Additive Manufacturing Benefits to Engine Design

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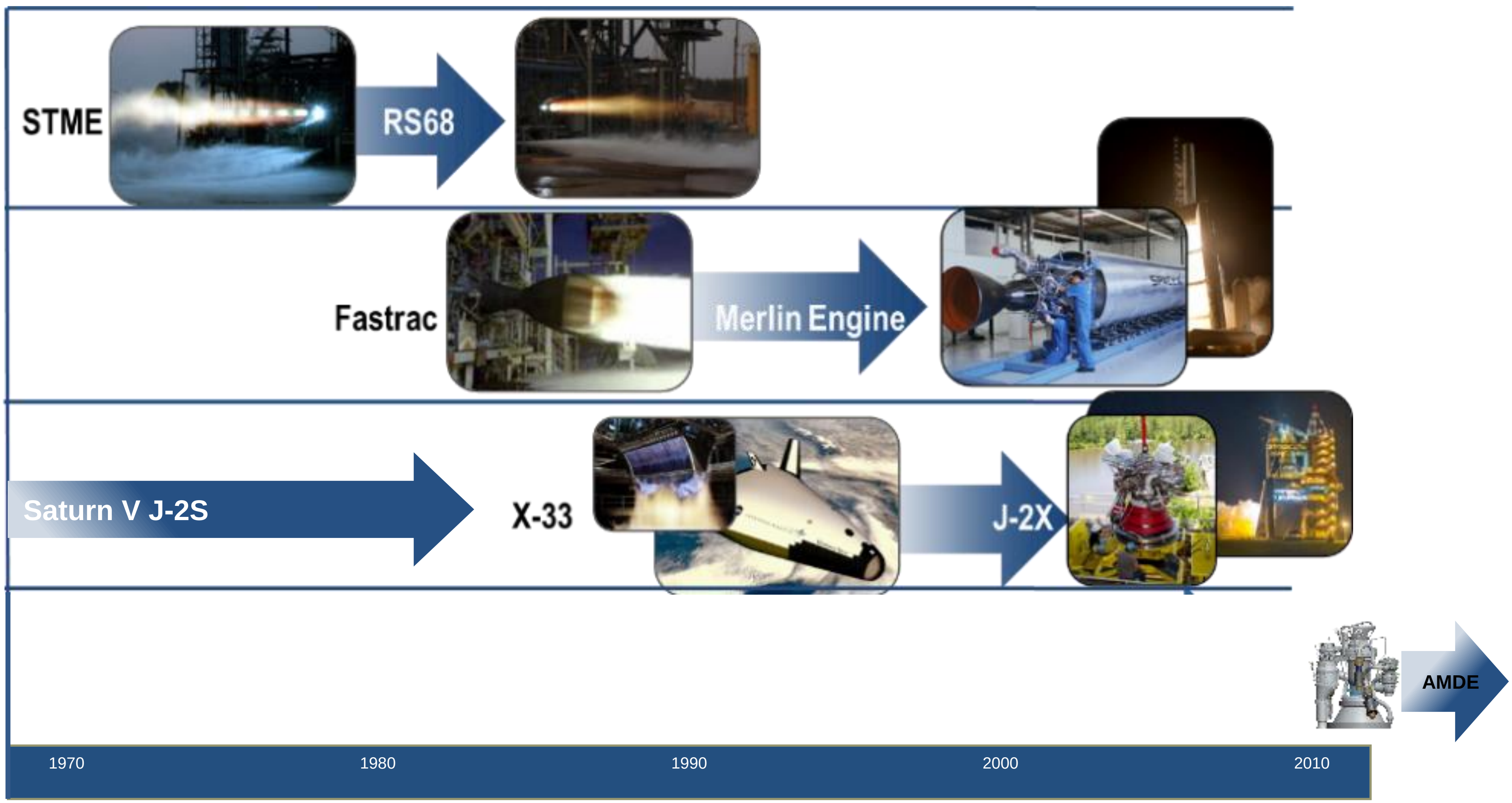
Background

- Data collected from multiple MSFC Propulsion Systems Department efforts:
  - RS-25
  - Low Cost Upper Stage Project (LCUSP)
  - Additive Manufacturing Demonstrator Engine (AMDE)

Game Changing Aspects

State of the Art		Additive Manufacturing Demonstrator Engine (AMDE)
• DDT&E Cost – $1-4 Billion – 500 FTE	***$1/10^{th}$ Dev Cost & Resources***	• AMDE Cost – $50 Million (projected) – 25 FTE
• DDT&E Time – 7-10 years	***1/2 Dev Lead Time***	• AMDE DDT&E Time – 2-4 years
• Hardware Lead Times – 3-6 Years	***$1/6^{th}$ Production Time***	• Hardware Lead Times – 6 - 12 Months
• Engine Cost – $20 - $50 Million	***$1/10^{th}$ Reoccurring Cost***	• LPS Engine Cost – $1-5 Million
• Test-Fail-Fix Cycles – 150 – 300	***Low Cost Test-Fail-Fix Cycles***	• LPS Test-Fail-Fix Cycles – TBD
• NASA PM and Insight – 30-50 FTE	***Trained PM/CE's***	• LPS Management – LSE Model



Demonstrated History of Technical & Commercialization Successes

From Saturn to the future: MSFC Leverages 50 Years of Space Flight Experience

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AMDE Project Objectives

Primary Objectives:

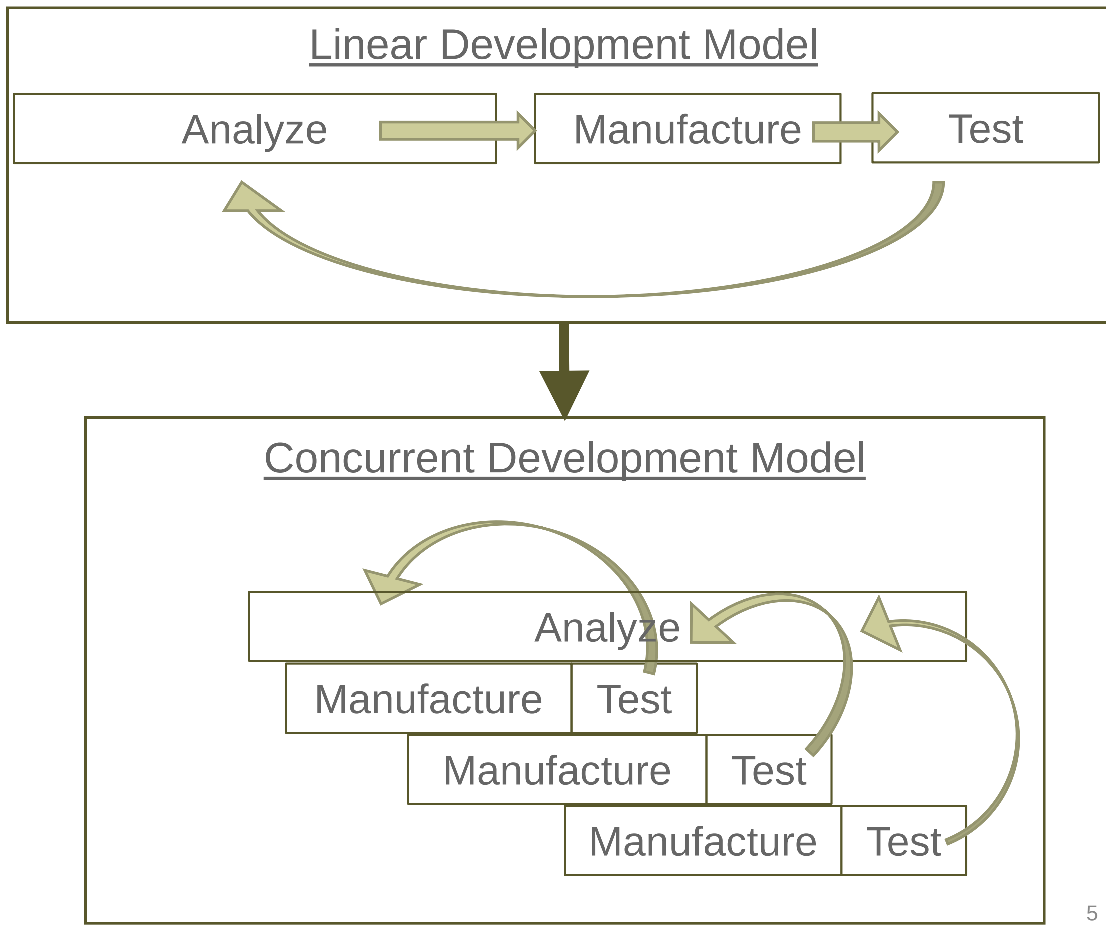
1)Demonstrate an approach that reduces the cost and schedule required for new rocket engine development

- **Prototype engine in 2.5 years**
- Operate lean
  - (~ 25 people/year; $5M/year hardware and testing)
- Shift to Concurrent Development
  - Use additive manufacturing (AM) to facilitate this approach

2)Advance the TRL of AM parts through component/system testing

3)Develop a cost-effective prototype

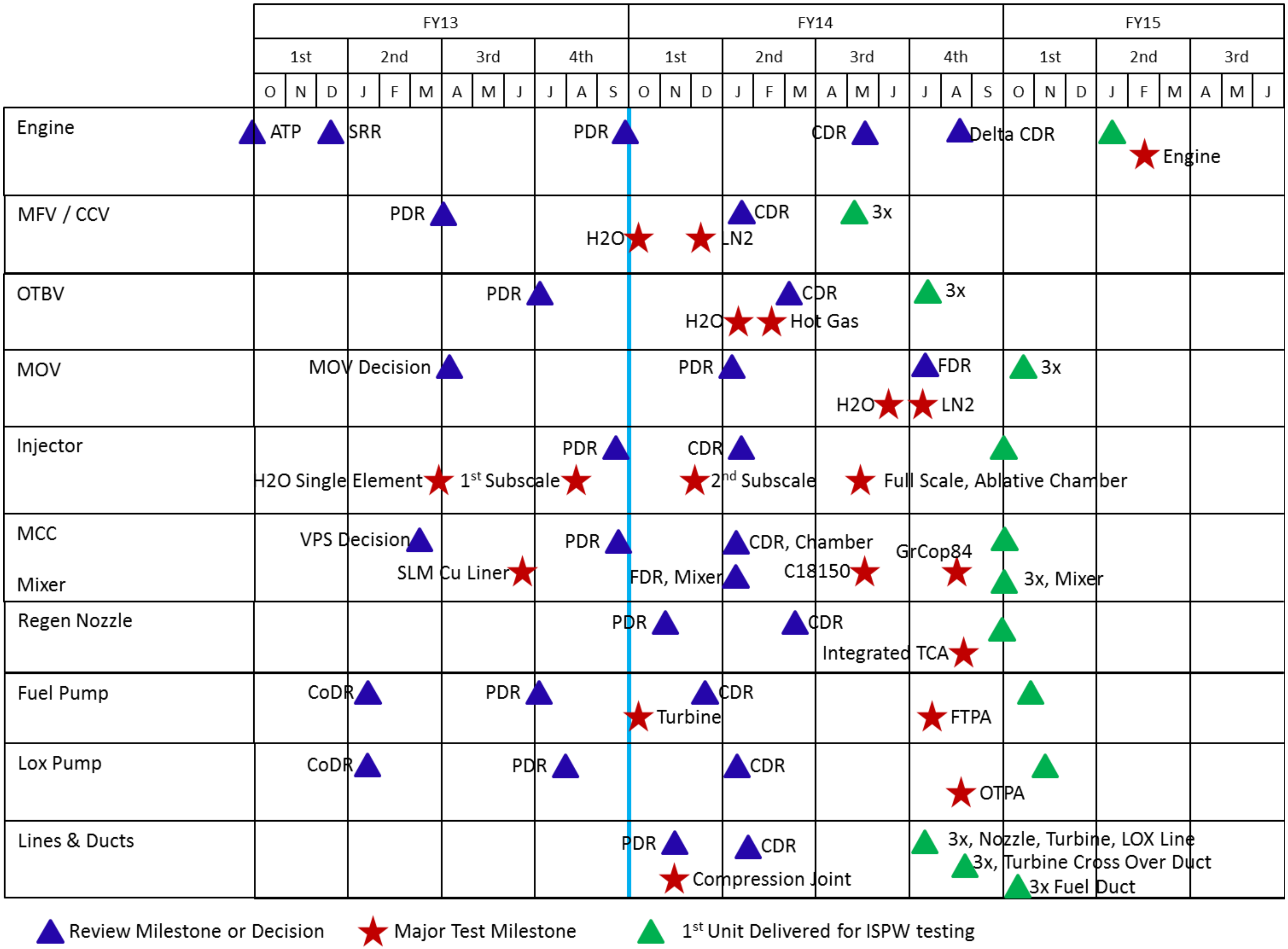
- Upper-Stage or In-Space Class



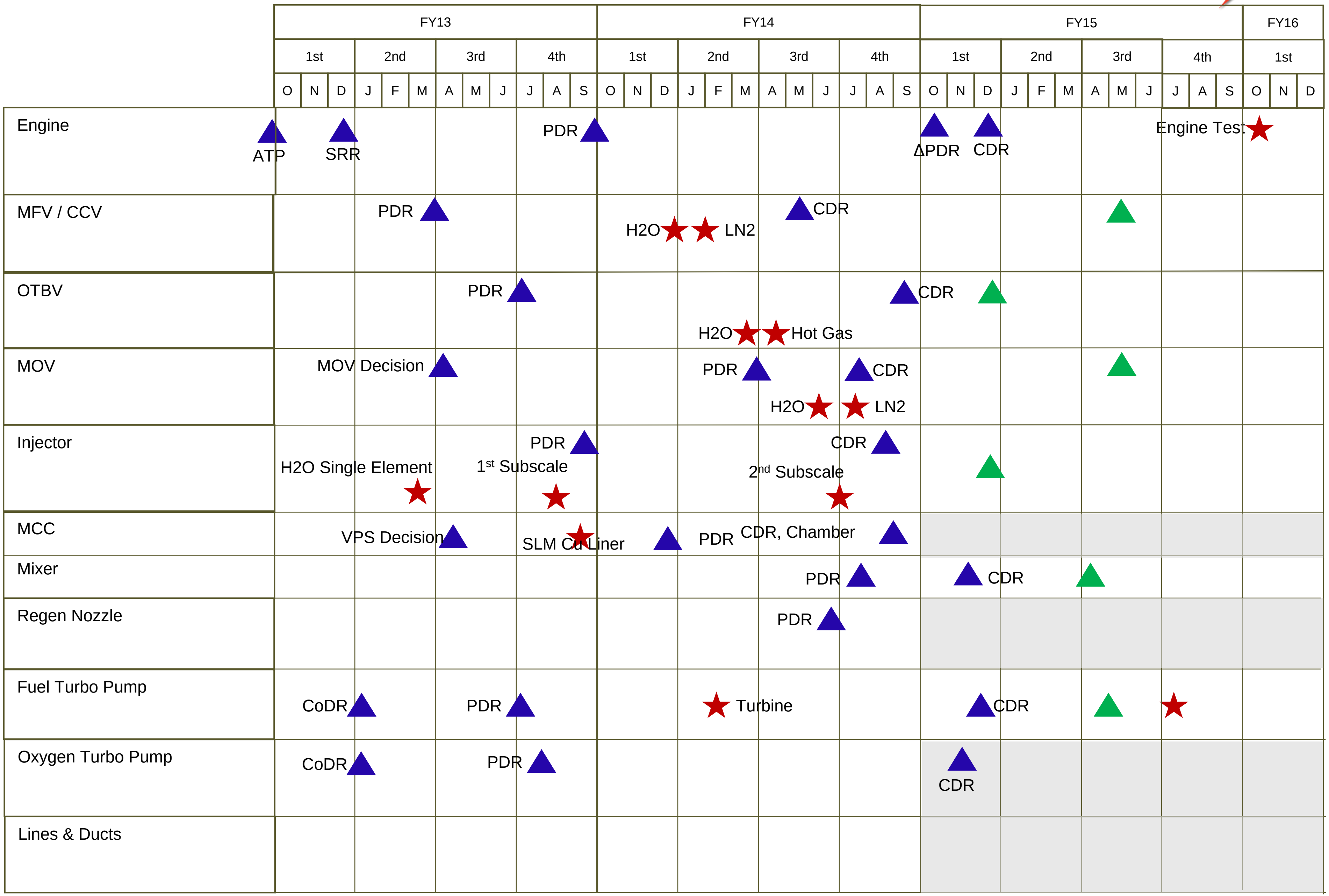
Lessons Learned

- Additive manufacturing reduces costs throughout the product life cycle
  - Reduced part counts translate to reduced drawings, processes, configuration management, increased reliability, shorter and simplified assembly and potentially a smaller workforce and manufacturing footprint
  - Reduced cost and schedule for parts translates to earlier risk reduction testing, reduced need for early analysis, hardware available for early manufacturing and assembly trials.
  - Flexible design options translate to lower mass, reduced interfaces and seals, increased performance, and more efficient packaging.
- Additive manufacturing properties, while still uncertain, are better than traditional cast parts allowing for reduced mass.
- Procuring hardware early while the design is immature allows for early iterations with vendors and the ability to gather test and assembly data to reduce long term cost and schedule impacts. Early data feeds designs and analysis.

AMDE Baseline Development Schedule



AMDE Actual Development Schedule



Review Milestone or Decision   Major Test Milestone   1st Unit Delivered for AMDE testing

Overview

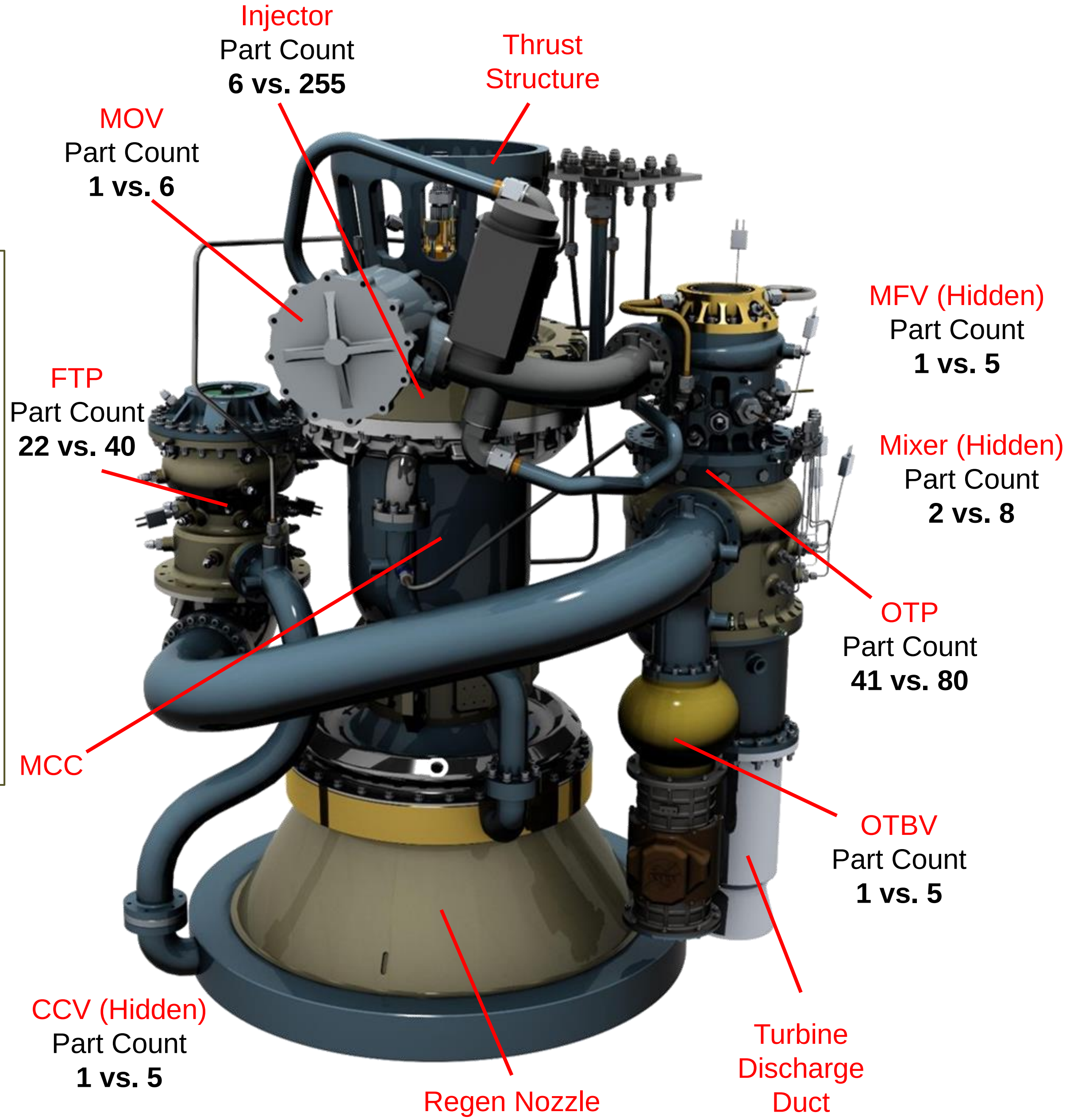
	Interfaces	Part Count	Processing	Packaging	Design Flexibility	Development	Production Unit Cost	Mass	Schedule
Engine System	Reduced interfaces		Reduced welds, process development	More efficient packaging	Build more efficient parts and systems	Reduced tooling; Early testing; Compressed dev cycle	Potential savings, reduced touch labor and processes	Optimize for mass reduction	Streamline processes from development through production
Turbomachinery	Internal interfaces simplified		Reduced processes, assembly steps, parts	More efficient packaging	Internal passages, efficient geometries	Early testing to reduce uncertainty; high dev risk with castings	Part dependent; Casting is cheaper for some parts	Material properties are better than cast	Shorter lead times than traditional methods
Injectors		85% decrease	Reduced processes, assembly steps, parts	Efficient element spacing	Allows for more complex geometries	30% reduction in cost	Greater than 30% reduction in cost		Likely decreased due to fewer operations
Regen chambers and Nozzles			Eliminates process to close out channels		Vary channel geometries and wall thicknesses	30% reduction in cost		Potential savings for manifolds and interfaces	~50% savings for first unit
Valves	Integrate housings with other components	Reduced part count & seals	Reduced processes, assembly steps, parts	Design freedom creates packaging flexibility	Allow for better flow control and complex geometries	Earlier testing, overall cost/schedule may not change	Decreased cost for complex geometries	Increased properties (over cast) and design flexibility	Decreased schedule for complex geometries
Ducts & Flexible Elements	Incorporate lines into other components .	Reduce overall part count;	Reduce weld development.	Create new geometries	Remove constraints based on standard radii and thicknesses	Early fab demonstration and test. Early assembly & machining trials.	Decreased costs for complex geometries	Eliminate thinning at bends, optimize thicknesses	Decreased schedule for complex geometries

Legend: Demonstrated | Design Dependent | Unproven

AMDE Reduced Part Count for Major Hardware

H_2/O_2
35,000 lb_f
thrust
452 s ISP

- 0 Flexible Elements
- <30 welds vs 100+ traditionally
- Compressed Development Cycle
  3 years vs. 7
- Reduced part counts
- Invested 10M, 25 FTE over 3 years
- Estimated production & test cost for hardware shown $3M

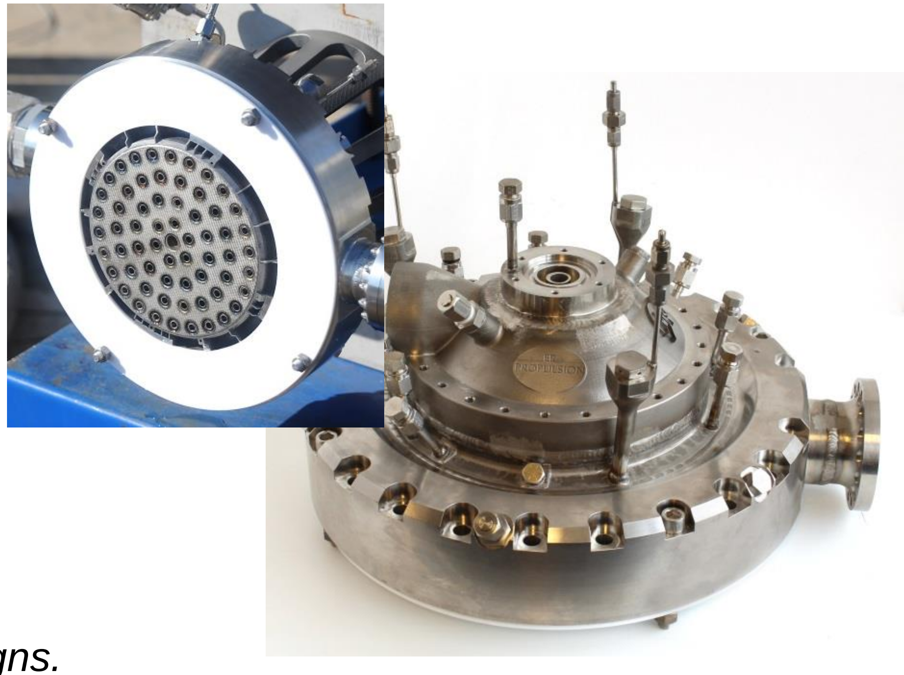


Note: Part count examples are for major piece parts and do not include bolts, nuts, washers, etc.

Example: Full Scale Swirl Coaxial Injector Assembly

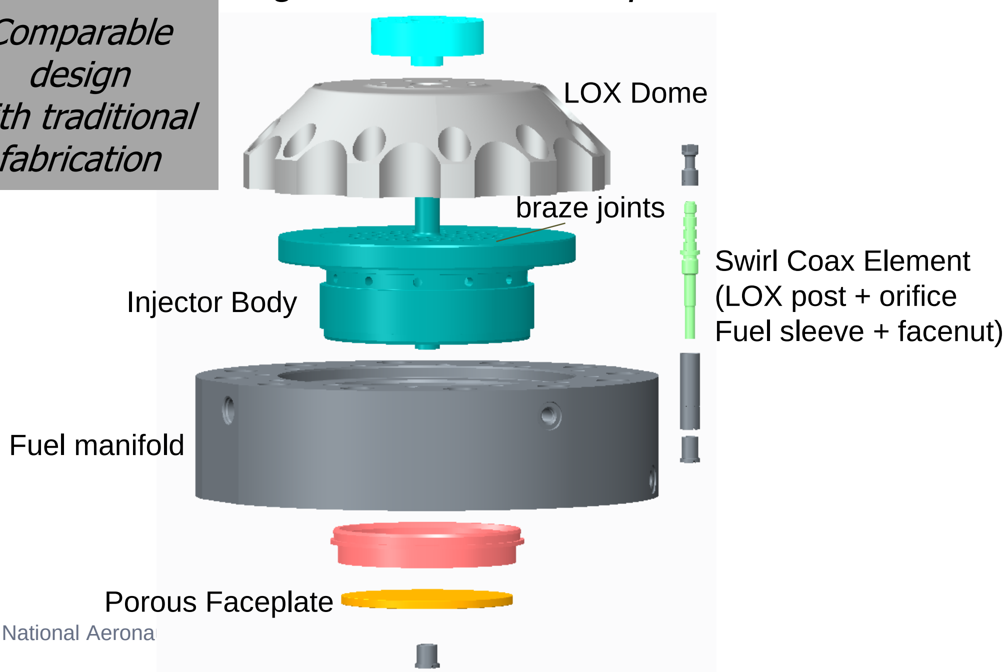
Compared to traditional injector fabrication, using AM…

- Decreased cost by 30%
  (higher cost savings likely for production units)
- Significant part count reduction from **252 to 6** parts
- Allowed unique design features to be used
  - individual elements integrated directly into injector body - no threaded joints required
  - instrumentation ports strategically placed/integrated into injector body (some in places not possible with traditional fab techniques)
- Eliminated critical machining to reduce fabrication risks
- Eliminated critical braze joints to reduce operating risks (no more interpropellant leak paths)

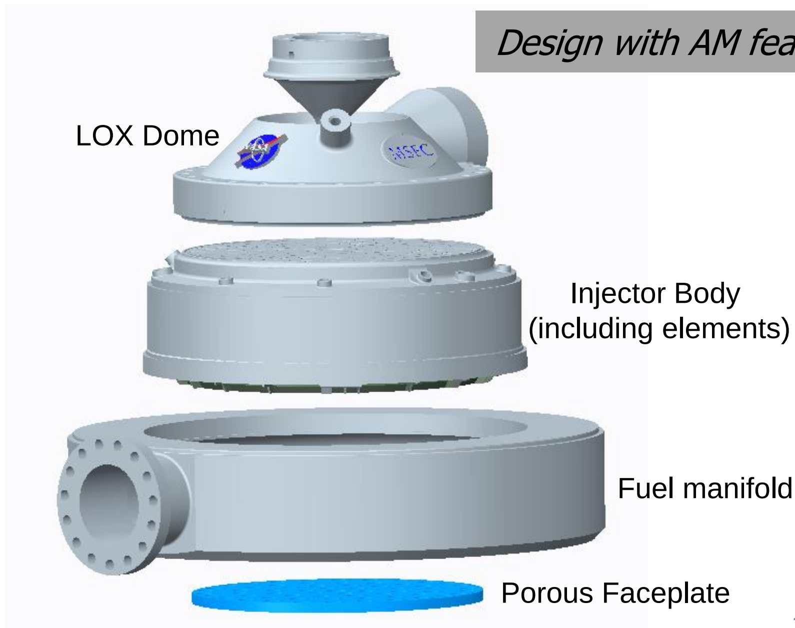


Hot-fire testing confirmed similar performance between designs.

Comparable design with traditional fabrication



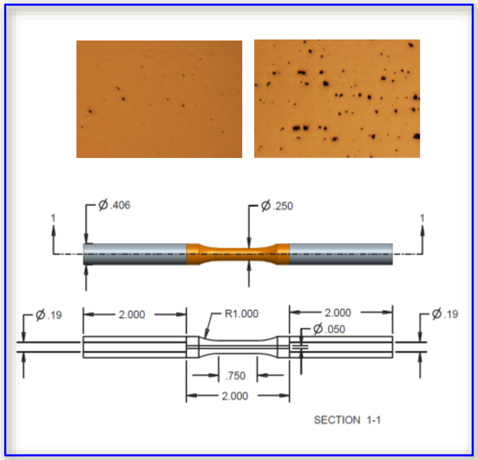
Design with AM features

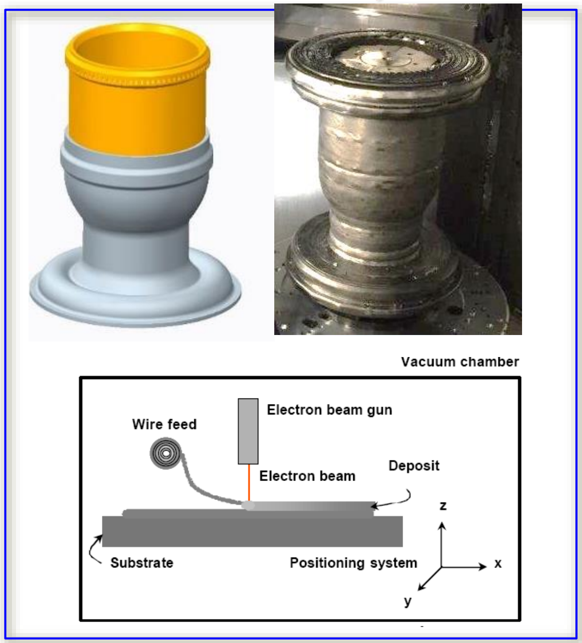


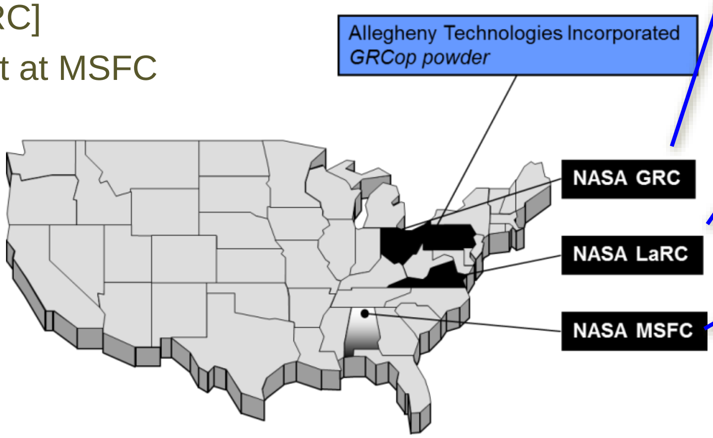
LCUSP: Low Cost Upper Stage Propulsion

- **LCUSP is a multi-center partnered project funded by the Space Technology Mission Directorate Game Changing Development Program with the goal of demonstrating cost reductions and >50% schedule reduction**

- **The technical approach for the LCUSP project element is:**
  - Develop materials properties and characterization for SLM manufactured GRCop. [GRC]
  - Develop and optimize Selective Laser Melting (SLM) manufacturing process for a full component GRCop chamber and nozzle. [MSFC]
  - Develop and optimize the Electron Beam Freeform Fabrication (EBF^3) manufacturing process to direct deposit a nickel alloy structural jacket and manifolds onto an SLM manufactured GRCop chamber and nozzle. [LaRC]
  - Hot Fire Test at MSFC



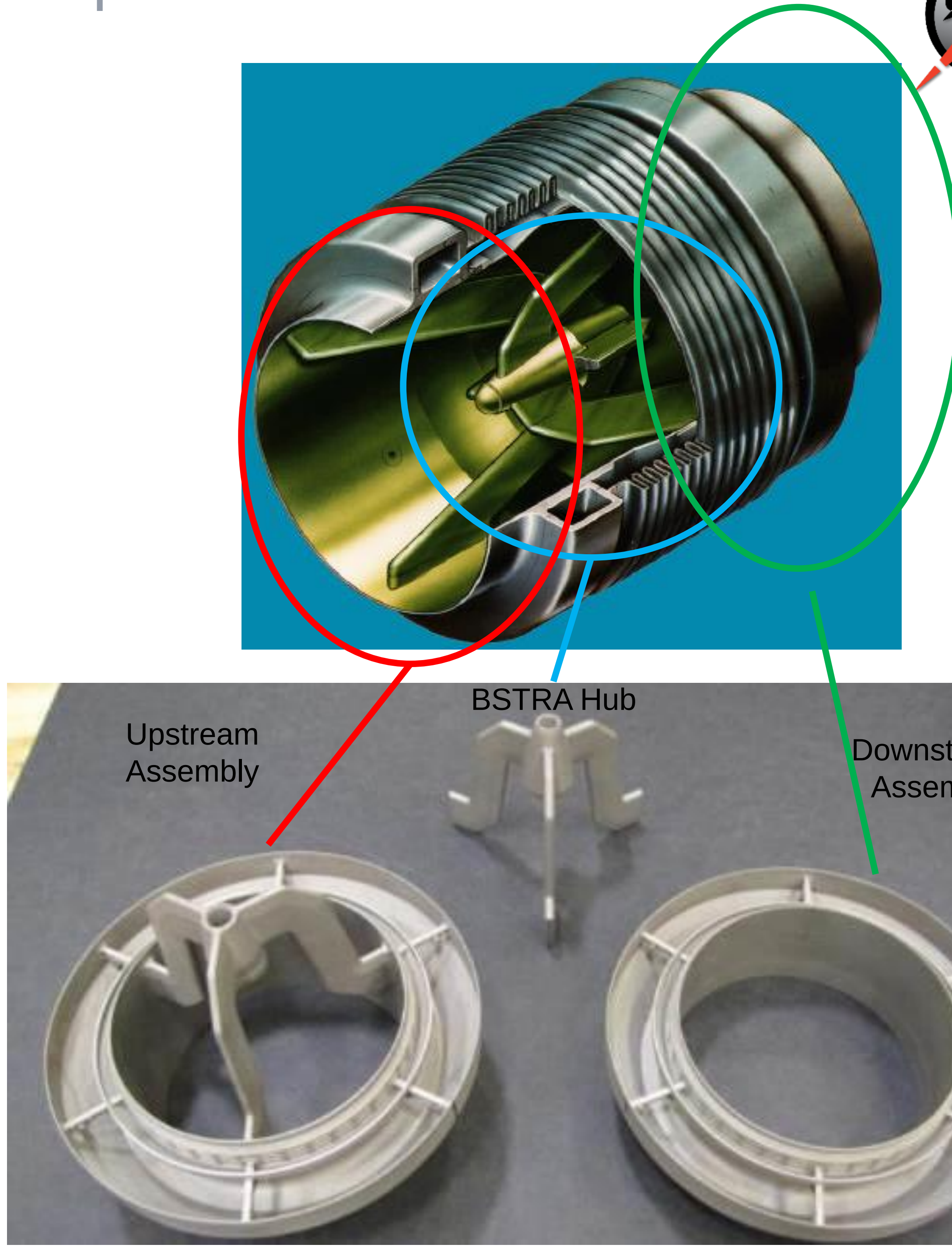




Example: Flex Joint

Heritage vs. Additive Design

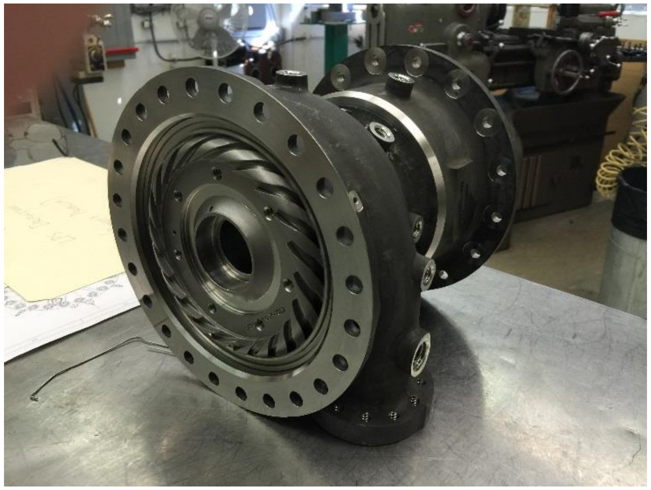
- Upstream Assembly
  - 16 Parts to 1 part
  - ~48 machining ops ‡ to 7
  - 24 welds to 0
- BSTRA Hub
  - 4 Parts to 1 part
  - ~12 machining ops‡ to 6
  - 3 welds to 0
- Downstream Assembly
  - 11 Parts to 1
  - ~45 machining ops‡ to 4
  - 17 welds (including screens) to 0
- Estimated 50% reduction in cost

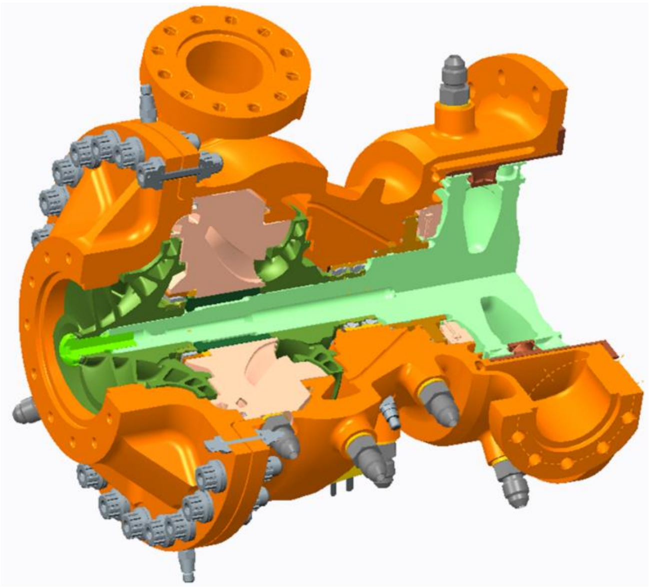


‡ Note: estimates 3 machining operations per piece part.

Example: Fuel Turbopump (FTP)

- First additively manufactured turbopump built and tested
  - Reduced part count by at least 50% from traditional designs, 90% AM by mass
  - Schedule Reduced by 45%
  - Hardware Cost $300K
  - Tested AM hardware in enveloping environment (LH2/GH2)
  - 25+ starts on first unit
  - 90,000 RPM, 1900 HP
- Illustrated lean and aggressive development approach
  - Design philosophy of adapt and overcome
  - Small, flexible team with relevant hardware experience





Summary

- AM has significant advantages over traditional manufacturing especially for complex parts
  - Reduced part count, flexibility, schedule and cost
- Post AM machining can be significant
  - Traditional machining may be more effective for some parts
  - Uncertainty in surface finishes still exist
- AM increases design flexibility by allowing for part designs that were previously impossible
- AM allows for early part fabrication and test which has a huge schedule advantage over traditional lead times for material, castings, or manufacturing
  - Can be cheaper to build, test and redesign based on the data as opposed to a traditional, more serial design cycle
- Unknowns:
  - Cost impacts of certification
  - Inspection techniques for
  - Surface finish treatments

LPS Breadboard Test Video

NASA

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