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Title: Macro-Segregation in Uranium-6wt%Niobium

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Macro-Segregation in Uranium-6wt%Niobium

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Presented by John W. Gibbs

Los Alamos National Laboratory
Materials Science & Technology: Metallurgy (MST-6)

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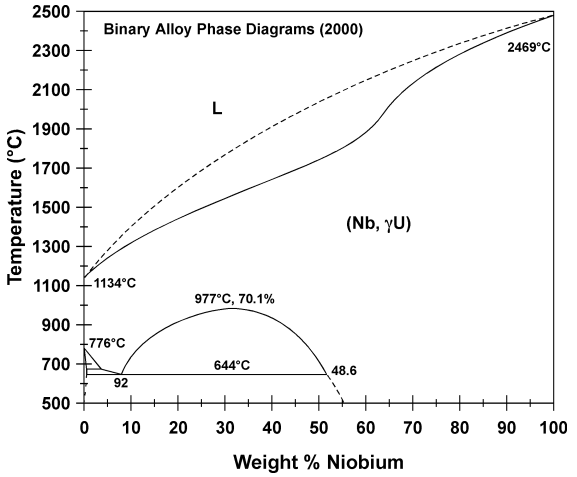
Motivation

- Historically U-Nb alloys are produced by vacuum arc-remelting (VAR) and subsequent wrought processing, but it would be convenient to produce shape castings by vacuum induction melting (VIM)
- Chemical macro-segregation of the Nb and micro-porosity remains a issue for castings produced by VIM
- This study aims to better understand macro-segregation in cast U-6wt%Nb
  - Influence of solidification time
  - Influence of casting thickness
  - Influence of solidification against and with gravity
- Understanding of solidification behavior is complicated by the fact that allotropic transformations wipe out solidification microstructure



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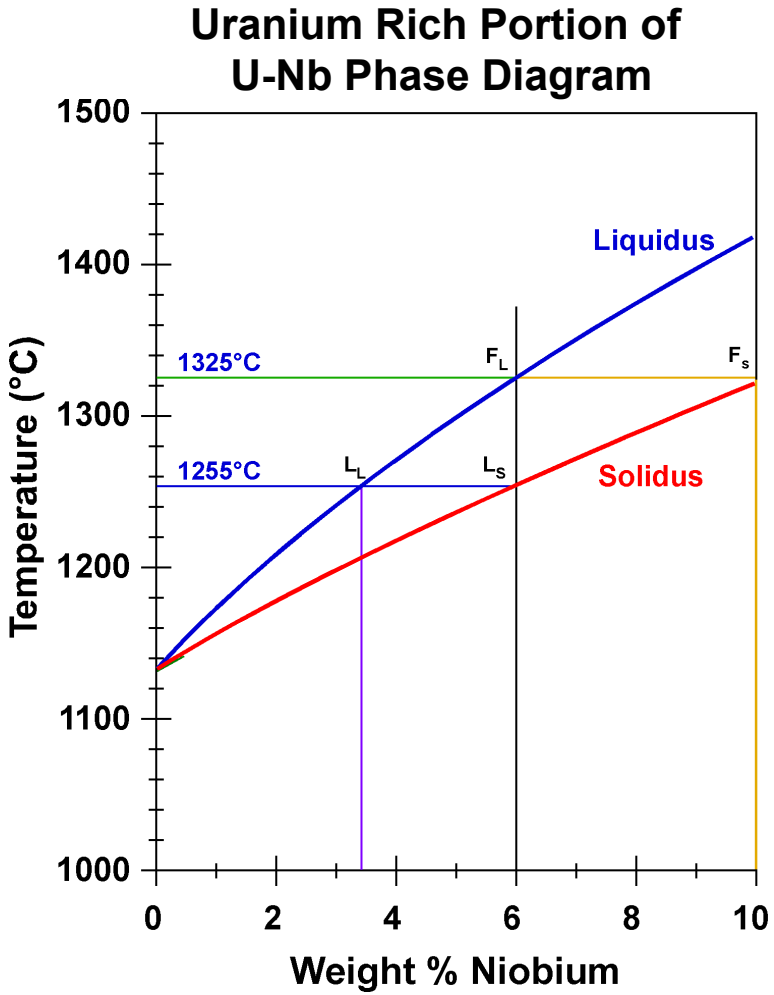
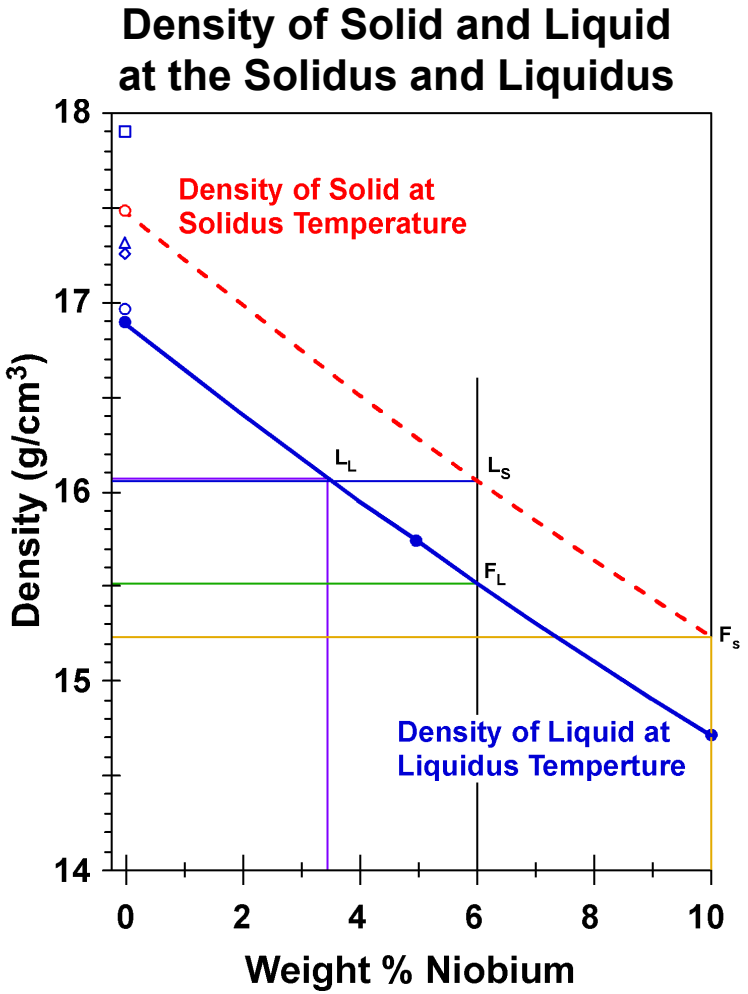
Density Changes During Solidification





Phase diagram after:
B.A. Rogers, et al, Trans. Metall. Soc. AIME (1958)
D. J. Thoma, unpublished data (2004)

- Liquid density from W.D. Drotning, *High Temp. High Press.*, 14, 253-258 (1982)
- Solid density estimated from published pure U density and Drotning's U-Nb composition dependence of liquid

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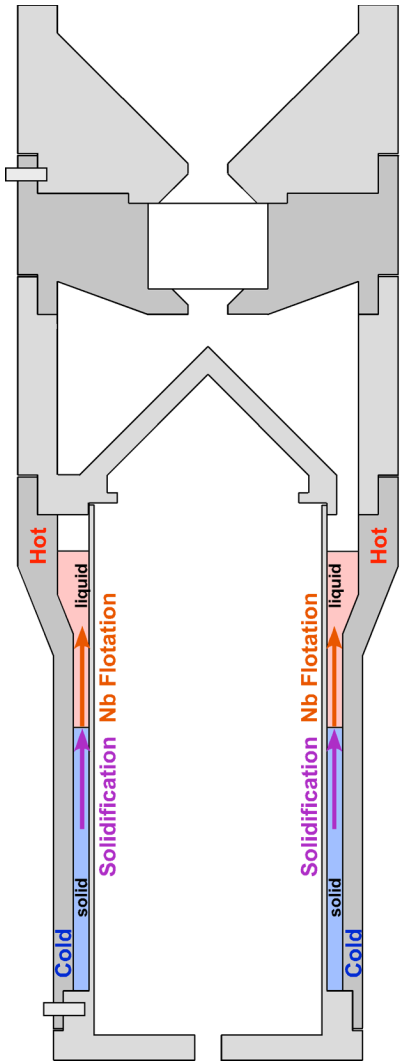
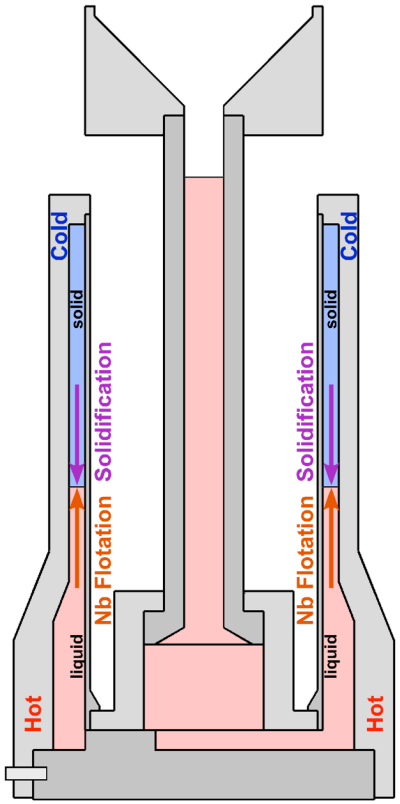
Growth Direction and Segregation

Assume Macro-Segregation by Buoyancy Driven Flow

Conventional Mold Design

- Top-to-bottom fill
- Bottom-to-top solidification
- Solidification front 'chases' Nb flotation





Solidification-Down Mold Design

- Bottom-to-top fill
- Top-to-bottom solidification
- Solidification direction is opposite Nb flotation
- Need to keep down-sprue filled and liquid to maintain pressure on casting and feeder

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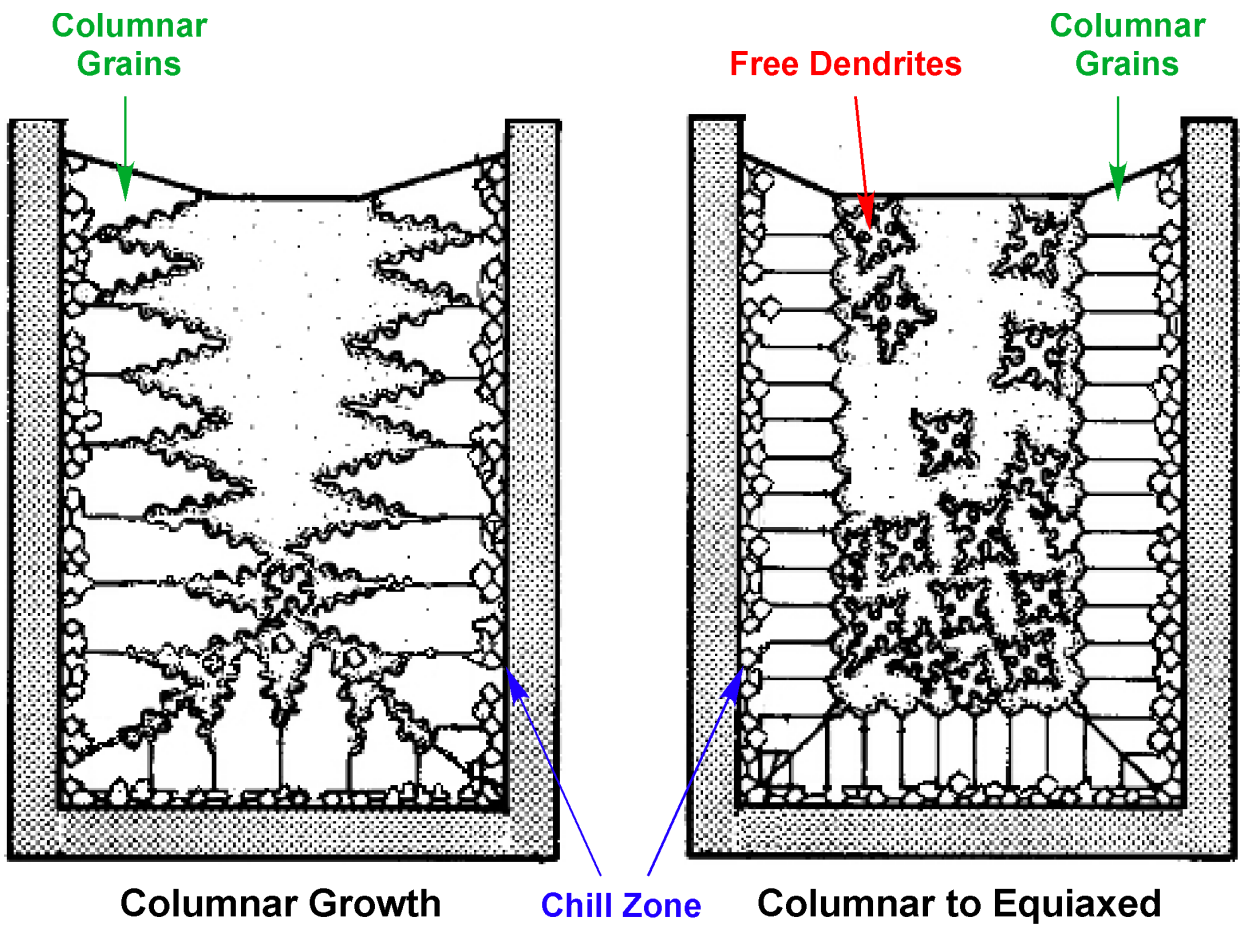
Columnar vs. Free-Dendritic Growth



after W. Kurz and D.J. Fisher, Fundamentals of Solidification, Trans Tech Pub (1984).

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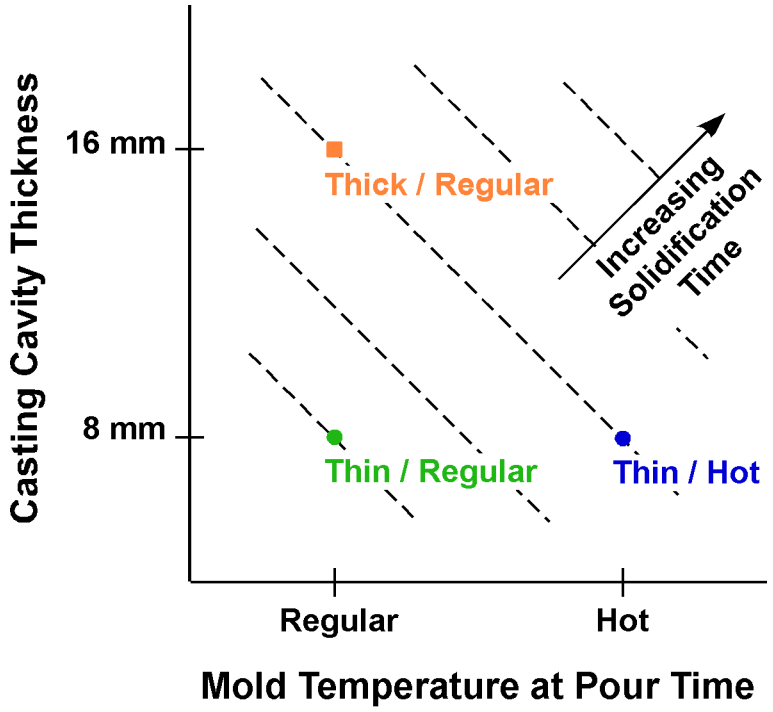
Experiment Design

Look at three aspects of macro-segregation:

1) **Influence of solidification time**
2) **Influence of casting thickness**
3) **Solidification-up vs. solidification-down**



"Hot temperature" was determined by process modeling to try to give same solidification time as the Thin/Regular

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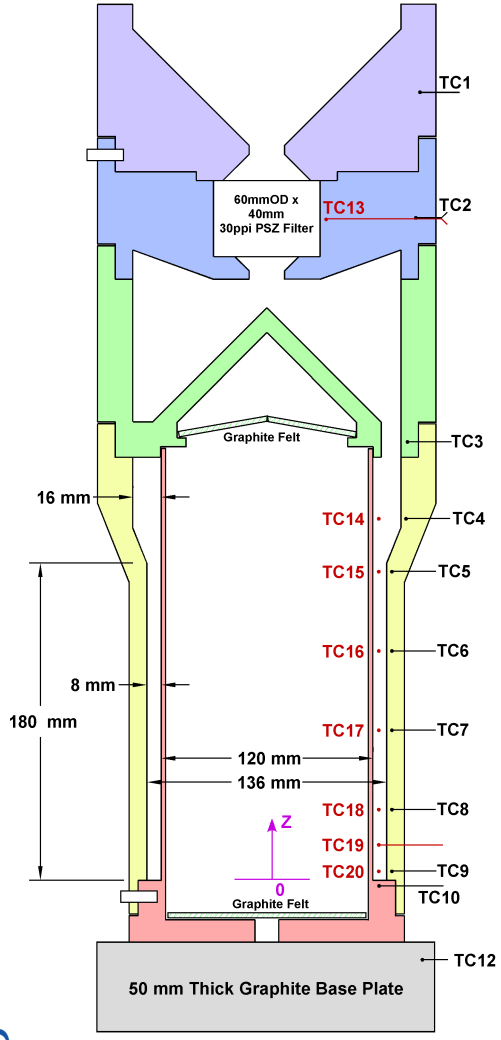
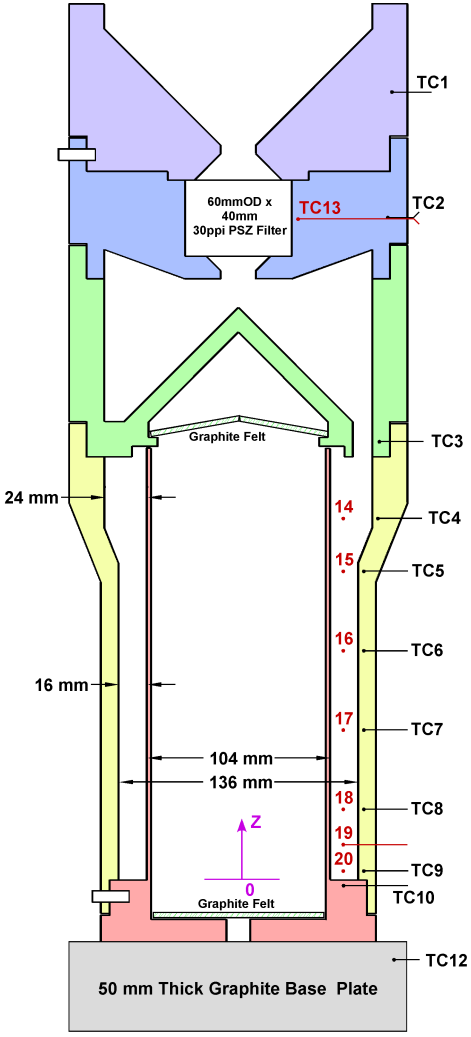
Comparison of Molds for Cylindrical Castings

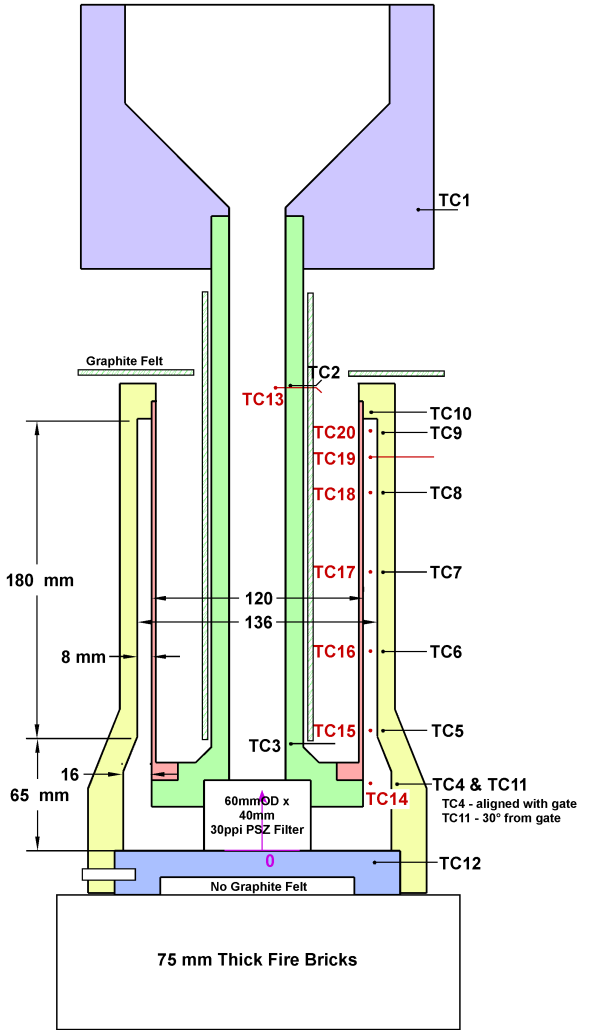
Thin Wall (8 mm)



Thick Wall (16 mm)



Solidification Down (8 mm)



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Locations of type-K thermocouples in the mold are indicated in black

Locations of type-C thermocouples in the casting cavity are indicated in red

Castings Details

- Mold made from fine-grained isotropically pressed graphite (Stackpole 2020)
- Mold coated with Yttria with a cellulose binder (Type-Y from ZYP Coatings)
- Stainless-steel sheathed Type K thermocouples inserted in holes in mold
- Alumina sheathed Type C thermocouples cemented in though-holes in mold wall; bare TC junction in mold cavity
- Wrought U-6Nb plate (scrap) used as charge material
- Same metal pouring temperature used for all 4 castings (1415°C / 60°C superheat)
- Metal filtered though a 30 ppi partially-stabilized zirconia foam filter
- Mold charge and yield

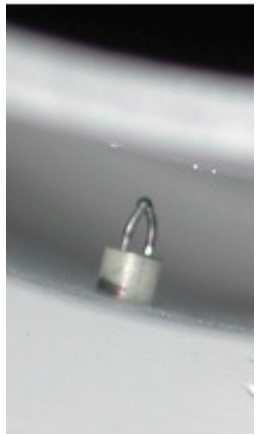
Name	Charge wt (kg)	Casting wt (kg)	Casting Yield
Thick / Regular	28.07	25.28	0.90
Thin / Hot	15.02	13.47	0.90
Thin / Regular	15.13	13.36	0.88
Thin / Top Down	28.01	20.26	0.72

Mold Stack – Solidification Up Mold

Mold stack with thermocouples

Mold stack with 12" diameter induction coils for mold heating and insulation

Bare junction type-C thermocouples in the mold cavity



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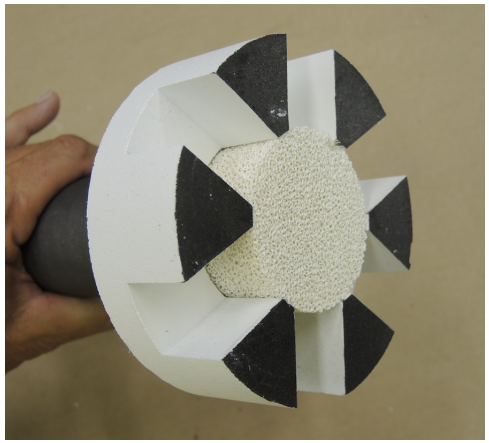
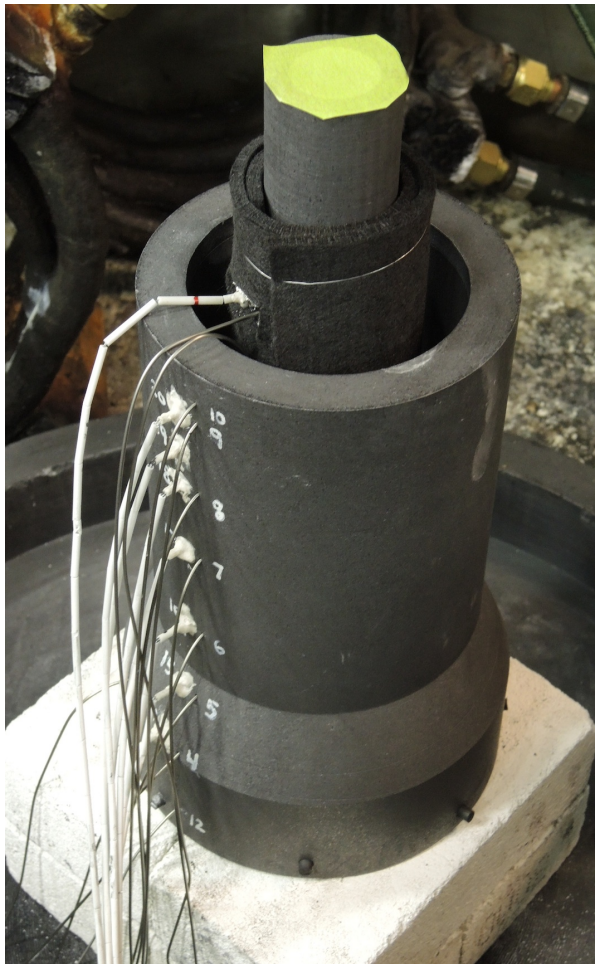
Solidification Down Casting Mold

Mold Components Prior to Assembly

Detail of Sprue/Filter Holder with Porous Zirconia Filter



Partially Assembled Mold Showing Thermocouples in Mold and in Casting Cavity



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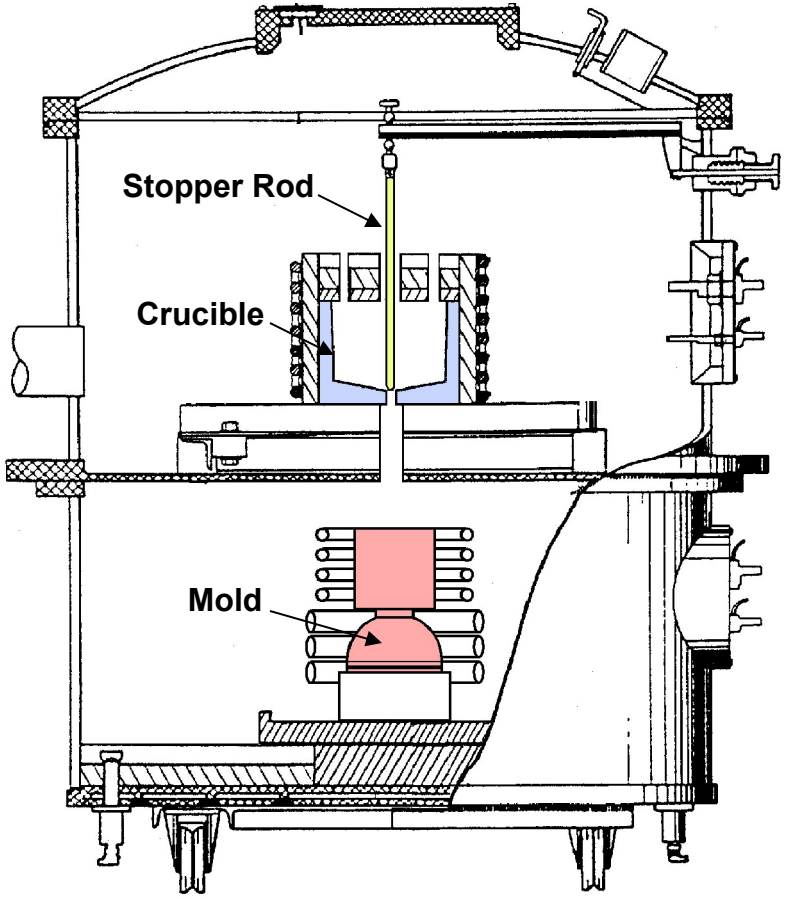
Three Zone Vacuum Induction Furnace

Three separately controlled induction coils:

- **Melting crucible coil (35 kW at 9.6 kHz)**
- **Two mold heating coils (50 kW at 3 kHz)**



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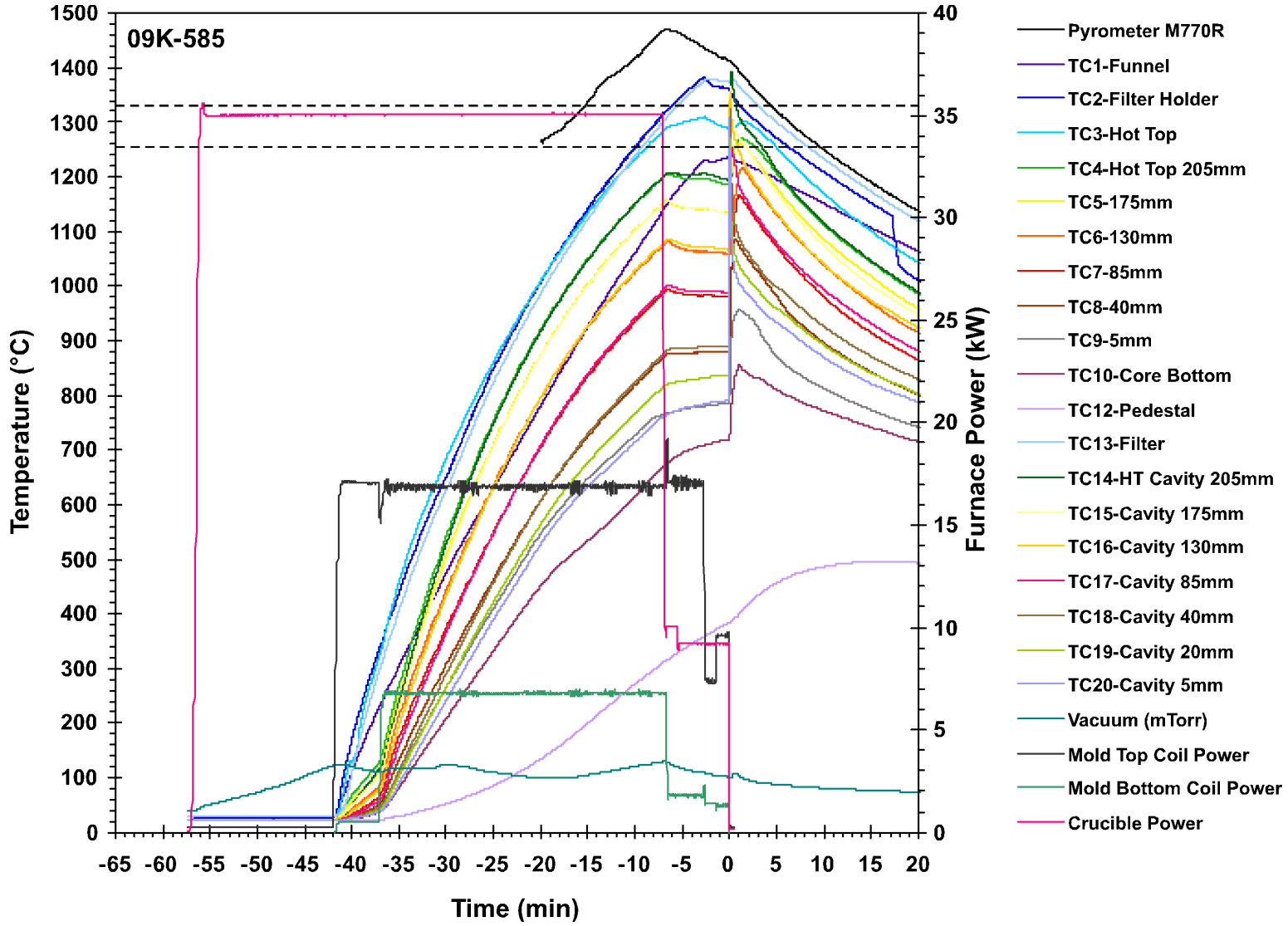
Run Chart - Thin / Regular Mold Temperature



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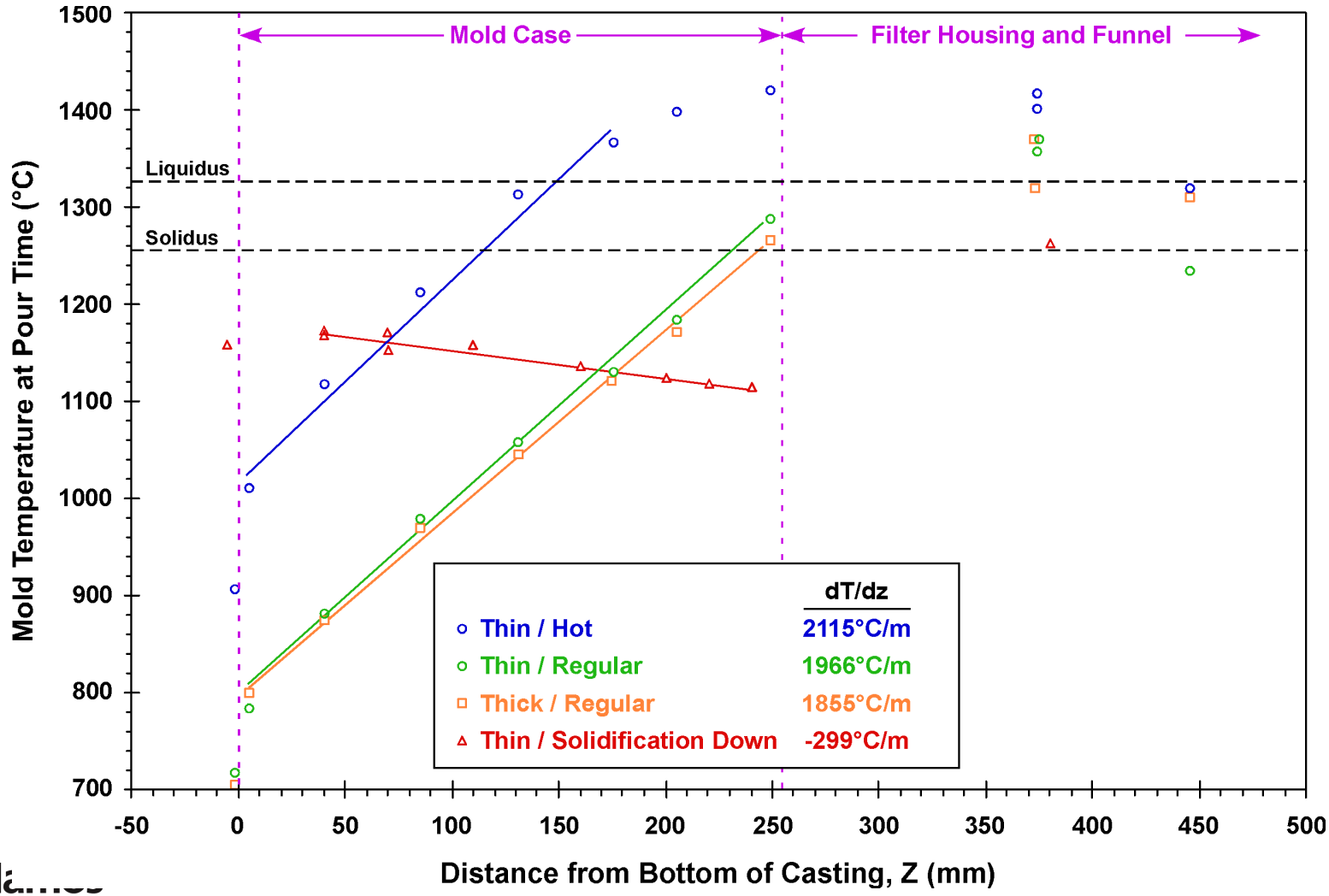
Mold Temperature at Pouring Time

Differing Initial Mold Temperature
Same Metal Pouring Temperature = 1415°C



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Cast Parts

Thick Wall (16 mm) Casting

Casting just after removal from mold. Thermocouple remnants and residual mold coating can be seen.

Solidification Down (8 mm) Casting

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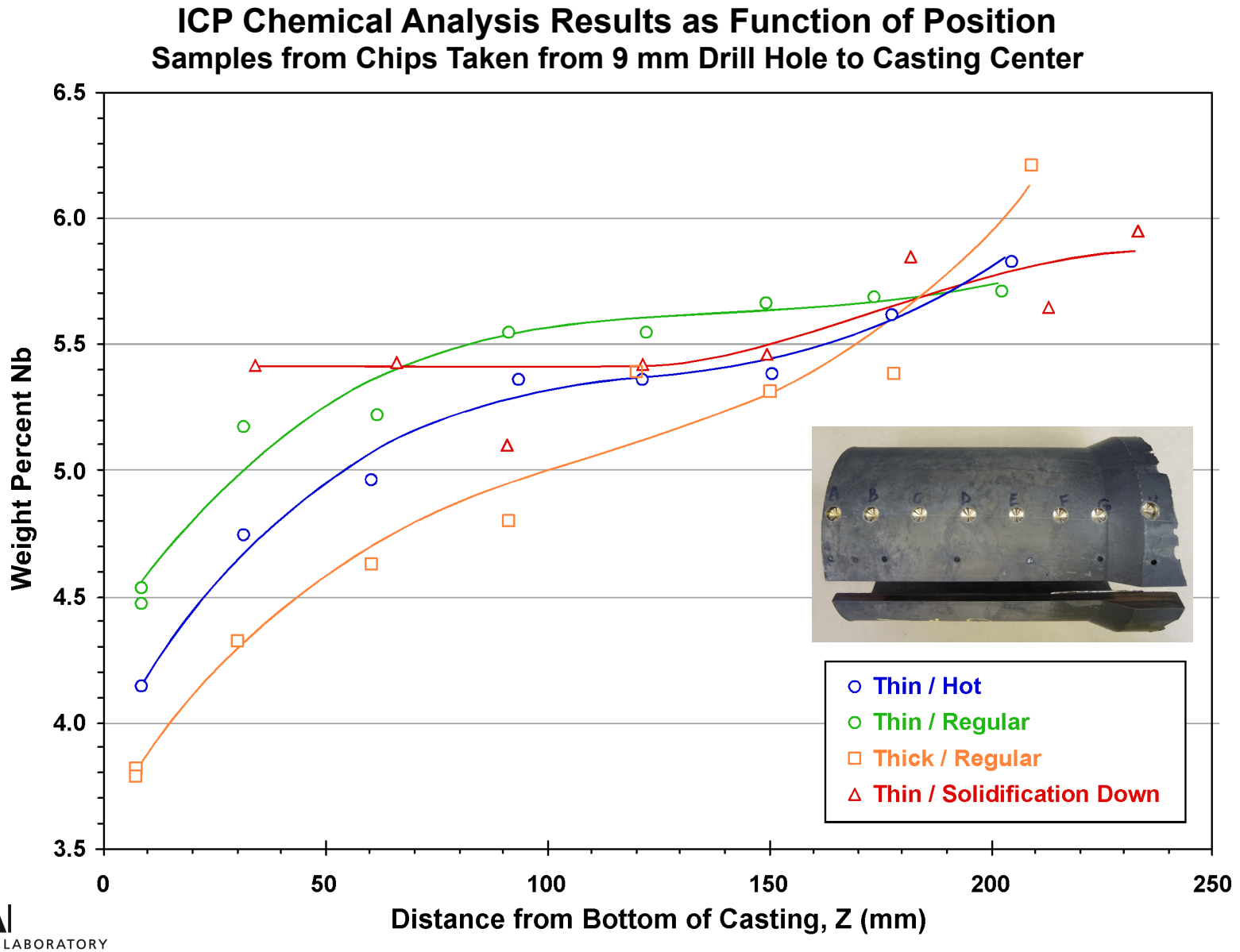
Segregation: Thickness vs. Solidification Time



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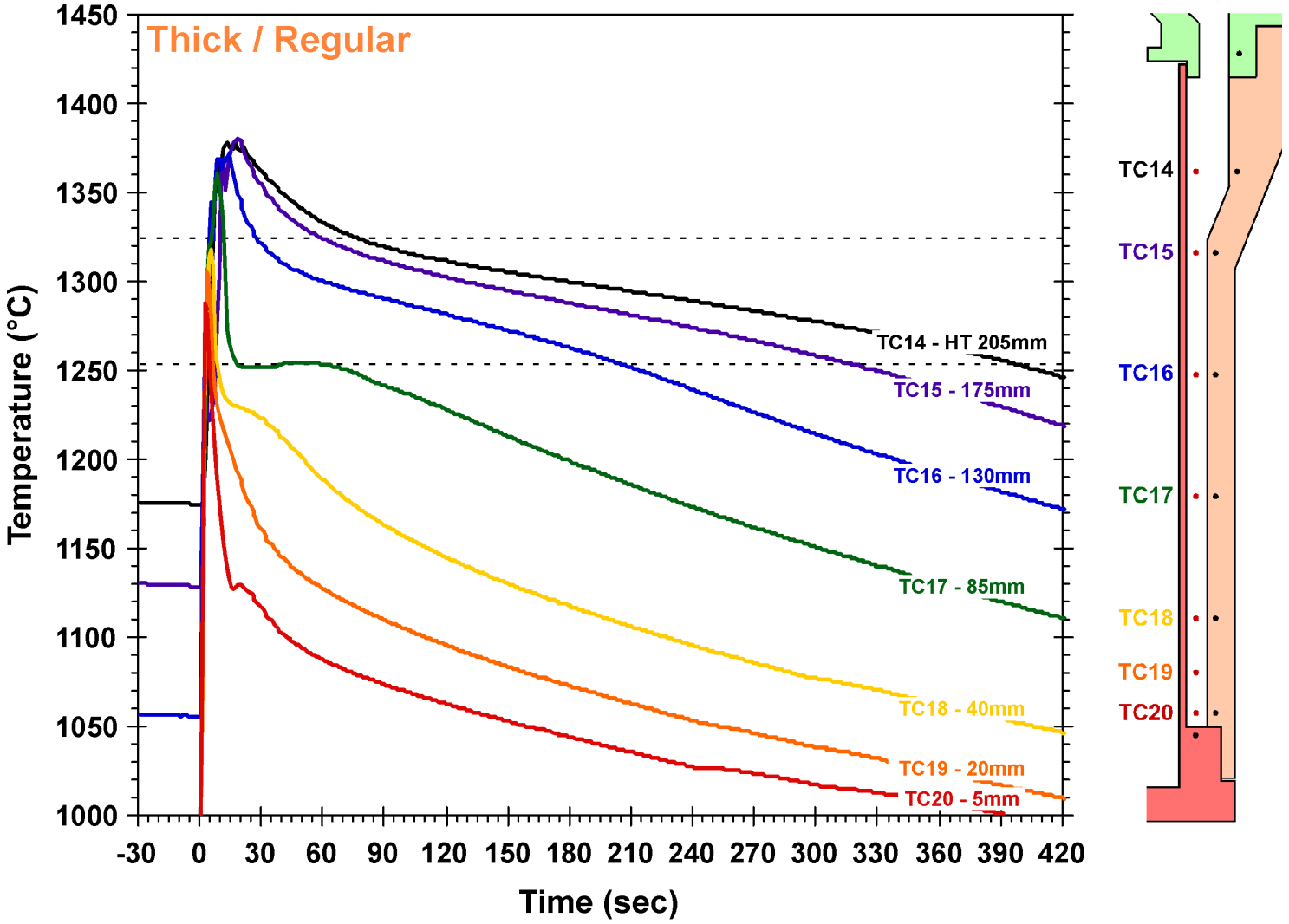
Cooling Curve - Thick / Regular Mold Temperature



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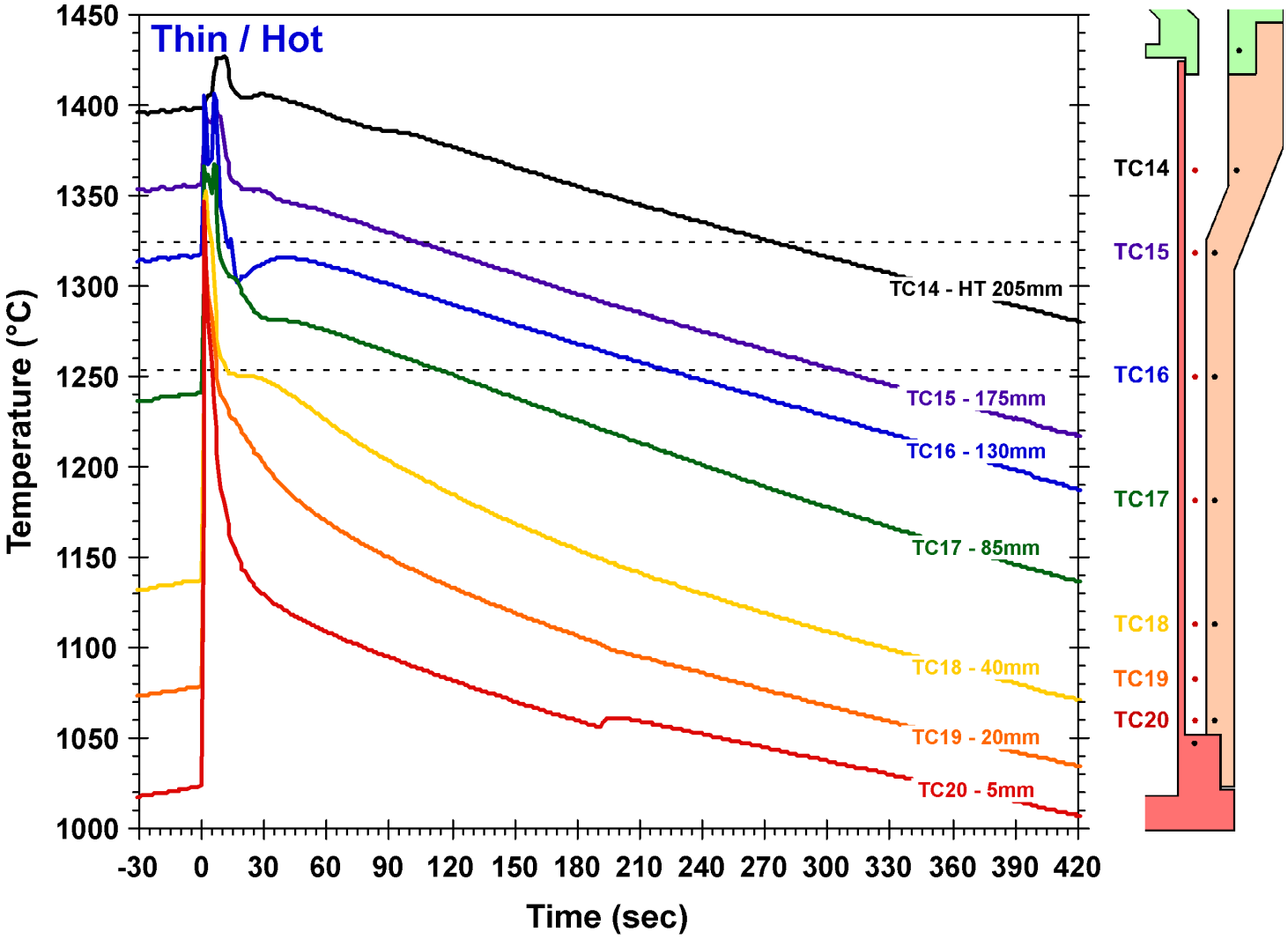
Cooling Curve - Thin / Hot Mold Temperature



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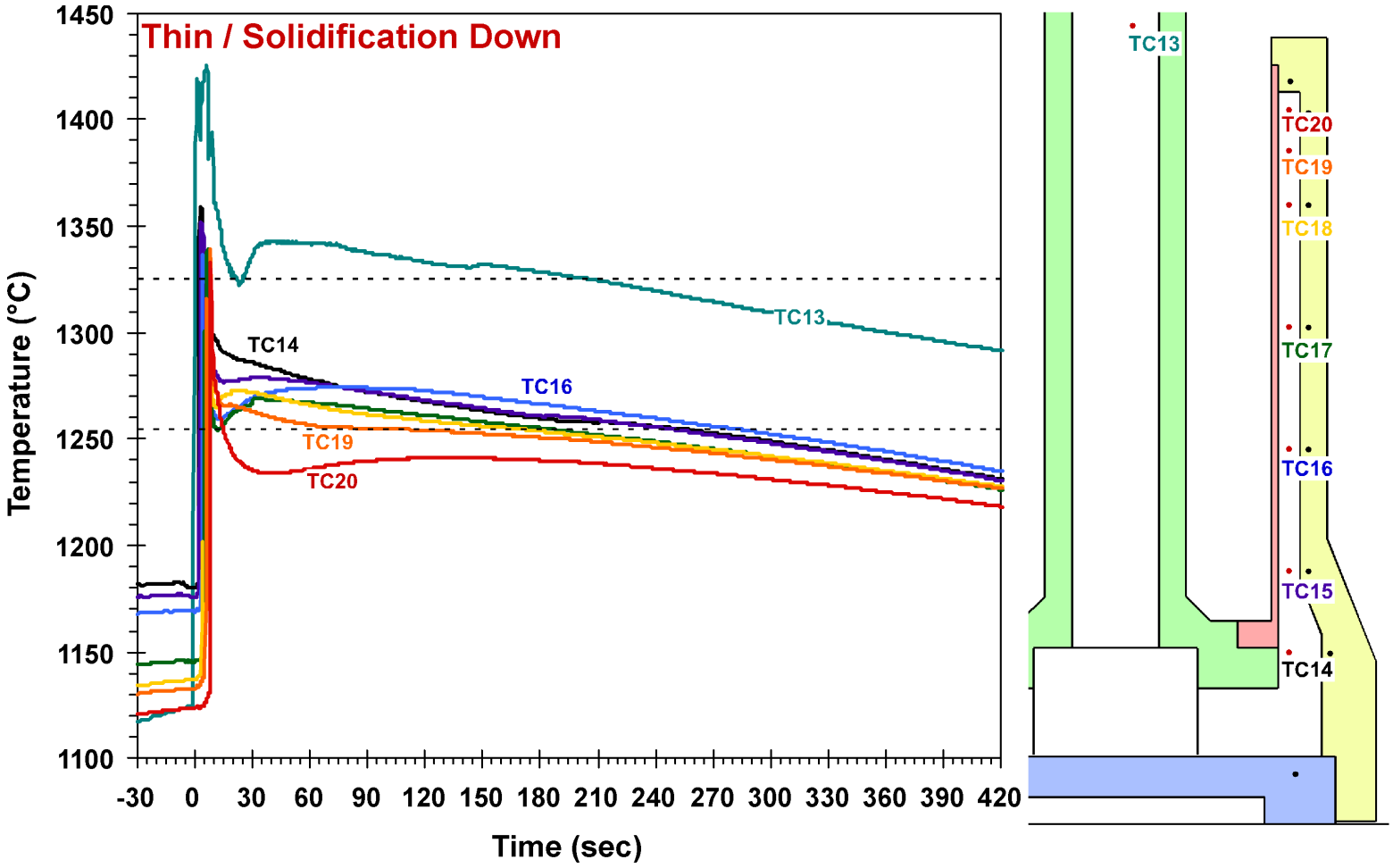
Cooling Curve - Solidification Down



- Mold progressively filled from bottom to top
- Mold *mostly* solidified from top to bottom (TC16 is a hot spot)
- Very shallow thermal gradient; everything mushy at same time

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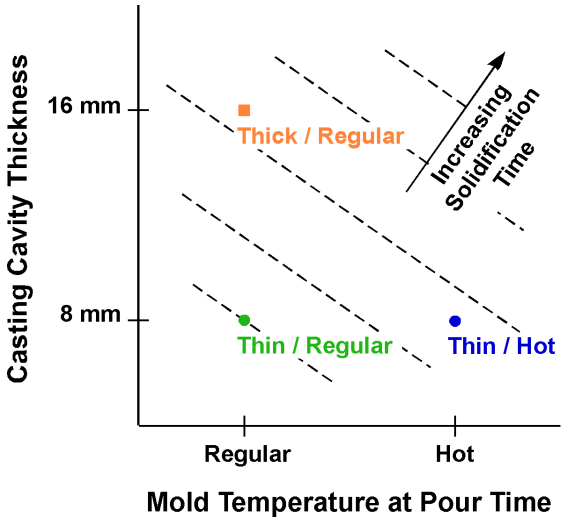
Solidification Time

Solidification and Local Solidification Time from Cooling Curves

		Cavity							Down Sprue
	Thermocouple ID	TC20	TC19	TC18	TC17	TC16	TC15	TC14	TC13
	Distance from Bottom, Z (mm)	5	20	40	85	130	175	205	
Solidification Time (s)	Thin/Hot	5	7	11	109	217	298	506	
	Thin/Regular	3	4	6	14	54	107	206	
	Thick/Regular	4	6	8	59	198	312	389	
	Distance from Top (mm)	5	20	40	85	130	175	205	-25
	Distance from Bottom, Z (mm)	240	225	205	160	115	70	40	270
Solidification Time (s)	Thin / Top Down	17	74	158	176	275	239	244	365

	Distance from Bottom, Z (mm)	5	20	40	85	130	175	205	
Local Solidification Time (s)	Thin/Hot			7	100	206	211	252	
	Thin/Regular			3	9	49	103	165	
	Thick/Regular				53	174	264	326	
	Distance from Top (mm)	5	20	40	85	130	175	205	-25
	Distance from Bottom, Z (mm)	240	225	205	160	115	70	40	270
Local Solidification Time (s)	Thin / Top Down	8	69	158	168	269	233	239	636



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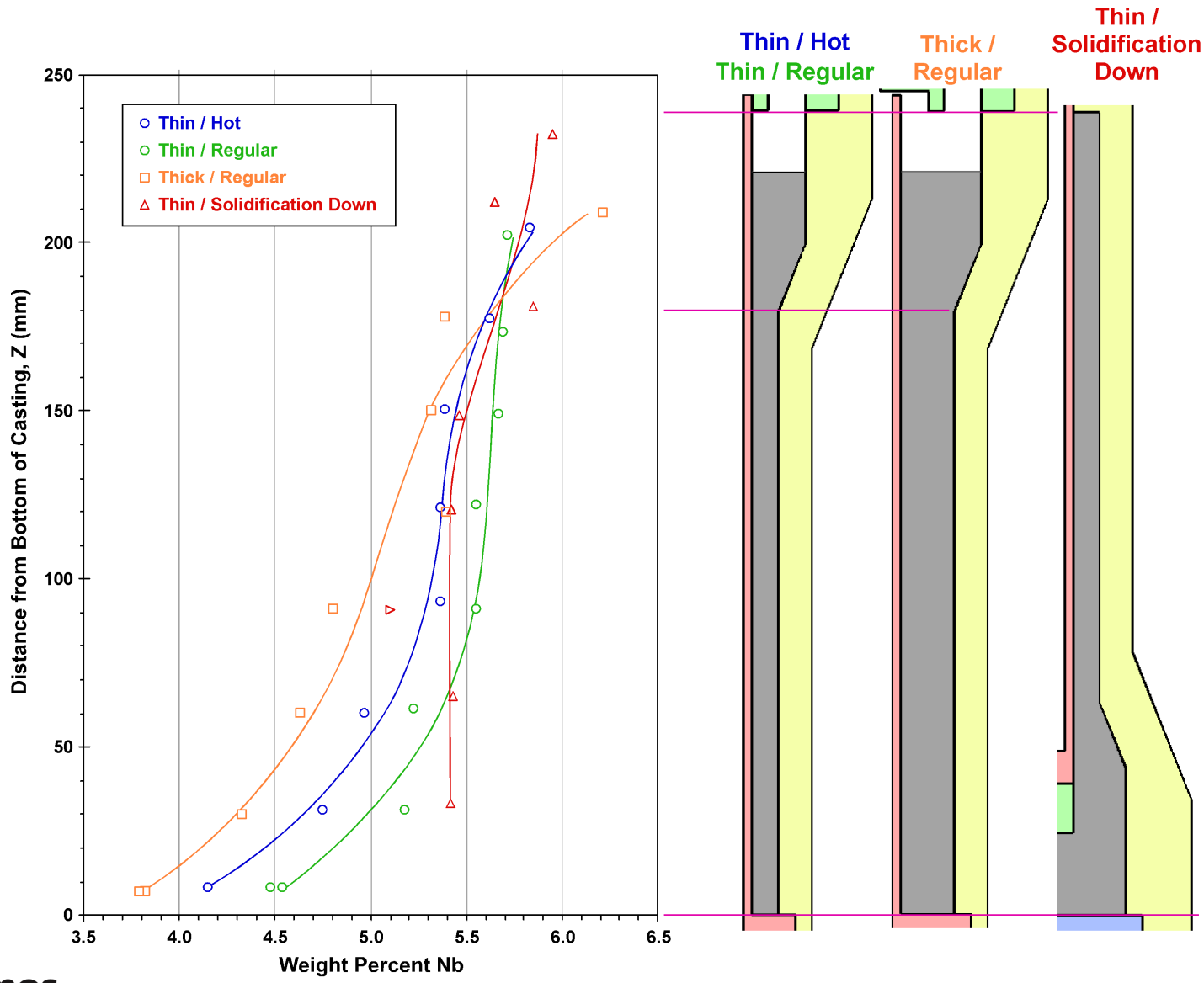
Segregation: Thickness vs. Solidification Time



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Conclusions

- For U-6wt%Nb castings solidified bottom-to-top:
  - Segregation is most strongly related to solidification time
  - Macro-segregation is most severe in the bottom of the conventional castings; this is the region which also solidifies most rapidly
  - For similar solidification times there does appear to be a thickness effect (for the 8 to 16 mm thickness examined)
- For casting solidified down (top-to-bottom):
  - Macro-segregation is mostly eliminated
  - A higher thermal gradient than obtained in this experiment would be beneficial to better cast structure and a better cast part
- The observed macro-segregation is consistent with free-dendritic growth with flotation (buoyancy driven and/or filling driven advection of liquid?)