National Aeronautics and Space Administration

Space Technology Mission Directorate

Game Changing Development Program — RAMPT

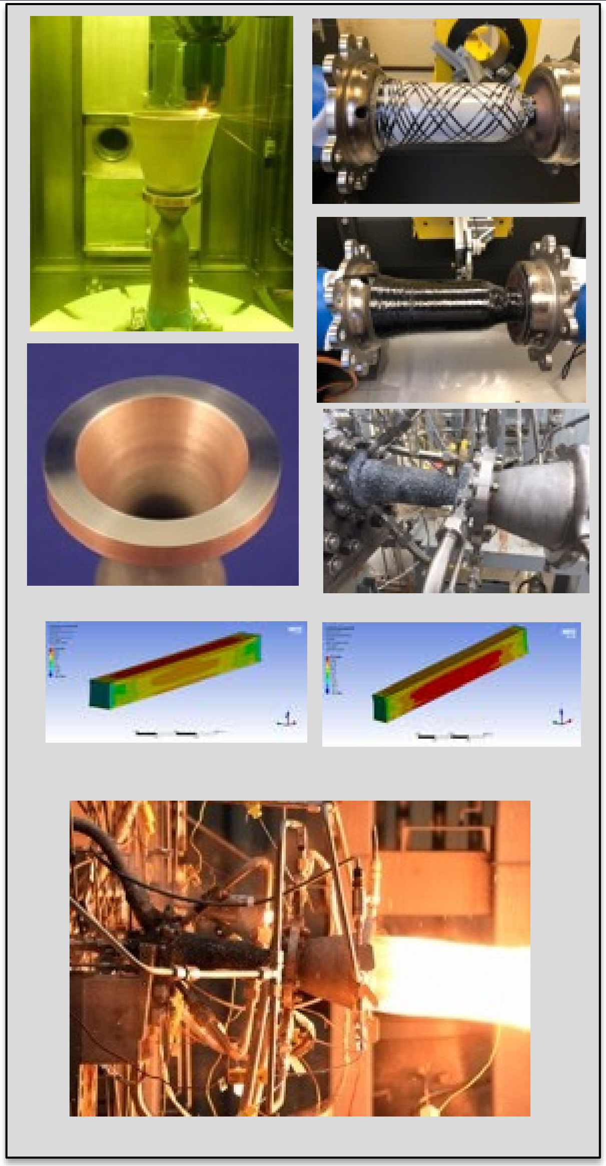
John Fikes | FY19 Annual Review | September 24, 2019

RAMPT Technology Overview

- Technology Goal
  - The RAMPT project will develop and advance large scale and light-weight regeneratively-cooled liquid rocket engine components utilizing multi-metallic freeform manufacturing and composite overwrap techniques as well as analysis capabilities required to implement them to reduce design and fabrication cycles. RAMPT will reduce design, fabrication, assembly schedules while allowing for reduced parts, increased reliability, significant weight reduction and create a healthy American supply chain.

- Technical Capabilities
  - Directed Energy Deposition (DED) freeform blown powder nozzle
  - Composite overwrap structural jacket
  - Bimetallic radial deposition for manifolds
  - Modeling and analysis tools for additive and regeneratively-cooled design.

- Exploration & Science Impact
  - Addresses longest lead, highest cost and heaviest component in engine.
  - Applicable to Lunar Lander Engine, Booster Engines, Upper Stage Engines, and NTP Technology.
  - Public-private partnerships with specialty industry vendors, government partners, Commercial Crew, and infusion into commercial space companies and manufacturers.



RAMPT
Mission Infusion & Partnerships

- Contributing partners and/or stakeholders
  - Public-private partnerships with Auburn University and specialty industry vendors developed under RAMPT project contract.
  - Synergy with SLS Engine Office.
- Infusion/transition plan
  - NASA Projects (SLS, Landers, NTP, Gateway)
  - RAMPT impacts all phases of the engine Thrust Chamber Assembly (TCA) life cycle by reducing design, fabrication, and assembly schedules; allowing for reduced parts, increased reliability, weight reduction and developing a healthy American supply chain.
  - Public-private partnerships with specialty manufacturing vendors, government partners, Commercial Crew, and infusion into commercial space companies and manufacturers.

RAMPT Technology Goals & Project Objectives

Technology Goals	
Goal #1	Develop additive and advanced manufacturing methods and design processes that enable new regeneratively-cooled thrust chamber assembly technology.
Goal #2	Identify and optimize additive manufacturing design and fabrication processes that lead to reduced production lead times and analysis life cycle for large scale thrust chamber assemblies.
Goal #3	Engage manufacturing community organizations in the development effort and facilitate infusion of technology into the commercial industry.

Project Objectives	
Objective 1	Freeform deposition additive manufacturing techniques to fabricate an integrated regeneratively-cooled channel wall nozzle structure.
Objective 2	Composite overwrap techniques to significantly reduce weight and provide structural capability for a large Thrust Chamber Assembly (TCA).
Objective 3	Bimetallic and Multi-metallic additive manufacturing and deposition techniques, including copper-alloy to superalloy transitions to optimize material performance.
Objective 4	Advance modeling and simulations of large-scale deposition techniques to obtain optimal property predictions, material designs, and develop “smart” tool-paths to reduce distortion and provide acceptable components.
Objective 5	Develop an integrated regen-cooled combustion chamber and nozzle design tool to significantly reduce design cycles and take full advantage of additive technologies.

RAMPT Performance

Key Performance Parameters				
Performance Parameter	**State of the Art**	**Threshold Value**	**Project Goal**	**Estimated Current Value**
Composite Overwrap Weight (%)	Nickel alloy clad	<75	<50	**<67 [1]**
Freeform Deposition Strength/Weight (%) [2]	Bolt or welded flanges	>50	100	SOA
Bimetallic Deposition Thrust Class (lbf) [3]	Inco 625 to Copper.	>1200	25,000	SOA
Design Cycle Time (%)	100	<75	<60	**<85 [4]**

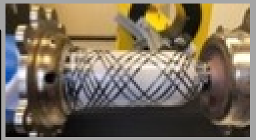
Notes:

1) Demonstrated by design for 1.2k thrust chamber assembly (sub-scale)
2) Hybrid deposition of integrally built axial joint chamber technology
3) Demonstrate bi-metallic have mechanical properties sufficient for thrust class representative geometry
4) Completed design of 1.2K and 7K chambers; validated analysis capabilities with empirical data hot fire test campaign

RAMPT Performance
Progress Toward KPP Goals

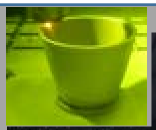
Composite Overwrap Weight Reduction

- ✓ Demonstrated 1.2K subscale overwrap
- ✓ Completed hot-fire testing
- ✓ Data showed 33% weight reduction on identical chamber


Large Scale Direct Energy Deposition (DED)

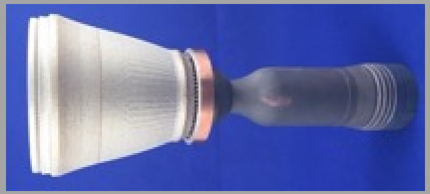
- ✓ Trials of integral channel nozzles and hot-fire testing for performance
- ✓ Developing NASA HR-1 material and process development in-work
- ✓ Demonstrated large scale 44”dia. (non-integral channels)





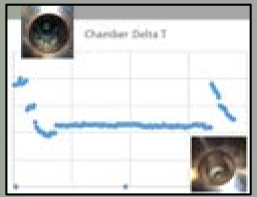
Bimetallic Joint

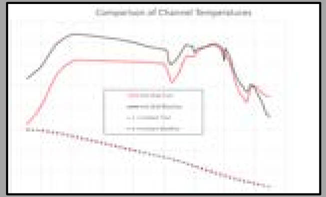
- ✓ Completed trials of bimetallic axial joint
- ✓ Completed initial characterization

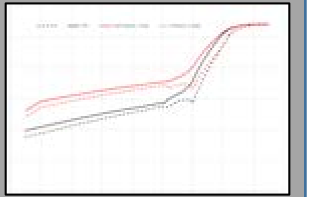


Design Tool Improvement

- ✓ Completed hot-fire testing to anchor models and validate new tools
- ✓ Demonstrated reduction in process by 15%
- ✓ Published data and presenting to propulsion community (AIAA, JANNAF)







RAMPT Technical Assessment

Technical Elements	TRL			AD[2]	
	Entry	Current[1]	Exit	Entry	Current
Thermal cycling resistance of composite overwrap - differential CTE	2	**3**	6	8	8
High temperature durability/performance of composite overwrap	2	**3**	6	8	8
Interfacial bonding of composite to thrust chamber – surface prep, adhesive (Table this as baseline is unbonded 8/13/2019)	2	**3**	6	8	8
Minimal feature size of bimetallic region for joining nozzle to chamber is unknown	2	**3**	6	8	8
Joint process development	2	2	6	8	8
Differences between axial and radial interfaces – applying lessons learned from radial joints to fabrication and design of axial joints/interfaces - Fabrication of axial joints/interfaces is less developed technology	2	**3**	6	8	8

[1]Date of last TA was 9/5/2019

RAMPT Technical Assessment

Technical Elements	TRL			AD²	
	Entry	Current[1]	Exit	Entry	Current
Effects of temperature on materials parameters are not well characterized – processes for measuring some of these parameters have not been used with RAMPT materials	2	2	3	6	6
Unknown how physics models will scale with size (layers) and from coupon to component – could affect accuracy of models	2	**3**	3	7	7
Calibration and validation of models – in situ and external sensors	2	**3**	3	8	8

Date of last TA was 9/5/2019

RAMPT Technical Assessment

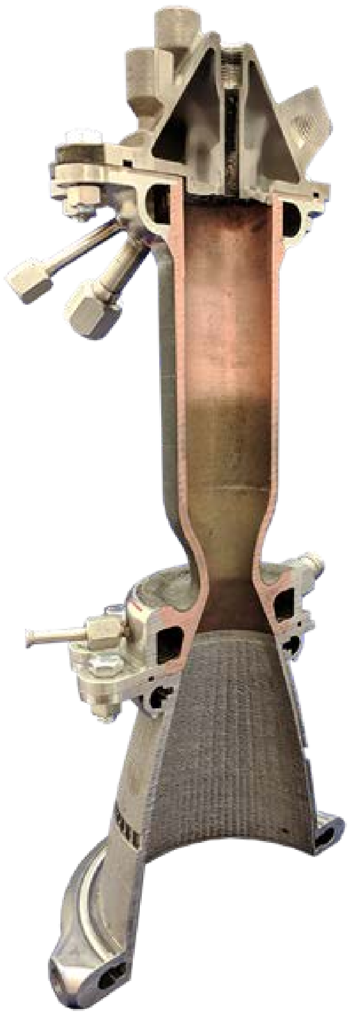
Technical Elements	MRL			AD[2]	
	Entry	Current[1]	Exit	Entry	Current
DED ability to get to wall thicknesses within 20 thousandths or less	2	2	6	8	8
Powder removal from small coolant channels	2	**3**	6	8	8
Mechanical properties of DED vs. conventional fabrication – effects of processing anomalies on material properties	2	**3**	6	8	7
Processing scale-up – more opportunities for voids, mfg flaws, residual stress build-ups	2	2	6	8	8
Residual stresses (Bimetallic)	2	2	6	8	8

Date of last TA was 9/5/2019

RAMPT Technical Approach

- Project plans to accomplish objectives
  - Develop and validate significantly reduced mass thrust chamber assembly (TCA) technology using integrated multi-material manufacturing techniques and demonstrate through hot-fire testing.
  - Develop, characterize, and integrate manufacturing and design processes relative to regeneratively-cooled thrust chamber assembly including:
    - Directed Energy Deposition (DED) freeform blown powder nozzle
    - Composite overwrap structural jacket
    - Bimetallic radial deposition for manifolds
    - Modeling and analysis tools for additive and regeneratively-cooled design.
  - Complete process development and subscale testing to obtain early manufacturing process evaluations of concepts.
  - Focus manufacturing process and material characterization development leading towards scale up of the integrated thrust chamber assembly.
  - Complete large-scale manufacturing of the integrated thrust chamber assembly hardware.
  - Perform full scale hot-fire testing of TCA.
  - Partner through public-private partnerships with commercial companies to complete manufacturing process developments to enable a long-term supply chain available to government and commercial rocket industry.

RAMPT Public-Private Partnership with Auburn University

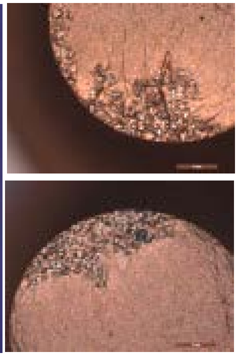
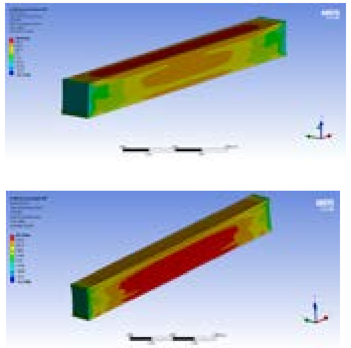


- Awarded contract with Auburn University for the Additive Manufacturing Public/Private Partnership on March 25, 2019.
- Auburn University has RPM Innovations under contract (July 29, 2019) for the Directed Energy Deposition (DED) blown powder technology development (public-private partnership with 25% cost share).

Auburn University (AU) Public-Private Partnership Tasks under RAMPT Project

Task	Description
1	Composite Overwrap Additive TCA development
2	Freeform Directed Energy Deposition (DED) nozzle development
3	Bimetallic additive joint development
4	Assist in material characterization
5	STMD Community College Pilot for Additive Manufacturing



Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Chamber Design Tool Code for Additive Subscale Design

Project Manager: John Fikes, MSFC

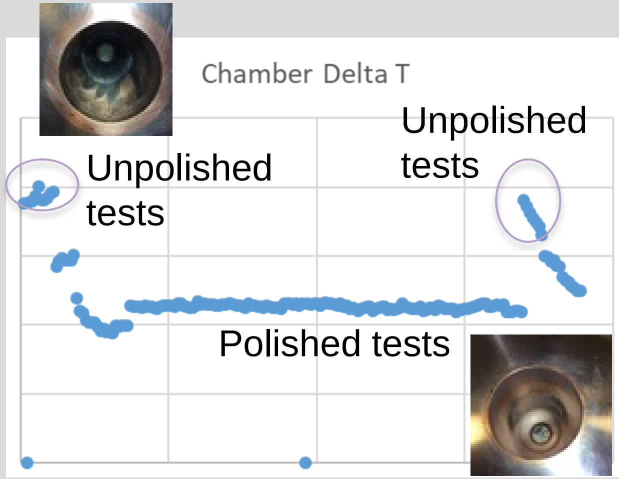
Objective: First iteration of chamber design tool to be developed and used to accommodate and accelerate additive subscale design.

Date	
Scheduled	6/28/2019
Actual	7/1/2019

Key Accomplishment: The Chamber Design Tool was evaluated by combustion devices experts and data on actively cooled additive parts in a relevant environment was collected in subscale testing.

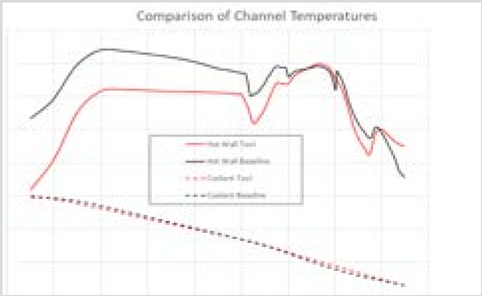
The first iteration of the Chamber Design Tool was received from the partner May 2019. Senior experts in the liquid engines components development and technology branch at MSFC evaluated the tool and compared its analysis flow to our existing processes for both conventional and additively manufactured designs. Initial features that speed processes include combining chamber geometry, coolant channel geometry, chemical equilibrium and preliminary heat transfer analysis into one tool with dedicated inputs and outputs. Also, coolant pressure drop is more representative of additive channels as shown in LCUSP test data (and does not require empirical corrections). New tool results also indicate more favorable wall temperatures in additive hardware – giving an area for future margin testing.

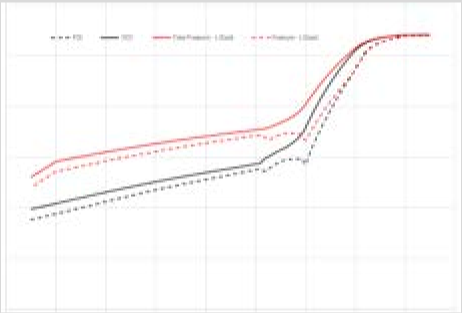
Heat transfer data on subscale additive chambers in the polished and unpolished states was also collected in RAMPT testing and in other testing utilizing RAMPT derived GRCop-42 printed chambers. This data will be used to further refine the design tool.



Subscale data collected for polished and unpolished conditions shows increase in heat transfer (shown as coolant delta temperature) relative to polished tests.

Also shown is the gradual reduction in heat transfer due to deposits from the ignition hypergolic propellant as its products bind to the rough wall.





New tool output in red vs. prior process in black showing the reduced pressure drop and more favorable hot wall temperatures

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Process Development for Freeform Nozzle onto Copper Chamber (Subscale)

Project Manager: John Fikes, MSFC

Objective: Demonstrate Process Development for Freeform Nozzle onto Copper Chamber (Subscale) showing relevant geometries and materials (hydrogen embrittlement resistant nozzle alloy onto copper based alloy combustion chamber)

Date	
Scheduled	8/23/2019
Actual	6/29/2019

Key Accomplishment: Freeform nozzle onto copper chamber process development was carried out and 1.2k (pounds thrust) scale manufacturing demonstrators were produced at RPM Innovations, a vendor selected for public-private partnership.

The bimetallic interface remained intact after full build of the nozzle and after stress-relief processing indicating a qualitatively good joint. The feature sizes for coolant channels and coolant fabrication processes for coolant inlet and outlet features have been successfully developed and demonstrated. One lesson learned was the need to include an inner wall contour step for initiating the nozzle. This manufacturing process has already flowed into designs for the next articles.

Planned next steps include hot wall finishing to ~0.020" thickness and mechanical testing of axial bimetallic interfaces utilizing this process.

Two initial axial bimetallic manufacturing demonstrators fabricated (shown at right).
Both were built using JBK-75 powder (HMI) as HR-1 powder was unavailable at the time of fabrication.
Both parts were deposited onto IN625 plated GRCop-84 chambers.

- Shorter build was the partial build for development.
- Second build was the full build.

Parts built to near net shape.

Job 190069 Powder Information	
Powder Type	HMI JBK75
Lot #	75A1
Powder Use	1x Used

Photos Courtesy RPM Innovations

Technology Advancement: Initial process at the 1.2k (pounds thrust) scale has produced an intact joint indicating residual stresses from processing at this scale are likely able to be mitigated, thus advancing MRL in this category.

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Composite Overwrap Process Development (Subscale)

Project Manager: John Fikes, MSFC

Objective: **Demonstrate composite overwrap process development through production of subscale test articles with geometries and materials relevant to combustion devices.**

Date	
Scheduled	9/20/2019
Actual	9/18/2019

Key Accomplishment: **Composite Overwrap process development was carried out on a PBF GRCop-84 1.2k liner unit printed to the same design model as will used for hotfire testing in the 1.2k coupled test campaign. The liners for the test units are undergoing DED nozzle deposition.**

Successive dry winding trials were completed in order to ensure adequate laydown over the axial load takeout features (ribs) and through the chamber convergence. Wet winding and curing of the composite overwrap demonstrated the successfully process and hotfire test will validate load containment in these regions.

Planned next steps include 1) overwrap of at least one hotfire testable unit while specialty vendors are evaluated and brought into public-private partnership for future builds, 2) process development with the recently selected higher temperature capability M65 resin, and 3) winding trials on 7k COMET sized hardware and 35k size hardware

Description of process

1. Polish & apply release agent to liner
2. Apply 1st helical layer
3. Apply 1st hoop layer (2-plys)
4. Apply 2nd helical layer
5. Apply 2nd hoop layer (2-plys)
6. Trim overwrap from injector side of liner
7. Cure resin

Wind Details	
Helical Wind Angle	+/-34°
Fiber	PV42
Resin	828/W

Technology Advancement: **Automated winding methods and geometries that conform to the specialized features and geometries in RAMPT thrust chambers have been successfully demonstrated, thus advancing MRL in this category.**

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Validated Thermal Analysis (IN625)

Objective: Define validated thermal and fluid-thermal models for the SLM process given measured melt pool dimensions.

Date	
Scheduled	8/30/2019
Work complete	8/28/2019
Written Report	9/27/2019

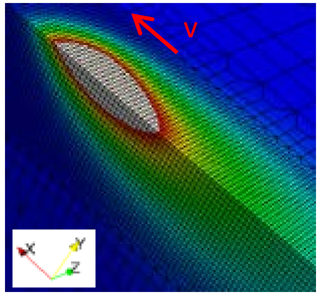
Key Accomplishment/ Deliverable/Milestone:
Developed an optimization approach to define SLM thermal model inputs to correlate with measured melt pool dimensions which can be applied to any material system. Complete thermal model defined utilizing IN625 data from AFRL. Developed fluid-thermal model for any material system. Complete fluid-thermal model compared with IN-625 with published results.

Validation Approach:

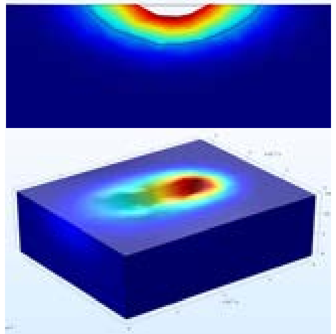
An accurate heat input distribution for the SLM thermal model is required but depends on many factors and difficult to define. The validation approach utilizes measured melt pool dimensions to characterize the heat input distribution as well as the absorptivity. Multi-fidelity thermal models are implemented to efficiently reach the optimal solution.

Completed Model for IN625:

A volumetric ellipsoidal heat source[1] and absorptivity have been defined for the SLM IN625 thermal analysis using measured melt pool dimensions from AFRL[2]. The thermal model provides the temperature history and melt pool dimensions during the process for a given set of process parameters, which is required for residual stress predictions. The fluid-thermal model predicts melt-pool shape due to evaporation.



Analysis temperature field with the melt pool region depicted in white


Fluid-thermal model with the melt pool cross profile

[1] J Goldak. A new finite element model for welding heat sources. Metall. Trans. B 15(6):299-305. 1984.
[2] AFRL AM Modeling Challenge Series (http)

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

Mechanical Testing of Axial Bimetallic Interface

Project Manager: John Fikes, MSFC

Objective: Evaluation of Process Development for Freeform Nozzle onto Copper Chamber (Subscale): characterizing joints through phase analysis, metallography, and mechanical testing.

Date	
Scheduled	9/20/2019
Actual	9/09/2019

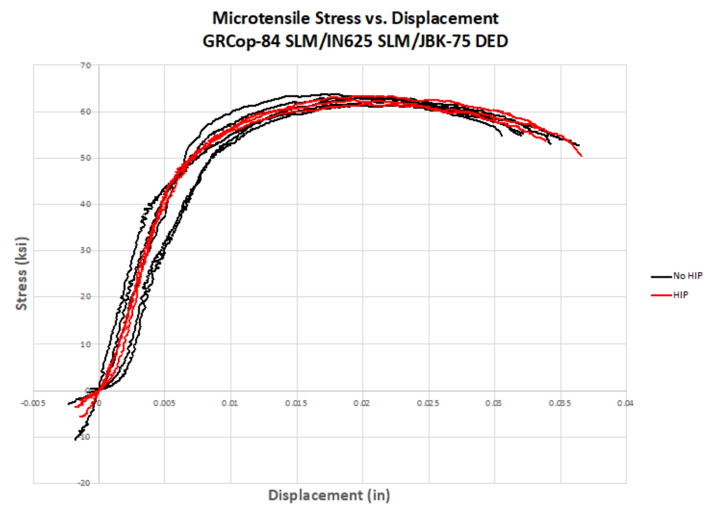
Key Accomplishment: The 1.2k (pounds thrust) scale manufacturing demonstrators were sectioned for phase analysis, metallography, and mechanical testing. One assembly was stress relieved, the other assembly was stress relieved and underwent HIP.

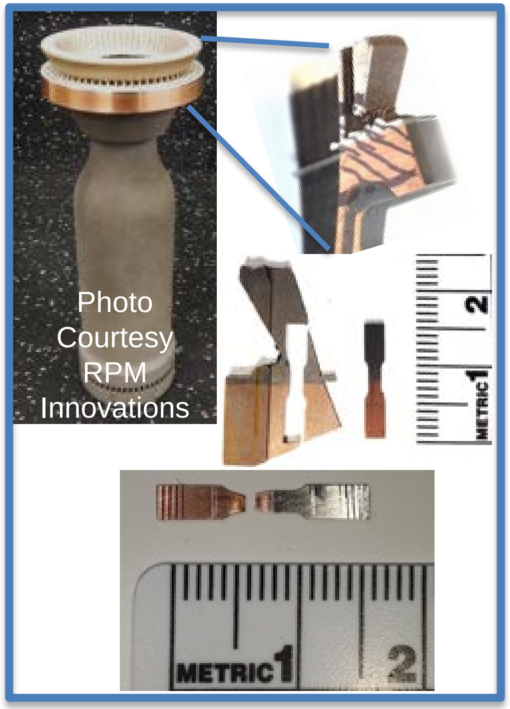
The bimetallic interface was prepared for metallography and phase analysis and machined to generate tensile specimens and extract UTS from joined material**.** Phase analysis was comparable to phase modeling results, and **all samples tested failed as desired in the GRCop-84 with an average UTS of 63ksi (430MPa), consistent in magnitude with wrought and AM GRCop-84. The ductile failures at consistent magnitudes suggest the tested interface exhibits a good joint and expected strength. Build quality demonstrated no voids, with well fused areas. Initial results suggest that joints will achieve desired strength, failure mode, and are compatible. HIP samples demonstrated much less scatter than stress-relieved only samples.**

Further tensile and fatigue tests at low and high temperatures as well as crack growth will be done in FY20 to fully characterize the HR-1 to GRCop-42 joint, with appropriate interlayer material as necessary.

The interface of the initial axial bimetallic manufacturing demonstrator fabricated (shown at right) was subjected to mechanical testing.

DED JBK-75 nozzle was deposited onto SLM GRCop-84 chambers with an interlayer of SLM IN625. Parts built to near net shape.



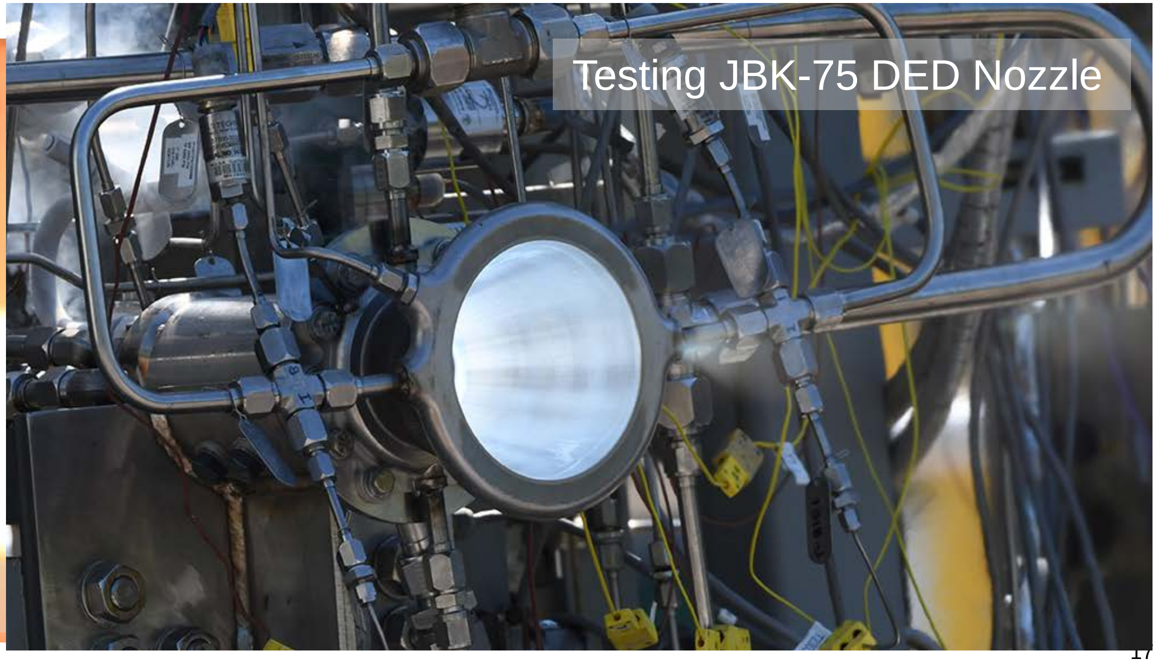


Technology Advancement: Initial process at the 1.2k (pounds thrust) scale has produced an intact joint of desired strength, failure mode, and compatibility, thus advancing MRL in this category. Initial post-processing heat treatment has shown promising tensile results.

Hot-fire Testing Demonstrated Feasibility
Blown Powder Directed Energy Deposition (DED)

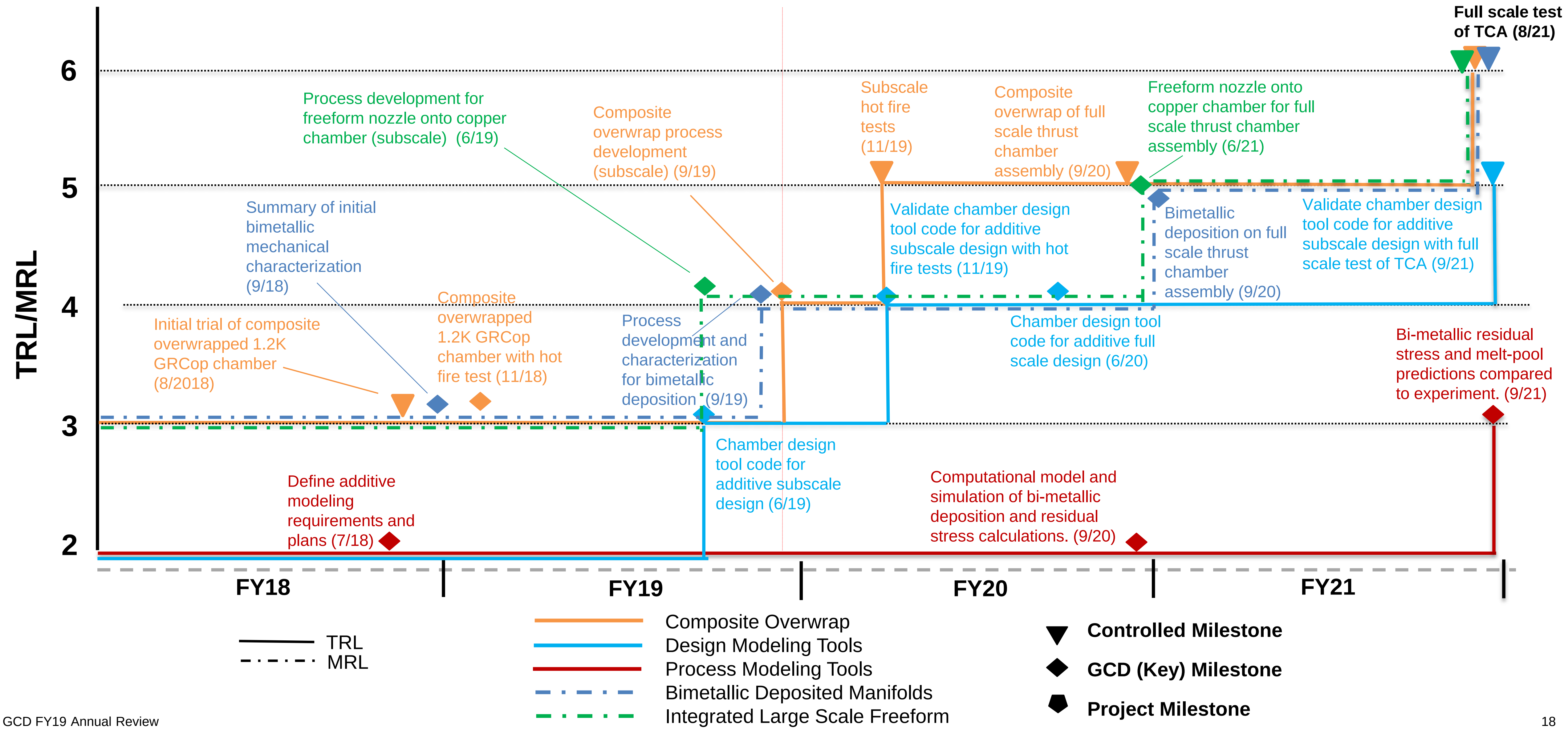
- Completed hot-fire testing at MSFC Test Stand 115
  - Various test series conducted including LOX/GH2 and LOX/RP-1
  - Conducted December 2018 through June 2019
- Water cooling initially to characterize, followed by full regen-cooling
  - Durations up to 60 sec in LOX/RP-1
  - Durations up to 180 sec in LOX/GH2
- Additively manufactured GRCop-84 and GRCop-42 combustion chambers and additively manufactured injectors

Testing Inconel 625 DED Nozzle

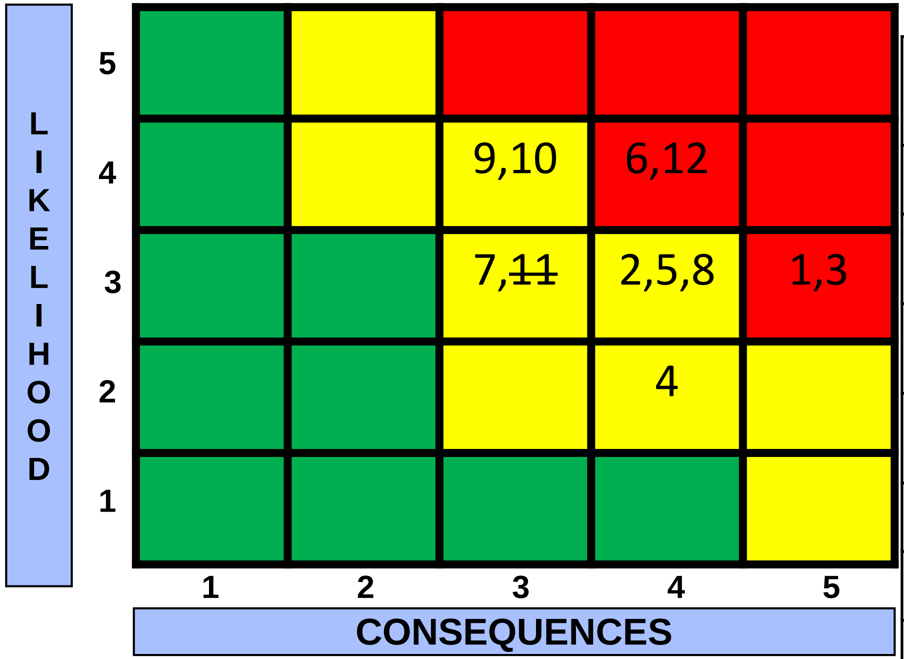


Testing JBK-75 DED Nozzle

RAMPT
IMS/TRL Alignment



Technical Risk Summary



ID	Trend	Approach/ Affinity	Risk Title
1	⇨	M/T,Sc	Localized high residual stresses in bimetallic joints
2	⇨	M/T,P	Nozzle geometries cause localized high temperature regions
3	⇩	M/T,P	Polymer Matrix Composites Not Suitable for Application
4	⇩	M/Sc	Limited production capacity of GRCop-84 chambers
5	⇩	M/Sc	Limited Production Capacity of New Technologies
6	⇨	M/T,C,Sc	Failures during large scale freeform deposition
7	⇩	M/C,Sc	Powder removal difficult in parts with small channels
8	⇨	W/C,Sc,P	Full scale chamber/nozzle availability for integration
9	⇨	W/Sc	Modeling Requires Material Parameter Curves
10	⇨	W/Sc	Design Suite Requires Empirical Data from Newly Fabricated Hardware
11	⇧	W/Sc	Manufacturing or Testing Availability *CLOSED*
12	⇧	**W/Sc**	**Test Stand Conflicts**

Criticality
- High
- Med
- Low

L x C Trend
- ⇩ Decreasing (Improving)
- ⇧ Increasing (Worsening)
- ⇨ Unchanged
- ☐ New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Last updated: September 5, 2019

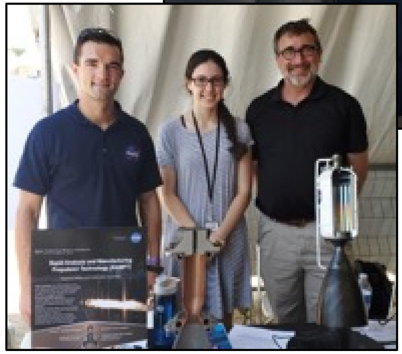
EPO Summary Chart

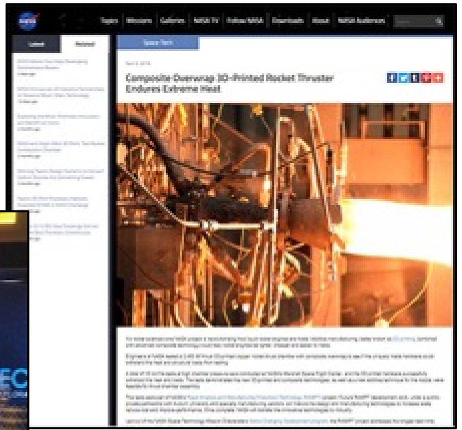
➢ Summary of Education and Public Outreach

- 4/18/2019 - NASA Technology Day in Montgomery, AL
- 5/23/2019 - Space Technology Day at Florida Tech
- 6/7/2019 - NASA Tech Day on the Hill, Washington D.C.
- 6/24-27/2019 - NSMMS - National Space & Missile Materials Symposium
- 7/18-20/2019 - Apollo 50th Anniversary on the Mall, Washington D.C.

➢ Significant Media Coverage

- 4/5/2019 NASA Image Feature: Composite Overwrap 3D-Printed Rocket Thruster Endures Extreme Heat
- 8/27/2019 - NASA Tumblr website: National Composites week





Annual Summary

- Project received concurrence on Project Plan from GCD Program Office for final signatures.
- Completed the RAMPT API Milestone **"Process Development for Freeform Nozzle onto Copper Chamber (Subscale)"** on June 29, 2019.
- Awarded contract with Auburn University for the Additive Manufacturing Public/Private Partnership on March 25, 2019.
- Auburn University has RPM Innovations under contract (July 29, 2019) for the Directed Energy Deposition (DED) blown powder technology development (public-private partnership with 25% cost share).
- RAMPT team has chosen NASA-developed NASA HR-1 (Fe-Ni-Cr-Co-Ti) as the baseline material for the channel-cooled nozzle using blown powder directed energy deposition (DED) process. The HR-1 material is hydrogen resistant and provides high strength.
- Completed initial process development and materials characterization of NASA HR-1.
- Completed hot-fire testing of RAMPT 1.2K lb_f composite overwrap combustion chambers on February 21, 2019. This demonstrated feasibility of the core key technology areas for RAMPT. Total of 18 tests were completed on various composite overwrap chambers from GRC, Langley, and MSFC.
- Held successful TAPR review on September 12, 2019 with the GCD Program Office.
- Presented initial RAMPT results to industry through AIAA and meetings with commercial space for infusion.


BACKUP

Project Assessment Summary

Project	Performance				Comments
	C	S	T	P	
Mid Year	Green	Yellow	Green	Yellow	Schedule is yellow due to the award of the Auburn Public/Private Partnership contract award being delayed. The proposal was received from Auburn on December 14, 2018 and a NASA technical evaluation of the proposal was delayed due to the furlough. The NASA technical evaluation was completed on February 8, 2019. The contract was sent to Auburn University for review and signature and contract award occurred on March 26, 2019. Programmatic is yellow due to the award of the Auburn Public/Private Partnership contract award being delayed. This increases risk on meeting funding metrics and FY19 milestones. Since the contract with Auburn University has been awarded, the project will work with Auburn to assess the impacts and baseline future milestone dates.
Annual	Green	Green	Green	Green	Cost is green. Project received FY19 procurement forward funding for FY20 that is being placed on the Auburn University public-private partnership contract. Programmatic is green due to the award of the Auburn Public/Private Partnership contract. Auburn University has RPM Innovations under contract (July 29, 2019) for the Directed Energy Deposition (DED) blown powder technology development. Schedule is green due to the award of the Auburn Public/Private Partnership contract and the project receiving concurrence on Project Plan from GCD Program Office for final signatures. Technical is green. Successfully completed the Technical Assessment Periodic Review (TAPR). Completed the RAMPT API Milestone **"Process Development for Freeform Nozzle onto Copper Chamber (Subscale)"** on June 29, 2019 and met all other FY19 technical milestones.

EPO Summary Chart

- Conferences attended

Conference Name	Papers/Posters/Panel Discussions
TMS -Annual Meeting for Minerals, Metals, Materials Society	1 Paper
NASA & NCAME Workshop: Composites Materials and Manufacturing Technologies for Space Applications	
AIAA Propulsion & Energy	4 Papers
International Astronautical Congress (IAC) *October 2019*	

- Academic involvement

# of Students	Education Level	School Name
1	PhD Graduate Candidate	Penn State University
1	Masters	Case Western Reserve University
1	Masters	University of Alabama at Huntsville (EPSCoR)
1	Masters	University of Texas at El Paso
1	Undergraduate	Princeton University
1	Undergraduate	South Dakota School of Mines
1	Undergraduate	University of Puerto Rico, Mayaguez

1. Localized high residual stresses in bimetallic joints (Evans)

1

Trend

⇨

Criticality

H

Current LxC
3x5

Affinity Group
T/Sc

Planned Closure
TBD

Open Date
5/17/18

- **Risk Statement**: Given that joints between dissimilar metals are subject to cracking due to deposition technique/heat load/CTE mismatch/differential cooling/solidification rates and due to specific geometries that create localized high residual stresses, there is a possibility that fabrication technique-induced cracking will limit the achievable bond strength, thereby causing a risk to meeting the KPP of testing bimetallic joints at thrust classes.
- **Approach**: Mitigate
- **Context**: EBF^3 direct bimetallic deposition was performed successfully on LCUSP, allowing high stress fuel blowdowns and hot fire tests on a full scale test article. Work with direct bimetallic deposition, including in the LCUSP project, has shown the potential for forming localized hot-cracking and high residual stresses, and these results are also geometry dependent. Work in RAMPT will further mitigate these side effects.
- **Status**: 09/05/2019 – No status change.

  08/22/2019 – Preliminary results suggest sufficient bond between GRCop84-IN625-JBK75: successful fabrication and stress relief of liner/nozzle assembly. Samples are in progress for mechanical testing. Samples (6/10) are still in progress.

  06/10/2019 – Samples in progress to experimentally investigate the interface with new materials (interlayers, direct bond, variety of fabrication techniques).

  03/21/2019 – No status change.

  02/28/2019 – Have started modeling to better understand the interface. Investigating if an interlayer will be needed. Planned closure date pending Auburn contract.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Evaluating metallurgical causes for cracking observed in recent bimetallic work and new experimental interface samples in order to determine alternate jacket alloys or to eliminate the formation of secondary phases that can lead to cracking.		10/01/2018			3x5
2. Phase 1 of solicitation includes requirements for samples. GRC to characterize and evaluate for phase 2 awards					3x5
3. Geometry trials with geometries representative of test article geometries.					2x5
4. Perform deposition on specimens with high fidelity test article geometries before proceeding to test article.					1x5

3. Polymer Matrix Composites Not Suitable for Application (Pelham)

3

Trend

Criticality

H

Current LxC
3x5

Affinity Group
T/P

Planned Closure
TBD

Open Date
5/17/18

- **Risk Statement:** Given the extreme environments experienced by the chamber, a suitable fiber-reinforced polymeric material may not adequately transfer the necessary loads. (i.e. properties degrade over the temp/load range).
- **Approach**: Mitigate
- **Context**: Composite materials will have a significant CTE mismatch vs the metallic substrate, the degradation of bond line due to thermal cycling from -300F for cryogenic fuels or ambient for kerosene to 500F under hot fire conditions could initiate cracking and thus the loss of load transfer.
- **Status**: 09/05/2019 – No status change.

  08/22/2019 – Updated LxC from a 4x5 to a 3x5 resulting in a downward trend. Have acquired a high temperature, toughened BMI resin that can go to high temperatures. Not using an epoxy resin for 7k hotfire.

  06/10/2019 – Evaluation continuing for 7k hotfire material.

  03/21/2019 – No status change.

  02/28/2019 – Selected initial material. May have to choose another material for hydrogen work. Sub-scale hot fire tests performed with kerosene. Planned closure date pending Auburn contract.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Perform robust material survey and substantiate with coupon level testing to demonstrate adequate materials and processes.		10/01/2018			4x5
2. Initial 1.2k tests conducted with kerosene.		11/15/2018		02/21/2019	4x5
3. Vendors submitting to the RFQ will be rated on their plans for addressing this risk area.					3x5
4. Cryotest with 4k methane.					2x5
5. In-house material survey and coupon level testing results will be transferred to industry/RFQ awardees.					2x5
6. Cryotest with hydrogen					1x5

6. Failures during large scale freeform deposition (Protz/Gradl)

6

Trend

➡

Criticality

H

Current LxC
4x4

Affinity Group
T/C/Sc

Planned Closure
TBD

Open Date
5/17/18

- **Risk Statement:** Given that RAMPT will develop fabrication technologies and ramp up the size of articles produced over time, there is a possibility that new failures will be encountered during large scale freeform deposition, that were not observed in smaller scale development, thereby causing schedule delays as failures are investigated and recovery plans undertaken.
- **Approach**: Mitigate (limited)
- **Context**: Recent experience shows that as advanced manufacturing technologies have been scaled up, there is a potential for new challenges to be discovered.
- **Status:** 09/05/2019 – No status change.

  8/20/2019 – Feasibility in a similar material, JBK-75 demonstrated a continuous build of greater than a week without any build failure or interruptions with integral nozzle channels. Development will continue. Demonstrated builds with NASA HR-1 but not in a nozzle configuration.

  06/10/2019 – Early feasibility studies demonstrated potential for longer builds.

  03/21/2019 – No status change.

  02/28/2019 – Tested small, sub-scale blown powder nozzle on 02/21/2019. Risk of scale-up dependent on vendor experience and capabilities. Vendor selection pending on Auburn contract. Planned closure date pending Auburn contract.

  05/17/2018 - Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Include schedule margin for failed build based on past experience.					4x4
2. Include designs and schedule for trial builds of small wedges before full builds to test buildability and larger geometries.					3x4
3.					
4.					

12. Test Stand Conflicts (Protz/Gradl)

12

Trend

↑

Criticality

H

Current LxC
4x4

Affinity Group
T/C/Sc/Sa/P

Planned Closure
TBD

Open Date
5/17/18

- **Risk Statement:** Given that multiple projects may require capabilities of a single test position, there is a risk that RAMPT testing could be delayed due to test stand conflicts causing milestone slips.
- **Approach**: Watch
- **Context**: Test and schedules are subject to agency priorities. Frequent open communication ensures opportunities for testing are capitalized.
- **Status**: 9/5/19 – Updated LxC from 3x3 to 4x4. Lander and commercial testing scheduled at MSFC, which is new since the development of the risk.

  08/20/2019 – Trending upward. RAMPT team continues to work the 12 month outlook schedule with the test area. Continuing to monitor but the likelihood of being bumped for priority is increasing.

  06/10/2019 – 12-month schedule provided to test area to be integrated into test area master schedule.

  03/21/2019 – No status change.

  02/28/2019 - No status change.

  05/07/2018 - Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Proper test coordination and scheduling with the test area and teams with potentially conflicting tests.		10/01/2018			1x2
2.					1x2
3.					1x2
4.					1x2

RAMPT TAPR
Technical Challenge Assessment
Thermal cycling resistance of composite overwrap - differential CTE

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	N/A Basic f ements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Operational limits of design fully specified and documented.
Rationale		Operational environments from thermal and structural analysis and prior testing in similar cooled chambers validated in subscale component with preliminary composite overwrap designs and materials. Completed higher fidelity environment definition.	Initial chamber geometry flows from prior relevant hardware and test and has been modified for overwrap. Initial chambers (1.2 Kip decoupled) have been integrated with composite overwrap and hot-fire tested. Hot fire testing with interface temperature to 250 F successful. Modified chamber geometry successfully wrapped with preliminary composite overwrap designs and materials.		Structural and thermal modeling and 1.2k hotfire testing provide expected pressure and temperature for integrated system with composite overwrap.	Operational environments from thermal and structural analysis and prior testing in similar cooled chambers inform materials selection. Trial cylinder parts have been cycled to cryo temperatures. Hot fire testing with interface temperature to 250 F successful. Hot-fire testing on initial chambers with composite overwrap indicate chamber/composite overwrap interface functions in operational environments. Preliminary materials successfully overwrapped and hot fire tested.	Structural models of preliminary hardware are utilized to derive operational needs for new materials

2018 2019

AD2 Level 8

RAMPT TAPR
Technical Challenge Assessment
High temperature durability/performance of composite overwrap

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Operational limits of design fully specified and documented.
Rationale	Survey of materials shows advanced composites potentially capable of temperatures needed. 1.2k Testing to 250F was successful. Resin with high temperature durability identified and similar resin successfully filament wound onto chamber. Successful sub-scale hot fire tests performed on a variety of preliminary composite overwrap designs and materials	Operational environments from thermal and structural analysis and prior testing in similar cooled chambers. Completed higher fidelity environment definition. validated in subscale component with preliminary composite overwrap designs and materials					

2018 2019

AD2 Level 8

RAMPT TAPR
Technical Challenge Assessment
Minimal feature size of bimetallic region for joining nozzle to chamber is unknown – potential for large uncooled region with localized hot spots

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Operational limits of design fully specified and documented.
Rationale 2018 2019 AD2 Level 8	Preliminary trials of a variety of bimetallic interfacing techniques have been performed. Trial parts show interface region of ~0.150” axially is possible.	Operational environments from thermal and structural analysis and prior testing in similar cooled chambers suggest early trial interfaces of ~0.150” are reasonable.	Initial bolted flange chamber geometry from prior relevant hardware has been modified and tested for bimetallic joining and 1.2k coupled hardware design is complete.	Structural and thermal models of prior hardware are utilized to inform initial bimetallic interface region. CALPHAD analysis completed to examine material compatibility for optimum joint.	Structural and thermal modeling provide relevant range of expected pressure and temperature and preliminary trials of a variety of bimetallic interfacing techniques offer reasonable expected performance. 1.2k coupled and 7k COMET test requirements established.	Pull test specimen of initial trial piece indicated no major obstacles. Operational environments from thermal and structural analysis and prior testing in similar cooled chambers inform structural analysis.	

RAMPT TAPR
Technical Challenge Assessment
Differences between axial and radial interfaces – applying lessons learned from radial joints to fabrication and design of axial joints/interfaces – Fabrication of axial joints/interfaces is less developed technology

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Operational limits of design fully specified and documented.
Rationale 2018 2019 AD2 Level 8	Radial EBF3 technology joint demonstrated in LCUSP and preliminary trials in axial interfaces have been performed. Demonstrated feasibility of deposition and initial material characterization completed. Radial and axial interfaces have been prepared	Operational environments from thermal and structural analysis and prior testing in similar cooled chambers. Materials trade completed to determine necessary chamber and nozzle materials and potential intermediate alloys. Initial axial interface prepared	Initial bolted flange chamber geometry from prior relevant hardware has been modified for bimetallic joining axial interface has been fabricated. Materials trade completed to determine necessary chamber and nozzle materials and potential intermediate alloys.	Structural and thermal models of prior hardware are utilized to inform initial bimetallic interface region. CALPHAD analysis completed to examine material compatibility for optimum joint.	Structural and thermal modeling provide relevant range of expected pressure and temperature and preliminary trials of a nozzle/chamber axial interface offers reasonable expected performance. 1.2k coupled and 7k COMET test requirements established.	Pull test specimen of initial trial piece indicated no major obstacles. Operational environments from thermal and structural analysis and prior testing in similar cooled chambers inform structural analysis.	

RAMPT TAPR

Technical Challenge Assessment

Don't know how physics models will scale with size (layers) and from coupon to component – could affect accuracy of models

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Operational limits of design fully specified and documented.
Rationale 2018 2019 AD2 Level 7	ANSYS results show good agreement on NIST coupon compared to published results.	ANSYS stress predictions work on different materials if curves are known.	ANSYS stress predictions work on different materials if curves are known.	ANSYS stress prediction has been demonstrated on 3 different types of coupons, one with 400 layers.	ANSYS prediction results although approximate agree well with experiments by NIST.	Predictions have been successful for IN-625.	

RAMPT TAPR
Technical Challenge Assessment
Calibration and validation of models – in situ and external sensors

TRL	Functional Elements	System Definition	System Integration	Modeling and Simulation Tools	Capability Validation	Environmental Validation	Life-cycle Design
2: Technology concept and/or application formulated.	Basic functional elements of technology have been identified.	An apparent engineering design approach has been identified.	System architecture defined in terms of basic functions to be performed.	Operational requirement of functional elements verified through modeling or simulation.	Preliminary performance predictions have been made for basic functional elements.	Critical functional experiments for operational environment are known.	N/A
3: Analytical and experimental critical function and/or characteristic proof-of-concept.	Operation of functional elements verified through bench-scale tests.	Definition of relevant operational environment defined for basic functional components.	A conceptual design of the integrated system has been defined.	Models exist to extent that computer analysis and simulations are possible.	Preliminary system performance measurements have been identified and estimated.	Modeling or experimental results show feasibility of basic functions in expected environments.	N/A
4: Component and/or breadboard validation in laboratory environment.	Subsystem tests in a simulated laboratory environment show element interfaces will function.	System performance metrics and test requirements have been defined for relevant operational environment.	Preliminary functional testing of integrated system completed at laboratory bench-scale.	Modeling shows subsystem interfaces will function at system level to satisfy functional requirements.	System performance metrics verified under simulated use conditions.	Laboratory scale tests indicate components and subsystem interfaces will function in operational environments	Operational needs for all material properties have been identified.
5: Component and/or breadboard validation in relevant environment.	Functional element and interfaces sufficiently understood at engineering-scale to provide system design tradeoffs.	Prototypical system testing for the ranges of critical operational environments validates design.	Engineering scale-up challenges understood and resolved for functional system.	Modeling shows subsystem interfaces will function at system level in operational environment.	System and subsystem functional parameters are demonstrated on a bench scale.	System testing in approximate operational environment completed.	Operational capability of all materials has been demonstrated.
6: System/sub-system model or prototype demonstrated in a relevant environment	Functional elements and interfaces provide optimized system design.	Full-scale engineering design specifications complete and documented.	Full technology system integration demonstrated at an engineering scale.	Performance predictions verified by engineering-scale testing and documented.	Functionality of a high-fidelity engineering design unit demonstrated.	Engineering-scale tests demonstrate functionality over full range of design critical environments	Operational limits of design fully specified and documented.
Rationale	We understand which in-situ measurements would help			The modeling capability exists, but continues to be developed for understanding the approximations necessary for scaling with respect to accuracy and the required validation.	Predictive computational models demonstrate necessary measurements.		

2018 2019

AD2 Level 8

RAMPT TAPR
Technical Challenge Assessment
(Freeform Blown Powder Deposition)
Powder removal from small coolant channels

	Manufacturing Tech Development	Producibility	Design Maturity	Materials Maturity	Modeling and Simulation	Manufacturing Process Maturity
2: Manufacturing Concepts Identified.	New manufacturing concepts and potential solutions identified.	N/A	Applications defined. Broad performance goals identified that may drive manufacturing options.	Material properties characteristics pre N/A	Initial models d applicable. N/A	Materials and/or process approaches identified.
3: Manufacturing Proof of Concept Demonstrated.	Manufacturing technology concepts identified through experiments/models	Relevant materials/processes evaluated for manufacturability using experiments/models	Top level performance requirements defined. Trade-offs in design options assessed based on experiments. Product lifecycle and technical requirements evaluated.		Identification of proposed manufacturing concepts or producibility needs based on high-level process flow models.	Critical manufacturing processes identified through experimentation.
4: Manufacturing Process in Lab Environment.	Manufacturing Science & Advanced Manufacturing Technology requirements identified.	Initial producibility and manufacturability assessment of preferred systems concepts completed. Results considered in selection of preferred design concepts	System characteristics and measures to support required capabilities identified. Form, fit, and function constraints identified and manufacturing capabilities identified for preferred systems concepts.	Projected materials have been produced in a laboratory environment.		Critical processes demonstrated and assessed in the laboratory.
5: Prototype components in Production Relevant Environment.		Producibility and manufacturability assessments of key technologies and components initiated. Ongoing design trades consider manufacturing processes Manufacturing processes assessed for capability to test and verify in production.	Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies and components identified and product lifecycle considered. Evaluation of design key characteristics initiated. Product data required for prototype component manufacturing is available.		Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Maturity has been assessed on similar processes in production. Process capability requirements have been identified for pilot line, low and full rate production.
6: System or Subsystem in a Production Relevant Environment	Required manufacturing technology development solutions demonstrated in a production relevant environment.	Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Preliminary designs assessed against manufacturing processes..		Material maturity verified through technology demonstration articles. Preliminary material specifications in place and material properties have been adequately characterized.	Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Manufacturing processes demonstrated in a production relevant environment. Process capability data is available (actual or modeled) from prototype build and process capability req'ts are refined based on this data.
Rationale		Fabricated demonstrator DED hardware has successfully had all powder removed from coolant passages.	Full powder removal in all channels is required. 1.2k coupled hardware design 100% complete. Fabricated demonstrator DED hardware has successfully had all powder removed from coolant passages. Channel geometry trials underway to search for optimum trade between heat transfer characteristics and powder removability.			Fabricated demonstrator DED hardware has successfully had all powder removed from coolant passages.

2018 2019

AD2 Level 8

Was not accessed at MRL=2 prior to FY19

RAMPT TAPR
Technical Challenge Assessment
(Freeform Blown Powder) Mechanical properties of blown powder vs. conventional fabrication – effects of processing anomalies on materials properties

	Manufacturing Tech Development	Producibility	Design Maturity	Materials Maturity	Modeling and Simulation	Manufacturing Process Maturity
2: Manufacturing Concepts Identified.	New manufacturing concepts and potential solutions identified.	N/A	Applications defined. Broad performance goals identified that may drive manufacturing options.	Material properties and characteristics predicted.	Initial models d N/A applicable.	Materials and/or process approaches identified.
3: Manufacturing Proof of Concept Demonstrated.	Manufacturing technology concepts identified through experiments/models	Relevant materials/processes evaluated for manufacturability using experiments/models	Top level performance requirements defined. Trade-offs in design options assessed based on experiments. Product lifecycle and technical requirements evaluated.		Identification of proposed manufacturing concepts or producibility needs based on high-level process flow models.	Critical manufacturing processes identified through experimentation.
4: Manufacturing Process in Lab Environment.	Manufacturing Science & Advanced Manufacturing Technology requirements identified.	Initial producibility and manufacturability assessment of preferred systems concepts completed. Results considered in selection of preferred design concepts	System characteristics and measures to support required capabilities identified. Form, fit, and function constraints identified and manufacturing capabilities identified for preferred systems concepts.	Projected materials have been produced in a laboratory environment.		Critical processes demonstrated and assessed in the laboratory.
5: Prototype components in Production Relevant Environment.		Producibility and manufacturability assessments of key technologies and components initiated. Ongoing design trades consider manufacturing processes Manufacturing processes assessed for capability to test and verify in production.	Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies and components identified and product lifecycle considered. Evaluation of design key characteristics initiated. Product data required for prototype component manufacturing is available.		Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Maturity has been assessed on similar processes in production. Process capability requirements have been identified for pilot line, low and full rate production.
6: System or Subsystem in a Production Relevant Environment	Required manufacturing technology development solutions demonstrated in a production relevant environment.	Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Preliminary designs assessed against manufacturing processes..		Material maturity verified through technology demonstration articles. Preliminary material specifications in place and material properties have been adequately characterized.	Initial models/simulation (product or process) developed at the component level and used to determine constraints.	Manufacturing processes demonstrated in a production relevant environment. Process capability data is available (actual or modeled) from prototype build and process capability req'ts are refined based on this data.
Rationale 2018 2019	Identified materials, processes and vendors and are making parts to test. We've completed experiments.	We have req and have built with several vendors and getting properties as expected.	Production methods have been designed and vendors identified	preliminary properties have been produced on representative subscale and small -scale 1.2K parts. (we have not shown full mechanical properties of nozzles)		Test coupons and test sections used to compare multiple processes and vendors and down select to best available processing route.

RAMPT

Provide a brief caption for each picture

Caption: Composite filament winding overwrap onto chamber

Caption: 1.2K GRCop Thrust Chamber with Composite Overwrap

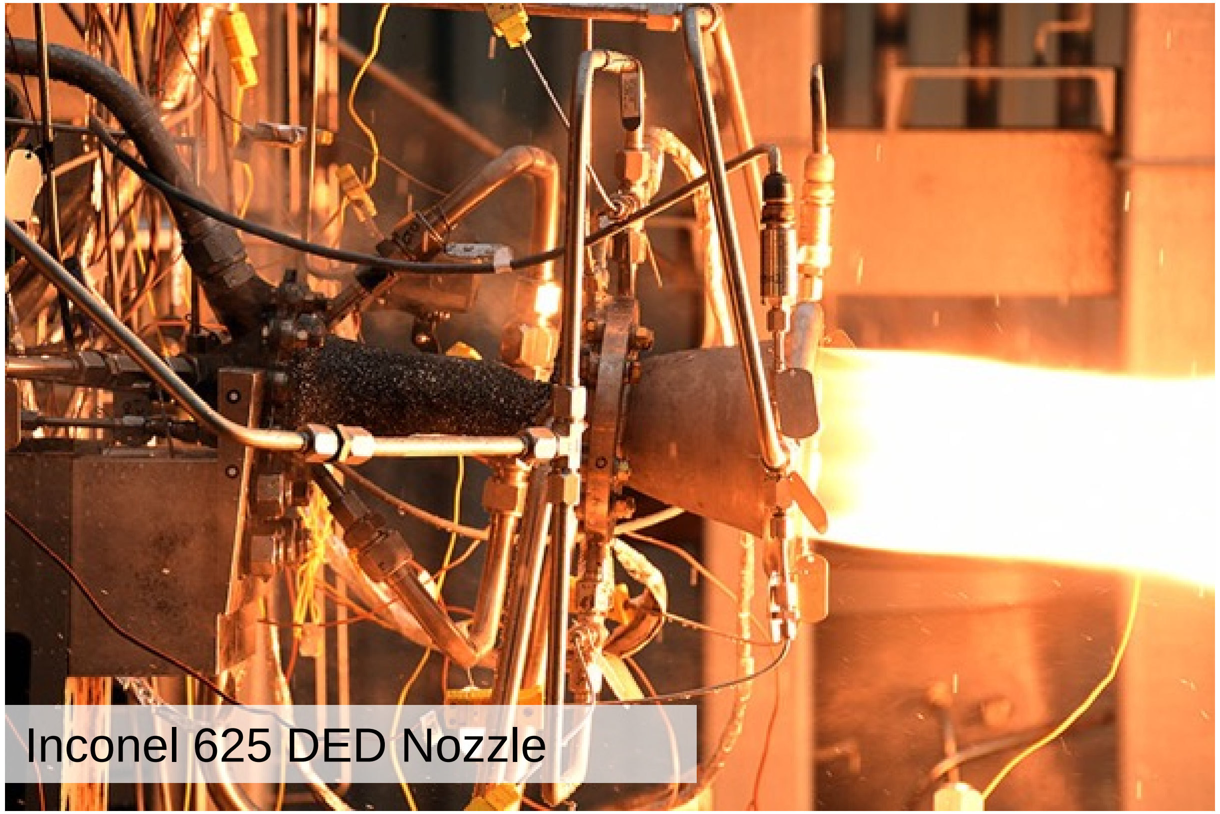
Caption: Composite filament winding overwrap onto chamber

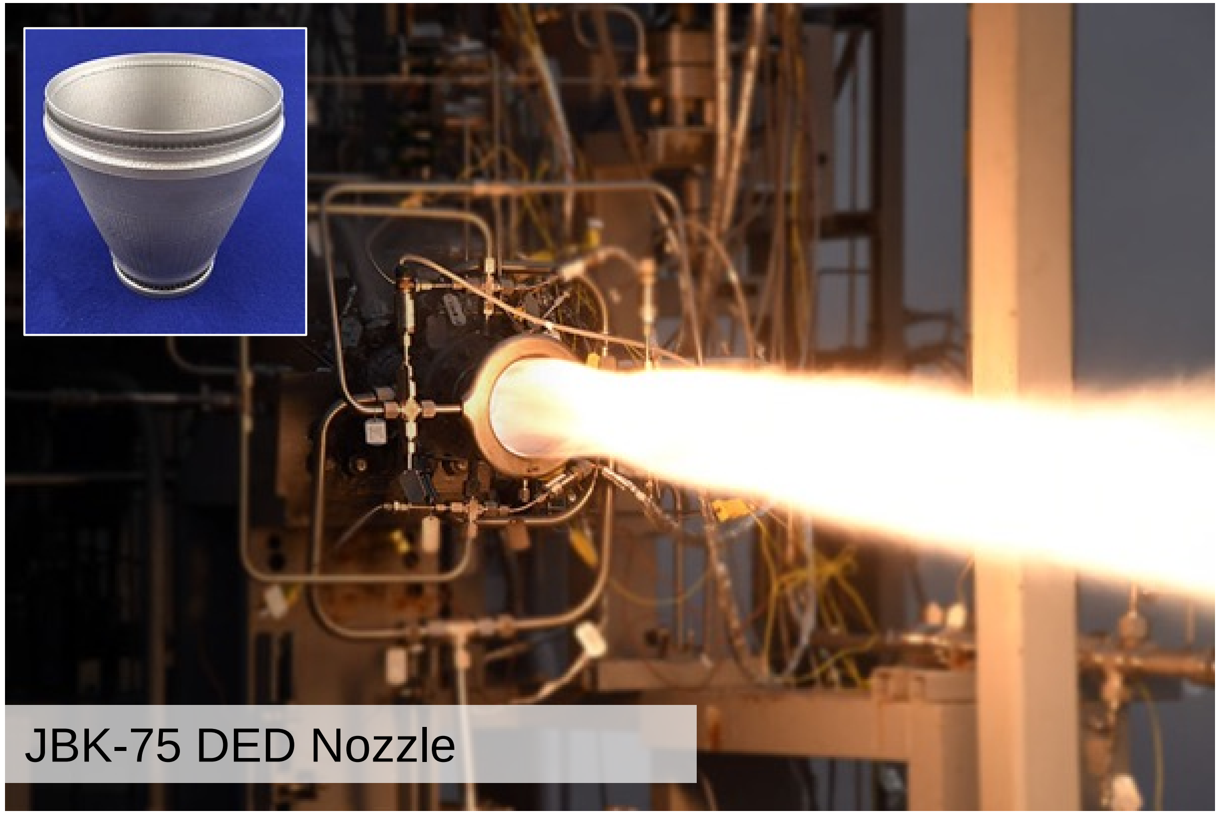
Caption: Hot Fire Test

Caption: Initial trials show feasibility of JBK-75 being built using Directed Energy Deposition (DED) process.

Caption: Insert Text

Additional Pictures






Inconel 625 DED Nozzle


JBK-75 DED Nozzle