



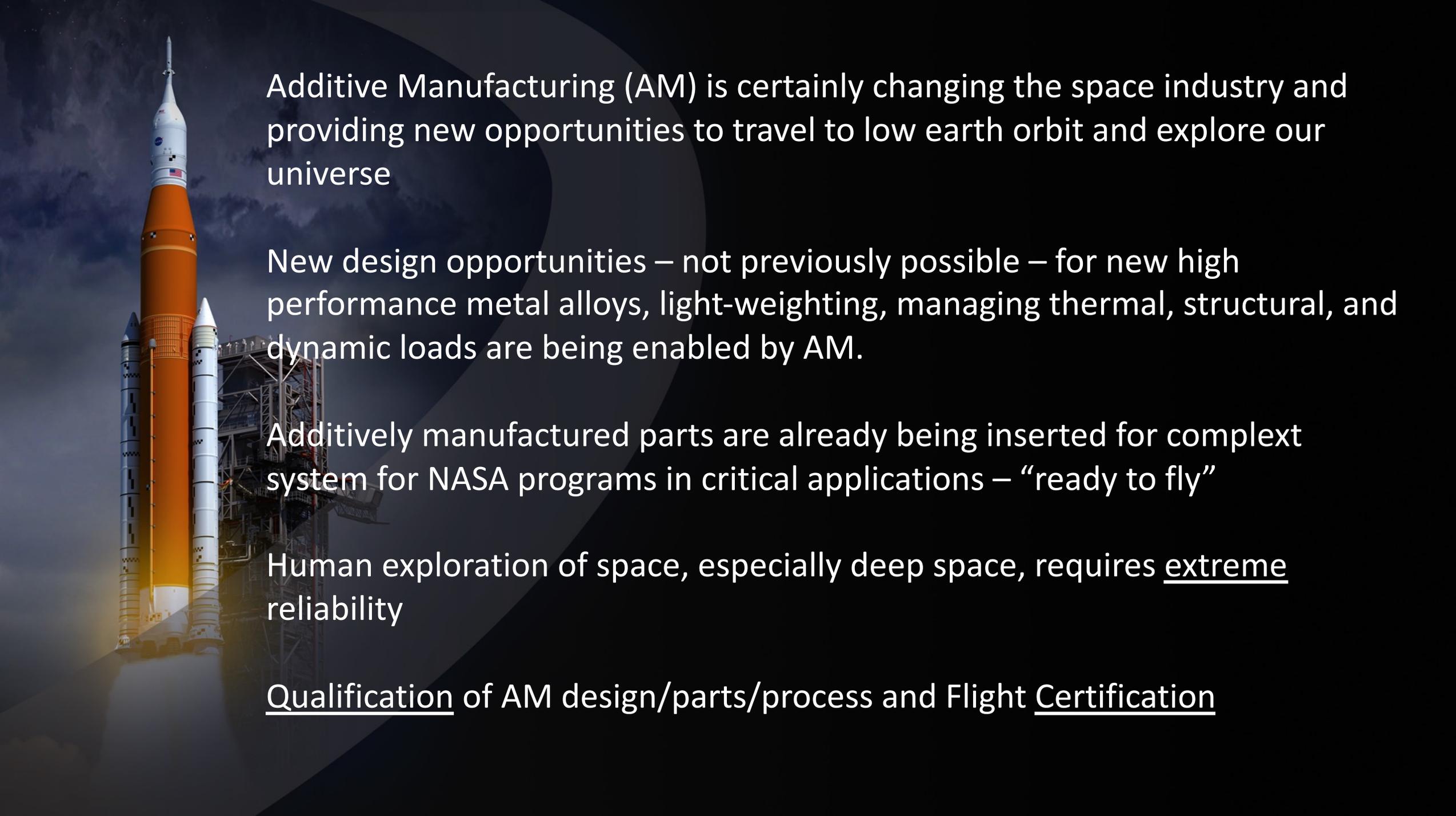
EXPLORE

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**“Additive Manufactured Hardware Qualification and
Certification at NASA”**

ASME IDETC/CIE 2024 – IAWG Meeting, Aug 27th, 2024

A large orange and white rocket stands on a launch pad at night. The rocket is the central focus, with its orange boosters and white core stage clearly visible. The launch pad structure is partially visible to the left. The background is a dark, cloudy sky.

Additive Manufacturing (AM) is certainly changing the space industry and providing new opportunities to travel to low earth orbit and explore our universe

New design opportunities – not previously possible – for new high performance metal alloys, light-weighting, managing thermal, structural, and dynamic loads are being enabled by AM.

Additively manufactured parts are already being inserted for complex system for NASA programs in critical applications – “ready to fly”

Human exploration of space, especially deep space, requires extreme reliability

Qualification of AM design/parts/process and Flight Certification

AM Qualification and Certification



- American National Standards Institute (ANSI) coordinated an activity to clarify the current and desired future AM landscape ([version 3 Roadmap released](#), Feb 2024)
- Identified AM Qualification and Certification as having the greatest number of high-priority open gaps
- We have been qualifying flight parts for a long time
- We know how to integrate parts into complex systems
- AM Qual is not that special, BUT we need to be reminded of...
 - Individual nature of AM
 - Potential failure modes on a stand-alone operation
 - Process sensitive
 - Rapidly evolving tech
 - Lacking in experiences and standards of performance
 - Need increased scrutiny on build-to-build material quality + periodic review and confirmation (process control)
- Need to establish a common framework of AM Standards and Specifications

Qualification and Certification – “NASA Definition”



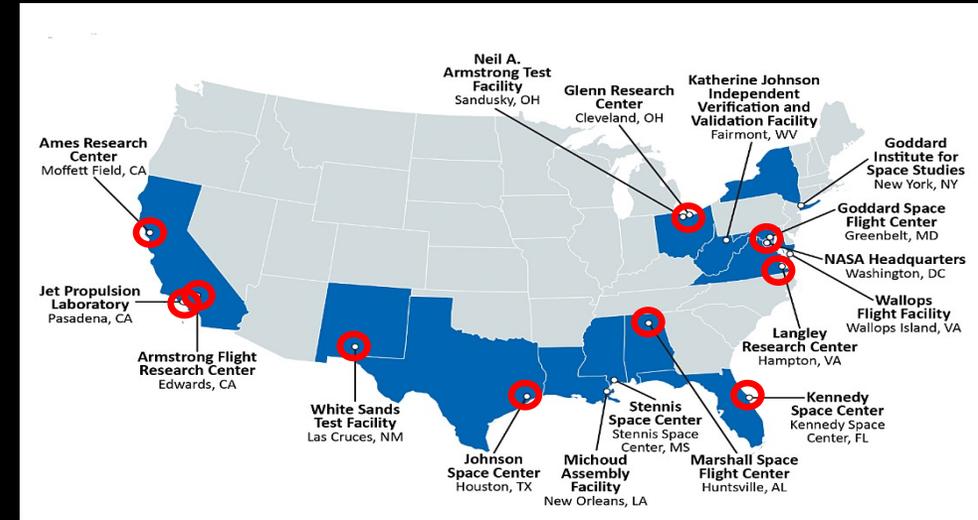
- Answer varies by industry and even by culture within industries
- The following interpretations are common within NASA, in context of AM:
 - Qualification applies to
 - Parts and components
 - Processes
 - Certification applies to
 - Design (e.g., status following Design Certification Review)
 - Subsystems (e.g., engine level certification test series)
 - Integrated system (e.g., collective certification for flight for launch vehicle)

Certification is granted by the responsible reviewing authority when the **verification process is complete**, assuring both **design and as-built hardware** will meet the established **requirements** to safely and reliably complete the intended mission

Additive Manufacturing at NASA



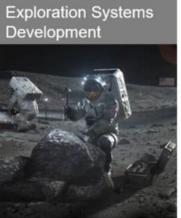
- “NASA is an user of AM” means...
 - NASA engineers utilizing AM processes to make hardware = NASA has the design authority
 - NASA procuring sub-system (rocket engine) or system (lunar lander spacecraft) from a commercial vendor/partner = NASA does not have the design authority; vendor does



- NASA is NOT monolithic
 - Geographically different
 - Flight Center vs. Research Center
 - Mission Directorate Focused
- Each Center is supposed to be “mission-agnostic” but heritage center culture still exists and gets reflected in project execution and practices
- End goal → Safe and successful missions

NASA Mission Directorates



Aeronautics	Space Technology	Science	Exploration Systems Development	Space Operations
				
NASA explores technologies that reduce aircraft noise and fuel use, get you gate-to-gate safely and on time, and transform aviation into an economic engine at all altitudes.	NASA technologies developed for spaceflight benefit our everyday life. The Artemis program proves and matures what those technologies can do and reduces risk for exploration of Mars and beyond.	NASA and the nation's science community use space observatories conduct scientific studies of the Earth from space to visit and return samples from other bodies in the solar system, and to peer out into our galaxy and beyond.	NASA's Artemis program is defining and creating the steps path from Earth back to the Moon and on to Mars, including the Orion capsule, the Space Launch System, Exploration Ground Systems, the Gateway, and Human Landing System.	NASA's work in beyond low-Earth orbit includes commercial launch services to the International Space Station, exploration systems, space transportation systems, and broad scientific research on orbit.



AM at NASA – past, present, and future

- Past (2010 ~ 2020)
 - AM Tech Development - Focused on the **understanding AM processes** through material characterization and testing, standards development, component design iteration, and **infusion into rocket propulsion development**
 - Having **insights and oversights** on other people’s AM design and hardware (**Commercial Space** companies)
- Present (2020~now)
 - **AM-enabled** Alloy Development (Refractory, Oxide Dispersion Strengthened, Cu-Cr-Nb)
 - AM Tech Development – **Large scale** for rocket nozzles, Multi-metallic and multi-AM process
 - Outreach – Technical Journal articles, Conference presentations, Webinars, AM 101, AIAA Book
 - Partnership with AM and Commercial Space Community
 - **Certifying** and **Flying** AM hardware on NASA missions
 - Release of NASA Technical Standard for “AM Requirements for Spaceflight Systems”, **NASA-STD-6030 and 6033**
- *Future*
 - *NASA being the **prolific user of AM** (NASA being a maker for certain missions) leveraging Generative Design AI to evolve optimal design*
 - *NASA **working with other Federal Agencies** on AM Certification Strategy and Lessons Learned*
 - *NASA Centers having its own AM User Group and integrated with each other*
 - ***Digital Twin based** AM Certification approach*
 - *AM enabling manufacturing “for space, in space, and in-situ”*



Digital Twin-based AM Certification - Future

- The ideal “digital twin” (DT) concept bridges both design certification and hardware certification
- The DT lends itself to an evolutionary implementation because its development is inherently incremental and when complete the twin exists as a collection of digital entities that combine to form a substantiation of the process and part
- The implementation of the DT concept in certification is best done as an evolution as opposed to a revolution
- We need to watch for opportunities, even if small, to augment the certification process with Computational Modeling (CM) while the DT concept matures.



Digital Twin-based AM Certification - Design

- Modeling for build success and build material quality
 - Optimal orientation, thermal control, support strategies
 - Coupon to part geometry correlations based on flaw population and microstructure
 - ***Prediction-based planning for pre-production article assessment***
- Assistance in definition of AM Process Box for process qualification
 - Computational validation of parameters
 - Prediction of process box boundaries
 - ***“Challenge Part” design – prove process box reliability through geometry and thermal history***
- Intelligent risk-based part zoning through integrated assessment tools
 - Prediction of process quality: flaw populations / microstructure
 - Prediction of inspection capability



Digital Twin-based AM Certification - Hardware

- Efficiencies in routine part acceptance
 - Machine learning tools
 - Microstructural evaluation
 - Powder feedstock characterization and acceptance
- Validation of in situ monitoring techniques and data
 - Causal relationship must be established between defects and monitored response
 - Modeling of process and monitoring methods may reduce empirical burden
 - ***Enable in situ monitoring to serve a quantitative NDE role***
- Computational non-destructive evaluation (NDE)
 - Understanding detection capability in complex geometries
- Hardware acceptance activities are ripe for near-term implementation of CM

Ensuring Safe AM Insertion

- Goal – Safe and Successful Mission
- AM technology is demonstrating incredible benefits in widespread applications, design flexibility, affordability, schedule, performance, sustainability, and production on demand
 - **Certification challenge:** complexity, unknowns, and delays can negate the benefits
- NASA continues to be a leader in the advancement of policies for the Certification of AM processes and parts
 - NASA-STD-6030 and 6033, Agency standard for additive manufacturing; actively being used for critical NASA flight programs at NASA and Commercial Space Companies
 - NASA's 6030 Framework and policy is being leveraged at AM Community, other US agencies and International partners



SpaceX Dragon – ISS Crew



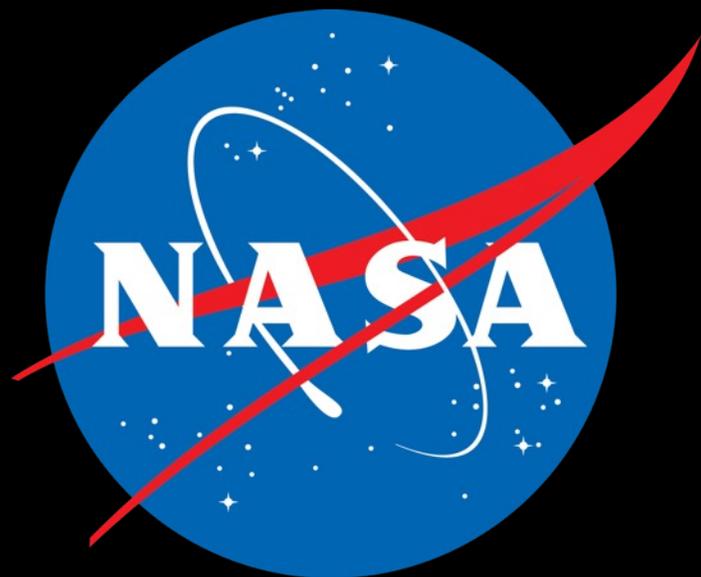
Boeing Starliner – ISS Crew



SpaceX Starship Lunar Lander



Blue Origin Lunar Lander



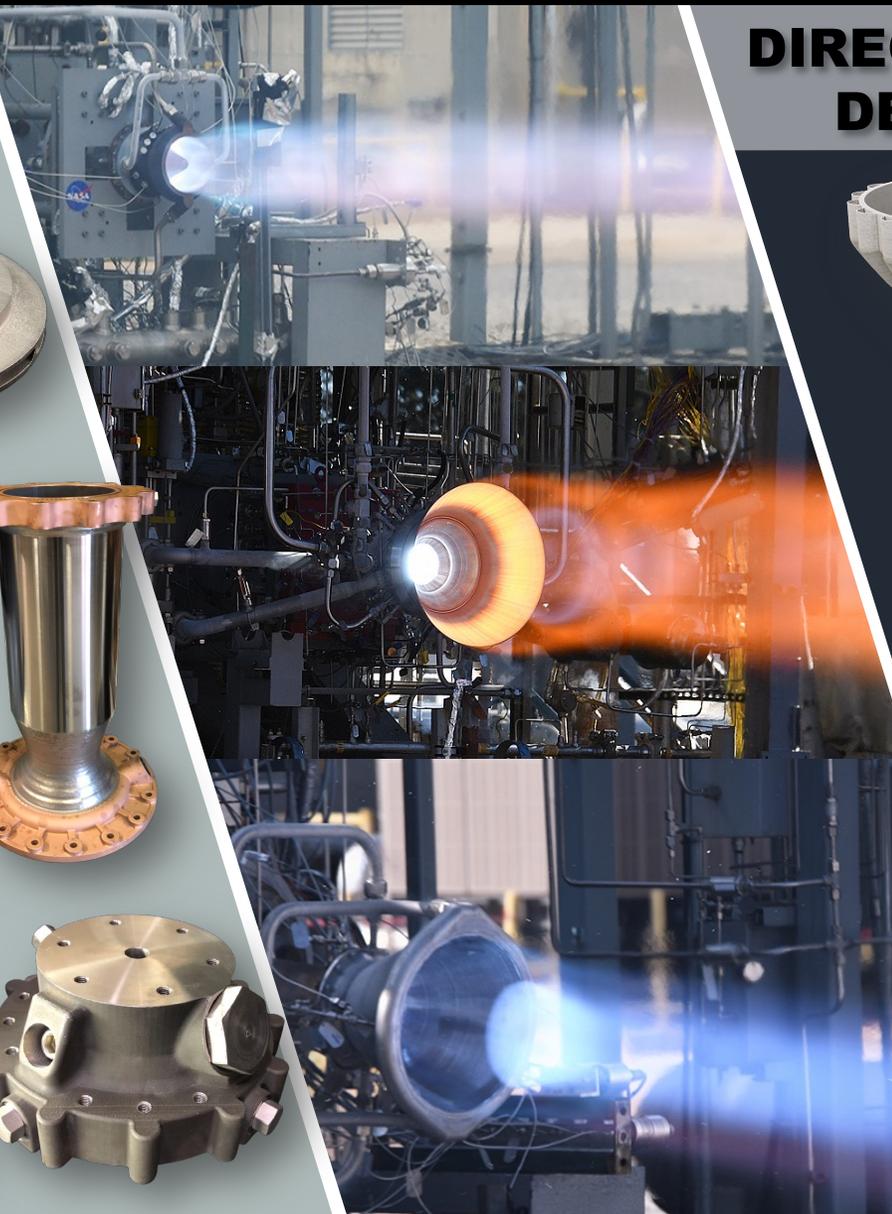
Advancing Metal AM – Real Hardware!



LASER POWDER BED FUSION



DIRECTED ENERGY DEPOSITION



Credit – Paul Gradl (NASA MSFC)

Fostering – Partnership with Commercial Space

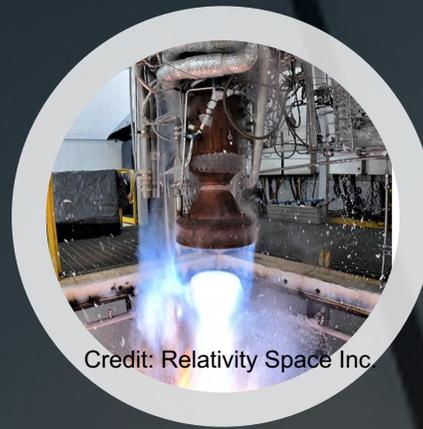
- NASA Partnership Office published an article on a success story on NASA-enabled innovation in AM that helped a commercial company
- *“Through a series of Space Act Agreements, engineers at Marshall Space Flight Center have helped Relativity Space Inc. of Long Beach, California, 3D print its Aeon rocket engines using a NASA-invented copper alloy, and the company leases space and facilities at Stennis Space Center to test the engines. These partnerships have saved the company untold time and money.”*

https://spinoff.nasa.gov/Additive_Manufacturing_Subtracts_from_Rocket_Build_Time

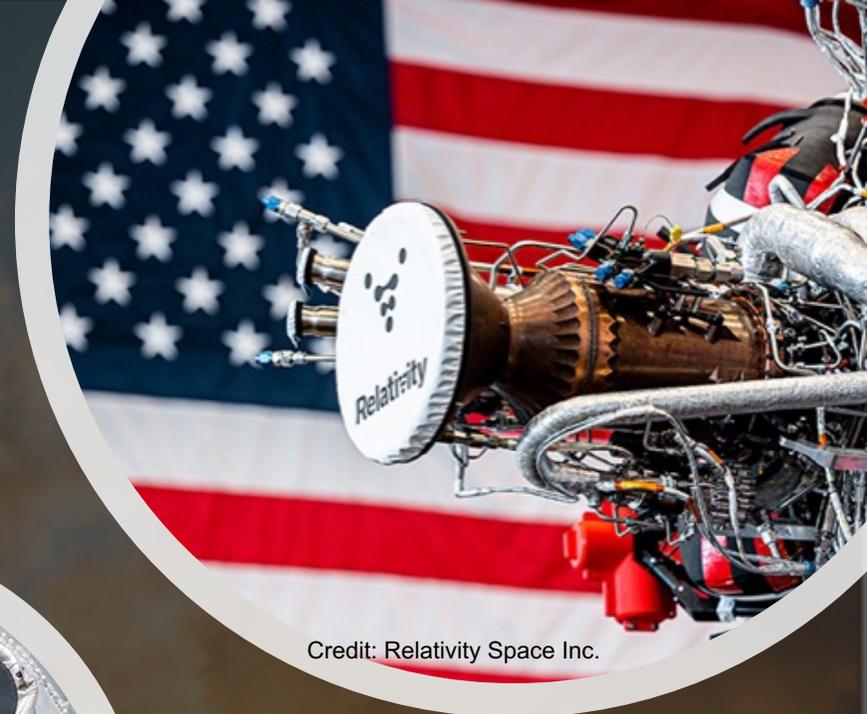


GRCop-42 Chamber

- Paul Gradl and his NASA Marshall Spaceflight Center engineers worked collaboratively with Relativity engineers to insert AM GRCrop-42 alloy and processes and meet mission requirements
- *“partnerships like this help the space agency stay on top of the challenges facing the commercial space industry and work on solutions to those challenges.”*



Credit: Relativity Space Inc.



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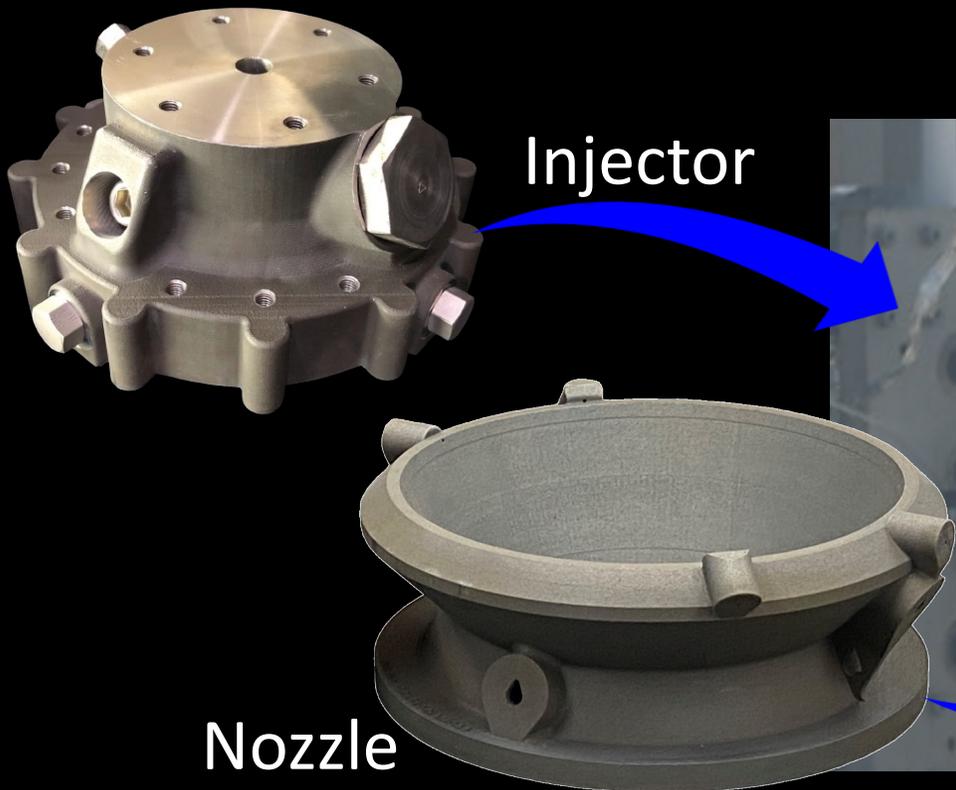


Credit: Trevor Mahlmann

Advancing Metal AM – New AM-enabled Alloy



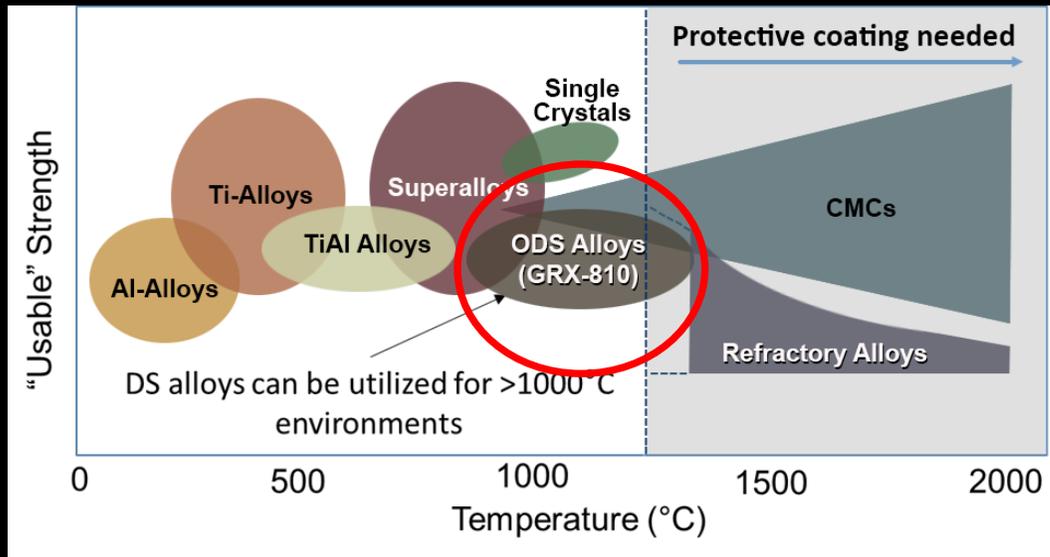
- GRX-810 Injector achieved 84 starts and 2,228 sec (Liquid Oxygen/Methane)
- Similar injectors with Inconel 718/625 would see erosion after 8-10 starts
- GRX-810 nozzle achieved 91 starts and 2,309 sec
- Average temperatures in excess of 1500°F for sustained durations



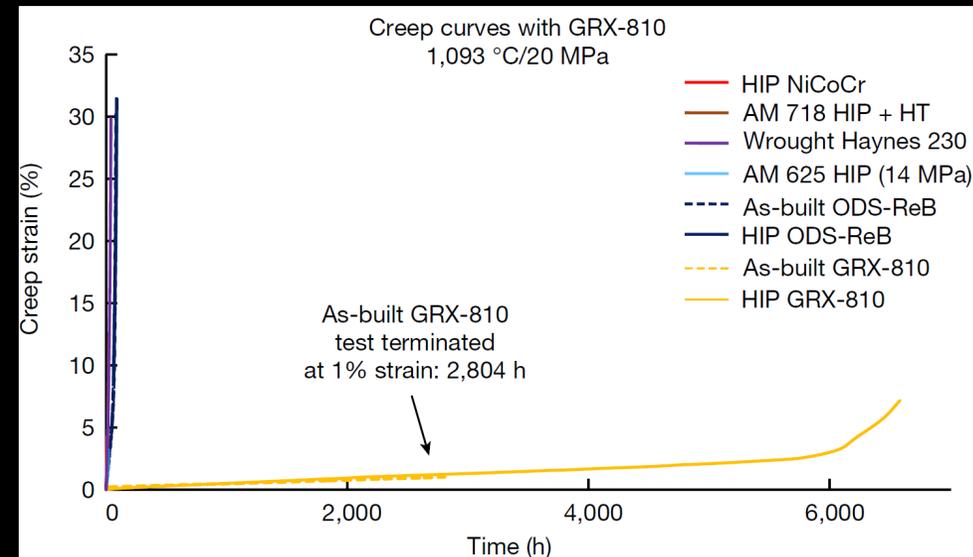
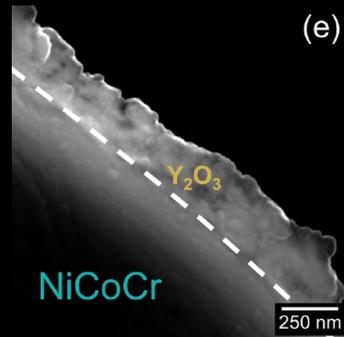
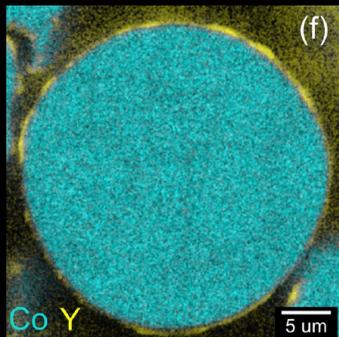
Credit – Paul Gradl (NASA MSFC)

Advancing Metal AM – New AM-enabled Alloy

Motivation



- Glenn Research Center eXtreme temperature alloy (GRX-810) was developed using ICME
- Ni-Co-Cr medium entropy alloy with nano-scale Y_2O_3 coating.
- Significantly improved properties:
 - 2x strength at elevated temperatures ($1100^\circ C$)
 - 1,000x better creep rupture
 - 2x better resistance to oxidation





Generative Design & Lattices (GSFC)



<https://www.nasa.gov/science-research/nasa-turns-to-ai-to-design-mission-hardware/>

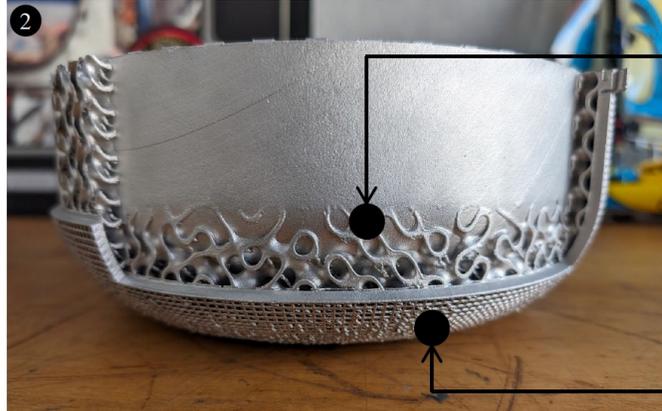


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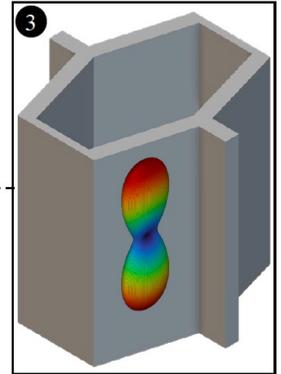
Lattice Structure (Variable Lattice Network) Metal Additively Manufactured Component



Lattice Structure Network (Close-Up)

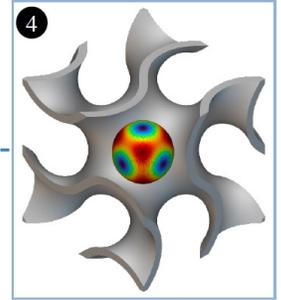


Hexagonal Honeycomb (Internal Stiffness)



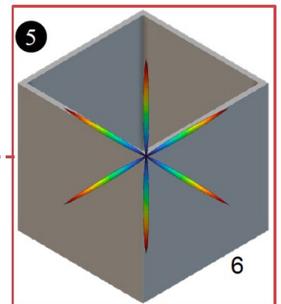
Lattice 1

TPMS Gyroid (Thermal Efficiency)



Lattice 2

Square Honeycomb (Shock Absorption)



Lattice 3



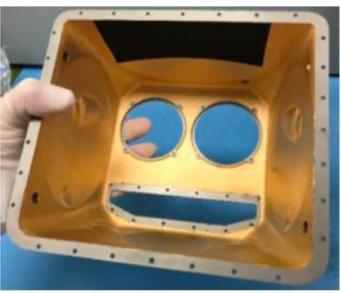
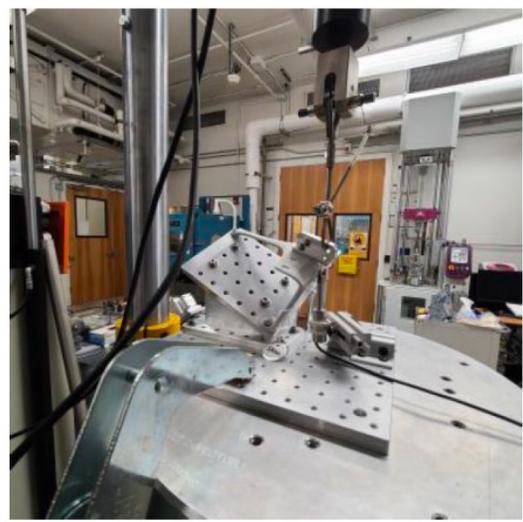
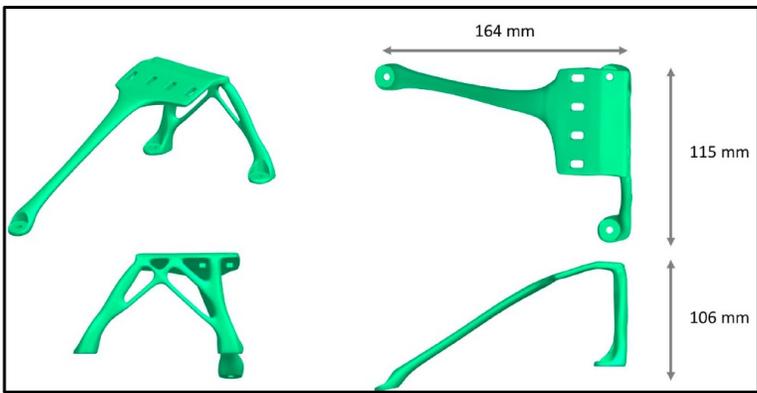
To Mars and Beyond (JPL)



X-ray bench and support



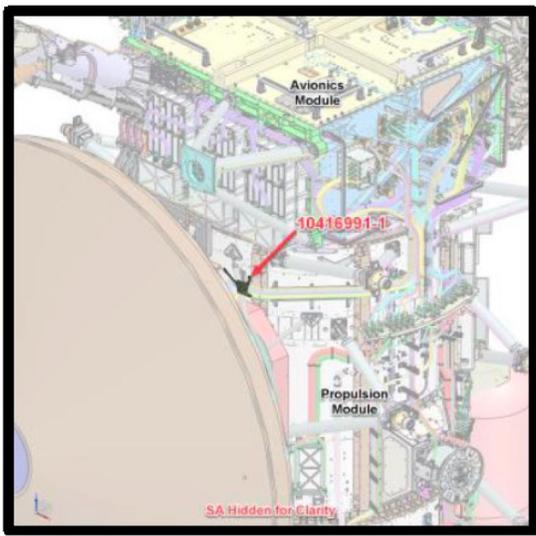
Mounting frame



Back cover



Front cover



Images courtesy NASA/JPL-Caltech

Images courtesy NASA/JPL-Caltech

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