EBF^3 Design and Sustainability Considerations

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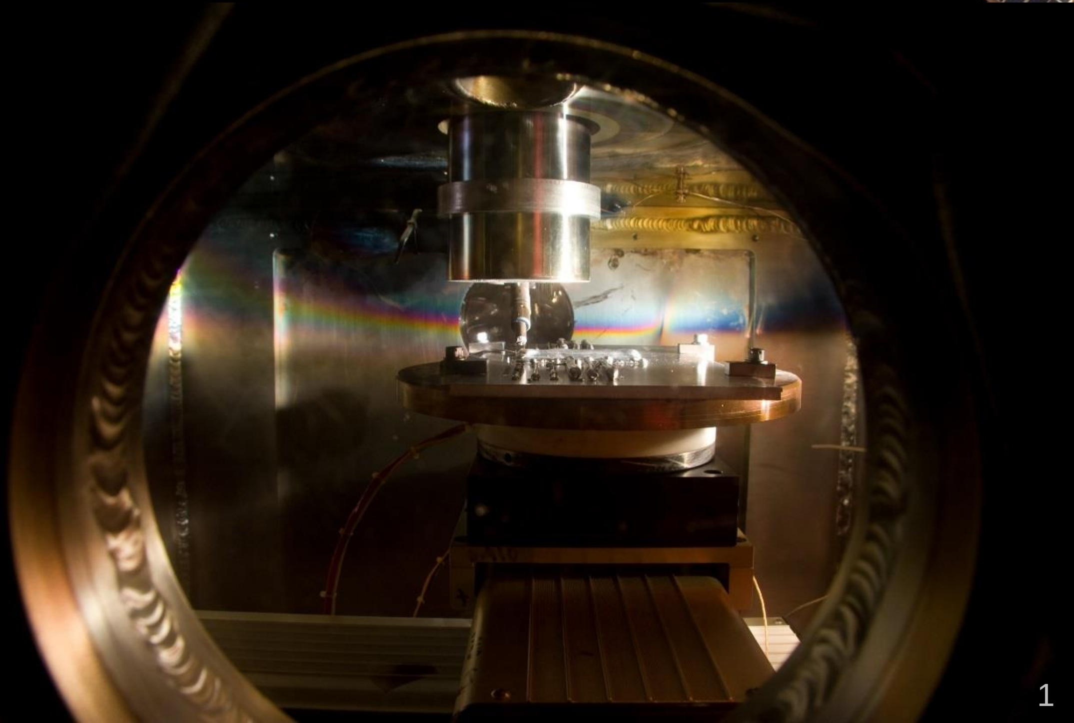

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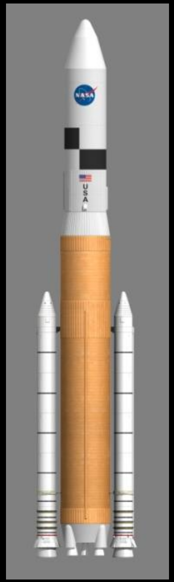
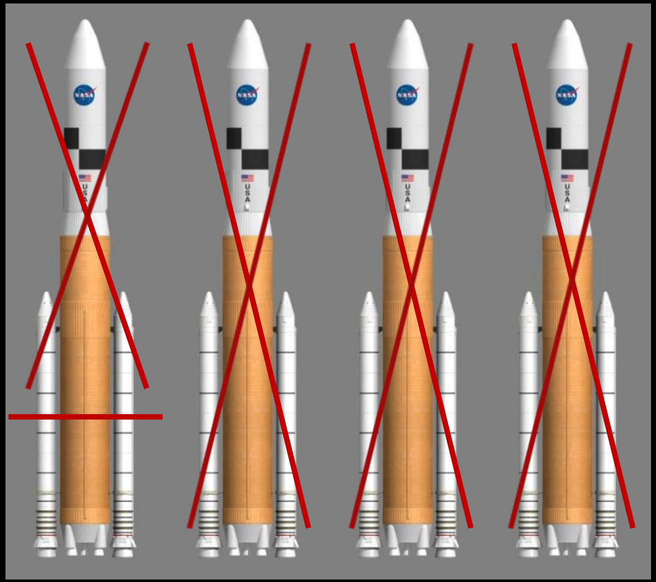
Mars Mission Spares Upmass Reduction Through New Replacement Paradigm

- Monte Carlo simulations could not reproducibly predict which parts may fail on extended missions; conventional approach is to bring all spares that may fail, but that results in significant mass of spares being manifested that do not end up being used
- On-demand fabrication enables producing only spares needed during missions
- This approach has been successfully demonstrated in-theater: Army Mobile Parts Hospital build-as-you-go paradigm shortened resupply time and enhanced mission success by producing unanticipated parts not in the supply chain



Initial upmass

Reduced upmass component-level replacement for bring → build



Reduced upmass ORU → component-level replacement

Spares upmass

In-Space Manufacturing Challenges Due to the Space Environment

	Free Space	Lunar Surface	Martian Surface
Gravity	0	1/6 Earth's gravity	1/3 Earth's gravity
Atmosphere	<1x10^{-12} torr vacuum	2x10^{-12} torr vacuum	4 torr (95% CO_2; traces of Ar, Ne, O_2, CO)
Temperature	Shade: -200°F Sun: +200°F	Shade: -250°F Sun: +250°F	Shade: -125°F Sun: -25°F
Raw Materials	spent satellites, space debris	regolith (SiO_2 with traces of Al, Fe oxides)	SiO_2, Fe_2O_3, Al_2O_3

- Extremes in the space environment must be considered for in-space manufacturing processes
- Difficult to test for space environmental effects on additive manufacturing processes

Comparison of Metal Additive Manufacturing Processes for In-Space Applications

Metal Fabrication Process	Power Efficiency	Size Adaptability	Consumables	Resolution	Suitability in 0-g
EBF^3: Electron beam/wire (Electron Beam Freeform Fabrication)	+	+	+	– wire diameter	+ +
EBM: E-beam/powder bed (Electron Beam Melting)	+	– powder bed size	o powder	+	– – powder handling
DMD/SLM: Laser/powder bed (Direct Metal Deposition/Selective Laser Melting)	–	– powder bed size	– powder, gas	+	– – powder handling
LENS: Laser/powder feed (Laser Engineered Net Shaping)	–	o deposition rate	– powder, gas	+	– – powder handling
SMD: Arc or plasma/wire (Shaped Metal Deposition)	o	+	o gas	– wire diameter	o gas
Subtractive machining	o	o	o chips	+ +	– chip handling

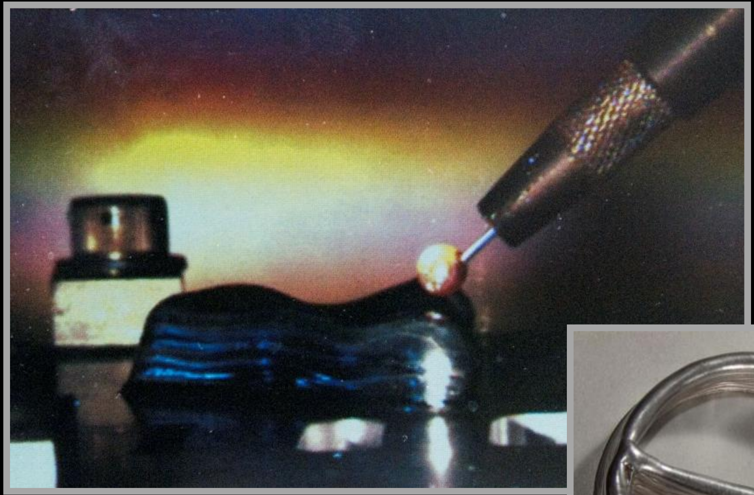
Legend: + + = best, + = above average, o = average, – = below average, – – = worst in class

- Electron beam deposition using wire feedstock offers high energy and feedstock efficiency and compatibility with the space environment
- Techniques are being developed to improve resolution for the EBF^3 process

Electron Beam Freeform Fabrication (EBF^3) Process

Basics

- Layer-additive process to build parts using computer numerically controlled (CNC) techniques
- Electron beam melts pool on substrate, metal wire added to build up part
- LaRC has ground-based and portable systems



EBF^3 deposition during 0-g parabolic flight tests

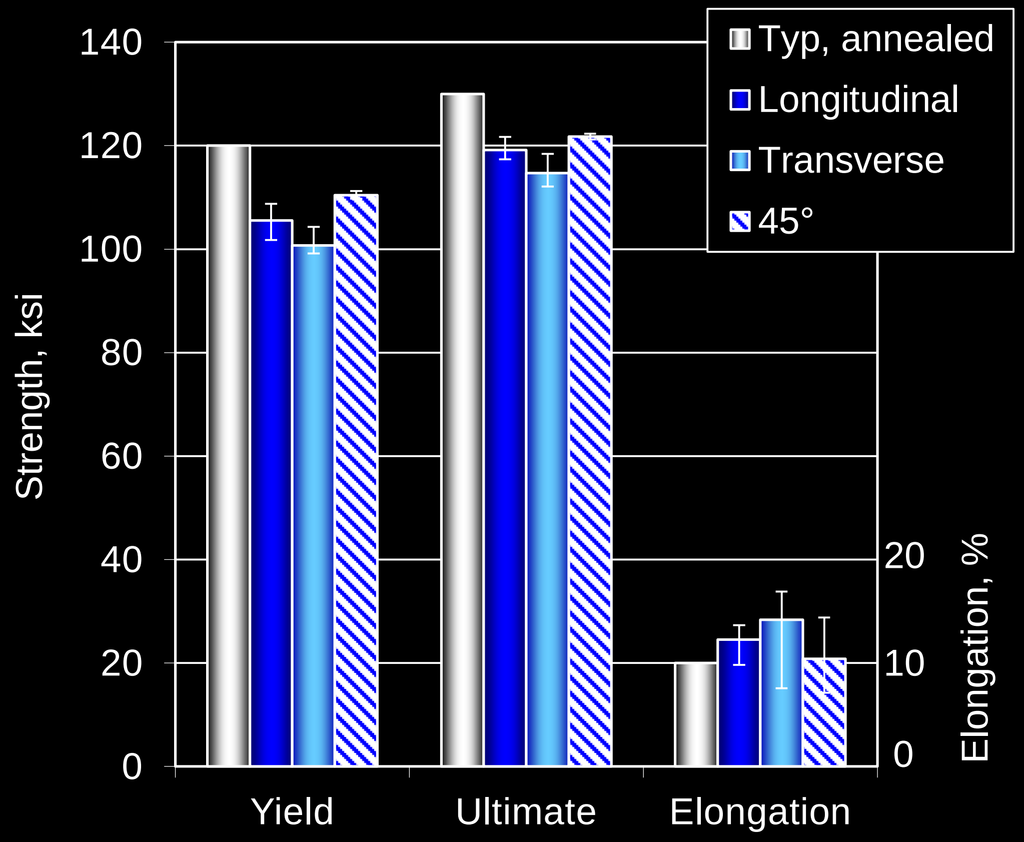
Example of finer scale 2219 Al EBF^3 deposits (built in lab)

Benefits

- Near-net shape parts minimize scrap & reduce part count
- High energy efficiency and feedstock usage efficiency
- Efficient design improves weight, assembly time, performance
- Intricate, complex geometries, functionally graded parts & structures
- Cross-cutting technology with numerous potential applications

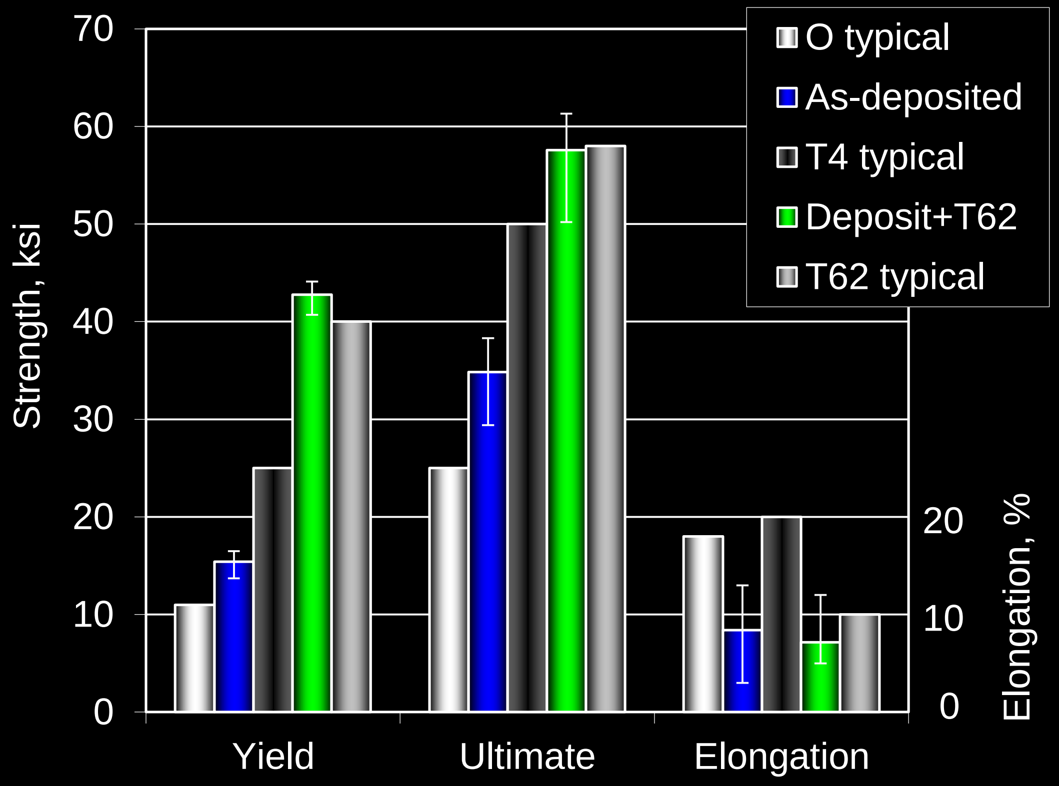
Ti-6Al-4V and 2219 Al Produced by EBF^3

Ti-6Al-4V



- As-deposited Ti-6-4 strength within 15% of annealed wrought product
- Slight anisotropy noted with respect to deposition direction

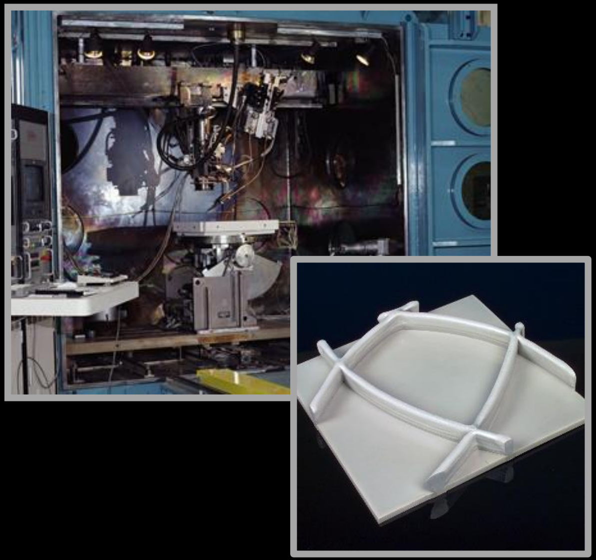
2219 Al

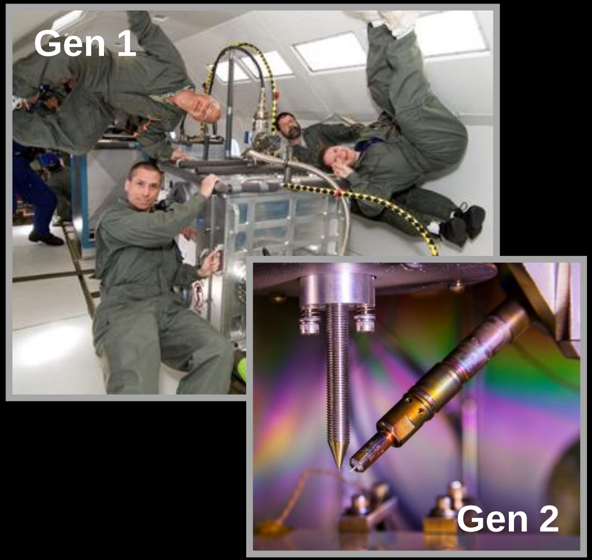


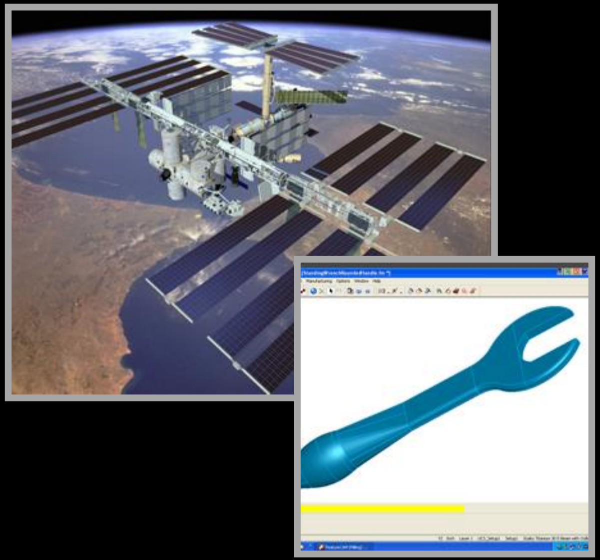
- As-deposited 2219 Al strength between handbook annealed and T4 temper values
- T62 heat treatment increases 2219 Al deposition strength comparable to handbook values

Electron Beam Freeform Fabrication (EBF^3) Capabilities

- In-house EBF^3 systems enable R&D of new materials and structures for NASA's applications
- Future investments in a space-based system will demonstrate concept to build anything anywhere for autonomy in remote locations without resupply, and understand basic materials science physics and dynamics of molten metals in sustained 0-g







Ground-based:
- 7 ft. x 9 ft. x 9 ft. chamber
- 100,000 lbs.
- 60 in. x 36 in. x 24 in. build volume

Portable (2 systems):
- 3 ft. x 3 ft. x 3 ft. chamber
- 1800-2000 lbs.
- 8 in. x 12 in. x 8 in. build volume

Space-based (proposed):
- Currently unfunded
- Size, mass & power based on internal or external installation on ISS

Functionally Graded Rocket Engine Components

Application:

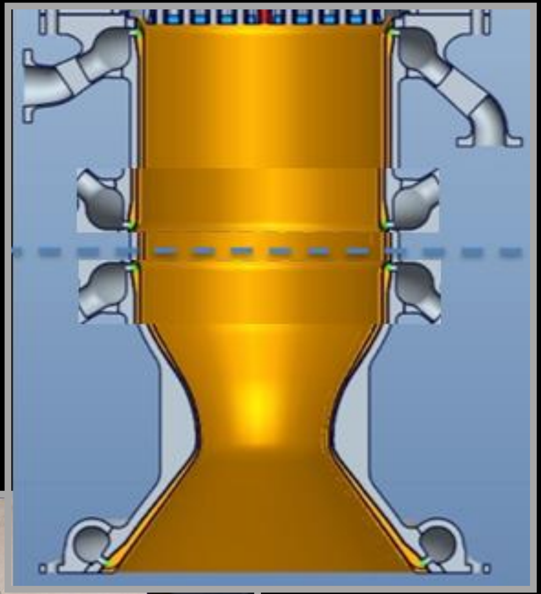
- U.S. liquid rocket engine manufacturers are experimenting with additive manufacturing techniques for next generation rocket engine components

Design Considerations:

- Use of combination of additive manufacturing processes takes advantages of benefits of each
- Intricate copper combustion chamber and nozzle produced by selective laser sintering
- Grading from copper to nickel to deposit a structural jacket and manifolds using electron beam freeform fabrication

Sustainability Benefits:

- Reduce injector manufacture time from months to weeks
- Potential to reduce full scale injector cost by nearly an order of magnitude (~90% reduction) and enhance performance through designs customized to additive manufacturing processes
- Successful hot-fire experiments will infuse additive manufacturing tech into US rocket engine industrial base



Schematic of integrated SLM copper/EBF^3 Inconel nozzle

Large scale EBF^3 deposited Inconel nozzle (without copper SLM insert)

Rapid Fabrication of Custom Tools and Components

Application:

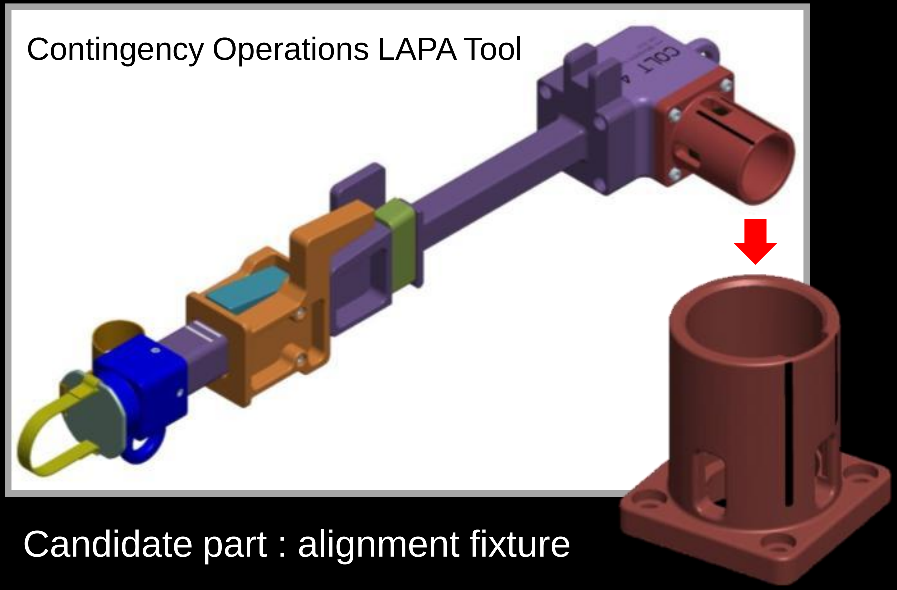
- Contingency Operations LAPA Tool (COLT) -- Extra Vehicular Activity tool used during the STS-135 ISS mission

Design Considerations:

- First demonstration = structural, non-critical, custom tool, conventional and additive built in parallel
- Future applications can be more complex/critical after additive processes are certified and accepted by community

Sustainability Benefits:

- Rapid fabrication of custom, flight-quality hardware as part of ground support for space systems



Candidate part : alignment fixture

EBF^3 deposited 2219 Al alignment fixture (built in lab)

Location of Pump Module replaced on ISS

Additive Manufacturing Repairs in Space and on Planetary Surfaces

Application:

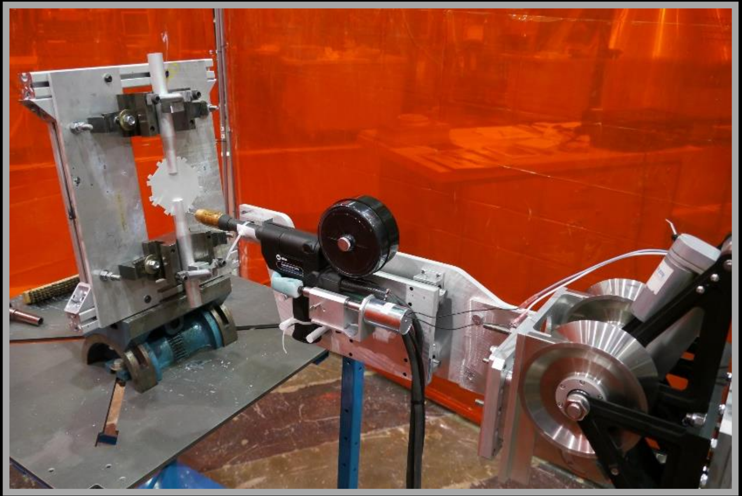
- Concept to support long duration human exploration mission can reduce upmass by repairing instead of replacing damaged structure
- Simulations predict different components fail in each simulation – bringing spares along will result in unneeded spares being manifested (uncertainty in which spare are required)

Design Considerations:

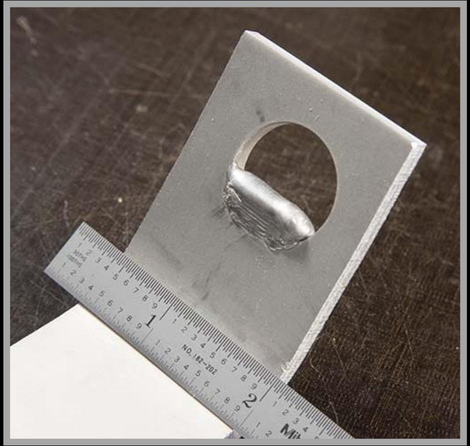
- Overall system architecture, including material selection, part accessibility and repairability/replaceability considered up-front
- Additive manufacturing capabilities must be compatible with materials, level of detail required, and robust to survive operations in the space environment
- Remote and/or automated operation of additive manufacturing system key to minimizing crew time

Sustainability Benefits:

- Potential to use in-situ resources and recycle discarded components into feedstock
- Modular system has multiple uses: fabrication, assembly, repair
- On-demand manufacturing provides flexibility to overcome unforeseen circumstances

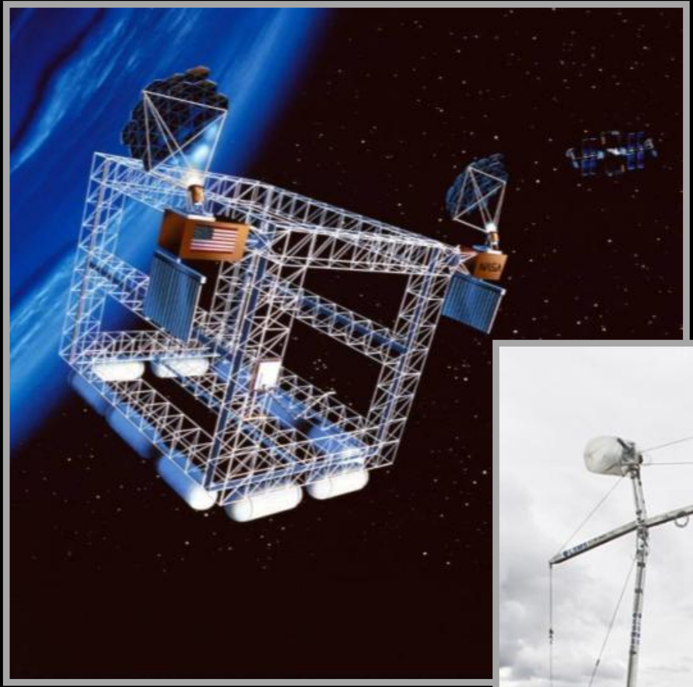


Robotic arm end effector for repairs (lab demo hardware)



EBF^3 hole repair on 2219 Al (built in lab)

On-Orbit Fabrication & Assembly of Large Space Structures



On-orbit fabrication depot (concept)

Application:

- Portable EBF^3 system integrated with larger manipulator for fabrication and assembly of large space structures in space or on other planetary surfaces
- Combination system enables flexibility, size not limited by capacity of additive manufacturing system

Design Considerations:

- Design for space loads, not stow/deploy and sustaining launch loads from Earth
- Architecture designed using materials and geometries applicable to additive manufacturing

Sustainability Benefits:

- Reduces upmass and complexity by building when you get there to meet load requirements in service (no launch loads)
- Residual benefit of hardware capable of performing modifications and repairs once structure is built

Large scale positioning for surface operations can be retrofitted with additive head for building hardware (concept)

EBF^3 Design & Sustainability Considerations: Summary

- Long duration human space missions will be challenged by mass and volume constraints for spare parts
- Use of additive manufacturing can reduce the need for pre-manufactured spares by generating parts on demand
- Electron beam deposition using wire feedstock offers high energy and feedstock efficiency and compatibility with the space environment
- Additive manufacturing capabilities like EBF^3 will have significant benefits for sustaining different space missions if considerations are accounted for in design

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