Qualification of Laser Powder Bed Fusion-AM for Nuclear Pressure Retaining Applications

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Advanced Manufacturing for Nuclear: Applications, Techniques, Needs, and Challenges and AMM Annual Program Review
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Outline

- Background on AM
- Anticipated Nuclear Applications—Laser-Powder Bed Fusion #
- Qualification of L-PBF-AM for Nuclear Pressure Retaining # Applications #
  – ASME Data Package Development
  – Component Builds (not just X,Y,45-degree)
  – Code Case Development
  – Project Status

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Lots of Additive Manufacturing Technologies…

- *Binder jetting* – **metals,** polymers, ceramics, composites, **fuels**, and prototyping
- ***Powder bed fusion*** – **metals,** composites, and polymers
- ***Directed energy deposition*** – **metals**
- *Material extrusion* – polymers, composites, **metals**, and plastics
- *VAT photopolymerization* – polymers and plastics
- *Material jetting* – polymers, plastics, composites, prototyping
- *Sheet lamination* – paper, plastic, sheet materials

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Only Two AM Technologies Applicable for “Nuclear Metallic” Components %

Laser-Powder Bed Fusion (L-PBF)

- Parts/Components **up to ~50lbs**
- Uses laser or electron beam to melt or fuse powder together in bed of powder
- **Common names**:
  - #Direct laser metal sintering (DLMS)
  - #Electron beam melting (EBM)
  - #Selective laser melting (SLM)
  - #Selective heat sintering (SHS),
  - #Selective laser sintering (SLS)

Directed Energy Deposition (DED)

- Parts/Components **up to ~500lbs**
- Wire or powder fed through nozzle into laser or electron beam
- Fundamentally welding using robotics/ computer controls.
- **Common names**:
  - #Electron Beam DED—Wire
  - #Electron Beam-enabled Advanced Manufacturing (E-Beam) #
  - #Laser Direct Energy Deposition-Powder
  - #Laser Direct Energy Deposition-Wire
  - #Laser-Wire Directed Deposition
  - #Wire Plus Arc AM (WAAM)
  - #Shaped Energy Deposition (SED)
  - #Bulk Area Manufacturing (BAM)

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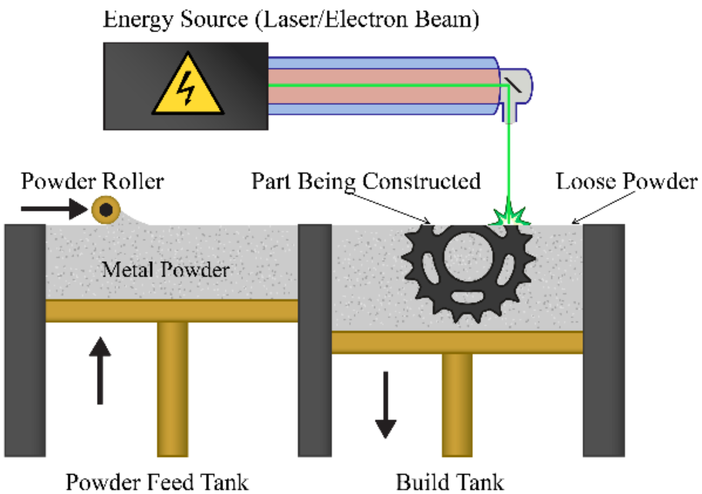
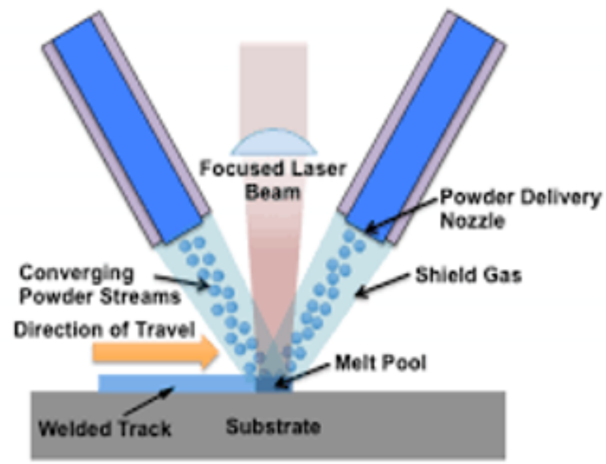
Laser-PBF vs. Directed Energy Deposition AM

Laser-PBF



courtesy of 3DEO

Directed Energy Deposition



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Why Is Industry Interested in AM Technologies?

1. #Produce replacement parts for the **existing fleet** with # a very short turn around #
   - Obsolete parts—remember some units are over 40 years old #
2. #Produce new or complex parts for the **new fleet** of ALWRs, SMRs and Gen IV applications #
3. #Design to include improved flow characteristics or # special features that can't be done through # casting/forging/ machining #
4. #Introduce favorable properties via unique # microstructures #
5. #Design for performance

Chamber size: 250mm x 250mm x 300mm (~10x10x12)
(courtesy of Renishaw)

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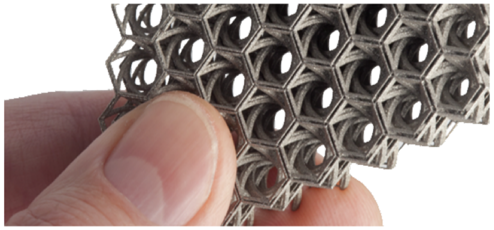
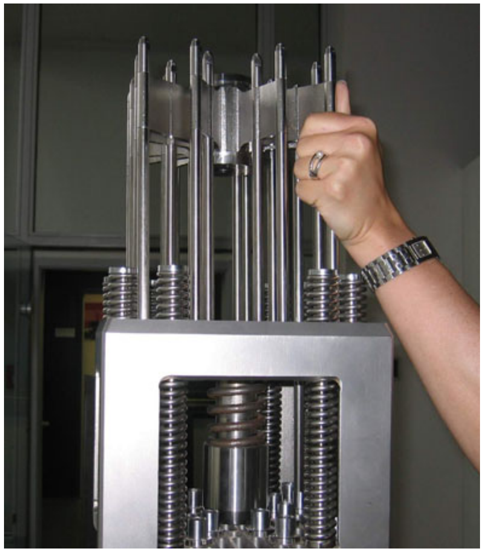
Examples: Nuclear Applications for Laser-PBF AM *
--Reactor Internals and Fuel Assemblies *



- **Smaller parts (<50 lbs, 23kgs)**

Potential Reactor Internals

- Small valves, tees, wyes
- Fuel assemblies (next slide)
- Control rod drive internals
- Alignment pins & springs
- Small spray nozzles
- Instrumentation brackets
- Stub-tube/housing
- Steam separator inlet swirler
- Flow deflectors
- GEN IV—cooling channels



PWR Control Rod Assembly

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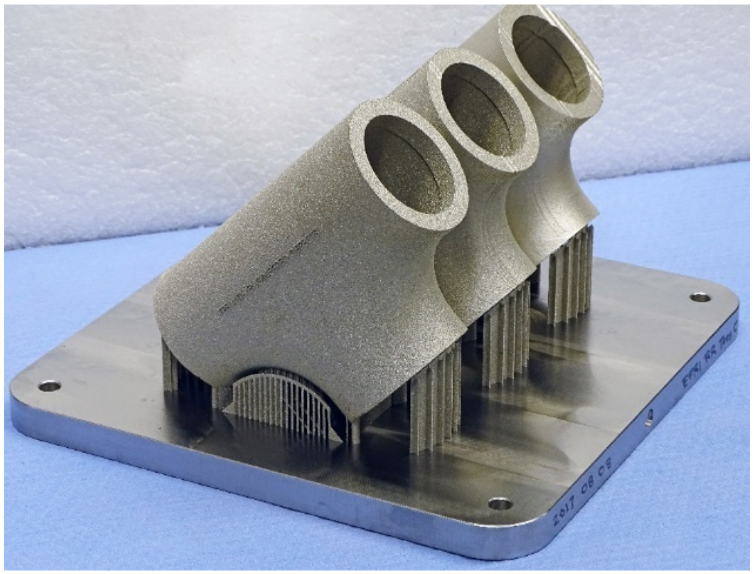
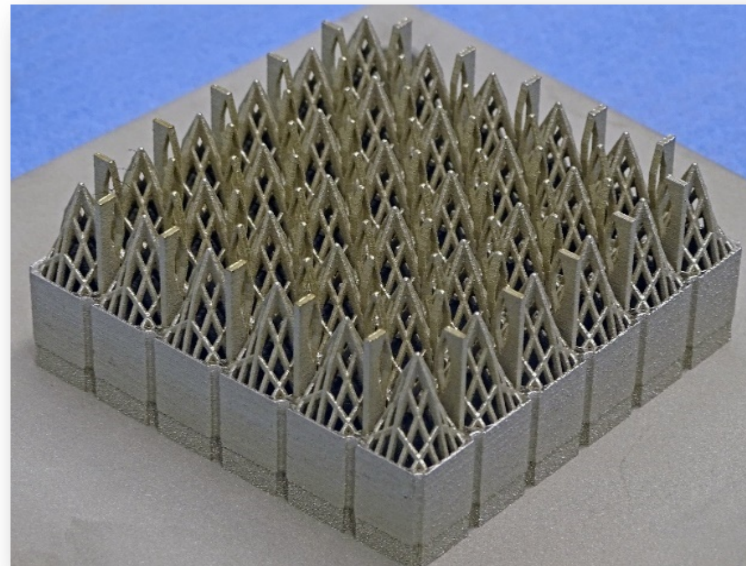
Additive Manufacturing (AM) of Nuclear Components '



Rolls-Royce 2” diameter 316L SS Pipe
Tee-Sections, Build Time ~67 hrs



Westinghouse 3” x 3” Inconel 718
Debris Filter, Build Time ~10.5 hrs

DOE/EPRI/ORNL/Westinghouse/Rolls-Royce

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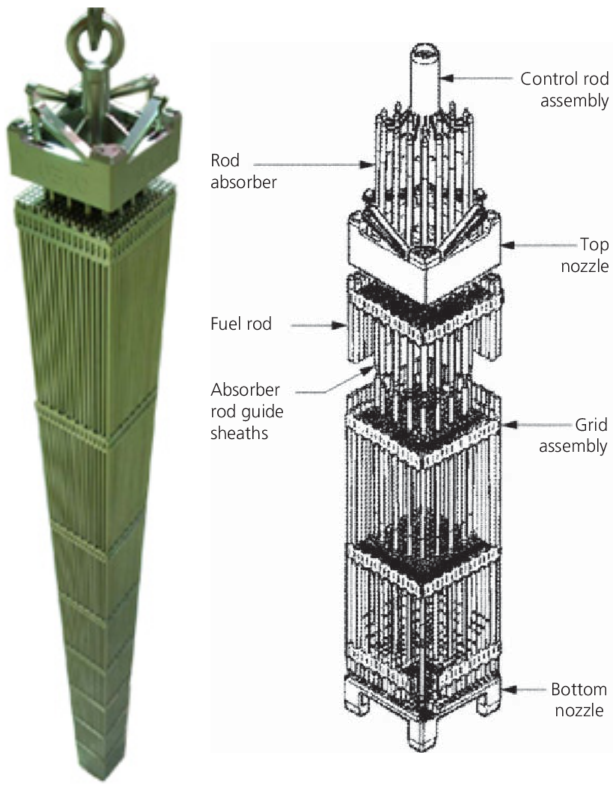
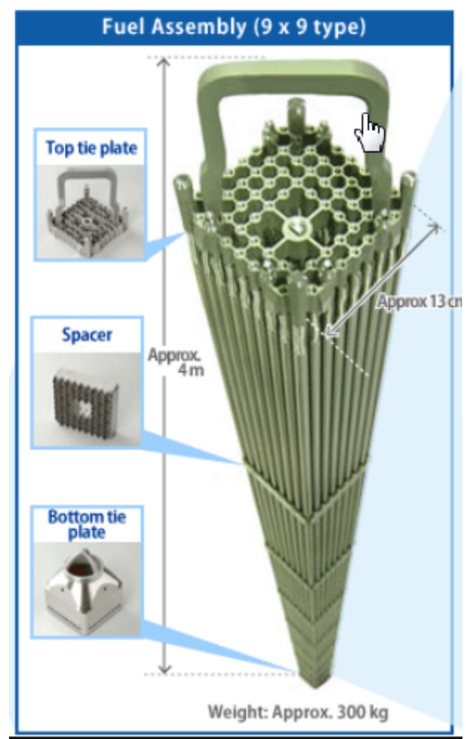
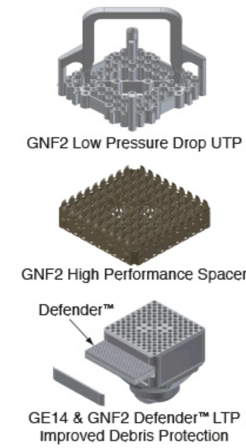
Fuel Assemblies--Examples

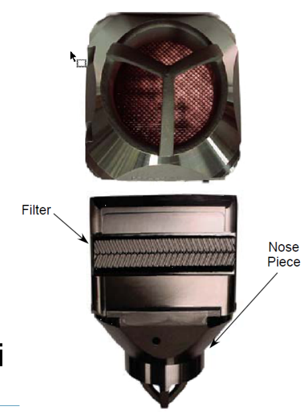


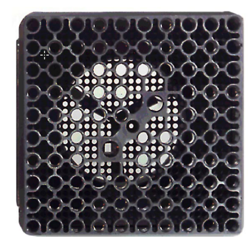
Courtesy of WEC



Courtesy of Hitachi







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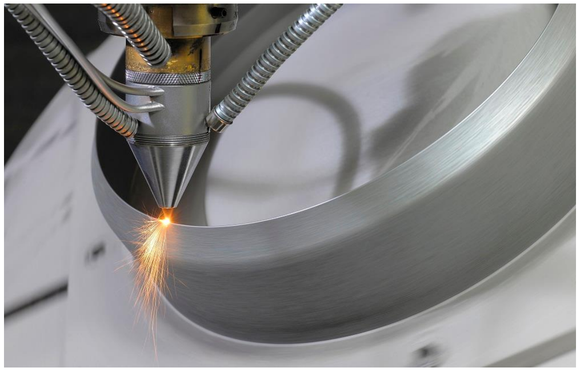
Examples: Nuclear Applications for DED-AM

- Pipe attachments
- Small-to-medium size nozzles
- Penetration tubes (eg., CRDM, stub tubes) $
- Flanges
- Hardfacing/Surfacing
- Turbine blade/discs/jounals



Courtesy: Sciaky, Inc.

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Technical Issues & Challenges

Laser-Powder Bed Fusion (L-PBF)

- Chamber size (microwave size limits)
- Deposition rates, single laser or EB
- Porosity or lack of fusion
- Residual stresses/distortion
- Understanding (bulk and deposited) material properties and performance
- Post processing required, HIP
- Layer-by-layer qualification (nuclear)

Directed Energy Deposition (DED))

- Optimization of process parameters to limit the effects of the process on the parent material
- Intelligent control of input parameters and variables to minimize dilution, distortion and fracture toughness of the parent material;
- Understanding bulk and deposited material properties/performance
- Potential material degradation concerns and loss of toughness over plant operating life
- Process qualification to satisfy regulatory codes and standards

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EPRI/DOE Evaluation Is Focused on Laser-PBF Applications (

1. $ICME assessment, coupled with “in-process” control (highlighted during 2017 AMM meeting)
   - Demonstrated microstructural controls
   - Demonstrated “in-process” control capability
   - Large data (terabytes) characterization and feedback

2. ASME BPVC Qualification
   - Database development
   - Code Case development

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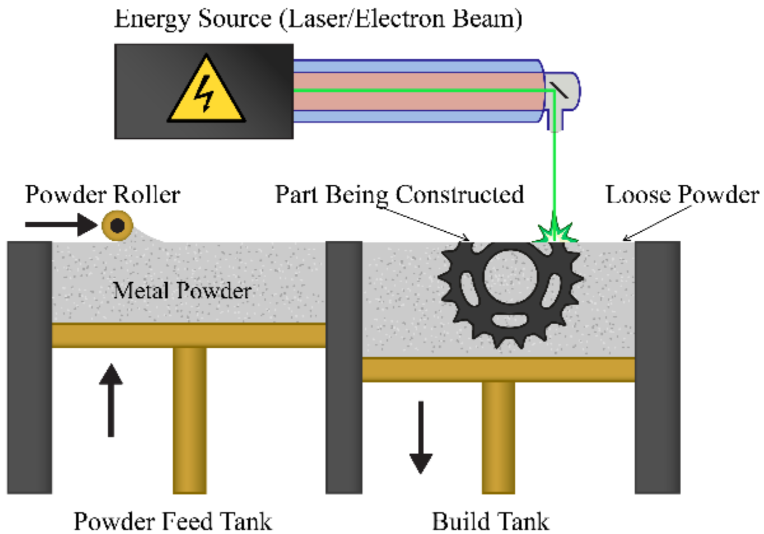
AM Qualification for Nuclear Applications
--ASME Data Package Development

- DOE Project: **DE-NE0008521**
- EPRI lead
- Five organizations involved
  - Rolls-Royce
  - Westinghouse
  - ORNL
  - Auburn University
  - TBD
- Laser Powder Bed-AM
- 316L SS



Laser Powder Bed-AM (*courtesy of 3DEO*)

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AM Qualification for Nuclear Applications
--ASME Data Package Development

- 3 Types of machines
  - EOS, Renishaw, and SLM
- 5 sets of processing parameters
- 5 different 316L powder heats
- 3 different components (next slide)
- Components are >8-inches in diameter and $
  ~0.5-inch thick $
- Different build environments
  - argon and nitrogen
- Vertical control/witness samples included
- Parameter data sheet recorded for each build

Renishaw AM 250 System

Courtesy: ORNL/Renishaw

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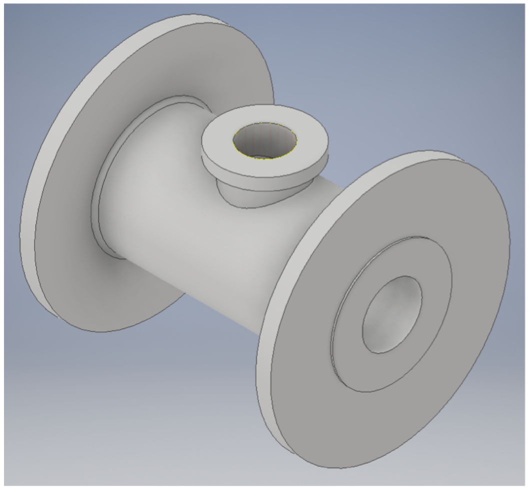
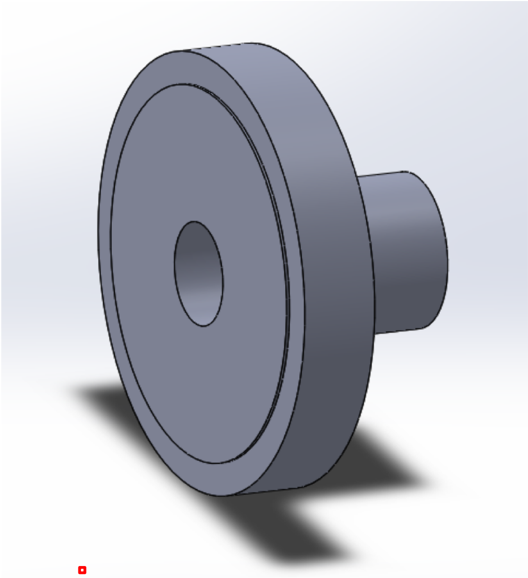
AM Qualification for Nuclear Applications
--ASME Data Package Development



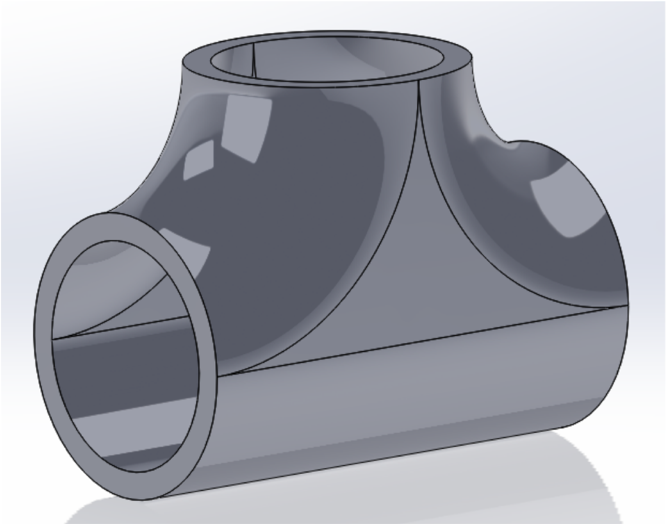
- Class 300 Forged Gate Valve Body

8”Ø x 2”bore x 4”OD x ½”T



- Ring Flange End Connection

8.5”Ø x 1.5”T x 2” bore



- Straight Pipe Tee

8-1/4”W x 4-1/8”T

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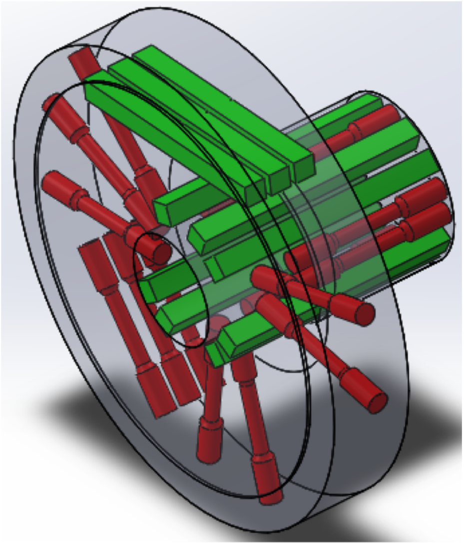
Westinghouse Build—Ring Flange End Connection +

Completed 8.5” Ø x 1-3/4” ring flange;
2” bore x 3” tall (courtesy of Westinghouse)



Tensile Bars: 18 samples, 8 radial in pipe section, 7 radial in flange section, 3 parallel to face in flange section

Charpy Bars: 10 samples, 7 radial in pipe section, 3 parallel to face in flange section

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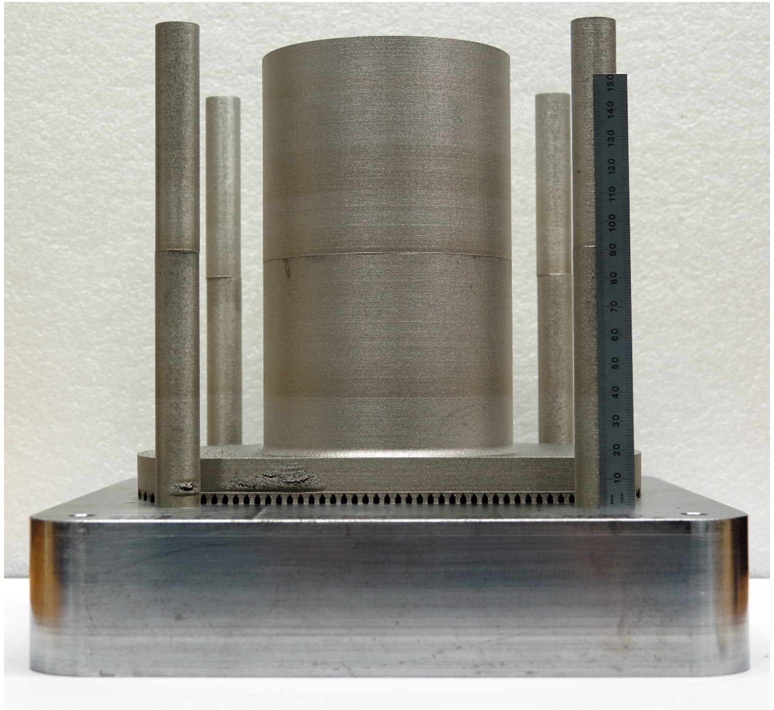
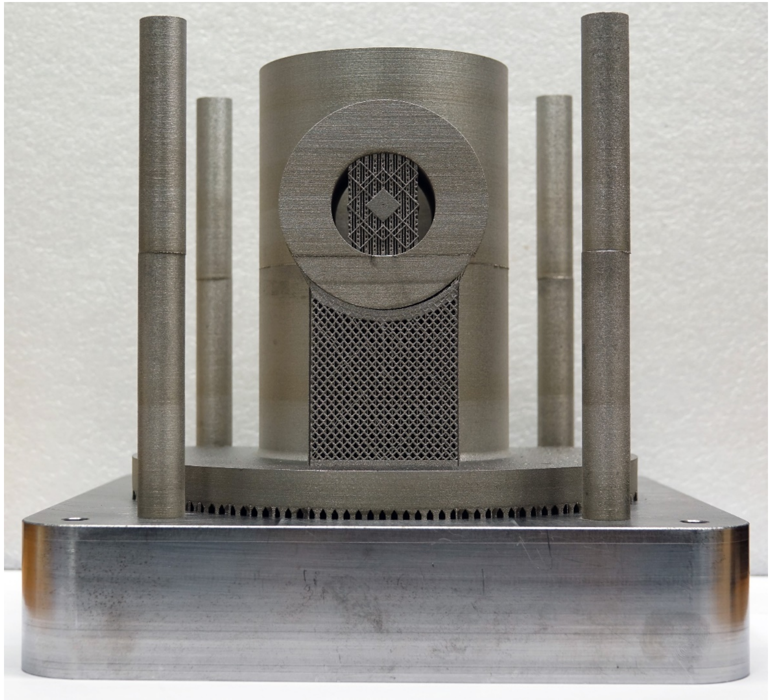
ORNL Build—Gate Valve Body %





Build Time = 6.6 days

Valve Body Mass = 23.6 lbs.

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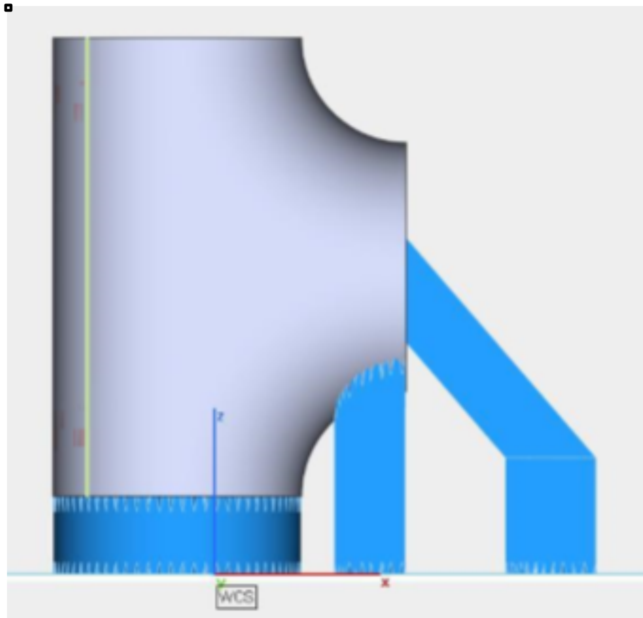
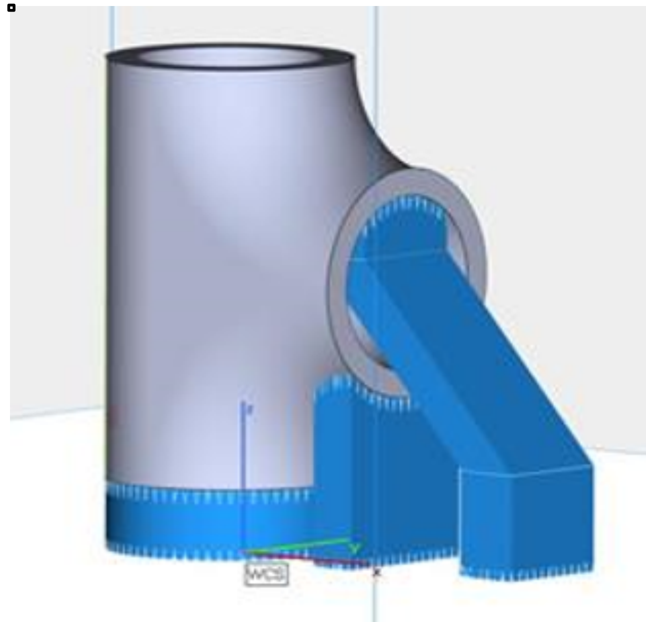
Auburn U. – Straight Pipe Tee (to be performed)





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Basis: ASTM F3184-16 Standard Specification Requirements &

Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion

- Condition A,B,C
  - A – SR or SA
  - B -- SA
  - C -- HIP
- Ordering Information
- Manufacturing Plan
- Feedstock (metal powder)
- Processing*
- Chemical Requirements
- Microstructure*
- Mechanical Properties*
- Thermal Processing (Conditions A,B,C)
- Hot Isostatic Pressing*
- Dimensions & Variations*
- Inspection*
- Certification, Product Marking
- Quality Program Requirements

* Agreed upon between Component Supplier and Purchaser

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AM Qualification for Nuclear Applications
--ASME Data Package Development

<u>General</u>

- To ASTM F3184-16 Requirements
- Component Build--Process Information (Parameter Data Sheets for each Build)
- Photographs of the final component
- Drawings of components
- Geometric inspection of final component
- Chemical analysis – powder and final $ component $
- Hot Isostatic Pressing parameters
- Heat treatment – solution anneal $ parameters $
- Inspection data captured--Digital RT/UT

<u>Microstructural Information</u>

- Microstructure – multiple magnifications
- Grain size $
- Density $
- Inclusion content

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AM Qualification for Nuclear Applications
--ASME Data Package Development

Mechanical Information

- Provide ASME requirements for wrought 316L
- Hardness mapping
- Tensile to 800F (50F increments)
  - Include stress/strain curves
- Tensile (RT) for 3 vertical build control samples
- Charpy impact toughness
- Side bends
- Fatigue (one component only)
- Plan to meet ASME stress allowable values

Weldment Property Data

- TBD

Corrosion Data

- TBD

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ASME Code Case Development

- To be modeled after Code Case N-834 (PM-HIP of 316L SS).
- Plan toward BPV-III application.
- Case N-XXXX – ????
- DRAFT Inquiry: *May ASTM F3184-16 (UNS 31603) be used for Section III, Division 1, Subsection NB, Class 1 Construction?*

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

CASE
N-834

Approval Date: October 22, 2013

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case N-834
ASTM A988/A988M-11 UNS S31603, Subsection NB, Class 1 Components
Section III, Division 1

Inquiry: May ASTM A988/A988M-11 UNS S31603 be used for Section III, Division 1, Subsection NB, Class 1 Components construction?

Reply: It is the opinion of the Committee that, ASTM A988/A988M-11 UNS S31603 may be used for Section III, Division 1, Subsection NB, Class 1 Components in construction provided the following additional requirements are met:

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-No. 8.

(b) The design stress intensity values and the maximum allowable stress values, fatigue design curves, tensile strength and yield strength values, thermal expansion and other properties shall be the same as for SA-240 UNS S31603.

(c) The maximum allowable powder particle size shall be 0.020 in. (0.5 mm) or less.

(d) Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere.

(e) An 8 in. (200 mm) or longer protrusion (extension) shall be added to one end of each item that equals or exceeds the thickest section of that item. The protrusion shall be removed upon completion of isostatic pressing and heat treatment of the item and shall be used for micro structural characterization, density measurements, chemical testing, mechanical testing, and intergranular corrosion testing as required below:

(1) Density measurements and microstructural examination shall be performed at the midsection of coupons removed from the protrusion in accordance with ASTM A988/A988M-11 paras. 8.1.1 and 8.1.2.

(2) In addition to a chemical composition analysis of the final blend powder, an analysis of a sample from each component shall be required.

(3) Intergranular corrosion tests shall be performed using test coupons removed from the protrusion in accordance with ASTM A262 Practice E.

(4) Mechanical property tests, including tension tests and hardness tests, shall be performed using test coupons removed from the protrusion in accordance with ASTM A988/A988M-11, Section 9, Mechanical Properties.

(f) The material shall be examined using the ultrasonic examination method in accordance with NB-2540 over 100% of its entire volume using both straight and angle beam methods. Items that are produced in the form of tubular products shall be examined in accordance with NB-2550.

(g) The material shall not be used for components where the neutron irradiation fluence levels will exceed 1×10^{17} n/cm^2 (E > 1 Mev) within the design life of the component.

(h) Following final hot isostatic-pressing, all surfaces exposed to the process fluid shall be removed by machining or grinding to a depth of 0.008 in. (0.2 mm) or greater. Final accessible surfaces shall be examined by the liquid penetrant method in accordance with NB-2576.

(i) All other requirements of NB-2000 for austenitic materials shall apply.

(j) This Case number shall be marked on the material and listed on the Certified Material Test Report and on the Component Data Report.

The Committee's function is to establish rules of safety, relating only to pressure integrity, governing the construction of boilers, pressure vessels, transport tanks and nuclear components, and inservice inspection for pressure integrity of nuclear components and transport tanks, and to interpret these rules when questions arise regarding their intent. This Code does not address other safety issues relating to the construction of boilers, pressure vessels, transport tanks and nuclear components, and the inservice inspection of nuclear components and transport tanks. The user of the Code should refer to other pertinent codes, standards, laws, regulations or other relevant documents.

1 *(N-834)* NC – SUPP. 3

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Summary--Status

- One component—Ring Flange has $ been produced to date. $
- Completing LPBF-AM builds (5 total) $ Q4-2018 $
- Testing and Assembly of Data Package
  – Q1 & Q2-2019
- Code Case Development
  – Q2 & Q3-2019
- Planned Submittal to BPV-III
  – Q4-2019

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Additive Manufacturing vs Powder Metallurgy-Hot Isostatic Processing

L-PBF Additive Manufacturing:
<50 lbs (23kgs)

Powder Metallurgy-HIP:
100-10,000 lbs (45-4500kgs)

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Acknowledgements & Team Members .

- DOE – T. Selekler, B. Landrey
- ORNL – F. List, S. Babu, C. Hensley
- Westinghouse – B. Cleary, C. Armstrong
- Rolls-Royce – D. Poole, T. Hare, L. Burling $
- Auburn U. – X. Lou, J. Pegues

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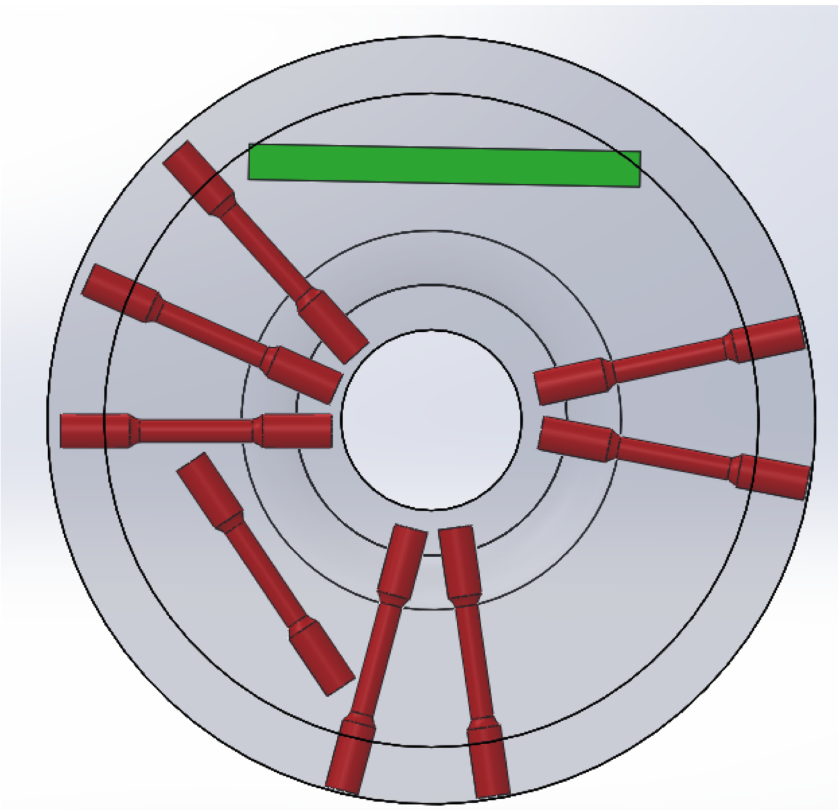
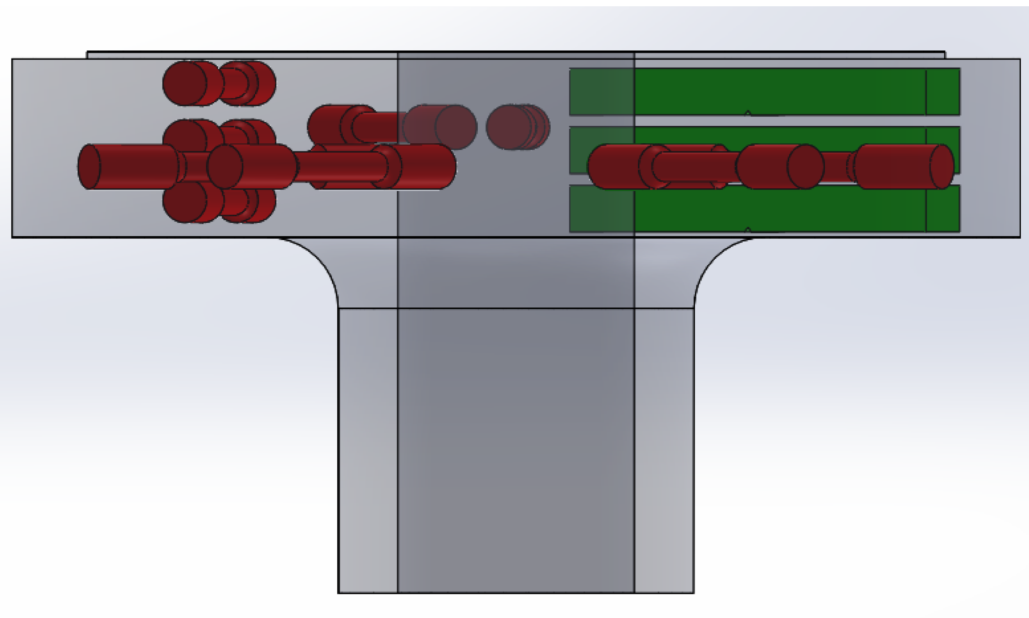
Flange Section

10 Tensile Bars, 3 Charpy





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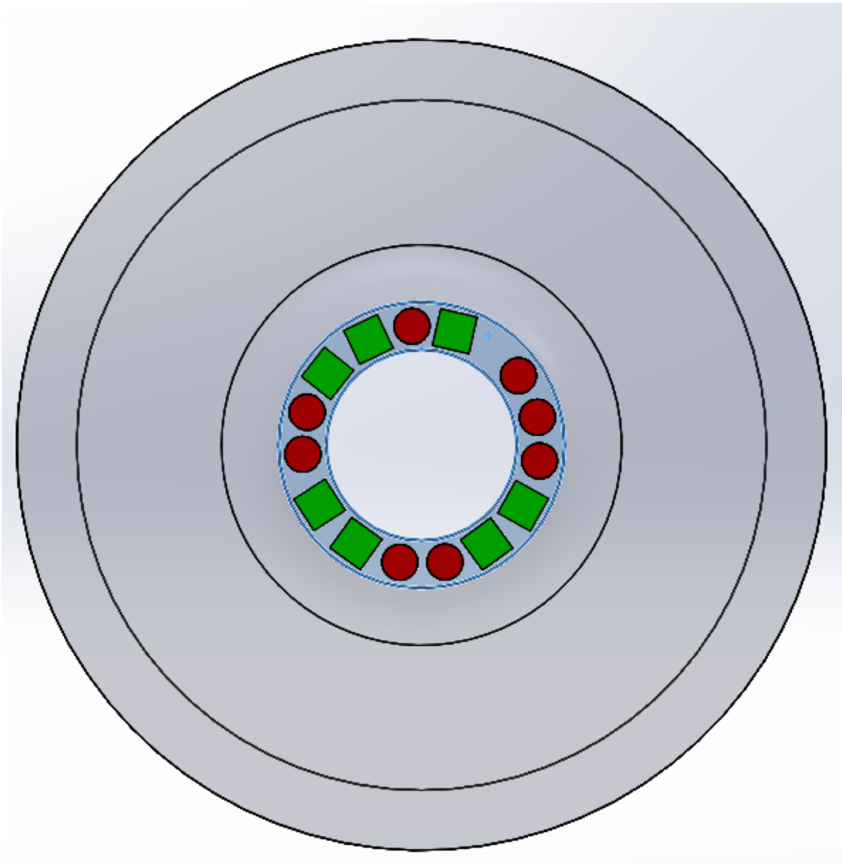
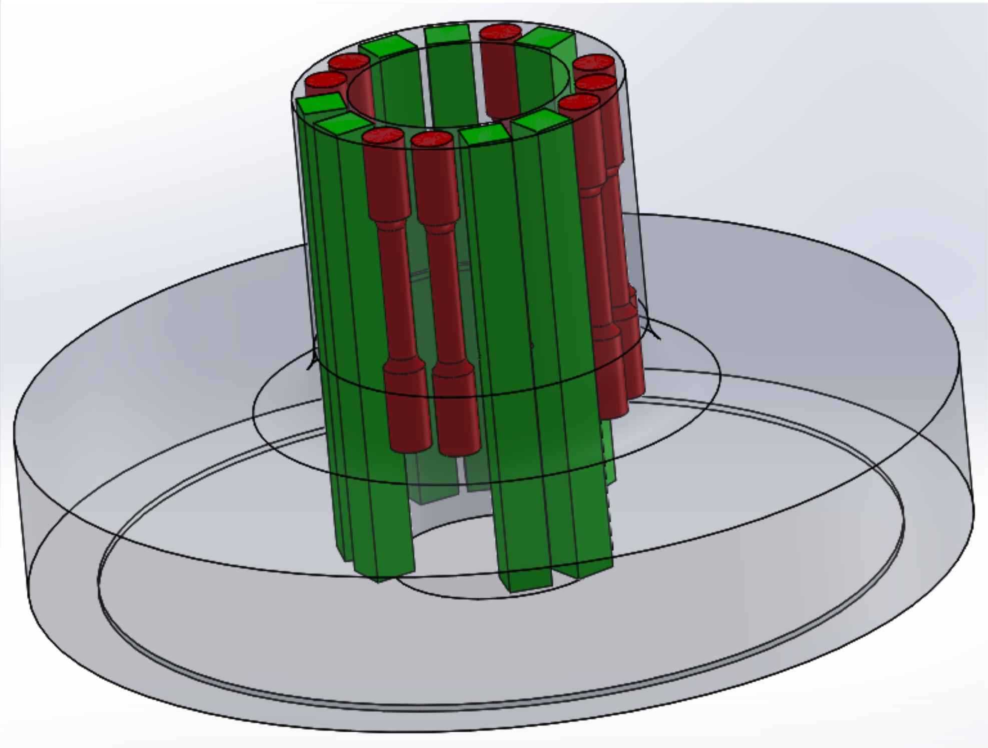
Pipe Section



8 Tensile Bars, 7 Charpy



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