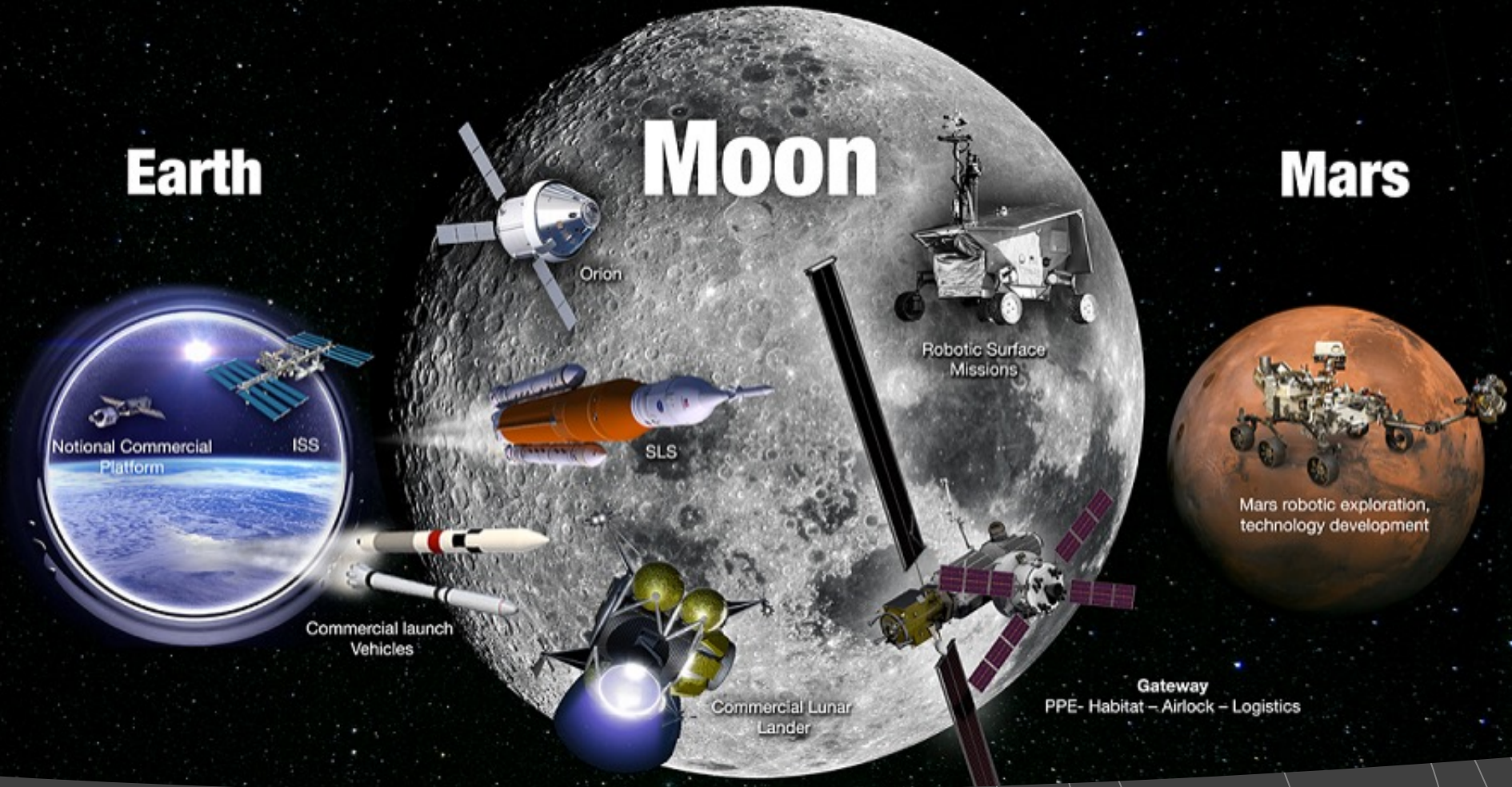


Additive Manufacturing at NASA



Alison Park- NASA NESC at Langley
Sarah Ludeman – NASA at JPL



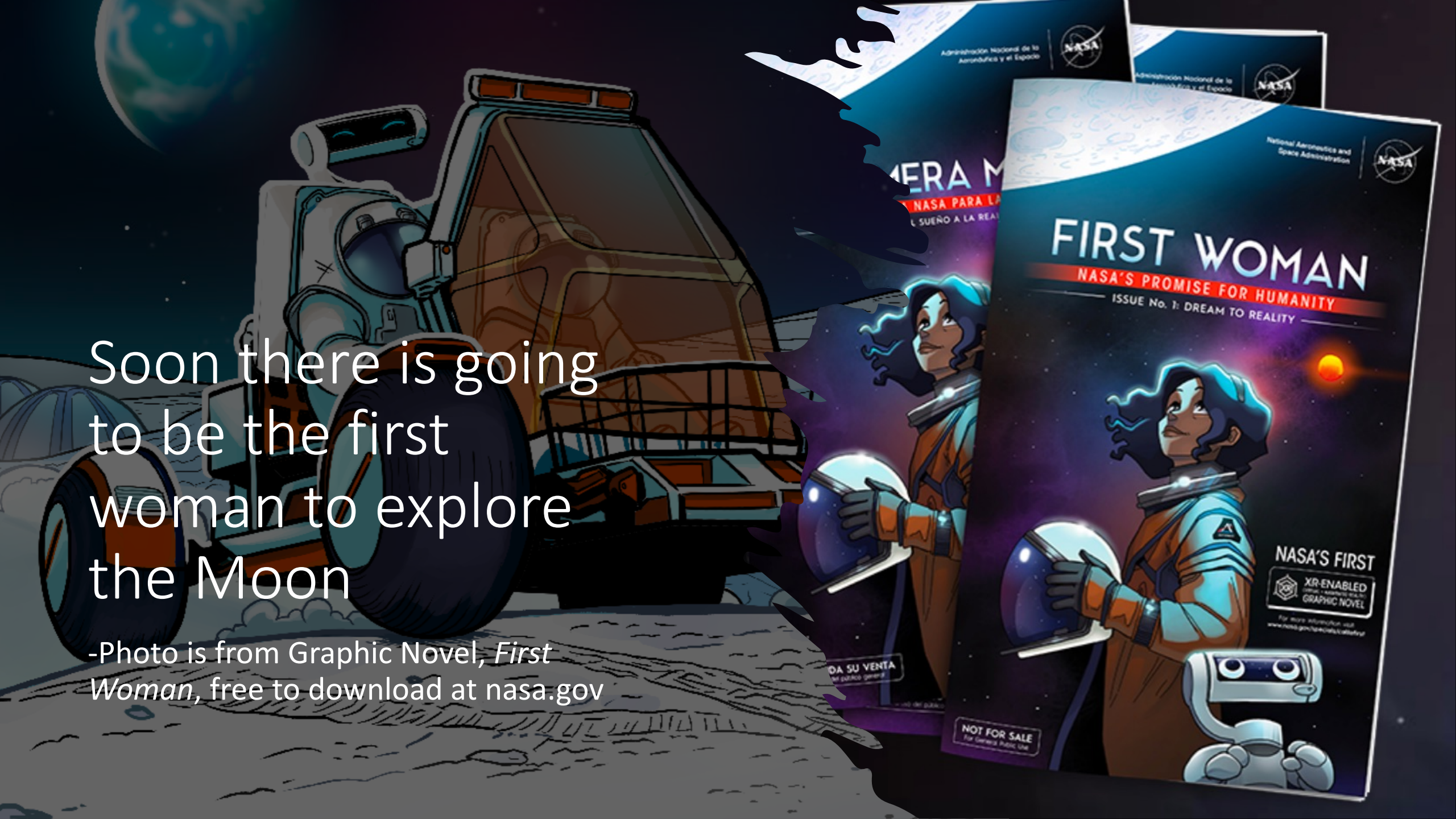


Exciting time at NASA with a lot of activities around Earth Orbit, getting ready to go to the Moon with eyes on Mars



Deep Space exploration- Moon to Mars Overview

- Starts with commercial companies delivering scientific instruments and tech demos to the lunar surface
- Followed by Gateway
- Followed by Human Landing System that would take astronauts to the surface of the Moon



Soon there is going
to be the first
woman to explore
the Moon

-Photo is from Graphic Novel, *First Woman*, free to download at nasa.gov





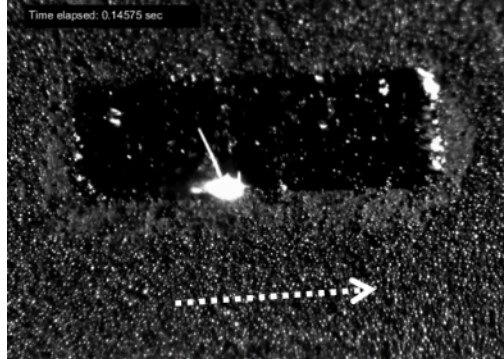
Additive Manufacturing at NASA

- **Fully embraces advantages of AM** – lead/cost time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles...
- But we **understand the challenges**, especially in delivering high value/performance AM hardware
- **NASA has dual roles**
 - Drive and foster **AM Technology Research and Development effort** in support of broad industry adoption and industrialization
 - **Spaceflight hardware certification** to assure AM hardware for access to space can safely meet mission objectives
- Today's talk will cover examples of NASA's **AM tech development** activities, especially in **Rocket Propulsion** and a **Case Study of AM Hardware Certification activity at JPL**

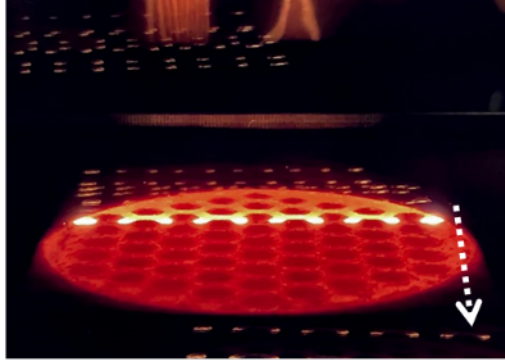




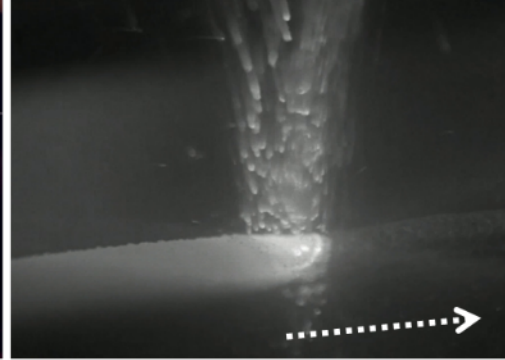
Different AM Processes – what would fit your application?



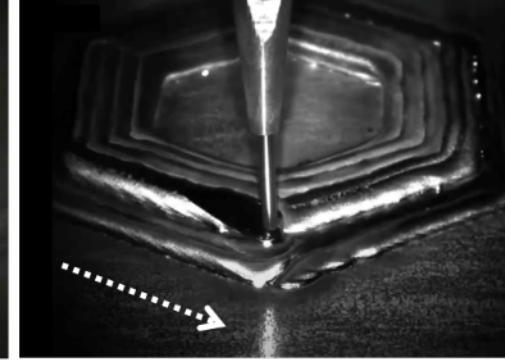
Laser Powder Bed Fusion



Electron Beam Powder Bed Fusion



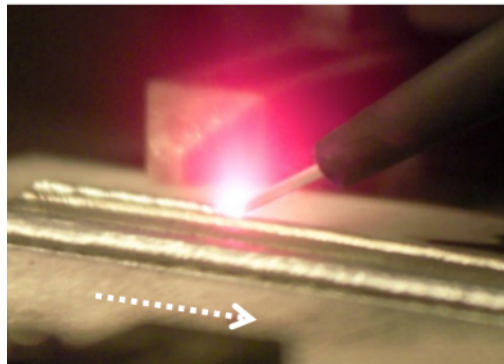
Laser Powder DED



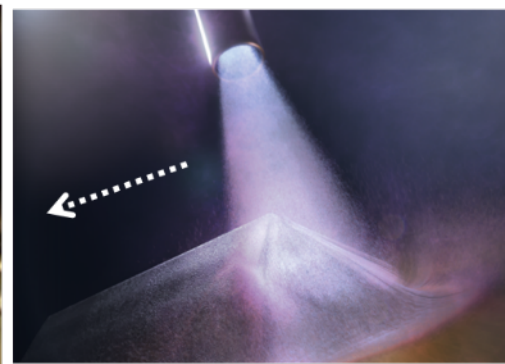
Laser Wire DED



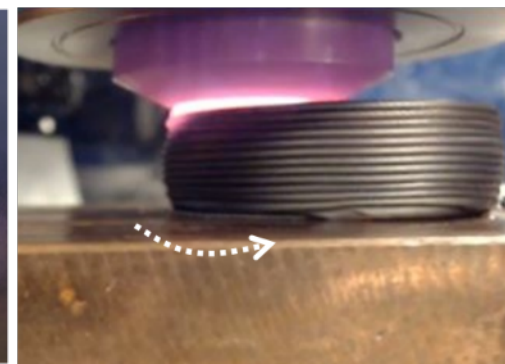
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

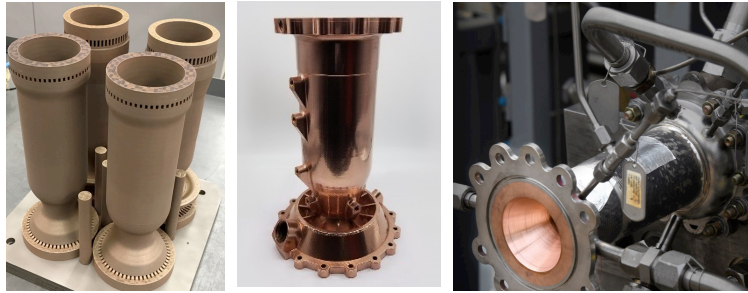


Ultrasonic Additive Manufacturing

A) Laser Powder Bed Fusion [<https://doi.org/10.1016/j.actamat.2017.09.051>], B) Electron Beam Powder Bed Fusion [Credit: Courtesy of Freemelt AB, Sweden], C) Laser Powder DED [Credit: Formalloy], D) Laser Wire DED [Credit: Ramlab and Cavitar], E) Arc Wire DED [Credit: Institut Maupertuis and Cavitar], F) Electron Beam DED [NASA], G) Cold spray [Credit: LLNL], H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM [Credit: Fabrisonic].

Reference: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., McKinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Review)

NASA's AM Insertion - Liquid Rocket Propulsion System



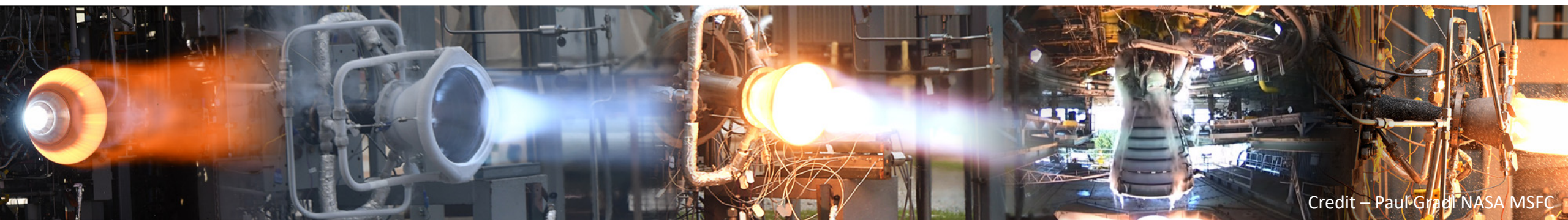
Laser Powder Bed Fusion (L-PBF)
Copper Alloys combined with other
AM processes to provide bimetallic



Directed Energy Deposition



L-PBF of complex components, new
alloy developments for harsh
environment





Why AM makes sense for Propulsion component

			
Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCo-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCo-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	\$310k	\$200k (35%)	\$125k (60%)

Cost comparison for a 156kN (35,000 lbf) Bimetallic Rocket Combustion Chamber in 2020 USD

Reference: F. Kerstens, A. Cervone, P. Gradl, End to end process evaluation for additively manufactured liquid rocket engine thrust chambers, Acta Astronaut. 182 (2021) 454–465. <https://doi.org/10.1016/j.actaastro.2021.02.034>.



Examples of Other AM Projects at NASA

- **AM Tech maturation**
 - Continuous hot-fire and component testing to advance various combustion chambers, injectors, nozzles, ignition systems, turbomachinery, valves, lines, ducts, in-space thrusters
 - Polishing (surface enhancements internally) and post-processing development
 - Combining various AM processes for multi-alloy solutions
 - New alloy development (Refractory, Ox-rich environments, very high and very low temperature alloys, AM-specific alloys)
- **Rapid Process Qualification using Integrated Computational Materials Engineering (ICME)**
 - Microstructure, thermal, failure mechanism modeling for processing and part performance prediction
 - Simulate operative physical processes at relevant length scales
 - Characterize the physics of damage via experimental evaluation
 - Development of reliable and traceable in-situ inspection techniques
- **In-Space 3D Printing and Off-Earth Manufacturing**
 - At International Space Station since 2014; FabLab next gen multi-material fabrication Lab (2022), Archinaut (2022), Spider (2022)
 - Motivation is to repair, recycle, reuse and use in-situ resources
 - At Lunar – surface manufacturing, construction of habitat, landing and shielding infrastructure
- **NASA AM Standards and Handbooks**
 - Chief of Engineer's office driven development effort of Agency-wide Standards and Specs : Standard 6033 and 6033 released in April 2021
 - Set the framework for AM qualification and certification methodologies and implementation approach for flight readiness
 - Currently being cited in human spaceflight programs (used in Insight/Oversight effort with Industry partners)