Metal Additive Manufacturing In Space

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JASON Study on AM Integrity In Space

June 23, 2021

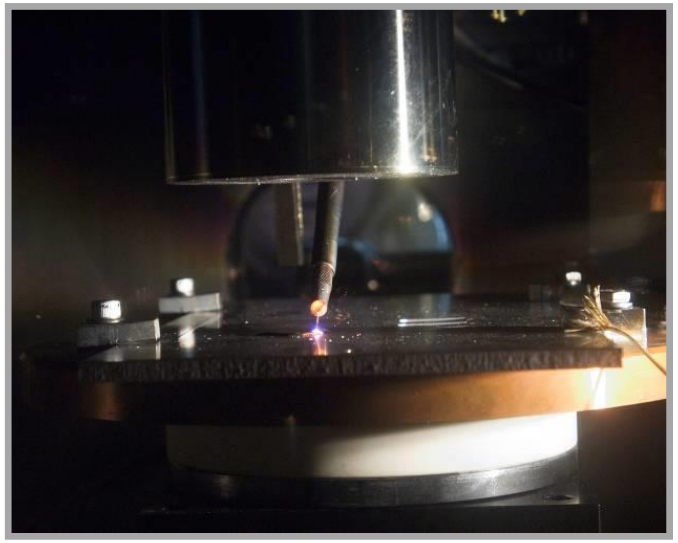
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Metal Additive Manufacturing In Space : Outline

- Challenges of Additive Manufacturing (AM) in space
- Electron Beam Freeform Fabrication (EBF^3)
- Effects of microgravity on EBF^3
- Applications of EBF^3 in space
- Summary of answers to JASON study questions





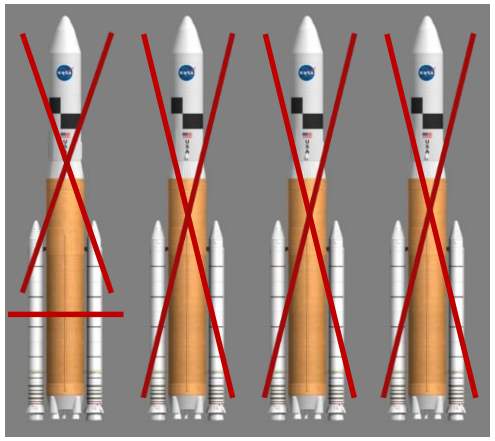
Mars Mission Spares Upmass Reduction with In-Space AM

- 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 AM 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**



Spares upmass

Reduced upmass ORU → **component-level replacement**

Manufacturing Challenges in 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

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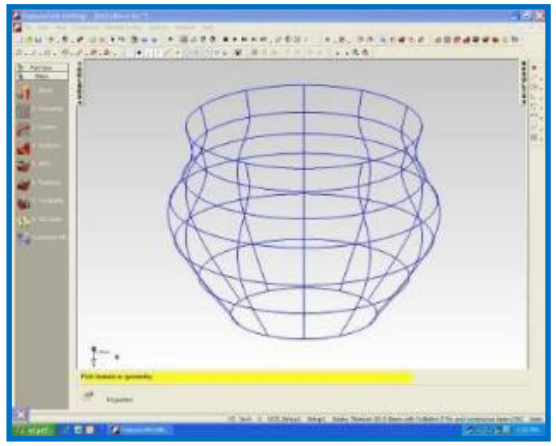
Comparison of Metal AM Processes for In-Space Applications

Metal Fabrication Process	Power Efficiency	Size Adaptability	Consumables	Resolution	Suitability in 0-g
EBF³: 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

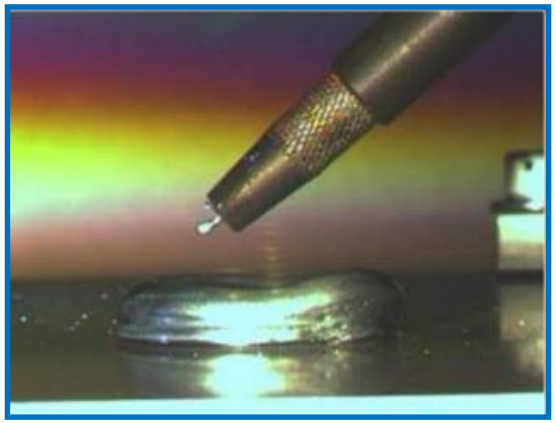
Legend: + + = best, + = above average, o = average, – = below average, – – = worst in class

- 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 EBF³ process

Electron Beam Freeform Fabrication (EBF^3) Process



Slice CAD drawing



Melt with electron beam, adding wire

- Directed Energy Deposition (DED) process using electron beam energy source and wire feedstock in vacuum
- Electron beam melts pool on substrate, metal wire added to build up part
- Demonstrated on Al, Ti, Ni, Fe-based alloys and Ni on Cu bimetallic
- Electron beam can be modulated to use as multi-functional tool : imaging, welding, AM deposition, cutting



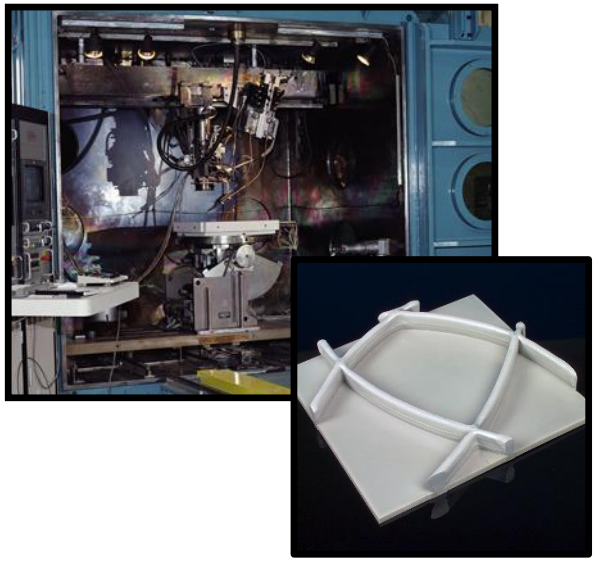
Example of finer scale 2219 Al EBF^3 deposits (built in lab)

Ground-based EBF^3 Process in Action (video)

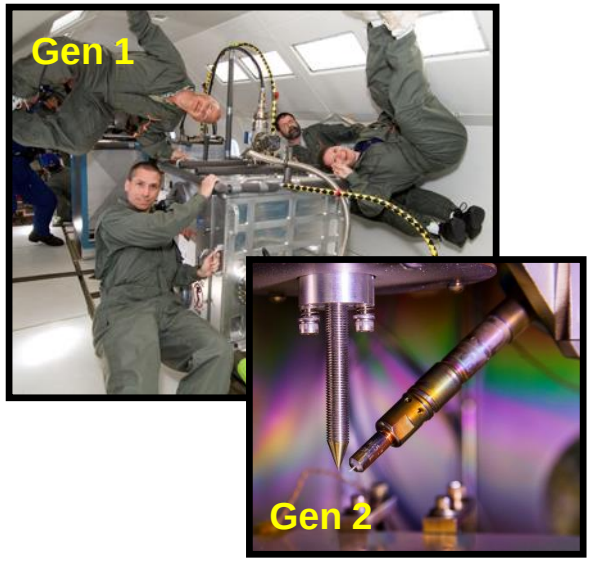


EBF^3 Capabilities at NASA LaRC

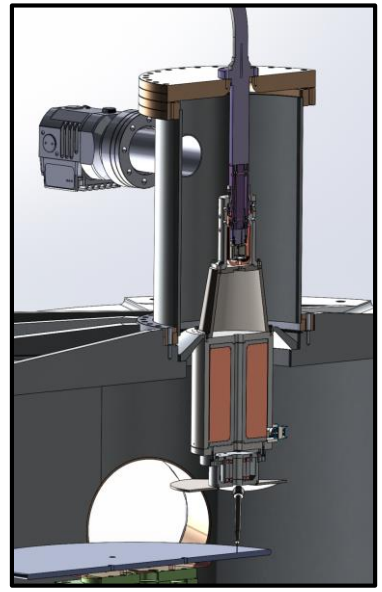
- In-house EBF^3 systems enable R&D of new materials and structures for NASA's applications
- Space-based system under development by COSM will integrate real-time electron beam imaging during DED and address robust gun deign and hands-off operations critical for AM in space



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

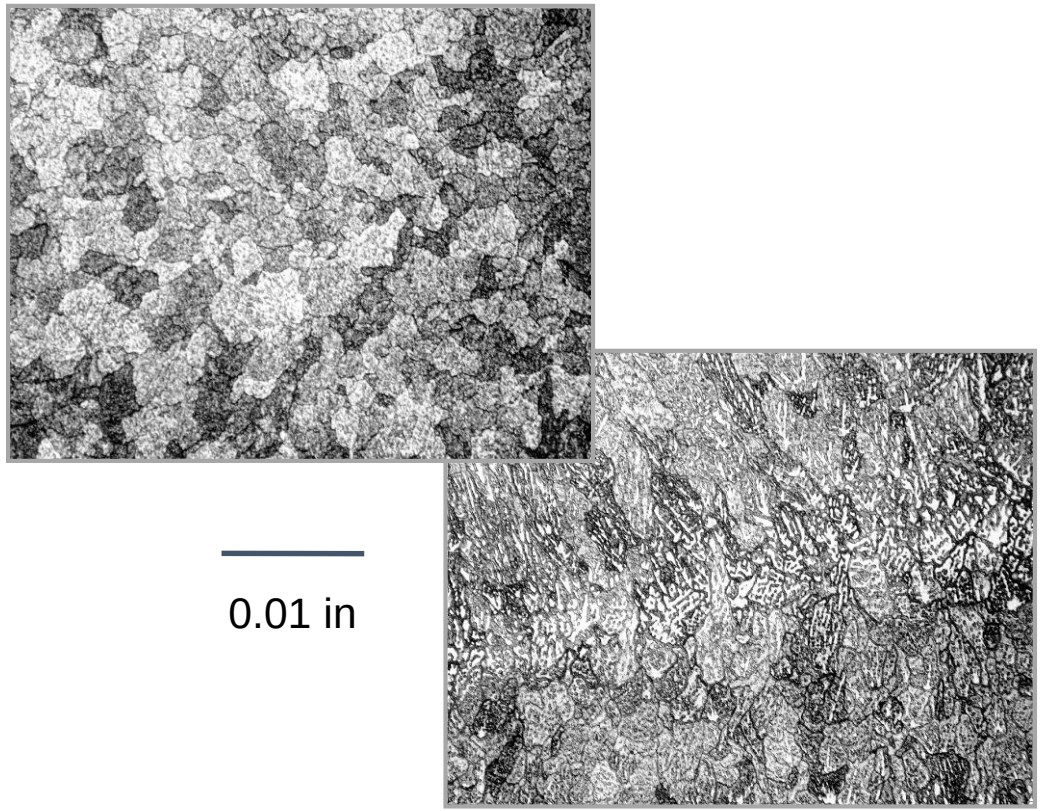


Portable (2 systems):
- 3 ft. x 3 ft. x 3 ft. chamber
- 1800-2000 lbs.
- 8 in. x 12 in. x 8 in. build volume

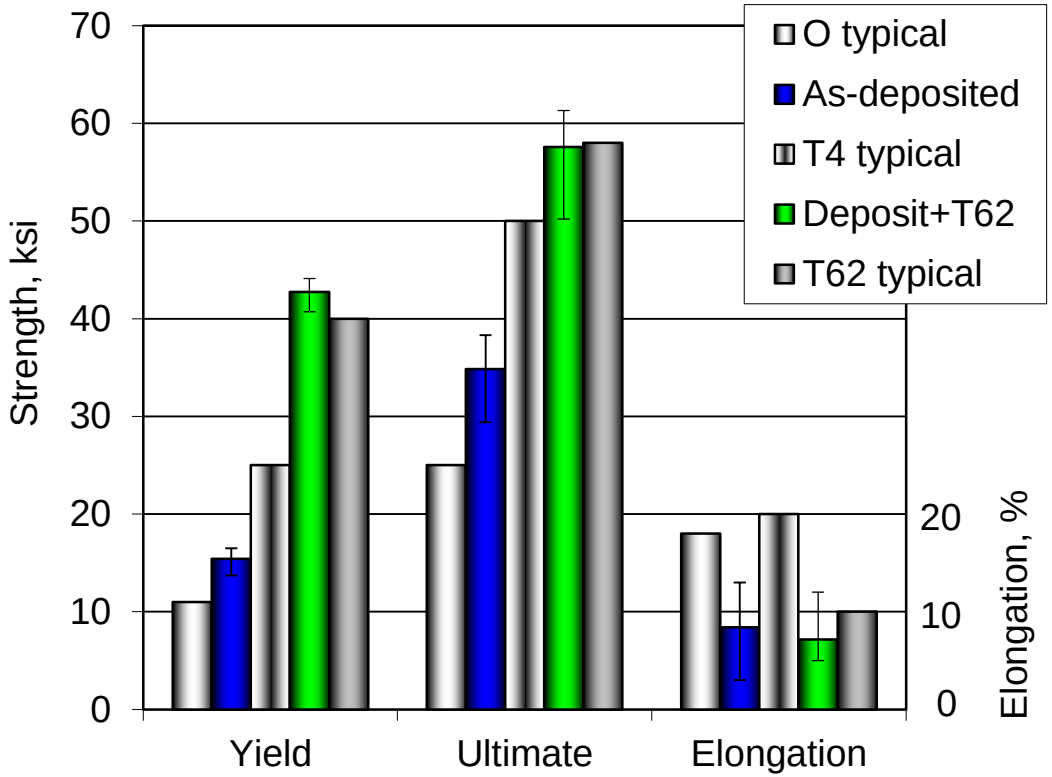


Space-based (under development):
- COSM Ph 2 Sequential SBIR award ($5M, 2 years)
- Size, mass & power targeting space-compatible requirements

2219 Al Produced by EBF^3

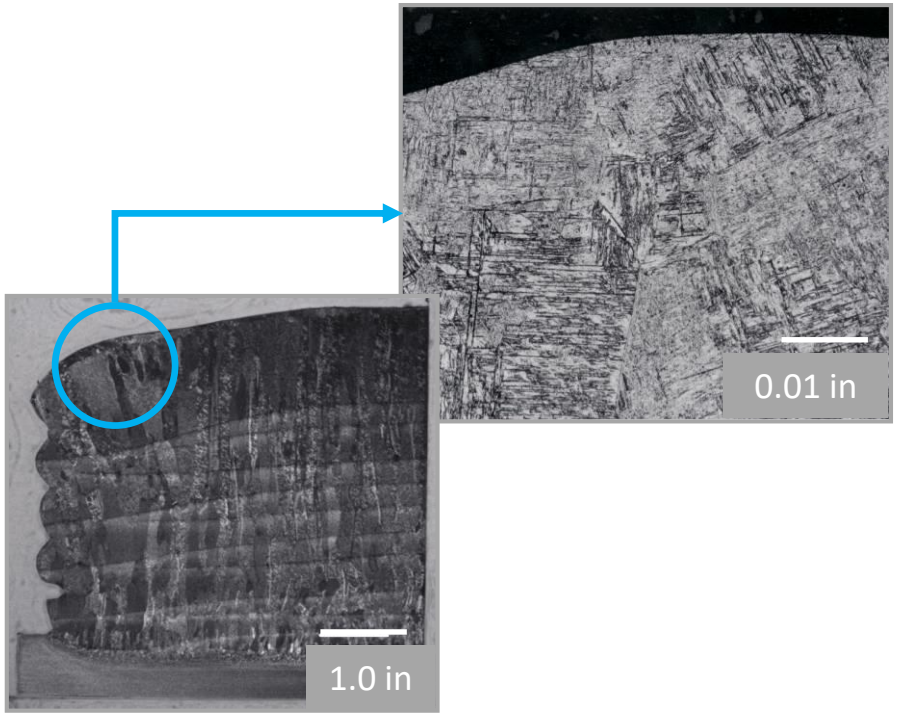


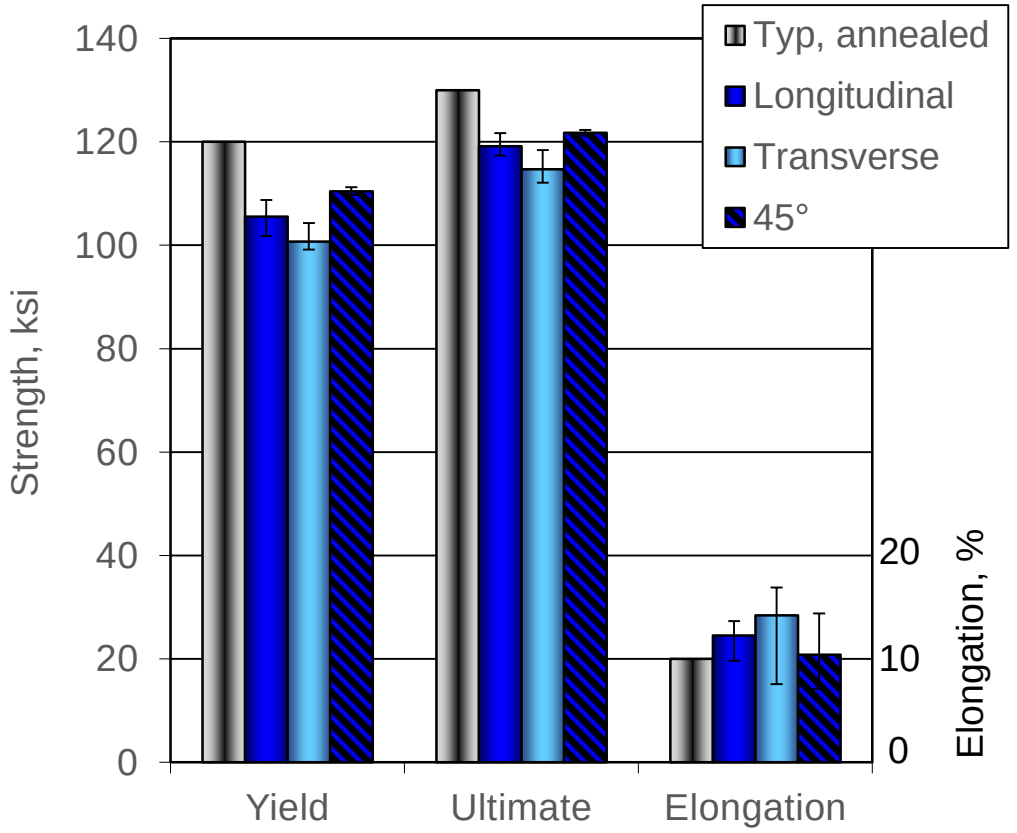
- Equiaxed or dendritic grain structure forms depending on deposition parameters



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

Ti-6Al-4V Processed by EBF^3

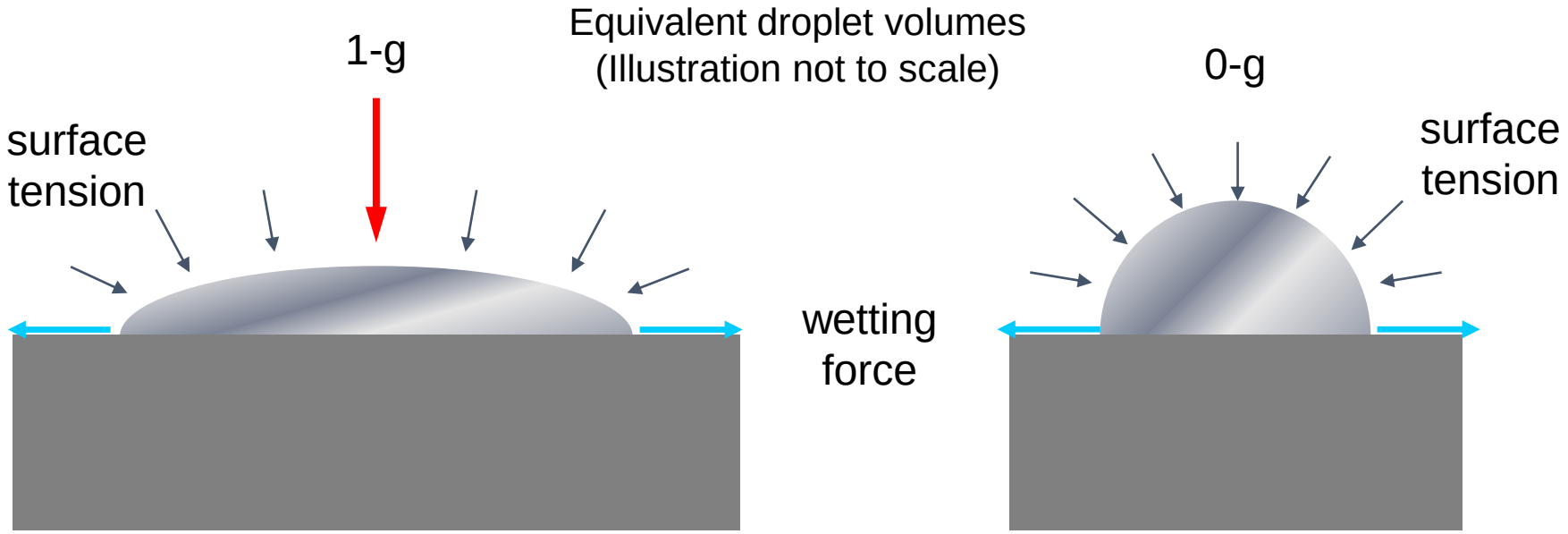




- Large columnar beta grains grow epitaxially from substrate
- Forms typical alpha-beta lath microstructure within grains

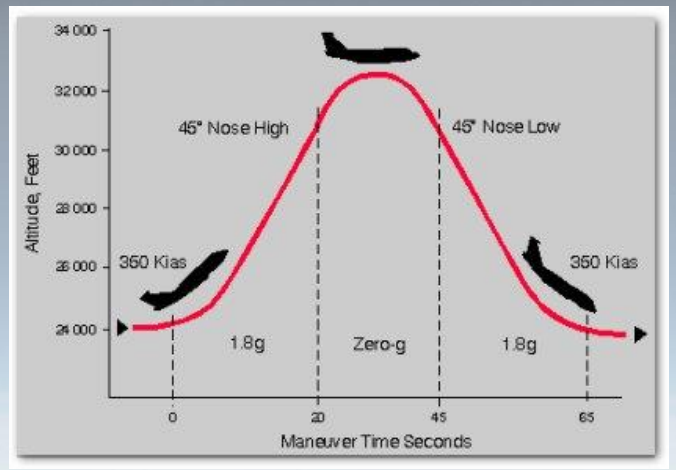
- As-deposited Ti-6-4 strength within 15% of annealed wrought product
- Slight anisotropy noted with respect to deposition direction

Theoretical Effect of Gravity on Surface Tension



- Surface tension strong function of temperature
- Body forces eliminated – surface tension dominates
  - May affect surface topography and microstructure of finished part
  - Influence on closed-loop control target values

Microgravity Testing Aboard NASA JSC's C-9





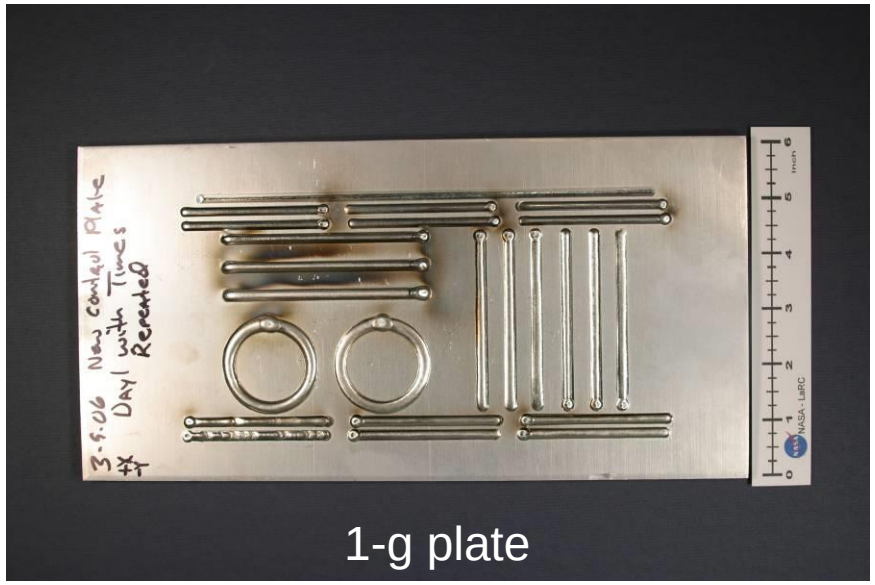
- **C-9 Capabilities**
  - **10^{-2}-g, Lunar-g, Martian-g capability**
  - **15-20 second duration for 10^{-2}-g, longer for partial-g**
  - **1.8-g during pullout**
  - **40 parabolas per flight typical**



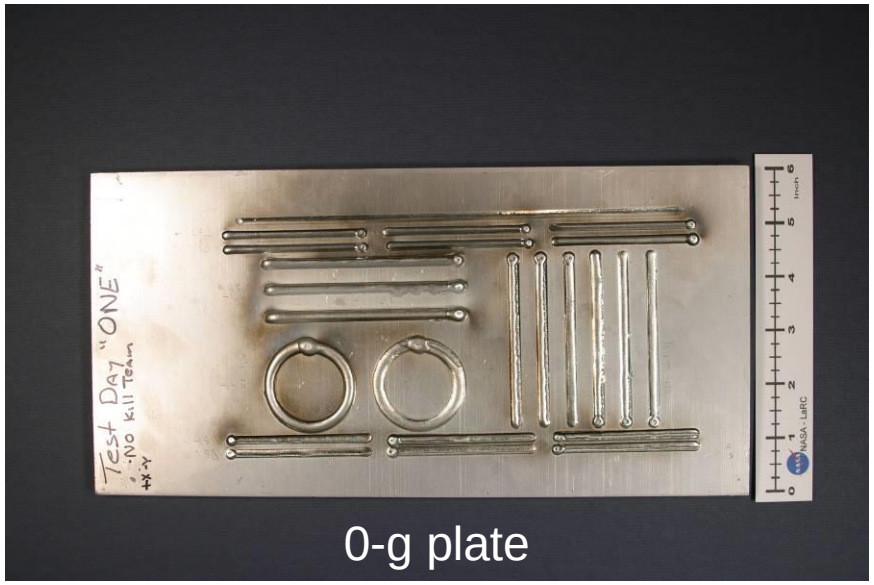




Typical 0-g Test Flight Plates



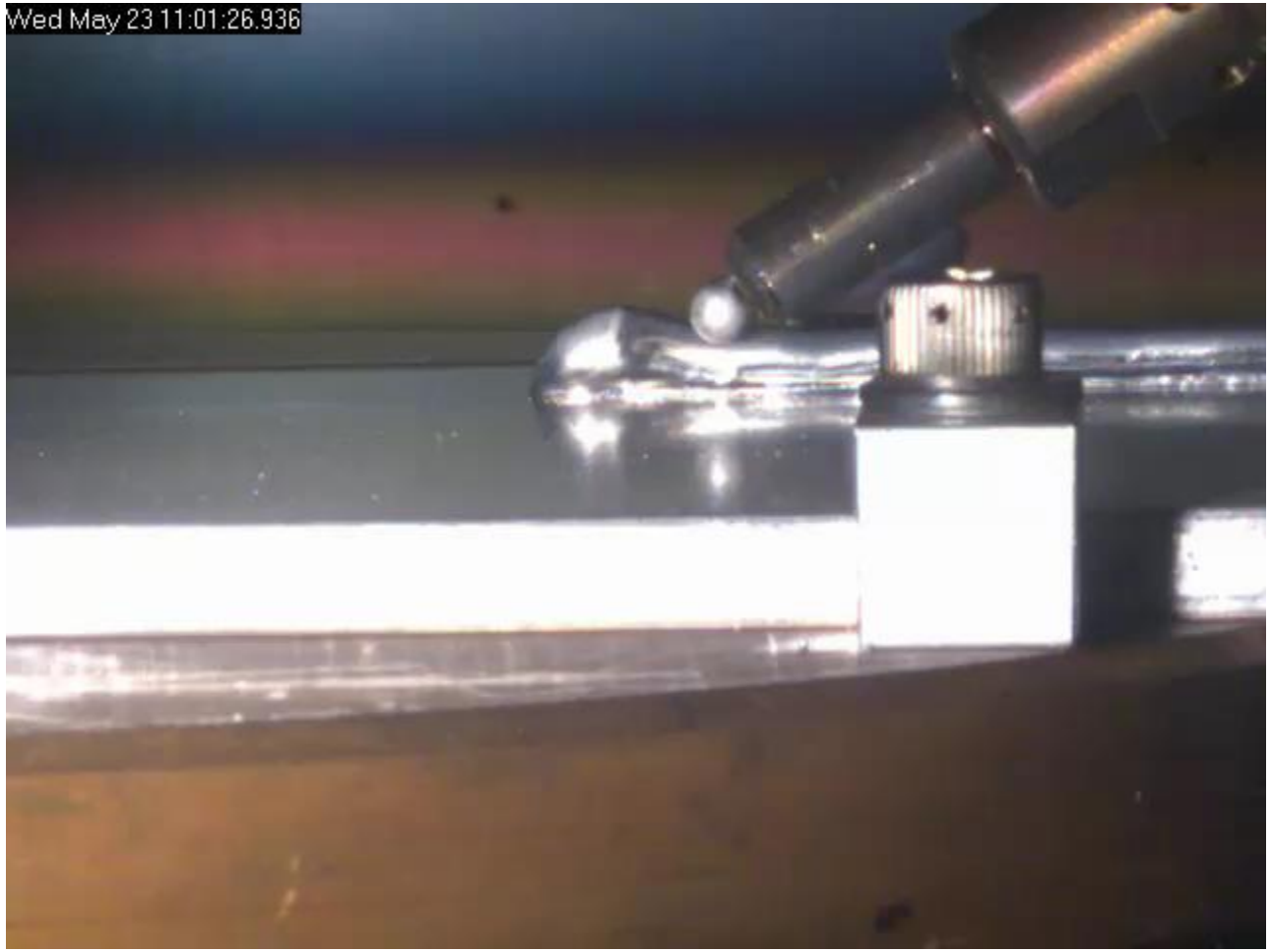
1-g plate



0-g plate

- Typically only deposit 1-2 layers during 0-g portion per parabola, depending upon translation speeds and feature size
- Lines built in different directions (+/- X & Y), 1-4 layers high
- Plates planned to include elements for 40 0-g parabolas

Direction and Height Trials for Process Control :
Wire Fed into Leading Edge of Molten Pool



- Wire fed into leading edge is easiest to control

Direction and Height Trials for Process Control :
Wire Fed into Trailing Edge of Molten Pool



- Wire fed into trailing edge pushes deposit in front of wire tip

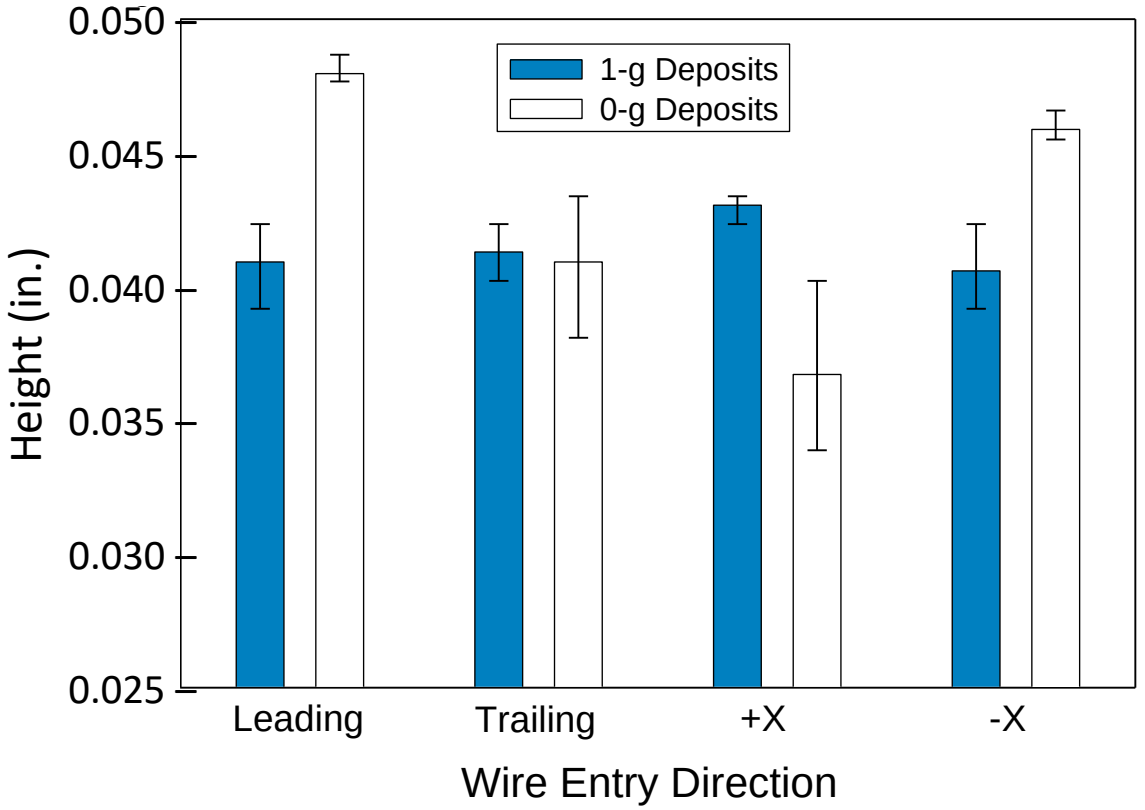
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Direction and Height Trials for Process Control :
Wire Fed into Side of Molten Pool



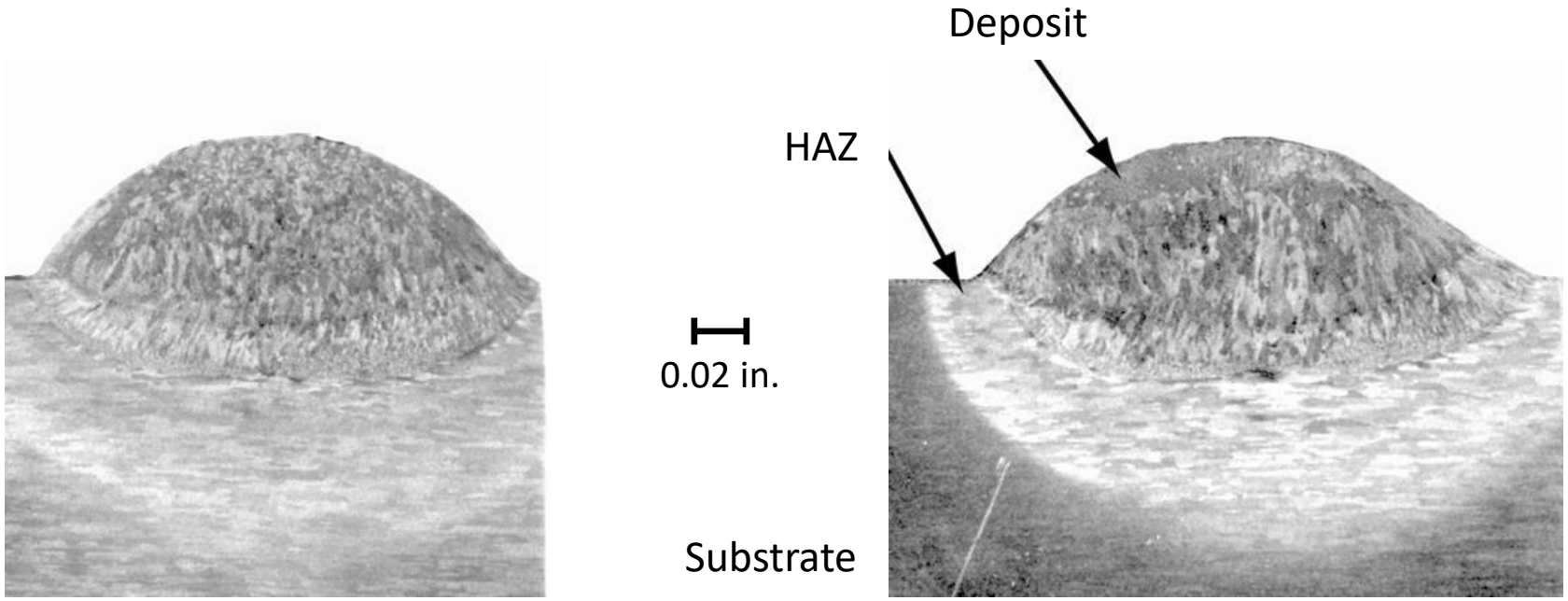
- Wire fed into side rolls molten pool off sides of deposit

Effect of Wire Entry Direction into Molten Pool



- Successfully deposited in 1-g and 0-g with translations in all directions in X-Y plane
- Deposits made in 0-g showed more variability in height than 1-g due to different wire entry direction into molten pool

Microstructure of Single Layer 2219 Al EBF^3 Deposits



1-g deposit

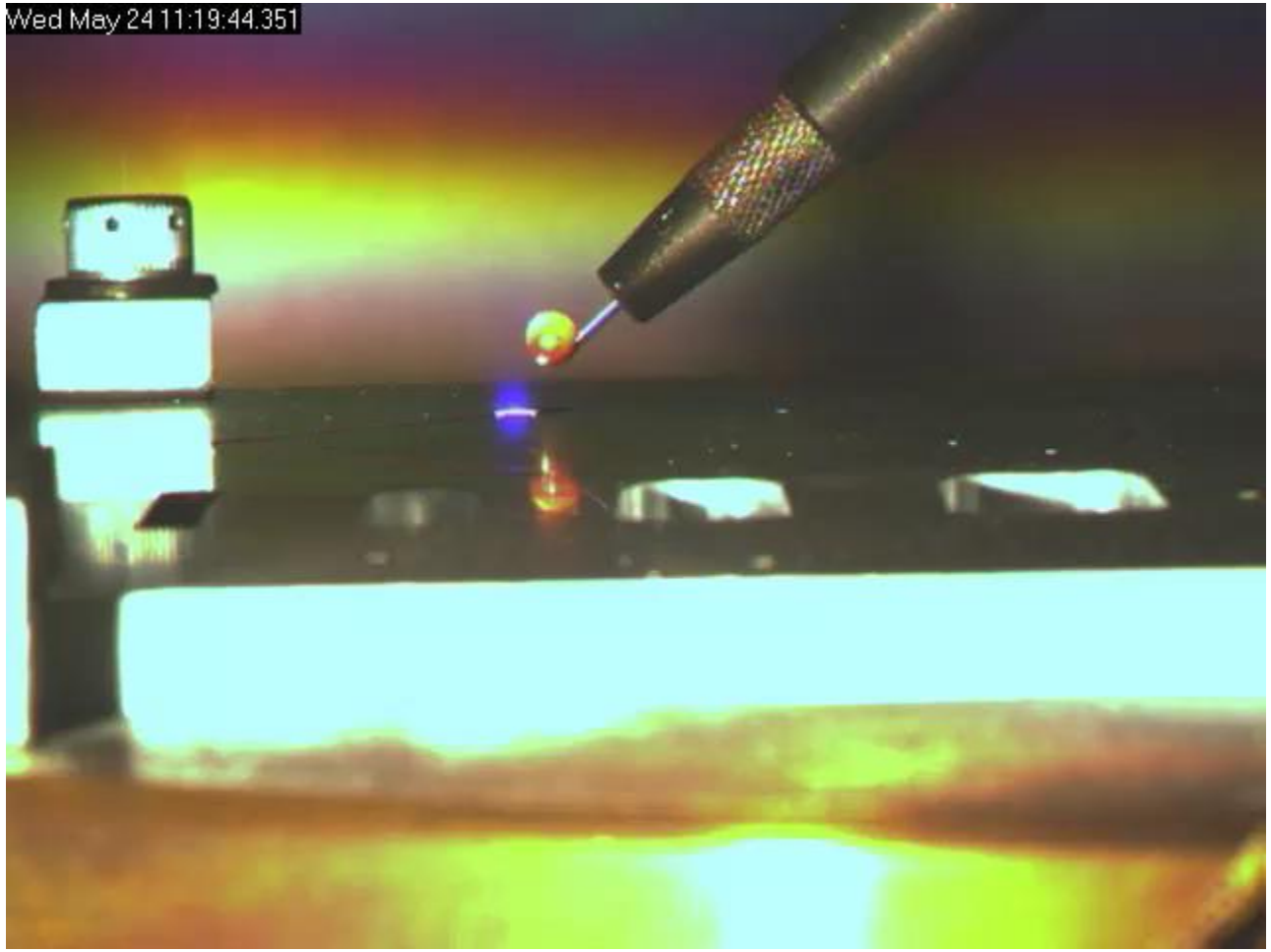
0-g deposit

- Microstructure and bead shape of 2219 Al single bead EBF^3 deposits unaffected by changes in gravity
- Fine grain cast aluminum structure with columnar grains nucleating from bottom of molten pool
- No apparent porosity, even in the absence of buoyancy forces

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0-g Deposit with Incorrect Standoff Distance

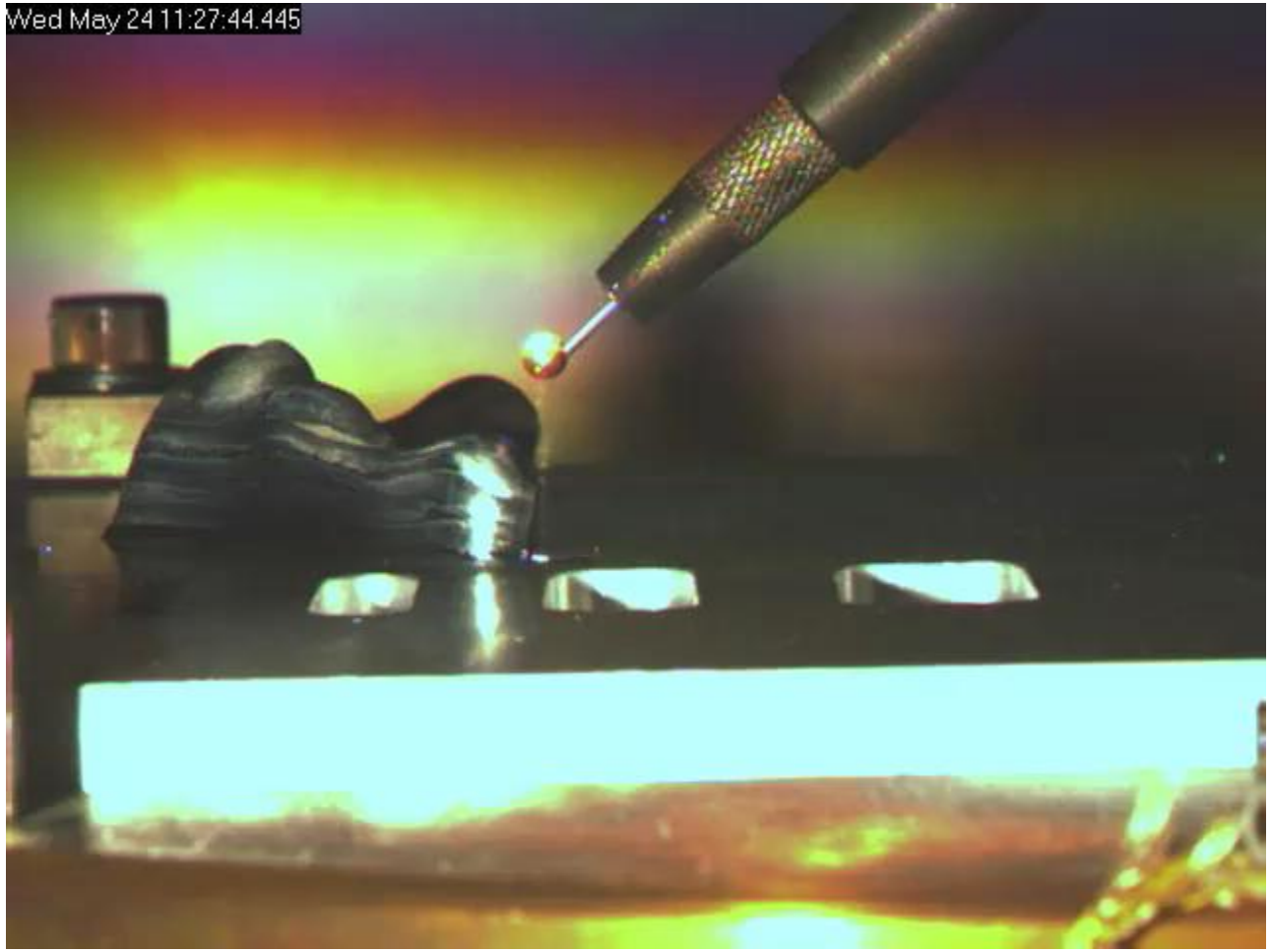
Chevron, Layer 1



- Started too high off substrate, molten ball adheres to wire tip
- Upon contact with plate, wetting forces overcome surface tension

0-g Deposit with Incorrect Standoff Distance

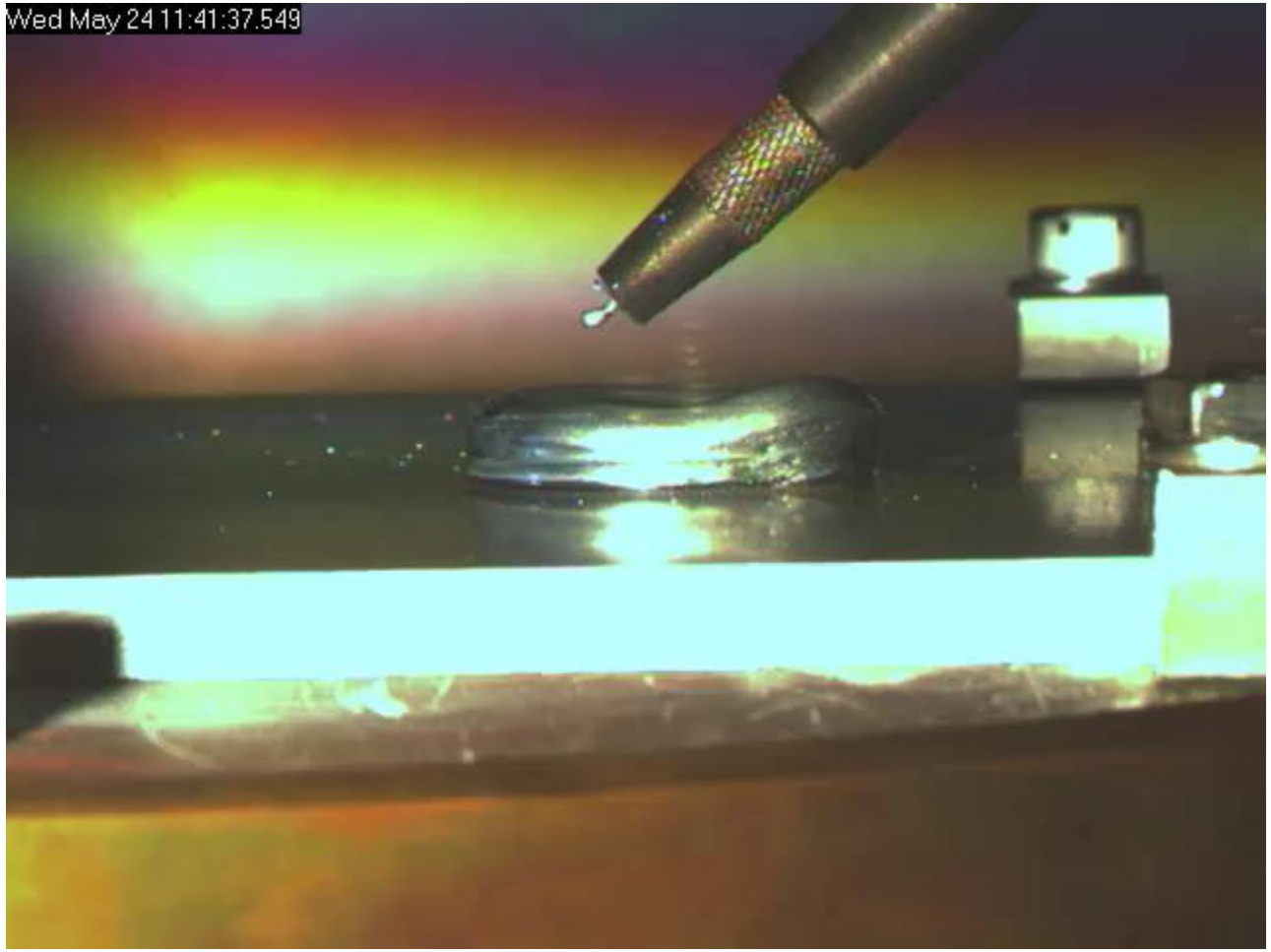
Chevron, Layer 8



- Attach/detach heights useful for developing height control
- Maintaining correct distance more important to process control in 0-g

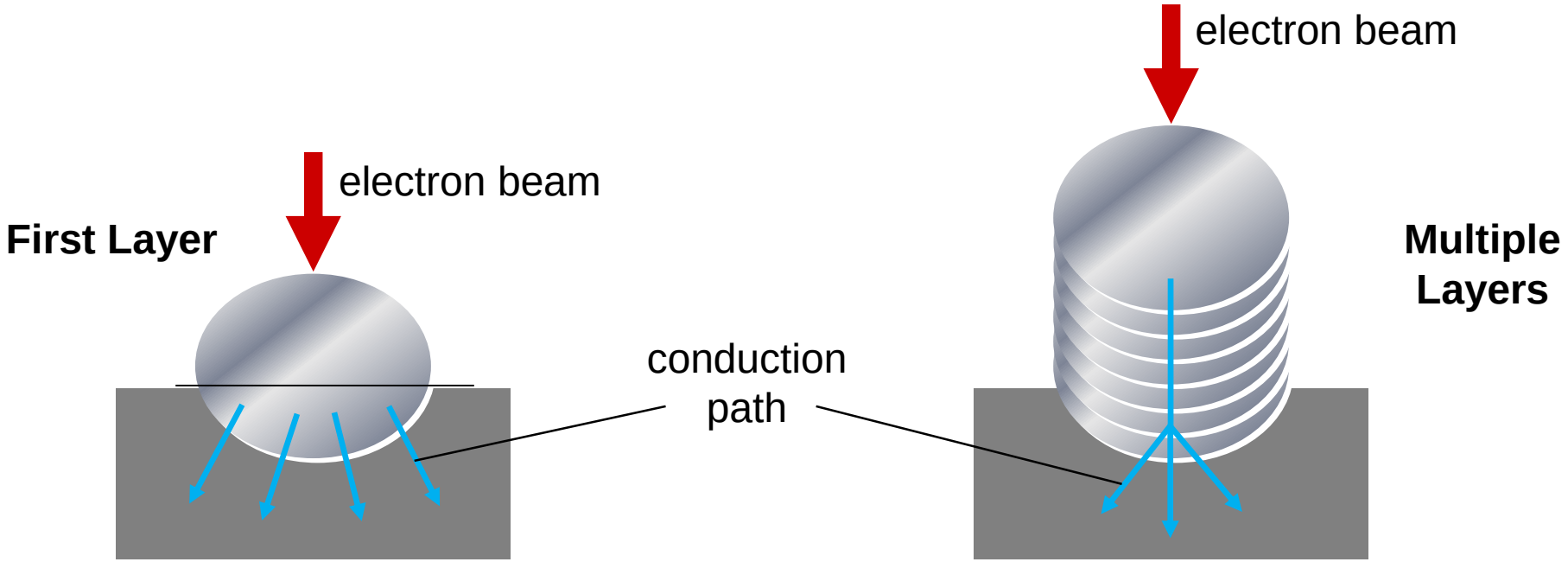
Successful Demonstration of EBF^3 in 0-g

Circle, Layers 7 & 8



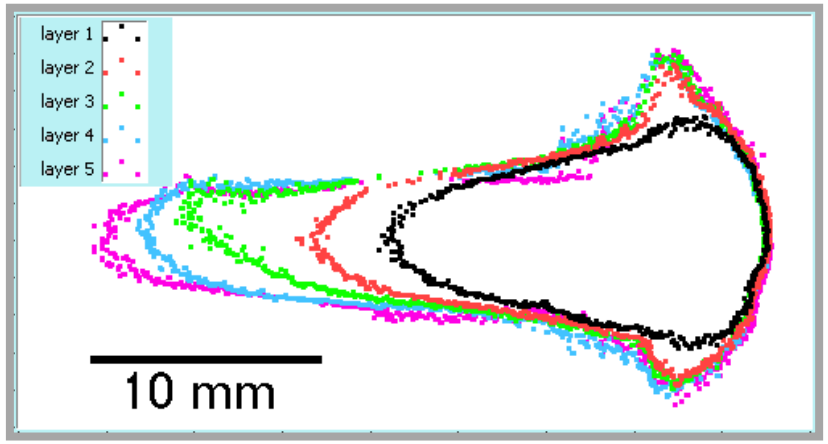
- Process able to heal surface irregularity from initial ball
- Process works well if correct distance maintained

Effect of Deposit Height on Cooling Path

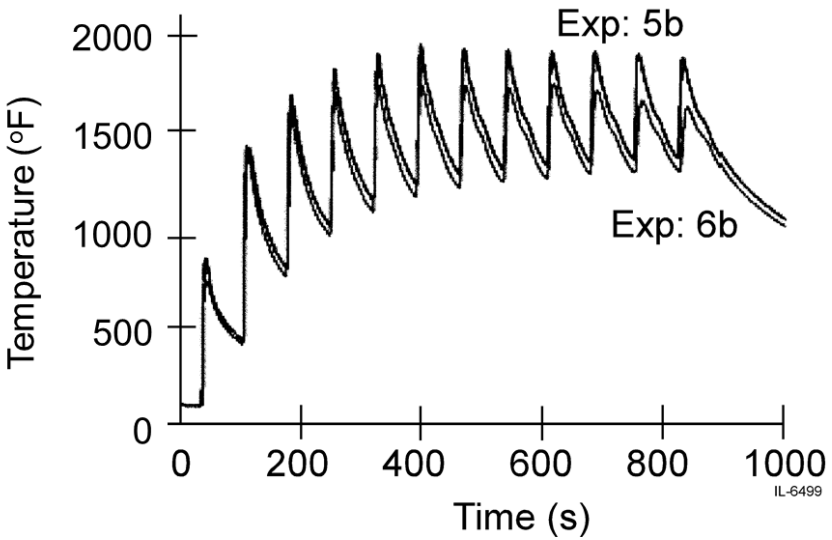


- Cooling rate is conduction-limited resulting in increasing temperatures with increasing deposit height

Layer-Additive Processes are Inherently Transient



Liquidus temperature of EBF^3 Ti-6-4 outlined over 5 layers with constant power and travel speed.

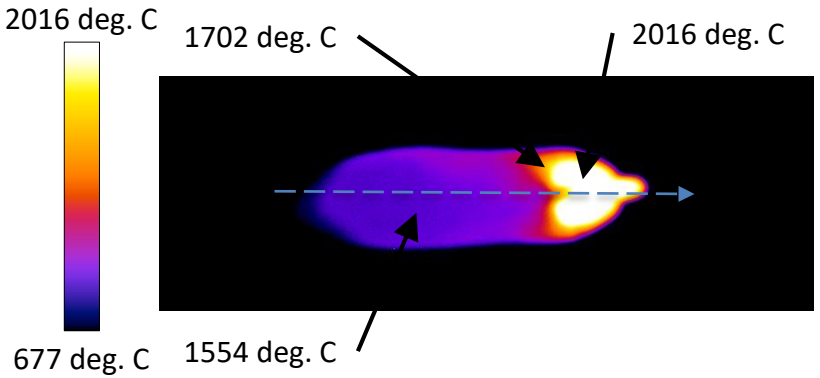


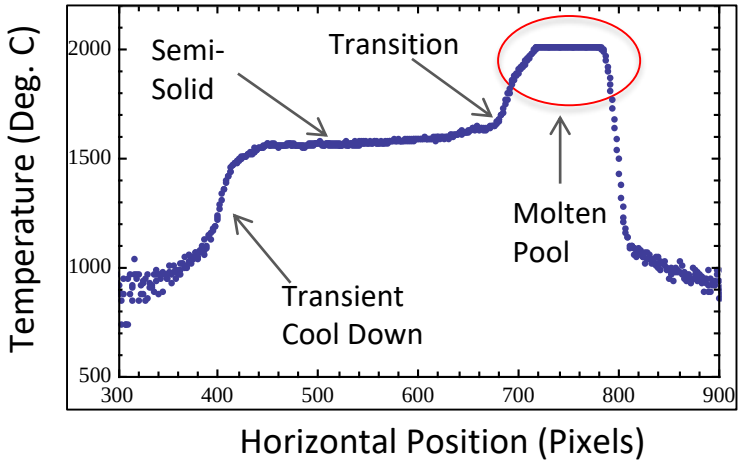
Thermocouple trace of EBF^3 Ti-6-4, measured on back side of baseplate during 11-layer deposition.

- Melt pool changes with temperature from one layer to the next
- Melt pool size and temperature need to be monitored to maintain controlled process
- Refine control logic to correct for other process anomalies and record data in real time
- Integrated sensors and intelligent on-board control system required for space-based operations due to transmission delay times

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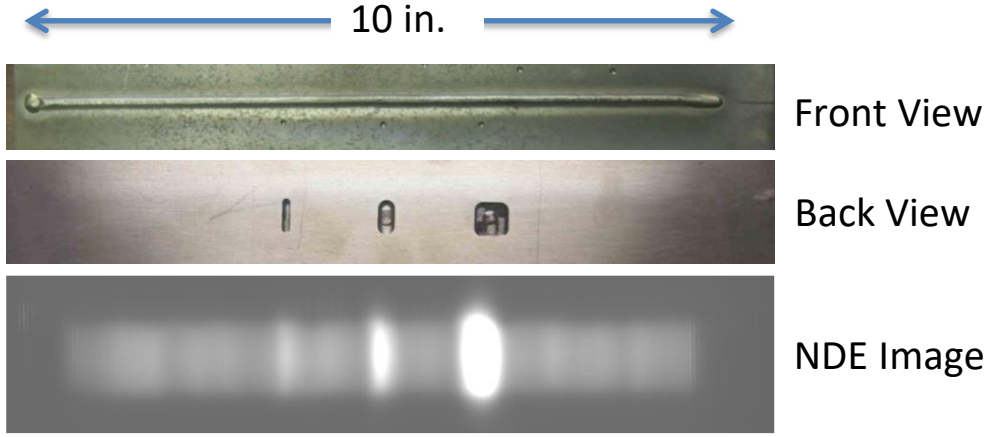
Thermal Monitoring During EBF^3 Deposition





- Thermal imaging using near-IR cameras provides real-time information during EBF^3 deposition
- Melt pool region used for process control
- Transient cool-down region used for internal flaw detection
- Next step is correlating transient signals with types of defects

NDE Results from Single Bead Experiments



Rapid Fabrication of Custom Tools and Components

Application:

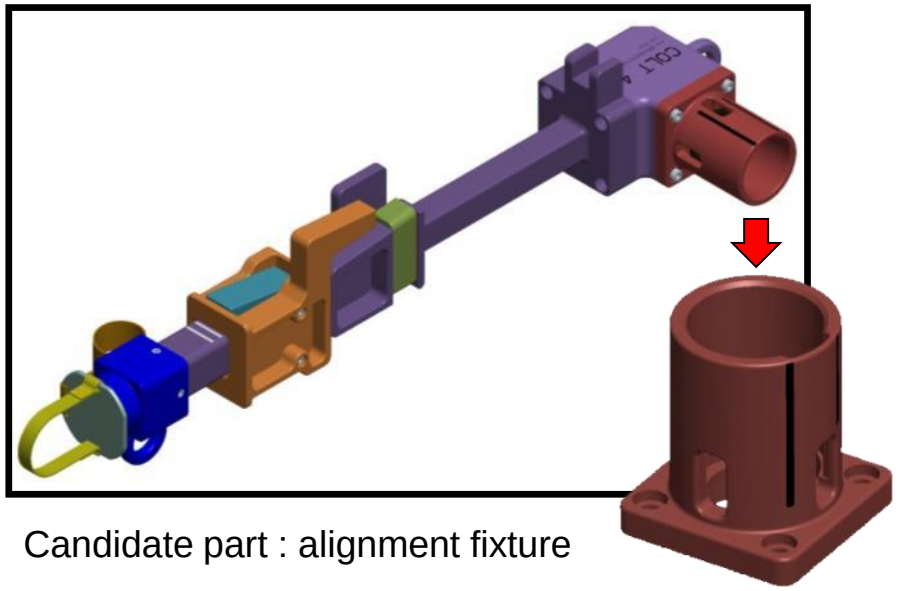
- Contingency Operations LAPA Tool (COLT) -- Extra Vehicular Activity tool used during the STS-135 ISS mission

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:

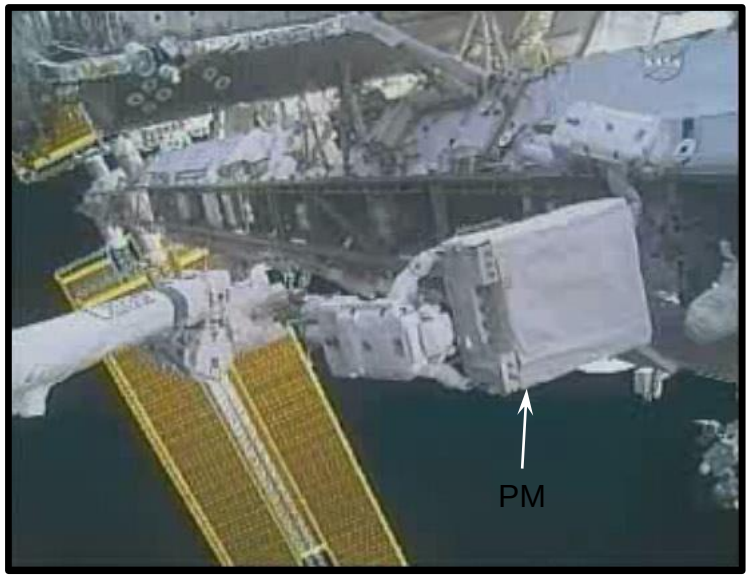
- Rapid fabrication of custom, flight-quality hardware as part of ground support for space systems



Candidate part : alignment fixture



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



Location of Pump Module replaced on ISS

AM Repairs in Space and on Planetary Surfaces

Application:

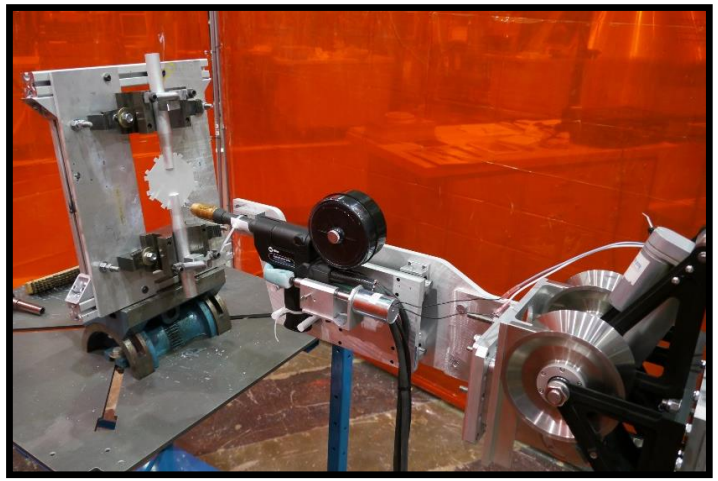
- Support long duration human exploration mission can reduce upmass by repairing instead of replacing damaged structure

Design Considerations:

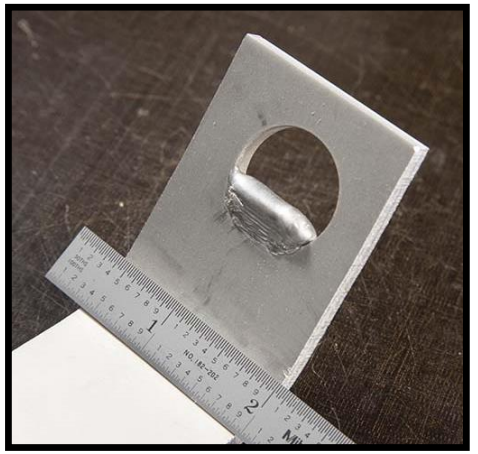
- Overall system architecture, including material selection, part accessibility and repairability/replaceability considered up-front
- Additive manufacturing capabilities must be compatible with materials, level of detail required, and robust to survive operations in the space environment
- Remote and/or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

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

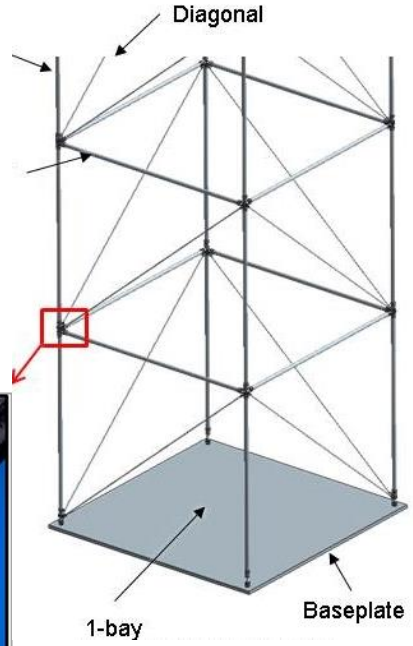
Design Considerations:

- 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

Truss structure assembled in space with welded joints (concept, demo in lab)





EBF^3 system used as an electron beam welder to weld and sever truss elements onto central node point (demo in lab)

Metal Additive Manufacturing In Space : Summary

- Long duration space missions will be challenged by mass and volume constraints for spare parts
- AM can reduce the need for pre-manufactured spares by generating parts on demand
- Electron beam / wire deposition offers high energy and feedstock efficiency and compatibility with the space environment
  - Initial demonstrations showed wetting forces aid bead attachment to base plate in EBF^3 process at 0-g
  - Surface tension dominates bead shape
  - Distance between wire tip and substrate and thermal input are more critical to control EBF3 process in 0-g
- AM capabilities like EBF^3 will have significant benefits for sustaining different missions if considerations are accounted for in design



JASON Study Questions (p. 1 of 2)

JASON Question	Response	Ref. Slide #
1. What inspection methods are needed? Are such methods feasible in space?	Real-time thermography enables inspection of embedded defects; may be post-processed to create inspection report	8, 23, 24
2. Are hybrid methods combining processing with computation needed? If so, what requirements must one place on computational tools to enable virtual processes?	Robust process control with built-in intelligence required for safe operations; computational efforts for metal DED systems are not currently available but may be applicable	n/a
3. To what extent are methods of validation in terrestrial settings transferrable to space?	Surface tension dominates bead shape irrespective of gravity; duplication of thermal mass in space-based system with terrestrial-based system enables ground-truth	6-8, 18
4. Do we have to return parts to Earth periodically for secondary inspection?	Depends on service requirements and life of parts built in space (more highly loaded will require more inspection)	n/a
5. Are there real-time screening methods potentially suitable for the space environment that have yet to be investigated?	Real-time thermography and use of electron beam as probe for visual inspection may be integrated into EBF^3 controls (feasibility demonstrated; funding required to mature)	24
6. What are the requirements for machine learning (ML); are such methods robust enough to capture details, assess uncertainty, and guide changes, especially for rare events that result in defects?	ML has largely not been applied to wire DED systems yet, but would be beneficial to catalog nominal conditions and anomalies/defects	17, 18, 22-24

n/a = not addressed in this presentation

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JASON Study Questions (p. 2 of 2)

JASON Question	Response	Ref. Slide #
7. How do we make our design procedures flexible enough to provide added performance margin to account for larger unknowns?	Components need to be designed for accessibility for assembly and repair; connections for mating parts and mechanisms require planning to accommodate AM surface variations	25-27
8. What are the differences and commonalities between metals and polymers for monitoring and assessment?	Visual monitoring approaches are applicable to both material types; thermal less effective with polymers due to low infrared signature	5
9. What systems-level considerations are required in the building of parts using in-space AM; for example, how should one account for the effect of heat dissipation on AM parts in densely packed sub-systems?	Time delays between layers and pulsed beam/wire deposition can reduce overall heat input; radiation and conduction paths aid dissipation; built-in thermal sensors can monitor and control process to avoid overheating	26, 27
10. What are practical sources of feedstock materials for AM in space?	Recycle spent tanks, lander hardware, tow along rocket upper stage to reconfigure into metallic feedstock (discarded materials already highly refined so reuse is more attainable than in-situ resource utilization in the near term)	n/a
11. Might the near-vacuum and absence of gravity in space provide opportunities for developing new AM techniques that would be difficult on the ground?	Electron beams can exploit vacuum for operations; 0-g presents feedstock handling challenges with powders (addressed by using solid feedstock/wire)	12-21

n/a = not addressed in this presentation

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