SOLAR ON-ORBIT WELDER FOR ASSEMBLY, REPAIR, AND MANUFACTURING. A. T. Brewer[1], A. Carter[2], and T. Southard[3]; Outward Technologies, 155 Commerce St. Broomfield, CO 80020; [1]abrewer@outward.tech, [2]acarter@outward.tech, [3]tsouthard@outward.tech.

Introduction and Project Overview: Blueshift, LLC d/b/a Outward Technologies is developing a Solar On-Orbit Welder for Repair, Assembly, and Manufacturing (SO-WARM) through an ongoing NASA SBIR Phase II project. SO-WARM represents a revolutionary technology for In-Space Servicing, Assembly, and Manufacturing (ISAM) by offering a lightweight, power-efficient, and versatile welding solution for on-orbit operations. Unlike conventional welding methods that rely on electrical power sources, SO-WARM harnesses Concentrated Solar Energy (CSE) as its primary heat source. This innovative approach drastically reduces electrical power requirements and launch mass, making it exceptionally well-suited for space applications. This NASA SBIR Phase II project (Contract 80NSSC23CA075) has progressed SO-WARM from TRL 4 to TRL 5, demonstrating continuous operation in a relevant vacuum and reduced gravity environment.

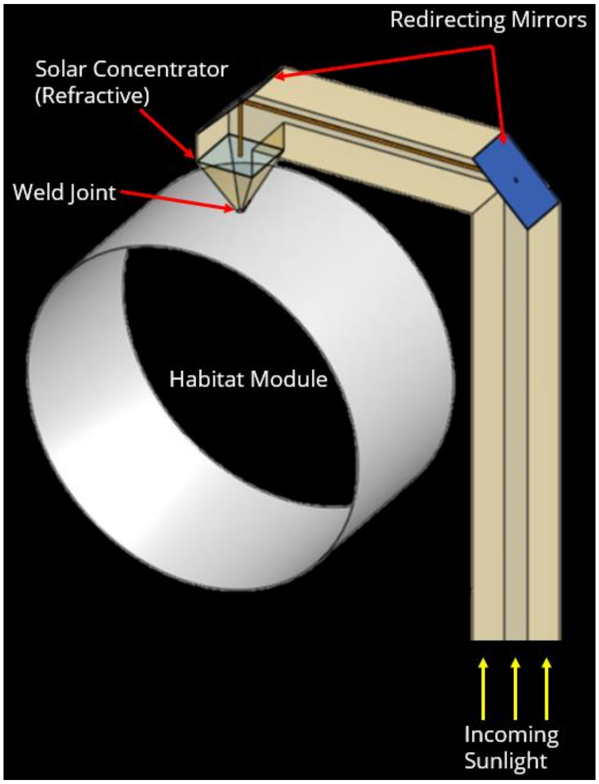

Figure 1: SO-WARM concept.

Innovation and System Description: The SO-WARM system employs a novel approach to in-space welding, centered on the direct use of CSE, enabling the fusion of both metallic and non-metallic materials. A refractive optic acts as the primary concentrator. Adjustable secondary optics then allow for precise control of the concentrated solar energy, directing it onto the welding target with a consistent, normal incidence angle enabling welding in extreme conditions such as on the shadowed side of a large space habitat module (Figure 1). A suite of novel weld control subsystems allows for precise control of the thermal environment during the solar welding process to improve weld quality and protect nearby systems and personnel. *In situ* process monitoring, perception, and control with a robotic mobility platform will enable autonomous functionality in space.

Phase II Achievements and Key Results: The Phase II project is focused on developing a medium-fidelity SO-WARM prototype, characterizing its performance, and demonstrating its capabilities in relevant environments. Key accomplishments include:

Successful Solar and Laser Welding. The SO-WARM system has demonstrated the capability to produce fusion welds on PEEK thermoplastic, aluminum, commercially pure titanium, and titanium alloy, Ti64. Both a solar concentrator (Figure 2) and an analog laser heat source were successfully used, allowing for controlled experimentation and comparison.

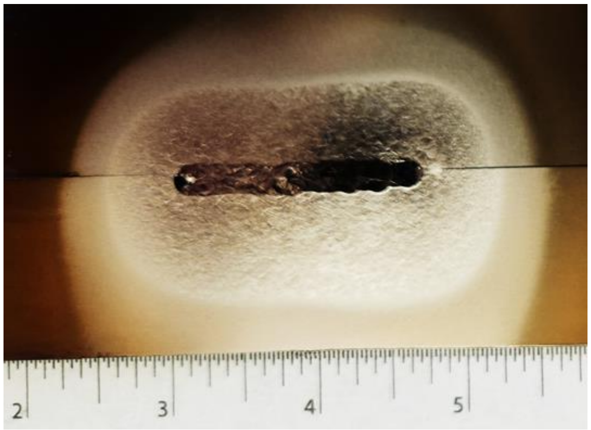

Figure 2: Titanium welded with CSE.

High Joint Efficiencies. Tensile testing, performed by the Colorado School of Mines, revealed *high joint efficiencies* for the welds produced. CP-Ti welds achieved up to 87% joint efficiency, while Ti64 welds achieved up to 88%. These results significantly exceeded the project's performance target of 50%

Weld Control Subsystem Functionality. Three weld control subsystems have been implemented and shown to influence weld characteristics, demonstrating the ability to control the thermal environment during the welding process. One subsystem in particular has been demonstrated to improve overall welding efficiency for solar and laser welding processes, enabling lower-power welding, faster welding speeds, deeper penetration, and improved weldability of reflective materials.

Reduced-Gravity Flight Testing. The SO-WARM system, configured with the laser analog, was successfully operated during a series of reduced-gravity parabolic flights. Five Ti64 welds were produced in microgravity, demonstrating the feasibility of the core welding process in a space-relevant environment. Initial observations suggest that microgravity influences the welding process, increasing the sensitivity to blow-through, but still allowing for high quality fusion welds.

In-Situ Process Monitoring. A Xiris high-dynamic-range welding camera and a two-color pyrometer were integrated into the system for process development and characterization. Software was developed to analyze the camera data in real-time, extracting key parameters like melt pool size, and to utilize pyrometer data for feedback control of weld speed. This lays the foundation for autonomous, closed-loop control.

Digital Twin Development. A digital digital twin of the SO-WARM system is being developed to further progress autonomous functionality and expediate process development through simulation. Components of the digital twin under development include a solar ray-tracing model of the solar energy, a computational fluid dynamics (CFD) model of the melt pool, and a mechanical model of the complete space system with an actuation and control interface.

Space System Design. Collaboration with industry partners has helped define four different space systems for incremental TRL advancement including a small-sat demonstration payload, a space-station hosted demonstration payload, a space station hosted solar welding testbed, and a full-scale SO-WARM space system. For the full-scale system, two different concentrator systems have been defined and compared: One using a rigid, refractive concentrator and one using an inflatable, reflective concentrator. While the inflatable option is lighter, it also requires an ever increasing amount of makeup gas in order to hold its shape as micrometeorite impacts create holes for gas to escape. The full impact on launch mass for an inflatable system is currently being analyzed.

Challenges and Mitigation Strategies: The project encountered and addressed several technical challenges, which have led to new innovations for weld control. The most significant challenges that have been overcome include component fouling, a large heat affected zone with CSE, and increased key-holing during reduced gravity flights, which may or may not be an effect of microgravity.

Conclusions and Future Work: The SO-WARM Phase II project has significanty improved weld quality for solar welding when compared to Phase I feasibility demonstrations. Phase II testing has also advanced the technology to TRL 5 in a simulated space environment (vacuum + microgravity). The project has exceeded key performance targets with very high joint efficiencies from solar and laser welded specimens.

Future work will focus on optimizing weld parameters for various materials, thicknesses, and joint configurations; advancing the TRL through staged space deployments; and continuous advancement of the digital twin system.