The Current State of Additively Manufactured Ni-Based Superalloys and a Future Look at AMT's within the Casting and Forging Industries

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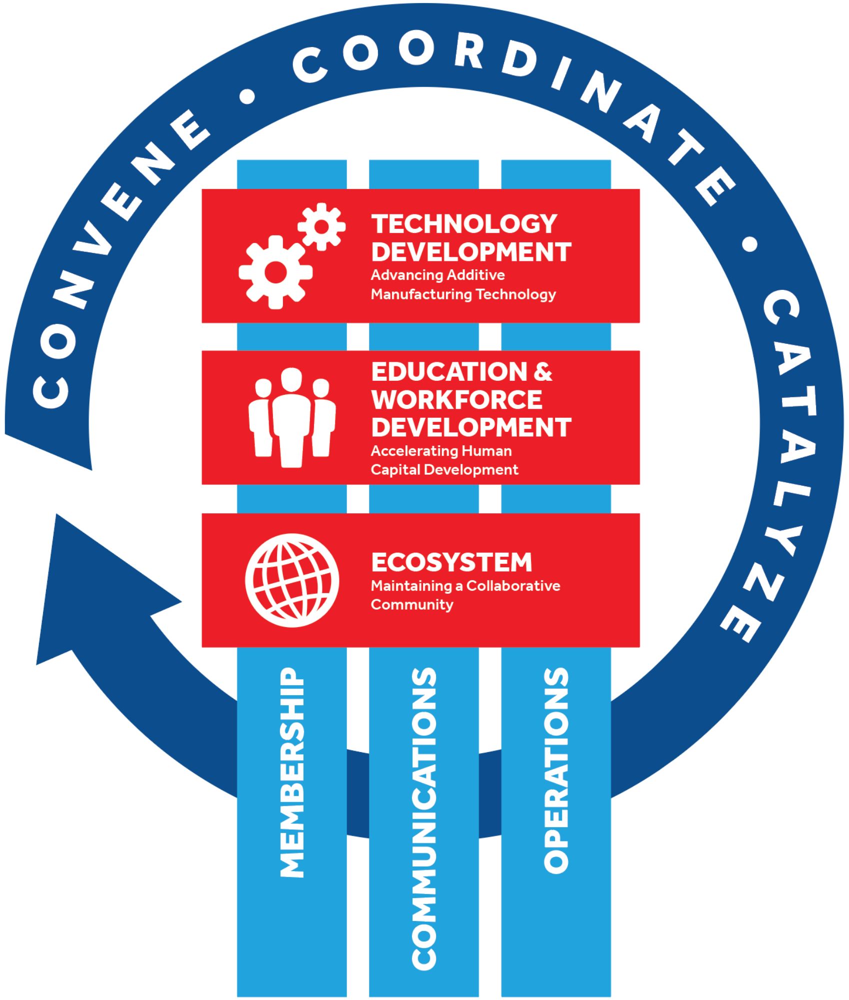
Overview

The three core activities of the Institute are:

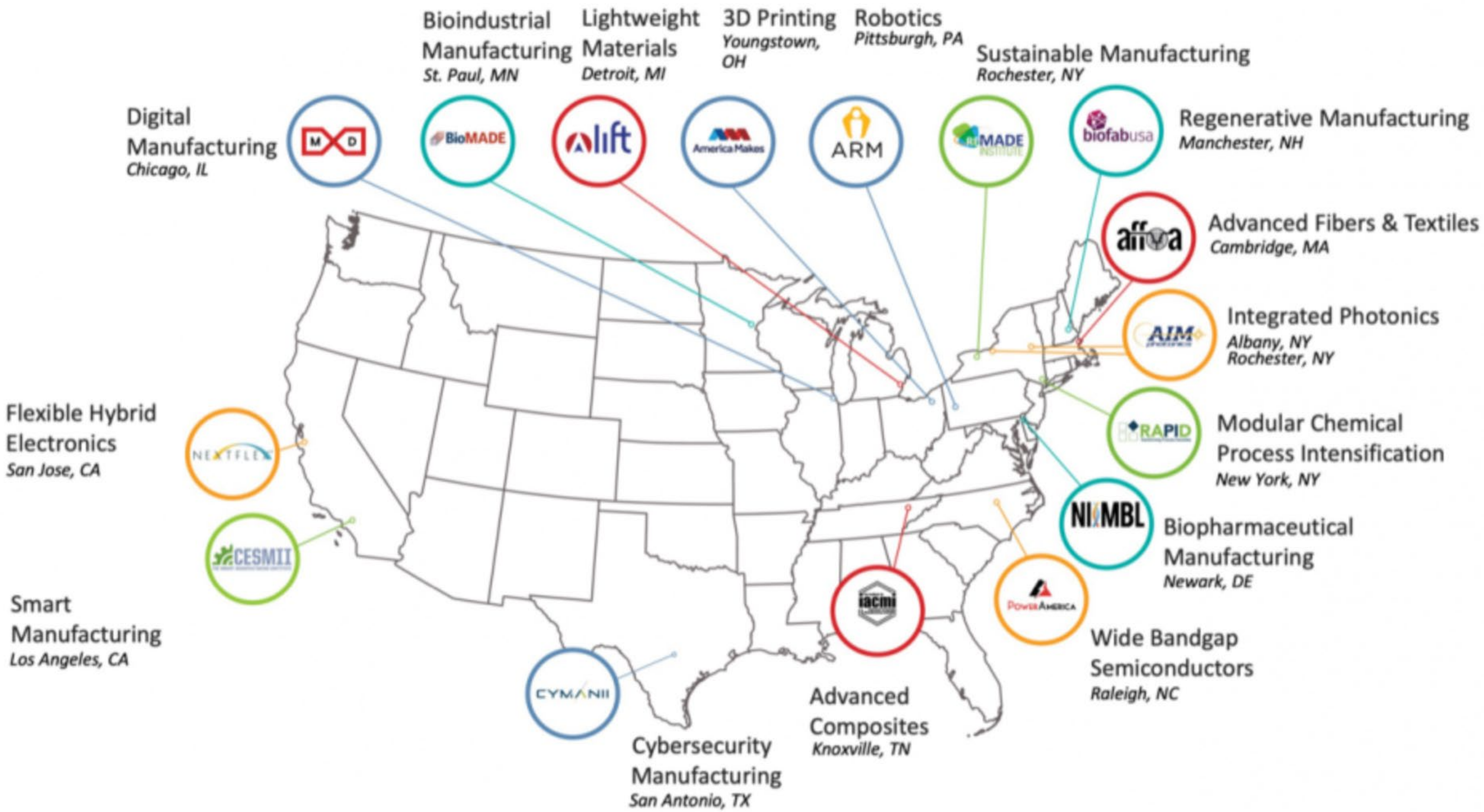
- **Develop Additive Manufacturing Technology:** Projects, Innovation, Technology Transfer, Implementation
- **Accelerate Human Capital Development:** Workforce, Education, Training, Outreach
- **Energize Collaborative Ecosystem:** Government, Membership, Community

These focus areas are enabled by:

- **Membership:** Driving engagement and collaboration with our nation's brilliant minds from government, industry and academia to advance Additive Manufacturing
- **Communications:** Driving awareness and spreading the word to government, members, stakeholders, community
- **Operations:** Run by a not-for-profit organization with a lean and collaborative structure



Manufacturing USA Network



Geographic Representation of America Makes Membership

- 42 States are represented by America Makes members.
- More information is needed to more accurately represent the additive manufacturing ecosystem.

Project Team – Roles and Responsibilities

Team	Roles
NIST National Institute of Standards and Technology; AFRL The Air Force Research Laboratory	• Technical oversight
America Makes	• Program management • Customer interface
Colorado School of Mines	• Technical management • Data management • Testing & characterization
Renishaw; EOS; Open Additive; AddUp Global Additive Solutions; 3D Systems; Xact Metal; Concept Laser a GE Additive company; Velo3D; Aconity3D	• Data pedigree assurance • Specimen manufacturing

Technical Approach

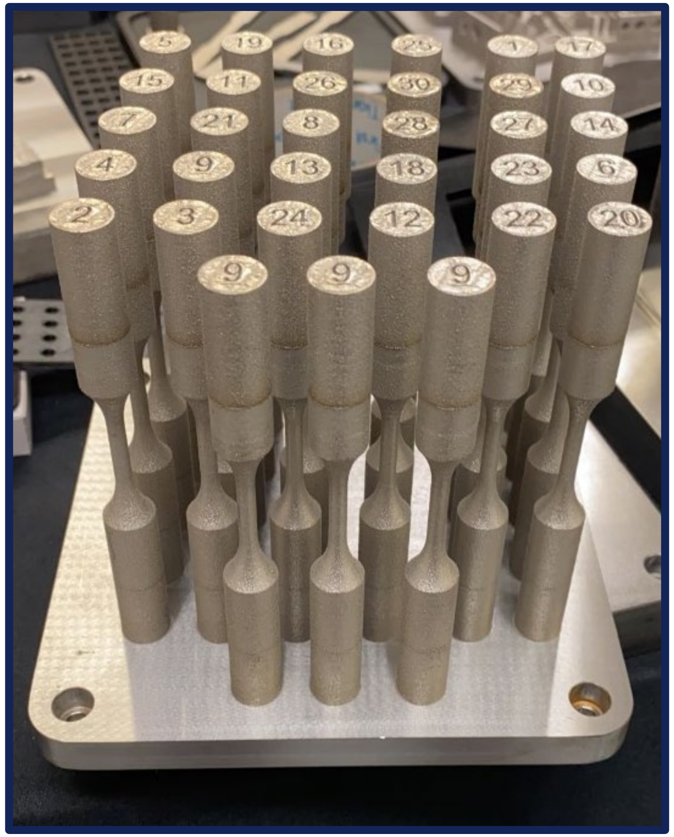
- The project aims to investigate cross-platform consistency in PBF-LB technologies.
- We will engage with 9+ different PBF-LB original equipment manufacturers (OEMs)
  - Develop a neutral manufacturing plan to establish consistency across platforms
  - Determine methods for analyzing and improving the consistency of PBF-LB processes.
- This project will provide the industrial supply chain with the knowledge of cross-platform printing for broad implementation

Technical Approach

- Focus on the tensile properties of PBF-LB IN 718
  - Establish **processing control data requirements** for multiple PBF-LB platforms
  - Conduct a **round-robin test** for tensile properties across 9+ different PBF-LB platforms
  - Evaluate the **effect of heat treatments** to create process consistency
  - Analyze the influence of **process parameters and machine features**
  - **Document recommendations** for test methods and data requirements for qualification and future standards needs
- *The raw data will be made available to the America Makes community for further analysis*

Task 1 – Test Method Development

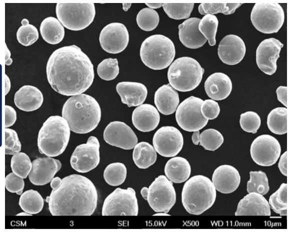
- Develop the test method for the **data collection and printing strategy** for the round robin tests
  - Prior lessons learned from NIST round robin testing
  - The overall test architecture will be developed in collaboration with NIST, AFRL and America Makes.
- Focus on tensile properties
  - Including the influence of post processing heat treatment
  - Net shape geometry using best practice processing
- All proposed test methods will be reviewed with the NIST/AFRL team
  - A sample dataset from Mines will be validated with the NIST AM team to ensure compatibility and suitability.

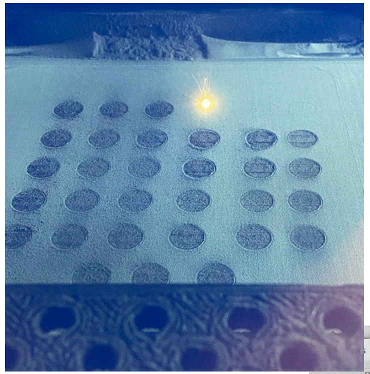


Task 2 – Definition of Processing Pedigree

- Identify what processing pedigree is documented from the different platforms
  - Collaborative discussions to identify the machine process control parameters for at least 9 different platforms
  - Bridge gaps in terminology between all the OEMs leveraging the ASTM Common Data Dictionary
  - Ensures consistency in data reporting during the round robin studies.
  - Definition of post-processing steps

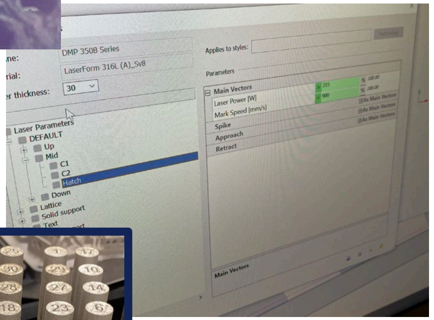
Feedstock

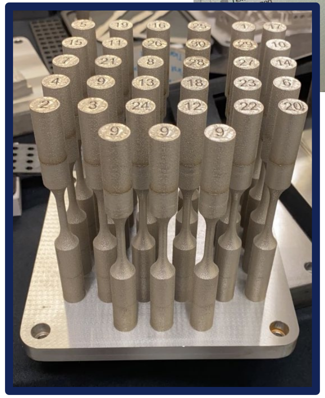




Machine

Parameter

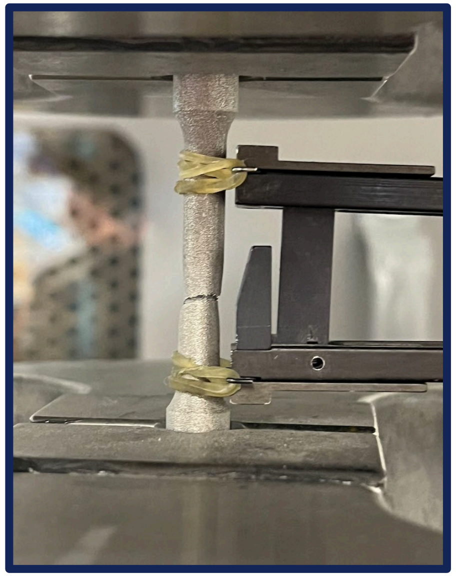




Build

Task 3 – Round Robin Studies

- Obtain a minimum of **40 tensile bars from each platform** and tensile test to failure
  - A minimum of 9 platforms will be tested
  - Powder feedstock characterization
- Analyze the **microstructure and porosity** through cross-sections
- Optional fatigue bars depending on project time
- Gather all process control data as well as any in-process data
- A summary report will be developed
  - Raw data will be delivered to the America Makes community



Test Matrix

(Number of bars per platform: total)

As-built (3: 27)

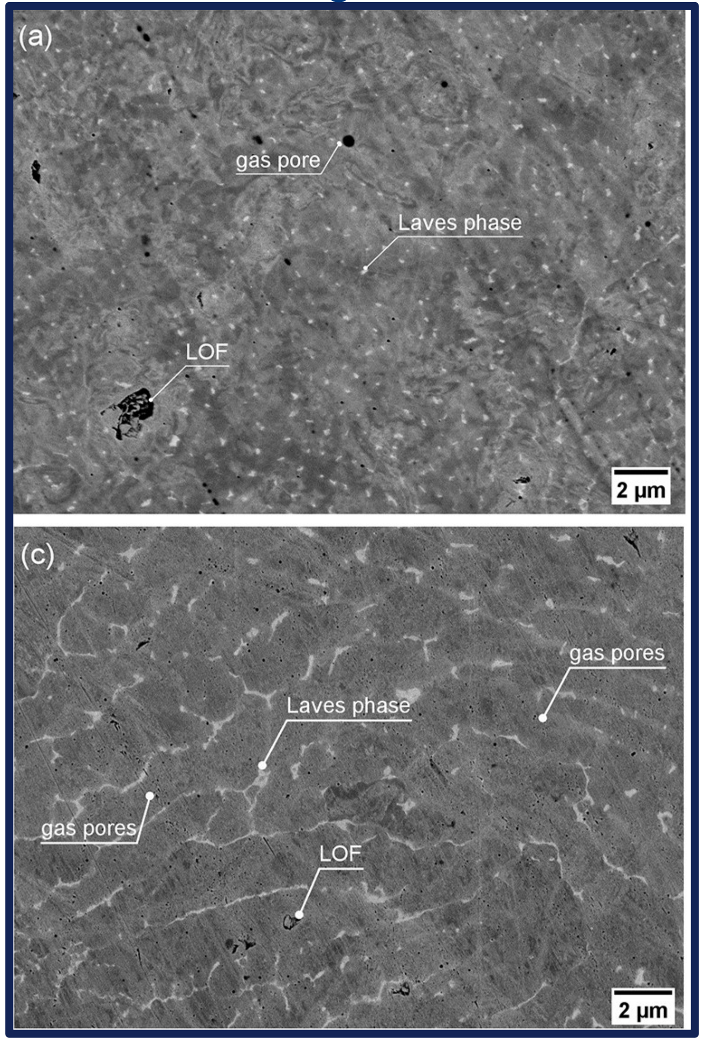
Standard Heat Treatment (15: 135)

Full Recrystallization (15: 135)

Task 5 – Data Analysis

- Correlative analysis of processing inputs to tensile properties
  - Processing and machine variables
- Microstructural analysis of as-built and both heat treatments
  - Influence of starting microstructure on heat treatment response
- Microstructure impact on tensile properties

718 Microstructure at Different Processing Parameters



Lesko, C.C., Sheridan, L.C. and Gockel, J.E., 2021. *Journal of Materials Engineering and Performance*, *30*(9), pp.6630-6639.

Task 6 – Measurement Method Specification

- Develop a measurement method specification that may be used for analyzing consistency of various PBF-LB equipment
  - Expose future gaps and needs for standards development and new America Makes roadmap requirements.

Velo Sapphire 1MZ Install and Qualification

Summary:

- Build Module Docking and Sealing
    - Cable routing updated
    - Software update for communication issue
    - Sealing/docking fix
- Herding Integration (3rd party system)
    - Velo design for improved discharge bin/lid
    - Procedure created for discharge bin removal
    - Safer, more reliable, ergonomic operation

For Reference:

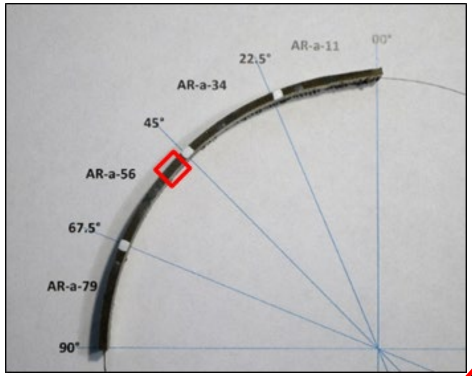
- 4 XC 1MZ systems fielded
- >400,000 layers of accumulated printing

Technical Approach

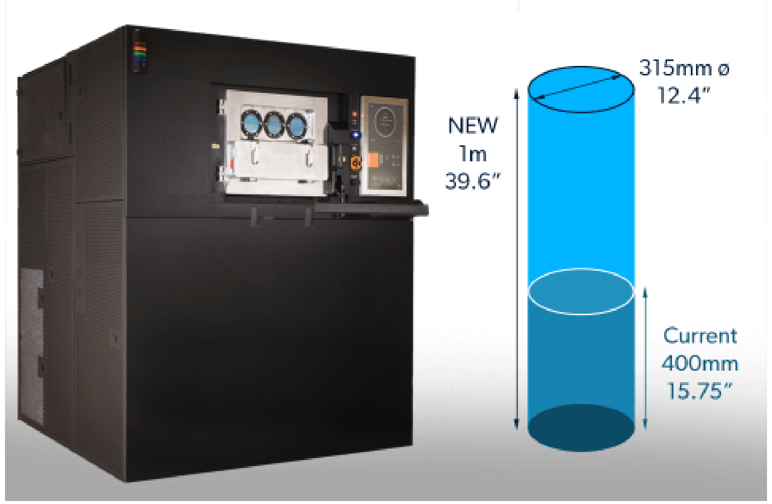
Goal: Checkout machine and process for program use.

- Evaluate to determine if in family to specifications or need to generate additional procedures
- Consistent, repeatable and controllable fabrication

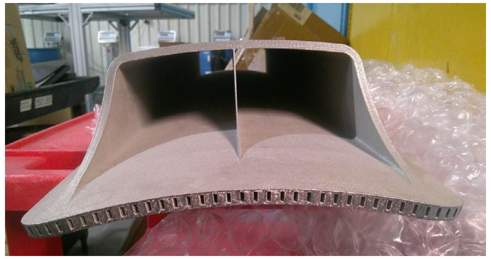
- Machine operations
- Material and Parameter checkouts
  - Microstructure (As-built and Heat Treated)
  - Tensile properties are in family of other Velo and conventional
  - 3 ranges: 0°< Angle < 20°, 21°< Angle < 44°, 45°<Angle
- Geometry checkouts – Feature builds, residual stress distortion
- Limit builds – Hole sizes, wall thicknesses

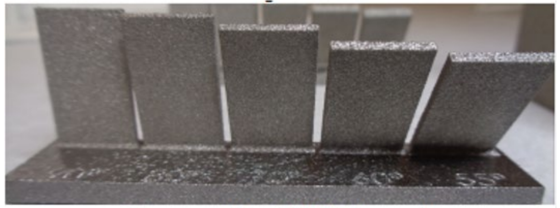


Velo Material Checkouts

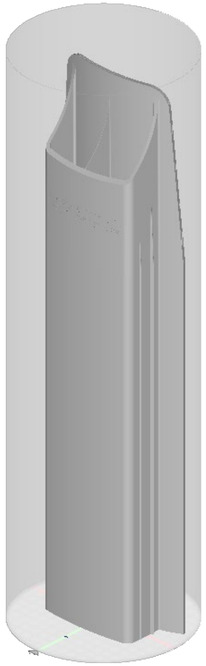


- At the build plate:
  - Microstructure samples around the build plate
  - Horizontal, Vertical, and 45° tensile tests
  - Design and build impossible samples
- Vertical checkouts:
  - Full height samples – Microstructure evaluation
  - Iteration 2 samples
- Geometry Samples
  - Flat plate samples
  - Feature build samples (Tough to build sections)
  - Full geometry
  - Test unit geometry



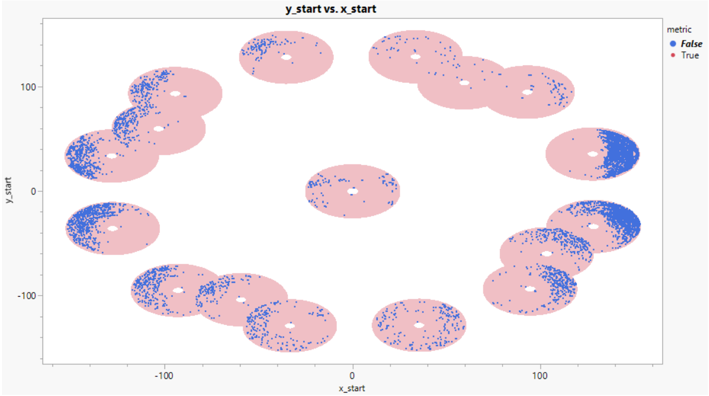


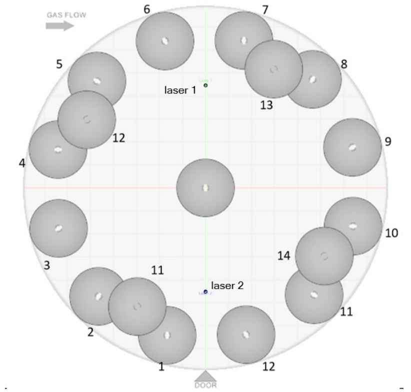
Downward face (90-55 degrees)



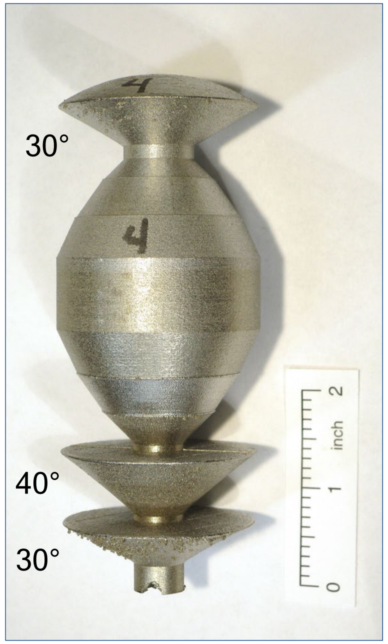
Build 1 – Velo Head Quarters

- Goal: Review consistency of multiple parameter microstructure around the build envelope and response to heat treatment. Heat Treatment development
- Clocking is not important on the samples
- At Build plate:
  - 4X Process Tree – Center
  - 8X Process Tree – Edge
- At Top of envelop:
  - 4X Process Tree – Center
  - 4X Support bar, .5” OD





Overhang angles:



Sample arrayed as on build plate, viewed from below build plate

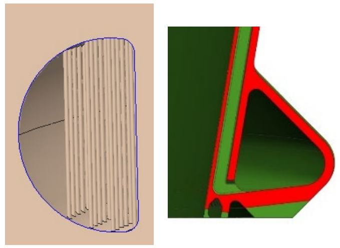
Geometry Demonstration Plan

Air →

Goals:

- Make sample that meets 1m z-height
- Utilize Velo capabilities
  - "Cavity Feature" >45°
  - Injector holes ID .010"
  - Manifold features >1.5" OD
  - Thin walls .030" Min
- Demonstrate joining elimination
- Test geometric distortion □→○
- Complex contouring

Conventional vs. Velo

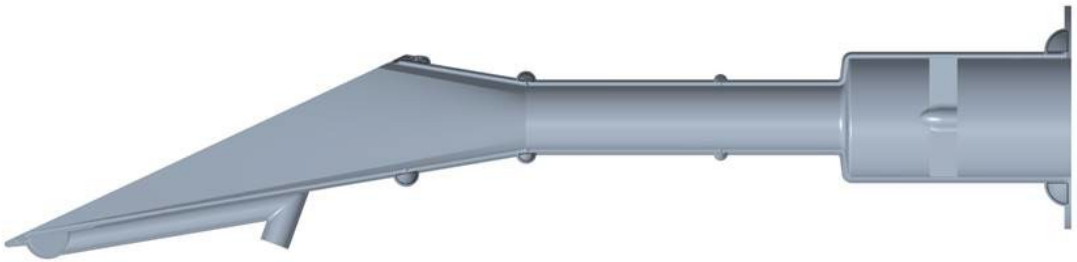


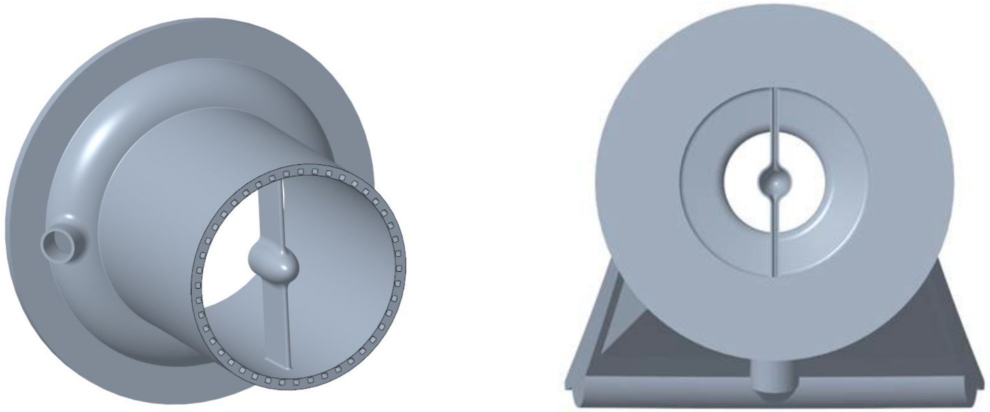
Detail Requirement:

- Inlet to Combustor
- Balance realism vs. inherent design

Submitted for review to feature or de-feature

Side View: Fluid Schematic





CAD-toon of notional envelope geometry

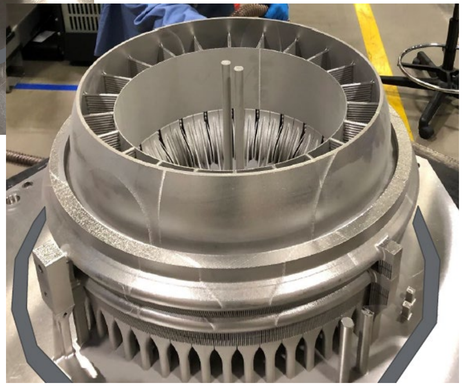
Problem Statement

- Joining is often required to leverage LPBF. This requires additional manufacturing steps, tooling, post-processing, and inspections.
- Enabling large-scale LPBF eliminates the need for joining operations, reduce associated cost, weight, part defects, and lead times.

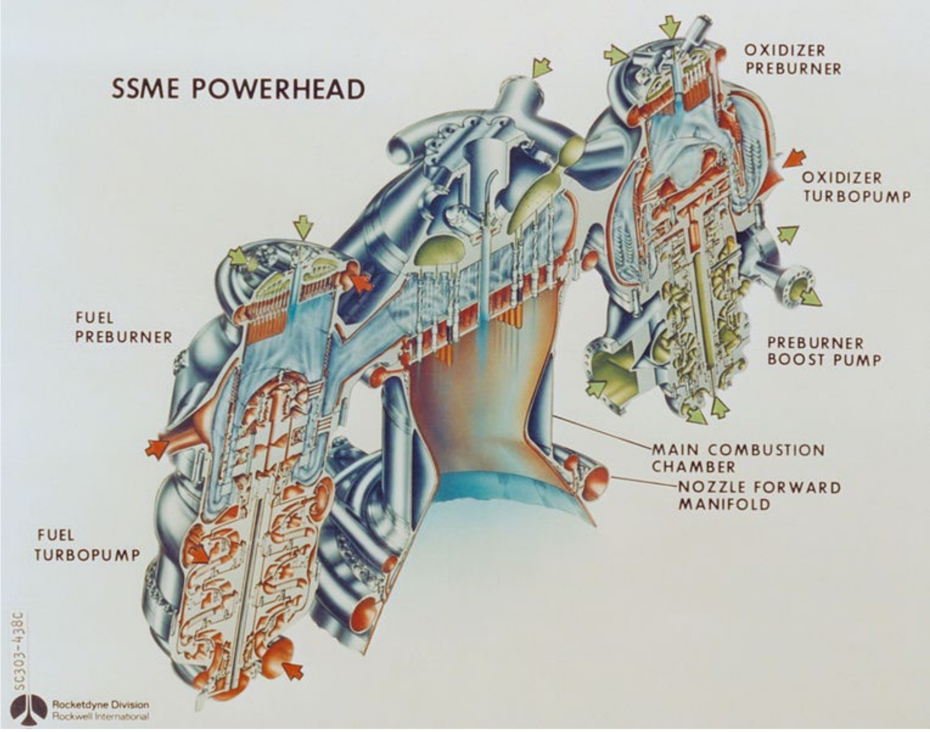
GE's Project ATLAS beta machine

- Build envelope:
  - 1,000mm x 900mm x 300mm
- 1 kW laser
- 3D scanner translates with laser
- Optimal air flow over the print area
- Geometric flexibility/versatility
- Scalable platform (multi-laser)

GE ATLAS 2019 (85 days)



GE ATLAS 2020 (54 days)



SSME/RS-25 – Powerhead
"Backbone of the Engine"

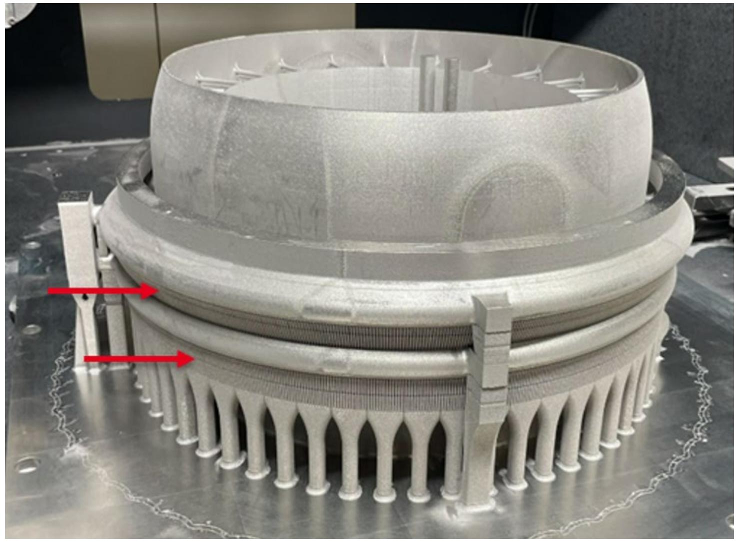
- Technology demonstration
- Representative size, joining, and fine feature risks
- Representative material certification requirements

ATLAS removes >1000 parts and >500 joints

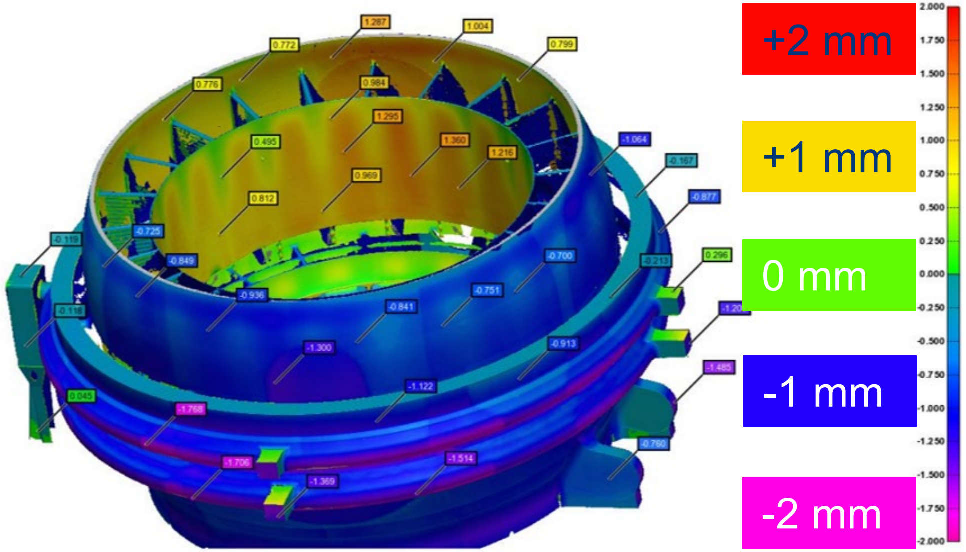
Phase 4 – Full Scale Component Build

- Goals
    - Demonstrate feasibility for ATLAS platform (large, jointless components)
    - Provide accompanying mechanical data
    - Demonstrate productivity improvement on “real world” large format part
- Build Preparation
    - Identical build layout to HEX Print on ATLAS platform in 2020
    - Updated bulk parameter (Phase 1) and downward surface parameter (Phase 3a)
- Results
    - RS-25 HEX successfully printed (600mm OD, 300mm height)
    - Reduction in total build time of ~43%
    - Dimensional deviations associated with global part shrinkage
    - Tensile, HCF, and LCF all similar to previous results in this program

RS-25 HEX Build on ATLAS	Baseline Parameter (2020)	High Productivity (2022)	% Difference
Scan Time	35.8 days (859 hrs)	19.0 days (455 hrs)	**-47.0%**
Total Build Time	53.9 days (1295 hrs)	30.8 days (739 hrs)	**-42.9%**



RS-25 HEX Part (High Productivity)



Dimensional scan with point cloud (mm)

The U.S. casting and forging industry faces challenges related to capability and capacity, workforce, and U.S. Government policies

Reductions Across Foundries

- With a **67% reduction in the number of U.S. foundries since 2000**, the U.S. Castings and Forgings ecosystem supply chain is clearly dwindling

Customer Prioritization

- High-quality, domestic purveyors of castings and forgings tend to **prioritize high-value/high-quantity customers** such as in automotive and other high-demand industries

DoD Supply Chain Implications

- The **DoD's high mix/low volume quantities** are **not as profitable for domestic foundry operations**

The challenges with the CF supply chain can pose immediate risks to our national security interests and wartime readiness for critical platforms

Fortunately, AM has shown potential to improve CF lead times

America Makes is leading the way by convening AM and CF ecosystems to strategically assess opportunities for augmenting casting and forging with additive manufacturing.

Roadmap Objectives:

Identified the significant issues affecting CF supply chains and their common characteristics

Prioritized and mapped AM opportunities to those issues, defined the **scope and investment** required

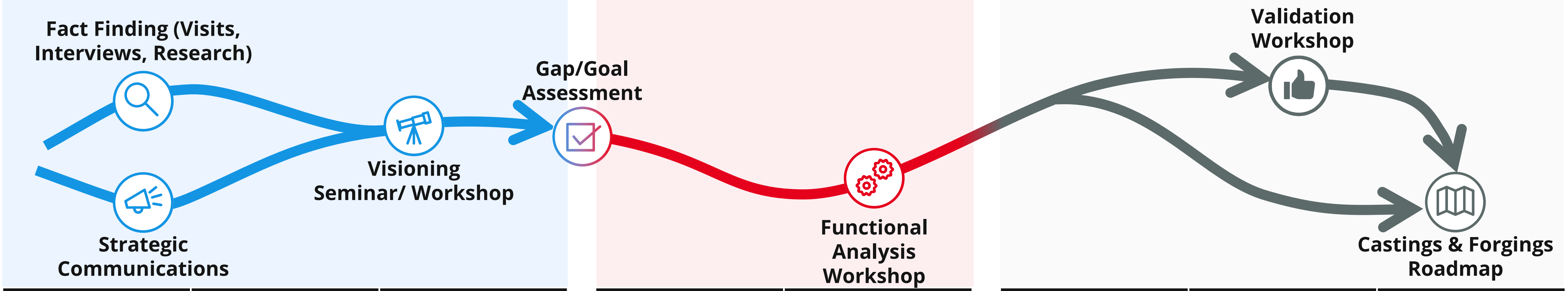
Examples may include:

- Leveraging AM for Tooling
- Leveraging AM for Replacement Parts
- Hybrid Manufacturing

Determined what infrastructure is needed to address the challenges identified

The Journey

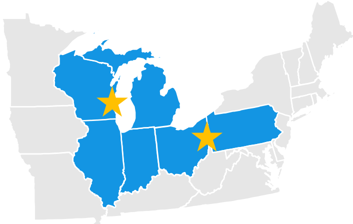
Discovery			Functional Analysis		Synthesis		
January	February	March	April	May	June	July	August



- *Identified **100** articles and peer-reviewed them for **technical solutions***
- *Conducted **41 expert** interviews*

*Identified industry **Pain Points** and **Opportunities** for AM*

***4 workshops** in Milwaukee and Youngstown; representing casters, forgers, and the DIB*



** Blue illustrates where the casters and forgers who participated are located*

131 Workshop Participants

96 Organizations Represented

4 Swim Lanes

21 Technical Projects

Insights + Key Discoveries

KEY THEMES:

AM for Tooling	**AM for tooling is the most feasible solution** as the final part is not being altered, easing qualification requirements while speeding up the time to get tooling and lowering the cost
Confidence in AM	Due to underdeveloped standards and limited characterization of the material properties, there is a **general lack of confidence in the repeatability of AM** compared to casting and forging
Modeling and Simulation	Desire to **improve modeling and simulation tools** to improve decision-making, increase confidence in part performance, and speed up the qualification process
Assisted 3D model creation	Desire for **improved tools** to assist with converting **2D drawings to 3D CAD models** when the drawing exists and **tools for reverse engineering** when it does not
Workforce Enablement	**Workforce enablement** was cited as a current pain point with CF, and as a gap to implementing AM solutions

TOP PAIN POINTS

- The qualification process is challenging, lengthy, and costly
- The wealth of knowledge in the DIB is declining
- Converting 2D drawings to 3D CAD models
- Bidding on low volumes is too risky
- Tooling can be difficult to manage

TOP OPPORTUNITIES

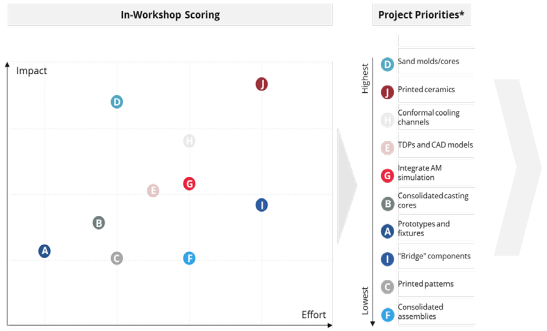
- Modeling & simulation to improve the design process
- Printed tooling for forgings and castings
- AM for tool & equipment repair to keep manufacturing “in the fight”
- AM for hybrid manufacturing
- Tools/guides to assist with technology selection and design

What Is Needed to Succeed

KEY INGREDIENTS:

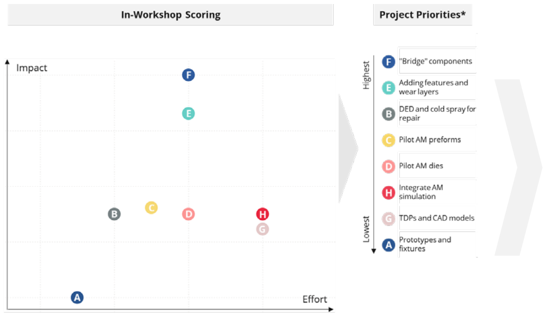
- **Path to Print** — Playbooks to deploy AM technology for patterns, molds, dies, and repairs
- **Shared Understanding** — Common guidance on when to print, capable vendors, and how to measure performance
- **Integrated Tools** — AM material property predictions as input to broadly used software
- **Digital Foundation** — Common TDP structure with processes to build digital stockpiles
- **Sustainable Training** — Accessible AM resources contained and grown within Casting and Forging communities

Casting Project Priorities and Impact



- Reduced NRE cost
- Reduced variation
- Removed bottlenecks with parallel path
- Improved confidence in AM outcomes

Forging Project Priorities and Impact

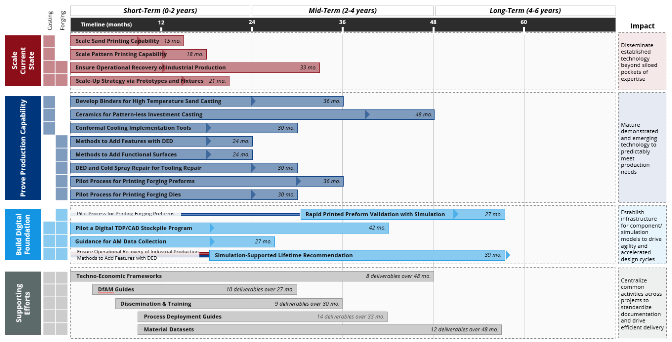


*Prioritization calculated using a weighting of 75% Impact and 25% Effort.

- Extended tooling life
- Simplified supply chain
- Reduced cost/time of tooling repair
- Increased process flexibility

Elements of a U.S. Casting and Forging Roadmap

The Roadmap consists of 5 key elements: 1) swim lanes demonstrating the focus areas; 2) stages organized into 3 phases; 3) projects that collectively enable a capability; 4) ecosystem(s) that the projects apply to; and 5) impact in support of DoD's mission



Swim Lanes

Focus areas that structure the implementation of initiatives and facilitate organization of resources to execute

Stages

Time horizons broken into three distinct phases: near-term (0-2 years), medium-term (2-4 years), and long-term (4+ years)

Projects

Targeted actions in support of program objectives through strategic alignment and drive the planning and execution phases

Ecosystem(s)

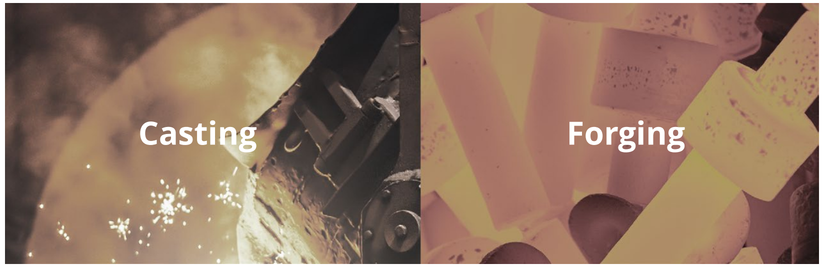
Designation of whether the individual projects apply to the casting and/or forging industry

Impact

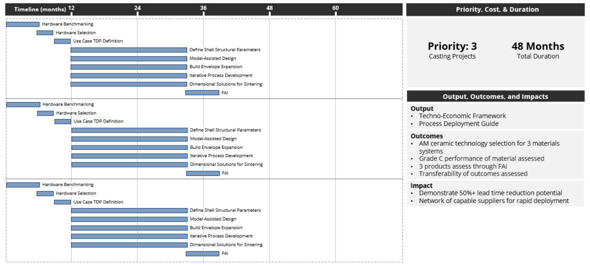
Comprehensive value that each swim lane will drive; includes stakeholder benefits and aligns with the future vision

The Roadmap Structure

1 Roadmap



21 Projects



4 Swim Lanes

Scale Current State — Disseminate established technology beyond siloed pockets of expertise

Prove Production Capability — Mature demonstrated and emerging technology to predictably meet production needs

Build Digital Foundation — Establish infrastructure for component/simulation models to drive agility and accelerated design cycles

Supporting Efforts — Centralize shared activities across projects to standardize documentation and drive efficient delivery

Making the Roadmap Actionable

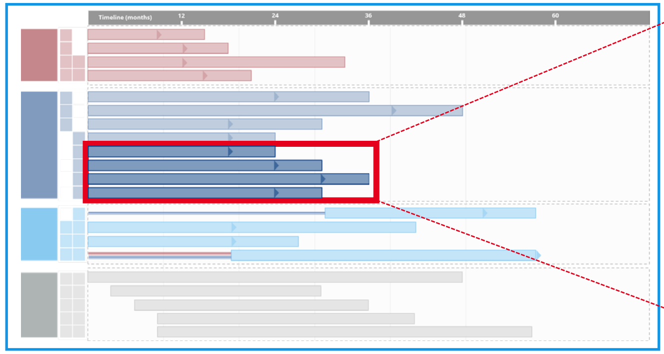
Implementation Activities
Identified over three stages: near-term, mid-term, and long-term

Impact, Output, and Outcomes
Results and products of project delivery

Interdependencies
Connectivity outlined across projects, lines of effort, and sub-tasks

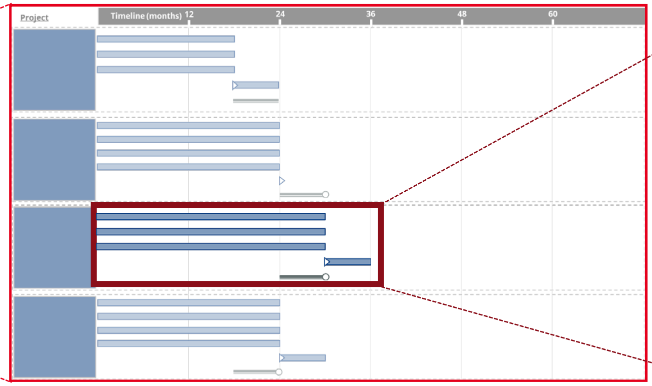
Navigating the Roadmap

ROADMAP LEVEL



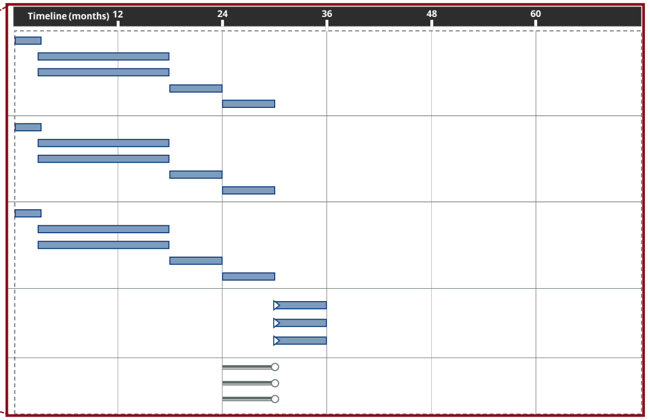
The highest level depicts the multi-year view of all projects, summarizing their attributes and impacts. It provides the framework for down-selecting projects and their activities for funding, organizing the overall projects by applicable ecosystem (casting/forging) and area of focus (swim lane).

SWIM LANE LEVEL



The swim lane level organizes projects that aim to achieve similar outcomes, and are delineated along the lines of technology maturity and the digital-physical nature of AM. This level of the roadmap presents a deeper look into each swim lane and its projects.

PROJECT LEVEL



The project level details execution plans that drive individual activities to a specific application domain and outcome. They provide a structured and comprehensive breakdown that describes the attributes of priority, schedule, and results (output, outcomes, and impact).

Casting Projects Overview

Scale Sand Printing Capability	Disseminate leading practices and promote adoption of 3D printed sand molds/cores
Scale Pattern Printing Capability	Develop and disseminate leading practices and promote adoption of 3D printed patterns for casting
Develop Binders for High Temperature Sand Casting	Develop enhanced binder materials and strategies to drive processing efficiency of 3D printed sand
Ceramics for Pattern-less Investment Casting	Mature ceramic AM technology to enable rapid pours into integrated shell and cores
Conformal Cooling Implementation Tools	Develop and disseminate performance-enhancing tools for implementing AM conformal cooling

Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Forging Projects Overview

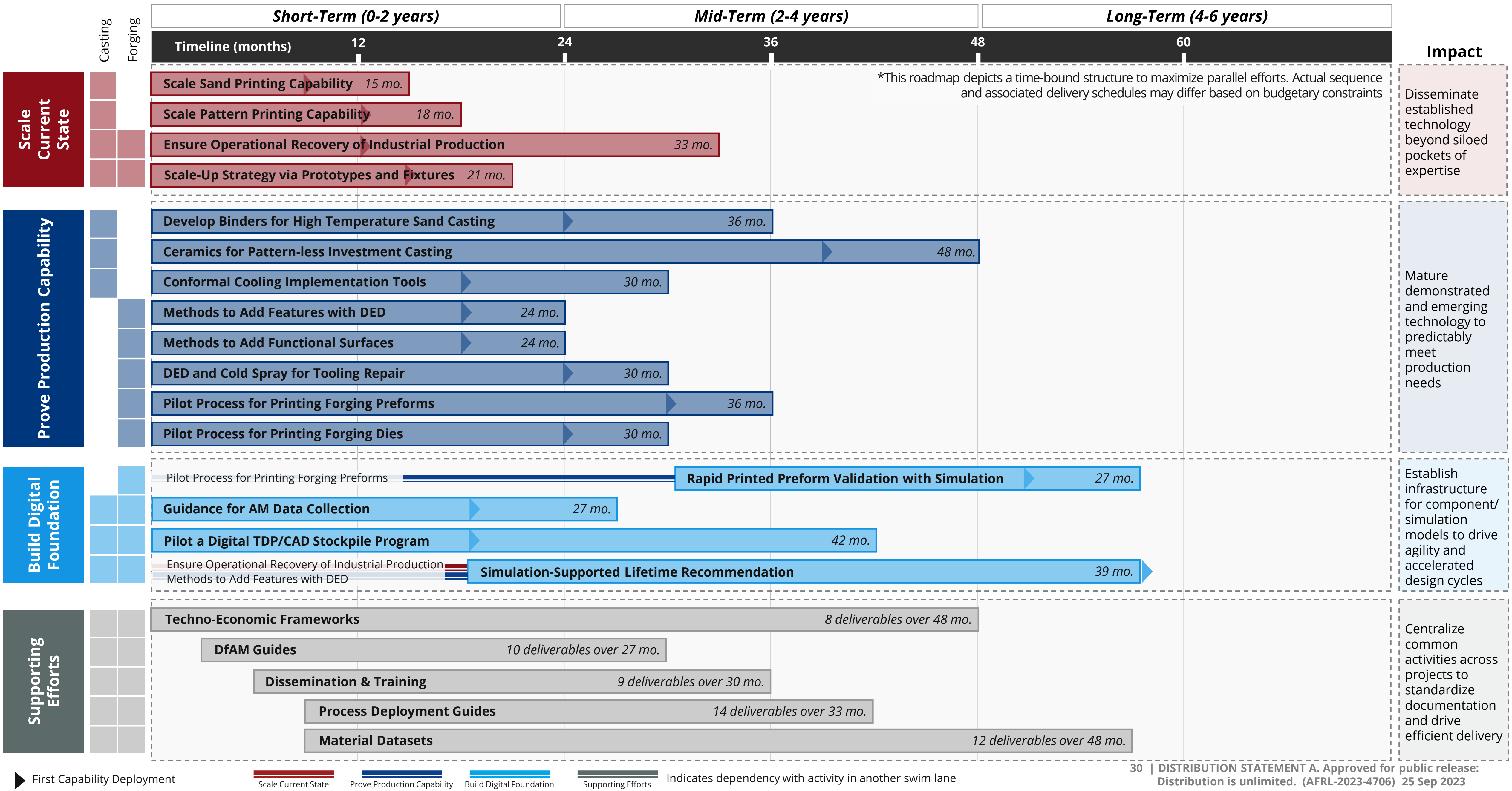
Methods to Add Features with DED	Established, assess, and demonstrate transferable capability to add complex geometric features to forgings
Methods to Add Functional Surfaces	Established, assess, and demonstrate transferable capability to add functional surfaces to forgings
DED and Cold Spray for Tooling Repair	Establish methods for planned and unplanned tooling repair and modification applications
Pilot Process for Printing Forging Preforms	Pilot the industrialization of AM preforms to expedite the forging process for low volume components
Pilot Process for Printing Forging Dies	Pilot the industrialization of AM dies to expedite the forging process for low volume components
Rapid Printed Preform Validation with Simulation	Enable optimized process setups with predictable performance using preforms with heterogenous microstructures

Shared Projects Overview

Ensure Operational Recovery of Industrial Production	Establish scalable sourcing model for AM industrial equipment replacement parts to keep critical production equipment running
Scale-Up Strategy via Prototypes and Fixtures	Define an optimal dissemination strategy for design/deployment guides through prototypes & fixtures
Guidance for AM Data Collection	Establish data infrastructure and application-based guidance to collect store data spanning AM process flows
Pilot a Digital TDP/CAD Stockpile Program	Accelerate the creation of TDPs and CAD models for legacy components by building a program of record for continued conversion
Simulation-Supported Lifetime Recommendation	Develop material and geometric performance software solutions to integrate into DoD process flows
Techno-Economic Frameworks	Drive AM utilization by establishing frameworks that clearly define when, where, and how to print feasibly and economically
Design for Additive Manufacturing Guides	Enable confident and efficient usage of AM by documenting proven design rules across parts, tooling, and accessories
Dissemination & Training	Scale the adoption of technical development with focused and strategic communication to build a pipeline of SMMs ready to leverage AM capabilities
Process Deployment Guides	Build delivery mechanisms for technical development by documenting clear and tested procedures for implementing and controlling AM processes on the shop floor
Material Datasets	Enable cross-functional sharing with standardized management and storage of material data gathered during development activities

Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Additive Manufacturing Technology Roadmap for Castings and Forgings



No Regrets Next Steps

It is imperative to enhance national security by maturing our industrial base with investments that free up CF capacity and streamline throughput

Lower adoption risk by disseminating resources and tools to make informed decisions for when to use AM.

Invest in technology deployment by transferring key capabilities and outcomes to the shop floor

Incentivize knowledge sharing by early adopters to replicate advanced capabilities at scale across the industrial base

Incorporate non-technical solutions to policy and workforce issues that will generate long-term success

To improve our nation's wartime readiness, we must address CF supply chain challenges and build on the momentum generated during roadmap development through continued ecosystem collaboration and targeted investment

Scale Current State

America Makes

Scale Current State

Short-Term | Mid-Term | Long-Term

Timeline (months) 12 24 36 48 60

Project	Activities	Time to Deployment & Total Duration (months)	Impact
Scale Sand Printing Capability (Casting)	Molds for Aluminum Sand Casting Molds for Magnesium Sand Casting Supporting Efforts Transferability Demonstration	• First Deployment: 9 • Total Duration:15	• Increase supply base quoting for low-volume DoD parts • Realize 20%+ improvement in throughput
Scale Pattern Printing Capability (Casting)	Patterns for Aluminum Investment Casting Patterns for Nickel Investment Casting Supporting Efforts Assess Scalability of Post-Processing Automation Transferability Demonstration	• First Deployment: 12 • Total Duration:18	• Reduced engineering development cost by 10%+ • Demonstrate 25%+ lead time reduction potential
Ensure Operational Recovery of Industrial Production (Casting and Forging)	Supplier Network Risk-Based Selection Framework Techno-Economic Framework Common Data Model Deployment - Shop 1 Deployment - Shop 2 Deployment - Shop 3 Deployment - Shop 4 Deployment - Shop 5 Supporting Efforts	• First Deployment: 12 • Total Duration: 33	• Drive reduction in equipment downtime • Build common understanding of when and how to implement industrial equipment replacement parts

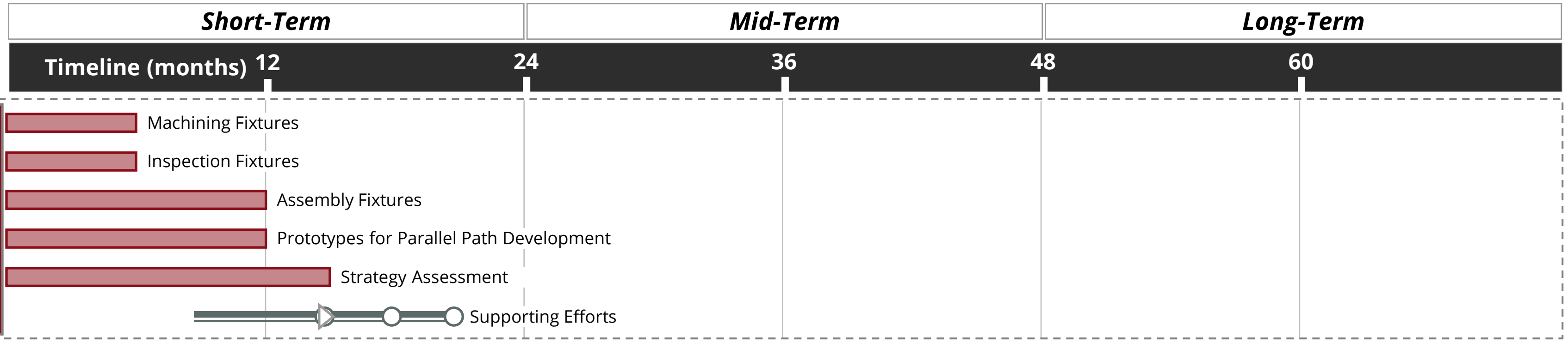
First Capability Deployment | Deliverable | Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Indicates this activity is interdependent of an activity in another swim lane

Scale Current State

Project

Scale-Up Strategy via Prototypes and Fixtures (Casting and Forging)



Time to Deployment & Total Duration (months)

- First Deployment: 15
- Total Duration: 21

Impact

- Shorten development cycles by 10%+ by parallelizing activities
- Build a common training and knowledge dissemination strategy

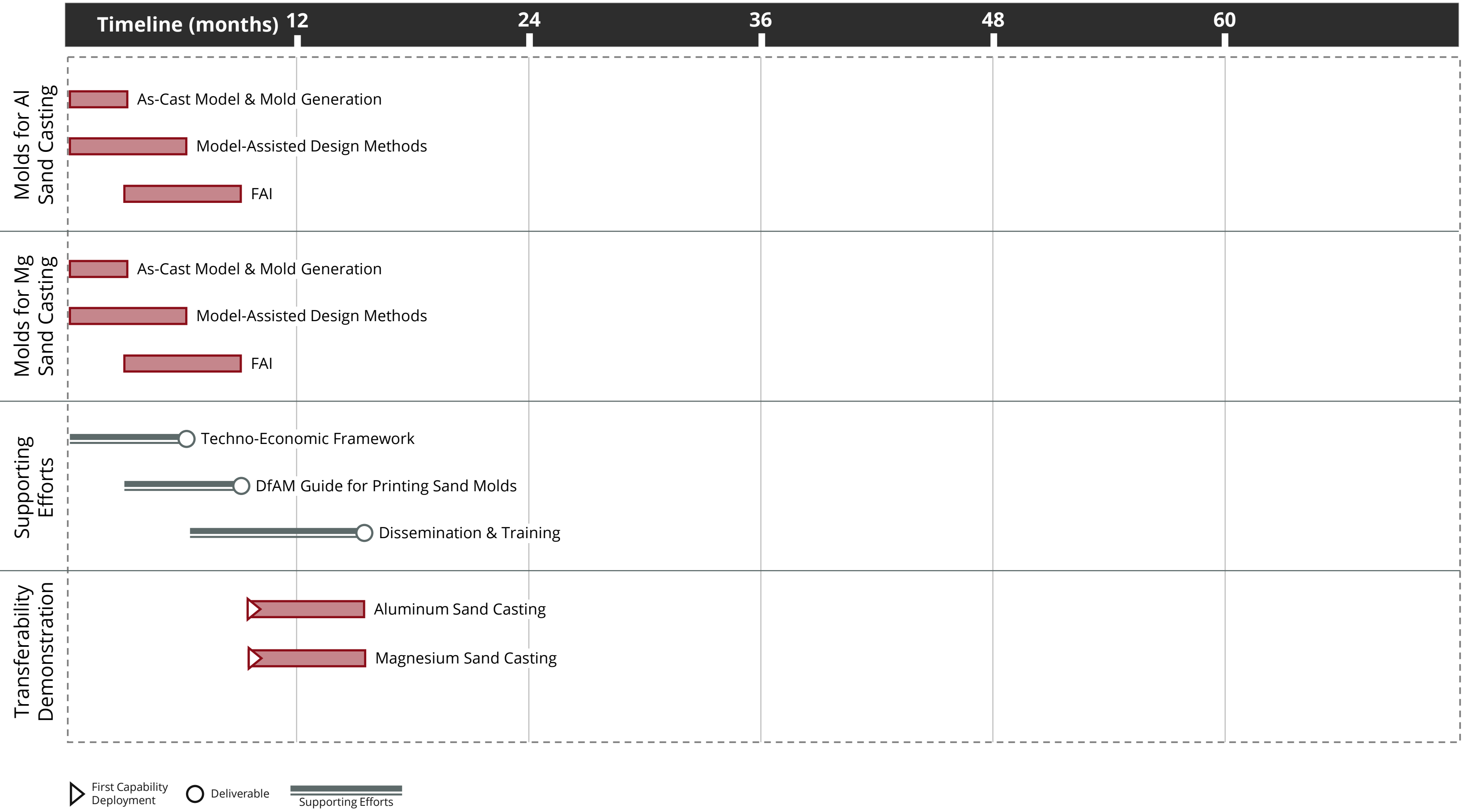
First Capability Deployment | Deliverable | Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Indicates this activity is interdependent of an activity in another swim lane

Scale Sand Printing Capability

Disseminate leading practices and promote adoption of 3D printed sand molds/cores

Casting Forging



Priority, Cost, & Duration

Priority: 1
Casting Projects

15 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Techno-Economic Framework
- DfAM Guide for Printing Sand Molds

Outcomes
- 2 material systems characterized: Aluminum and Magnesium
- 2 tailored products designed, manufactured, and validated

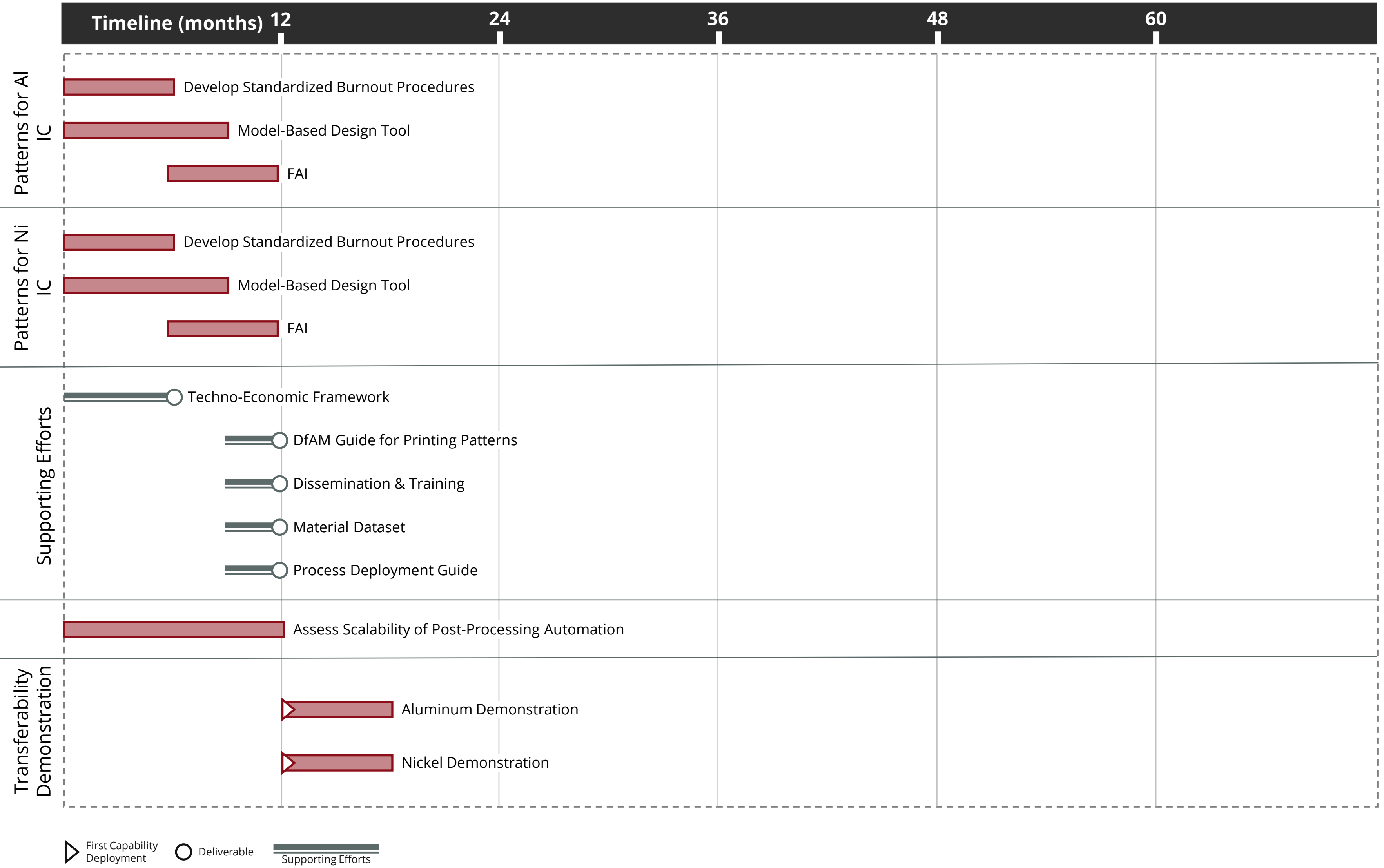
Impact
- Increase supply base quoting for low volume DoD parts
- Realize 20%+ improvement in throughput

America Makes

Scale Pattern Printing Capability

Develop and disseminate leading practices and promote adoption of 3D printed patterns for casting

Casting Forging



Priority, Cost, & Duration

Priority: 5
Casting Projects

18 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Techno-Economic Framework
- DfAM Guide for Printing Patterns
- Material Dataset
- Process Deployment Guide

Outcomes
- 2 material systems characterized: Aluminum and Nickel
- 2 products assess through FAI
- Transferability of outcomes assessed

Impact
- Reduced engineering development cost by 10%+
- Demonstrate 25%+ lead time reduction potential

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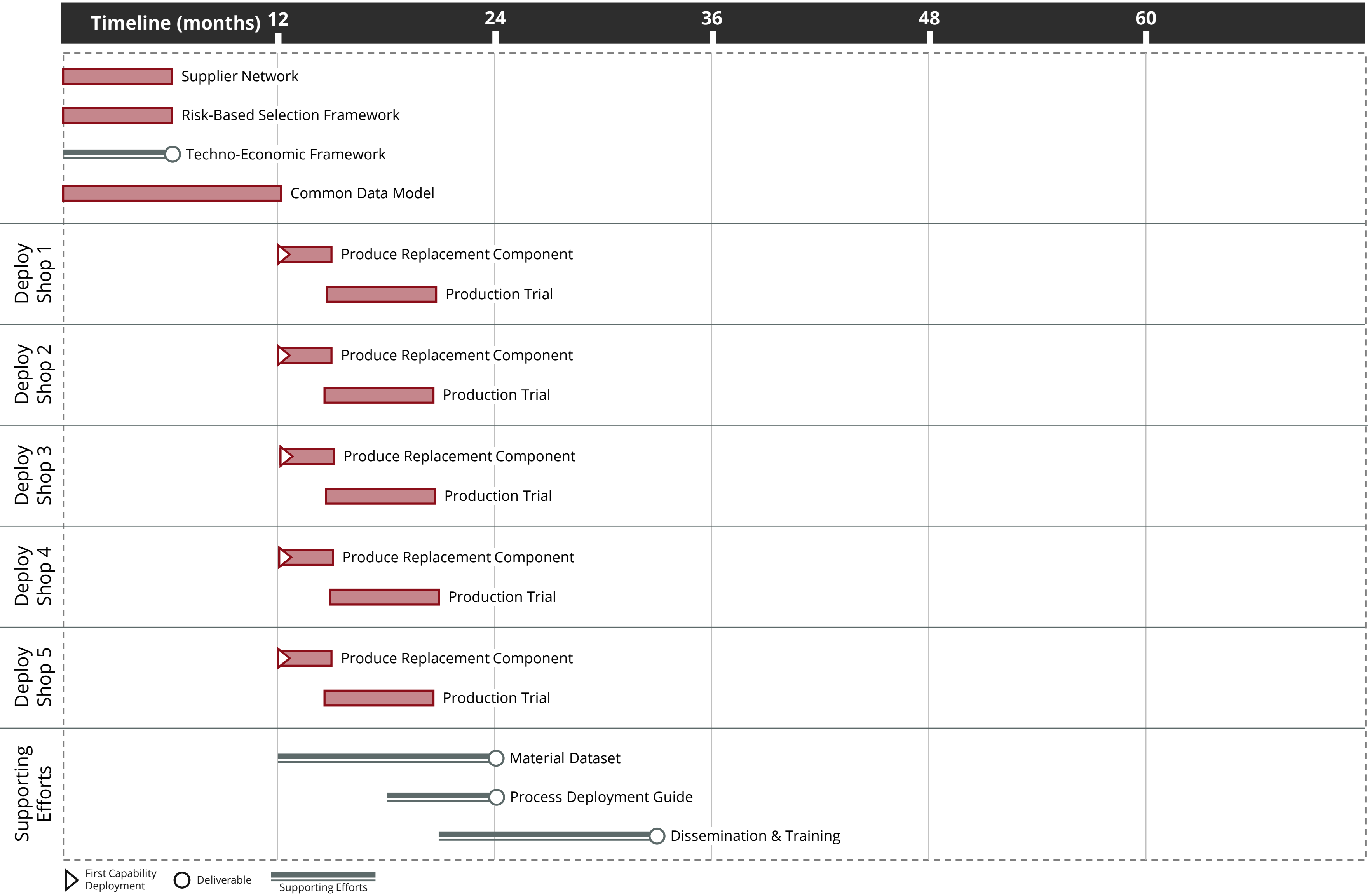
Ensure Operational Recovery of Industrial Production

Establish scalable sourcing model for AM industrial equipment replacement parts to keep critical production equipment running

Casting / Forging



Priority, Cost, & Duration

Priority: 1
Shared Projects

33 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Common Data Model for Industrial Equipment Replacement Parts
- Techno-Economic Framework
- Process Deployment Guide for Industrial Equipment Replacement Parts (including process selection)

Outcomes
- Produce and Validate 5 Components
- Deploy to 5 production facilities

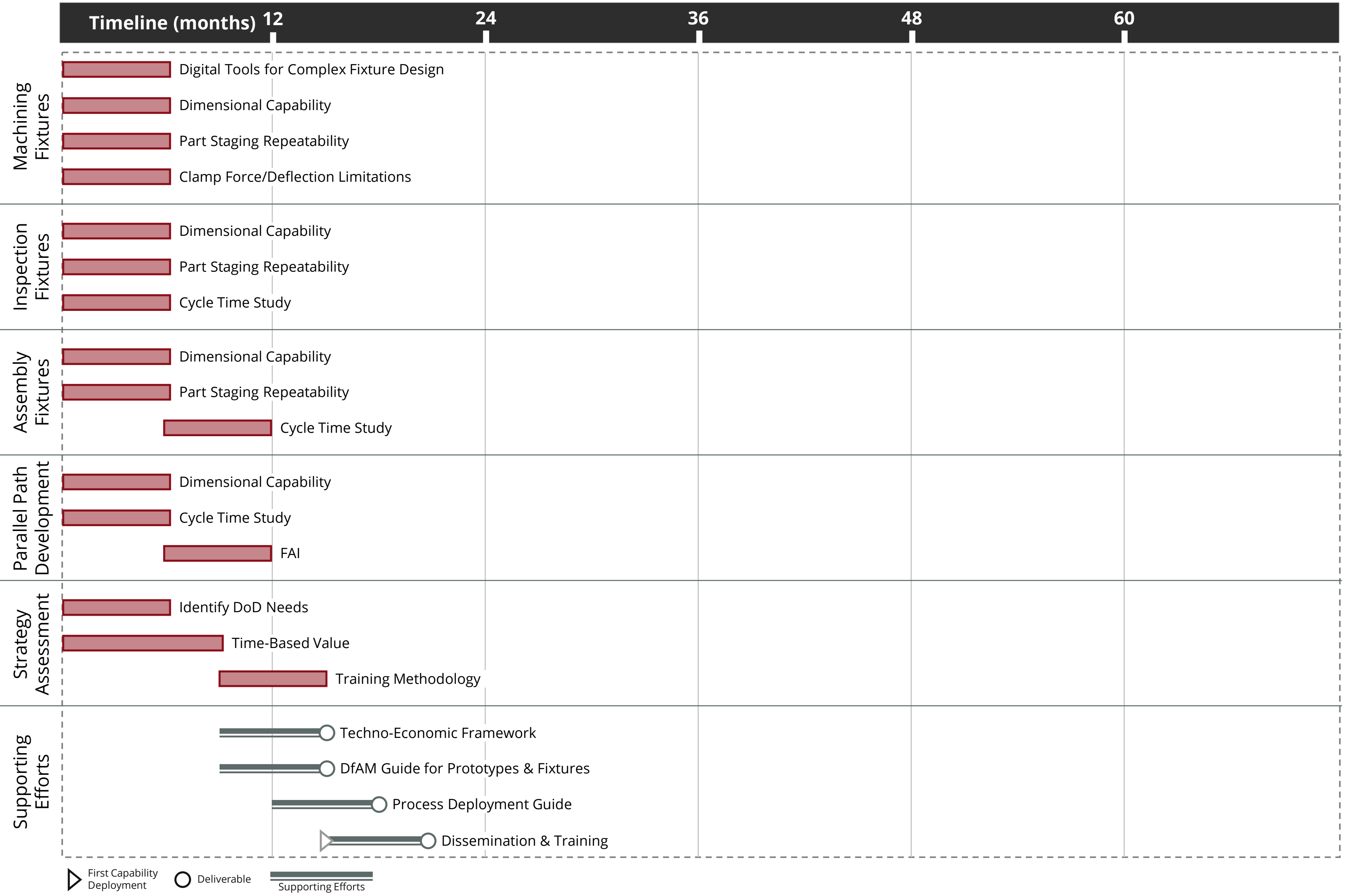
Impact
- Drive reduction in equipment downtime
- Build common understanding of when and how to implement industrial equipment replacement parts

America Makes

Scale-Up Strategy via Prototypes and Fixtures

Define an optimal dissemination strategy for design/deployment guides through prototypes & fixtures

Casting / Forging



Priority, Cost, & Duration

Priority: 4
Shared Projects

21 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Techno-Economic Framework
- DfAM Guide for Prototypes and Fixtures
- Process Deployment Guide

Outcomes
- 5 products assessed through stages of development cycle
- 3 AM materials assessed through stages of development cycle
  - 2 polymer (ABS/Nylon)
  - 1 composite

Impact
- Shorten development cycles by 10%+ by parallelizing activities
- Build a common training and knowledge dissemination strategy

When America Makes America Works

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