Laser Beam Welding Benchmark Experiments Performed in Reduced Gravity and Vacuum

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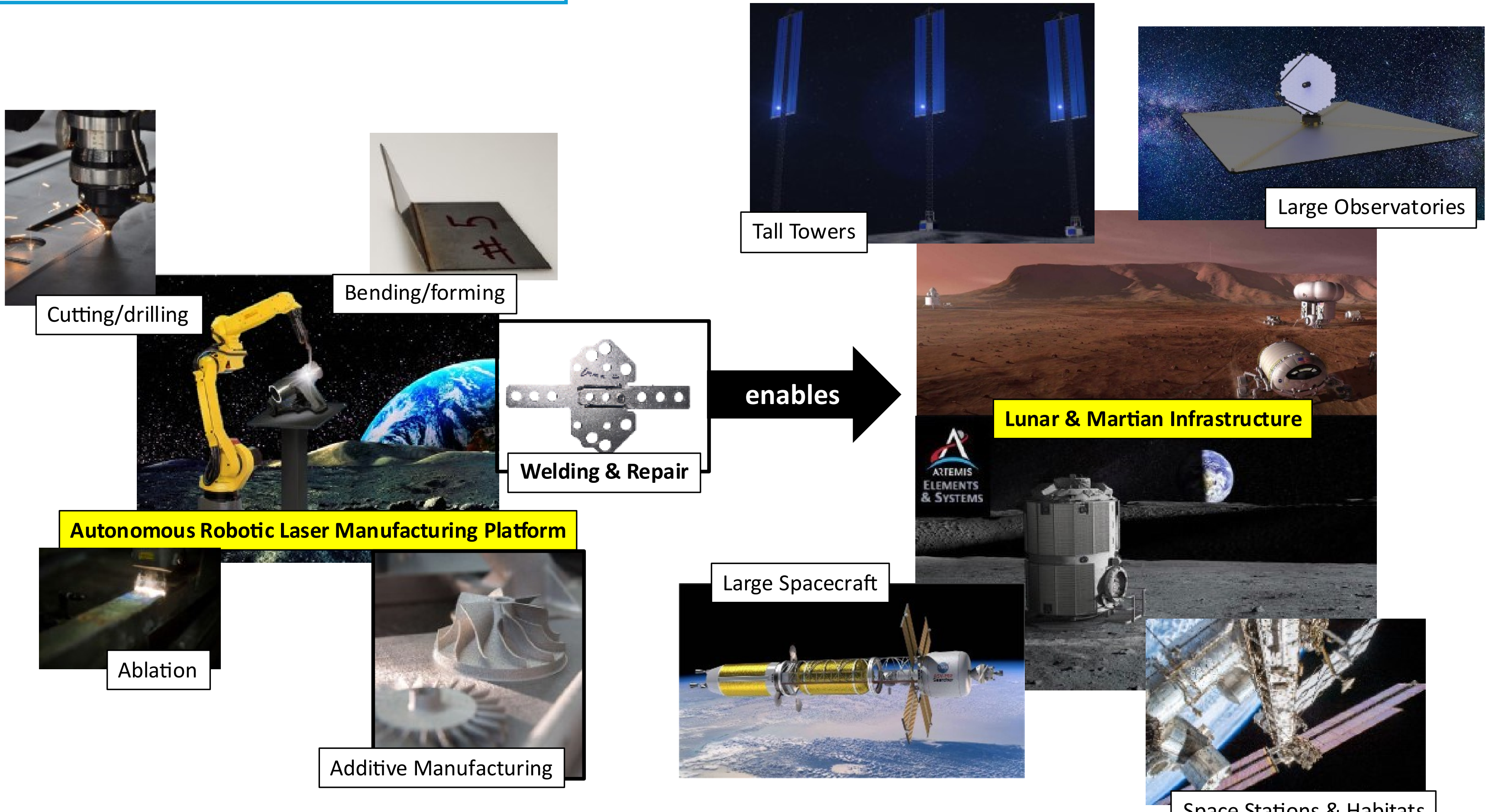
History and motivation for in-space welding (ISW)

With particular emphasis on high energy density beam welding

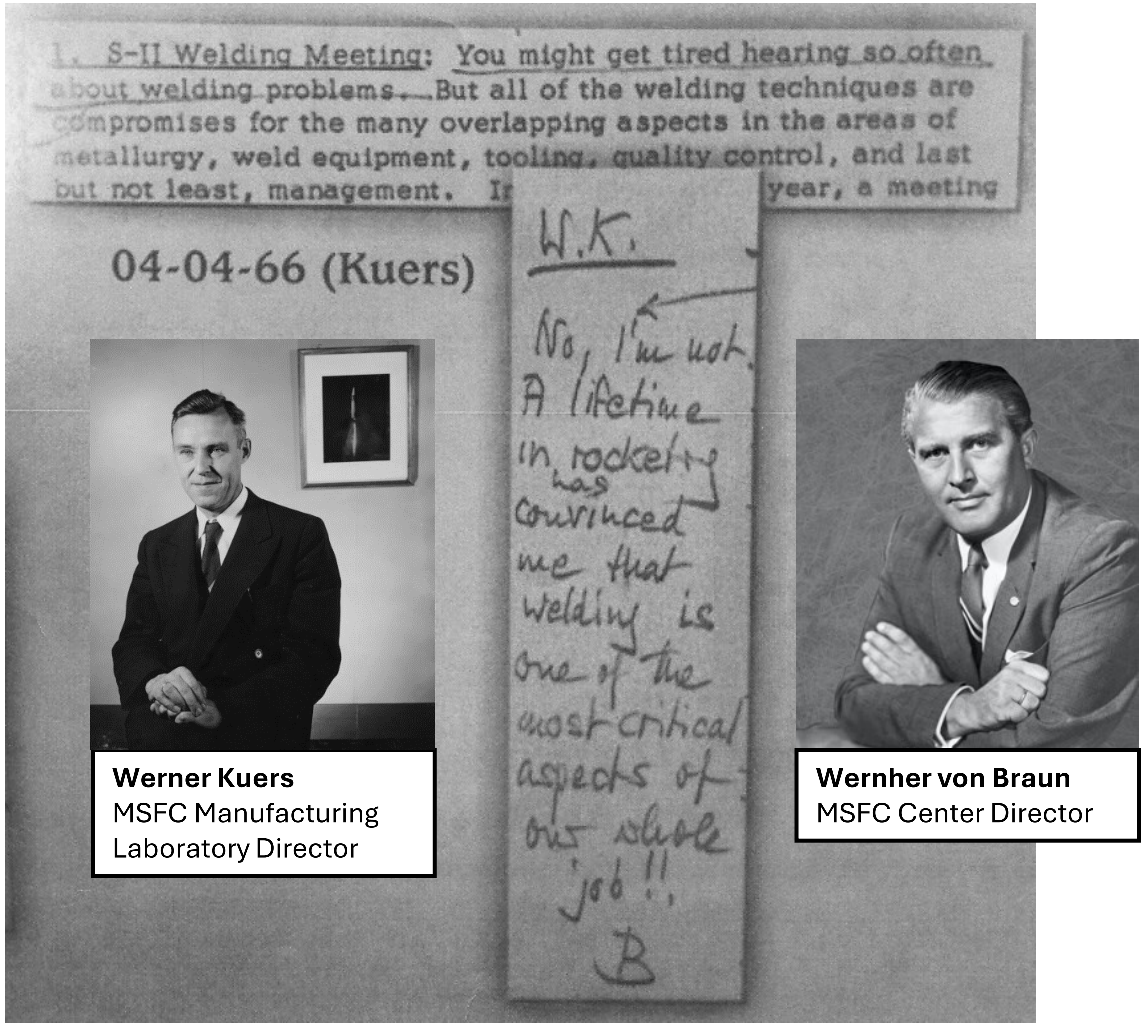
In-space laser manufacturing enables space infrastructure

Initial work on in-space welding (ISW) as a heritage process

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



Welding enables space exploration



Werner Kuers
MSFC Manufacturing Laboratory Director

Wernher von Braun
MSFC Center Director

1966 correspondence between Wernher von Braun and Werner Kuers
"...welding is one of the most critical aspects of our whole job!!" ~Wernher von Braun

"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."

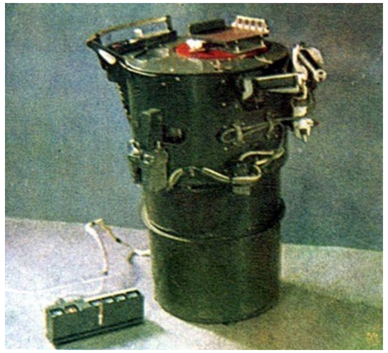
Thomas Eagar, MIT, 1990

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.

Timeline of In-Space Welding and Joining

ISAM
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING



Progress in Space Stagnated and Moved to Parabolic Flights

Credit: Tasha Dixon/Zero-G

FIRST SPACE WELD
1969. "Vulkan" on Soyuz 6. 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. EBW (USSR)
FIRST MANUAL OPEN SPACE WELD

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

1993. Parabolic
CO_2 LBW (CAN)

1999. ISWE on Shuttle
(USA/UKR/RUS) **CANCELLED**
Components went to Mir as FLAGMAN

2021. SUBSA-BRAINS braze metal.
2023-. Lockheed NASA Public-private JOINS.
2024. EBW in space by ThinkOrbital
2024-2025. Parabolic fiber LBW Flight.
Ohio State and NASA

1960s | 1970s | 1980s | 1990s | 2000s | 2010s | *2020s*

Parabolic (USSR). 1965-

Parabolic EBW for Skylab (USA). 1972

Parabolic Nd:YAG LBW (USA). 1988/89

Parabolic EBW (UKR/RUS). 1993
Parabolic EBW (USA/UKR/RUS). 1994

Drop Tower GTAW Experiment (JP). 1998

Parabolic GHTA Weld Experiment (JP). 2001

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

n.b.
EBW = Electron beam welding,
LBW = Laser beam welding,
UHT = Universal Hand Tool,
ISWE = In-Space Welding Exp.;
not all experiments included

2018. New Ukrainian EBW tool patented

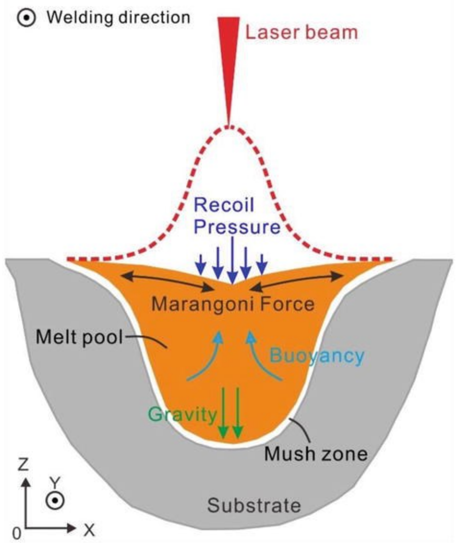
2024-2026. NASA Early Career Initiative:
LBW within TVAC
2025-. NASA Early Stage Innovations grant
(computational models of Lunar welding)
2025-. DISCMAN LBW parameter
development on ISS. NASA

NASA

In-space effects that influence welding

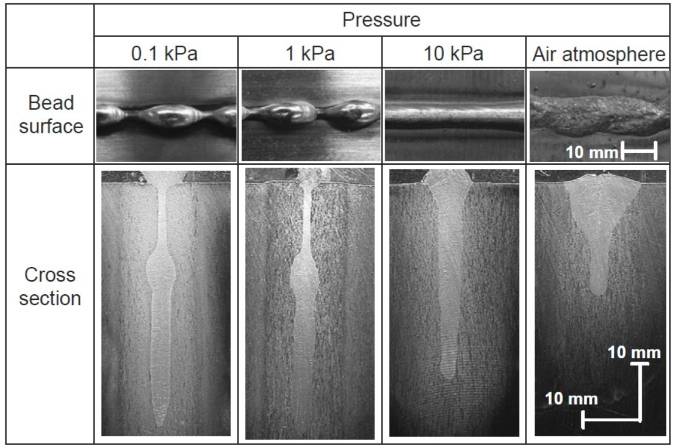
Variable	Case 1: In Space	Case 2: Chamber Inside Space Habitat	Case 3: Inside Space Habitat	Case 4: Lunar Surface	Case 5: Martian Surface	Baseline: Earth	Capabilities Needed at Present
Gravity	μg	μg	μg	0.17 *g*	0.38 *g*	1 *g*	μg to 0.38 *g*
Atmosphere	Vacuum (10^{-19} Pa)	Vacuum (10^{-4} Pa)	>21% O_2, <101 kPa	Vacuum (10^{-9} Pa) or habitat	$95CO_2$-$2.6N_2$-1.9Ar-$0.2O_2$-0.06CO (0.6 kPa) or habitat	$78N_2$-$21O_2$-0.9Ar-0.1other, 101 kPa	HV (10^{-1} Pa) UHV (10^{-5} Pa) XUHV (10^{-9} Pa)
Temperature	Extremely low ISS Exterior: 120 K – 395 K	~ 293 K	~ 293 K	40 K – 400 K	133 K – 300 K	~ 293 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

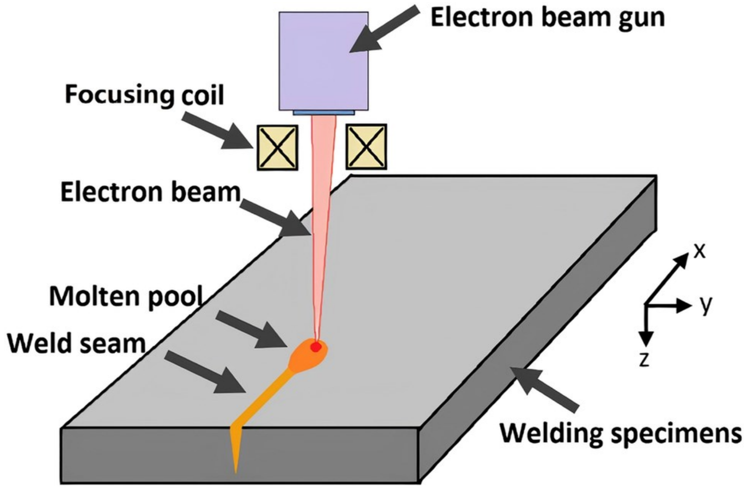


Reduced gravity is unique among the above effects in that it cannot be reproduced for prolonged periods on earth.

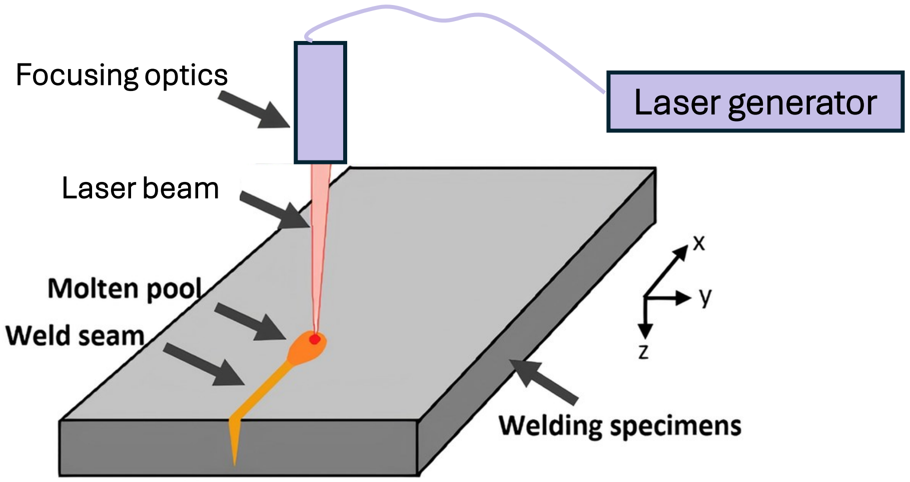
Current Work: Integrate existing capabilities across academia, government, and industry to investigate space environmental effects on welding processes to inform computational models, and to create public-private partnerships to develop and implement space welding technologies.



Why laser beams in space?



Licensed under CC BY 4.0 from Yin et al., 2023, doi: 10.1007/s00170-022-10682-6. Adapted version below.



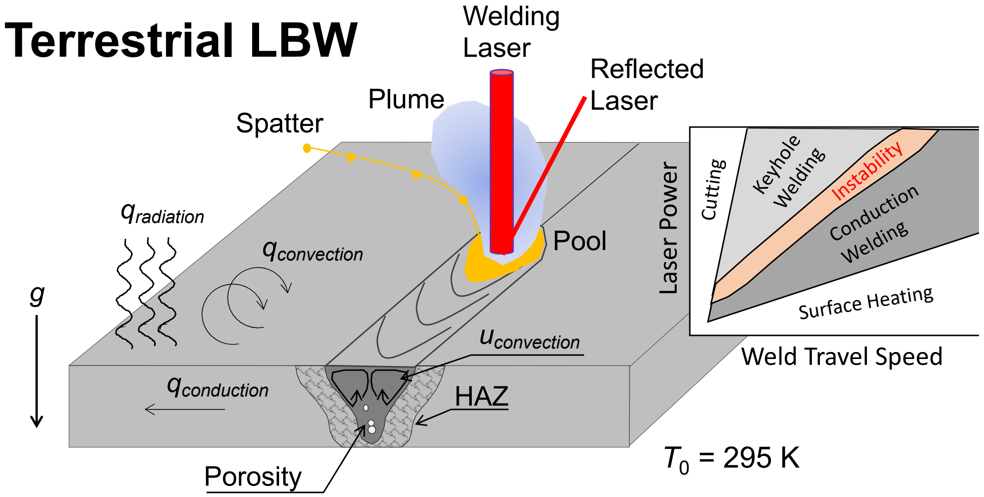
High-energy Beam Process → ↓ Criteria	Electron	Laser	Status
IVA flexibility (e.g. in habitat) & EVA flexibility (e.g. in vacuum, Lunar surface, on Mars)	●	○	Capability available after planned development
Workpiece variety (e.g. geometry, material)	◒	○	
Suitable for operation on end effector of robotic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

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

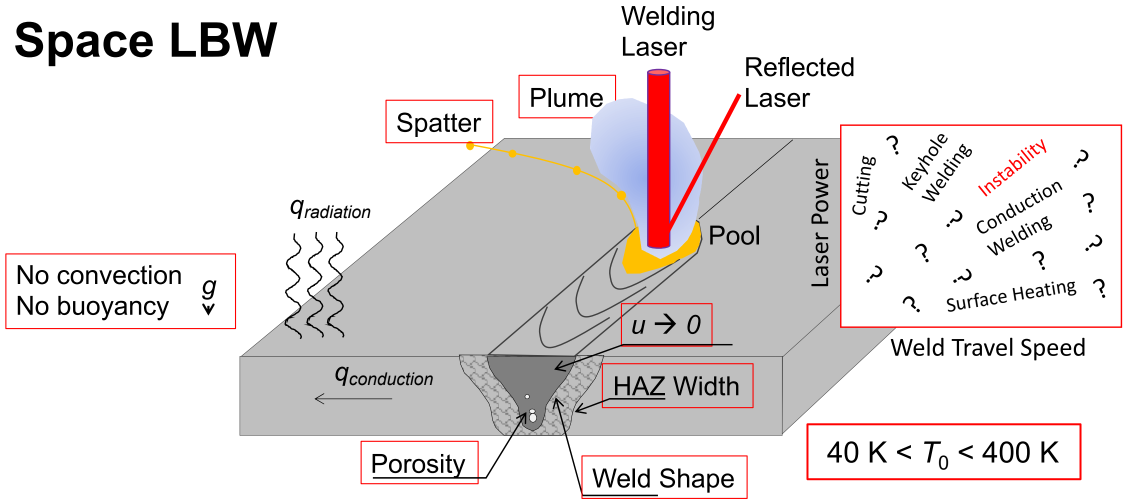
Key effects to consider for in-space LBW

Red boxes indicate instrumentation and modeling opportunities.

Terrestrial LBW



Space LBW



Consideration #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

Consideration #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)

Consideration #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.

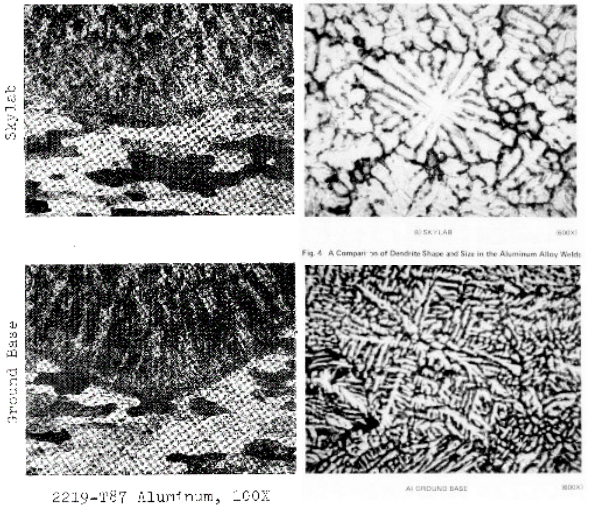
From: Sowards, *American Welding Society Professional Program*, 2023.

One vignette of past experimental work

Skylab M551 Metals Melting Experiment, July 1973

Led by NASA Marshall Space Flight Center;
development contemporaneous to von Braun's quote about welding

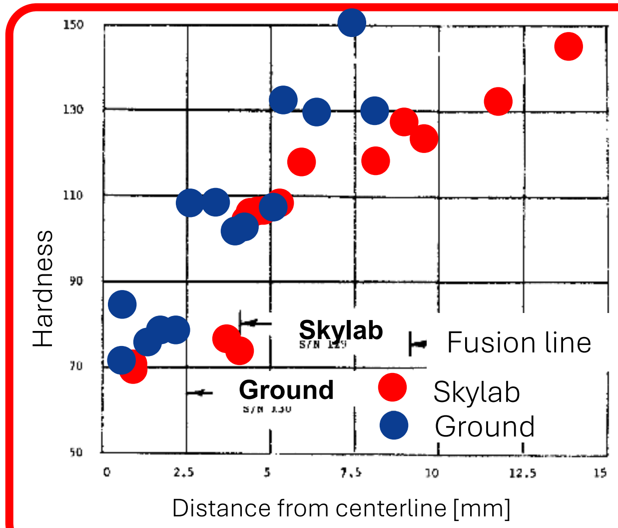
Skylab 2: first American weld in space (M551 experiment)



- In the ground-based samples, the dendrites are much larger at the root region than at the crown region. For Skylab samples, reduced difference in size.
- Concluded some unknown combination of ***G*** *(temperature gradient)* and ***R*** *(solidification range)* varied between ground and flight

G. Busch. Grumman Report (1976). https://ntrs.nasa.gov/citations/19770024270

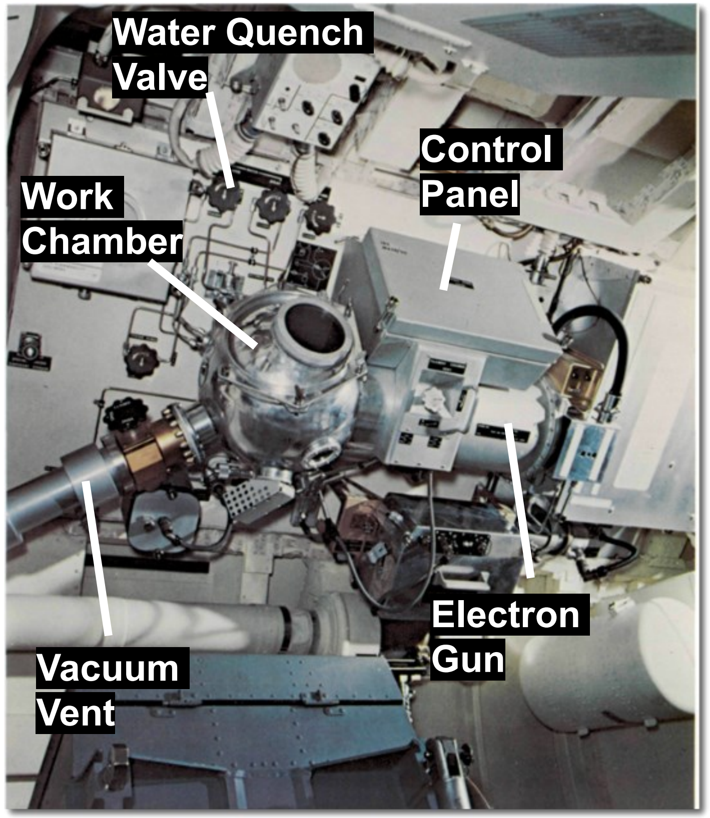
Structure



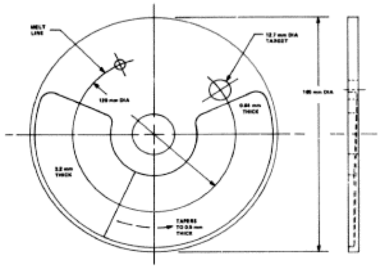
R.E. Monroe. NASA CR-129041 (1974). https://ntrs.nasa.gov/citations/19750002046

Properties

- Monroe (1974) produced hardness plots for full penetration Skylab and Ground welds.
- Li et al. (1976) concluded that no significant differences in hardness were observed between the ground-based and Skylab samples of 2219. Tantalum discs did show a significant difference, but no explanation was provided.



Processing



Travel speed = 1.61 cm/s, E = 20 kV, I = 50-80 mA

Alloys: Stainless Steel (304), Aluminum (2219-T87), CP Tantalum.

After 2 hr space vent, Vacuum = 10^{-4} Torr (~10^{-2} Pa)

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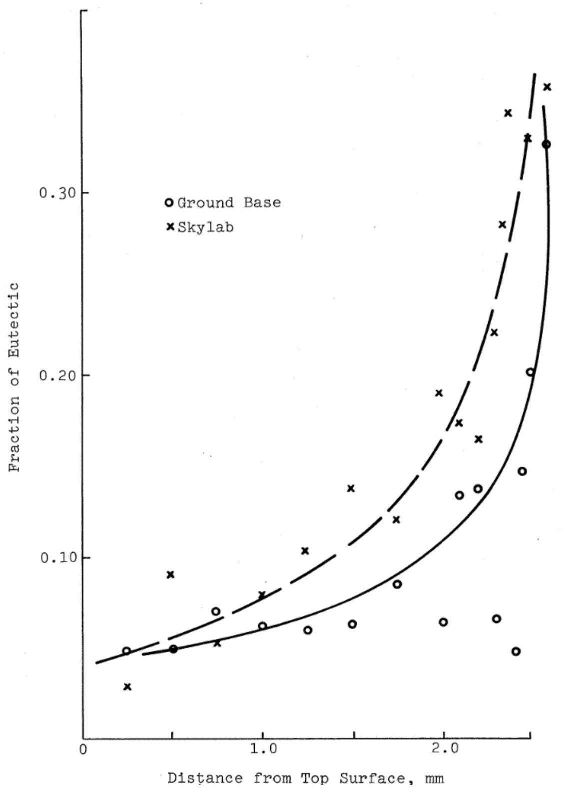
AA2219-T87 aluminum microstructure affected by microgravity

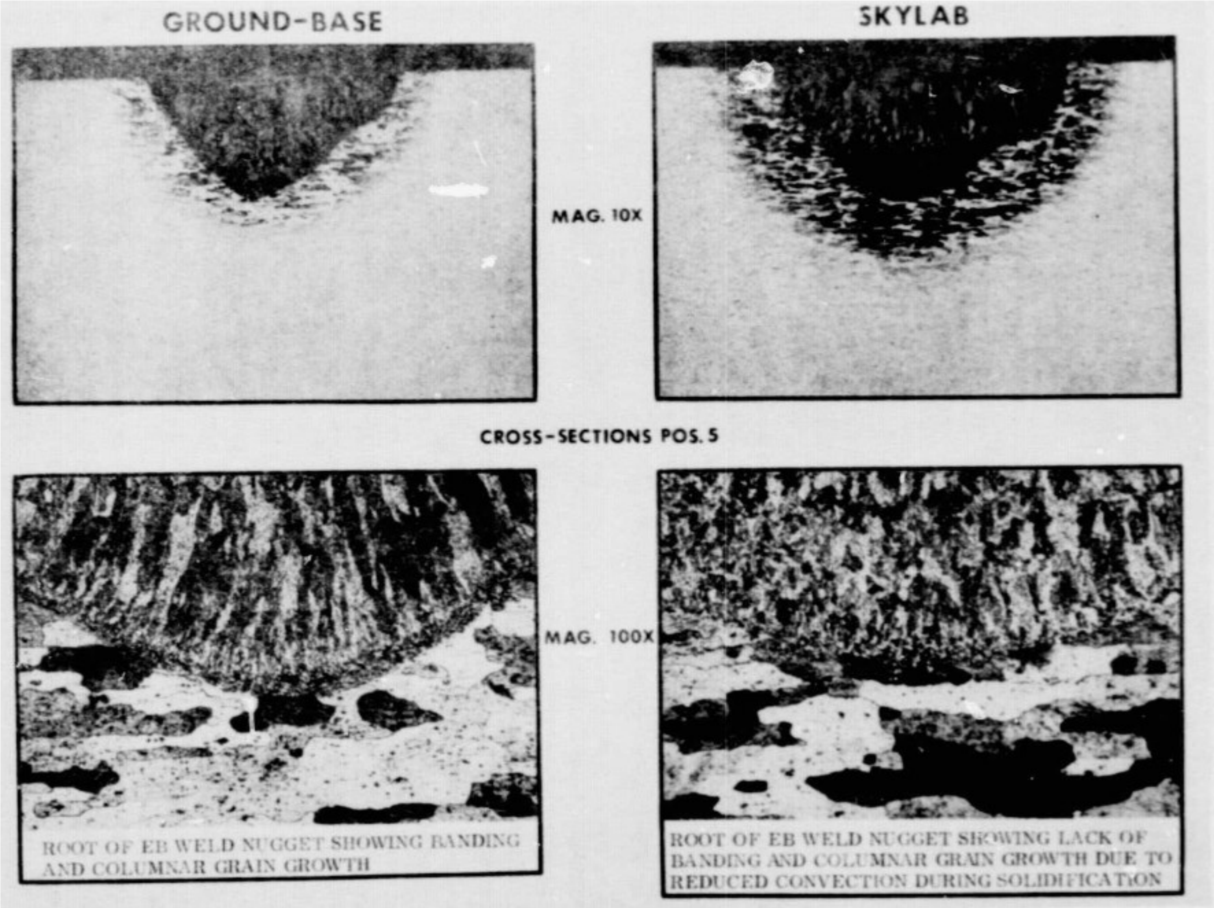


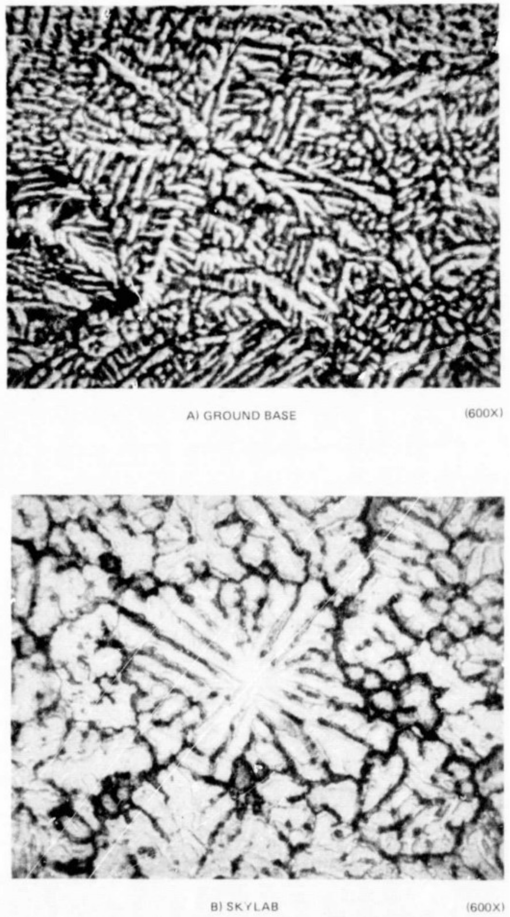
Fraction of eutectic along the centerline, indicating increased macrosegregation of copper for flight welds

Li, Busch, and Creter, NASA-CR-149927, 1976. USG work. Available: https://ntrs.nasa.gov/citations/19760020313

Flight welds evidence a wider chill zone and more equiaxed grain structure, ostensibly due to molten state quiescence in microgravity

Poorman, NASA-TM-X-64960, 1975.USG work. Available: https://ntrs.nasa.gov/citations/19760003076

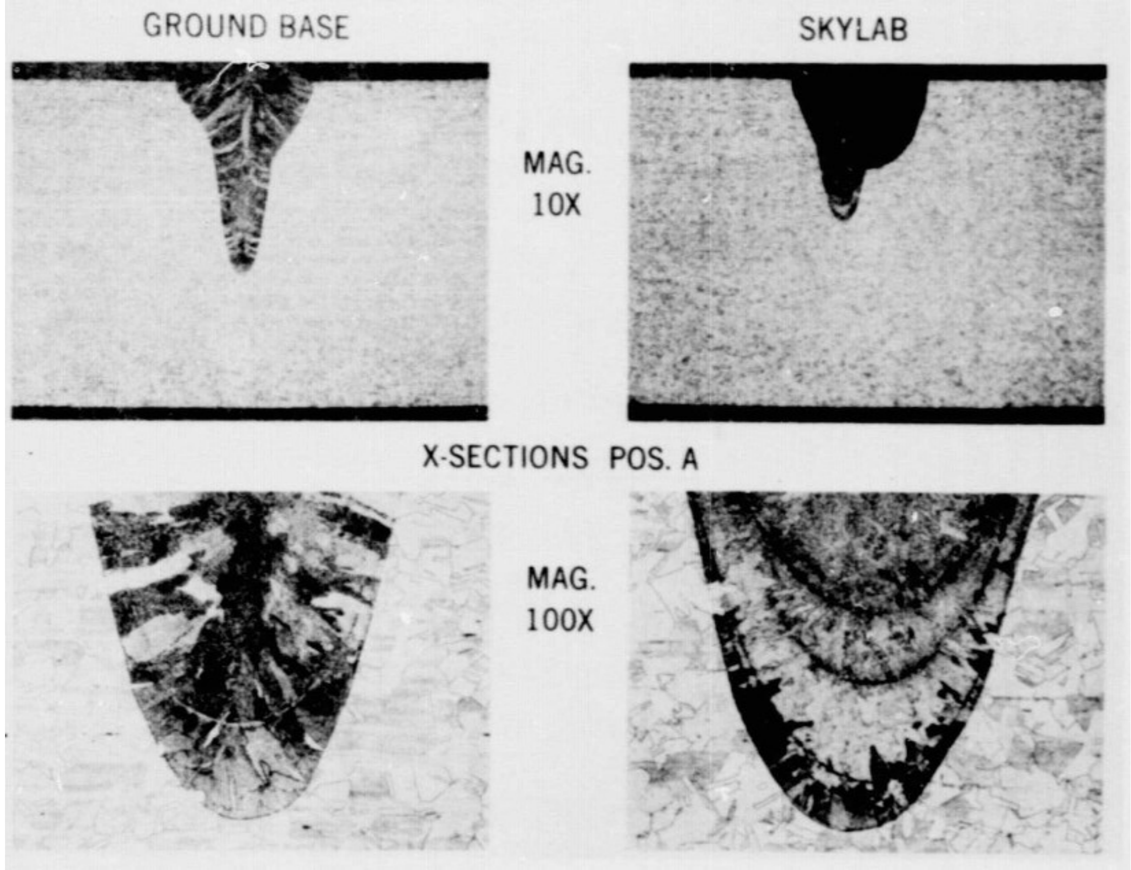




Busch, NASA-CR-150383, 1977. USG work. Available: https://ntrs.nasa.gov/citations/19770024270

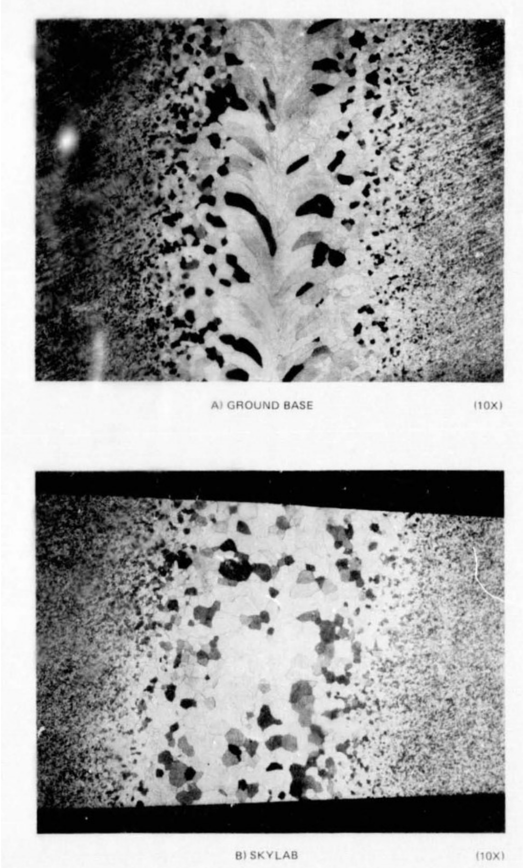
Similar changes in microstructure and even mechanical properties for AISI 304 stainless steel and tantalum

AISI304 stainless steel: wider chill zone, more equiaxed, and more refined grains



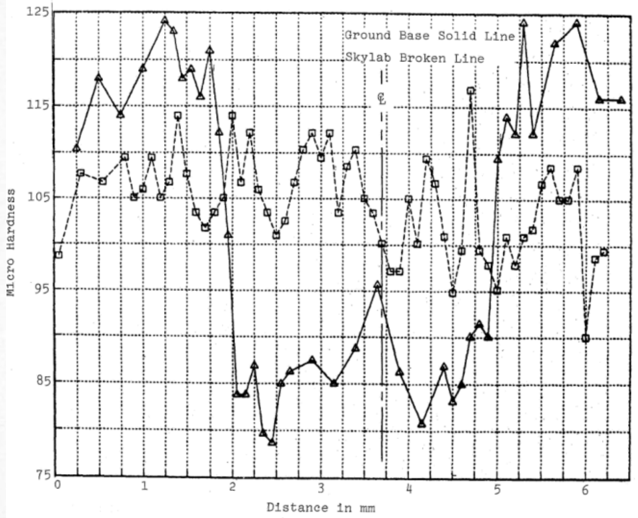
Poorman, NASA-TM-X-64960, 1975.USG work. Available: https://ntrs.nasa.gov/citations/19760003076

Tantalum: drastic change in grain structure to fully equiaxed



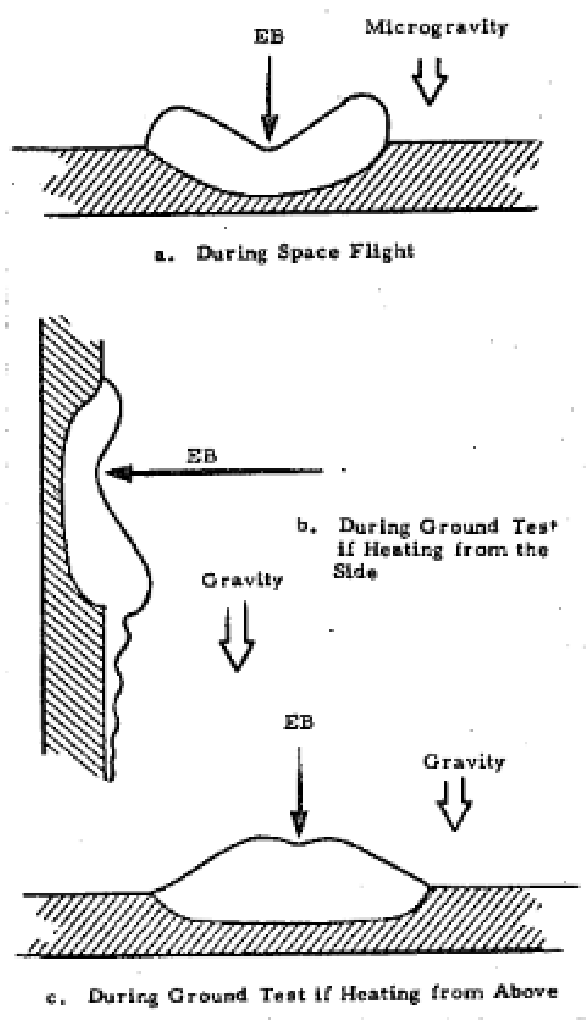
Poorman, NASA-TM-X-64960, 1975.USG work. Available: https://ntrs.nasa.gov/citations/19760003076

More favorable grain structure lead to reduced softening in flight welds



Li, Busch, and Creter, NASA-CR-149927, 1976. USG work. Available: https://ntrs.nasa.gov/citations/19760020313

Ground replicates complicate the Skylab M551 story



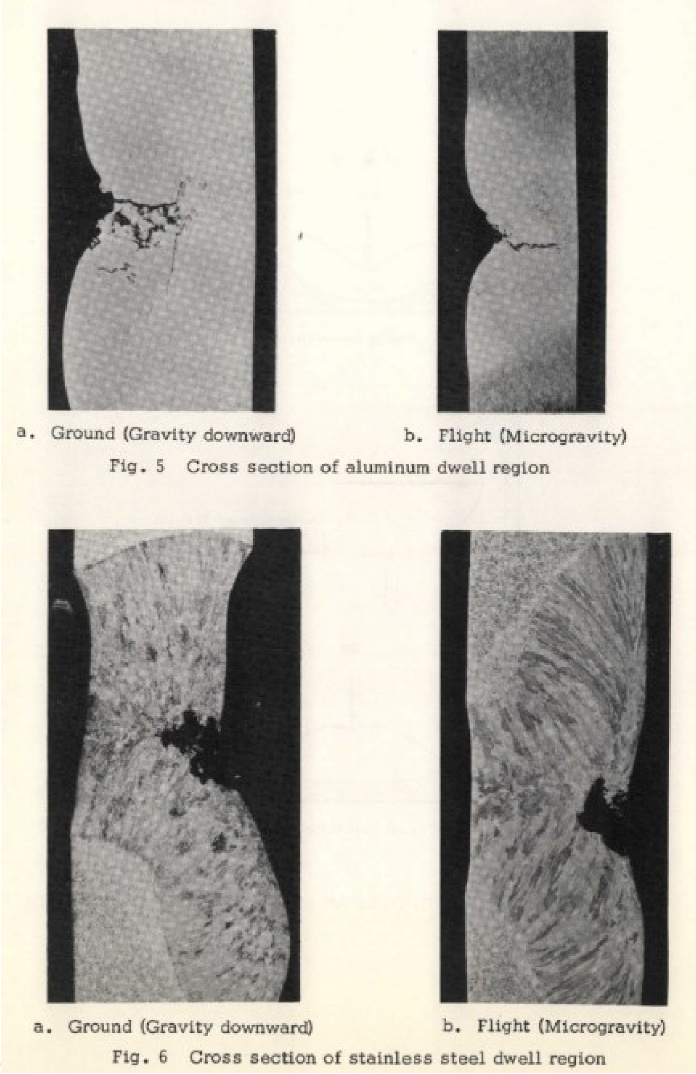

a. Ground (Gravity downward) b. Flight (Microgravity)

Fig. 5 Cross section of aluminum dwell region

a. Ground (Gravity downward) b. Flight (Microgravity)

Fig. 6 Cross section of stainless steel dwell region

Bourgeois, NASA-CR-129037, 1974. USG work. Available: https://ntrs.nasa.gov/citations/19750002045

Ground replicates were performed with the direction of gravity orthogonal to the electron beam and penetration of the weld bead; thus, deconvolving the influence of the direction of the gravitational component remains challenging.

Bourgeois, NASA-CR-129037, 1974. Available: https://ntrs.nasa.gov/citations/19750002045
Bourgeois, NASA-CR-124329, 1973. Available: https://ntrs.nasa.gov/citations/19730020120

Nogi *et al*. (1998) performed similarly oriented experiments with arc welding in a drop tower. They found accordingly similar sagging but also showed changes in porosity distribution and size in microgravity.

doi: 10.1016/S1359-6454(98)00084-6

Lessons learned from Skylab M551

Useful outcomes to inform future efforts

- There are microstructural (grain morphology) and macroscopic (sagging, beading, etc.) differences due to microgravity, even in somewhat-rapid EBW solidification
- These differences do influence properties (at least hardness) and thus likely performance
- Welding is a viable joining process in space with intriguing technical challenges and scientific merit

Opportunities to improve experimental design and data collection

- Gravity not oriented coaxial with beam during ground replicates – complicates interpretation
- Single welds – no chance to modify welding parameters or schedule based on quick-look feedback; only bead-on-plate welds performed
- No thermal data
- No serial sectioning or longitudinal cross-sections
  - How does weld change over time?
- Incomplete chemical analysis
  - Macrosegregation intriguing but only part of the story; later re-characterization by Colo. Sch. Mines offered tantalizing hints
- No porosity characterization
  - How does this impact joining efficiency, fatigue, etc.?
- No mechanical testing
  - How does weld actually perform? What about service-relevant loads?

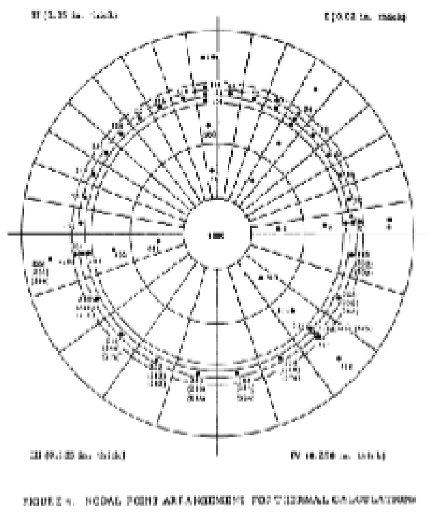
Exemplar linkage of experiment to computation & prediction

Thermal modeling of Skylab M551 and extension to predict ISW properties

Case study: Skylab M551 thermal modeling

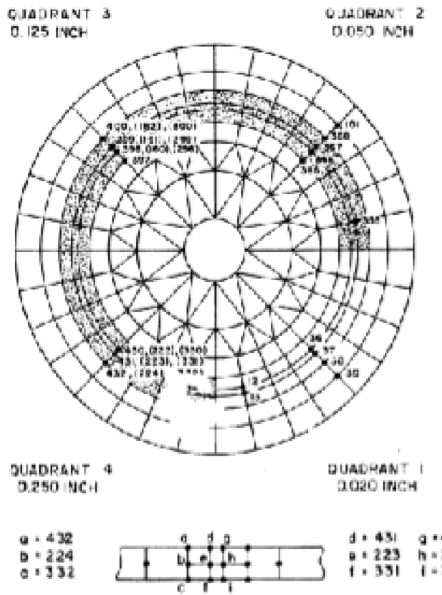
- Thermal model anchored to Skylab data at ambient (room) temperature but extended to extremes of Lunar surface
- Predict weld bead size, thermal history, and thus hardness

1974 Lockheed Martin Analysis. >370 Nodes



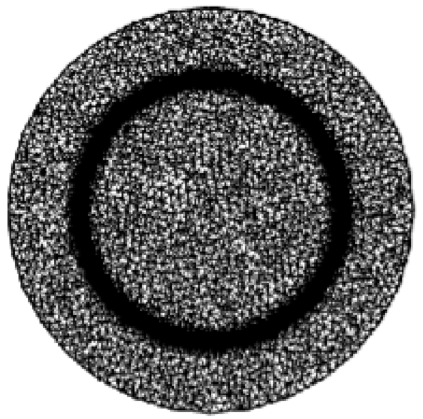
1974. Brashears and Roberts. Little detail provided.

1975 MIT Analysis. 232 Elements & 216 Nodes.



1975. Muraki and Masubuchi. Conduction and Radiation with constant thermophysical properties. Ability to consider melting and solidification.

Current Analysis. 166K+ Elements.



Mathematica v.14
- Temperature-dependent thermophysical properties
- Distributed heat source (assumed distribution for EBW)
- Radiation, internal heat conduction, vaporization BCs
- Phase change melting/solidification are being tested

Navier Stokes solution and complex boundary conditions in further iterations

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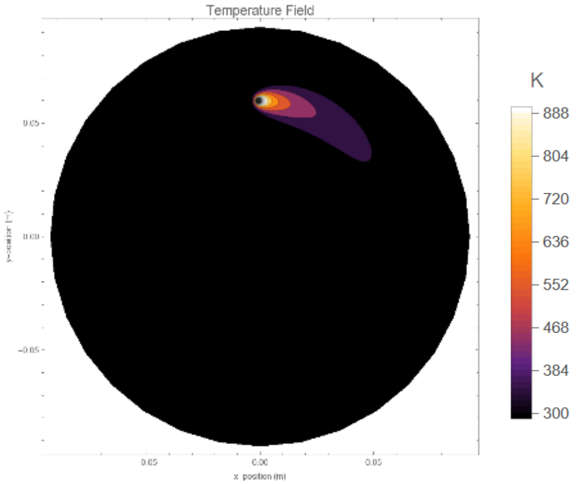
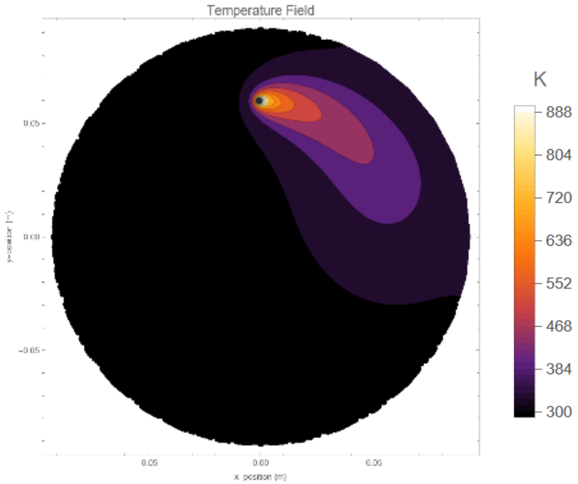
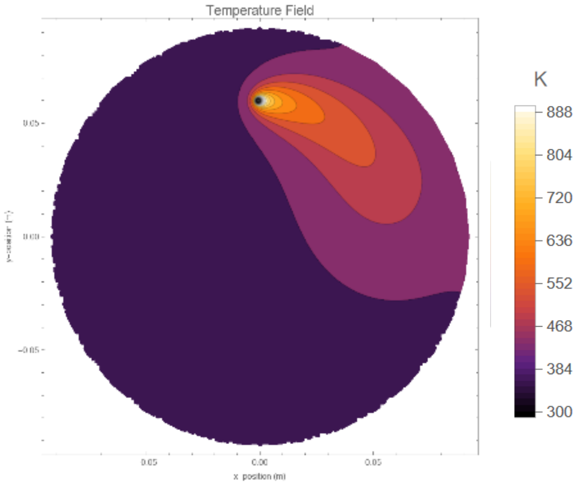
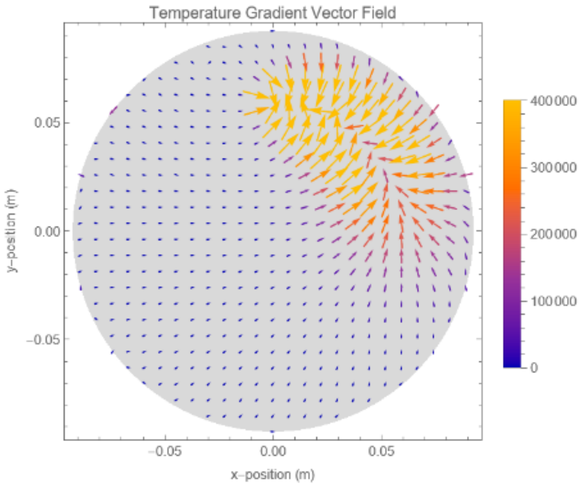
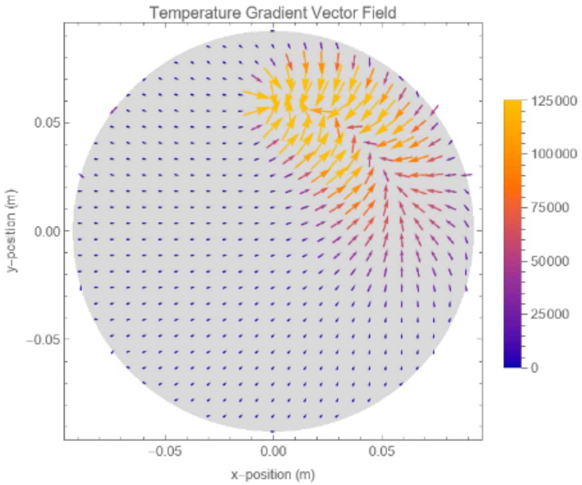
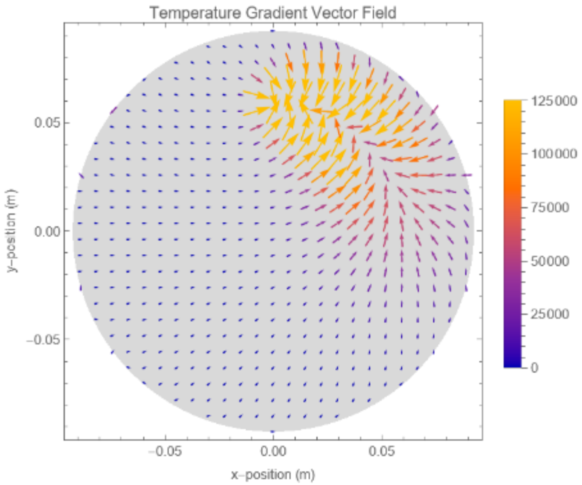
Temperature & gradient maps of Skylab AA2219-T87 disc

T_0 = 100 K	T_0 = 293 K	T_0 = 400 K
		
		

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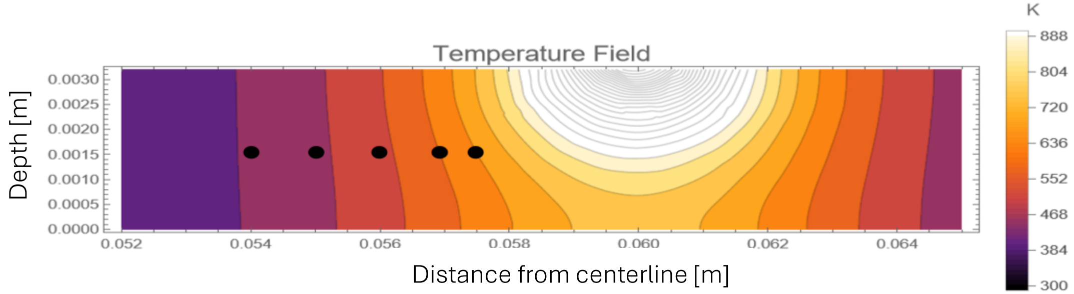
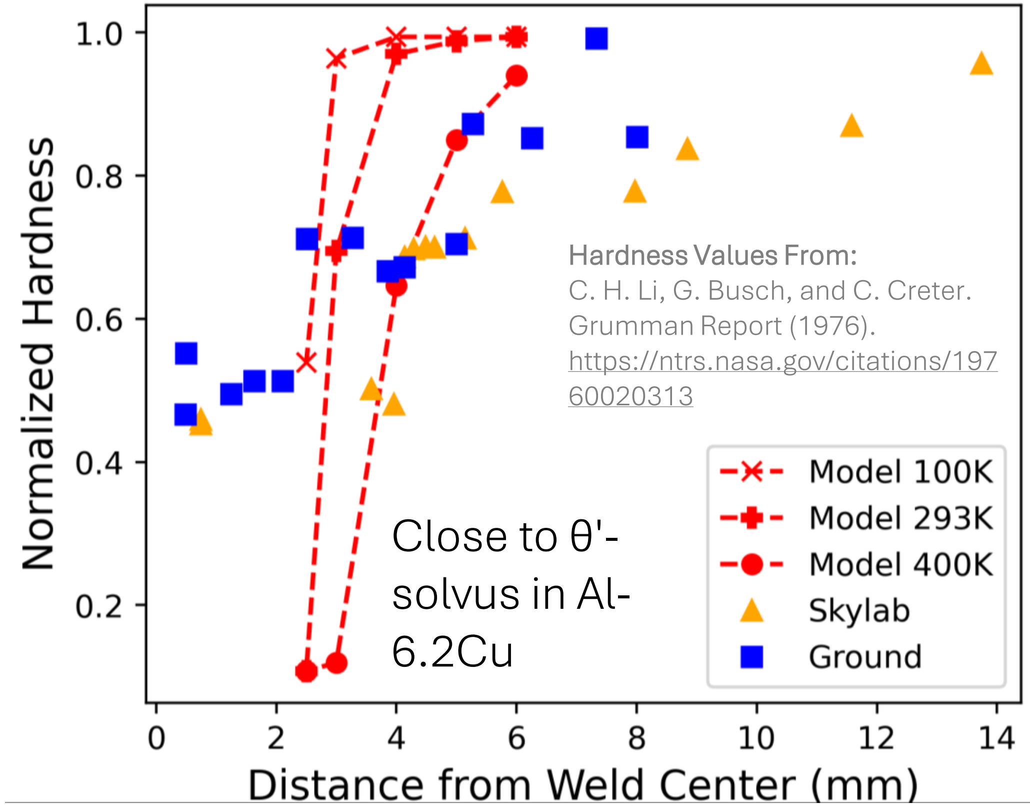
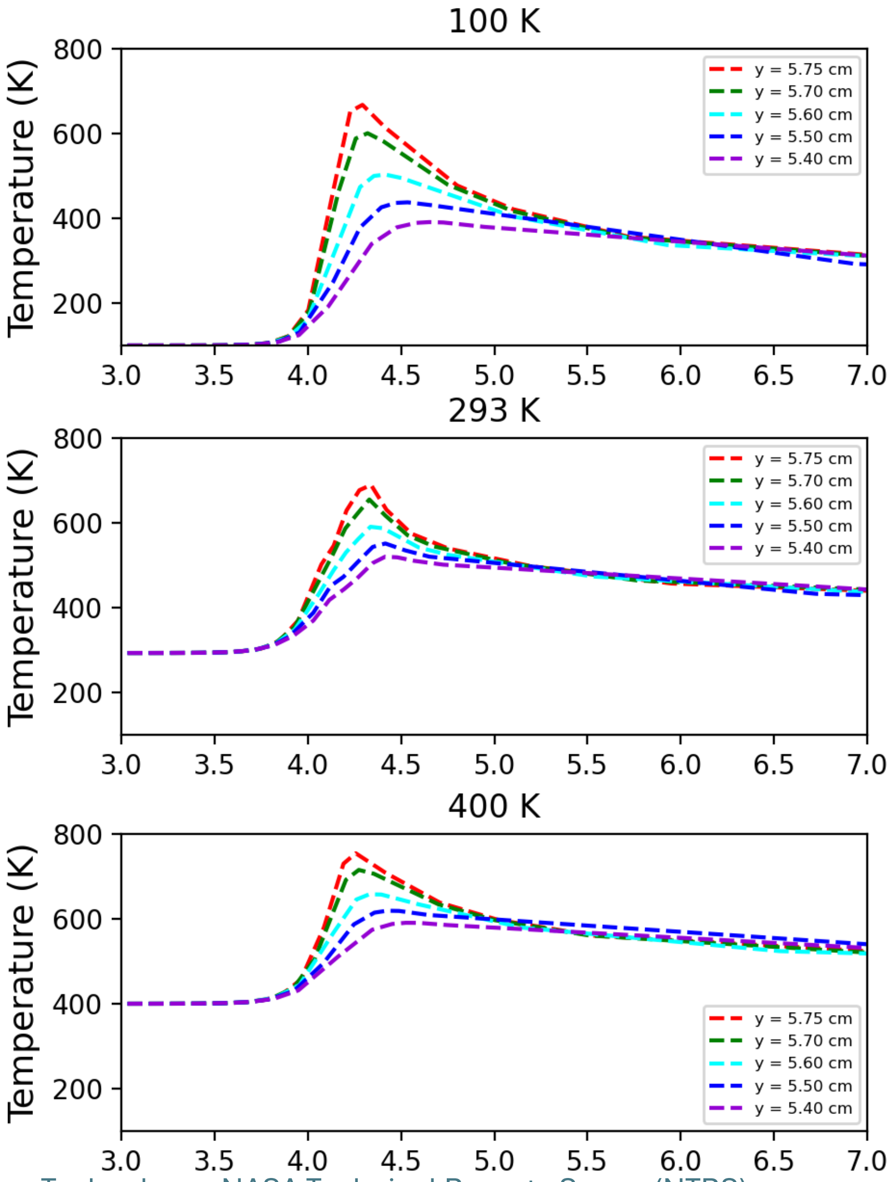
Properties: Hardness by Starting Disc Temperature







A modern path forward, building upon Skylab M551

- We know that welding in space is possible
- We know that there is influence of vacuum and microgravity

Ultimately:

Skylab M551 was a technology demonstration that did not appreciably reduce the amount of testing required for modern-era infusion and qualification

- Would **need to weld many times over** and in an operational context (ISWE)
- We need to further **capture differences**, **precisely quantify** these, and leverage these data to **accelerate infusion** of ISW into upcoming missions and activities

How?

- Generate high-fidelity **benchmark datasets to anchor computational models** that can **reduce the overall experimental burden** of ISW qualification
  - An exemplar case of Integrated Computational Materials Engineering, if implemented

Modern ISW benchmark experiments

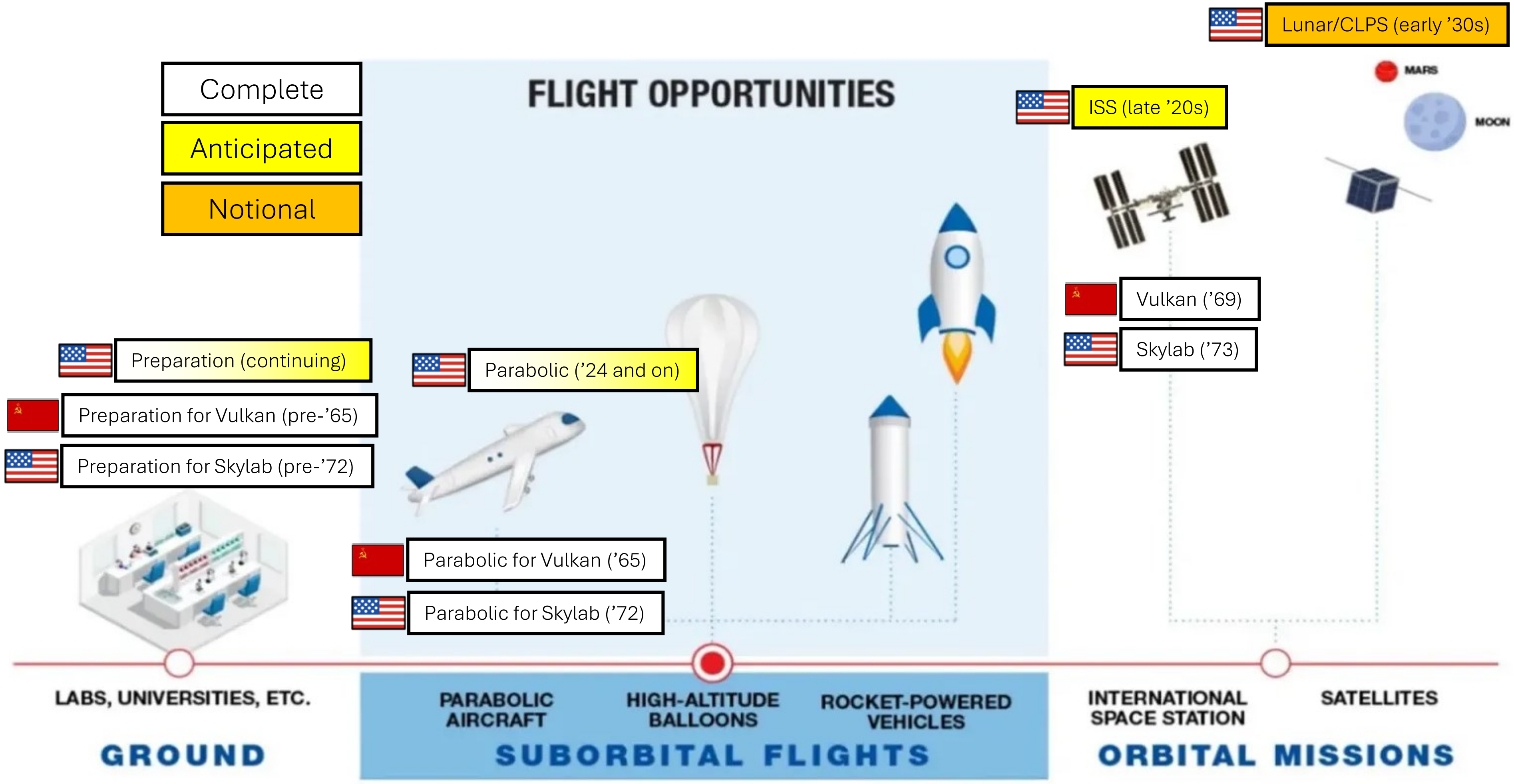
NASA-OSU collaborative parabolic flights; NASA/MSFC persistent LBW testbed

Progression of flight experiments

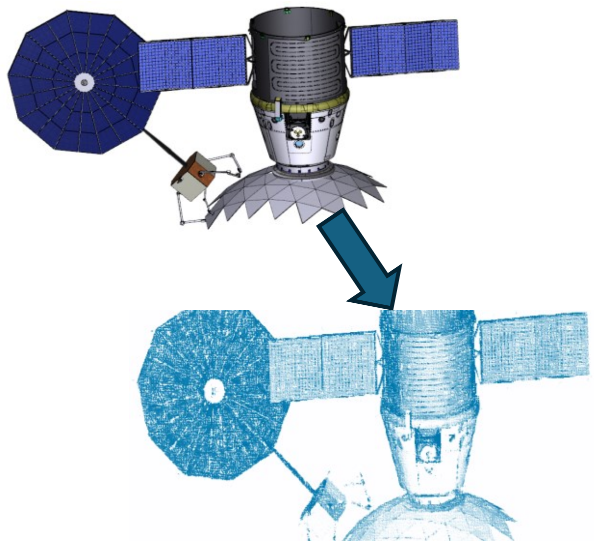
Complete

Anticipated

Notional

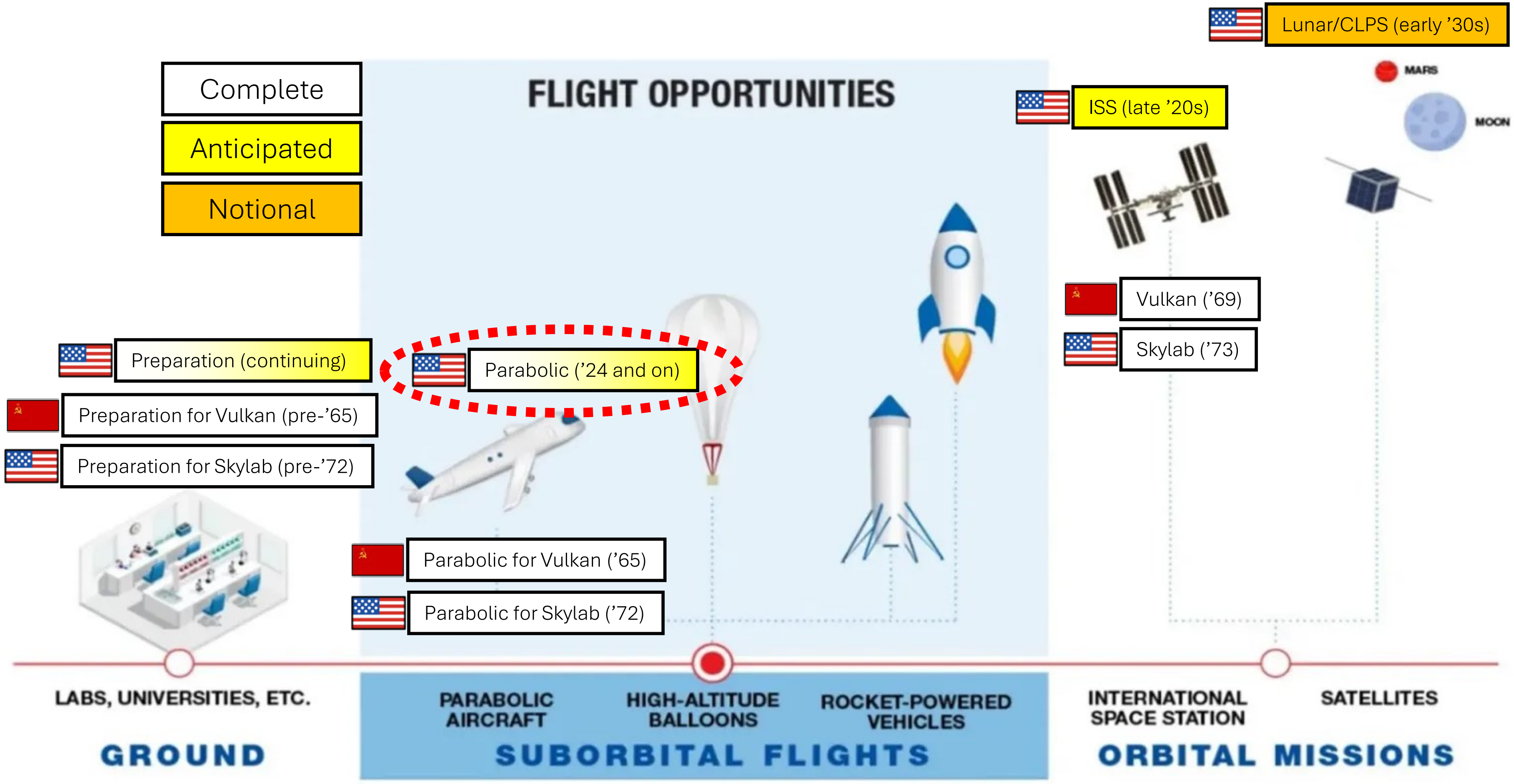


Concurrent development of Digital Twin using collected data

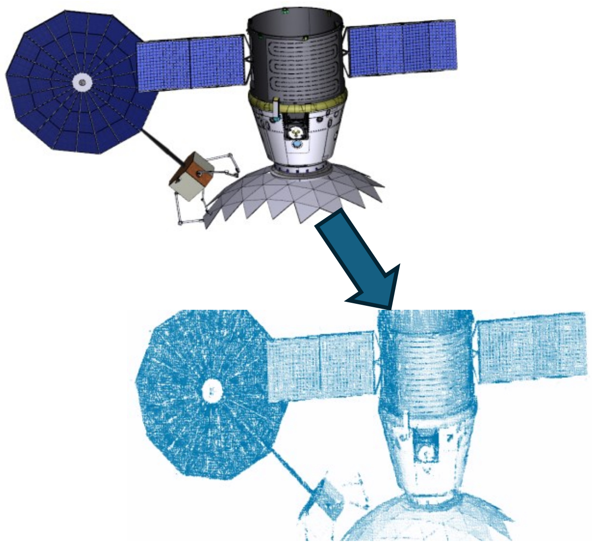


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Progression of flight experiments



Concurrent development of Digital Twin using collected data

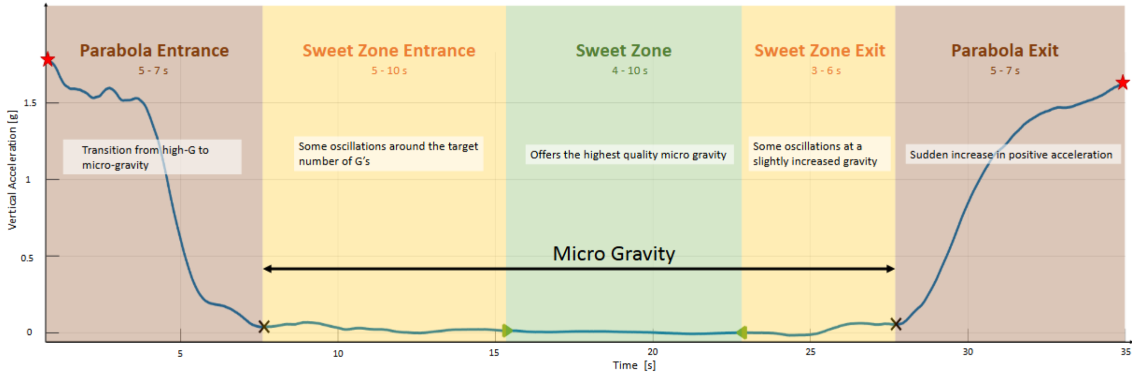


Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

Parabolic flight sufficient for initial ISW investigations

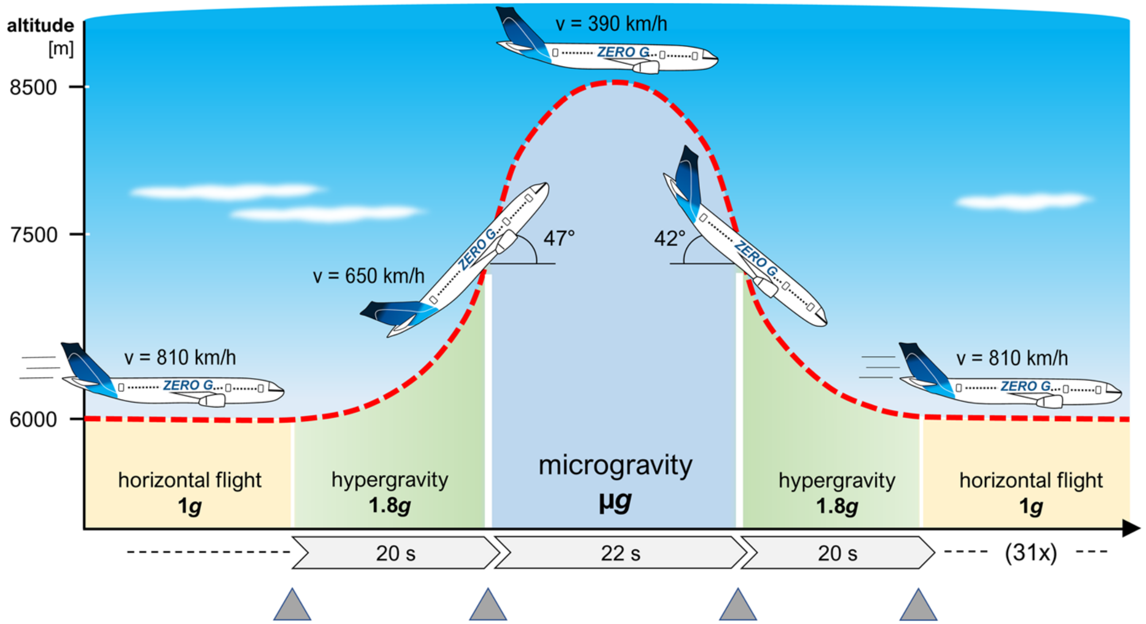
Actual gravity quality is variable

- 12 to 26 seconds of usable low gravity
- Really milli-gravity (typically $<2 \cdot 10^{-2}$ g)
- Subject to manual piloting, buffeting by air currents & atmospheric disturbances, vibrations inherent to airframe, impact by personnel, etc.
- For molten metal processes like soldering and welding, this approaches required gravity level



Lambot and Ord, "Analysis of the Quality of Parabolic Flight," 2016. USG work. Available: https://ntrs.nasa.gov/citations/20160007932

Typical parabolic flight profile

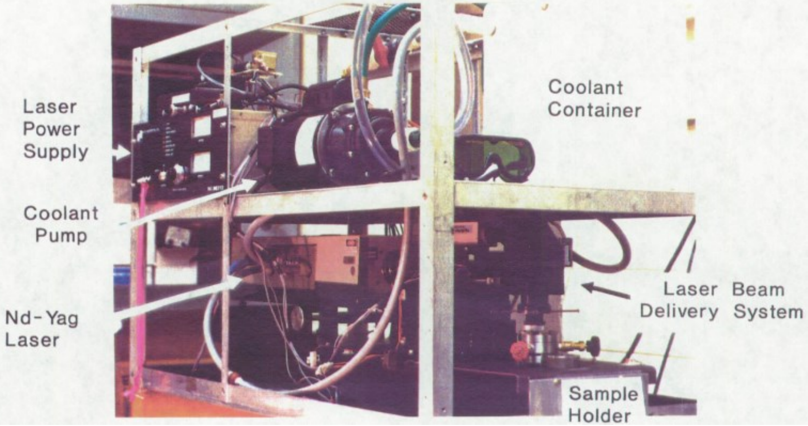


See for further detail:
Struk *et al.*, "The Effects of an Unsteady Reduced Gravity Environment on the Soldering Process," 2004. doi: 10.2514/6.2004-1311
Runyon *et al.*, *Planet. Sci. J.*, 2025, doi: 10.3847/PSJ/adb74c.

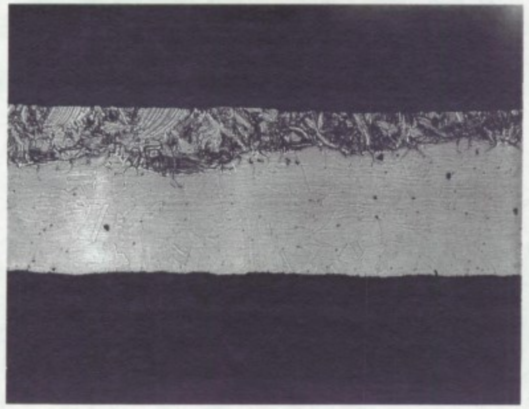
Vacuum LBW parabolic flights by Workman & Kaukler (1989)

- Simultaneous vacuum and low gravity
  <u>but</u> low power, low beam quality laser
  - No greater than 18 W delivered to workpiece
- No mechanical, porosity, chemistry, etc. data

BREAKOUT OF THE LASER WELDER
FLOWN ON THE KC-135



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



LOW G (0.1) TO HIGH G (1.8)

OXALIC ACID ELECTRO-ETCH, BRIGHT FIELD OPTICAL, 200X

SPECIMEN T310S1

Sample T38S1 is also stainless steel 304 (0.127 mm thick). Micrograph shows 17% reduction in bead width in transit from high to low G. Rippling is also slightly greater in low G.

Collaboration with the Ohio State University on parabolic flight

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. Undergrad capstone team. Grad students: Eugene Choi, Aaron Brimmer, Will McAuley.
- NASA. Jeff Sowards, Karen Taminger (LaRC), Will Evans, Zach Courtright, Louise Littles, Andrew O'Connor, Emma Jaynes, Ben Rupp, Tom Bryan.

Modern fiber lasers enable high-power LBW

Courtesy: IPG Photonics

Retrofitted flight-proven vacuum chamber from NASA/LaRC for LBW

Leverage LBW expertise & workforce development at OSU

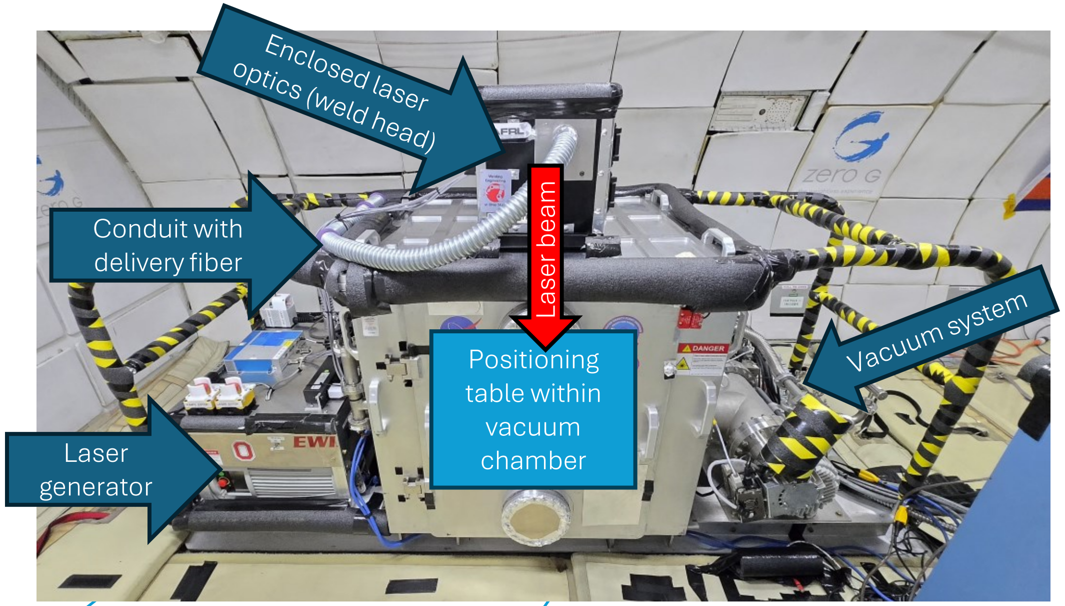
Vacuum LBW experiment during parabolic flight

Credit: Tasha Dixon/Zero-G

Expand range of materials, joint geometries, weld types, etc. using modern laser beam welding technology and instrumentation

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

Extended flight campaign using proven hardware



in situ thermal data and videography

<u>First flown in August 2024:</u>
Successfully welded during 69 out of 70 total parabolas – including both Lunar (0.17 g) and low gravity (~0.01 g) profiles

<u>Flight in May 2025:</u>
Hermetic welds (pressure vessels, etc.) and **realistic joints** (lap, butt-lap, etc.)

<u>Upcoming publication on results:</u>

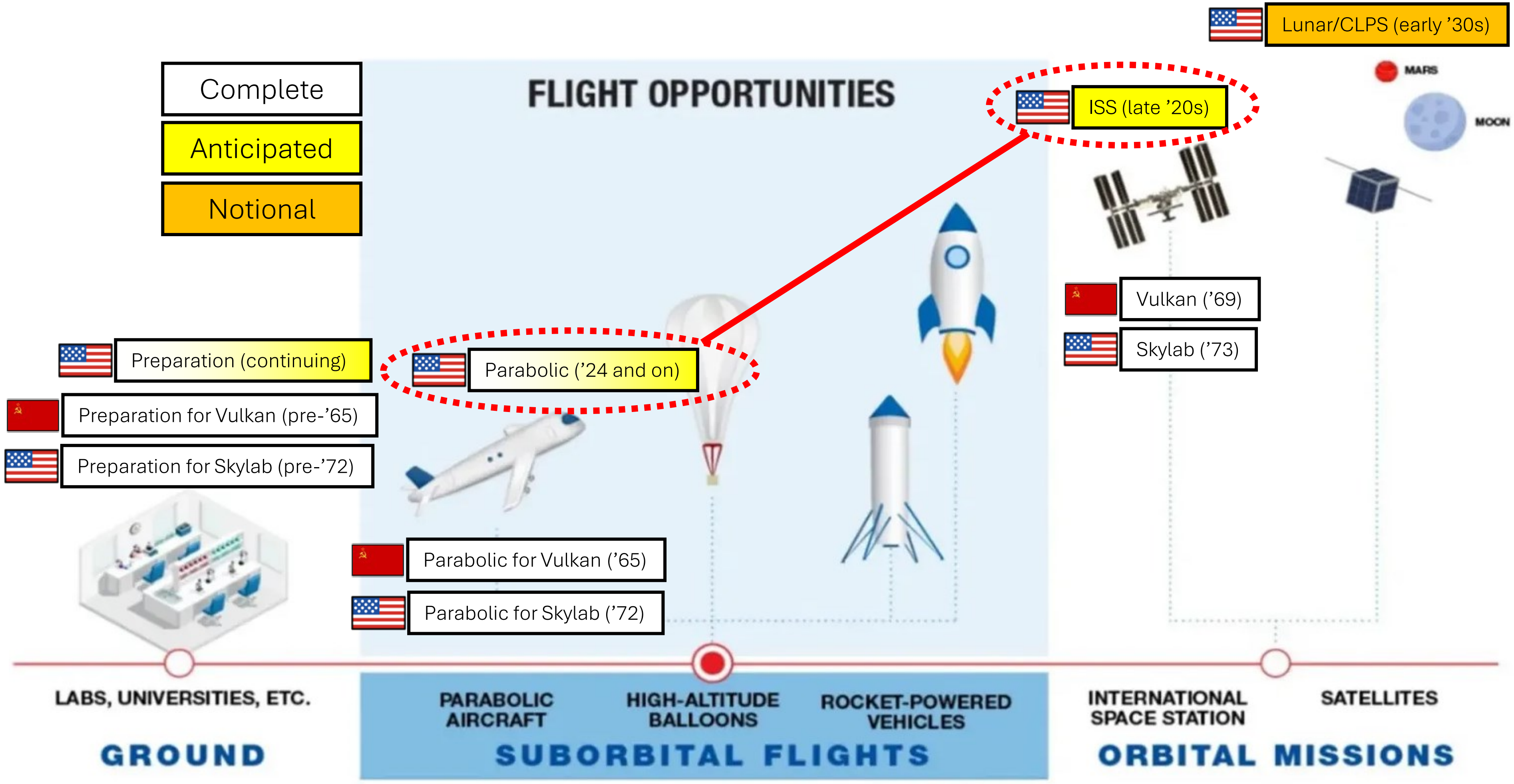
- Microstructure via metallography, electron microscopy, EBSD
- Thermal modeling
- Porosity via radiography and micro-CT scans

<u>Further publications to come:</u>

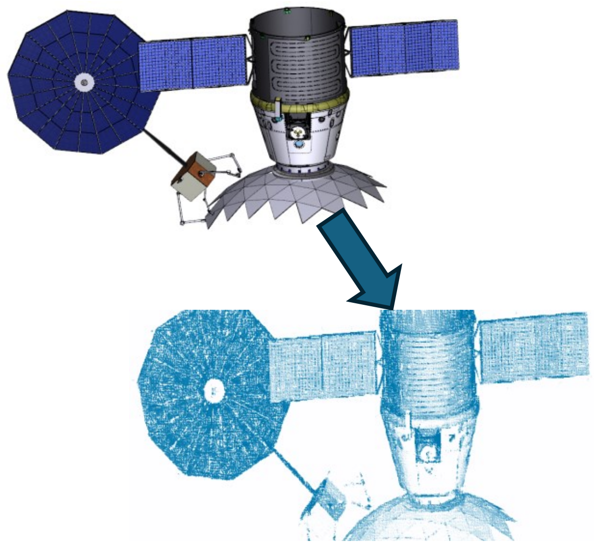
- Mechanical properties (tensile)
- Hermiticity (leak test)

Credit: Tasha Dixon/Zero-G

Progression of flight experiments



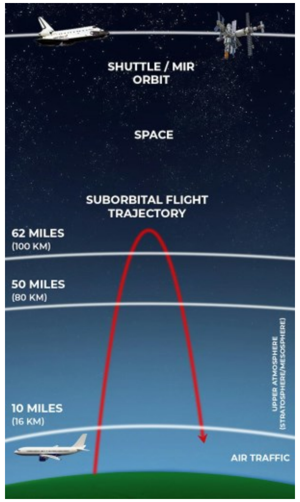
Concurrent development of Digital Twin using collected data



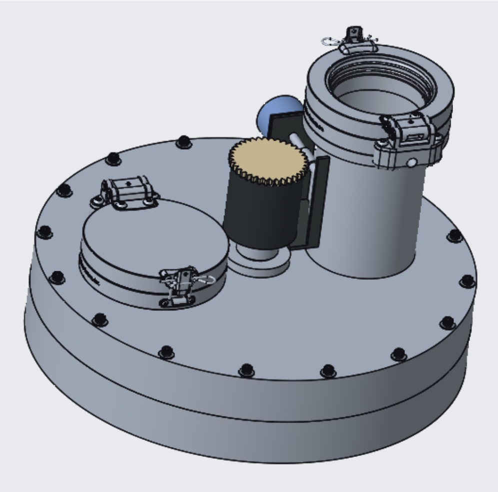
Underlying graphic from Kelly *et al.* in *ASCEND 2020*, 2020. doi: 10.2514/6.2020-4135. USG work.

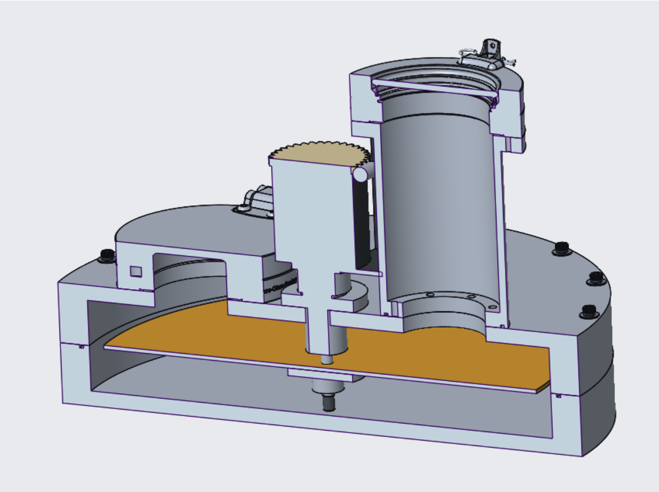
Evolve from parabolic to suborbital flight experiments

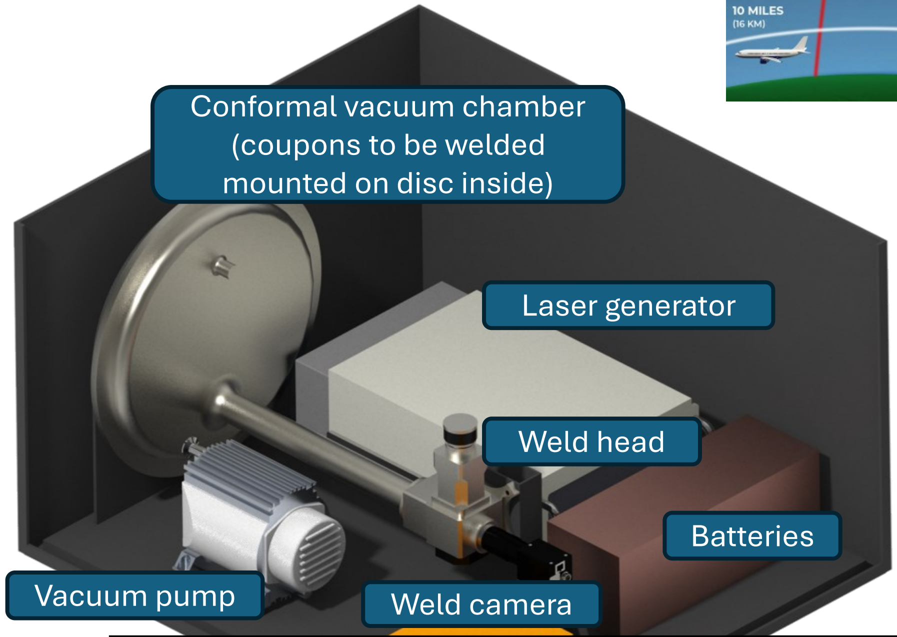
Parabolic	Suborbital
Tens of seconds in reduced or µg	Minutes in reduced or µg
Two-*g* during pull out (weld solidified?)	Hi-*g* only before welding (launch)
g-jitter complicates effect of gravity	Reduced *g*-jitter



Initial protoflight hardware design

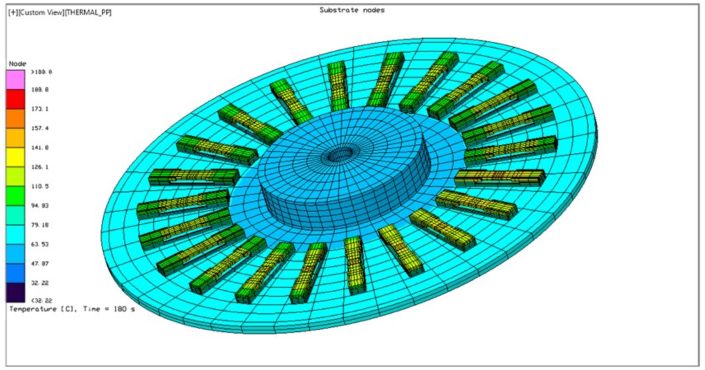






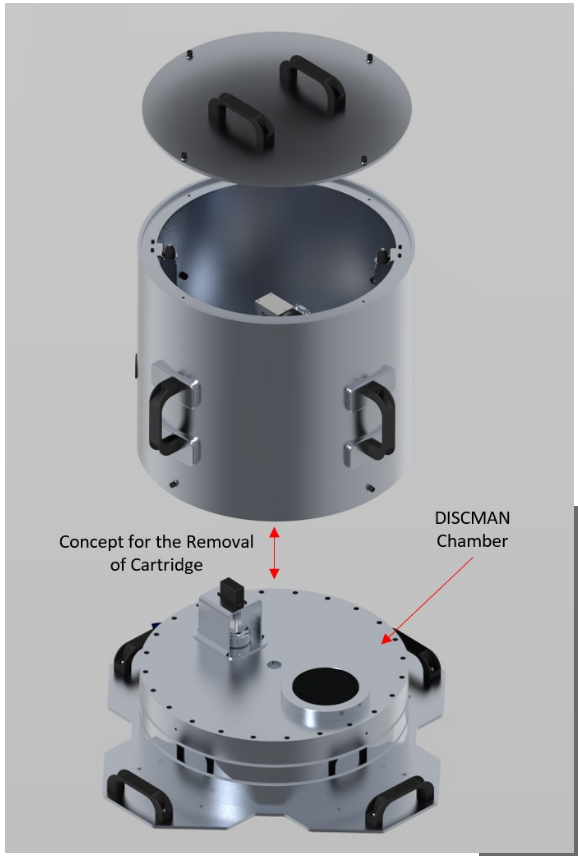
Conceptual design developed with MSFC Advanced Concepts Office

Thermal and structural modeling



Serendipitous opportunity to re-target for Bishop Airlock on ISS: <u>long microgravity duration</u> with ability to pause, reflect, and <u>change welding parameters & schedule mid-flight</u>!

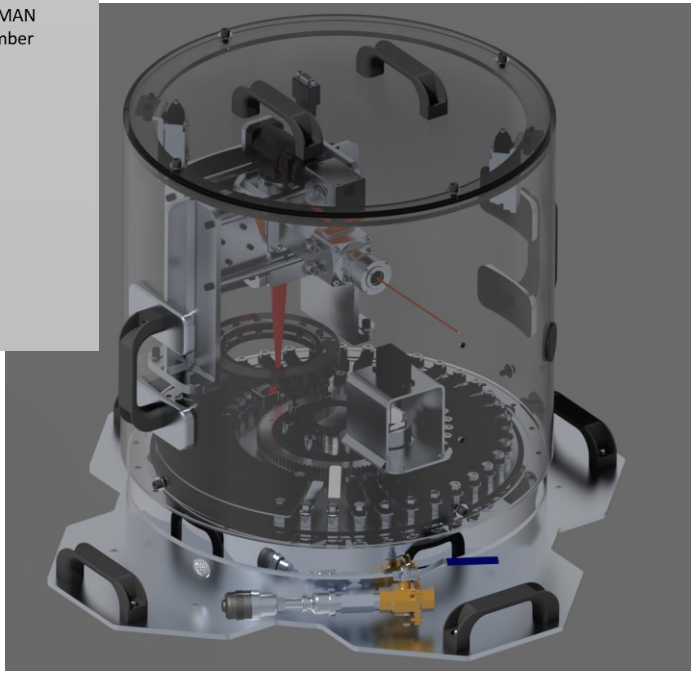
DISCMAN – A persistent platform for LBW process development



Key innovation:
Vacuum chamber as <u>swappable cartridge</u> that can be <u>exchanged on orbit by crew</u>; cartridge contains disc with pre-mounted workpieces

DISCMAN can support any experiment requiring laser, vacuum, motion, microgravity (or just a subset)

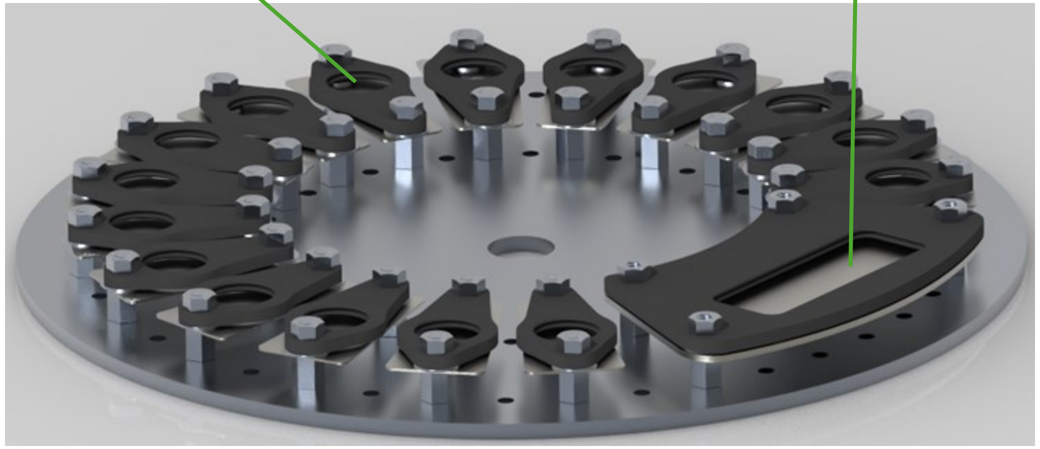
Simplified render of swappable cartridge and enclosure for laser



Translucent render of cartridge and enclosure

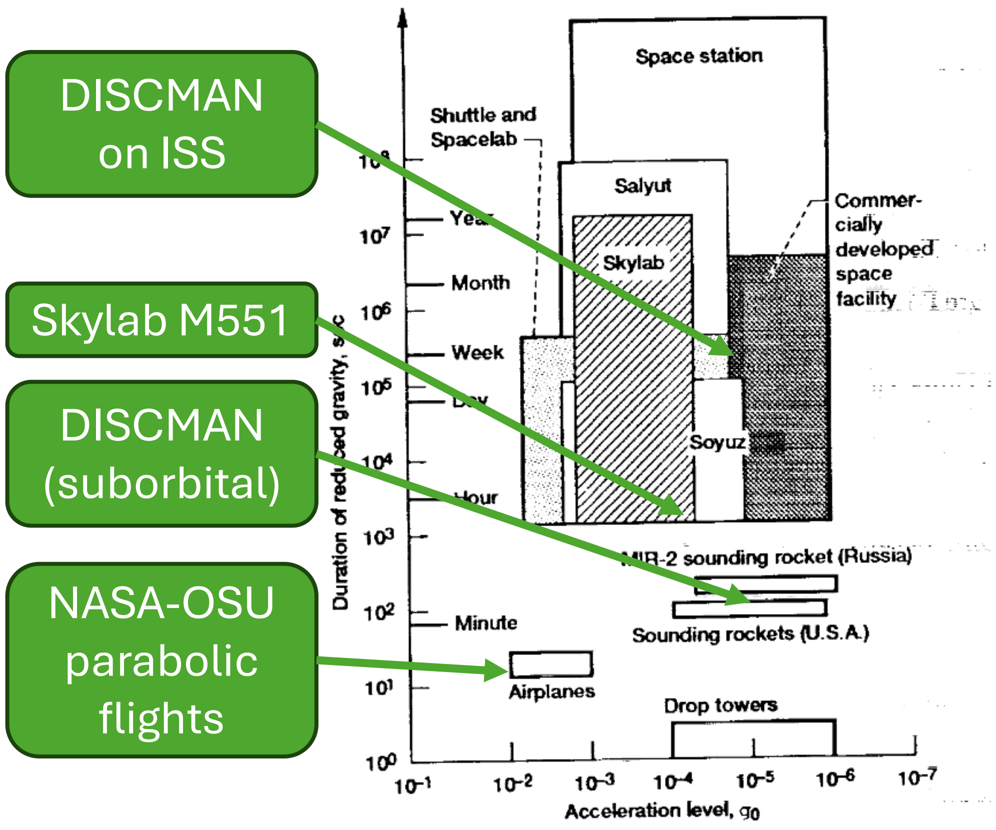
Notional DISCMAN workpieces and welds:

- Spots for characterization and shear testing
- Short line welds for more realistic butt-lap joints
- Long, linear welds to characterize steady-state
- Future workpieces (cutting/drilling, forming)



Microgravity and vacuum level for ISW experiments

Microgravity quality and especially duration enhanced on orbit



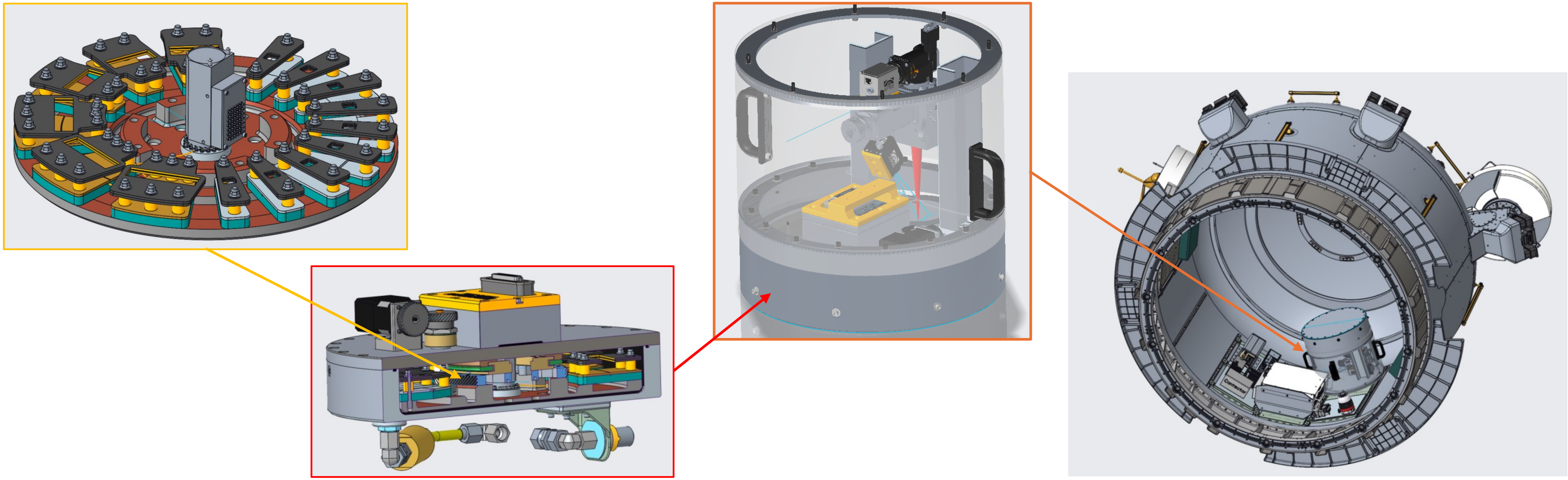
Lekan, Neumann, and Sotos, "Capabilities and constraints of NASA's ground-based reduced gravity facilities," 1993. USG work. Available: https://ntrs.nasa.gov/citations/19930010995

High vacuum required to fully investigate ISW

- Suita *et al.* (2004) found that for SUS304 stainless steel:
  - penetration saturated below 10 Pa
  - metal vapor deposition saturated between 10^0 and 10^{-2} Pa
- Abe *et al.* (2010) found that penetration saturated below 10^3 Pa for SUS304 stainless steel but slightly regressed for AA5052 aluminum (due to Mg vaporization)

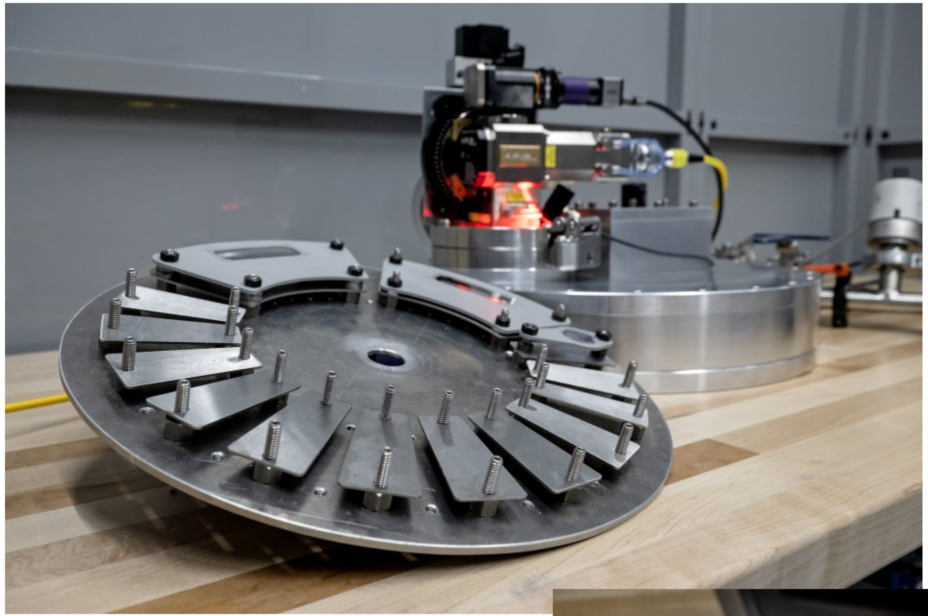
Suita *et al.*, *Journal of the Japan Society for Aeronautical and Space Sciences*, 2004, doi: 10.2322/jjsass.52.45.
Abe *et al.*, ICALEO 2010. doi: 10.2351/1.5062094.

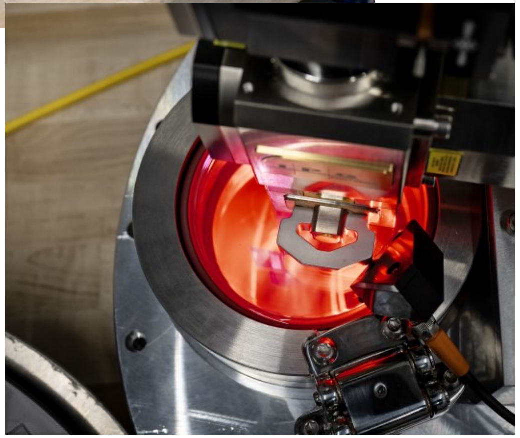
Current DISCMAN effort: initial ISS design and preliminary payload safety



- Design evolving to meet more stringent safety and persistence requirements of ISS and Bishop Airlock
- Continuing to focus on LBW as first use case with ability to upmass additional, different cartridges later
- Recently added to Integrated Payload List and engaging with Voyager Technologies as integrator

Ground testing unit (GTU) maturing design and demonstrating *in operando* data collection





Depiction of GTU integrated for functional and operational testing; rapid reconfiguration ability enables responsive design and development

Courtesy: IPG Photonics

Nominal 1500 W max. (pulsed), 250 W (continuous) **fiber laser**

Compact turbomolecular pump to achieve **high vacuum** (10^{-2} Pa)

Highly instrumented to collect data to anchor computational models

High dynamic range (140+ dB) **welding camera** to monitor melt pool and spatter

Courtesy: Xiris Automation

Short-wave infrared (SWIR) **thermal camera** to monitor thermal history, augmented by **thermocouples** on workpieces

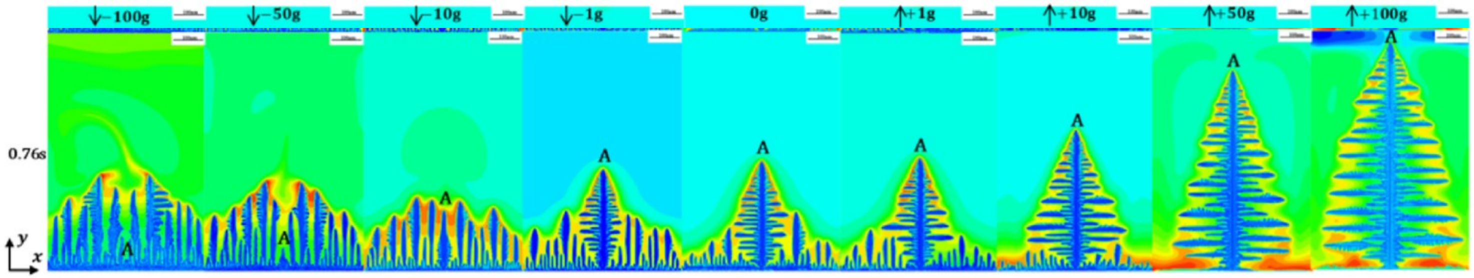
Post-flight data collection to anchor computational models

- Porosity morphology, size, and distribution quantified by micro/nano-CT
  - Potentially augmented by radiography and serial sectioning
- Macrosegregation quantified by chemical mapping via EDS/WDS
- Defect identification and characterization by NDE
- Microstructure characterized by metallography and electron microscopy with grain structure quantified by EBSD
- Structural utility as mechanical properties quantified by hardness mapping and tensile/shear testing
- Macrographs of weld bead surfaces including profilometry to quantify rippling

High-fidelity (and open science) datasets anchor reliable computational models and accelerate ISW infusion

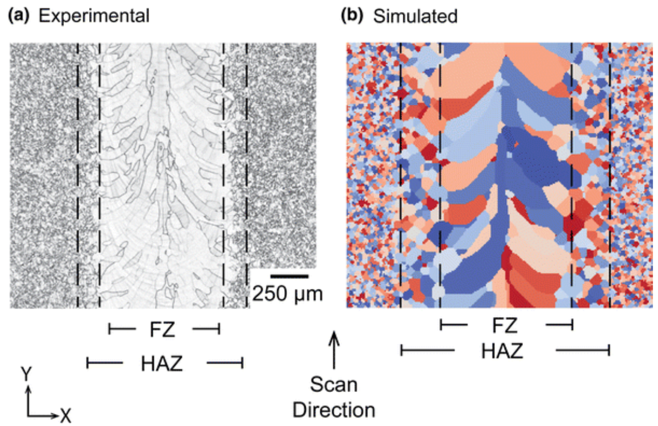
- High-fidelity collected data anchors computational modeling, eventually enabling confidence in one-shot welds in space
- Drastically reduce required testing and inspection to accelerate infusion and mitigate qualification burden
- Dovetails with Early Stage Innovations (ESI) grants on "Computational Materials Engineering for Lunar Metals Welding"

Important linkages for ISW: thermal & thermodynamic/precipitation to solidification, fluid flow, and grain structure; all with appropriate uncertainty quantification



Example of a phase-field lattice-Boltzmann simulation for dendritic growth during alloy solidification in negative gravity, zero gravity, Earth-normal gravity, and hypergravity

(Zhang et al., 2024, doi:10.1016/j.heliyon.2024.e27008); licensed under CC BY-NC 4.0



Example of a Monte Carlo Potts model in SPPARKS code to simulate grain growth in e-beam welding

(Rodgers et al., 2016, doi:10.1007/s11837-016-1863-8); licensed under CC BY 4.0

Concluding thoughts

Summary, opportunities for engagement, and acknowledgements

NASA leads the way to in-space welding

- NASA is rapidly advancing the state-of-the-art of in-space welding (ISW) through numerous efforts, of which this presentation focused on internal efforts in –
  - Laser beam welding (LBW): parabolic to orbital benchmark flight experiments
  - Integrated computational materials engineering (ICME): datasets from benchmark flight experiments
- Demonstration of ISW in space-like environments to:
  - Understand combined effects of reduced gravity, reduced pressure, varied temperatures
  - Provide validation datasets to anchor computational models
  - Mature ISW technology to enable joining structures in space
- Building ISW ecosystem of hardware, expertise, and partnering opportunities:
  - Modular flight unit hardware
  - Parabolic and orbital flight experiment know-how
  - Computational models anchored by collected data
  - Network of academic, government, and industrial collaborators

Opportunities for engagement

- Ask for our lessons learned on flight experiments (parabolic, ISS, etc.)
- Pursue a collaboration leveraging our data & expertise and your specialty
- Consider ways in which in-space welding could benefit your organization – what use cases can you think of that would be ripe for further discussion?
- Share your students!
  - Space technology fellowship (NSTGRO): NSPIRES - NNH26ZTR001N-26NSTGRO_B6*
  - Internships for summer 2026: Experimental support of in-space laser manufacturing and Flat Floor Robotics Laboratory *

*Recently closed but stay tuned for future cycles.

Acknowledgements

- NASA support from Marshall Space Flight Center Center-directed funds, Biological and Physical Sciences Division of NASA Science Mission Directorate, NASA Space Technology Mission Directorate, etc.
  - STMD: DISCMAN (GCD/Enable), ESI, etc.
- OSU support from Marshall Space Flight Center Center-directed funds via

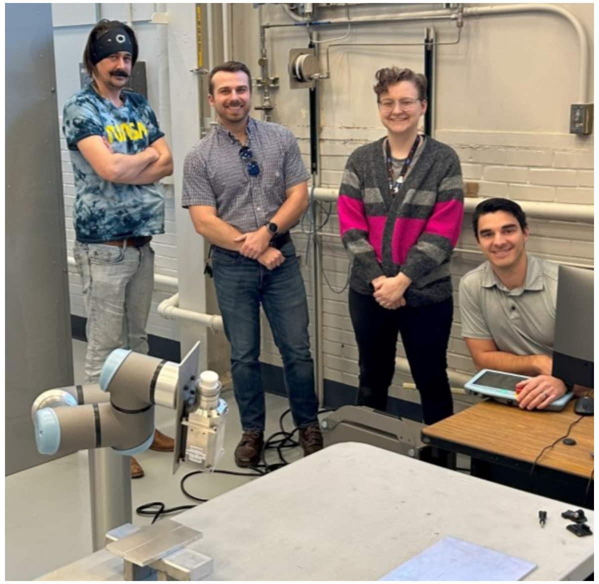
  80NSSC22M0209 - Integration and Demonstration of Self-contained Laser Welding System for Microgravity Experiments –NASA CAN
- Second parabolic flight day Aug' 24 and future MSFC-OSU re-flight support from NASA Flight Opportunities

Any brand names or companies mentioned in this presentation do not constitute an endorsement by NASA.

Thank you

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

Interns from collaborating universities



Multiple NASA Field Centers

Rich network of academic, government, and industrial partners

In-flight photos credit: Tasha Dixon/Zero-G