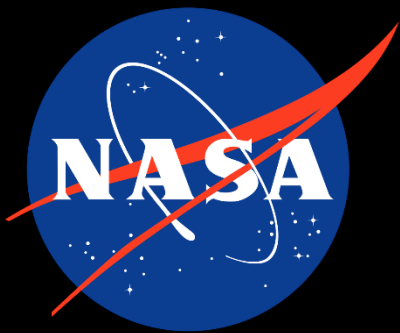




EXPLORE MOON *to* MARS

Lightweight Thrust Chamber Assemblies using Multi-Alloy Additive Manufacturing and Composite Overwrap

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Motivation and Overview

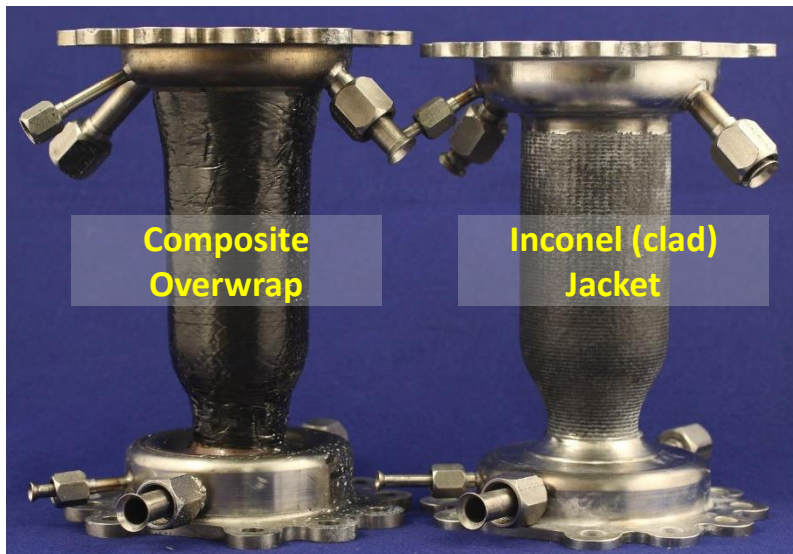


- Additive Manufacturing (AM) has provided new opportunities for liquid rocket engine components to reduce cost, reduce lead time and improve performance
- NASA and commercial industry have demonstrated AM on various development and flight programs as a feasible technology
- High performance alloys, such as GRCo-42 and GRCo-84, are continuing to be advanced and evolved for use in several applications
 - NASA has demonstrated >20,000+ sec of hot-fire time and 400 starts on GRCo alloys
 - Bimetallic AM applications have also been demonstrated at subscale and large scale
- Current AM technology using Laser Powder Bed Fusion (L-PBF) has limitations of volume that can be built
- There is a need to develop large scale additive manufacturing techniques for engine components such as regeneratively-cooled combustion devices and further improve performance through weight reduction

The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project was established to develop large scale additively manufactured and composite overwrap actively-cooled thrust chamber assemblies

Enhancing Prior AM Technology Developments

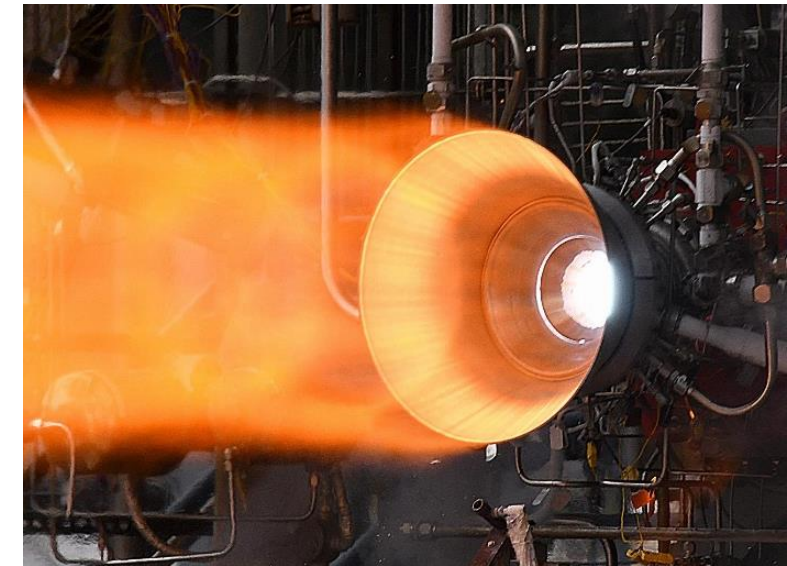
- NASA's Low Cost Upper Stage Propulsion (LCUSP) project developed the process for L-PBF of GRCop-84 (Cu-8 at.% Cr-4 at.% Nb)
- Demonstrated bimetallic additive manufacturing combustion chambers with GRCop-84 and Inconel 625 structural jacket (using Electron Beam Directed Energy Deposition)
- Project was successful through full scale hot-fire testing
- Observed shrinkage of the bimetallic jacket
- AM provides an opportunity for fully closed-out coolant channels and use of a composite overwrap structural jacket



Same GRCop-84 L-PBF Liner (difference in height post-clad)



NASA's LCUSP Bimetallic AM Combustion Chamber / Hot-fire Testing



Overview of RAMPT Project

Bimetallic Deposited Manifolds and Nozzle Interface

- Develops commercial supply chain
- Optimizes weight based on selective material deposition
- Reduces costs
- Evaluating DED and solid state AM processes

Integrated Large Scale DED Freeform Manufacturing Deposition Regen-Cooled Nozzle

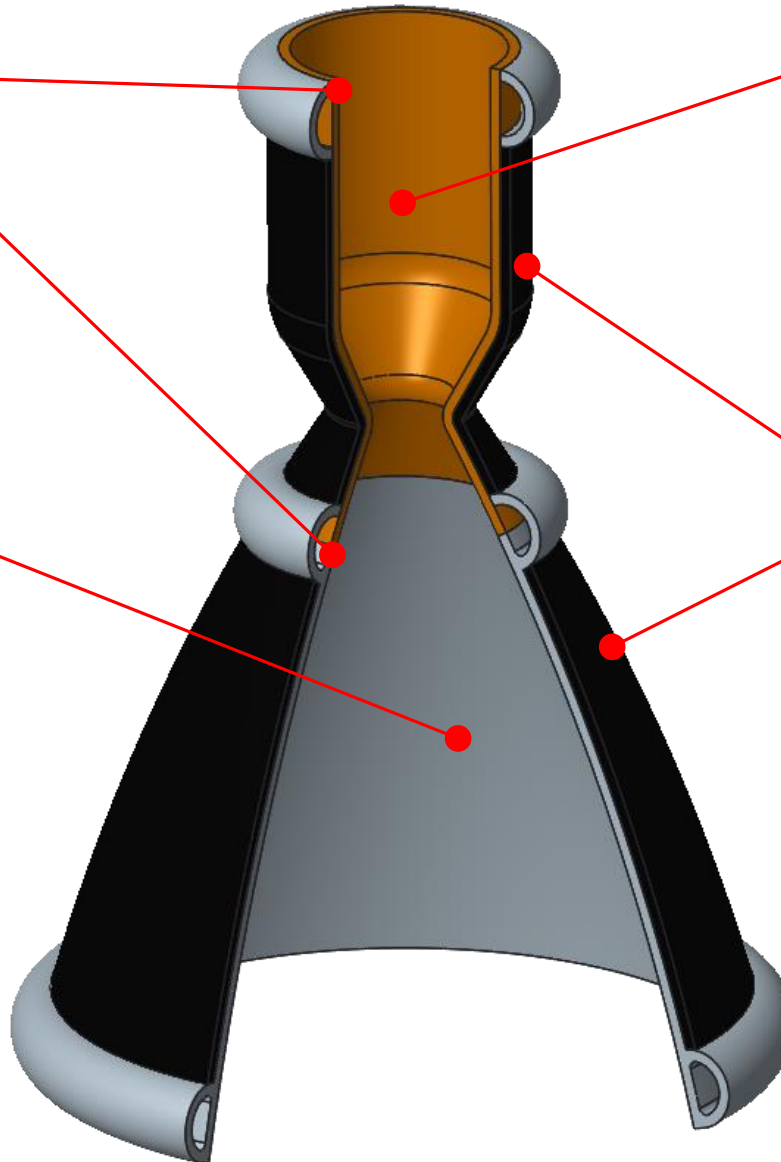
- Selected Blown Powder Directed Energy Deposition (DED) Demonstrate integral channels using DED process
- Demonstrate coupled chamber and nozzle configuration to reduce weight
- Reduces complexity
- Significantly increases scale for AM processes for regen-cooled components

L-PBF AM Copper Chamber

- Based on prior LCUSP development
- Proven Technology for GRCop alloys
- Expand to GRCop-42
- Advances and expands commercial supply chain

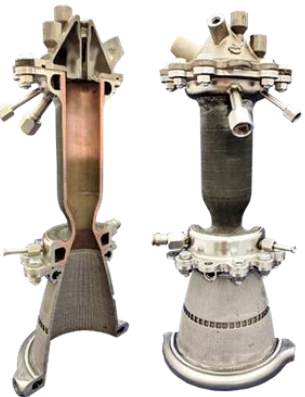
Composite Overwrap Thrust Chamber Assembly

- Significantly reduces weight for high chamber pressure TCA's
- Reduces distortions caused by bimetallic cladding
- Reduces overall cost and fabrication schedules
- Builds upon prior composite overwrap pressure vessel (COPV) technology



Key Technology Developments for RAMPT Project

- Demonstrate key technologies through process development, characterization, component fabrication, hot-fire testing and infusion into industry
- Demonstrates technologies through progression of hardware scale, coupling of technologies, thrust levels and propellant combinations
- Makes use of Public Private Partnerships through industry investments

2k-lb _f Decoupled	2k-lb _f Coupled	7K-lb _f Coupled	40K-lb _f Coupled
LOX/RP-1 <i>Room Temp Fuel Testing Completed</i>	LOX/LH2 <i>Demonstrates Cryogenic through elevated temps Axially bimetallic deposition</i>	LOX/LCH4 <i>Cryogenic through elevated temps at larger scale Axially bimetallic deposition</i>	LOX/LH2 <i>Cryogenic through high temp, High Pc Axial and Radial Bimetallic Interfaces</i>
 			

Combining key technologies into an integrated thrust chamber assembly using:

1. Large scale blown powder directed energy deposition
2. Composite overwrap jacket
3. Bimetallic and multi-alloys for joints
4. GRCop-42 L-PBF



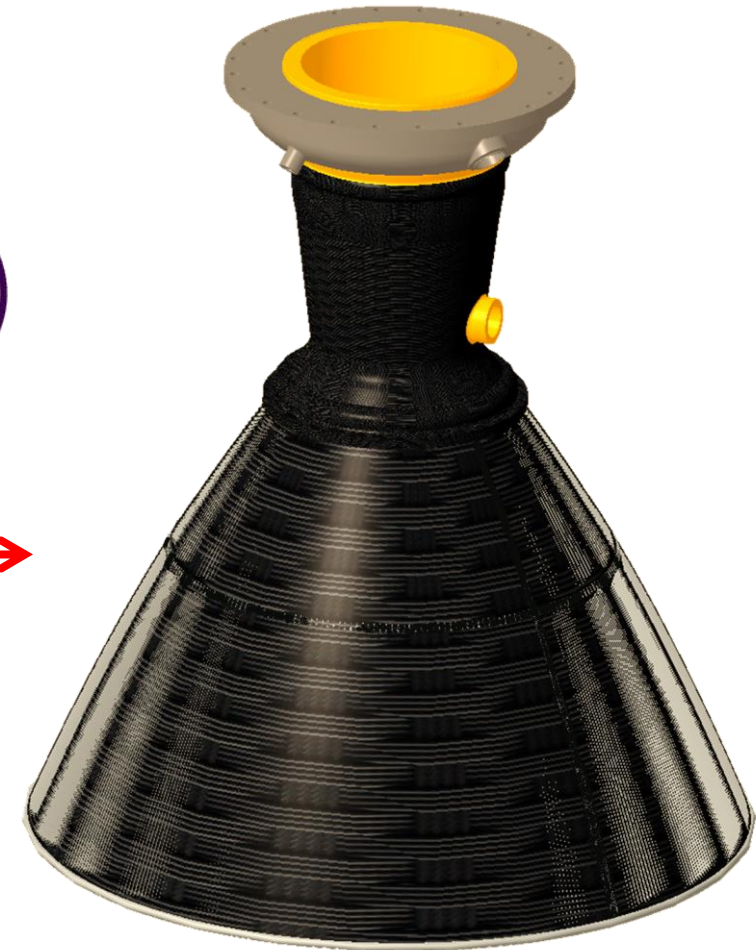
L-PBF GRCop-42
Chamber Liner



Manifolds applied using
bimetallic AM DED



Blown Powder DED of Regen-
nozzle directly on chamber



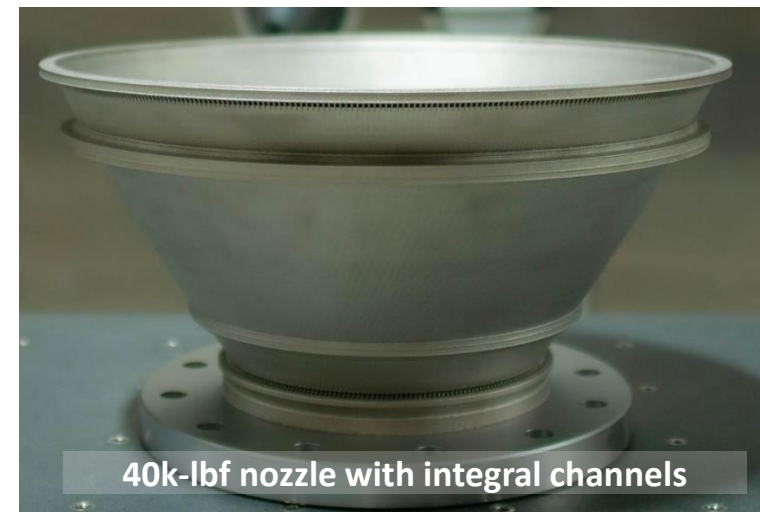
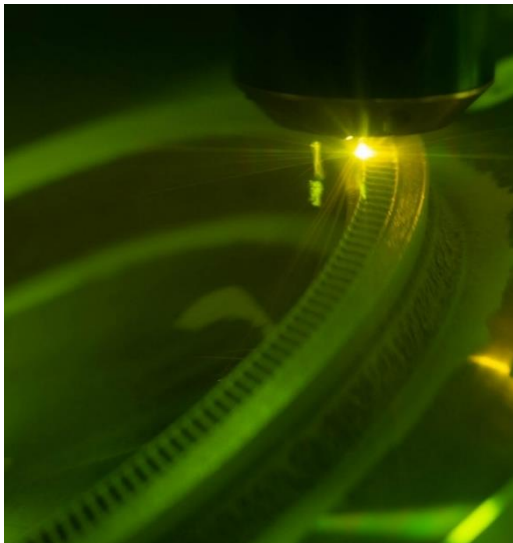
Composite Overwrap of TCA



Large Scale Blown Powder Directed Energy Deposition (DED) for Regeneratively-cooled Nozzles



- Blown powder DED (BP-DED) was selected for the integral channel large-scale integrated nozzle providing significant scale options
 - Process being developed with industry partners
- Prior publications detailed early process and hardware development work on the BP-DED and successful subscale hot-fire testing
- Process selected as it provided a good trade of deposition rates along with feature resolution needed for integral channels
- Channels have been demonstrated in various configurations, providing new design options



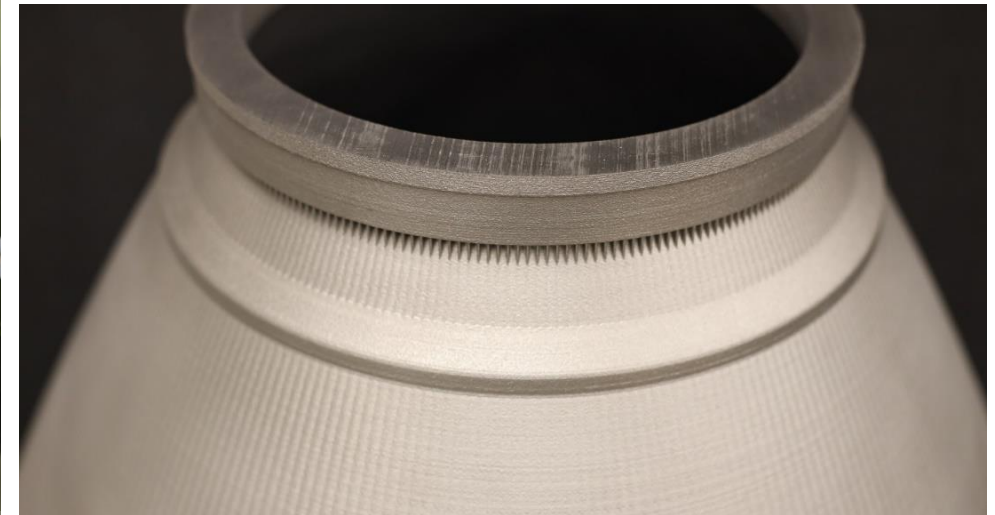
40k-lbf nozzle with integral channels



Large Scale Blown Powder DED for Regeneratively-cooled Nozzles



- RAMPT project has completed various decoupled BP-DED nozzle fabrication demonstrators and hardware for hot-fire testing
 - Significantly reduces number of parts and assembly time compared to traditional
- Ongoing characterization of material and mechanical property testing
- Completed large scale milestone with 40" (1016 mm) dia and 38" (965 mm) length nozzle in 30 day deposition time
 - Post-test inspections showed limited distortion and met intended geometry

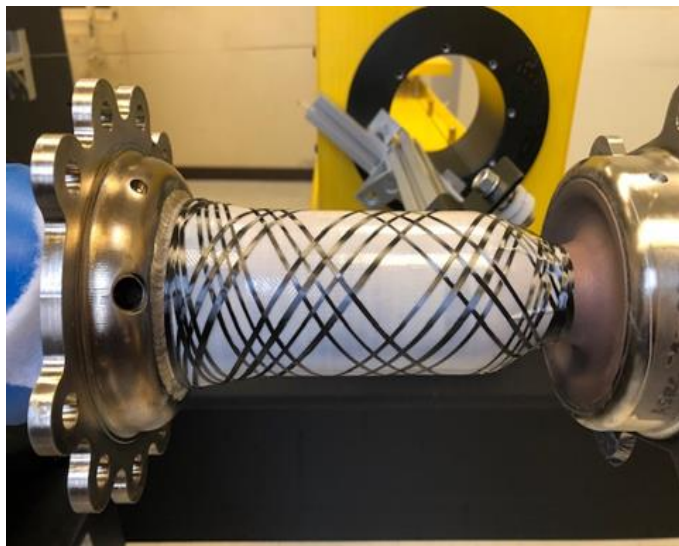




Composite Overwrap Process Development for Combustion Chambers

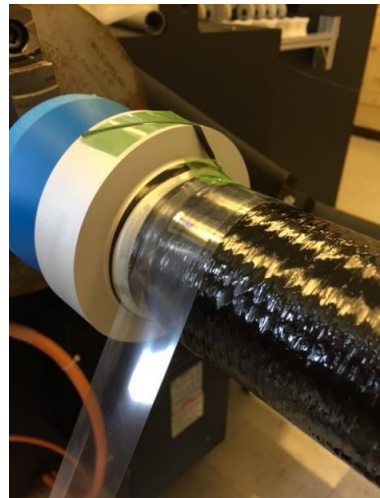


- Composite overwrap being developed for structural support of the combustion chamber (light weight jacket)
- Polymeric matrix composite (PMC) using filament winding, tape wrapping, hand layup and combination of techniques
- Focuses include evaluation of surface preparation, resins and processing to meet combustion chamber requirements
 - Cryogenic up to 450°F (232°C)



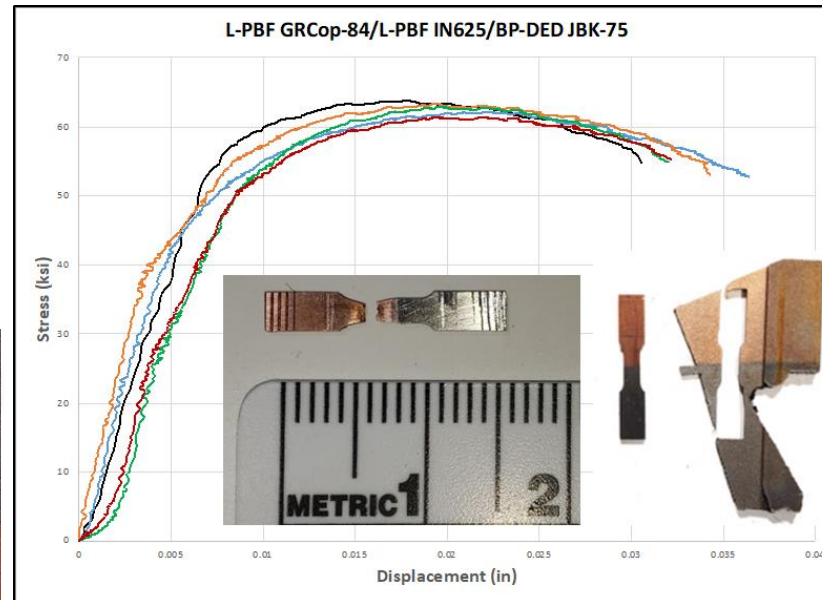
Composite Overwrap Process Development

- Analytical modeling drove design to a “floating” liner approach, which is addressed in the composite surface preparation development
- Resins being evaluated and selected based on wide temperature range, but driven by higher temperatures
- Curing processes also being evaluated and vary based on chamber requirements and available facilities
- Plastic models being used for toolpath programming for manufacturing demonstrators



Bimetallic and Multi-metallic Additive Manufacturing for Thrust Chambers

- Bimetallic and multi-metallic joints necessary to join various alloys to optimize strength-to-weight materials by using materials locally based on component requirements
 - Locations include for joining manifolds on the chamber and axial joint between chamber and nozzle
- Evaluation various processes including Cold Spray, Laser Hot Wire, and Blown Powder DED



Microtensile testing of Bimetallic/Multi-metallic Joints

Advancement of GRCop-42 Alloys and Supply Chain

- GRCop-42 (Cu-4 at.% Cr-2 at.% Nb) is a high conductivity, high strength copper-alloy being advanced for the RAMPT project for the channel-cooled combustion chamber
- Details previously provided in prior publications
- Developing database of material properties and continuing to expand supply chain (powder and L-PBF service providers)
- Various thrust-class chambers completed fabrication under RAMPT



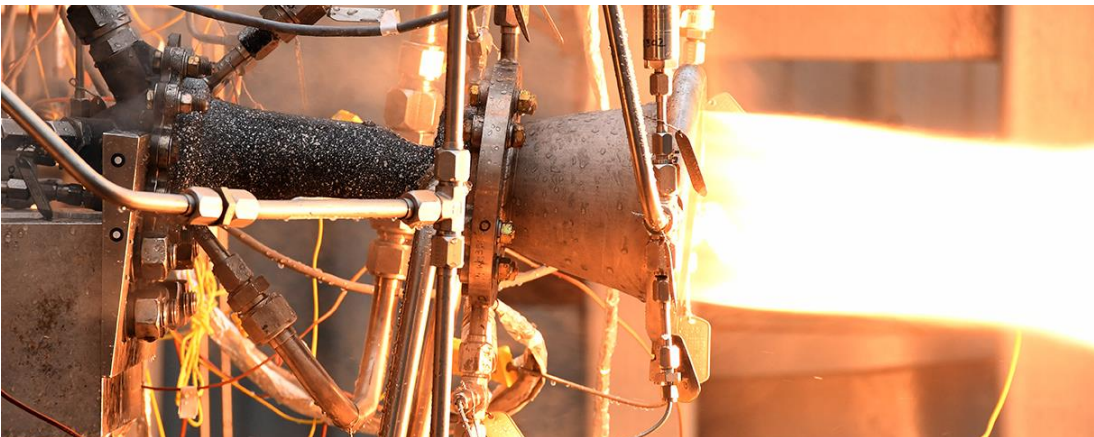
Hot-fire Testing Development

- Hot-fire testing completed at 2,400 lbf with decoupled (bolted) hardware on composite overwrap chamber and DED nozzle
- Demonstrated composite and resin up to temperatures of 250 °F

Propellant	Chamber & Material	Nozzle	Material	Starts	Time (sec)
LOX/GH2	GRCop-42 L-PBF w/ Slip Jacket	BP-DED	JBK-75	114	4,170
LOX/GH2	GRCop-42 L-PBF w/ Slip Jacket	BP-DED	Inco 625	1	15
LOX/RP-1	GRCop-84 L-PBF w/ Composite Overwrap	BP-DED	Inco 625	17	617
LOX/RP-1	GRCop-84 L-PBF w/ Bimetallic Jacket	BP-DED	Inco 625	10	440



2k-lbf Decoupled Assembly with Digital Image Correlation applied to composite overwrap to obtain strains



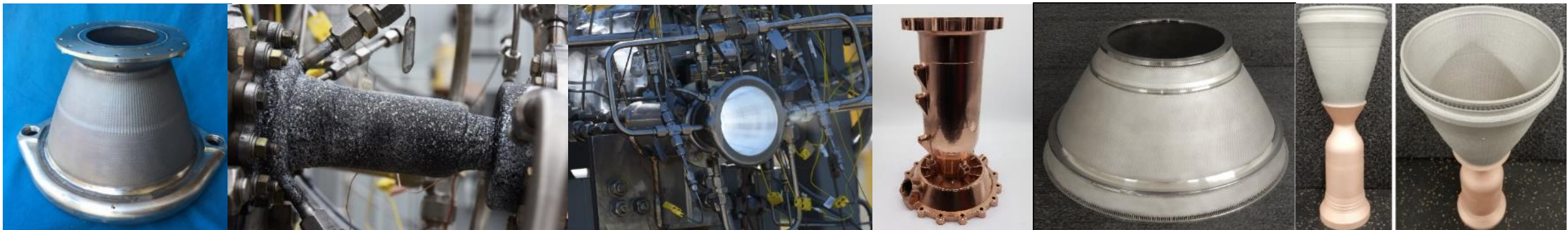
2k-lbf Decoupled Assembly during Hot-fire (LOX/RP-1)



Conclusions and Future Development



- The RAMPT project was established to develop large scale additively manufactured and composite overwrap thrust chamber assemblies (TCA) for channel-cooled chambers and nozzles
- Significant progress has been made for several key technologies under RAMPT including integration/coupling of these technologies working towards a large scale integrated assembly
 - Demonstrated integral channel blown powder directed energy deposition (BP-DED) at large scale
 - Demonstrated composite overwrap techniques at subscale and working towards scale-up
 - Demonstrated robust joints using bimetallic and multi-metallic additive manufacturing techniques
- Future work includes several milestones for integral chambers and hot-fire testing
 - Complete hot-fire testing using BP-DED nozzles at 7K-lb_f and 40K-lb_f scales
 - Complete hot-fire testing of 2K-lb_f integrated chambers with all key technologies in LOX/LH2
 - Complete hardware fabrication and testing of integrated TCA's at 7K-lb_f and 40K-lb_f with LOX/LCH4 and LOX/LH2
 - Complete process characterization, material testing and data dissemination to government and commercial partners



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Many others in Industry, commercial space and
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References



- Fikes, J., 2018. Space Technology Mission Directorate: Game Changing Development Program: Rapid Analysis and Manufacturing Propulsion Technology (RAMPT). MSFC-E-DAA-TN61457. Space Technology Mission Directorate (STMD) Game Changing Development Program (GCD) Ann
- Gradl, P.R., Brandsmeier, W.C., Medina, C.R., Protz, C.S. and Mireles, O., National Aeronautics and Space Administration (NASA), 2019. *Method for Fabricating Seal-Free Multi-Metallic Thrust Chamber Liner*. U.S. Patent Application 15/965,389.
- Gradl, P.R., Brandsmeier, W.C., Medina, C.R., Protz, C.S. and Greene, S.E., National Aeronautics and Space Administration (NASA), 2019. *Seal-Free Multi-Metallic Thrust Chamber Liner*. U.S. Patent Application 15/965,184.
- Gradl, P.R., Brandsmeier, W.C., Medina, C.R., Protz, C.S. and Jackson, J.R., National Aeronautics and Space Administration (NASA), 2019. *Composite-Overwrapped Multi-Metallic Thrust Chamber Liner*. U.S. Patent Application 15/965,239.
- Protz, C.S., W.C. Brandsmeier, K.G. Cooper, J.C. Fikes, P.R. Gradl, Z.C. Jones, C.R. Medina., D. L. Ellis, K.M. Taminger Thrust Chamber Assembly Using GRCOP-84 Bimetallic Additive Manufacturing and Integrated Nozzle Film Coolant Ring Supporting Low Cost Upper Stage Propulsion., 10th JANNAF Liquid Propulsion Subcommittee Meeting, Long Beach, CA. 2018.
- Gradl, P.R. Protz, C.S, Ellis, D.L, Greene, S.E. "Progress in Additively Manufactured Copper-Alloy GRCop-84, GRCop-42, and Bimetallic Combustion Chambers for Liquid Rocket Engines." IAC-19.C4.3.5x52514. Washington D.C., United States, 21-25 October (2019).
- Gradl, P.R., Protz, C., Greene, S.E., Ellis, D., Lerch, B., and Locci., I. "Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications", 53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2017-4670)
- Garcia, C.P., Gradl, P.R., Protz, C.S., Wood, J., and Greene, S. E. Characterizing Performance of Additively Manufacturing Regenerative Cooled Combustion Chambers through Hot Fire Testing, Paper presented at 65th JANNAF Propulsion Meeting/10th Liquid Propulsion Subcommittee, May 21-24, 2018. Long Beach, CA.
- Kasper, H.J. and Nota-Donato, J.J., 1979. Effect of low-stiffness closeout overwrap on rocket thrust-chamber life. NASA Technical Report NASA-TP-1456, E-9870.
- Ferraiuolo, M., Petrillo, W. and Riccio, A., 2017. On the thermo-structural response of a composite closeout in a regeneratively cooled thrust chamber. *Aerospace Science and Technology*, 71, pp.402-411.
- Lawrence, T., Beshears, R., Burlingame, S., Peters, W., Prince, M., Suits, M., Tillery, S., Burns, L., Kovach, M. and Roberts, K., 2001. Fabrication of composite combustion chamber/nozzle for fastrac engine. Proceedings of the 4th Conference on Aerospace Materials, Processes, and Environmental Technology. ASA/CP-2001-210427.
- Brown, K.K. Sparks, D. A regeneratively cooled thrust chamber for the fastrac engine, in: 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 16–19 July 2000, Huntsville, Alabama, A1AA 2000-3286.
- Elam, S., Effinger, M., Holmes, R., Lee, J. and Jaskowiak, M., 2000, January. Lightweight chambers for thrust cell applications. In *36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit* (p. 3131).
- Gradl, P.R., Greene, S. and Wammen, T., 2019. Bimetallic Channel Wall Nozzle Development and Hot-fire Testing using Additively Manufactured Laser Wire Direct Closeout Technology. In *AIAA Propulsion and Energy 2019 Forum* (p. 4361).
- Gradl, P.R. and Protz, C.S., (2020). Technology advancements for channel wall nozzle manufacturing in liquid rocket engines. *Acta Astronautica*. Vol 174. Pages 148-158. <https://doi.org/10.1016/j.actaastro.2020.04.067>
- Gradl, P. R., & Protz, C. S. (2019). "Channel Wall Nozzle Manufacturing Technology Advancements for Liquid Rocket Engines". IAC-19.C4.3.4x52522. Washington D.C., United States, 21-25 October.
- Boman, A., Haggander, J., & Hass, J. (1999). Laser welded channel wall nozzle design, manufacturing and hot gas testing. 35th AIAA Joint Propulsion Conference and Exhibit. doi:10.2514/6.1999-2750 ual Program Review; 25-26 September. Cleveland, OH. (2018).



References



- Brox, L., Wir, M., Almqvist, M., Hallberg, M., Pettersson, A., Lind, A. (2019). "Status Report SWAN sandwich nozzle program for Ariane 6". International Astronautical Congress. October 21-25. Washington, DC. IAC-19,C4,10,12,x49373.
- Immich, H., Alting, J., Kretschmer, J., & Preclik, D. (2003). Technology developments for thrust chambers of future launch vehicle liquid rocket engines. *Acta Astronautica*, 53(4-10), 597-605. <https://doi.org/10.1016/j.cja.2013.07.045>
- Gradl, P.R., Brandsmeier, W. and Greene, S.E., "Channel Wall Nozzle Manufacturing and Hot-Fire Testing using a Laser Wire Direct Closeout Technique for Liquid Rocket Engines". (2018). p. 4860. <https://doi.org/10.2514/6.2018-4860>
- Gradl, P.R., Protz, C.S., Cooper, K., Ellis, D., Evans, L.J. and Garcia, C., 2019. GRCop-42 Development and Hot-fire Testing using Additive Manufacturing Powder Bed Fusion for Channel-Cooled Combustion Chambers. In AIAA Propulsion and Energy 2019 Forum (p. 4228). <https://doi.org/10.2514/6.2019-4228>
- Woods, S. and Lee, J.A., Hydrogen Embrittlement. NASA/TM-2016-218602 (JSC-CN-36009). 1 April 2016.
- Katsarelis, C., Chen, P., Gradl, P.R., Protz, C.S., Jones, Z., Ellis, D.E., Evans, L. "Additive Manufacturing of NASA HR-1 Material for Liquid Rocket Engine Component Applications." Paper presented at 2019 JANNAF 11th Liquid Propulsion Subcommittee (LPS), December 9-13. Tampa, FL. (2019).
- Chen, P. S., B. Panda, and B. N. Bhat. "NASA-HR-1, A New Hydrogen-Resistant Fe-Ni-Base Superalloy." *Hydrogen Effects in Materials* (1994): 1011-1020.
- Andersson J.O., Helander T., Höglund L., Shi P.F., and Sundman B., (2002). Thermo-Calc and DICTRA, Computational tools for materials science. *Calphad*, 26, 273-312.
- Dykhuisen, R. C., and M. F. Smith. "Gas dynamic principles of cold spray." *Journal of Thermal spray technology* 7.2 (1998): 205-212.
- T. Hussain, DG McCartney, PH Shipway, D. Zhang, "Bonding Mechanisms in Cold Spraying: The Contributions of Metallurgical and Mechanical Components", *Journal of Thermal Spray Technology* 18, 364-379 (2009)
- Irissou, E., Legoux, J. G., Ryabinin, A. N., Jodoin, B., & Moreau, C. (2008). Review on cold spray process and technology: part I—intellectual property. *Journal of Thermal Spray Technology*, 17(4), 495-516.
- Liu, S., Liu, W., Harooni, M., Ma, J., & Kovacevic, R. (2014). Real-time monitoring of laser hot-wire cladding of Inconel 625. *Optics & Laser Technology*, 62, 124-134.
- M. Kottman, S. Zhang, J. McGuffin-Cawley, P. Denney, B. Narayanan, "Laser Hot Wire Process: A Novel Process for Near-Net Shape Fabrication for High-Throughput Applications", *JOM* 67, 622-628 (2015)
- Gradl, P., Protz, C., Wammen, T. "Additive Manufacturing Development and Hot-fire Testing of Liquid Rocket Channel Wall Nozzles using Blown Powder Directed Energy Deposition Inconel 625 and JBK-75 Alloys". 55th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. August 19-22. Indianapolis, IN. (2019). <https://doi.org/10.2514/6.2019-4362>
- Gradl, P. R. (2016). Digital image correlation techniques applied to large scale rocket engine testing. In 52nd AIAA/SAE/ASEE Joint Propulsion Conference (p. 4977).
- Protz, C.S., Gradl, P.R., Fikes, J., Garcia, C.P., Pelham, L, Clark, A., Hudson, T., Miller, S., Ogles, M. "Large-scale Lightweight Composite Overwrap Combustion Chambers and Nozzles under the Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)". Paper presented at 2019 JANNAF 11th Liquid Propulsion Subcommittee (LPS), December 9-13. Tampa, FL. (2019).
- Protz, C.S., W.C. Brandsmeier, K.G. Cooper, J.C. Fikes, P.R. Gradl, Z.C. Jones, C.R. Medina., D. L. Ellis, K.M. Taminger Thrust Chamber Assembly Using GRCOP-84 Bimetallic Additive Manufacturing and Integrated Nozzle Film Coolant Ring Supporting Low Cost Upper Stage Propulsion., 10th JANNAF Liquid Propulsion Subcommittee Meeting, Long Beach, CA. 2018.