Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper Stage Liquid Rocket Engines

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Motivation for Extension Development

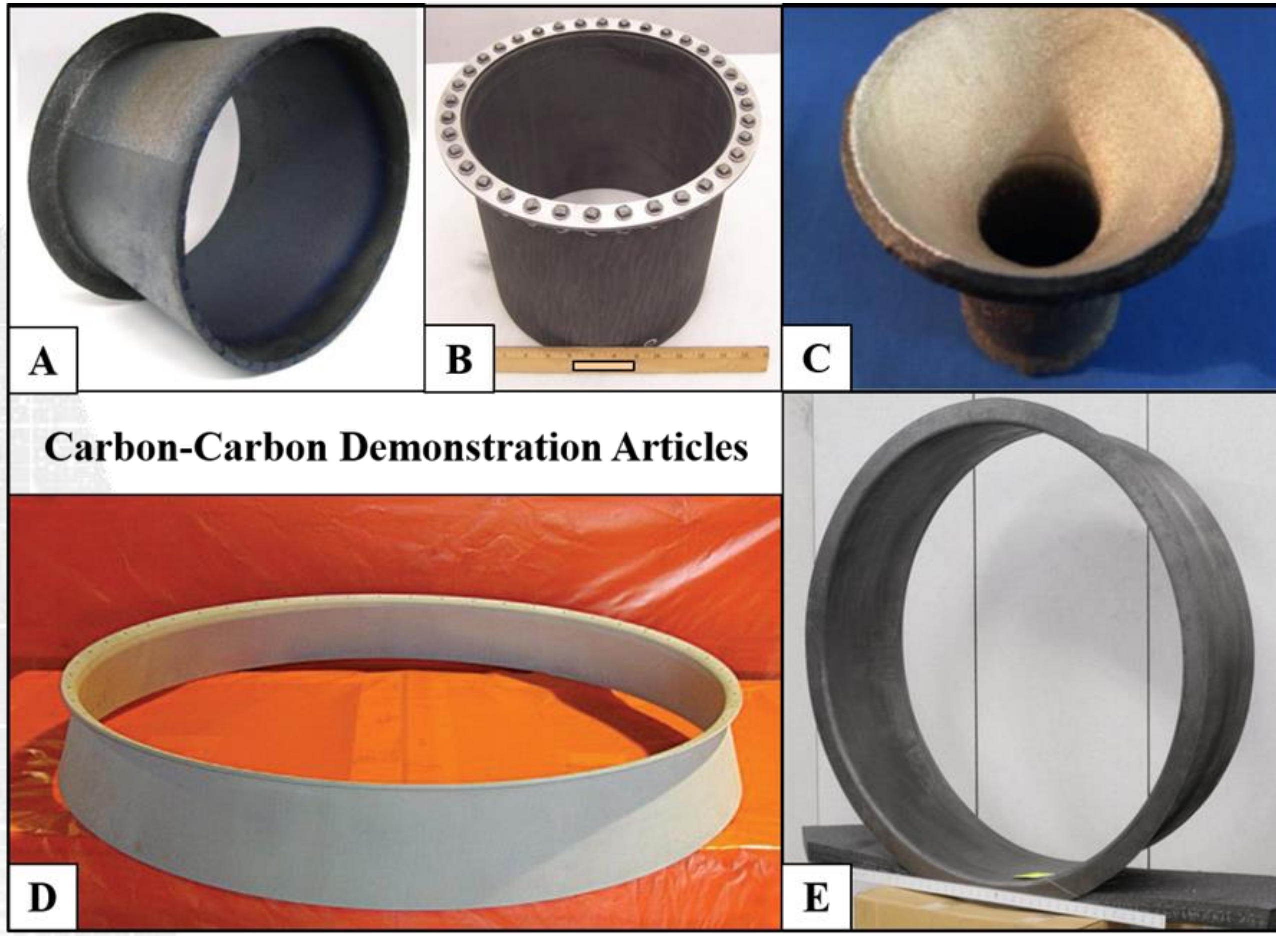
- NASA and commercial space partners are interested in developing a commercial supply chain for Carbon-Carbon Nozzle Extensions (CCNE)
- Provides significant advantages for a variety of upper-stage engines and in-space engines
  - Weight Reduction – 50% savings vs. metallic
  - Improved thermal design margins – 500-1500°F
  - Less complex designs and/or manufacturing processes
  - Cost Reduction
  - New design opportunities to further optimize regen-extension joint
- Evaluate high temperature nozzle extension fabrication processes and obtain preliminary hot-fire test data in a relevant environment to characterize materials

Goal: Advance the state of the U.S. Carbon-Carbon (C-C) technology to the point that domestic C-C nozzles can be considered as viable candidates for use on U.S. cryogenic upper stage engines, in-space, ascent/decent lander engines and nuclear engines

NASA Funded Tasks – SBIR/STTR, IRAD, and Industry Partnerships

SBIR/STTR Development

A. **PAN-based hybrid C-ZrC/C-C**
   Ultramet, C-CAT
B. **Rayon-based involute C-C**
   MR&D, Orbital ATK
C. **PAN-based Ir-lined involute C-C**
   MR&D, Orbital ATK, Plasma Processes
D. **PAN-based C-C with "high-melt" and SiC coating systems**
   C-CAT
E. **Lyocell-based C-C**
   C-CAT, Southern Research

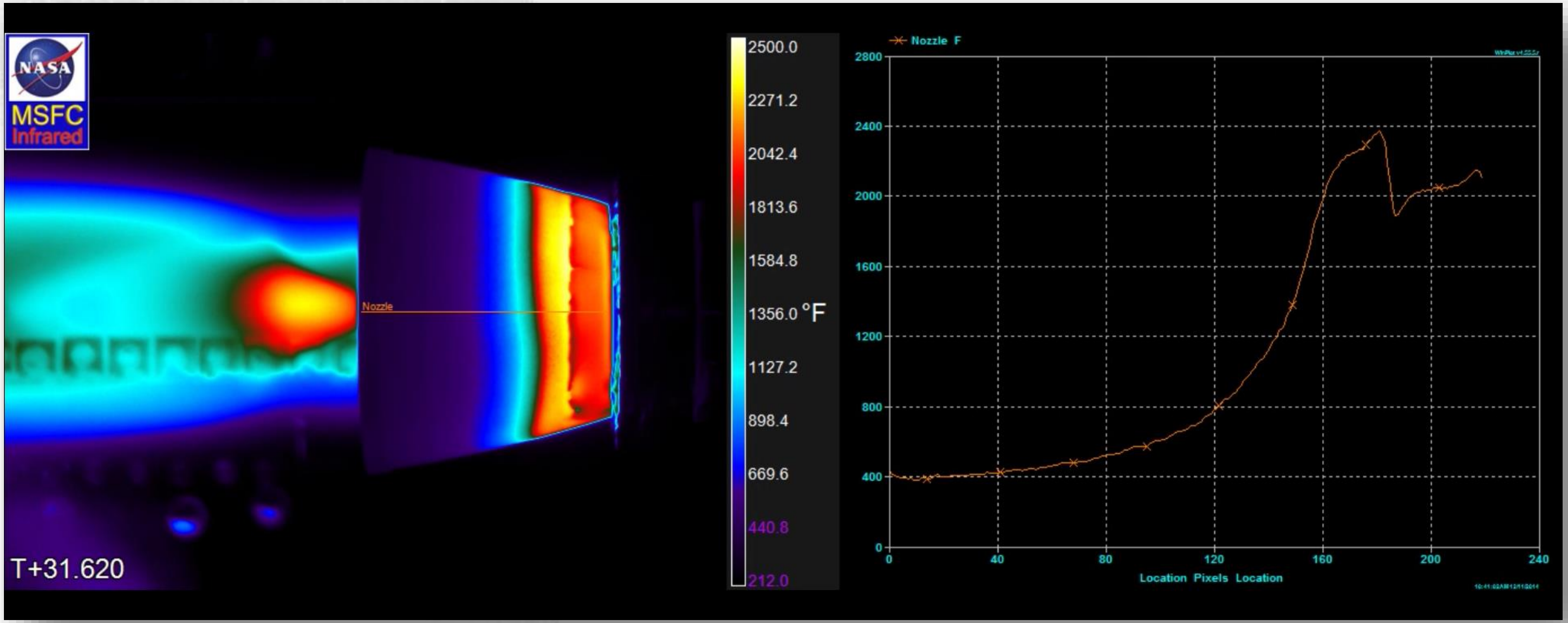


MSFC In-House Technology Development Projects

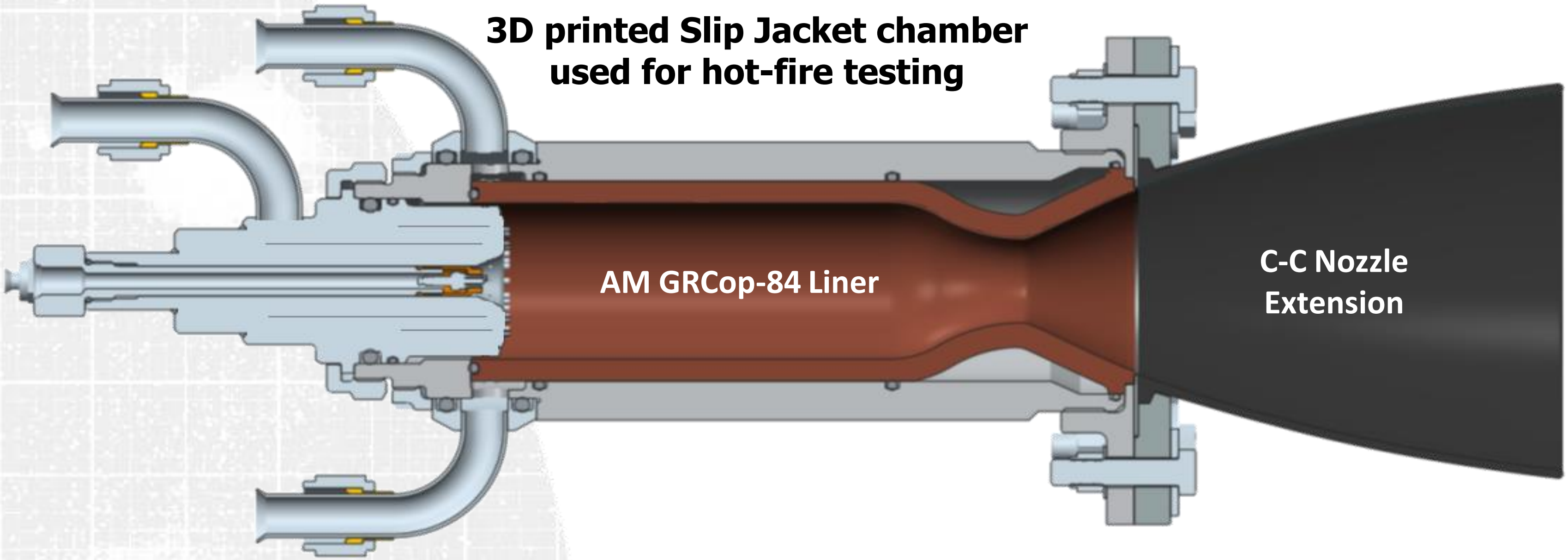
- Materials screening via 1.2K-lb_f LOX/GH_2 small thruster testing
- Moderate-scale demonstration via 35K-lb_f LOX/LH2 chamber to evaluate material feasibility
- Component and coupon level material testing

Background of MSFC Test Rig

- Starting in 2014, MSFC created a subscale nozzle test rig to conduct affordable, long-duration hot-fire testing for NASA and commercial partners
  - LOX/GH2, LOX/CH4, or LOX/RP capabilities
  - Durations up to 180 seconds
  - Previous testing used a vintage chamber, which caused flow separation limiting the length of the nozzle



Design of New Chamber Assembly



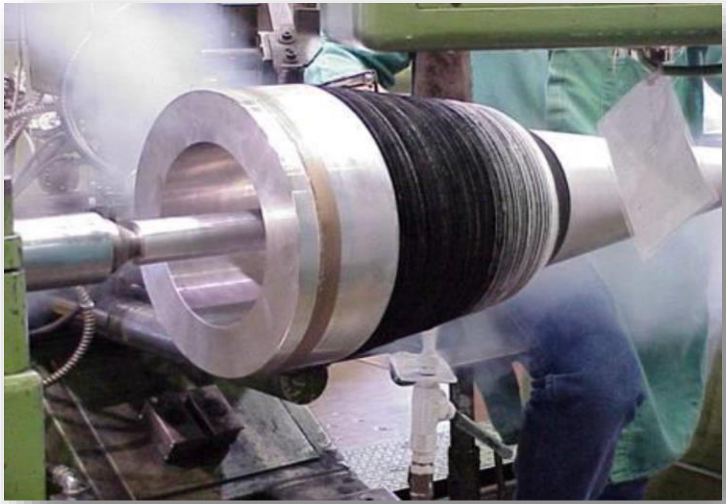
- New contour design allows for full-flow extended length nozzles and extensions
- 27:1 expansion
- Pc = 750 psig
- 1,200 lb_f thrust
- Duration up to 180 sec
- Additive manufactured (AM) GRCop-84 liner

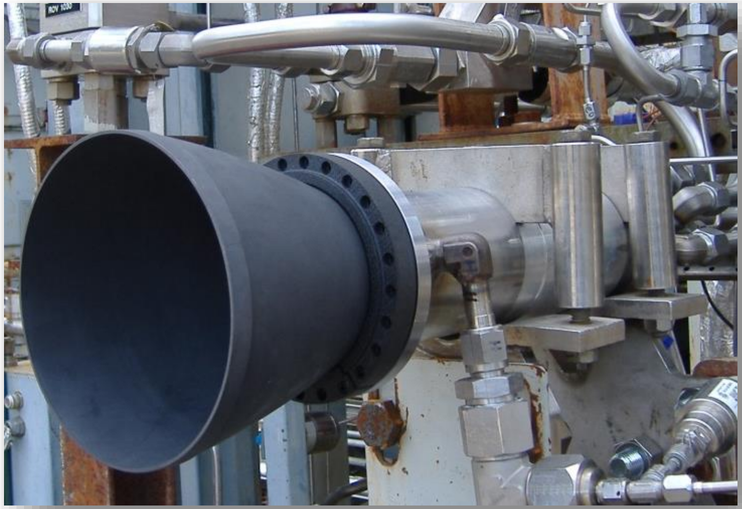
	Heritage Design	New Design
Thrust Chamber Assembly, Drawing Reference	MER00060-101	MER01446-001
Main Combustion Chamber, Liner	MED04227-1	MER00664-001
Maximum Chamber Pressure, Pc (psia)	850	1350
Water Coolant Inlet Pressure, (psia)	1000	2000
Chamber Barrel Diameter (in)	2.25	2.25
Chamber Barrel Length (in)	6.77	5.26
Divergent Radius, Rd/Rt	2	0.5
Throat Diameter (in)	1.2	1.2
Nozzle Attach area ratio (AR)	8.1:1	4.4:1

Orbital ATK CCNE Testing at MSFC TS115

Joint MSFC/OATK effort to demonstrate new test and material capabilities

- Scale-up and demonstration of low cost manufacturing processes using tape wrapped preforms, a rapid densification process, and a variety of oxidation barriers.
- Static testing of extensions included:
  - Demonstration of attachment and sealing concept for 2D CCNE's
  - Demonstration of 2D C-C/oxidation-barrier systems in long duration, multiple start/stop tests. Oxidation protection systems provided by:
    - COIC -- 3 systems
    - Exothermics -- 1 system
    - Plasma Processes -- 2 systems
- Seven nozzle extensions manufactured and successfully tested in December 2014.
- Additional testing in Aug-Sep 2016.





C-CAT CCNE Testing at MSFC TS115

Joint MSFC / Carbon-Carbon Advanced Technologies (C-CAT) effort

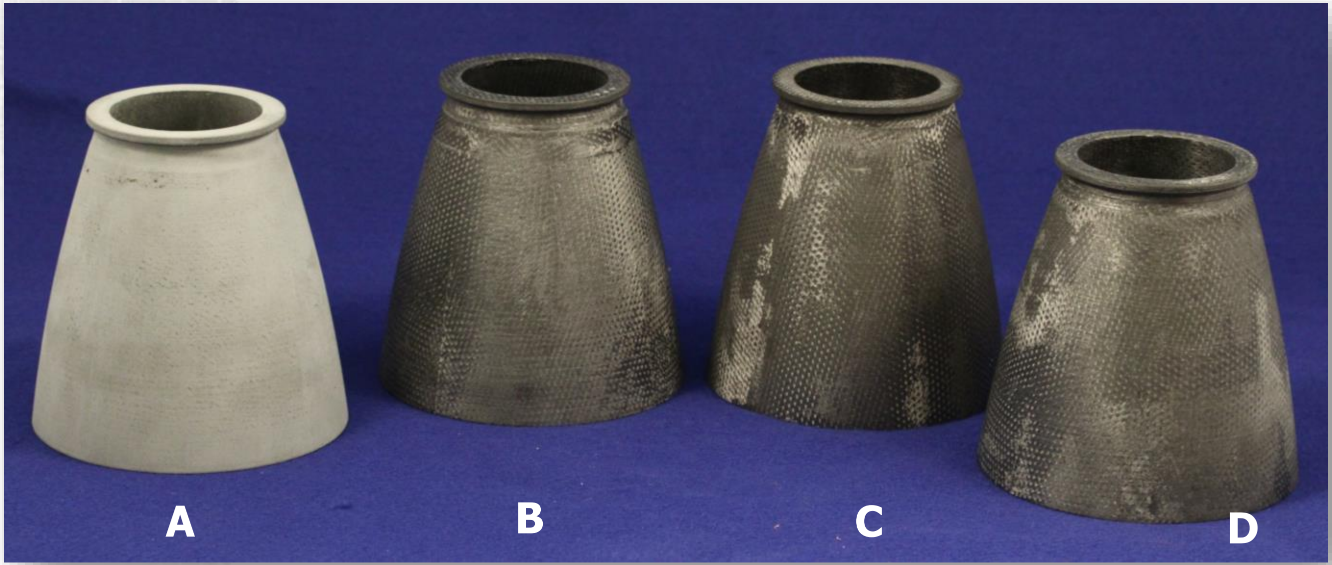
- Demonstrate SiC coated C-C, which is being considered for LOX/LH2 nozzle extension applications
- Experimental enhanced-matrix C-C (EMCC) systems that do not require use of high-cost protective coatings

Four 2D C-C Materials Tested

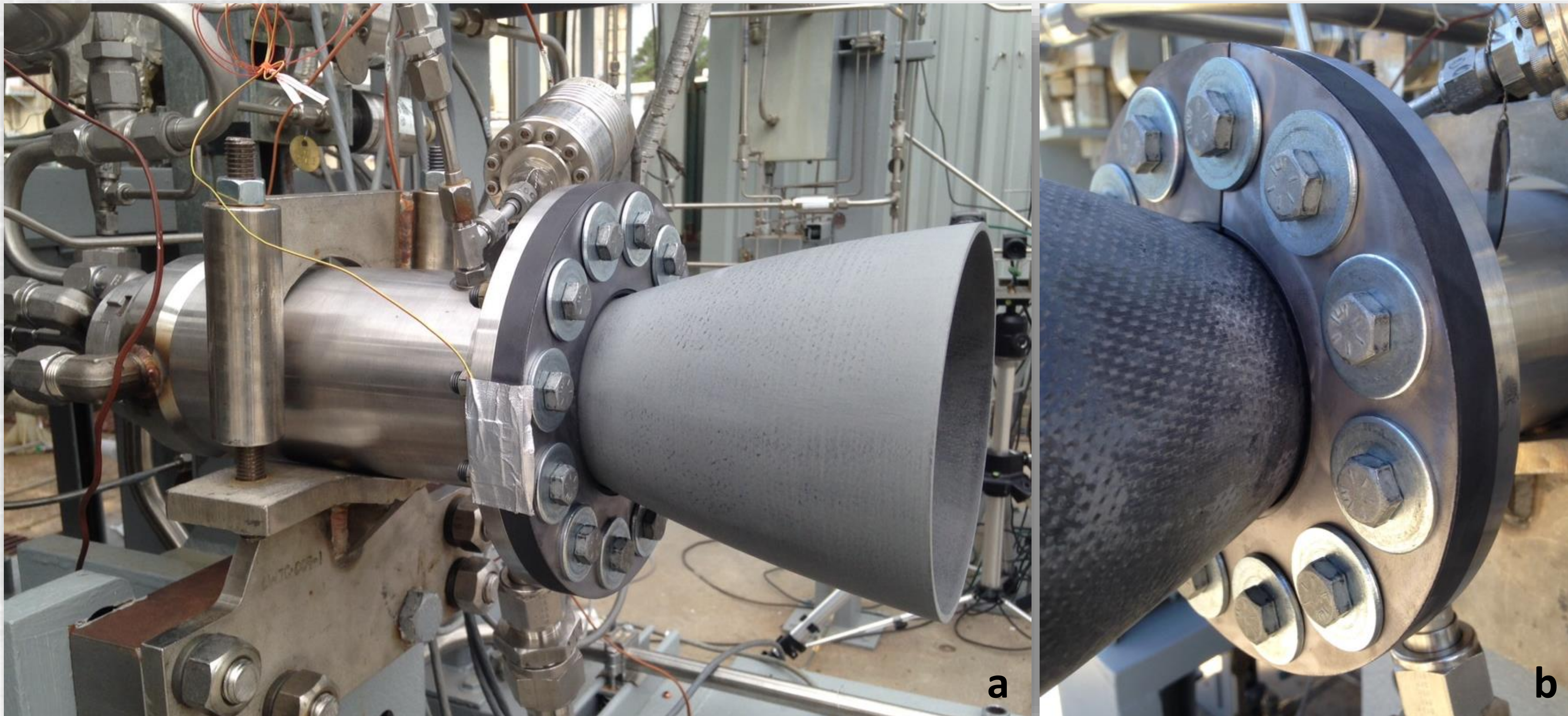
A. ACC-6 with silicon carbide (SiC) pack cementation coating
B. ACC-6 with SiC enhanced matrix – *an experimental material*
C. ACC-4 with no coating
D. ACC-6 with zirconium diboride (ZrB2) plus hafnium carbide (HfC) enhanced matrix – *an experimental material*

CCNE's Prior to Hot-Fire Testing

- All use T-300 PAN 3K heat treated material
- All used the same tooling.



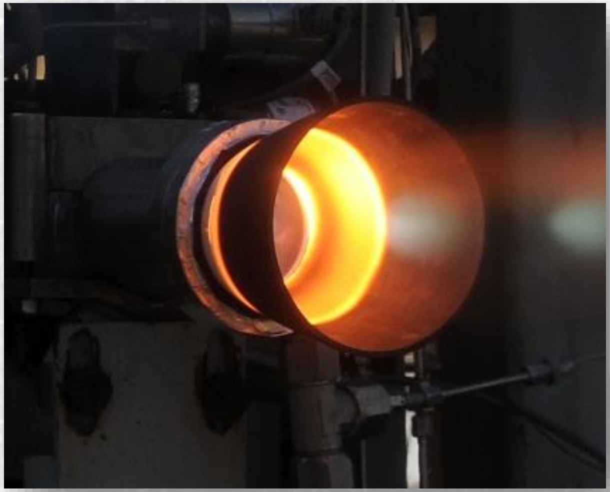
Extension Design and Chamber Interface (C-CAT)



Nozzle Extension Installed on Thrust Chamber Assembly

a. Full assembly at MSFC TS-115.
b. View of tantalum backer split ring, graphite split ring, and overall interface region.
   - C-C extensions attached to aft flange of combustion chamber using GES Graphite (PFI-25 and PFI-45) split rings.
   - Grafoil, grade GTB flexible graphite, 0.060" thick compressed seal at interface between graphite and combustion chamber flange.
   - Tantalum split-ring backer plate at aft end of graphite split ring.

C-C Extension Hot-fire Testing Results

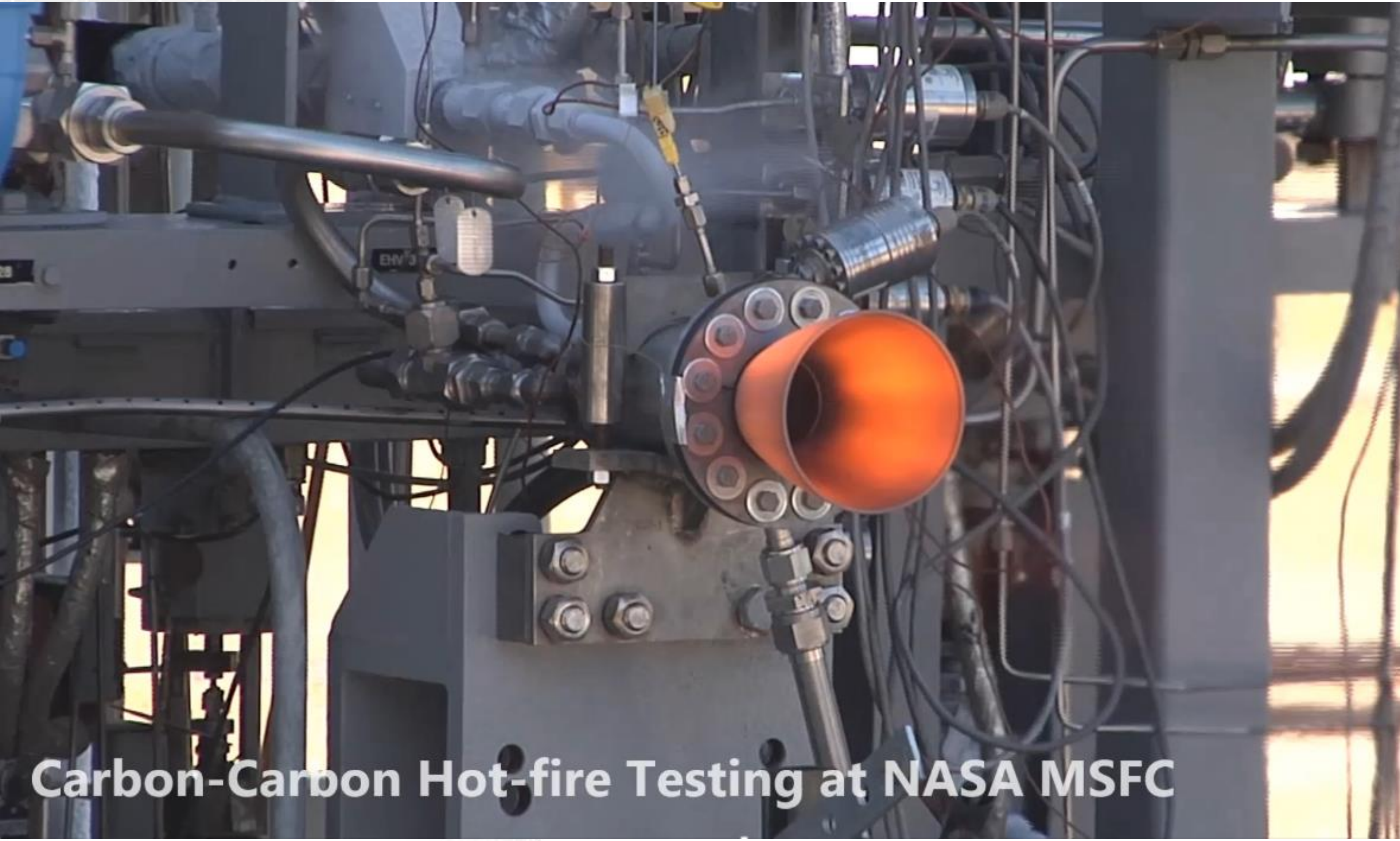


Orbital ATK Extension Test with COIC SiC + Hf

C-CAT Extension Test, ZrB2/HfC EMCC

Base Material	Anti-Oxidation Protection *coating*	Accumulated Duration *sec*
OATK TW Rapid Densification 3 Cycles	Bare	10
OATK TW Rapid Densification 3 Cycles	COIC-SiC, No Filler	90
OATK TW Rapid Densification 3 Cycles	PPI ZrB2+SiC, APS	30
OATK TW Rapid Densification 3 Cycles	Exothermics Si-Partial SiC	155
OATK TW Rapid Densification 3 Cycles	PPI MoSi2-based, VPS	30
OATK TW Rapid Densification 3 Cycles	COIC-SiC + Hf-based Filler	720
OATK TW Rapid Densification 3 Cycles	COIC-SiC + Zr-based Filler	480
C-CAT 40 ACC-4	Bare	240
C-CAT 40 ACC-6	SiC Conversion	2050
C-CAT EMCC ACC-6	None, SiC-enhanced resin EMCC	10
C-CAT EMCC ACC-6	ZrB2/HfC enhanced matrix EMCC	64

Video of Hot Fire Testing



Orbital ATK Extension, COIC Hf-based filler

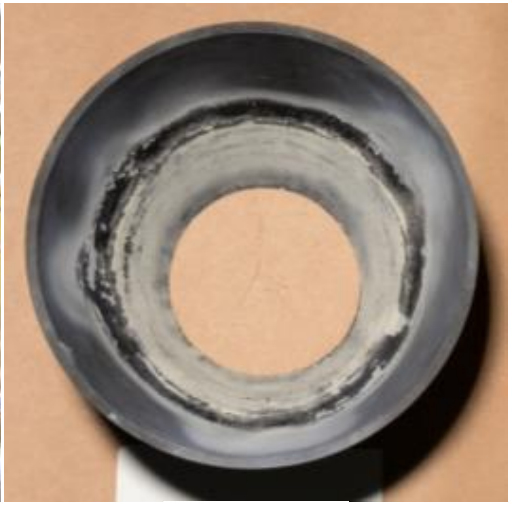
3 Starts, Post-120 sec

240 sec

360 sec

480 sec

600 sec



720 sec

<23% weight loss at elevated mixture ratios, although attributed to flow separation region as predicted

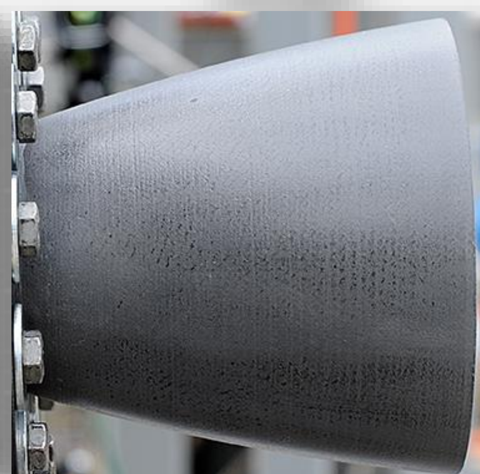
C-CAT ACC-6 with silicon carbide (SiC) coating


Pretest


72 sec


222 sec

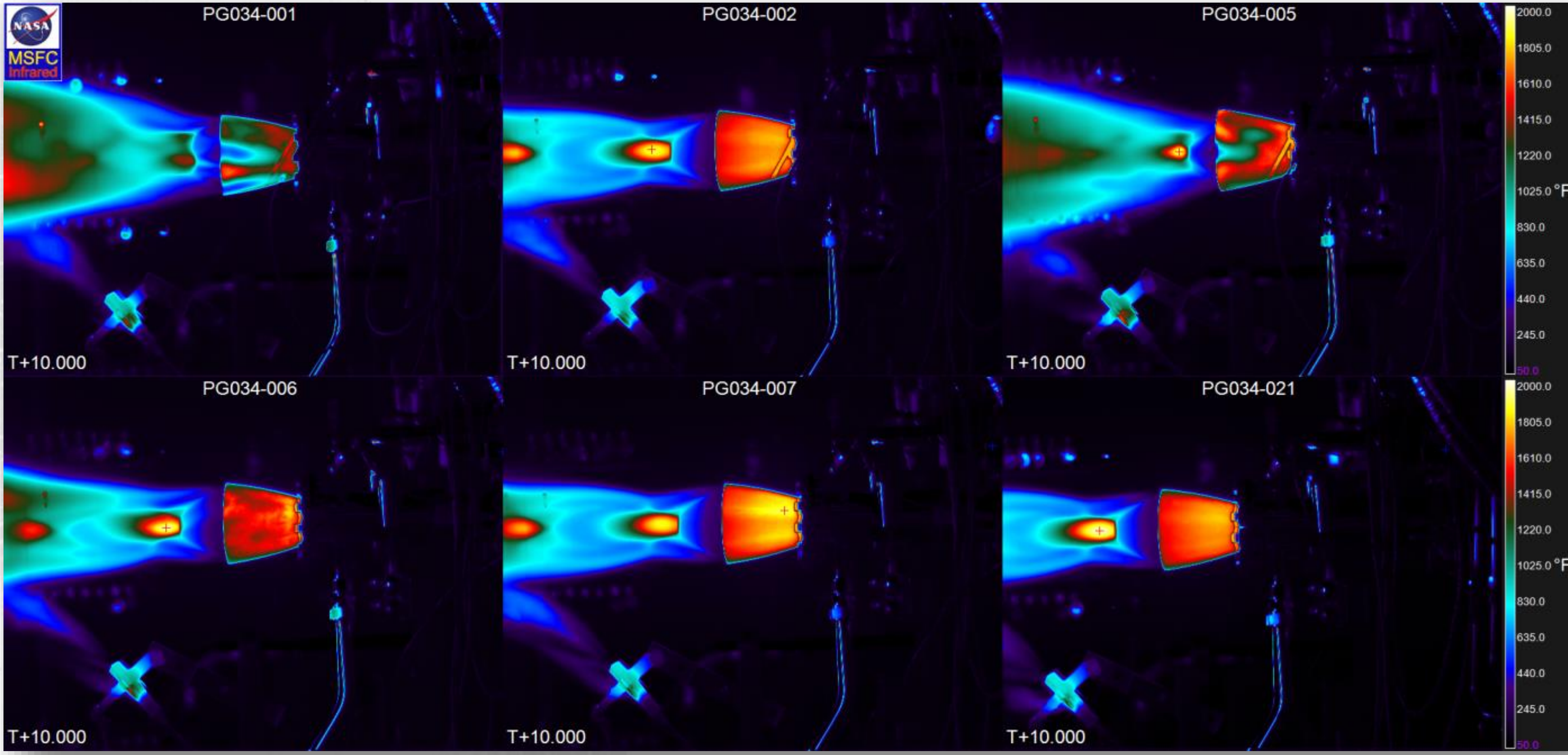

790 sec


1690 sec


2050 sec

No erosion observed on ID surface; *Note: oxidation more prevalent on OD aft end due to entrainment flow; based on results from EMCC material and uncoated testing*

Infrared Thermography during C-CAT Testing



Comparison of infrared (IR) thermography imaging for C-CAT extensions at start +10 seconds with various amounts of streaking observed.

- Ply lifts observed in EMCC
- Operated at temperatures up to 2400°F

Note: Tests -002, -007, -021 are with the SiC conversion coating.

Moderate-scale C-C 35K-lb_f Technology Demonstrator

Polyacrylonitrile- (PAN-) based C-C

- **T-300 3K fiber**, with heat treatment
- **ACC-6 condition**
- **Silicon carbide (SiC) coating**

LCUSP Thrust Chamber Assembly with C-C Extension

Approx. 25" diameter

Lyocell-based C-C

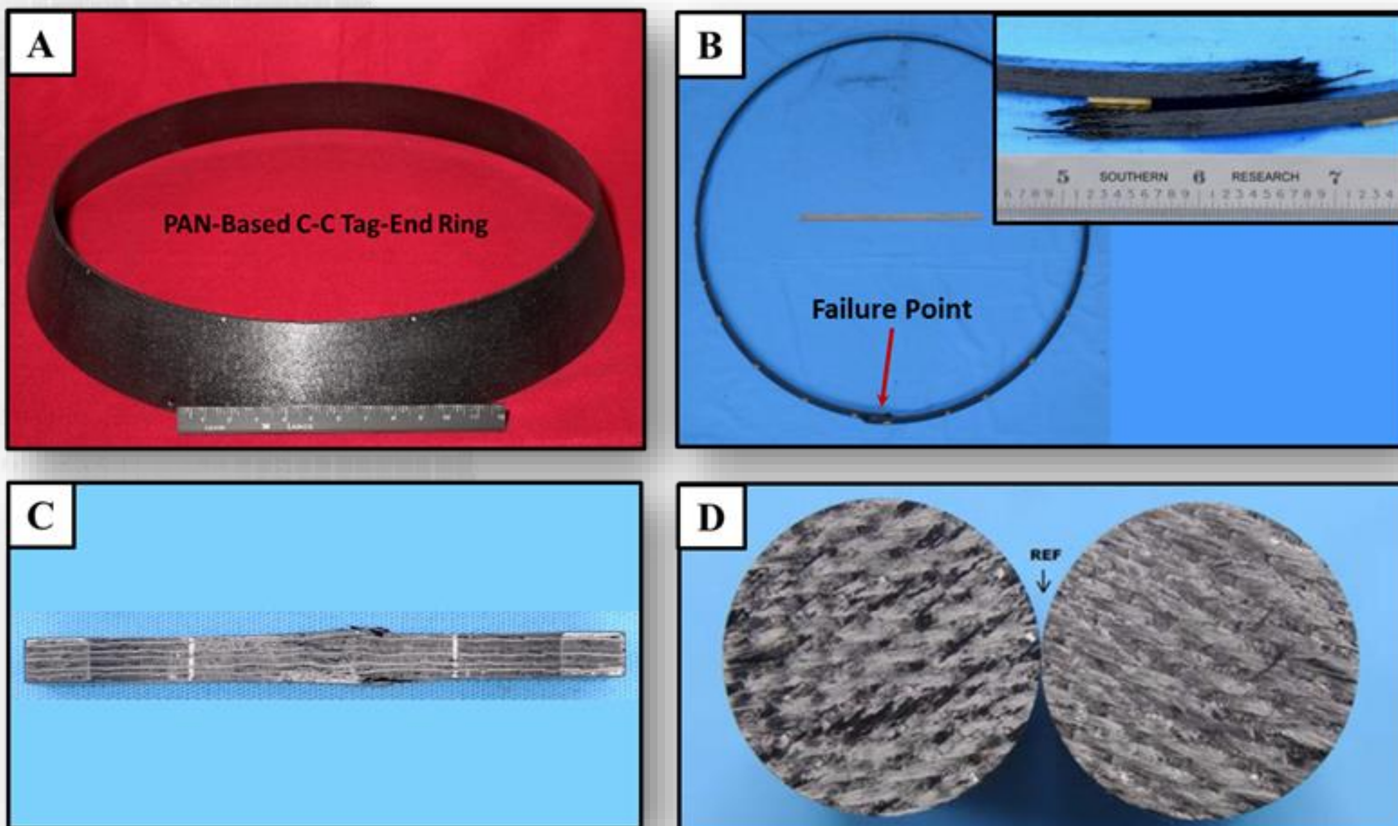
- **Lyocell fiber**, with heat treatment
- **ACC-4 condition**
- **Uncoated,** due to fiber heat treat limit

LCUSP = Low Cost Upper Stage Propulsion / Fully 3D Printed Multi-metallic combustion chamber

- Both extensions fabricated using the same tooling

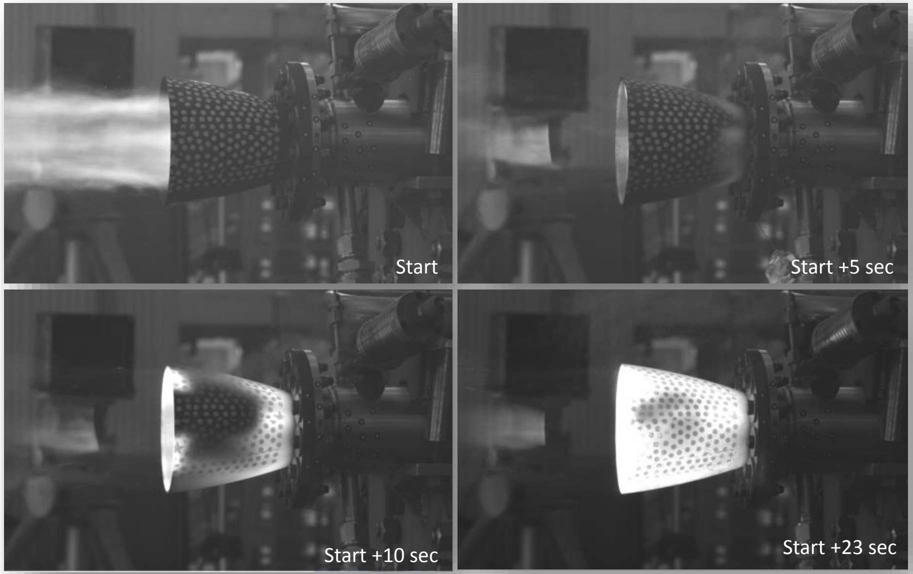
C-C Subelement and Coupon Testing

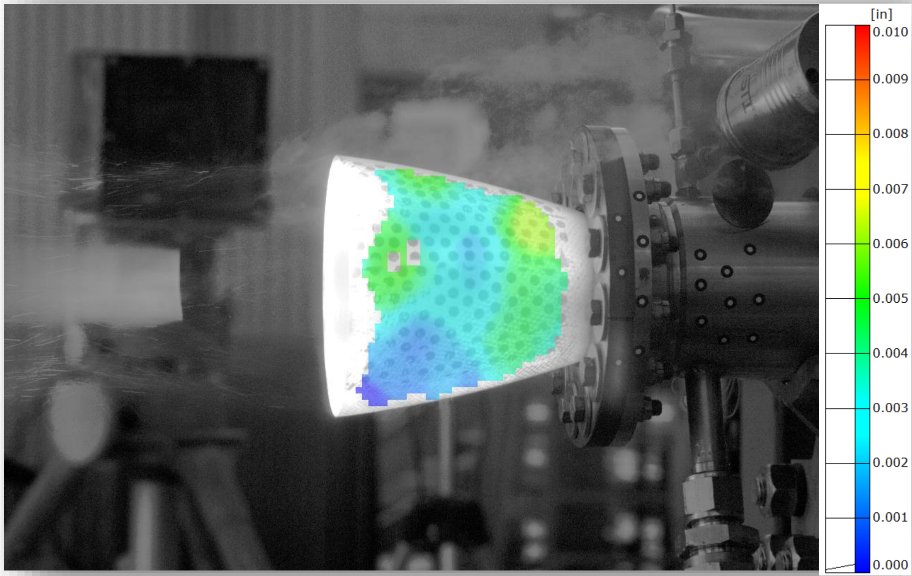
- **Tag-end rings sectioned from 35K demonstrator extensions**
  - Developed NDE techniques for C-C extensions
  - Coupon material testing (axial compression, interlaminar tension, hoop thermal expansion)
  - Hydrostatic loading of conical ring full diameter sections



Digital Image Correlation Support C-C Development

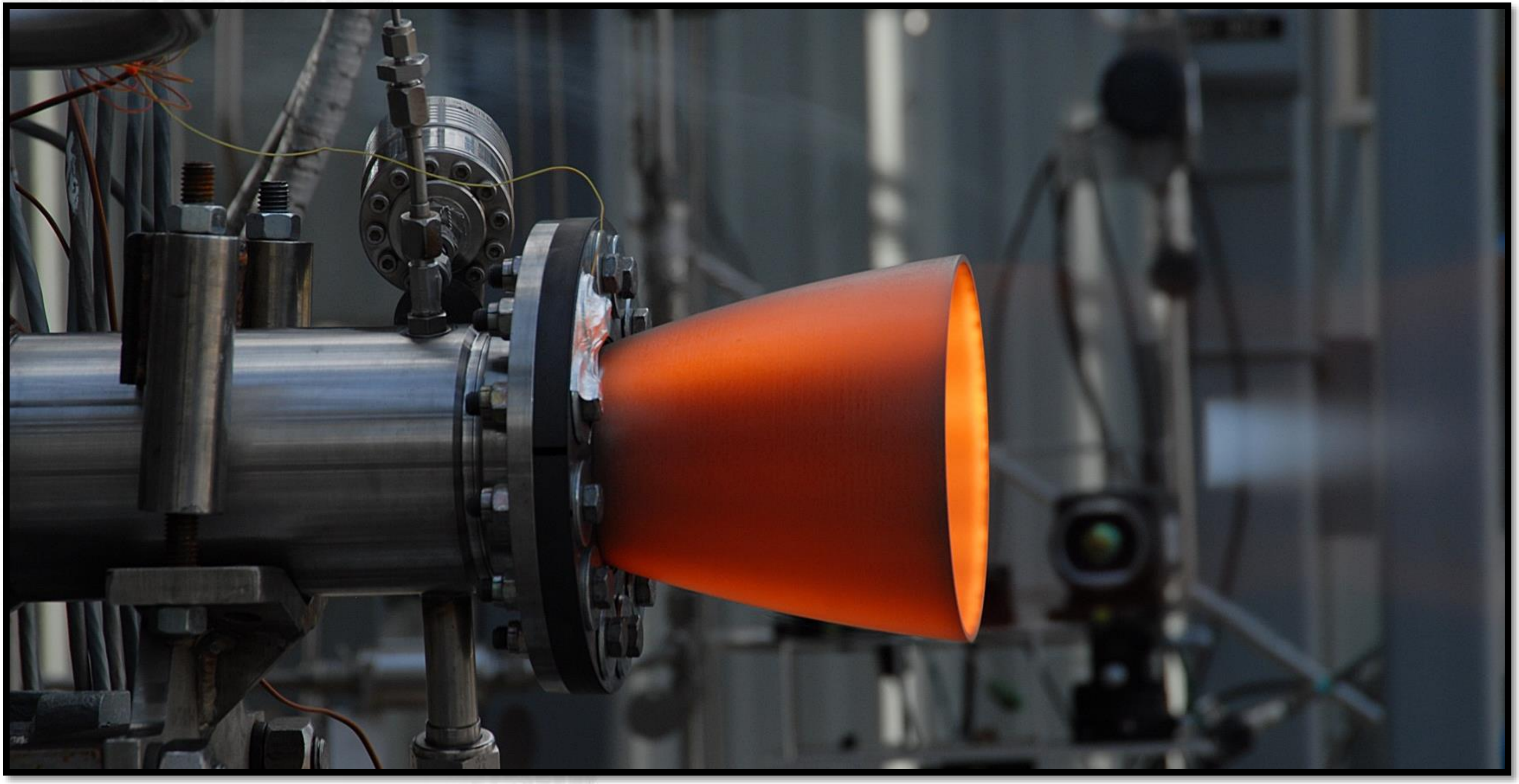
- Optical non-contact measurement development supporting C-C development
  - Using digital image correlation (DIC) to obtain full field surface strains and displacements
- Elevated temperatures during hot-fire testing using visible wavelength (DIC) caused issues during transients
  - Evaluating alternate DIC techniques such as UV-DIC
- DIC techniques have been proven during full-scale lab testing





Conclusions and Future Work

- **NASA and its commercial space partners are interested in advancing a domestic commercial supply chain for Carbon-Carbon Nozzle Extensions (CCNE's).**
- **MSFC is interested in evaluating materials appropriate for cryogenic upper stage engines and obtaining preliminary hot-fire test data in relevant environments.**
- **C-C nozzle extension efforts have proceeded primarily through the following:**
  - Small business contracts investigating: attachment concepts, material systems, etc.
  - MSFC in-house technology development projects:
    - C-C material systems, databases, advancement of technology and material readiness levels (TRL, MRL), geometry effects on properties for flat vs. complex shapes, etc.
    - Materials screening with 1.2K-lb_f LOX/GH2 thruster to obtain preliminary hot-fire test data.
      - **Completed testing on variety of materials from C-CAT and Orbital ATK.**
    - Moderate-size demos via 35K-lb_f LOX/LH2 engine – low-budget feasibility assessments.
- **Extended duration subscale testing has demonstrated extension and coating technology**
  - C-CAT PAN ACC-6 w/ SiC Conversion Coating = 2,050 sec hot-fire
  - Orbital ATK Tape Wrap w / COIC Hf-based filler = 720 sec hot-fire
- **NASA MSFC to complete testing of 35k-lb_f truncated extensions on 3D printed copper chamber in Fall-2017**



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