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UNIQUE METHODS FOR ON-ORBIT STRUCTURAL REPAIR, MAINTENANCE, AND ASSEMBLY

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INTRODUCTION

Current and future missions by NASA to establish a permanent presence in space include establishing a permanent space station in low Earth orbit for conducting scientific research, and in the long term establishing an outpost on the moon and landing of personnel on Mars. The currently planned NASA Space Station Freedom will be constructed and joined on Earth, with final assembly being performed on orbit by astronauts and telerobotics. Tools and procedures that are both extravehicular activity (EVA) and telerobotically compatible will be required for maintenance and repair for this most ambitious NASA effort.

Reliability and continued operational performance become major factors for future manned space vehicles with long-duration life expectancies. On-orbit systems such as life support fluid and gas lines, habitation module walls, and structural support components will require repair and maintenance during their continued exposure to the hostile environment of space. Such operations will be performed in both EVA and intravehicular activity (IVA) using astronauts or a combination of astronauts and telerobotics. The NASA space shuttle has an extensive inventory of tools compatible with both EVA and IVA use to perform temporary repairs in space, but these tools do not possess the required capability of long-term performance or telerobotic capability.

Welding would be a highly effective and reliable method by which repairs could be performed on orbit for damaged fluid lines, truss assemblies, pressurized habitation modules, and critical structural supports. The United States has been slow in developing an on-orbit welding capability, although NASA did perform a self-contained electron beam welding experiment aboard Skylab in 1973 (Reference 1) and has proposed development of a space welding capability through its IN-STEP programs (References 2 and 3).

The former Soviet Union, on the other hand, has continued to develop welding in space since 1965. This resulted in a weld repair being successfully performed in space in 1986 aboard Soyuz T12 using Universal Hand Tool (UHT) electron beam space welder, shown in Figure 1, developed by the Paton Welding Institute (Reference 4). A 1.5-kW version of the UHT currently resides as a permanent repair tool on the Mir Space Station.

Mechanical tube fittings offer an established option to welding for the near-term on-orbit repair of tubular compo-

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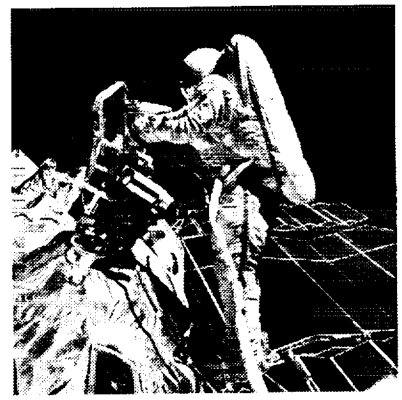

Figure 1. Soviet Union Cosmonaut Successfully Performing Welding in Space on Soyuz T12

nents such as fluid lines or structural components. One-piece mechanical fittings have been evaluated extensively by the Air Force as reliable hardware for in-place repair of tubes and tube components on aircraft. Such repairs are defined as depot maintenance and involve the use of special installation tools and procedures. Tools and hardware demonstrations for on-orbit line repair are required for mechanical repair procedures to be acceptable for use by NASA on near-term structures such as the Space Station.

McDonnell Douglas Aerospace (MDA) has been investigating both welding and mechanical tube fittings since 1986 as viable methods for on-orbit tube repair. Emphasis was initially placed on mechanical tube fittings as this technology had progressed to a higher degree in the United States, thereby minimizing risks for use in near-term space applications. Since 1990, MDA, through the Paton Welding Institute in Kiev, Ukraine, has placed increased emphasis on welding in space, evaluating the Paton space welding and metal processing capabilities and their potential application to NASA's near-term requirements as defined for Space Station Freedom.

This paper reviews the MDA independent research and development (IRAD) efforts since 1986 in the development of two distinctly different approaches to on-orbit tube repair: (1) one-piece mechanical tube fittings that are forced, under pressure, onto the tube outer surface to effect the repair and (2) electron beam welding as demonstrated with the Paton-developed UHT space welding system for the repair of fluid lines and tubular components. Other areas of potential

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on-orbit repair using the UHT include damage to the flat or curved surfaces of habitation modules and truss assemblies. This paper will also address MDA evaluation of the Paton UHT system for on-orbit coating, cleaning, brazing, and cutting of metals. MDA development of an on-orbit compatible NDE system for the inspection of tube welds is an important part of this complete space welding capability and will be discussed in a separate paper.

ON-ORBIT REPAIR DEVELOPMENT

Repair Scenario Definitions

A single scenario was established for the MDA development of procedures and tools for the on-orbit repair of tubes. This scenario includes (1) removal of the defective tube section, (2) use of the precut tube length to replace defective sections, and (3) installation of the precut length using either mechanical fittings or welding. Defects in either curved or flat metal places would be repaired by welding a metal patch over the defective area.

Mechanical Tube Fittings

Preliminary Studies. Based on past experience in aircraft, commercial, and space usage, 10 fitting types were evaluated for use in the MDA on-orbit repair development program. These fittings, along with their ability to meet certain functional requirements, are described in Table 1. The MDA program concentrated its effort on fittings that were simple in design and nonseparable in operation and that required minimum EVA involvement for installation and removal. MDA selected the Raychem heat shrink fitting and the Aeroquip Rynglok fitting as best meeting these requirements. Both fittings are designed for one-piece installation and, once installed, cannot be disassembled. Seals for each fitting are formed by high pressure exerted between the tube outer diameter and fitting inner diameter. The two fittings selected for evaluation are shown in Figure 2.

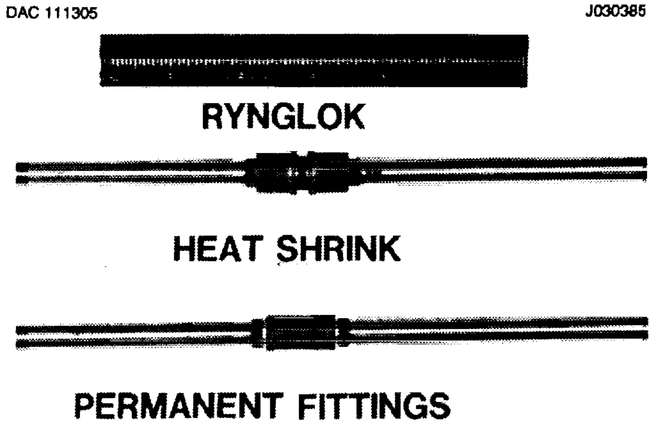

Figure 2. Nonseparable Tube Fittings Selected for On-Orbit Repair Development

Tool Development. Two types of tools are required for use of any mechanical fitting for on-orbit tube repair: (1) a tube cutter and (2) a fitting installation tool. The selected fittings must also have a fool-proof method, readily visible to astronauts, that indicates an acceptable installation.

Tube Cutter. MDA developed an EVA-compatible modular power tool (MPT) fitted with a tube cutter head capable of cutting metal tubes in minimum clearance openings while producing a cut that is externally free of burrs and minimizing contamination (Figure 3). The MPT is modular in design and capable of operating a variety of different heads in addition to the tube cutter. The cutter head has the capability of capture, alignment, and hard docking to the tube prior to cutting. The cutter wheel feeds at a preselected rate until the tube cut is completed. At that time, the MPT will automatically shut off. The MPT is automated and is capable of hands-off operation after hard docking is complete. The cutter will produce an external burr-free tube surface cut and minimal internal burr formation, which will eliminate the need for additional fluid line repair preparation.

Table 1. Mechanical Tube Requirements for Use in Space Fitting Rquirements

No.	Fitting type	Zero leak at 10^{-9} cc/sec	Metal-to-metal seal	Simple to Install	Simple to Repair	Complete installation in space	Simple design	Go/no-go indicator	High reliability	Cost (tools and fitting)	Installed with small tools	Qualified for high-pressure service up to 6000 psi
1	Rynglok	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Moderate	Yes	Yes
2	Swagelok	No	Yes	Moderate	No	Yes	No	Yes	Yes	Low	Yes	No
3	Dynatube	Yes	Yes	No	No	No	No	Yes	Yes	High	Yes	Yes
4	Cryofit	Yes	Yes	Yes	No	Yes[1]	Yes	Yes	Yes	Moderate	(1)	Yes
5	Permaswage	No	No	No	No	No	No	Yes	No	High	No	No
6	37-deg flare	No	No	No	No	No	Yes	No	No	Low	Yes	No
7	Flareless	No	Yes	No	No	No	No	Yes	No	Low	Yes	No
8	Wiggins	No	No	No	No	No	No	Yes	No	Moderate	Yes	No
9	Gamah	Yes	Yes	Moderate	No	No	No	Yes	Yes	Moderate	Yes	Yes
10	Heat shrink	Yes	Yes	Yes	No	Yes[2]	Yes	Yes	Yes	Moderate	Yes[2]	Yes

Notes: 1. Requires portable storage in liquid nitrogen
2. Requires heat source

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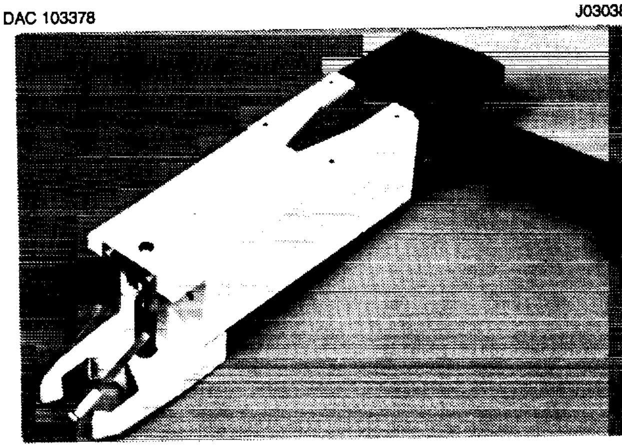

Figure 3. Modular Power Tool

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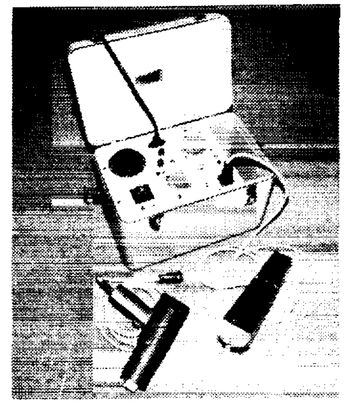

Figure 5. Inductron Torobonder for Installation of Heat Shrink Fittings

Fitting Swage Tool. The Rynglok nonseparable tube fitting is installed by sliding two sleeves forward until they contact a center flange. Upon contact, the sleeves have exerted sufficient pressure between mating tube and fitting surfaces to effect a seal. This swaging action of the fitting sleeve is performed by an EVA-compatible swage tool developed under the program (Figure 4). The tool is hydraulically operated through a pneumatic intensifier pump. The swaging action is controlled by an EVA-compatible switch. This switch, shown in Figure 4, is separate from the swaging head. Total time to effect a swage is approximately 5 to 10 sec per sleeve. Once the two sleeves have been moved forward against the center flange, the fitting is successfully swaged to the fluid line.

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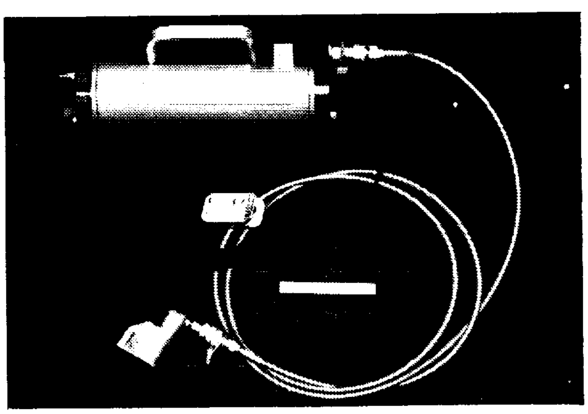

Figure 4. Rynglok Fitting Swage Tool

Torobonder. The Raychem heat shrink fitting is a one-piece nonseparable unit fabricated from a titanium-nickel "memory" alloy that shrinks a predetermined amount when heat is externally applied. NASA has developed an EVA-compatible source for this heat application, which was evaluated on this program (Figure 5). This heat source, known as an Inductron Torobonder, is supplied with a number of different heat source configuration heads. Each fitting half is heated separately with the Inductron Torobonder until it has shrunk onto the tube outer diameter. This operation is complete when the color indicating pads on each fitting turns from light green to black (approximately 300°F). It takes approximately 5 sec for each side of the fitting to shrink onto the tube surface.

Hardware Demonstrations. The MPT and tube cutter head have been successfully demonstrated by both NASA and MDA in various environments. Stainless steel tubing representative of sizes proposed for SSF were cut in the underwater test facility at MDA at tube clearances typical of those for space fluid systems (Figure 6). A precut tube length was manually placed in the space where the section had been removed. Rynglok fittings were then manually slid over the cut joints to hold the precut length in place. The fitting swage tool (Figure 4) was operated by extravehicular mobility unit (EMU) suited subjects to successfully install the Rynglok fittings.

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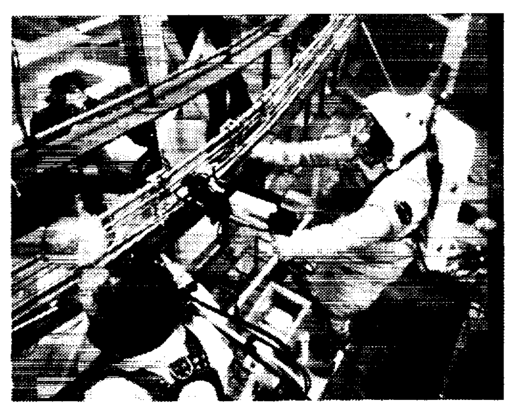

Figure 6. MPT Demonstration in Neutral Buoyancy Environment

The MDT cutter was successfully operated and Rynglok fittings installed in the 0-g environment of the NASA KC-135 (Figure 7). The tools were operated and fittings installed by members of the NASA astronaut crew. Tube sizes representative of fluid lines on SSF were used in the demonstration. Tube samples containing the swaged fittings were leak-tested to determine conformance to selected

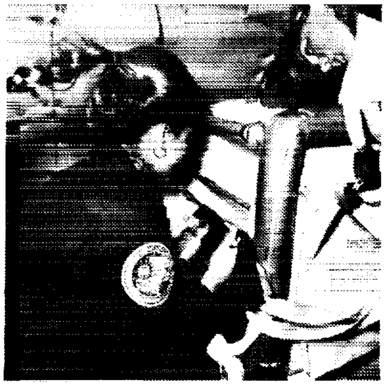

Figure 7. Swaging of Rynglok Fitting on KC-135

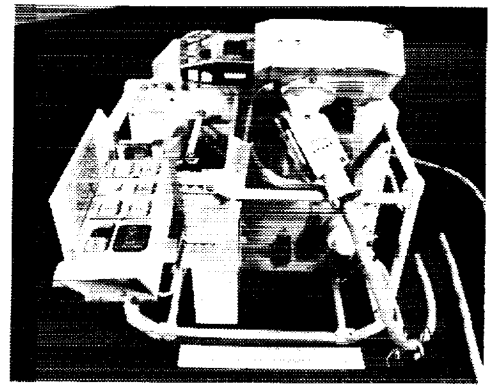

Figure 8. Paton-Developed Universal Hand Tool Space Welding and Metal Processing System

leakage requirements (10-6 scc/sec He at room temperature). Leak rates of all prepared tube samples were between 5×10^{-5} and 8×10^{-5} scc/He at room temperature.

The heat shrink fittings were successfully installed on both stainless steel and titanium tube samples using the Inductron Torobonder. All fittings were installed in a laboratory 1-g environment. Leak testing of the prepared samples indicated acceptable leak rates on all tube samples at 3000 psi and temperature cycles between room temperature and 160°F. Heat shrink fittings installed on stainless steel tubes leaked excessively at temperatures between −50° and −100°F. Differences in coefficient of thermal expansion between the Ti-Ni fitting material (3.67×10^{-6}/°F) and the stainless steel tubing material (9.6×10^{-6}/°F) resulted in contraction of the tube away from the fitting resulting in excessive leakage (> 10^{-3} sec/sec He). Because the heat shrink fitting is developed around the metallurgy of a "memory" Ti-Ni composition, it cannot be fabricated from any other metal alloy composition. The Rynglok fitting can be fabricated from a variety of materials (titanium, stainless steel, aluminum) and can be compatible with a variety of line materials.

Welding

Preliminary Studies. Several studies by both NASA and industry have proposed various welding processes and demonstrations of welding in space. Explosive welding has been proposed by NASA-Langley (Reference 5). Electron beam, laser, plasma arc, and gas tungsten arc welding were proposed for a shuttle flight demonstration through the initial NASA IN-STEP program (Reference 2). NASA also flew an electron beam experiment as a part of its Skylab program. However, none of these activities has led to any further welding-in-space development activities.

The former Soviet Union has been studying welding in space since 1965 and selected electron beam welding as the single process that met all of its requirements and was suitable for the space environment. Paton Welding Institute of the Ukraine developed an operational space welding and metals processing system based on electron beam technology. The system is shown in Figure 8. This space-qualified system, the Universal Hand Tool (UHT), can weld, braze, cut, clean, and coat metals in space. As shown in Figure 1, the welding unit was used successfully in 1986 to repair a damaged line segment on Soyuz T12. No data were available on the resultant weld quality except that it met operational requirements.

MDA Approach. The MDA approach to space welding is to develop a complete on-orbit capability to prepare weld joints, perform the welding operation, and inspect the completed welds. To this end, MDA has developed and demonstrated tools and procedures that will provide a capability to weld in space. MDA has concentrated its effort in understanding and demonstrating the space-qualified Paton UHT because it is the single system most applicable to near-term NASA space vehicle repair. To complement the UHT system, MDA has developed the MPT tube cutter, investigated joint preparation procedures, and developed an on-orbit tube weld inspection tool.

Tool Development. The MPT tube cutter (Figure 3), developed as part of the mechanical tube fitting repair procedure, is compatible with on-orbit weld joint preparation procedures. The MPT tube cutter produces a burr-free external tube cut and is capable of being both soft- and hard-docked to the tube, providing for crew freedom and safety, reaching into areas of minimal fluid line clearance, and cutting all weldable metal tubes proposed for space structure fluid line assemblies.

The Paton-developed UHT (Figure 8) is currently designed to weld flat plate and sheet materials. MDA, as a part of its 1993 joint IRAD program with MSFC, is developing a fixed tube welding head that is compatible with the UHT system. The tube weld head is stationary and provides electron beam orifices through which the tube weld is prepared. This fixed tube weld head will be demonstrated in 1993 as a part of the MSFC-MDA joint IRAD program. The Paton-developed UHT weighs approximately 65 lb and contains a manually operated, EVA-compatible hand-held weld gun that weighs approximately 5 lb (Figure 8). Safety devices built into the system protect the EVA operator and provide for complete crew control. MDA is evaluating the 1.5-kW UHT in its 1993 joint MSFC-MDA IRAD program. Our program will prepare various joint designs in plate, sheet, and tubes using the tools and procedures developed in previous and current IRAD programs.

The 1993 IRAD program will also evaluate other metal processing capabilities of the UHT. Metal cleaning, brazing, cutting, and coating capabilities will be demonstrated. The 1993 IRAD program will also evaluate the on-orbit compatible tube weld nondestructive evaluation (NDE) system being developed for MDA by Oceaneering Space Systems.

MDA is also investigating variations in joint preparation procedures and their effects on weld quality. Such weld joint parameters as squareness, bevel, burr retention, and gap can vary as a result of the space environment in which a weld joint is prepared. Harvey Mudd College has completed a subcontract under the MDA 1993 IRAD program, and the data are currently being analyzed. Leak tests of tube samples prepared with controlled weld parameters have indicated that acceptable electron beam welds can be prepared with significant variations in these joint preparation parameters.

Tool Demonstrations. Our demonstrations to date have involved human interfaces with a high-fidelity model of the UHT; however, no actual welding has been performed until this year. Welding using an operational UHT will begin in 1993 under the MSFC-MDA joint IRAD program. Welding and UHT demonstrations will be performed in a vacuum chamber containing gloves or other provisions for hand-controlled remote UHT operation. Welds will be performed on both flat material and tubes. Tube welds will be inspected using the MDA-developed NDE system. Weld joint designs will be designed and prepared by MSFC. Joint preparation variations developed by Harvey Mudd College will be incorporated as a part of the weld joint designs. UHT performance, MDA-developed tool operation, and weld joint designs will also be evaluated in 1993 through a series of KC-135 flight demonstrations. Participants in the evaluations will include both NASA astronaut crew and MSFC personnel.

MDA has demonstrated the MPT tube cutter extensively through a series of neutral buoyancy and KC-135 evaluations. This modular system has successfully cut various tube materials, sizes, and clearances typical of those proposed for SSF (Figure 6).

MDA has also performed extensive crew interface evaluations with the UHT in both neutral buoyancy (Figure 9) and KC-135 0-g environments. The demonstrations concentrated on crew interfaces, operational scenarios, workstation performance, and safety issues. Crew feedback was vital and has been utilized extensively by Paton scientists to upgrade the UHT system design.

The telerobotic compatibility of the UHT system has been demonstrated by MDA (Figure 10). Using a supervised programmed Kraft telerobotic arm and a specially designed robotic interface, the task scenarios included UHT removal from its storage basket, controlled movement of the UHT along a series of weld joint seams, and return of the UHT to its storage basket. Telerobotic demonstrations utilized both computer- and personnel-monitored tasks. This was a milestone first evaluation of a telerobotic interface with the Paton-developed UHT.

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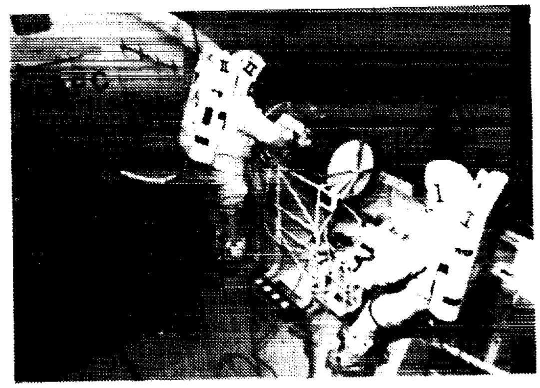

Figure 9. NASA-MDA Space Welding Activity

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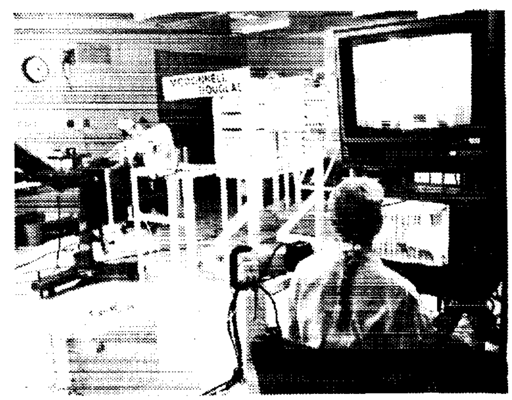

Figure 10. Telerobotic Manipulation of the UHT Space Welding System

CONCLUSIONS

Both welding and mechanical fitting technology are compatible with future on-orbit repair and maintenance tasks for long-duration space vehicles. On-orbit repair by welding will require further study and development for selecting the weld system most appropriate for NASA future applications. The following specific conclusions apply to these two space repair technologies.

Mechanical Tube Fittings

Technology is well developed and adaptable to on-orbit repair scenarios of fluid lines and tube components. Further tool refinements are required to simplify the process and make it more EVA-compatible.

MDA-developed EVA-compatible tools and procedures, when qualified for flight, will have direct application to NASA's near-term space vehicles.

Technology developed on this IRAD program with the Rynglok nonseparable mechanical tube fittings forms the basis upon which MDA Space Station Division WP-2 has developed its on-orbit fluid line repair capability for SSF.

Welding

The Paton-developed electron beam space welder and metal processing system is space-qualified but requires further evaluation and demonstration to understand its full operational potential and performance safety.

MDA-developed tools will complement the UHT and any other selected space welding system to provide a complete on-orbit weld capability for space structure repair and maintenance.

A Space Shuttle EVA flight experiment in 1996 has been jointly proposed to NASA Headquarters by MSFC, JSC, and MDA to demonstrate an on-orbit welding capability using the UHT system and MDA Space Station Division developed tools and procedures.

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ACRONYMS

EB	electron beam
EMU	extravehicular mobility unit
EVA	extravehicular activity
He	helium
ID	inner diameter
IN STEP	In Space Technology Experiments Program
IRAD	internal research and development
IVA	intravehicular activity
JSC	(NASA) Johnson Space Center
KC-135	NASA aircraft for 0-g research
MDA	McDonnell Douglas Aerospace
MPT	Modular Power Tool
MSFC	(NASA) Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
Ni	nickel
OD	outer diameter
scc	standard cubic centimeters
SSD	Space Station Division
SSF	Space Station Freedom
Ti	titanium
UHT	Universal Hand Tool
WP-2	Work Package 2