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/\(\text{GH}_2\) small thruster testing
- Moderate-scale demonstration via 35K-lb\(_f\) LOX/LH2 chamber to evaluate material feasibility
- Component and coupon level material testing
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
- $P_c = 750 \text{ psig}$
- 1,200 lb$_f$ thrust
- Duration up to 180 sec
- Additive manufactured (AM) GRCop-84 liner

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

<table>
<thead>
<tr>
<th>Base Material</th>
<th>Anti-Oxidation Protection</th>
<th>Accumulated Duration</th>
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<tbody>
<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>Bare</td>
<td>10</td>
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<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>COIC-SiC, No Filler</td>
<td>90</td>
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<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>PPI ZrB2+SiC, APS</td>
<td>30</td>
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<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>Exothermics Si-Partial SiC</td>
<td>155</td>
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<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>PPI MoSi2-based, VPS</td>
<td>30</td>
</tr>
<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>COIC-SiC + Hf-based Filler</td>
<td>720</td>
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<tr>
<td>OATK TW Rapid Densification 3 Cycles</td>
<td>COIC-SiC + Zr-based Filler</td>
<td>480</td>
</tr>
<tr>
<td>C-CAT 40 ACC-4</td>
<td>Bare</td>
<td>240</td>
</tr>
<tr>
<td>C-CAT 40 ACC-6</td>
<td>SiC Conversion</td>
<td>2050</td>
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<tr>
<td>C-CAT EMCC ACC-6</td>
<td>None, SiC-enhanced resin EMCC</td>
<td>10</td>
</tr>
<tr>
<td>C-CAT EMCC ACC-6</td>
<td>ZrB2/HfC enhanced matrix EMCC</td>
<td>64</td>
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</tbody>
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### C-CAT Extension Test, ZrB2/HfC EMCC
Video of Hot Fire Testing

Carbon-Carbon Hot-fire Testing at NASA MSFC
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

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-lbf Technology Demonstrator

Polyacrylonitrile- (PAN-) based C-C
- T-300 3K fiber, with heat treatment
  - ACC-6 condition
  - Silicon carbide (SiC) coating

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

Both extensions fabricated using the same tooling

LCUSP = Low Cost Upper Stage Propulsion / Fully 3D Printed Multi-metallic combustion chamber
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-lbf LOX/GH2 thruster to obtain preliminary hot-fire test data.
      - Completed testing on variety of materials from C-CAT and Orbital ATK.
  - 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-lbf truncated extensions on 3D printed copper chamber in Fall-2017
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