Innovative Manufacturing Process for Nuclear Power Plant Components via Powder Metallurgy & Hot Isostatic Pressing Methods

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Innovative Manufacturing Process for Nuclear Power Plant Components via PM-HIP

Objective: Conduct design, manufacturing, and validation studies to assess PM-HIP as a method to produce both large, near-net shaped components for nuclear applications across 3 families of alloys:

1. low alloy steels
2. austenitic stainless steels
3. nickel-based alloys

Rolls-Royce CARPENTER HITACHI U.S. DEPARTMENT OF ENERGY

Four Years Ago at Start of DOE Project…

- No Experience in Power Industry with PM-HIP
- Good industry experience in Aerospace, Aircraft, and Off-Shore Oil & Gas:
  - However, Power Industry had/has a lot to learn….
- Began work on 316L SS and Grade 91 (toward Code Acceptance)

Since 2012….

- Four ASME Code Cases—316L SS, Grade 91, Duplex SS
- Currently working to recognize A988 (austenitics), A989 (ferritics), & B834 (nickel-base) into ASME Section II.
- Developed Detailed EPRI Roadmaps for PM-HIP
- Developed New Co-free Hardfacing Alloy--NitroMaxx
- Began research/Code acceptance to recognize A508
- Crack growth and SCC testing to support NRC recognition of 316L SS

Since 2012….

- Research at NSUF (ATR) on radiation embrittlement for multiple PM-HIP alloys—2016
- Valve and hardfacing project with EDF and Velan--2016
- ORNL/EPRI project on “Can Fabrication”
- Very Strong industrial Collaborations with Carpenter Powder Products, GE-Hitachi, Rolls-Royce, U. of Manchester, Nuclear AMRC, ORNL, Synertech.
- Initiated development of ATLAS Consortium
- Continue to strive to meet Goals established by AMM Roadmap targeting Heavy Section Manufacturing

Powder Metallurgy Methods for Large Nuclear & Fossil Components

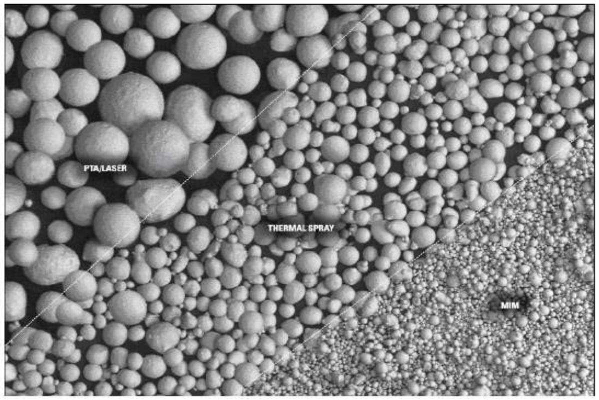
- Project Objectives
- Why Consider Powder Metallurgy for Large or Complex Nuclear Components?
- Review 7 Project Tasks & Descriptions
  - 4 major components
- Defining Success
- The Bigger Picture…

Why Consider PM-HIP for Large ALWR, SMR, or Gen IV Components?

Powder Metallurgy and Hot Isostatic Processing

- Near-net shaped (NNS) production of complex and/or large components (minimizes both machining and material volume required)
- Excellent INSPECTION characteristics
- Eliminates casting quality issues & rework
- Precise chemistry control
- Alternate supply route
- Hard-facing applications

Today’s Powder Metallurgy & Hot Isostatic Pressing (HIP)



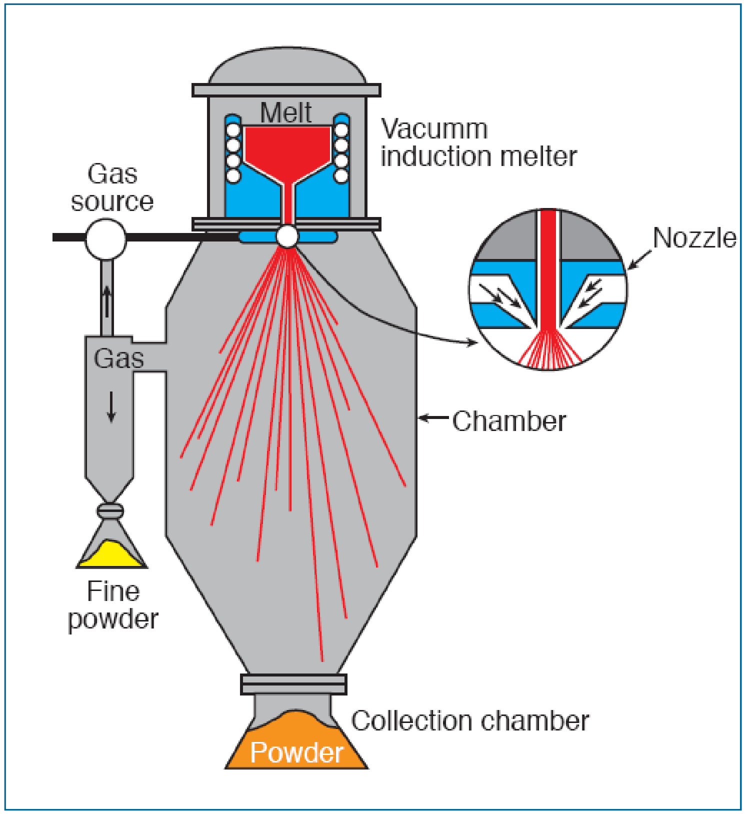
1. Gas Atomized Metal Powders

2. Mold of Component in Can

3. Hot Isostatic Pressing Apply High Pressure (>15,000psi), Temperature (>2000F)

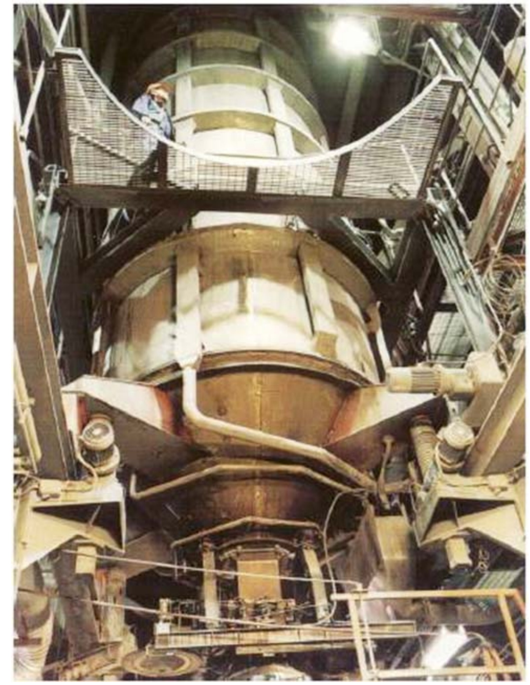
4. Final Component

The Key Difference…….



Why is Gas Atomization Important?

- No milled powders used today
- Eliminates oxides in powders & porosity in final product
- Improved packing density



(courtesy of Carpenter Technology)

Comparison of Additive Manufacturing (AM) and Powder Metallurgy-Hot Isostatic Pressing (HIP)

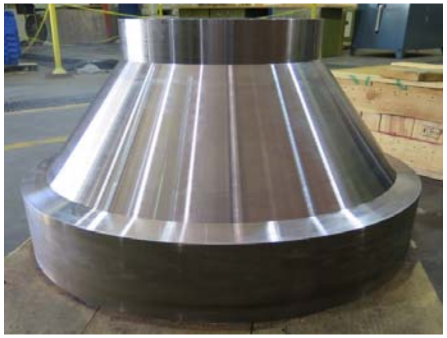
Additive Manufacturing (or 3-D Printing)

- Complex or small parts: <100 lbs
- Working envelope of ~40x40x40cm (16x16x16inch)
- Just-in-time manufacturing
- Replacement of obsolete parts
- Repeatability
- Availability schedule
- Material property enhancements
- Gradient materials (corrosion, strength, cost)

Powder Metallurgy-HIP

- Near-net shaped complex or large components (internals and valves/pumps)
- Parts up to ~60 inches (150cm) in diameter
- Improved Inspection
- Alternate supply route
- Eliminates casting quality issues/repairs
- Hardfacing applications

DOE Project Tasks



1. Modeling of NNS Component Alloy & Mold/Can Design
2. Test Coupon Development, Demonstration, & Screening for Surfacing Applications
3. Low Alloy Steel PM/HIP Component Development
4. Nickel-based Alloy PM/HIP Component Development
5. Austenitic Stainless Steel PM/HIP Development
6. Mechanical & Metallographic Characterization
7. Corrosion Testing of Test Coupons

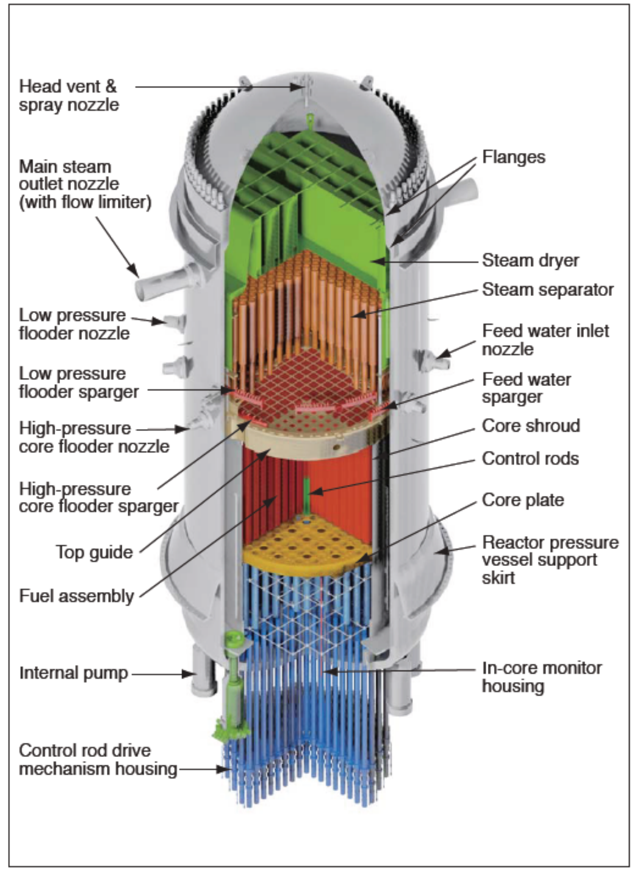
Task 5--Austenitic Stainless Steel PM/HIP Development

Lead Organization: GE-Hitachi

<u>Steam Separator Inlet Swirler</u>

(Austenitic Stainless Steel)

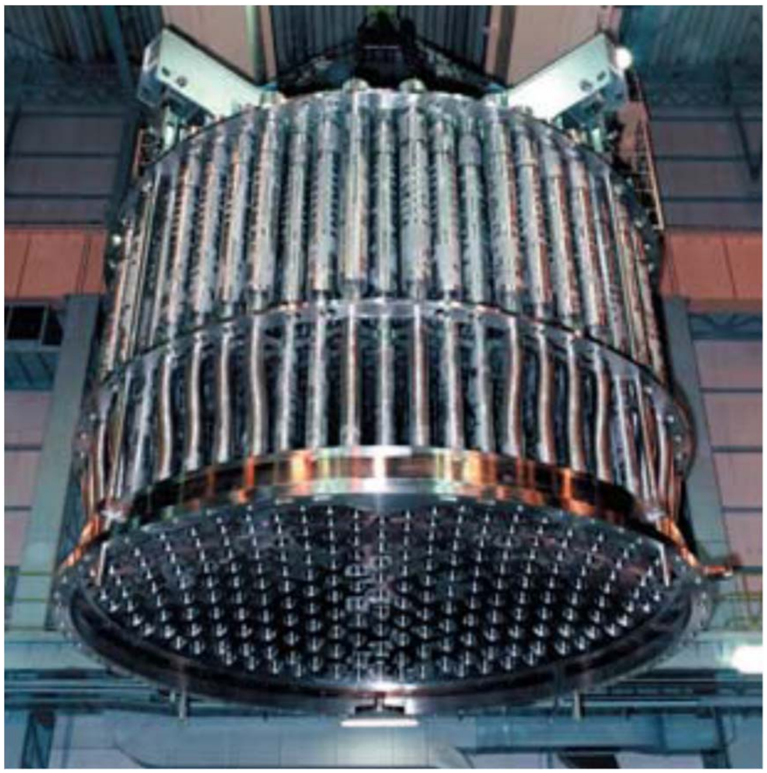
- Manufacture of a *complex geometry* to demonstrate PM/HIP for 316L SS
- SMR, ALWR, GEN IV applications
- Produce a NNS Inlet Swirl via PM/HIP
  - Evaluate dimensionally, metallurgically, and mechanically
  - Corrosion assessment is Task 7

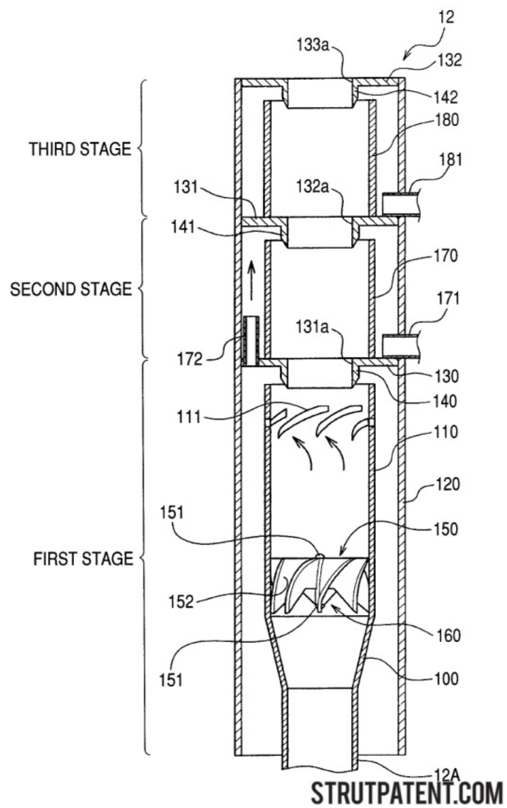


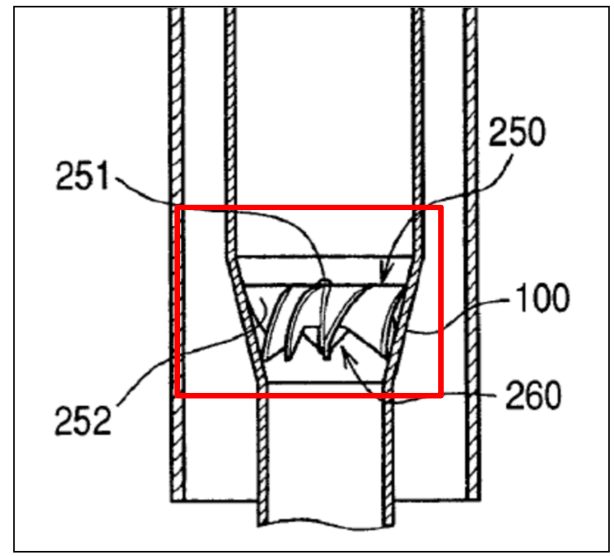
Structural sketch of reactor pressure vessel and reactor internal components

GEH → Validation of 316L PM capabilities

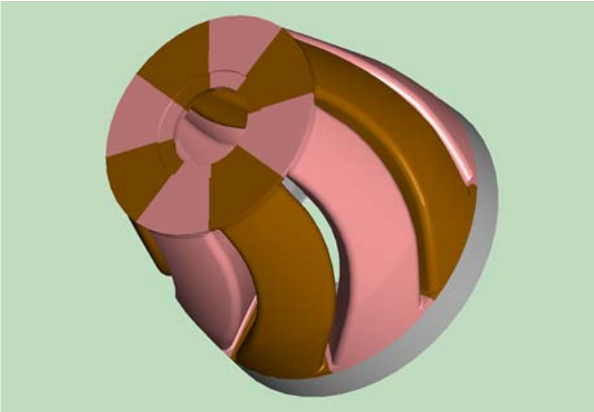
BWR or ALWR Steam Separator Inlet Swirl

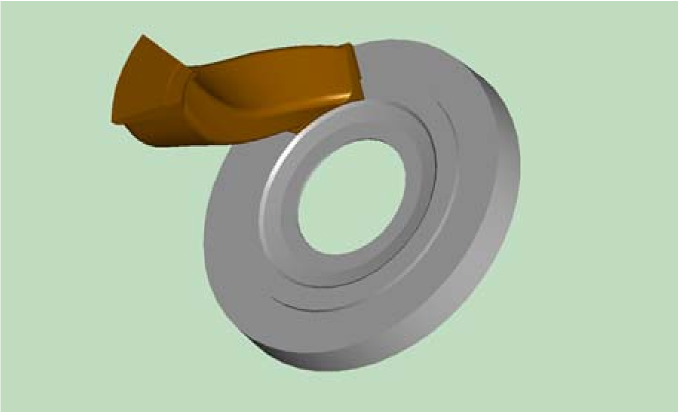






Inlet Swirler Design & Manufacture --Modeling





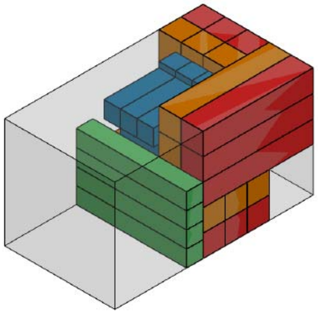
Inlet Swirler Design & Manufacture
--Fit up

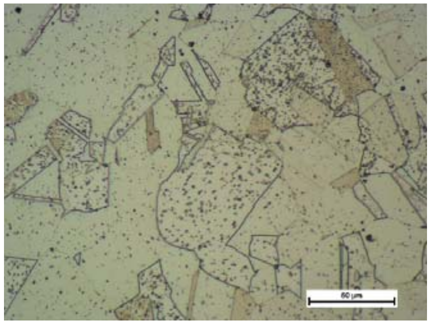
Inlet Swirler Can Design & Manufacture

Inlet Swirler Manufacture

Inlet Swirl Block—Mechanical Properties

- **Tensile Properties @ RT**
  - UTS = 88.2 ksi (608 MPa)
  - YS = 49.8 ksi (343 MPa)
  - Elongation = 50.3%
  - ROA = 73.3%





Porosity – 99.9%

Density – 7.959 g/cm^3

Grain Size – ASTM 7.0

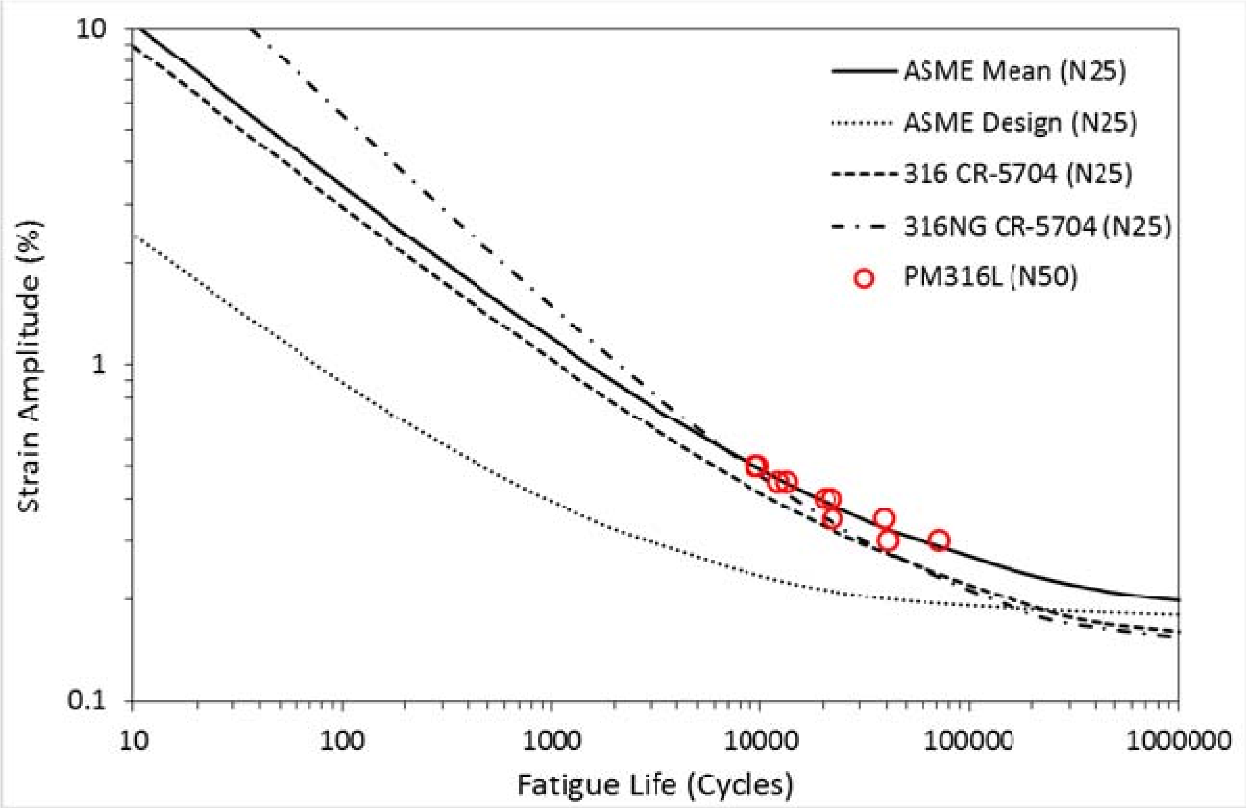
- **Toughness** (Charpy Impact)
  - 173 ft-lbs (235 J) avg across 3 directions

- **Hardness**
  - 87.0 RHB

	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	O	Fe
CF3M-ASTM A351	0.03 max	1.5 max	0.040 max	0.040 max	1.5 max	17-21.0	9-13.0	2-3.0	NA	NA	Bal
Powder	0.013	1.70	0.009	0.006	0.50	17.60	12.30	2.46	0.05	0.0145	Bal
Block--Inlet Swirl	0.014	1.73	0.023	0.007	0.49	17.67	12.34	2.49	0.04	0.02	Bal

Meets GEH 316L wrought/cast requirements

Fatigue Data—316L SS



Measured 316LSS LCF data compared with ASME and NUREG- 5704 data.

NUREG-5704: Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels

Corrosion Testing
--SCC Crack Growth Rates

- Tested as-received, 20% cold worked, and HAZ conditions
- Under BWR and PWR Conditions

- Results: PM-HIP coupons produced similar Crack Growth Rates to Wrought 316L SS

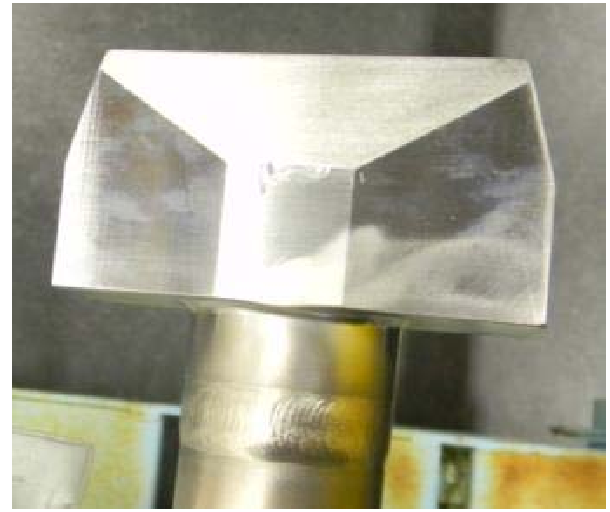
			SCC Growth Rate, mm/s	
Alloy	**Specimen**	**K, MPaÖm**	**High ECP ***	**Low ECP ***
			As-Received	
Wrought 316L	---	~40	(»3 x 10^{-8})	(»2 x 10^{-9})
PM 316L	C720	~49	~9 x 10^{-8}	~3 x 10^{-9}
PM 316L	C725	~32	~7 x 10^{-8}	~2 x 10^{-9}
			20% Cold Work	
Wrought 316L	C126	~30	~2 x 10^{-7}	~2 x 10^{-8}
PM 316L	C719	~36	~3 x 10^{-7}	~7 x 10^{-9}
PM 316L	C723	~30	~2.6 x 10^{-7}	~3 x 10^{-8}
			HAZ-Aligned	
Wrought 348	C111	28	~2.5 x 10^{-7}	~5 x 10^{-9}
PM 316L	C724	28	~5 x 10^{-8}	~2 x 10^{-9}
			As-Received	
Wrought 600	---	---	(»3 x 10^{-8})	(»2 x 10^{-9})
PM 600	C735	~37	~3 x 10^{-8}	~2.5 x 10^{-9}
			20% Cold Work	
Wrought 600	C129	~30	~2 x 10^{-7}	~2 x 10^{-8}
PM 600	C734	~33	~1.3 x 10^{-7}	~1.5 x 10^{-8}

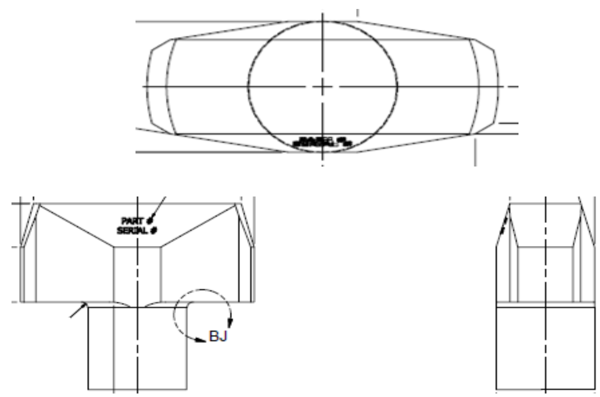
Task 4--Nickel-based Alloy (600M) PM/HIP Component Development

Lead Organization: GE-Hitachi

Chimney Head Bolt (Ni-based Alloy)

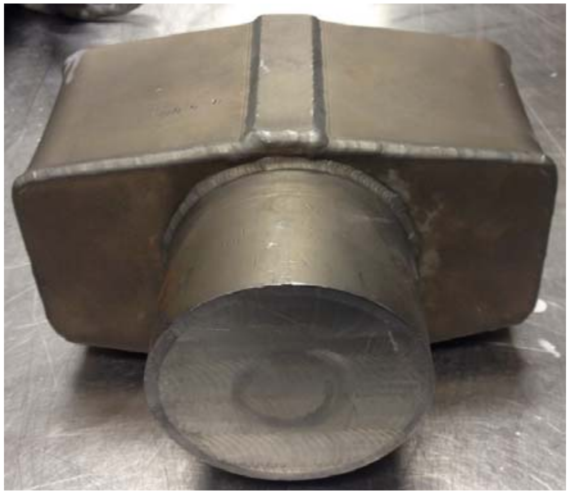
- Using PM/HIP, manufacture NNS bolt from Alloy 600M.
- Normally forged, then welded.
- Perform dimensional, microstructural, and mechanical characterization



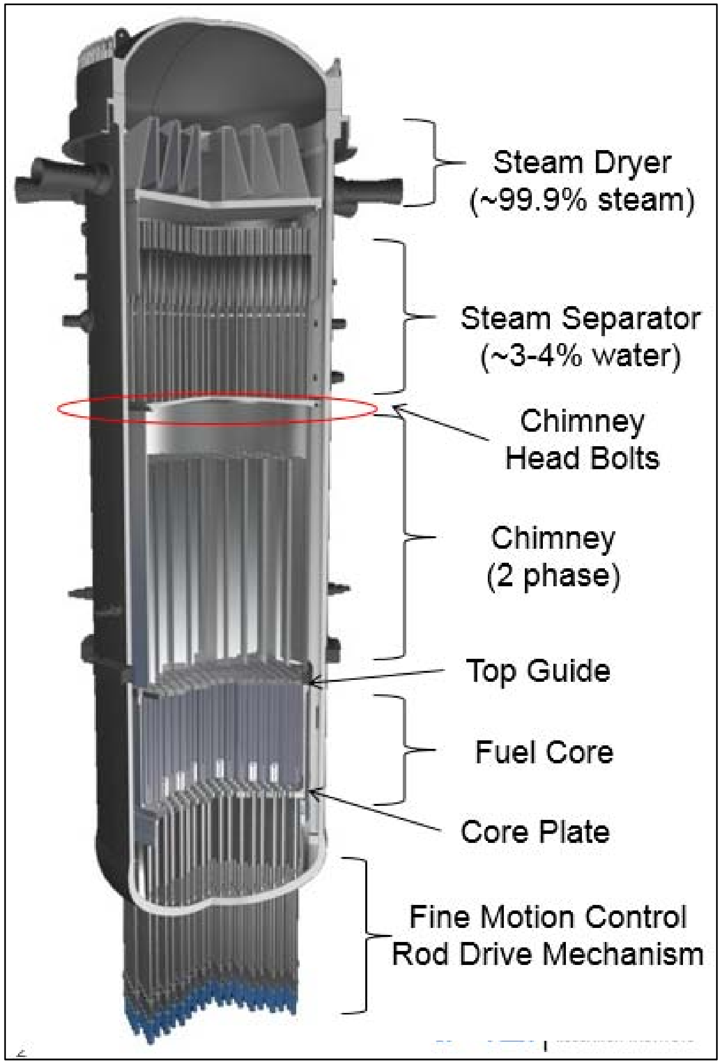


Chimney Head Bolt

Huge savings in machining and materials costs



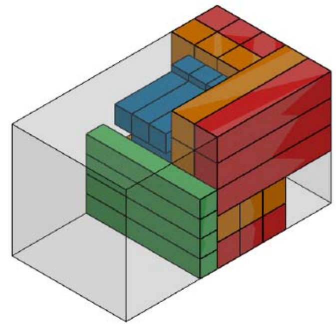
Note: Mild steel can is still attached.

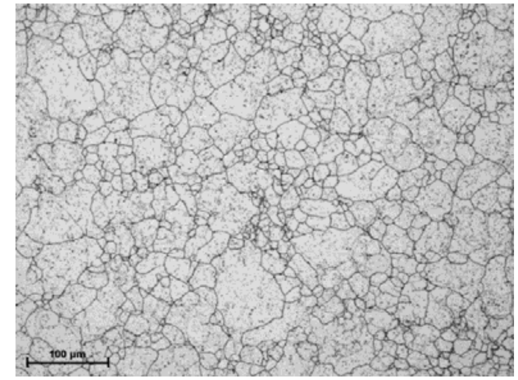


EPRI ELECTRIC POWER RESEARCH INSTITUTE

Chimney Head Test Block—Mechanical Properties

- **Tensile Properties @ RT**
  - UTS = 102.5 ksi (706 MPa)
  - YS = 46.2 ksi (318 MPa)
  - Elongation = 45.7%
  - ROA = 68.2%





- **Toughness** (Charpy Impact)
  - 144 ft-lbs (195 J) ave, 3 directions
- **Hardness**
  - 84.3 (HRB) ave

Porosity – 99.7%

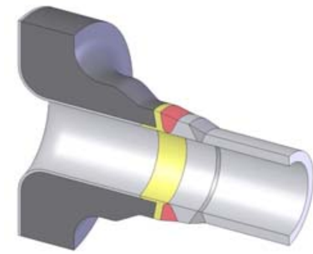
Density – 8.469 g/cm^3

Grain Size – ASTM 8.5

	C	Mn	S	Si	Cr	Ni	Cu	Fe	Cb
600-ASTM A351	0.15 max	1.00 max	0.015max	0.50 max	14.0-17.0	72min	0.50 max	6.0-10.0	N/A
600M-N-580-1	**0.05 max**	1.00 max	0.015 max	0.50 max	14.0-17.0	72min	0.50 max	6.0-10.0	**1.0-3.0**
Block – C Head Bolt	0.024	<0.01	0.001	0.05	15.96	Bal	0.02	8.73	1.31

Task 3--Low Alloy Steel PM/HIP Component Development

Lead Organization: EPRI



Reactor Pressure Vessel Steels (Low Alloy Steel)

- Demonstrate feasibility of PM/HIP to produce low alloy steel RPV sections (8 x 8 x 24” coupons) – SA508 Class 1, Grade 3 steels
- Perform mechanical & microstructural characterization
- Manufacture a NNS RPV nozzle
- Manufacture a large RPV section

Task 3. Status -- Nozzle

- Manufactured three 8” x 8” x 24” test blocks with different CE’s
- Performed tensile, hardness, Charpy, microstructural characterization

3 Test SA508 Class 1, Grade 3 Test Blocks

Table 1. Low Alloy Steel “Actual” Chemistries and Calculated Hardenability Values.

	C	*Mn*	*P*	*S*	*Si*	*Ni*	*Cr*	*Mo*	*V*	*Cu*	*Al*	C_{eq}*
A 508 Cl 3 Min	--	1.20	--	--	--	0.40	--	0.45	--	--	--	--
A 508 Cl 3 Max	0.25	1.50	0.025	0.025	0.40	1.00	0.25	0.60	0.05	0.20	0.025	--
Carpenter 160114	0.20	1.46	0.011	0.003	0.16	0.84	0.13	0.50	0.01	0.02	0.02	0.62
Carpenter 160115	0.24	1.48	0.012	0.008	0.018	0.85	0.19	0.55	0.01	0.03	0.02	0.69
Carpenter 160116	0.17	1.26	0.014	0.006	0.18	0.84	0.09	0.48	0.01	0.03	0.02	0.55

*C_{eq} = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4

Task 3. Status –
Test Block Properties

Grade: SA508

Heat	O	N
160114	0.024	0.022
160115	0.022	0.018
160116	0.018	0.020

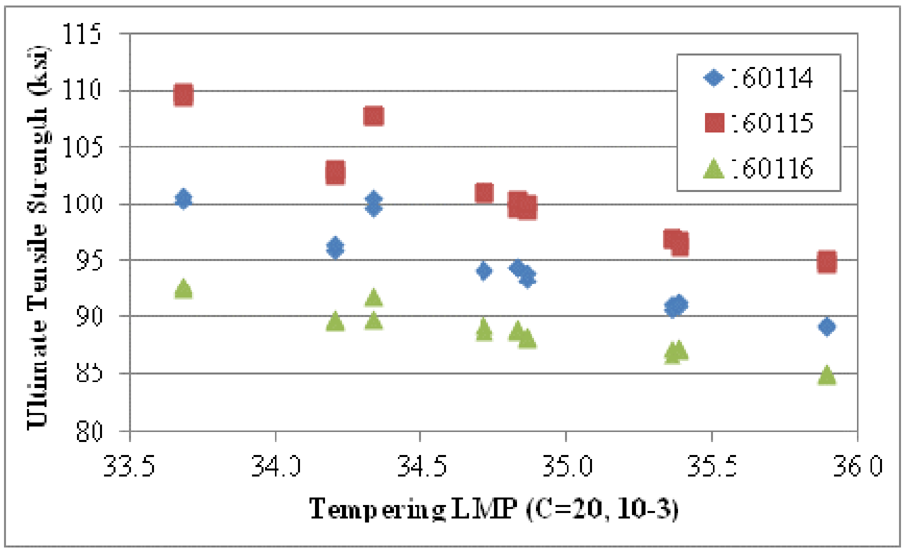
Temperature	Tempering Time (h)		
1175 °F	4	10	20
1200	4	10	20
1225	4	10	20

- Low – CE = 0.55 ➡ 160116
- Med – CE = 0.62 ➡ 160114
- High – CE = 0.69 ➡ 160115

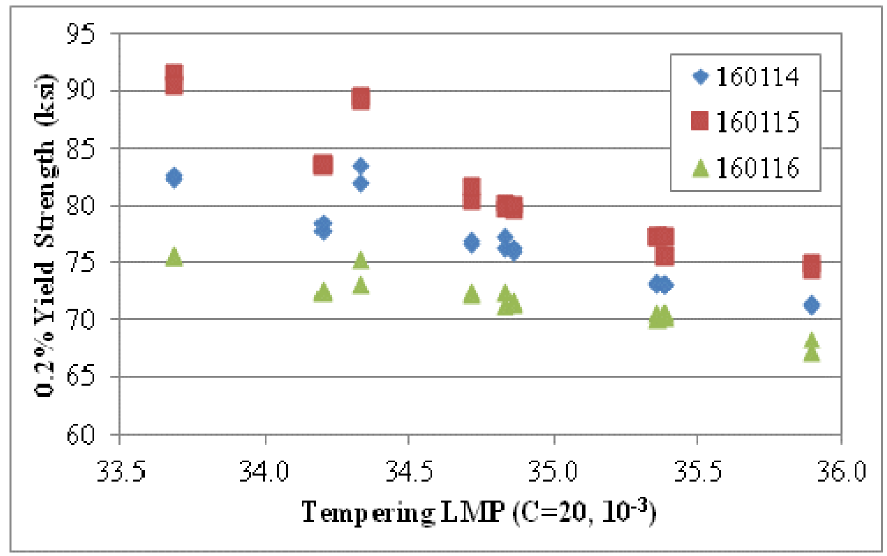
Task 3. Status –
Test Block Properties

Low –160116
Med –160114
High –160115

Ultimate Tensile Strength (ksi)



Yield Strength (ksi)



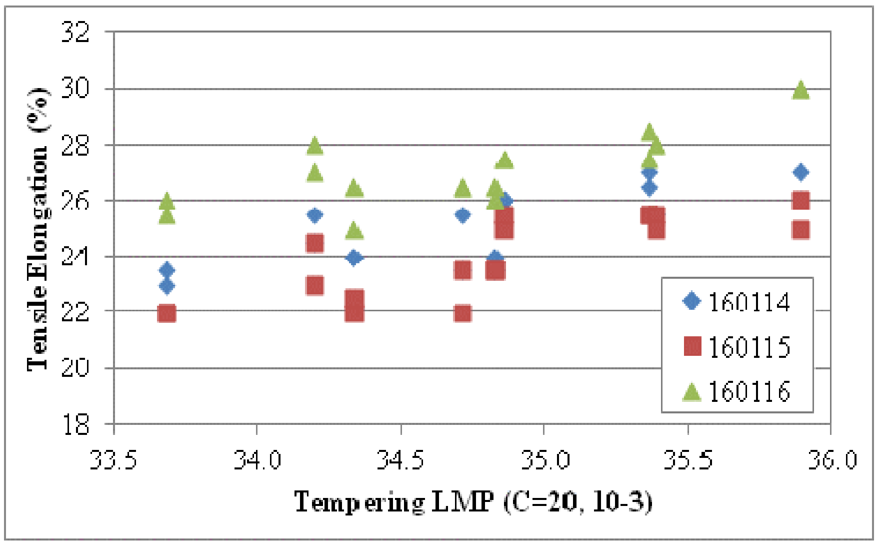
- UTS ranged from 85-110 ksi (586-758 MPa)
- YS ranged 67-92 ksi (462-634 MPa)

UTS spec = 85-105 ksi
YS spec = >50 ksi

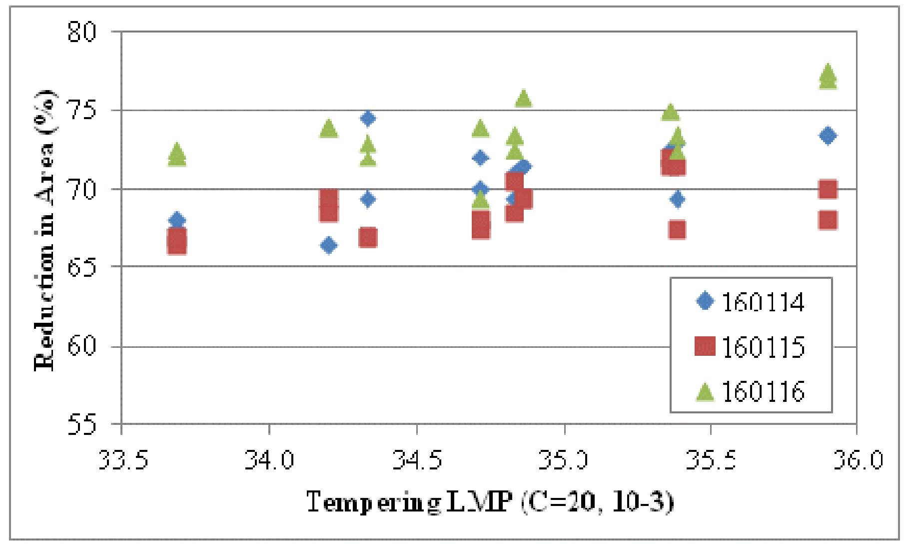
Task 3. Status – Test Block Properties

Low –160116
Med –160114
High –160115

Elongation (%)

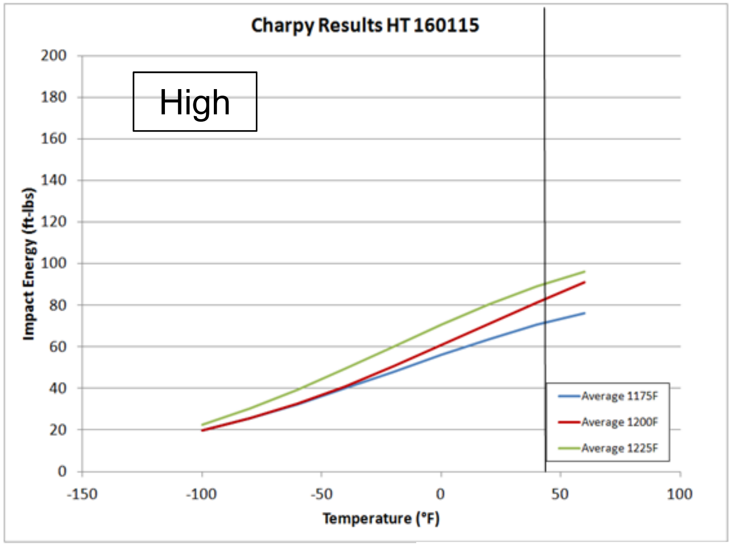


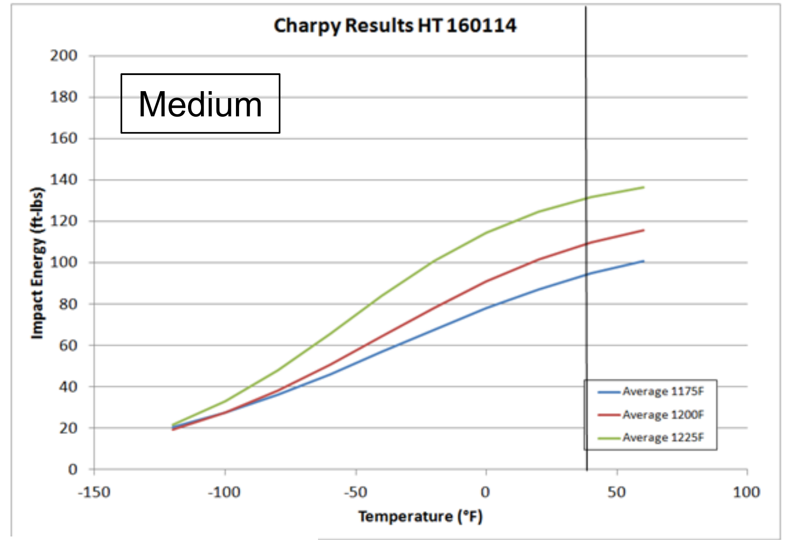
Reduction of Area (%)

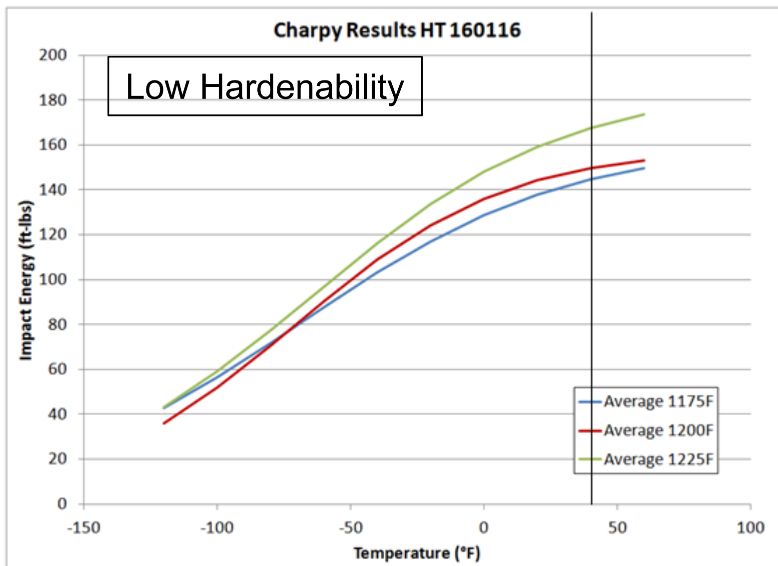


- Elongation: 22-30%
- ROA 67-77%

Spec Elongation = 18% min
Spec ROA = 38% min

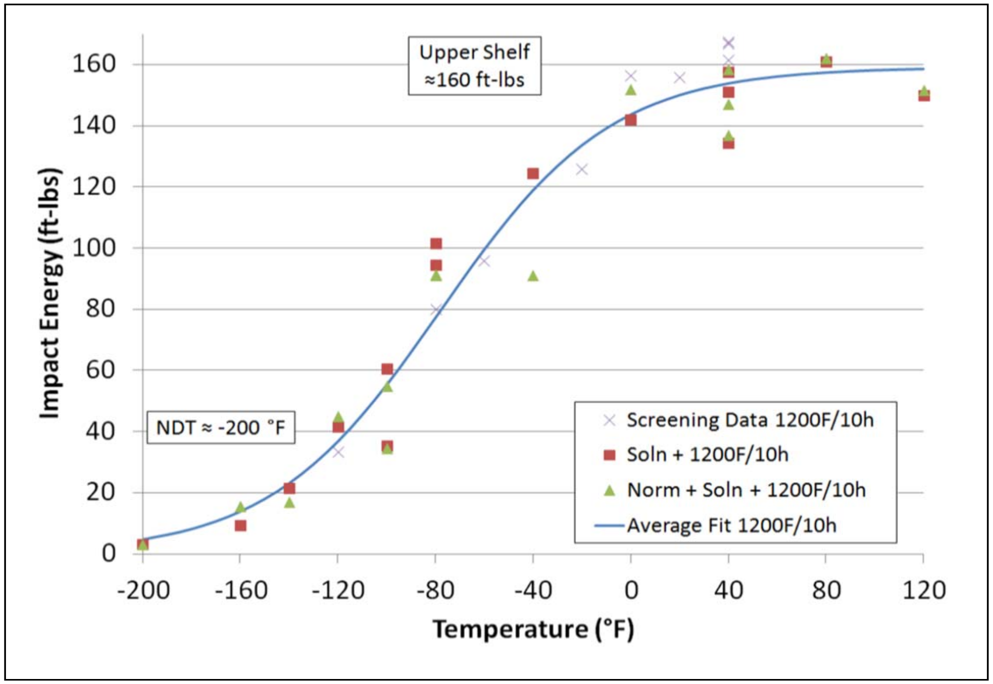

Charpy Results HT 160115
High
Impact Energy (ft-lbs)
Temperature (°F)
Average 1175F
Average 1200F
Average 1225F


Charpy Results HT 160114
Medium
Impact Energy (ft-lbs)
Temperature (°F)
Average 1175F
Average 1200F
Average 1225F

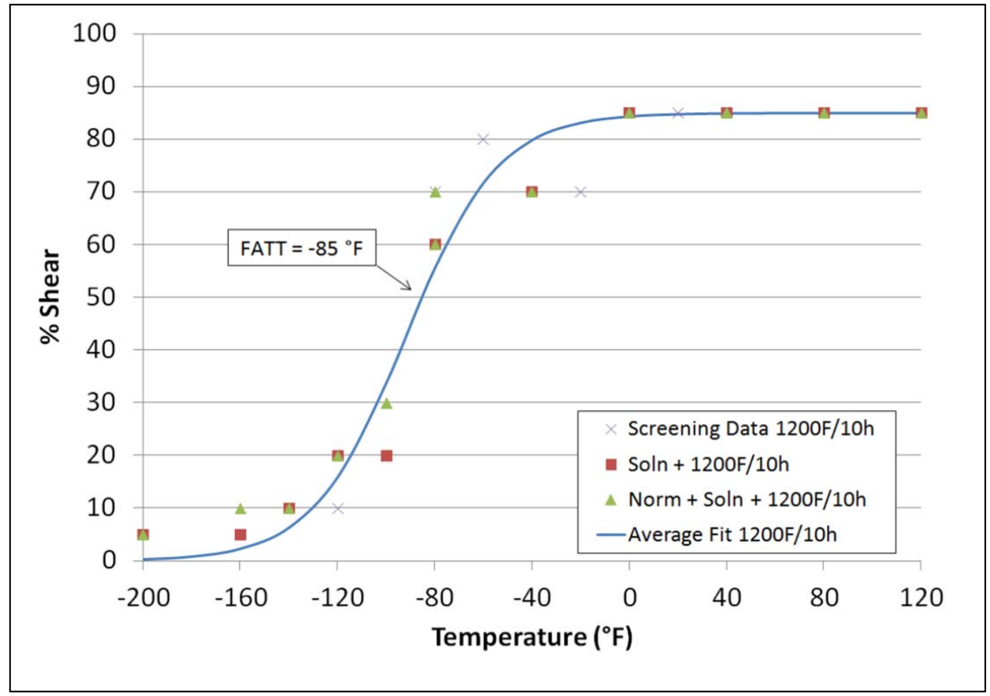

Charpy Results HT 160116
Low Hardenability
Impact Energy (ft-lbs)
Temperature (°F)
Average 1175F
Average 1200F
Average 1225F

Charpy Impact Data for the Low Hardenability Test Block

Charpy Impact vs Temperature

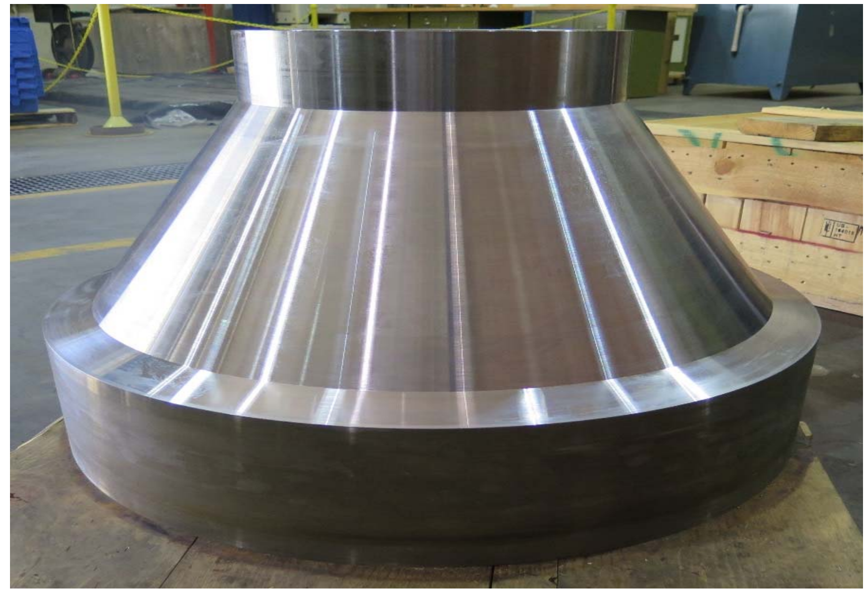


Percent Shear vs Temperature



Solution Annealed at 2050F/10hrs, quenched, normalized 1650F and tempered at 1200F/10 hrs

A 508, Class 1, Grade 3 Nozzle



- Manufactured a NNS 16” BWR Feedwater Nozzle
  - 3700 lbs
  - 36 inches vessel diameter x 16 inches pipe diameter

A 508, Class 1, Grade 3 Ring Section

Defining Success….

- Success in this project was defined as:
  1. Manufacture of 4 large components from low alloy steel, stainless steel, and a Ni-based alloy (3 different alloy families)
     - Nozzle, curved RPV section, steam separator inlet swirl, chimney held bolt.
     - Establish design criteria, shrinkage & NNS quality
  2. Generate excellent mechanical properties, along with good product chemistry & uniform grain size
  3. Application of wear resistant surfacing material to a substrate alloy
  4. Corrosion performance comparable to forgings

Summary

PM-HIP for Structural & Pressure Retaining Applications:

- Large, complex, near-net-shape components
- Alternate supply route for long-lead time components
- Improves inspectability
- Eliminates rework or repair in castings
- Hardfacing applications

The Team….

- Lou Lherbier & Dave Novotnak (Carpenter Powder Products)
- Myles Connor, James Robinson, Ron Horn (GE-Hitachi)
- Steve Lawler and Ian Armson (Rolls-Royce)
- Will Kyffin (N-AMRC)
- Dave Sandusky (X-Gen)
- Ben Sutton, Dan Purdy, Alex Summe (EPRI)

Together…Shaping the Future of Electricity