

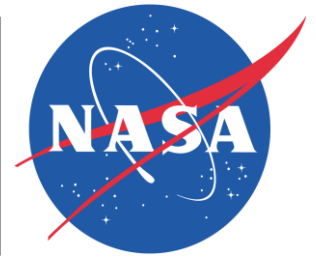
**Channel Wall Nozzle  
Manufacturing and Hot-Fire  
Testing using a Laser Wire  
Direct Closeout Technique  
for Liquid Rocket Engines**

**July 11, 2018  
AIAA-2018-4860**

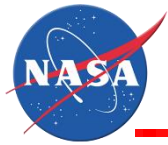
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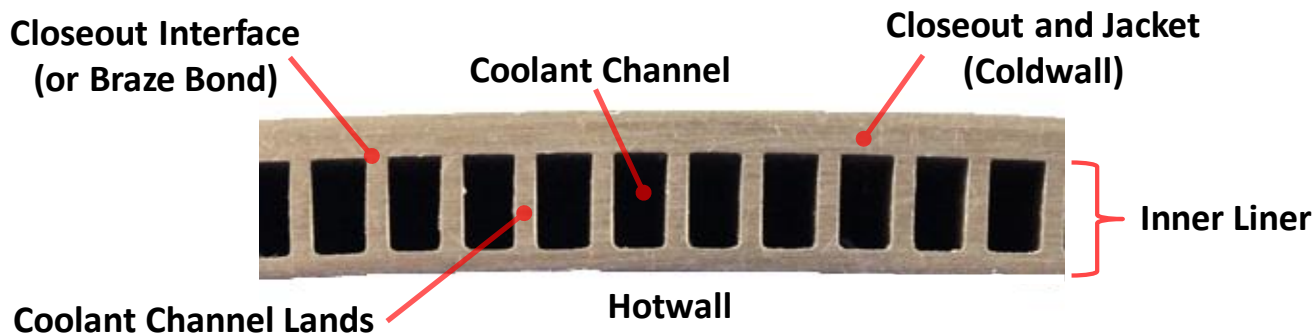


**MARSHALL**  
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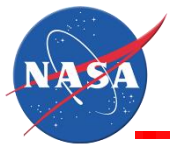


# Motivation for Channel Wall Nozzle (CWN) Technology

- Channel wall nozzles have been evaluated as a cost savings technology for current and future missions for a variety of engine programs
- NASA has evaluated and worked with vendors and contractors on fabrication of “traditional” large scale channel wall nozzles (CWN) on several programs over the last few decades
- Recent CWN manufacturing technology has been limited based on minimal investments and scale to mature technology
  - Current State of the art focused on brazing technology
  - GKN (formally Volvo) evolved the laser welded sandwich wall technology
  - Other domestic technology has limited public data available



**Goal:** Evaluate alternate manufacturing techniques to reduce fabrication cycle (and subsequent costs) and improve performance for large scale channel wall nozzles



# What about using Selective Laser Melting for Nozzles?

Although new additive manufacturing machines are being introduced, current state of the art is limited in size...

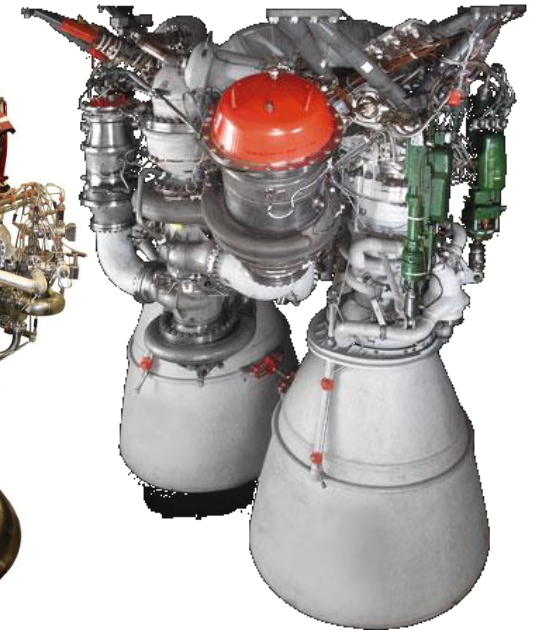
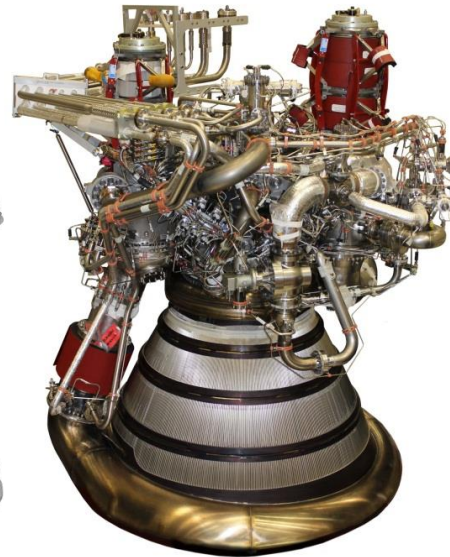
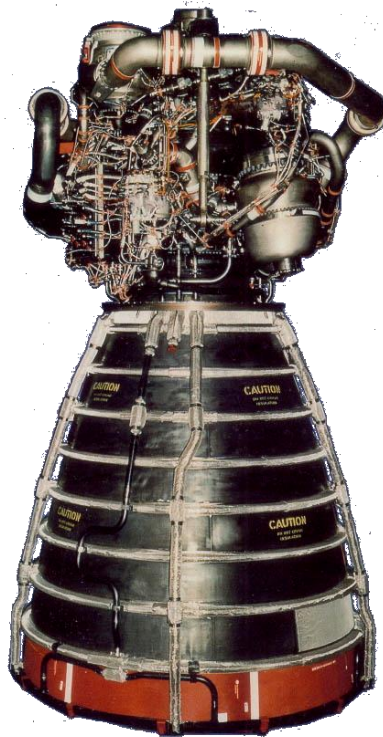
## Engine

SSME/RS-25

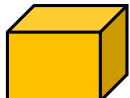
RL-10A-4

J-2X, Regen Only

RD-180



### SLM Build Boxes



10x10x10 15.5x24x19  
(inches)

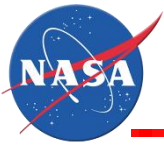
90"

46"

70"

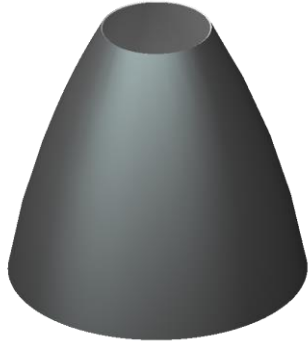
56"

**Nozzle Exit Dia.**



# Overview of Techniques

## Liner Fabrication



- Forging
- Spin Forming
- Shear Forming
- Powder Metallurgy
- Freeform AM Deposition
  - Powder-based Laser
  - Wire-based Laser
  - Arc-based Wire
- Multi-Piece SLM
- Platelets
- Explosive Forming
- Coldspray
- Casting
- Vacuum Plasma Spray

## Channel Forming/Slotting



- Slitting Saw
- End Milling
- Water Jet Milling
- Electro or Photochemical
- Plunge EDM
- Multi-Piece SLM
- Platelets
- Freeform AM Deposition

## Channel Closeout and Jackets

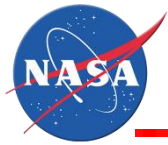


- Pressure Assisted Braze
- Standard Atmosphere Braze
- Multi-Piece SLM
- Vacuum Plasma Spray
- Electroplating
- Coldspray
- Freeform AM Deposition
  - Wire-based Laser
  - Powder-based Laser
  - Arc-based Wire
- Explosive Bonding
- Ultrasonic
- Laser Welding
- Diffusion Bonding
- Platelets
- Casting
- Composite Overwrap

## Manifold Application



- Wrought and Machined
- Freeform AM Deposition
  - Wire-based Laser
  - Powder-based Laser
  - Arc-based Wire
- Multi-Piece SLM
- Platelets
- Casting
- Molded Composites



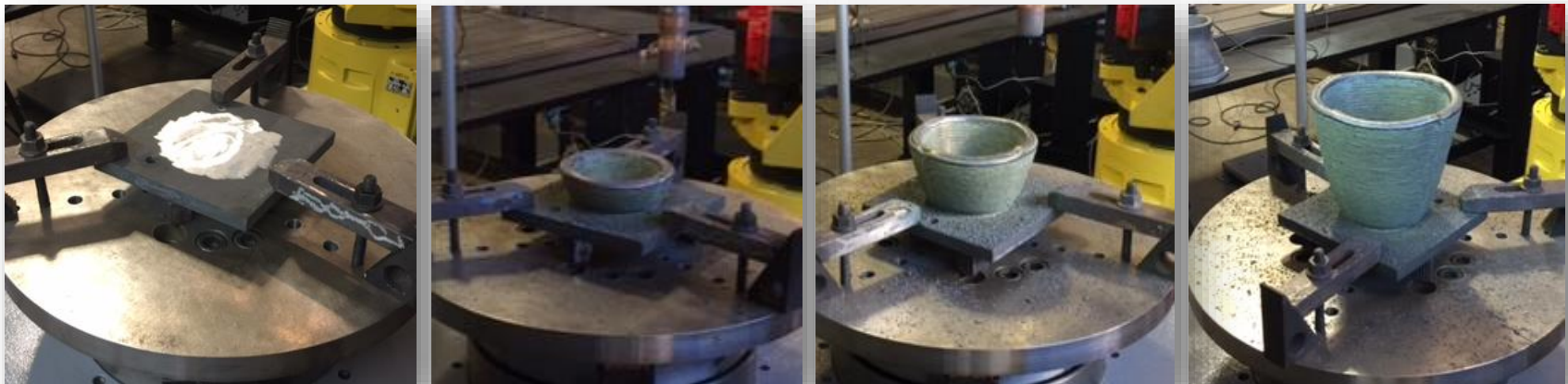
# Deposition Techniques for Forming Liner

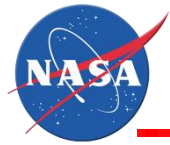
## Directed Energy Deposition (DED)

Liner  
Fabrication

### Arc-based Deposition Metal Direct Digital Manufacturing (MDDM)

- Provides high deposition rate (20+ lbs/hr) using wire-based arc welding techniques; near net shape deposition

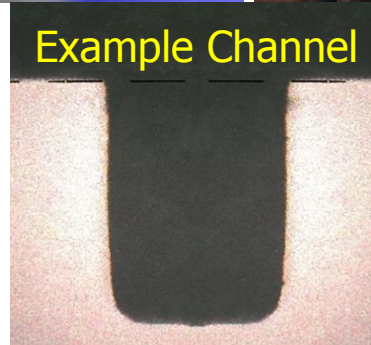
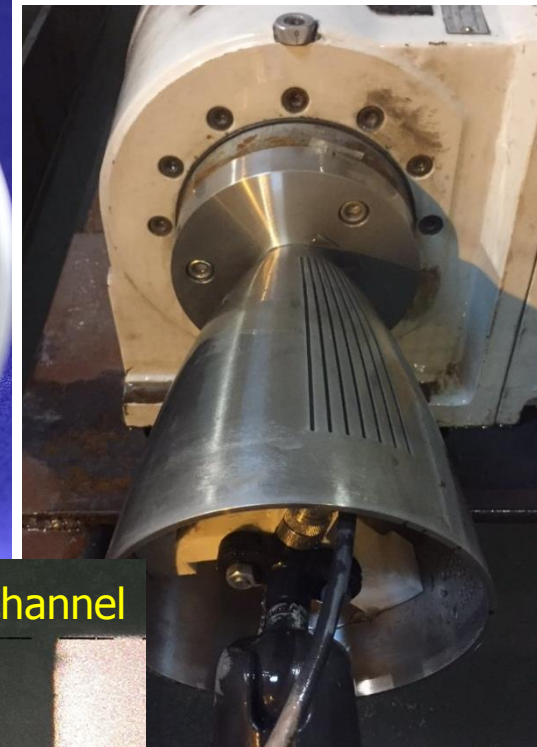
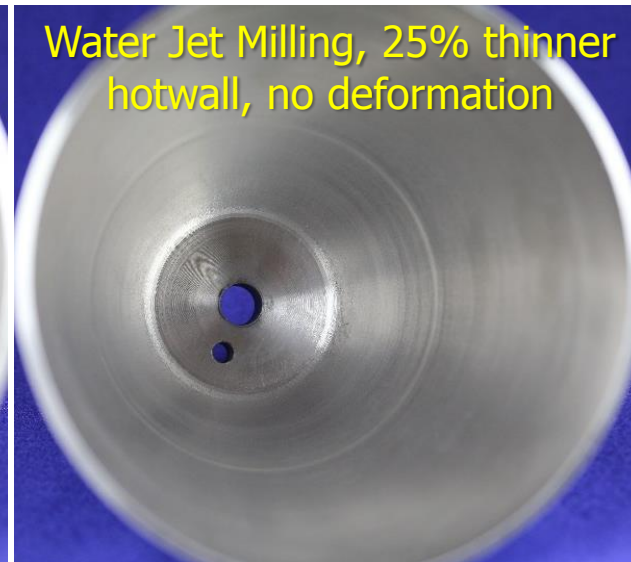




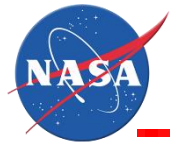
# Water Jet Milling

Channel  
Forming/Slotting

- Abrasive blind Water Jet Milling technique to form coolant channels (*akin to slotting*)
  - Low load technique, reduced wall thicknesses
  - Allows for easy milling of difficult materials in a variety of geometries
  - Current development to “mimic” features of slotting



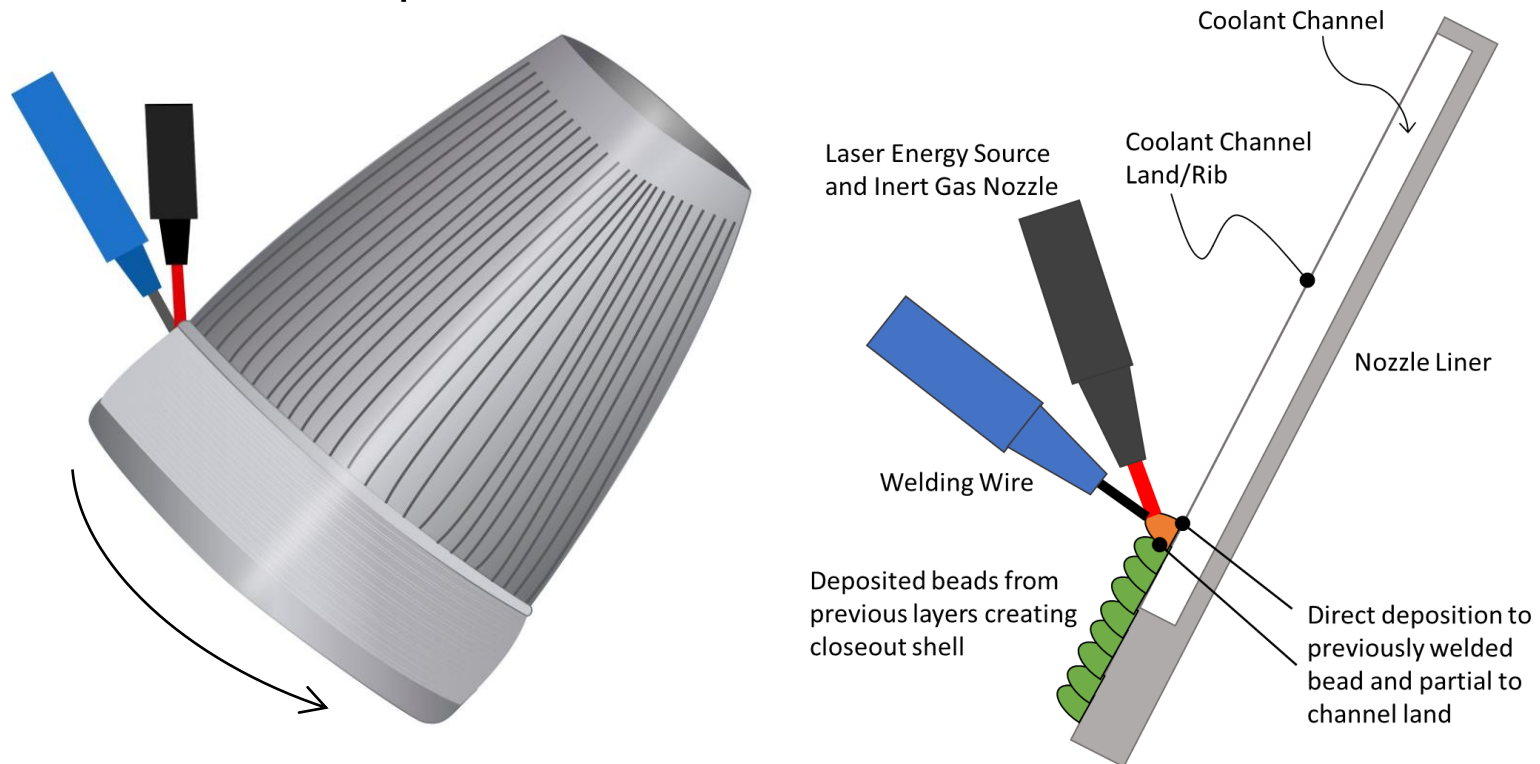
- Ability to hold +/- 0.001" in subscale applications
- Rougher surface finish than traditional machining, but acceptable during hot-fire and flow testing

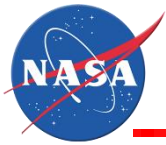


# Closeout – Laser Wire Direct Closeout

Channel Closeout and Jackets

- Laser Wire Direct Closeout (LWDC) is an additive technique that locally bonds a wire to the channel ribs and provides a structural jacket in place
  - Freeform welding process without need for filler
- Uses laser energy source and off-axis wire
- Complete bond at ribs and previously deposited layers
- No material “drop-thru” into channels





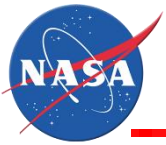
# Closeout – Laser Wire Direct Closeout

Channel Closeout  
and Jackets

- Demonstrated on a variety of materials including Inco 625, SS347, Bimetallic (Cu-Inco), Al-6061
- Allows for interim starts-stops and real-time inspection







# CWN Techniques Hot-fire Tested

## Nozzle #1

CRES 347 Forging

Water Jet Milled Channels

SS247 Laser Wire Direct Closeout (LWDC)



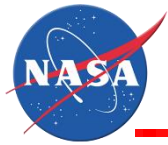
## Nozzle #2

Inconel 625 Arc-Deposited Liner

Water Jet Milled Channels, Thin-wall

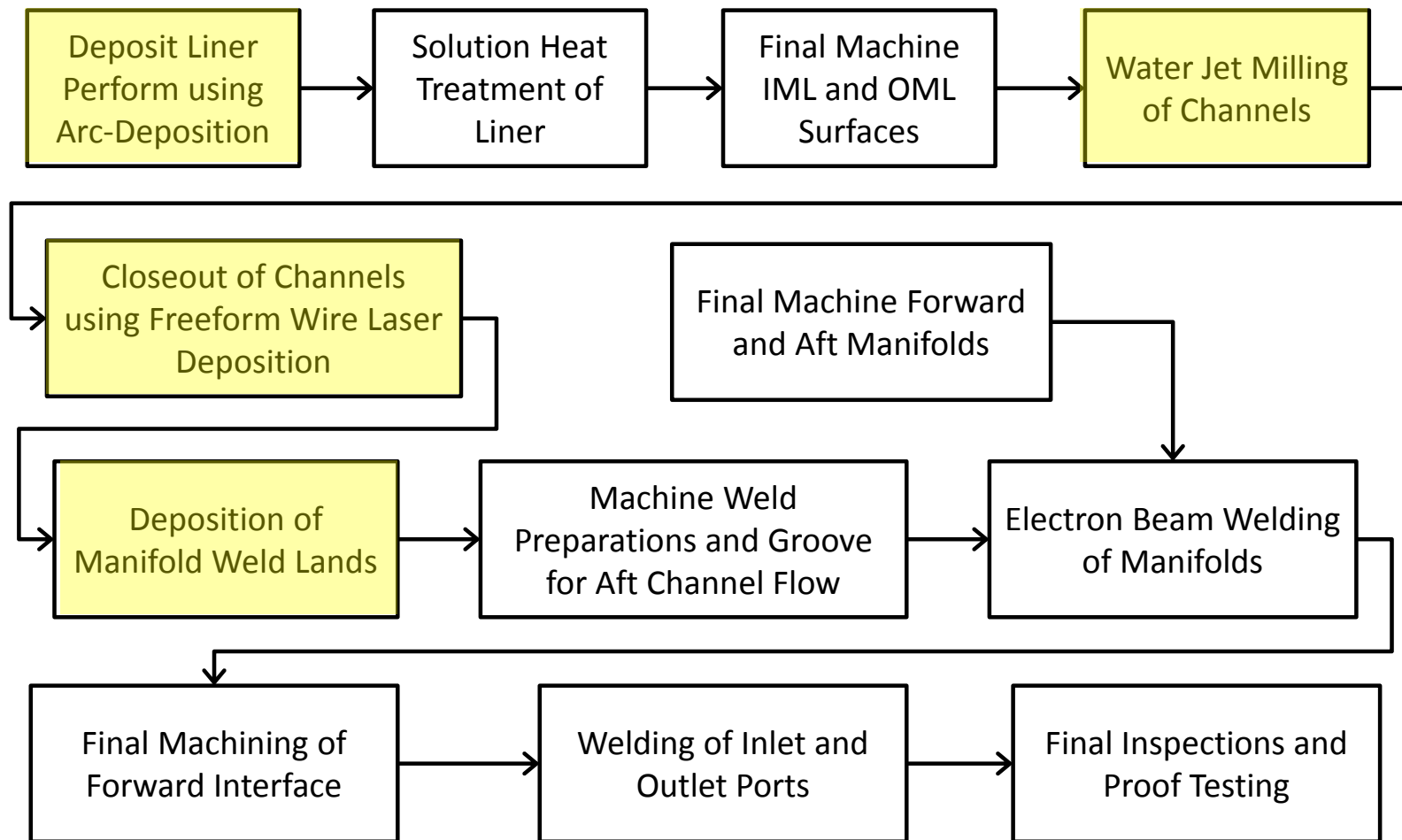
Inco 625 Laser Wire Direct Closeout (LWDC)

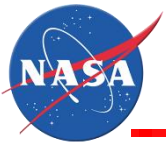




# Fabrication Process for LWDC Nozzles

- Process for fabrication of Inco 625 Nozzle #2 shown
- Near net-shape deposition of liner and LWDC closeout significantly reduced machining required

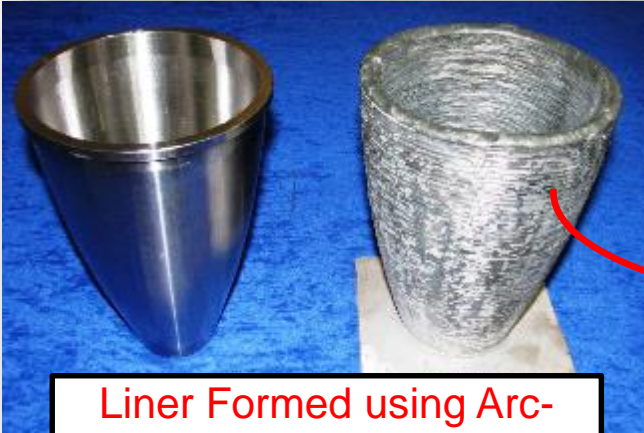
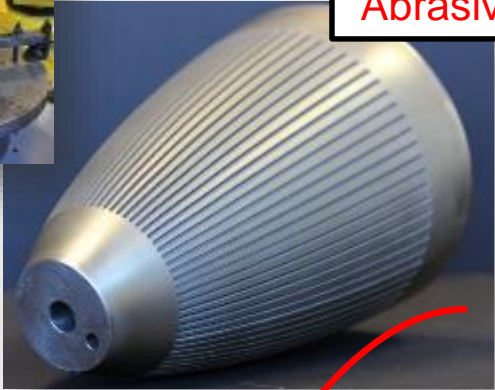




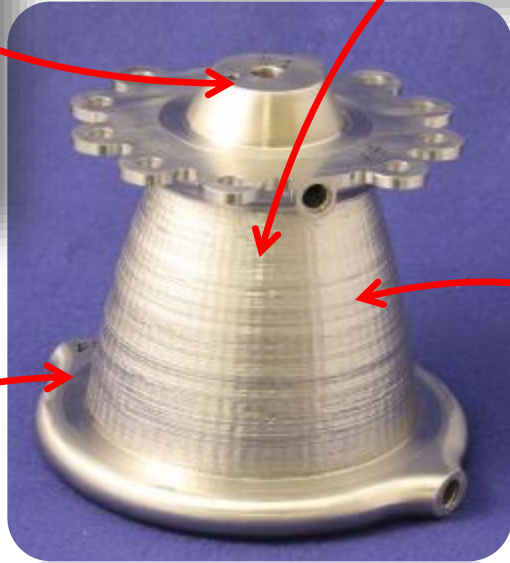
# Nozzle #2 – Inco 625 LWDC



Abrasive Water Jet Milling



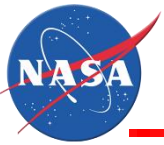
Liner Formed using Arc-Deposition Additive



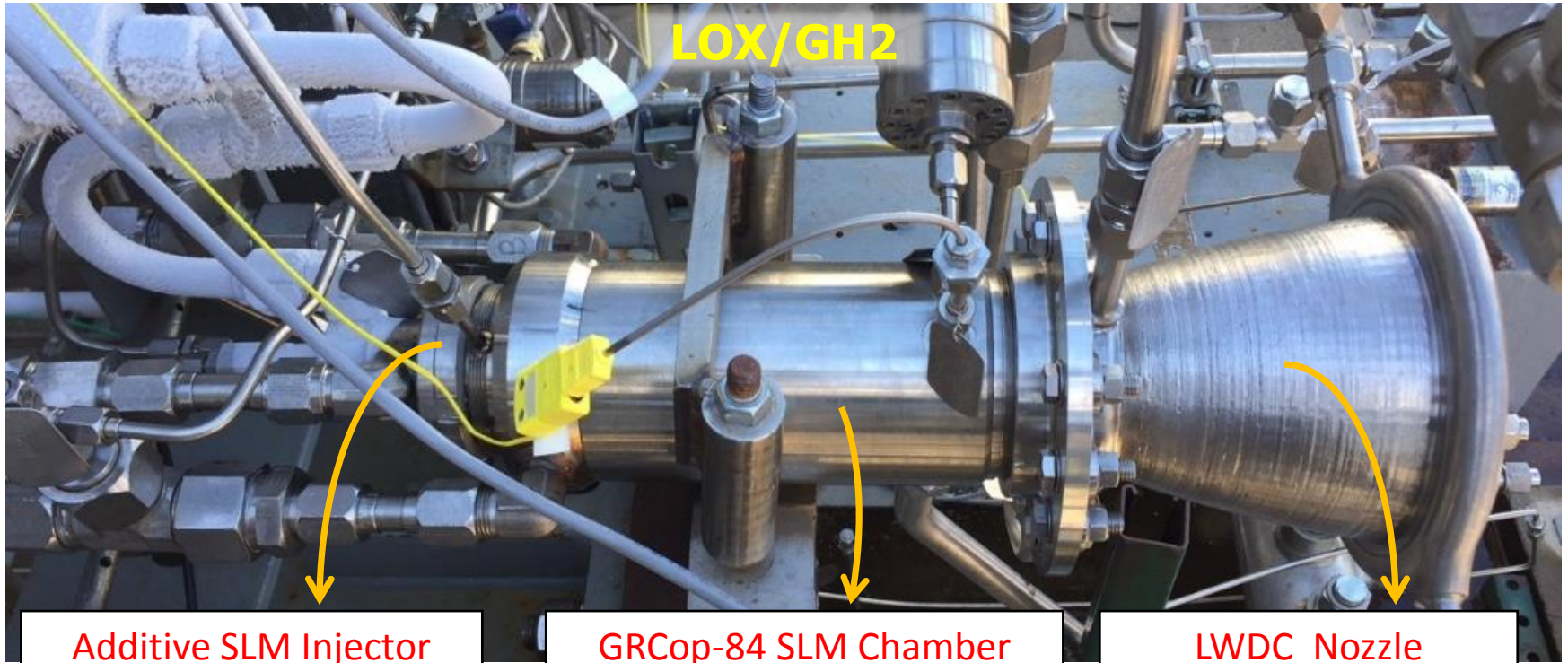
Traditionally machined manifolds



Laser Wire Direct Closeout



# CWN Supporting Test Hardware All-Additive Thrust Chamber Assembly

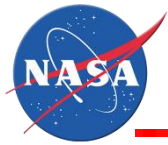


Additive SLM Injector

GRCop-84 SLM Chamber

LWDC Nozzle





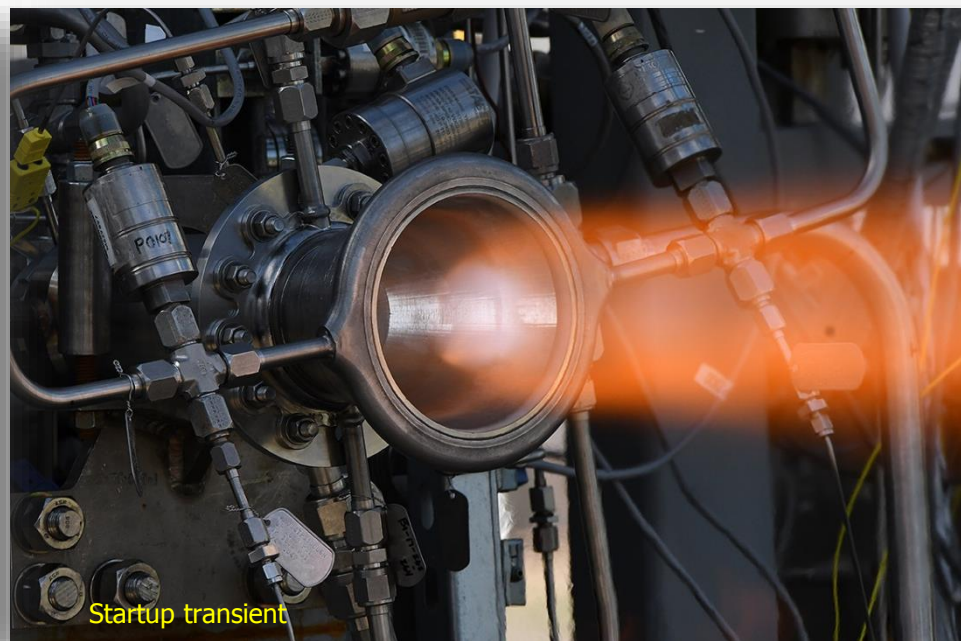
# Hot-Fire Testing of LWDC and DED Nozzles

- Completed hot-fire testing at MSFC TS115, November 2017 (PH034)
- LOX/GH2,  $P_c=800$  psig and  $MR = 5.6 - 6.7$  (1,200-1,500  $lb_f$  thrust)
- Completed 13 hot-fire tests

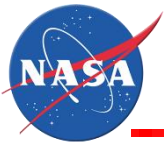
Nozzle Identifier and Technique	Starts	Accumulated Time (seconds)
Nozzle #1 - LWDC SS347	4	160
Nozzle #2 - LWDC Inco 625, Fully AM	9	880



**Nozzle #1 - SS347**



**Nozzle #2 - Inco 625, Fully Additive** 13



## Results of Hot-fire Testing

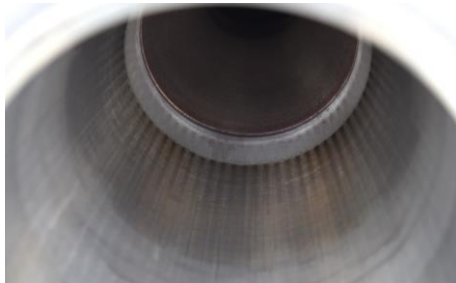
- ✓ No issues observed with arc-based deposited liner, material behaved as-expected at elevated temperatures and strain ranges
- ✓ Pressure-drop measured during hot-fire testing using water jet milled channels met predictions
- ✓ LWDC closeout performed as-expected during startup and steady state hot-fire loads



Post-PH034-009 (4 starts)



Post-PH034-011 (6 starts)



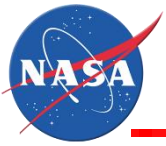
Post-PH034-014 (9 starts), 6 o'clock



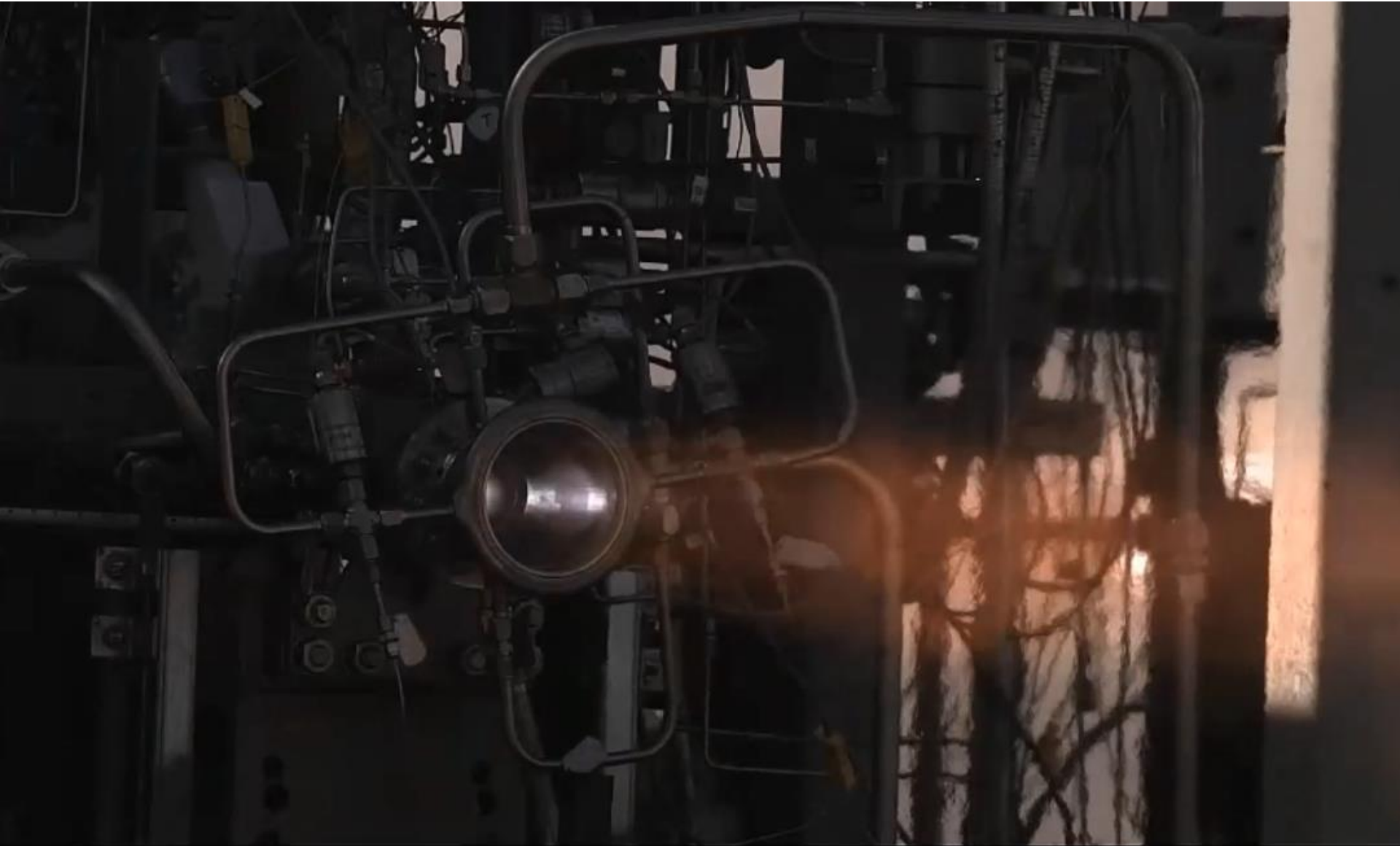
Post-PH034-014 (9 starts), 12 o'clock

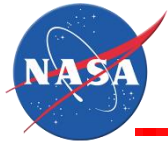


Nozzle #2, LWDC with Arc-based Additive Liner



# Video of Hot-Fire Test





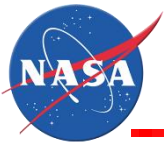
# Conclusions

- New manufacturing technologies have been developed and advanced for use in channel wall nozzle applications
  - **Deposition techniques offer alternatives for rapid forming liners**
    - Material properties confirmed in mechanical test and hot-fire
  - **Water Jet Milling offers an alternative to slotting for difficult to machine materials**
    - Met pressure drop expectations
  - **Laser Wire Direct Closeout (LWDC) offers a new method for closeout of nozzle and chambers**
    - Demonstrated subscale hardware and process for fabrication
- NASA is continuing to invest in these technologies through Project Funding, IRAD, Space Act Agreements, SBIR/STTR programs and fabricating larger-scale hardware for testing
- The process is continued to be scaled up and hardware being developed
- Alternate materials being investigated including bimetallic hardware
- Data on techniques and vendors available to industry





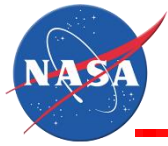
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# Acknowledgments

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- Cynthia Sprader
- Test Crew at TS115
- Bryant Walker – Keystone
- Albert Hammeke – Laser Tech
- Dan Alberts – Ormond
- Judy Schneider – UAH
- Dave Brasher – HEMI
- Joe Sims – ASRC Federal
- ProCAM
- Ken Cooper
- Jim Lydon
- Zach Jones
- Omar Mireles
- Dave Ellis
- Bob Carter
- Brad Lerch
- Ian Locci
- Jeff Clouch
- Craig Wood
- Steve Wofford
- Carol Jacobs (retired)
- Mike Shadoan
- John Fikes
- Jim Turner
- Gregg Jones
- Chris Protz
- Chance Garcia
- Jessica Wood



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