Laser Beam Welding for in-Space Joining Demonstrated Under Vacuum on the Ground and By Parabolic Flight Experiments

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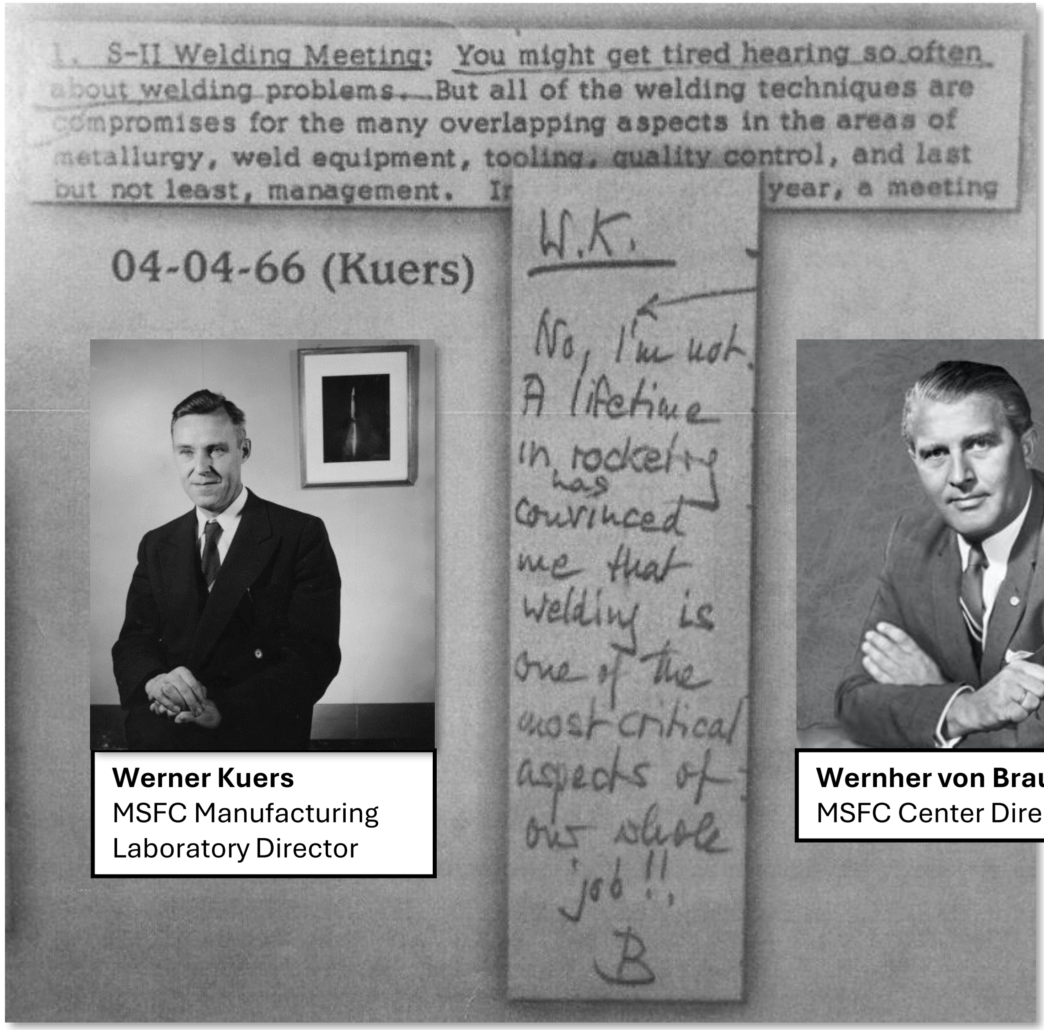
COLLEGE OF ENGINEERING

NASA

Welding enables space exploration



1966 correspondence between Wernher von Braun and Werner Kuers

"The complexity of welding is readily apparent when one considers that fusion welding involves temperature gradients of thousands of degrees, over distances of less than a centimeter, occurring on a time scale of seconds, involving multiple phases of solids, liquids, gases, and plasma."

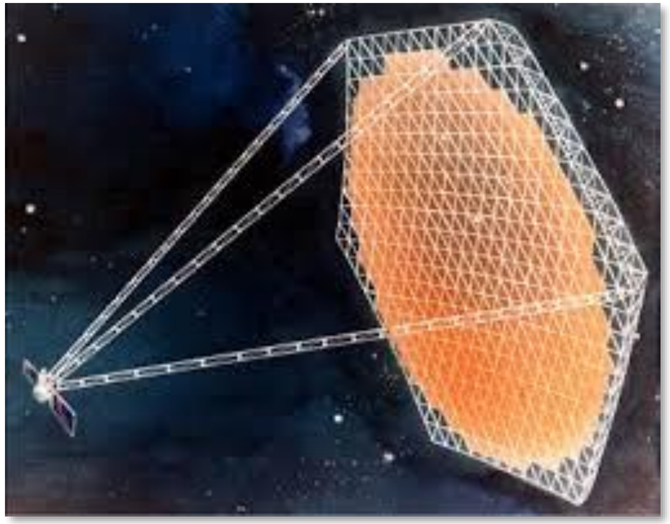
Thomas Eagar, MIT, 1990

Quoted in North, Ed., *Advanced joining technologies: proceedings of the International Institute of Welding Congress on Joining Research*, 1990.

Adapted from: Sowards, *American Welding Society Professional Program*, 2023.

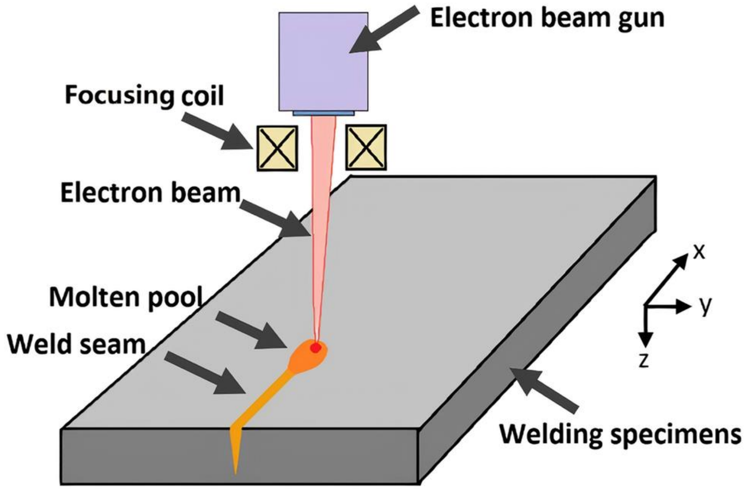
Why welding in space?

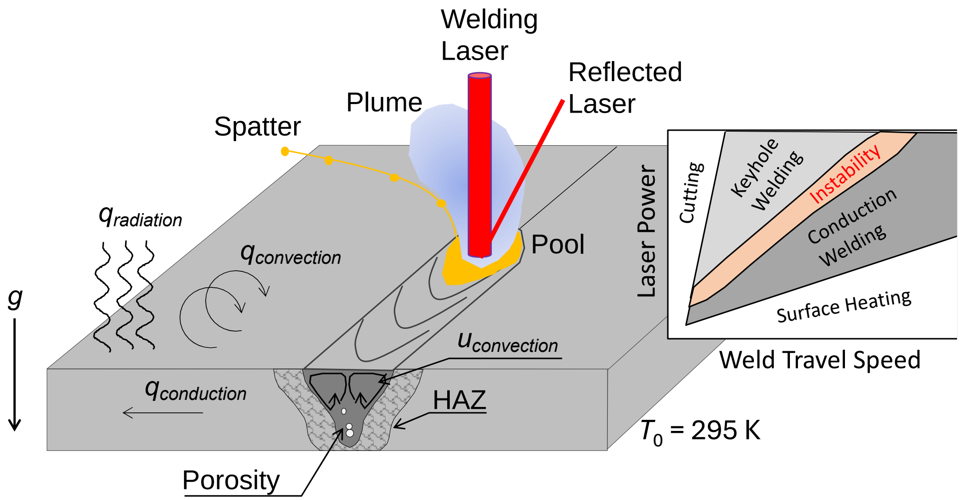
Method → ↓ Criteria	Fasteners/ rivets	In–Space Welding (ISW)
Joint strength & rigidity	◒	○
Joint hermeticity	●	○
Joint mass	●	○
Joint design & manufacturing simplicity	◒	○
Joint reliability	◒	○
Repair versatility	●	○
Associated cost & upmass	◒	○
● - Poor	◒ - Satisfactory	○ - Good



List adapted in part from: Tamir et al., *Thirtieth Space Congress*, 1993.

Why laser beam welding in space?

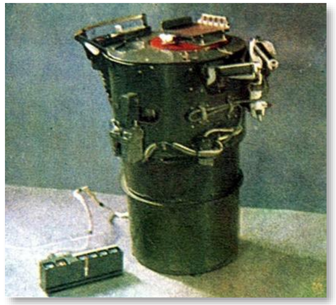




High-energy Beam Process → **↓ Criteria**	**Electron**	**Laser**	**Status**
IVA flexibility (*e.g.* in habitat) & EVA flexibility (*e.g.* in vacuum, Lunar surface, on Mars)	●	○	Capability available after planned development
Workpiece variety (*e.g.* geometry, material)	◒	○	
Suitable for operation on end effector of robotic arm (*e.g.* EMI, mass, power delivery, heat rejection)	●	○	
Compatible with inspection tools & able to repair welds	●	○	
Power requirements & energy efficiency	○	◒	Commercial lasers
Suitable for additive manufacturing	◒	○	Future work (GCD, etc.)
Perform subtractive manufacturing – cutting, drilling, etc.	●	○	
Capable of bending/forming structures	●	○	
● - Poor ◒ - Satisfactory ○ - Good			

List adapted in part from: Tamir et al., *Thirtieth Space Congress*, 1993.

Timeline of in-space joining



FIRST SPACE WELD
1969. Soyuz-6 Vulkan. EBW, PAW, GMAW (USSR)

FIRST AMERICAN SPACE WELD
1973. Skylab. EBW, braze experiments (USA)

1979. Salyut-6. Isparitel braze coating(USSR)

1983. Salyut-7. Isparitel M, deposition (USSR)

1984. Salyut-7. UHT (USSR)
FIRST MANUAL OPEN SPACE WELD

1988. Mir, Yantar EB melt/weld (USSR)

1993. Parabolic CO_2 LBW Experiment

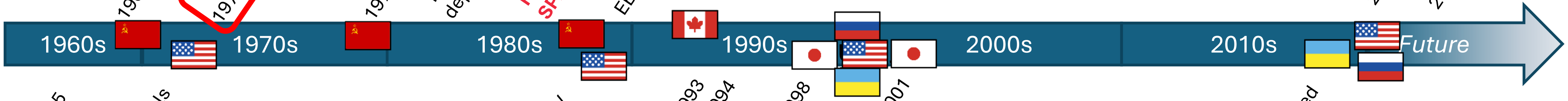
Progress in Space Stagnated and Moved to Parabolic Flights

1999. ISWE components went to MIR USA/UKRAINE/RUSSIA CANCELLED

It has been over 50 years since NASA has performed a weld in space.

2021. SUBSA-BRAINS braze metal USA/RUSSIA

2024. NASA Public-private partners.



Parabolic Vulkan Experiment (USSR) 1965

Parabolic Skylab Materials station (USA) 1972

Parabolic Nd:YAG LBW Experiment 1988/89

Parabolic UHT Experiment 1993

Parabolic ISWE Experiment 1994

Drop Tower GTA Weld Experiment 1998

Parabolic GHTA Weld Experiment 2001

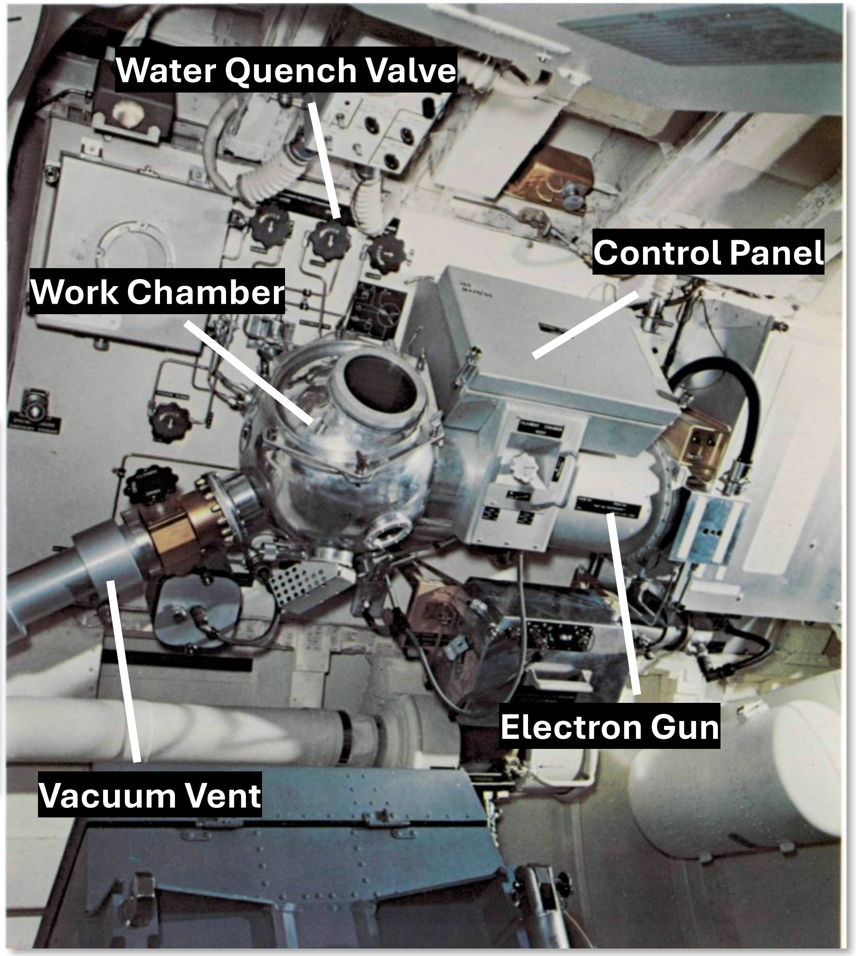
2018. New Ukrainian EBW Gun Patented

2025-2026. LBW within TVAC

Adapted in part from: Sowards, *American Welding Society Professional Program*, 2023.

Skylab experiments (1973)

Skylab M512 Materials Processing Experiment



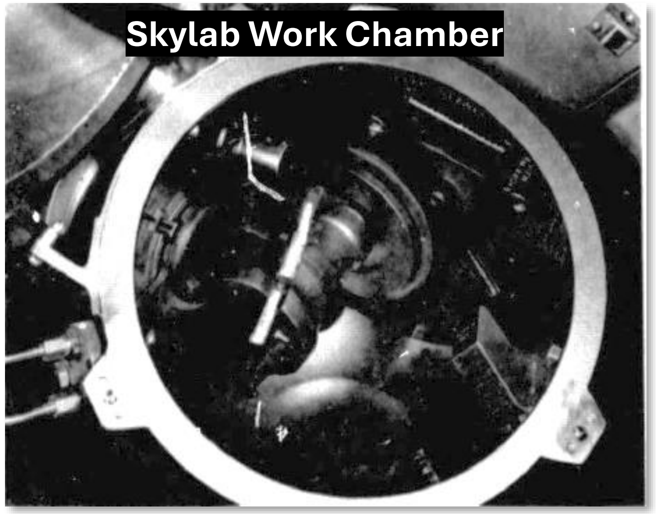
NASA-SP-401
Hooper, Contractor report NAS8-37756, 1989, https://ntrs.nasa.gov/citations/19900006115
Siewert et al., *Welding Journal*, 1977.

Outcome: Demonstrated physical and metallurgical behavior of electron beam welds and brazes in microgravity/vacuum.

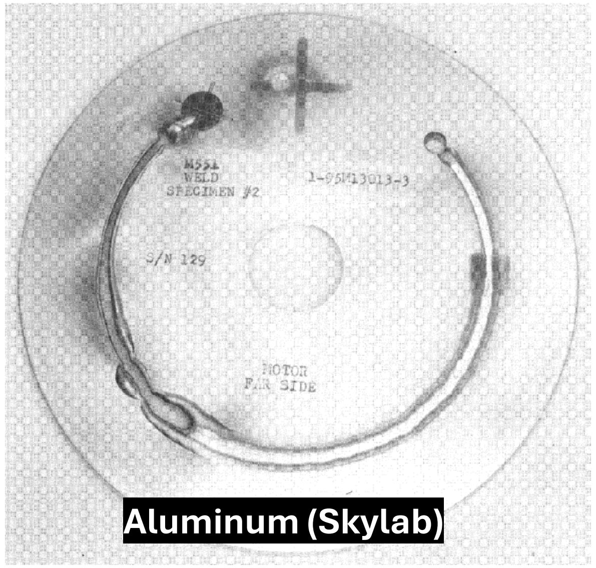
- Electron Beam Welding was proposed at a S-IVB Workshop in 1964 and Westinghouse developed a portable system.
- The M493 EBW experiment was formally approved in 1966 and eventually redesignated as the M551 Metals Melting Experiment.
- Skylab materials experiments were tested in 1972 aboard an Air Force KC-135.
  - 15-25 s was not enough time to complete melting and solidification cycle.
- **Materials Science and Manufacturing in Space:**
  - M551 Metals Melting experiment
  - M552 Exothermic Brazing experiment
  - M553 Sphere Forming experiment
- **Welding Chamber Details:**
  - 40 cm spherical vacuum chamber connected to space by a 10.2 cm diameter, 1 m long tube.
  - An electron beam was used as the welding heat source. It had focusing and deflecting coils operated from a control panel. System was powered by a battery.
  - Contained a light, a 16 mm camera, vacuum cleaner and water spray for metal quenching.

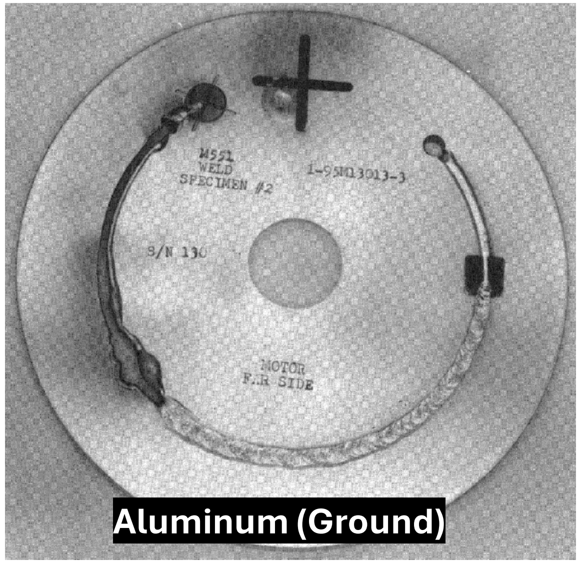
From: Sowards, *American Welding Society Professional Program*, 2023.

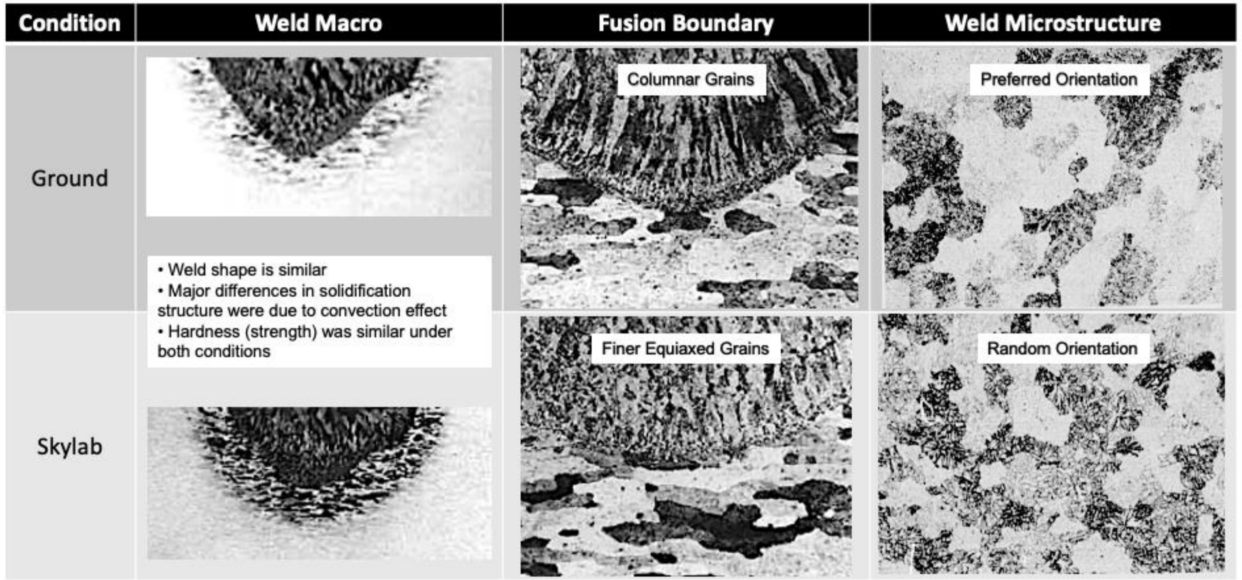
Skylab M551 Metals Melting Experiment



- Skylab published far more detail on experimental results than Soviet experiments.
- Three discs with tapered thickness were processed by the stationary EBW gun.
  - **Alloys:** Stainless Steel (304), Aluminum (2219-T87), CP Tantalum
- Weld started at the thin section and thickness increased with rotation of the disc (from 0.64 to 6.4 mm).
  - **Parameters:** Travel speed = 89 cm/min, E = 10 kV, I = 80 mA
  - **Pressure:** After 2 hr space vent, Vacuum = 10-4 torr (1.3 E-4 mbar)
- Differences in solidification and grain structure in the welds.
- Experiments were deemed a major success.







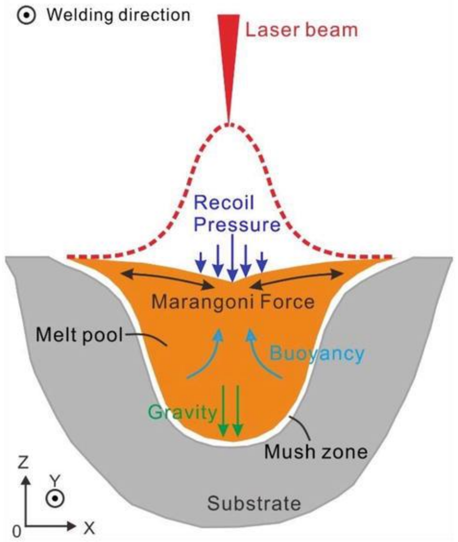
Poorman, NASA-TM-X-64960, 1975.

From: Sowards, *American Welding Society Professional Program*, 2023.

In-space effects that influence welding

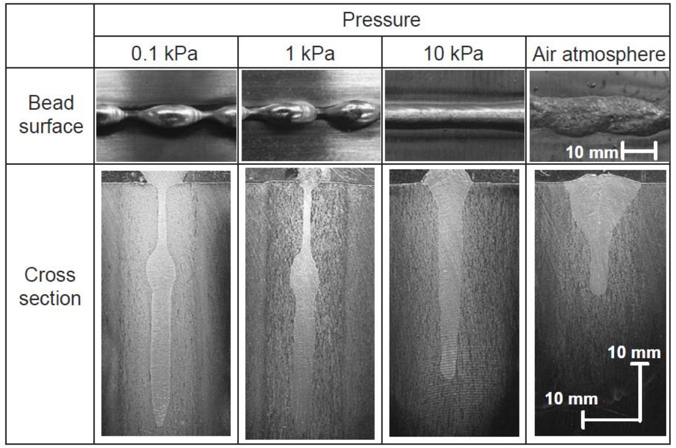
Variable	Case 1: In Space	Case 2: Chamber Inside Habitat	Case 3: Inside Habitat	Case 4: Lunar Surface	Case 5: Martian Surface	Baseline: Earth	Capabilities Needed at Present
Gravity	μg	μg	μg	0.17 *g*	0.38 *g*	1 *g*	μg to 0.38 *g*
Atmosphere	Vacuum	Vacuum / Pressurized	Air	Vacuum	$95CO_2$-$2.6N_2$-1.9Ar-$0.2O_2$-0.06CO	$78N_2$-$21O_2$-0.9Ar-0.1other	HV (10^{-3} mbar) UHV (10^{-7} mbar) XUHV (10^{-11} mbar)
Temperature	Extreme Low ISS Exterior: 120 K – 395K	~ 295 K	~ 295 K	40 K – 396 K	133 K – 300 K	~ 295 K	40 K – 400 K
Space Suit	Yes	No	No	Yes	Yes	No	

Table adapted and expanded from original source: Masubuchi, 1990, doi: 10.2207/qjjws1943.59.421



Reduced gravity is unique among the above effects in that it cannot be reproduced for prolonged periods on earth.

Current Work: Integrate existing capabilities across academia, government, and industry to investigate space environmental effects on welding processes to inform computational models, and to create public-private partnerships to develop and implement space welding technologies.



Adapted in part from: Sowards, *American Welding Society Professional Program,* 2023.

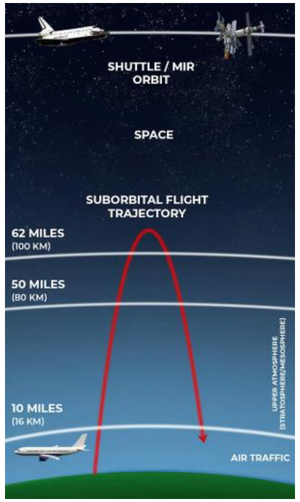
Simulating space conditions for welding

Microgravity / Reduced Gravity

Experimental platform → ↓ Criteria	Drop tower	Parabolic flight	Suborbital flight
Length of microgravity [s]	<5	20-25	>180
Gravity (quality) [g]	10^{-5}	10^{-3}-10^{-2} (up to 2.0)	10^{-4}
Mass allowed [kg]	10^2	10^2	10^1
Cost [$]	$	$$	$$$

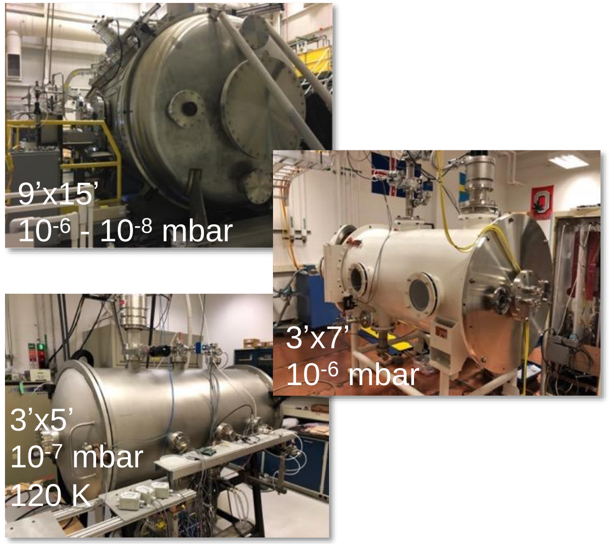
Drop tower

Parabolic flight

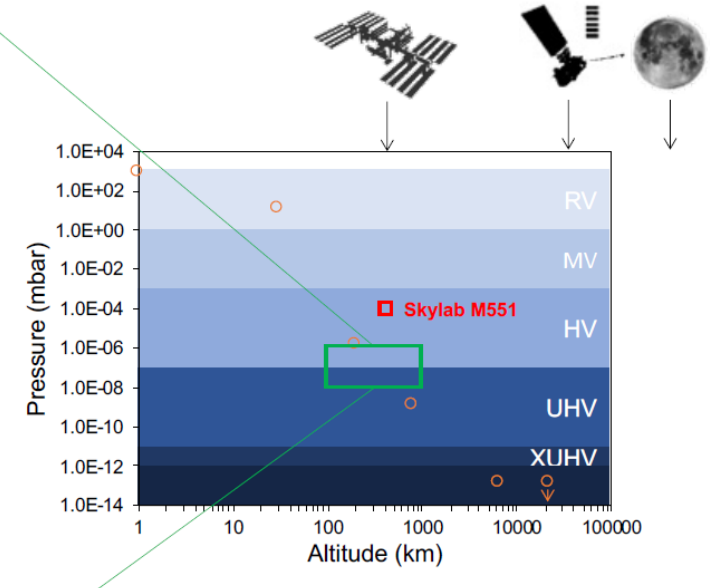


Suborbital flight

Vacuum and Reduced Temperature



Example of MSFC capabilities to simulate reduced pressure / vacuum at 100 to 1000 km altitude.



Numerous experiments have placed welding systems in vacuum chambers on parabolic flights.

Mladenov, Koleva, and Trushnikov, *E+E*, 2019.

Low Earth Orbit (LEO)
μg

Lunar surface
0.17 *g*

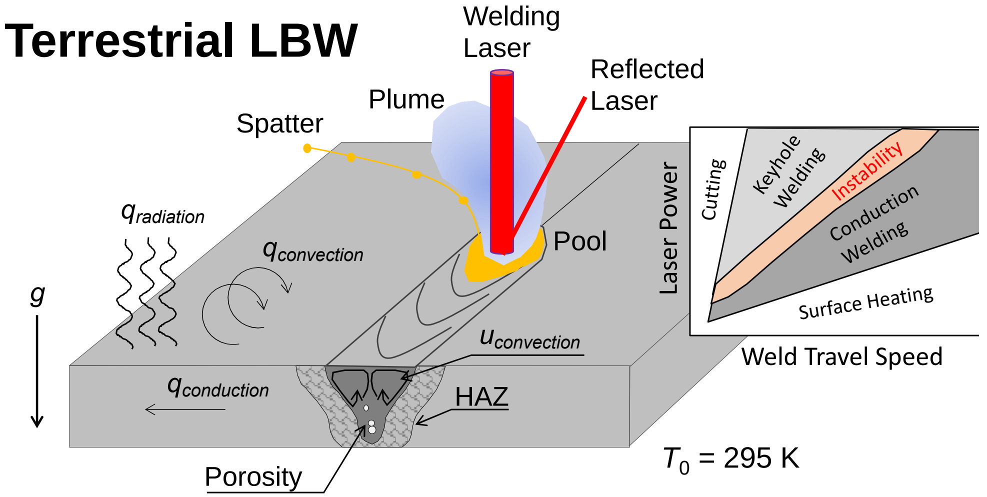
Martian surface
0.38 *g*

Adapted in part from: Sowards, *American Welding Society Professional Program,* 2023.

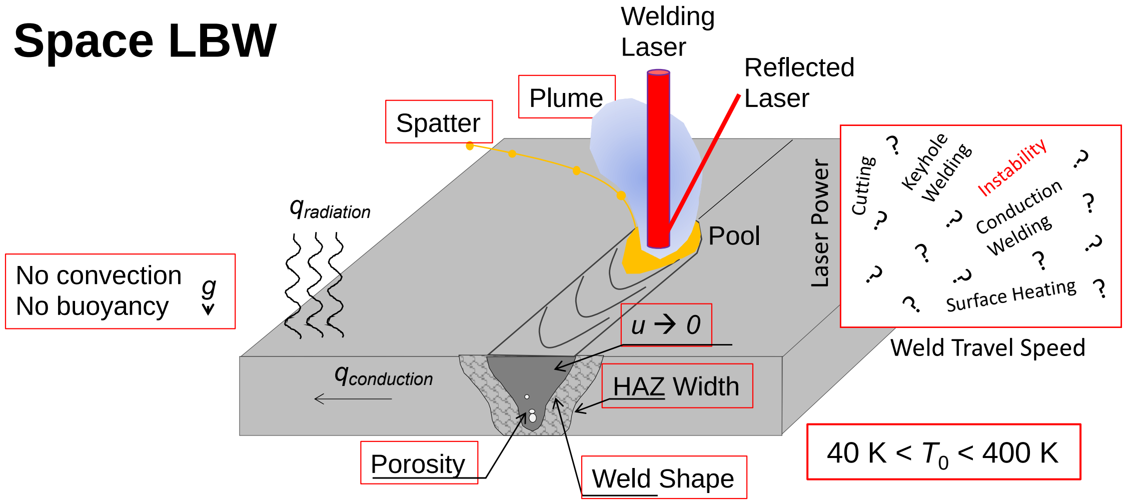
Key effects to consider for in-space LBW

Red boxes indicate instrumentation and modeling opportunities.

Terrestrial LBW



Space LBW



Issue #1 Weld heat transport has profound effect on size of a weld and its metallurgical transformations and hence weld properties:

Temperature gradient and cooling rate are proportional to thermal conductivity and T_0^2

Issue #2 Reduced gravity reduces buoyancy-induced convection:

Development of weld pool shape and porosity evolution are altered, and chemical effects become dominant, e.g., surface-active elements influence weld penetration due to thermocapillary flow. (minute alloy chemistry changes are important)

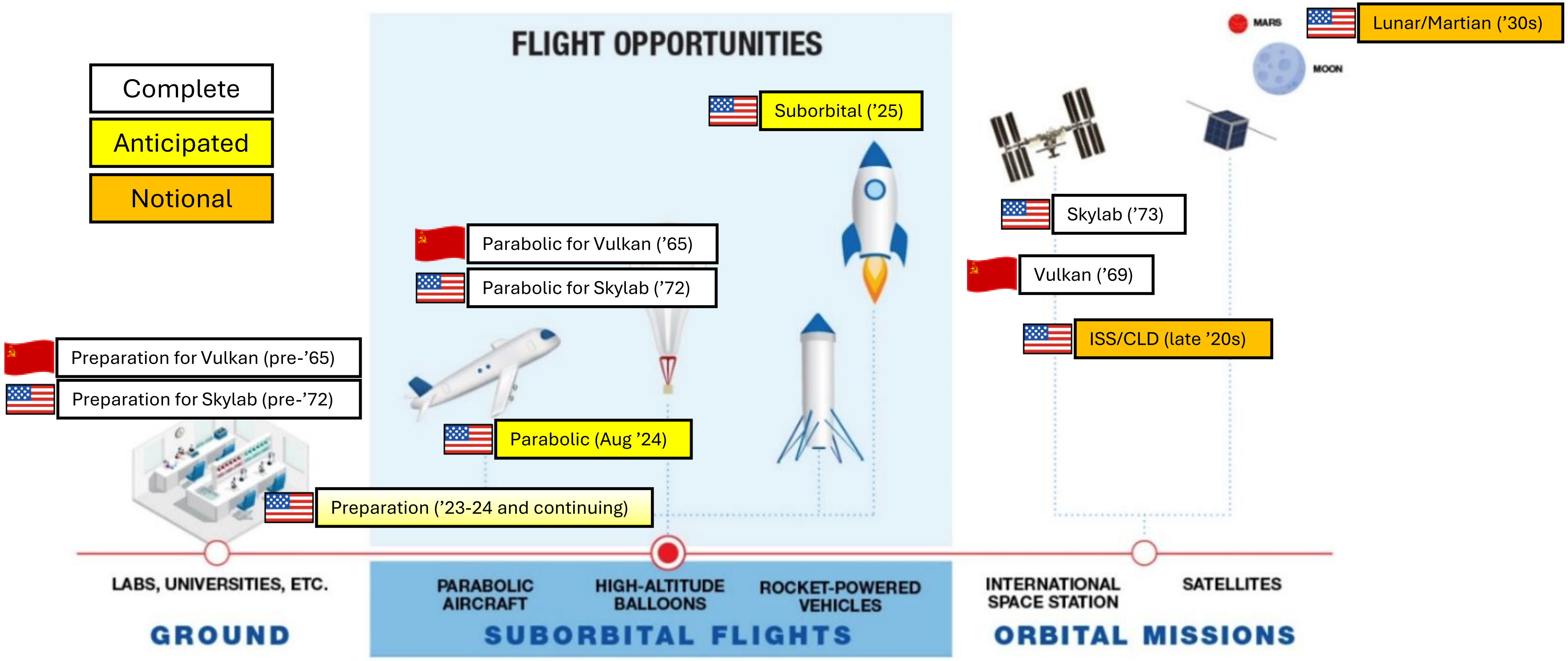
Issue #3 Reduced pressure/vacuum in space:

Heat transport is dominated by radiation and conduction rather than by convection. Weld shape and width, and weld strength will be influenced by change in weld cooling.

Reduced pressure influences laser beam keyhole stability, evaporation of volatile species, safety issues, etc.

From: Sowards, *American Welding Society Professional Program*, 2023.

Progression of flight experiments



Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Ground testing: 3 degree-of-freedom welding

Handheld Laser

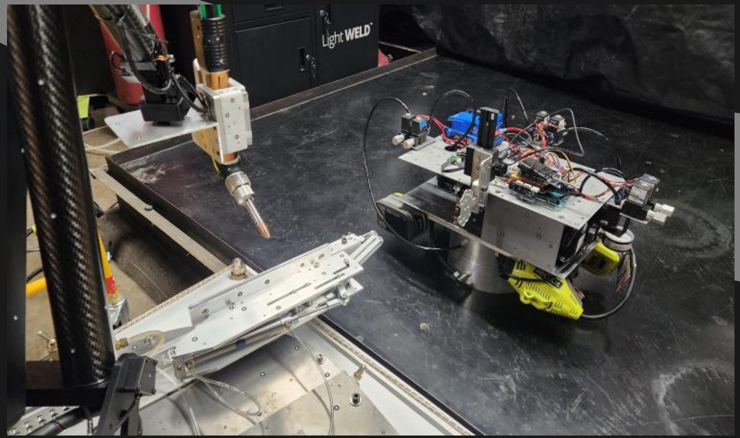
Courtesy: IPG

• Portable laser that cuts, cleans, and welds
• Process demonstrated on most important space alloys in a lab setting (aluminum, stainless steel, titanium)

Integration and development of 3DOF welding system.

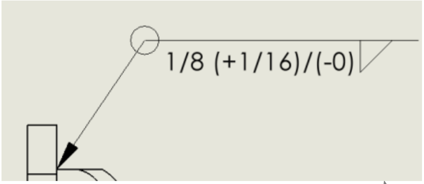
Flat Floor Integration

• Integrate laser onto robotic fixturing.
• First demonstration of laser in 3 degrees-of-freedom space simulator
• Identify challenges by investigating fitup, mismatch, weld quality, kinematics of welding recoil forces
• Augment Digital Twin model development.

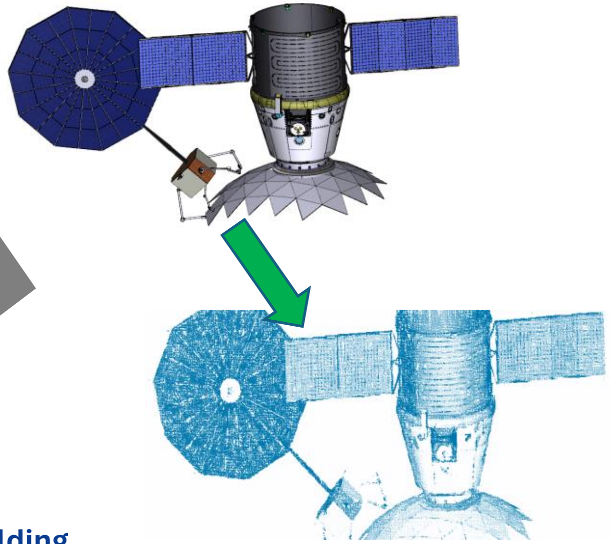


Digital Twin Modeling

3D scanning and 3D model comparisons will allow us to:
• Build a virtual counterpart of in-space weld.
• Determine and document defects and tolerances to inform requirements and further 3D simulations.



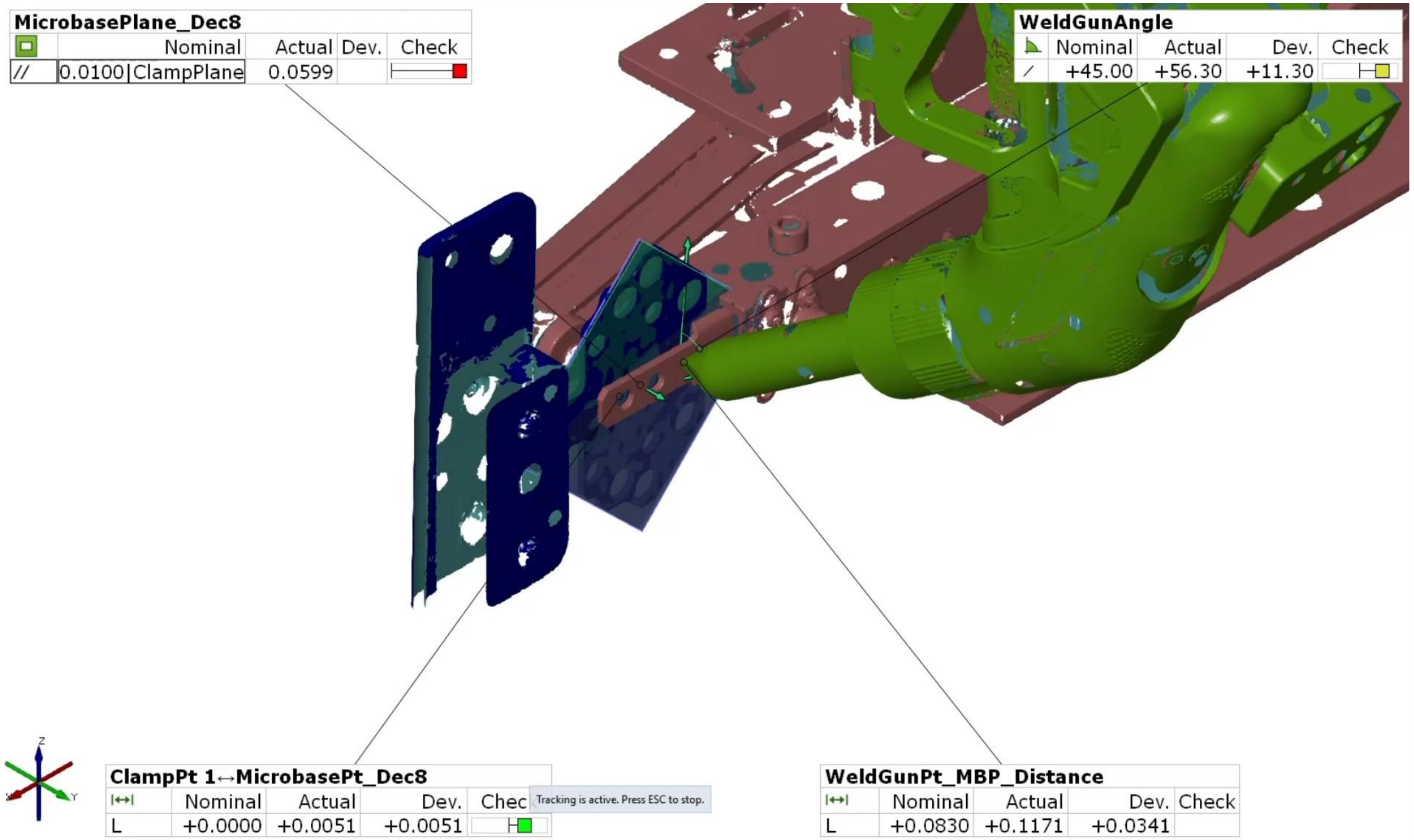
End Goals:
1) Identify manufacturing challenges with autonomous in-space laser welding.
2) Demonstrate a digital twin modeling capability for in-space welding.
3) Demonstrate laser beam welding technology as viable approach for in-space manufacturing.



Digital Twin of In-space Welding

Adapted in part from: Sowards, *American Welding Society Professional Program*, 2023.

Real-time capture of process geometry

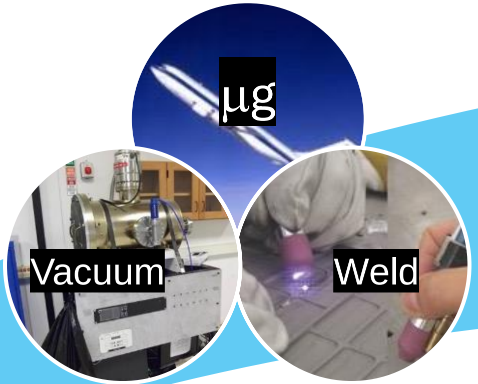


2024 Parabolic Flight of Laser Beam Welding

Integration and Ground Demonstration of Self-contained Laser Welding System for Parabolic Microgravity Experiments.

- OSU. Profs. Ramirez, Panton, Horack, Nassiri, Williams, Nate Ames, Bob Rhoads. Multidisciplinary capstone team.
- NASA. Jeff Sowards, Karen Taminger (LaRC), Eugene Choi (WE intern), Will Evans, Zach Courtright, Louise Littles, Andrew O'Connor, Emma Jaynes, Tom Bryan.

Generate Model Calibration Data



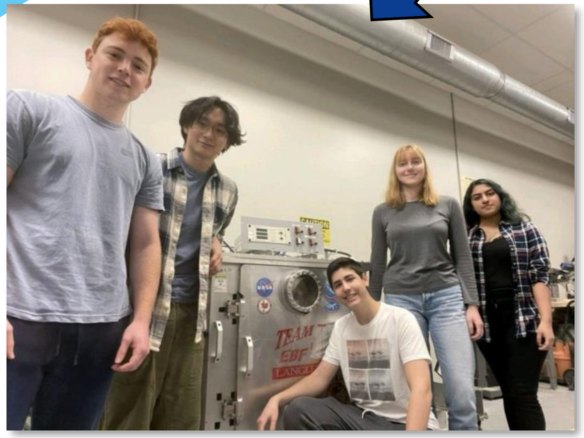
OSU-NASA CAN

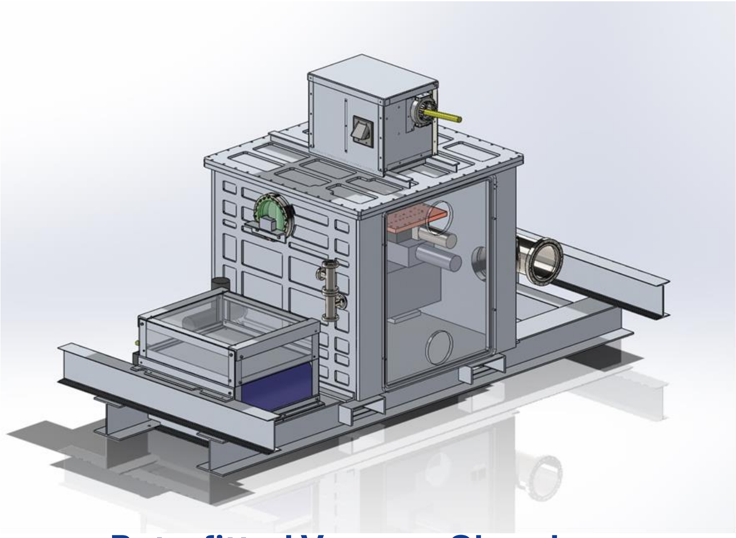
Integrated Computational Materials Engineering (ICME)

Heritage Vacuum Chamber

Laser Beam Welding

Cycle times of fiber Laser Beam Welding are shorter than 15 to 25 s parabolic arcs that were too brief for Skylab experiments.





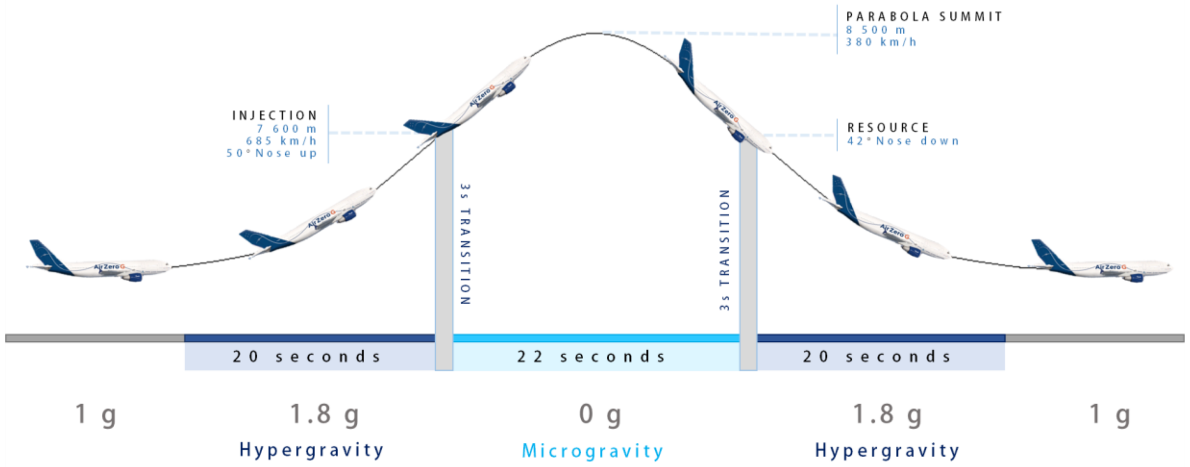
Retrofitted Vacuum Chamber

Adapted in part from: Choi, *Worldwide Advanced Manufacturing Symposium* (2024).

Development of self-contained laser welding system to achieve space-like conditions

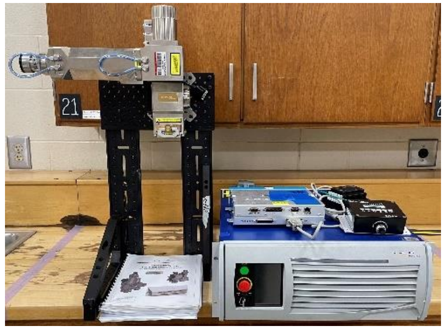
- Comparison analysis between on earth & In-Space Laser Beam Weld
  - Reduced gravity (Parabolic Flight)
  - Vacuum (Vacuum Chamber)
- Various reduced gravity conditions
  - Micro-gravity (0.001~0.01 g)
  - Lunar gravity (0.17 g)
  - Martian gravity (0.38 g)

- In-Situ Data Acquisition
  - Optical videography and thermography
  - Thermocouple for validation of thermography
  - Accelerometer for gravity



Parabolic profile for micro-gravity environment Credit: ESA

Cutaway of parabolic plane Credit: ESA/Novespace

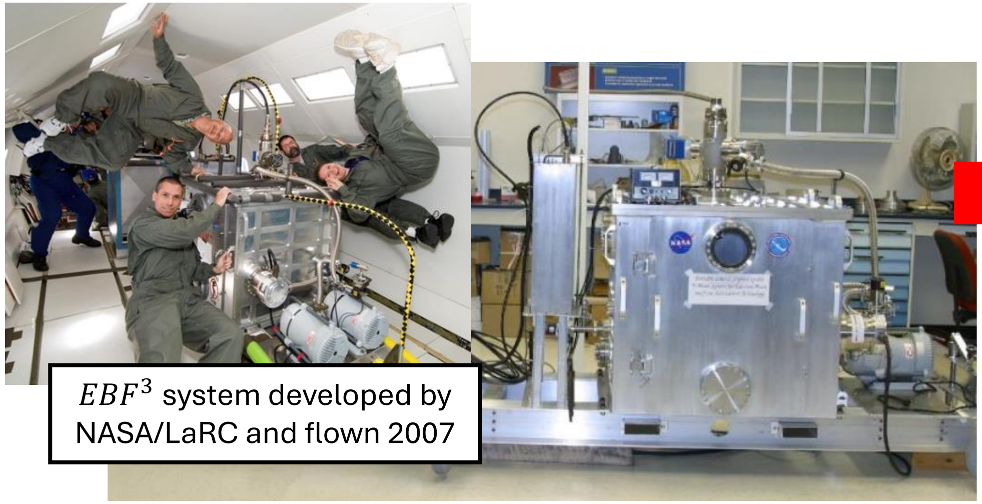


IPG D30 Wobble head & YLR-150/1500-QCW-AC

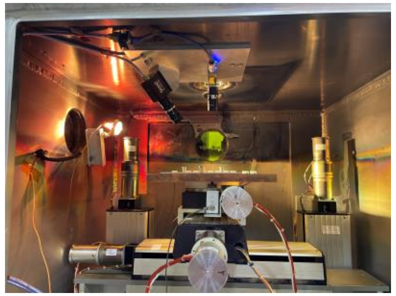
Adapted in part from: Choi, *Worldwide Advanced Manufacturing Symposium* (2024).

Retrofit for LBW

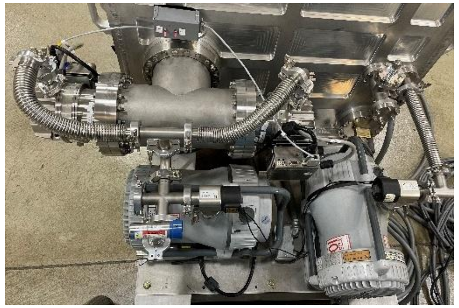
- 2007 EBF³ (Electron Beam FreeForm Fabrication) parabolic flight test chamber from NASA Langley (NASA/LaRC)
    - Flown on NASA C-9B parabolic plane
- Laser integration
- New axial control system
- New electrical breakout box
    - Different plane, different electrical supply
- Vacuum pump system check
- Axial motor check
- Laser-safe viewing window



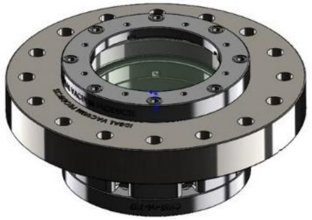
EBF^3 system developed by NASA/LaRC and flown 2007



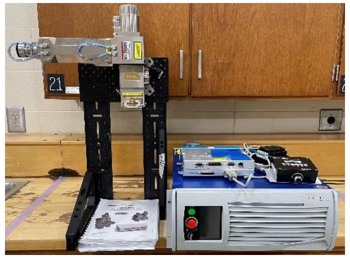
Motor functionality check



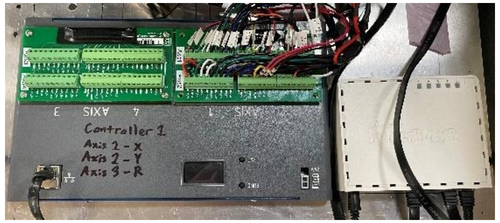
Vacuum pump check & automation



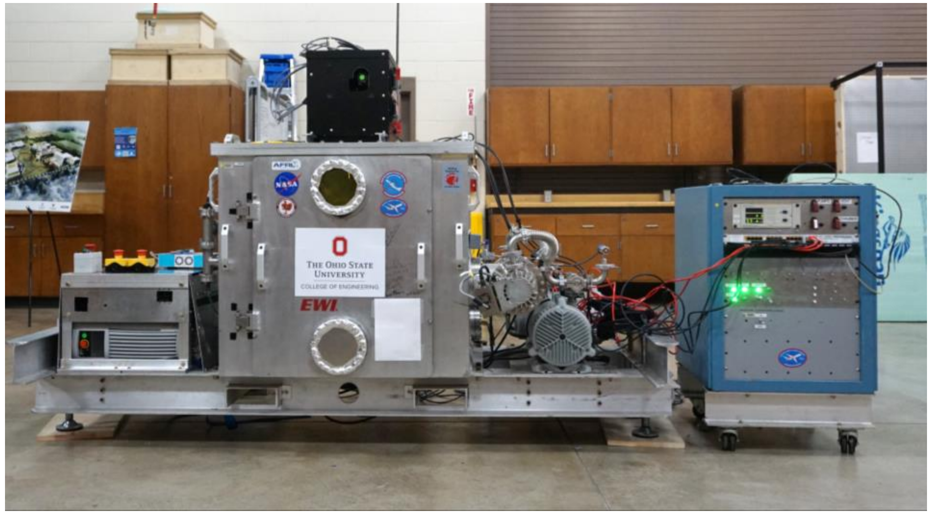
Laser passthrough



Laser and sensor integration (DAQ)



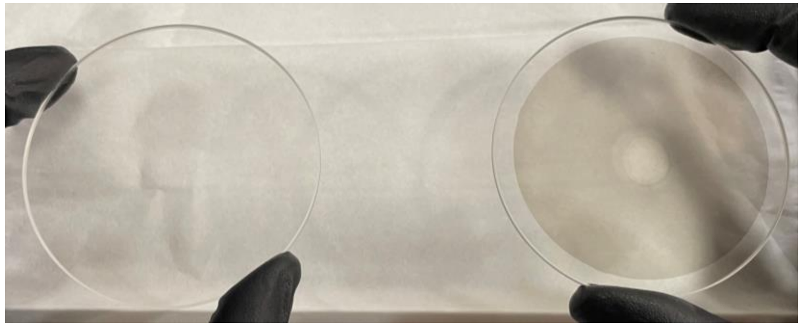
New axial motor controller



Adapted in part from: Choi, *Worldwide Advanced Manufacturing Symposium* (2024).

Laser integration

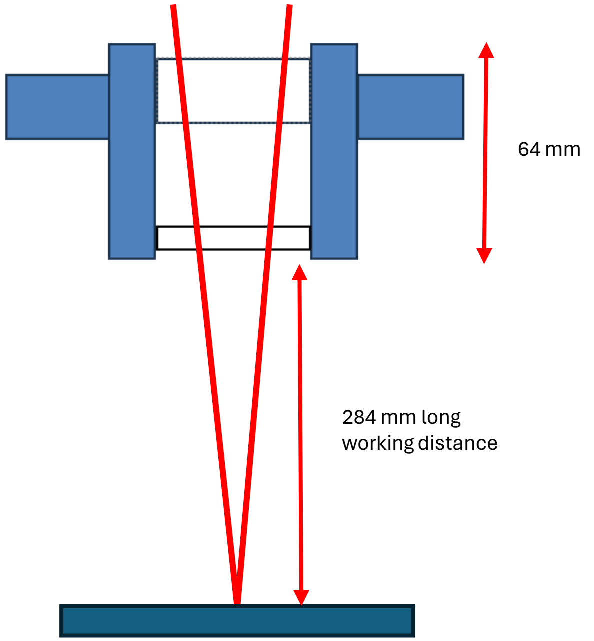
- Power: IPG YLR -150/1500-QCW-AC
  - 1070nm Nd:YAG fiber laser
  - CW Mode= 250W, Pulse Mode= 150-1500W
- Wobble-head laser focusing system
- Metallization concern on inner vacuum lens
  - Increase focus; Focus= 400mm
  - Working distance = 284mm (13.7”)
- Increase Power density; Collimator= 200 mm
  - Focus power density = $318.31\frac{W}{mm^2}$

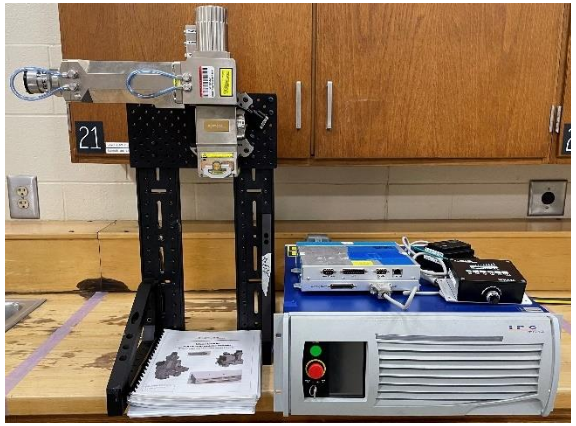


Metal deposition observed during testing

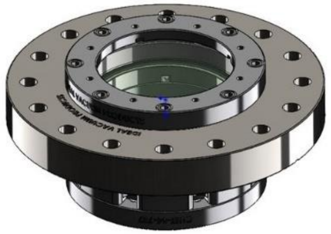
Increasing metal vapor deposition on optical passthrough (<65 mm distance to workpiece) from atmospheric pressure to ~10 Pa and below

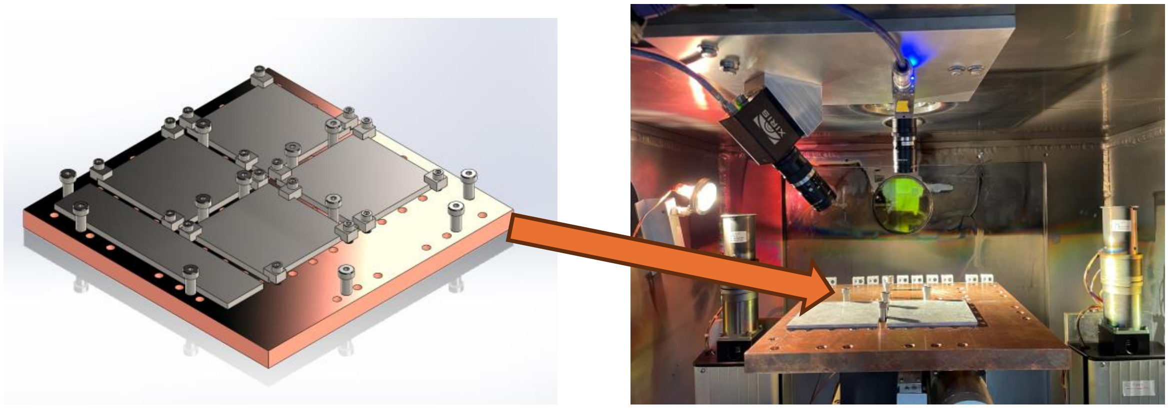
Suita et al., 2005, doi:10.2322/tjsass.48.86





IPG D30 Wobble head & YLR-150/1500-QCW-AC

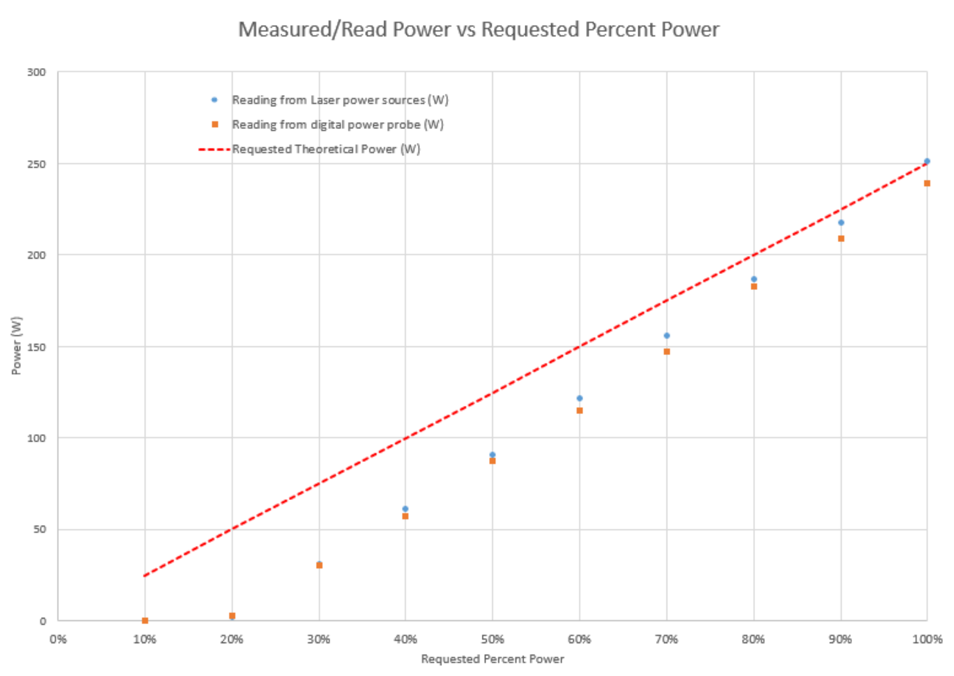


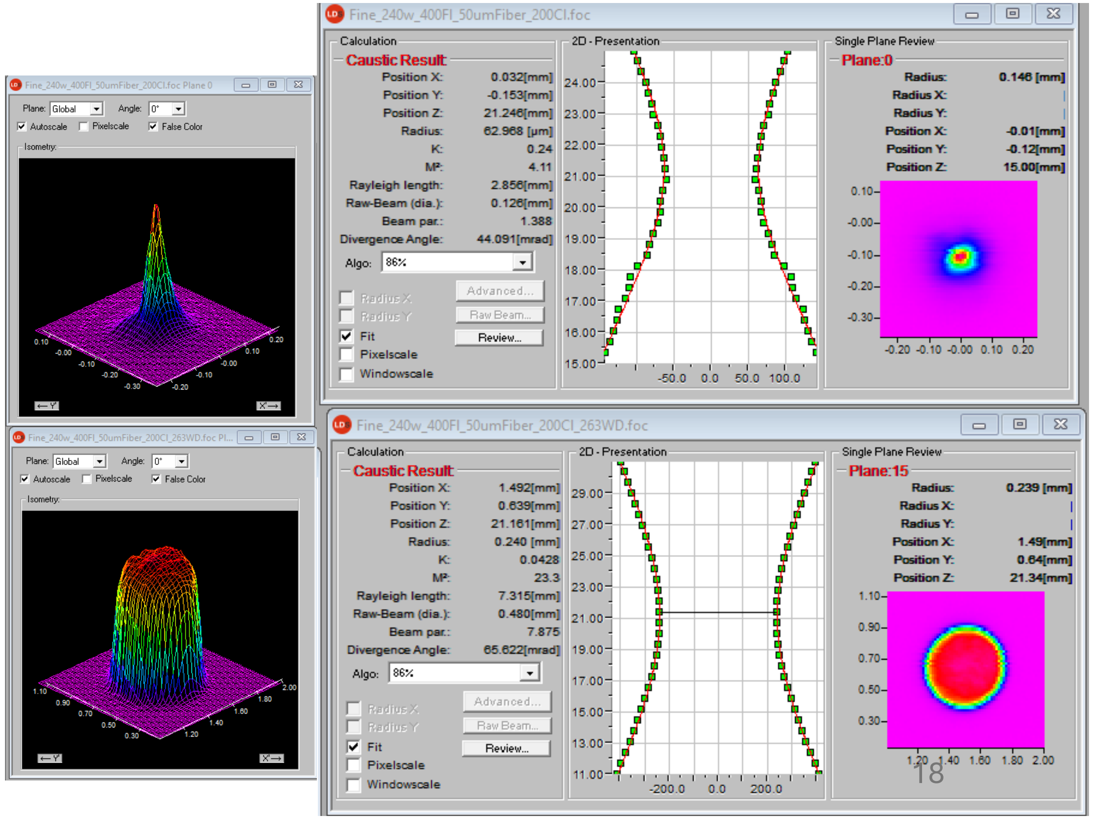


Adapted in part from: Choi, *Worldwide Advanced Manufacturing Symposium* (2024).

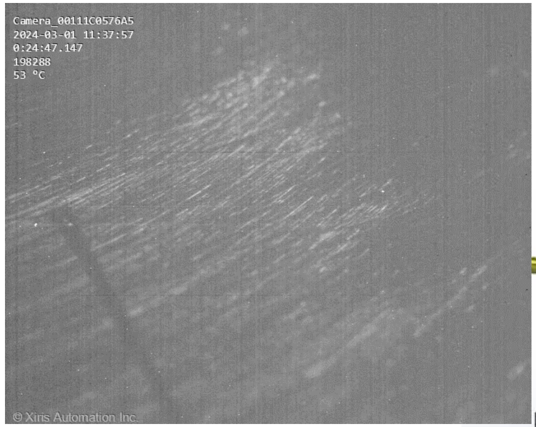
Laser beam diagnostics

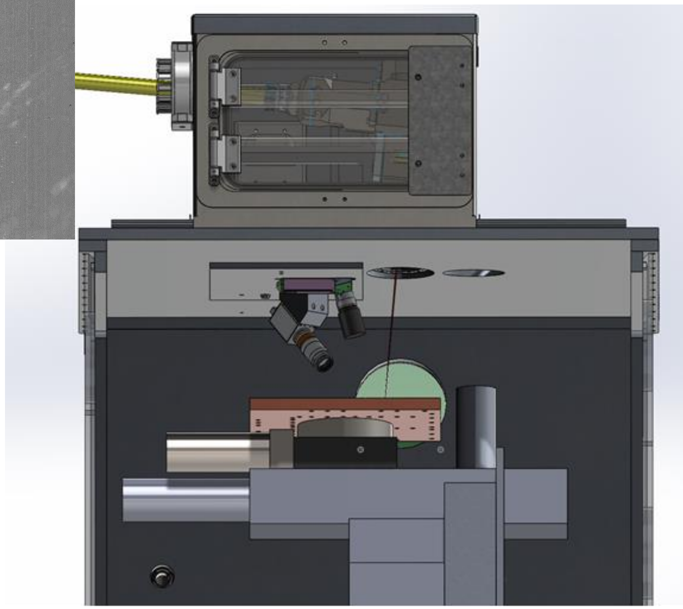
- Macken Instruments digital power probe confirms power profile – reduction due to optical passthrough
- PRIMES laser beam focus monitor defines caustics and focus of beam after passing into vacuum chamber



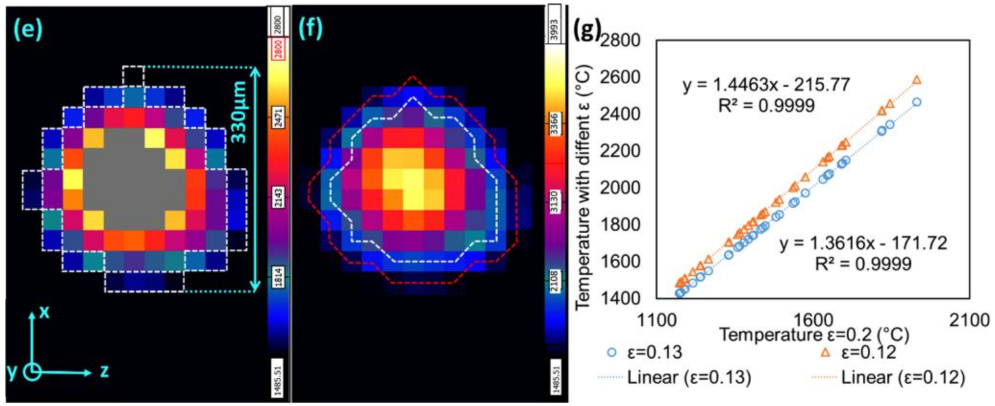


Instrumentation for thermal history

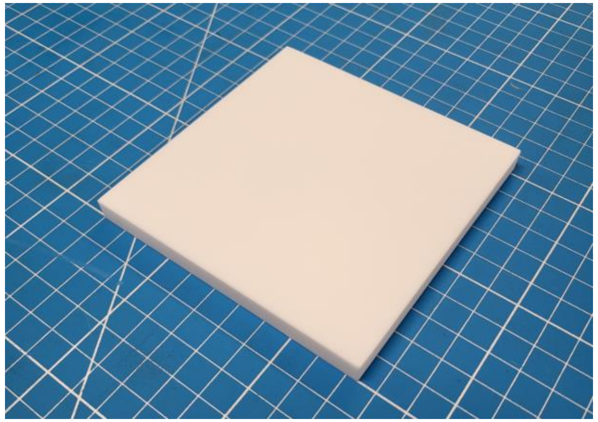




Example of *in situ* temperature monitoring for laser melting



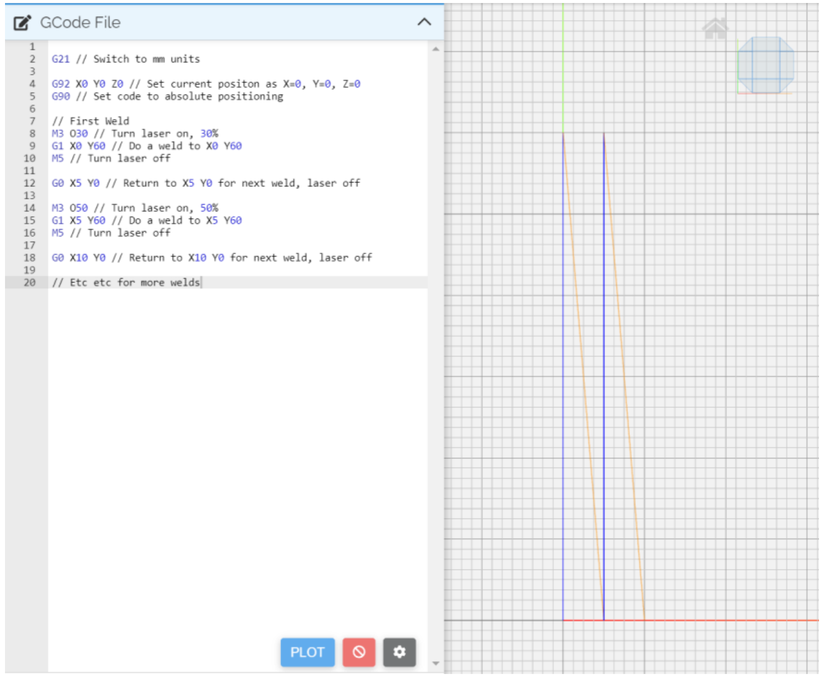
- Xiris XVC-700 weld camera
  - Monitors melt pool size and morphology
- Xiris XIR-1800 thermal-weld camera
  - Short-wave infrared suitable for varying emissivity metals

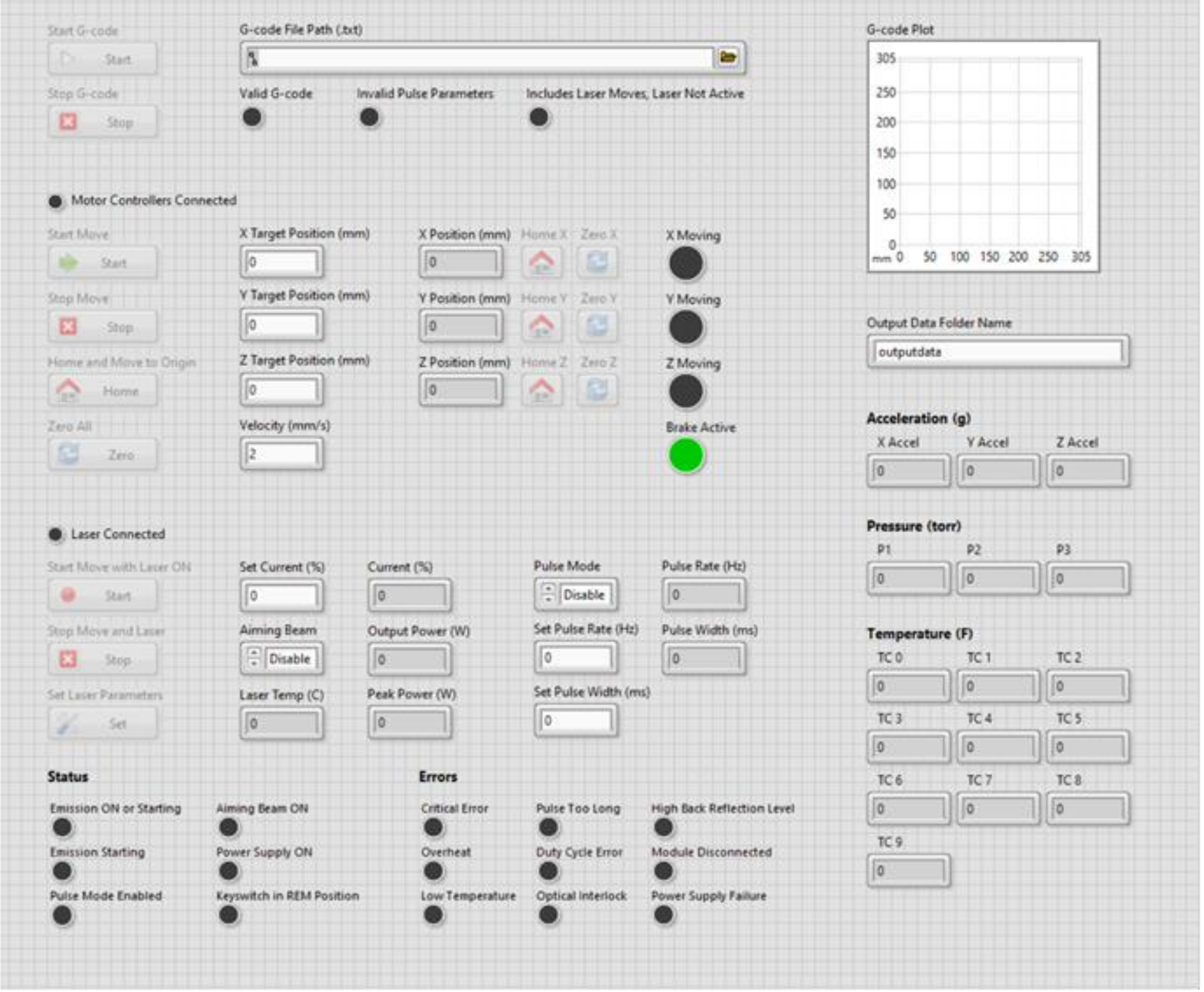


High-temp glass-mica ceramic thermocouple & K-type connectors

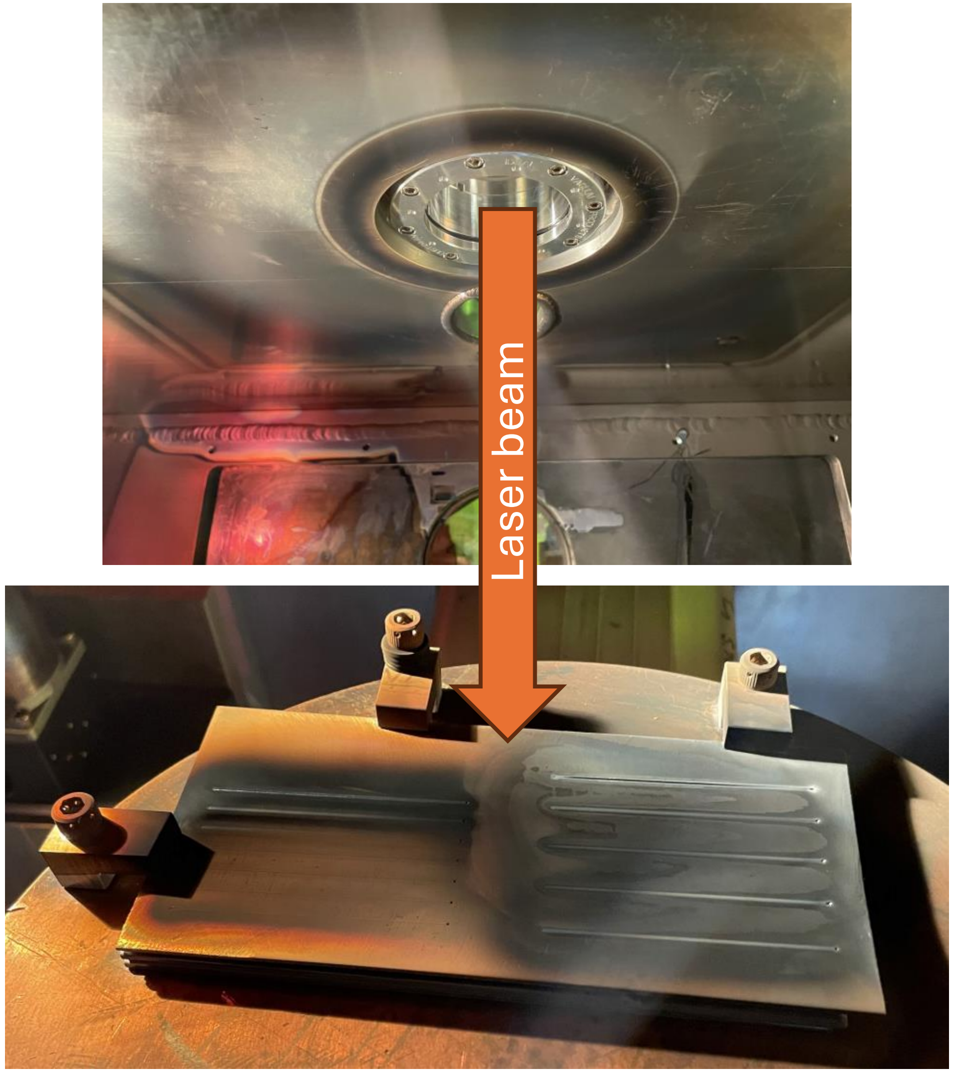
Semi-automated operation during parabolas

- Manual start/stop upon µg call
- G-code for positioning and remote laser control

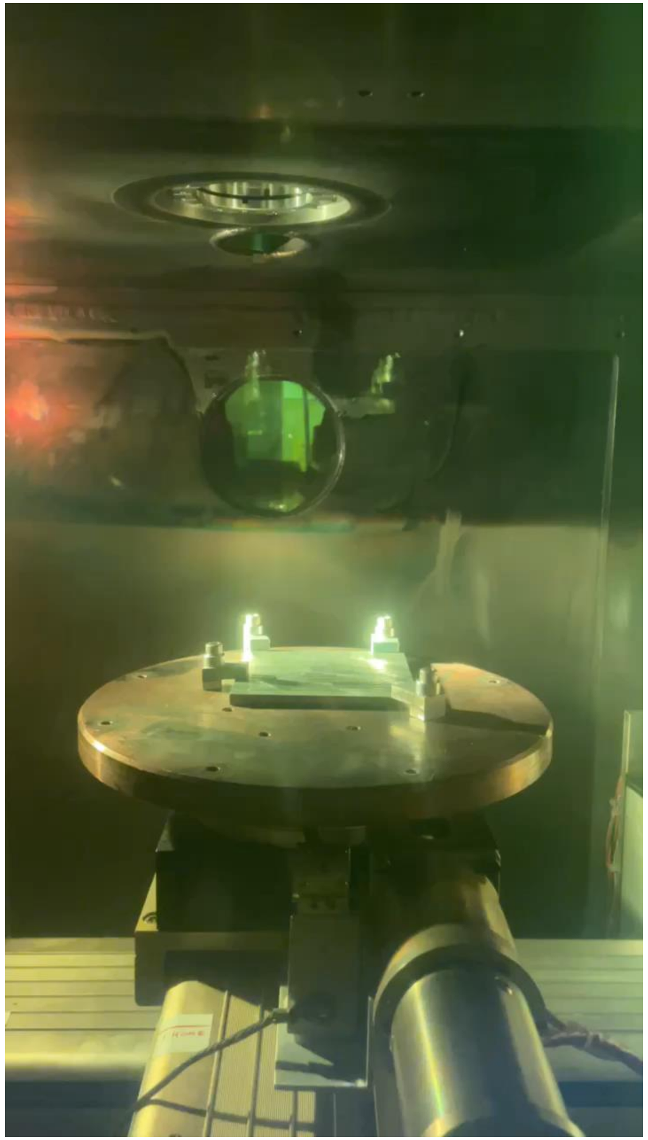




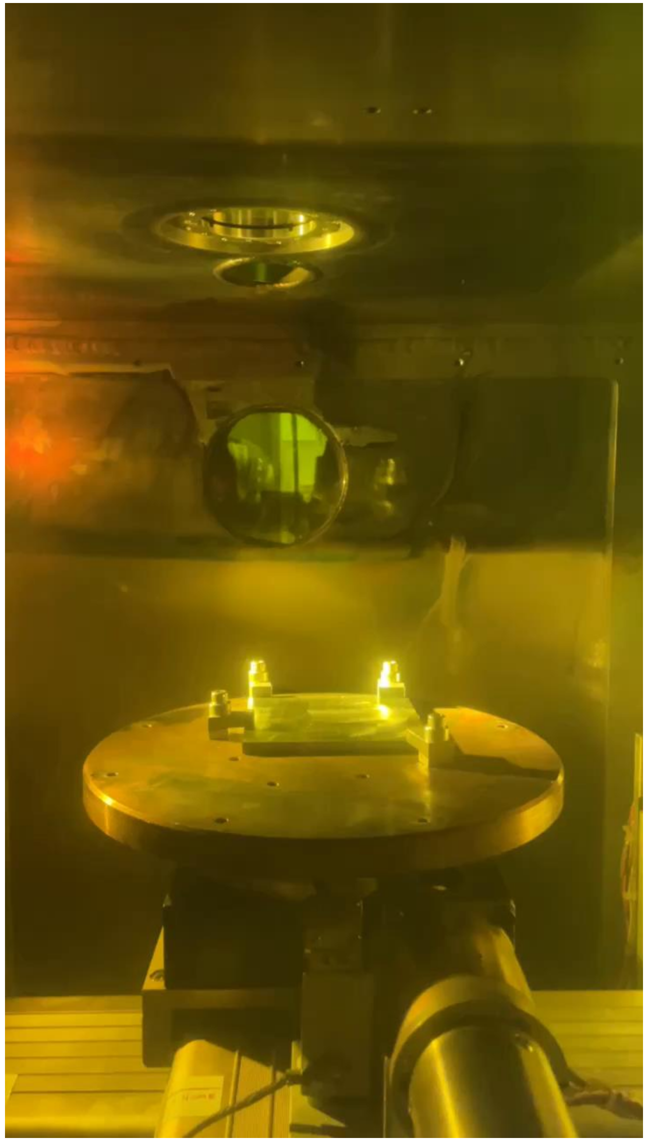
Initial LBW trials



In air



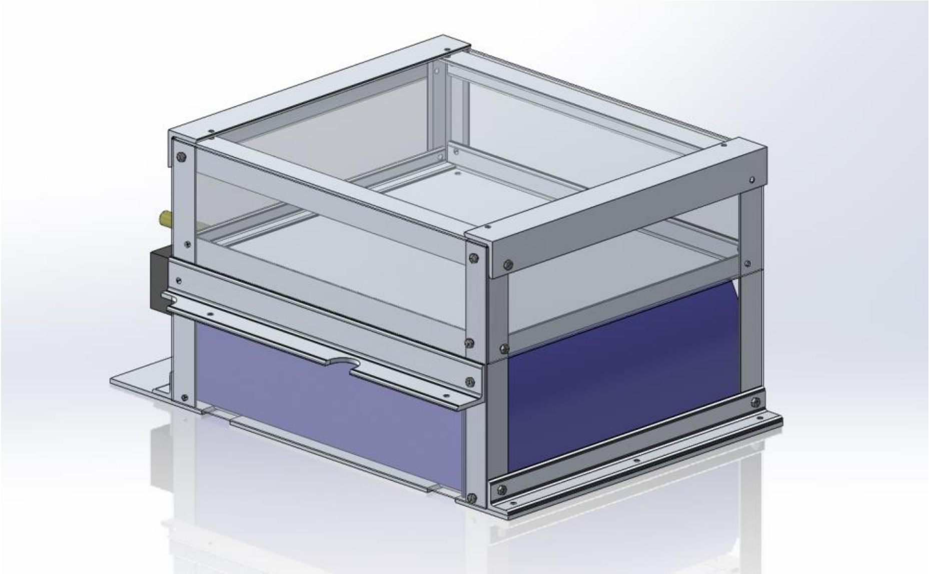
Under high vacuum (~mPa)



n.b. parameters not exactly same, illustrative only

Safety is critical!

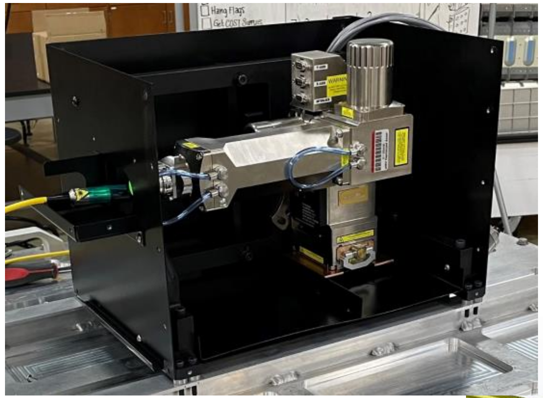
As NASA-funded payload, satisfy both NASA/AFRC and Zero-G requirements



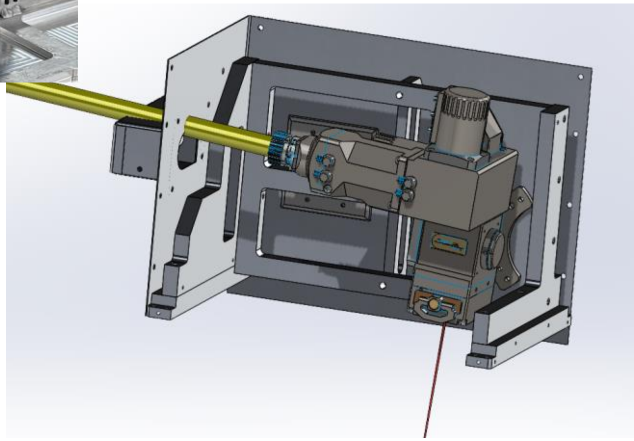
Example: electrical box and laser generator

Failure Type	Factor of Safety
Tensile Ultimate	+8.268
Tensile Yield	+3.617
Shear Ultimate	+9.794
Fastener Pullout	+3.141
Bearing Stress	+7.211
Shear Tearout	+12.129
Net Section	+5.66

Re-wire, re-wrap electrical cabling to reduce flammability risk



Laser-safe enclosure with laser optics rotated off-axis and window anti-reflective coated to reduce back-reflection



Parabolic flight expected August 2024

During flight

- Two flight days consisting of lunar and microgravity profiles
- Engineering alloys:
  - Aluminum 2219-T87 (Al-Cu-)
  - Stainless steel 316L
  - Ti64 (Titanium-6wt% Al-4wt% V)
- Considering Al-Cu binaries
  - More tractable for computational models
  - Similar to previous flight experiments investigating solidification

Post-flight

- *in situ* data analyzed
  - Melt pool size and morphology
  - Thermal imaging
- Post-flight characterization
  - Cross-section of weldment for metallography
  - Hardness, mechanical testing
- Detailed interpretation of data to determine suitability as validation datasets for computational modeling

Beyond parabolic: an in-space laser beam ecosystem

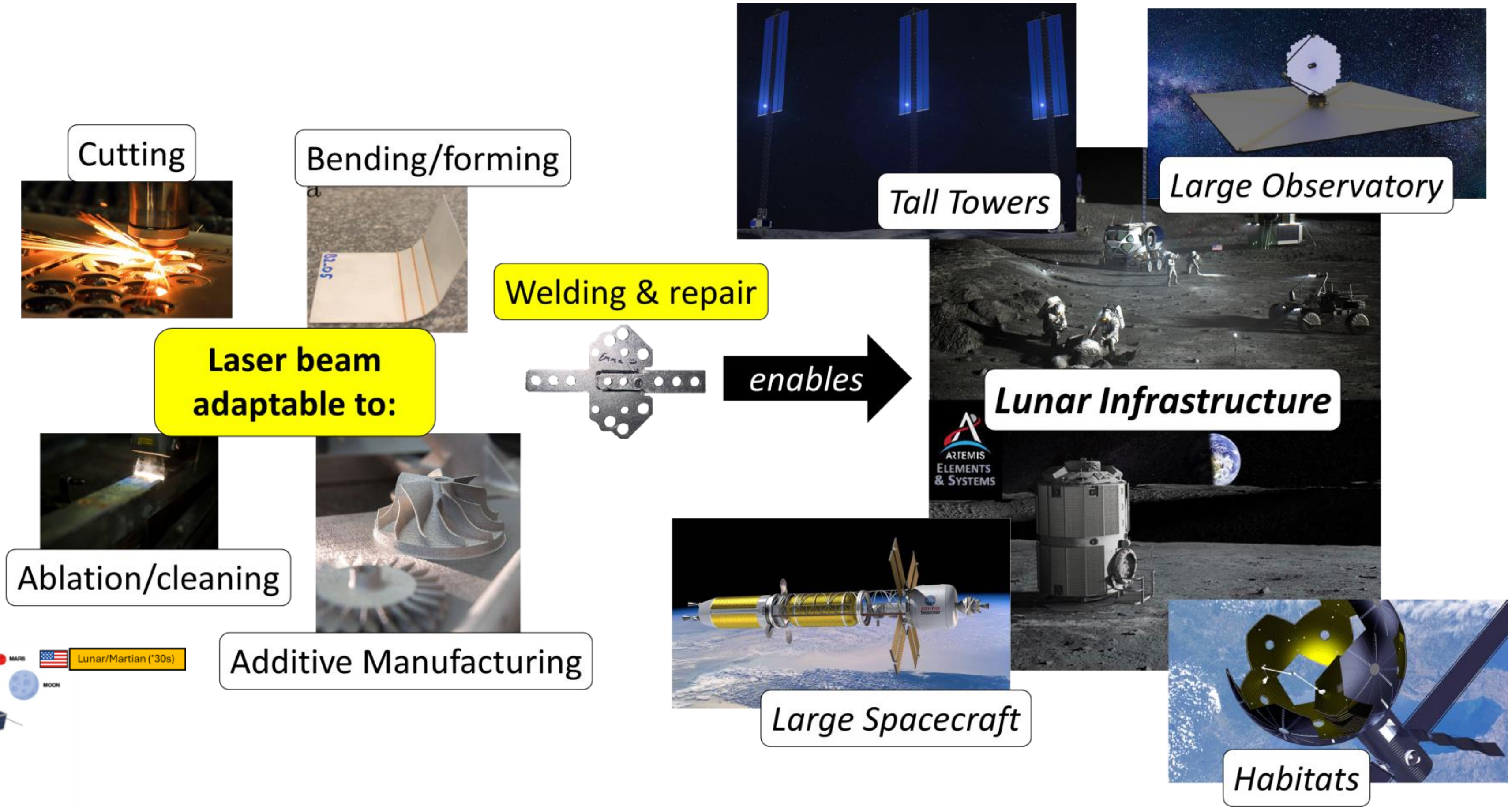
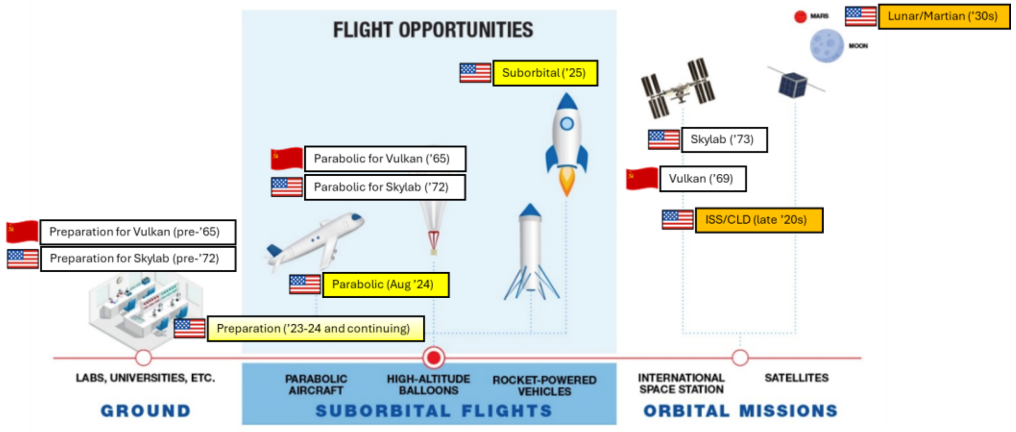


Image credit: ThinkOrbital, www.mechanicalcaveman.com, Thomsen, et al., "2019, doi: 10.1016/j.promfg.2019.08.025 (CC BY-NC-ND 4.0)

Progression of ground to flight experiments for all aspects of ISAM laser beam ecosystem?



Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135.

Acknowledgements

- NASA support from Marshall Space Flight Center internal funds, Biological and Physical Sciences Division of NASA Science Mission Directorate, Space Nuclear Propulsion, etc.
- OSU support from Marshall Space Flight Center internal funds via
  - 80NSSC22M0209 - Integration and Demonstration of Self-contained Laser Welding System for Microgravity Experiments –NASA CAN
- Second parabolic flight day support from NASA Flight Opportunities
- John Ivester (NASA/MSFC-EM42) for structured light scans of Flat Floor experiment