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 GE HITACHI

U.S. DEPARTMENT OF ENERGY

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Three 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)

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Since 2012….

- Three ASME Code Cases—316L SS and Grade 91
- Developed Detailed EPRI Roadmaps for PM-HIP
- Developed New Co-free Hardfacing Alloy--NitroMaxx
- Initiated R&D aimed at Eliminating DMWs—Phase 2
- Began research/Code acceptance to recognize several other alloys:
  - 304L, 625, 690, 718, and SA508
  - ASTM and ASME
  - Aimed at SMRs and ALWRs
- Crack growth and SCC testing to support NRC recognition of 316L SS

Since 2012….

- Very Strong Collaborations with Carpenter Technology, GE-Hitachi, Rolls-Royce, U. of Manchester, NAMRC, ORNL, Synertech.
- Research at NSUF (ATR) on radiation embrittlement for multiple PM-HIP alloys—starts in 2016
- Valve and hardfacing project with EDF and Velan (2016)
- ORNL/EPRI project on “Can Fabrication”
- 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 Intricate Nuclear Components?
- Optimize an Alloy for Nuclear Performance
- Review 7 Project Tasks & Descriptions
  – Highlight 2 Components Manufactured
- Defining Success
- EPRI Roadmap on PM-HIP
- The Bigger Picture…

Why Consider Powder Metallurgy-HIP To Produce Pressure Components?

- Industry leadership in the manufacture of large NPP components (Gen III & SMRs)
  - eg., RPVs, SG, valves, pumps, turbine rotors
- Transformational technology
  - Moves from forging and rolled & welded technologies to powder met/HIP
- Enables manufacture of large, complex "*Near-Net Shape*" components
- Excellent Inspection characteristics
- Eliminates casting quality issues
- Alternate supply route for long-lead time components

P/M-HIP Valve

Optimize An Alloy for Nuclear Performance

Valve/Pump Housing/Flange

- Tensile/Yield Strength
- Adequate Ductility & Toughness
- Weldability (optional)
- Corrosion Performance

RPV Internals

- Tensile/Yield Strength
- High Ductility & Toughness
- Weldabililty
- Corrosion Performance
- Fatigue Resistance
- Radiation Resistance
- Good Inspection Characteristics

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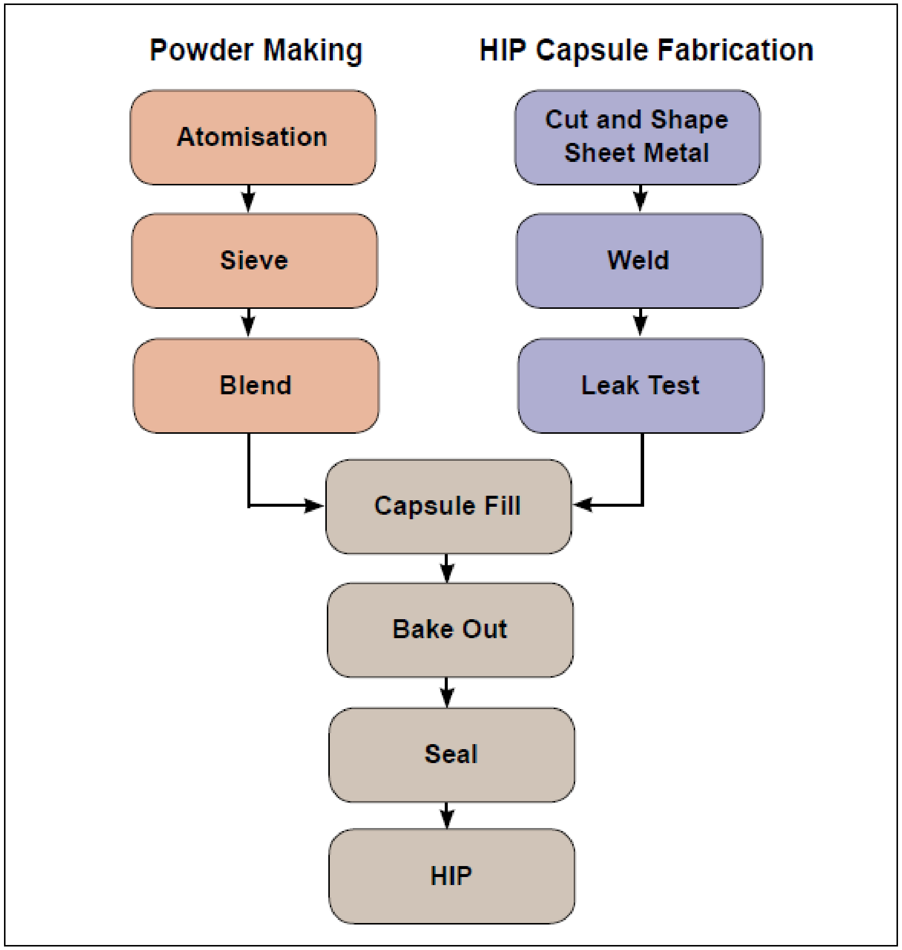
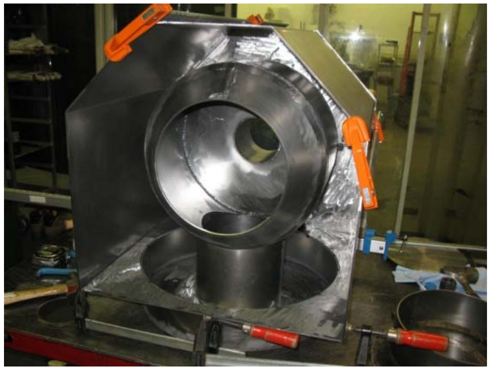
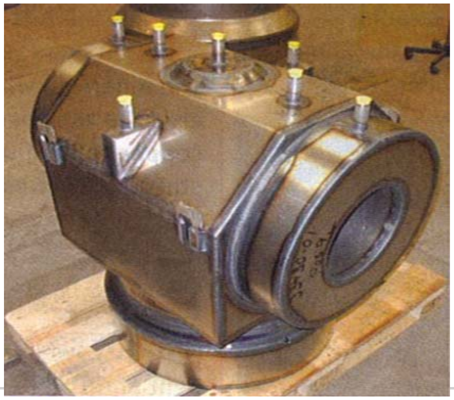
- Near-Net Shape Capabilities
- Alternate Supply Route for Long-Lead Time Components

Powder Metallurgy-Hot Isostatic Processing



Courtesy of Steve Mashl, Z-Met Corporation

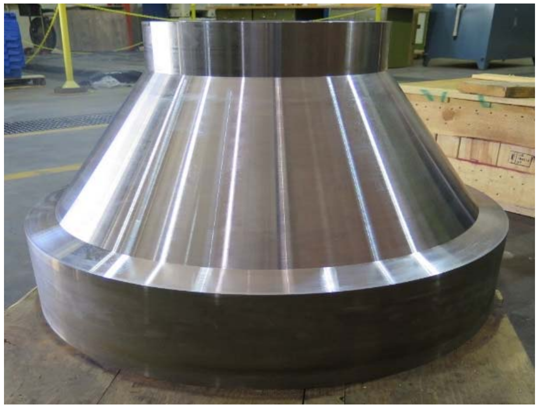




(courtesy of Carpenter Technology)

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



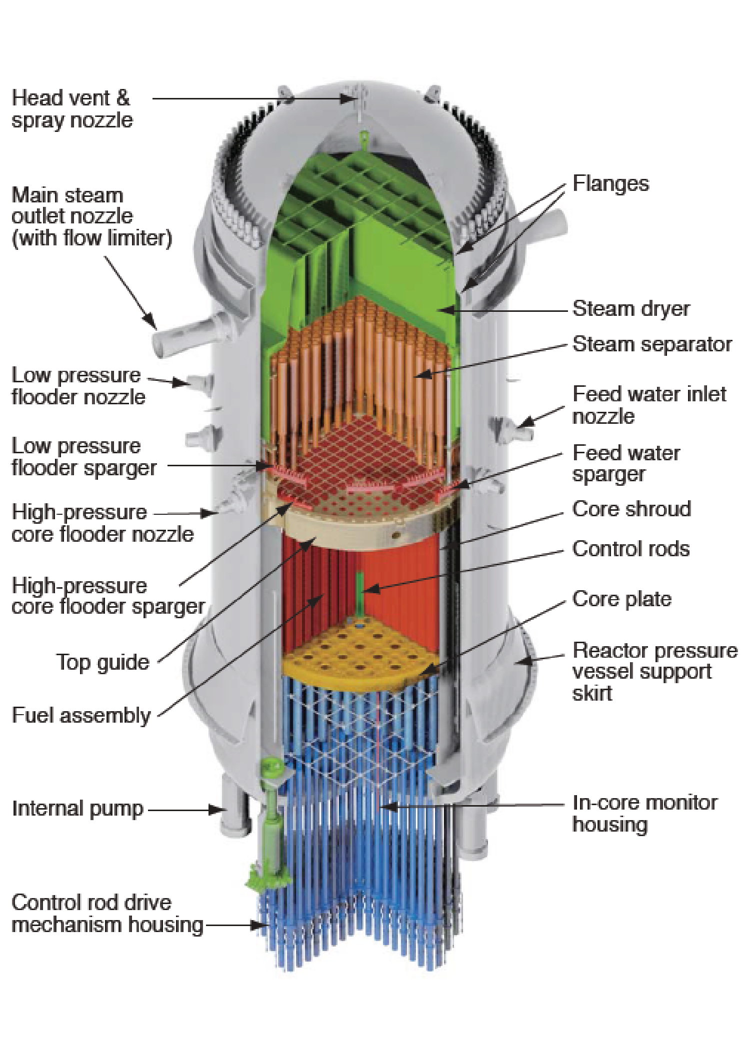
Task 5--Austenitic Stainless Steel PM/HIP Development

Lead Organization: GE-Hitachi

<u>Steam Separator Inlet Swirler</u>

(Austenitic Stainless Steel)

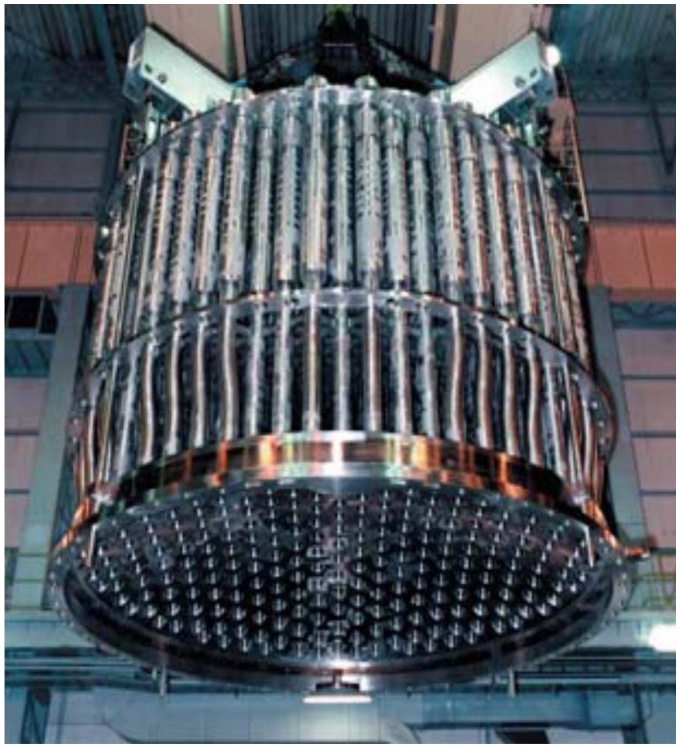
- Manufacture of a *complex geometry* to demonstrate PM/HIP for 316L SS
- SMR and ALWR applications
- Produce a NNS Inlet Swirl via PM/HIP
  - Evaluate dimensionally, metallurgically, and mechanically
  - Corrosion assessment is Task 7
  - **Status: <u>Year-3</u> (2015).**

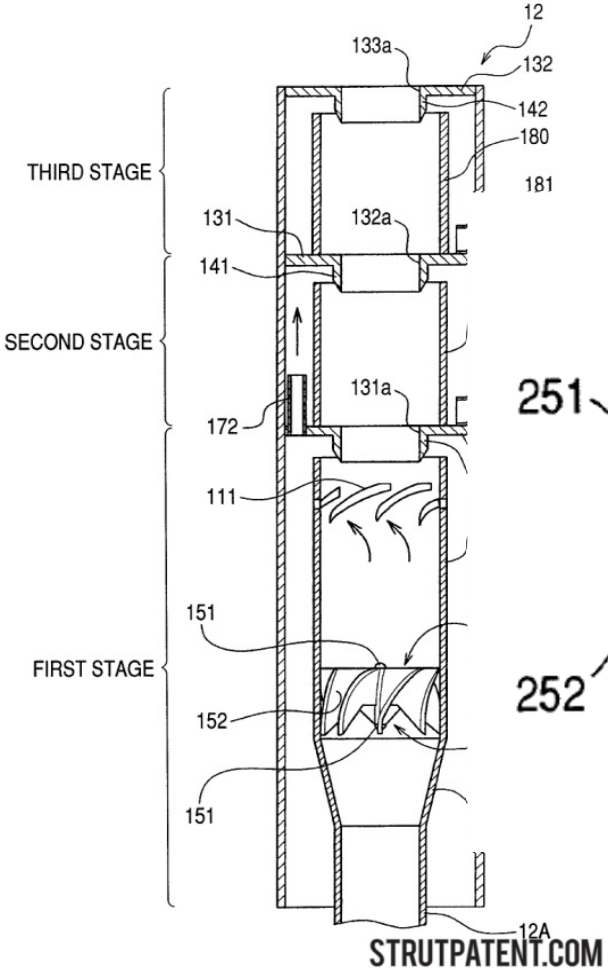


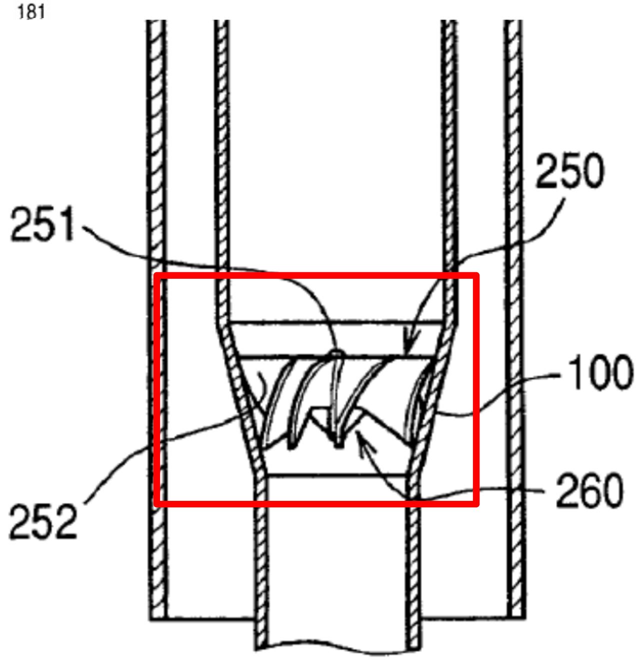
Structural sketch of reactor pressure vessel and reactor internal components

GEH → Validation of 316L PM capabilities

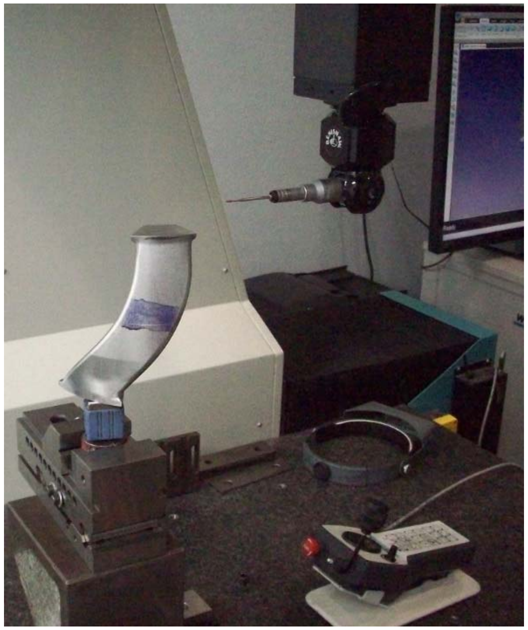
BWR or ALWR Steam Separator Inlet Swirl

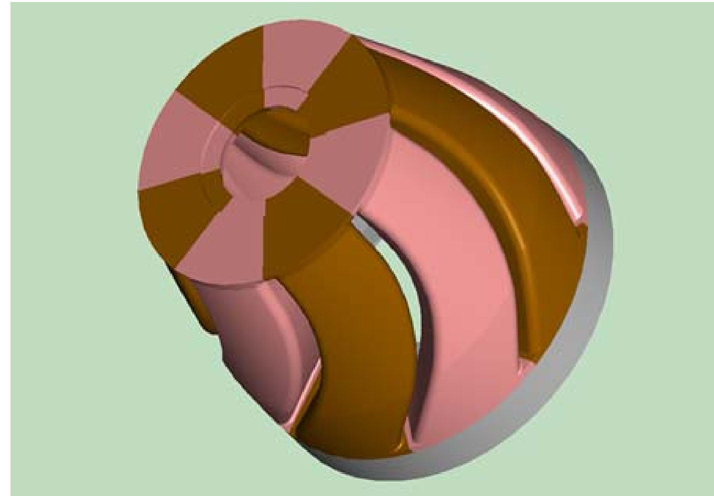


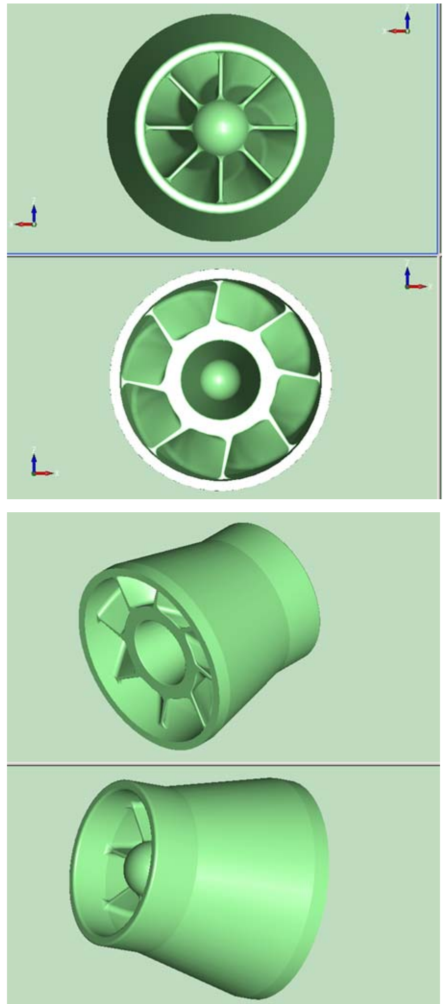


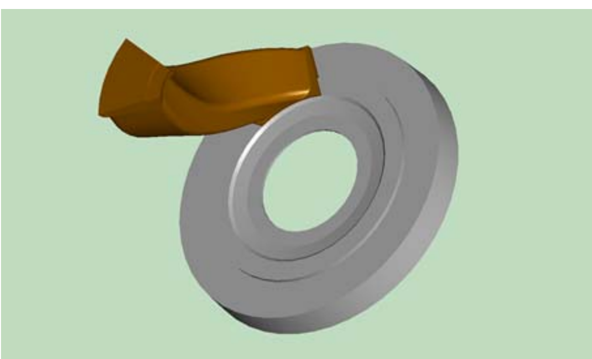


Inlet Swirl
-- 3D Geometry



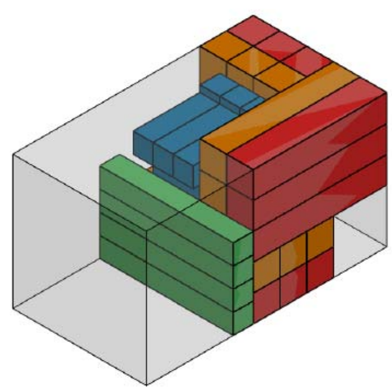


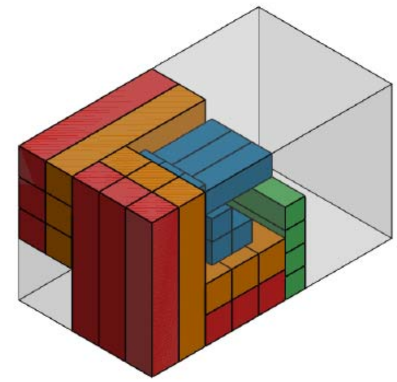




Vane Insert—one of 8
that fit into the swirler

Inlet Swirl Block—Mechanical Properties

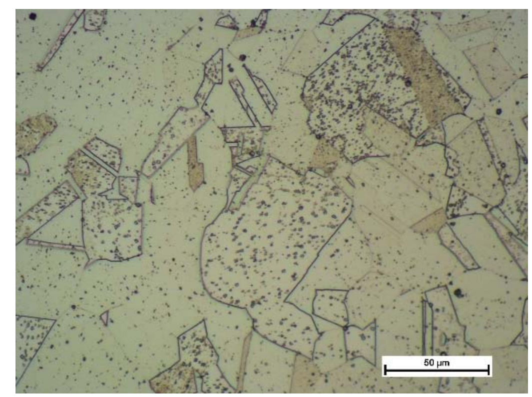




- **Tensile Properties @ RT**
  - UTS = 88.2 ksi (608 MPa)
  - YS = 49.8 ksi (343 MPa)
  - Elongation = 50.3%
  - ROA = 73.3%

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

- **Hardness**
  - 87.0 RHB

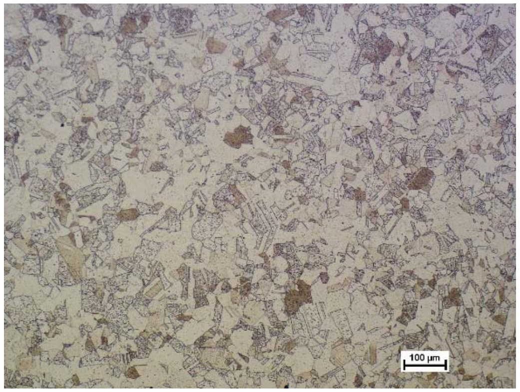


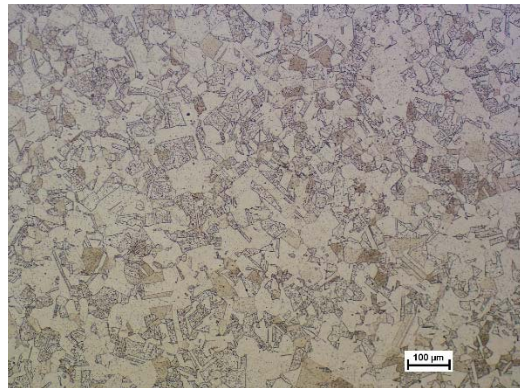
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	O	Fe
CF3M-ASTM A351	0.03 max	1.5 max	0.040 max	0.040 max	1.5 max	17-21.0	9-13.0	2-3.0	NA	NA	Bal
Powder	0.013	1.70	0.009	0.006	0.50	17.60	12.30	2.46	0.05	0.0145	Bal
Block--Inlet Swirl	0.014	1.73	0.023	0.007	0.49	17.67	12.34	2.49	0.04	0.02	Bal

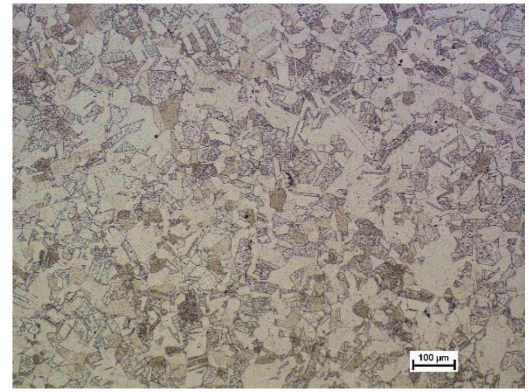
Meets GEH 316L wrought/cast requirements

Sensitization Susceptibility (ASTM A262) -- Acceptable

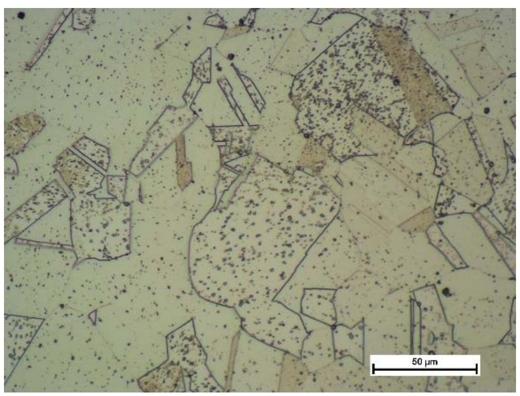
100x

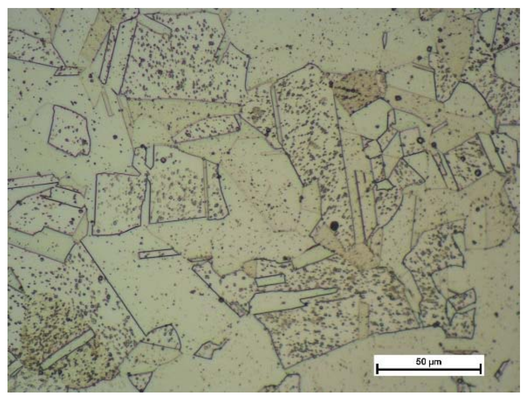


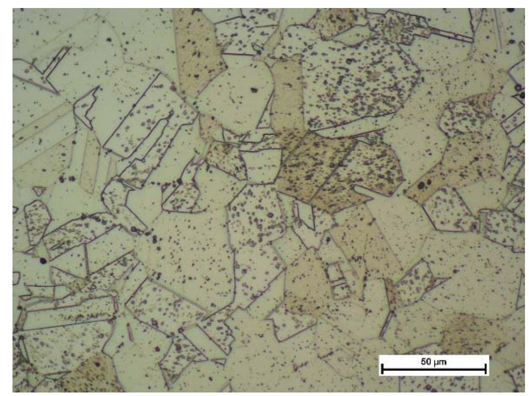




500x







Direction 1 | Direction 2 | Direction 3

Density, Porosity, Inclusions, Grain Size

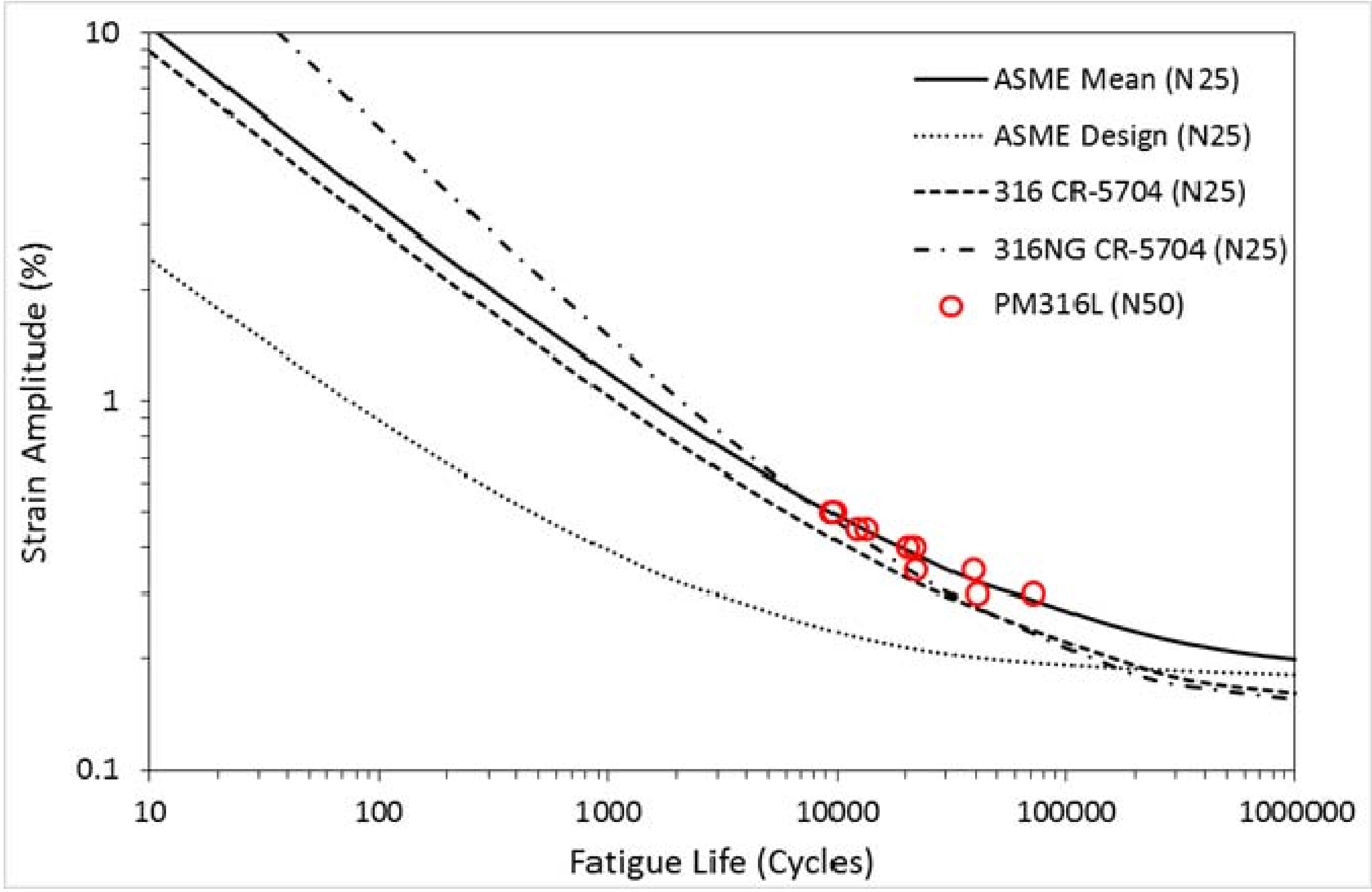
- Porosity – 99.9%
- Density – 7.959 g/cm^3
- Grain Size – ASTM 7.0

Laboratory Number	Type A	Type B	Type C	Type D	Series	Direction
15757-MET1	0	0.5	0	2.0	Thin	X
	0	0	0	1.0	Heavy	
15757-MET2	0	0.5	0	2.5	Thin	Y
	0	0	0	0.5	Heavy	
15757-MET3	0	0.5	0	2.0	Thin	Z
	0	0	0	1.0	Heavy	

Samples were taken at the longitudinal direction and examined at 100x magnification.
Method(s): ASTM E45-13

Grain structure and inclusion content exceed GEH SS CRB wrought 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

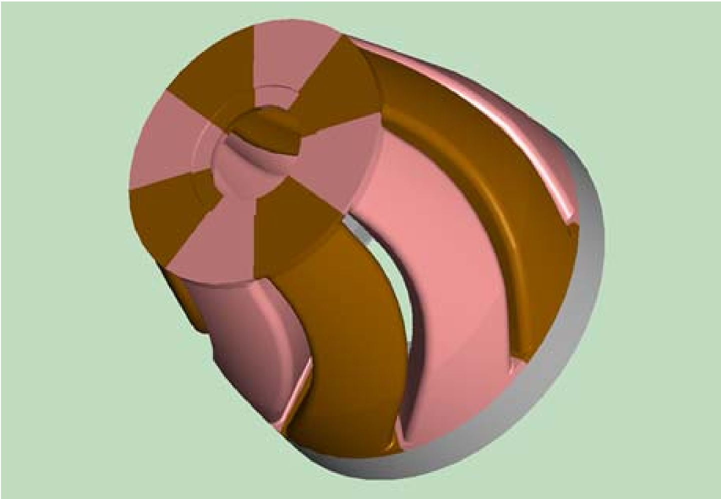
Corrosion Testing
--SCC Crack Growth Rates (Preliminary Results)

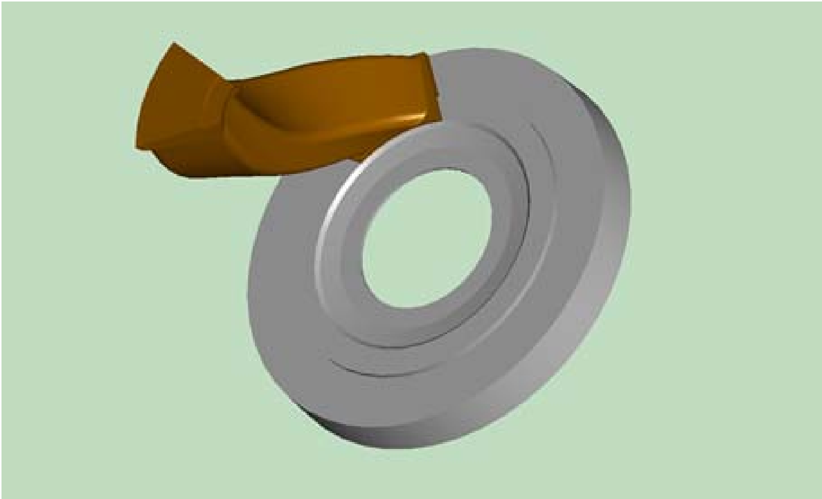
Preliminary Table of SCC Growth Rates of Wrought and Powder Metallurgy 316L and 600M
288C Water with 20 ppb Sulfate as H_2SO_4 – ~30 MPa√m

			SCC Growth Rate, mm/s	
Alloy	**Specimen**	**K, MPa√m**	**High ECP**	**Low ECP**
			As-Received	
Wrought 316L	---	~40	(≈3×10^{-8})	(≈2×10^{-9})
PM 316L	C720	~40	~1×10^{-7}	~2×10^{-9}s
			20% Cold Work	
Wrought 316L	C126	~30	~2×10^{-7}	~2×10^{-8}
PM 316L	C719	~30	~2×10^{-7}	~1×10^{-8}
			As-Received	
Wrought 600	---	~35	(≈2×10^{-8})	(≈1×10^{-9})
PM 600M	C735	35	5×10^{-8}	2×10^{-9}
			20% Cold Work	
Wrought 600	C129	30	2×10^{-7}	3×10^{-8}
PM 600M	C734	30	1×10^{-7}	1×10^{-8}

* High ECP is 2 ppm O_2, which is ~150 – 200 mV_{she} Low ECP is 63 ppb H_2 which is ~-510 mV_{she}

Inlet Swirler Design & Manufacture --Modeling





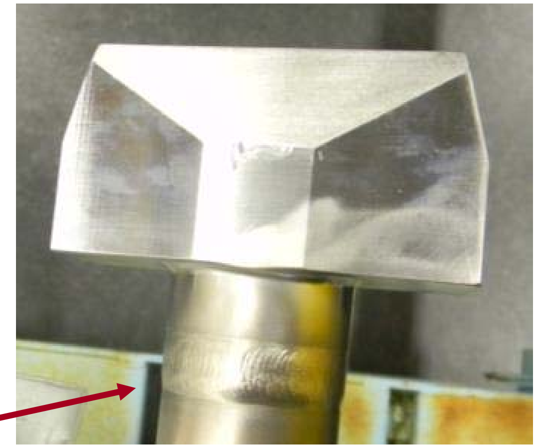
Inlet Swirler Design & Manufacture --Fit up

Inlet Swirler Can Design & Manufacture

Inlet Swirler Manufacture

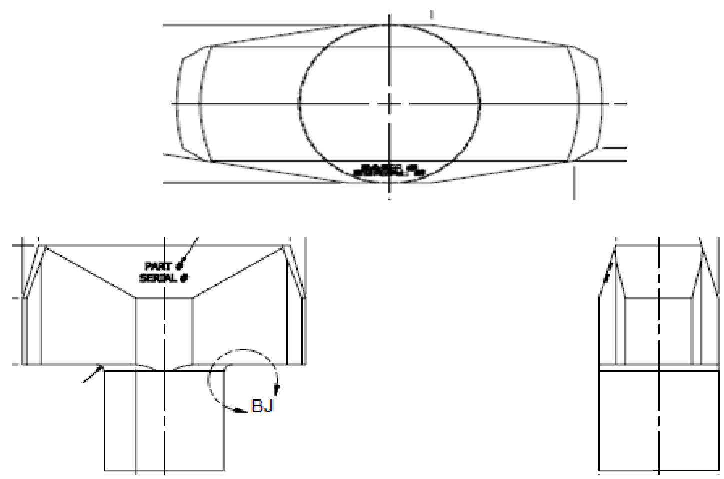
Task 4--Nickel-based Alloy (600M) PM/HIP Component Development

Lead Organization: GE-Hitachi



<u>Chimney Head Bolt</u> (Ni-based Alloy)

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



Status: <u>Year-3</u> (2015).

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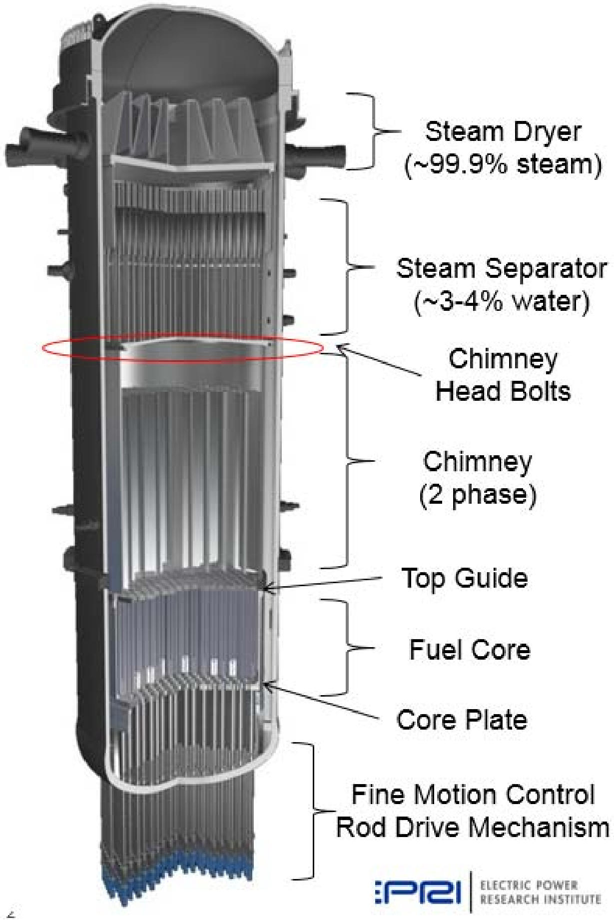
Chimney Head Bolt

Note: Mild steel can is still attached.



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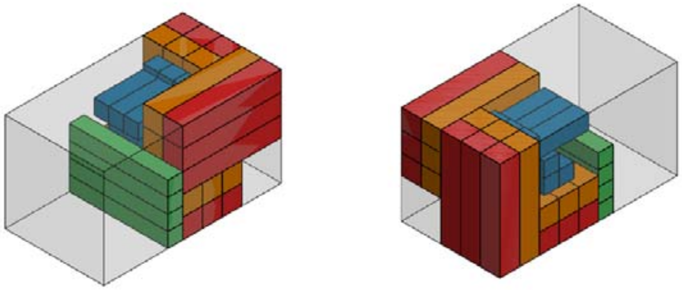
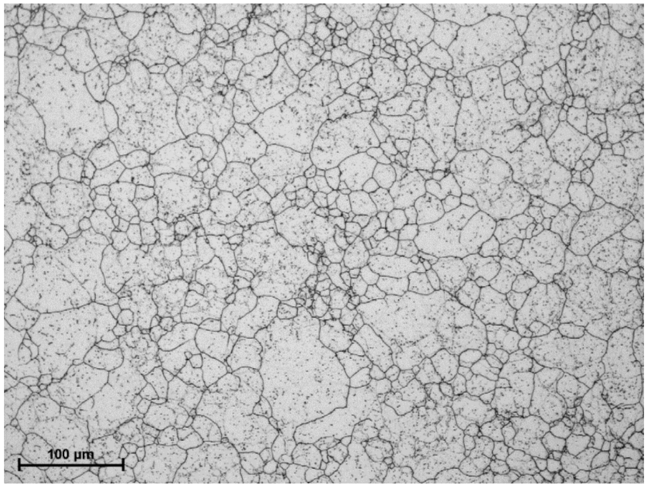
Chimney Head Test Block—Mechanical Properties

- **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





	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

Density, Porosity, Inclusions, Grain Size

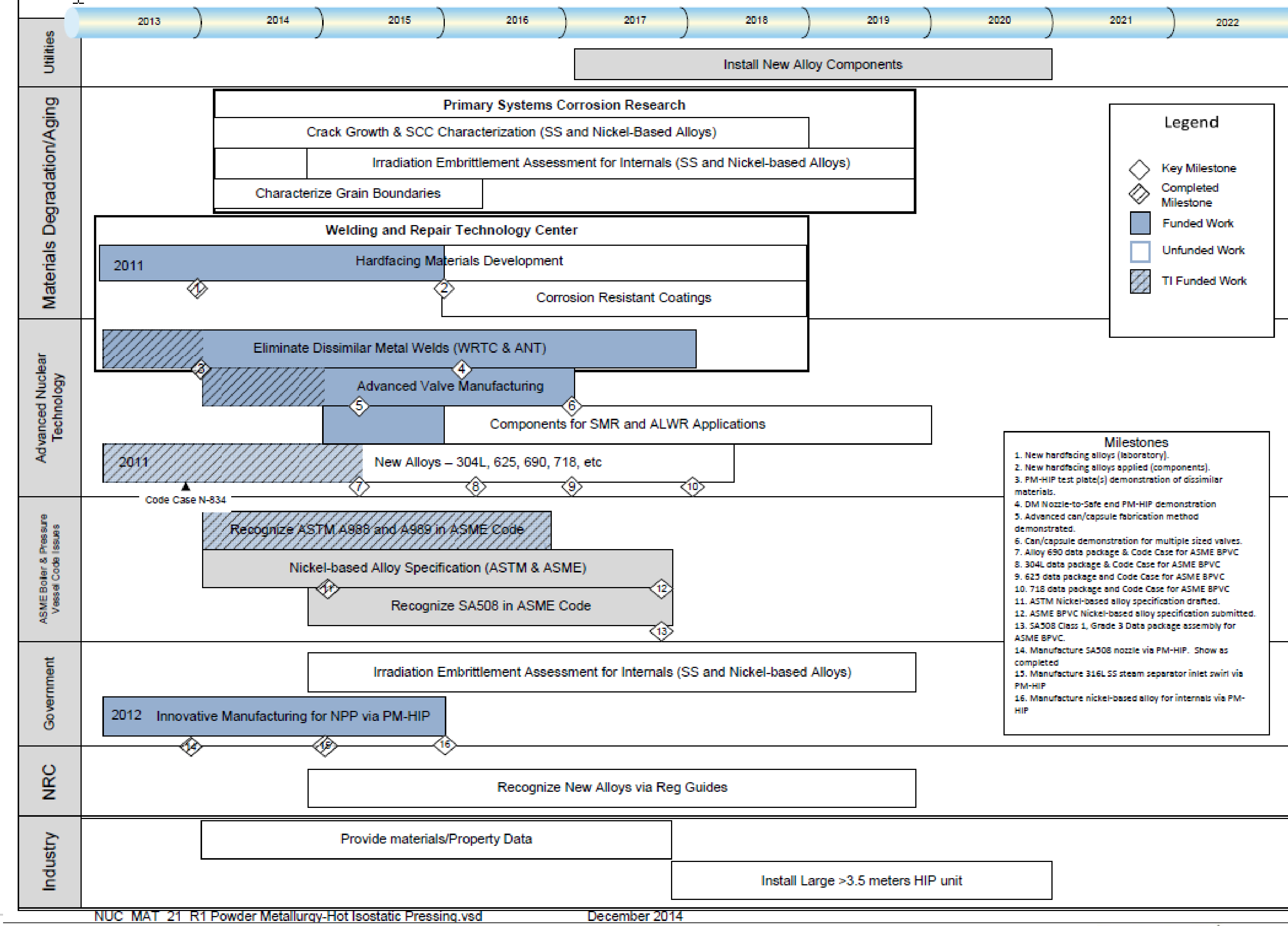
- Porosity – 99.7%
- Density – 8.469 g/cm^3
- Grain Size – ASTM 8.5

Lab Number	Type A	Type B	Type C	Type D	Series	Direction
5977-MET1	0	0.5	0	0.5	Thin	X
	0	0	0	0	Heavy	
5977-MET2	0	0	0	0.5	Thin	Y
	0	0	0	0	Heavy	
5977-MET3	0	0.5	0	0.5	Thin	Z
	0	0	0	0	Heavy	
Samples were taken at the longitudinal direction and examined at 100x magnification						
Method(s): ASTM E45-13						

Defining Success….

- Success in this project is 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

Powder Metallurgy-Hot Isostatic Pressing for RPV Internals and Pressure Retaining Applications



Technology Gaps/Applications Covered by PM-HIP Roadmap (1)

- Recognize ASTM A988 & A989 in ASME Code
- Nickel-based Alloy Specification Additions (ASTM and ASME)
- Recognize Alloys—304L, 625, 690, 718 & Property Data
- Recognize SA508 (RPV steels) in ASME Code
- Components for SMR and ALWR Applications
- Crack Growth and SCC Characterization (SS and Ni-based)
- Irradiation Embrittlement Assessment for Internals

Technology Gaps/Applications Covered by PM-HIP Roadmap (2)

- Hard-facing Materials Development
- Eliminate Dissimilar Metal Welds
- Advanced Valve Manufacturing
- Innovative Manufacturing for Nuclear
- Silicon Carbide Alloys
- Recognize Alloys via Regulatory Guides (NRC)
- Corrosion Resistant Coatings

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 Bigger Picture……

Supporting DOE AMM Roadmap toward Heavy Section Manufacturing

Highest Priority Items

1. Develop technical position paper that allows welds in vessels outside the beltline region.
2. Develop/Demonstrate Powder metallurgy – HIP of Plate (Ring Sections)
3. Develop/Demonstrate Nozzle Manufacturing Capabilities
4. Install/Commission large diameter HIP Unit – 3.1 meters
5. Manufacture vessel internals via nickel-based alloys

The Team….

- Lou Lherbier & Dave Novotnak (Carpenter Technology)
- 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