Welding in Space:

Past, Present, and Future

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Image Credit:
Loree Beth F Sowards

Impact of OSU Welding Engineering at NASA

OSU Welding Engineering Graduate	Major NASA Programs	Contributions to Welding Technologies for Human and Science Space Flight
Carolyn Russell*, MSFC (BS 1984)	Shuttle, Constellation, SLS, Science Missions	VPPA Welding, Welding Standards, Agency Welding SME
Jeff Ding, MSFC (BS 1986)	Shuttle, Constellation, SLS, Science Missions	Friction-Stir Welding, AWS D17 Committee, NASA Standards
Scott Murray*, KSC (BS)	Division Chief, Laboratory and Test Facilities Division	M&P and Welding Ground Systems, Past Chair AWS D17 Committee
Tamra George, JSC (BS 1999)	Hardware Manager for Astronaut EVA	Robotic Operations
Bob Carter*, GRC/MSFC (BS 2000)	Deputy Chief Materials and Structures, Shuttle, ISS, Constellation, SLS, NESC	FSW & Self-Reacting FSW Development, AM Alloy and Standards Dev.
Chad Carl*, KSC (BS 2001)	Constellation, Artemis, Falcon 9, and Launch Services Ground Systems	KSC M&P Chief Engineer, AWS D17K, Materials & Processes Lead Engineer
Jeff Sowards*, MSFC (BS 2003, MS 2006, PhD 2009)	Deputy Chief of Metallic Materials & Processes, SLS, HLS, Science Missions	Fusion and FSW, Computational Materials Engineering
Andrea Ellis, MSFC (BS)	Shuttle, Constellation	Fusion and FSW
Junhua Pan, JSC (MS 2005)	Orion, Gateway, Commercial Crew	Fusion and FSW
Shane Brooke, GRC/MSFC (BS 2007)	Deputy Branch Chief, Constellation, Orion, SLS, Gateway	Friction Pull-Plug Welding, Linear Friction Welding, FSW
Todd Renz, MSFC/Boeing (BS 2008)	Constellation, ECLSS, SLS, ABEDRR (Boosters)	Fusion and FSW, Standards Development, Risk Reduction
Lucie Johannes*, JSC (MS 2013)	Deputy Chief of Structural Engineering Division, Orion, Gateway, ISS	FSW
Kiersten Dutenhaver, MSFC (BS 2014, MS 2021)	SLS	Fusion Welding
Zach Courtright, MSFC (BS 2015, MS 2017)	SLS, Science Missions	Fusion Welding, Solid-State Additive Manufacturing, In-space manufacturing
Stacy Bagg, KSC, MSFC, JPL (MS 2016)	SLS EUS, RS-25 Engine AM and Welding, Artemis Stacking & Operations	Fusion Welding and Additive Manufacturing Modeling, FSW
Will Evans, MSFC (BS 2017, MS 2019)	SLS, HLS, Habitats	Fusion and FSW, DED Additive Manufacturing
Eric Brizes, GRC (BS 2018, MS 2020, PhD 2022)	Aerospace Materials Research	EBW and Additive Manufacturing of Refractory Alloys

OSU WE Interns: Beau Hammond (2006), John Brunnett (2007), Jason Hurst (2008), Rick Brawley (2008), Brian Hanhold (2009), Adam O'Brian (2009), David Stone (2014), Taylor Scott Wyan (2014), Rama Diop (2022), Eugene Choi (2023), plus many others!

- At least 27 OSU Welding Engineers have worked or interned across the agency at five centers since the early 1980s.
- *Six OSU Welding Engineers have held positions as Division-level Managers or Chief Engineers.
- Prof. Richardson, a WE Faculty Emeritus was a NASA NRC Postdoc and former employee.
- OSUWE has performed over $1M in NASA-Sponsored research over the past 5 years on Self-Reacting Friction-Stir Weld Modeling, Welding Metallurgy, In-Space Welding, and AM.

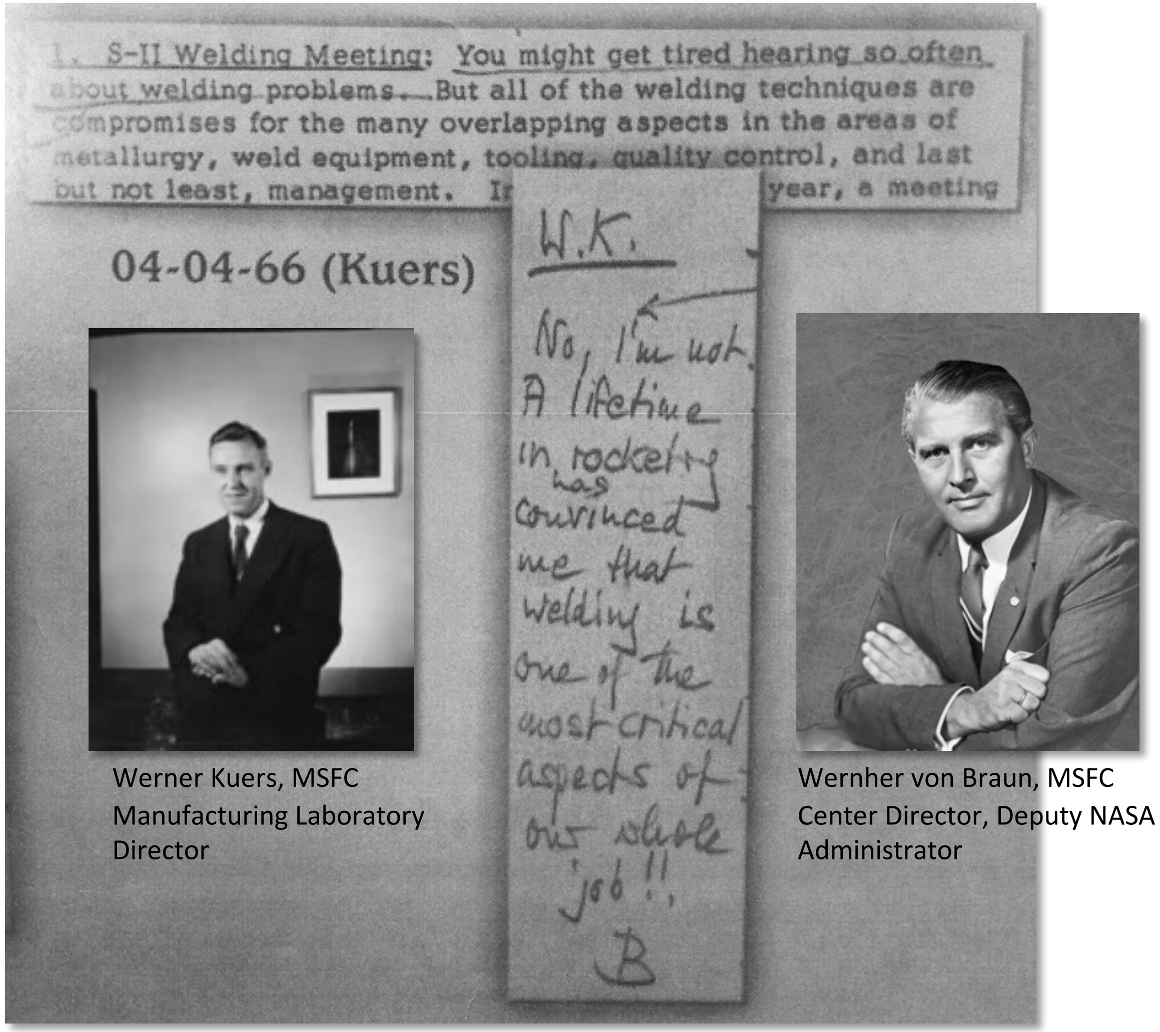
Welding in Space at Ohio State

- March 2002. OSU WEs participated in microgravity research flight.
  - Jarrod Bichon (BS 2002), Stacey Maag (BS 2002), Bill Dawson, and Mike Lantz (BS 2002) were flyers. Ground crew members include Kerry Boone, Peter Kinney (MS 2003), and Brian Thomas
- ca. 2002-2005. Prof. Dave Dickinson ran a special topics course WE694.Z 'Welding in Space".
- ca. 2003-2004. Matt Gonser (BS 2004, MS 2006) led a team that developed a parabolic flight experiment that investigated camphene "welds" via soldering iron heat source.
- 2010. Microgravity combustion experiments.
  - Team advised by Prof. Suresh Babu and led by David Bajek (BS 2010).
- 2024. OSU WE Program and MSFC and LaRC engineers are teaming up to fly a laser welding experiment aboard a parabolic flight.

https://news.osu.edu/story-ideas-for-media---040102/
https://engineering.osu.edu/news/2009/12/nasa-selects-microgravity-team-2010-experiment-program
https://mse.osu.edu/news/2023/05/demand-manufacturing-space-provides-out-world-opportunities-buckeye-engineers-and#:~:text=NASA

Welding Enables Space Exploration

ISAM IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING


1. S-II Welding Meeting: You might get tired hearing so often about welding problems. But all of the welding techniques are compromises for the many overlapping aspects in the areas of metallurgy, weld equipment, tooling, quality control, and last but not least, management. In ... year, a meeting

04-04-66 (Kuers)

W.K.

No, I'm not. A lifetime in rocketry has convinced me that welding is one of the most critical aspects of our whole job!!

B

Werner Kuers, MSFC Manufacturing Laboratory Director

Wernher von Braun, MSFC Center Director, Deputy NASA Administrator

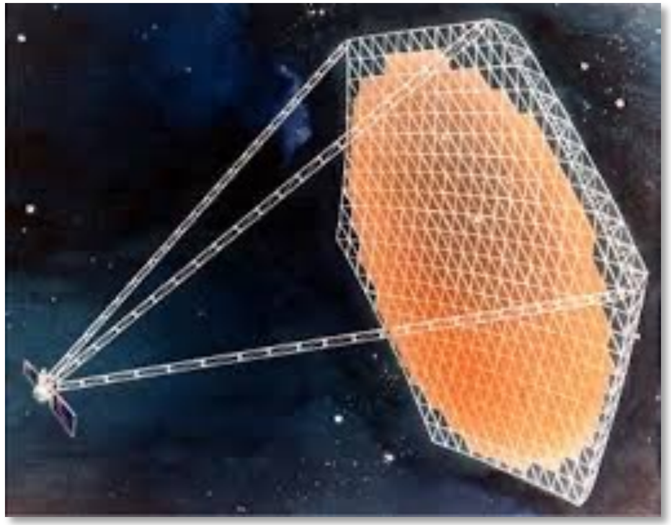
1966 correspondence between Wernher von Braun and Werner Kuers

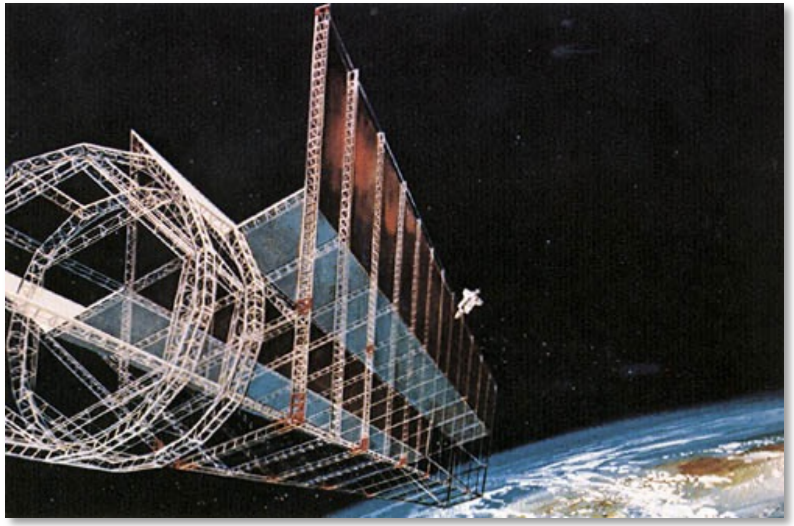
"The complexity of welding is readily apparent when one considers that fusion welding involves temperature gradients of thousands of degrees, over distances of less than a centimeter, occurring on a time scale of seconds, involving multiple phases of solids, liquids, gases, and plasma."

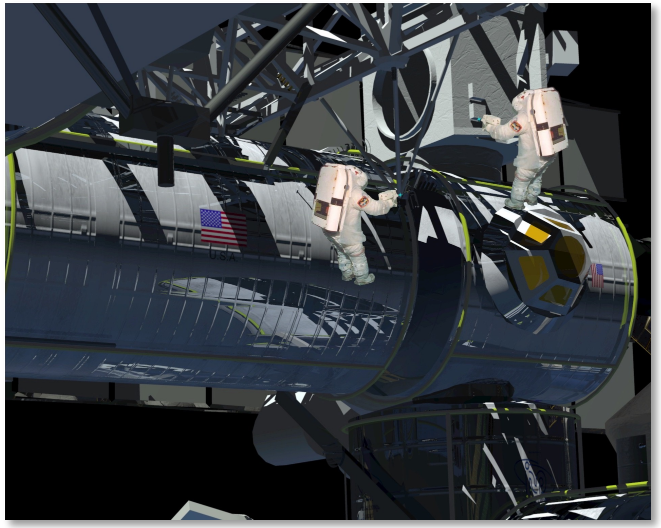
-Thomas Eagar, MIT, 1990

Source: T.W. Eagar, *Advanced Joining Technologies*, T.H. North, ed., Chapman and Hall, London, 1990.

Benefits of In-Space Welding



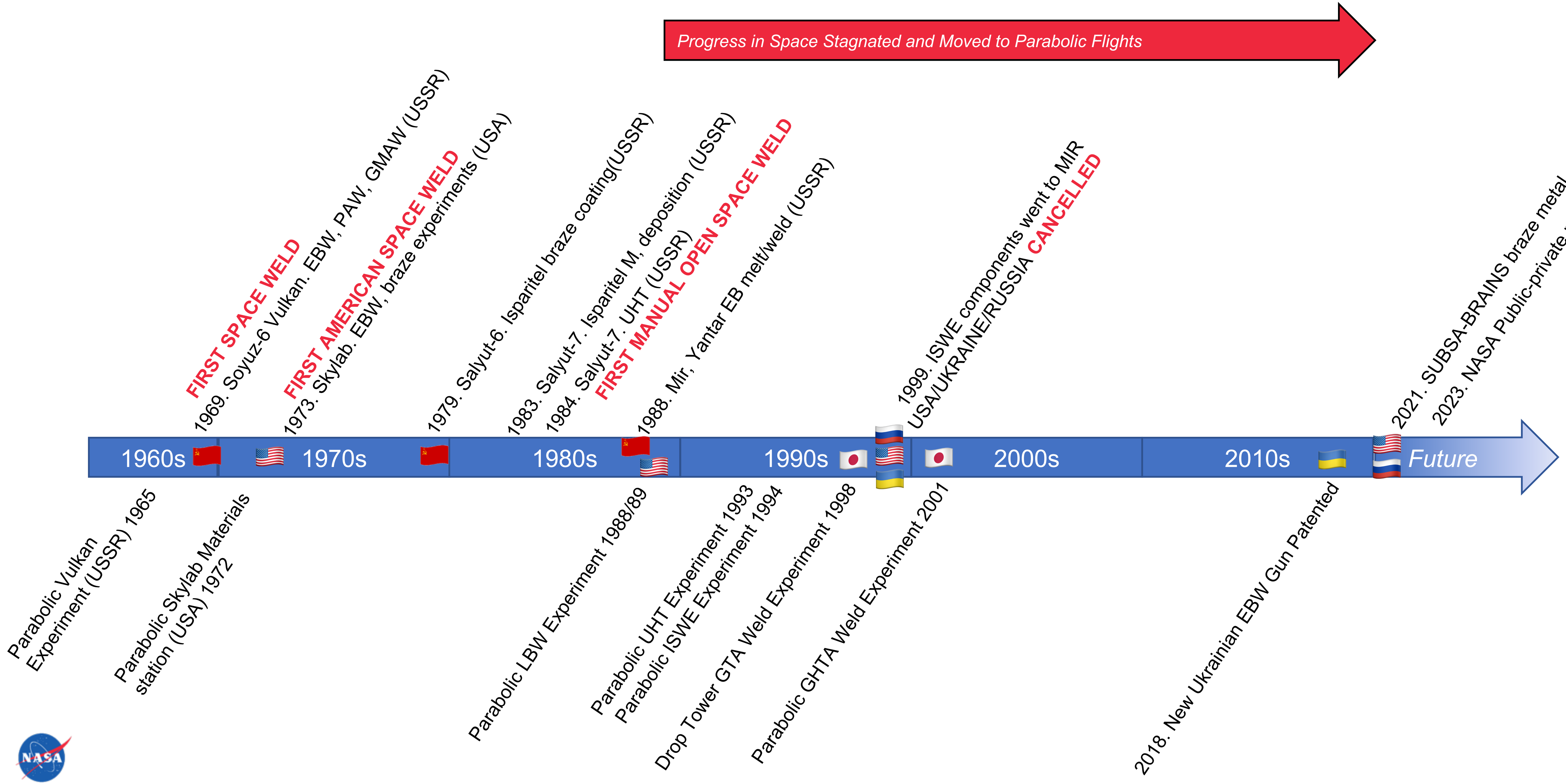




Time/Complexity	A single spot weld is much faster than a bolting operation for each connection in a complex structure.
High Rigidity	Welds are more rigid than fasteners and adhesives.
High Strength	Weld strength often approaches that of the parent material.
Less Mass	Autogenous welds add no mass.
Greater Reliability	Fasteners and adhesives are more susceptible to thermal fatigue and can loosen over time.
Hermeticity	Welds ensure complete encapsulation as opposed to mechanical seals and gaskets and damage-susceptible adhesives.
Repair	Patches can be welded over punctures and damaged or bent parts can be cut out or heated for straightening.
Large/Complex Structures	Launch vehicle size and volume constraints are overcome by welding structures in space.

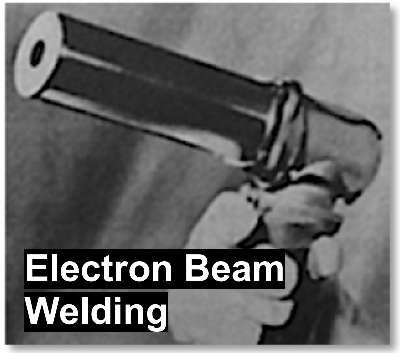
List Adapted in part from: Siewert, Tamir, Masubuchi, Eagar, Flanigan, Su. Thirtieth Space Congress (1993)

Timeline of Space Welding and Joining



Soyuz 6. Vulkan Experiment (1969)

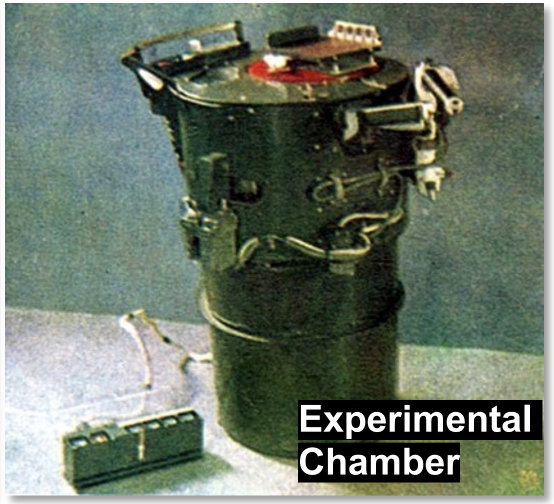
Georgy Shonin and Valeri Kubasov



Electron Beam Welding

Gas Metal Arc Welding

Tu Aircraft Parabolic Flight



Experimental Chamber

Plasma Arc Welding

Outcome: First demonstration of on-orbit space welds made Oct. 16, 1969 on Soyuz 6.

- The objective was to test several methods of welding stainless steel, aluminum, and titanium using remote handling equipment in the high vacuum and weightless conditions of space.
- Cosmonauts controlled weld experiments in the depressurized orbital compartment using instruments installed in the descent compartment.
- Three processes were tested were: plasma arc welding, electron beam welding, and gas metal arc welding.
- Experiments defined a path for to take future welding experiments from ground to parabolic to space.

Alloys Welded (Approximate U.S. Equivalent):
1X18H9T (SS 321), AM-6 (Al-Cu), BT-1 (C.P. Ti A-55)

Mladenov, GM et al. E+E, vol. 54, (5-6), 2019.
https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1969-085A
http://www.alfa-industry.ru/news/104/2835/

Skylab Materials Processing Facility Experiments (1973)

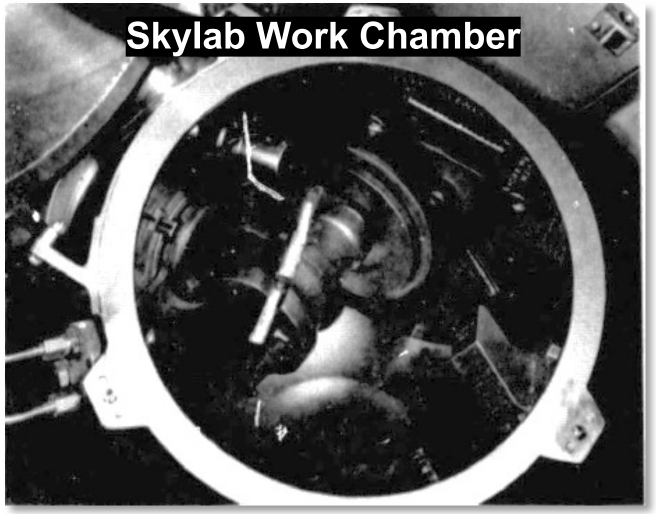
Skylab M512 Materials Processing Experiment

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

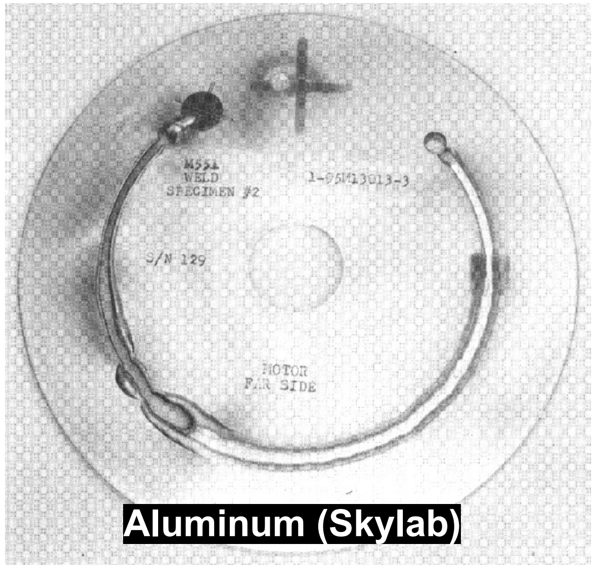
- Electron Beam Welding was proposed at a S-IVB Workshop in 1964 and Westinghouse developed a portable system.
- The M493 EBW experiment was formally approved in 1966 and eventually redesignated as the M551 Metals Melting Experiment.
- Skylab materials experiments were tested in 1972 aboard an Air Force 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.

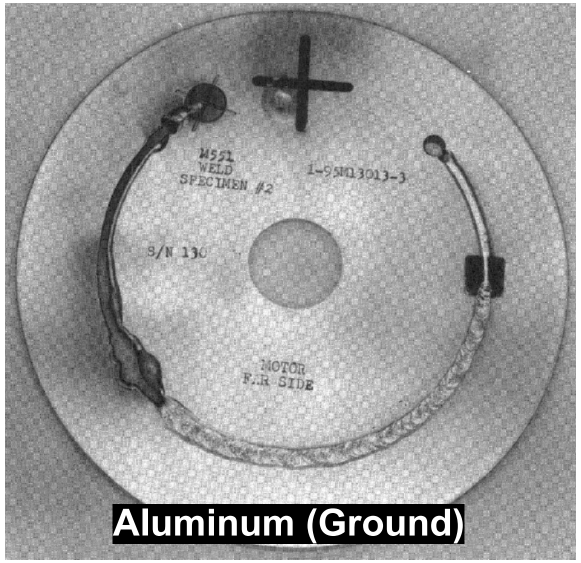
https://history.nasa.gov/SP-401/ch1.htm
Hooper, WA. Final Report Contract NAS8-37756, 1989.
Siewert, TA et al. Welding Journal, October, 291s-300s, 1977.

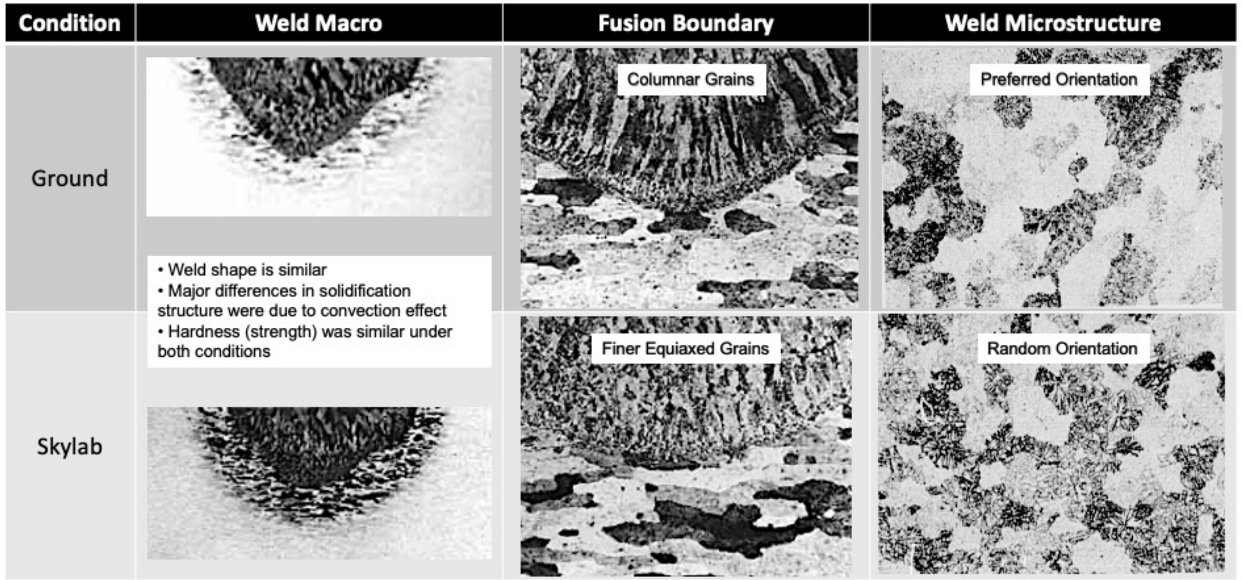
Skylab M551 Metals Melting Experiment (1973)



- 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.

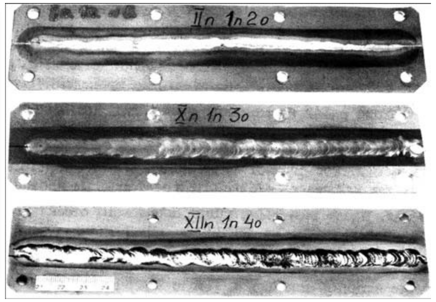






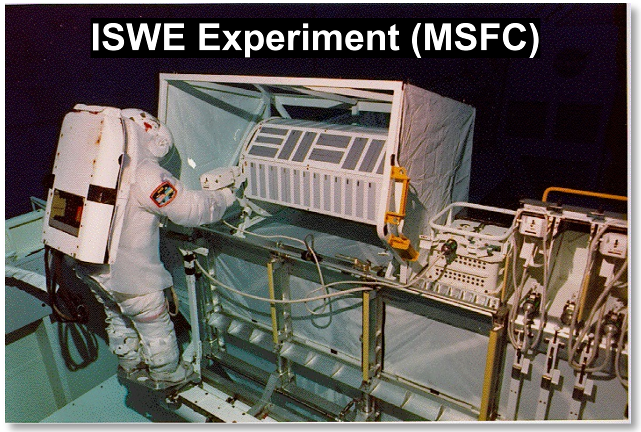
Poorman, RM. NASA TM X-64960 Skylab M551 Metals Melting Experiment, 1975.

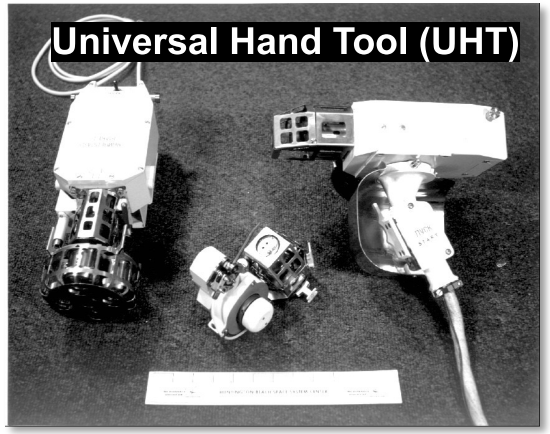
1980s and 90s Salyut-7 to ISWE



Salyut-7 Outcome: Demonstration of astronaut manual manipulation of electron beam welding in open space.

- On July 25, 1984 cosmonauts Vladimir Dzhanibekov and Svetlana Savitskaya entered open space and welded, brazed, coated, and cut metal for three hours with the Universal Hand Tool, a hand-held electron beam gun.
- Experiments produced high-quality stainless steel and titanium welds.
- Experiments demonstrated reliable equipment and that welding in open space could be done.
- The Universal Hand Tool was the basis of the future International Space Welding Experiment (ISWE) – Cancelled in late 90s – **Outcome: Indicated safety challenges with astronaut manual welding.**

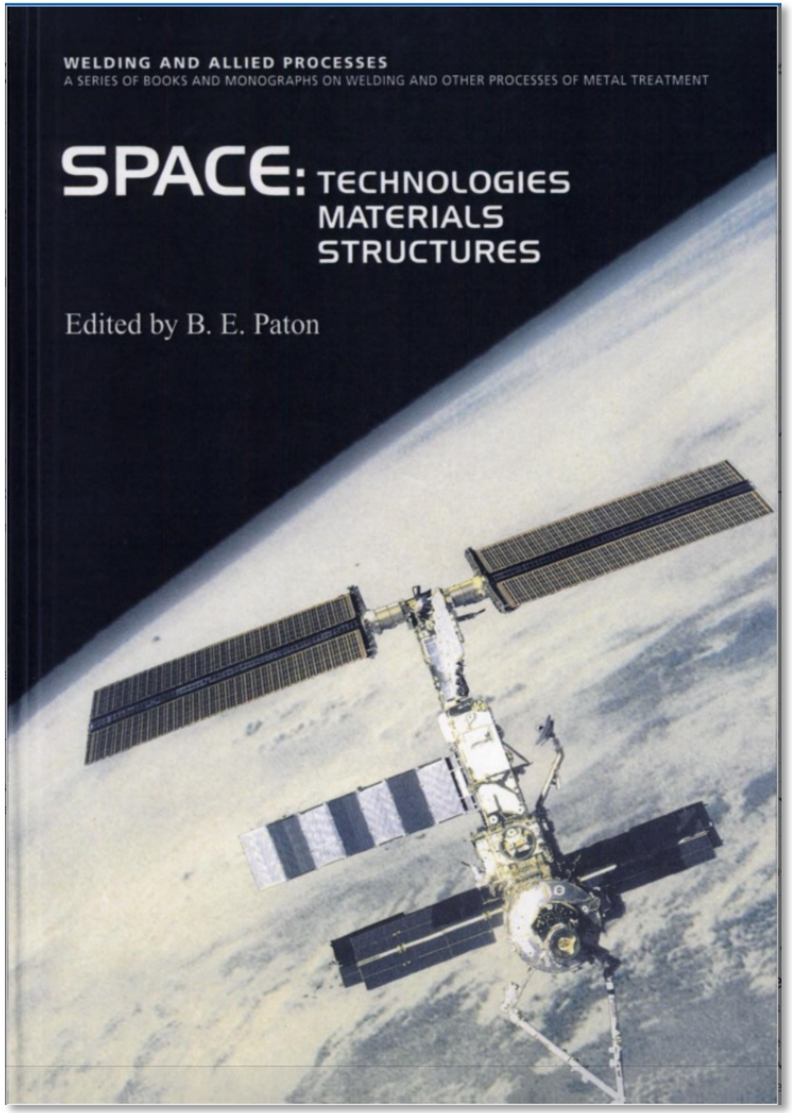

ISWE Experiment (MSFC)


Universal Hand Tool (UHT)

Paton, B.E. 25 Years of Welding in Open Space. PWJ 7 (2009) 2-6.

Space Welding: Ukrainian Impact

(L to R). Svetlana Savitskaya, Boris Paton, Vladimir Dzhanibekov



Paton, B.E. 25 Years of Welding in Open Space. PWJ 7 (2009) 2-6.

Significant Findings of Past Work and Future Opportunities

ISAM IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

Successes with Space Welding

- Space welding is a demonstrated technology
- Several processes have been demonstrated: Electron Beam, Gas Tungsten Arc, Plasma Arc, and Gas Metal Arc Welding
- Electron Beam Welding has produced high-quality welds in space
- Other weld processes have been demonstrated under vacuum and microgravity: Laser Beam Welding, Hollow Electrode Gas Tungsten Arc Welding
- The common alloys used in space vehicles are weldable in space: Aluminum, Titanium, Stainless Steel, Refractory Metal
- Weld pool shape and penetration were “in family” with terrestrial welds but must be modified to address porosity, cracking, different heat flow conditions
- Strength of space welds are comparable to terrestrial welds made with similar weld parameters

Opportunities for Space Welding

- Reduce intensive workload on astronauts and potential safety challenges with primary and reflected energy beams, secondary energy, spatter, fumes, plating
- Parabolic flights are time-limiting, longer-duration in-space experiments are needed
- Improve the physical and metallurgical insight of space welds:
  - Weld porosity may be greater in space welds apparently due to lack of convection
  - Cracks were observed in some Skylab welds processed in space while not in ground-based welds
  - The weld heat-affected zone appears wider in some space welds indicating slower weld cooling
  - Crystallization grain structure of welds was different apparently due to microgravity, influence on properties
- Establishing mechanical property design ”Allowables” of space welds, which do not require robustness of terrestrial welds designed for launch from earth
  - Mechanical behavior studies are limited. Soviet experiments noted strength increases of up to 30 to 40% (explanation was finer grains) however Skylab welds had similar strengths to ground-based welds

Present: 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	

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

Current Work: Integrate existing capabilities within MSFC and NASA 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.

Table adapted and expanded from original source: K. Masubuchi, J.Weld.Soc, 59(6) p.421-427 (1990).

Present: Simulating Space Conditions for Welding

Microgravity / Reduced Gravity

- **Parabolic Flights**
  - 20 to 25 s
  - 0.01 g to 2.0 g
  - MM
  - $$

- **Sounding Rockets**
  - 300 s to 1,200 s
  - 0.00001 g
  - MMM
  - $$$

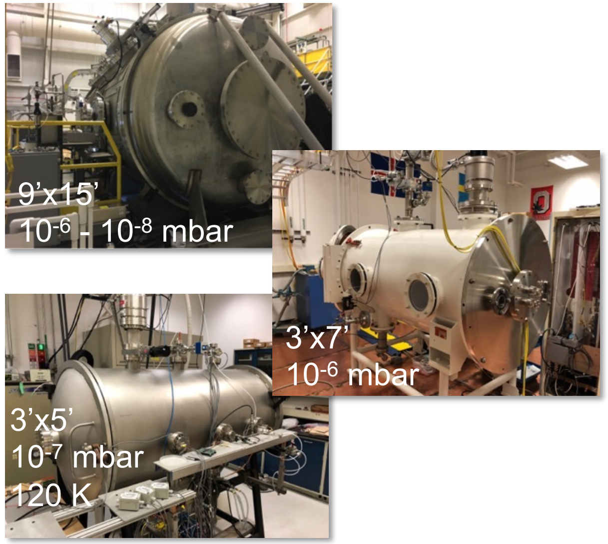
- **Drop Towers**
  - 2.2 to 5.5 s
  - 0.000001 g
  - MM
  - $

Low Earth Orbit μg

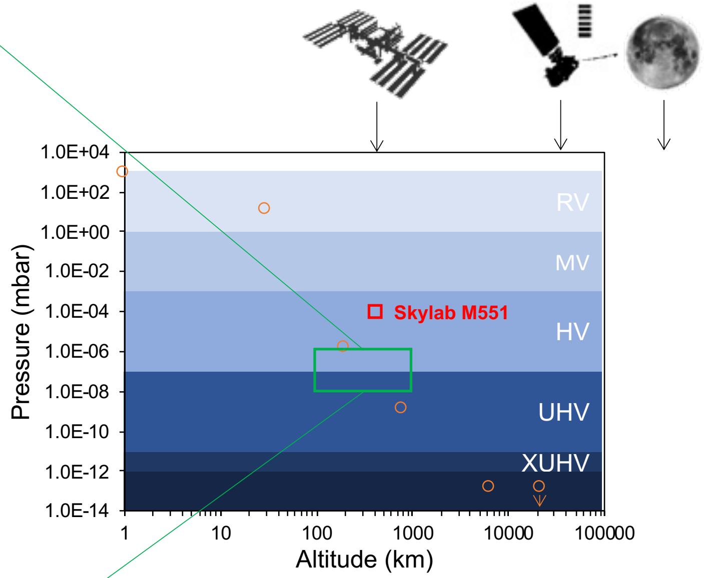
Lunar Surface 0.17 g

Martian Surface 0.38 g

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, GM et al. E+E, vol. 54, (5-6), 2019.

Present: Trade Analysis of Welding Processes

Table-3
Candidate Processes for In-Space Applications

CRITERIA \ PROCESS	EBW	GTAW	PAW	LBW
OPERATOR/MISSION SAFETY	◒	○	●	●
MICRO-G WELD QUALITY	○	○	○	○
IVA & EVA FLEXIBILITY	●	○	○	○
WORKPIECE VARIETY	◒	◒	○	○
OPERATION MODE FLEXIBILITY	○	○	○	●
TOLERANCE FLEXIBILITY	◒	○	○	●
POWER REQUIREMENTS	○	○	○	●
ENERGY EFFICIENCY	○	○	◒	●
CONSUMABLES REQUIREMENTS	○	◒	●	●
EQUIPMENT SERVICEABILITY	◒	○	◒	●

LEGEND: ○ GOOD ◒ SATISFACTORY ● POOR

Siewert, et al. Thirtieth Space Congress (1993)

Comparison of EBW and LBW for Space Welding

Criteria	Electron Beam Welding	Laser Beam Welding
Vacuum Environment	Vacuum is a requirement to function	Works in pressurized habitat or in a vacuum
Energy Delivery	Bulky head with line of sight through electromagnetic coils to the joint	Flexible delivery through a fiber
Wall plug efficiency	Up to 85%	Up to 50%
Wear Components	Metal plating on filament	Metal plating on optical components
Human Safety	Bremsstrahlung X-Rays	Specular reflection
Electromagnetic Interference	Produced at the welding head where the beam emanates	Produced at diodes which can be isolated from the beam

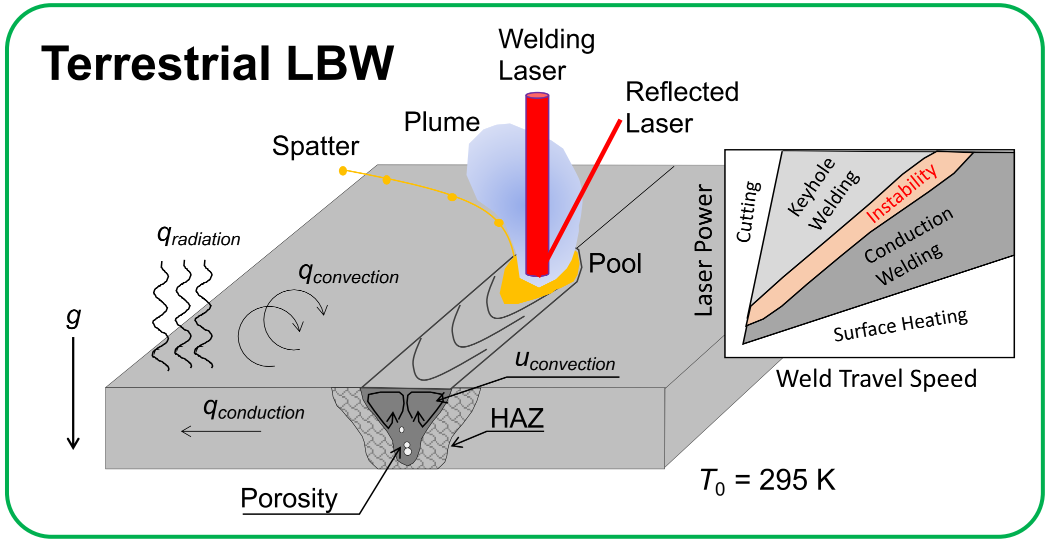
Lasers have advanced greatly in compactness, operating mode, power, efficiency, and serviceability since the 1993 trade study with the emmergence of fiber lasers.

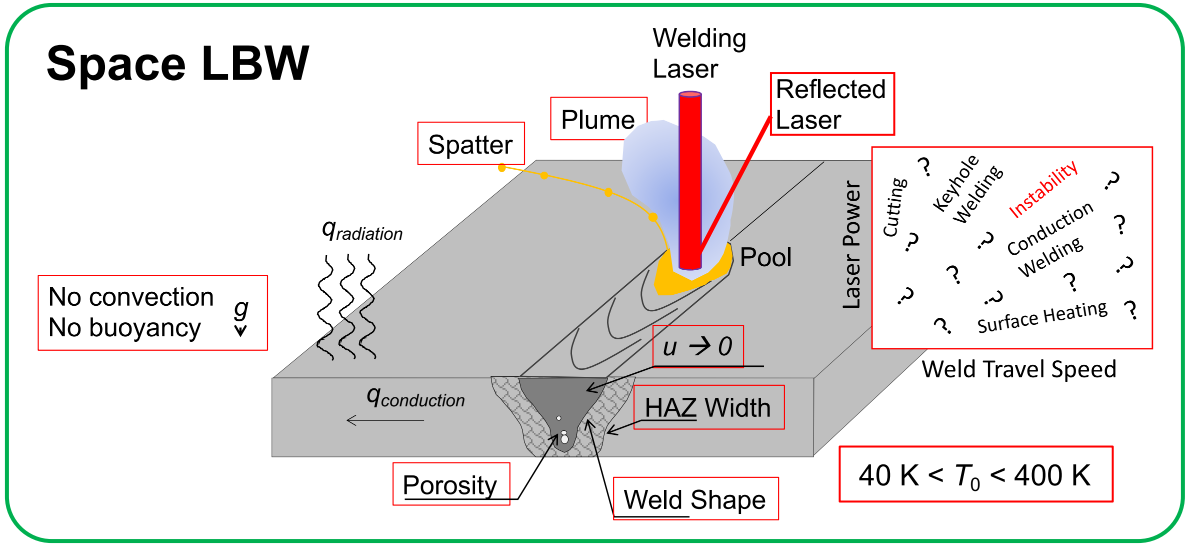
Present: Computational Models for Space Welding

ISAM IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

- **Problem:** Welding in space is subject to 1) large temperature variation, 2) reduced gravity, and 3) vacuum/reduced atmosphere compared to terrestrial welds. Weld development is Edisonian and there are no welding process parameter windows for critical one-shot welds in space that account for these physical changes.
- **Opportunity:** Use computational materials modeling as an enabling tool to inform experimental design for rapid weld parameterization by interrogating process physics in a virtual environment. Inform and validate models with parallel experimental approaches.
- **Metrology Needs:** Test platforms that provide the correct physics of space, characterization of the welds, thermophysical properties particularly above the liquidus temperature, heat-source coupling/reflection, spatter formation (MMOD), structure-property-process data, etc.
- **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.
- Physics of Terrestrial vs Space LBW are compared to the right.

Modeling/Measurement opportunities indicated in red.



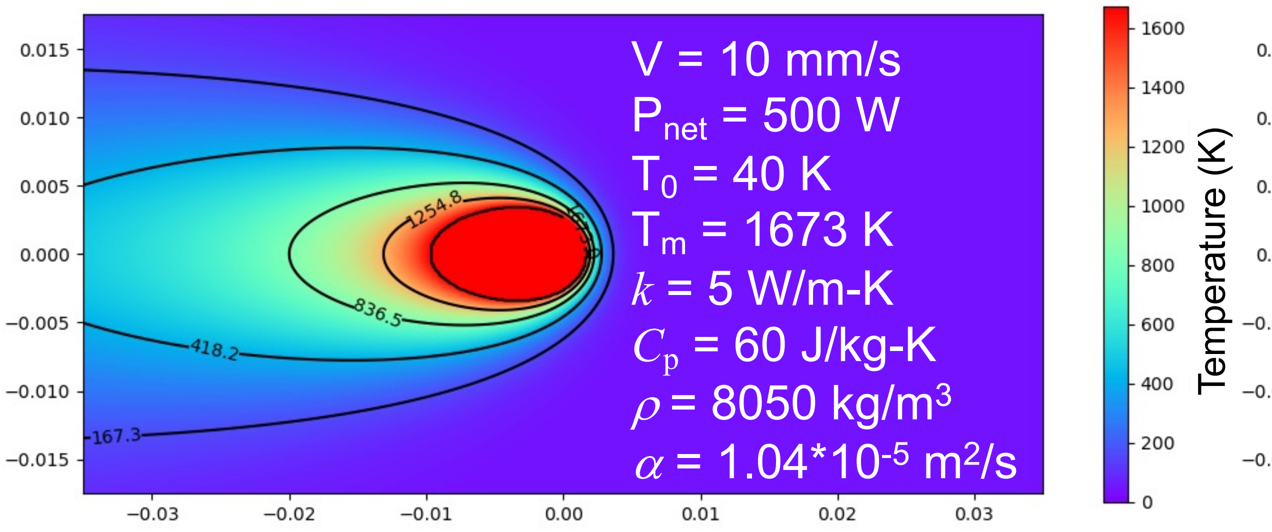


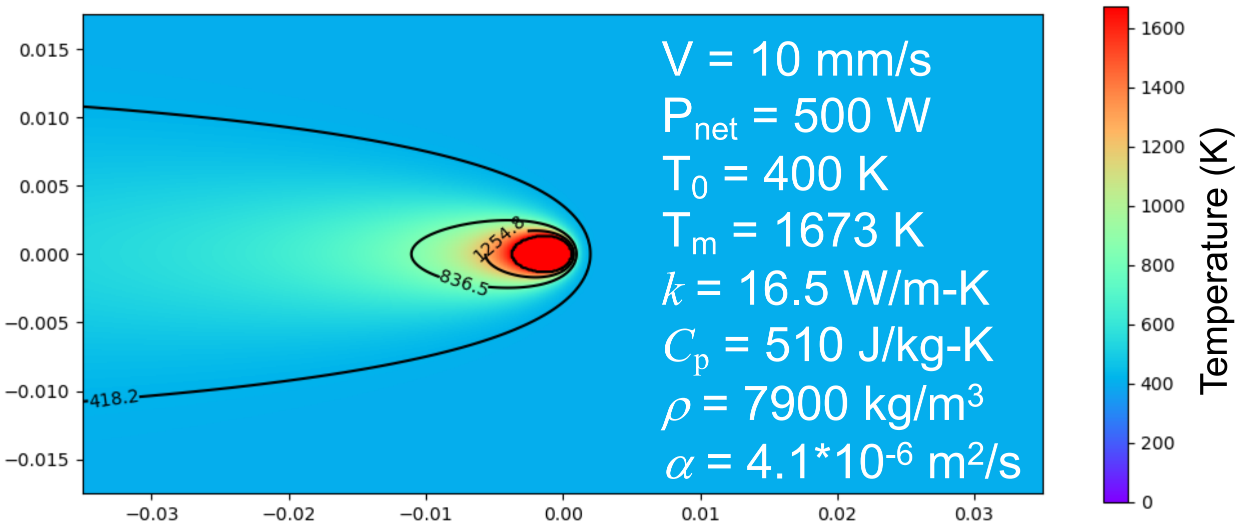
Weld Heat Flow Analytical Solution: 304SS at 40K vs 400K

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

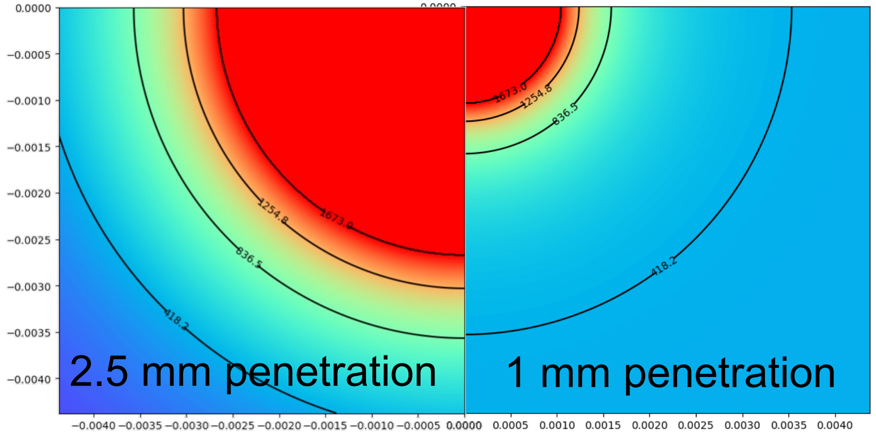
Rosenthal Model on Semi-infinite Plate (SI units J m kg s K):

- Point heat source ⟶ small laser spot size
- Isotropic body ⟶ constant thermophysical properties, no phase change (buoyant force ⟶0 the weld pool mixing is reduced)
- No heat exchange with environment ⟶ Space vacuum environment eliminates convection, laser weld conduction vs radiation





500W weld on 304SS at 40 K



500W weld on 304SS at 400 K

https://trc.nist.gov/cryogenics/materials/304Stainless/304Stainless_rev.htm

Present: 3 Degree-of-Freedom Welding

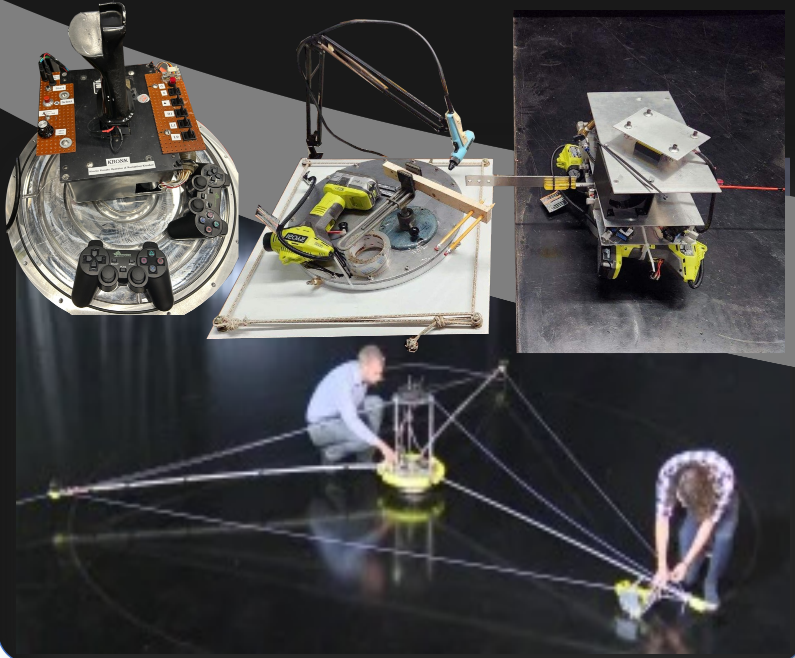
Handheld Laser

- 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 3 Degree of Freedom welding system.

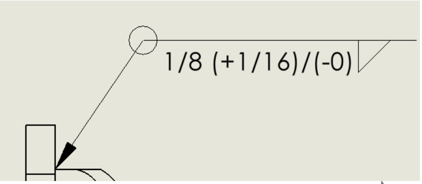
Flat Floor Integration

- 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.



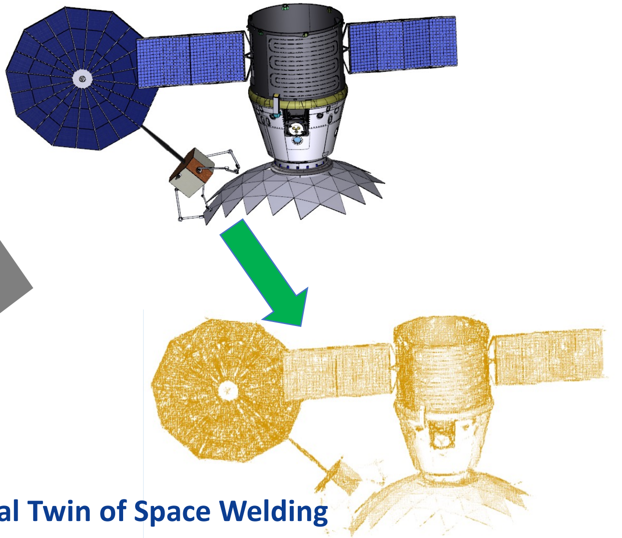
Digital Twin Modeling

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.



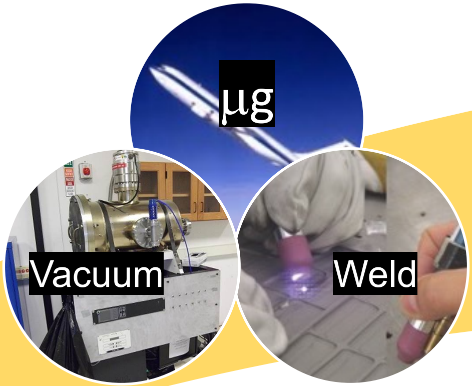
Digital Twin of Space Welding

2024 Parabolic Flight of Laser Beam Welding

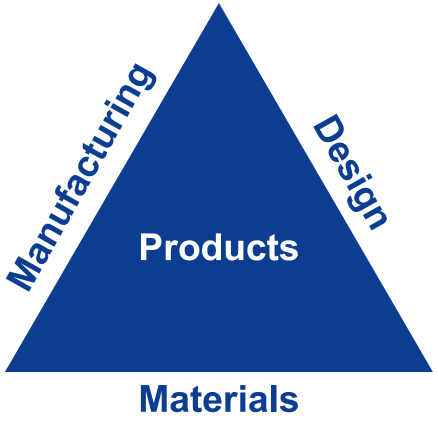
Integration and Ground Demonstration of Self-contained Laser Welding System for Parabolic Microgravity Experiments.

- OSU. Profs. Ramirez, Panton, Horack, Nassiri, Williams, Nate Ames, Bob Rhoads. Multidisciplinary capstone team.
- NASA. Jeff Sowards, Karen Taminger, Eugene Choi (WE intern), Will Evans, Zach Courtright.

Generate Model Calibration Data

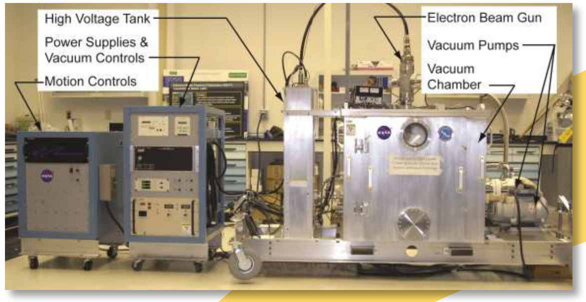


OSU-NASA Partnership



Integrated Computational Materials Engineering (ICME)

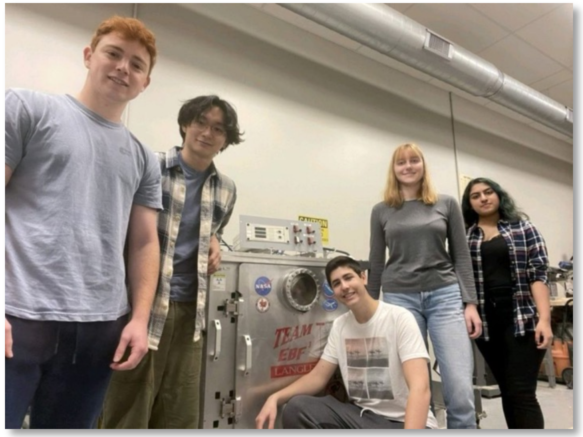
Vacuum Chamber



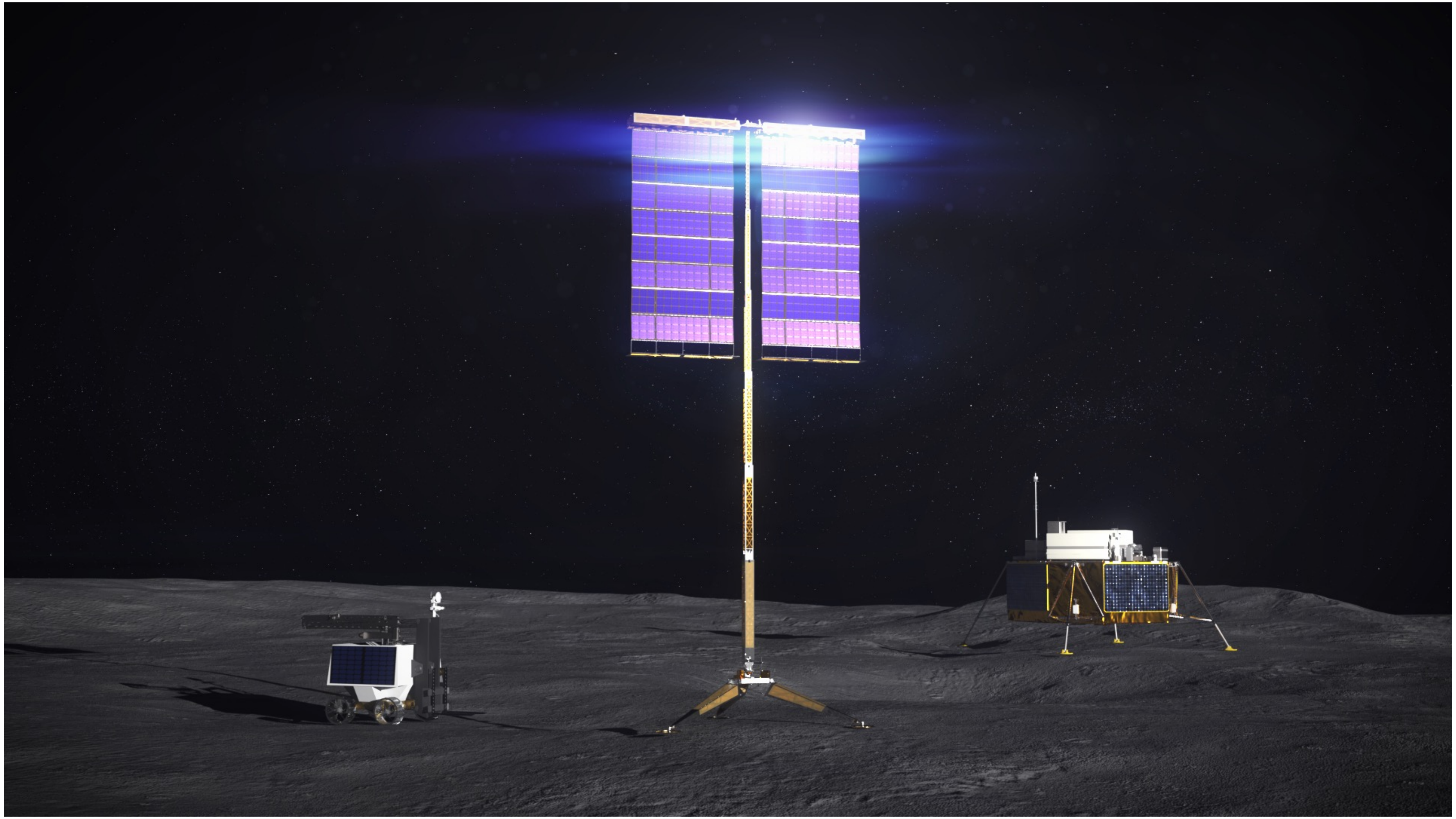
Laser Beam Welding

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

Undergraduate research team: Evan Sichel (ME), Eugene Choi (WE), Carlos Gelada (WE), Martina Moncolova (EE), Diya Adengada (EE).

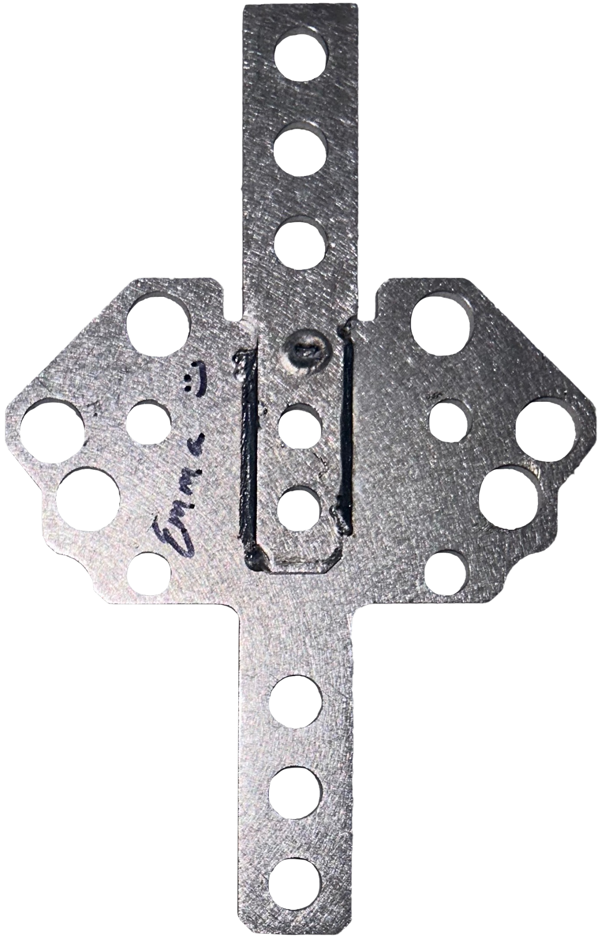


Future: NASA Application of Lunar Surface Welding

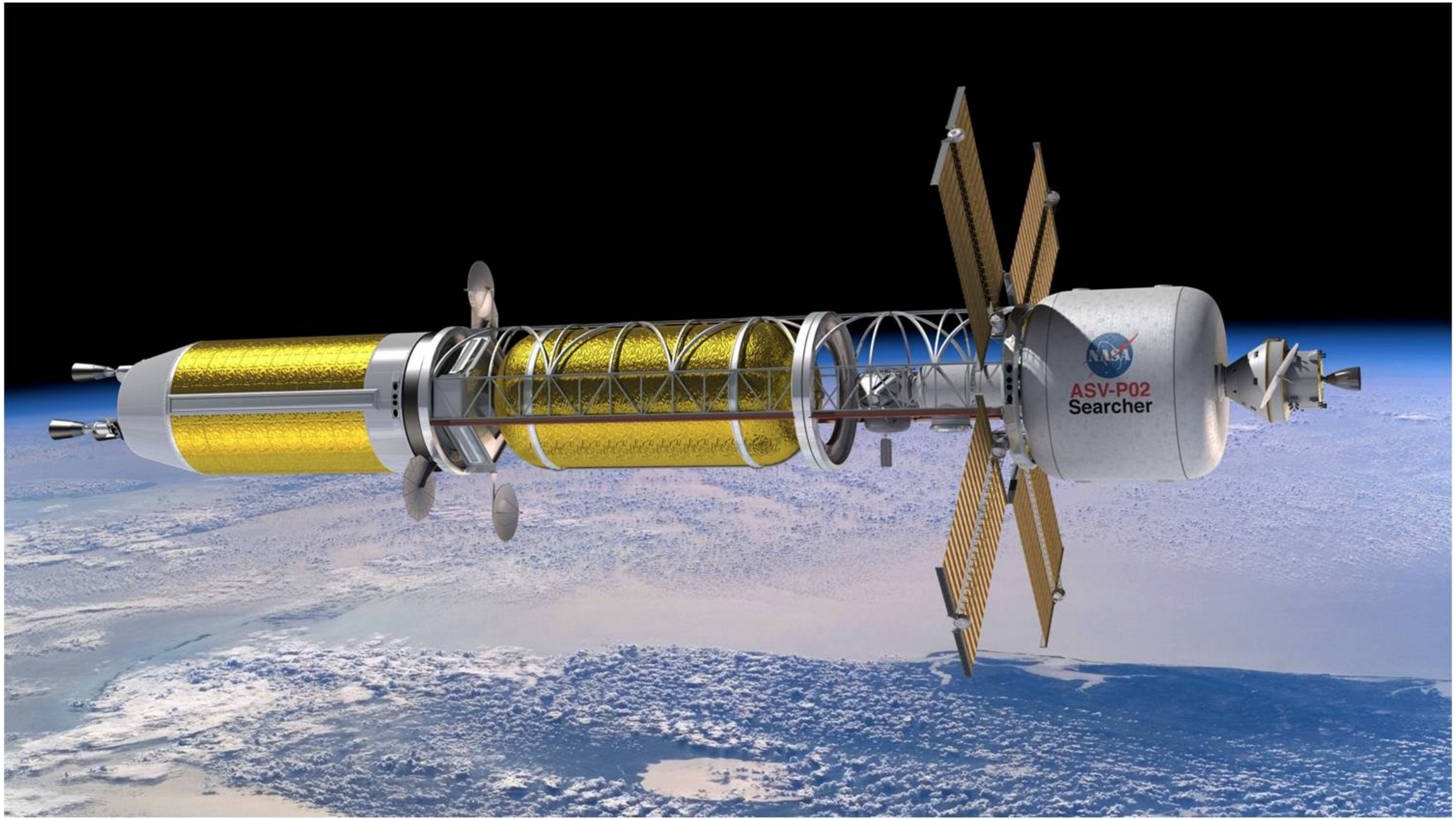


A conceptual vertical solar array being used as a power source on the lunar surface. Welding is being considered for joining truss connections of lunar solar arrays and communication towers. Credits: NASA

Tower truss connection made with handheld laser beam spot weld and lap welds. AA 6061 with 5183 filler metal.



Future: NASA Applications of In-Space Welding

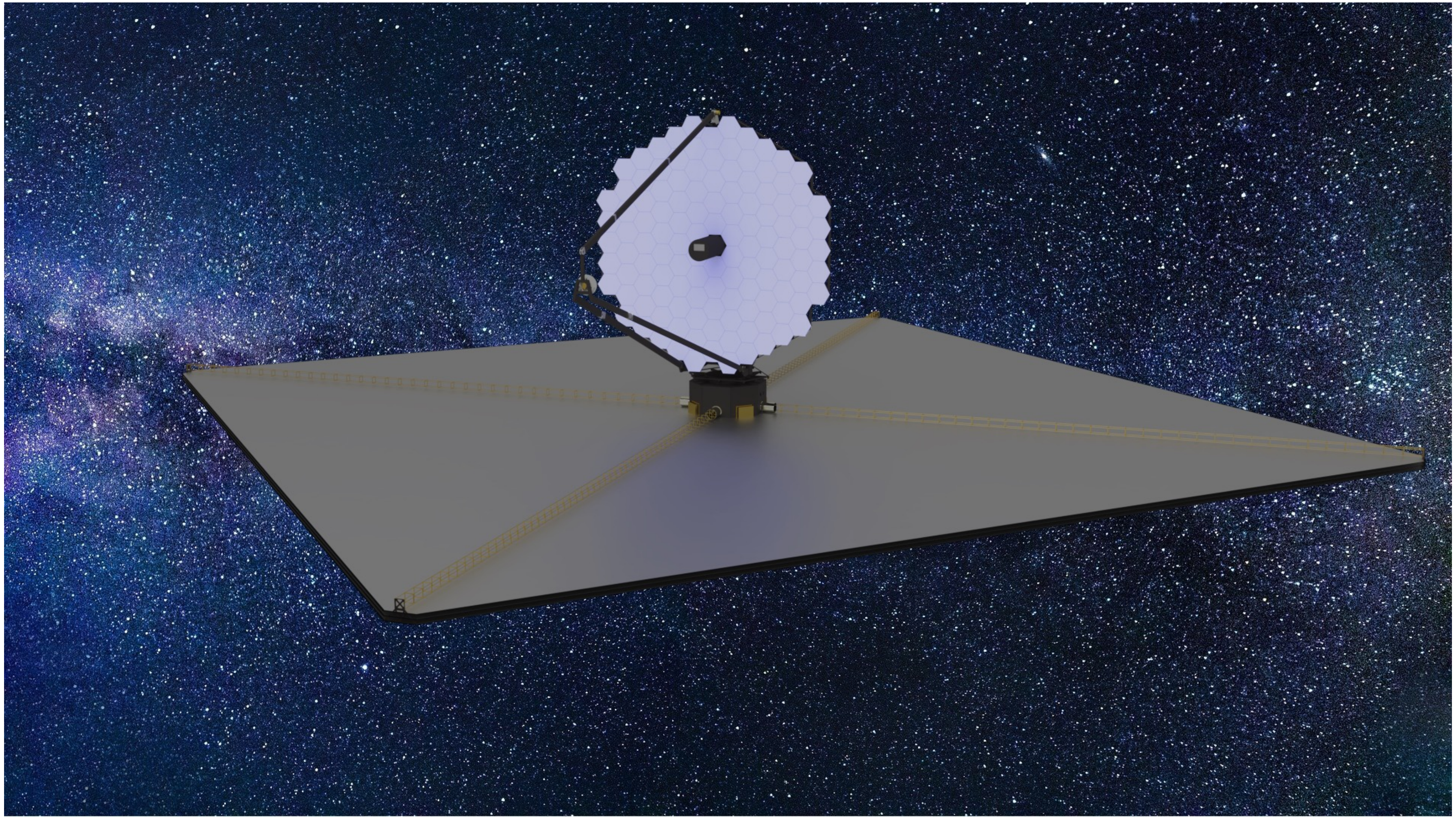


A concept spacecraft, powered by a nuclear rocket engine, must place distance between inhabitants and the nuclear reactor to ensure astronaut safety from radiation. Welding is a candidate assembly process for building such a structure.

Credits: NASA

Future: NASA Applications of In-Space Welding

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING



The future Great Observatory could benefit from welding in space. Shown above is the proposed Large UV/Optical/IR Surveyor (LUVOIR) telescope with its 15 m mirror and large sunshield system with truss structure.

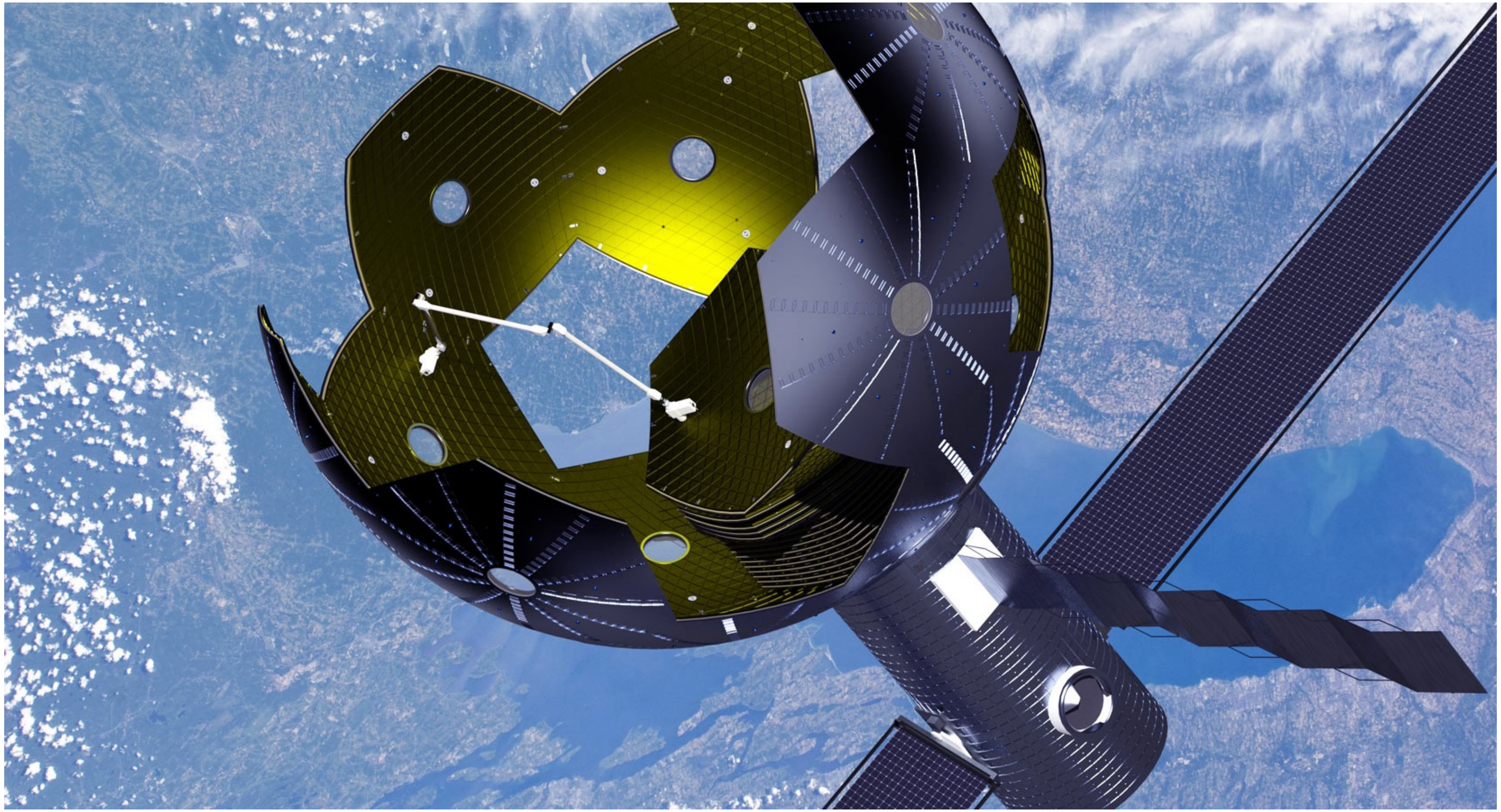
Credits: NASA

Future: Industry Application of In-Space Welding

In-space joining demonstration will verify integrity for future space applications such as lunar surface infrastructure, orbital persistent platforms, and several space-system elements including antennas, solar arrays, sunshades, optical systems and radiators that will be essential to building out the lunar economy.

Credits: Lockheed Martin/Robert Biggs

Future: Industry Application of In-Space Welding



A proposed 20 m diameter habitat to be manufactured in space with electron beam welding. The robot arm installs and welds the panels.

Credits: ThinkOrbital/Vojtech Holub

Path Forward

- It has been 50 years since America made an in-space weld. The AWS community can proactively embrace the challenges and opportunities presented by the new in-space economy. By investing in space welding and allied joining technologies, the welding community can position itself at the forefront of this new frontier.
- Trade studies are crucial in identifying the suitability of current welding processes and developing new ones tailored for space environments.
- Compact and power-efficient welding and joining processes are essential, especially those capable of working with a variety of metals and alloys. Aluminum alloys, stainless steels, and titanium alloys, widely used in spacecraft, will demand versatile welding capabilities.
- Experiments and demonstrations in realistic space environments will further mature welding technology readiness for space applications and provide the data needed to create reliable space-based production weld processes in the future.
- Establishing a permanent orbital capability and analytical tools to develop and apply welding and joining processes in the space environment is vital.