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Paper Session I-A - In-Space Welding Visions & Realities

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IN-SPACE WELDING
Visions & Realities

presented to

Thirtieth Space Congress
"Yesterday's Vision is Tomorrow's Reality"
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Advanced Technology Development
Session

by

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ABSTRACT

This paper establishes the value of having an in-space welding capability and identifies its applications, both near-term for Shuttle-Spacelab missions and Space Station Freedom, and longer-term for the First Lunar Outpost and Manned Mission to Mars. The leading candidate technologies, consisting of Electron Beam, Gas Tungsten Arc, Plasma Arc, and Laser Beam, are examined against the criteria for an in-space welding system. Research and development work to date, striving to achieve an in-space welding capability, is reviewed. Finally, a series of strategic NASA flight experiments is discussed as the remaining development required for achieving a complete in-space welding capability, which can fully serve the Space Exploration Initiative. This paper summarizes the visions and realities associated with in-space welding.

INTRODUCTION

Yesterday's vision of in-space construction, repair, and maintenance by welding will become tomorrow's reality for Shuttle-Spacelab missions, Space Station Freedom (SSF), First Lunar Outpost (FLO), and Manned Mission to Mars (MMM). The significance of welding, as a fabrication process, is demonstrated by its predominance in terrestrial construction, repair, and maintenance of buildings, automobiles, ships, submarines, aircraft, and spacecraft. Almost any high performance system, employing metal structure, also employs welding as the joining method for that structure. There is no denying that welding is our most advanced and practical building methodology on Earth. We have even found ways to weld underwater, in the oceans, where undersea settlements are already occurring. Consequently, it is only natural that we should extend this terrestrial construction, repair, and maintenance methodology with its benefits into space, as we begin to make our way into this next frontier.

WHY HAVE A WELDING CAPABILITY IN SPACE ?

NASA's existing in-space construction, repair, and maintenance capabilities are inadequate as the sole building blocks for upcoming aggressive Shuttle, SSF, FLO, and MMM programs. NASA's in-space joining techniques are currently limited to mechanical fastening and adhesive bonding. An in-space welding capability would offer NASA much higher performance joining techniques for construction, repair, and maintenance (see table-1).

Table-1
IN-SPACE WELDING OFFERS:
- Higher joint strength and rigidity
- Better joint hermeticity
- Lower joint mass
- Simpler joint design
- Simpler joint manufacturing
- Higher joint reliability
- Broader repair versatility
- Consequent cost savings

Joint Strength & Rigidity: Imminent in-space construction of large truss, aerobrake, radiator, antenna, solar panel, and even solar sail structures will require the highest achievable joint strength and rigidity. A mechanically fastened or adhesively bonded joint cannot compete with the welded joint's superior mechanical properties. The strength and rigidity of a welded joint so closely approach those of the parent material, that from a mechanical stress perspective, it's almost as if there is no joint and that the parent material is simply continuous.

Joint Hermeticity: The need for pressurized vessels and modules for our thermal, propulsion, and life support systems in the hostile space vacuum environment, dictates employment of the most reliable hermetic joining methodology. Mechanical joints, involving gaskets or "O" rings, and adhesively bonded joints cannot provide a hermetic seal which is as strong and durable as a welded joint's seal. With a welded joint, from a hermetic perspective, it's almost as if there is no joint and that the parent material is simply continuous.

Joint Mass: The high cost of shipping building materials into low Earth orbit (LEO) dictates employment of construction methodologies which minimize joint mass. Extra components and increased gage of parent members, at a mechanically fastened or adhesively bonded joint, are necessary for joining with acceptable strength and hermeticity. However, welded joints can easily meet the same joint integrity requirements with no or almost negligible mass added to the parent material. Autogenously welded joints (requiring no filler wire) are ideal, as shown in figure-1, because from a mass perspective it's as if the parent material was continuous and no joint existed. Non-autogenous welding involves the addition of filler metal, via a wire feed spool, which melts into the weld pool to allow joint reconstruction, deeper penetration joints, or joint gap bridging. Nevertheless, any filler material addition is negligible when compared with respective oversized mechanically fastened or adhesively bonded joints.



Figure -1
Welding Enables Ideal Joint Mass

Joint Design: Designing in-space joints with mechanical fastening or adhesive bonding techniques is more demanding and time consuming than with a welding technique. Mechanical fastening and adhesive bonding techniques require design of added components, increased gage of the parent material, and special machining of the joint. Whereas with welding, most of the above design efforts are eliminated or significantly reduced.

Joint Manufacturing: Manufacturing a joint in space involves challenging manual, semi-automated, teleoperated, or robotic operation modes, which require extensive design, training, and adaptation to the joining tools and joint components. Varying mechanical fasteners and adhesive bonders increase the joint components and, therefore, the complexity of the manufacturing operation. Welding eliminates the need for these added elements at the joint, hence, reducing manufacturing complexity (see figure-2).

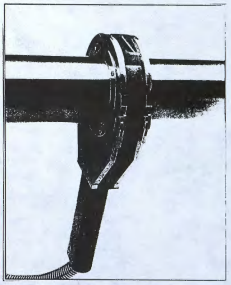


Figure -2
Semi-Automated Orbital Tube Welding Involves Simpler Manual Set-Up and Activation

Joint Reliability: Due to difficulty of construction, repair, and maintenance in the hostile space environment, joint reliability needs to be maximized in order to minimize joint servicing. A mechanically fastened or adhesively bonded joint is much more susceptible to fatigue failure than a welded joint, especially with the thermal, corrosion, and radiation stresses present in the space environment. Non-metallic components in these joints may also suffer from monatomic oxygen erosion (LDEF lessons learned). On the other hand, metal to metal welded joints approach the durability of the parent metallic material. In fact, Skylab lessons taught us that in-space fluid line joints employing mechanical and adhesive techniques require high maintenance, and that welded joints would be a far more effective alternative [2].



Figure -3
More Durable Patch Repair of Crew Module Punctures is Enabled by Welding

Repair by Joining: Orbital debris collision or fatigue damage to crew/lab modules, radiators, fluid lines, or structure will require quick repair to mitigate ensuing hazards in the hostile space environment, and to restore mission operations. A puncture in an SSF crew module wall (similar to the one shown from the Solar Max Satellite in figure-3) may be quickly plugged with an adhesive patch from inside the module. However, a more durable fix (supplementing the adhesive patch) can be provided by welding the puncture shut from the modules' exterior. Welding is far more versatile than any other metal repair method, since it does not require the extensive machining preparation and corresponding tooling, specialized fasteners, and hermetically sealing adhesives or gaskets associated with mechanical or adhesive repair.

Joint Cost: In-space joint cost reductions are achievable through higher joint strength and rigidity, better joint hermeticity, lower joint mass, simpler joint design and manufacturing, higher joint reliability, and broader repair versatility. Welding exhibits these characteristics, when compared to mechanical fastening and adhesive bonding techniques. With upcoming aggressive in-space ventures (see figure-4) the importance of cost effective joining techniques is tremendous.



Figure -4
Upcoming Missions Require More Cost-Effective
Joining Techniques, such as Welding

APPLICATIONS FOR AN IN-SPACE WELDING CAPABILITY

Expected applications for an in-space welding capability span existing NASA Shuttle-Spacelab missions, and upcoming SSF, FLO, and MMM programs.

Shuttle-Spacelab Missions: On-going Shuttle-Spacelab missions carry two tool kits for in-flight contingencies. The intra-vehicular activity (IVA) kit is termed In-Flight Maintenance (IFM) tools, and is stowed in a middeck locker. The extra-vehicular activity (EVA) kit is termed Payload Stowage Assembly (PSA) tools, and is stowed in the cargo bay. IVA and EVA welding tools will improve the IFM's and PSA's existing repair capabilities during a Shuttle-Spacelab contingency, such as repair of an orbital debris puncture or fatigue damage to the crew/lab modules, radiator panels, or vehicle structure (i.e. cargo-bay doors and latching mechanisms). In addition, shuttle servicing missions of LEO platforms and satellites could employ welding for repair and maintenance of these spacecraft. In-space welding tools could be employed with Shuttle-Spacelab missions via manual or semi-automated operation modes (see figure-5). Teleoperated welding applications may also be feasible, should the Shuttle arm, the remote manipulating system (RMS), be improved for more dexterous operations.

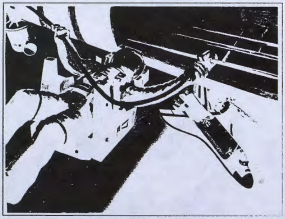


Figure -5
Semi-Automated Fluid Line Construction
on LEO Platforms, by Welding

SSF Program: SSF will present multiple opportunities for in-space construction, repair, and maintenance over its projected 30 year life-span. In-space welding tools may become critical for repair of orbital debris or fatigue-damaged crew/lab modules, radiators, pressurized fluid systems, and structure (see figure-6). Construction of modifications or expansions to the station structure, crew/lab modules, and power and thermal systems will become a required routine well suited for welding. Even general metallic laboratory equipment, aboard SSF, will require repair, maintenance, and modification; welding is commonly used for such purposes terrestrially.

FLO Program: FLO program will open a myriad of opportunities for welding to be heavily employed both IVA and EVA in construction, repair, and maintenance of structures, crew/lab modules, antennae, solar collector arrays, power plants, fluid lines (plumbing), surface vehicles, descent-ascent vehicles, and various equipment (see figures -7 & -8).

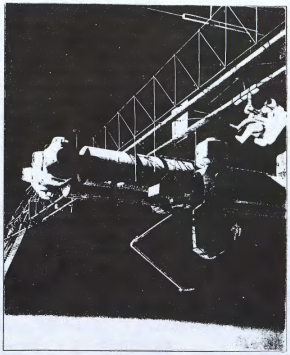


Figure -6
SSF Truss and Crew/Lab Module Repair by Welding



Figure -7
FLO Construction, Repair, and Maintenance by Welding



Figure -8
Lunar Based Antennae Construction by Welding

MMM Program: The eventual MMM program will consist of LEO preparation, interplanetary transfer, low Mars orbit, landing and exploration, and return to Earth phases. Over all these phases, MMM missions may employ welding tools, both IVA and EVA, on the orbital transfer, descent, ascent, and surface vehicles. The vehicles' construction, repair, and maintenance tasks suited for welding will involve structures, crew/lab modules, aerobrakes, antennae, solar collector arrays, radiators, power plants, fluid lines and various equipment (see figure-9).

HOW DO WE DEVELOP AN IN-SPACE WELDING CAPABILITY ?

Developing an in-space welding capability will naturally employ our gained expertise with terrestrial welding. Any terrestrial welding process modified for space-based applications should strive to meet the ideal criteria set fourth in table-2.

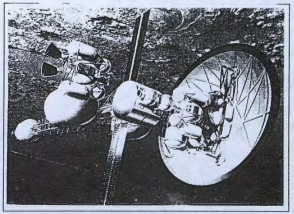


Figure -9
Earth-Mars Orbital Transfer Vehicle Construction
(i.e. Aerobrake) by Welding

Choosing a Welding Process: There are four welding processes which come closest to satisfying table-2's requirements for an in-space welding capability: Electron Beam Welding (EBW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), and Laser Beam Welding (LBW). To develop one single ideal welding process, which satisfies each and every one of table-2's requirements, is impossible. Even terrestrially, there is no one "can-do-it-all" process. Instead, a variety of terrestrial welding processes have been developed, and are employed side

by side to suit various applications and their individual requirements. For example, the Rockwell Rocketdyne Space Shuttle Main Engine, the highest performance rocket engine in the world, employs a combination of GTAW and EBW for producing its hundreds of critical welds. It is only natural that upcoming in-space welding tasks will demand a combination of processes as well.

Evaluating Potential In-Space Welding Processes: Data derived from various preliminary trade-off studies, comparing the potential in-space welding processes against table-2's criteria, is shown in table-3. The various studies were performed by Massachusetts Institute of Technology, Ohio State University, California Polytechnic State University, Rockwell International Corporation, Russia's NPO Tekhnomash Company, and Ukraine's Paton Institute [1-5]. There are many detailed evaluation factors associated with each of the comparison categories, which are not shown here. But, it is evident that compatibility with in-space operation requirements is better for some processes than others. Only one of these candidates will probably become the most commonly used, for general in-space tasks. Nevertheless, unique characteristic capabilities, exhibited by each of these processes, will be best suited for certain unique tasks. Terrestrially, GTAW is the most commonly used process due to its simplicity, safety, adaptability, and high process controllability [1, 2]. However, EBW, PAW, and LBW are all critically needed processes as well, which are used for requirements exceeding GTAW's capabilities. It is, therefore, essential for NASA to develop each of these processes for in-space application, and to also develop a solid knowledge base which characterizes the in-space performance capabilities of each process. A consequent user-friendly computerized database will allow astronauts to match each different in-space welding application with the process which is best suited for that task.

Table-2: IDEAL PERFORMANCE CRITERIA FOR AN IN-SPACE WELDING PROCESS

- Conform to rigid operator (astronaut) and mission safety
- Not have fundamental problems with microgravity
- Function both inside pressurized life supported compartments and in the outside vacuum
- Produce first class quality welds (strong, hermetic, durable) on all aerospace materials (such as metals and composites) with a wide spectrum of work geometries
- Easily adapt to manual, semi-automated, teleoperated, and robotic operation modes
- Tolerate joint mismatch and fit-up problems
- Operate efficiently with lower power levels available in space
- Minimize use of consumable materials
- Exhibit high equipment reliability and simple serviceability

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

Performing Research & Development: Research & Development (R&D) efforts, which are naturally required for establishing an in-space welding capability, need to target combined interactions between the welding process (EBW, GTAW, PAW, LBW), the intra- and extra-vehicular environments (microgravity, vacuum, thermal gradients), and the workpiece (different aerospace materials). In addition, R&D efforts need to focus on the various welding operation modes (manual, semi-automated, teleoperated, robotic) and their implications on crew and mission safety. These R&D efforts should maximize utility of ground based in-space simulation tools, such as KC-135 parabolic flights, vacuum chambers, neutral buoyancy water tanks, and numerical modelling. R&D efforts should obviously proceed to space-based validation and verification using Shuttle Small Payload experiments (i.e. Get Away Special, Complex Autonomous Payload, Hitchhiker), Spacelab IVA experiments (i.e. glove-box), and Shuttle EVA experiments (i.e. a cargo-bay mounted workstation). These R&D efforts should concentrate on near-term applications such as: patching punctured crew / lab modules or pressure vessels damaged by collision with LEO debris, and tubular welding for fluid line and structural construction.

How Close Are We Today to Having an In-Space Welding Capability ?

Since the 1960's, R&D efforts have been directed toward generating EBW, GTAW, PAW, and LBW tools for in-space construction, repair, and maintenance applications [3]. These efforts have mainly occurred, and continue, in former Soviet Union (in Russia and Ukraine) and in the U.S. However, the Japanese and Europeans have also entered this field of endeavor. Today, the in-space EBW process development is being lead by the Paton Institute of Ukraine, the in-space GTAW process by Rockwell International Corporation of the U.S. and NPO Tekhnomash of Russia, the in-space PAW process by NASA Marshall Space Flight Center (MSFC), and the in-space LBW process by University of Tennessee-Calspan (CO2 laser) and University of Alabama (Nd-YAG laser).



Figure -10
Former Soviet Union EVA Welding Experiment

In-Space EBW Status: The former Soviet Union, via the Paton Institute in Ukraine, successfully accomplished the following R&D for in-space EBW: ground based vacuum chamber tests, microgravity simulation aircraft flight tests, on-orbit spacecraft autonomous flight experiments (with Soyuz-6), on-orbit space station autonomous experiments (with Salyut-6, -7, and MIR), ground-based neutral buoyancy water tank EVA simulation tests, and finally on-orbit manual EVA experiments (off of Salyut-7, and MIR, see figure-10) [3]. These aggressive efforts have resulted in Paton's in-space EBW tool, which is known as "URI" or the "Versatile Hand Tool (VHT)" (also shown in figure-10). Today, the VHT is incorporated into MIR's on-board tool base. In-fact, the VHT has already been applied in real operations, including truss construction (by welding joints), emergency repair of a broken antennae (by cutting it loose), and refurbishment of solar panel performance (by cleaning debris off panel surfaces) [4]. The VHT's performance with U.S. alloys, and safety characteristics under NASA on-orbit operation standards are yet to be determined. Currently, NASA Goddard Space Flight Center (GSFC) is pursuing funding for an extensive series of Shuttle experiments to safely and effectively characterize in-space EBW methods with Paton devices. NASA GSFC plans to incorporate a yet to be announced consortium of U.S. experts, comprised of NASA centers, other government agencies, industry, and universities. McDonnell Douglas is also pursuing funding, but for an EVA type experiment with a Paton developed semi-automated EBW device, applicable to SSF fluid line in-space construction.

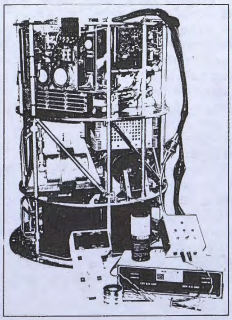


Figure -11
Rockwell's G-169 Get Away Special Shuttle Welding Experiment

In-Space GTAW Status: Rockwell International Corporation of the U.S. successfully accomplished the following via Independent R&D, and some direct contracts from NASA MSFC and a NASA Headquarters In-STEP program: development of hollow electrode patents for GTAW in a vacuum (4,803,339 & 5,149,932), ground based vacuum chamber tests, microgravity simulation KC-135 flight tests of semi-automated and manual welding tasks, development of an autonomous Get Away Special (G-169) Shuttle payload for on-orbit testing (see figure-11), KC-135 flights of G-169, design of a more capable Complex Autonomous Payload type Shuttle experiment, ground-based neutral buoyancy water tank EVA simulation tests of semi-automated welding tasks, and design of an on-orbit Shuttle EVA experiment [5]. Currently, NASA GSFC is pursuing funding for

an extensive, consortium developed, series of Shuttle experiments to safely and effectively characterize in-space GTAW methods. Outside of the U.S., NPO Tekhnomash of Russia has successfully accomplished efforts very similar to Rockwell's. Recently (August 1992), Tekhnomash presented photographs of their in-space EVA-GTAW torch prototypes, including manual and semi-automated orbital versions. Tekhnomash is preparing to test these in space. In summary, all ground-based evaluations of the in-space GTAW promise success on-orbit, with effective applications for NASA's upcoming challenges.

In-Space PAW Status: NASA MSFC and a California based sub-contractor, which specializes in arc-jet propulsion technology, are currently developing a PAW device for vacuum operation. The potential for this technology's successful development is high. But, few details are known at this time, due to the infancy of the technology and its consequent proprietary nature.

In-Space LBW Status: The University of Tennessee-Calspan is currently pursuing development of a Shuttle-Small-Payload-type (cargo-bay) LBW experiment with a CO2 laser. This experiment is manifested for flight around 1995, and is being funded through a NASA Headquarters' Center for the Commercial Development of Space. On the other hand, University of Alabama in Huntsville conducted microgravity simulation aircraft flight experiments on NASA MSFC's KC-135. These experiments targeted LBW with an Nd-YAG laser. The University of Alabama is currently pursuing funding to continue this work. Even though lasers seem to be the "thing of the future," LBW's potential utility in space suffers from very high power requirements.

WHAT REMAINS TO BE DONE ?

Today, we have the technologies necessary for achieving an in-space welding capability. The GTAW system shown in figure-12 is currently capable of supporting semi-automated and manual construction, repair, and maintenance tasks in an IVA microgravity environment (i.e. on-orbit in SSF's crew/lab modules). However, validation and verification of these technologies in space, by NASA, have yet to occur. With increasing Shuttle mission-challenges and upcoming monumental endeavors such as SSF, FLO, and MMM, it has become critical and timely that NASA provide itself with the tools which it needs to survive in the difficult frontier of space. In-space EBW, GTAW, PAW, and LBW tools can perform required welding tasks, but also metal vapor coating, cutting, and localized heat treating tasks. NASA must seriously fund flight experiments which will serve to complete the development of these tools, and their incorporation into the nation's Space Exploration Initiative. Experiments, targeting all four candidate in-space welding processes, should be cost-effectively carried out with the same flight platform, such that the various processes' capabilities can be equally characterized and evaluated against near-term applications. Shuttle Small Payloads are effective for carrying out safely an autonomous series of such experiments. Consecutively, more demanding Spacelab glove-box IVA experiments and Shuttle cargo-bay EVA experiments can be undertaken to validate and verify manual, semi-automated, teleoperated, and robotic welding operation modes for near-term applications. Rockwell International Corporation has developed flight hardware and designs for such Shuttle experiments [5].

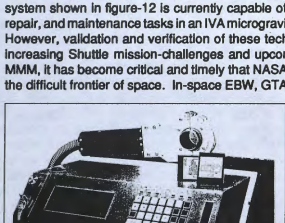


Figure -12
Dimetric's Commerically Proven State-of-the-Art Programmable GTAW System

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