Vision of Advanced Manufacturing Technology (AMT) Use in the Nuclear Industry

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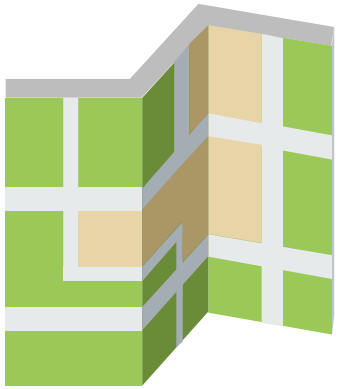
Outline – Roadmapping EPRI's Vision to Deploy AMTs

- Advanced Manufacturing Technologies (AMT) Roadmap
- Additive Manufacturing Roadmap
- Additive Manufacturing for Obsolete and Replacement Components
- EPRI R&D Methodology to Deploy AMTs
  - Teaser for future presentations this week



Collaboration Will Be Key within the Industry

EPRI AMT Roadmap – Background and Genesis

- Advanced ≠ Value Added 
  - Numerous AMTs of interest for nuclear → where is the value/need?
    - Near net shapes, complex geometries (reduced machining and waste)
    - Flexible production, improved time to market
    - Improved material properties (in certain cases) = improved reliability
- Applicability
  - ALWRs and Repair/Maintenance of operating plants
  - Extends to advanced plants (SMRs, non-LWR ARs)
- Deployment Timeline:  Industry Needs
  - TRL level, lack of standards, reactor type applicability, ASME acceptance, regulatory approval

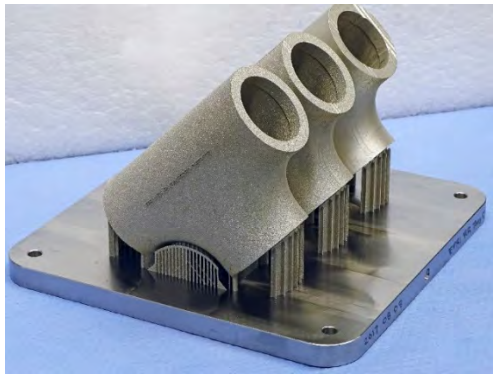
Compliments/refines NEI *"Regulatory Acceptance of AMM in Nuclear Energy"* Roadmap & Technical Report

EPRI AMT Roadmap – Structure

Aligns with "Approach to Codifying New Manufacturing Methods"
- Dec. 8 discussion from GE-Hitachi and EPRI during NRC AMT Workshop

- Understanding AMTs and Applicability of Each
  - Component size often dictates AMT to be used
    - Review of LWR Component Opportunities for Powder Metallurgy-HIP (3002005432)
    - ALWR Primary System Candidates for Advanced Manufacturing Methods (Q1 2021)
    - SMR Candidate Components for Advanced Manufacturing Methods (2021)
    - Easily extends to advanced plants (SMRs, non-LWR ARs)
  - Process parameters and their impacts on properties (e.g., microstructure, etc.)
- Demonstrations of the AMTs at Scale
  - Understand applicability, advantages/disadvantages, prove-out implementation
- Development of ASME Data Packages and Code Cases to Support Implementation of Certain AMTs
- Development/Compilation of Environmental Effects for Regulatory Approval

Size Often Dictates Advanced Manufacturing Process



Laser Powder Bed Fusion Additive Manufacturing:
<75 lbs (35 kg)

Direct Energy Deposition Additive Manufacturing:
<500 lbs (225 kg)

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

Candidate AMT Processes for Nuclear Components

- Powder Metallurgy-Hot Isostatic Pressing: PM-HIP
  - ~4 ft (1.2m) diameter
    - Larger HIP allowing ~ 10ft (3.05m) diameter, est. completion 2023/24
- Directed Energy Deposition AM: DED-AM
  - < 500 lb. (227kg) max.
- Powder Bed Fusion AM: L-PBF or EB-PBF
  - ~75 lb. (34kg) max.
- Advanced Cladding Processes:
  - e.g., diode laser cladding, hot wire laser welding, friction stir additive, cold spray & laser assisted cold spray, PM-HIP
  - Further development/qualification needed
- Electron Beam Welding: EBW
  - For large components (RPVs, SGs, pressurizers, fusion components, etc.)
- Other AMTs of interest not included with the roadmap:
  - Advanced welding technologies, machining techniques, surfacing technologies

Three AMT Roadmaps

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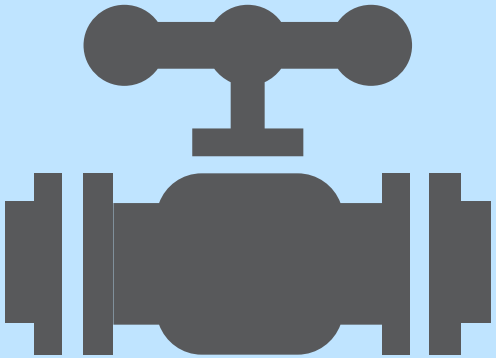
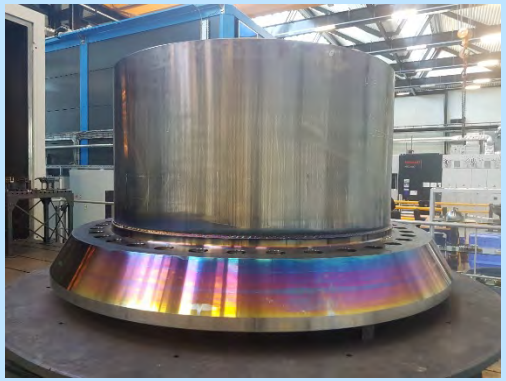
Primary Pressure Boundary (Class 1) Components

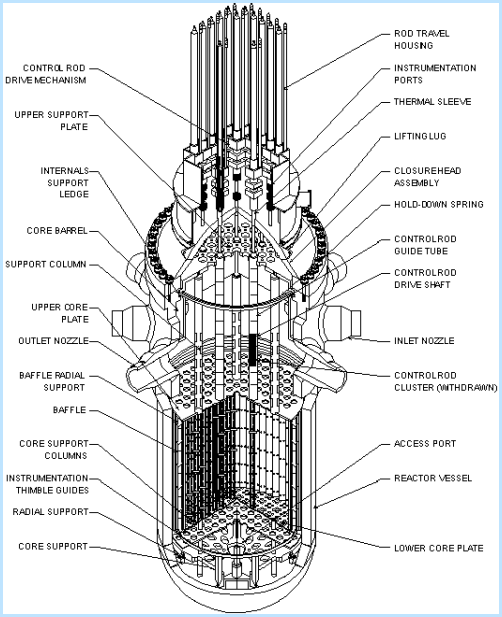




Reactor Internals

Courtesy of
Westinghouse Electric Company LLC

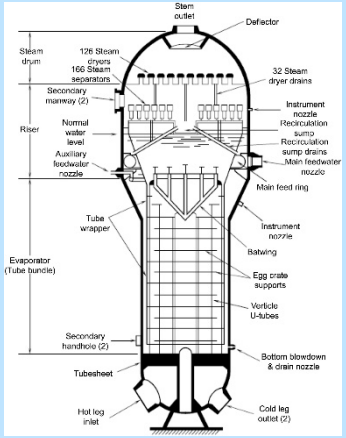
Photo credit:
Fred List – ORNL, US DOE



Other components (Obsolete parts, Classes 2 & 3, etc.)

Courtesy of
Siemens Power & Gas

Courtesy of
Westinghouse Electric Company LLC



Courtesy of
US NRC

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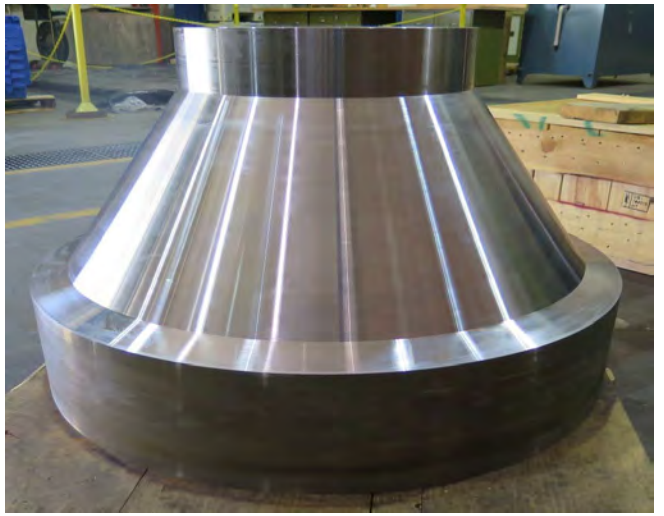
1. Primary Pressure Boundary (Class 1) Roadmap

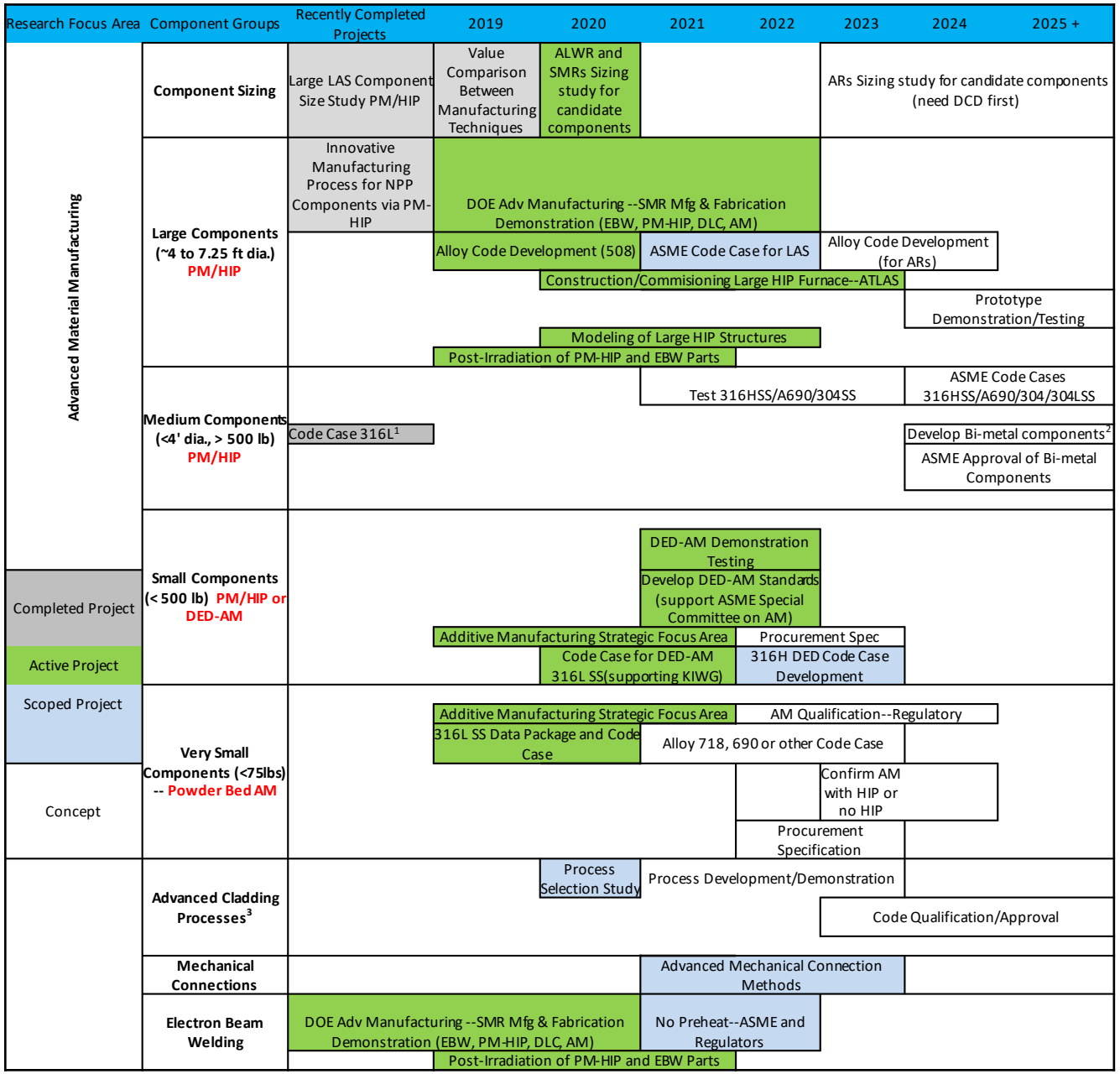


16” BWR Feedwater Inlet Nozzle (LAS)

- Roadmap includes an initial sizing study to identify candidate components
  - Many large LWR Class 1 components exceed limitations of certain AMTs.
- Developments identified are specific to: size groups/processes/materials
  - **Larger Class 1 components** can be manufacture **using PM/HIP**
    - Demonstration pieces of LWR components already produced
    - 316L already accepted by ASME, but other alloys require qualification testing and ASME approval
  - **Smaller Class 1 components** may be produced **by DED-AM or Powder Bed-AM**
    - Process development, qualification testing, ASME approval shown
    - Few Class 1 components candidates for Powder Bed AM (size limitation)

Advanced Manufacturing Roadmap – Class 1 Pressure Boundary

Roadmap is Magnified on following 2 slides



Footnotes:

1. Applicable to all PM/HIP component sizes
2. LAS Nozzle/SS Safe End
3. Diode Laser Cladding development is part of EPRI Advanced Manufacturing--DOE Mfg. & Fabrication Demonstration project.

1. Primary Pressure Boundary (Class 1) Roadmap – upper half

Research Focus Area	Component Groups	Recently Completed Projects	2019	2020	2021	2022	2023	2024	2025 +
Advanced Material Manufacturing	**Component Sizing**	Large LAS Component Size Study PM/HIP	Value Comparison Between Manufacturing Techniques	ALWR and SMRs Sizing study for candidate components			ARs Sizing study for candidate components (need DCD first)		
	Large Components (~4 to 7.25 ft dia.) PM/HIP	Innovative Manufacturing Process for NPP Components via PM-HIP	DOE Adv Manufacturing --SMR Mfg & Fabrication Demonstration (EBW, PM-HIP, DLC, AM)						
			Alloy Code Development (508)		ASME Code Case for LAS		Alloy Code Development (for ARs)		
				Construction/Commisioning Large HIP Furnace--ATLAS				Prototype Demonstration/Testing	
				Modeling of Large HIP Structures					
			Post-Irradiation of PM-HIP and EBW Parts						
	Medium Components (<4' dia., > 500 lb) PM/HIP				Test 316HSS/A690/304SS			ASME Code Cases 316HSS/A690/304/304LSS	
		Code Case 316L[1]						Develop Bi-metal components[2]	
								ASME Approval of Bi-metal Components	

Footnotes:

1. Applicable to all PM/HIP component sizes
2. LAS Nozzle/SS Safe End
3. Diode Laser Cladding development is part of EPRI Advanced Manufacturing--DOE Mfg. & Fabrication Demonstration project.

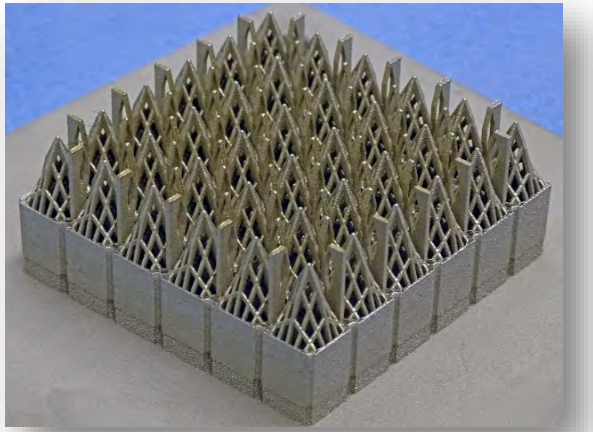
1. Primary Pressure Boundary (Class 1) Roadmap – lower half

Research Focus Area	Component Groups	Recently Completed Projects	2019	2020	2021	2022	2023	2024	2025 +
Advanced Material Manufacturing	**Small Components (< 500 lb) PM/HIP or DED-AM**				DED-AM Demonstration Testing				
Completed Project					Develop DED-AM Standards (support ASME Special Committee on AM)				
			Additive Manufacturing Strategic Focus Area			Procurement Spec			
Active Project				Code Case for DED-AM 316L SS(supporting KIWG)		316H DED Code Case Development			
Scoped Project	**Very Small Components (<75lbs) -- Powder Bed AM**		Additive Manufacturing Strategic Focus Area			AM Qualification--Regulatory			
			316L SS Data Package and Code Case		Alloy 718, 690 or other Code Case				
Concept						Confirm AM with HIP or no HIP			
						Procurement Specification			
	Advanced Cladding Processes [3]			Process Selection Study	Process Development/Demonstration				
							Code Qualification/Approval		
	Mechanical Connections				Advanced Mechanical Connection Methods				
	Electron Beam Welding	DOE Adv Manufacturing --SMR Mfg & Fabrication Demonstration (EBW, PM-HIP, DLC, AM)			No Preheat--ASME and Regulators				
			Post-Irradiation of PM-HIP and EBW Parts						

Footnotes:

2. LAS Nozzle/SS Safe End
3. Diode Laser Cladding development is part of EPRI Advanced Manufacturing--DOE Mfg. & Fabrication Demonstration project.

2. Reactor Internals Roadmap



- Internals Roadmap generally follows similar pattern set for Class 1
  - Up front sizing study
- Some significant differences:
  - No low alloy steel components
  - Fuel Hardware and Control Rod Drive components (unique shapes and materials)
  - High strength Ni-base alloys and cobalt-free alloys
- **Interaction with ASME is limited** for Internals Roadmap
  - Only core support structures require ASME approval
  - Interaction with NRC may be required for some Safety Related Internals
  - Other internals: free to use ASTM, AMS, etc. or no standard at all (a potential case for fuel hardware or control rod drive components)

Advanced Manufacturing Roadmap – Reactor Internals

Roadmap is Magnified on following 2 slides

Research Focus Area	Research Task/Component Groups	Recently Completed Projects	2019	2020	2021	2022	2023	2024	2025 +
	Sizing Study			ALWR and SMRs Sizing study for candidate components			ARs Sizing study for candidate components (need DCD first)		
Advanced Material Manufacturing	**Large Internals (~4 to 7.25 ft dia.) PM/HIP**	**Note: PM-HIP of Reactor Internals are covered by Class 1 Pressure Boundary Roadmap**							
	Medium Internals (<4' dia., >50 lb) PM/HIP								
	Small Internals (< 500 lb) PM-HIP/DED AM/Powder Bed AM[2]			DED-AM Demonstration Testing; Develop DED-AM Standards (support ASME Special Committee on AM); Additive Manufacturing Strategic Focus Area; Code Case for DED-AM 316L SS(supporting KIWG)		Procurement Spec; 316H DED Code Case Development			
	Fuel Hardware (inc. thin parts) Powder Bed AM[2]			Additive Manufacturing Strategic Focus Area; 316L SS Data Package and Code Case		Build/Test AM Demonstration Components (Includes X-750/718/725); AM Qualification/Standards Development; Confirm AM with HIP or no HIP; Procurement Spec			
	Control Rod Drive Components					Process Selection Study AM/DED and/or PM/HIP (Includes Co Replacement Alloys)		Process Demonstration/Testing; Process Qual/Standards Development	

Completed Project

Active Project

Scoped Project

Footnotes:
1. Applicable to all PM/HIP Internals sizes
2. Powder Bed AM < 75 lb

2. Reactor Internals Roadmap – upper half

Research Focus Area	Research Task/Component Groups	Recently Completed Projects	2019	2020	2021	2022	2023	2024	2025 +
Advanced Material Manufacturing	**Sizing Study**			ALWR and SMRs Sizing study for candidate components			ARs Sizing study for candidate components *(need DCD first)*		
	Large Internals (~4 to 7.25 ft dia.) PM/HIP		**Note: PM-HIP of Reactor Internals are covered by Class 1 Pressure Boundary Roadmap**						
	Medium Internals (<4' dia., > 500 lb) PM/HIP								

Footnotes:
1. Applicable to all PM/HIP Internals sizes
2. Powder Bed AM < 75 lb

2. Reactor Internals Roadmap – lower half

Research Focus Area	Research Task/Component Groups	Recently Completed Projects	2019	2020	2021	2022	2023	2024	2025 +
Advanced Material Manufacturing					DED-AM Demonstration Testing				
					Develop DED-AM Standards (support ASME Special Committee on AM)				
			Additive Manufacturing Strategic Focus Area			Procurement Spec			
				Code Case for DED-AM 316L SS(supporting KIWG)		316H DED Code Case Development			
	Fuel Hardware (inc. thin parts) **Powder Bed AM[2]**					Build/Test AM Demonstration Components (Includes X-750/718/725)			
			Additive Manufacturing Strategic Focus Area				AM Qualification/Standards Development		
			316L SS Data Package and Code Case		Confirm AM with HIP or no HIP				
						Procurement Spec			
	Control Rod Drive Components					Process Selection Study AM/DED and/or PM/HIP (Includes Co Replacement Alloys)			
								Process Demonstration/Testing	
								Process Qual/Standards Development	

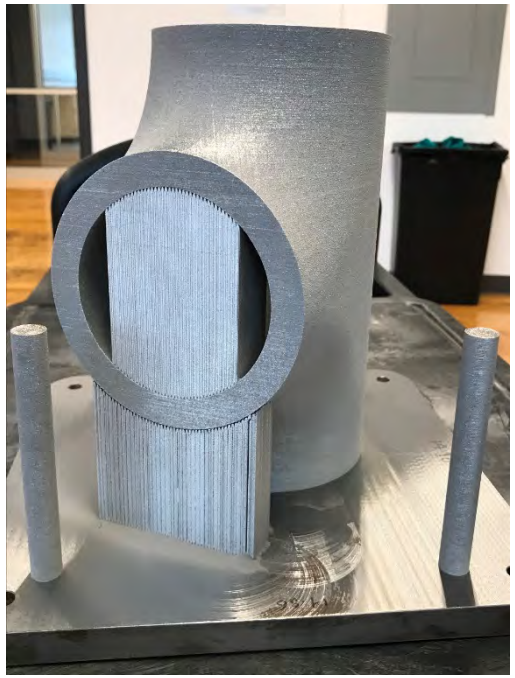
Completed Project

Active Project

Scoped Project

Footnotes:
1. Applicable to all PM/HIP Internals sizes
2. Powder Bed AM < 75 lb

3. All Other Components Roadmap --Obsolete Parts, Class 2 & 3, etc.



- Primary Pressure Boundary and Reactor Internals Roadmaps fully address needs of "Other Components" category
  - e.g., ASME acceptance of a process/material for Class 1 immediately applicable to Class 2 & 3
  - **Other "Components Roadmap" may not be required**

- Sizing study to identify potential AMM candidate components still required
  - Complicated by the broad range of components in this category
    - Potentially different materials of interest
  - Many likely Class 2 & 3 components and steam generator shell/internals
  - Outcome of sizing study may dictate development of separate Roadmap

Examples of Candidate AMM Components

Primary Pressure Boundary

Reactor Type	Component	AMM Process	Material
AP1000	Vessel Shell (Six ring segments)	PM/HIP	LAS
AP1000	Pressurizer Shell (Four ring segments)	PM/HIP	LAS
US EPR	Pressurizer Shell (Four ring segments)	PM/HIP	LAS
US APWR	Pressurizer Shell (Four ring segments)	PM/HIP	LAS
BWR	CRD Stub Tubes	PM/HIP	CC N-580
PWR	CRDM Housings	PM/HIP	A690
ABWR	Reactor Internal Pump Case	PM/HIP	LAS
AP1000	Recirculation Pump Case (top section)	PM/HIP	SS
BWR/PWR	Medium Size Valve Bodies and Bonnets	PM/HIP	SS
BWR/PWR	Reactor Vessel Nozzles	PM/HIP	LAS
BWR/PWR	Small Valves & Fittings	PM/HIP or DED	SS
BWR/PWR	Very Small Valves and Fittings	Powder Bed AM	SS

Reactor Internals

Reactor Type	Component	AMM Process	Material
AP1000	Core Barrel (Six ring segments)	PM/HIP	SS
Advanced PWRs	Core Barrel Nozzles	PM/HIP	SS
AP1000	Upper Guide Tube Components	PM/HIP	SS
AP1000	Control Rod Guide Cards	Powder Bed AM	SS
AP1000	Core Barrel Support Lugs	PM/HIP	A690
BWR/PWR	Dome Cooling Spray Nozzles	PM/HIP or DED	SS
EPR	Heavy Reflector Positioning Keys	PM/HIP	SS
ABWR/ESBWR	Control Rod Guide Tube Base Plate	PM/HIP	XM-19
ABWR/ESBWR	Steam Separator Swirlers	PM/HIP	SS
ABWR	Shroud Head Bolt Tees	PM/HIP	CC N-580
BWR	Fuel Spacers	Powder Bed AM	X-750
BWR	Fuel Tie Plates	Powder Bed AM	SS
BWR/PWR	Fuel Debris Filters	Powder Bed AM	SS
BWR/PWR	Control Rod Drive Components	PM/HIP, DED, or Powder Bed AM	SS or Co-Free Alloys

Other Components

Reactor Type	Component	AMM Process	Material
AP1000	Steam Generator Upper Shell (Six ring segments)	PM/HIP	LAS
AP1000	Steam Generator Lower Shell (Six ring segments)	PM/HIP	LAS
US EPR	Steam Generator Lower Shell (Six ring segments)	PM/HIP	LAS
US APWR	Steam Generator Lower Shell (Six ring segments)	PM/HIP	LAS
Advanced PWRs	Steam Generator Manways/Nozzles/ Handholes	PM/HIP	LAS
All LWRs	Class 2/3 Valve Bodies/Bonnets	PM/HIP or DED	SS
All LWRs	Class 2/3 Pipe Fittings	PM/HIP or DED	SS
Advanced PWRs	Steam Generator Internals	PM/HIP or DED	SS/A690
Operating BWRs	Jet Pump Beams	PM/HIP	X-750/718
All LWRs	Class 2/3 Small Valves and Fittings	Powder Bed AM	SS
BWR	Internals Repair Hardware	PM/HIP, DED, or Powder Bed AM	SS/XM-19/X-750
BWR/PWR	Very Small Valves and Fittings	Powder Bed AM	SS

AMM Roadmap – Summary

- Two Roadmaps will likely cover >95% of components
  - Primary pressure boundary (Class 1) Roadmap
  - Reactor Internals Roadmap
- Roadmaps are focused on LWRs, ALWRs and SMRs
  - Easily expanded to ARs in future
- Roadmap development generated based on component size/materials
- Central feature of each is ASME BPVC standards development & regulatory approval

Additive Manufacturing Roadmap for the Nuclear Industry

AM Roadmap Contents

- Discuss state-of-the-art applications of additive manufacturing technologies for metallic materials.
- Discuss industry specifications and standards for AM
  - Current documents
  - Major documents in the pipeline
  - Availability and applicability to the nuclear power industry
- Identify key concerns for AM use in nuclear power applications
- Assessment of gaps in qualifying additive manufacturing techniques for AM components to be used in the nuclear power industry
- Develop a roadmap for additive manufacturing
  - highlights the identified gaps as well as steps to be taken to address those gaps

Motivations for AM Adoption in Nuclear Industry

- Complex geometries not previously practical
  - Example: novel fuel assembly debris filters
- Reduce cost to build complex geometries
  - Examples: valve bodies, Transformational Challenge Reactor
- Simplify inventory management
  - Just-in-time manufacture of low-volume spares from digital library

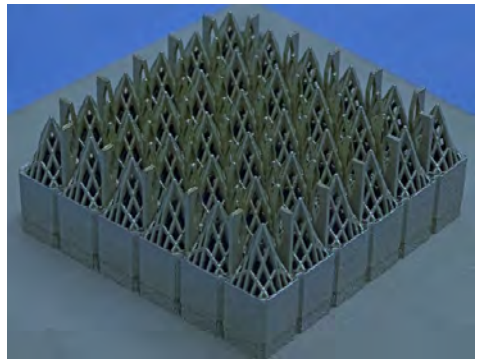


Photo Credit: Westinghouse Electric Company, LLC

Photo Credit: Fred List/ORNL, U.S. DOE, Framatome

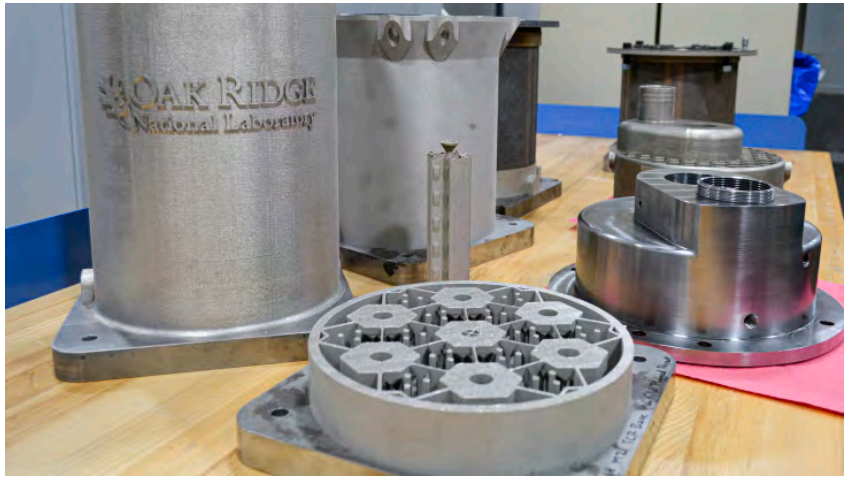


Photo Credit: ORNL

Motivations for AM Adoption in Nuclear Industry (cont'd)

- Increase reliability and decrease part count with integrated assemblies
  - Example: thimble plug assembly
- Simplify supply chain
  - Reduce number of active qualified vendors
- Manufacture in-kind replacements for obsolete parts
  - Example: fire protection pump impellers
- Other motivations
  - Reduce environmental footprint, functionally graded materials, infill lattices

Photo Credit: Westinghouse Electric Company, LLC

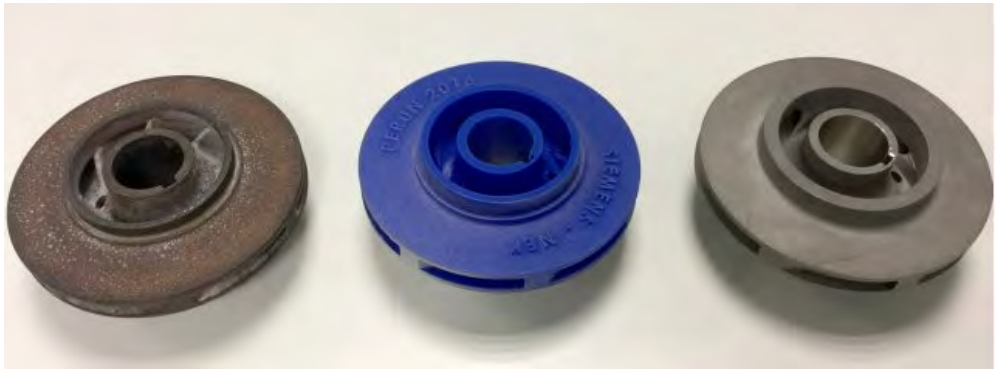
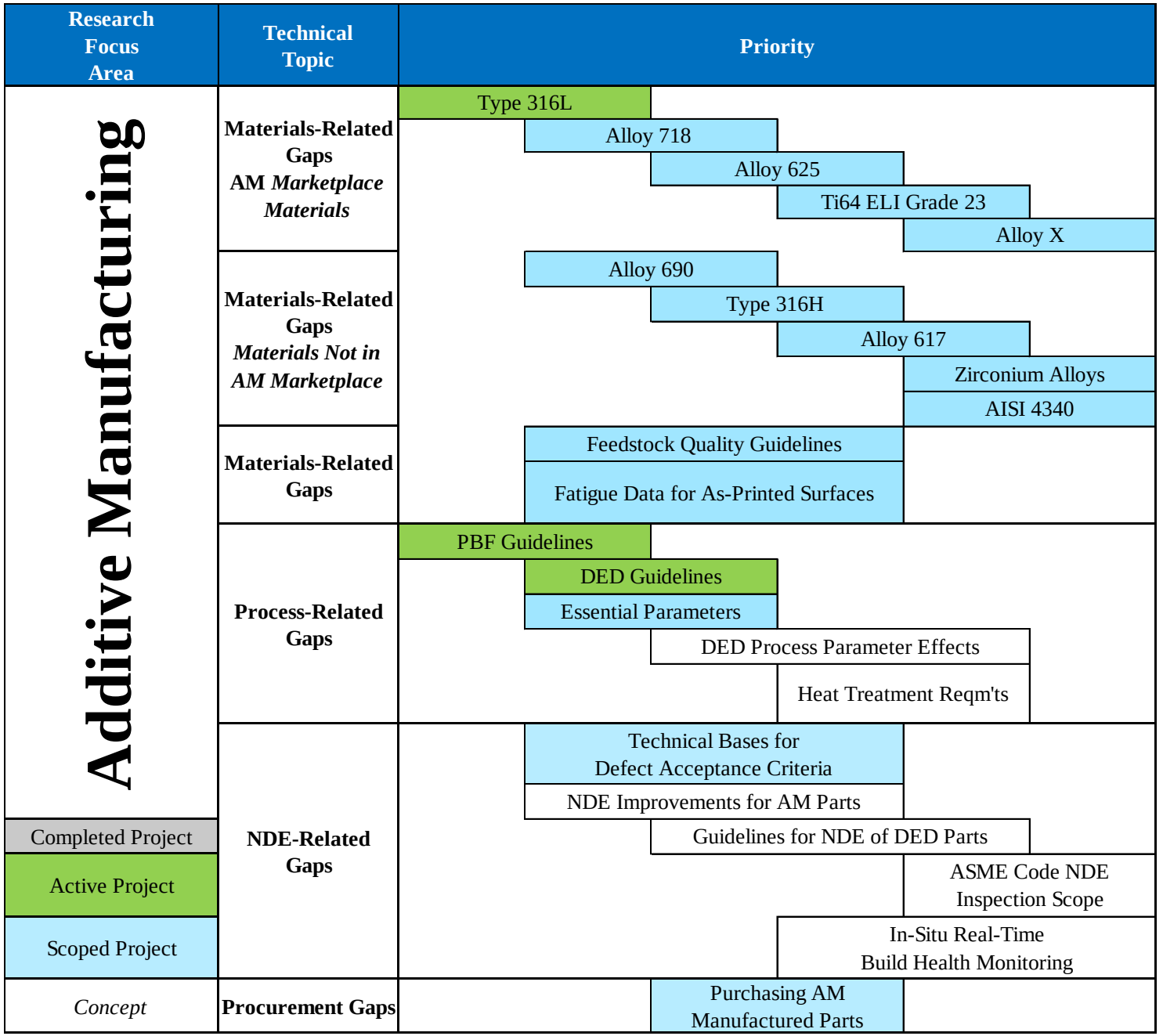


Photo Credit: NEI, Siemens, Krško

AM Roadmap

EPRI Report: 3002018276

- Material Development and ASME Code Case Priorities
  - AM Marketplace Materials
  - Non-AM Marketplace Materials
  - Feedstock Quality Guidelines
  - Fatigue Data
  - SCC and Irradiation Data
- Process Related Gaps
  - ASME PTB Guideline for DED
  - Industry consensus regarding minimum essential parameters for each AM process
  - Heat Treatment Effects (HIP and SA)
- Non-Destructive Examination Related Gaps
  - Technical Basis for Defect Acceptance Criteria
  - NDE Improvements for AM Parts
  - Guidelines for NDE of DED Parts
  - In-situ Real-Time Build Health Monitoring
- Recommended Practices for Purchases AM Parts



Additive Manufacturing

To Support Spare and Replacement Items

Marc H. Tannenbaum
Technical Executive

Overview

Range of available materials

- Ceramics
- Glass
- Sand
- Metals (wire, powder, sheet)
- Polymers
- Reinforced polymers

Wide range of technologies and methods

- Binder Jetting
- Directed Energy Deposition (DED)
- Laser Powder Bed Fusion (PBF)
- Material Extrusion / Fused Deposition Modeling (FDM)
- Material Jetting
- Sheet Lamination
- VAT Photopolymerization

Various replacement item applications

Manufacturing parts on-demand

Rapid prototyping

Creating tooling

Many non-structural, non-pressure-retaining applications

Fewer barriers to use in plant applications

Benefits to spare and replacement items

IMPROVED

replacement item designs

SIGNIFICANT cost reductions

for low-volume parts and complex assemblies

SHORTER

lead-times

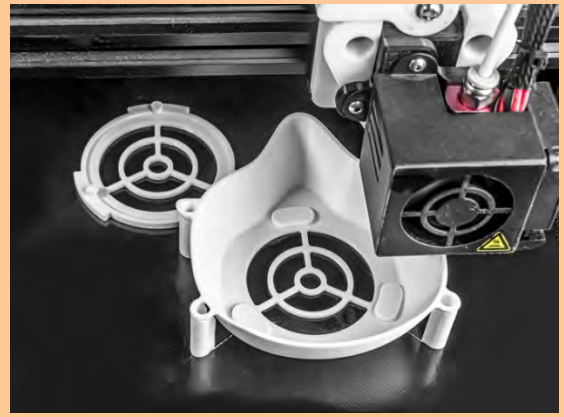
ENHANCED

ability to establish design suitability of proposed replacement items

Obsolescence

Instead of building "to meet" a design, smart manufacturing technologies build "from" a design

- Certain aspects of conformance with design are inherent in the processes



Traditional Manufacturing

- Mold $10,000s
- Component run $1,000 ea. (100 min)

Months-long
LEAD-TIME

Additive Manufacturing Fused Deposition Modeling

- **Scan + Build** **$100s ea. (no min)**

3-hour
PRINT-TIME

3-week
LEAD-TIME

Advanced Manufacturing Research Focus Area

EPRI Advanced Manufacturing Research Focus Area

GOAL & VALUE

Identify, develop, qualify and implement more economical manufacturing technologies that enable:

Higher Quality Components | Reduced Lead Times | Alternative Supply Chains | Cost Competitiveness

Additive Manufacturing

316L LPBF Code Case & Data Package
(submitted to ASME August 2020)

Additive Manuf. Roadmap for Nuclear Applications *(Q4 2020)*

DED-AM Component Demonstration

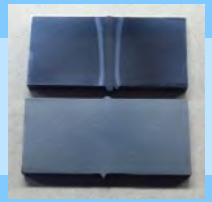
Advanced Manufacturing Demonstration Project

PM-HIP

EB Welding

DLC

Heat Treat



Advanced Welding Techniques

Adaptive Feedback Welding

ANT + WRTC

Modular In-Chamber EBW

What's Next for the Nuclear Industry?

SMRs and ARs Factory Manufacture/Fabrication

- Modular Construction
  - Have to get it right this time…
- Smaller unit size is ideal for factory production
- Economy of scale
- Must bring to bear new manufacturing and fabrication technologies to be cost effective.

Reference: Bailey, J., "What's Nu and What's Next," April 2017.

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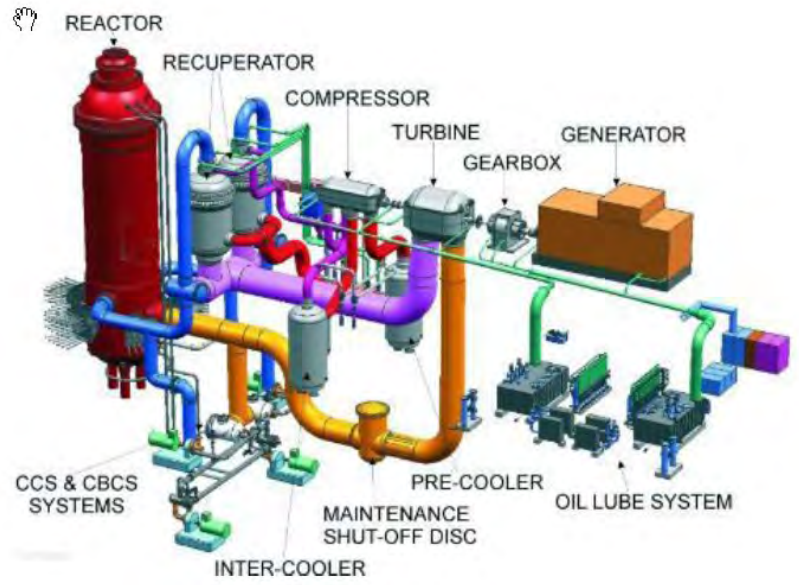
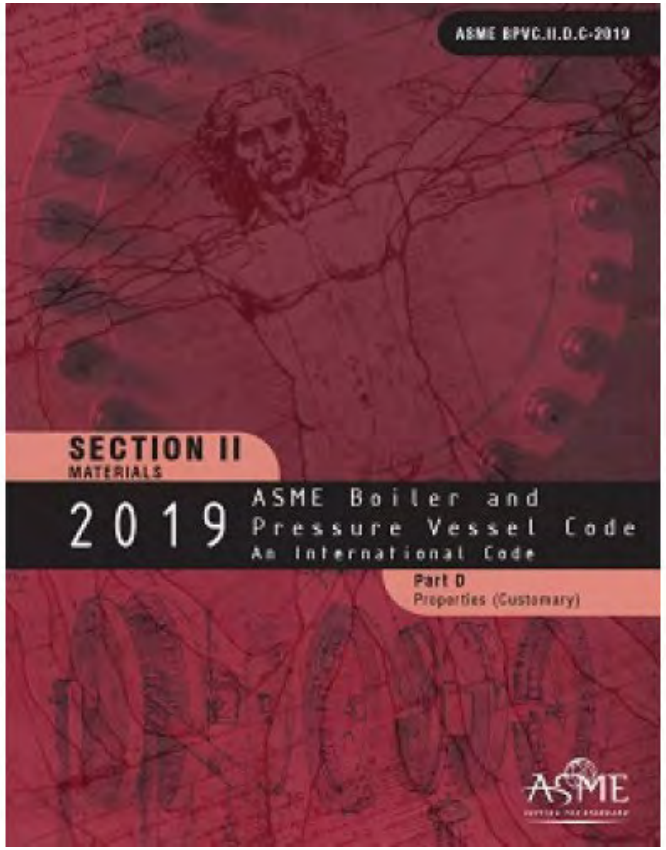
Advanced Reactor Manufacturing/Fabrication

- **Micro-Reactors**
  - Heat pipe reactors will use AMTs to produce core
- **GEN IV Reactors**
  - Rely heavily on nickel-based alloys and complex cooling geometries.
  - HIP provides economic avenue to produce nickel-based components
  - Eliminates welds and minimizes machining due to near net-shape
  - Cladding of complex alloys (Moly or other)
  - Joining through EB Welding



What Is Required To Bring These Technologies Forward For SMR, Micro-Reactor, or AR Applications?

- Code Data Packages (mechanical, microstructural, welding data)
- ASME or RCC-M Code acceptance
- Regulatory Acceptance
- Corrosion Testing
- Irradiation Studies
- Clearly separate pressure retaining applications from structural applications



Summary – EPRI Vision of AMT Use in Industry

- Advanced Manufacturing Technologies Roadmap
  - ALWRs → Easily extends to advanced plants (SMRs, non-LWR ARs)
  - Two Roadmaps will likely cover >95% of components
  - Development generated based on component size/materials
  - Central feature of each is ASME BPVC standards development & regulatory approval
- Additive Manufacturing Roadmap
  - Assesses key concerns/gaps for AM use in nuclear power applications
  - Develops a roadmap for AM to address the gaps identified
- Additive Manufacturing for Obsolete and Replacement Components
- EPRI R&D to Deploy AMTs
- What's Next

Together…Shaping the Future of Electricity