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**FEASIBILITY OF REMOTELY MANIPULATED WELDING IN SPACE -
A STEP IN THE DEVELOPMENT OF NOVEL JOINING TECHNOLOGIES**

**Koichi Masubuchi
John E. Agapakis
Andrew DeBiccarl
and Christopher von Alt**

**Massachusetts Institute of Technology
Cambridge, Massachusetts 02139**

ABSTRACT

A six-month research program entitled "Feasibility of Remotely Manipulated Welding in Space - A Step in the Development of Novel Joining Technologies" was performed at the Massachusetts Institute of Technology for the Office of Space Science and Applications, NASA, under Contract No. NASW-3740. The work was performed as a part of the Innovative Utilization of the Space Station Program. The final report from M.I.T. was issued in September 1983 (ref. 1). This paper presents a summary of the work performed under this contract.

The objective of this research program was to initiate research for the development of packaged, remotely controlled welding systems for space construction and repair. The research effort included the following tasks:

- Task 1: Identification of probable joining tasks in space
- Task 2: Identification of required levels of automation in space welding tasks
- Task 3: Development of novel space welding concepts
- Task 4: Development of recommended future studies
- Task 5: Preparation of the final report.

Probable joining tasks have been classified, depending upon the complexities and scales of the tasks, into the following three categories:

- Category 1: Construction and repair of simple, small tools, equipment, components, and structural members
- Category 2: Maintenance and repair of major members of space stations
- Category 3: New construction of large, complex structures.

The following six research programs have been recommended for further developing technologies for space welding:

- Program #1: Development of space stud welding which can be remotely manipulated
- Program #2: Development of "instamatic®" GTAW systems for space applications which can be operated by an astronaut with no welding training
- Program #3: Development of flexible space welding systems
- Program #4: Research on space welding using GMAW, EBW, and LBW processes
- Program #5: Research on spatial joining techniques suited for space applications
- Program #6: Development of integrated fabrication systems for certain complex structures.

INTRODUCTION

The objective of this six-month research program was to initiate research for the development of packaged, remotely controlled welding systems for space construction and repair. The research effort included the following tasks

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- Task 4: Development of future studies
- Task 5: Preparation of the final report.

In order to establish permanent human presence in space we must develop technologies of constructing and repairing space stations and other space structures. In early states of the Space Station Program, most construction jobs will be performed on earth and the fabricated modules will then be delivered to space by the Space Shuttle. Only limited final assembly jobs, which may be primarily mechanical fastening, will be performed on site in space. Such fabrication plans, however, limit the designs of these structures, because each module must fit inside the transport vehicle and it must withstand launching stresses that could be considerable. It is evident that large-scale utilization of space will necessitate more extensive construction work on site. Furthermore, continuous operations of space stations and other structures will require maintenance and repairs of these space structures. It is therefore very important to develop metal joining technology, and especially high-quality welding, in space.

It should be mentioned that close relationships exist between welding technologies and structural designs. Many space structures designed so far appear to be based on an assumption that welding fabrication in space is not possible. Much more versatile structural design can be achieved once the space welding technology is well developed.

Welding is a relatively complicated joining process which requires certain scientific knowledge and human skills. Proper processes, equipment, and consumables, as well as joint design and welding conditions (welding current, arc voltage, torch travel speed, etc.) must be used to successfully weld certain materials in given thicknesses. Welding operations, including manipulation of the welding torch, must be performed in a proper manner in order to produce a weld free from defects such as cracks, lack of fusion, porosity, and slag inclusion. Welding engineers have spent considerable effort to minimize the adverse effects caused by oxygen, nitrogen, and hydrogen.

Welding in space certainly creates great challenges and opportunities for welding engineers. The lack of an atmosphere in space will be helpful in obtaining uncontaminated welds and also will readily permit the use of high power-density welding processes such as electron beam welding. However, a number of problems will be posed by the particular nature of the space environment and the great distance from the earth. In order to successfully perform welding construction and repair in space, we must first study problems associated with welding in space and then develop welding technologies suitable for space applications.

ADVANTAGES OF WELDING OVER MECHANICAL JOINING AND ADHESIVE BONDING

HIGHER STRENGTH OVER A WIDE RANGE OF TEMPERATURES
MORE RIGIDITY
AIR AND WATER TIGHTNESS

COMPLEX CHARACTERISTICS OF WELDING FABRICATION

1. MANY DIFFERENT PROCESSES, MATERIALS, AND STRUCTURES
2. ADDITIONAL PROBLEMS WITH WELDING FABRICATION OF COMPLEX STRUCTURES
3. SKILLS REQUIRED
4. WELDING IS ONLY A PART OF TOTAL FABRICATION SYSTEM INCLUDING:
 - A. PLATE CUTTING, FORMING (IF NECESSARY), AND EDGE PREPARATION
 - B. ASSEMBLY OF PARTS TO BE WELDED AND TACK WELDING
 - C. WELDING
 - D. INSPECTION

Before discussing welding in detail, let us discuss briefly the advantages of welding over mechanical joining such as riveting and adhesive bonding. First of all, welded joints normally have higher strengths over a wide range of temperatures than mechanical and adhesive-bonded joints. Welded joints have higher rigidity than mechanical and adhesive-bonded joints. It is easier to obtain air and water-tight welded joints than mechanical and adhesive-bonded joints.

Although welding is widely used because of its advantages over other joining methods, there are some problems with welding fabrication, one of which is that it is rather complicated and requires some knowledge and skill.

First, there are many different processes which are commercially available today. Many of these processes may be used for space applications. In space applications, on the other hand, we must consider many different materials and different structures.

Even though the welding of simple joints in a certain material is successfully made, it does not necessarily mean that welding fabrication of a complex structure would be successfully achieved. There are certain problems associated with welding fabrication of complex structures composed with a number of members. One of the problems is related to residual stresses and distortion.

Manual arc welding, which is still widely used, is performed by people who are specially trained and qualified. Even in the case of automatic welding, most machines need to be operated by people who have received special training.

Welding is only a part of total fabrication system that includes (a) plate cutting, forming (if necessary), and edge preparation, (b) assembly of parts to be welded and tack welding, (c) welding, and (d) inspection. In considering welding in space, we must also consider how to perform total fabrication in space.

NUMBER OF EXISTING PUBLICATIONS ON SPACE WELDING AND RELATED SUBJECTS

(a) Classification by Countries

	<u>WELDING AND BRAZING</u>	<u>OTHER</u>	<u>TOTAL</u>
U.S.A.	19	52	67
U.S.S.R.	22	11	33
GERMANY	12	5	17
U.K.	3	0	3
FRANCE	1	0	1
TOTAL	53	68	121

(b) Classification of Publications on Welding and Brazing

ELECTRON BEAM WELDING	10
BRAZING	6
SOLAR ENERGY WELDING	4
COLD WELDING AND DIFFUSION BONDING	3
EXPLOSIVE WELDING	2
GENERAL	28
TOTAL	53

As the first step for identifying probable joining tasks in space, a survey was made on examining publications on space welding and related subjects. The result of the literature survey is presented in APPENDIX A of reference 1. The emphasis of the discussion is placed on identifying (a) those who are studying, (b) which processes are being considered, (c) which materials are being used, and (d) which kinds of applications are being examined.

Serious technical publications on space welding started to appear around 1966, when Lawrence and Schollhammer prepared a report entitled "Hand Held Electron Beam and External Power Supply" (ref. 2). APPENDIX A of reference 1 contains 121 citations on space welding and related subjects, of which 53 publications cover welding and brazing as major topics (see table above). Most of the information on space welding and fabrication has been generated by two countries, U.S.A. and U.S.S.R. In preparing the table, efforts have been made as much as possible to identify the country where the work was performed. For example, when a Soviet author presented a paper in a technical journal published in U.S.A., the paper was regarded as a publication from U.S.S.R. On the other hand, when an author in U.K. wrote a paper referring to work done in U.S.S.R., the paper was regarded as a publication from U.K. Papers published in the Federal Republic of Germany and the German Democratic Republic are combined and listed as papers from Germany.

Among the 53 publications on welding and brazing, electron beam welding has been discussed in the largest number of articles, as shown in the table above. Other processes that have been discussed for space applications include solar energy welding, cold welding and diffusion bonding, and explosive welding.

PAST WELDING EXPERIMENTS ON SPACESHIPS

1. U.S.S.R., SOYUZ-6, 1969

PROCESSES: ELECTRON BEAM
PLASMA ARC
GMA

MATERIALS: STAINLESS STEEL
ALUMINUM ALLOY
TITANIUM ALLOY

2. U.S.A., SKYLABS, 1973

- A. METALS MELTING EXPERIMENT, M551
- B. BRAZING EXPERIMENT, M552
- C. SPHERE FORMING EXPERIMENT, M553

M551: ELECTRON BEAM
ALUMINUM ALLOY, STAINLESS STEEL, NICKEL
M552: EXOTHERMIC BRAZING OF STAINLESS STEEL TUBES
M553: ELECTRON BEAM
TUNGSTEN

So far, there have been only two sets of welding experiments performed aboard a spaceship whose results have been published. They are those performed in 1969 by the U.S.S.R. during the Soyuz-6 mission and those performed in 1973 by the U.S.A. on board the Skylab. APPENDIX A of reference 1 presents a summary of the results obtained in these experiments. Both experiments, however, were aimed at demonstrating experimentally that welding of metals could be achieved in space.

(1) Soyuz-6 Experiments. Descriptions presented here come primarily from a paper by Paton (ref. 3). Welding experiments were performed in an enclosed unit, called the "Vulkan" welder, especially designed for the experiments. As an autonomous unit, it was connected to the vehicle system only with telemetry cables. It had two sections, one of which contained the welding burners and an electron beam gun, and a rotating table with samples. The second module consisted of power sources, control devices for measuring and converting units, and automatic communication systems. The machine was activated by pilot-cosmonauts. The experiments were performed using the three processes and the three materials shown above.

(2) Skylab Experiments. On board the Skylab, 54 experiments were performed. Among them, 18 were related to materials science and manufacturing processes. Experiments related to welding were performed in M551, M552, and M553.

In the M551 experiment, the electron beam was used to conduct typical welding tests. Experiments were performed on three materials including (a) an aluminum alloy (22019), (b) a stainless steel (321), and (c) a thoria dispersed nickel.

The M552 experiments were performed with the primary objective of demonstrating feasibility of brazing as a method of space repair and maintenance. A single assembly comprising four brazing packages was mounted in the same vacuum chamber as M551.

The M553 experiment was not exactly on welding, but it was closely related to welding. The main objective of the M553 experiment was to study the mechanisms of sphere melting under zero gravity. The experiment was performed using the same equipment used for the M551 experiment.

UNIQUE REQUIREMENTS FOR SPACE WELDING FABRICATION

(1) DIFFERENCES IN ENVIRONMENTS

	Space			Earth
	Case 1 Outside Space Station	Case 2 In a Chamber Inside Space Station	Case 3 Inside Space Station	
Gravity	Zero	Zero	Zero	One
Atmosphere	Vacuum	Vacuum	Air	Air
Temperature	Extreme	Room Temperature	Room Temperature	Room Temperature
Space Suit	Yes	No	No	No

(2) REMOTENESS FROM THE EARTH

- (A) TELEPRESENCE OF EXPERTS
- (B) REMOTE MANIPULATION
- (C) PACKAGING OF OPERATIONS INVOLVED IN WELDING FABRICATION
- "INSTAMATIC"® WELDING SYSTEMS -

Welding construction and repair in space have rather unique requirements, different from ordinary welding jobs on earth. Major differences between space welding and ordinary welding on earth come from (1) differences in environment and (2) remoteness of space welding from the earth.

1. Differences in Environment. The table shown above compares differences in environments between space welding and ordinary welding on earth. The space welding environments may be divided into the following three cases:

Case 1: Outside a space station. Gravity is zero. The atmosphere is a vacuum, and the temperatures are extreme. Welding may be done manually, but a worker is in a space suit which greatly restricts his/her movements.

Case 2: In a vacuum chamber inside a space station. Gravity is zero. The atmosphere is a vacuum, but the temperature is at room temperature. A worker does not wear a space suit, but welding must be done remotely or through gloves attached to the chamber. The M551, M552, and M553 experiments performed in the Skylab were done under Case 2.

Case 3. Inside a space station. Gravity is zero. The atmosphere is air, and the temperature is at room temperature. Workers wear no special space suits.

2. Remoteness from the earth. Space welding must be performed in locations extremely far from the earth, where there are no large numbers of people with vast knowledge and experience and no abundant amounts of material and energy resources. In a space station, only a small view is available.

CLASSIFICATION OF PROBABLE JOINING TASKS IN SPACE

- **Category 1: CONSTRUCTION AND REPAIR OF SIMPLE, SMALL TOOLS, EQUIPMENT COMPONENTS, AND STRUCTURAL MEMBERS**

- **Category 2: MAINTENANCE AND REPAIR OF MAJOR MEMBERS OF SPACE STATIONS**

- **Category 3: NEW CONSTRUCTION OF LARGE, COMPLEX SPACE STRUCTURES**

Probable joining tasks in space may be classified, depending upon the complexities and scales of the tasks, into the three categories shown above. We believe that it is a good idea to start working on simple cases (Category 1) and gradually expand the effort to cover more and more complex cases (Categories 2 and 3) as the technology develops.

Category 1. It would be extremely useful if techniques could be developed in the welding of various joints of tools, equipment components and structural sections in space. Some welding jobs will be done inside a space station, while other jobs will need to be done outside the space station. One could probably say that most of necessary welding jobs inside a space station could be done almost immediately, if experienced welding engineers and qualified welders were sent to a space station. However, this would be difficult to do, since a space station will be manned by a limited number of crew members who must do many things besides welding. Therefore, the major problem here is how to accomplish simple welding tasks without having welding engineers and welders present.

Category 2. There will also be the need for developing capabilities of performing limited maintenance and repair jobs on some major structural members, such as platforms, bulkheads, shell structures, etc., of space stations. However, since these jobs tend to require complex and delicate operations, only limited jobs will be performed in the near future.

Unlike structures such as ships, pressure vessels, and even automobiles which are mainly fabricated with metal plates and sheets, space structures are mainly fabricated with composite panels. These panels may be made with thin metals in honeycomb structures, they may be made with metals and non-metals, or they may even be made with non-metals such as fiber reinforced plastics. Welding repairs of these composite panels are very difficult, and in some cases impossible. Nevertheless, there still will be some maintenance and repair jobs which can be done by welding. A few such examples are presented later.

Category 3. The use of welding to assemble large complex structures has many advantages. Due to Space Shuttle payload considerations, it will be more economical to launch only structural components, saving the final joining of these sub-structures until they are in orbit.

APPLICABILITIES OF EXISTING WELDING PROCESSES TO SPACE

(1) PROCESSES WHICH APPEAR TO HAVE BROAD, GENERAL APPLICATIONS

GAS TUNGSTEN ARC WELDING (GTAW)
GAS METAL ARC WELDING (GMAW)
PLASMA ARC WELDING AND CUTTING (PAW AND PAC)
ELECTRON BEAM WELDING AND CUTTING (EBW AND EBC)
LASER BEAM WELDING AND CUTTING (LBW AND LBC)

(2) PROCESSES WHICH APPEAR TO HAVE LIMITED BUT UNIQUE APPLICATIONS

STUD WELDING
EXOTHERMIC BRAZING
SOME RESISTANCE WELDING PROCESSES

One could perhaps say that almost all welding processes which are currently in use on earth can be used in space. This is because the only environmental difference between ordinary welding on earth and space welding inside a space station (Case 3) is the lack of gravity. It does not mean, however, that almost all welding processes will be or should be used in space. On the contrary, only a limited number of processes will actually be used in space in the near future.

An important factor is that many space structures will be made of light and high-performance materials such as aluminum alloys, titanium alloys, stainless steels, etc., since it is extremely costly to transport anything from the earth to a space station. To achieve light weight, most structures will be made with thin plates and composite materials. Very few structures will be made with plates over 12 mm (1/2 inch) thick. Therefore, the welding processes which may be used in space will be those which are suitable for joining light and high-performance metals. It is important that these processes do not require heavy equipment using a large amount of electrical power.

Efforts have been made to identify welding (and cutting) processes which appear to be suitable for space applications. The results are given in two different categories: (1) processes which appear to have broad, general applications and (2) processes which appear to have limited but unique applications.

Those welding and cutting processes which appear to have broad, general applications in space include gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), plasma arc welding and cutting (PAW and PAC), electron beam welding and cutting (EBW and EBC), and laser beam welding and cutting (LBW and LBC). Detailed discussions regarding possible uses of these processes are presented in reference 1.

A number of welding processes may be used for limited but unique applications in space. However, it is rather difficult to identify these processes and their possible applications without knowing specific structures and tools to be welded. Once specific joint tasks, including materials and plate thicknesses, are identified, one could select the process most suitable for the specific applications. The uses of stud welding, exothermic brazing, and some resistance welding processes have been discussed

PROBABLE JOINING TASKS IN SPACE

Category 1: CONSTRUCTION AND REPAIR OF SIMPLE, SMALL TOOLS, EQUIPMENT COMPONENTS, AND STRUCTURAL MEMBERS

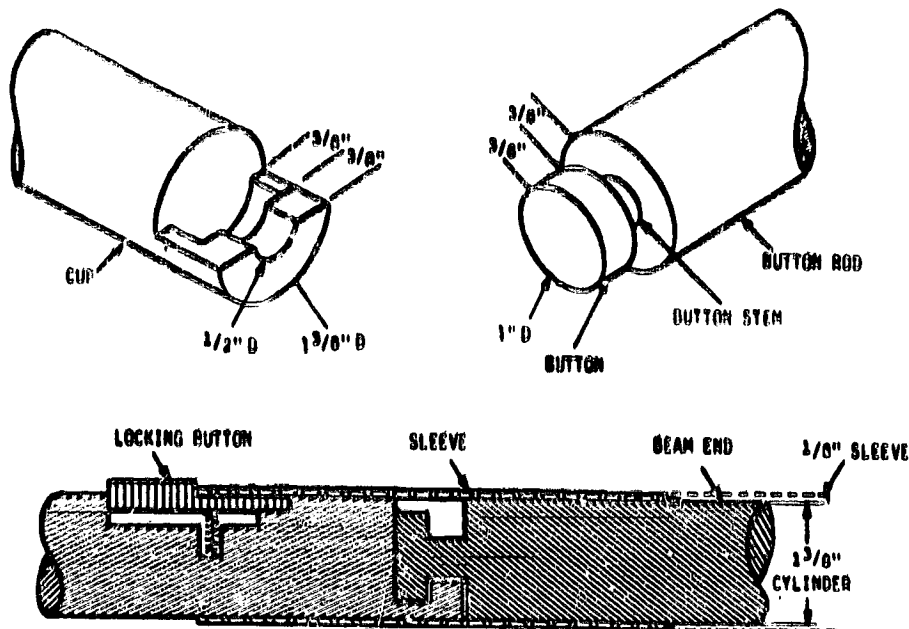
The information generated thus far, including that obtained during welding experiments performed in space ships, indicates that welding of metals in space can be achieved using processes similar to those which have been used for fabricating similar structures on earth. Vacuum and microgravity do not seem to cause significant problems with welding metals. In fact, when joining some metals using certain processes, it is easier to weld them in space than on earth.

The major problem associated with space welding comes from the fact that the work must be performed by a limited number of crew members with no or little knowledge, experience, and skills in welding, using limited supplies of materials (welding machines, filler metals, shielding gas, etc.) and energy resources (electricity, etc.).

There are obviously many joining tasks to be performed in space using various processes to join different materials in different shapes and thicknesses used for a variety of structures. However, it is rather difficult to determine details of joining tasks such as joint designs, processes to be used, and welding conditions employed, unless some details of structural designs are defined.

Nevertheless, certain discussions still can be made if we focus on certain types of generic welding technologies which can be used for construction and repair of various structures in space. For example, once the technology of welding fabrication of aluminum structures for airplanes is established the same basic technology can be used for fabricating aluminum structures for space applications, or even ships and storage tanks. Since the major objective of this research program is to develop novel welding technologies that could be used for fabricating and repairing various tools, machine components, and structures in space rather than to develop details of welding procedures for certain specific applications, discussions here are focused on the development of generic technologies of space welding fabrication.

Probable joining tasks in space have been classified into Categories 1, 2, and 3 as discussed earlier. Presented in the following are some examples of Category 1 joining tasks, which are to construct and repair simple, small tools, equipment components, and structural members.



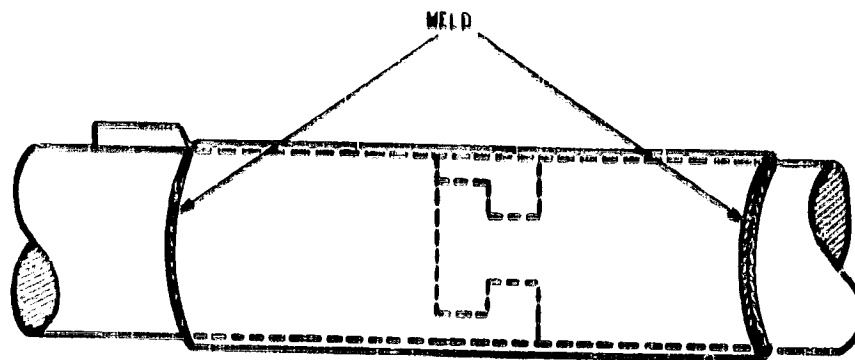
M.I.T. CONNECTOR DESIGN

An example of the use of welding machines to perform simple construction tasks is the seal welding of mechanical joints. Although mechanical fastening is simple, it has some inherent problems as follows:

- (a) Mechanical joints do not have high rigidity. Therefore, it is rather difficult to maintain their exact shapes, especially when a number of modules are joined.
- (b) Mechanical joints may become loose during service.
- (c) It is difficult to obtain air tightness during service.

Many structures that are currently being considered for construction in space utilize the joining of pipes to form truss elements. These structures are designed to be assembled by hand by the astronauts in an extra-vehicular (EVA) mode. This will require joints that can be easily fit-up and assembled.

A prototype of this joint has been designed by the Space Systems Laboratory of the Massachusetts Institute of Technology, and is shown above. The joint uses two cylinder machines in such a manner that they interlock. A sleeve is attached to one of the interlocking cylinders, and this sleeve is pushed into place over the connected joint to keep the pieces in place. The sleeve is held in place by a spring lock. This prototype has been used to construct a number of truss elements in the Marshall Neutral Buoyancy Facility.

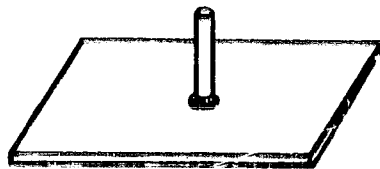


Possible permanent fastening of the M.I.T. connector

Mechanical joints are designed to have some play in them in order to aid the astronaut/builder in fitting up the pieces to be assembled and also to allow the connector to perform properly even if some dirt or other contaminant should somehow get in the way. Also, some clearance is necessary to prevent the sleeve from cold welding itself to a cylinder before the connection is completed.

However, once the joint connection has been completed, it would be beneficial if all potential motions in the joint could be eliminated (remove the play in the joint). This could be accomplished by welding the connecting sleeve in place after the mechanical fastening is done. Two welds, one at each end of the sleeve, as shown above, would fix the joint in place permanently. This would allow for the ease in assembling structures and still obtaining high rigidity of the structure.

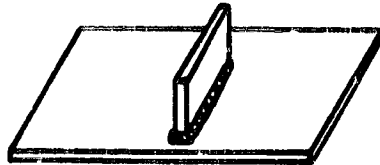
For the welding of the sleeve, a device similar to that used to automatically weld pipes on earth could be developed. This space pipe welder would only need to be placed into position by the astronaut. Once in place, the welding machine would automatically make the circumferential weld needed. This totally automatic welding machine would eliminate the need for a welding engineer in space for this task, and an astronaut could be trained to use it in a minimum amount of time. Some examples of totally automatic welding systems which are capable of performing certain simple, prescribed tasks are discussed in the following page.



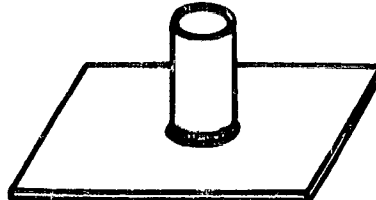
g. Stud Welding a Bar to a Flat Plate



b. Stud Welding a Bar to a Pipe



c. Joining a Plate to a Plate by Fillet Welding



d. Joining a Pipe to a Plate by Fillet Welding



e. Lap Welding a Cover Plate to a Flat Plate



f. Replacing a Section of a Pipe

"instamatic®" systems

It is technically possible to develop totally automatic welding systems capable of enabling an astronaut with little or no training for welding to perform certain simple, prescribed tasks in space. In fact, researchers at M.I.T. under the direction of Professor K. Masubuchi have been working during the last several years to develop a group of fully automated and integrated welding systems which package many operations involved in welding, including feeding the electrode and manipulating the torch. These machines have been nicknamed "instamatic welding systems", since they are similar to easy-to-operate "instamatic®" cameras with which a person with little knowledge of photography can take good pictures. The idea of developing "packaged dedicated welding systems" was originally conceived while M.I.T. researchers were studying means of performing underwater welding in deep sea.

In past research programs at M.I.T. the six types of joints shown above were studied:

- Type 1: Stud welding of a bar to a flat plate
- Type 2: Stud welding of a bar to a pipe
- Type 3: Joining of a flat plate to a flat plate by fillet welding
- Type 4: Joining of a pipe to a flat plate
- Type 5: Lap welding of a cover plate to a flat plate
- Type 6: Replacing a section of a pipe

Actual hardware for Types 1, 3, and 5 joints has been built and tested. Further details of these designs are presented in APPENDIX B of reference 1. We believe that similar systems could be developed for space applications.

Category 2: MAINTENANCE AND REPAIR OF MAJOR MEMBERS OF SPACE STATIONS

- 1. ON-SITE WELDING OF STUDS FOR MECHANICAL FASTENING OF STRUCTURAL MODULES OF SPACE STATIONS
- 2. PLACING STUDS FOR VARIOUS PURPOSES
- 3. WELDING PATCHES ON SOME STRUCTURAL MEMBERS

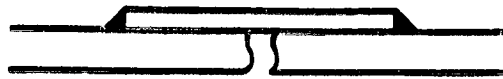
Now we would like to discuss welding jobs under Category 2. There will be some maintenance and repair jobs which can be done by welding, of which a few examples are:

- (1) On-site welding of studs for mechanical fastening of structural modules of space stations,
- (2) Placing studs for various purposes, and
- (3) Welding patches on some structural members.

On-Site Welding of Studs. As stated earlier, most construction jobs in the early stages of the Space Station Program will be performed on earth, and fabricated modules will be joined, probably by mechanical fastening methods such as bolts and nuts. Although most bolts will be placed on earth, we may find it necessary to place some bolts on site in space. Or we may find that some joints are mismatched, requiring some bolts to be cut and new bolts placed in different locations. The stud welding process can be extremely useful for welding studs on site.

Placing Studs for Various Purposes. Stud welding may be useful for placing studs on some major structural components for various purposes. For example, there will be many occasions in which insulation materials will need to be placed over some structural members. By using stud welding it is possible to place studs without piercing holes through the structural members; then these studs can be used to secure the insulation materials.

Welding Patches. Some structural members may be damaged during service. For example, a hole may be pierced in a wall of a space station when it is hit by a meteorite or other space debris. It is possible to develop techniques for repairing some of the damages on site, for example by placing a patch over the damaged areas - a "bandage" over the damaged area of the space station. Three typical methods of placing a patch over a damaged structural member of a space station are shown on the next page.



a. Attach a patch by lap welding



b. Butt weld an insert plate



c. Stud weld bolts on the structure and then securely fasten the cover plate work holes by nuts

Three typical methods of placing a patch plate over a damaged structural member of a space station

A patch may be lap welded to the structure as shown in Figure a. In the case shown in Figure b, the damaged areas are removed, and an insert plate is butt welded to the structural member. In the case shown in Figure c, bolts are stud welded to the structure, and a patch plate with holes is placed over the structure to cover the damaged areas; then the patch plate is securely fastened to the structure by tightening nuts on the bolts.

Each of the above three methods has advantages and disadvantages over the other methods. In repairing the structural members of a space station which is composed of light structures in thin metals, the third method of placing bolts by stud welding may be a good method because stud welding can be made with very little heat effect to the structure.

Category 3: New Construction of Large, Complex Space Structures. There will be a need for welding fabrication of new, large and complex structures in space. For example, by performing the final construction in space, the structure does not have to be designed to withstand the high stresses which could occur during launch. The M.I.T. final report discusses a few examples including:

- (a) Attachment of a multiple docking adapter/airlock module to an external fuel tank used for an orbital platform, and
- (b) The beam builder

However, details of these discussions are not given here, since welding jobs under Category 3 will not be performed until welding jobs under Categories 1 and 2 are successfully accomplished.

TASK 2: IDENTIFICATION OF REQUIRED LEVEL OF AUTOMATION IN SPACE WELDING TASKS

1. WELDING TASK ANALYSIS

- A. GENERAL TASK CONSIDERATION
- B. TOOL MANIPULATION
- C. SELECTION OF PROCESS TYPE AND PARAMETERS
- D. PROCESS CONTROL
- E. INSPECTION AND QUALITY CONTROL

2. OPERATIONAL MODES FOR SPACE WELDING FABRICATION

- A. MANUAL WELDING BY AN OPERATOR AT THE REMOTE SITE
- B. REMOTELY MANIPULATED WELDING
- C. TOTALLY AUTONOMOUS SYSTEMS

3. EXPERIMENTAL STUDY

Under Task 2 efforts were made to identify the required level of automation in space welding tasks. In order to rationally decide on the degree of required or attainable automation and autonomy in space welding applications, one should consider the requirements of the task on hand, the availability of human operators on site, and the current or projected state of the art in the field. The following studies were made:

- (1) Welding task analysis
- (2) Operational modes for space welding fabrication, and
- (3) Experimental study.

Welding Task Analysis. Due to the limitations of the existing technology, most of the currently planned space structures are not designed for welded construction. Therefore, only a limited number of possible welding tasks can be fully identified at this point. Efforts were made to identify some "generic" welding tasks. The analysis covered the following subjects:

- (a) General task consideration
- (b) Tool manipulation
- (c) Selection of process type and parameters
- (d) Process control, and
- (e) Inspection and quality control.

Details are presented in reference 1.

Operational Modes. Some discussions are presented on the next page.

Experimental Study. An experimental study was initiated at M.I.T. in order to rationally establish the fundamental components of the generic remote joining tasks that can or should be automated. Since the current state of the art limits the extent of such automation, there will be necessarily some higher level tasks that need to be performed by the human operator. The tasks that are most difficult (or even impossible) to effectively perform remotely, and that disproportionately increase the total completion time, are more likely to be passed on to a local computer. In the confines of this initial investigation, only the positioning and path tracking manual control tasks were examined. For simulation of remote manipulation, the facilities in the Machine Systems Laboratory of the Mechanical Engineering Department at M.I.T. were used. The results obtained to date indicate that welding performance can be significantly impaired during remote manipulation, especially when time delay is present. The results are presented in APPENDIX D of reference 1.

OPERATIONAL MODES FOR SPACE WELDING

A. MANUAL WELDING BY OPERATOR ON-SITE

A.1 WELDING IN ENCLOSED LIFE-SUSTAINING HABITAT

A.2 WELDING OUTSIDE AN ENCLOSED HABITAT

A.2.1 UNAIDED EXTRA-VEHICULAR ACTIVITY (EVA)

A.2.2 AIDED E.V.A.

MANNED MANEUVERING UNIT (MMU)

OPEN CHERRY PICKER (OCP)

B. REMOTELY MANIPULATED WELDING

B.1 REMOTELY MANIPULATED WELDING

B.1.1. MANIPULATION USING REMOTE MANIPULATOR SYSTEM (RMS)
OF THE SHUTTLE

B.1.2. MANIPULATION FROM A MANNED REMOTE WORK STATION (MRWS)

B.2 REMOTE MANIPULATION FROM EARTH (TELEPRESENCE)

C. FULLY AUTONOMOUS UNMANNED WELDING SYSTEMS

A number of different operational modes for space welding are possible. These modes range from fully manned to fully autonomous and can be classified as shown above, depending upon the level to which a human operator is used, his/her proximity to the task site, and the means used for translation and effecting the work task.

Manual Welding. If welding is performed inside an enclosed life-sustaining habitat, then it is no different, operationally, than that performed on earth. However, if welding is performed outside the space station by an operator in a space suit, then we can further discriminate between the following modes:

- (1) Unaided extra-vehicular activity (EVA), and
- (2) Aided E.V.A. in which other means are used to transport and position the operator in the remote site. This case is further classified into:
 - 2.1. Manned maneuvering unit, and
 - 2.2. Open cherry picker

A manned maneuvering unit is a self contained system which can provide the operator with a pressurized means for translation to and from the welding site. An open cherry picker is a special platform mounted on the end of a manipulator system which can provide means for transporting and positioning an EVA operator.

Remotely Manipulated Welding. Remote teleoperation is essentially an interim case between fully manual and fully autonomous operations. Remotely manipulated welding can be further classified into:

- (1) Remotely manipulated welding
 - 1.1. Manipulation using a remote manipulation system of the shuttle
 - 1.2. Manipulation from a manned remote work station
- (2) Remote manipulation from earth (telepresence of welding experts).

Fully Autonomous Welding. In both the previously mentioned cases, a human operator is available and performs certain tasks. In a completely autonomous system, on the other hand, the role of the operator will be diminished and the computer will handle all the decision making. However, it is not feasible to develop such a welding system in the near future.

TASK 3: DEVELOPMENT OF NOVEL SPACE WELDING CONCEPTS

I. DEVELOPMENT OF SPACE WELDING TECHNOLOGIES WHICH DO NOT REQUIRE THE ON-SITE PRESENCE OF WELDING ENGINEERS AND WELDERS

- 1.A. COMPLETELY REMOTE WELDING TECHNOLOGY
- 1.B. INTEGRATED AND AUTOMATED WELDING SYSTEMS WHICH CAN BE OPERATED BY PERSONS WITH NO WELDING SKILL
- 1.C. WELDING TECHNOLOGIES THROUGH TELEPRESENCE

2. DEVELOPMENT OF NEW WELDING PROCESSES AND PROCEDURES UNIQUELY SUITED FOR SPACE APPLICATIONS

In order to successfully accomplish construction, maintenance, and repair of space stations, we need to develop novel welding concepts. The necessary research and development efforts may be classified into:

- (1) Efforts to develop space welding technologies which do not require the on-site presence of welding engineers, and
- (2) Efforts to develop new welding processes and procedures uniquely suited for space applications.

Space Welding Technologies Which Do Not Require On-Site Presence. The efforts necessary to develop space welding technologies which do not require the on-site presence of welding engineers and welders will include the following:

- (1) Efforts to develop welding systems which can perform certain welding jobs through completely remote manipulation,
- (2) Efforts to develop welding systems by which operators with no welding knowledge and skill can perform certain welding jobs, and
- (3) Efforts to develop technologies for performing certain welding jobs through proper guidance and assistance from the earth station (telepresence of welding experts).

Welding Technologies for Special Applications. There is also a need to develop new welding technologies uniquely suited for space applications, which are radically different from the welding technologies used on the earth. A few examples are as follows:

- (1) Electron Beam Welding. One can develop a new system of electron beam welding uniquely suited for space applications. Electron beam welding guns small enough to be portable may also be developed. Some efforts along this line have already been made.
- (2) Exothermic Brazing. Some basic work was already done during the M552 experiment on the feasibility of accomplishing the joining of tubes by exothermic brazing. It is worth exploring the feasibilities of developing designs for devices which can perform certain joining tasks in space.
- (3) Solar Welding. Another very likely method of welding in space is to utilize solar heat by use of properly designed optical lens systems. Again, some efforts along this line have already been made.

TASK 4: RECOMMENDED FUTURE STUDIES

GROUP A: RESEARCH PROGRAMS RECOMMENDED TO BE PERFORMED IMMEDIATELY

- PROGRAM #1: SPACE STUD WELDING SYSTEMS WHICH CAN BE REMOTELY MANIPULATED
- PROGRAM #2: "INSTAMATIC"® GTAW SYSTEMS FOR SPACE APPLICATIONS WHICH CAN BE OPERATED BY AN ASTRONAUT WITH NO WELDING TRAINING
- PROGRAM #3: FLEXIBLE SPACE WELDING SYSTEMS

GROUP B: RESEARCH PROGRAMS RECOMMENDED TO BE PERFORMED AFTER SOME RESULTS OF GROUP A RESEARCH HAVE BEEN OBTAINED

- PROGRAM #4: SPACE WELDING USING GMAW, EBW, AND LBW PROCESSES
- PROGRAM #5: SPECIAL JOINING TECHNIQUES SUITED FOR SPACE APPLICATIONS
- PROGRAM #6: INTEGRATED FABRICATION SYSTEMS FOR CERTAIN COMPLEX SPACE STRUCTURES

Under Task 4 efforts were made to develop recommended research programs on space welding. Six research programs as shown above have been recommended. Discussions on the first group including Research Programs #1, #2, and #3 are rather specific and in detail, since we already have concrete ideas about (a) what should be done and (b) what is perhaps achievable. On the other hand, discussions on the second group including Research Programs #4, #5, and #6 are rather general and brief, since plans for these programs may be significantly affected by the outcome of Programs #1, #2, and #3.

In developing space welding technologies, we must recognize that not a single actual weld has ever been made in space. Welding experiments were performed in 1969 by the U.S.S.R. during the Soyuz-6 mission and in 1973 by the U.S.A. during the Skylab mission. However, these were scientific experiments to demonstrate that welding can be achieved successfully under microgravity conditions.

If we compare the state of the space welding technology to that of a human, we could probably say the present state of the space welding technology is similar to that of an unborn fetus. What we are proposing under the Research Programs #1, #2, and #3 is equivalent to an effort to make an infant successfully crawl and totter a few steps. This would lead to a healthy, walking child who will soon run and jump. Just like parents of a child who would like to see their child grow as soon as possible, we are very anxious to see space welding technologies develop as fast as possible and as far as possible. But we must have enough patience to develop the technologies step by step, first developing methods of performing simple welding tasks using processes which we know will work, and then gradually expanding our capability to perform increasingly more complex tasks using more sophisticated techniques.

**Program 1: STUD WELDING SYSTEMS WHICH CAN BE
REMOTELY MANIPULATED**

RESEARCH PHASES	YEARS AFTER THE INITIATION OF THE RESEARCH PROGRAM										
	1	2	3	4	5	6	7	8	9	10	
PHASE 1: BASIC STUDY	■										
PHASE 2: LABORATORY TESTING OF THE FIRST GENERATION STUD WELDING SYSTEM			■								
PHASE 3: SIMULATED ZERO GRAVITY TESTING OF SYSTEMS DEVELOPED IN PHASE 2				■							
PHASE 4: DEVELOPMENT AND LABORATORY TESTING OF INTEGRATED STUD WELDING SYSTEMS					■						
PHASE 5: SIMULATED ZERO GRAVITY TESTING OF SYSTEMS DEVELOPED IN PHASE 4						■					
PHASE 6: TESTING IN SPACE OF THE INTEGRATED STUD WELDING SYSTEMS							■				

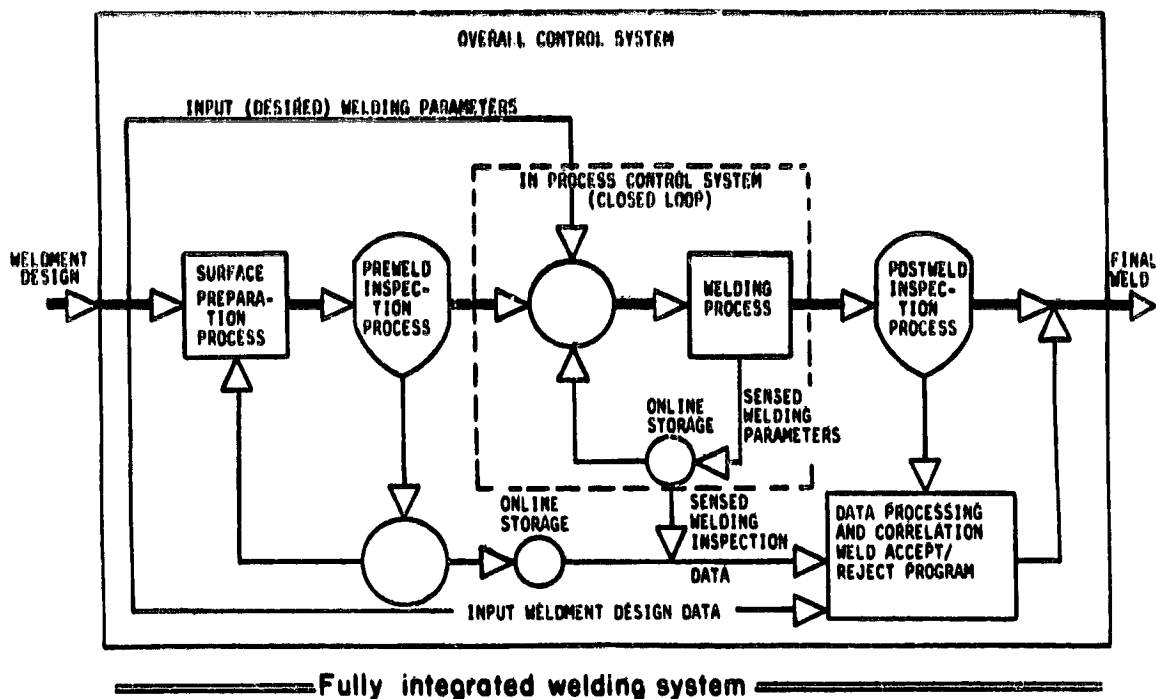
It is recommended that a research program be carried out with the objective of developing space stud welding systems which can be remotely manipulated. The only thing that an operator aboard a space station must do is to place the welding system at the right location, either manually or using a simple manipulator. Then all other necessary operations, including selection of appropriate welding parameters and activation of the welding, are to be performed in the command station. APPENDIX C of reference 1 identifies some technical problems which need to be solved in order to achieve the objective, and discusses possible ways for solving the problems.

It is recommended that the research be carried out in six phases with different specific objectives and time frames as shown above. We should be ready for testing in space of the integrated space stud welding systems (Phase 6) in six years after completing Phases 1 through 5. Reference 1 discusses details of these phases. Given below is a brief discussion of Phase 1, the objective of which is to conduct a basic study on space stud welding.

Phase 1, which will be completed in two years, will consist of the following steps:

- Step 1-1: Stud welding experiments in a vacuum
- Step 1-2: Development of stud welding materials and optimum welding conditions for selected 2000 series aluminum alloys
- Step 1-3: Development of initial designs of the first generation space and stud welding systems.

In Step 1-1, a study will be made to determine whether it is possible to perform stud welding in a vacuum. The experiments will be performed using the pressure chamber presently installed at M.I.T. Efforts will include determining whether the existence of certain gases or mixture of gases would facilitate the initiation and maintenance of an arc in a vacuum. In selecting the materials and stud sizes to be investigated, close contacts will be made with representatives from NASA. Our choices at present are 2219 (primary) and 2014 (secondary) as materials, and stud size of 1/4 inch (6.4 mm) in diameter as the primary candidate. Step 1-3 is to develop initial designs of the first generation space stud welding system, the hardware of which will be constructed in Phase 2.



In order to develop a reliable welding fabrication system, it is essential to develop an integrated system which covers all important operations involved in welding fabrication. Development of an integrated system is especially important for welding fabrication in space, where no experienced welding engineers and skilled welders are present. Although development of such an integrated system for various welding processes can become very complicated, we strongly believe that stud welding is simple enough that an integrated system can be developed within the time and cost anticipated in the proposed research.

The above figure shows schematically what subsystems should be included in an integrated stud welding system (in time sequence of from left to right):

- (1) A subsystem to prepare surface conditions suitable for stud welding,
- (2) Make sure that the surface conditions are adequate, before commencing welding. If the surface conditions are not adequate, recondition the surface.
- (3) Select appropriate welding conditions, including welding current, arc voltage, and welding time, for particular applications (materials, plate thickness, etc.),
- (4) Inspect the weld after it is completed. The inspection may be performed by use of a non-destructive testing method such as the ultrasonic technique and the acoustic emission technique, or it may be done by applying some external load to the stud.

We do not expect to develop a completely integrated stud welding system shown above in Phase 2; however, we should be able to develop in Step 1-3 an initial design of a system which will incorporate at least some portions of the system shown above.

Program 2: DEVELOPMENT OF "INSTAMATIC"® GTAW WELDING SYSTEMS FOR SPACE APPLICATIONS WHICH CAN BE OPERATED BY AN ASTRONAUT WITH NO WELDING TRAINING

RESEARCH PHASES	YEARS AFTER THE INITIATION OF THE RESEARCH PROGRAM										
	1	2	3	4	5	6	7	8	9	10	
PHASE 1: IDENTIFICATION OF SEVERAL TYPES OF "INSTAMATIC"® WELDING SYSTEMS	████████████████████										
PHASE 2: CONSTRUCTION AND LABORATORY TESTING OF SOME PROTOTYPE MODELS		████████████████									
PHASE 3: CONSTRUCTION AND LABORATORY TESTING OF THE FIRST GENERATION INTEGRATED "INSTAMATIC"® WELDING SYSTEMS				████████████████							
PHASE 4: SIMULATED ZERO GRAVITY TESTING OF SYSTEMS DEVELOPED IN PHASE 3				██████████							
PHASE 5: CONSTRUCTION AND LABORATORY TESTING OF INTEGRATED "INSTAMATIC"® WELDING						██████████					
PHASE 6: FURTHER IN-FLIGHT TESTING OF HARDWARE SYSTEMS DEVELOPED IN PHASE 5							██████████				
PHASE 7: TESTING IN SPACE OF INTEGRATED "INSTAMATIC"® WELDING SYSTEMS								██████████			

It is recommended that a research program be carried out with the objective of developing "instamatic®" gas tungsten arc welding (GTAW) systems, or enclosed welding boxes which can perform certain prescribed welding jobs by an operator with no welding training. The research should be started immediately to cover the first two phases (Phases 1 and 2) shown above. If the results of the initial two phases are positive, the research program should be continued to cover Phases 3 through 7. Presented below is a short discussion of Phase 1. Reference 1 contains further details of Research Program #2.

The objective of Phase 1 of Research Program #2 are (1) to identify several types of joints for which "instamatic®" welding systems can be developed for space application and (2) to develop initial designs for these systems. Phase 1 is extremely important for the success of Research Program #2, because we must select examples which are simple enough so that "instamatic®" welding systems can be developed within the time and research budget available, yet these examples must be important for activities using the Space Station. Close coordination among M.I.T. researchers, representatives from NASA, and people in the space industry is important in identifying the examples to be investigated. Attempts also will be made to identify some joints which are useful for some other research projects included in the Innovative Utilization of the Space Station Program.

Reference 1 presents some discussions on four types of joints which are likely to be selected. They include (a) joining a flat plate to a flat plate by fillet welding, (b) lap welding a circular cover plate over a flat plate, (c) seal welding along a girth joint between two cylinders mechanically fastened, and (d) replacing a section of a pipe. These joining tasks are already explained in earlier portions of this report.

PHASES WHICH WILL BE INCLUDED IN THE RESEARCH PROGRAM #3: DEVELOPMENT OF MAN-MACHINE GTAW SYSTEMS FOR PERFORMING CERTAIN WELDING JOBS THROUGH PROPER GUIDANCE AND ASSISTANCE FROM THE COMMAND STATION ON EARTH

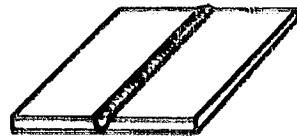
RESEARCH PHASES	YEAR AFTER THE INITIATION OF THE RESEARCH PROGRAM									
	1	2	3	4	5	6	7	8	9	10
Phase 1: Identification of several welding tasks and development of strategies for developing man-machine GTAW systems	■									
Phase 2: Development of initial designs for man-machine GTAW systems for certain applications and plans for later phases		■								
LATER PHASES	DETAILED PLANS WILL BE DEVELOPED IN Phase 2									

The objective of Research Program #3 is to develop flexible systems capable of performing various types of space welding jobs with the necessary guidance and assistance from a command station on earth. It is recommended that Phases 1 and 2 be initiated immediately as shown above. Presented below is a brief discussion on Phase 1.

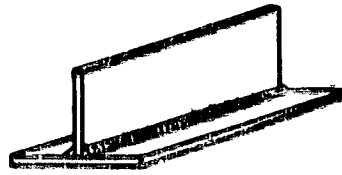
The objective of Phase 1 is to (a) identify several welding tasks and (b) develop strategies for developing man-machine gas tungsten arc welding (GTAW) systems. Phase 1 is extremely important for the success of Research Program #3, because we must select welding tasks which are (1) simple enough so that the proposed systems can be developed within the time and budget available, and (2) important for activities using the Space Station. Close coordination among M.I.T. researchers, representatives from NASA, and people in the space industry is very important in identifying the examples to be investigated. Attempts also will be made to identify some welding tasks which will be useful for other research projects included in the Innovative Utilization of the Space Station Program.

Discussions on the six types of welding tasks being considered are presented below (see figures shown on the next page). They represent different types of welds with different levels of complexity in welding fabrication.

Welding Task No. 1: Joining Two Flat Plates by Butt Welding. Joining of two flat plates by butt welding, as shown in Figure (a) on the next page, is perhaps the most fundamental welding task. Therefore, any flexible system able to perform useful welding tasks ought to be able to perform this task, at least. The task will be simple if joints to be welded are always the same. That is, if they are of the same material, same thickness, and same joint preparation. If they are different, however, we must find some way to select the right filler metal and right welding conditions (welding current, arc voltage, arc travel speed) for each joint condition.



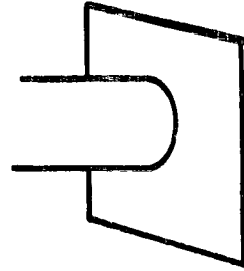
(a) BUTT WELDING FLAT PLATES



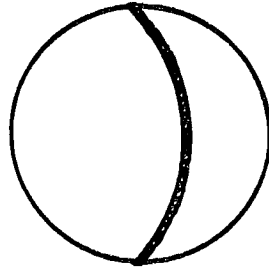
(b) FABRICATING A T-BEAM



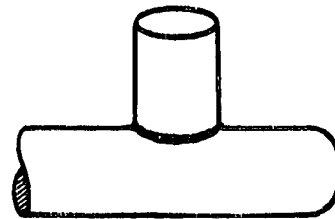
(c) JOINING OF PIPES



(d) JOINING OF A PIPE TO A
FLAT PLATE



(e) JOINING OF TWO SEMI-
SPHERICAL SHELLS



(f) JOINING OF TWO INTERSECTING
PIPES

Welding tasks in Program #3

Welding Task No. 2: Fabricating a T-Beam. T-beams and I-beams are commonly used as elementary members of many structures. Instead of fabricating these beams on earth and transporting them to space, it will be more economical to simply transport the metal pieces and join them in space.

Welding Task No. 3: Joining of Pipes. Joining of pipes in a fixed position, especially in a small diameter, can be performed by using an "instamatic" welding system. However, joining of larger-diameter pipes will probably require a more flexible welding system.

Welding Task No. 4: Joining of a Pipe to a Flat Plate. The joining of a pipe to a flat plate is another basic welding task.

Welding Task No. 5: Joining Two Semispherical Shells. The joining of two semispherical shells to form a spherical hull is an important but difficult fundamental joining problem. We may have difficulties in finding ways to securely hold the pieces to be welded during welding, due to distortion. If one could successfully perform this task, this would demonstrate that many other complex structures could be fabricated in space.

Welding Task No. 6: Joining of Two Intersecting Pipes. This task is again cited to test the limit of the technical capabilities of flexible welding systems.

PROGRAMS # 4, #5, and #6

RESEARCH PROGRAMS	YEAR AFTER THE INITIATION OF THE RESEARCH PROGRAM									
	1	2	3	4	5	6	7	8	9	10
RESEARCH PROGRAM #4: SPACE WELDING USING GMAW, EBW, AND LBW PROCESSES PHASE 1: INITIAL STUDY LATER PHASES		■								
RESEARCH PROGRAM #5: SPACE JOINING TECHNIQUES SUITED FOR SPACE APPLICATIONS PHASE 1: INITIAL STUDY LATER PHASES				■						
RESEARCH PROGRAM #6: INTEGRATED FABRICATION SYSTEMS FOR CERTAIN COMPLEX SPACE STRUCTURES PHASE 1: INITIAL STUDY LATER PHASES					■					

Research Program #4. The reason for recommending Research Programs #1, #2, and #3 is that we think that NASA would be interested in having some welding systems which can do certain welding jobs in space as soon as possible. When we think about the distant future, however, we must consider uses of such processes as gas metal arc welding (GMAW), electron beam welding (EBW), and laser beam welding (LBW). EBW and LBW may well be prime joining processes in space in the future. It is recommended that an initial Phase 1 study be conducted perhaps during the second year of the Space Welding Fabrication Research, as shown above.

Research Program #5. There will be a number of joining processes which are uniquely suited for some applications under space environments. They include solar welding, exothermic brazing, diffusion bonding, explosive welding, ultrasonic welding, etc. It is recommended that an initial Phase 1 study be conducted perhaps during the fourth year, as shown above.

Research Program #6. There are basically two approaches in developing technologies of fabricating structures. One is to think about welding processes first and then develop the technologies of using these processes. This approach has been taken in planning Research Programs #1 through #5. The other approach is to think in the reversed direction, that is to think about structures first and develop fabrication techniques most suitable for the structures being considered. This second approach can be useful in fabricating some structures. It is recommended that a research program be carried out to look at welding problems from the view point of the structures being fabricated. We recommend an initial Phase 1 research with the following objectives:

- (1) To identify space structures being planned, to which introductions of new concepts in welding may make significant effects, and
- (2) To develop future plans of further R & D work.

CLOSING REMARKS

A study was made on feasibilities of remotely manipulated welding in space. Major results obtained in this study may be summarized as follows:

(1) Literature Survey. As the first step for identifying probable joining tasks in space, a survey was made of existing publications on space welding and related subjects. The result of the survey is presented in APPENDIX A of reference 1, which contains 121 citations.

(2) Unique Requirements for Space Welding Fabrication. Welding construction and repair in space has rather unique requirements, different from ordinary welding jobs on earth. Major differences between space welding and ordinary welding on earth come from (a) differences in environment and (b) remoteness of space welding from earth.

(3) Probable Joining Tasks in Space. Probable joining tasks in space may be classified, depending upon the complexities and scale of the tasks, into the following three categories:

Category 1: Construction and repair of simple, small tools, equipment components, and structural members,

Category 2: Maintenance and repair of major members of space stations, and Category 3: New construction of large, complex space structures. We believe that it is a good idea to start working on simple cases and gradually expand the effort to cover more and more complex cases.

(4) Required Levels of Automation in Space Welding. Under Task 2, studies were performed on (a) analysis of welding tasks in space, (b) operational modes for space welding fabrication, and (c) simple experiments on supervisory control of torch positioning and seam tracking.

(5) Development of Novel Space Welding Concepts. In order to successfully accomplish construction, maintenance, and repair of space stations, we need to develop novel welding concepts. Discussions have been held on (a) efforts to develop space welding technologies which do not require the on-site presence of welding engineers and (b) efforts to develop new welding processes and procedures uniquely suited for space applications.

(6) Recommended Future Studies. Six research programs have been recommended. Discussions on the first group including Research Programs #1, #2, and #3 are rather specific, since we already have concrete ideas about (a) what should be done and (b) what is perhaps achievable. Discussions on the second group including Research Programs #4, #5, and #6 are rather general and brief, since plans for these programs may be significantly affected by the outcome of Programs #1, #2, and #3.

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