EXPLORE

Alison Park
Deputy Tech Fellow – NASA Engineering and Safety Center
KARI Mfg Tech Talk| Dec 5, 2023| South Korea

Technology Drives Exploration: How NASA is embracing Additive Manufacturing

Executive Summary of Today’s Presentation

NASA has over 60 years of technology development that enabled human space and space science exploration “for the benefit of all humankind”. This presentation will start with the overview of NASA’s organization structure; the roles NASA’s leadership plays as well as 10 regional centers’ focused areas and capabilities. It will also highlight NASA’s Mission Directorates – Science, Human, Aeronautics, and Technology. With the onset of the newer and still evolving procurement business model (NASA being a buyer, instead of maker), a question remains: which is the right framework under which NASA can best integrate the capabilities of commercial, international, and other US government entities into a coherent exploration strategy? Another critical consideration is identifying which critical technologies to invest in NASA and which capabilities are better suited for commercialization as NASA as a buyer.

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. This presentation will showcase the vast portfolio of NASA’s AM activities in the last 13 years; transportation from Earth to Destination, Habitat at Destination, Lander from Station to Surface, and Science mission spacecrafts. NASA’s technical excellence is being leveraged heavily in the AM and Commercial Space community through collaborative projects, partnership agreements, tech transfer program. Examples of challenges of AM implementation as well as opportunities will be discussed.

Today's Topics

- *NASA Organization Structure + Mission Directorates*
- *New Space Economy and NASA*
- *Technology Drives Exploration*
  - *Why* and *When* to use AM: Alison's perspectives
  - AM at NASA and around the US Space Community

- Case Study: How AM is being used/should be used
  - AM-enabled Alloy Development (GrCop Alloys, GRX-810)
  - AM Qualification and Certification
    - Classic Process Control-based approach (Current)
    - Digital Twin-based approach (Future)

- Backup – Space Tech Mission Directory Portfolio

Speaker Introduction

Alison Park – Deputy Tech Fellow at NASA

Works at NASA Chief Engineer's Office – NASA Engineering and Safety Center

Responsible for safe implementation of Additively Manufactured Hardware for critical NASA missions – AM Qualification and Flight Certification Rationale (Higher TRL AM Techs)

Being involved in Additive Technology Innovation and Maturation activities around the agency (Lower TRL AM Techs)

B.S. Materials Science and Engineering, Purdue University
M.S. Aerospace Materials Engineering, UCLA

24 years of experiences working for both commercial (Rocket Propulsion) and Government (NASA) - 14 Years in Additive Manufacturing

Editor's note: An accessible version of the information on this chart is available at the NASA organization web page.

NASA Administrator
Bill Nelson

Deputy Administrator *
Pam Melroy

Associate Administrator
Bob Cabana

Chief of Staff
Susie Perez Quinn

Deputy Associate Administrator
Casey Swails

Advisory Groups
NAC and ASAP

Inspector General

Office of the Chief Financial Officer
Margaret Vo Schaus

Chief Scientist and Senior Climate Advisor
Kate Calvin

Office of Technology, Policy, and Strategy
Charity Weeden

Office of International and Interagency Relations
Karen Feldstein

Office of Diversity & Equal Opportunity
Elaine Ho

Office of Small Business Programs
Glenn Delgado

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Dave Mitchell

Chief Safety and Mission Assurance
Russ DeLoach

Chief Health and Medical Officer
J.D. Polk

Chief Engineer
Joe Pellicciotti

Mission Directorates

Space Operations Mission Directorate
Ken Bowersox

Aeronautics Research Mission Directorate
Robert Pearce

Exploration Systems Development Mission Directorate
Jim Free

Space Technology Mission Directorate
Prasun Desai (acting)

Science Mission Directorate
Nicky Fox

Mission Support Directorate
Bob Gibbs

Office of Procurement
Karla Smith Jackson

Headquarters Operations
Nichole Pickney

Office of the Chief Human Capital Officer
Kelly Elliott

Office of Protective Services
Joseph Mahaley

NASA Shared Services Center
Jaime Krauk (acting)

Office of Strategic Infrastructure
Joel Carney

NASA Centers

Ames Research Center
Eugene Tu

Glenn Research Center
James Kenyon

Johnson Space Center
Vanessa Wyche

Langley Research Center
Clayton Turner

Jet Propulsion Lab (JPL)
Laurie Leshin

Stennis Space Center
Richard Gilbrech

Armstrong Flight Research Center
Brad Flick

Goddard Space Flight Center
Makenzie Lystrup

Kennedy Space Center
Janet Petro

Marshall Space Flight Center
Joseph Pelfrey (acting)

NASA Office of JPL Management & Oversight
Andrea Razzaghi

*Designated as Chief Acquisition Officer (CAO)

JPL is a Federally Funded Research and Development Center (FFRDC

Current as of Oct. 18, 2023

NASA's Mission Directorates

Science Mission Directorate

Science Missions

Peering into the creation of the universe and traversing Mars

The James Webb Space Telescope is an orbiting infrared observatory that will look to the beginning of time and to hunt for the unobserved formation of the first galaxies, as well as to look inside dust clouds where stars and planetary systems are forming today.

Much closer to home, NASA has sent five robotic vehicles, called rovers, to Mars. Rovers help scientists in their quest to understand what different parts of the planet are made of.

View All Science Missions

NASA's James Webb Space Telescope's mid-infrared view of the Pillars of Creation strikes a chilling tone. Thousands of stars that exist in this region seem to disappear, since stars typically do not emit much mid-infrared light, and seemingly endless layers of gas and dust become the centerpiece. The detection of dust by Webb's Mid-Infrared Instrument (MIRI) is extremely important – dust is a major ingredient for star formation.
NASA, ESA, CSA, STScI; Joseph DePasquale (STScI), Alyssa Pagan (STScI)

Human Mission Directorate

Human Missions

From low Earth orbit to the Moon and Mars

Rotational crews have been living in low Earth orbit continuously aboard the International Space Station since 2000. Located about 250 miles above Earth, the space station is a full-time microgravity laboratory. On behalf of researchers worldwide, station crews conduct experiments only possible in the unique conditions of space, observe Earth as a system, and test new technologies that ultimately will help send humans far beyond Earth.

Artemis missions will send humans to the Moon for long-term scientific exploration and discovery. Artemis I was an uncrewed flight test that traveled 40,000 miles past the far side of the Moon and back to Earth to validate the Space Launch System rocket, Orion spacecraft, and other key systems. Artemis II will be the first flight test with astronauts to validate crew life support systems, and Artemis III will mark the beginning of humanity's return to the lunar surface.

Living and working in low Earth orbit and at the Moon will help NASA and its partners prepare for the next giant leap: sending humans to Mars.

View Human Spaceflight Missions

Clockwise from left, Expedition 68 flight engineers Anna Kikina, Josh Cassada, Nicole Mann, and Koichi Wakata pose for a fun portrait aboard the International Space Station.
NASA

Aeronautics Mission Directorate

Quesst

Lowering the Sonic Boom

NASA's aeronautical innovators are leading a government-industry team to collect data that could make supersonic flight over land possible, dramatically reducing travel time in the United States or anywhere in the world.

More on the Quesst Mission

Artist illustration of the X-59 Quiet SuperSonic Technology aircraft, which will soon take skies as NASA's first purpose-built, supersonic experimental plane in decades.
Lockheed Martin

Technology Directorate

Space Technology

Demonstrating the innovations that help us go, land, live, and explore in space

Technology drives exploration and the space economy. Technology demonstrations enable NASA to mature the cutting-edge, laboratory-proven technologies and new capabilities that will transform future science and space exploration goals. Through these missions, we conduct ground-based or in-space testing to determine the feasibility of technologies and systems for use in NASA missions, for other government agencies, and with the commercial space industry

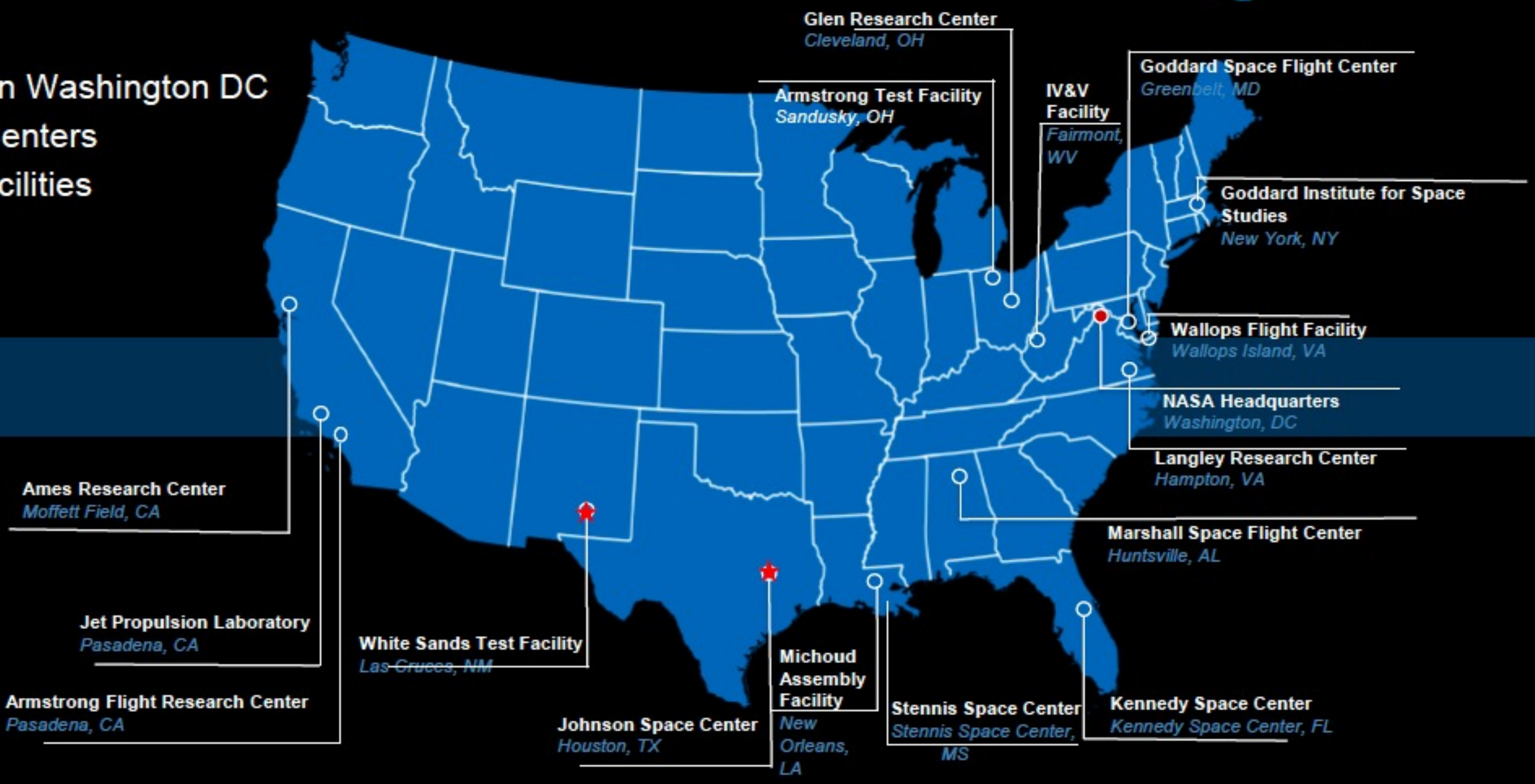
View Technology Missions

The flight demonstration unit of the next-generation 4-bed CO2 Scrubber (4BCO2) is targeted for launch aboard NG16 NET August 1, 2021. Once aboard the space station, this unit will be mounted in a basic express rack. This four-bed technology is a mainstay for metabolic CO2 removal and crew life support.

NASA Near You!

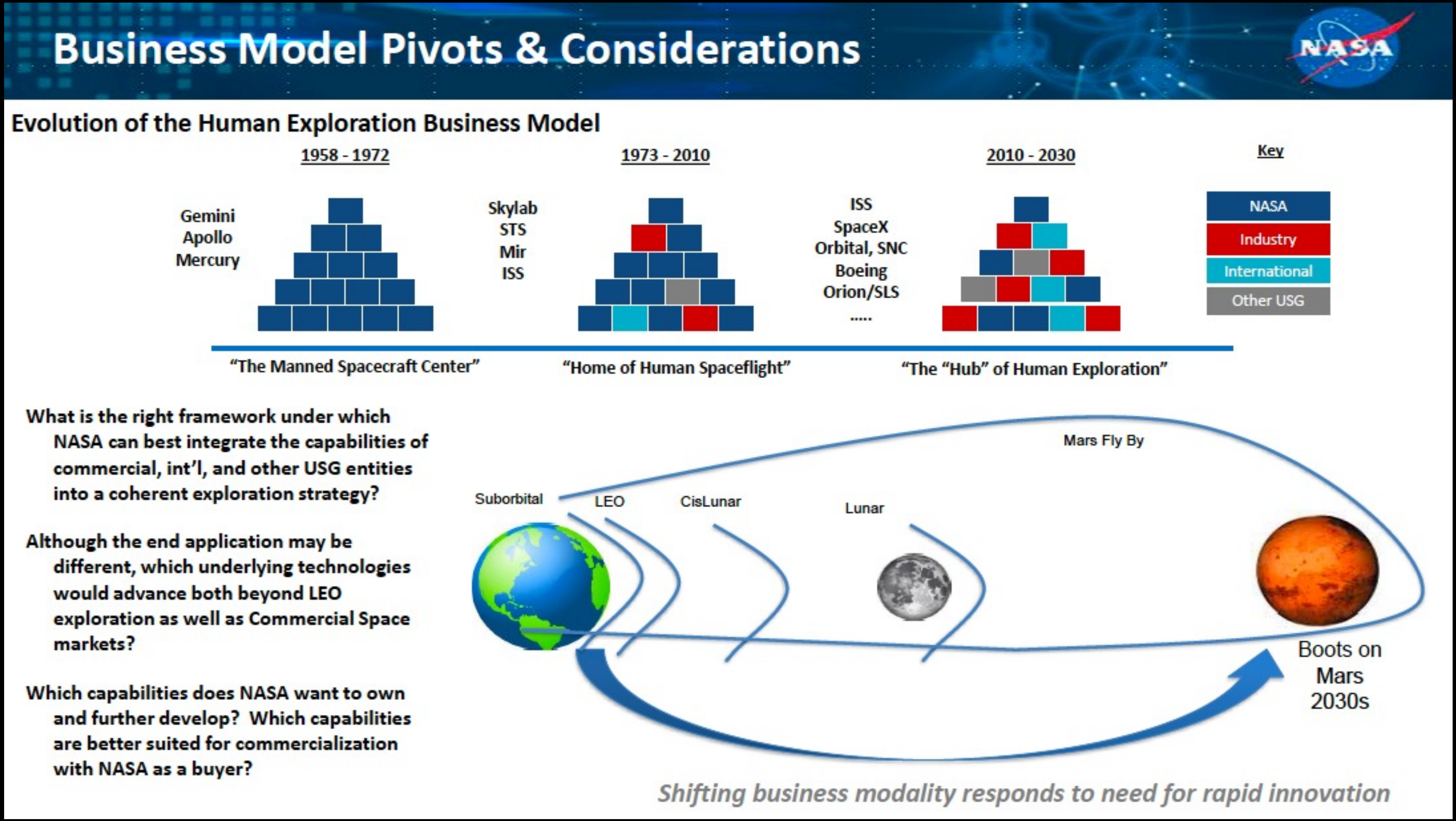
NASA TECHNOLOGY TRANSFER PROGRAM

- HQ in Washington DC
- 10 Centers
- 7 Facilities



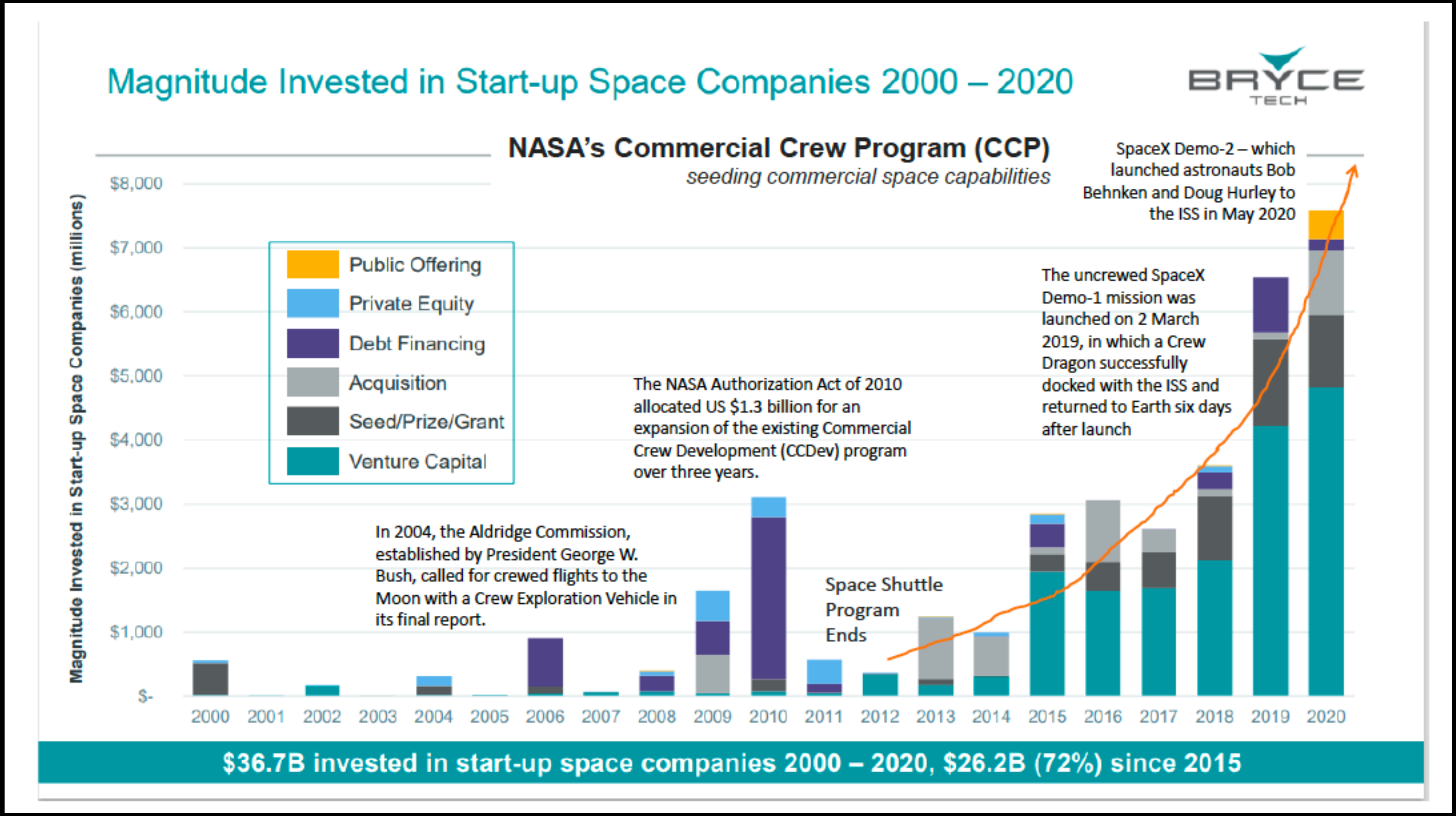
https://www.nasa.gov/centers-and-facilities/

NASA is adjusting to changing Space Economy



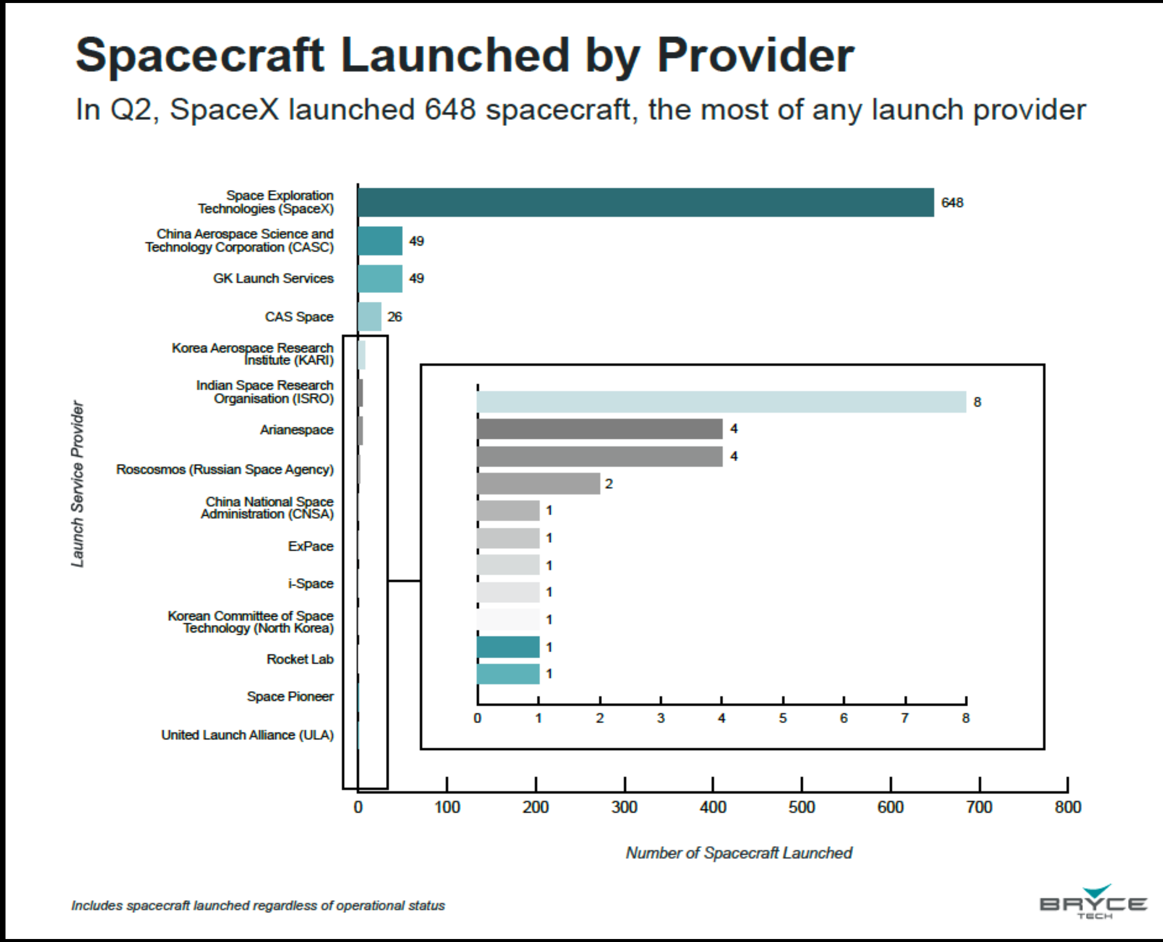
Courtesy of Walt Ugalde (NASA JSC)

Space Economy

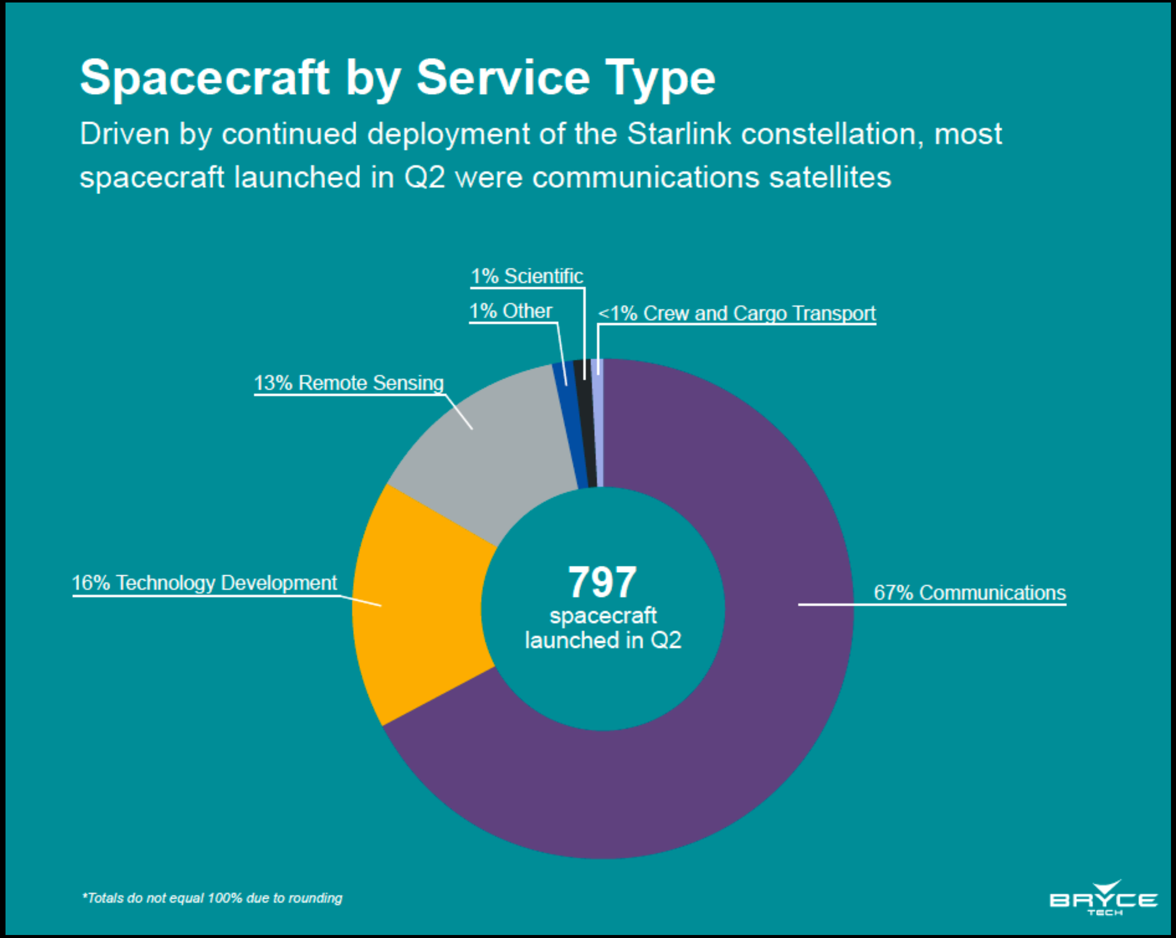


Courtesy of Walt Ugalde (NASA JSC)

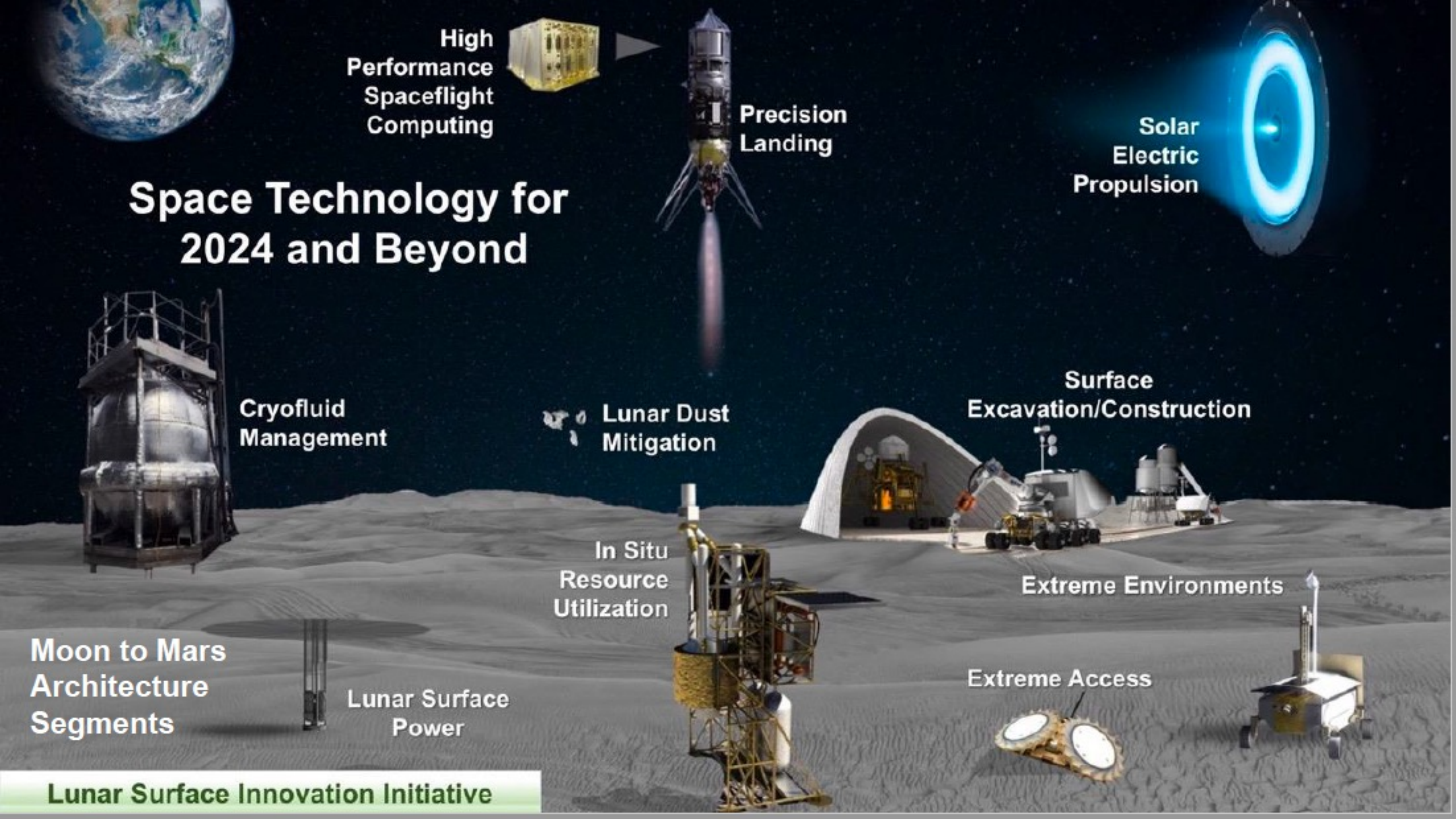
Players in Global Orbital Space Launches, Q2 2023

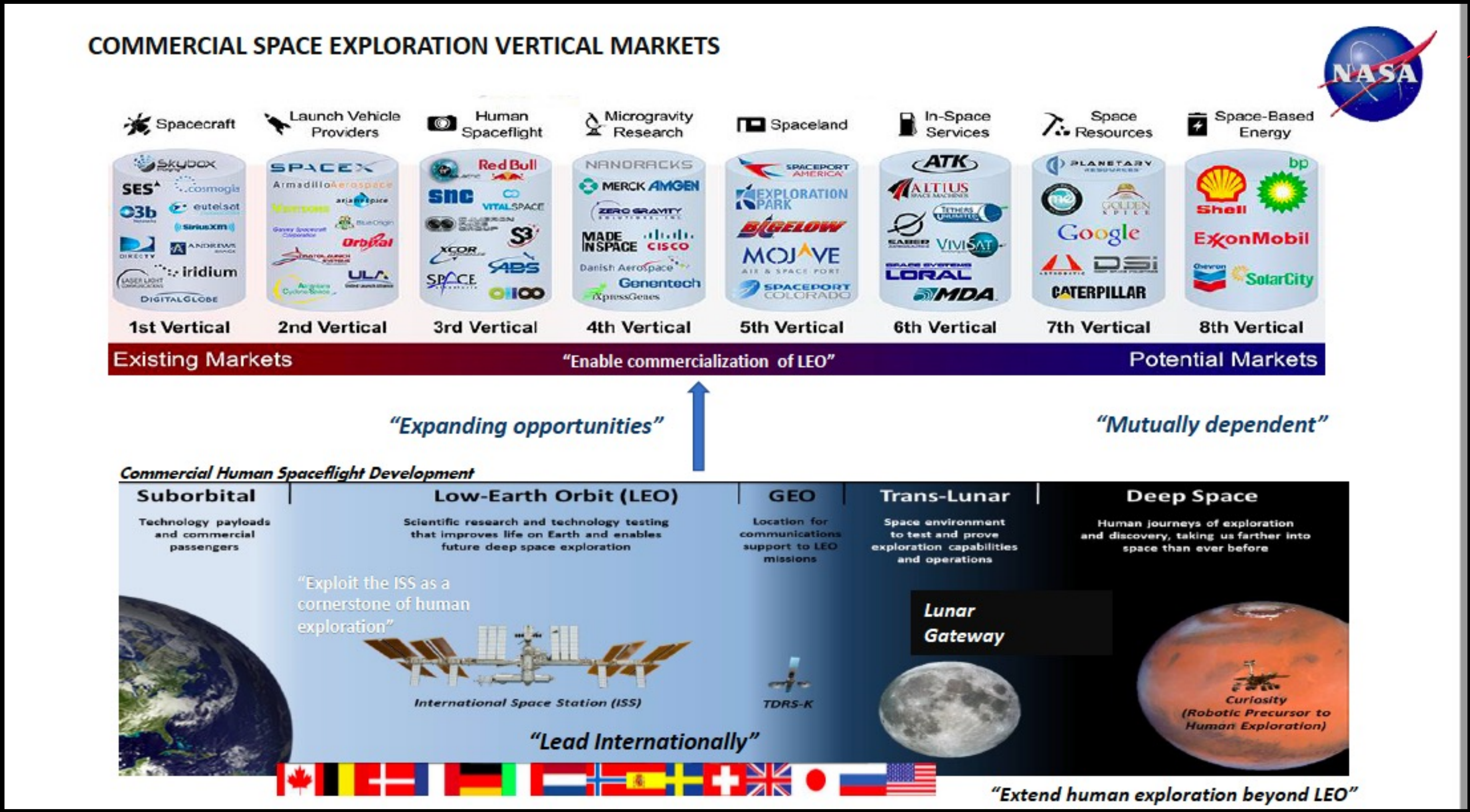


Courtesy of Bryce Tech Report



Courtesy of Bryce Tech Report


Space Technology for 2024 and Beyond
High Performance Spaceflight Computing
Precision Landing
Solar Electric Propulsion
Cryofluid Management
Lunar Dust Mitigation
Surface Excavation/Construction
In Situ Resource Utilization
Extreme Environments
Moon to Mars Architecture Segments
Lunar Surface Power
Extreme Access
Lunar Surface Innovation Initiative



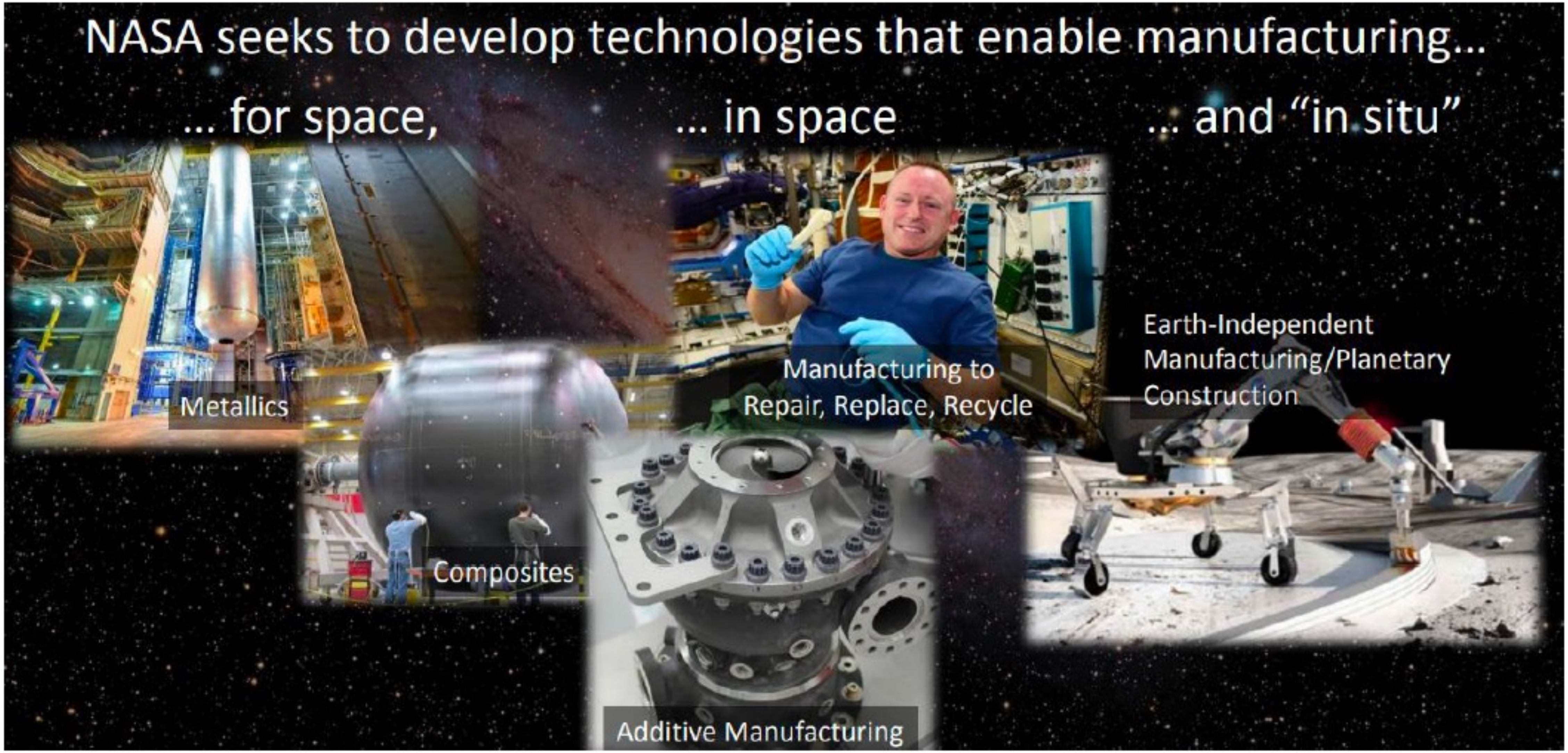
Courtesy of Walt Ugalde (NASA JSC)

What’s Next in Commercial Space

- Large LEO Constellations
- SmallSat Launch Ventures
- Space Tourism/Commercial Human Spaceflight
- Commercial Habitat and Stations
- Exploration
- On-Orbit Servicing, Assembly, and Manufacturing
- National Security

Reference from Bryce Tech ‘s Star-Up Space Report, 2022
Brycetech.com

MANUFACTURING TECHNOLOGY DEVELOPMENT DOMAINS



Courtesy of Walt Ugalde (NASA JSC)

Alison’s Perspectives on Additive Manufacturing

- Yes, It’s a cool technology but use it with purpose
- Embrace the benefits and appreciate the challenges
- Do your homework before you try to implement on critical missions
- Exciting opportunities in adjacent technologies (Integrated Computational Materials Engineering, Digital Twin, Modeling and Simulation, in-situ Monitoring Sensors, Advanced Non-Destructive Evaluation, Design AI…) exist now and will continue to be advanced

When to Use (Metal) Additive Manufacturing

- ~~You have a fully designed part~~
- ~~You need it to be good~~
- ~~You need it to be cheap~~
- ~~You need it quickly~~

} Recipe for Disappointment

- You need to prototype and/or iterate a *lot*
- You need an *extremely* optimized part (i.e., topology optimization)
- You can't easily make the part using legacy "subtractive manufacturing"
- You need a part with a high "buy to fly" ratio
- You literally *can't* make it any other way
- You want to decrease part count
- Novel Alloys not feasible with traditional manufacturing
- Sustainability/Local Manufacturing

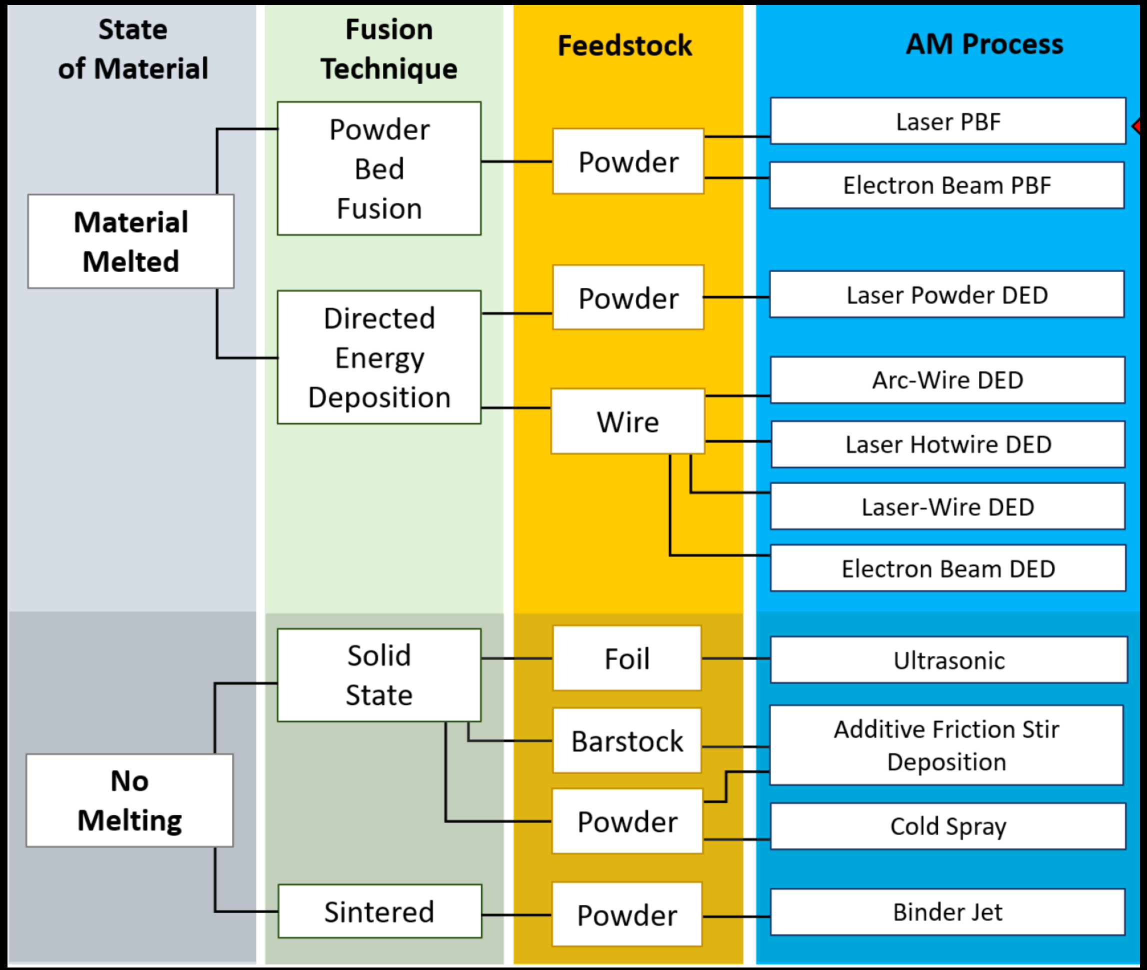
Additive Manufacturing (AM) – Which one??

<u>Definition</u>:

Process of joining materials to make parts from 3d model data, usually layer upon layer

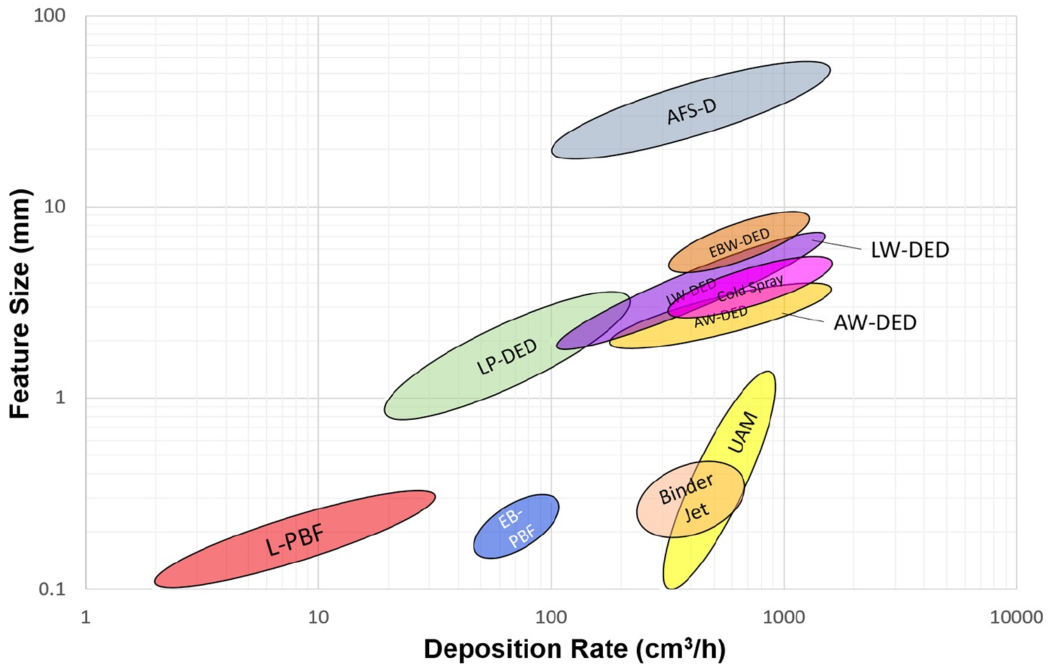
AM processes =

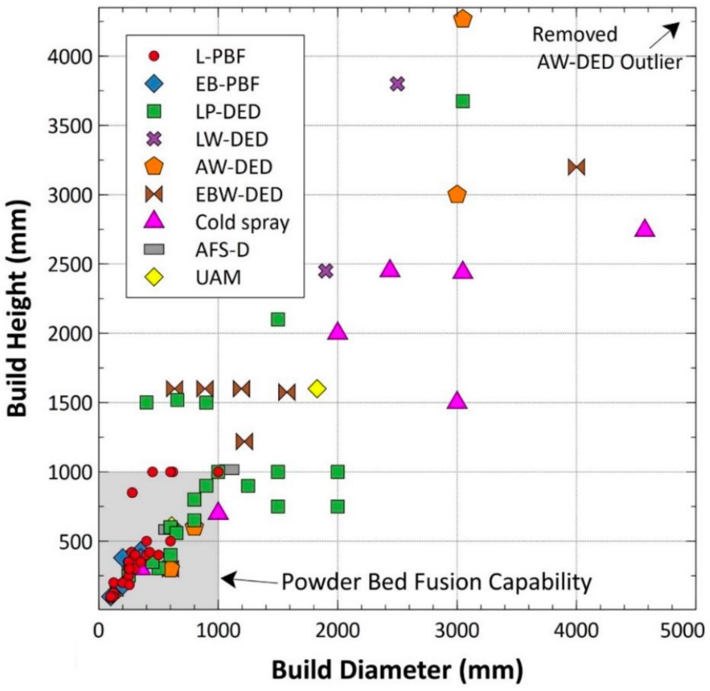
Material feedstock + Energy Source



Excerpt from "*Metal Additive Manufacturing for Propulsion Applications*"
AIAA Progress in Astronautics and Aeronautics Book Serie
P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

Things to consider to pick the right AM Process





Complexity of Features | Scale of Hardware | Material Physics | Cost | Material Efficiency

Speed of Process | Material Properties | Internal Geometry | Availability | Post Processing

Gradl, P., Tinker, D., Park, A., Mireles, O., Garcia, M., Wilkerson, R., Mckinney, C., 2021. Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components. Journal of Materials Engineering and Performance, Springer. https://doi.org/10.1007/s11665-022-06850-0

Excerpt from " *Metal Additive Manufacturing for Propulsion Applications"*
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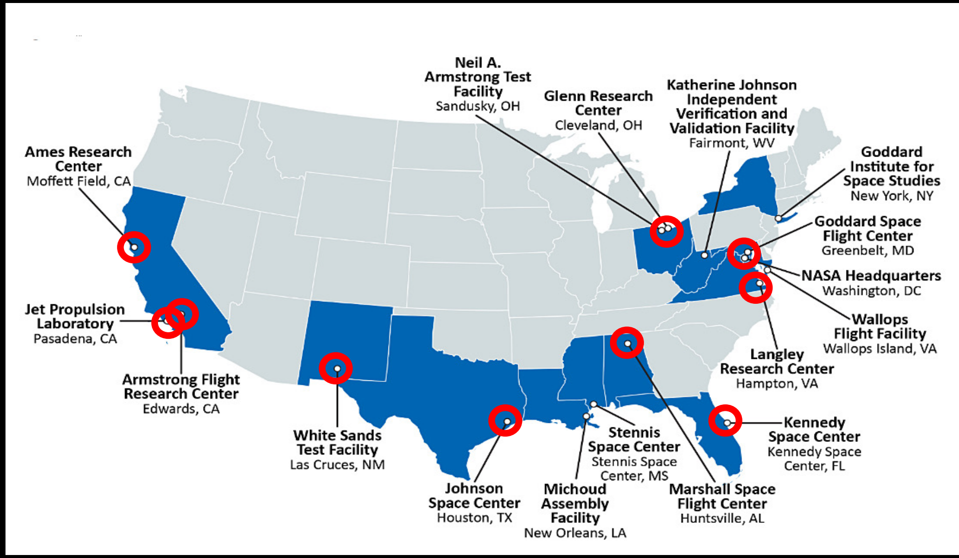
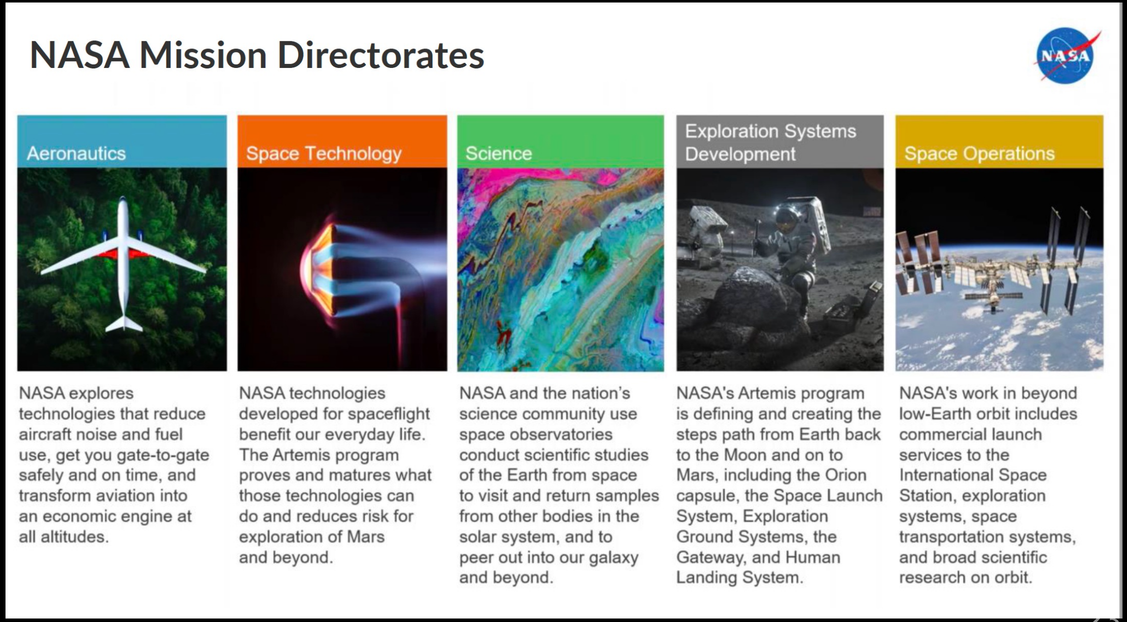
P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

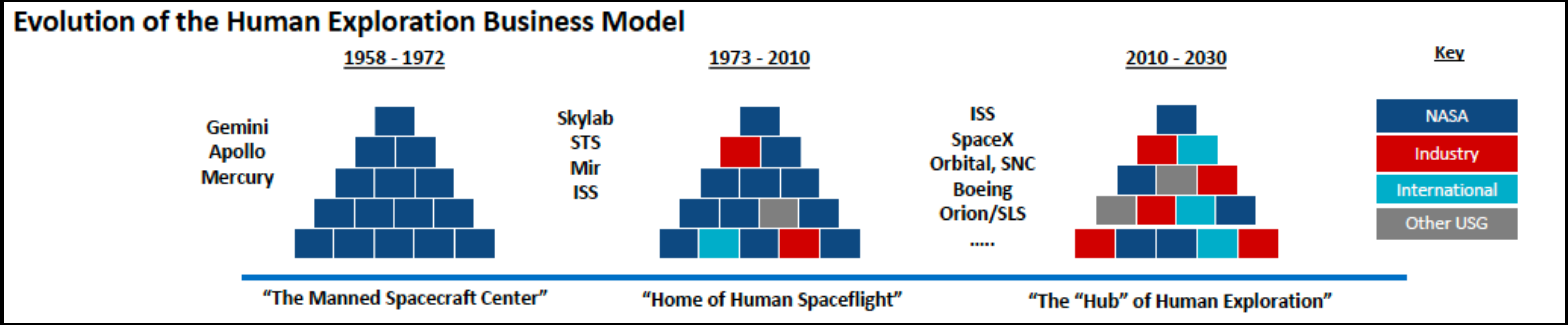
NASA is NOT monolithic

- 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





Space Business Model has been changing



Courtesy of Walt Ugalde (NASA JSC)

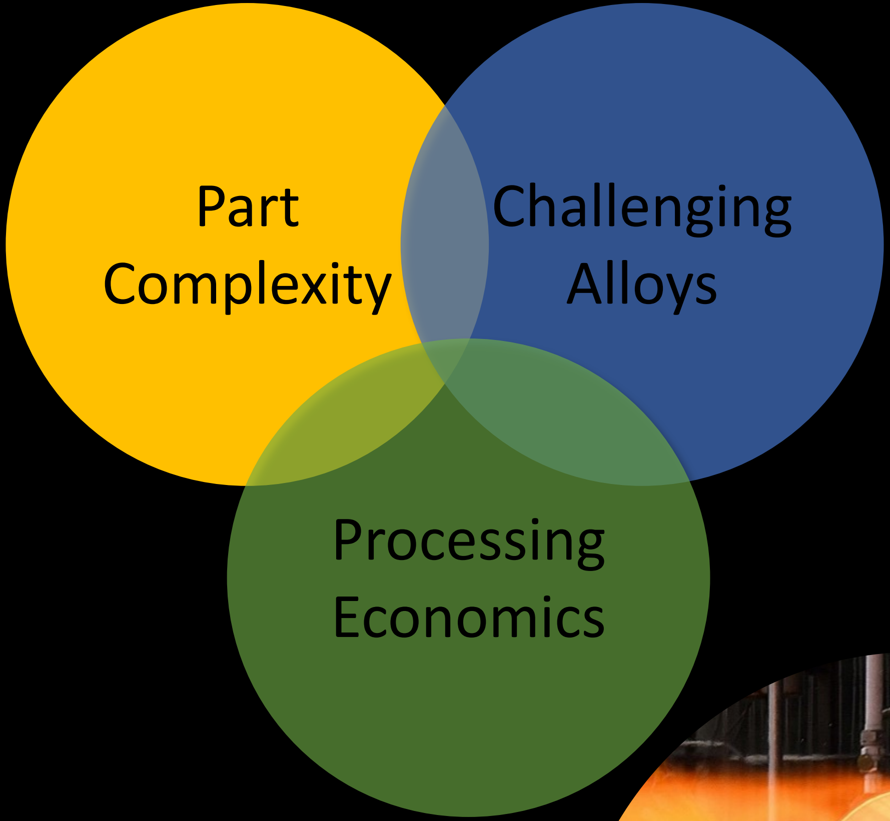
- *With NASA's newer procurement model (NASA being a buyer), NASA's need for production the flight hardware is shrinking*
- *But we deeply care about the underlying technologies that would advance us to beyond LEO exploration*
- ***Which technologies does NASA want to take a lead to own and further develop - AM***
- *Which technologies does NASA want Commercial Space market to lead*

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 Commercial Space AM hardware on NASA missions
- *Future*
  - *NASA being the prolific user of AM (NASA being a maker for certain missions) leveraging Generative Design AI to evolve optimal design*
  - *NASA walking the talk*
  - *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"*

The Case for AM in Rocket Propulsion

- Metallic AM can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new designs, part consolidation, and performance opportunities.
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.



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NASA's earlier work – case study for AM Rocket Combustion Chamber

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 GRCop-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 GRCop-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310,000	$200,000 (35%)	$125,000 (60%)

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Examples of NASA's AM Dev Work for Rocket Propulsion

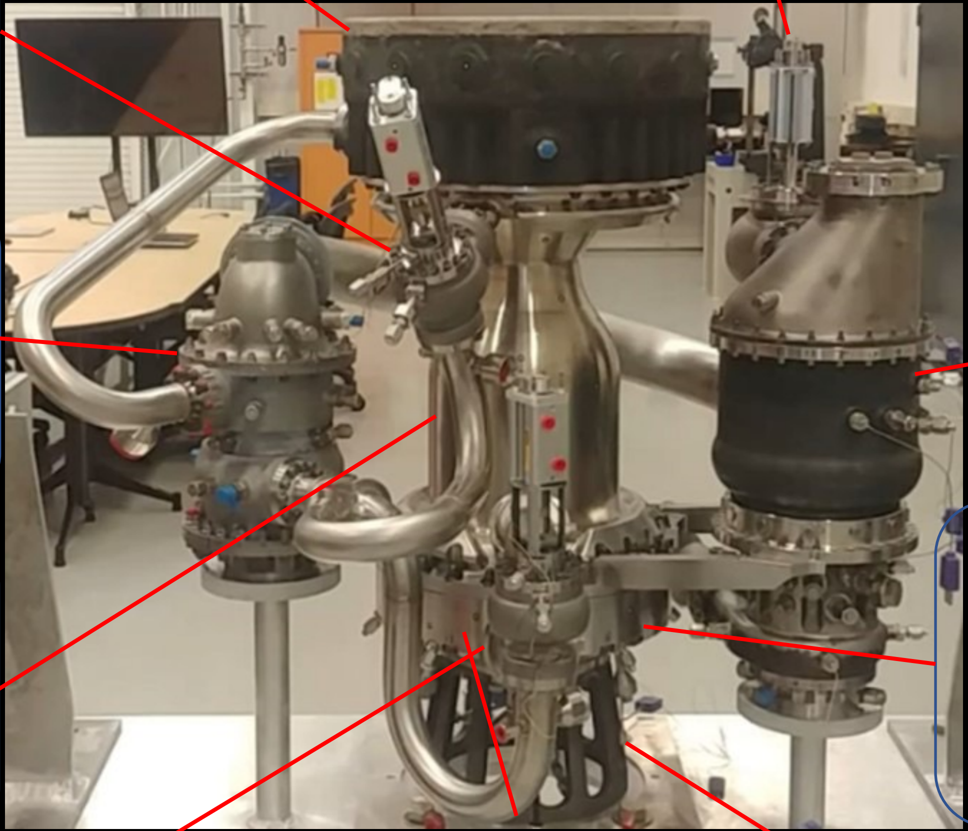
Main Fuel Valve
Part reduction: 5 to 1
Successfully tested

Fuel Turbopump
Schedule reduction by 45%
Part reduction: 40 to 22
Tested to 90,000 RPM

Combustion Chamber
Schedule Reduction: > 50%
Bimetallic L-PBF/DED
Tested to 100%

Regen Nozzle

Oxidizer Turbopump Bypass Valve
Part reduction: 5 to1



Mixer
Part reduction: 8 to 2

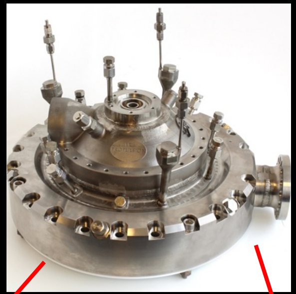
Coolant Control Valve
Part reduction: 5 to 1

Thrust Structure

Main Oxidizer Valve
Part reduction: 6 to 1
Successfully tested

Oxidizer Turbopump
Part reduction: 80 to 41
Tested to 40,000 RPM.

Injector
Cost Reduction: 30%
Part reduction: 252 to 6
Eliminated braze joints
Tested to 100%



Courtesy Paul Gradl, NASA MSFC

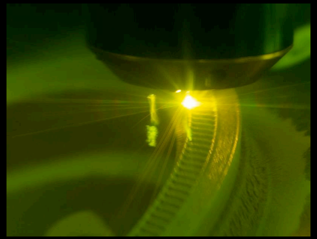
Project lead – NASA Marshall Space Flight Center, 2013~2016

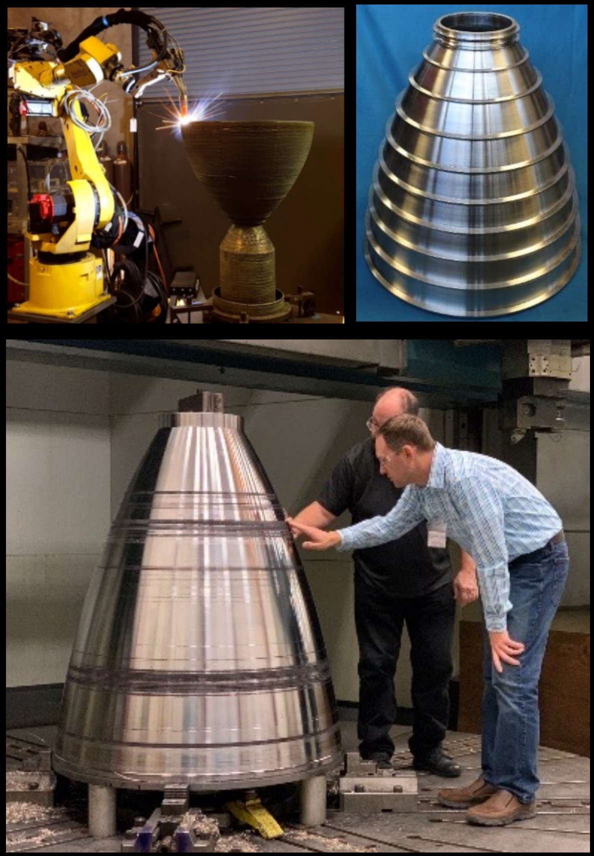
Examples of NASA's AM Dev Work for Rocket Propulsion

Laser Powder Bed Fusion (L-PBF) GRCop42. *Courtesy Dr. Dave Ellis (NASA GRC).*

Hybrid bi-metallic AM

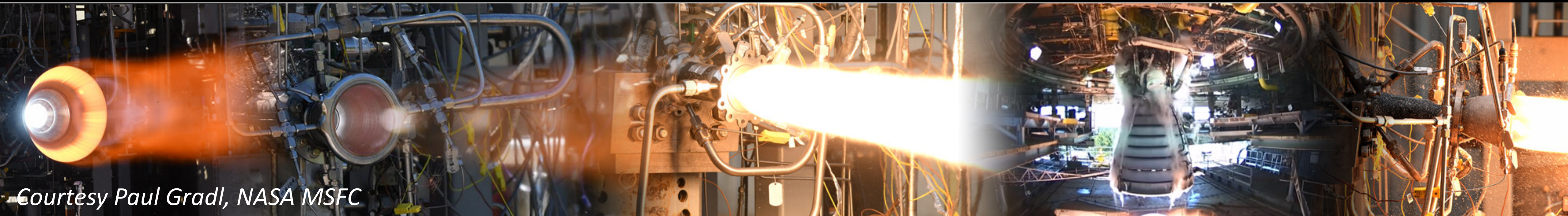
Laser Powder Directed Energy Deposition (LP-DED)





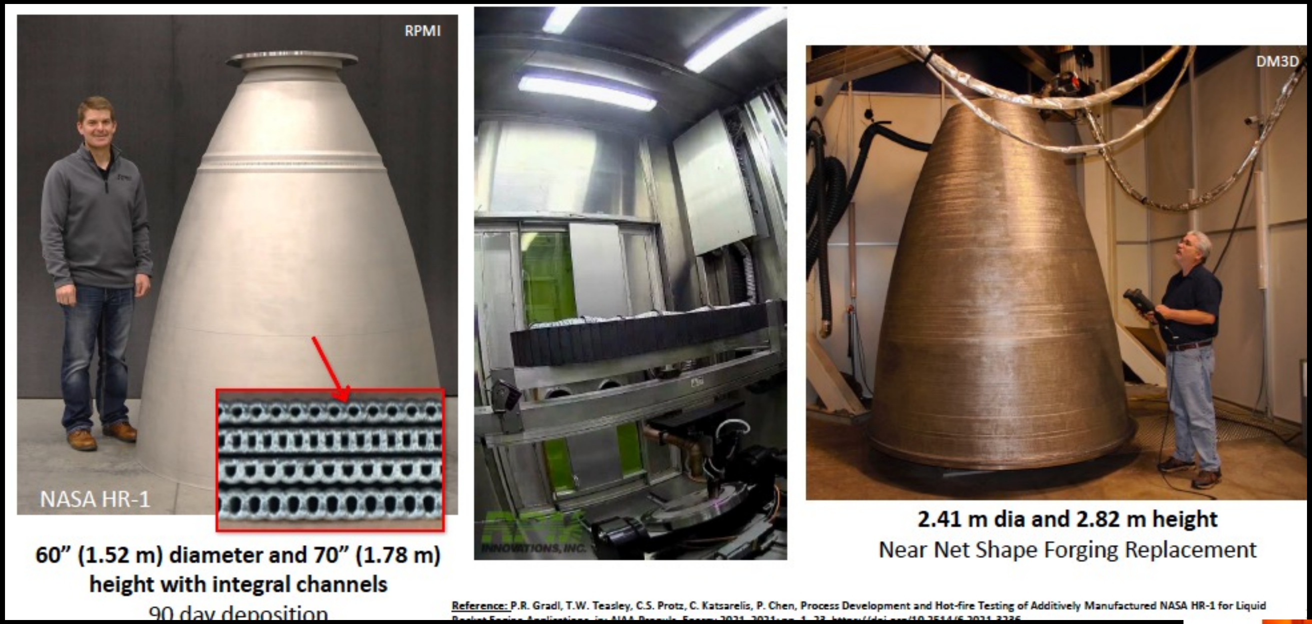
L-PBF AM turbomachinery.

GRX-810 combustor. *Courtesy Dr. Tim Smith (NASA GRC).*



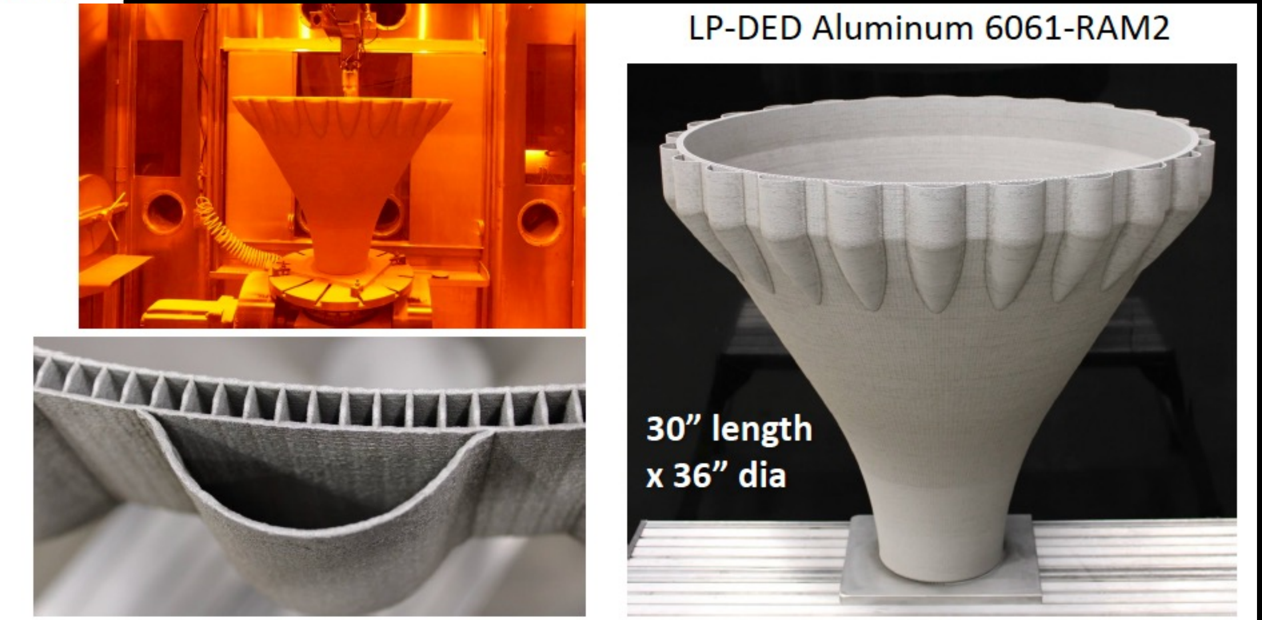
Courtesy Paul Gradl, NASA MSFC

Current AM Development for Rocket Propulsion Components



Laser Powder Directed Energy Deposition (LP-DED) Large Scale Rocket Nozzle with integrally printed cooling channels

Demonstrator Aerospike LP-DED Nozzle



Photos Courtesy Paul Gradl, NASA MSFC
Excerpts from Gradl’s presentation
”Advancing Additively Manufactured Al6061 RAM2 Using Laser Powder Directed Energy Deposition”, Oct 2023, ICAM 2023

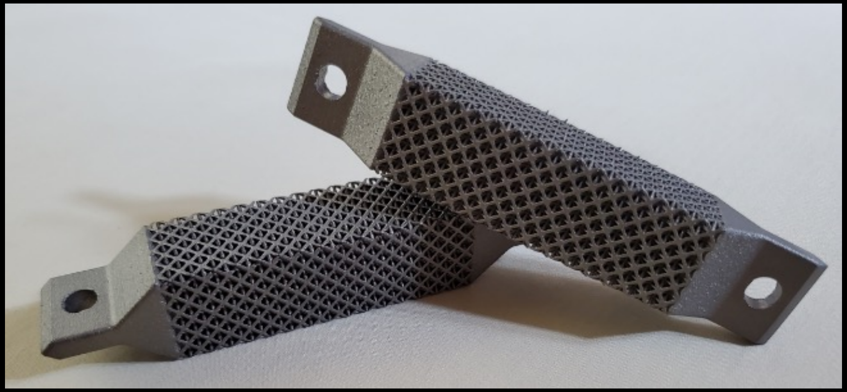
Multi-metallic and Multi-AM Process Rocket Chamber Dev

Photos Courtesy Paul Gradl, NASA MSFC
Excerpts from Gradl's presentation
"Introduction to Metal Additive
Manufacturing for Aerospace", Nov 2023

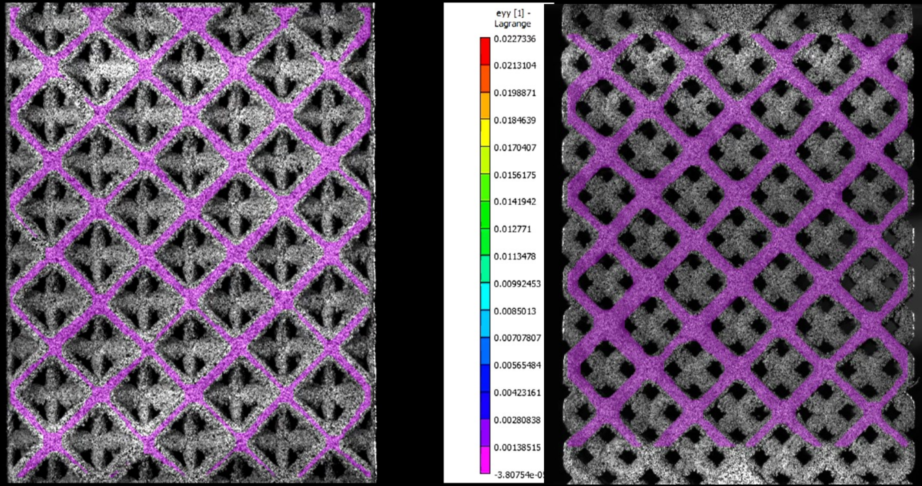
NASA's AM Dev Work for Cryogenic Fluid Management (CFM)

- Long-Duration Propellant Storage
  - LH_2 at 20 K.
  - LOX at 90 K.
- Component Optimization
  - Heat Exchangers
  - Augmented Injectors
  - Tanks with integral cooling channels
  - Galleries
  - Sponges
  - Lattice Struts

L-PBF AM IN718 TVS Augmented Injector. *Courtesy Travis Belcher (NASA MSFC).*



L-PBF AM Ti6Al4V Cryo Lattice Struts. *Courtesy Travis Belcher (NASA MSFC).*



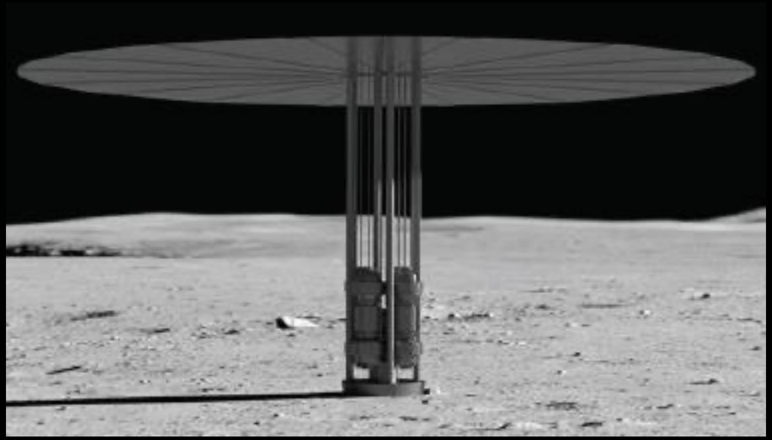
Node strain localization of Octet-Truss-30%RD (left) and **Strut** strain localization of Rhombic Dodecahedron (20 %RD), a = 4 mm, IN718 in SR+HIP+SA condition. *Courtesy Dr. Kavan Hazeli (University of Arizona).*

LP-DED AM A6061-RAM2 propellant tank with integral cooling channels. *Courtesy RPM Inc.*

Excerpt from Omar Mireles's Keynote talk, RAPID 2023, Chicago

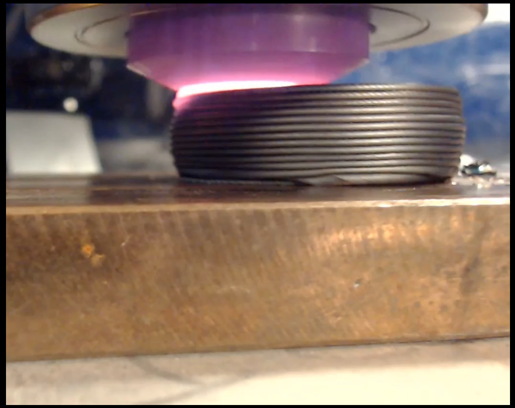
NASA's AM Dev Work for Nuclear Power Systems

- Heat Pipes
  - L-PBF AM Ni- or Nb- base
  - Surface conformal
  - Integrated wicking structures
- Stirling Alternator
  - Lattice Regenerator from L-PBF AM Tungsten
- Fuel
  - Additive Friction Stir Deposition (AFS-D) of depleted U-8wt%Mo
- Shielding
  - Multi-material
  - Hybrid AM
  - Multi-physics topology optimization

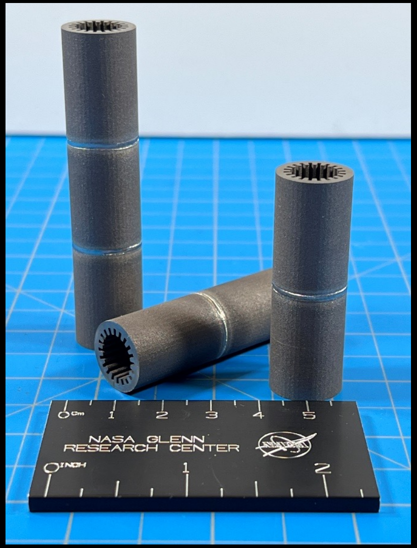


10 kWe surface power reactor concept

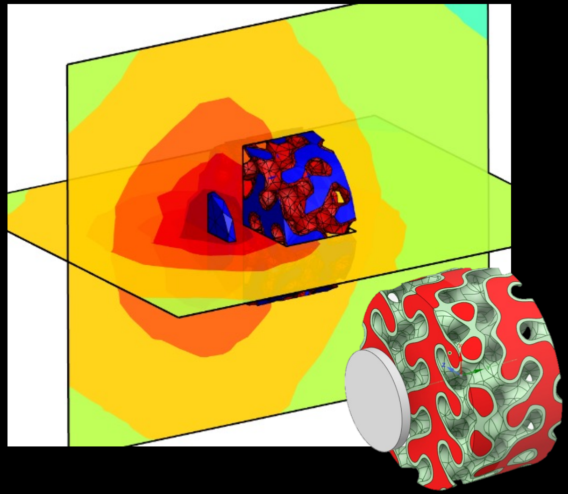
L-PBF AM IN718 integrated heat pipe funnels



AFS-D of dU-8Mo.



L-PBF AM C103 heat pipe segments. *Courtesy Dr. Justin Milner (NASA GRC).*



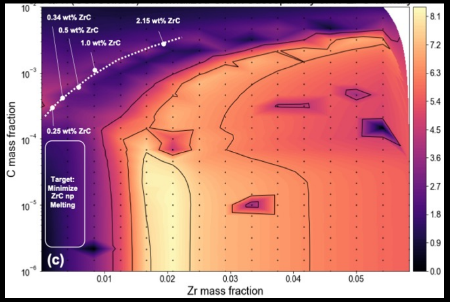
Hybrid AM shield topology optimized for neutron/γ-ray radiation attenuation, loads, and active cooling. *Courtesy Dr. Jarvis Caffrey (NASA MSFC).*

Excerpt from Omar Mireles's Keynote talk, RAPID 2023, Chicago

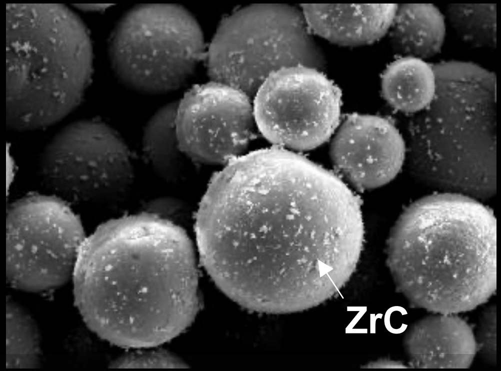
NASA's AM Dev Work in Refractory Metal AM

- Refractory metals for extreme high temperatures
  - Reaction Control System (RCS): chambers
  - Space Nuclear Power & Propulsion: clad, structure, heat pipes
  - Hypergolic / green propulsion: chambers and catalyst.
  - Electric propulsion: grids
  - Hypersonics: wing leading edges

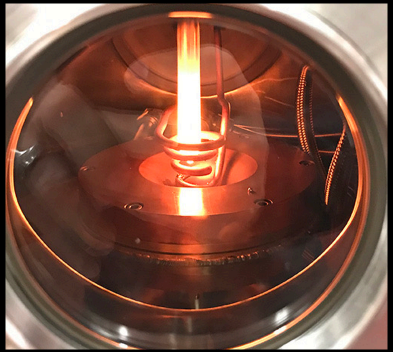
- Development Areas:
  1. ICME, Simulation, Modeling
  2. Feedstock Production
  3. Parameter Development / Part Prod.
  4. Heat Treatment & Joining
  5. Novel Non-Destructive Evaluation
  6. Surface Finishing & Coatings
  7. Property Characterization
  8. Component Test



Crack susceptibility modeling. *Courtesy Carly Romnes (Univ IL, Urbana-Champaign).*

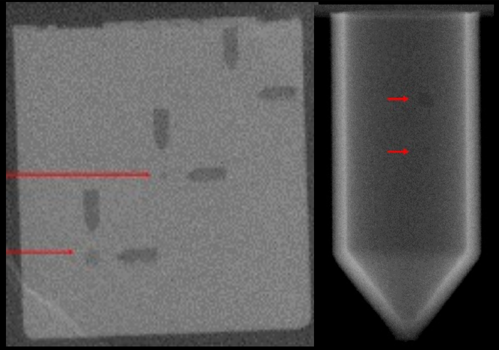


Mo with ZrC nano-powder. *Courtesy Dr. Fernando Reyes (NASA MSFC).*



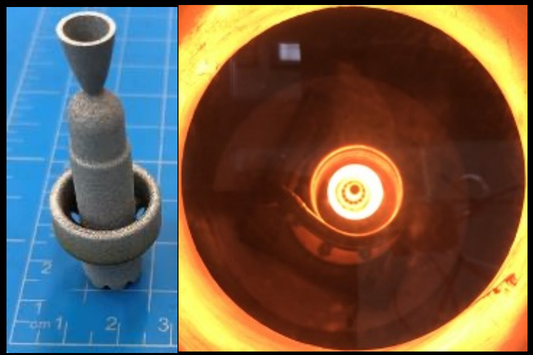
EIGA of Mo44Re rod.

LP-DED AM C103 development. *Courtesy Univ. of Texas, El Paso (UTEP).*



Neutron radiograph of L-PBF W with engineered defects. *Courtesy Phoenix.*

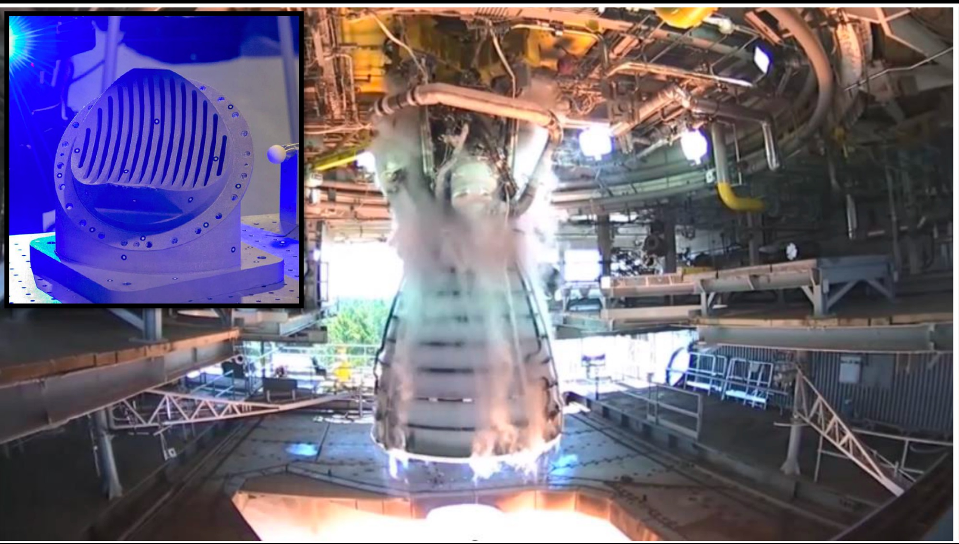
L-PBF AM Mo RCS Chamber



L-PBF AM W chamber test at 1900 °C. *Courtesy Dr. Jamelle Williams (NASA MSFC).*

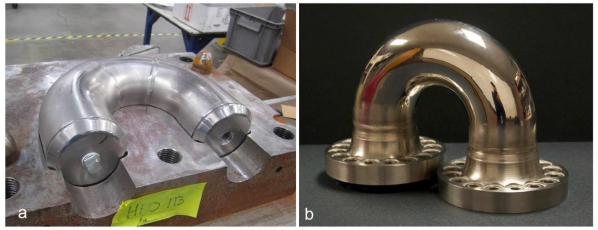
L-PBF AM C103 Nozzle Extension. *Courtesy Brandon Colon, UTEP.*

Great Insertion of AM in Spaceflight – Commercial Space



GE Aviation fuel nozzle (L-PBF)

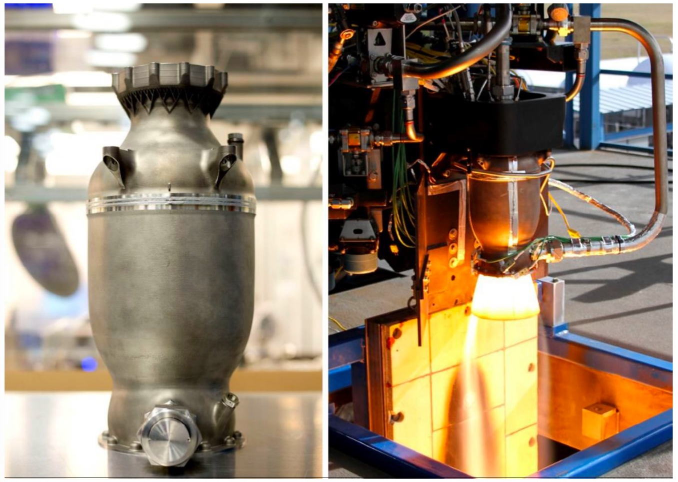
Titanium pylon rib for F-15 replacements using DED (2003)



J-2X Rocket Engine Gas Generator Duct:
a) Traditional tooling, b) L-PBF part

Ti6Al4V propellant tank using electron beam wire DED

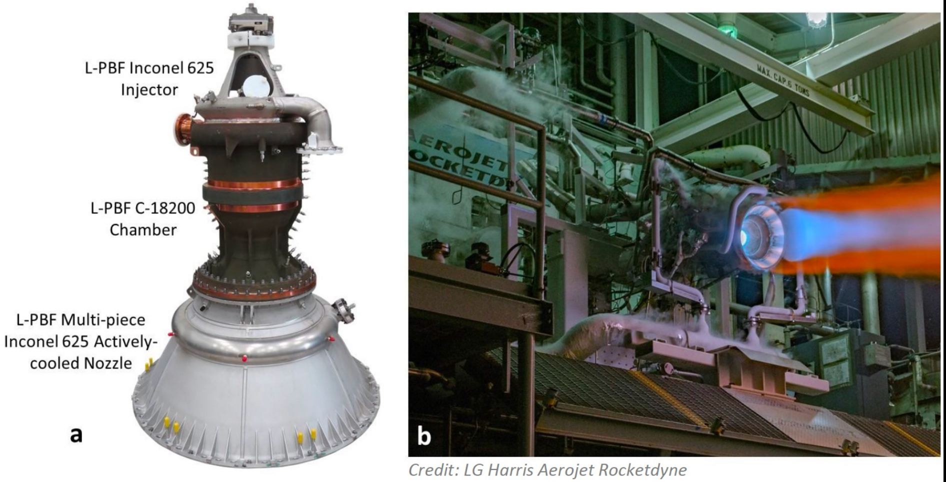
Excerpt from Online AM Training "*Metal Additive Manufacturing for Propulsion Applications*"
AIAA Progress in Astronautics and Aeronautics Book Serie
P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).



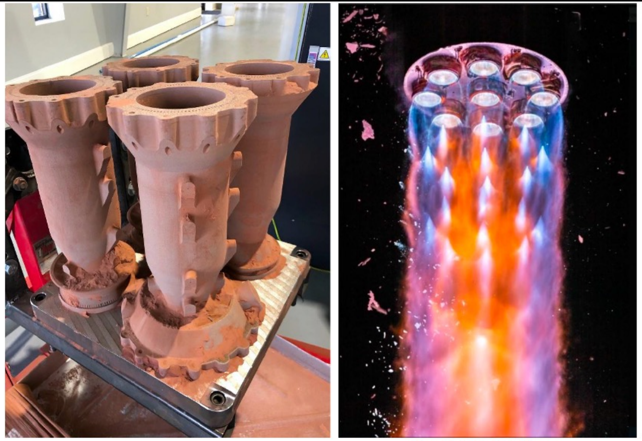
Credit: SpaceX

SpaceX SuperDraco Inconel 718 combustion chamber using Inconel 718 L-PBF

Aerojet Rocketdyne RL-10CX All-additive thrust chamber assembly



Credit: LG Harris Aerojet Rocketdyne



Credit: Relativity Space

Relativity Space – DED for tanks and L-PBF engine components, including NASA alloy GRCop-42

Turbomachinery components using L-PBF

Excerpt from Online AM Training "*Metal Additive Manufacturing for Propulsion Applications*"
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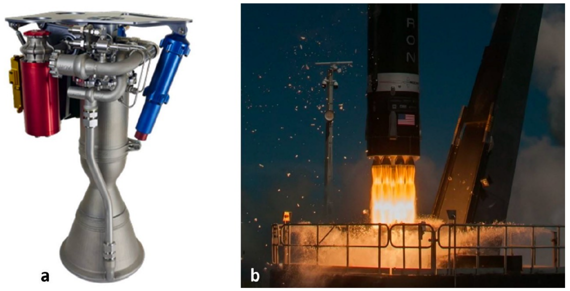
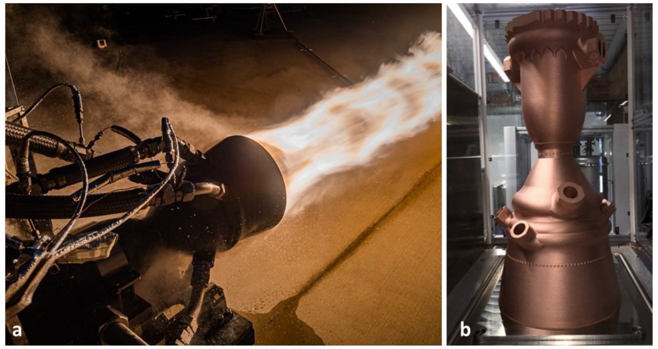


Credit: Rocket Lab / Andrews Burns and Simon Moffatt

Rocket Lab Rutherford engine using L-PBF Inconel 718 combustion chamber

Launcher Space L-PBF CuCrZr 1 meter height combustion chamber



Credit: Vast / Launcher

In-Space Manufacturing (ISM)

On-Demand Manufacturing & Recycling of Plastics

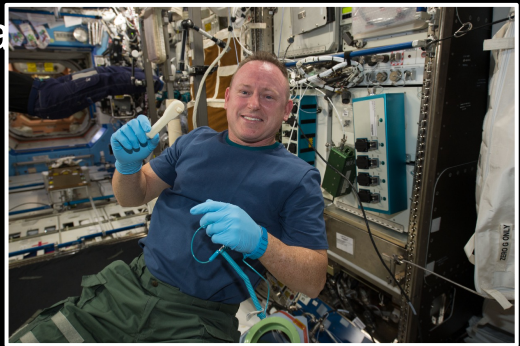
- 3D printing and recycling system designed to repeatedly recycle plastic materials into feedstock f manufacturing in the microgravity environment of the ISS.

On-Demand Manufacturing of Metal

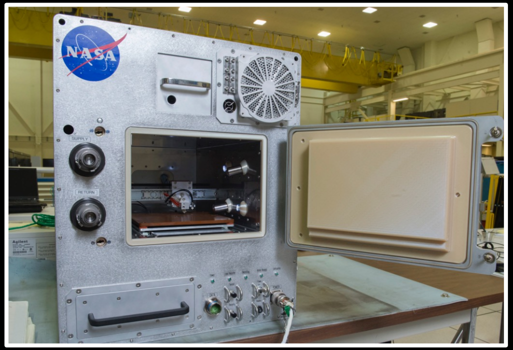
- Additive and subtractive manufacturing systems for creating metal parts on demand.

On-Demand Manufacturing of Electronics

- Ability to fabricate electronics during missions, such as crew and structural monitoring systems a



First 3D printer in space, 2014 ISS Demonstration



Refabricator ISS Demonstration

Redwire Commercial ISS Additive Manufacturing Facility (AMF)

Techshot Fabrication Laboratory

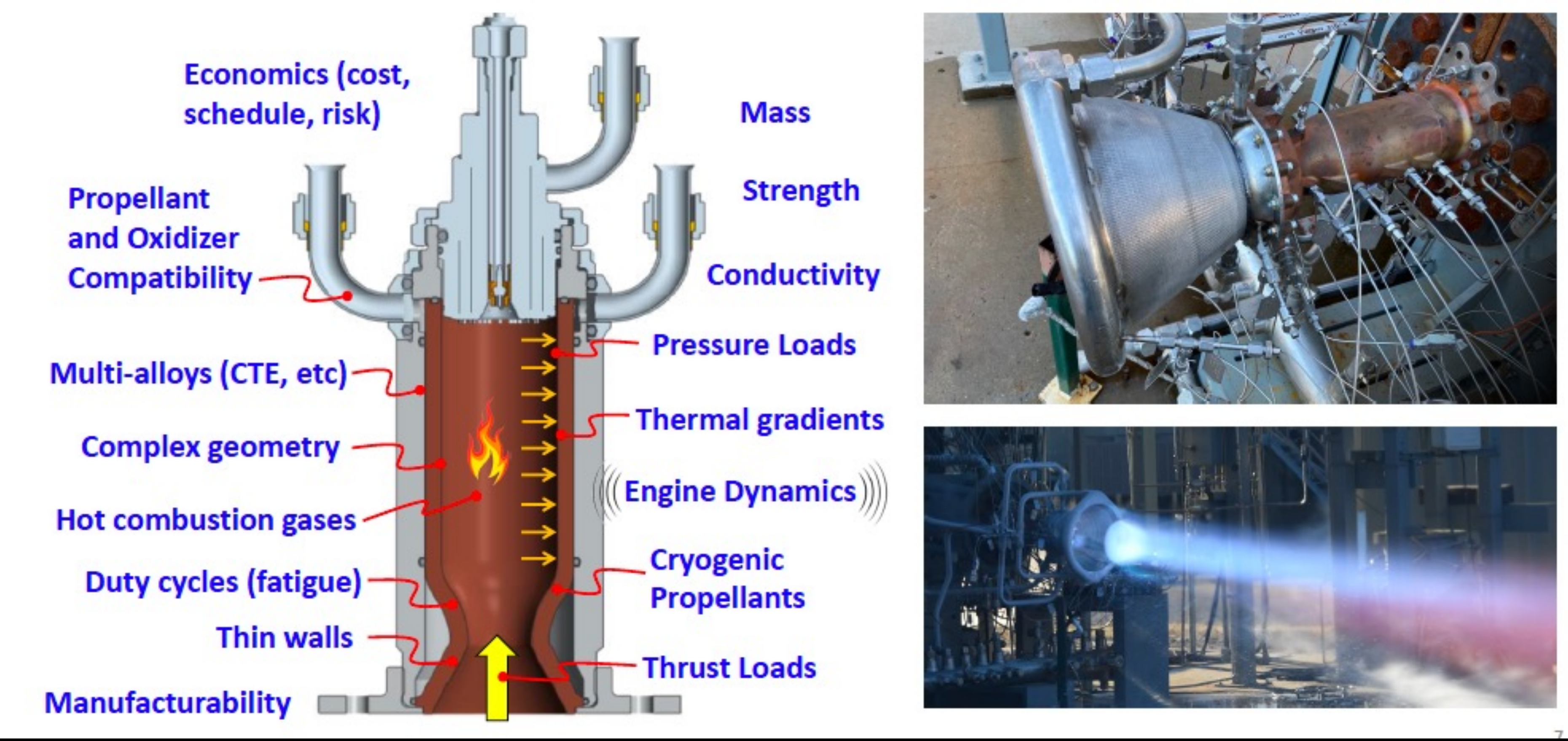
Moon-to Mars Planetary Autonomous Construction Technology (MMPACT)

Develop, deliver, and demonstrate capabilities to:

- Protect crew and hardware
- Build infrastructure
- Construct landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials

Partners: ICON, SEArch+, USAF, Defense Innovation Unit, Texas Air National Guard

Materials Consideration in Extreme Rocket Engine Environment



Excerpt from " *Metal Additive Manufacturing for Propulsion Applications"*
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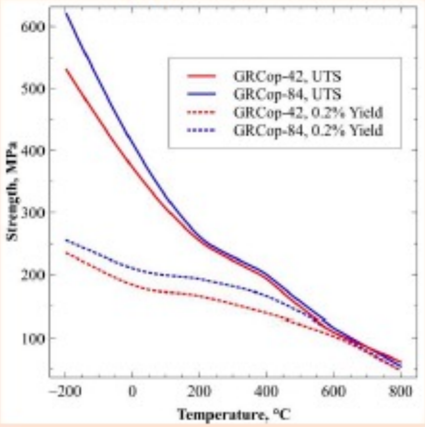
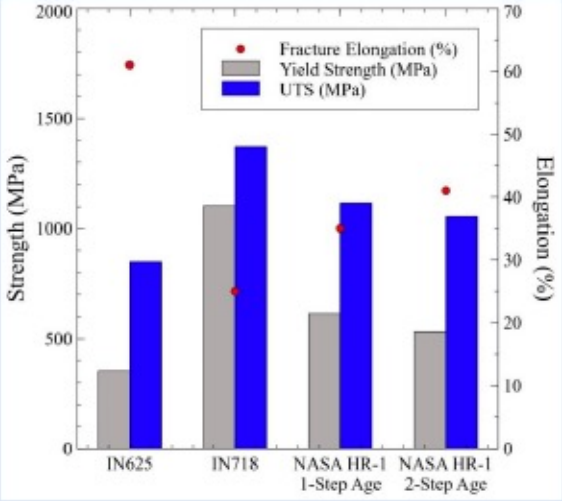
AM enabling novel Alloy Systems

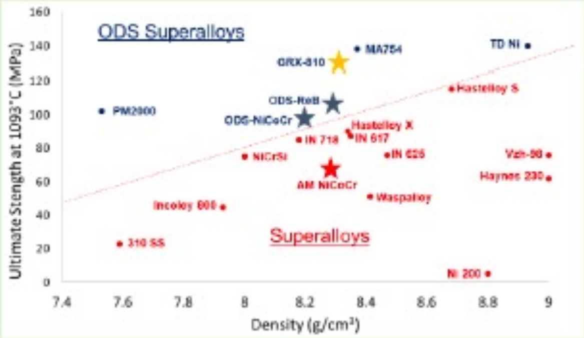
GRCop-42, High conductivity and strength for high heat flux applications



NASA HR-1, high strength superalloy for hydrogen environments



GRX-810, high strength, low creep rupture and oxidation at extreme temperatures



Ref: Tim Smith, Christopher Kantzos / NASA GRC 46

Excerpt from " *Metal Additive Manufacturing for Propulsion Applications*"
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P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

NASA's motivation for AM alloy development

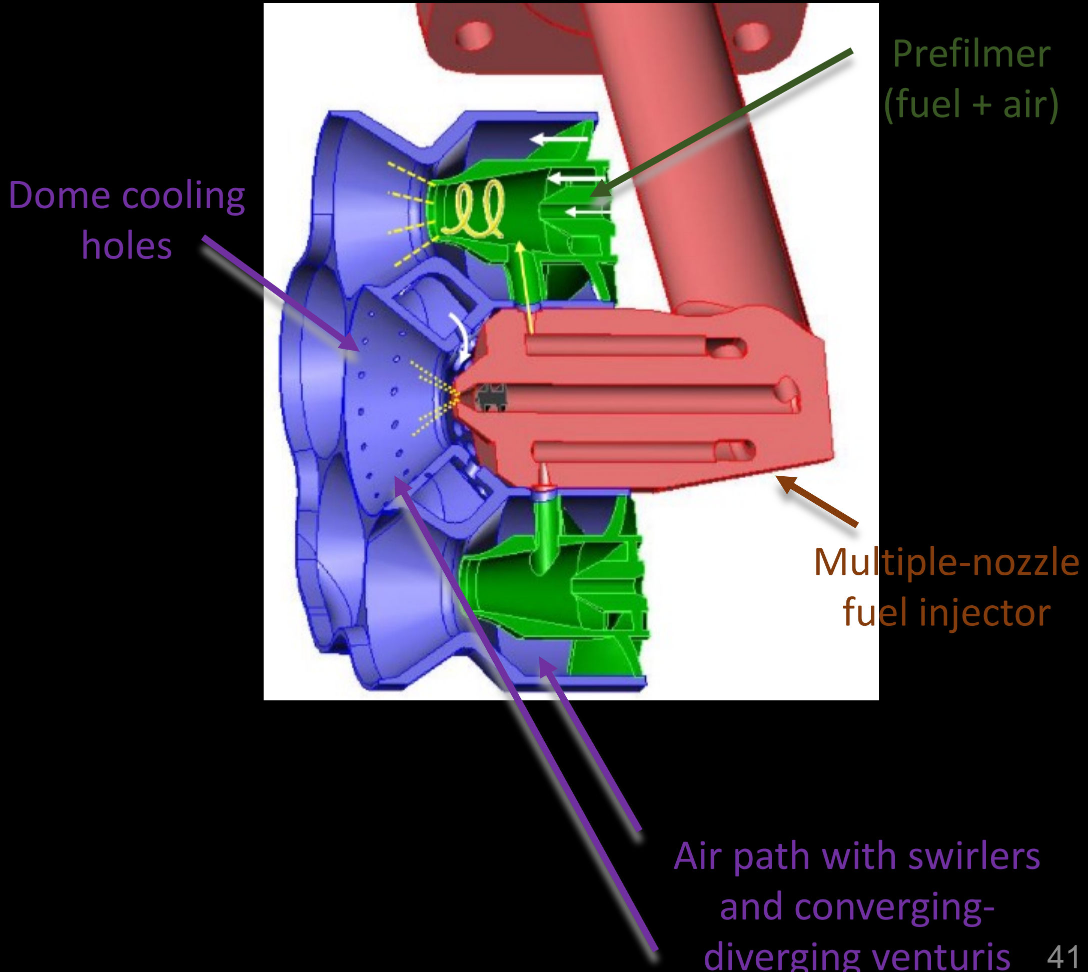
- NASA Missions typically require operation in extreme conditions
- Conventional materials and processing limit design and operation
- Success Case Study—GRX-810

Problem: Optimized Combustor Dome requires AM fabrication and higher than SOA temperatures

Proposed Solution: Develop a high ductility, high temperature material for an additively-manufactured (AM) combustor fuel nozzle and dome for supersonic aircraft (>1093°C (2000°F) operating temperature).

New Alloy and AM fabrication Enabled:

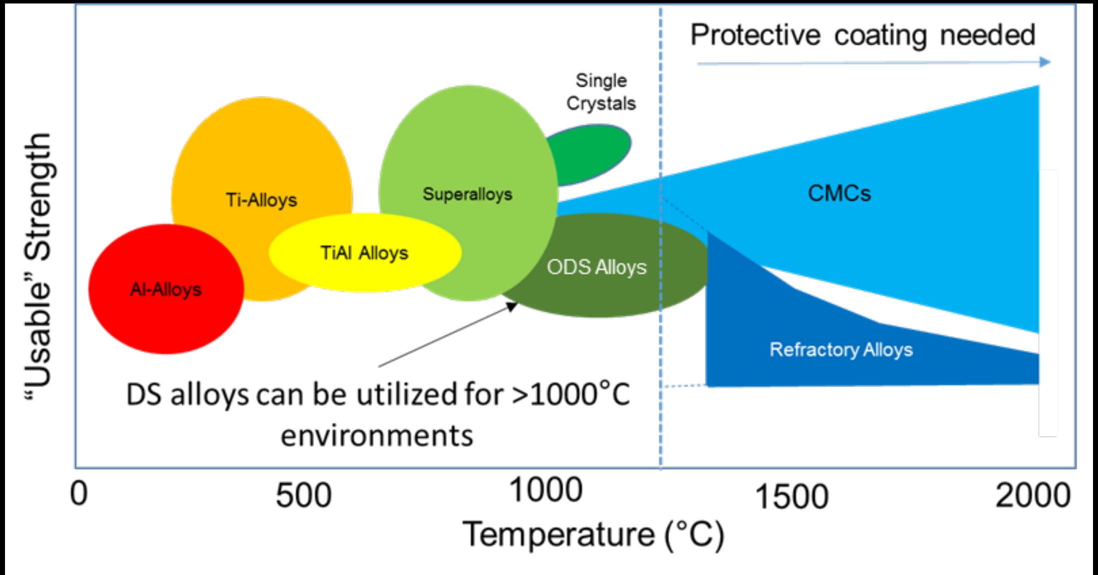
- Improvements to the turbine combustor design reducing NOx pollution and lowering weight
- Lean-front-end small-core combustors



High Temperature AM Compatible Materials

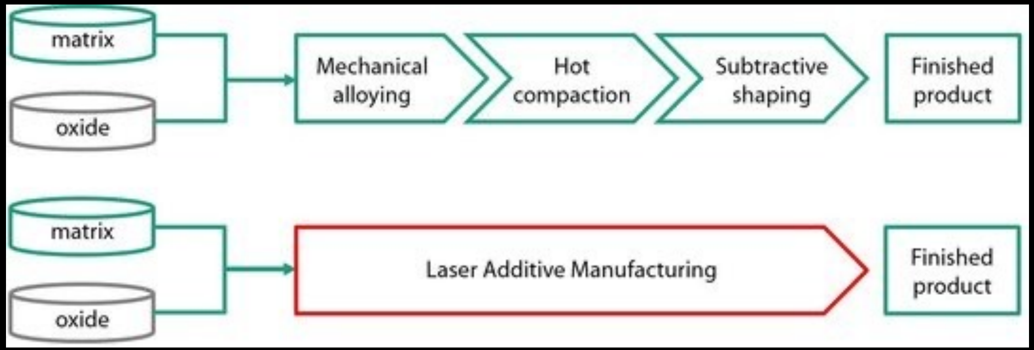
High Temperature Material Options:

- Refractory metals
- Carbon-Carbon composites
- CMC’s
- Ni-base superalloys
- Oxide Dispersion strengthened (ODS) alloys



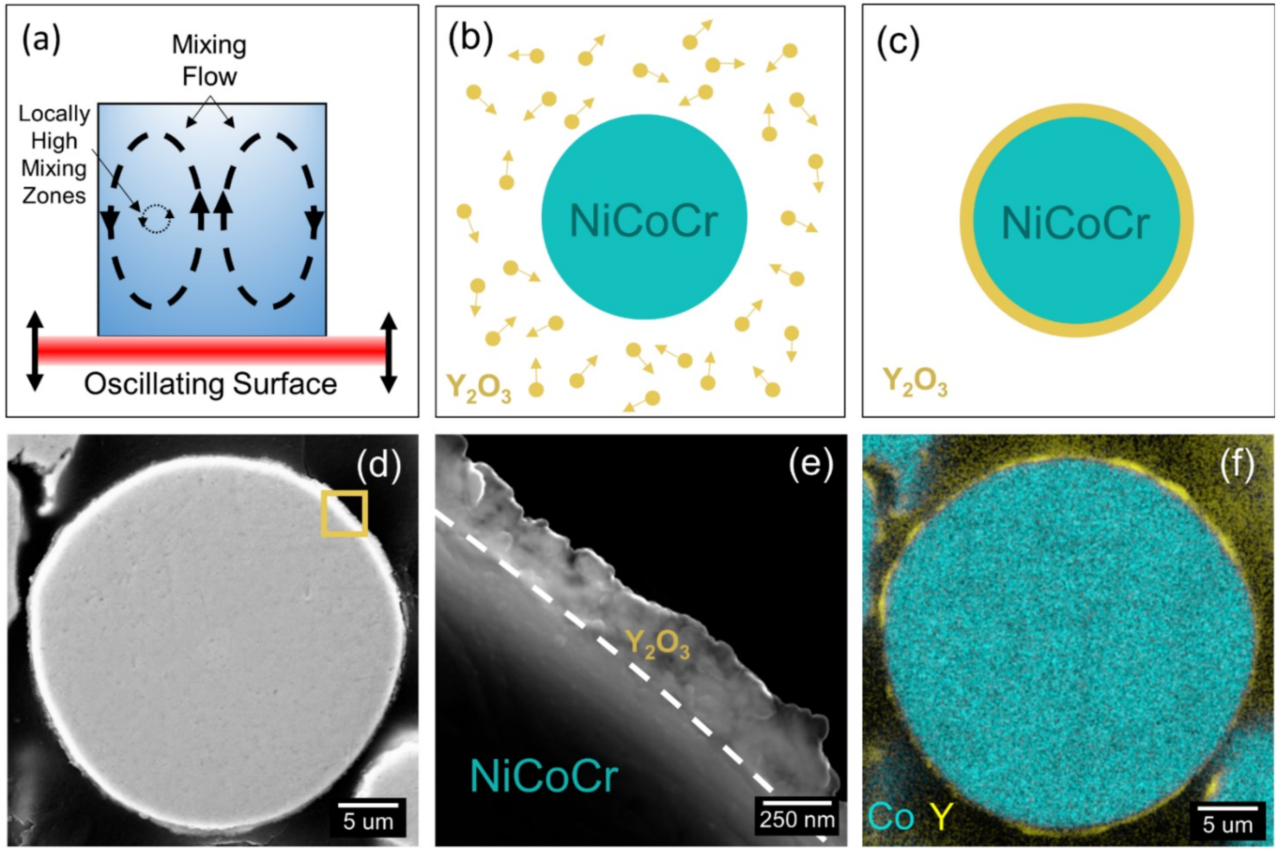
(ODS) alloys offer higher temperature capabilities compared to Ni-base superalloys. However, it has been a challenge to produce ODS alloys through conventional manufacturing methods.

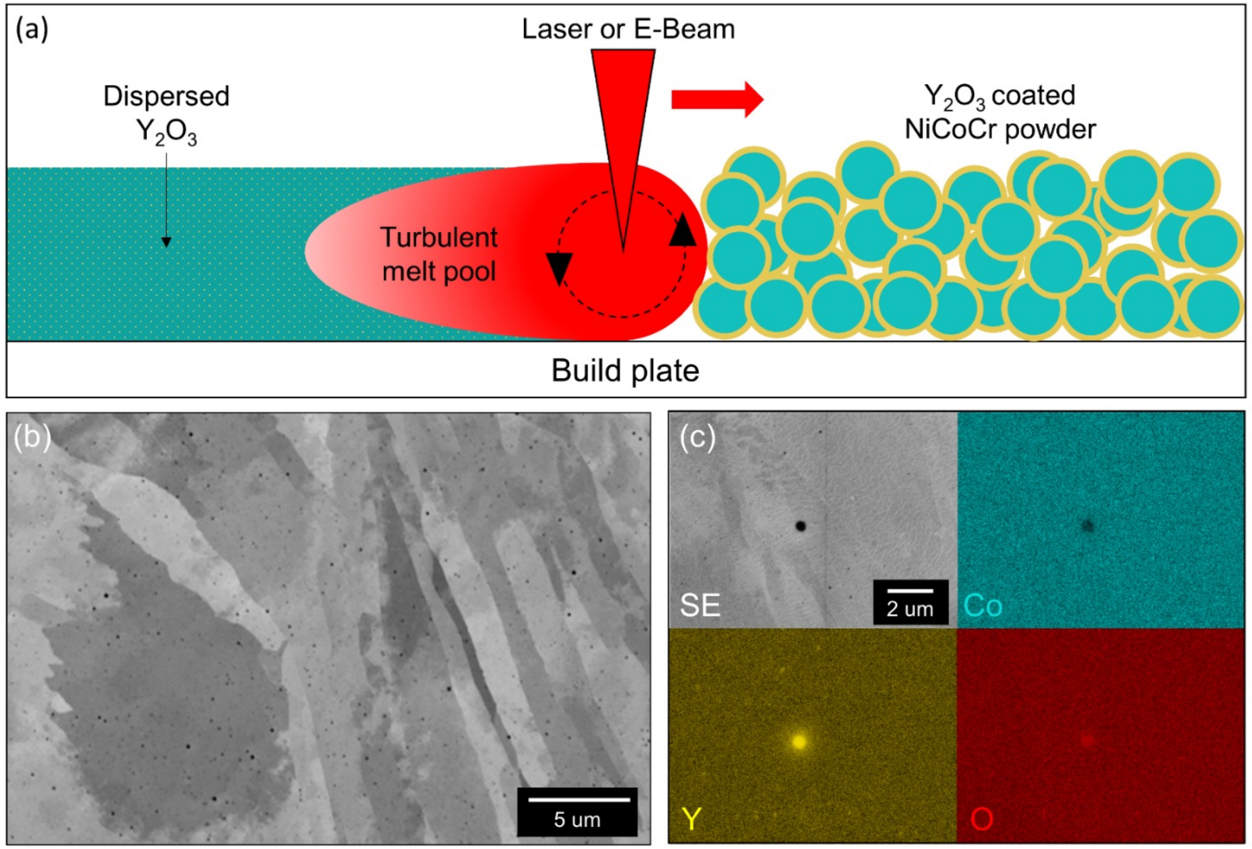
ODS Conventional Manufacturing vs AM



Radical New Approach Developed for ODS AM

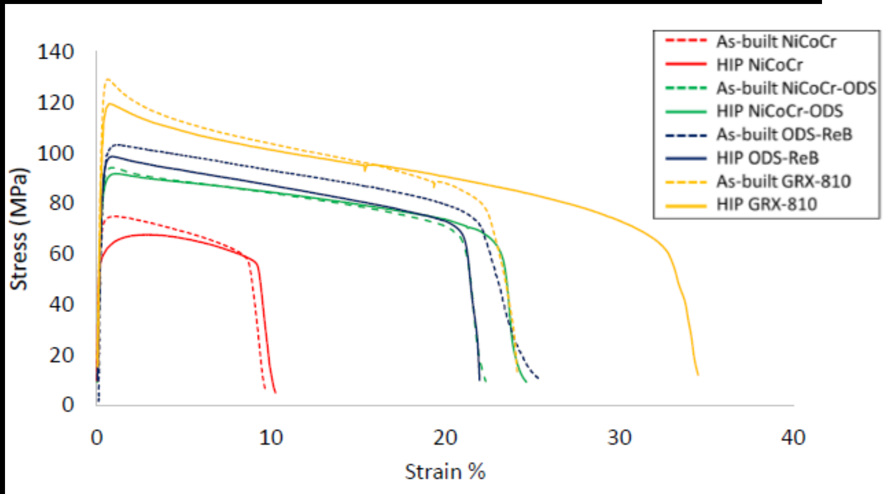
Technique for coating metal powders with fine dispersoids was developed and demonstrated first for simple NiCoCr powders and then transitioned to ICME developed alloy Glenn Research Extreme-Temperature above 810°C (GRX-810)

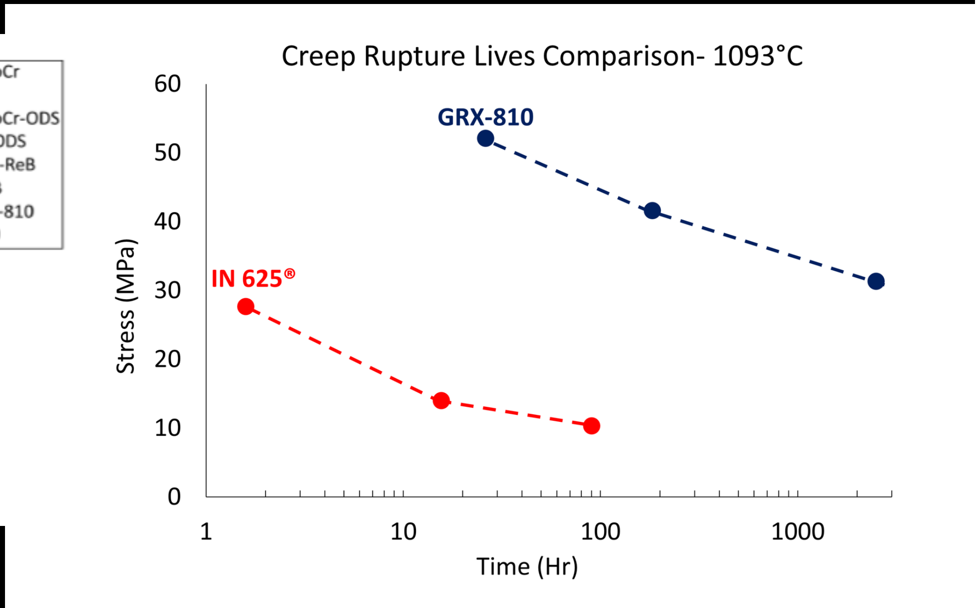


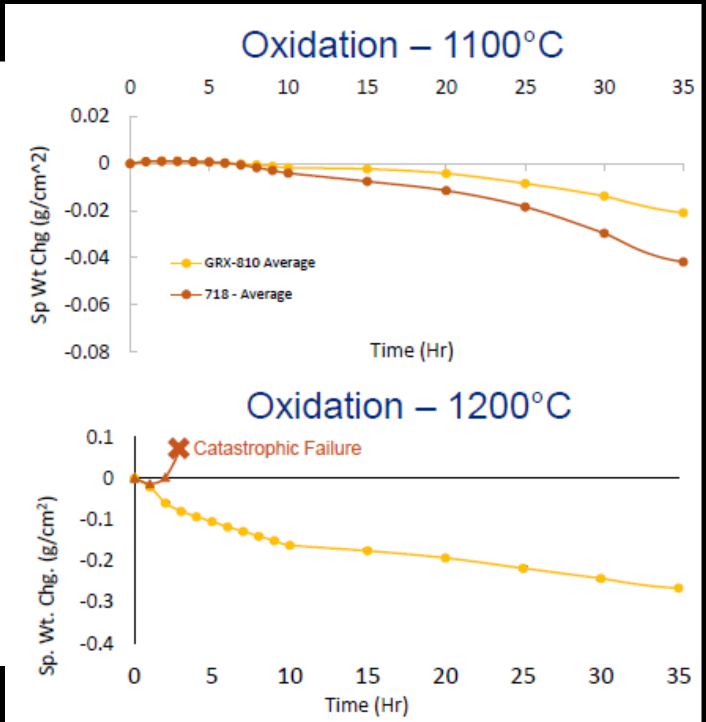


ODS and AM Provides Substantial Improvements

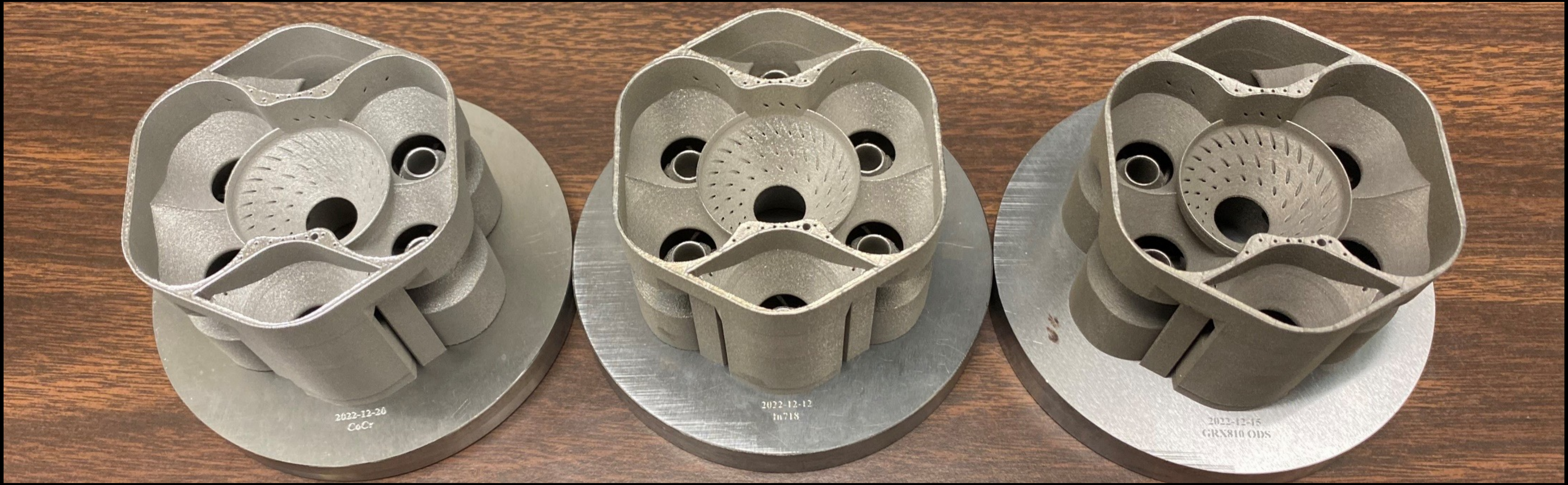
NASA alloy GRX-810 is an example of what can be achieved when a matrix is designed for optimum printing and solid solution strengthening then combined with dispersion strengthening for high temperature stability







Component Demonstration: Combustor Dome



Only GRX-810 dome survived without crack formation

Component Demonstration: Injector / Nozzle

- Nozzle achieved 90 starts and 2,309 seconds of accumulated time
- Injector achieved 84 cycles and 2,228 seconds of accumulated time
- Injector provided at 5x improvement in erosion life compared to previously tested Alloy 718 and Alloy 625 injectors

- Separate design and testing of GRX-810 as a LOX/H2 injector also completed without erosion seen in conventional alloys

NASA is moving from Low Earth paradigm to Deep Space paradigm

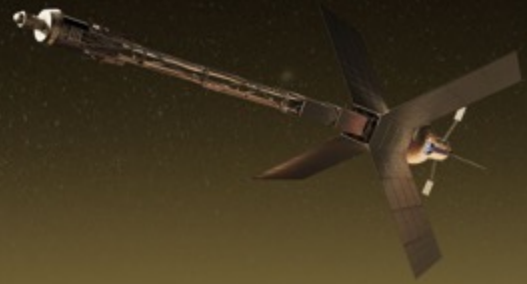
Additively manufactured parts are already being used for NASA programs in critical applications – “ready to fly”

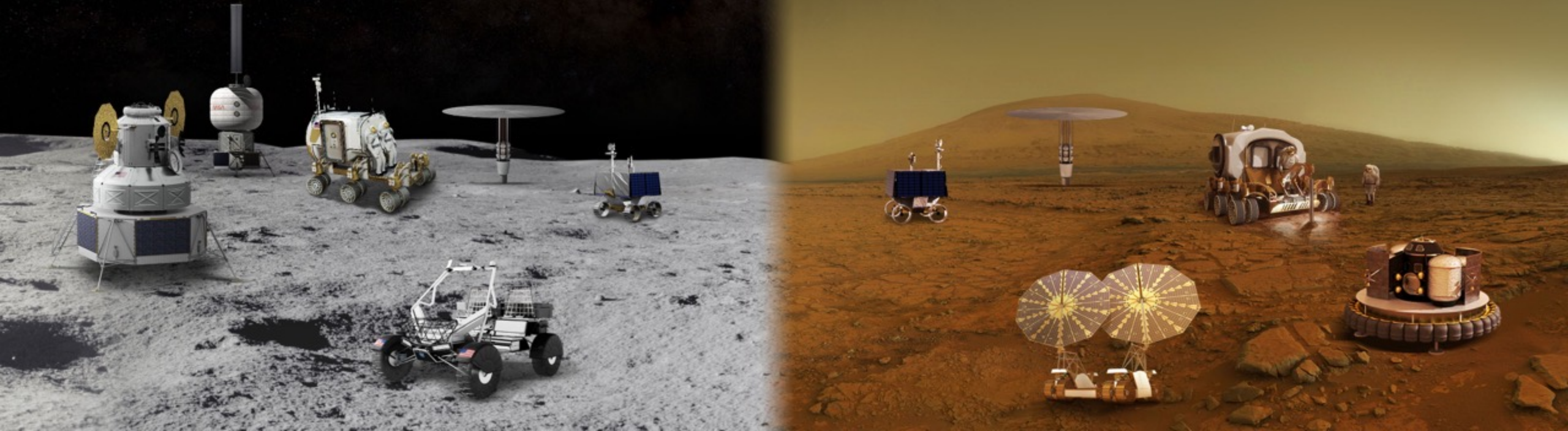
- -Transportation from Earth to Destination
- -Stations at Destination
- -Lander from Station to Surface
- -Spacecraft for Science Missions
- -Sample Return from Mars

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

AM technology is demonstrating incredible benefits in wide-spread applications, design flexibility, affordability, schedule, performance, sustainability, and production on demand.

- **Certification is the #1 challenge:** complexity, unknowns, and delays are severely negating the benefits.
- ***Certification of remotely produced products is an unresolved technology gap.***





Certification focus in Advanced Manufacturing

- NASA continues to be a leader in the advancement of policies for the Certification of AM processes and parts
  - NASA-STD-6030, Agency standard for additive manufacturing
  - ASTM CoE projects
  - Agency-wide AM Certification Support Team (AACT) activities
  - NASA University Leadership Initiative (ULI)
    - *Development of an Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation*
  - NASA Space Technology Research Institute (STRI)
    - *Institute for Model-Based Qualification & Certification of Additive Manufacturing (IMQCAM)*

Certification focus in Advanced Manufacturing

To meet the certification goals of the future, the role of computational materials (CM) will have to grow to meet expectations

- Shortened certification schedules
- Cost pressures
- Rapidly evolving technologies and capabilities in advanced manufacturing

We must acknowledge that the certification process is a human endeavor, often relying on judgement in accepting new materials and processes

- Engineers and managers holding the certification responsibilities are frequently not experts in CM
- The introduction of CM into the certification process must be **measured and pragmatic**
- This requires **planning and a strategy** to lead to well-substantiated acceptance of new roles for CM
- Do **NOT** expect the certification community to readily accept an instantaneous revolution
  - There are strong reasons the community is notoriously conservative
  - Incremental progress must start **NOW**.

Certification focus in Advanced Manufacturing

Two aspects of qualification & certification to consider:

1. Design Certification
    - Demonstration that design meets all requirements of the defined mission
2. Hardware Certification
    - Demonstration that hardware meets all requirements of the certified design

Opportunities for computationally-assisted certification

- ***To Begin, focus primarily on augmenting the existing cert. processes, NOT replacing them***
- NASA AM requirements neither endorse nor prohibit such methods
- Tools used in certification require verification and validation
- Best approach to leverage opportunities:
    - Support incremental progress in addition to revolutionary tools
    - Focus on beneficial tools with tractable validation strategies
    - Identify areas of emphasis for industry tool development
    - Strongly leverage partnerships across government, academia, and industry

Today’s Certification Approach

- Current approaches for certification rely heavily on empirical methods where the outcomes from numerous combinations of parameters are evaluated experimentally.
- Experimental iteration is the accepted method—Costly in both time and resources
- Endless variations arise due to the sensitive nature of the metallurgical process and individual aspects of AM machines.
- Under current paradigms, once qualified, the **AM process is not extensible**, limiting the ability to make design or manufacturing changes.

Example Laser Powder Bed Fusion Process

Iteration required on Steps 2-6 to Mature/Qualify Part and Processes

The Goal: Digital Twin based Cert

- The ideal “digital twin” (DT) concept bridges both design certification and hardware certification.
- This is the “keep your eyes on the prize” goal
  - See presentation on the NASA STRI scope
- The implementation of the DT concept in certification is best done as an evolution as opposed to a revolution
- 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.
- We need to watch for opportunities, even if small, to augment the certification process with CM while the DT concept matures.

Design Certification Opportunities

Examples of Design Certification opportunities to leverage CM

- 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

Hardware Certification Opportunities

Examples of Hardware Certification opportunities to leverage CM

- 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

Challenges for CM Implementation

- Acceptance of Computational Materials in the Certification Environment
  - Generate acceptance through gradual implementation
  - Overcome the extensibility issue through broad-based verification and validation
    - Anticipate the same limitations that drive cost in the empirical method will exist for a CM-based approach to certification
      - Most any uniqueness or change in process currently requires empirical evidence to re-certify
      - The same will be true for CM approaches
        - Modeling and simulation approaches in CM will face the same V&V scrutiny whenever the application extends beyond the initial scope of CM tool development and V&V
        - We must plan for ongoing V&V efforts for CM tools as they extend to prediction objectives for various material systems and processes
        - Extended use of CM technologies will not be “free”
  - Keep the human element in mind as we communicate the intend to leverage the use of CM
      - Use well-substantiated, limited scope, incremental advances
  - Start now

NASA STMD – Space Tech Research Institute 2023

Institute Overview

MSFC ENGINEERING

What's an STRI?

Long-term sustained investment in research and technology critical to NASA's future. Highlights include:

- **Empowered** university-led team
- Specific research objectives with **credible expected outcomes** in 5 years
- Talented, **diverse**, cross-disciplinary and fully **integrated** team
- Low to mid TRL

Award Details

- Expected duration: **5 years**
- Award amount up to **$3M per year**
- Institutes expected (and *empowered*) to implement their own review internal processes
- NASA oversight – annual reviews and brief quarterly status reports

Research Areas

1. A furthered understanding of **materials-processes-structure-property relationships** for AM through advanced computational toolsets coupled with innovative experiments, laying the foundation for accelerated product certification.
2. Development of **uncertainty-quantified, physics-based models and simulations** to understand the factors that can affect the formation, distribution, and the effects of process-induced defects and to address other principal sources of variability.
3. Integration and application of methodology, software tools, artificial intelligence (AI), machine learning (ML), and/or databases, etc., based on computational and experimental tools to a **model-centric certification approach**.

itters

Awarded to Team led by A.D. (Tony) Rollett (Carnegie Mellon's U), PI & Somnath Ghosh (Johns Hopkins U)

NASA led book on Metal Additive Manufacturing

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).
Metal Additive Manufacturing for Propulsion Applications.
AIAA Progress in Astronautics and Aeronautics Book Series
https://arc.aiaa.org/doi/book/10.2514/4.106279

Online version and hardcopy available

AM processes are an enabling technology and revolutionizing the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace.

The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.

STMD Portfolio and Solicitations

https://www.nasa.gov/space-technology-mission-directorate/ - STMD Portfolio and Programs

https://www.nasa.gov/stmd-solicitations-and-opportunities/
STMD Solicitation and Opportunities

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