National Aeronautics and Space Administration

Additive Manufacturing of Liquid Rocket Engine Combustion Devices:
A Summary of Process Developments and Hot-Fire Testing Results

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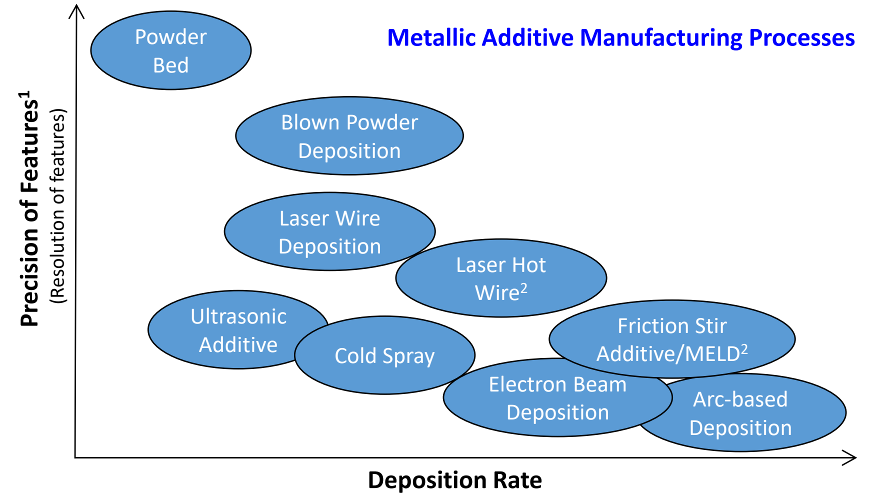
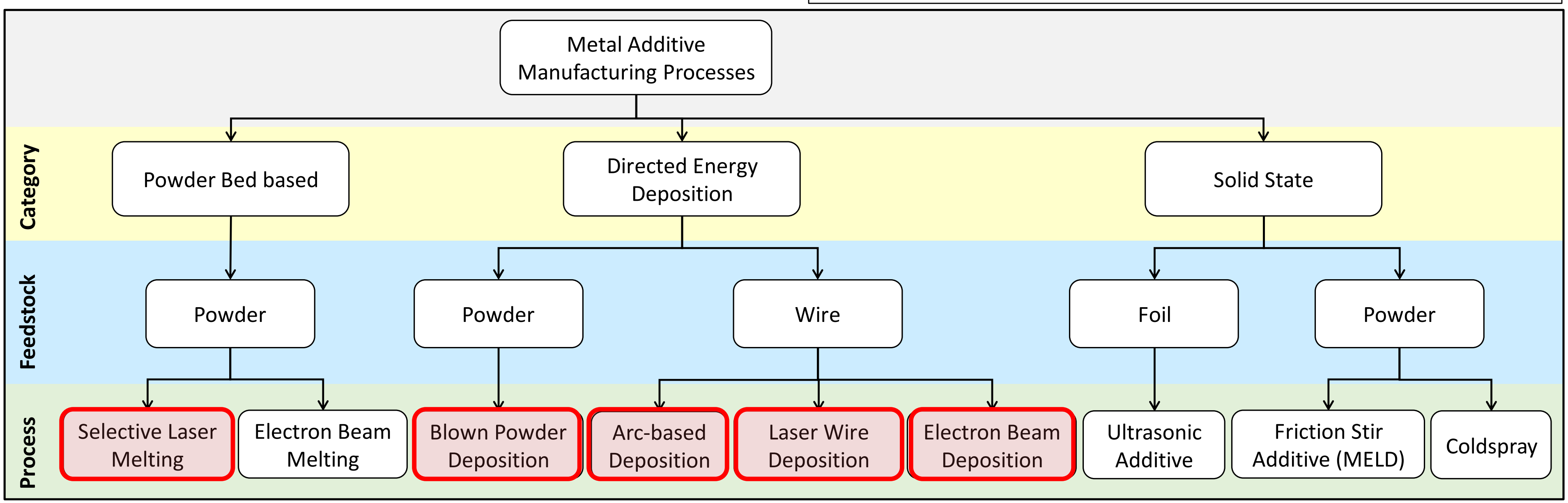
Additive Manufacturing (AM) Overview

- Additive Manufacturing (AM) is an emerging technology with a focus on complex metallic component fabrication
  - Enables complex shapes and internal features that were not possibly with traditional manufacturing techniques
  - Significant schedule and overall lifecycle cost reductions
- To date at the NASA Marshall Space Flight Center (MSFC), combustion devices component hardware ranging in size from 100 - 35,000 lbf has been designed and manufactured using AM and many of these pieces have been hot-fire tested.

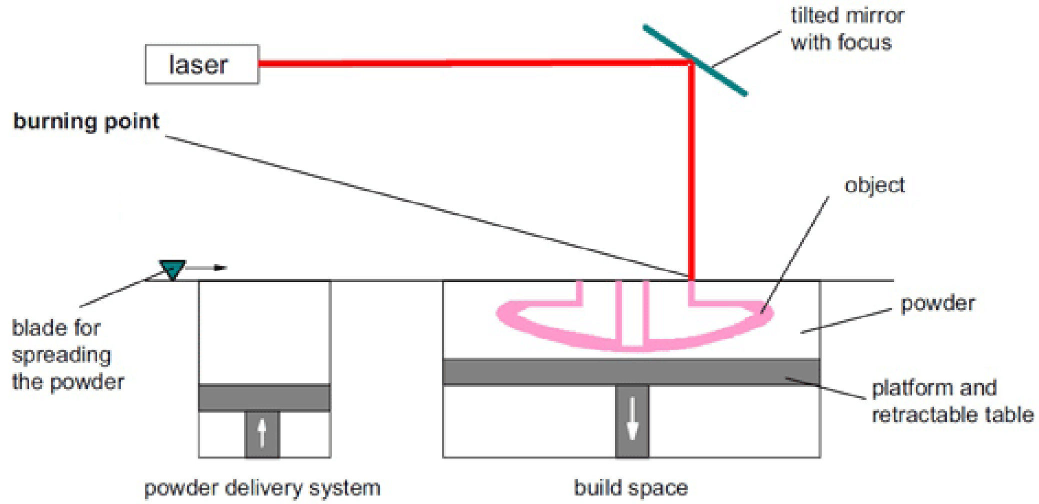


[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.
[2] Technology still under development



Metal AM Processes: Powder Bed Based

- **Selective Laser Melting (SLM)**
  - Basic Process: Uses a layer-by-layer powder-bed approach in which the desired component features are sintered and subsequently solidified using a laser. Used widely in combustion devices applications.
  - Advantages: Allows for high resolution, fine features, including complex internal designs to be fabricated, such as cooling channels
  - Disadvantages: The scale for SLM is limited and does not provide a solution for all components
- **Electron Beam Melting**
  - Basic Process: Similar to SLM, but uses an electron beam instead of a laser. Not frequently used in combustion devices applications.
  - Advantages: Build is performed under vacuum, which can be useful for reactive materials such as titanium



SLM Fabrication Process Overview.

Metal AM Processes: Directed Energy Deposition (DED)

Freeform fabrication technique focused on near net shapes as a forging or casting replacement and also near-final geometry fabrication. Can be implemented using powder or wire as additive medium.

<u>Blown Powder Deposition / Hybrid</u>

Melt pool created by laser and off-axis nozzles inject powder into melt pool; installed on gantry or robotic system



<u>Arc-Based Deposition (wire)</u>

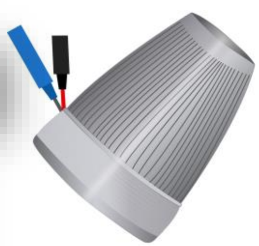
Pulsed-wire metal inert gas (MIG) welding process creates near net shapes with the deposition heat integral to a robot



<u>Laser Wire Deposition</u>

A melt pool is created by a laser and uses an off-axis wire-fed deposition to create freeform shapes, attached to robot system






<u>Electron Beam Deposition (wire)</u>

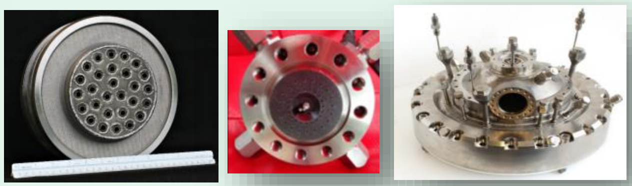
An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.



Overview of Additive Manufacturing Component Focuses

Augmented Spark Igniters

Injectors



Combustion Chambers

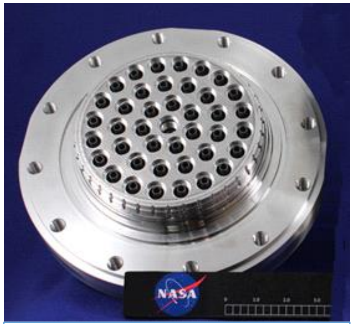
Channel-cooled Nozzles

AM Thrust Chamber Injectors: Overview

100lbf LOX/Propane Nanolaunch Injector. Built 2012. Tested 2013.

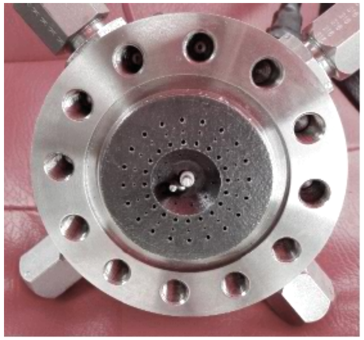
1.2K LOX/Hydrogen Injector First Tested in June 2013. >7200 seconds hotfire

20K LPS Subscale Injector. Tested August 2013



Methane 4K Injector with printed manifolds, parametric features. Tested Sept 2015.

35K AMDE Injector with Welded Manifolds, Tested 2015



LOX/Methane Gas Generator Injector, Tested Summer 2017

- MSFC has developed a total of 10 unique AM injectors between 2012-2018
  - Materials: Inco 625, Inco 718, Monel K-500
  - Element Types: swirl coax, shear coax, FOF
  - Number of Elements: ranging from 6 to 62
  - Diameters: ranging from 1.125” to 7.5”
  - Hot fire tests performed on 7 of these 10 AM injectors
- To date, all MSFC injector designs have been manufactured with a powder-bed process.
- Advantages of AM application to injectors:
  - Reduction of reducing part count, braze/weld operations, cost, and schedule
  - Allows non-conventional manifolding schemes and element designs
- Challenges of AM fabrication of injectors:
  - Feature size resolution (particularly radial to the build direction)
  - Excessive surface roughness
  - Removing powder prior to heat treatments (even stress relief) is both necessary and challenging

AM Thrust Chamber Injectors: Test Evaluations

- Pathfinder approach for comparing AM against conventionally machined injectors
  - To evaluate structural and performance capabilities of AM in liquid rocket injector applications, two early test programs were initiated at NASA MSFC to directly compare the operating characteristics of conventionally manufactured 20 Klbf LOX/H2 swirl coaxial element injectors to those of similarly designed SLM manufactured injectors.
  - Results of hot-fire testing showed characteristic exhaust velocity efficiencies for the two different manufacturing techniques to be within measurement error.
- Follow-on efforts included successful hot fire test firings of a range of element types (swirl coaxial, shear coaxial, impinging), propellant combinations (LOX/H2, LOX/CH4, LOX/C3H8), and thrust classes (100 lbf to 35K lbf) to validate AM use in these applications.

Stable performance of AM Injectors and Efficiency Approaching Traditional (98-99%)

Water Flow of the AMDE Injector LOX Circuit; Hot Fire Test of the AMDE Injector.

Four Thrusters with 1200 lbf Shear Coaxial Injectors.

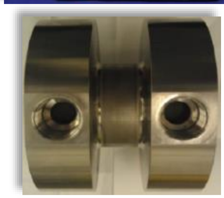
AM Combustion Chambers: Overview

- MSFC has developed over 10 unique AM chambers between 2013-2018
  - Materials: Inco 625, Inco 718, GRCop-84, C-18150, Monel K-500
  - Propellants: LOX/GH2, LOX/LCH4, LOX/RP-1
  - Additive Process: SLM and SLM/DED
  - Over 110 starts and 6100+ seconds of hot fire test.
- Chambers have been fabricated using SLM powder bed AM technique, with a few test articles incorporating DED techniques for a bimetallic end product.

Total Accumulated Hot-fire Time on Copper-alloy Chambers = >6100 sec

2013 – 2015 | 2016 | 2017 | 2018

Feasibility Hardware

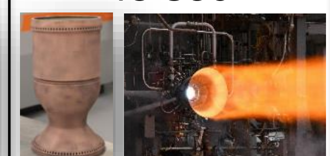


1.2K Workhorse
2365 sec

MET1
25 sec

LOX/RP1 Faceplate
25 sec

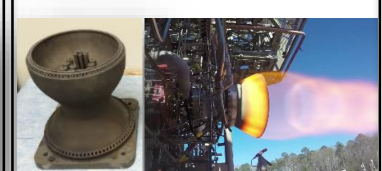
LCUSP 3.0
45 sec



META4
26 sec

1.2K Commercial Liners
2500 sec

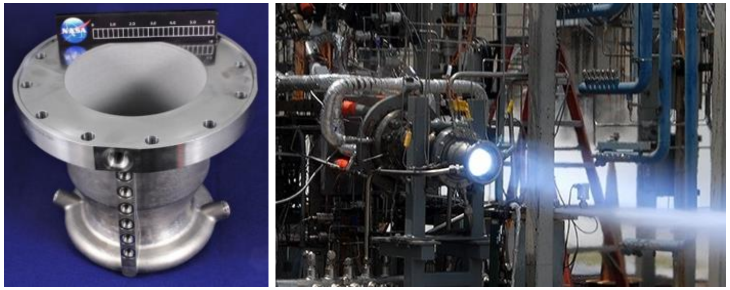
LCUSP 2.2
102 sec



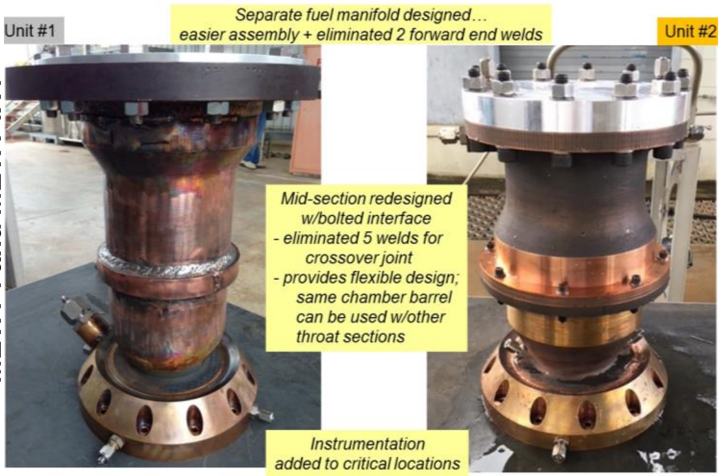
META4 #2
134+ sec

AM Combustion Chambers: Methane Engine SLM Chamber Development

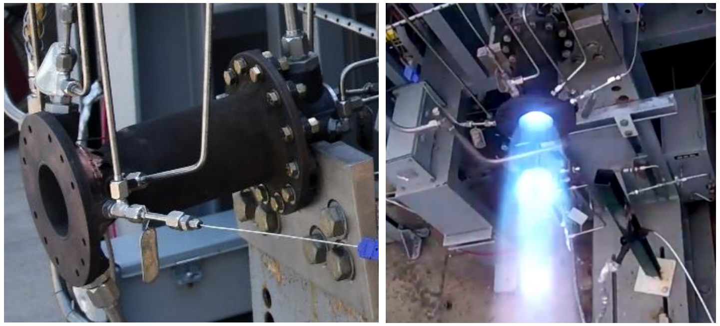
Inco 625 Pathfinder



META 4 and META 4X4

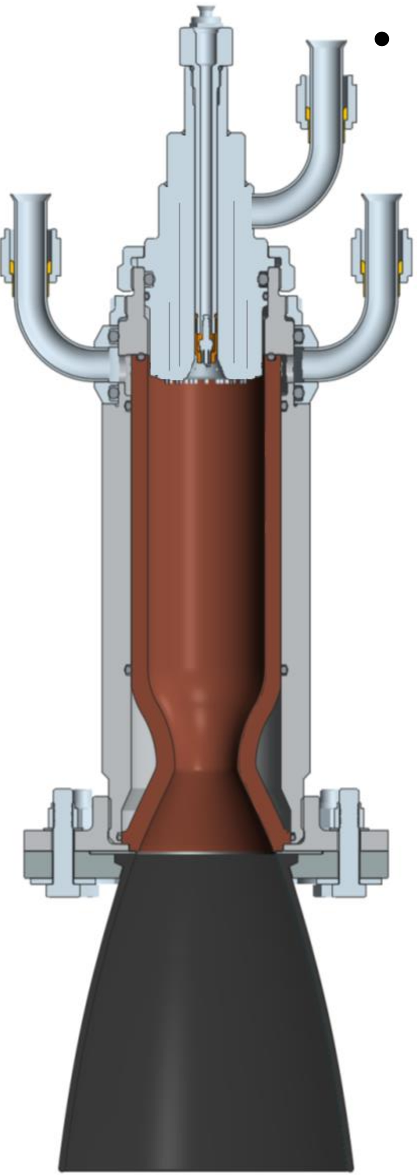


MET1

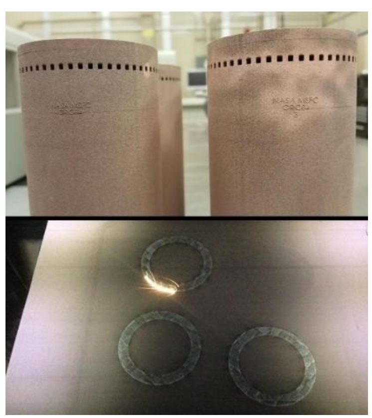


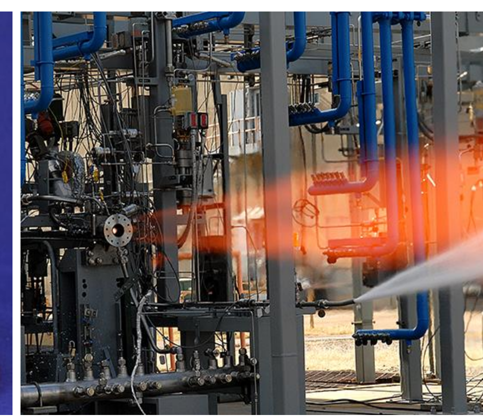
- **Inco 625 Pathfinder**: Included pressure and temperature ports along the length of one coolant channel to gather critical data for thermal models.
- **META4**: Full-length, regeneratively cooled GRCop-84 chamber developed for LOX/LCH4 in-space applications; fabricated in two sections and welded together due to SLM build height limitations
- **META4X4**: Second iteration of META4 concept; same thrust level but smaller package with a bolted center interface in place of a welded joint
- **MET1**: Scaled down approach from META4 for smaller in-space missions or for clustering together to provide multiples of 1 Klfb thrust; could be printed in one build with no mid-section interface

AM Combustion Chambers: Workhorse SLM Chamber Development



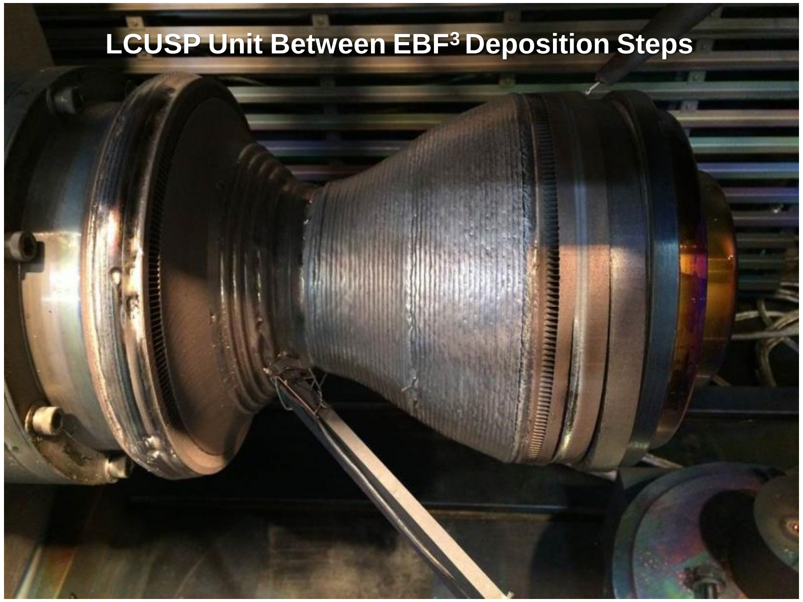
- NASA MSFC built a series of SLM workhorse chamber liners to allow liners to be rapidly tested and changed in a simplified test bed to demonstrate various materials.
  - Objective of liner tests was to complete cyclic testing on material and demonstrate SLM lifecycle. Liners were successfully tested and did not show indications of erosion even with wall temperatures over 1,000 °F.
  - A total of three chambers were tested: two manufactured from GRCop-84 using different SLM build parameter settings and one from C-18150.
  - Designed for water-cooling, LOX/GH2 and 1,200 – 1,500 lbf.
  - Chambers were fabricated at MSFC and from commercial vendors.

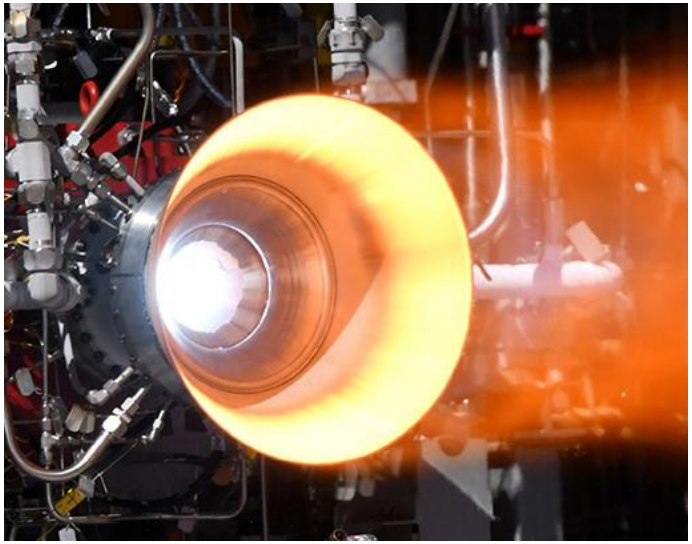




AM Combustion Chambers: Bimetallic AM Combustion Chambers

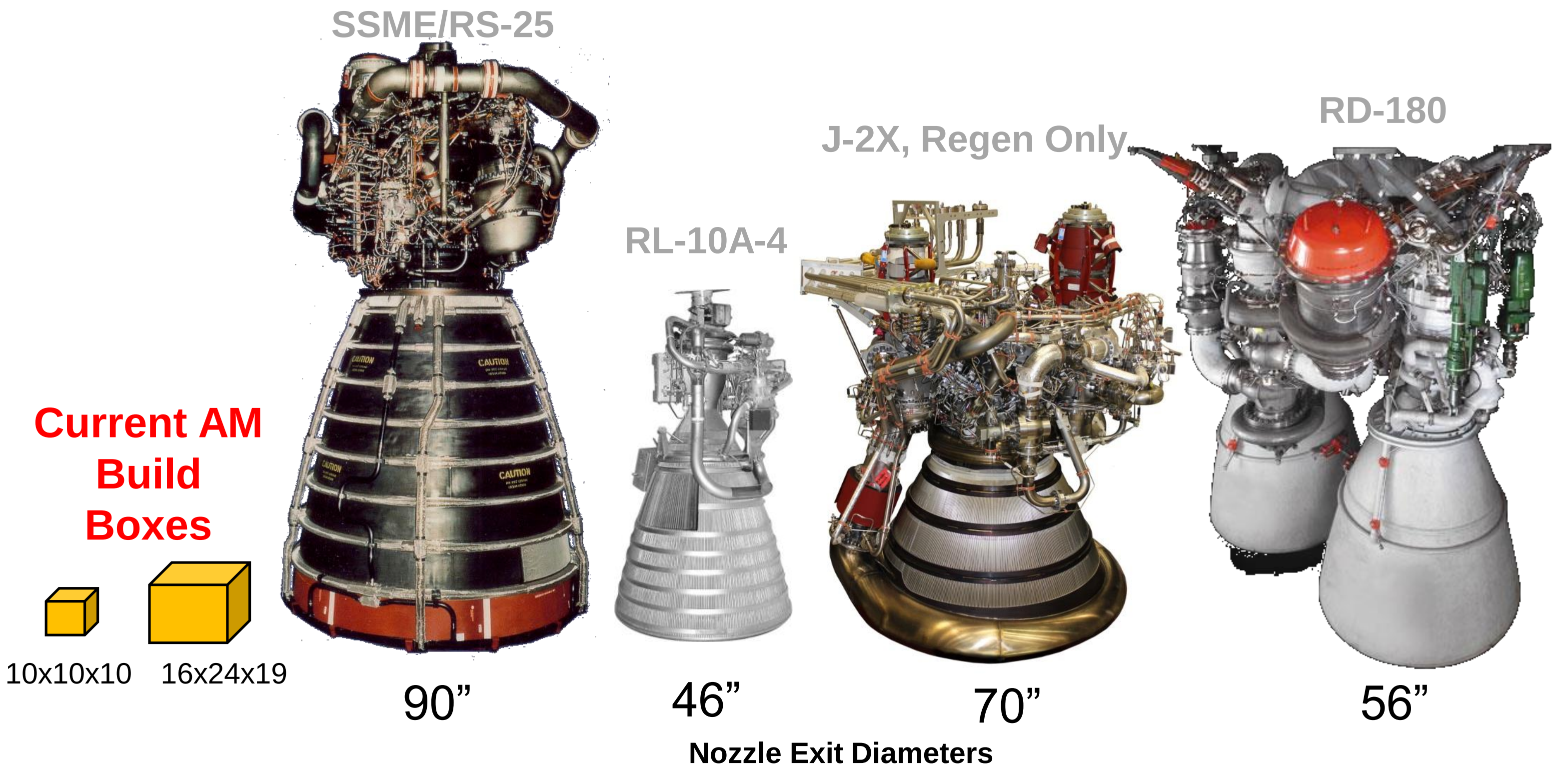
- The Low Cost Upper Stage-Class Propulsion (LCUSP) project developed SLM fabrication of GRCop84 and DED Electron Beam Free Form Fabrication (EBF^3) with Inco 625 manufacturing technologies to produce a combustion chamber at a lower cost and schedule.
  - Chamber was designed and fabricated by MSFC, GRC, and LaRC, and hot-fire tested at MSFC.
  - LOX/LH2, nominal thrust of 35,000 lbf.
  - Demonstrated key manufacturing technologies in a relevant environment, taking the AM LCUSP chamber and the one piece AM cooled nozzle to 100% of design conditions.





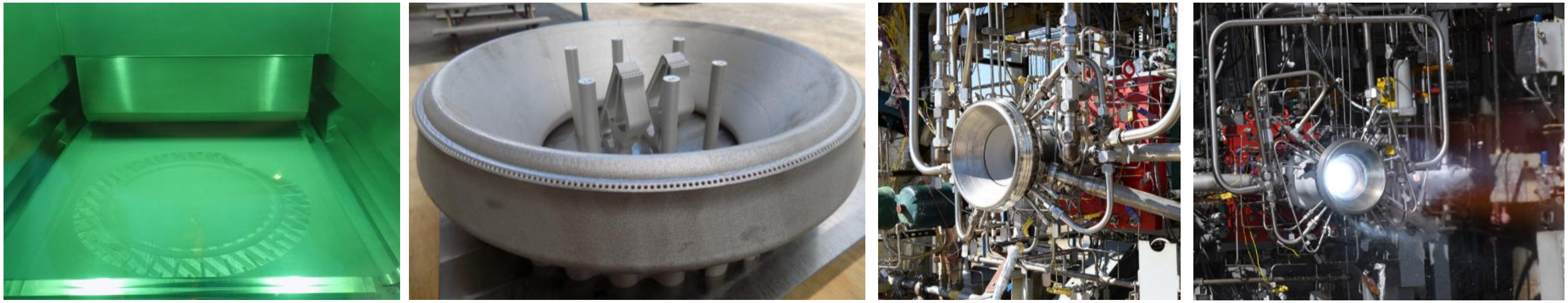
AM Channel-Cooled Nozzles: Overview

- NASA is investigating AM methods for targeting increased scale required for current NASA and commercial space program channel wall nozzle applications.
- Channel-cooled nozzles present a unique manufacturing challenge due to the scale and complexity required at these scales.



AM Channel-Cooled Nozzles: Evolution to Large-scale

- NASA is evolving scale of nozzle hardware through additive new additive manufacturing technologies
  - Current SLM technology limited to ~16-inches (400mm)
  - Developing new processes using DED processes
    - Blown Powder Deposition, Laser Wire Closeout, Arc-based Deposition



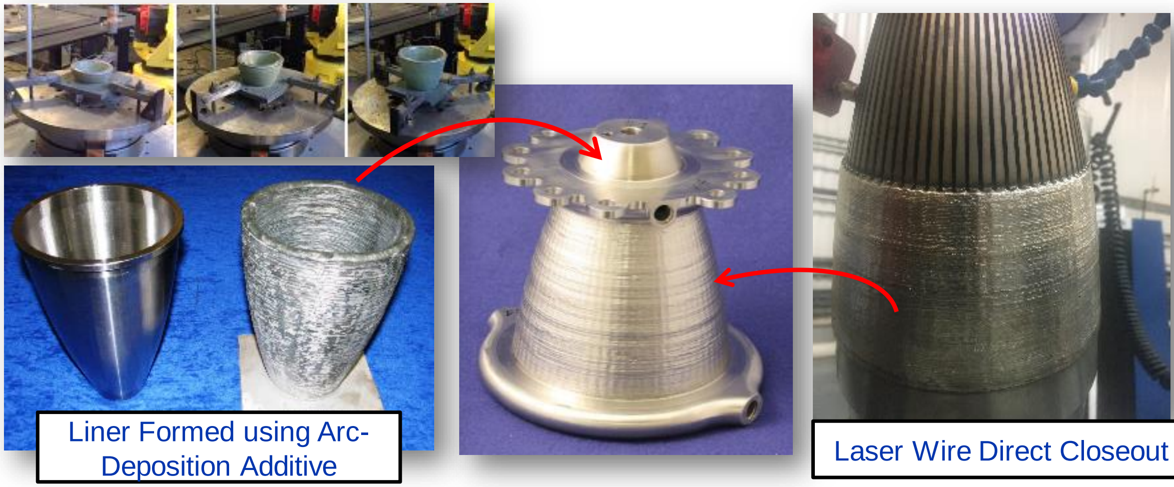
Hot-fire testing of “maximum” scale SLM Inco 625 nozzle on LCUSP chamber

Large Scale DED Techniques for Forming Nozzles and Chambers

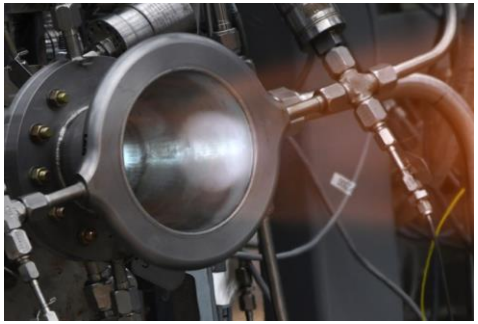
AM Channel-Cooled Nozzles: Development at MSFC

- Several AM methods are being investigated for forming the inner liner, producing the coolant channels, and fabricating the manifolds and combinations of channels and manifolds:
  - Laser Wire Direct Closeout (LWDC)
  - Arc-Based Wire Deposition
  - Blown Powder Deposition (BPD)
  - Selective Laser Melting (SLM)

Nozzle Component Description	Propellants	Additive Process	Material	Starts	Hot-fire Time (sec)
1,200 lbf LWDC Regen Nozzle, PH034	LOX/GH2	LWDC	SS347	4	160
1,400 lbf LWDC Regen Nozzle, Additive Liner, PH034	LOX/GH2	LWDC	Inco 625	9	880
Integrated Nozzle Film Coolant Ring (INFCR), PF086	LOX/GH2	SLM	Inco 625	12	147
1,200 lbf DED Regen Nozzle, PH034	LOX/GH2	DED	Inco 625	1	15
800 lbf Radiatively-cooled Nozzle, PD020C	LOX/GH2	SLM	Inco 718	1	30
			TOTAL	23	1232



Arc-based additive deposition and LWDC integrated into channel wall nozzle for hot-fire.

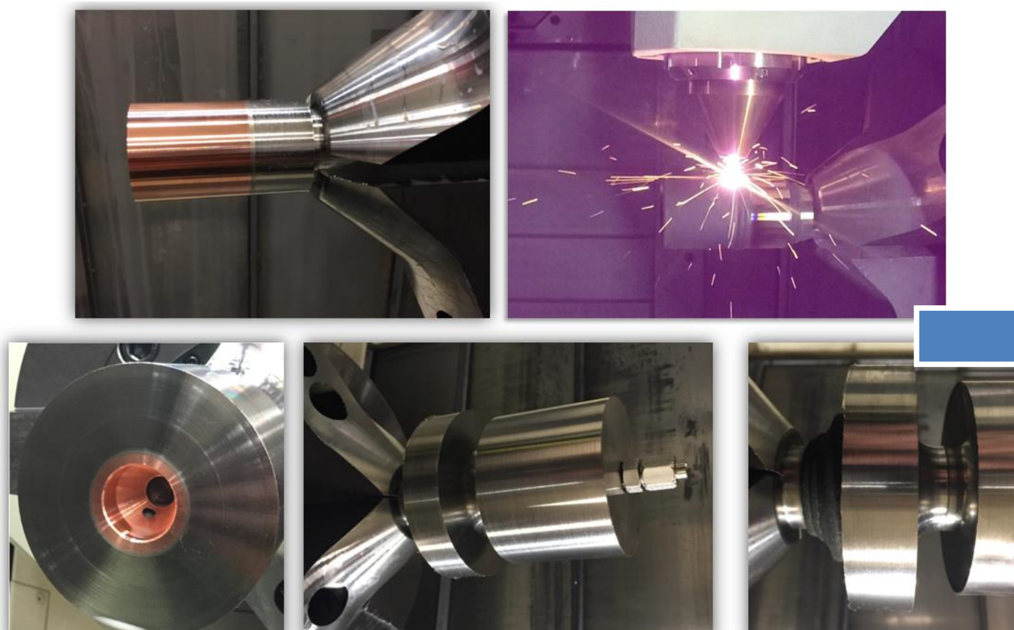


DED Blown Powder Nozzle and DED Nozzle during feasibility hot-fire test.

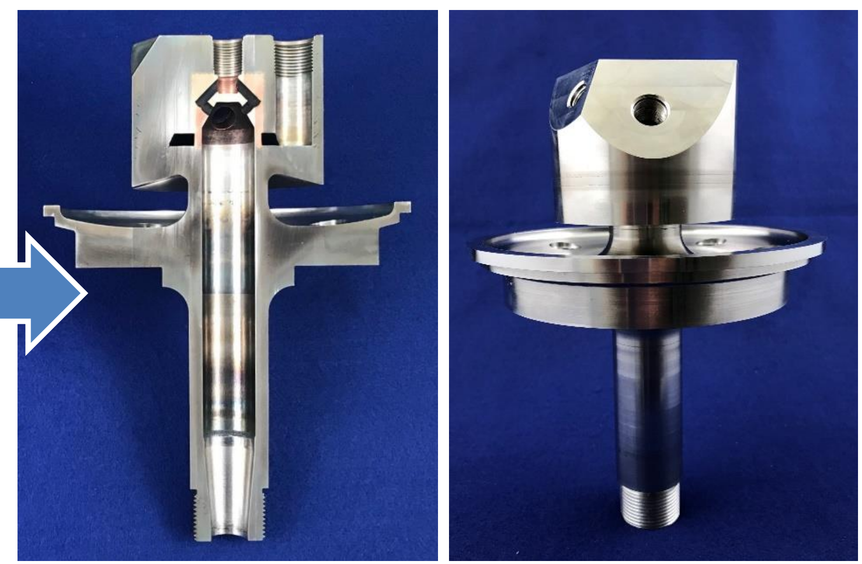
AM Augmented Spark Igniters

- AM of Augmented Spark Igniters (ASI) has been targeted as a potential upgrade for the RS-25 engine. The use of hybrid DED/CNC process allows for the bimetallic copper and nickel alloy design to be fabricated through an AM process.
  - Approach offers the advantage of smooth, machined finishes in locations that are not possible with SLM

ASI Description	Propellants	Additive Process	Material	Starts
Regen-cooled ASI, AR-1	LOX/LH2	SLM	Inco 625	11
Regen-cooled ASI, AM-3	LOX/LH2	SLM	Inco 625	16
Baseline ASI, AR-B-1	LOX/LH2	SLM	Inco 625	15
Baseline ASI, AR-B-2	LOX/LH2	SLM	Inco 625	21
Regen-cooled ASI, API-1	LOX/LH2	SLM	Inco 625	13
Hybrid, Bi-metallic ASI	LOX/LH2	Hybrid	Inco 625 / C18150	33
			TOTAL	109



Photos taken during the BPD build process of the prototype RS-25 ASI.



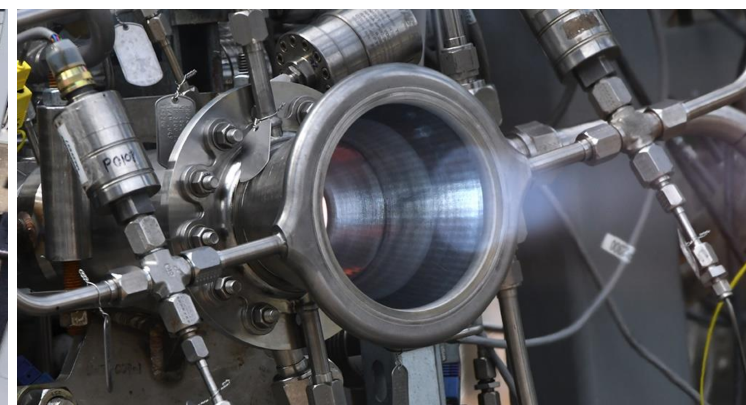
Bi-metallic prototype of the RS-25 ASI, built using hybrid manufacturing.

Summary

- Numerous combustion devices components – injectors, combustion chambers, channel-wall nozzles, and augmented spark igniters – have been designed and built using AM and hot-fire tested over the past 8 years at NASA MSFC.
  - Component level and integrated system level testing in a variety of propellants have been conducted and performance derived from these tests.
  - AM technologies – specifically SLM and DED – have been found to be readily applicable for combustion devices components.
- NASA is continuing to evolve these technologies on a path towards flight systems

Nanolaunch Injector Water Flow Test

META4X4 Chamber Hot-Fire Test



LWDC Nozzle #1 Hot-Fire Test

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