BY JEFFREY W. SOWARDS

The Space Economy:
A New Frontier for the Welding Industry

Liftoff and learn about historic missions and what's possible in the future

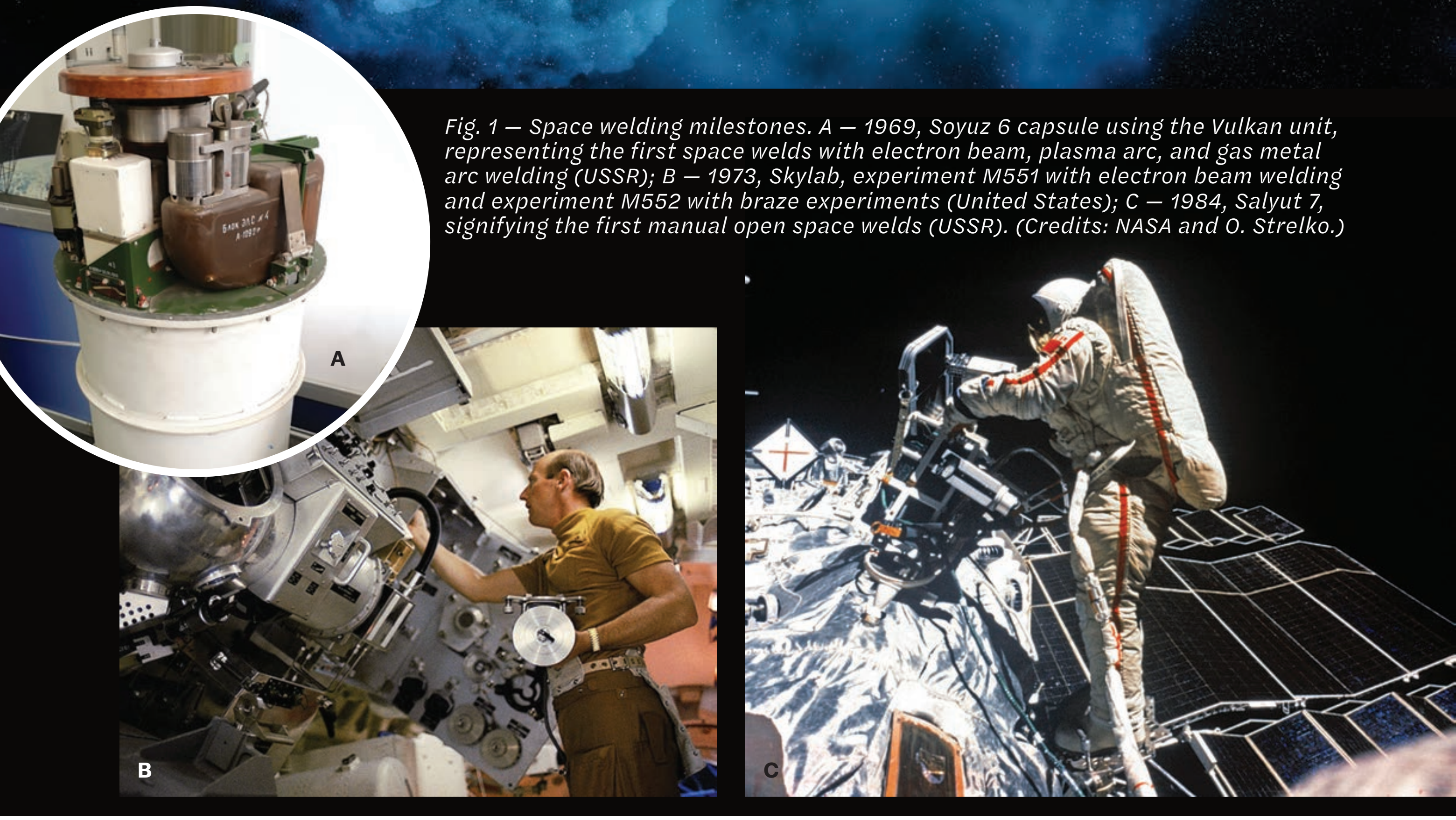

Fig. 1 — Space welding milestones. A — 1969, Soyuz 6 capsule using the Vulkan unit, representing the first space welds with electron beam, plasma arc, and gas metal arc welding (USSR); B — 1973, Skylab, experiment M551 with electron beam welding and experiment M552 with braze experiments (United States); C — 1984, Salyut 7, signifying the first manual open space welds (USSR). (Credits: NASA and O. Strelko.)

Space is an inhospitable environment with extreme temperatures that will freeze nitrogen in the shade and boil water in the sunlight. Its vacuum is so extreme, it cannot be fully replicated on Earth. And constant bombardment by atomic oxygen and high-energy radiation threatens any object not protected by shielding. Moreover, the microgravity conditions of objects orbiting the Earth nearly remove the sensation of weight. Despite these formidable conditions, the allure of space exploration and permanent space habitation continues to captivate humankind. As industries across the globe, including the welding profession, recognize the potential of the space economy, we find ourselves at the boundary of a new era of in-space servicing, assembly, and manufacturing (ISAM).

The space economy encompasses the goods, services, and activities performed off Earth that benefit humanity. According to the U.S. Bureau of Economic Analysis, it is a

TABLE 1 — BENEFITS OF WELDING FOR IN-SPACE ASSEMBLY AND MANUFACTURING*	
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 Ref. 3.

rapidly expanding sector (Ref. 1). In the United States alone, the space economy has experienced more than 17% growth in the past decade, with manufacturing constituting nearly a third of the value added. Generating more than $200 billion in gross output and supporting 360,000 private sector jobs, it offers tremendous potential for industries to thrive. And it contributes nearly $500 billion to the global output annually, according to the Space Foundation (Ref. 2). Within this realm, welding will play a critical and enabling role, much like it has since the inception of space exploration. Wernher von Braun, often considered the father of the U.S. space program, once emphasized the importance of welding by writing the following:

"A lifetime in rocketry has convinced me that welding is one of the most critical aspects of our whole job!!"

Given that welding is indispensable in creating durable goods on Earth, it will surely hold equal significance in performing manufacturing and assembly operations in space. The numerous advantages offered by welding in space compared to other manufacturing and assembly methods are shown in Table 1 (adapted from Ref. 3).

A Brief History of Welding in Space

Looking back over the last 50 years, here are some significant milestones in space welding, including Fig. 1.

'60s In 1969, Soviet Cosmonauts Georgy Shonin and Valeri Kubasov conducted the first space welding and cutting of metals in their Soyuz 6 capsule using the automated and battery-powered Vulkan unit (Refs. 4, 5). The employment of the unit, which used electron beam welding and low-pressure arc welding, marked a groundbreaking achievement by demonstrating critical manufacturing methods in a space environment. The work showed that electron beam welding was a highly suitable energy source for fabricating metals in space.

'70s Subsequently, in 1973, American Astronaut Charles "Pete" Conrad Jr., the Skylab 2 mission commander, performed automated bead-on-plate electron beam welds and braze joints on the Skylab orbital space station (Refs. 6, 7). These experiments aimed to develop reliable metal repair methods and laid the foundation for present and future space manufacturing capabilities. Returned samples were evaluated extensively and showed that mechanical properties of aluminum and stainless steel welds made in a space station were similar to those made on Earth.

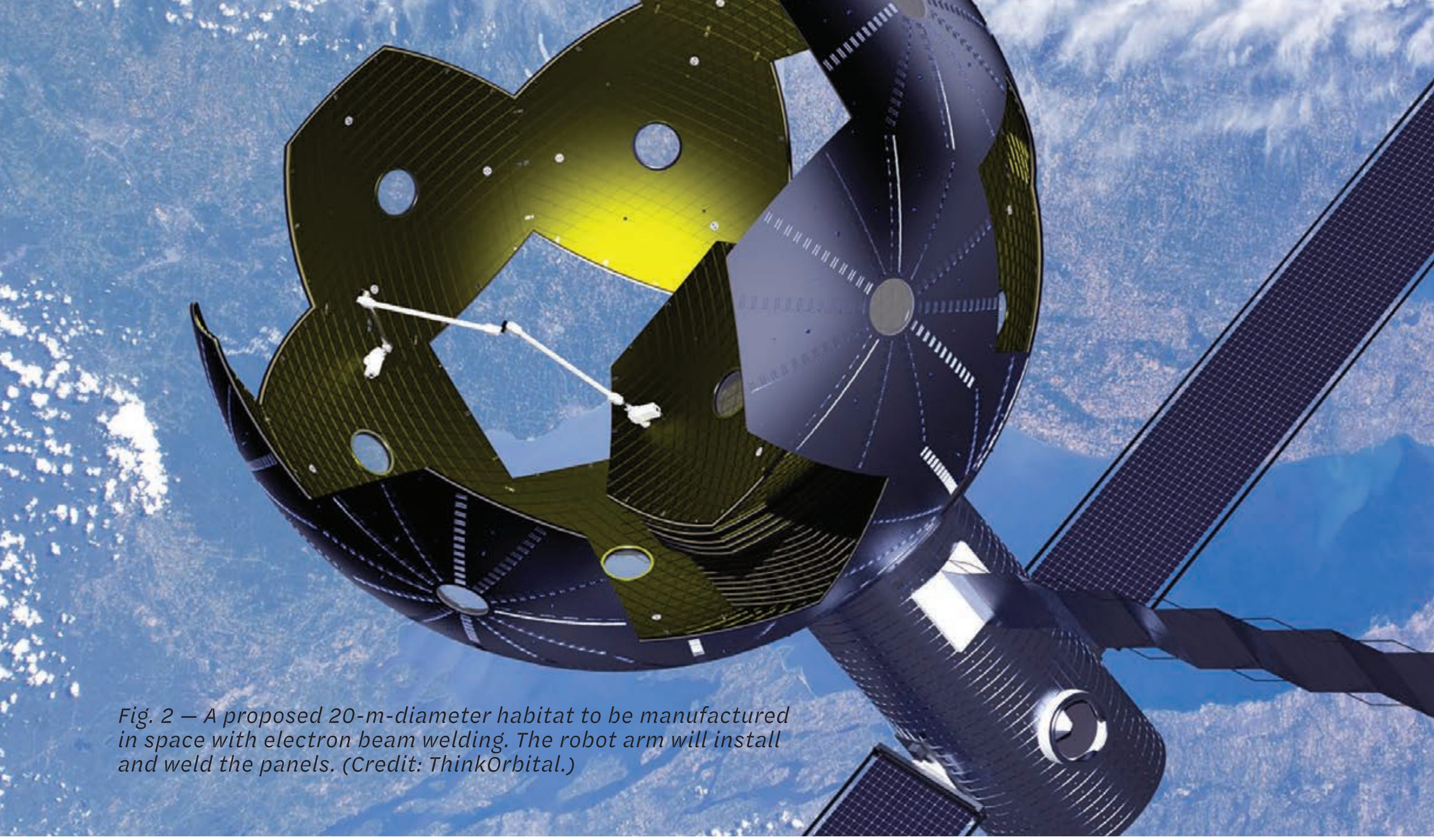

Fig. 2 — A proposed 20-m-diameter habitat to be manufactured in space with electron beam welding. The robot arm will install and weld the panels. (Credit: ThinkOrbital.)

’80s

In 1984, Soviet Cosmonauts Svetlana Savitskaya and Vladimir Dzhanibekov achieved another milestone by conducting the first weld in open space (Refs. 4, 5). Their three-and-a-half-hour spacewalk demonstrated several critical manufacturing processes. Savitskaya used an electron beam to cut titanium and then welded, brazed, and coated titanium and stainless steel while Dzhanibekov filmed the process. Samples were returned to Earth for study, revealing that the mechanical properties of welds made in open space are also comparable to those made on Earth. This flight showcased the potential of welding beyond the confines of a spacecraft habitat. In 1986, the electron beam welding tool, designed by the E.O. Paton Welding Institute (PWI) in Ukraine, was used again by Cosmonauts Vladimir Solovyov and Leonid Kizim to manually weld truss structures on the outer surface of the Salyut space station.

’90s

In the late 1990s, NASA collaborated with PWI to develop the International Space Welding Experiment. This experiment involved astronauts making manual welds using the Universal Hand Tool electron beam welding system developed at PWI and experimental hardware developed at the NASA Marshall Space Flight Center, Huntsville, Ala. (Ref. 5). Although the experiment was almost flown on the space shuttle, it was ultimately canceled and never flown due to safety concerns (potential exposure of astronauts to x-rays produced by the electron beam) and conflicting priorities, ending the last attempt by NASA to produce welds in space. PWI later sent components of the experiment to the Russian Mir space station, but the tool was never used again due to deorbiting of that station.

Welding in the Space Environment

The uniqueness of the space environment poses distinct physics-related challenges for welding (and other joining) processes.

Weightlessness, for instance, eliminates the buoyancy effect that helps mix the molten metal in weld fusion zones on Earth. It alters metal solidification and changes the formation and evolution of porosity. The ejection of weld spatter into space could result in micrometeoroids that orbit Earth with an average speed of 10 km/s, threatening other spacecraft. Moreover, high vacuum conditions, coupled with weightlessness, prevent convective cooling that enables the fast cooling that weld joints experience on Earth. High vacuum conditions in space promote intense vaporization of metals that can plate out on nearby components within line of sight, leading to potential damage. Additionally, vacuum conditions may disrupt the smooth flow of gases required for generating the plasma used in arc welding heat sources. Finally, the extreme temperatures experienced by parts exposed to sunlight or shade further complicate the weldability and cooling rates of joints. Adaption of welding processes to these unique circumstances is vital for successful ISAM operations.

Current Efforts to Weld in Space

Recognizing the importance of space welding processes, public-private partnerships have emerged between government agencies like NASA and Space Force, academia, and industry.

At the 2019 International Space Station Conference, leaders from both the public and private sectors expressed consensus on the criticality of further investigation of joining technologies for in-space use (Ref. 8). To answer that call, NASA, in conjunction with The Ohio State University and The University of Texas at El Paso, has begun pursuing the evaluation of fiber lasers for welding in low Earth orbit, with a microgravity research flight planned for 2024.

Industry has also begun numerous efforts. Lockheed Martin was recently awarded a NASA Tipping Point proposal to develop and demonstrate welding and inspection technologies for in-space assembly of structural, electrical, and fluid systems (Refs. 9, 10). ThinkOrbital is spearheading an initiative to develop and implement electron beam welding processes as well as cutting, inspection, and additive manufacturing tailored for construction of large habitats in space (Refs. 11, 12). Its plan is to unfurl and weld a set of hexagonal and pentagonal panels in low Earth orbit, creating a pressurized and habitable 20-m-diameter spherical structure — Fig. 2. Gateway Spaceport and Above: Space have realized the importance of welding as an assembly process for large rotating wheel space stations (also known as von Braun wheels) and have incorporated welding in space into their manufacturing plans to obtain diameters approaching nearly 500 m (Ref. 13).

By investing in space welding and allied joining technologies, the welding community can position itself at the forefront of this new frontier.

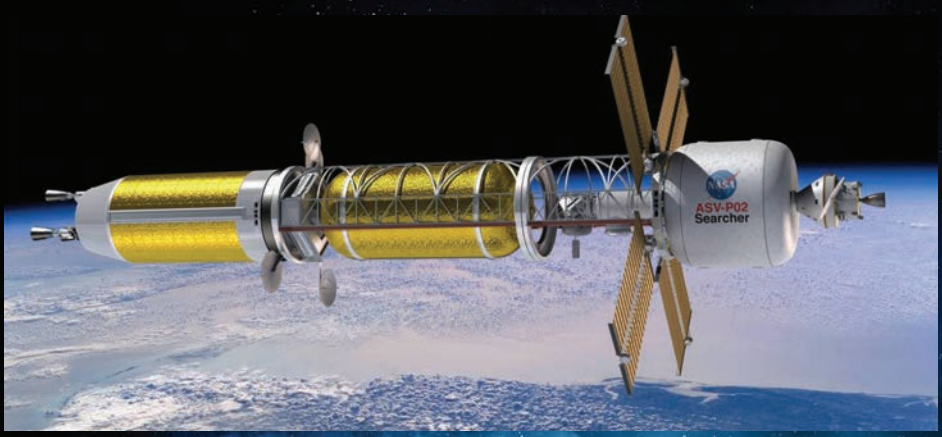

Fig. 3 — A concept spacecraft, powered by a nuclear rocket engine, must place distance between inhabitants and the nuclear reactor to ensure astronaut safety from radiation. Welding is a candidate assembly process for building such a structure. (Credit: NASA.)

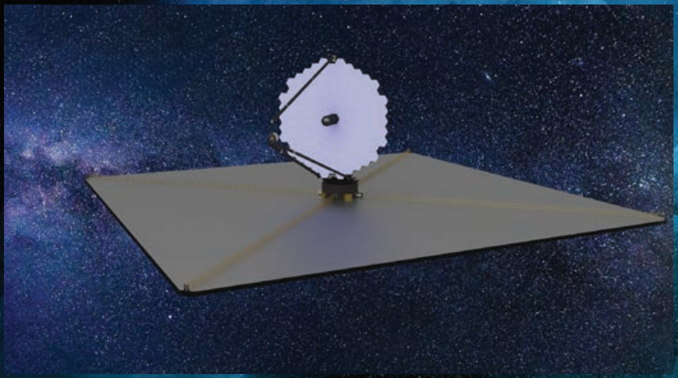

Fig. 4 — The future Great Observatory can benefit from welding in space. Shown is the proposed Large UV/Optical/IR Surveyor (LUVOIR) telescope with its 15-m mirror and large sunshield system with truss structure. (Credit: NASA.)

Fig. 5 — 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. (Credit: NASA.)

Opportunities Await

Looking to the near future, several space environments, including Earth, the moon, and Mars, will be considered as test grounds for welding. The Earth's orbit serves as a platform for assembling structures, with nuclear rocket engines and the next generation of observatories — Figs. 3, 4. On the lunar surface, the need for communication infrastructure necessitates 50-m-tall transmission towers, surpassing the scale of any rocket payload fairing — Fig. 5. Finally, as missions extend to the moon and Mars, the ability to repair hardware located vast distances from Earth becomes increasingly critical. These applications will benefit greatly from welding because of the numerous advantages discussed above.

To navigate challenges and seize upon opportunities, 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, demand versatile welding capabilities. Conducting 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. Finally, establishing a permanent orbital capability and analytical tools to develop and apply welding and joining processes in the space environment is vital (Ref. 14).

Shape the Future of Space

This is a call to action for the welding community to proactively embrace the challenges and opportunities presented by the new space economy. By investing in space welding and allied joining technologies, the welding community can position itself at the forefront of this new frontier. The time is at hand to embark on this exciting journey to shape the future of space through innovation, collaboration, and excellence in welding. WJ

As industries across the globe, including the welding profession, recognize the potential of the space economy, we find ourselves at the boundary of a new era of in-space servicing, assembly, and manufacturing.

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