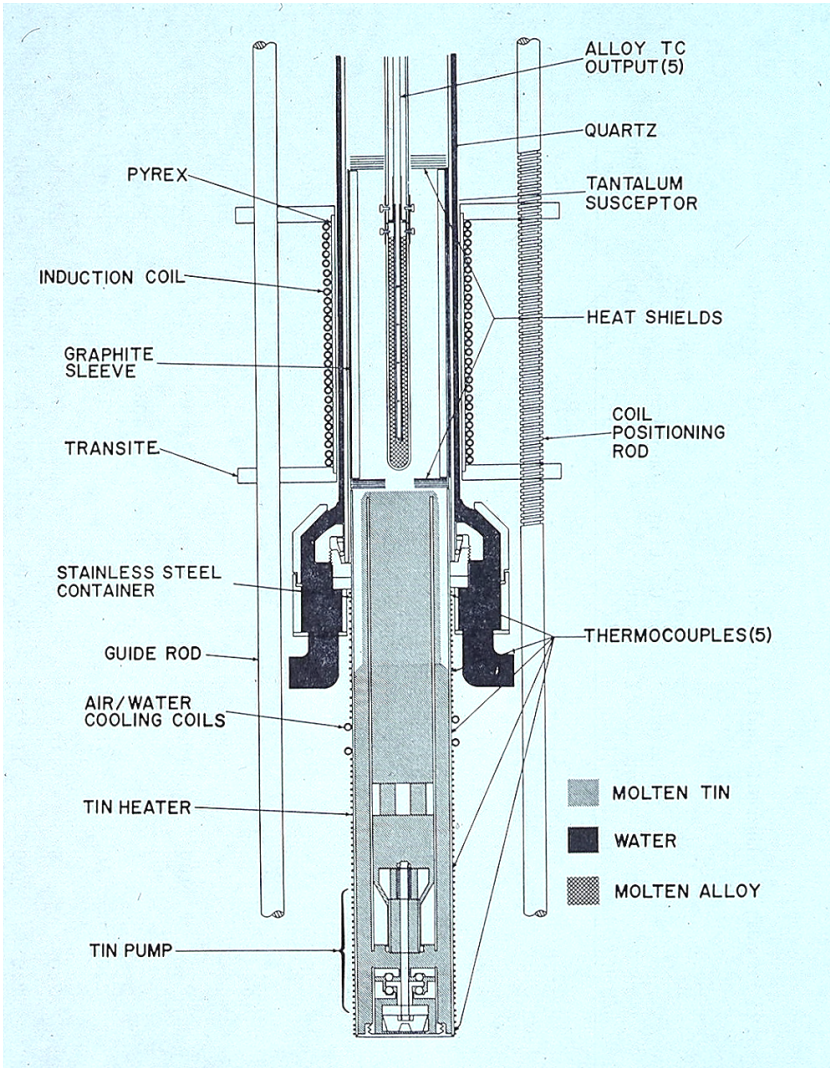
Columnar grains

Single crystal

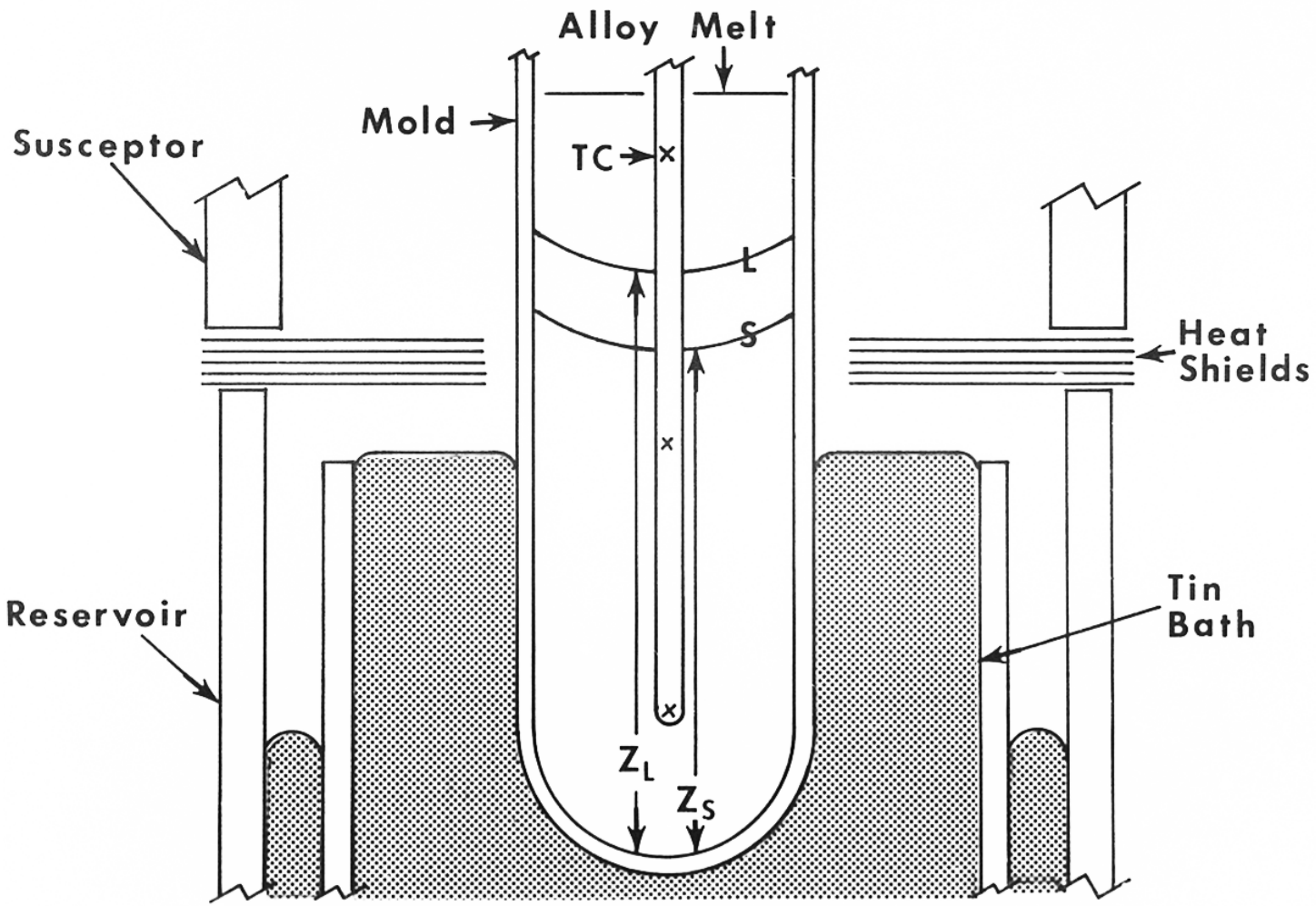
Single crystal growth methods



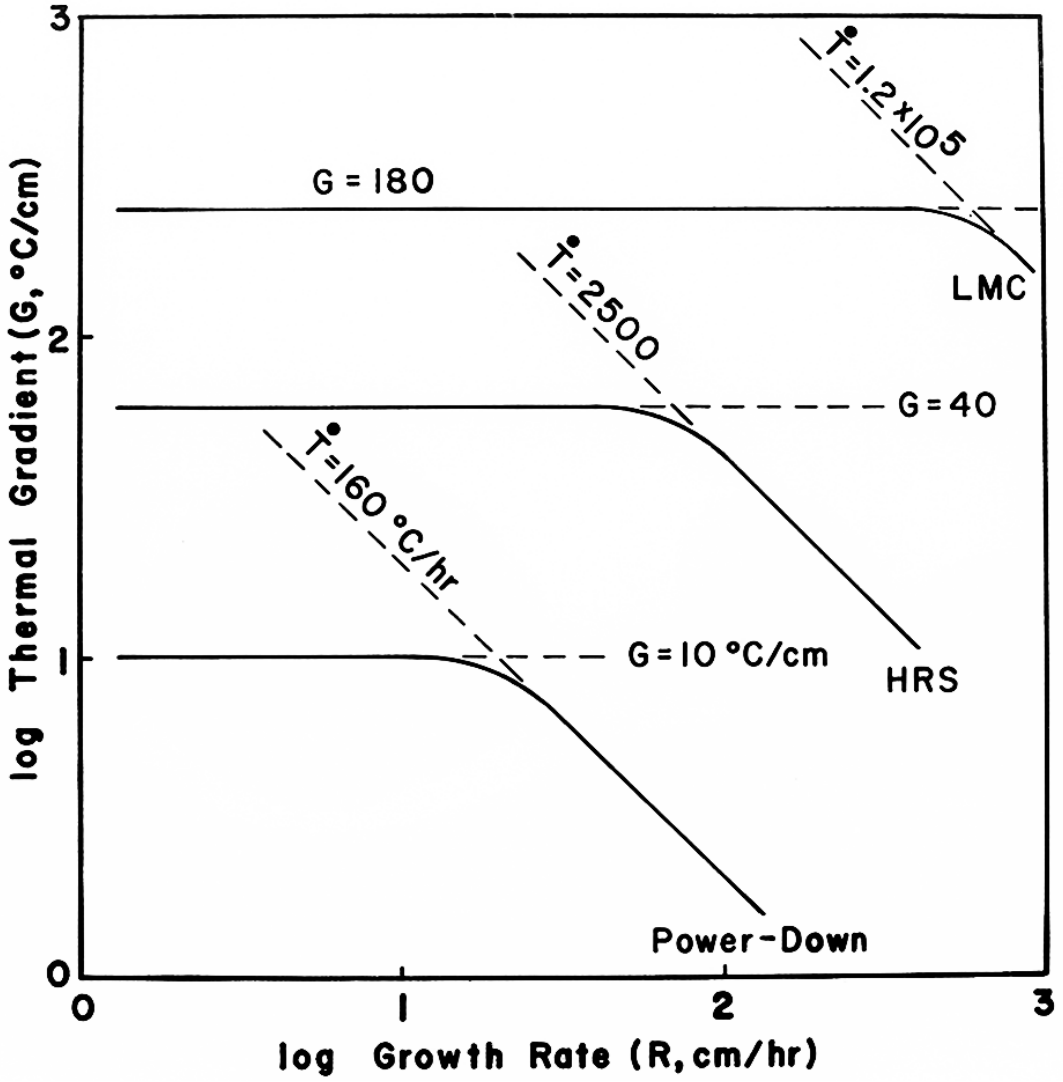
Laboratory Liquid Metal Cooling apparatus



Liquid metal cooling



Thermal gradient and cooling rate limits of three DS processes



Computer simulations

1. Pre-processing

- Define geometry:
  surface and volume elements
- Operative "physics" +
  Boundary Conditions & Initial Cond.

2. Analysis

- Analytical solutions
- Numerical solutions: iterations, timesteps
- FDM, FEM, BEM
- Analog, TOSS, MARC, PROCAST

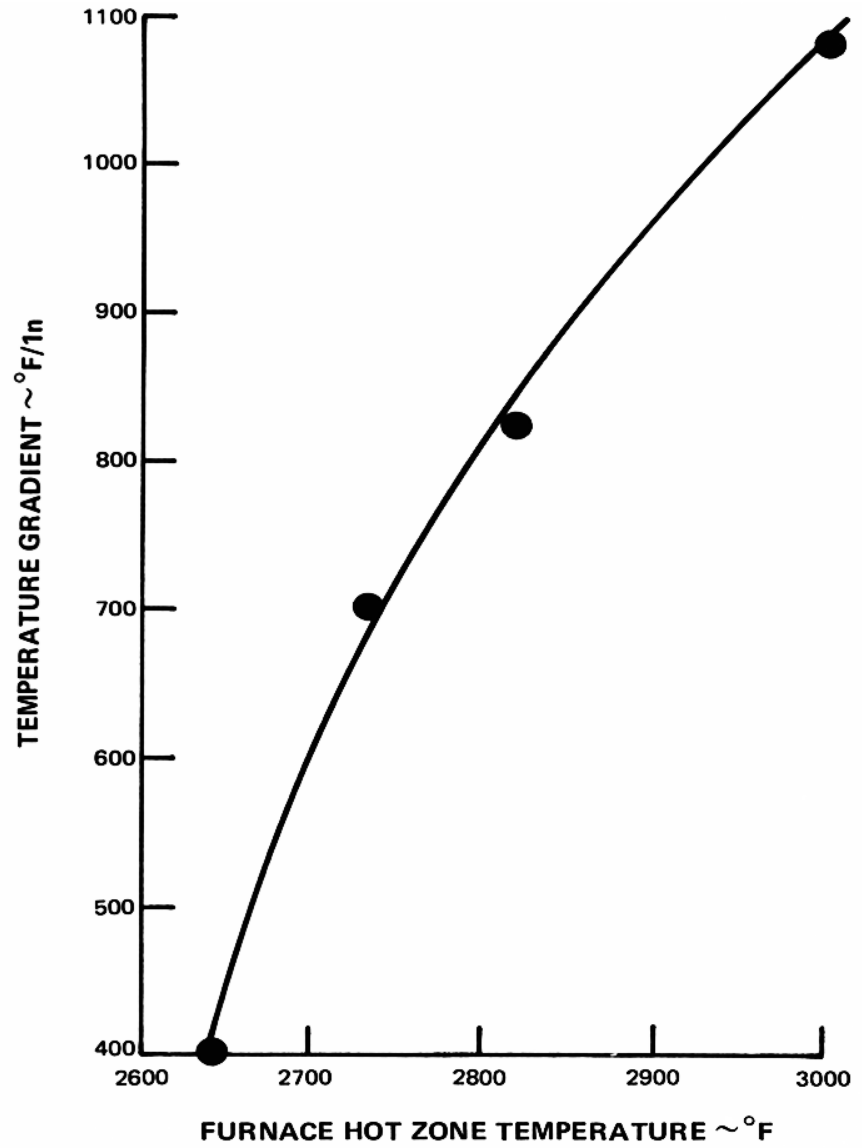
3. Post-processing

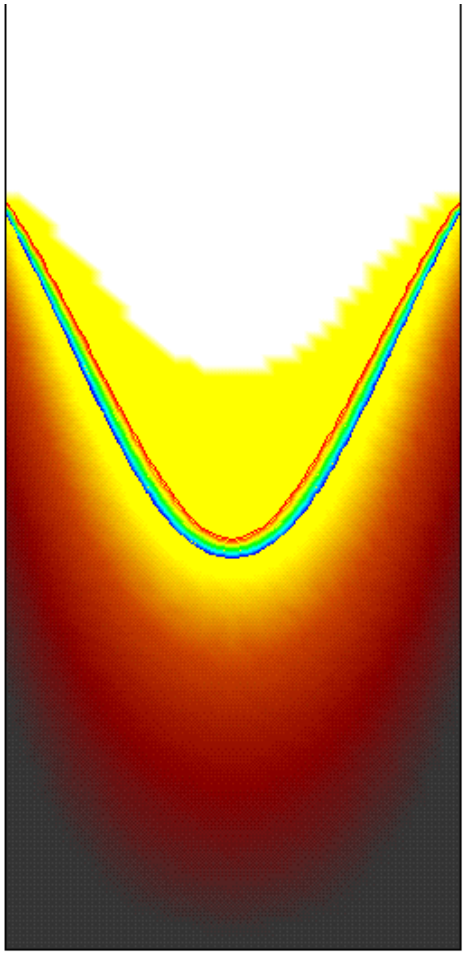
- Display of spatial & temporal data: AVS, pV3
- Color/realism/graphics/animation

4. Utilization

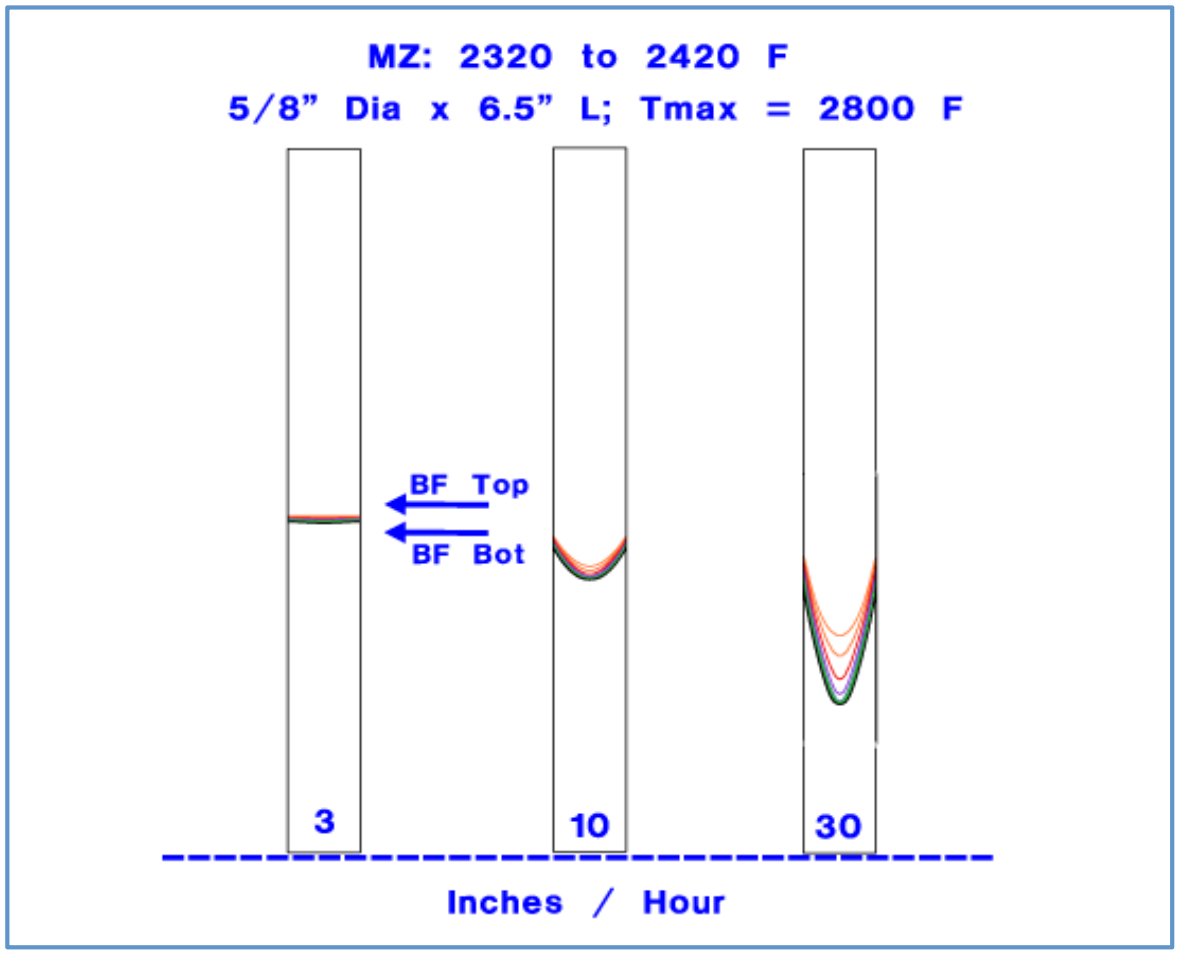
- Sensitivity analysis (model interrogation)
- Design/process optimization
- Comparison with experiments
- Training artificial intelligence: black box

Dynamic steady state simulation of directional solidification

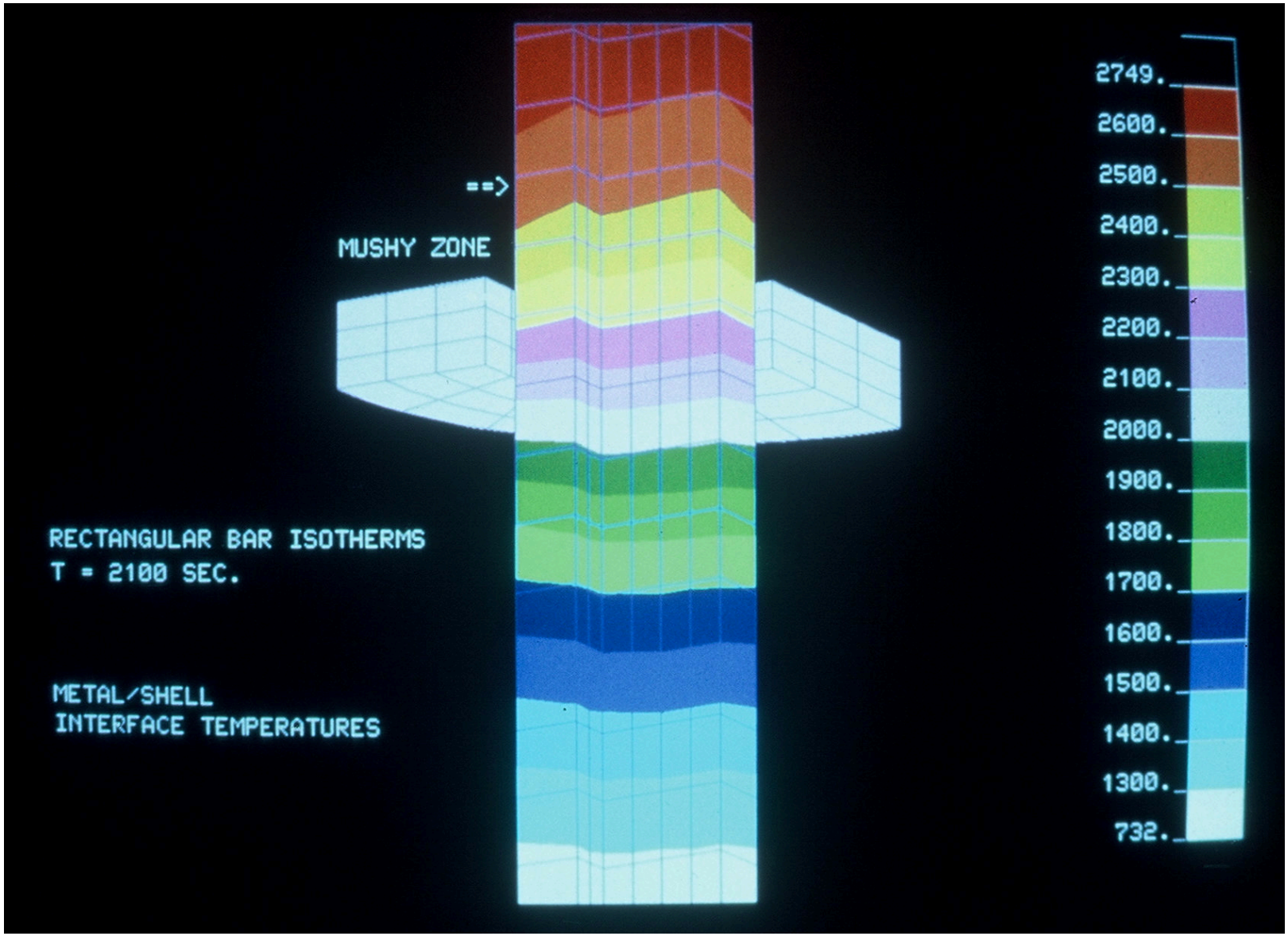




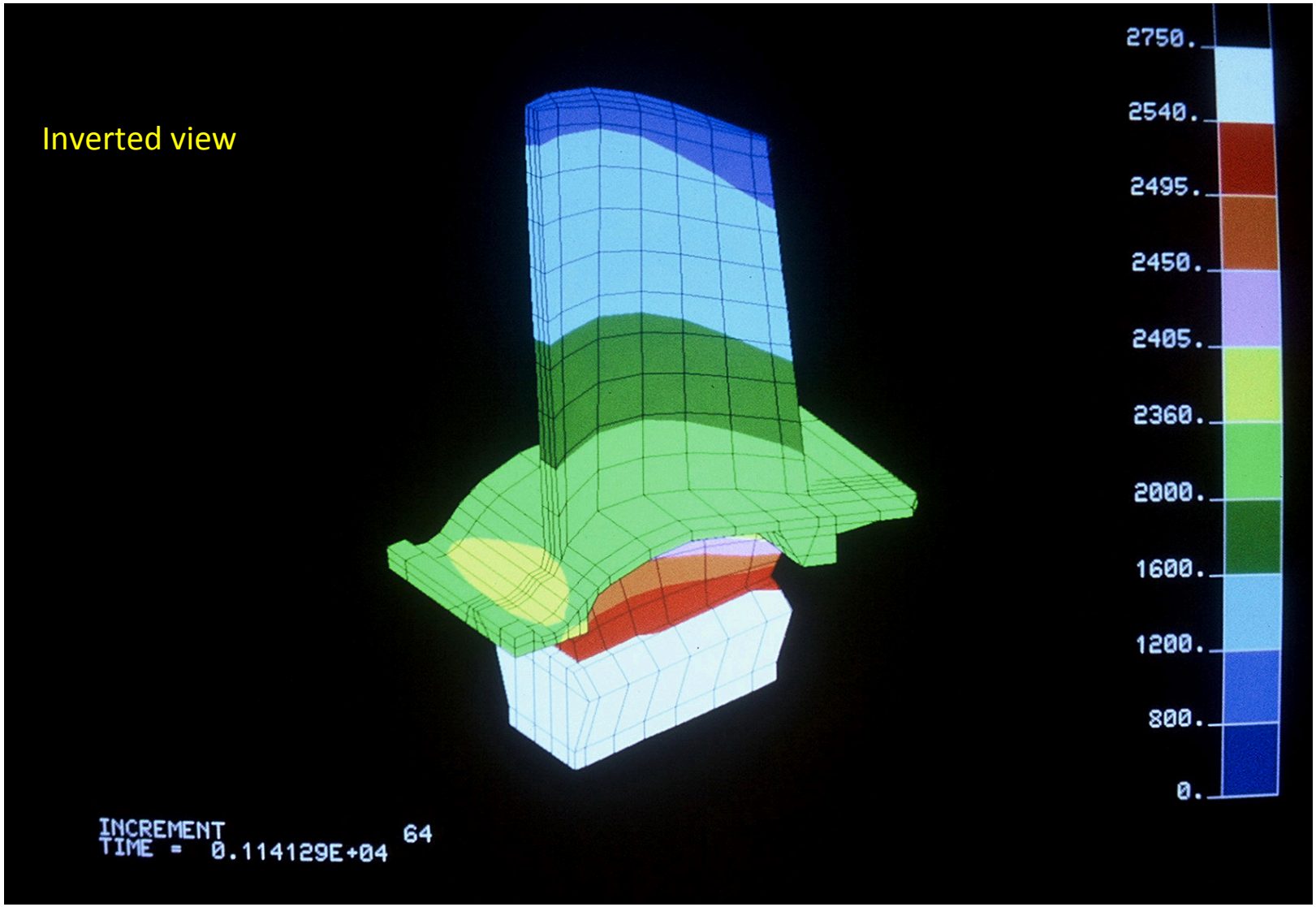
Ni alloy during withdrawal.
Low gradient case
showing MZ contours



Parametric study using dynamic Steady State model



FDM simulation of DS for rectangular bar with ceramic shell and baffle.

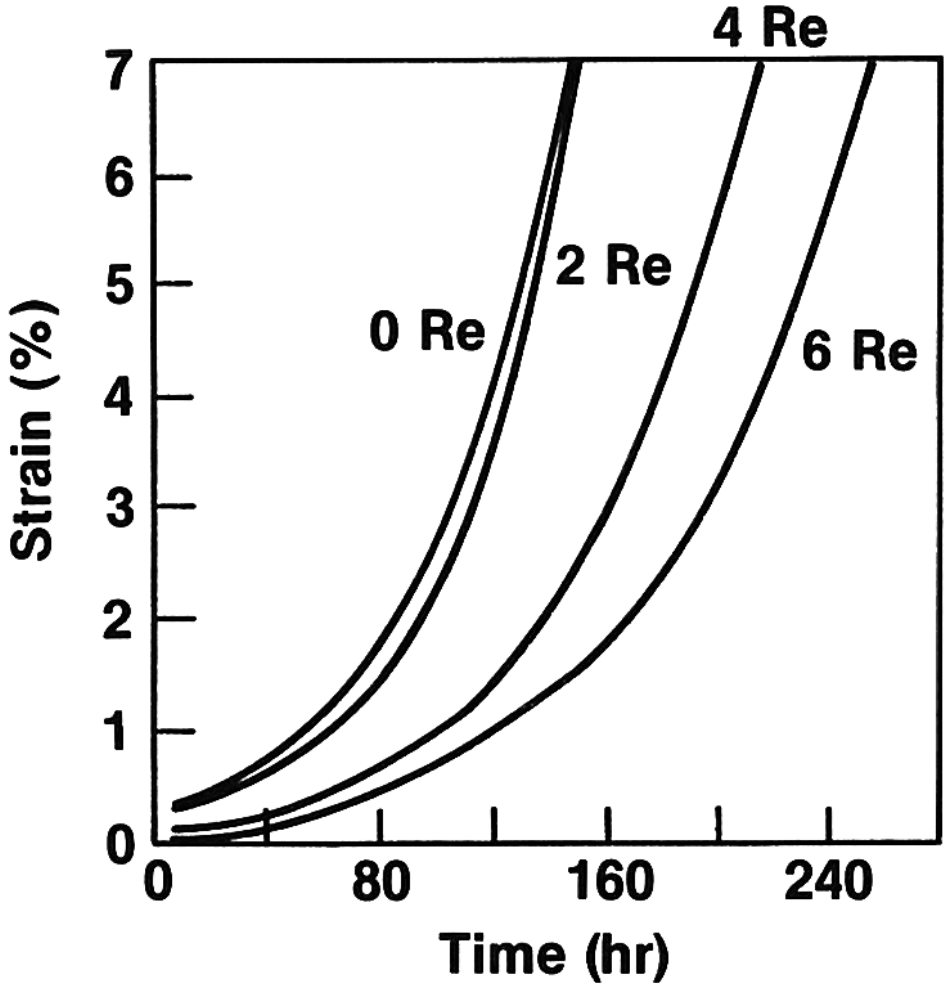


Finite Element simulation of single crystal turbine blade casting.

Single crystal applications

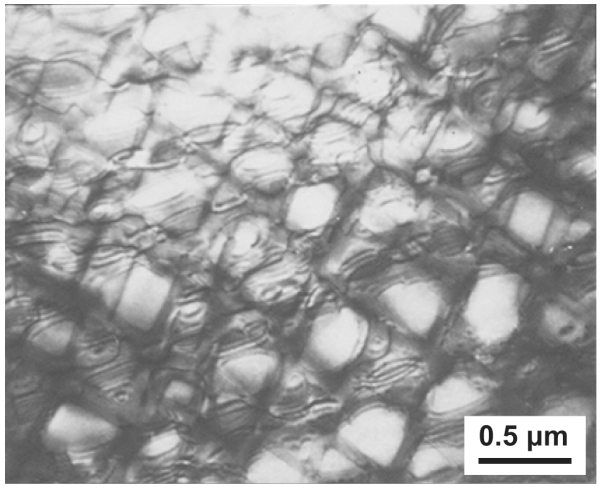
	Engine	Components	Certification date
Military	T400-WV-402	1B	11/81
	F100 derivative	1V, 1B, 2V, 2B, 3B	12/83
	JTDE	1V, 1B	-
Commercial	JT9D-7R4 A-E	1B	9/80
	PT-5 – A65	1B	8/82
	JT9D-7R4 G-H	1B, 2V, 2B	9/82
	2037	1B, 2B	6/84
	4000	1V, 1B	6/85

Rhenium effect

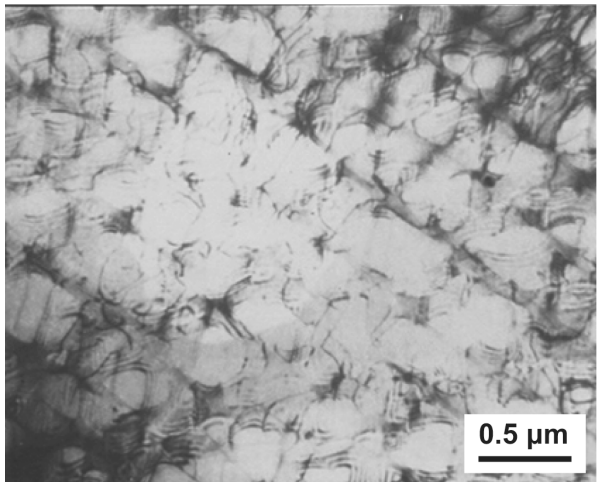


- Alloy 444
- Crept along [100]
- 899°C (1650°F)
- 380MPa (55ksi)

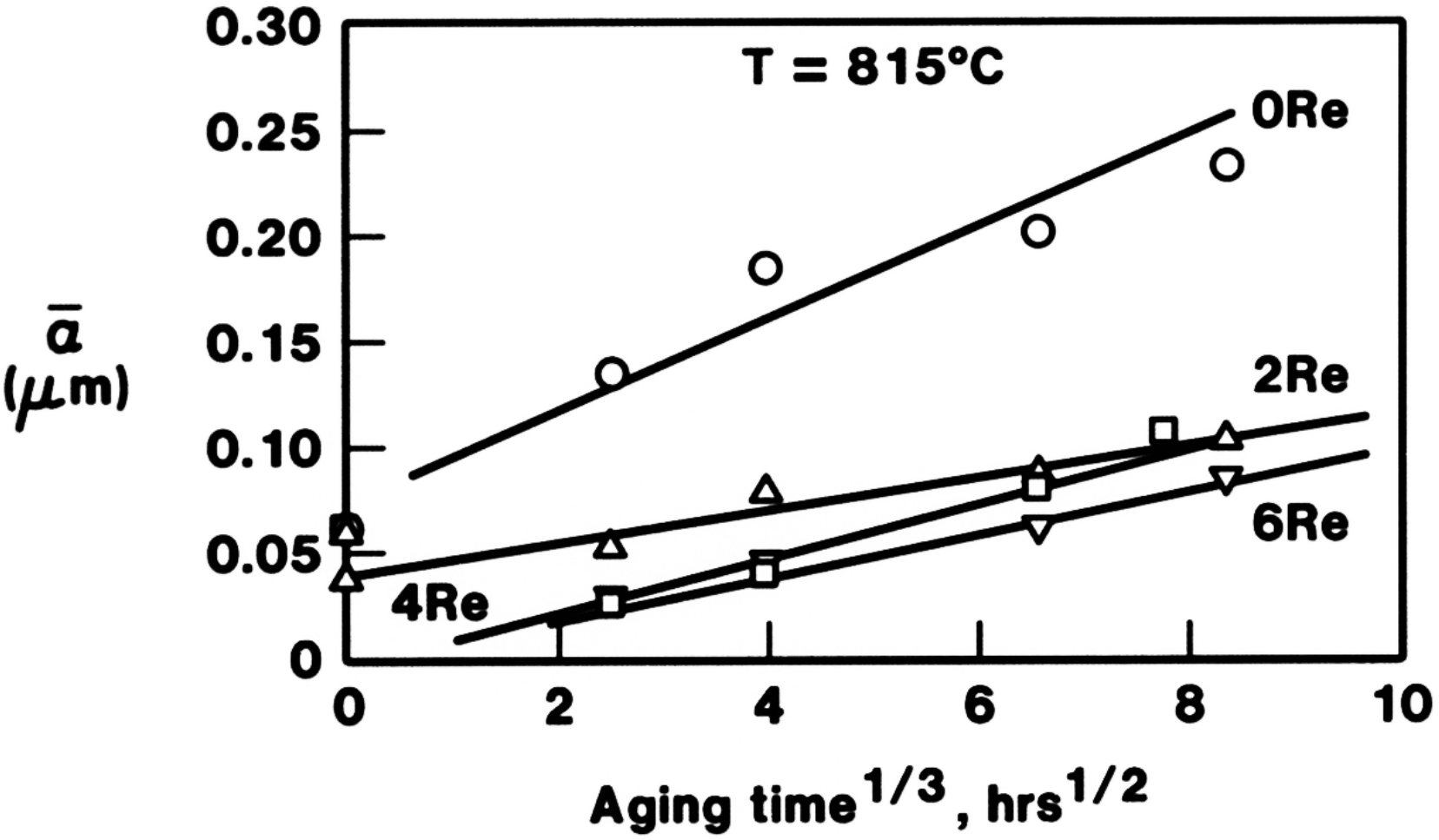
TEM of model superalloy with Re addition



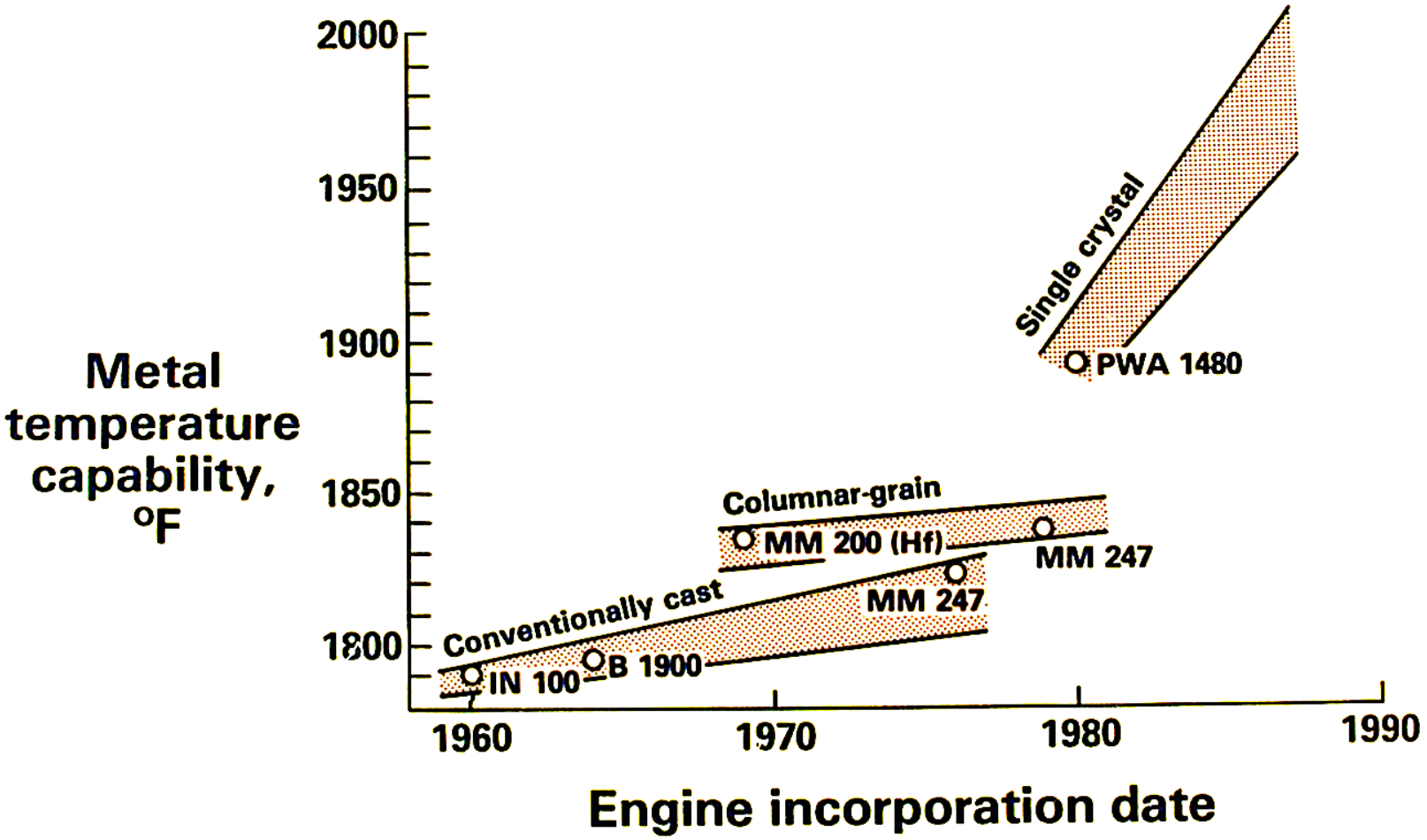
- Alloy 444 (6wt.% Re)
- 899°C (1650°F)
- 380MPa (55ksi)
- 0.2% strain



γ' coarsening in model superalloy plus Re



Improved temperature capabilities for CG and SC materials



Lessons learned

- Keep your options open and be flexible
- Look to the future
- Fight disbelievers
- Hire good talent
- Keep a spirit of optimism and dedication
- Recognize the value of professional societies
- Science vs. Engineering: both have merits
- Daily starter: morning coffee

Memorable moments

- Passing final PhD exam – you just never know
- Figuring out the freckle formation mechanism and the cure – hire those summer students
- TMS battle on fluid flow within a dendrite field – new kid on the block
- Switching from DS eutectic blades to single crystal & awaiting results – opportunity knocks
- Watching as so many users wanted to go to single crystal
    - 1480 – AF tear-down – incredible
    - 1484 – despite bad reputation for Re – persistence
- Passing 60klb of thrust; shaking of test stand; afterburner w/ AF guests – exciting
- Meade medal – awesome

…but, most importantly…

Technicians

Peers within the company

Government research organizations

Bosses/Managers

Interns

TEAMWORK

Academics

Superalloy community

Outside professionals

Supply chain