# Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications


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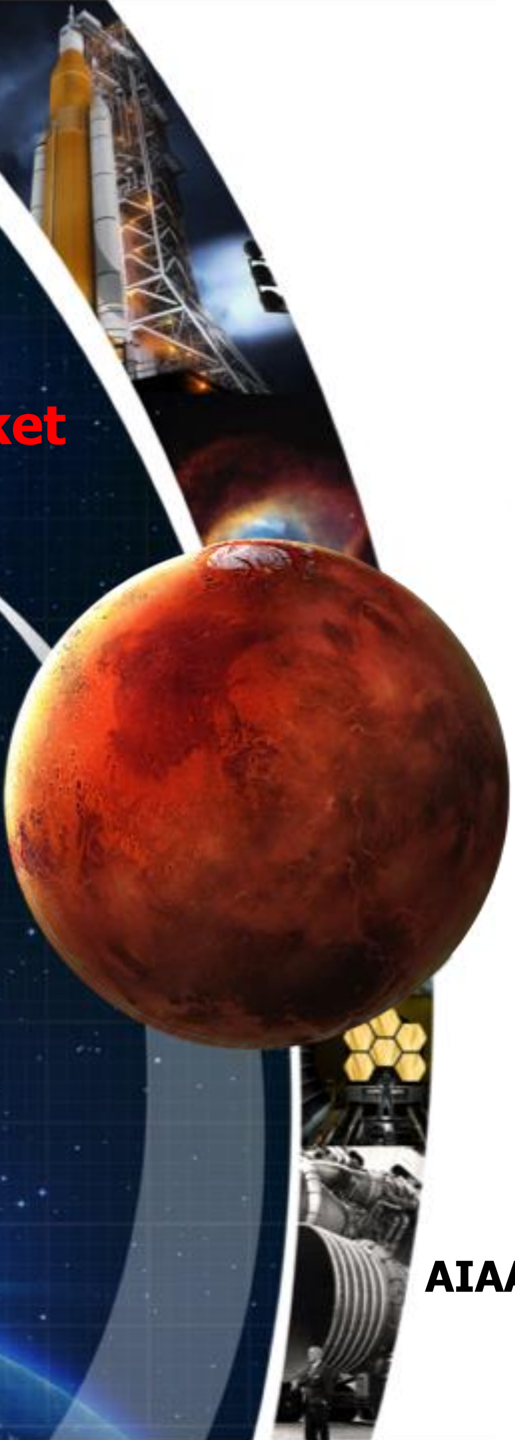

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# Objectives

Develop AM Processes to Reduce Costs/Schedules for Liquid Engine Components

➡ Reduce Overall Mission Costs

➡ Transfer Technologies to Industry to Enable Long Term Supply Chains

## Techniques Evaluated:

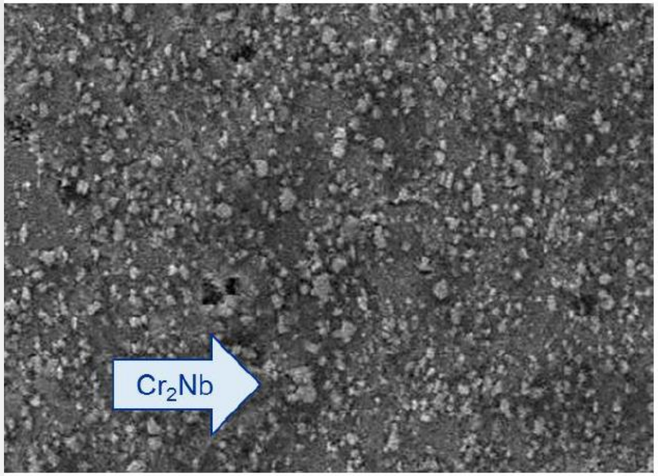
- Additive Manufacturing (AM) / Selective Laser Melting (SLM) GRCop-84 (Cu-8Cr-4Nb)
  - Also evaluating C-18150 (CuCrZr) and Glidcop
- Direct Metal Laser Sintering (DMLS) Copper & Nickel Alloys
- Bimetallic AM Chambers
  - Laser Cladding
    - Direct Metal Deposition (DMD)
  - Electron Beam Freeform Fabrication ($EBF^3$)
  - Arc-based Deposition
  - Freeform Blown Powder Deposition/Directed Energy Deposition

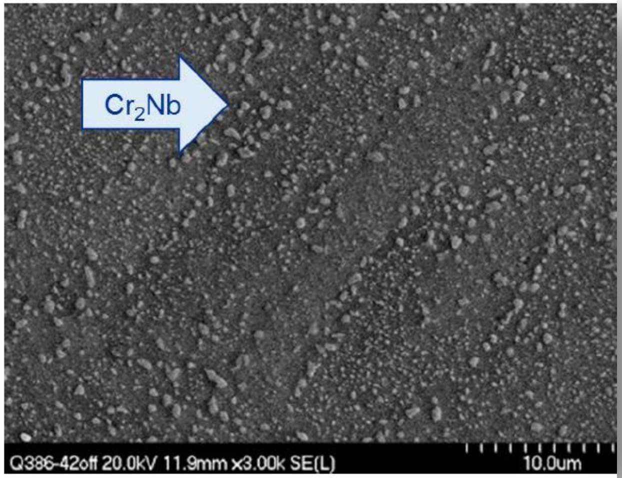
## Approach:

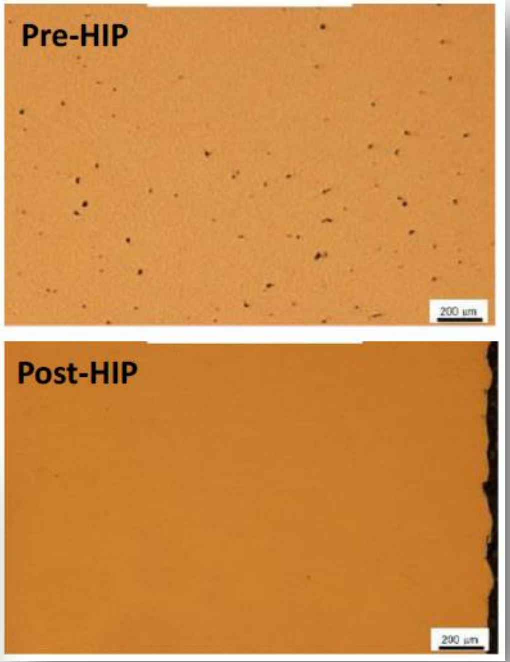
- Fabricate Various Thrust Chamber Designs with Multiple Techniques
  - Develop Process Parameters with Samples & Components
  - Characterize Material Properties
  - Proof Test Samples & Components
  - Apply Lessons Learned for Timely Design Mods
- Hot-fire Test Chambers in Relevant Environments

# Development of SLM GRCop-84 Material Processing

- Challenges in SLM processing for copper-alloys
  - Copper is highly reflective in red and near-IR spectrums
  - High conductivity so heat is rapidly conducted away from melt pool
- GRCop-84 was easily melted using SLM (14 vol.% $Cr_2Nb$)
  - SLM process did not result in segregation of $Cr_2Nb$ precipitates
  - $Cr_2Nb$ appears to have been refined in size



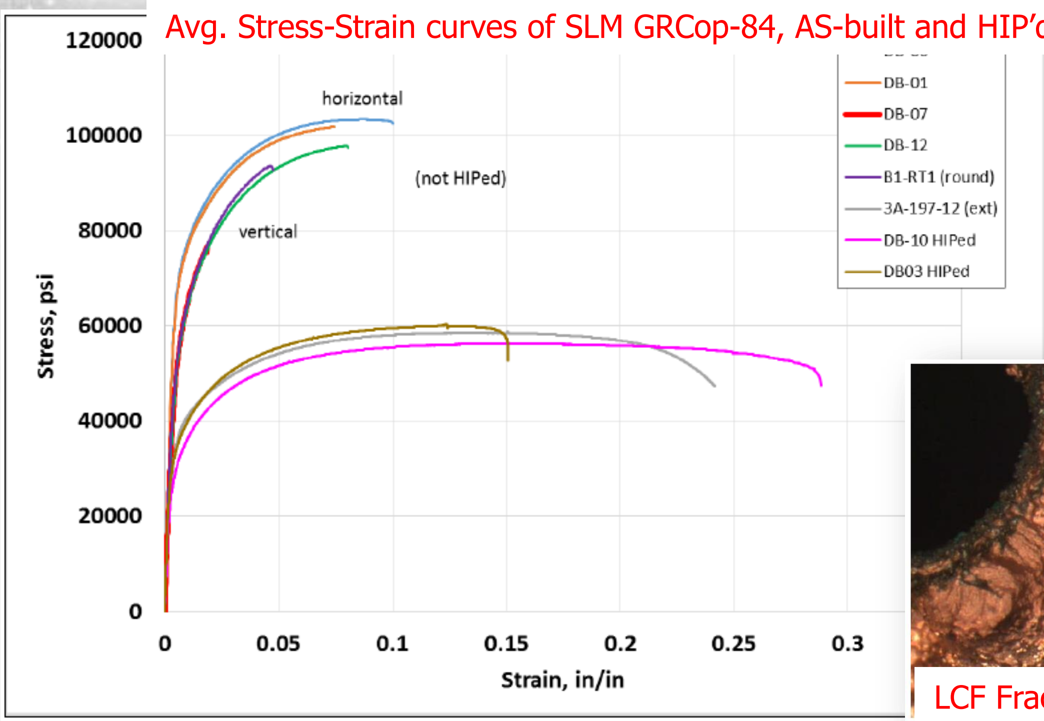



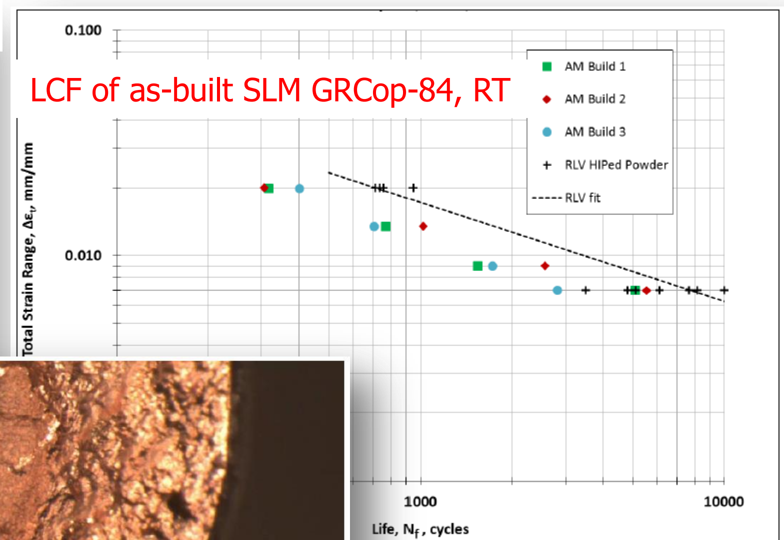

HIP process developed, well above annealing temperature (600°C / 1112°F)

# Mechanical Properties of SLM GRCop-84

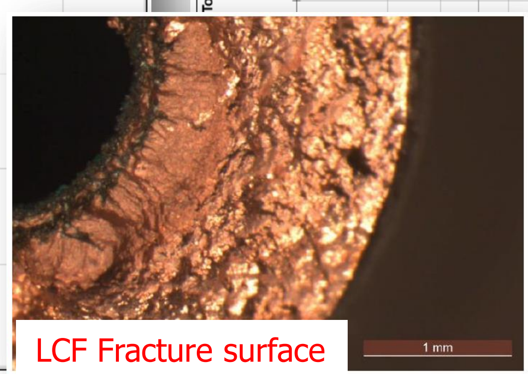
- Strength values similar to extruded GRCop-84, elongation increased significantly with HIP cycle
  - Differences observed in horizontal and vertical build orientations
- LCF testing completed in as-built condition (simulated channel)
  - Cracking initiated in as-built surface
  - LCF of as-built surface is lower than extruded, not unexpected



Avg. Stress-Strain curves of SLM GRCop-84, AS-built and HIP'd

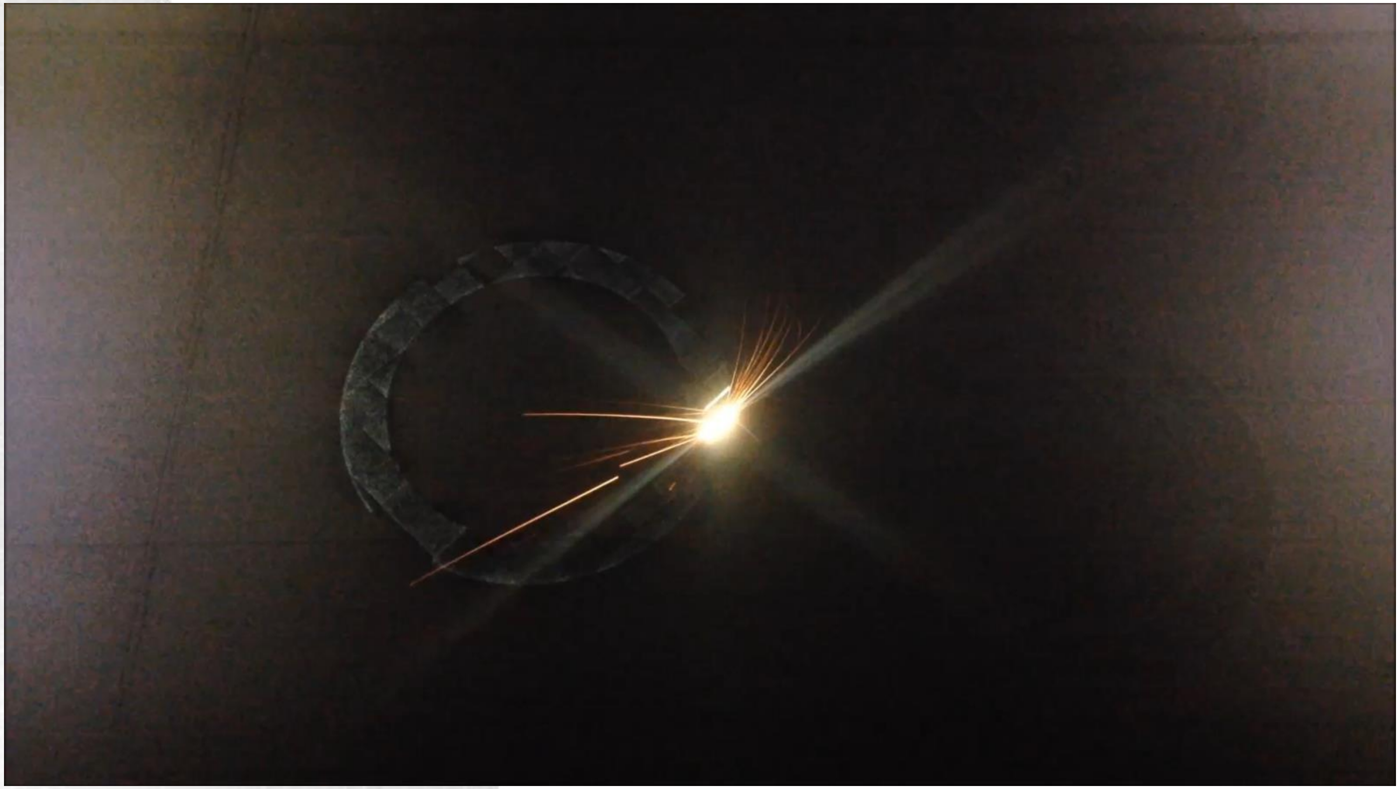


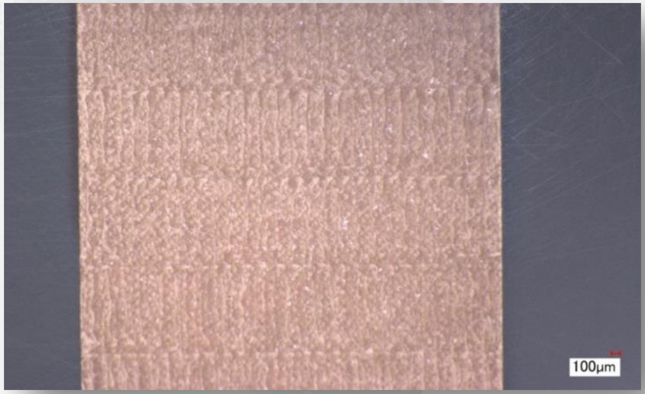
LCF of as-built SLM GRCop-84, RT

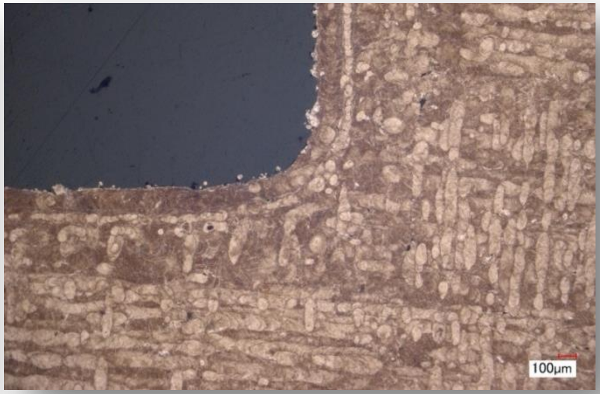


LCF Fracture surface

# Additively Manufactured SLM Material is Unique






SLM GRCop-84 Copper-alloy in the as-built condition (ASTS, Huntsville)

# Low Cost Upper Stage Propulsion (LCUSP) Program

## Multi-Center NASA Program under NASA STMD Game Changing

**MSFC**

- Project Management
- Component Design
- SLM GRCop-84 Chamber Liner
- C-C Nozzle Development

**GRC**

Material Property & Characterization for SLM GRCop-84 & EBF[3] Inconel

**LaRC**

EBF[3] development to direct deposit Inconel jacket onto SLM GRCop-84 Liner

LCUSP SLM GRCop-84 Liner with Inconel 625 EBF[3] Jacket

One-Piece Inconel 625 Integrated Nozzle/Film Coolant Ring

Carbon-Carbon Nozzle Extension

Program Goal

Advance select technologies by fabricating & hot-fire testing a 35K $lb_f$ Regeneratively Cooled LOX/H2 Thrust Chamber Assembly (TCA)

# LCUSP Chamber Fabrication

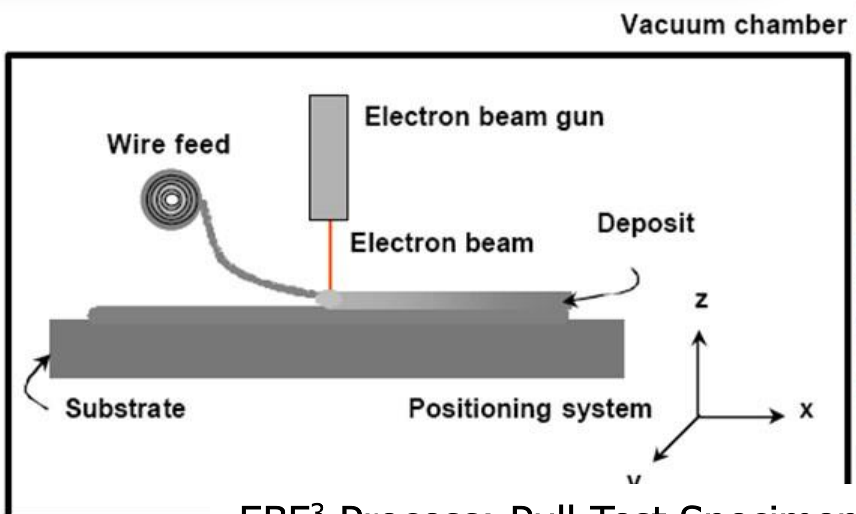
Water flow Testing

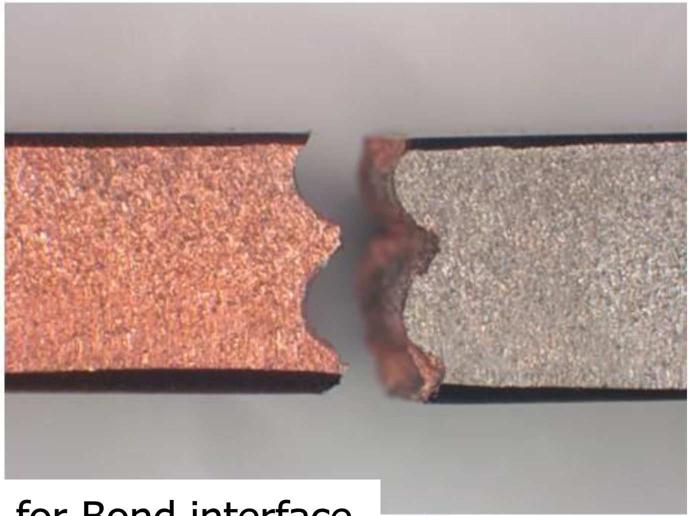
**Print samples evaluated**

- Hot wall thicknesses – successfully printed & proof tested
- Channel sizes as small as 0.030” with +/- .001” print tolerances

**Mechanical evaluation samples**

- Developed process using Electron Beam Freeform fabrication (EBF³) to deposit Inco 625 directly onto SLM GRCop-84

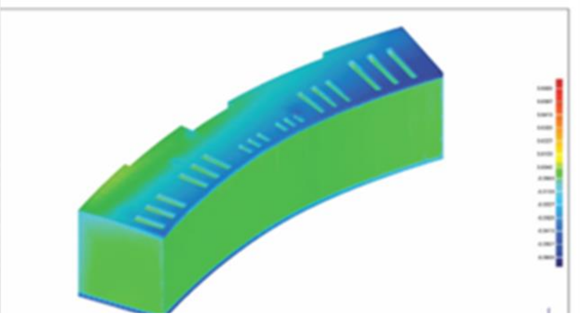


EBF³ Process; Pull Test Specimen for Bond interface

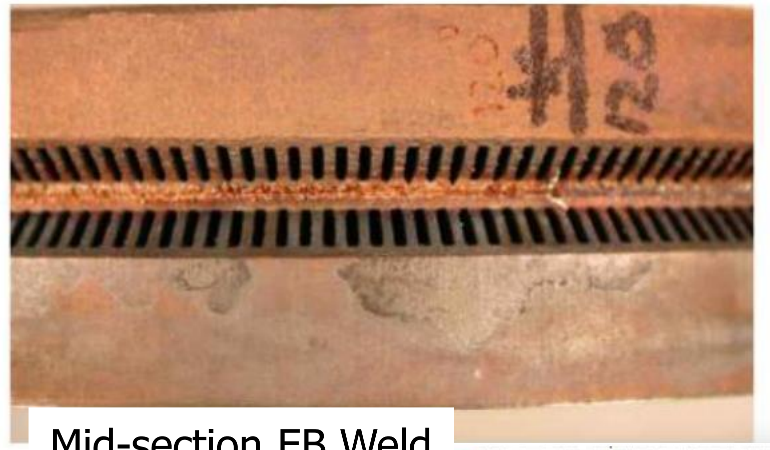
# LCUSP Chamber Fabrication

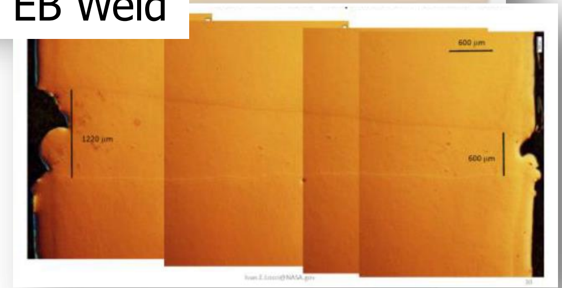
SLM GRCop-84 – Concept Laser M2 at MSFC



Wedge trial printed first – demo complex geometry
Structured light scan to compare print to model

Aft & Throat Sections on Build Plate (with material samples)





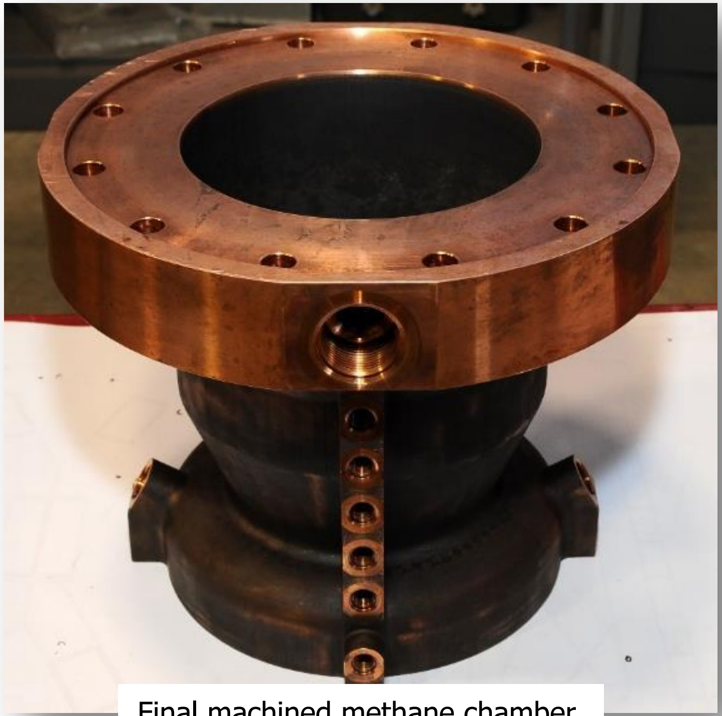
Mid-section EB Weld

Sections Stacked; Mid-section weld & EBF[3] Applied

# AM GRCop-84 Regen (LCH4) Cooled Chamber

- SLM GRCop-84 at NASA-MSFC (Concept Laser M2)
- Multiple prints and design modifications required to produce successful part
  - Reshaping open volume manifold with proper angles
  - Developing support features
- Printed structure includes:
  - Inlet/exit manifold volumes, inlet boss for threaded interface
  - Integral instrumentation for discrete thermal and performance
  - Forward flange welded post-SLM processing

As-printed methane chamber

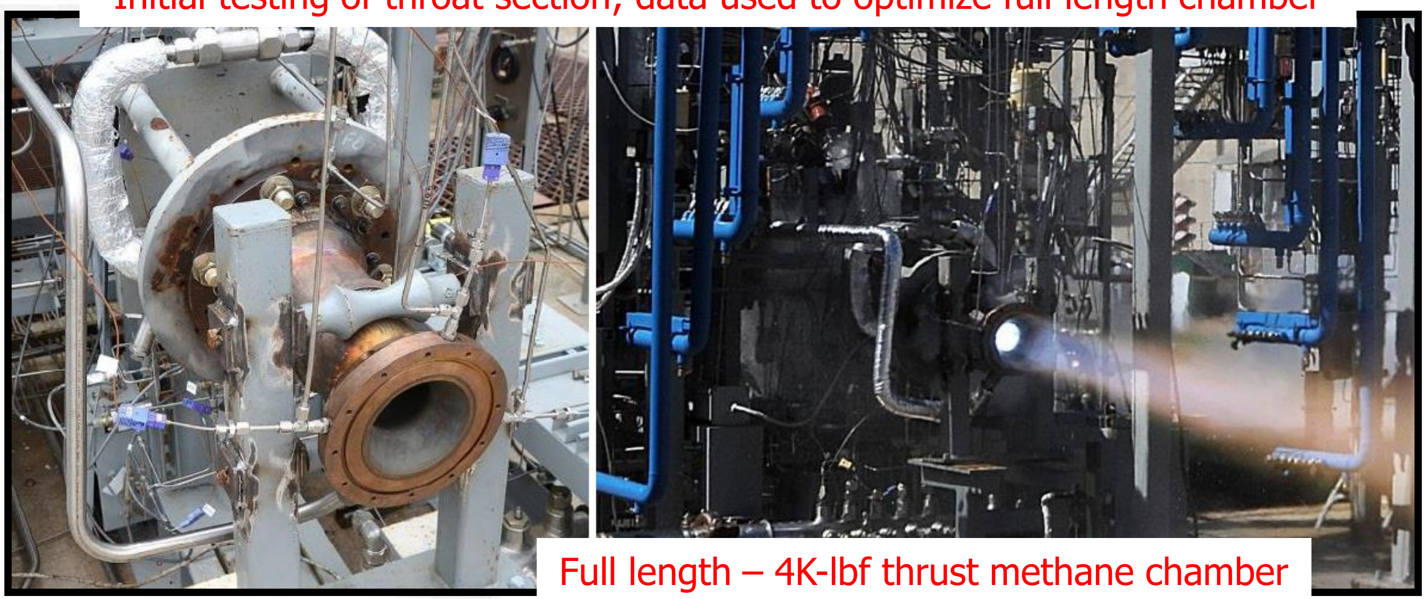


Final machined methane chamber

# AM GRCop-84 LCH4 Cooled Chamber - Testing

Hot-fire testing with LCH4 cooling – Chambers in excellent condition post-test

Initial testing of throat section; data used to optimize full length chamber



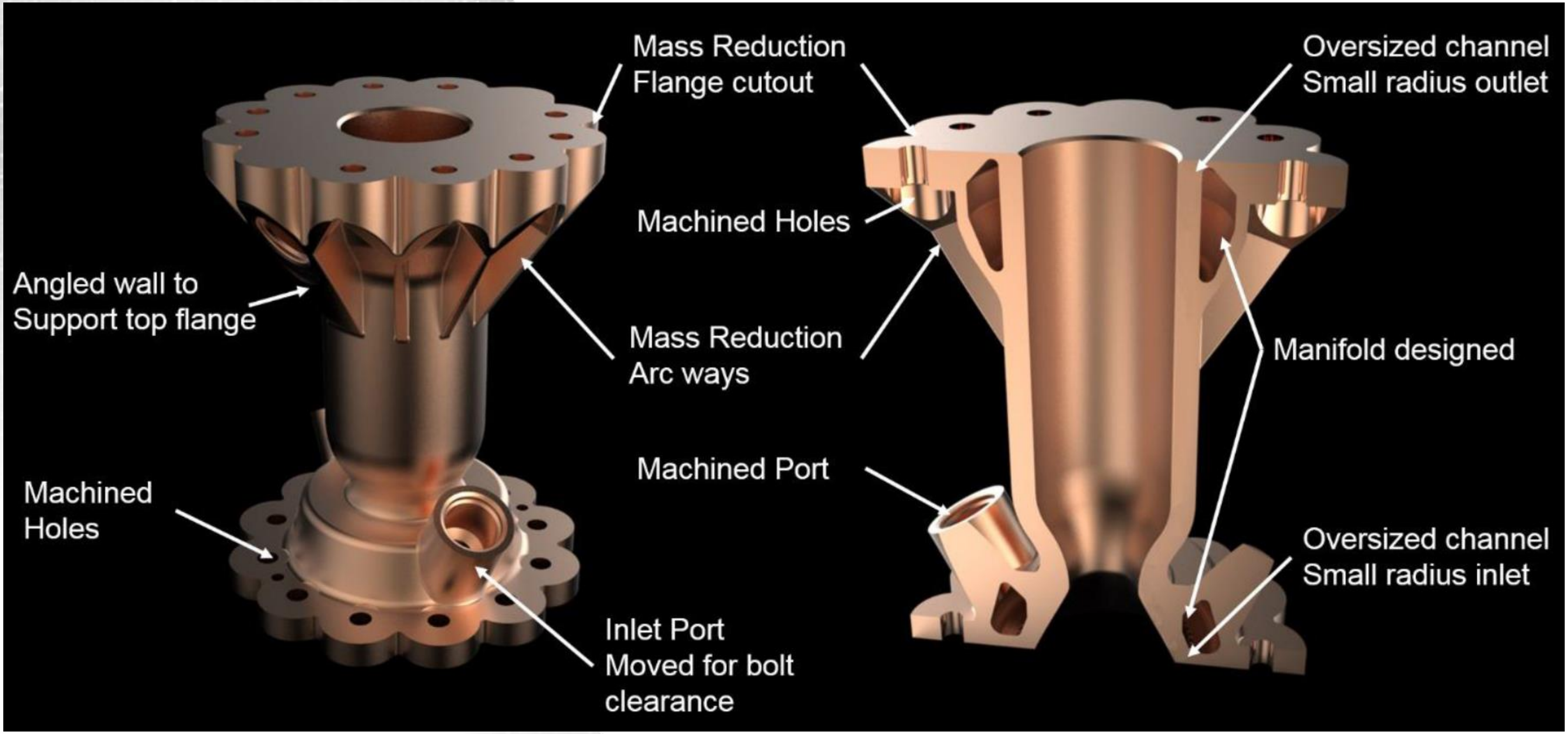
Full length – 4K-lbf thrust methane chamber

# 1.2K Additive Chamber Development

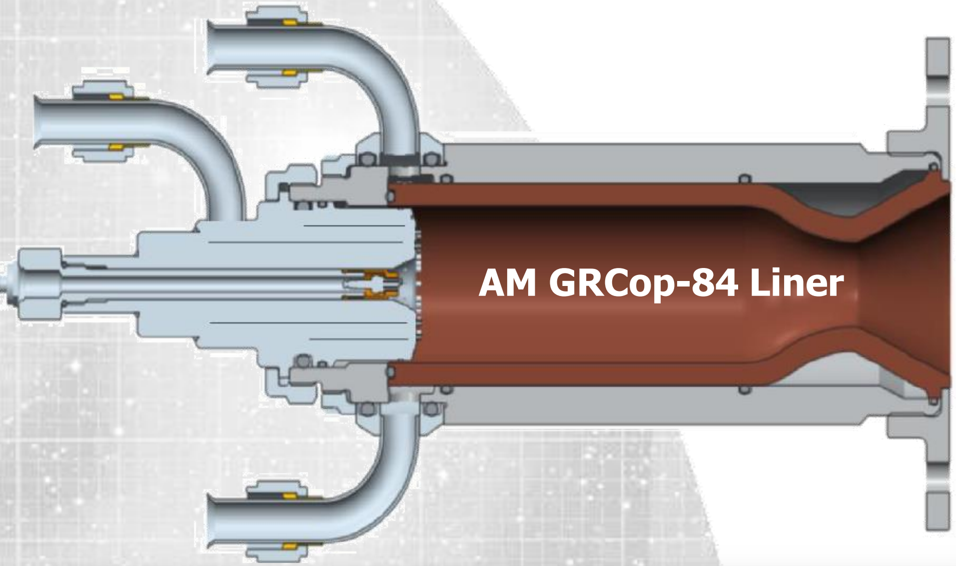
Designed to replace vintage subscale thrust chamber used for development testing since 1960’s at MSFC.

Nominal Pc ~ 750 psig; Water cooled design supports LOX/H2, LOX/LCH4, LOX/RP1 injector testing.

Overall size allows for one piece build in available SLM machines.



# 1.2K AM Chamber Development – Hybrid Design




**AM used to create GRCop-84 liner to slip into SS housing**

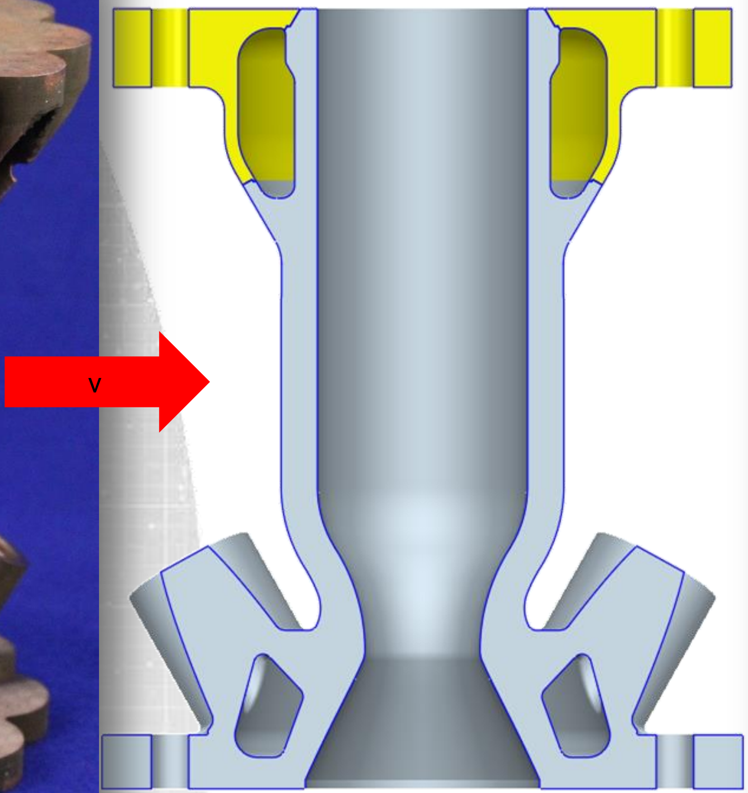
**Hybrid Chamber with AM Liner Installed at MSFC TS115**

**Hot-fire tested with Carbon-Carbon Extension**

**During Subscale Nozzle Testing at MSFC AM GRCop-84 liner accumulated <u>2365 seconds (23 starts)</u> of LOX/H2 hot-fire exposure**

# 1.2K AM 1-piece chamber design transitioned to 2-piece

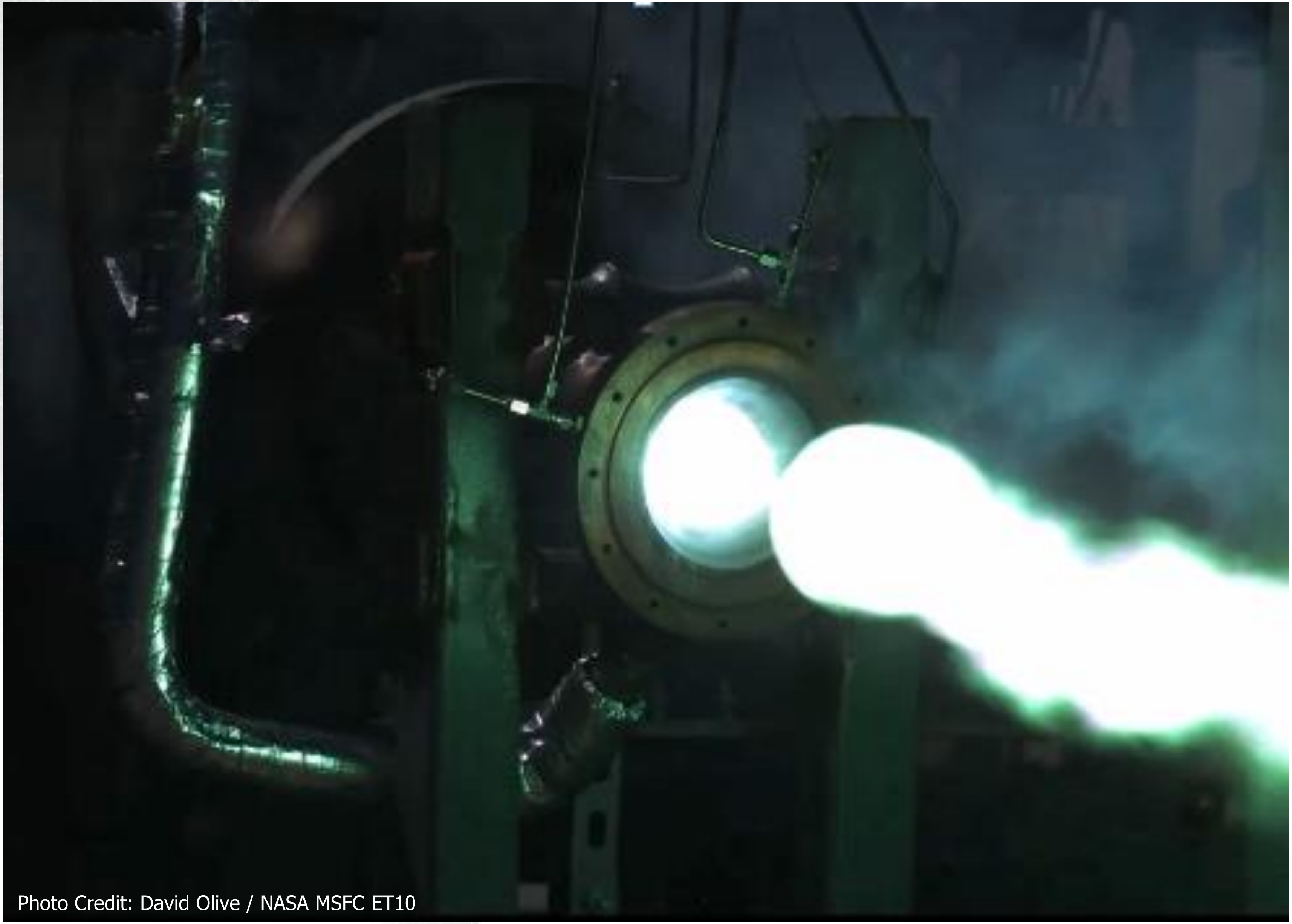
Allowed for easier removal of powder, simplified design, easier inspections, and reduced overall processing time



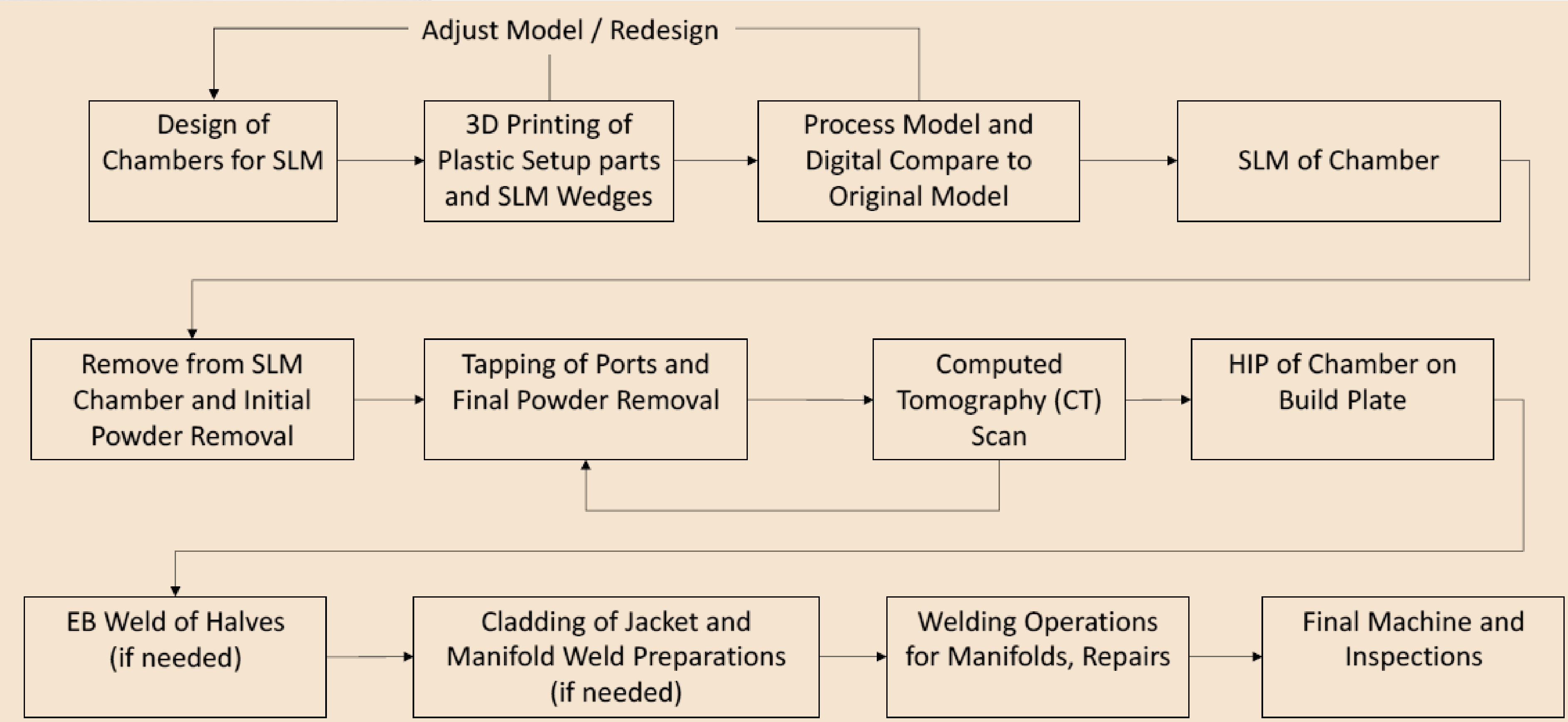

Printed at ASTS, Huntsville

**Designs will evolve with additive through print trials, testing and design and analysis tools**

# Video of AM GRCop-84 Chamber Hot-fire Testing



# Generic Flow for AM Chamber Fabrication Process



# AM Chamber Lessons Learned – Design and Build

- Features maintain maximum 45˚ from vertical, less angle enables more successful builds
- Optimized AM design may not be single-piece
  - Welding multiple AM pieces
    *reduces risk, eases powder removal, allows inspection of unique features*
  - Inlet/outlet ports can easily be welded on;
    *protruding features often experienced print failures*
- Coolant channels –
  - Leave access for powder removal
  - Increase effective area to account for rough surfaces…
    600-800 μin are possible, although 200-300 μin is being demonstrated
  - Maintain access for interior powder removal
- Design copper EB weld joints for excess penetration and material heating
- Minimize thick areas to eliminate residual stresses (thick flanges can lift off the build plates)
- Part orientation is critical for coater blade, so optimize design to minimize potential damage
- Include enough stock for secondary bonding ops, run-outs, &/or final machining
- Builds can deform as vertical height increases further from the build plate
- Compare exported CAD files back to original model
- Structured Light (3D scanning) continuously throughout process

# AM Chamber Lessons Learned – Design and Build

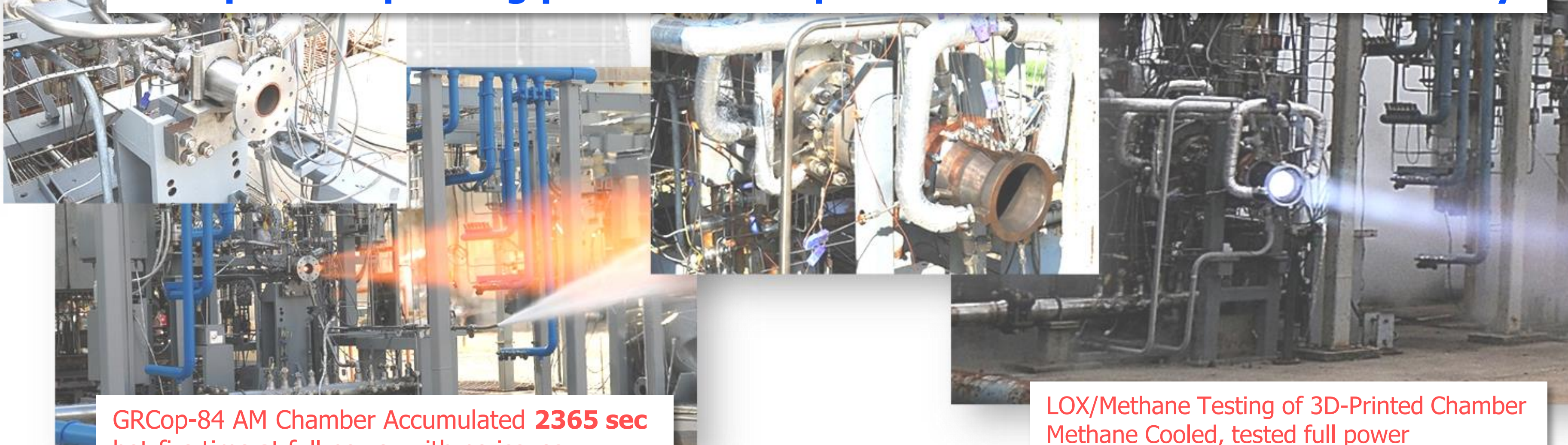
- ► Powder dose factor is critical as parts get taller.
- ► Design for Powder Removal
  - Physical efforts for powder removal can cause stress on the part.
    Mallet blows created microcracks in some components prior to HIP
  - High pressure (>500 psi) air/GN2 aided in powder removal
  - Alcohol evaporates and helped remove powder from select channels (although residual powder might clump when exposed to this fluid).
  - Include threaded ports that can be blocked off during powder removal to seal air flow properly (dry state/no oils).
  - CT scan continuously to verify powder removal.
  - Removing prior to HIP is ideal, but it can be removed after, since it does not all consolidate.
- ► Build direction is critical and overhangs may fail; 45 deg max build angles appear possible.
- ► Creating plastic models or building small wedges/slices to demonstrate parameters prior to metal designs can be helpful; identify potential issues prior to actual component builds.
- ► TIG braze repairs for debonds worked well; identical filler material is ideal.
  *Include weld wire within SLML builds.*
- ► Design for shrinkage/deformation in all process steps, such as welding and metal deposition.

# Summary and Future Work for AM Copper Chambers

- **NASA has successfully demonstrated additive manufacturing of copper-alloy combustion chambers for liquid rocket engines**
  - Processing time and cost reductions have been demonstrated
- NASA has completed parameter development for GRCop-84 using additive manufacturing / selective laser melting
  - Parameters are available for industry use
  - Property development complete and reports will be available
- Design for additive manufacturing techniques have advanced with development of AM copper-alloys
- NASA has completed hot-fire testing of chambers in LOX/H2 and LOX/CH4
  - 2365+ seconds accumulated on LOX/H2 chambers
  - 35K LCUSP chamber tested in 2017
  - Methane chambers being continuously hot-fire tested
- Additional development to evaluate C-18150 and Glidcop
  - Increase scale available for chamber fabrication

# QUESTIONS

**GRCop-84 3D printing process developed at NASA and infused into industry**



GRCop-84 AM Chamber Accumulated **2365 sec** hot-fire time at full power with no issues

LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power

# Acknowledgments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- MSFC Lander Office
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- John Vickers
- Linear Mold
- Stratasys
- ASTS, Huntsville

# Backup

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