Improved Cast Stainless Steel for ITER Shield Wall Modules

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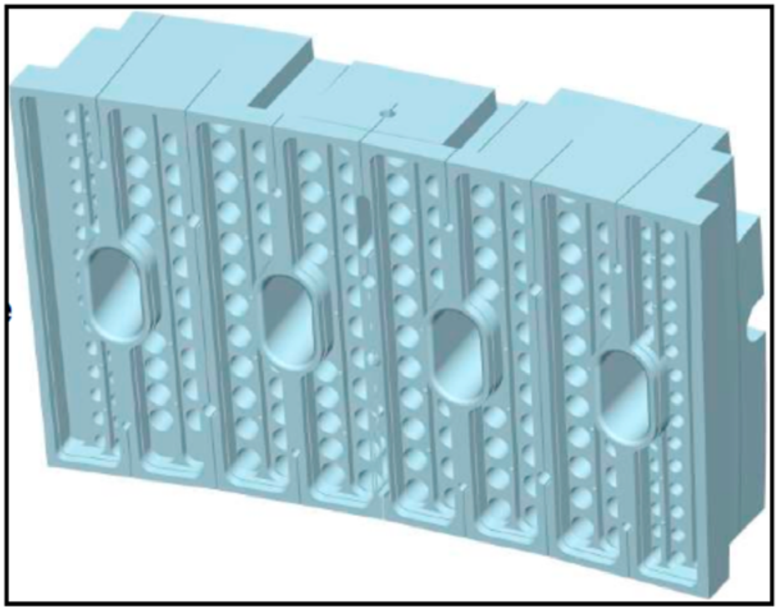
Motivation for improved cast stainless steel

- The complex geometry of the shield module will require considerable machining and heavy section welding of wrought 316SS.
- Casting methods may be viable to considerably reduce time and cost associated with fabrication.
- A previous EDA activity yielded encouraging results.
- However, greater strength is needed for the cast material to be accepted for use in ITER.



Shield Module

•The objective of this work is to develop and qualify cast stainless steels with improved properties

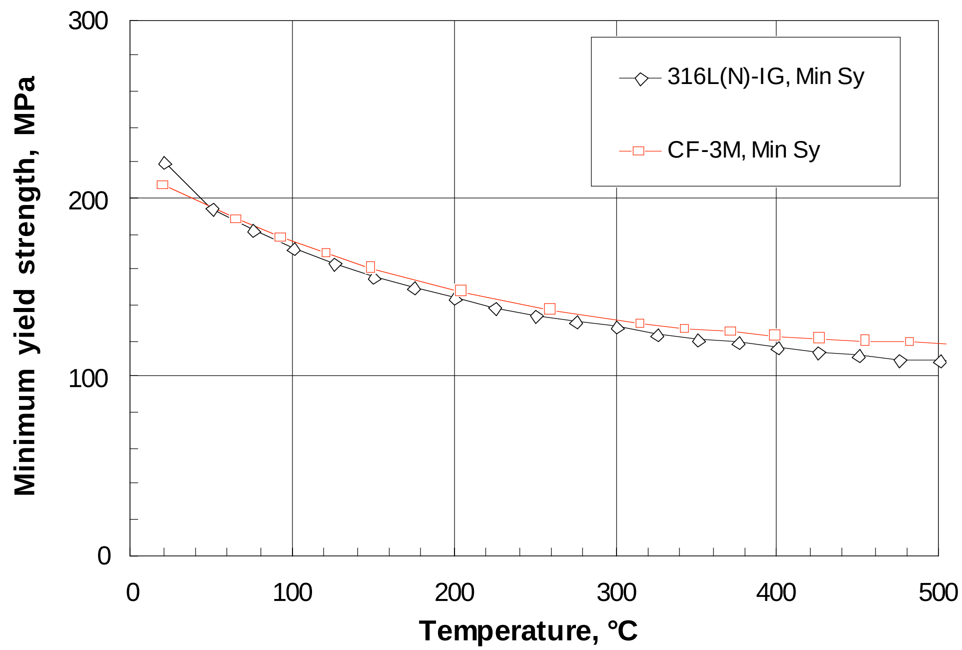
Qualification Requirements for Cast Stainless Steel

- ITER has provided preliminary requirements for using cast stainless steel in ITER
- *Memo from V. Barabash, 28 August, 2006.*

- Chemistry and Structure
  - Composition should be held as close as possible to 316LN grade steel
  - Ferrite content should be less than 1%
  - Grain size should be equal or finer than No.3 (ASTME112) for thicknesses < 100 mm and No.2 for larger thicknesses
  - Porosity should be analyzed, minimum requirements TBD.

Qualification Requirements for Cast Stainless Steel (cont.)

- Mechanical properties: as close to 316LN as possible



- Irradiation: comparable to wrought material
- Corrosion: comparable to wrought material
- Welding: demonstrate similar to wrought material
- Outgassing: similar to wrought material
- NDE: demonstrate similar to wrought material

A “science-based” approach to improving cast stainless steel

- To improve the stainless steel in a short time frame, modern materials science and experience are applied.
  - Analyze archived cast steel to identify potential mechanisms for improvement
  - Perform thermodynamic and solidification modeling to predict the most effective means of improvement
  - Determine alloy compositions and treatments for improved strength of cast steel based on the results of 1. and 2.
  - Validate the improved cast steel.

- This approach allows for improved materials in a reduced time and cost versus traditional, experimental metallurgy.

Archive analysis of EDA steel.

- **A section of the cast SS divertor produced in the EDA activity was provided for analysis.**
- **Part of section CC from Quaker heat 48798 is under analysis**
  - **Optical microscopy**
  - **SEM**
  - **TEM**
  - **Tensile testing**
  - **Heat treatments**

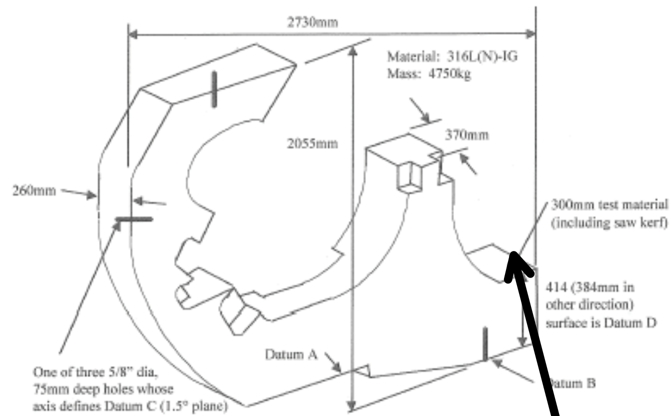
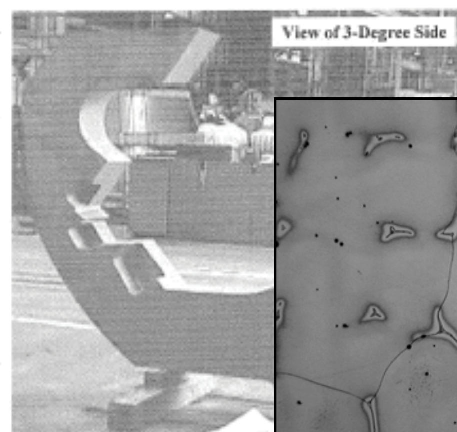
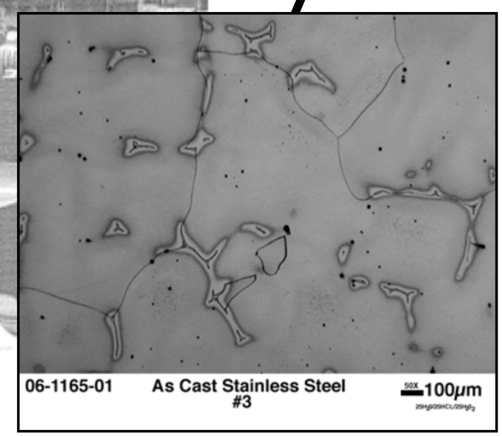


Figure 10: Configuration of Center Segment Casting

Section CC

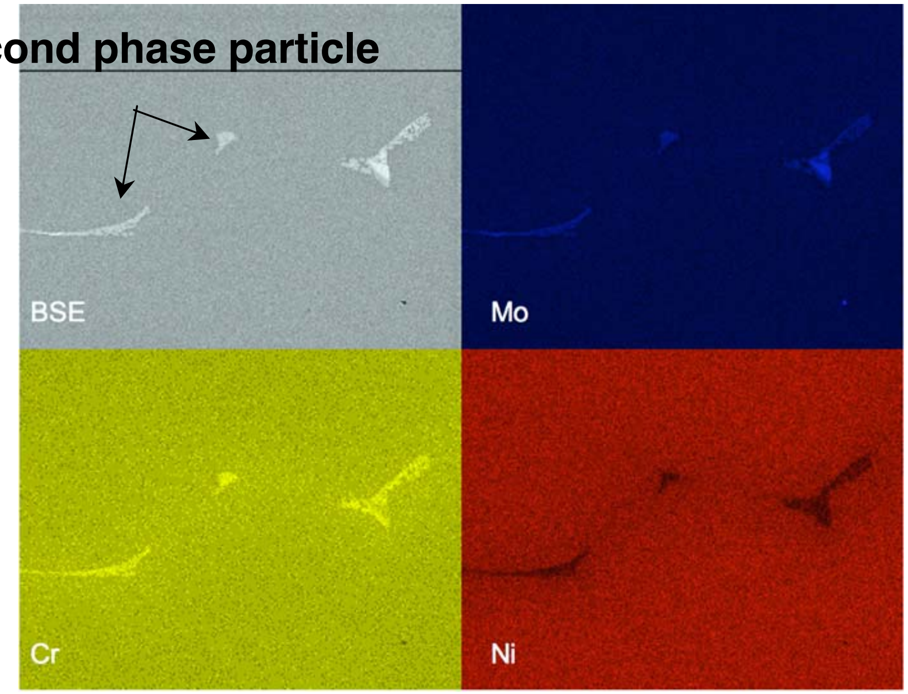




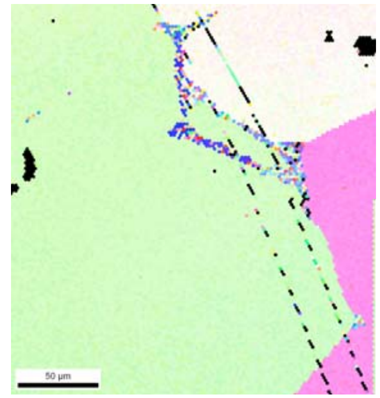
ITER Technical Note: K.T. Slattery and D.E. Driemeyer, "Cassette Body Cast/HIP Development," ITER/US/98/IV-DV-09, 1998.

SEM/TEM analysis reveals that second phase is not ferrite, but likely contains some sigma

Second phase particle

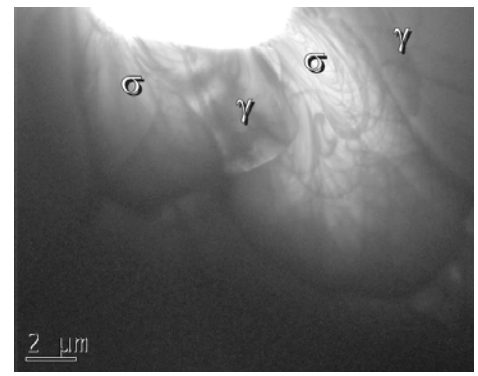


SEM and spectrum imaging



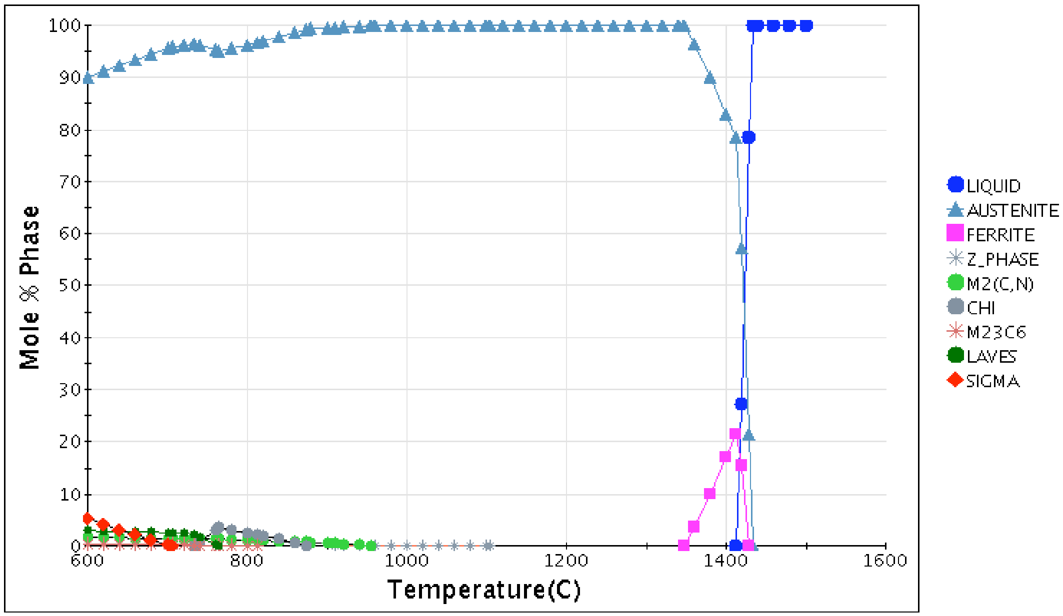
Backscatter analysis shows FCC phases

TEM and diffraction analysis indicate sigma phase

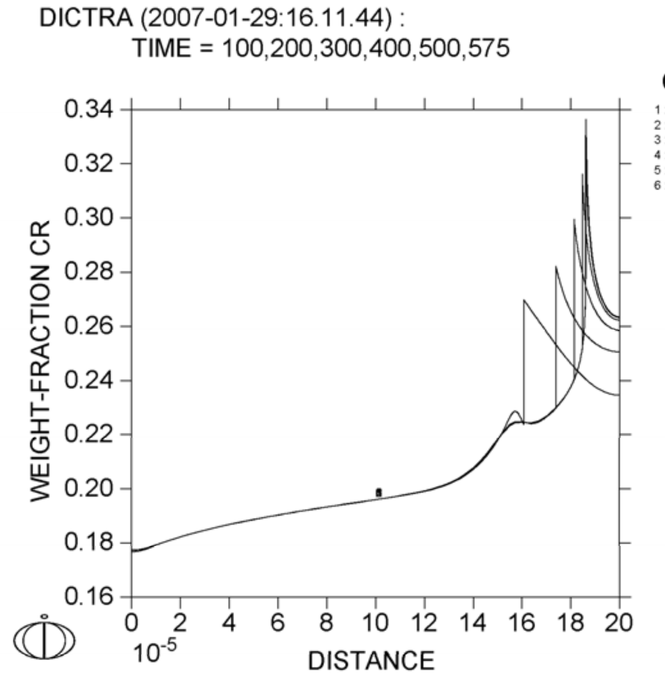


- SEM, spectrum imaging, and TEM analysis indicate there is very little ferrite (consistent with magnetic measurements of Slattery and Driemeyer).
- Cr and Mo are segregated near the second-phase regions and in the matrix over 100-500 μm lengths.
- Cr and Mo depletion in the austenite may also explain the reduced strength in the archive material.

Modeling and simulations help to analyze and understand improvement strategies before experimental trials



Equilibrium phase amounts vs. T



Cr composition profiles during solidification

- **Thermodynamic and solidification modeling of Atlas ht 48798 properly predict phases observed in archive material.**
- **Modeling also shows that increasing the content of austenite stabilizers will push alloy to full austenite upon solidification.**

Strategies for improved cast stainless steel

- Several different improvement strategies have been proposed.
- Strengthening by N and Mn
  - N is the most powerful solid solution strengthener (0.1 wt% should increase strength by 50 MPa).
  - Mn must also be increased to keep N in solution.
  - Mn is also an austenite stabilizer, increases strength, and strain-hardening rate.
- Strengthening by Cu and W
  - An alternative path using substitutional strengthening
  - Cu and W should improve corrosion performance and ductility
- Iterative thermodynamic modeling and industrial steel foundry feedback has helped refine test alloy matrix.

Target compositions for improved cast SS

Within ASTM Spec A774/A7447 specs for cast SS steel

Compositions in wt%

	Cr	Ni	Mo	Mn	N	Cu	W
Atlas 48798	17-18	12-12.5	2.3-2.7	1.6-2.0	0.08-0.14		
Mod1	17-18	12-12.5	2.3-2.7	**1.6-2.0**	**0.18-0.25**		
Mod2	17-18	12-12.5	2.3-2.7	**2.8-3.2**	**0.13-0.20**		
Mod2a	17-18	12-12.5	2.3-2.7	**2.8-3.2**	**0.18-0.25**		
Mod3	17-18	12-12.5	2.3-2.7	**3.8-4.2**	**0.28-0.35**		
Mod4	17-18	12-12.5	2.3-2.7	**4.8-5.2**	**0.38-0.42**	**2.5-3.0**	
Mod5	17-18	12-12.5	**1.8-2.2**	**4.8-5.2**	**0.38-0.42**	**2.5-3.0**	**1.0-1.2**

Solid-solution strengthening by N

Strengthening with Cu and W

Status of improved cast stainless steel

- Experimental heats of the improved cast stainless steel compositions were fabricated by Stainless Foundry and Engineering.
- Industrial partners were involved to help speed scale up to larger test articles.
- Stainless Foundry & Engineering melted six test cast heats (~100 lb. each) in March, 2007
- These heats included ingots, kiel blocks, and fluidity spirals
- St. Louis Testing Lab. has provided independent testing of the cast material (in addition to SF&E and ORNL testing).

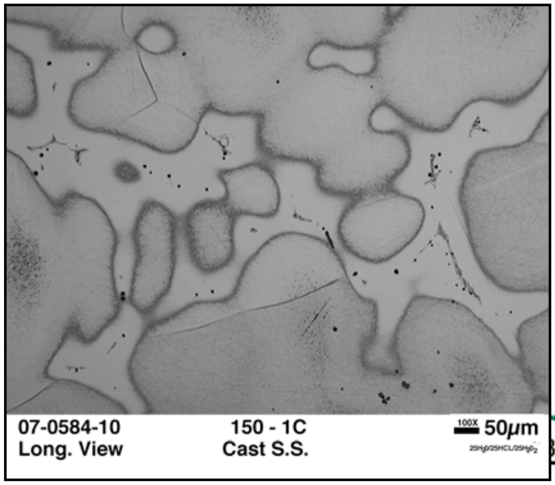
Fluidity of improved cast stainless steels

- Fluidity is a key property of a cast material and a function of composition and temperature.
- SF&E performed fluidity testing on the improved heats.
- SF&E concluded that all alloys had similar and acceptable fluidity.

Reference alloy

- A "reference" C3MN alloy was cast to duplicate previous work
- Alloy 150L: Fe-17.4Cr-12.6Ni-2.0Mn-2.5Mo-0.14N

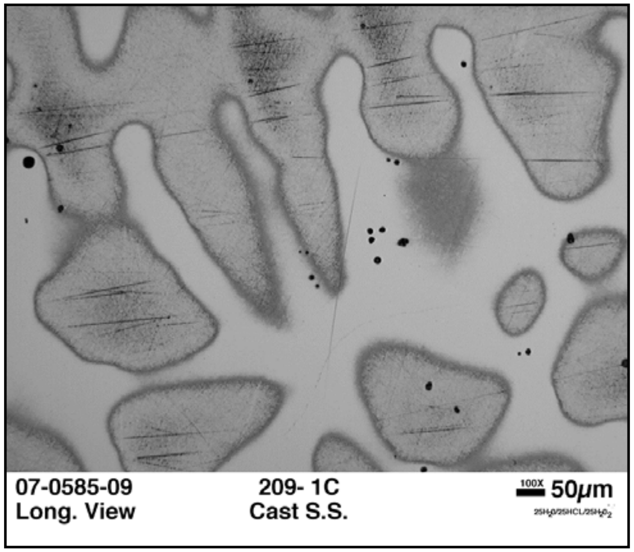
Alloy	Condition	YS (MPa)	UTS (MPa)	Elong. (%)
Atlas 48798-CC	As-cast	173±14	435 ±41	52
	Annealed	216 ±17	450±17	56
	ORNL/Annealed	230±15	444 ±3	46
150L	**As-cast**	**219±12**	**491±8**	**54**



“Mod 1”

- **Alloy 209L: Fe-17.4Cr-12.6Ni-2.0Mn-2.5Mo-*0.27N***

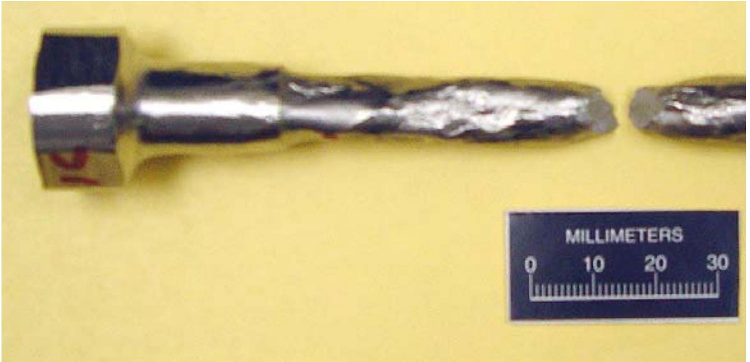
Alloy	Condition	YS (MPa)	UTS (MPa)	Elong. (%)
Atlas 48798-CC	As-cast	173±14	435 ±41	52
	Annealed	216 ±17	450±17	56
	ORNL/Annealed	230±15	444 ±3	46
209L	**As-cast**	**272±10**	**565±9**	**56**

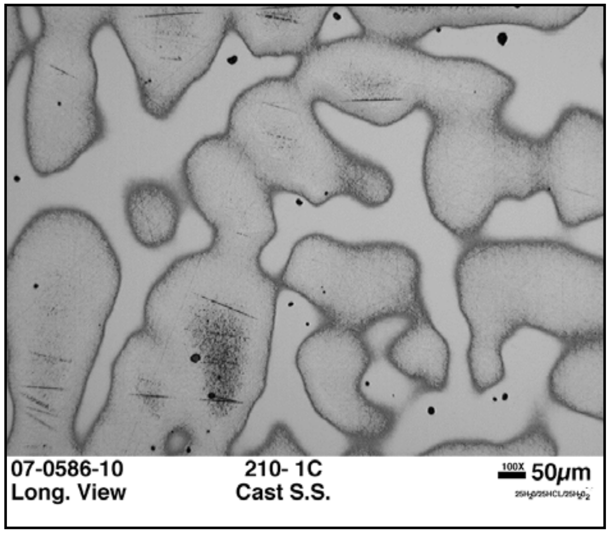


“Mod 2”

- **Alloy 210L: Fe-17.4Cr-12.6Ni-*3.1Mn*-2.5Mo-*0.23N***

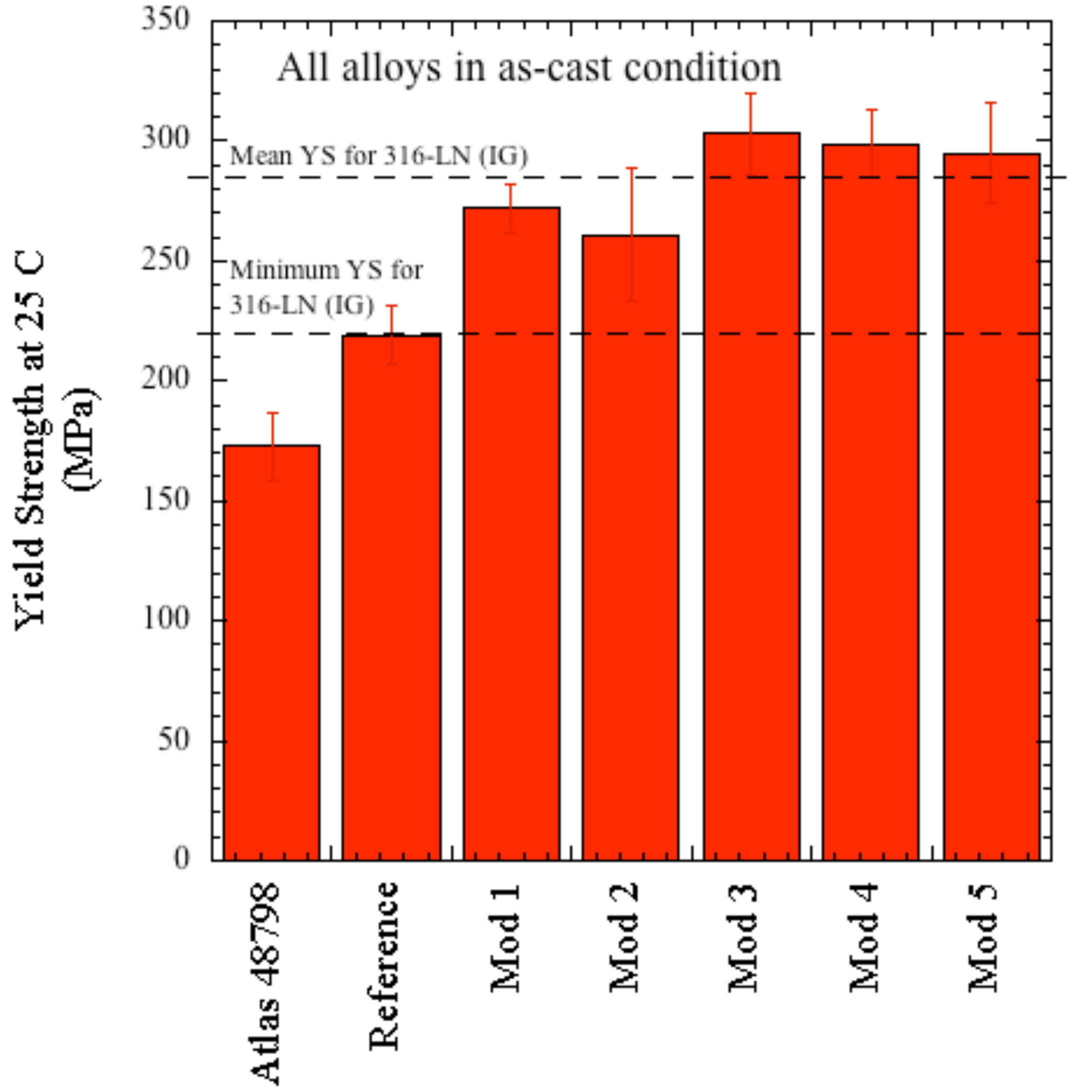
Alloy	Condition	YS (MPa)	UTS (MPa)	Elong. (%)
Atlas 48798-CC	As-cast	173±14	435 ±41	52
	Annealed	216 ±17	450±17	56
	ORNL/Annealed	230±15	444 ±3	46
210L	**As-cast**	**261±28**	**555±24**	**55**





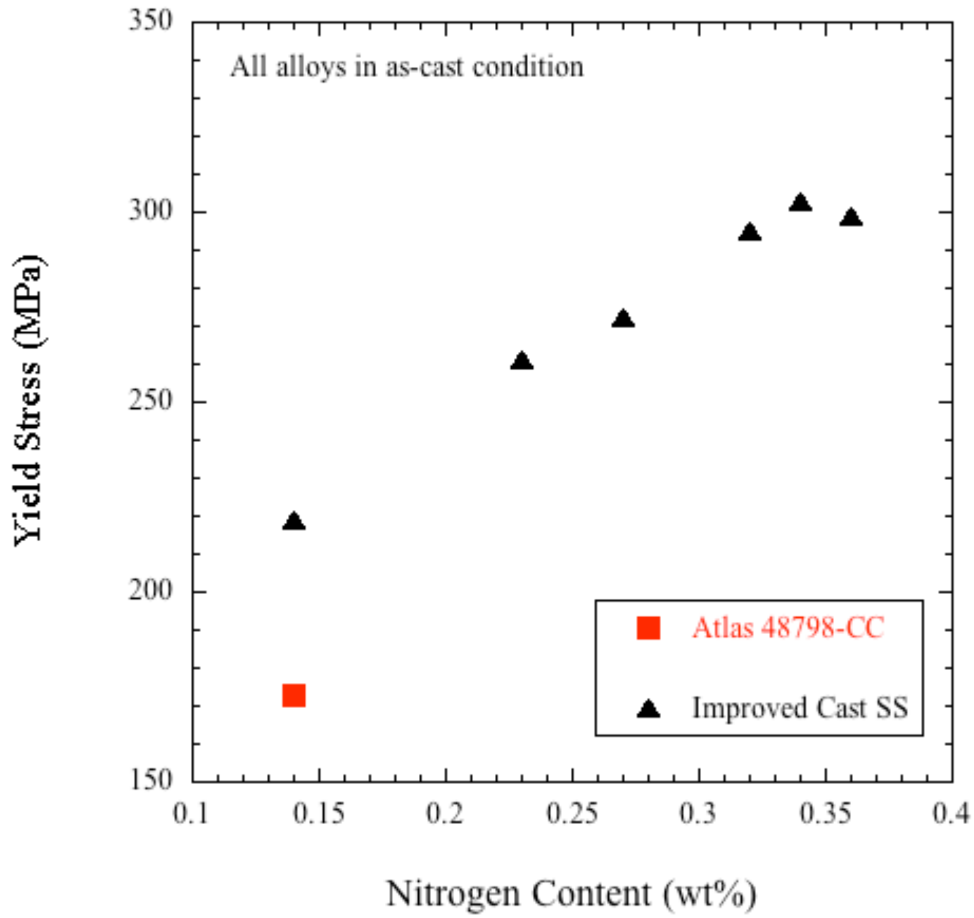
Strength Comparison: Yield stress

- **Tensile tests have been performed at room temperature**
- **Tests were performed on kiel blocks and samples cut from both the interior and surface regions of an ingot.**
- **All modified alloys have improved strength over archive and reference material.**



Impact of N content on strength

- **N in solution is one of the most powerful solid-solution strengtheners.**



Future testing on improved alloys

- Metallography **(in progress)**
- SEM/TEM analysis of microstructure **(in progress)**
- Additional tensile tests at 100 to 300ºC in as-cast condition **(in progress)**
- Homogenization treatments **(in progress)**
  – Additional tensile testing **(in progress)**
- Fracture toughness (bend bars) **(summer 2007)**
- Porosity/gas release **(summer 2007)**
- Joining **(summer/fall 2007)**
- NDE evaluation **(summer/fall 2007)**
- Irradiation performance **(summer/fall/winter 2007)**
- IASCC resistance **(fall/winter 2007)**

Summary

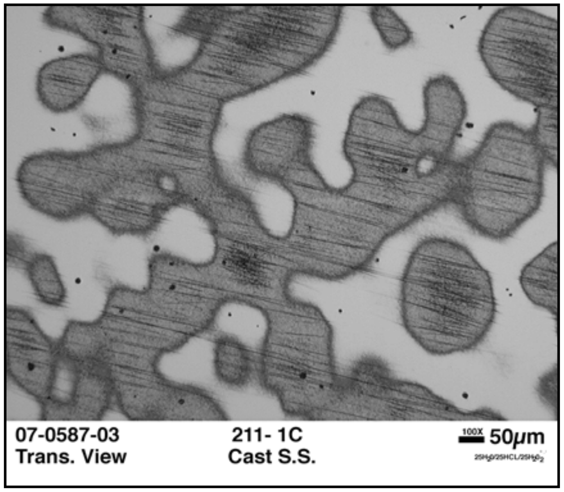
- A science-based approach has been applied to improving cast stainless steel for ITER shield modules.
- Analysis of archive cast SS for a divertor shows that second phase particles observed in the EDA are sigma and not ferrite.
- Simulations have been used to understand the solidification behavior and phases present and used to fine tune the improved cast steel compositions.
- Modified cast heats have been melted.
- First results on the modified cast stainless steel alloys are very promising with significantly improved strength and a cleaner microstructure.
- Additional testing is underway.
- 1/4-size and full-size articles may be of interest to further validate these materials.

Backup Slides

“Mod 3”

- **Alloy 211L: Fe-17.4Cr-12.6Ni-*4.1Mn*-2.5Mo-*0.34N***

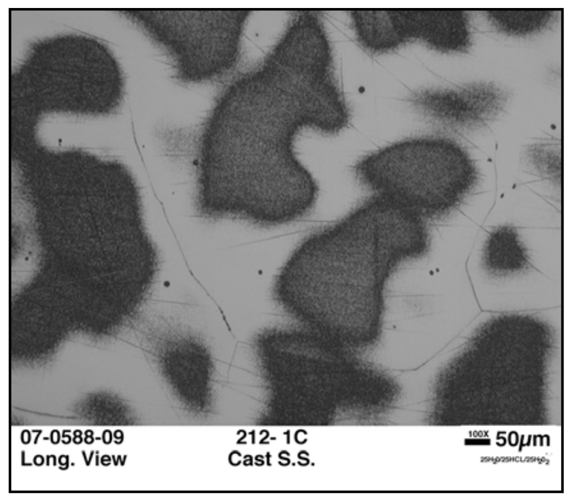
Alloy	Condition	YS (MPa)	UTS (MPa)	Elong. (%)
Atlas 48798-CC	As-cast	173±14	435 ±41	52
	Annealed	216 ±17	450±17	56
	ORNL	230±15	444 ±3	46
211L	**As-cast**	**302±17**	**591±24**	**56**



“Mod 4”

- **Alloy 212L: Fe-17.4Cr-12.6Ni-*5.1Mn*-2.5Mo-*0.36N-2.8Cu***

Alloy	Condition	YS (MPa)	UTS (MPa)	Elong. (%)
Atlas 48798-CC	As-cast	173±14	435 ±41	52
	Annealed	216 ±17	450±17	56
	ORNL	230±15	444 ±3	46
212L	**As-cast**	**299±14**	**592±9**	**55**



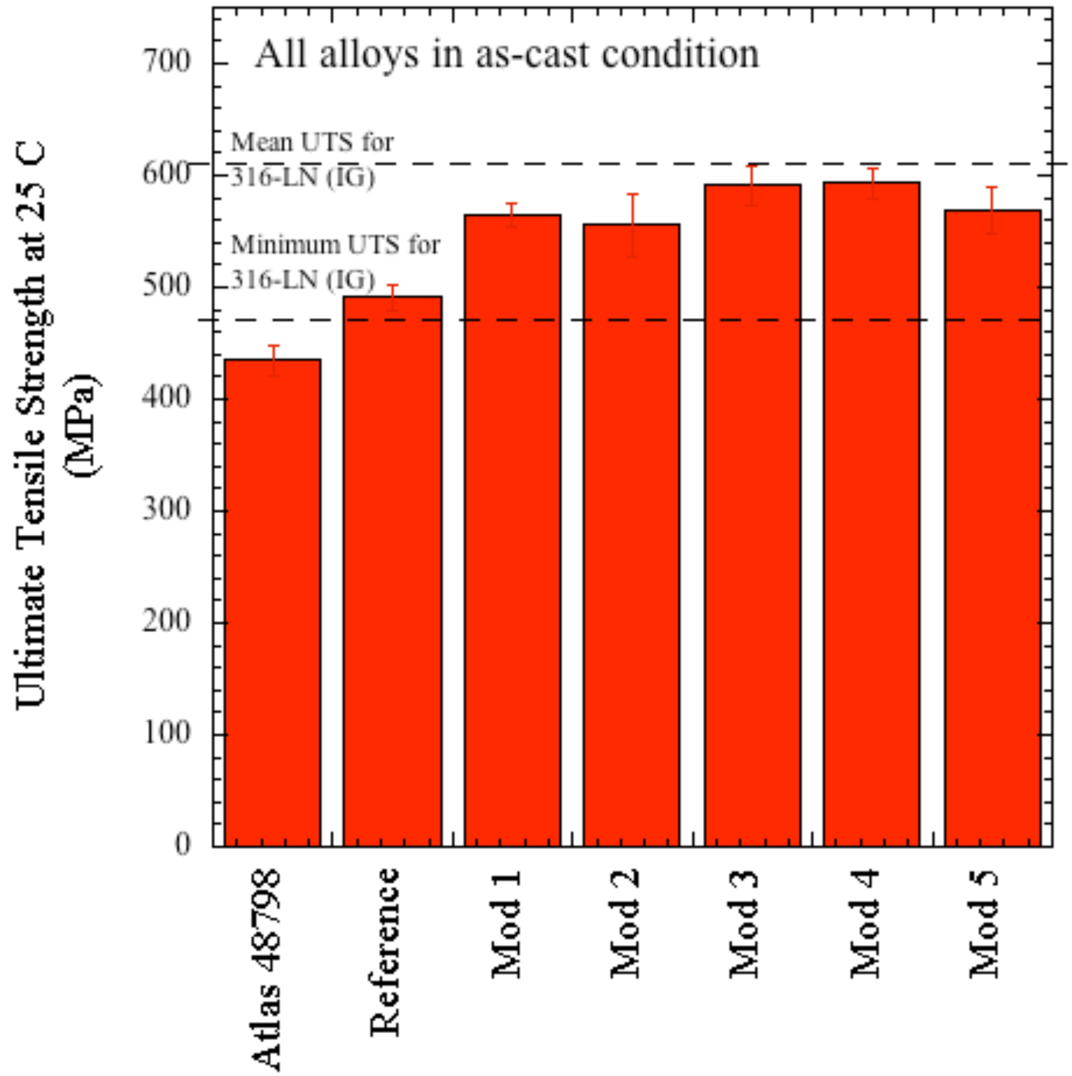
"Mod 5"

- **Alloy 213L: Fe-17.4Cr-12.6Ni-*5.1Mn*-2.5Mo- *0.32N-2.8Cu-1.0W***

Alloy	**Condition**	**YS (MPa)**	**UTS (MPa)**	**Elong. (%)**
Atlas 48798-CC	As-cast	173±14	435 ±41	52
	Annealed	216 ±17	450±17	56
	ORNL	230±15	444 ±3	46
213L	**As-cast**	**295±21**	**569±54**	**54**

Strength Comparison: UTS

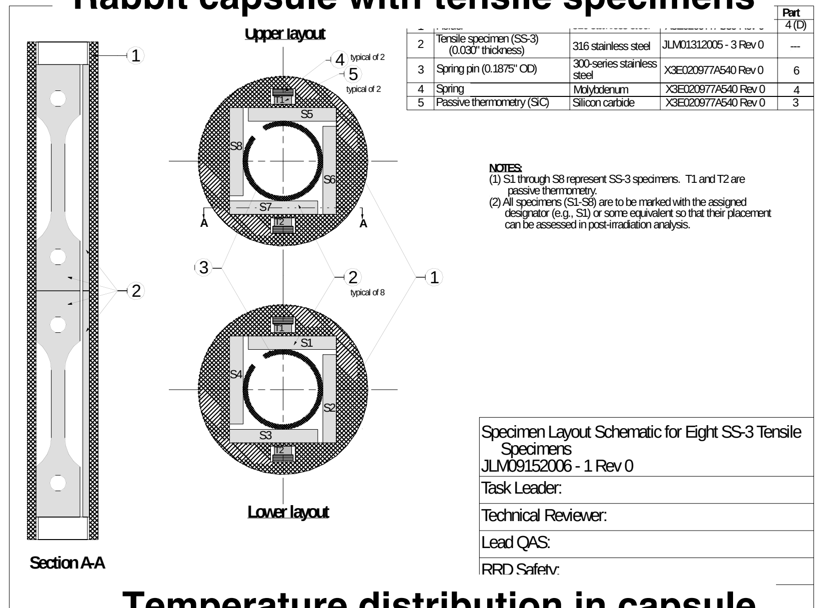
- **Tensile tests have been performed at room temperature**
- **Tests were performed on kiel blocks and samples cut from both the interior and surface regions of an ingot.**
- **All modified alloys have improved strength over archive and reference material.**



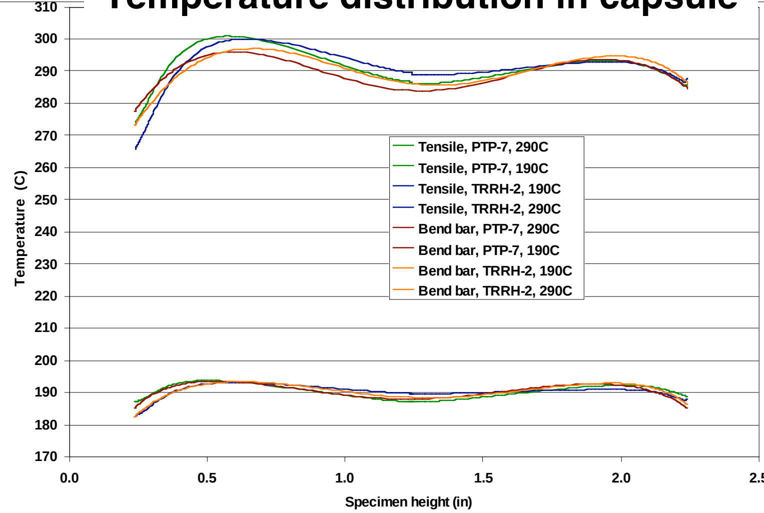
Evaluation of irradiation effects

- **Irradiations will be performed using “rabbit” capsules in the HFIR target region.**
- **An initial series of capsules will be irradiated with the archive material and wrought stainless steel controls to assess the impact second phase particles and segregation have on irradiation performance.**
- **A second series of capsules will assess the improved cast stainless steels.**

Rabbit capsule with tensile specimens



Temperature distribution in capsule



Irradiation matrix for cast SS

- **Irradiations will be conducted to provide data representative of expected ITER conditions.**

Irradiation matrix for archive material

Temperature	Fluence	dpa	Number of tensile specimens	Number of bend bar specimens
90°C	$1.8 \cdot 10^{21}$ n/cm^2	0.9	16	4
	$3.6 \cdot 10^{21}$ n/cm^2	1.8	0	0
190°C	$1.8 \cdot 10^{21}$ n/cm^2	0.9	16	4
	$3.6 \cdot 10^{21}$ n/cm^2	1.8	8	4
290°C	$1.8 \cdot 10^{21}$ n/cm^2	0.9	16	4
	$3.6 \cdot 10^{21}$ n/cm^2	1.8	8	4

Data for lower end of possible ITER cooling water

Data for most likely ITER conditions

Provides link to existing LWR database and worst case for IASCC

- **The same temperatures and fluences will be used for the improved steels.**
- **Capsules are under construction now and irradiations will be complete in summer 2007.**

Post-irradiation examination

- Following irradiation, there will be extensive PIE.
  - Tensile testing (at irradiation temperature)
  - Fracture toughness testing
  - Hardness
  - Swelling
- IASCC testing (to be performed at the University of Michigan)
  - Parallel tensile tests on multiple specimens
  - Water chemistry will be chosen to mimic ITER conditions.
- For the current budget and schedule, PIE will begin in October 2007.