NATIONAL ENERGY TECHNOLOGY LABORATORY

Addressing Materials Processing Issues for Steam Turbines: Cast Versions of Wrought Ni-Based Superalloys

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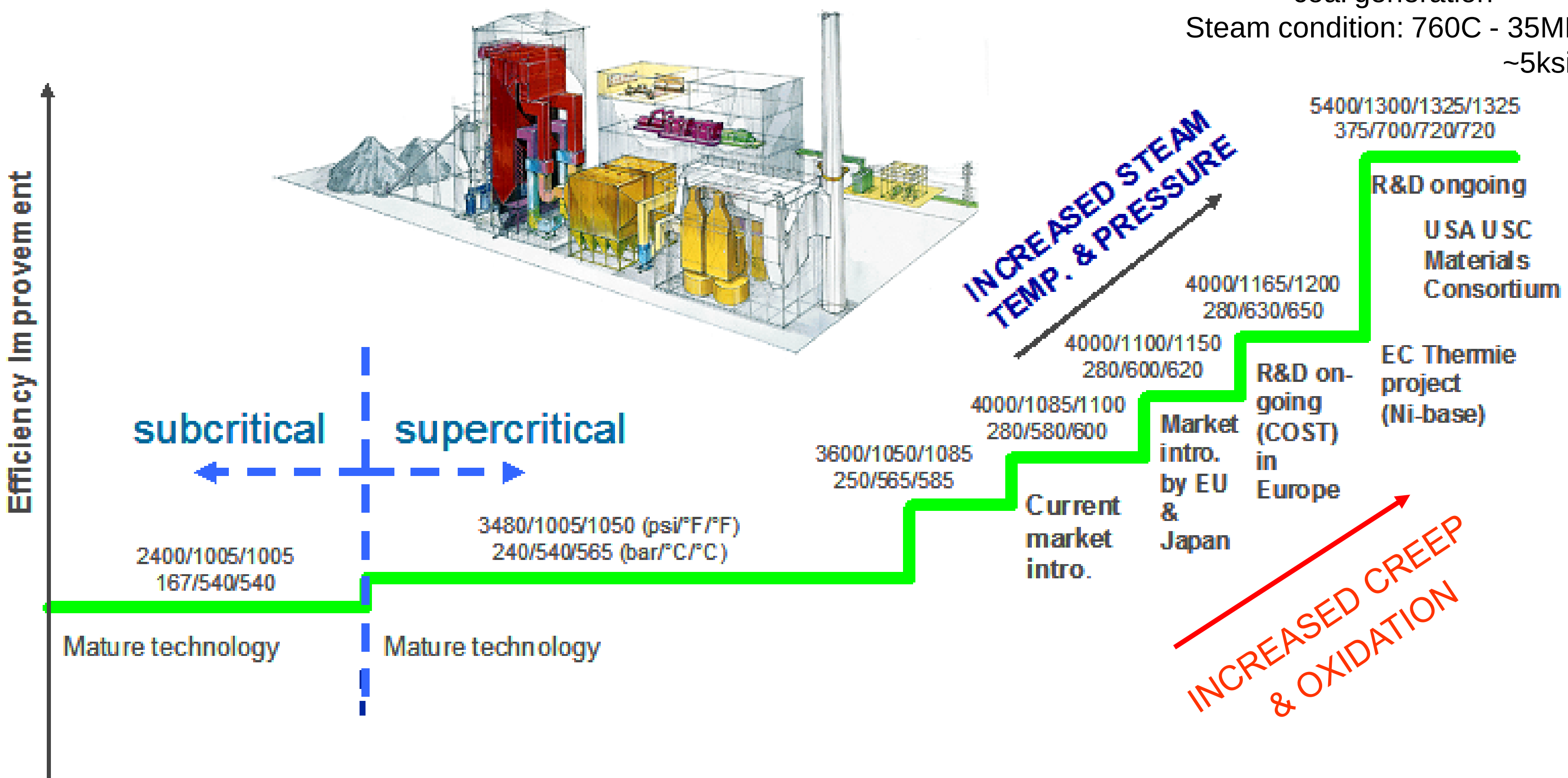
Increasing Efficiency: A-USC Plants

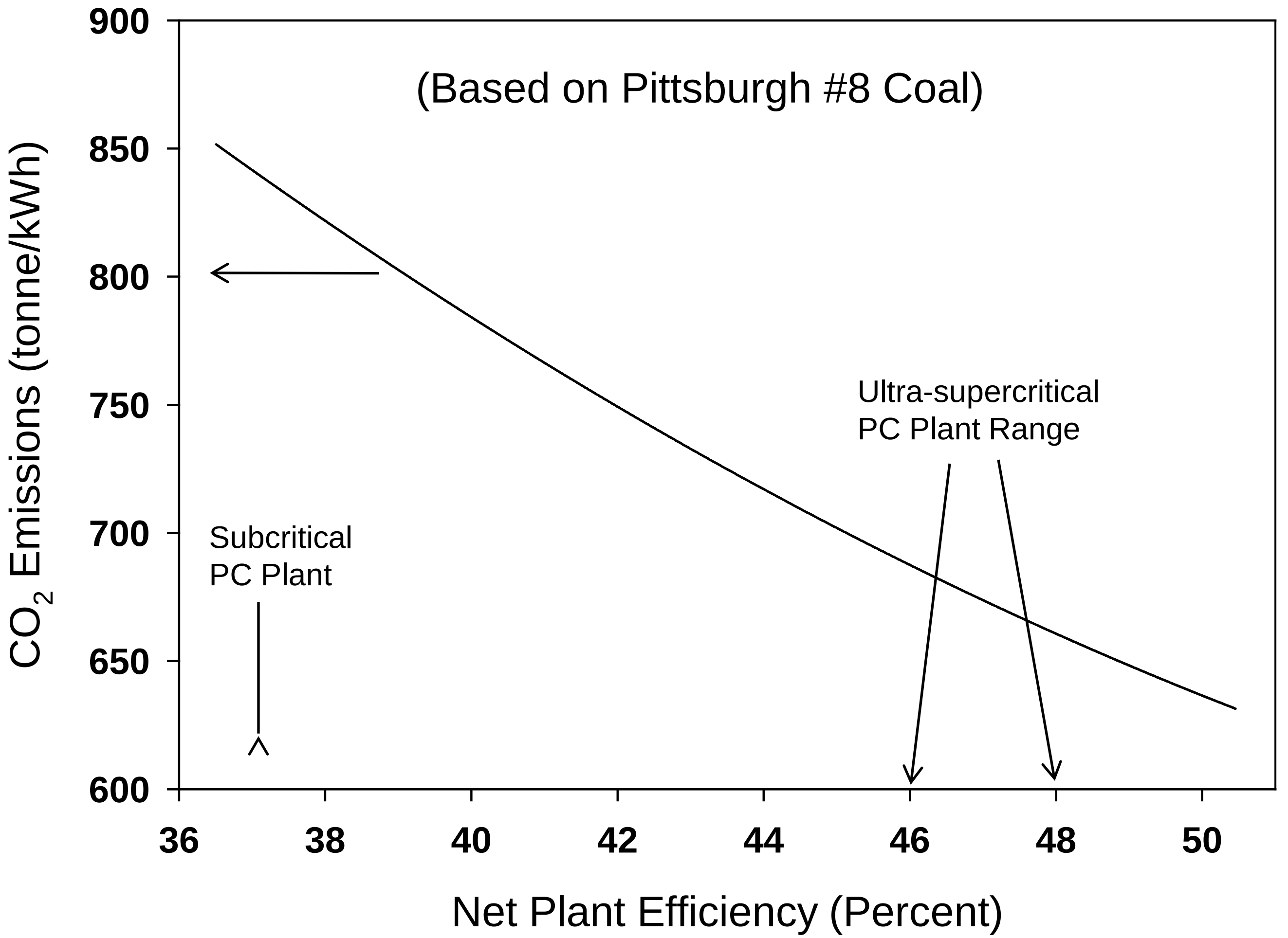
US-DOE Advanced Power System Goal: ~46% efficiency from coal generation
Steam condition: 760C - 35MPa ~5ksi



Plants operation above 22MPa at 538 to 565C are "supercritical"; above 565C are "ultra-supercritical" (USC)

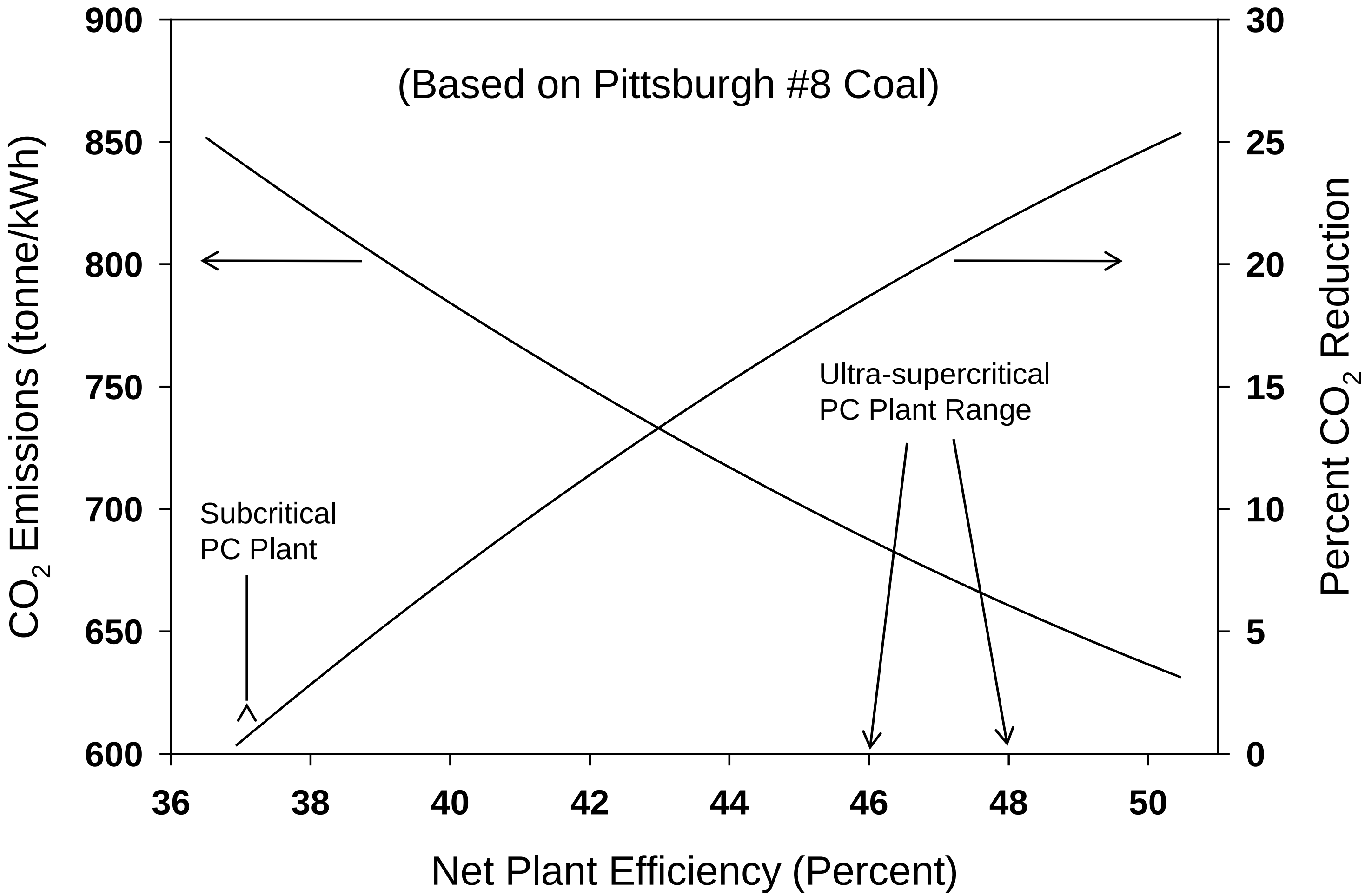
Source: Viswanathan, et al 2005

Effect of Increased Efficiency On CO_2



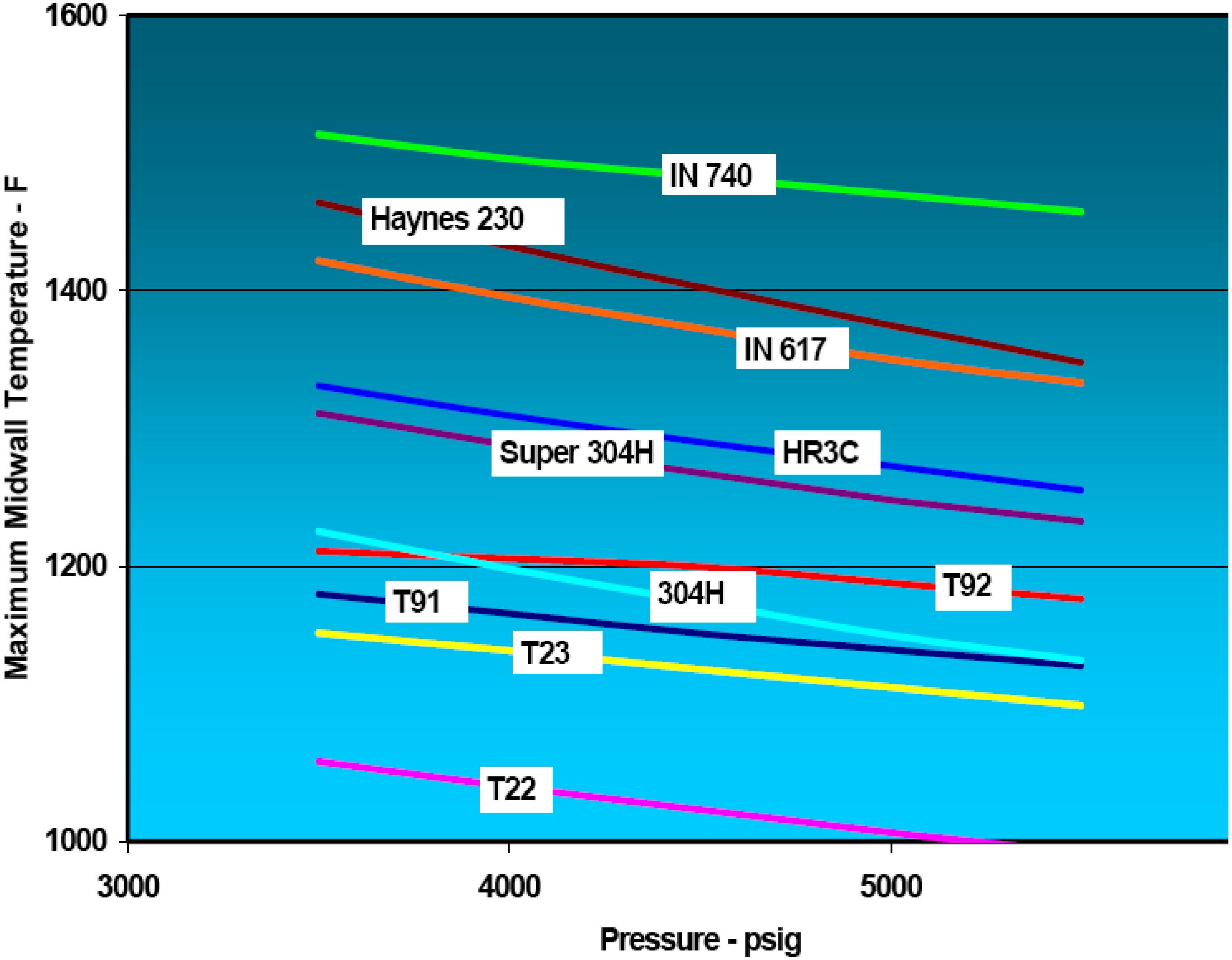
After Viswanathan et al.

Effect of Increased Efficiency On CO_2



After Viswanathan et al.

Maximum Use Temperature



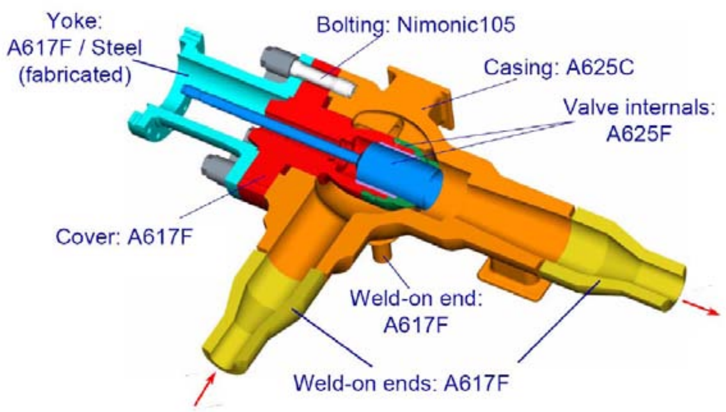
Source: Viswanathan, et al 2005

Technological Issues

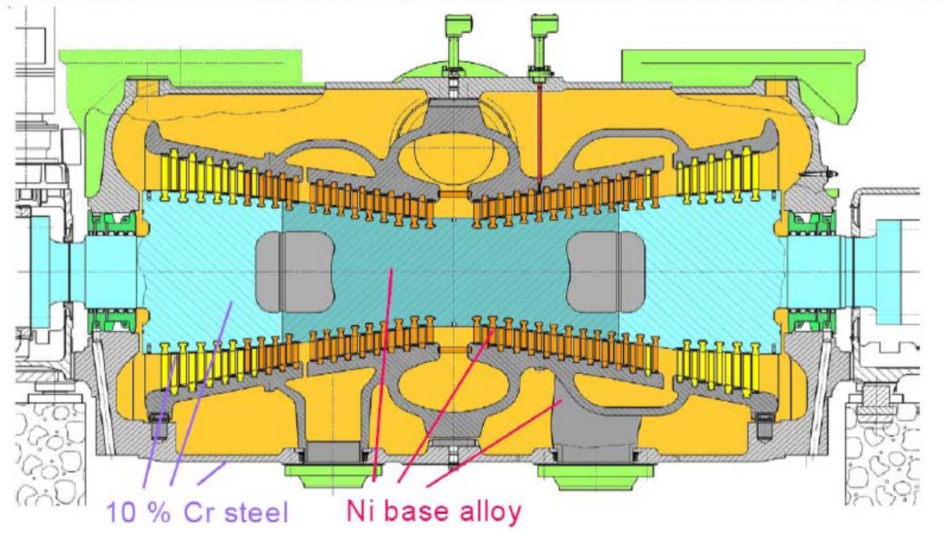
- There is an immediate and continuing need for increased power production.
- Increases in Temperature and Pressure increase efficiency and decrease CO_2 production along with other pollutants.
- Higher Temperature and Pressure place greater demands upon the Materials.
- Large castings are required for some components—many technical issues.

Example Components

- **Castings**
  - 1-15 tons
  - Up to 100mm in thickness



Valve Bodies



Turbine Casing

Courtesy Alstom

Challenges for A-USC Castings

- **Alloys contain elements with high oxygen affinity such as Al and Ti**
- **Large pour weights (1-15T)**
- **Thick section components**
  - Slow cooling rates
  - Segregation prone alloys
- **Our approach is to examine a suite of traditionally wrought Ni-based superalloys cast under conditions designed to emulate the full sized casting.**
- **Traditionally wrought alloys are being considered due to proven weldability in thick sections.**

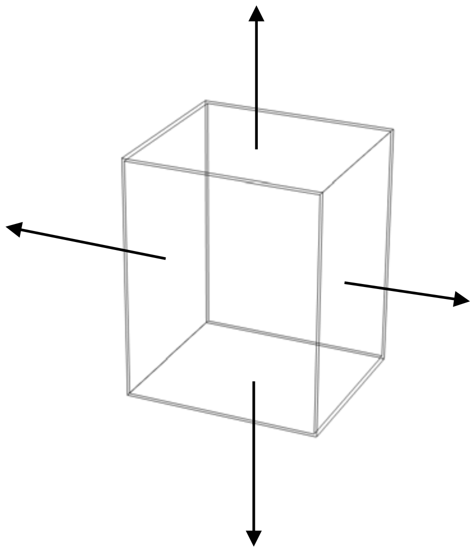
Project Tasks

- **Down select alloys from 7 to 2-3: *Complete***
- **Cast prototype heats of down select alloys and evaluate**
  - *Casting complete*
  - Evaluation underway
- **Further chemistry refinement: due 9/30**

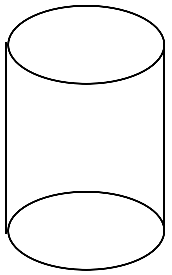
Alloys Under Consideration

Solid Solution	Age Hardenable
H230	N105
IN617	H263
IN625	H282
	IN740

Our Model Casting Geometry

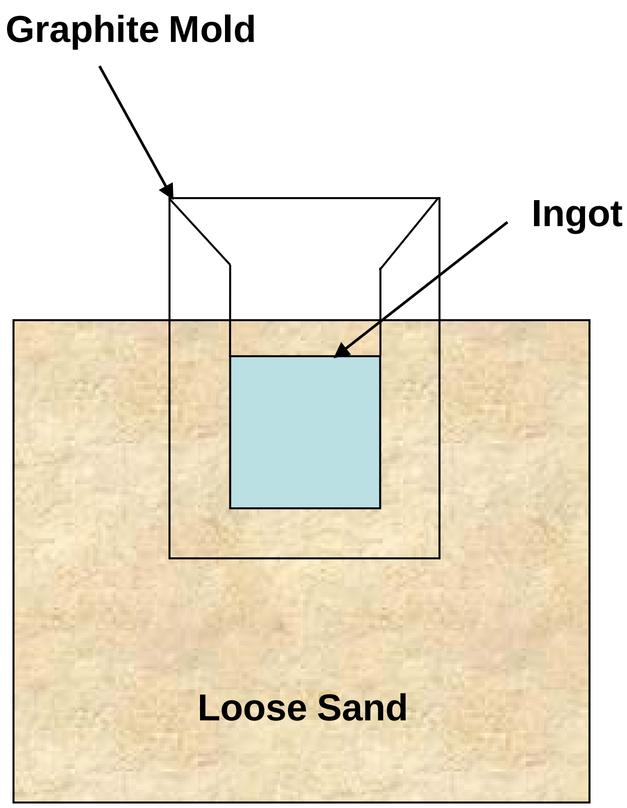


The actual component is nominally 4in thick and “infinite” in the other directions.



Our casting is nominally 4in in diameter and 4-5in tall.

“Enhanced” Slow Cooling



Our casting layout is shown schematically in cross section on the left. A permanent graphite mold was used. This mold was surrounded by loose sand such that the top of the casting was below the sand line. This is our attempt to emulate the “semi-infinite” plate model of the turbine casing.

Model Casting Results

Empty melt crucible.

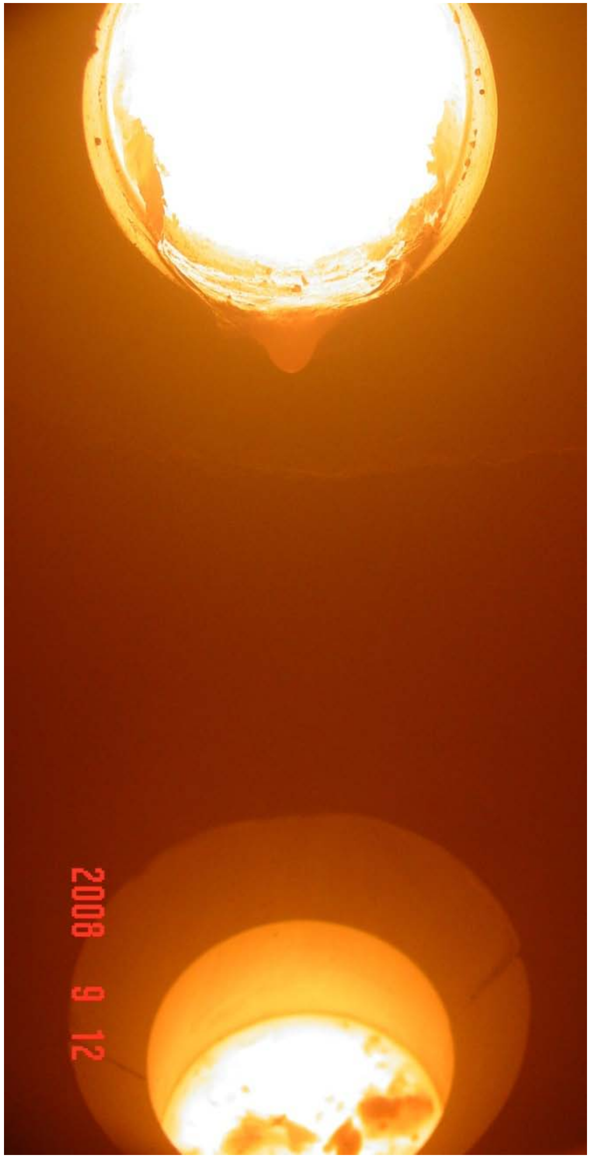
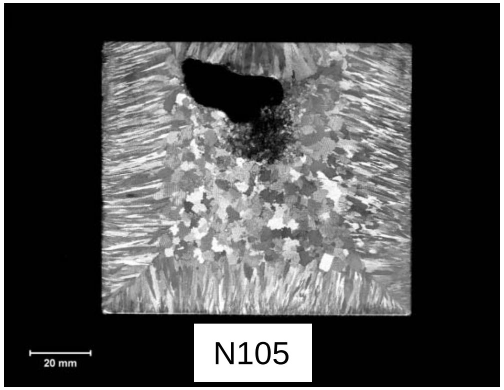


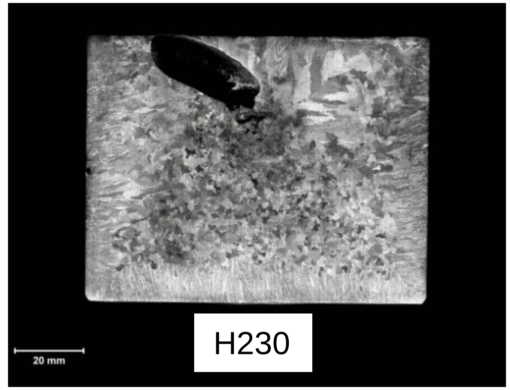
Photo taken moments after casting. The mold never showed any “color” which meant that the mold temperature stayed below about 550C. This gave us some confidence that slow cooling was achieved.

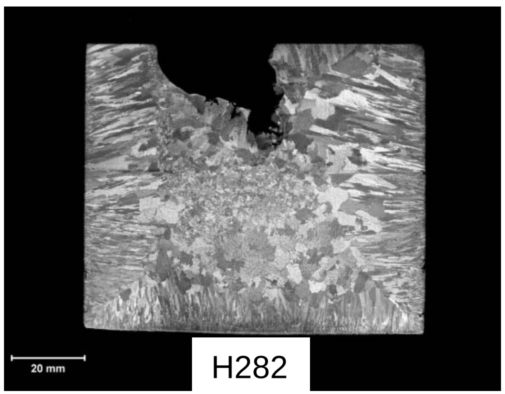
Full mold

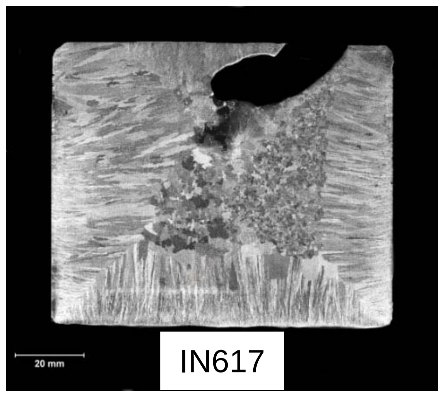
(Ingot top is below loose sand line).

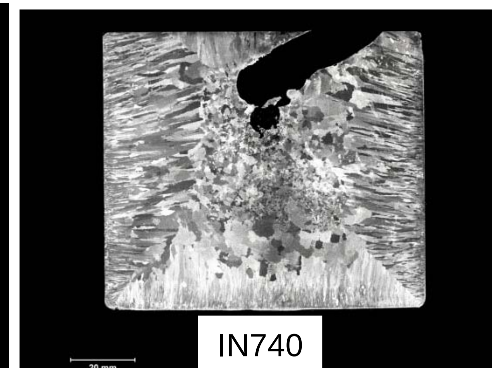
Grain Etched Ingot Cross Sections











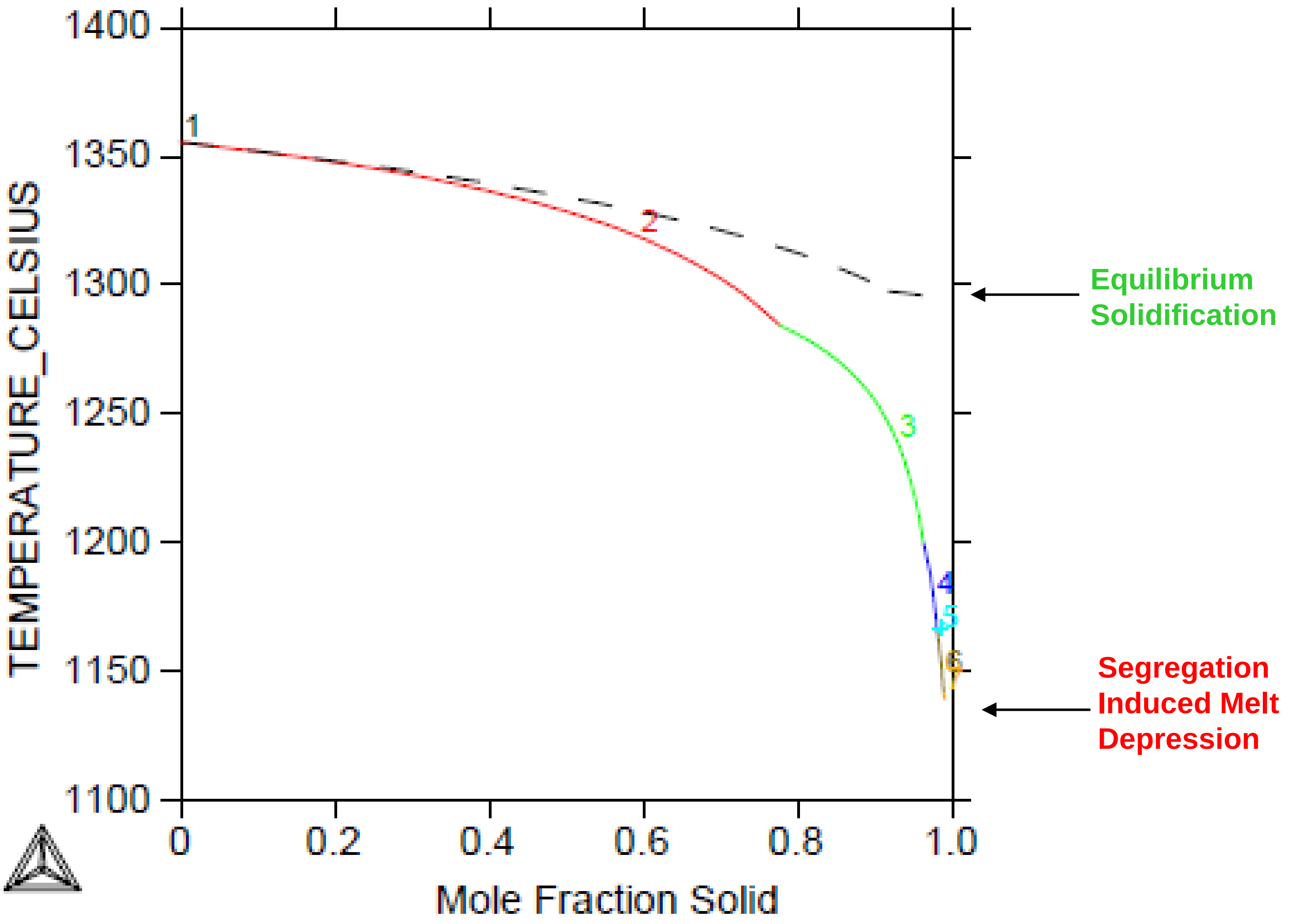
Ingots were sectioned to bisect the shrink cavity.

In general, the ingots have a columnar outer band ~1/4-1/3 of the radius thick and an equiaxed core. This is similar to the grain structure we would expect to observe in a large sand cast version of these alloys.

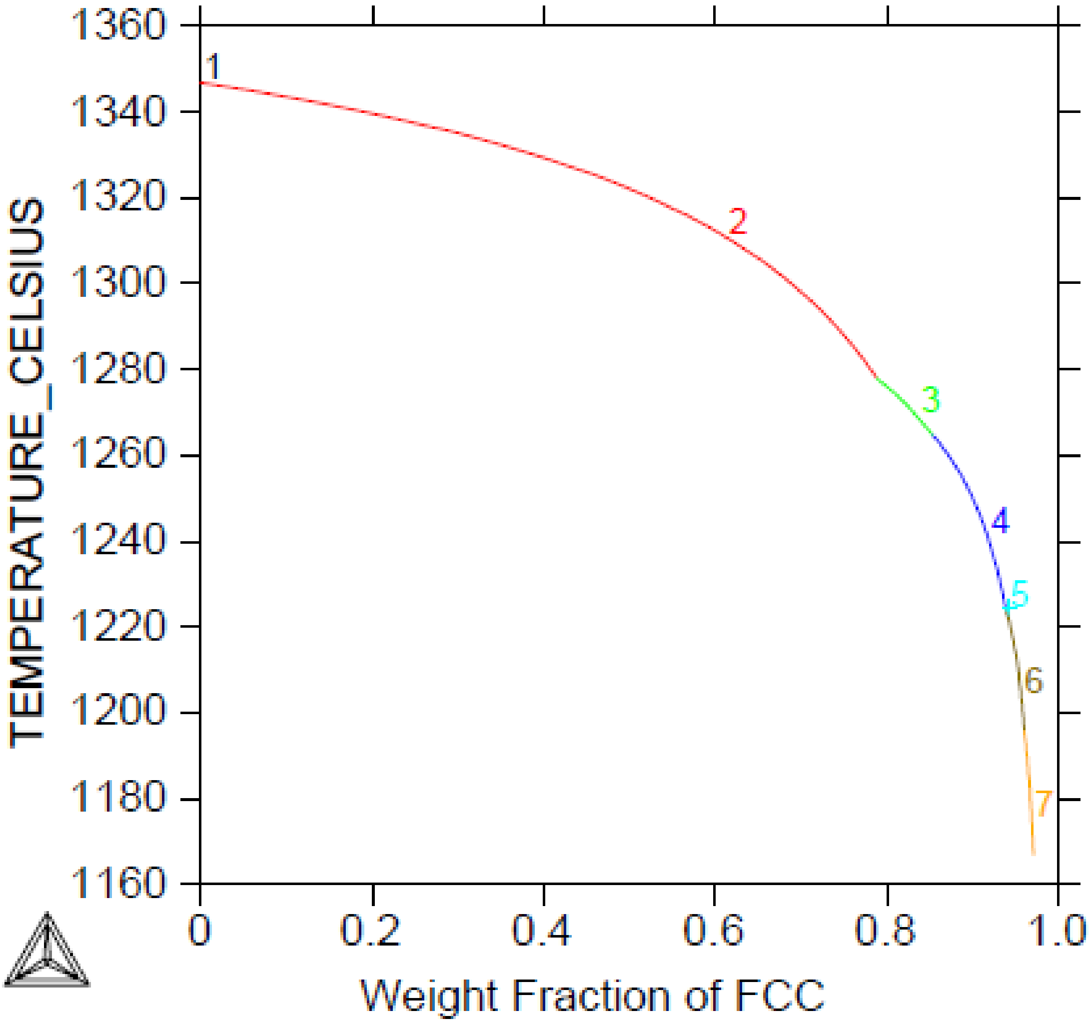
First Ingot Chemistries

	C	Cr	Mo	Co	Al	Ti	Cb	Mn	Si	B	W	
Nimonic 105	**0.15**	**14.85**	**5.00**	**20.00**	**4.70**	**1.10**		**0.50**	**0.50**	**0.05**		**Aims**
	0.16	***14.61***	***5.02***	***20.04***	***4.43***	***1.10***		***0.51***	***0.51***	***0.05***		***Results***
Haynes 230	**0.120**	**22.00**	**2.00**		**0.35**			**0.70**	**0.50**		**14.00**	
	0.12	***21.59***	***2.01***		***0.37***			***0.69***	***0.50***		***13.91***	
Haynes 263	**0.070**	**20.00**	**5.80**	**20.00**	**0.35**	**2.10**		**0.50**	**0.35**			
	0.07	***19.68***	***5.74***	***19.89***	***0.40***	***2.04***		***0.50***	***0.34***			
Haynes 282	**0.070**	**19.50**	**8.50**	**10.00**	**1.50**	**2.10**		**0.25**	**0.15**	**0.005**		
	0.07	***19.22***	***8.48***	***9.84***	***1.44***	***2.08***		***0.24***	***0.15***	***0.01***		
IN617	**0.120**	**22.00**	**9.00**	**12.50**	**1.10**	**0.30**		**0.50**	**0.50**			
	0.12	***21.73***	***8.96***	***12.35***	***1.04***	***0.31***		***0.50***	***0.49***			
IN625	**0.070**	**21.00**	**9.00**		**0.10**	**0.10**	**3.60**	**0.50**	**0.35**			
	0.07	***20.71***	***8.92***		***0.15***	***0.089***	***3.58***	***0.49***	***0.34***			
IN740	**0.030**	**25.00**	**0.50**	**20.00**	**1.30**	**1.50**	**1.50**	**0.30**	**0.30**	**Fe:**	**0.70**	
	0.04	***24.71***	***0.50***	***20.03***	***1.24***	***1.48***	***1.50***	***0.30***	***0.31***		***0.57***	

H263—Solidification



Weight Fraction FCC Phase—H282



2-FCC

3-MC

4-M6C

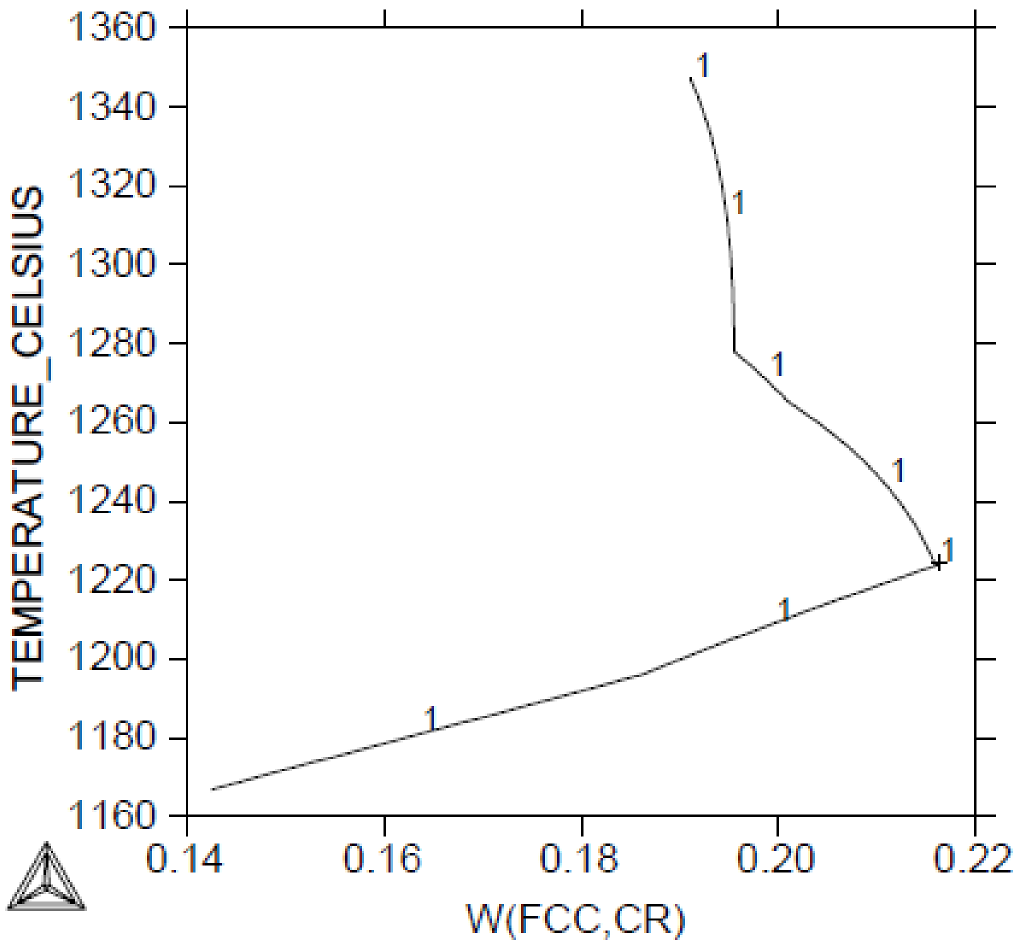
5-Sigma

6-M6C—leaves

7-Boride

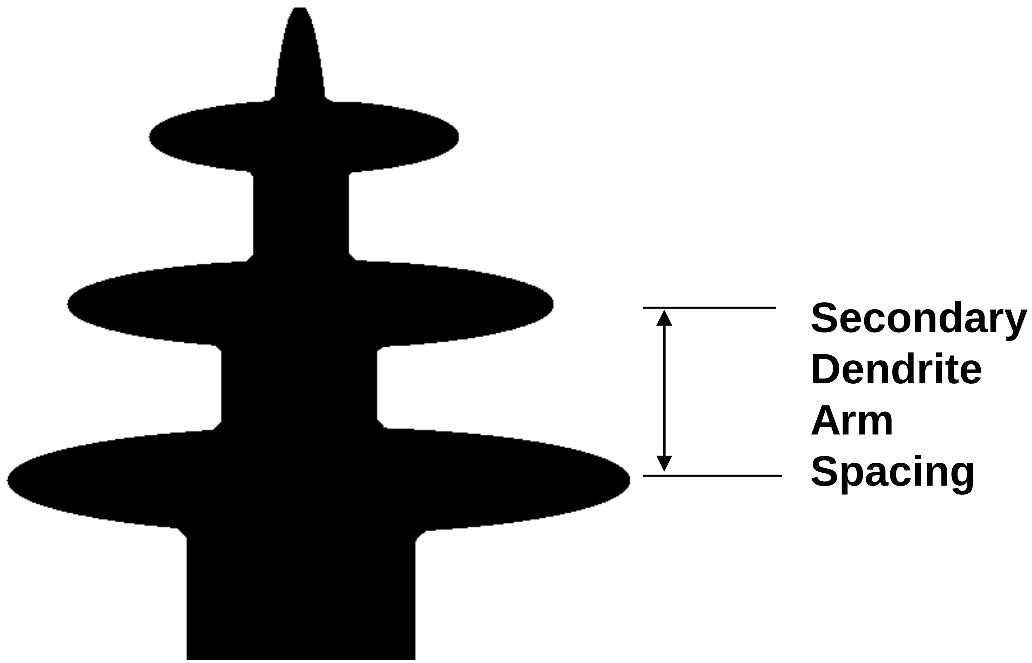
This plot shows how the weight fraction of FCC phase changes with temperature in H282. This is on a Scheil calculation basis.

Weight Fraction Cr in FCC Phase—H282



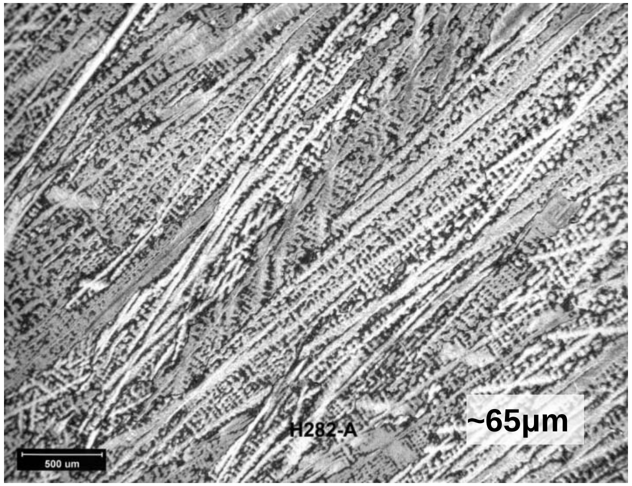
This plot shows how the weight fraction of Cr in the FCC phase changes with temperature in H282. This is on a Scheil calculation basis. The irregularity in the curve occurs at a second phase formation temperature.

Critical Microstructural Features

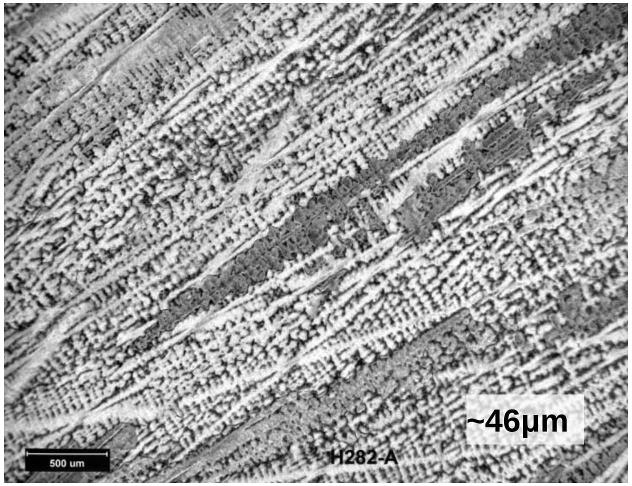


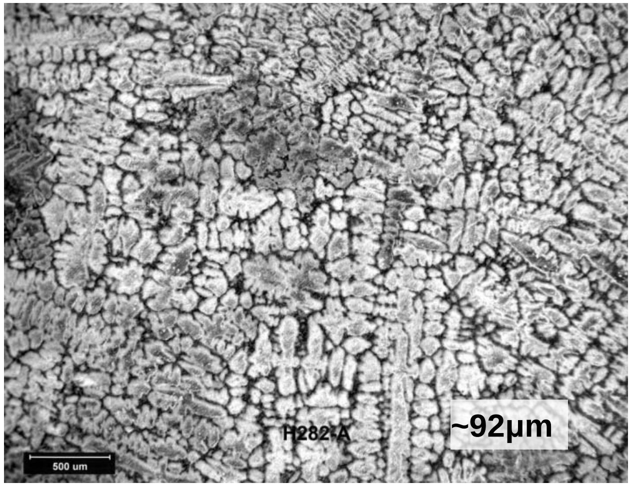
A very useful measurement is the secondary dendrite arm spacing (sdas). Solidification modelers can use this value to estimate the local cooling (solidification) rate. We can also use this as a characteristic diffusion distance to base our homogenization heat treatment: d=0.5x(sdas).

H282 Secondary Dendrite Arm Spacing

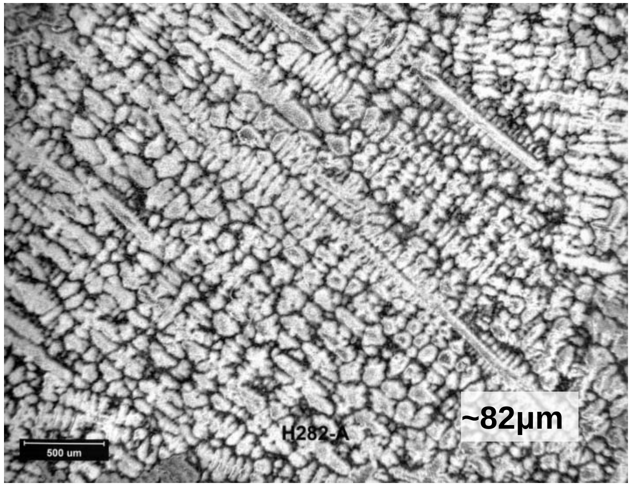


Columnar zone

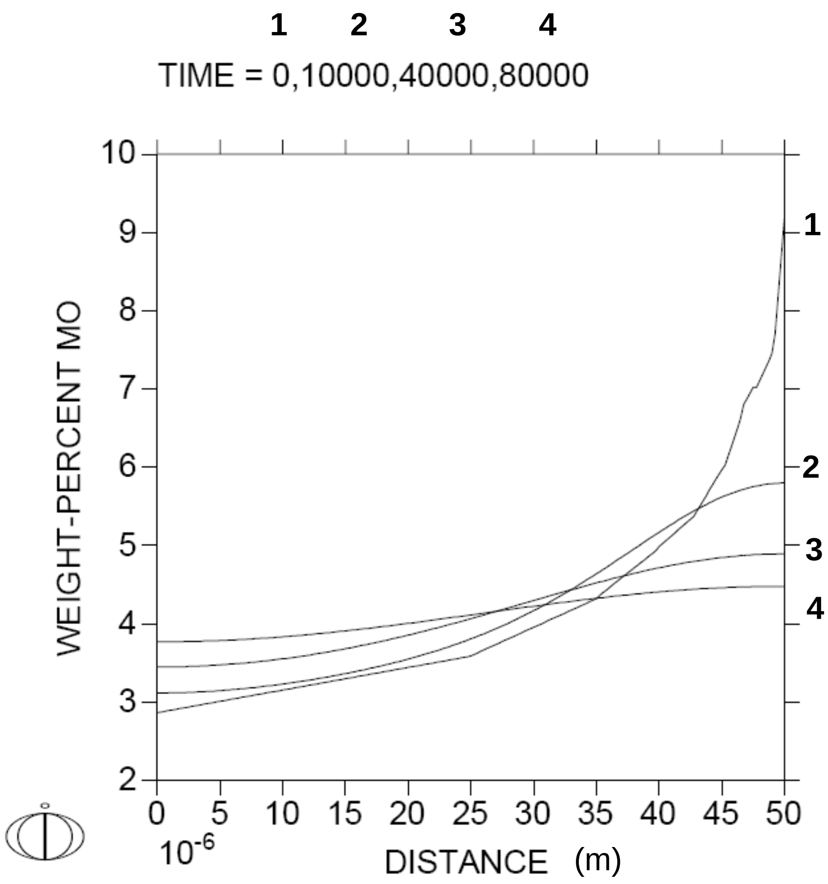


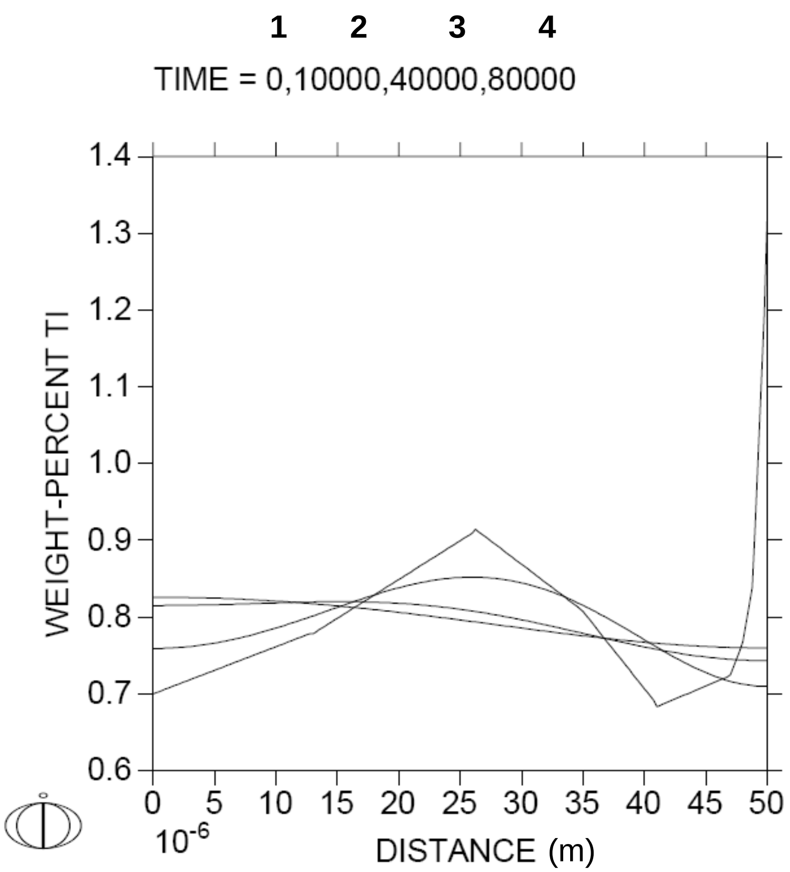


Equiaxed zone



N105—1100C Heat Treatment





Sorry about the SI units. The times listed above (seconds) are equivalent to 0, 2.8, 11.2 and 22.4h.

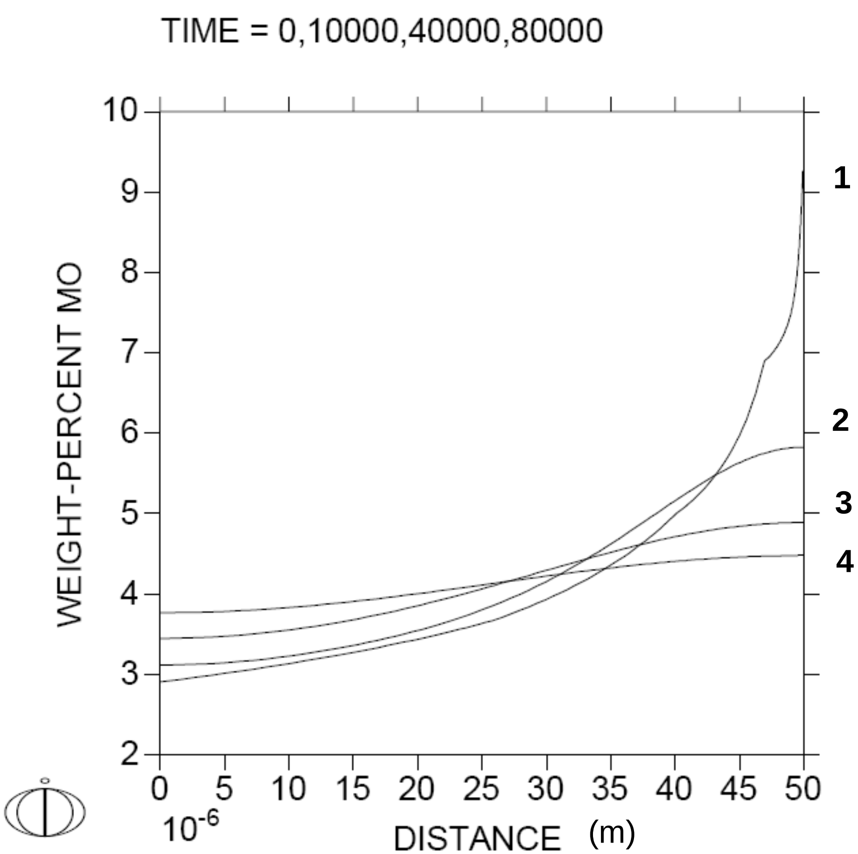
Neither Nb or Ti are fully homogenized even after 22.4h at 1100C.

Section Summary: As-Cast Profiles

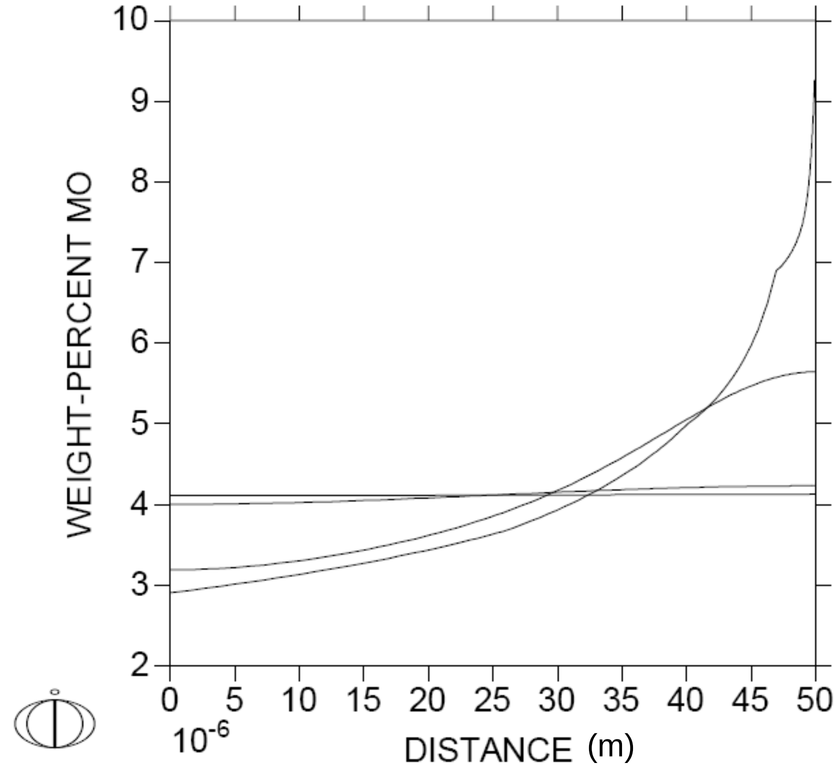
With 7 alloys and 8 or more alloying elements, there is just too much segregation/diffusion data to show here, but they are available for all the alloys. Here are the highlights:

- **The refractory elements W, Mo, and Nb do not homogenize after ~22h/1100C**
- **Significant segregation of the second phase strengthening elements Al, Nb and Ti were observed in many alloys…to the point that 1/2-2/3 of the casting would be considered "lean".**
- **In some cases, Cr poor regions are predicted.**
- **Significant Co segregation was observed in some alloys.**
- **Significant partitioning of Mn and Si to the interdendritic region was predicted. This result suggests that a turn down in the levels of these elements may be beneficial (e.g., welding).**

N105—Homogenization Heat Treatment Comparison



Isothermal at 1100C

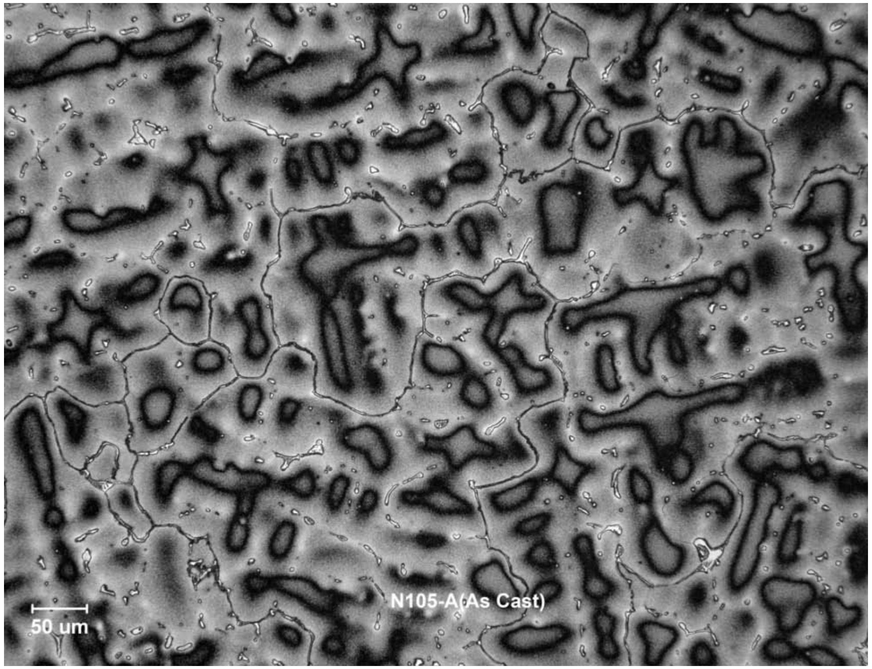


1100C/10,000s+1200C/remaining time

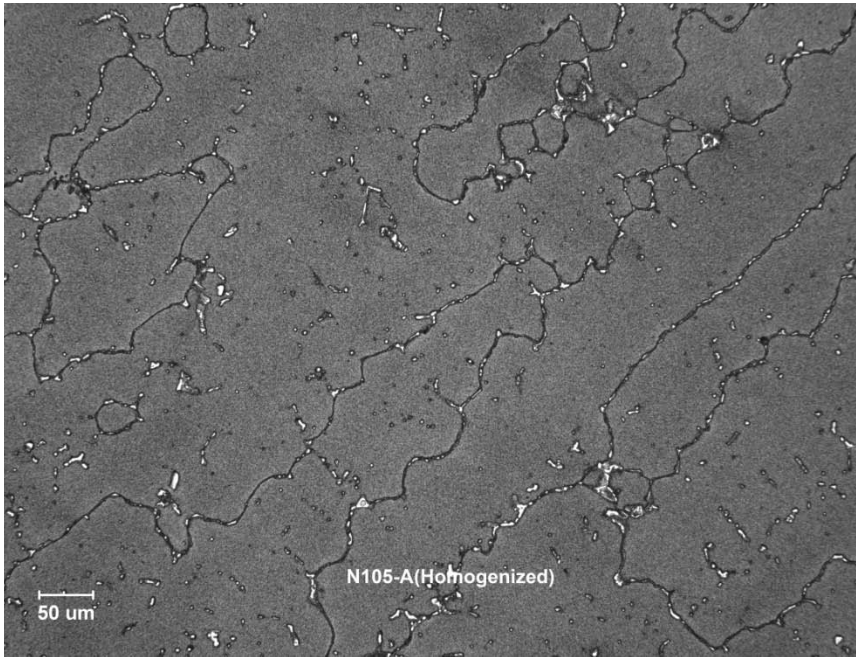
Patent Pending
*Metall. Trans. B, **40B**, (2009) 182.*

Nimonic 105

Qualitative Confirmation of the Effectiveness of the Homogenization Heat Treatment



As-Cast

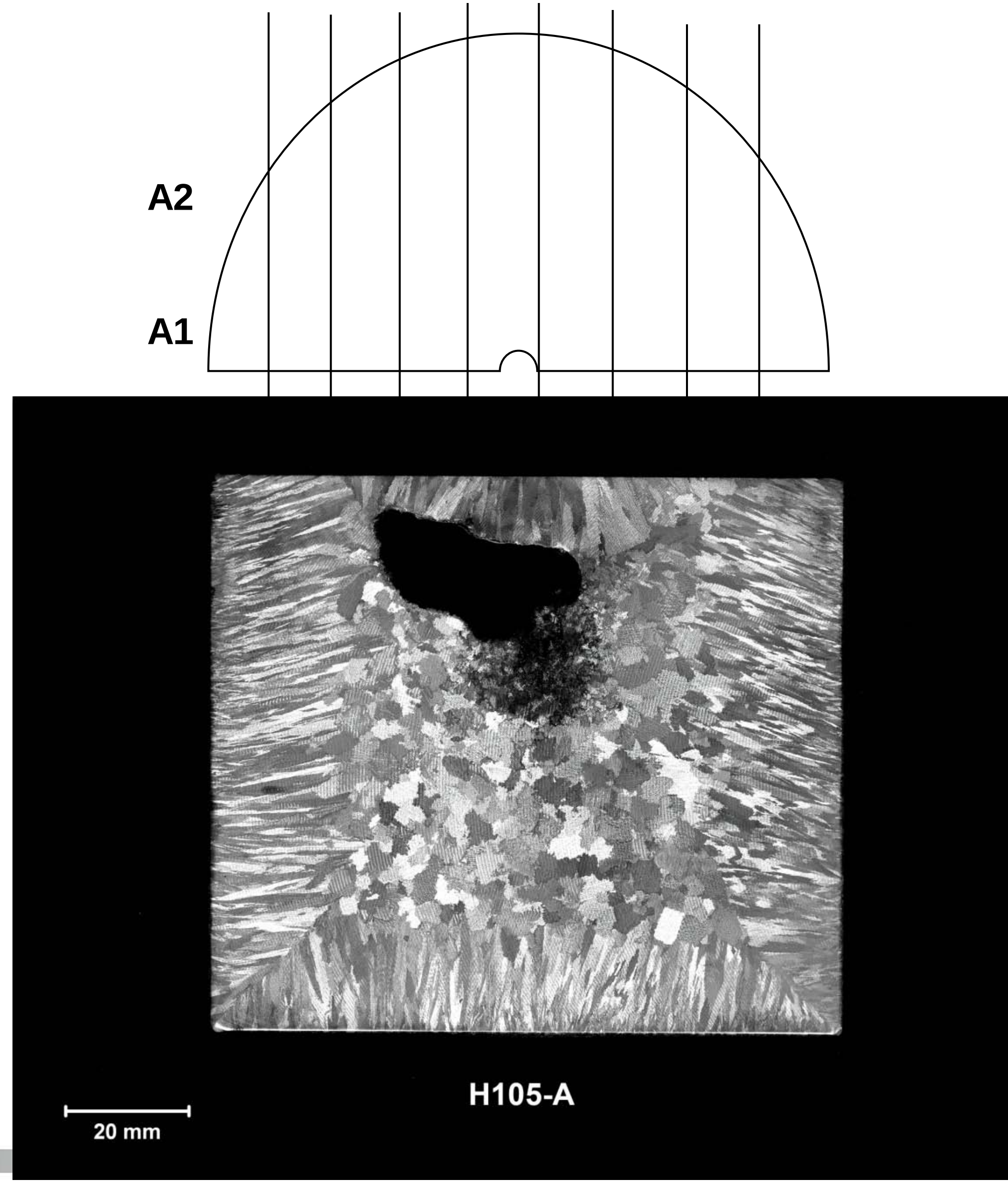


Homogenized

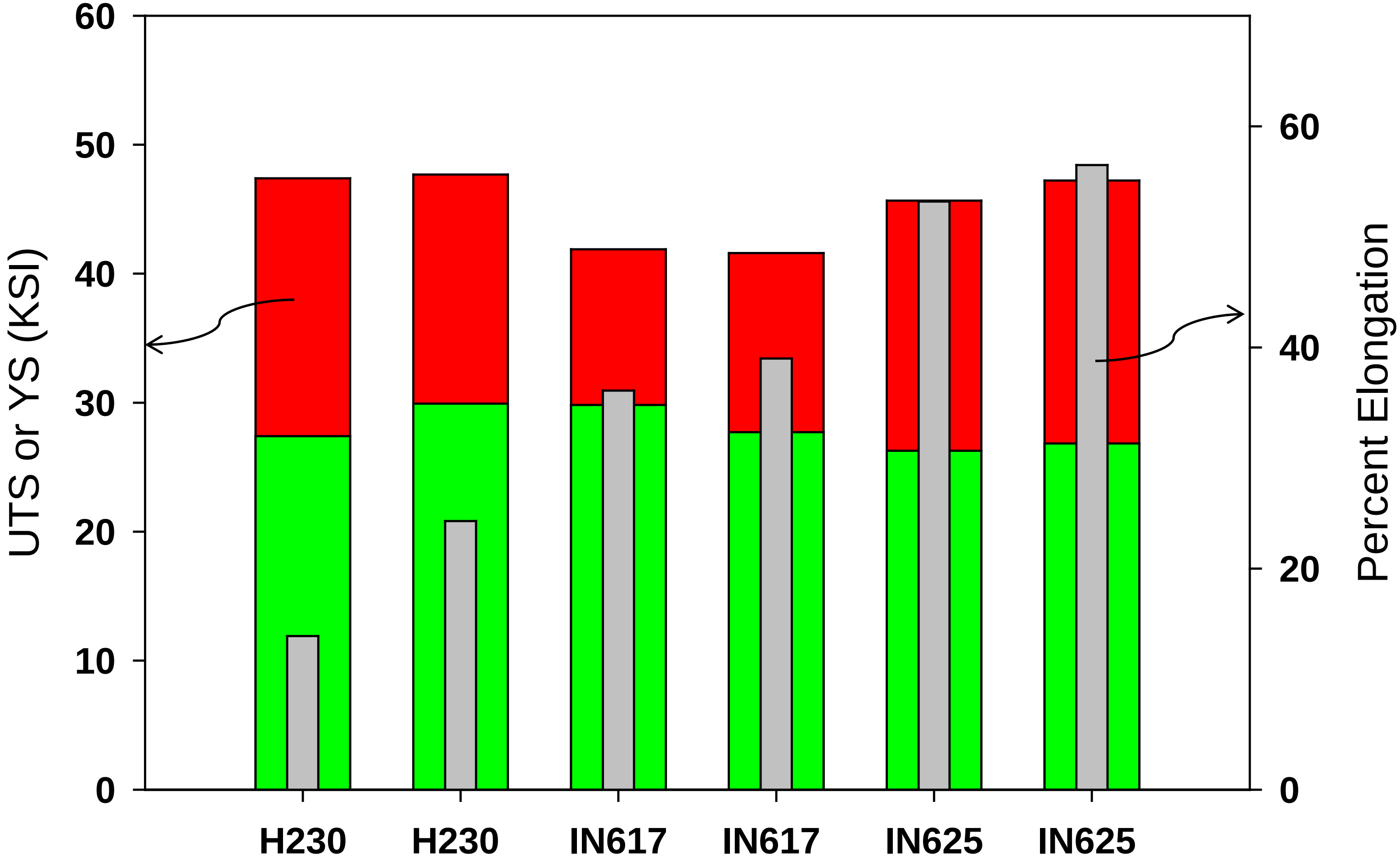
Can the Homogenization cycle replace the solution heat treatment?

Tensile Bar Layout

The ingot halves were cut into 0.4in wide slabs labeled A, B, etc. from the left side of the original tops. These were cut into 0.4in wide TB blanks labeled A1, A2, etc. from the ingot center.



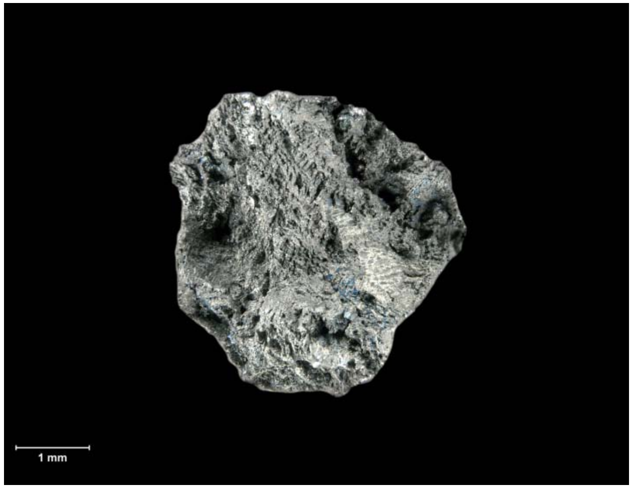
800C Hot Tensile Results
Solid Solution Alloys



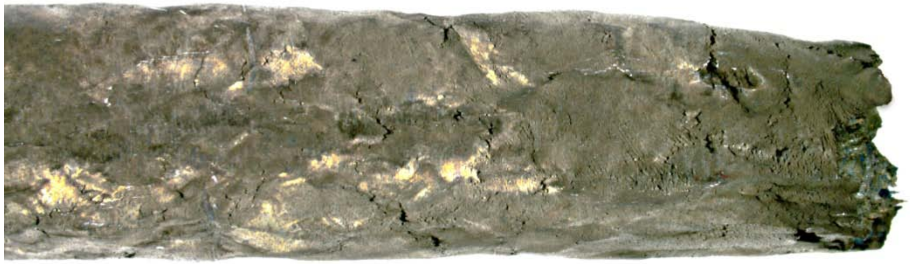
IN625 Fracture

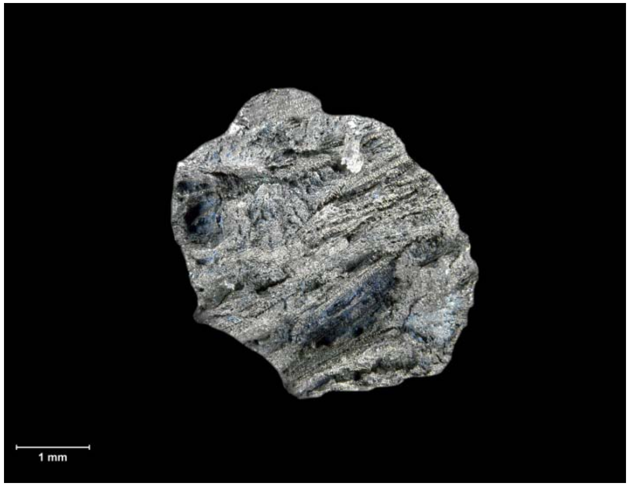
800C Hot Tensile

Equiaxed Region



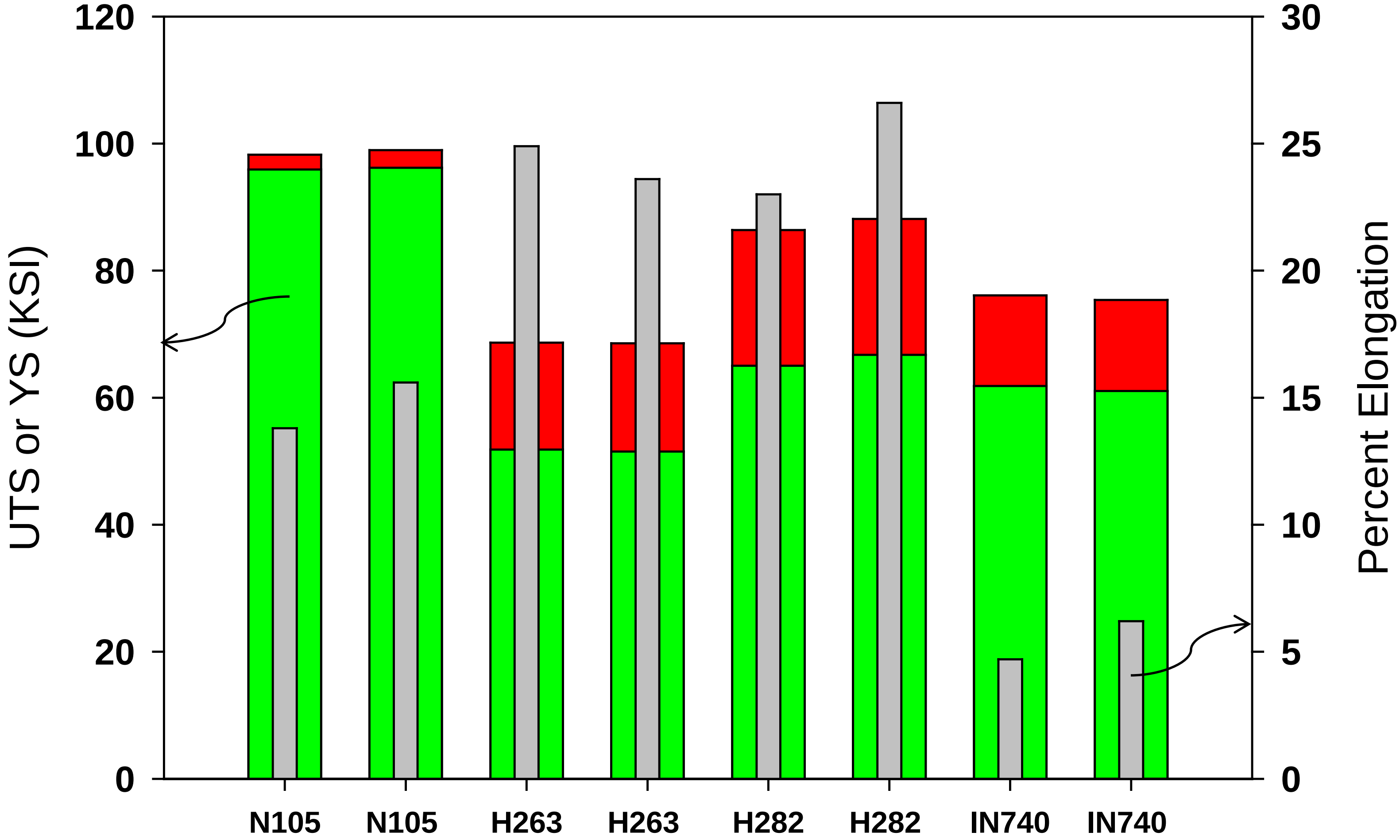
Columnar Region





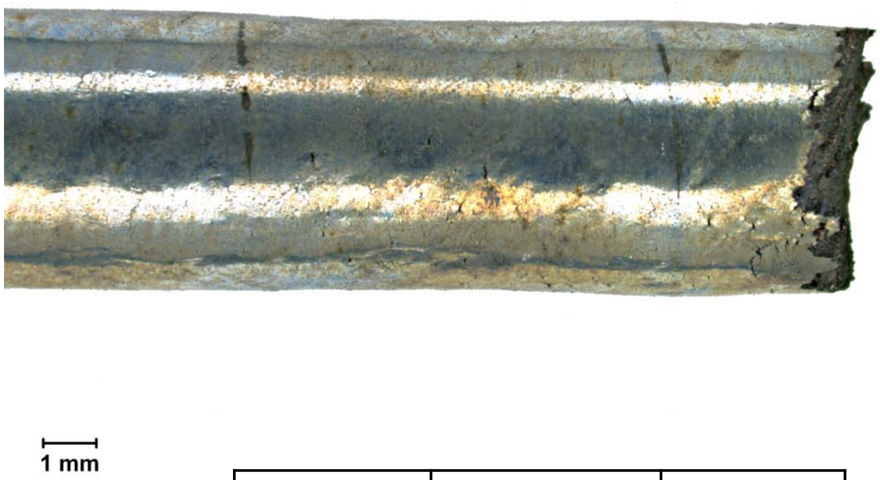
YS (Ksi)	UTS (Ksi)	% Elong.
26	46	53
27	47	57

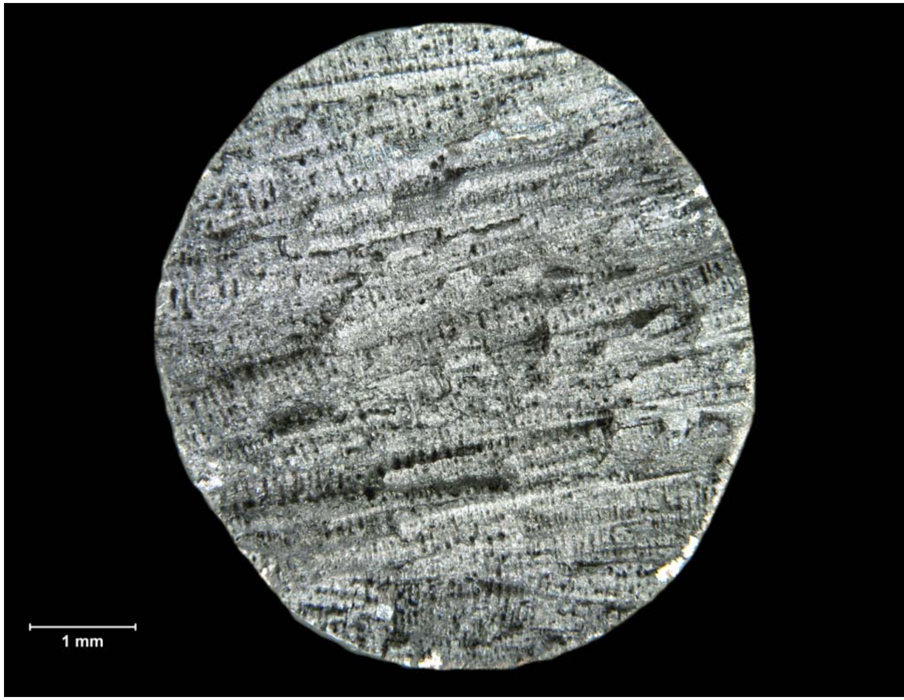
800C Hot Tensile Results
Age Hardenable Alloys



N105 Fracture

800C Hot Tensile





YS (Ksi)	UTS (Ksi)	% Elong.
96	98	14
96	99	16

H263 Fracture

800C Hot Tensile

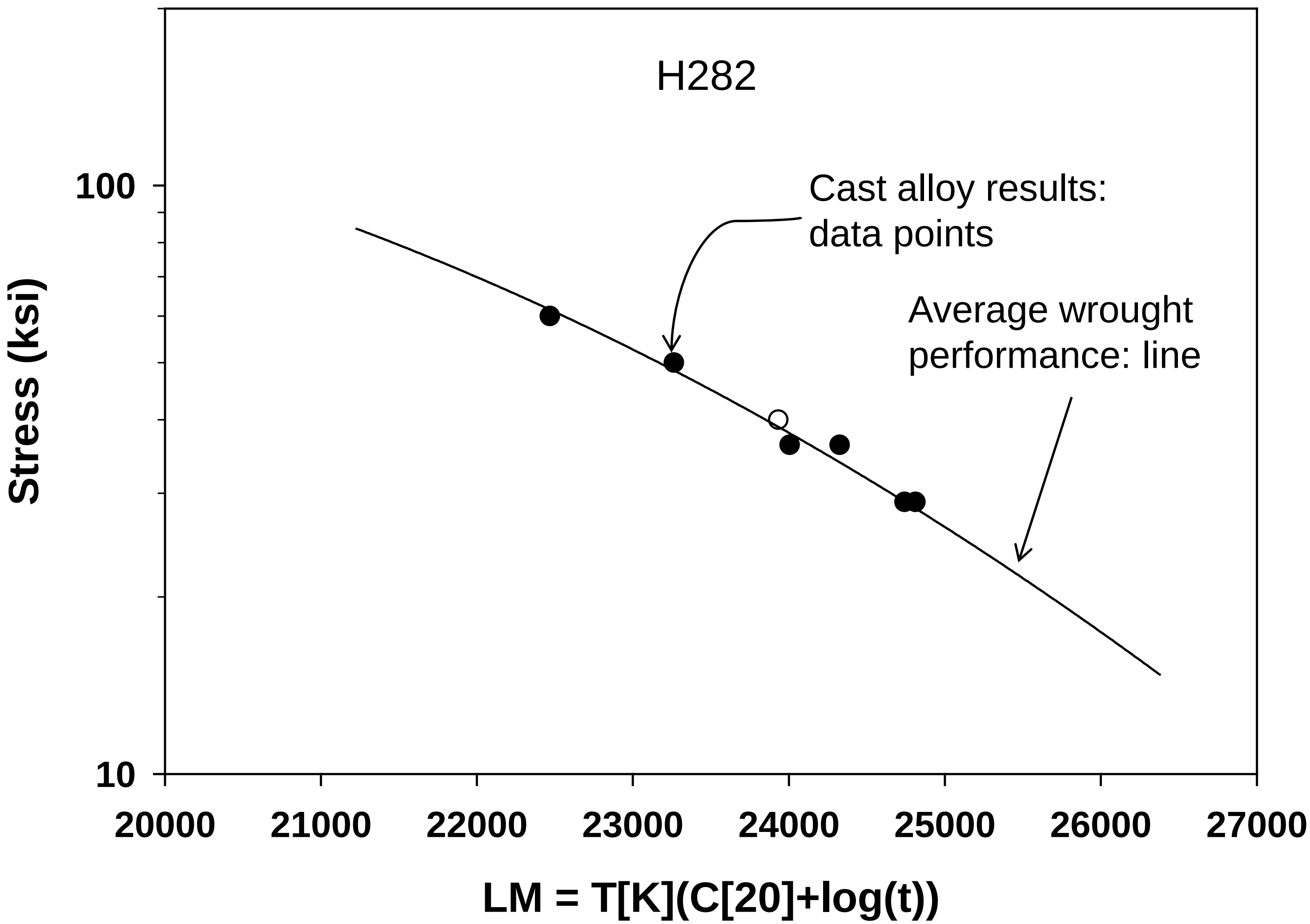
Equiaxed Region

Columnar Region

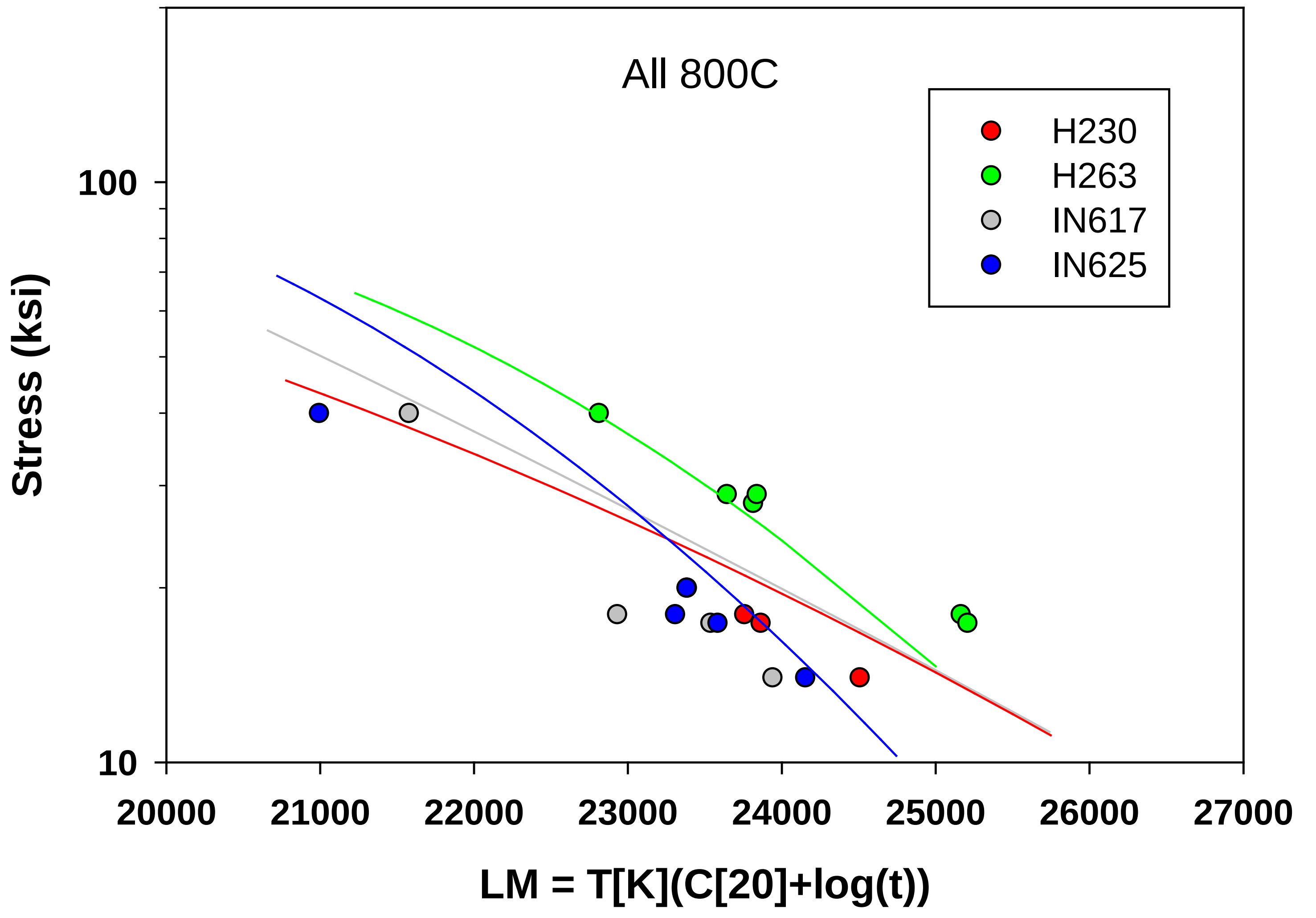
1 mm

YS (Ksi)	UTS (Ksi)	% Elong.
52	69	25
52	69	24

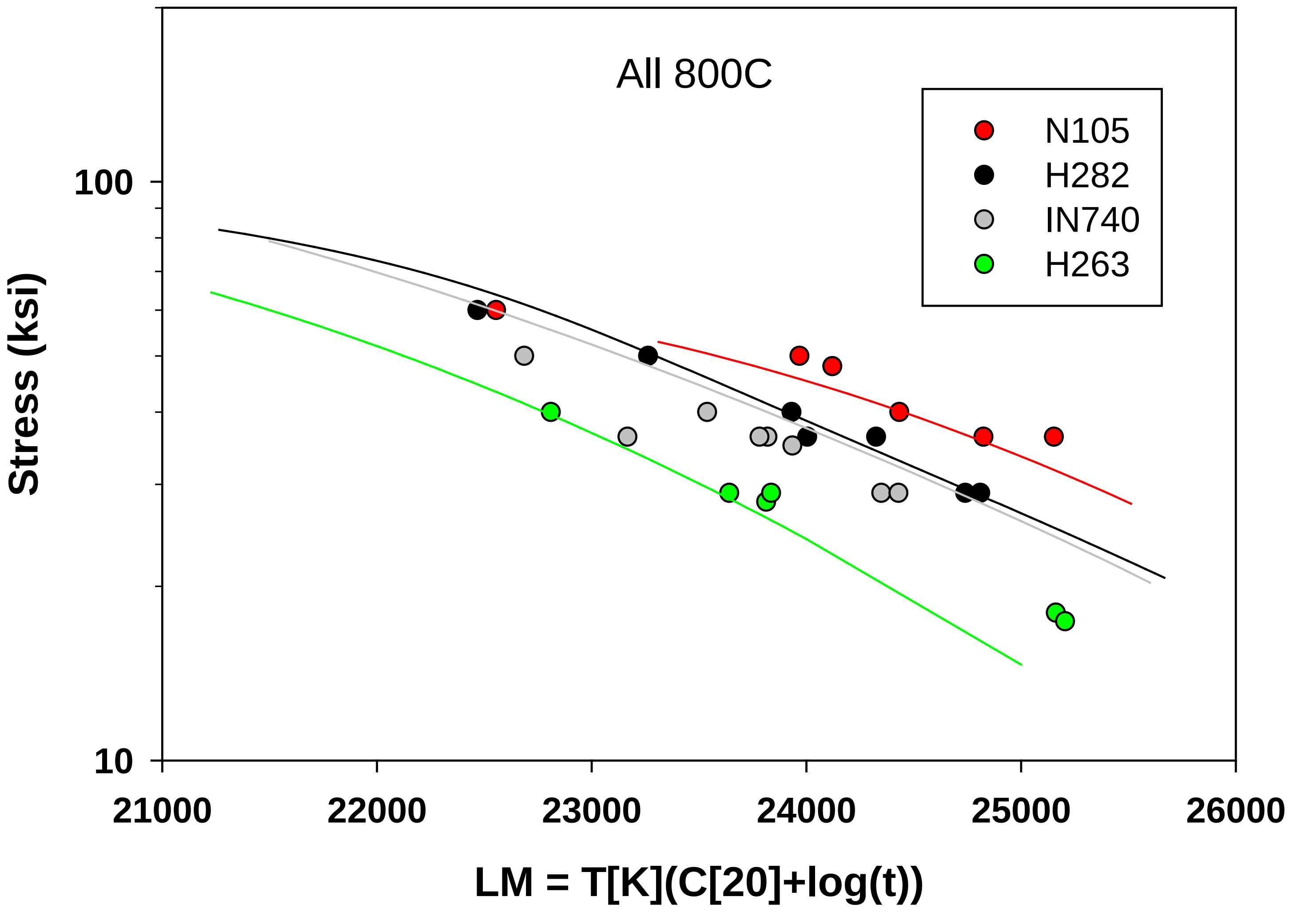
800C Creep Results



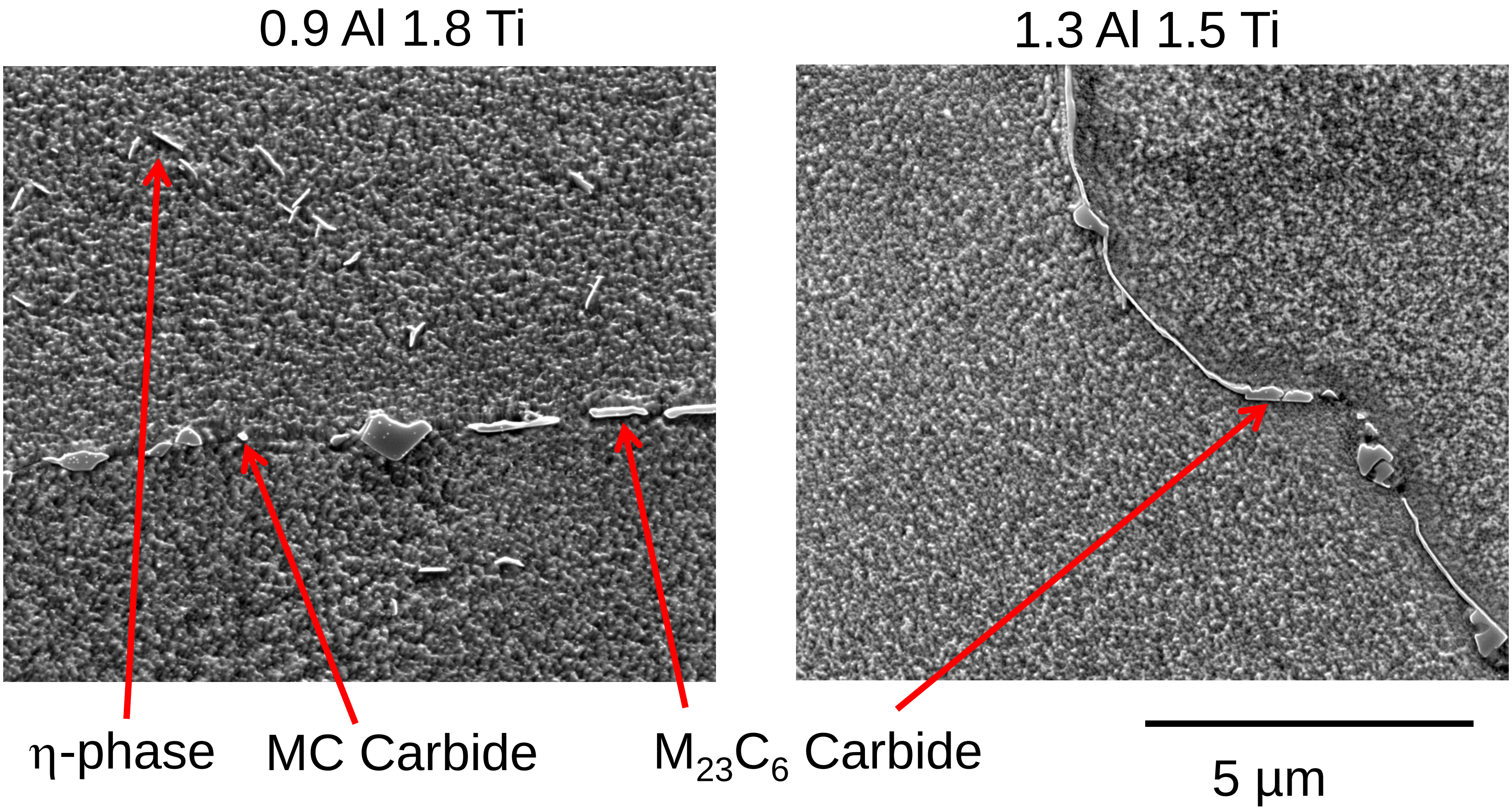
Solid Solution Alloys



Gamma Prime Formers



Cast Solution Treated + Aged Microstructures
Original Chemistry versus New Chemistry



Alloys Under Consideration

Solid Solution	Age Hardenable
H230	N105
IN617	H263
IN625	H282
	IN740

Remelt Stock and Fluidity Spiral

H263

H282

Fluidity Spiral

Fluidity Spiral Castings

H263

235

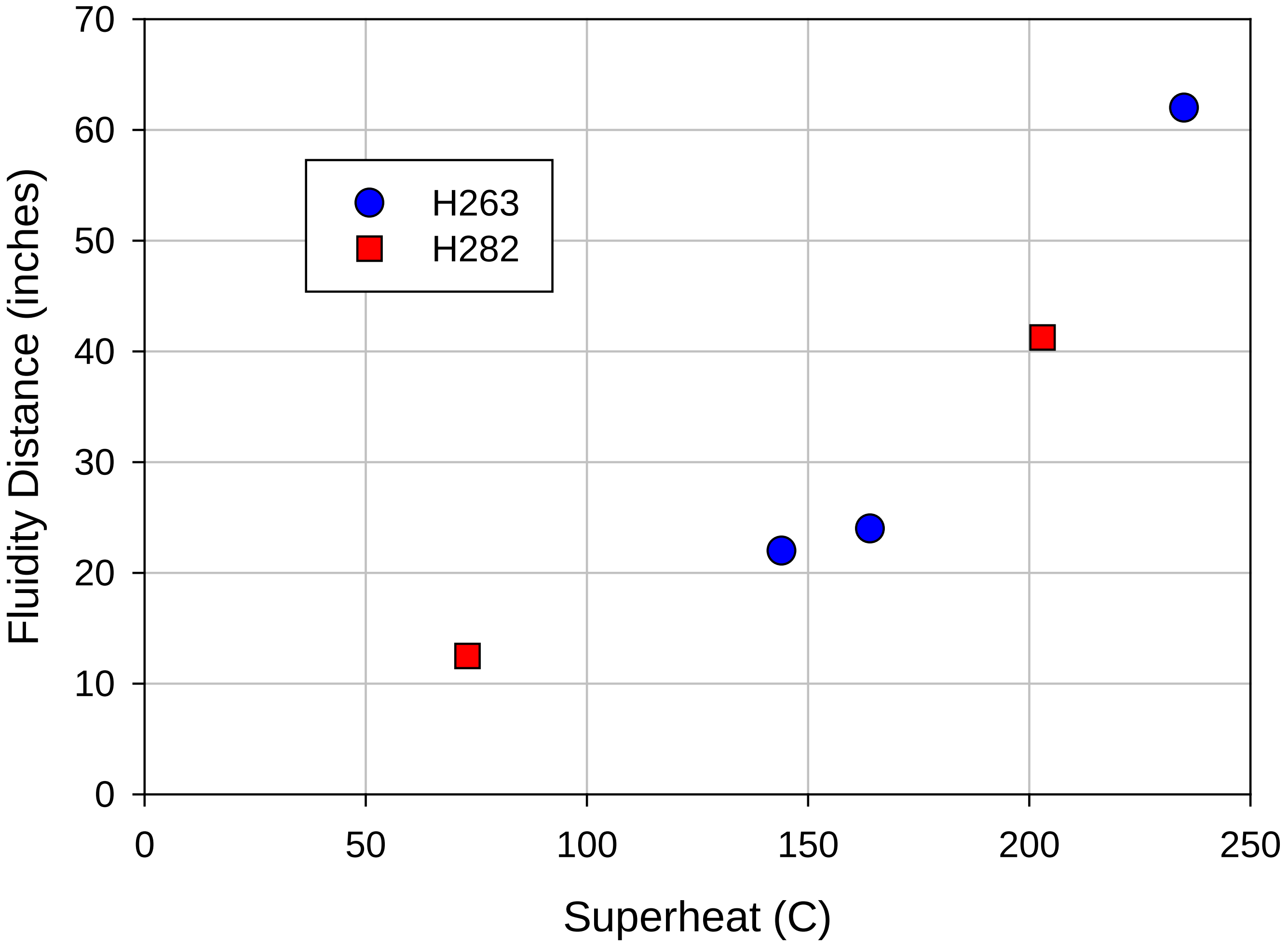
146

H282

73

203

Fluidity Spiral Results



Summary

- There is a backlog in power plant construction.
- If new plants operate under A-USC conditions enhanced efficiency and reduced pollution is anticipated.
- A-USC conditions will require advanced Ni-based alloys to operate.
- Small scale castings were made to evaluate the performance of cast forms of traditionally wrought Ni-based superalloys.
- A computationally optimized homogenization heat treatment was developed to improve the performance of these materials.
- The performance of these alloys, especially creep, looks promising and is comparable to the wrought analogue.
- The alloys appear to have adequate fluidity for casting.

Continuing Work

- Work with turbine manufacturers to produce/evaluate large scale castings of down-select alloys.
- Work with ORNL to produce/evaluate smaller scale castings of microstructurally relevant down-select alloys.
- Continue alloy modification for improved castability and cost improvement.
- Explore heat treatment modifications of the alloys.

Casting the Future