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ON

FEASIBILITY OF REMOTELY MANIPULATED WELDING IN SPACE

—A STEP IN THE DEVELOPMENT OF NOVEL JOINING TECHNOLOGIES—

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SUMMARY

This is the final report of a six-month research program entitled, "Feasibility of Remotely Manipulated Welding in Space - A Step in the Development of Novel Joining Technologies". The program was performed at the Massachusetts Institute of Technology for the Office of Space Science and Applications, NASA, as a part of the Innovative Utilization of the Space Station Program.

The objective of this research has been to initiate a research program 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.

As the first step for identifying probable joining tasks in space, a survey was made of existing publications on space welding and related subjects. Section 2.1 presents a summary of this survey. A more detailed account of the literature survey is presented in APPENDIX A, which includes 121 annotated references.

Probable joining tasks in space may be 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 space structures.

Section 2.4 discusses probable joining tasks in space under these categories. Regarding candidate materials to be investigated, aluminum alloys, especially those in 2000 series have been selected as primary materials. Since most space structures will be fabricated with light structures, research should be directed toward fabrication of metal structures in thin sheets. Gas tungsten arc welding (GTAW) and capacitor discharge stud welding have been selected as primary welding processes.

Under Task 2, the following subjects have been studied:

(1) Welding task analyses, including general task analysis, tool manipulation, selection of the process type and parameters, process control, and inspection and quality control.

(2) Operational modes for space welding fabrication, including manual welding by an operator in the remote site, remotely manipulated welding, and totally autonomous, unmanned welding systems.

(3) Experimental study. A limited experimental study was made to examine the positioning and path tracking manual control tasks.

Under Task 3, discussions are presented on the following subjects:

(1) Development of space welding technologies which do not require on-site presence of welding engineers and welders. Discussions cover (a) development of completely remote welding technology, (b) development of integrated and automated welding systems which can be operated by persons with no welding skill, and (c) development of technologies of welding through telepresence.

(2) Development of new welding processes and procedures uniquely suited for space applications. Discussions cover (a) space electron beam welding technology, (b) space exothermic brazing technology, and (c) solar welding systems.

Under Task 4, the following six research programs have been recommended:

Program #1: Development of space stud welding systems 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 special joining techniques suited for space applications.

Program #6: Development of integrated fabrication systems for certain complex structures.

KEYWORDS: Welding in space, Remotely manipulated welding in space, Space stud welding, Space "instamatic®" welding systems.

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1. INTRODUCTION

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, as a part of the Innovative Utilization of the Space Station Program. This is the final report of this research.

1.1 Statement of the Problem

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 stages 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 which could be considerably high. 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 structural components as well as of tools and equipment on these space structures. It is therefore very important to develop metal joining technologies, 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 designs can be achieved once the space welding technology is well developed.

Today well over 100 joining processes are used for a variety of applications on earth. These joining processes may be classified into:

(a) Mechanical joining methods, including bolts and nuts joining, riveting, etc.

(b) Adhesive bonding methods, and,

(c) Welding or metallurgical joining methods.

According to the Welding Handbook[1], welding processes are defined as those joining processes which produce local coalescence of metals and nonmetals either by heating the materials to suitable temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler metals. Today there are about 100 welding and allied processes which are commercially available, as discussed in a later part of this report (Section 2.2). Many of these welding processes are widely used for fabricating a wide variety of structures including aerospace structures, ships, bridges, nuclear reactor vessels, and pipelines. This is because welding processes have advantages over other joining methods in a number of ways, including (1) excellent mechanical properties of joints, (2) simple joint designs, and (3) ease of obtaining air and water tightness. Therefore, welding processes will undoubtedly be important in space construction and repair.

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. In fact, considerable efforts by welding engineers engaged in welding in conventional air have been 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. For example, we must study how to obtain the large amount of electric power that is needed for most conventional welding processes. We must also study how gravity, or the lack of it, will affect joining mechanisms and joint properties when different joining processes are used in space. The extreme temperatures encountered in space can drastically affect heat flow and metallurgy of the weldment. In order to successfully perform welding construction and repair in space, we must first study these problems and then develop welding technologies suitable for space applications. We must also develop means for selecting proper welding equipments, consumables, and welding conditions for given materials, plate thicknesses, and environmental conditions. How can we do this without sending welding engineers to a space station?

What is equally, if not more, important is the fact that welding is a process that normally requires high levels of manual skill and dexterity. These skills are not likely to be readily available in space, since it is not realistic to assume that we must send welders to a space station. Furthermore, under conditions encountered in space, for example wearing a bulky space suit, even simple manual tasks become extremely difficult to perform properly. Therefore, extensive automation and packaging of welding processes will be required for viable space welding techniques. Robots will be used extensively, and some welding operations may even be remotely performed through supervisory systems located on earth.

During the last 15 years or so, some research efforts have been made, mainly in U.S.A. and U.S.S.R., to investigate various aspects of space welding. In fact, some welding experiments were performed during the Soyuz-6 mission (U.S.S.R. in 1969) and aboard Skylab (U.S.A. in 1973). A review and analysis of past studies on space welding and related subjects is presented in a later part of this report. Most of the past studies on space welding were basic studies to investigate the effects of extremely low gravity on mechanisms of metal solidification and the properties of welds. Very little research, if any, has been done with the objective to develop actual technologies for welding construction and repair of space structures. In order to develop welding technologies in space, we must find answers to many questions, some of which are listed below:

(1) Which processes should be used for what purposes?

(2) Should we use human welders or should we use automatic machines; what kind of machines can be used for which jobs?

(3) Can we develop automated and integrated welding systems which can perform certain welding jobs? If so, should they be activated by astronauts or should they be remotely manipulated from a station on earth (teleoperation)?

(4) How can we select adequate welding processes and conditions without sending welding engineers to a space station (telepresence of experts , expert autonomous systems)?

The major objective of this research is to develop answers, or to propose ways to develop answers to these questions.

1.2 Objective and Tasks

This project has initiated a research program 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.

1.3 Possible Non-Space Applications of Novel Space Welding Concepts

Although the major objective of this research for NASA has been to develop novel concepts for welding in space, there are several possible uses of the novel concepts, for non-space applications. Presented here is a brief discussion on several examples of the non-space applications.

(1) Remote Welding for Non-Space Applications. There are a number of cases in which welding must be performed in locations where skilled human welders are not easily available. They include such cases as (a) welding in deep-sea for salvaging and repair of under-sea structures, (b) welding construction and repair of structures in the arctic and antarctic regions, and (c) welding repair of nuclear reactor components in radioactive environments. The remote technology developed for space applications can be used, perhaps with some modifications, for a variety of non-space welding jobs which are currently very difficult or impossible to perform.

(2) Welding Jobs which are Physically Difficult to Perform by Human Welders. In a number of cases, such as pipings in a submarine or a boiler, structures are designed in such a way that human welders can perform welding for construction and repair. However, some of the welding jobs are very difficult to perform due to the physical size of a human. Small, light-weight, integrated automatic welding systems

developed for space applications may be useful for various welding jobs which must be performed in a small, confined space.

(3) Possible Development of Novel Welding Concepts and Systems. Although numerous efforts have been made and are still being made to introduce mechanization and automation in welding fabrication, the basic process tends to remain virtually unchanged. Many automatic welding machines developed thus far tend to merely replace human welders by machines. Similar observations can also be made for most of the current industrial applications of robotic welding. Robots replace human activities, but the processes are not usually adapted to the totally different physical, sensory, and even "intellectual" characteristics of the computers and robots.

In space welding, we are forced to develop welding systems which can perform certain simple welding jobs without using skilled welders. We may then find that these systems can also be used for other non-space applications. By using these integrated systems, some simple welding jobs may be performed by millions of people rather than by a limited number of skilled welders.

(4) Development of Welding Systems under Controlled Environments. Until now most welding jobs, with the exception of electron beam welding which is performed in vacuum, have been done under the atmospheric conditions of the earth. The earth environment is characterized by (a) the air, (b) gravitational force, and (c) the ambient temperature. It is hard to believe that the earth environment is most ideal for welding many materials. As stated previously, a large portion of the welding research performed in the world during the last 100 years has been to develop techniques for minimizing adverse effects of oxygen, nitrogen, and hydrogen in the atmosphere. As long as welding is performed by human welders, it is extremely difficult and costly to perform welding in an environment different from the earth environment. Electron beam welding is done in a vacuum chamber; however, a large chamber is needed to perform EBW, and welding jobs must be done by a machine. With the

increased use of robots and other means of automation, it may become possible to perform certain welding jobs under a controlled environment without too much trouble. We may find that it is easier to weld some materials such as titanium for example, that are difficult to weld in the ordinary environment, in certain controlled environments (different shielding gas compositions and pressures, and even at different temperatures.)

2. TASK 1: IDENTIFICATION OF PROBABLE JOINING TASKS IN SPACE

2.1 Survey of Past Studies on Space Welding and Related Subjects

As the first step for identifying probable joining tasks in space, a survey was made on existing publications on space welding and related subjects. The result of the literature survey is presented in APPENDIX A. The emphasis of the discussions here 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. In 1966, Lawrence and Schollhammer[6601]* prepared a report entitled "Hand Held Electron Beam and External Power Supply" under a contract performed at the Hamilton Standard Division of United Aircraft Corporation for NASA. APPENDIX A contains 121 publications on space welding and related subjects, of which 53 publications cover welding and brazing as major topics [see Table 2-1(a)]. Most of the information on space welding and fabrication has been generated by two countries, U.S.A. and U.S.S.R., as shown in Table 2-1(a). Among the 53 publications on welding and brazing, electron beam welding has been discussed in the largest number of articles, as shown in Table 2-1(b). Other processes that have been discussed for space applications include solar energy welding, cold welding and diffusion, and explosive welding, also as shown in Table 2-1(b).

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*When publications included in the literature survey presented in APPENDIX A are referred in the main body of this report, the literature identification number used in APPENDIX A is also used. For example, [6601] is the article #1 published in 1966, and [8009] is the article #9 published in 1980.

Table 2-1 Numbers of publications on space welding and related subjects included in APPENDIX A

(a) Classification by Countries

	Welding and Brazing	Other	Total
U.S.A.	15	52	67
U.S.S.R.	22	11	33
Germany**	12	5	17
United Kingdom	3	0	3
France	1	0	1
TOTAL	53	68	121

*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.

**Includes both the Federal Republic of Germany and the German Democratic Republic.

(b) Classification of publications on Welding and Brazing by Processes

Electron Beam Welding	10
Brazing	6
Solar Energy Welding	4
Cold Welding and Diffusion Bonding	3
Explosive Welding	2
General	28***
TOTAL	53

***Includes two (2) publications on robotic welding and automation.

2.1.1. Welding Experiments on Spaceships.

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 U.S.A. on board the Skylab. APPENDIX A 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 printed in the January 1972 issue of Welding Engineer.[7201] 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 systems 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 following processes and materials:

Processes: Electron beam welding
Low-pressure constricted arc (plasma arc)
Consumable electrode (gas metal arc process)

Materials: Stainless steel 1X18H9T, of which nearest U.S. equivalent is AISI 321.[2]
Aluminum alloy AM-6, which is believed to an Al-Cu alloy.[2]
Titanium alloy BT-1, its nearest U.S. equivalent is A-55.[2]

Table 2-2 presents a summary of test conditions and important findings of the welding experiments on the Soyuz-6.

Table 2-2 Summary of test conditions and important findings of the welding experiments on Soyuz-6

PROCESS	CONDITIONS	RESULTS
Electron Beam	• Beam Power = 1 kw • Beam Current = 70 ma • Welding Speed = 3 m/h • Vacuum ?	• Weld shape and degree of penetration similar to ground based samples • Sound welded joints achieved with all alloys • Slight increase in porosity in space welded Al alloy, probably due to lack of buoyancy of trapped gas bubbles • EB cutting of all alloys demonstrated
Low Pressure Constricted Arc (plasma arc)	• Non-cooled torch • Argon atmosphere • Arc Current = 43-50 amps • Arc Voltage = 26-27 volts • Welding Chamber could be open to space • Nominal Arc Length = 5 mm	• Arc ignition, arc stability, and focus of anode spot affected by amount of vacuum • On thin samples, weld formation was similar on Earth and in space, and is controlled by surface tension forces • Sound welded joints obtained • Some porosity along fusion line in Ti alloy • Arc constriction difficult when chamber vented into space

Table 2-2 (continued)

PROCESS	CONDITIONS	RESULTS
Consumable Electrode (GMAW)	• Arc Power 1 kw • Arc current varied by wire feed speed • Voltage adjusted via storage battery • Samples were 1 mm thick • Welding performed in argon atmosphere or vacuum	• At low current, molten drops grew to a large size and remained attached to electrode for a long time • Increasing current increases electromagnetic pinch effect • Stable metal transfer achieved using short-circuit technique or impressed current • Weld bead bulged slightly in center due to surface tension forces, resulting in decreased penetration • When welding in vacuum, it was possible to obtain a stable arc in the vapor of electrode material

(2) Skylab Experiments. Presented here is a brief description of experiments related to welding performed in the Skylab, based upon the information given in a paper by Baker[7303] and a paper by Siewert, et al.[7702]

On board the Skylab, 54 experiments were performed. Among them, 18 were related to materials science and manufacturing processes. The following three experiments are related to welding:

a. Metals melting experiment, M551

b. Brazing experiment, M552

c. Sphere forming experiment, M553.

Table 2-3 presents a summary of test conditions and important findings of these experiments.

In the M551 experiment, the electron beam was used to conduct typical welding tests. The basic equipment consisted of an electric motor assembly driving disk-shaped metals at 2.5 rev/min within the work chamber. The electron beam traversed the disk-shaped plates, melting a track in the metal and creating a superheated spot in the centre of 1.5 mm (0.06 inch) beam. Experiments were performed on the following three materials:

a. Aluminum alloy (22019)

b. Stainless steel (321)

c. Thoria dispersed nickel.

The M552 experiment was performed with the primary objective of demonstrating feasibility of brazing as a method of space repair and maintenance. The equipment was simple. A single assembly comprising four brazing packages was mounted in the same vacuum chamber as M551. A 19 mm (0.75 inch) diameter thin wall tube of stainless steel was placed along the axis of each brazing package, with individual tubes slit in the center to simulate an end-to-end joining exercise. A stainless steel sleeve surrounded the simulated joints, brazed to the

Table 2-3 Summary of test conditions and important findings of M551, M552, and M553 experiments performed on board the Skylab

EXPERIMENT	CONDITIONS	FINDINGS
M 551 (metals melting)	• Beam Current = 50-80 ma • Beam Voltage = 20 kv Welding Speed = 58 m/hr • Samples had regions of cutting, full penetration welds, partial penetration welds, and a large molten pool	• The feasibility of doing EB welding, cutting, and melting in the low gravity environment of space was demonstrated • Large elongated grains were observed in ground based specimens, while the Skylab specimens had smaller, equiaxed grains. This indicates that there is a major difference in convection during solidification • Skylab specimens showed symmetric sub-grain patterns, while there was orientation associated with the solidification front in ground based specimens • Cracks or hot tears were observed in the specimens processed in space, while ground based welds did not exhibit cracks
M 552 (Brazing)	• Gaps tested 0.13 mm 0.25 mm 0.50 mm 0-0.75 mm tapered	• Wetting and spreading of Skylab samples superior to ground based, resulting in gaps that were better filled • Skylab joints of higher quality in terms of defects and porosity

Table 2-3 (continued)

EXPERIMENT	CONDITIONS	FINDINGS
M 552 (Brazing) cont'd	• Performed in vacuum • Braze melted by exothermic reaction	• Appears to be no upper limit to the braze gap in space, so joints with large fit-up tolerances may be brazed • Brazing can compete with welding in many applications in space where on Earth only welding would be considered
M 553 (Sphere forming)	• Alloys melted by EB • Some samples released while molten, solidified while free floating. Others retained on strings of same composition	• Samples solidified via surface nucleation and growth • Due to crystal growth during solidification, the surface morphologies were not as smooth as a polished ball bearing • Most drops were axially symmetric • None of the solidified drops were spherical, probably due to the fact that the drop solidifies before the internal fluid flow dampens

tube with an alloy containing 71.8% Ag, 28% Cu, and 0.2% Li. The exothermic material was encased in a fibrous aluminum oxide, removing the need for gaseous oxygen and limiting the reaction of the products.

The M553 experiment was not exactly on welding, but it was closely related to welding. Because of the ever-present gravity on earth, it is not possible to form metal balls completely symmetric in all directions. If metals are properly processed in space under zero gravity, it may be possible to produce metal balls perfectly symmetric in all directions. These perfect balls may then be assembled to manufacture an extremely high-performance ball bearing. 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.

Situated 152 mm (6 inches) away from the heat source, a tungsten sample was exposed to impingement by an electron beam 3.2 mm (1/8 inch) wide, which was then shut down by a crew member when the sample was completely melted. After calibration, 14 samples were exposed to the high melting-rate process in turn. Three of these were nickel, nickel-tin alloy, and Stellite, which were retained on pedestals during the solidification process. The other 11 samples were attached to supporters that permitted the globule to break free as soon as melting was completed.

2.1.2. Studies on Space Welding other than those Performed in Spaceships.

Besides the experiments performed in spaceships, which are described in the preceding section of this report, some other studies on welding in space have been made. They may be classified as follows:

(1) Studies including experiments under conditions that simulate space welding

(2) Studies with little or no experimental verification.

(1) Studies with Experiments under Conditions that Simulate Space Welding. Space conditions may be simulated by flying an aircraft through a planned trajectory to achieve up to 30 seconds of dynamic weightlessness, using a vacuum chamber or some other techniques. All the experiments described in the preceding section were first performed in experimental chambers aboard airplanes, with similar results.

Other studies which have not been duplicated in space include:

a. Spot Welding. The Soviets performed spot welding in a vacuum aboard an aircraft flown to simulate weightlessness.[7201] The simulated space conditions did not affect the spot welding process.

b. Cold Welding. Conrad and Rice[6904] studied cold welding in ultrahigh vacuum. Since no metal is melted using cold welding, the effect of microgravity can be ignored; therefore, by using an ultrahigh vacuum, the conditions of cold welding in space can be reproduced. The strengths of cold welded joints in metals with face-centered cubic (FCC) lattice structures, including silver, aluminum, copper, and nickel, were investigated. Frankel[6905] also studied the effect of vacuum on various materials (not joints).

c. Explosive Welding. Bement[7308] developed a totally confined explosive welding technique and was granted an U.S. patent. The use of this technique could be practical in the restricted area of a space station. Some tests were made on earth, but no test has yet been made in space.

d. Solar Welding. The Soviets have performed welding and brazing with the aid of focussed sunbeams.[7401] With suitable reflectors and adequate shielding of the welding location in a vacuum chamber, promising results have been obtained. This method may be particularly important to welding applications in space; however, the method has not yet been tested in orbit. Work along similar lines has been done in the U.S.[7507]

(2) Studies with Little or no Experimental Verification. Studies with little or no experimental verification include the following:

e. Diffusion Bonding. Derby and Wallace[8003] developed a theoretical model and computer programs in an attempt to gain understanding of diffusion bonding. The aim was to develop efficient methods to join metals in space.

f. Ion Beam. The use of ion thruster engines for spacecraft propulsion may serve as a source of ion beams.[7706] This may be useful for welding in space.

2.1.3. Studies on Various Subjects Related to Fabrication of Space Structures.

Studies have also been made on various subjects related to the fabrication of space structures. Presented here is a brief discussion of some of the studies, with special emphasis on those subjects that are related to welding.

The most extensive study in the United States related to space fabrication has been done by Grumman Aerospace Corporation in regard to the beam builder. The beam builder manufactures a structural building block designed for the construction of space structures. The building block is lightweight and includes a roll formed aluminum alloy truss, 1 meter deep and up to 300 meters long. Vertical braces are spaced every 1.5 meters and interconnected by diagonal members. The braces and diagonal members are connected to the beam caps by spot welding. A complete beam building unit has been successfully tested on land.

The beam builder can be used for automated fabrication in orbit. Many structures that could be fabricated using the basic building block of the beam builder have been proposed. These include a Large Space Structure Platform, communication antennas and orbiting solar power stations. Further information may be obtained from the following references: [7605], [7707], [7708], [7802], [7808], [7809], [7812], [7904], [8005], [8011], [8206]. The use of the beam builder using composite materials has also been discussed ([7803], [7907], [8005], [8010].

Other space structures proposed include utilizing the external tank (ET) of the Space Shuttle as a building block for a low orbit space station or a telescope. These proposals include welding and cutting of the ET to achieve the required specifications. The advantage of these structures is that little added thrust is needed to carry the ET into its low orbit.[8004] One of the key technological needs for fabricating large space structures is the joining of materials. Due to the limited payload and size capabilities of the Shuttle, the ability to perform a major part of the building process in space will make any project more economically attractive. Since these structures will most likely be composed of some aluminum or other high strength, low weight metal, the need for techniques of joining these materials in space is high.

2.2 Basic Considerations for Identifying Probable Joining Tasks in Space

Before discussing specific examples of probable joining tasks in space, a short discussion is given here on basic considerations on the complex characteristics of welding fabrication and the unique requirements for space welding fabrication.

2.2.1. Complex Characteristics of Welding Fabrication.

Although welding is widely used because of its advantages over other joining methods such as mechanical joining and adhesive bonding, welding has some problems, one of which is that it is rather complicated and requires some knowledge and skill as discussed below.

(1) Many Different Processes, Materials, and Structures. First of all, there are many different welding processes which are commercially available today. Figure 2-1, which is the master chart of welding and allied processes prepared by the American Welding Society[1], includes about 100 processes. Many of these processes may be used for space applications. There are many materials to be considered including steels, aluminum alloys, titanium alloys, etc. Welding may be used for construction and repair of various space structures. Although not

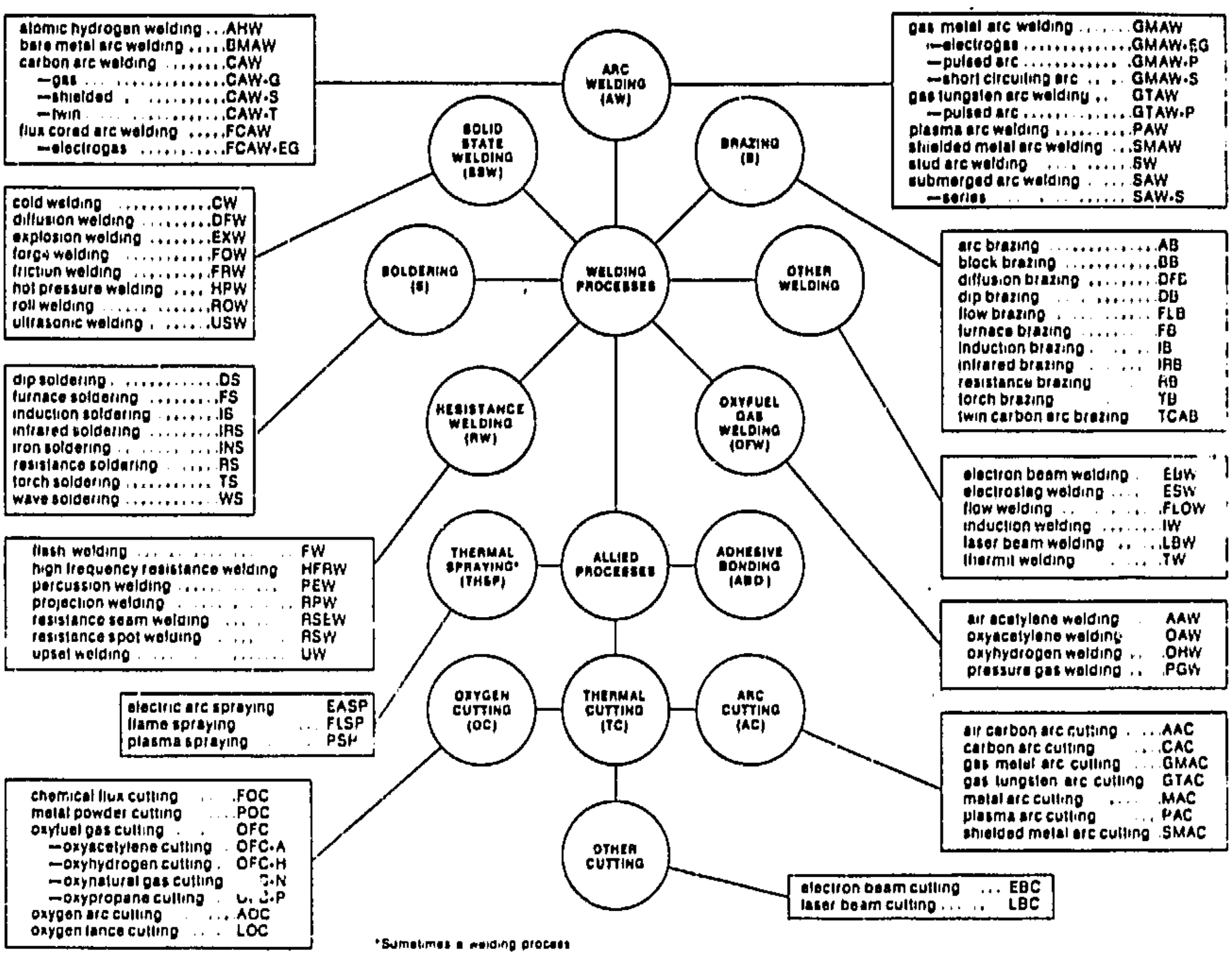


FIGURE 2-1 Master chart of welding and allied processes [1]

all the processes shown in Figure 2-1 can be employed for welding all of the materials used for all of the structures, we must consider certain combinations of (a) welding processes, (b) materials, and (c) structure and design parameters, as shown in Figure 2-2.

Major structure and design parameters that affect the selection of proper welding processes and details of welding conditions (such as welding current, torch travel speed, etc.) are:

(a) Plate thickness
(b) Plate configuration such as a flat plate, a curved plate, a pipe, a spherical shell, etc.
(c) Joint design such as a butt joint, a fillet joint, a lap joint, etc.

Regarding welding fabrication on earth, the technology or know-how of selecting proper welding processes and welding conditions for various materials in different structure and design parameters, has been reasonably well established. However, this has been achieved mainly through experiments and experience over the years with very little theoretical analysis. In order to successfully accomplish welding fabrication in space, we must develop a similar technology or know-how for space welding. A certain amount of research is needed to develop the technology of determining proper welding processes and welding conditions for a variety of applications. The research effort will undoubtedly involve many experiments. However, considering the extraordinarily high cost of conducting experiments in space, we should try to utilize theoretical analyses as much as possible in this research.

We must also solve another problem, of how to make sure that proper welding processes and welding conditions are selected for certain applications without the physical presence of experienced welding engineers.

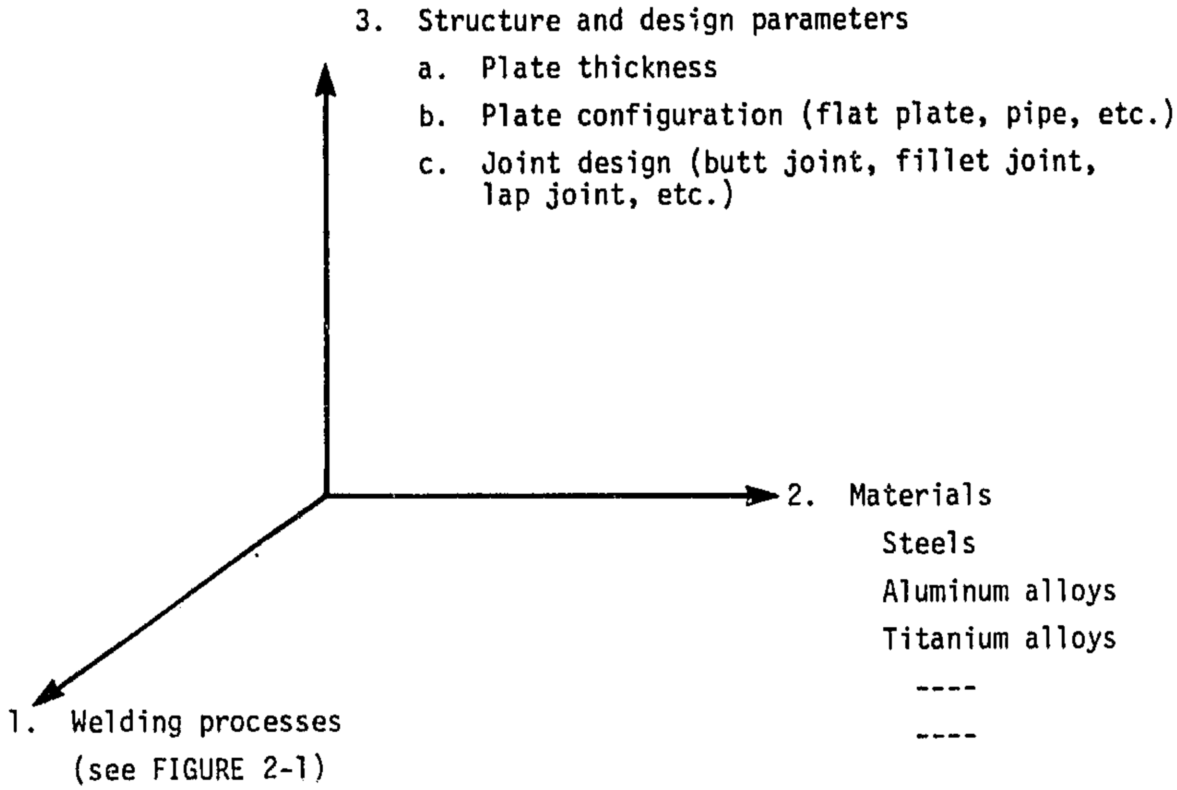


FIGURE 2-2 Combinations of welding processes, materials, and structure and design parameters

(2) Additional Problems with Welding Fabrication of Complex 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 using the same material would be successfully achieved. There are certain problems associated with welding fabrication of complex structures composed with a number of members.

One of the major problems with the welding fabrication of large, complex structures is related to residual stresses and distortion. Due to local heating during welding, complex thermal stresses occur and residual stresses and distortion remain after the welding is completed. Transient thermal stresses, residual stresses, and distortion cause mismatching of unwelded joints. Cracking may occur in joints highly restrained by other structural members. High tensile residual stresses that occur in regions near the weld may cause premature fractures of welded structures under certain conditions. Initial distortion and compressive residual stresses in the base metal region may reduce buckling strength of the structure. In fact, when a member is thin enough, welding residual stress alone can be enough to cause buckling of the member. Subjects related to residual stresses and distortion in welded structures are discussed in detail in a recent book by Masubuchi.[3] Since space structures tend to be light structures, special attention should be placed on control of weld distortion.

In the past, a number of problems occurred during the welding fabrication of large structures, especially when they were first fabricated. For example, when ships were first built by welding around 1910-20, engineers experienced severe distortion problems affecting the entire ship hull. The most severe problem that has occurred in welded structures so far is the brittle fracture of welded ships built in the United States during World War II.[3] Various problems including those related to distortion were also experienced during the welding fabrication of huge aluminum tanks containing fuel and liquid oxygen installed in the Saturn V space vehicle used for the Apollo lunar missions.[4] One way to avoid or minimize the risk of encountering catastrophic problems is to proceed with the development plan step-by-step, starting from welding of small, simple joints and gradually expanding the R & D efforts to larger and more complex structures. Many catastrophic failures experienced in the past occurred in hastily done programs.

Another important problem in the welding fabrication of a large, complex structure is how to establish the most suitable welding sequence. A common practice in the welding fabrication on earth is to arrange to perform as much welding as possible in downhand position, and to minimize welding in overhead and vertical positions. This is to improve the weld quality and fabrication speed. In space welding, however, the welding position should have no effect on weld quality and welding speed.

(3) Problems Associated with Skills Required for Welding and Possible Solutions. Manual arc welding, which is still widely used, is performed by people who are especially trained and qualified. Even in the case of automatic welding, most machines need to be operated by people who have received special training.

Let us take a common example of manual gas tungsten arc welding (GTAW) which is widely used for welding aluminum alloys. The welder holds a welding torch in one hand. He may also hold a filler wire in the other hand. After striking the arc, he watches the weld pool through a dark glass window of a helmet which he is wearing. He must hold the torch and wire at the right positions and manipulate them properly to produce a weld beam of an appropriate shape. He must also move the torch and wire as the weld metal solidifies. In addition to holding and manipulating the torch and filler wire, he must do several other things needed for welding such as cleaning the metal surface with a wire brush, and opening the valve of a cylinder containing the shielding gas. A welder normally goes to a welder training school to obtain the necessary training. He must also pass certain tests to be qualified as a welder.

We should also mention the problems of many automatic welding machines. Although many automatic welding machines have already been developed and used, they are most commonly used in factories where personnel trained to handle these machines are employed. The welding industry has always assumed that welding will be done by personnel with proper training. No automatic welding machine, with the exception of "instamatic® " welding machines developed recently at M.I.T.,[5-7] has been developed with an intention to be used by people with no welding skill. The following pages discuss (a) what has been done at M.I.T. so far and (b) some thoughts about possibilities of developing "instamatic® " welding systems for space applications.

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 manipulation of the torch. These machines can only make the certain welds for which they are designed, but they can be operated by a person with no welding skill. These systems 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.[5-7] APPENDIX B discusses the present status of the development of "instamatic® " welding systems.

The idea of developing "packaged welding systems" was originally conceived while M.I.T. researchers were studying means of performing underwater welding in deep sea.[5] It is very difficult to find a person who is an excellent diver and a good welder at the same time. Under the adverse conditions encountered in deep sea, even an excellent diver/welder cannot perform successfully all of the necessary operations needed to make good welds. As a means for solving this problem, "instamatic® " welding systems were originally developed.

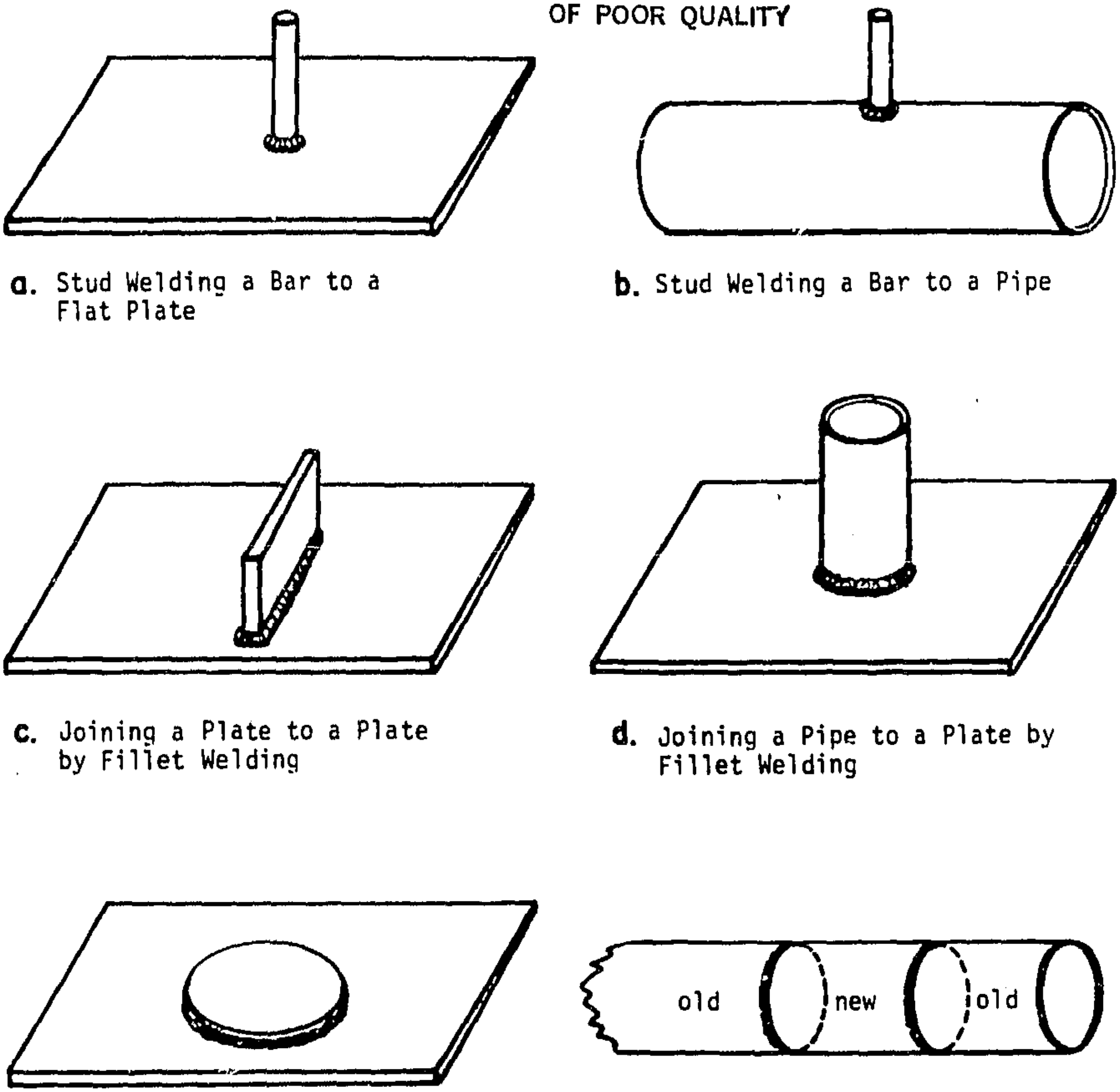
M.I.T. researchers then recognized that similar systems could be developed for various marine applications under both dry and wet conditions. A research project[6] was carried out to develop "instamatic® " welding systems which may be used for various applications, some of which are listed below:

(1) Certain repair jobs on board a ship and salvaging jobs which must be performed when no skilled welder is available
(2) Certain welding jobs which must be performed in a compartment where sparks from the welding arc may cause fire or explosion
(3) Certain welding jobs which must be performed in hazardous environment making it difficult or impossible for them to be performed by human welders.

In past research projects, the following six types of joints were studied (see Figure 2-3):

Type 1: Stud welding of a bar to a flat plate, as shown in Figure 2-3a,
Type 2: Stud welding of a bar to a pipe, as shown in Figure 2-3b,
Type 3: Joining of a flat plate to a flat plate by fillet welding, as shown in Figure 2-3c,
Type 4: Joining of a pipe to a flat plate, as shown in Figure 2-3d,
Type 5: Lap welding a cover plate to a flat plate, as shown in Figure 2-3e,
Type 6: Replacing a section of a pipe, as shown in Figure 2-3f.

The actual hardware for Types 1, 3, and 5 joints have been built and tested. Further discussions of these designs are given in APPENDIX B. Under the current three-year research program that started in July 1982, efforts are being made to develop systems capable of performing simple underwater welding and cutting operations by remote manipulation techniques. The "instamatic® " welding systems developed in earlier projects are being used with some modifications. An experiment is being



a. 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

FIGURE 2-3 Basic types of joints which have been studied for welding by "instamatic®"systems planned to weld a steel stud 19 mm (3/4 inch) in diameter to a steel plate using a stud welding gun mounted on a manipulator which is attached to a small undersea vehicle.

There is no precise definition of the "instamatic® " welding system. An "instamatic® " welding system is a "dedicated welding system" which performs only those certain welding jobs for which the system has been designed. The system may be operated by a person with no welding skill, or it may even be remotely operated.

Another important feature of an "instamatic® " welding system is that it contains the piece to be welded in the system, and the piece is released from the system after the welding is performed. An "instamatic® " welding system may be in a form of box containing components of welding machines and a piece to be welded in a "cassette", similar to a cassette tape installed in a tape recorder or a cassette-type film in a Polaroid camera. This idea is a radical departure from the current practice of welding fabrication. Currently, pieces to be welded are first assembled together, and a welder or a welding machine comes to the weld location to perform the welding. By contrast, what we have is a "welding box" which contains all important components of welding machines and a piece to be welded in a cartridge. In order to perform a certain welding job, a welding box which contains the right piece to be welded is placed at the right location on the workpiece. When the box is activated, welding is automatically performed inside the box. After welding is completed, the box is removed from the workpiece while the welded piece is released from the box and remains attached to the workpiece.

One obvious restriction of this new approach is that such a system can perform only those jobs which have been predetermined for the system. However, by properly selecting joints commonly used, a series of "instamatic® " welding systems may be developed which can perform significant amounts of welding jobs, especially those which must be performed under conditions unfavorable to human activities.

We believe that "instamatic® " welding systems are ideally suited for space applications. It is unrealistic, if not impossible, to train a crew member of a space station to be a welder at the same time, especially when the space station is manned with a small crew. Even if a crew member was trained to be a welder, he/she would be wearing a bulky space suit outside a spacecraft, and would have difficulties performing all the necessary manipulations needed to make a good weld. "Instamatic®"welding systems are not only useful but also indeed essential if we are to perform welding fabrication in space in the near future.

It is interesting to note that although it has been almost 100 years since arc welding was invented, almost all welding jobs have been performed in cities and villages where skilled welders are available. Very little serious effort has been made to perform welding in remote places and/or under hostile environments such as outer space, deep sea, high mountains, arctic and antarctic regions.

Welding in space by use of easy-to-operate welding systems presents to welding engineers new challenges and opportunities as follows:

(1) Accomplishment of welding fabrication in space by itself is a very significant expansion of man's ability.
(2) The technologies developed for space welding can be applied, with some modifications, to developing technologies of performing welding in other remote areas and under hostile environments.
(3) Once the technology of "instamatic® " welding is well established, various types of easy-to-operate welding devices may be developed. Then many simple welding jobs on earth may be performed by millions of people instead of only limited numbers of qualified welders.

It should be mentioned that the basic technologies and machine components needed for the construction of "instamatic® " welding systems are rapidly expanding today as follows:

(a) There is a surge of interest in the welding industry in the increased automation and miniaturization of welding machines and tools utilizing modern electronic technologies. Some welding machines and power supplies using solid state devices are very small. Some of them can even be operated by an ordinary 110 volt electric outlet available at home.

(b) There has been a tremendous increase in the use of robots in welding and other manufacturing processes. Some components of these robots can be used as parts of "instamatic® " welding systems.

(c) Many newly developed machines and tools are very "smart" or "intelligent", since they are equipped with various types of advanced sensing and control devices. At present there is a strong interest in developing "smart" welding machines which have adaptive control capabilities.[8] Until recently, all automatic welding machines have performed welding using predetermined welding conditions, with no adaptive control in process. However, M.I.T. researchers, under the direction of Professor Masubuchi, have been working on a research program for developing "smart" welding machines for the girth welding of pipes.[9, 10]

On the basis of the current technology of automatic welding machines, we believe that simple automatic welding machines with no adaptive controls are probably good enough for a number of "instamatic®" welding systems. However, more sophisticated machines which have adaptive control capabilities will be needed for other applications.

It is interesting to review what happened in the camera industry during the last 20 years. Until around 1960 many high-quality cameras such as Nikon and Canon became increasingly sophisticated and expensive having many accessories. When Kodak Co. first introduced a cheap but simple-to-operate camera with the trade name of "instamatic® ", many novice photographers were delighted with the new camera. But some expert photographers downgraded it as a "simple but stupid" camera. Since then, the easy-to-operate cameras have become increasingly "smart", and they have gradually taken over a significant portion of the camera market. In many families today, almost every member has at least one simple camera, while there may be only one very expensive camera. In fact, today's "smart and simple-to-operate" cameras are loaded with sensors, microprocessors and other electronic gadgets, a far cry from the all-mechanical cameras of 25 years ago.

(4) Welding as a Part of the Total Fabrication Systems. A unique characteristic of welding fabrication is that welding, though it is most critical, is only a part of the total fabrication system which 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.

A good joint preparation is essential for obtaining satisfactory welds. A joint surface must be clean, free of grease, moisture, dusts, and other foreign objects. Edges to be joined must be in exact shapes.

Since welds may have various types of defects such as cracks, porosity, and lack of fusion, welds need to be inspected. Today there are a number of nondestructive inspection techniques, including radiography, ultrasonic techniques, and magnetic particle techniques, are commercially available.

In developing technologies of welding fabrication in space, we must consider not only welding itself but also the entire welding fabrication. The welding operation itself may be performed by a robot installed in a space station, which can be remotely activated by the command station on the earth. However, how can we accomplish all other operations involved in welding fabrication without the presence of an expert welder? Task 2 of this research discusses the required levels of automation in space welding tasks.

One possible way to solve the problem is to develop integrated welding fabrication systems or devices which perform most, if not all, of the key operations involved in welding fabrication, including plate cutting, edge preparation, assembly, welding, and inspection, in one package. The "instamatic®" welding devices developed at M.I.T. package some of these operations. An important question to be answered is "how complete should the systems be that we develop for space applications?" More complete systems tend to become more expensive and heavier in weight. They tend to malfunction more often, requiring more frequent repairs. Further research on this subject is needed.

2.2.2. 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:

(1) Differences in environment

(2) Remoteness of space welding from the earth.

1. Differences in Environment. Table 2-4 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.

Table 2-4 Comparisons of environments between space welding and ordinary welding on Earth

	Space			Earth
	Case 1 Outside Space Station	Case 2 In a Chamber Inside Space Station	Case 3 Inside Space Station 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

The most significant difference between space welding and ordinary welding is that space welding is done under zero gravity. From the standpoint of ease of welding, Case 2 is the most suited. Case 3 is least different from the ordinary welding on earth. Case 1 is the most unique for space welding.

2. Remoteness from the Earth. Space welding must be performed in locations extremely far from the earth, where there are not 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 crew is available. Thus, an important subject is how to perform welding, among many other tasks which require special knowledge and experience. There are several ways to solve the problem, as follows:

a. Telepresence of experts. Make the necessary expert knowledge available through proper telecommunication systems.
b. Remote Manipulation. Utilize manipulators on board a space station to perform certain welding jobs through remote control from the earth.
c. Packaging of welding operations. Develop welding systems which package some of the welding operations in such a way that certain welding jobs can be performed by crew members with no welding training.

Another important subject in space welding is how to perform necessary jobs with only limited kinds and amounts of tools and consumables. Many commercially available welding processes require large amounts of electricity. Obtaining the electricity needed for space welding is an important subject. It is important to develop welding systems which can be operated by electricity generated from solar batteries. One idea that has been studied to some extent is to utilize the thermal energy of the sun by use of a proper lens system.

2.3 Applicabilities of Existing Welding Processes to Space

One could perhaps say that almost all welding processes which are currently commercially available 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 in Table 2-4), 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 here is that many space structures will be made of light and high-performance materials such as aluminum alloys, titanium alloys, high-strength steels, stainless steels, etc., since it is extremely costly to transport anything from the earth to a space station. To achieve light weight, most structures should 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. One obvious way to present the result is to discuss the space applicability of each of the current welding and allied processes, as shown in Figure 2-1. However, it will certainly take considerable space to present the results. What is done here instead is to pick those processes which we think have good potentials for space applications. The results are given in two different categories as follows:

(1) Processes which appear to have broad, general applications, and
(2) Processes which appear to have limited but unique applications.

2.3.1. Welding Processes which appear to have Broad, General Applications in Space.

Those welding (and cutting) processes which appear to have broad, general applications in space are listed below with a note for the reasons for their selection as well as possible problems (see Figure 2-1).

Gas Tungsten Arc Welding (GTAW). This process is widely used on earth for welding thin plates in aluminum alloys, titanium alloys, and many other high-performance materials. This process is one of most promising welding processes for space applications. One basic problem is how to initiate and maintain an arc in a vacuum. It may be that this can be achieved by providing a small supply of gas surrounding the arc. Some research is needed on this subject.

This process is easy to automate, because it uses a non-consumable electrode, and mechanisms of fusion are simpler than those in other arc welding processes such as gas metal arc welding and shielded metal arc welding. In fact, some of automatic GTAW machines currently available may be used for space applications with minor modifications.

Gas Metal Arc Welding (GMAW). This process also has a good potential for space applications, especially for welding thicker plates. Some experiments on GMAW were conducted aboard the Soyuz-6.

Several arc welding processes, which include such processes as gas metal arc welding (GMAW), flux cored arc welding (FCAW), shielded metal arc welding (SMAW), and submerged arc welding (SAW), use consumable electrodes. These processes, compared to GTAW, can produce larger amounts of weld metal, and thus are widely used for welding jobs on earth. In fact these four consumable electrode arc welding processes (GMAW, FCAW, SMAW, and SAW), combined, represent over 90% of all arc welding jobs in terms of weld length, and perhaps over 50% of all welding jobs currently done in the world.

However, GMAW and other consumable electrode arc welding processes have inherent problems for immediate applications in space. In these processes, metal is transferred from the electrode to the workpiece in small molten particles at very high temperatures; and thus mechanisms of welding in these processes are significantly more complicated than those in GTAW. Therefore, automatic welding machines using these processes tend to be more complicated than those using GTAW. Another related subject is mechanisms of metal transfer and fusion under zero gravity. Since GMAW can be easily done on earth in downhand position (plus g) and in overhead position (minus g), there is no reason to believe that welding cannot be performed under no gravity. However, since there has been almost no knowledge and experinece in performing welding fabrication using these consumable electrode arc welding processes, some studies are needed before considering the use of such processes in space.

Probably the most sensible thing to do is first develop the technology for using GTAW process for space applications, then decide whether additional efforts on GMAW and other consumable-eletrode processes are needed.

Plasma Arc Welding and Cutting (PAW and PAC). The term "plasma arc" is used to describe a family of metal working processes that use a constricted electric arc.[1] Constriction of the arc is usually accomplished by passing the arc through a water-cooled copper orifice. Plasma arc welding is basically an extension of the gas tungsten arc welding (GTAW) process. However, it has a much higher arc energy density and higher plasma gas velocity by virtue of the arc plasma being forced through a constricting nozzle.

Plasma arc welding and cutting processes will be useful for space applications. In fact, plasma arc welding was included in the experiments on board the Soyuz-6, as described earlier. A question here is, do we really need to constrict the arc by purging a large amount of shielding gas, since the supply of that is very limited in space. Plasma arc cutting may be useful for cutting aluminum alloy plates which are difficult to cut by the laser technique.

Electron Beam Welding and Cutting (EBW and EBC). Electron beam welding is ideal for welding in space where a vacuum is already available. Experiments on electron beam welding and cutting were performed during the Soyuz-6 mission, and aboard the Skylab an electron beam was used for the M551 metals melting experiment and the M553 sphere forming experiment. Among existing publications on space welding, the largest percentage cover electron beam welding. It is evident that small portable electron beam welding guns may be developed and used.[6601] Elder, Lowry, and Miller of Westinghouse Electric Corporation, under a contract for NASA, developed the design of a self contained electron beam welding gun which may be used in space as well as on earth.[11]

However, there are some problems to be solved. One is how to obtain high voltage needed for producing an electron beam with energy high enough to be used for welding and cutting. Another problem is how to ensure the safety of workers from the beam and radiation due to the high voltage used.

Laser Beam Welding and Cutting (LBW and LBC). Laser beam welding and cutting are also promising for space applications. A very attractive thing about the laser beam is that it can be used for a variety of applications including heat treatment, metal forming by heating, welding, and cutting. However, laser beam welding of aluminum alloys is very difficult due to the high refractivity of aluminum. Laser beams may be very useful for cutting.

There are some potential problems connected with the use of the laser beam in space. One is how to protect workers from accidental exposure to the powerful laser beam. Another problem is how to construct or transport the rather complex laser equipment and maintain it without having properly trained personnel.

2.3.2. Welding Processes which appear to have Limited but Unique Applications in Space.

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 defined, one could select the process most suitable for the specific applications. Presented here is a brief discussion on processes which appear to have some space applications.

Stud Welding. This is a simple, automatic process which can weld a stud to a metal surface. M.I.T. researchers, who have been working on underwater uses of stud welding, have already developed an integrated stud welding system which can be operated by personnel with no welding skill.[5-7] They believe that this process can be readily used for space applications with a minimum of further development work. Although this process can perform rather limited tasks of placing studs on metal surfaces, these tasks can be useful for a wide range of applications, some of which are identified in later parts of this report. The greatest advantage of this process is that it is possible to develop systems which can be completely remotely manipulated. Further discussions of possible uses of stud welding in space are given in later parts of this report. APPENDIX C presents some additional information on stud welding and its possible space applications.

Exothermic Brazing. Some fundamental research for the feasibility of accomplishing the joining of tubes by brazing, heated by exothermic materials, was performed during the M552 experiment on board the Skylab. A unique features of this experiment was that all the energy required for melting the brazing alloy and accomplishing joining was stored in exothermic powders packed in the welding device, and the powders were ignited by an ignitor which could be activated by a battery. This type of idea can be further implemented to develop a group of welding devices which contain all the necessary energy and materials needed for welding and perform certain predetermined joining tasks such as joining two tubes.

Some Resistance Welding (RW) Processes. Resistance welding process such as spot welding and seam welding may be used for some space applications. It has already been found that spot welding is little affected by gravity.[7201] It is quite possible that a space factory could install a spot welding machine for joining thin sheets of various materials. Spot welding is included in the study of the Automated Beam Building.[8009]

However, resistance welding processes tend to require large amounts of electric current and the machines are usually heavy. Therefore, uses of resistance welding processes in space will probably be limited, as it is on the earth. Extensive uses of spot welding are limited to such places as automobile assembly plants and some fabrication plants of aerospace companies where many spot welds of thin metal sheets are made. In many modern automobile assembly plants, completely automated spot welding machines are part of complex and integrated assembly systems in which most, if not all, spot welds are made by robots.

2.4 Probable Joining Tasks in Space

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 materials 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 at locations very far from the earth. Welding must be performed by a limited numbers of crew members with no or little knowledge, experience, and skills on 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. We need to know what kinds of structures are going to be needed in order to determine details of how to fabricate them.

However, certain discussions can still 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 vehicles, or even ships and storage tanks. Technologies for fabricating steel structures for ships, bridges, and pipelines are similar. 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 focussed on the development of generic technologies of space welding fabrication.

Probable joining tasks in space may be 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 components of space stations

Category 3: New construction of large, complex space structures.

As mentioned in an earlier part (2.2.1) of this report, 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. Hasty jumps to more complex cases without having sufficient knowledge and experience often lead to catastrophies which may result in considerable setbacks and delays in the development effort.

2.4.1. Category 1: Construction and Repair of Simple, Small Tools, Equipment Components, and Structural Members.

It would be extremely useful if techniques could be developed in the welding of various joints of tools, equipment components and structural components in space. Some welding jobs will be done inside a space station (Case 3 in Table 2-4), while other jobs will need to be done outside the space station (Case 1 in Table 2-4).

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 is how to accomplish simple welding tasks without having welding engineers and welders present. Completely new kinds of research and development efforts are needed.

Over the years, people in the welding industry and research laboratories related to welding have thought that welding fabrication is done by people who have an adequate education and training in welding. Of course, manual welding must be done by qualified welders. Even automatic welding machines are assumed to be operated by workers with adequate training. Many companies in various countries have recently developed welding robots. Again, however, none of these welding robots are designed to be operated by people with little or no training. It is always assumed that an operator of welding robots must be trained in how to operate them properly. People in the welding business perhaps did not want to think about developing machines which would not need their expertise to operate them.

Another underlying factor may be that some business leaders and research administrators have thought that there are enough people who are willing to do welding jobs. Thus there has appeared to be little economic incentive and justification for developing welding technologies which require no welding skill. We would like to mention, however, that there is a basic fault in this way of thinking. If a brand new technology is developed which will allow certain welding jobs to be accomplished using machines or devices which can be operated by people with no welding skill, this would certainly open new markets which have never been explored. Then some welding jobs can be performed by millions of ordinary people instead of only limited numbers of qualified welders.

An example of the use of welding machines to perform simple construction tasks in 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 its exact shape, especially when a number of modules are joined.

(b) Mechanical joints may become loose during service.

(c) It is difficult to obtain air tightness in mechanical joints.

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 activity (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 M.I.T., and is shown in Figure 2-4.[12] As seen in the figure, the joint uses two cylinders machined such that they interlock.

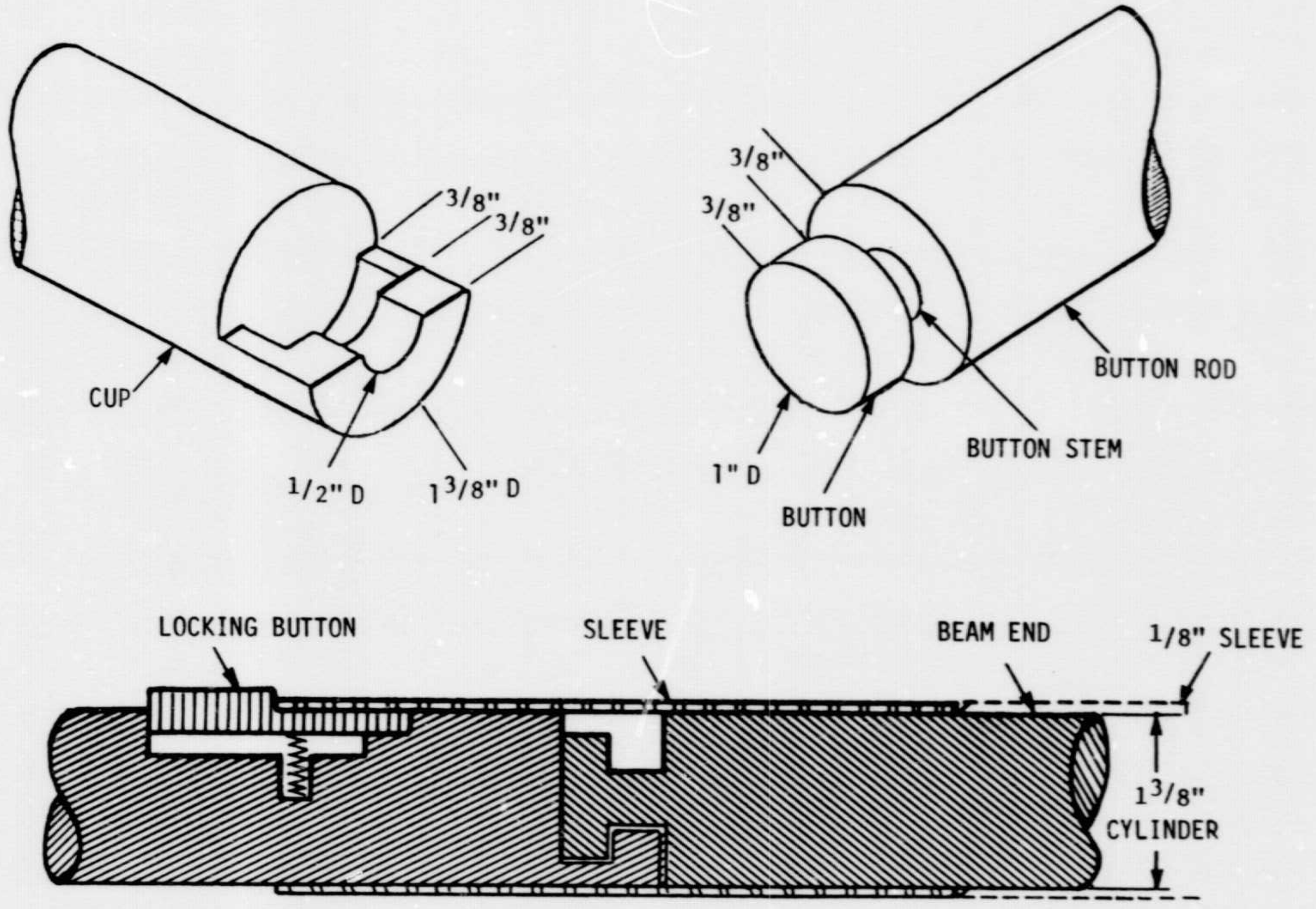


FIGURE 2-4 Prototype joint for use in space - M.I.T. Connector Design[12]

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, and examples are shown in Figure 2-5.[7902]

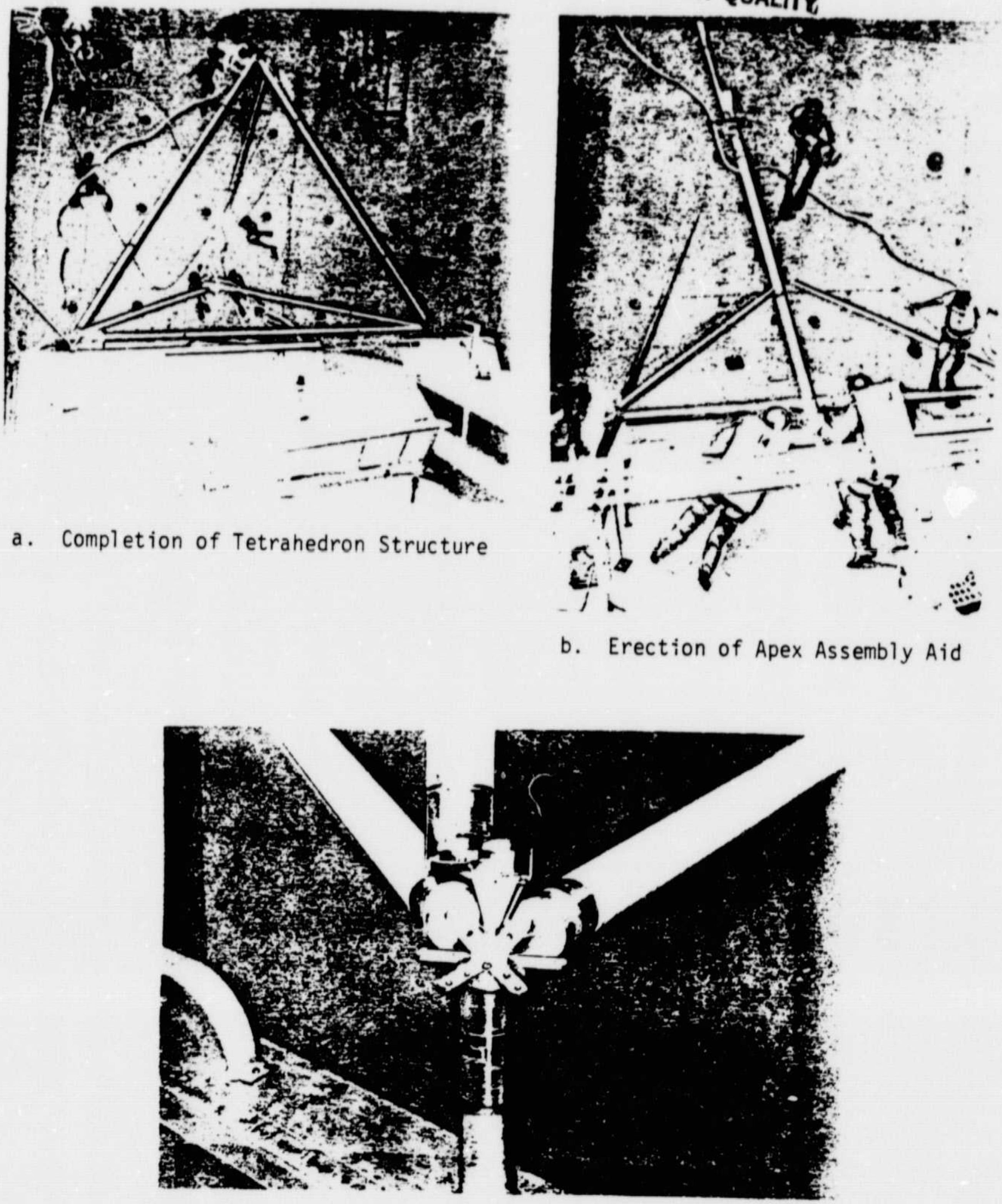
These mechanical joints are designed to have some play in them. This is necessary to aid the astronaut/builder in fitting up the pieces to be assembled, and also allows the connector to perform properly even if some dirt or other contaminant should somehow get in the way. Also, some clearance is necessary 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 motion 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 in Figure 2-6, would fix the joint in place permanently. This would allow for the ease in assembly the joint provides and still make of a rigid 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 "instamatic® " type welder would eliminate the need for a welding engineer in space (for this task), and an astronaut could be trained to use it in a minimal amount of time.

2.4.2. Category 2: Maintenance and Repair of Major Members of Space Stations.

There will also be needs 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



a. Completion of Tetrahedron Structure

b. Erection of Apex Assembly Aid

c. Snap joint/union

FIGURE 2-5 Fabricating Structures with Prototype Joint(12)

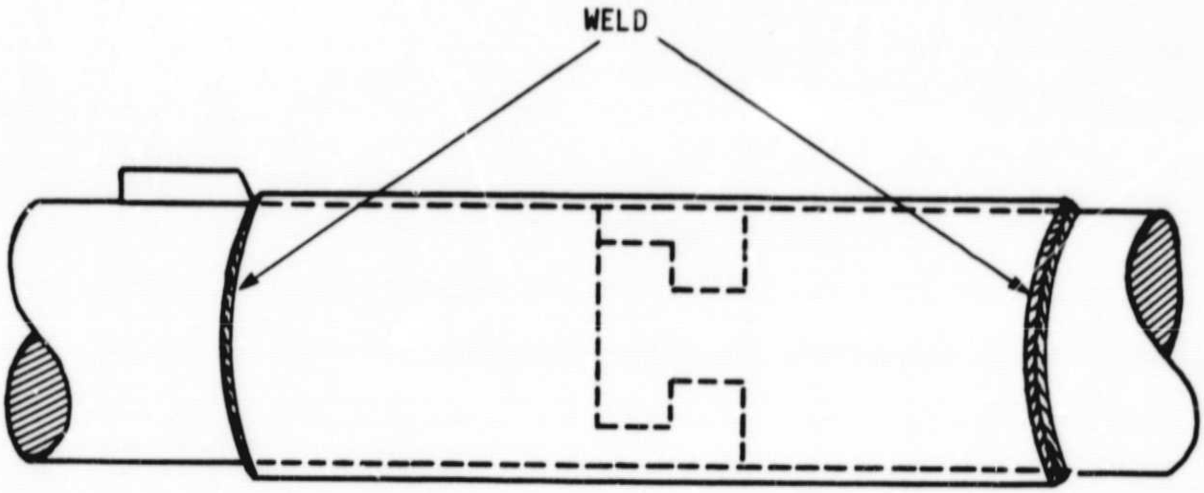


FIGURE 2-6 Possible permanent fastening of the M.I.T. connector

and possibly satellites. 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, pipelines, 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 as 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 below.

(1) On-Site Welding of Studs for Mechanical Fastening of Structural Modules of Space Stations. As stated in the beginning of this report, most construction jobs in the early stages of the Space Station Program will be performed on earth, and fabricated modules will be transported by the Space Shuttle to the space site. Then these 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.

(2) Placing Studs for Various Purposes. Stud welding may be useful for placing studs on some of major structural components for various purposes. For example, there will be many occasions in which insulation materials 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.

(3) Welding Patches on some Structural Members. 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 area - a "bandage" over the damaged area of the space station.

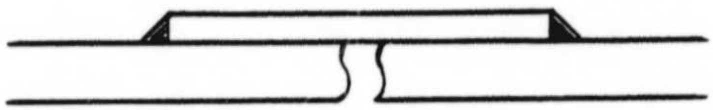
Figure 2-7 shows schematically three typical methods of placing a patch plate over a damaged structural member of a space station. A patch may be lap welded to the structure as shown in Figure 2-7a. In the case shown in Figure 2-7b, the damaged areas are removed, and an insert plate is butt welded to the structural member. In the case shown in Figure 2-7c, bolts are stud welded to the structure, and a patch plate with holes are 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 very good method, because stud welding can be made with very little heat effect to the structure.

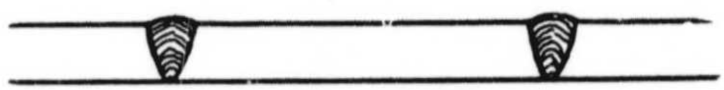
2.4.3. Category 3: New Construction of Large, Complex Space Structures.

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. 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. Also, one of the major benefits of welding over other joining processes is that welding produces air-tight joints.

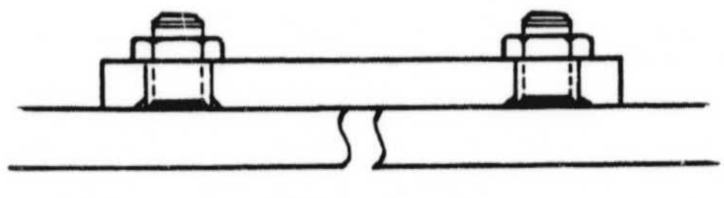
Air-tightness is particularly important when considering construction of facilities to be used by humans out in space. Without air-tight joints, these facilities would be unable to contain the environment necessary to



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

FIGURE 2-7 Three typical methods of placing a patch plate over a damaged structural member of a space station sustain life. Thus no space station, space factory, or other space structure which is to be inhabited by humans could even be considered if air-tight joints could not be guaranteed.

One proposal now under consideration is carrying the Shuttle's External Tank (ET) out into orbit and converting it into a space station. To modify the tank as a space station, a docking adapter/ airlock module (MDA) will have to be fitted to the nose cap of the ET, as shown in Figure 2-8. Preliminary drawings depict the MDA as identical to the one used in Skylab,[13] shown in Figure 2-9.

The MDA will be attached to the ET in orbit; it is unlikely that the MDA could survive lift-off if attached. While the initial connection of the MDA to the ET may be done by mechanical means, welding the connection in space should be done to insure that the seam is indeed air-tight. This is basically an extension of permanently securing mechanical fasteners, as described in Section 2.4.1, but here the geometry is much more complex and so either a welding engineer or a highly sophisticated robotic welder will be necessary.

The majority of structures assembled out in space will not be for human habitation, but will serve as supports for large communication antennas, production facilities, space power stations, and many as yet unimagined ideas. With the development of the beam building (see Section 2.1.3), a method of producing building blocks for these supporting structures in orbit has already been demonstrated.

The beam builder is capable of producing an aluminum truss up to 300 meters long.[7810] However, many space structures under consideration that utilize the beam builder will need beams in excess of 300 meters. One possible structure is the offset wrap rib antenna system, shown in Figure 2-10.[14] The beam builder may be used to manufacture the truss mast.

To use the beam builder to manufacture a beam in excess of 300 meters, it will be necessary to somehow connect two (or more) of the

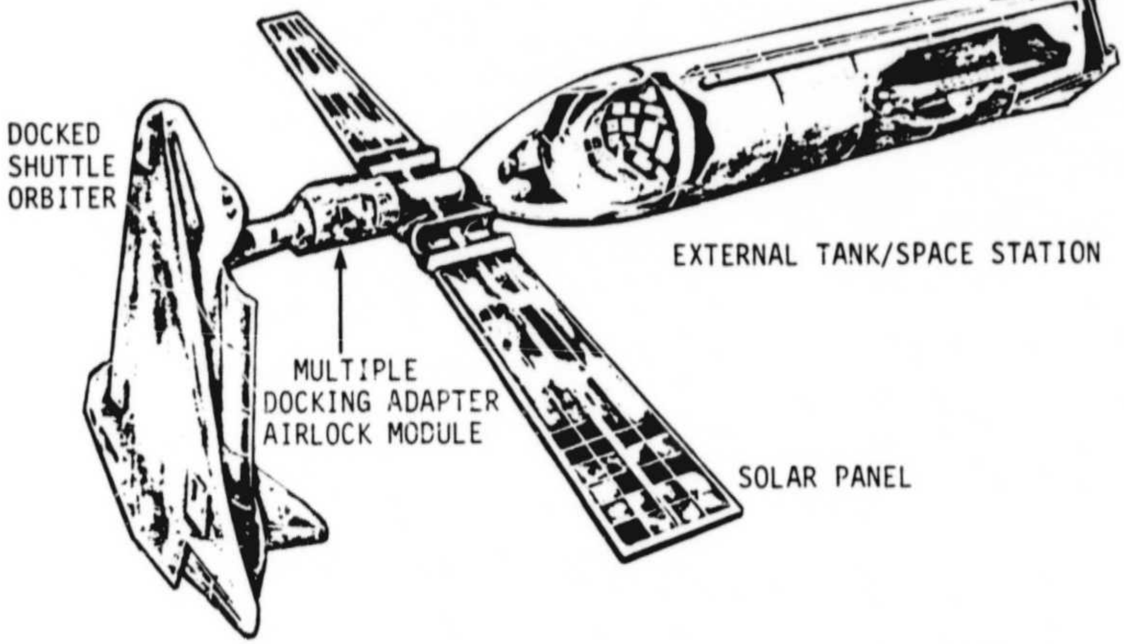


FIGURE 2-8 The need for airtight joints in space -- Attachment of a multiple docking adapter/airlock module to an external fuel tank used for an orbiting platform

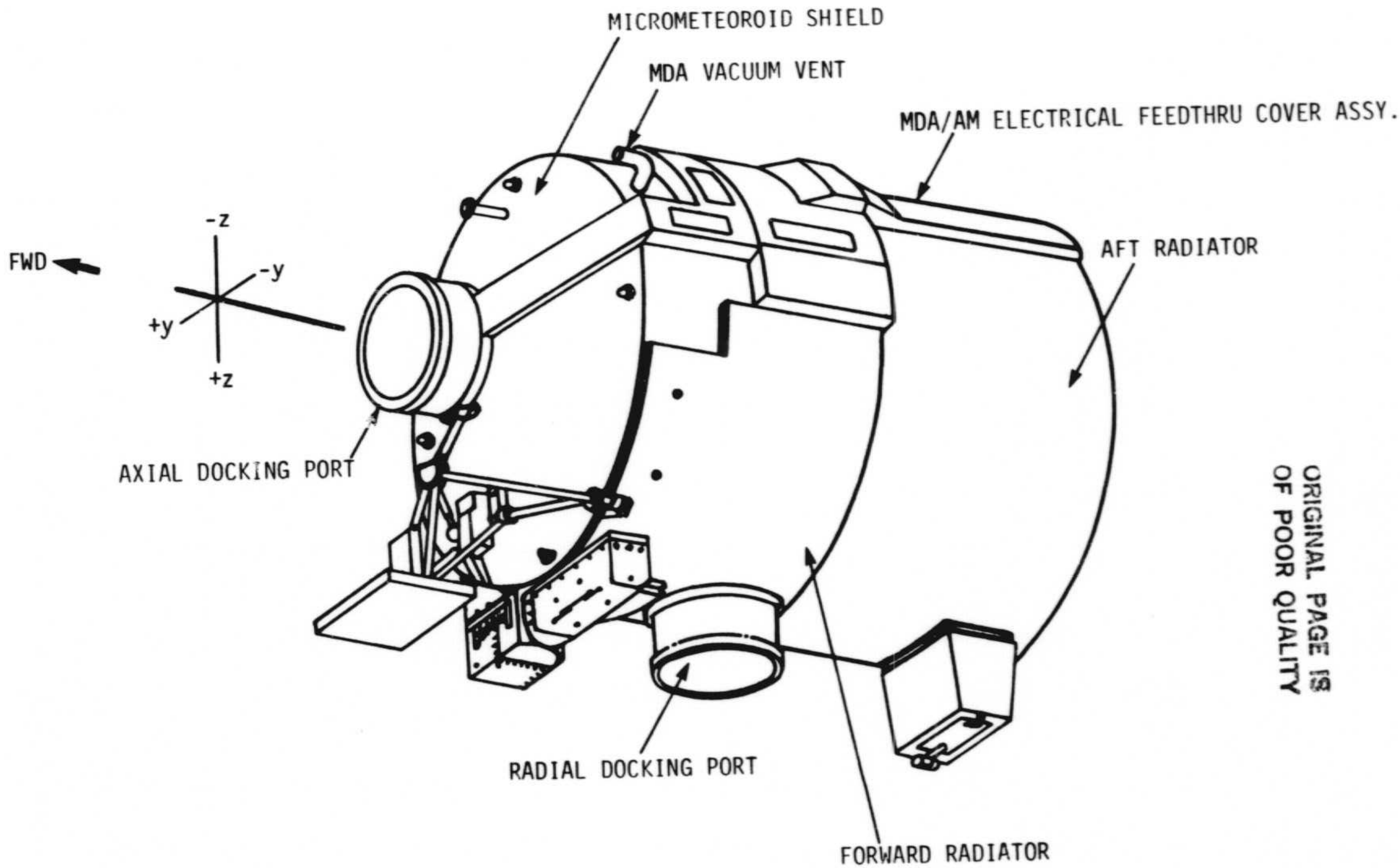


FIGURE 2-9 Skylab MDA

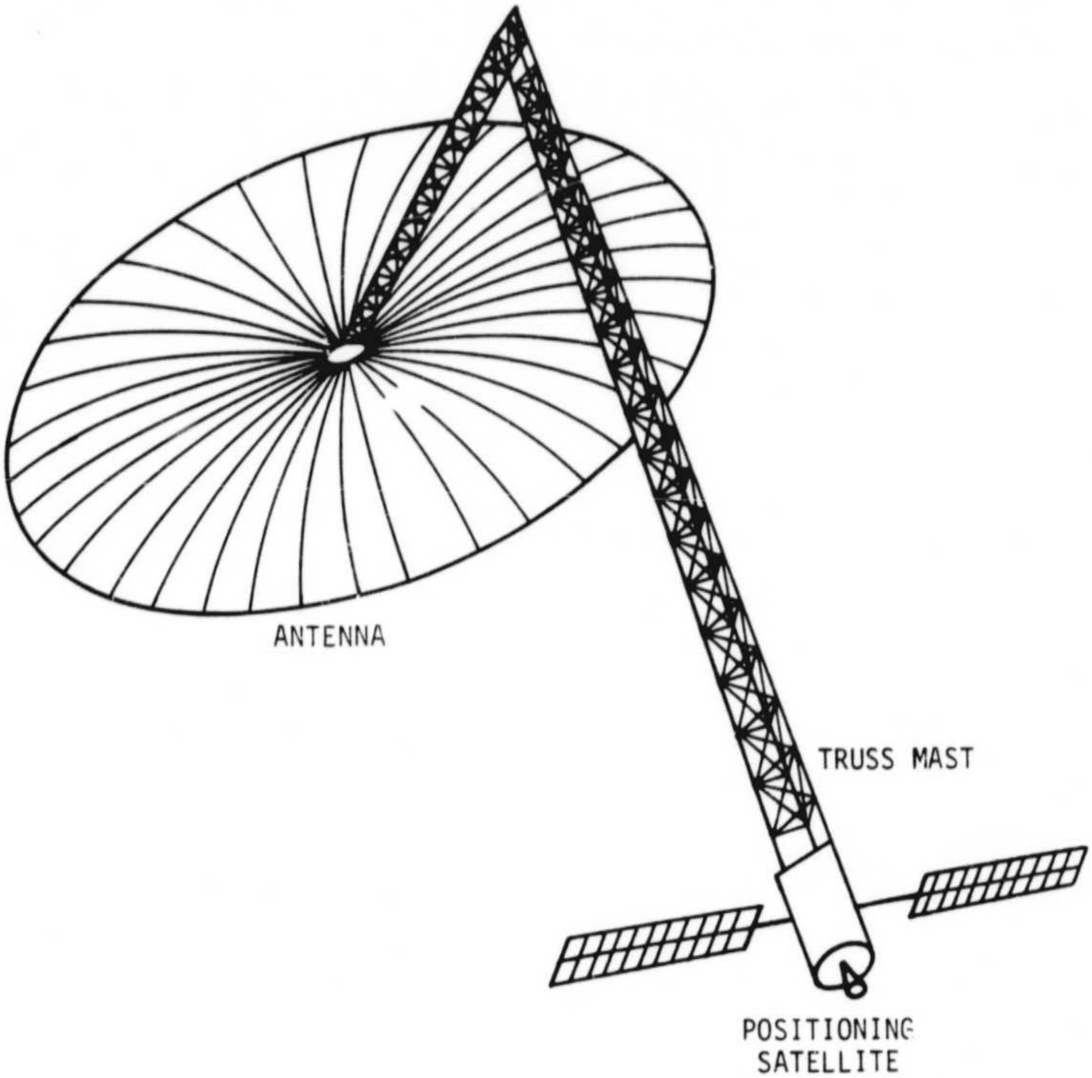


FIGURE 2-10 Offset wrap rib antenna system

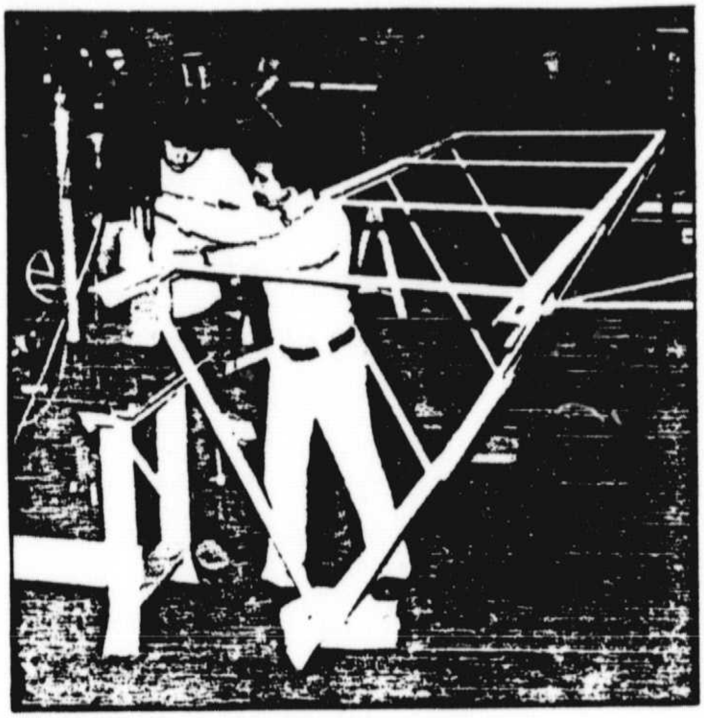
beams. Examination of prototype beams (Figure 2-11a) reveals that this can be accomplished by joining the three beam caps of two beams together. The shape of the beam cap is shown in Figure 2-11b.

It seems that the best and most efficient way to join the end caps together will be by welding. Mechanical fastening may be used, but this would involve first attaching the fasteners to the respective beam caps (possibly by bolts), then aligning the fasteners and completing the connections. In all likelihood this type of connection would not be rigid enough, and so seam welding (see Section 2.4.1) of these mechanical fasteners would also be necessary.

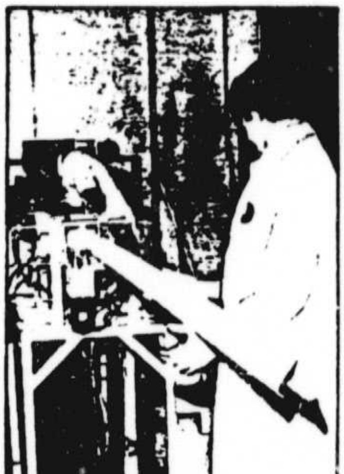
On the other hand, welding the beam caps together would require only alignment and the welding itself. By careful control of the beam builders raw materials on earth, the need for surface preparation can be eliminated, as no oxides would form on the aluminum in space. Once alignment is complete, a remotely manipulate welding machine, most likely using a GTA process, could complete the joining. The ability to weld these beams together will make the beam builder a very versatile space construction machine.

To fully comprehend the impact that welding in space may have, it is necessary to examine an entire system, such as the 10 GWe photovoltaic power satellite. This proposed system could provide a major fraction of the U.S. electric power by the early twenty-first century.[7806] It is composed of eight satellite modules and two antennas that would be constructed in orbit. Solar arrays, power distribution, and microwave units would be fabrication on earth but would still require installation in space.[7808]

An intriguing variation of this is to utilize the moon as a source of raw materials for the manufacture of the structure's components.[7806] The major advantage of this idea is the large reduction in energy needed to launch the raw materials and/or assembly components into orbit. It is estimated that only 4 to 8 percent of the earth launched requirement will be necessary.



a. Prototype Beam



b. Beam Cap

FIGURE 2-11 Beams from Beam Builder

In this lunar processing scenario, not only will the satellite modules and antennas need to be constructed in space, but all other components as well. Table 2-5 gives the equipment necessary to manufacture all of these components in space. As seen from this table, welding, cutting, and brazing are vital manufacturing processes.

Even if the lunar processing is not used, the construction of the support structure and the attachment of the earth fabricated components will require welding. The support structure itself will require beams to be welded together, while the joining of the eighth satellite modules may require air-tight welds. The attachment of the solar arrays and similar components may utilize stud welding, brazing, or other suitable space welding processes. If mechanical joints are used, permanent fastening of the joints may be accomplished by welding.

Although the preceding discussion has dealt with only a few examples of complex structures, it is clear that all large-scale construction in space will demand joining tasks. While it is most likely possible to design such a structure that will require no welding, the cost and degree of difficulty in its construction would probably make it unattractive. The ability to weld in space will make the design, material transportation, and fabrication of large space structures easier and more economical.

2.5 Selection of Candidate Base Materials and Potential Welding Problems.

A limited effort has been made:

(1) To select candidate base materials which are likely to be widely used in future space programs and on which future research should be performed, and

(2) To identify potential problems in welding these materials.

Table 2-5 Component assembly facilities of nonterrestrial materials processing and manufacturing of large space structures (Voniesenhauser[7806])

Component Assembly	Production Rate	Equipment Description	Indust Robot	Facility Estimate Mass (ton)	Power (kw)
dc-dc Converter	1.4 Assy/Day 4.45 ton/Assy	Fixture with Storage Bins, Wire Spools, Turntable and Locating Tools	2	12	30
Klystron Assy	25 Assy/hr 32 kg/Assy	Fixture with Turntable, Wire Winding, EB Welders and Tooling	12	30	180
dc-dc Converter Radiator Assy	1.4 Assy/Day 360 m^2/Assy	Alum Cutting, Forming Press, Roll Seam Welder and EB Welder	2	72	24
Klystron Radiator Assy	25 Assy/hr 2.6 m^2/Assy	Alum Cutting, Brazing Furnace, Fixtures and Tooling	8	14	30
Structural Member Assy	92 Assy/hr ℓ = 6.5-144 m	Furnaces, Swaging Machines, Crimping Machines and Fixtures	6	32	115
MPTS Waveguide Subarray Assy	1.74 Assy/hr 114 m^2/Assy	Lasar Welding Equip, Positioning Fixtures	2	25	30
TOTAL	114 Assy/hr		32	185	0.41 MW

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MPTS Waveguide Subarray Assy	1.74 Assy/hr 114 m^2/Assy	Lasar Welding Equip, Positioning Fixtures	2	25	30
TOTAL	114 Assy/hr		32	185	0.41 MW

2.5.1. Candidate Materials.

Since space structures are likely to be made of light-weight components, aluminum alloys will be most widely used. Table 2-6 compares some characteristics of the primary aluminum alloys considered in the selection for the orbiter crew module and the external tank of the Space Shuttle.[15] Although the Apollo command module inner cabin structure and the Saturn S-11 were fabricated from the 2014-T6 aluminum alloy, the 2219 aluminum alloy replaced the 2014-T6 on the Space Shuttle program. The combination of strength, stress corrosion, and toughness made the 2219 alloy a more desirable choice over the 2014-T6 for the requirements of the Space Shuttle, even though there was more experience with the 2014-T6, according to Whiffen, et al.[15] Furthermore, the 2219 could be repair welded by manual gas tungsten arc process with little risk of cracking, whereas the 2014-T6 did not lead itself to manual weld repair. Several different tempers of 2219 were used including -T62, -T81, -T851, and -T87.

The aluminum alloys shown in Table 2-6 may be considered representative of materials which will be used in future space programs. They include 2219, 2014, 2024, and 2124, with the primary candidate being the 2219. Thin sheets in these alloys are likely to be used extensively for space structures. A limited investigation conducted during this research has revealed examples of actual uses of materials in several space structures being studied as follows:

(1) The Automatic Beam Builder (see Figure 2-10). The beam builder used the 2024-T3 alloy.[7810] The beam end caps, when finished, are 4 mm thick. It is these end caps that must be welded together to manufacture beams longer than 300 meters.

(2) M.I.T. Connector (see Figure 2-4). The connector is made of the 2024 alloy.[12] The sleeve, 3.175 mm (1/8 inch) thick, must be welded to the cylinders that are 34.925 mm (1-3/8 inches) in diameter.

(3) Skylab MDA (see Figure 2-8). The shell is constructed of the 2218-T87 alloy, with a nominal thickness of 6.35 mm (1/4 inch).[13]

Table 2-6 Primary aluminum alloys considered in the selection of the orbiter crew module and external tank of space shuttle[(15)]

CHARACTERISTICS DESIRED	2219	2014	2024	2124
HIGH STRENGTH				+
WELDABILITY	+			
STRESS CORROSION RESISTANCE			+	+
FORMABILITY (Compound Curvature)	(a)	+	(b)	(b)
HISTORIAL EXPERIENCE (SD/Industry)		+		

(a) Weight penalty - cannot fully strengthen after forming

(b) Requires ice box treatment between the solution treating and the forming operations

(c) + indicates outstanding characteristics of the alloy

Table 2-6 Primary aluminum alloys considered in the selection of the orbiter crew module and external tank of space shuttle[15]

CHARACTERISTICS DESIRED	2219	2014	2024	2124
HIGH STRENGTH				+
WELDABILITY	+			
STRESS CORROSION RESISTANCE			+	+
FORMABILITY (Compound Curvature)	(a)	+	(b)	(b)
HISTORIAL EXPERIENCE (SD/Industry)		+		

(a) Weight penalty - cannot fully strengthen after forming

(b) Requires ice box treatment between the solution treating and the forming operations

(c) + indicates outstanding characteristics of the alloy

2.5.2. Potential Welding Problems.

Gas tungsten arc welding (GTAW) process has been most extensively used for fabricating space structures. A paper by Whiffen, et al.[15] describes problems that were experienced during the fabrication of the orbiter crew module and the external tank of the Space Shuttle. Although the 2219 aluminum alloy is readily weldable, strict control of welding procedures was exercised to meet the reliability and repeatability requirements of the Space Shuttle mission. The most difficult defect to overcome in GTAW was the control of porosity due to the inclusion of hydrogen gas during the welding operations. The welding operations took place in a controlled environment after strict requirements for surface cleanliness, part fit-up, shielding gas purity, weld position, and tooling were met. It was found that the 2219 alloy could be welded with a high level of weld quality and with a high degree of repeatability.

NASA Contractor Report CR-2064[16] summarizes results obtained in 19 research programs sponsored by NASA covering various subjects related to welding aluminum alloys. These studies were performed to solve problems encountered during welding fabrication of huge fuel and oxidizer tanks of the Saturn V spacecraft used in the Apollo lunar missions. The materials used were 2014 and 2219-T87 alloys, and they were welded by GTAW and GMAW processes. The most persistent problem was porosity in the weld metal. Other major problems are (a) distortion and (b) reduction of strength of the heat-affected base metal.

Hydrogen was the major cause of weld porosity. Possible sources of hydrogen contamination are:

(1) Surface contamination
(2) Contamination of the shielding gas
(3) Hydrogen impurities in the base and the filler metals.

It was found that the surface contamination was the most important cause of porosity. The surface contamination by hydrogen may be due to (a) moisture on the metal surface, (b) grease, finger prints, and other forms of hydrocarbons on the surface, and (c) hydrogen-containing chemical compounds of aluminum on the metal surface. Studies were also made to determine effective means of cleaning the metal surface. It was found that the most effective method of reducing the potential of weld porosity was to remove a thin layer of the metal surface by machining before welding. Other surface conditioning methods studied include benzene degreasing, trichloroethylene soaking, anodizing, and silicone coating. But none of the methods studied was found to be as effective as the machining in reducing the potential for porosity formation.

3. TASK 2 - IDENTIFICATION OF 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 both 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 understanding of the task requirements is very important because it can permit the specification of the necessary sensing, actuation, and decision making capabilities of any developed system. The availability of a human operator capable of performing high quality welding depends on the specific application, but most probably cannot be guaranteed in space construction or repair.

Since the state of the art is not such as to permit totally autonomous operation, some tasks will have to be handled by the operator and others by a machine. The question that this chapter will attempt to address is what tasks can and should each side handle.

3.1 Welding Task Analysis

Due to the limitations of the existing technology, most of the currently planned space structures are not designed for welded construction. Thus, only a limited number of possible welding tasks can be fully identified at this point; some of these have been presented in the previous sections of this report. Through the continued development of space welding technology, we will be able to achieve more versatile structural designs, which will be vital to the establishment of permanent human presence in space.

At our current level of research, we can readily identify some "generic" welding tasks which are not as application specific as those previously discussed in this report. At a first level of abstraction, welding tasks could be classified in a few categories, depending on:

(a) Whether initial construction, assembly of modules, or repair is performed,

(b) The type of structure in consideration (pressure vessel, structural truss, etc.),

(c) The type of structural members to be joined (plate-to-plate, beam-to-beam, pipe-to-pipe, plate-to-pipe, etc.),

(d) The type of joint being welded and the number of welding passes required (butt, fillet, lap etc. and single, or multi-pass welds),

(e) The detailed strength, tightness, and other quality, integrity and safety requirements imposed by the application (i.e., distinction between critical and non-critical applications).

At a next level of abstraction, it would be easy to realize that welding fabrication almost invariably involves three distinct sequential steps:

(a) Preparation (consisting of plate cutting and forming, edge preparation, assembly of parts to be welded, and tack welding),

(b) Actual welding process execution, and

(c) Inspection and quality control.

Carrying the abstraction even further, we can see that all the steps mentioned above are essentially composed of some very fundamental subtasks which include the following:

(a) Manipulation of welding, cutting, grasping, or inspection tools,

(b) Selection of the process, type, and parameters,

(c) Process control, and,

(d) Evaluation of the joint quality.

In the next few sections, we give a brief description of these fundamental subtasks and the required or attainable level of automation or autonomous operation for each of them.

3.1.2. Tool Manipulation.

Tool positioning and manipulation is necessary not only during welding but also during joint preparation (cutting, cleaning, etc.) and weld inspection, and usually involves:

(a) Positioning of the tool at an arbitrary position and orientation in space, and,

(b) Tracking of a two- or three-dimensional path at a constant speed while keeping a constant distance and orientation to an (arbitrary) surface. (This is not required by some processes such as spot or stud welding.)

Tool manipulation during welding fabrication on earth is conventionally handled by a human operator or a mechanical manipulator (robot). For space environments in particular, the use of a mechanical arm becomes advantageous due to the limited dexterity of the operator and due to safety considerations.

Current state of the art in manipulator technology readily permits a mechanical arm to handle effectively all of the above mentioned tool manipulation tasks. Such an arm typically consists of a series of mechanical linkages driven by a number of actuators, usually computer-controlled. The welding, cutting, or other tools are grasped and carried by the end-effector (hand) of the arm. Different end-effector configurations might, therefore, be necessary for different operations. It should also be mentioned here that manipulation or grasping of the actual workpiece might be required. This necessitates the use of welding jigs and/or workpiece positioners.

A detailed presentation of the various aspects of robotics is considered outside the scope of this study. An extensive treatment can be found in references (17) and (18). The basic manipulator performance measures that have to be given some consideration when designing or using a mechanical arm for tool manipulation during welding fabrication are:

(a) Number of degrees of freedom, which is the number of independent motions which the arm is capable of, and is usually the same as the number of joints connecting the arm links. Six degrees of freedom are needed in order to achieve an arbitrary position and orientation of the end-effector of the arm (and thus of the tool) in three-dimensional space. For welding and cutting, however, only five degrees of freedom are necessary due to the axisymmetry of the tools; the sixth degree of freedom is usually desirable in order to avoid workspace limitations.

(b) Workspace, which refers to the range of positions and orientations that the end-effector of the arm is capable to reach in the n-dimensional space (where n is the number of degrees of freedom). The extent of the workspace depends on both the geometrical dimensions of the manipulator links and the number of degrees of freedom.

(c) Load capacity, which is the maximum load that the arm can effectively position throughout the workspace. It usually depends on the mechanical stiffness of the arm structure and the characteristics of the actuator motors. Even under no gravity conditions, load carrying capacity is rather important because it is related to the arm dynamic characteristics, the maximum permitted accelerations, and the amount of static force that the end-effector can exert when in contact with a body.

(d) Accuracy, which is the maximum error between a commanded and an attained arm position. Positioning and path tracking accuracy is an important consideration in welding applications because it determines whether the weld is actually laid in the desired location. In robotic welding applications on earth, the required accuracy is usually specified to be at least comparable to half the diameter of the filer wire (if one is used by the welding process).

(e) Repeatability, which is the maximum difference in arm positions resulting from repeatedly commanding the same position under identical conditions in a short span of time. Both accuracy and repeatability are strongly dependent on the actual location of the commanded position inside the workspace, the type of the kinematic structure of the arm, and the mechanical design and manufacturing tolerances. Current, state-of-the-art manipulators can, nevertheless, readily achieve the accuracies and repeatabilities required for high quality welding.

(f) Resolution, which is the smallest movement which can be specified and realized by the control system of the manipulator, is also important for accurate path tracking and fine motions.

(g) Speed, which refers to the maximum linear speed of the end-effector and, as most of the previous performance measures, strongly depends on the arm configuration. The ability to follow a specified Cartesian path with a specified speed is very important for high quality welding applications, since the heat input, penetration, and weld bead geometry strongly depend on the welding speed.

The tool manipuation required for welding can be readily performed by a mechanical manipulator as long as the tool position, orientation and speed along the desired trajectory are known. These parameters can either be directly commanded by a human operator, pretaught and replayed by the arm, or extracted from a higher level task description by the computer, controlling the manipulator.

Further discussion on the subject of remote manipulation will be given in a later section of this chapter (3.2.3) where the issues of controlling and teaching the arm are being further examined.

3.1.3 Selection of the Process Type and Parameters.

This is the main function of a welding engineer and basically involves selection of the type of process to be used, the joint preparation required and the initial settings for the particular welding variables that will guarantee the size, shape, and quality of the welded joint that is required by the structural design.

The controllable welding process variables include the primary process parameters, such as arc voltage and current (for the case of arc welding), welding travel speed, filler metal feed rate (if any filler metal is used), etc., and secondary parameters such as welding tool-to-workpiece distance, and relative orientation.

The selection of all the above parameters is normally based on the expertise of a welding engineer and on possible process qualification tests that might be performed. The reason that a high level of expertise is usually required at both the level of the welding engineer and that of the welder, is that the man and the welding machine use essentially different languages. The designer can specify the required joint quality, and the welding operator can observe the joint preparation or the obtained weld bead parameters. The machine on the other hand can only respond to controls of the welding conditions (voltage, wire feed rate, etc.). The role of the welding engineer is therefore to interpret the requirements and the properly communicate with the machine.

In remote fabrication, however, such expertise cannot be readily available and these conditions either have to be preset for the particular task (thus somewhat limiting the flexibility of the overall system), or have to be adjusted using either remote consultation with earth-based experts (telepresence), or using some local intelligence, either in the form of a human operator or a computer-based "expert" system.

Such an "expert" welding machine should also have the appropriate sensing and control capabilities that would permit interfacing with the welding process, as well as the necessary intelligence to communicate with the user on a higher level. Furthermore, it should be capable not only of acquiring and using the expertise of welding engineers, but also to correct and improve its performance based on past experience.

Although fundamental work in this area is currently under way, no such expert systems are currently available for welding fabrication and at this time, a human expert (welding engineer) is required in order to select the proper welding process and conditions.

3.1.4. Process Control.

Welding process control could be generally defined as the procedure of sensing the weld characteristics, comparing them to the desired ones, and then correcting by changing the controllable welding process parameters. This general concept of welding process control is illustrated in Figure 3.1, where two levels of control can be clearly identified. The inner control loop refers to the regulation of the welding parameters (e.g., arc voltage, travel speed, etc.) in the presence of external disturbances, based on set-points specified by the higher level weld controller, that closes an outer control loop by monitoring and controlling the actually obtained weld characteristics.

The most peculiar problem in welding process control as defined above is the fact that the ultimate output of the process (the characteristics of the solidified weld bead) is only known after welding is completed, when there is no possibility of changing the relevant inputs (welding conditions). This inherent difficulty makes the development of models relating welding process parameters and resulting weld characteristics very important.

The major determinants of weld quality which can be used in the specification of the desired weld characteristics are:

(a) Weld bead location and geometry,

(b) Weld and base metal microstructure and metallurgical properties, and

(c) Structural integrity of the joint and the welded structure as a whole.

The final weld location basically depends on the accuracy in tracking the welding path (seam tracking). It is strongly affected by any changes of the position of the workpiece during welding, due to improper joint preparation, bad fixturing, or thermal distortions. On the other hand, the final weld bead geometry refers to both the shape and size of the bead (defined by the weld width and penetration), and is a function of

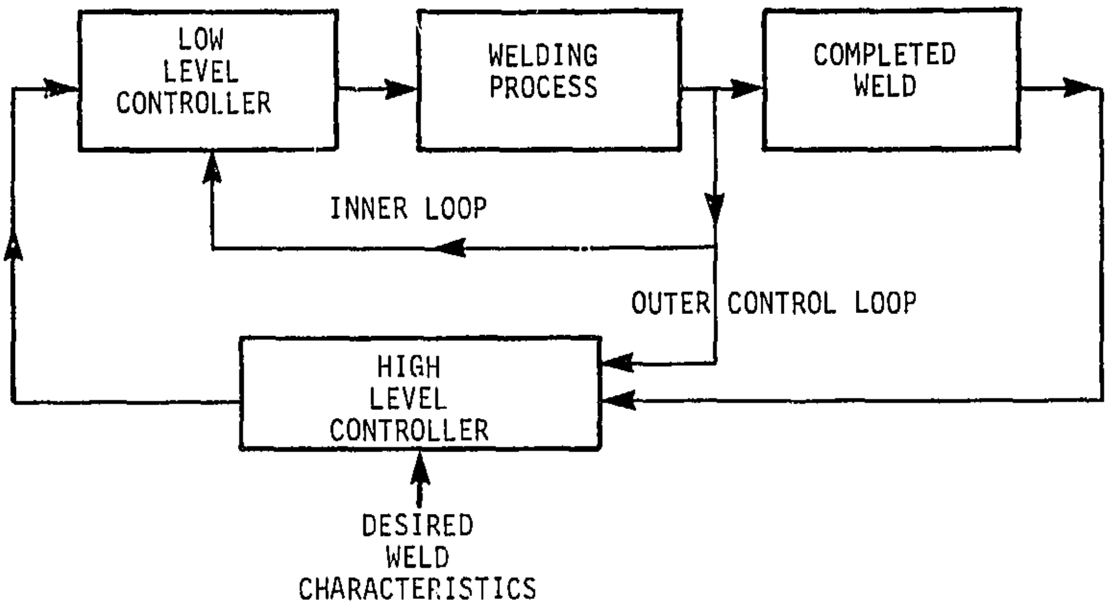


FIGURE 3.1 Welding process control

the welding conditions and parameters which affect the molten weld pool shape and size during welding.

The weld and base metal microstructure and metallurgical properties in general depend on the weld and base metal selection, and are strongly affected by the temperature history and distribution during welding, which determine the heating and cooling rates in the weld and base metal.

The nonuniform and changing with time temperature distribution also cause complex thermal strains that finally lead to residual stresses, distortion, buckling, or cracking, which directly affect the structural intetrity of the joint and the structure as a whole.

Conventional welding systems on earth usually incorporate only the inner control loop, regulating only some of the welding process parameters with no consideration given to the obtained weld characteristics. The outer control loop is probably to an extent closed by the human welder who can somewhat control the process, and adapt based on his expertise.

Sensing of the weld characteristics, process modelling, and adaptive welding control schemes have only recently received considerable attention in several research projects. In fact, the MIT welding research group has been very active in performing fundamental research on arc-physics, in-process sensing and control of the molten puddle and bead geometry[9,10].

Since human welders are not likely to be available in space, and since the sensing ability and dexterity of human operators is expected to be reduced, process control must necessarily be handled by a machine. The above studies must therefore be continued and intensified.

3.1.5 Inspection and Quality Control.

Inspection and quality control is an important part of all the fundamental steps in welding fabrication. Specifically, it is first required during joint preparation in order to determine whether the pre-weld joint geometry and gap sizes between the parts are acceptable. Evaluation of the attained weld quality (through sensing of the intermediate weld parameters) is also an important part of welding process control, as was analyzed in the previous section. Finally, post-weld inspection and quality control is always necessary in order to guarantee that the obtained welded joint is within the design specifications.

A number of different techniques have been developed and are currently used for the non-destructive-testing of welds. These methods include direct visual, radiographic, magnetic particle, ultrasonic, liquid-penetrant, and eddy current inspection techniques. Although inspection is conventionally performed by well-trained, qualified welding inspectors, current state of the art is such that automated welding inspection is considered feasible.

In particular, visual inspection is necessary for both the pre-weld joint evaluation and the post-weld quality control, and can be readily automated using an artificial imaging system.[19] Imaging, whether one- or two-dimensional, relies on irradiating the subject with energy, and then sampling the scattered or reflected energy in some regular manner. Although both radio and sound waves have been used, the most common energy source is light, usually visible.

Visual sensing transducers are usually TV cameras that scan a scene and convert a faster of reflected light intensity values into analog electrical signals. These signals are generated by opto-electrical devices, such as vidicons and solid-state linear or area arrays, pre-processed in hardware, and fed serially at a rate of 60 or 30 frames per second into a computer. The computer analyzes the data and extracts the required information, such as the presence, identity, stable state, position, and orientation of objects in the scene.

The major problem in using machine vision for inspection of the joint or weld bead geometry is the difficulty of extracting three dimension information from a two-dimensional image. This can be done either by using two cameras (stereo vision) or by employing special controlled illumination (structured lighting). For the case of weld inspection in particular, it seems that the latter approach of controlled illumination is preferable, because the former approach suffers from the additional problem of recognizing corresponding points in the two images.

In the structured lighting approach, a spot or line of laser light is scanned across the illuminated scene and the intercept of this laser light and the workpiece is a profile of the terrain geometry. A sequence of these slices can provide a rich base of information on the three-dimensional shape of the illuminated piece. Structured lighting has been successfully employed in robotic welding, for seam tracking applications. Its use has also been demonstrared for weld bead size geometry measurements.[20]

However, visual inspection can help only in determining the visible weld characteristics. Other techniques, such as radiographic inspection are important for the recognition of any internal defects. Digital image processing and computer vision is again very important in automating radiographic inspection procedures (as well as other Not Destructive Testing techniques).

3.2 Operational Modes for Space Welding Fabrication.

A number of distinct operational modes are envisioned as possible for space fabrication in general, and welding in particular. These modes range from fully manned to fully unmanned autonomous operation and can be broadly classified under the categories shown in Table 3-1. The main criterion for this categorization has been the level to which a human operator is used, his proximity to the task site, and the means used for translation and effecting the work task.

3.2.1. Manual Welding by an Operator in the Remote Site.

If, in the simplest case, 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:

Table 3.1 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 (E.V.A.)
		(a.2.2)	Aided E.V.A. . Manned Manuvering Unit (MMU) . Open Cherry Picker (OCP)
(b)	Remotely Manipulated Welding		
	(b.1)	Remotely manipulated from an operator on site	
		(b.1.1)	Manipulation Using the 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) Unaided EVA (Extravehicular Activity) where no special operator translation or positioning devices are employed, apart from handholds (i.e., handrails attached on the structure and other restraints (such as waist tethers) needed in order to achieve force emission capabilities.

(b) EVA using translation aids, where other means are used to transport and position the operator in the remote site. Several such alternatives for safely and conveniently placing a human operator at a work-site have been studied by NASA over the past decade and some of the research programs are referenced in the general bibliography [7006], [7409].

[7908]. The studied or developed translation and positioning techniques refer to both autonomous personal translation devices and to the use of a remote manipulator system.

In EVA using translation aids, an example of the first approach is the use of what is often referred to as a Manned Maneuvering Unit (M.M.U.) which is a self-contained system and can provide a suited and pressurized operator means for translation to and from various sites under external power. Propulsion in all directions, attitude control, and possibility for grasping to a worksite is provided by the unit.

The concept of an Open Cherry Picker (OCP), is an example of the latter approach, where a special platform mounted on the end of a manipulator system can provide the means for conveniently transporting and positioning an EVA operator, tools, and other mission hardware. The manipulator can be either the Shuttle Remote Manipulator System (RMS) or another general purpose manipulator, mounted on a station near the worksite.

The main advantage of the OCP approach is the increased capacity, permitting the transfer of possibly bulky joining hardware. Its main disadvantage (as compared to MMU) is the limited workspace and difficulty to reach confined worksites.

Regardless of the actual means used for translation, the human operator will have to manually position and manipulate the welding, cutting, or inspection tools. Since the space suit and the life support system will have to be carried at all times, the dexterity and sensing ability of the operator will be reduced. Furthermore, safety considerations cannot permit the use of not-enclosed welding arcs or high power processes. Electromagnetic interference might also be of some importance when working in the environment of the electrically noisy welding arc. Finally, task duration will be severely restricted by the limited autonomy of the personal life support equipment and the increased possibility of operator fatigue.

For the case of manually operated space welding, it seems important to develop totally enclosed welding systems (similar to the ones described in APPENDIX B) that simply need to be positioned in the proper place in order to perform a prespecified welding operation.

3.2.2. Remotely Manipulated Welding.

Remote teleoperation is essentially an interim case between fully manual and fully autonomous operation. Teleoperation usually refers to the process where a human operator performs sensing and/or manipulation tasks remotely by use of artificial sensors and actuators. In this way the sensory-motor functions of the operator can be extended to remote or hazardous environments.[21] Teleoperation becomes important in a number of applications, such as utilization of outer space or deep ocean, servicing of nuclear reactors, handling of contaminated or hazardous payloads etc.

In early teleoperator systems, sensing and control was entirely handled by the operator. Sensing usually consisted of direct visual (or video) feedback and possibly force feedback; actuation was performed by means of master/slave control or a joint rate joystick. In master/slave teleoperation, the operator uses the master (a scaled or life size copy of the remote manipulator) in order to command a particular motion of the slave. In rate control, a joystick is used to command the rates at which the individual joints of the slave arm are to be moved.

In current teleoperation systems, however, some of the sensing, decision making, and actuation tasks are usually handled by a computer. This mode of operation, where control is shared between the operator and the computer is usually called "supervisory control", since the human operator acts more like a "supervisor" of the process. This hierarchical control scheme has applications in several other areas in addition to remote manipulation such as industrial process control, vehicle control, and information systems.

In all these cases, the computer can either share control with the operator (thus extending his abilities or relieving him of some of the low-level control burden) or trade control totally replacing him for some particular preprogrammed tasks. The extent of this sharing or trading of control depends on the task at hand and the sophistication of the computer system.

The human operator usually performs the higher level task planning, deciding on overall goals, trade-offs, methods, and required low-level actions. He also teaches the computer the required procedures for each task, monitors the progress of the task (either directly, or indirectly through the computer) and decides when and whether it is required to intervene by correcting or totally bypassing the computer. Furthermore, the operator has learning ability and is able to use his experience to improve his future performance.

In remote manipulation systems, in particular, it is also not uncommon to further divide the computational effort and provide local intelligence both where the operator is located and at the remote task site. This is usually considered necessary in order to avoid communication problems, and is only currently possible due to the ready availability of compact and powerful microcomputers. The remote site computer is usually assigned the function of monitoring and locally controlling the remote task based on commands sent either by the other computer or directly by the operator. The computer at the operator site is used for displaying information to the supervisor and aiding him in his planning, teaching or learning functions.

Current progress in artificial intelligence makes possible the substitution of the operator even in these higher level functions. It also permits computers to perform increasingly more complex planning or learning tasks, giving them greater autonomy.

Operationally, we can distinguish between (a) <u>remote manipulation with the operator located in space</u>, and (b) <u>with the operator located</u> on <u>earth</u>. The latter case imposes the additional limitation of a communication time delay, but has the advantage that a trained welding "expert" can be used to perform the remote task.

(a) Remote manipulation with the operator located in space:

Some different possibilities for remote manipulation with the operator in space have already been studied by NASA and various subcontractors [6907], [7006], [7203], [7407], [7906], [7908]. The use of the remote manipulator system (RMS) of the shuttle has been proposed and examined as a first obvious choice. However, its applicability in complicated joining or other fabrication operations is rather limited due to its size, limited dexterity and sensing capabilities.

An operator base, equipped with several dexterous manipulator arms and sensing devices, is usually considered a proper alternative for such tasks. An example of such an operator base for manned space manipulation is the concept of the Manned Remote Work Station (MRWS) which will be a universal crew station to be used as a space crane turret, a railed work station, a closed cherry picker, an airlock, or a manned free flyer [7908].

In these modes, the MRWS will provide support for construction maintenance, repair and servicing operations. Its early versions will more probably evolve from an EVA support station or an open cherry picker (OCP), for use on the shuttle. Ultimately, however, it will be used in large scale space construction both at Low Earth Orbit (LEO) and at Geosynchronous Orbit (GEO).

A modular design has been proposed for the planned final configuration of the MRWS, which involves a cabin core with access hatches and other berthing or vehicle mating interfaces, a stabilizing grasping arm and two (or more) dexterous manipulators [7908].

(b) Remote manipulation from earth:

Remote manipulation from earth will permit the best use of human experts who are not likely to be available in space. It has the main disadvantage that the large distances involved introduce a significant communication time delay. This round trip time delay is composed of the time needed for a control command to travel to the teleoperator and for the first indication of response to travel back. The delay will therefore be twice the distance divided by the speed of signal propagation. The effects of transmission delay on human performance during remote manipulation have been studied in the past by various investigators. Transmission delay was also one of the factors studied in the experimental simulation of remote welding performed in this study, and presented in Appendix D.

Regardless of the proximity of the operator to the remote task, the welding cutting or inspection tools will be handled by the manipulator arm, whereas the human operator will be directing the whole operation enclosed in a life sustaining, "shirt-sleeve" environment. Therefore, unprotected open arcs or high power processes can be used, since the potential operator hazards are minimal. Furthermore, task duration can be longer since no personal life support equipment is used and operator fatigue is easier to avoid.

There are, however, several issues that need to be considered and resolved for the successful design and effective use of a remotely manipulated welding system. These basically include the following:

(a) Examination of the manipulator capabilities expressed by various performance measures such as number of degrees of freedom, extent of the workspace, accuracy, repeatability, resolution, and speed;

(b) Examination of the required sensing capabilities which can include visual, proximity, touch or force sensing, as well as sensing of welding variables and evaluation of the weld quality; and,

(c) Examination of the Man-Machine interface which basically refers to the selection of the relative roles of the human operator and the computer, the evaluation of various means for monitoring and displaying information relevant to the task, the development of teaching (or programming) modes and languages, and the provision for operator intervention.

The manipulation capabilities required in order to effectively perform remote welding have been examined in the section on tool manipulation (3.1.2). The sensing requirements have also been examined in the sections on welding process control and weld inspection (3.1.4 and 3.1.5).

Work on the various aspects of the man-machine interface design for remote manipulation in space has been performed by a number of investigators in the various NASA projects mentioned earlier. Fundamental work on the general subject of man-machine systems is being performed by Sheridan and co-workers at M.I.T.[21, 22, 23] In a recent study, Yoerger has investigated various aspects relevant to the man-machine interface design for remote underwater manipulation.[23] He was actually able to show that task performance was improved when manipulation was performed in a supervisory control mode, where a computer was used to perform a task that the operator taught.

3.2.3. Totally Autonomous Systems.

In both the previously examined cases (manual and remotely manipulated welding in space), a human operator is available and performs either the joining operation with hand-held tools or only handles the higher level functions, supervising the operation actually performed by a manipulator and a computer.

On the other hand, in a completely autonomous system, the role of the operator will be diminished and the computer will be handling even the higher level functions of planning, learning and decision making.

Although the development of such a totally autonomous system is not currently feasible, the very active research in artificial intelligence and related fields can most likely guarantee that such a development will soon be possible. NASA, recognizing the importance of these developments, has sponsored a number of studies on the subject such as for example [7906], [8012] and [8208].

The major research areas that are generally recognized as important in the development of autonomous systems are [8012]:

(a) Planning and Problem Solving,
(b) Machine Perception,
(c) Natural Language Understanding,
(d) Expert Systems,
(e) Automation, Teleoperation, and Robotics,
(f) Distributed Data Management,
(g) Cognition and Learning.

Because manual welding in space is not currently feasible, it is natural that the development of space welding systems and concepts should start with the simplest hand-held packaged tools, and proceed through the development of remotely manipulated and partially computer controlled systems. Then, after the major stumbling blocks in the development of autonomous systems are overcome (through research in the artificial intelligence fields mentioned above), the totally automated welding fabrication systems will become a reality.

Therefore in this study we will mainly concentrate in the first two directly feasible operational modes which will pave the way for future totally autonomous systems.

3.3 Experimental Study.

An experimental study was initiated at MIT 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 be effectively performed remotely, and that disappropriately 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. Welding process control will be handled to an extent by a machine and was not further investigated. This is justifiable since welding skills should not be expected to be available in space, the technology for regulating the welding variables is readily available, and the state of the art in welding process control is rapidly advancing.

For simulation of remote manipulation, the facilities in the Man-Machine Systems Laboratory of the Mechanical Engineering Department at MIT were used. Two sets of experiments were designed and a complete description of the experimental setup and the obtained results are presented in Appendix D.

This experimental study is still underway. The results obtained to date nevertheless indicate that welding performance can be significantly impaired during remote manipulation, especially when time delay is present. It is, therefore, preferable to avoid performing welding path tracking manually. As was previously detailed, this task can be readily handled by a computer controlled manipulator. The operator must be used to initially position the tools, teach welding paths, and plan the welding operations. This human supervision is considered particularly necessary in situations that are difficult to preplan, such as during repairs.

3.4 Discussion and Recommendations.

From the previous discussion, the following conclusions can be drawn:

(a) Because manual welding in space has not been feasible, it is natural that the development of space welding systems and concepts should start with the simplest hand-held packaged tools and proceed through the development of remotely manipulated and partially computer controlled systems. Then, after the major stumbling blocks in the development of autonomous systems are overcome (through research in other fields) the totally automated welding fabrication systems will become a reality. Therefore, in this study we will concentrate on the first two directly feasible operational modes which will pave the way for future totally autonomous systems.

(b) For the case of manually operated space welding, it seems advantageous to develop totally enclosed packaged welding systems (similar to the ones described in APPENDIX B) that simply need to be positioned in the proper place in order to perform a prespecified welding operation. Except for initial positioning, all other welding subtasks, such as tool manipulation, and process control will be handled by the system. This is considered necessary due to the limited dexterity and sensing ability of the operator, the reduced task duration, and operator safety concerns.

With these systems, no welding skill is required of the operator. However, the flexibility of such systems is minimal since they handle a single welding geometry and configuration and most of the parameters are expected to be known and preset. The stud welding gun and some of the "instamatic® " welding machines that are proposed later in this report are examples of such systems.

(c) In the case of remotely manipulated welding in space by an operator on site, high power and/or non-enclosed processes can be readily used. It seems that the operator must teach welding paths and plan the welding operations. Tool manipulation over the taught path, as well as process control, can and should be handled by the machine. Human supervision is considered particularly necessary in situations that are difficult to exactly preplan such as repairs.

(d) Remote welding from earth is affected by the time delay and is feasible only if a relatively high degree of autonomy is possible at the remote site that would require only minimal supervision from earth.

4. TASK 3: 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. 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 welders, and

(2) Efforts to develop new welding processes and procedures uniquely suited for space applications.

4.1 Development of Space Welding Technologies which Do Not Require the On-site Presence of Welding Engineers and Welders

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.

4.1.1. Development of Completely Remote Welding Technology

We believe that it is technically possible to develop welding systems which can perform certain simple welding tasks through completely remote operations. One possible example is a stud welding system. M.I.T. researchers are currently working on a research program which has the objective of developing technologies of underwater welding by remote manipulation techniques.[7] Efforts are being made to develop a stud welding system which can perform underwater welding by being attached to a manipulator which is then attached to an underwater work vehicle.

A similar stud welding system can be developed for space applications. APPENDIX C presents the results of a preliminary investigation of the feasibility of using stud welding in space. A major unsolved problem is that we do not yet know how to initiate and maintain an arc necessary for stud welding in a vacuum. It may be necessary to have some mechanisms, such as to feed a small amount of gas near the weld zone, to perform stud welding in space. The only thing that a crew aboard a space station needs to do is to place the welding system at the right location. Then all other necessary operations, including selection of appropriate welding parameters and activation of the welding operation, will be performed by personnel in the command station on earth. Once this technology is established, it will be possible to further advance the systems in such a way that even the positioning of the welding systems at right locations can be done by manipulators. If this technique is established, welding may even become possible using an unmanned space vehicle.

Completely remote welding techniques may be developed using processes other than stud welding; however, further research is needed to (1) identify good candidate processes and (2) to develop designs of feasible welding systems.

4.1.2. Development of Integrated and Automated Welding Systems which can be Operated by Persons with no Welding Skill

We believe that it is possible to develop technologies of performing certain simple welding jobs by using integrated and automated systems which can be operated by persons with no welding knowledge and skill. M.I.T. researchers have already developed basic systems of "instamatic® " welding for marine applications (see APPENDIX B). Similar systems can be developed for space applications. It is also important that newly developed systems will have additional features as follows:

(1) The systems should have in-process sensing and control capabilities ("smart" welding machines), and

(2) The system should be an integrated system covering all necessary actions involved in welding including cutting, edge preparation, welding as well as inspection.

Welding Machines with Adaptive Control Capabilities. An important feature of manual welding is that a human welder is a complete system with adaptive control capabilities. In other words, the human welder follows the welding operation and provides necessary manipulation of the electrode using his hand. Most automatic welding machines on the market today do not have such adaptive control capabilities. In using these automatic welding machines, optimum welding conditions are established by experiments for the particular joint conditions (joint type, plate thickness, etc.) and they are used in actual fabrication. Some modern automatic welding machines are equipped with seam tracking devices to guide the welding torch along the joint to be welded. However, almost all welding machines do not have adaptive control systems capable of sensing what goes on during welding and providing necessary adjustment in welding conditions in real time.

The development of "smart" welding machines with adaptive control capabilities is an important research subject in welding today. For example, M.I.T. researchers, including Professor K. Masubuchi, have been engaged in basic research whose objective is to improve reliability of welding by in-process sensing, analysis, and control.[9, 10] Studies on the automatic control of welding have been made in a number of laboratories. Efforts should be made to incorporate the results of these recent studies in the development of welding systems for space applications.

Integrated Welding Fabrication Systems. As stated earlier, welding is only a part of a total fabrication system which includes several steps including cutting, forming, assembly of parts, welding, and inspection of welds. And these steps are interrelated. For example, unless joint edges are properly cut and parts are assembled correctly, it is extremely difficult, if not impossible, to obtain good welds. If welds are found to be defective during the inspection, the portion of the weld containing defects must be cut again and rewelded. In ordinary fabrication on earth, there are specialists covering each of these important steps, including those in charge of cutting, forming, welding, and quality control. It will not be possible to have such specialists on each step in space fabrication. Therefore, it is extremely important that welding fabrication systems are adequately integrated to be capable of performing some, if not all, of the important steps involved in welding fabrication.

Complexity, Cost, Maintenance. An important subject here is how complicated a machine should be developed. If one develops an all-purpose machine which can weld many types of joints, it would become rather large and very complicated. These complex machines are not only expensive but also difficult to operate. Complex machines also tend to malfunction more often and requires more frequent repairs. Perhaps the most sensible way is to develop several different types of machines each capable of performing certain types of welds.

4.1.3. Development of Welding Technologies through Telepresence.

Utilizing of the current welding and robotics technologies, systems which are discussed in the preceding parts (4.1.1 and 4.1.2) will be able to perform very simple welding tasks. It is perhaps worth thinking about another approach that will develop technologies for performing certain welding jobs through technical assistance from the earth using telecommunication techniques including TV cameras, telephones, etc. In other words, welding experts in the command station on the earth provide the crews with necessary technical information. Through this method, much technical information, such as what welding conditions must be used for certain applications, can be transmitted. Certain actions may even be done by robots through remote manipulation.

The best approach may well be to utilize the combined capabilities of (a) automated machines, (b) human presence aboard the space station, and (c) expert knowledge available on earth. This combined system may be useful for performing the somewhat complex welding jobs which cannot be done by machines, which are discussed in 4.1.1 and 4.1.2.

4.2 Development of New Welding Processes and Procedures Uniquely Suited for Space Applications

There is 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) Space Electron Beam Welding Technology. When electron beam welding is used on earth, great efforts are made to obtain a vacuum. For example, samples to be welded must be placed in a vacuum chamber or a rather sophisticated system must be developed to provide vacuum environment to areas near the weld; thus, large machines are needed to produce the electron beam welds on earth. These are not necessary when electron beam welding in space. 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) Space Exothermic Brazing Technique. 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 Systems. 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.

5. TASK 4: RECOMMENDED FUTURE STUDIES

In earlier parts of this report, discussions are given on probable joining tasks in space (2.4) and the development of novel space welding concepts (Section 4). This section presents several research programs with specific objectives of accomplishing what has been discussed in 2.4 and Section 4. The recommended research programs are classified into two groups, as follows:

Group A: Research Programs Recommended to be Performed Immediately

Research Program #1: Development of Space Stud Welding Systems which can be Remotely Manipulated.

Research Program #2: Development of "Instamatic® " GTAW Systems for Space Applications which can be Operated by an Astronaut with no Welding Training.

Research Program #3: Development of Flexible Space Welding Systems.

Group B: Research Programs Recommended to be Performed After Some Results of Group A Research have been Obtained.

Research Program #4: Research on Space Welding using GMAW, EBW, and LBW Processes.

Research Program #5: Research on Special Joining Techniques Suited for Space Applications.

Research Program #6: Development of Integrated Fabrication Systems for Certain Complex Space Structures.

Discussions on 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 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 that the present state of the space welding technology is similar to that of an unborn fetus. What we are proposing under Research Programs #1, #2, and #3 is equivalent to an effort to make an infant successfully crawl and totter a few steps. This will lead to a healthy, walking child who will soon run and jump. Just like a parent 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.

We should also start looking at the space welding techniques that are likely to be used extensively in the distant future, say in 2020 or 2050. It is reasonable to assume that GTAW and possibly GMAW processes are likely to be used extensively for welding space structures which will be made in light metals and materials with high strength-to-weight ratios such as titanium alloys. However, if we imagine which processes are likely to be used extensively in space in 2020, many of us may agree that among the processes which are known to us now (see Figure 2-1), electron beam welding (EBW) and laser beam welding (LBW) look very promising. Therefore, possible uses of these processes in space should be studied extensively. This is the reason for proposing the Research Program #4.

There may be some joining processes which are very useful for some space applications. They include such processes as cold welding, diffusion bonding, explosive welding, exothermic brazing, and solar welding. In fact some studies on the possible space applications of these processes have already been made, as discussed in 2.1.1 and 2.1.2. Research Program #5 is to study these and other joining processes suited for some space applications. We recommend, however, that this research program be given a low priority unless some process becomes essential for certain important applications.

As stated earlier (Section 2.3) many joining processes which are available on earth today can be used in space if we decide to use them. Consequently, the joining processes to be used often depends on the structures which need to be fabricated. For example, spot welding has been selected for the Automatic Beam Builder.[8009] In developing space welding technologies, there are basically two approaches. One is to develop technologies around certain generic joining processes such as stud welding and the GTAW process. The emphasis of this research has been placed on this first approach. The other approach is to select and develop joining technologies which are most suitable for certain structures which need to be fabricated. For example, if we need to make a long pipeline in space, such processes as high-frequency resistance welding may become very attractive. In fact, for some specific applications, it may be possible to design and construct a completely integrated and automated fabrication system for certain applications.

The reason for recommending Research Program #6 is that there may be a need to look into space welding technologies from the viewpoint of structures needed to be fabricated. However, as far as the development of welding technologies are concerned, this research program should be given a low priority unless certain important applications are identified.

One suggestion along this line is to engage in cooperative efforts with researchers working on other research programs included in the Innovative Utilization of the Space Station. In the 18 programs currently included in the Space Station Project, many types of structures, tools and equipment need to be fabricated. Some of them may present interesting welding problems. The development of certain joining techniques in space may be very useful for performing some of the research programs. M.I.T. researchers are very willing to look into these possibilities.

The following pages describe further details of the six recommended research programs.

5.1 Research Program #1: Development of Space Stud Welding Systems which can be Remotely Manipulated.

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 operation, are to be performed by personnel in the command station.

APPENDIX C 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 (see Figure 5-1):

- Phase 1: Basic Study on Space Stud Welding (2 years)
- Phase 2: Development and Laboratory Testing of the First Generation Space Stud Welding Systems (2 years)
- Phase 3: Simulated Zero Gravity Testing of Systems Developed in Phase 2 (Concurrently with Phase 2)
- Phase 4: Development and Laboratory Testing of Integrated Space Stud Welding Systems (2 years)
- Phase 5: Simulated Zero Gravity Testing of Systems Developed in Phase 4 (Concurrently with Phase 4)
- Phase 6: Testing in Space of the Integrated Space Stud Welding Systems (2 years)

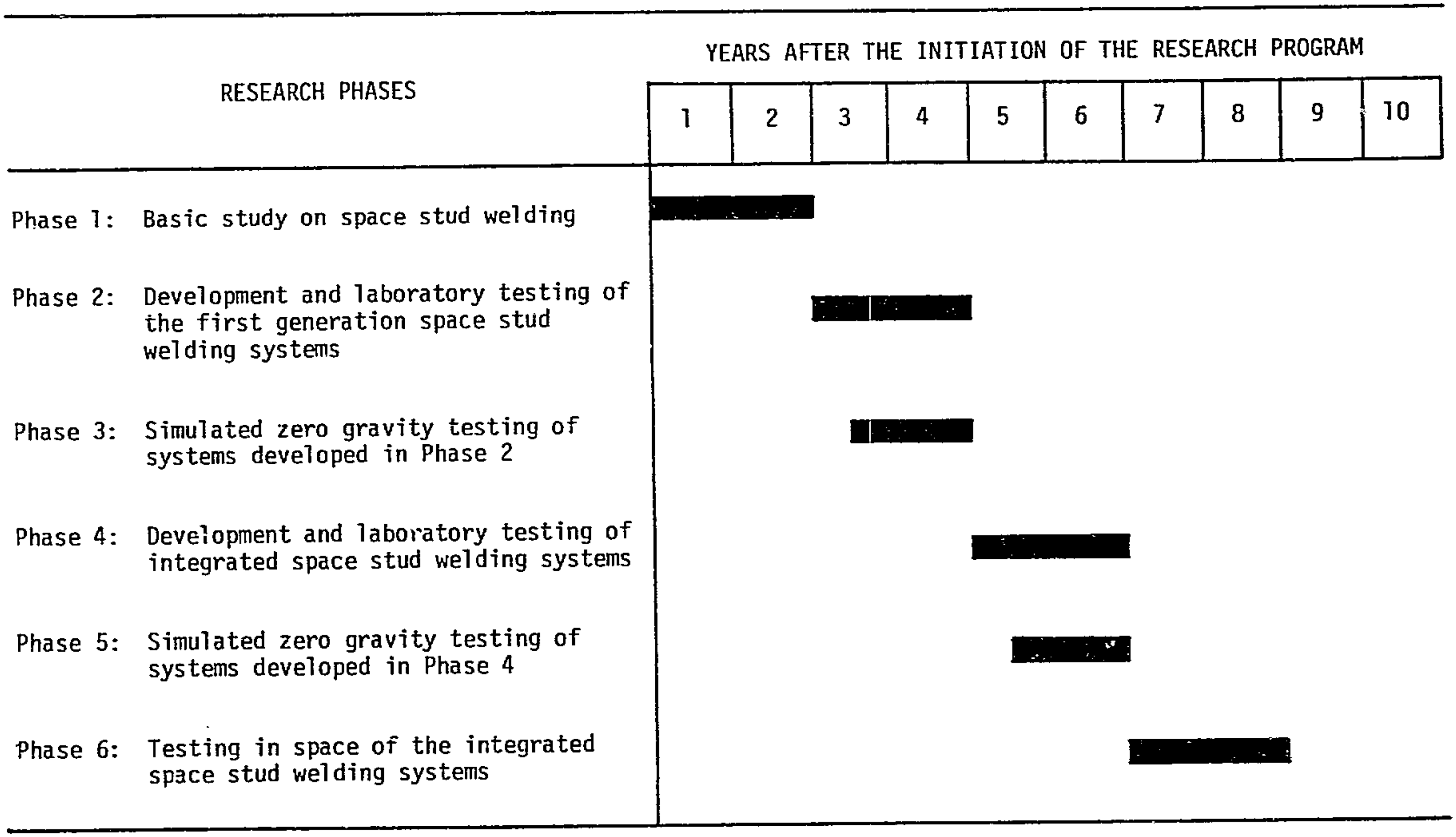


FIGURE 5-1 Phases which will be included in the Research Program #1: Development of stud welding systems which can be remotely manipulated

It is expected that the entire research program including Phases 1 through 6 will be completed in eight years. Stated differently, we should be ready for testing in space of the integrated space stud welding systems in six years. The period of research could be shortened by (a) accelerated funding and/or (b) increased collaboration with manufacturers of stud welding machines and aerospace companies.

5.1.1. Phase 1: Basic Study on Space Stud Welding.

The objective of Phase 1 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 materials and optimum welding conditions for selected 2000 series aluminum alloys

Step 1-3: Development of initial designs of the first generation space 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. (see Figure C-5 in APPENDIX C for the experimental set-up). Experiments will be made on several materials including aluminum alloys, high-strength steels, stainless steels, and titanium alloys. Efforts will also be made to determine whether the existence of certain gases or mixture of gases would facilitate the initiation and maintenance of an arc in a vacuum.

Step 1-2 is to develop suitable stud materials and optimum welding conditions for stud welding selected 2000 series aluminum alloys. Close contacts will be made with representatives from NASA in selecting the materials and stud sizes to be investigated. Our choices at present are:

(a) Materials: 2219 (primary) and 2014 (secondary)

(b) Stud size: 6.4 mm (1/4 in) diameter as the primary candidate.

Step 1-3 is to develop initial designs of the first generation space stud welding systems, the hardware of which will be constructed in Phase 2. Results which will be obtained in Step 1-1 should be helpful in determining whether some devices are needed to facilitate the initiation and maintenance of an arc in a vacuum.

Efforts will also be made to develop at least portions of an integrated welding system using stud welding. Figure 5-2, which is the same as Figure C-6 of APPENDIX C, is a block diagram of a control process for a fully integrated welding system. Further detailed discussions of this figure are presented in APPENDIX C (C.4.5.1). The basic concept shown in this figure is applicable to any welding process, although the emphasis of the discussion presented here is placed on stud welding, especially capacitor-discharge stud welding, which is likely to be investigated for space applications during early stages of development.

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, as discussed in various parts of this report. 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.

Figure 5-2 shows that an integrated stud welding system should have the following subsystems (in time sequences 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.).

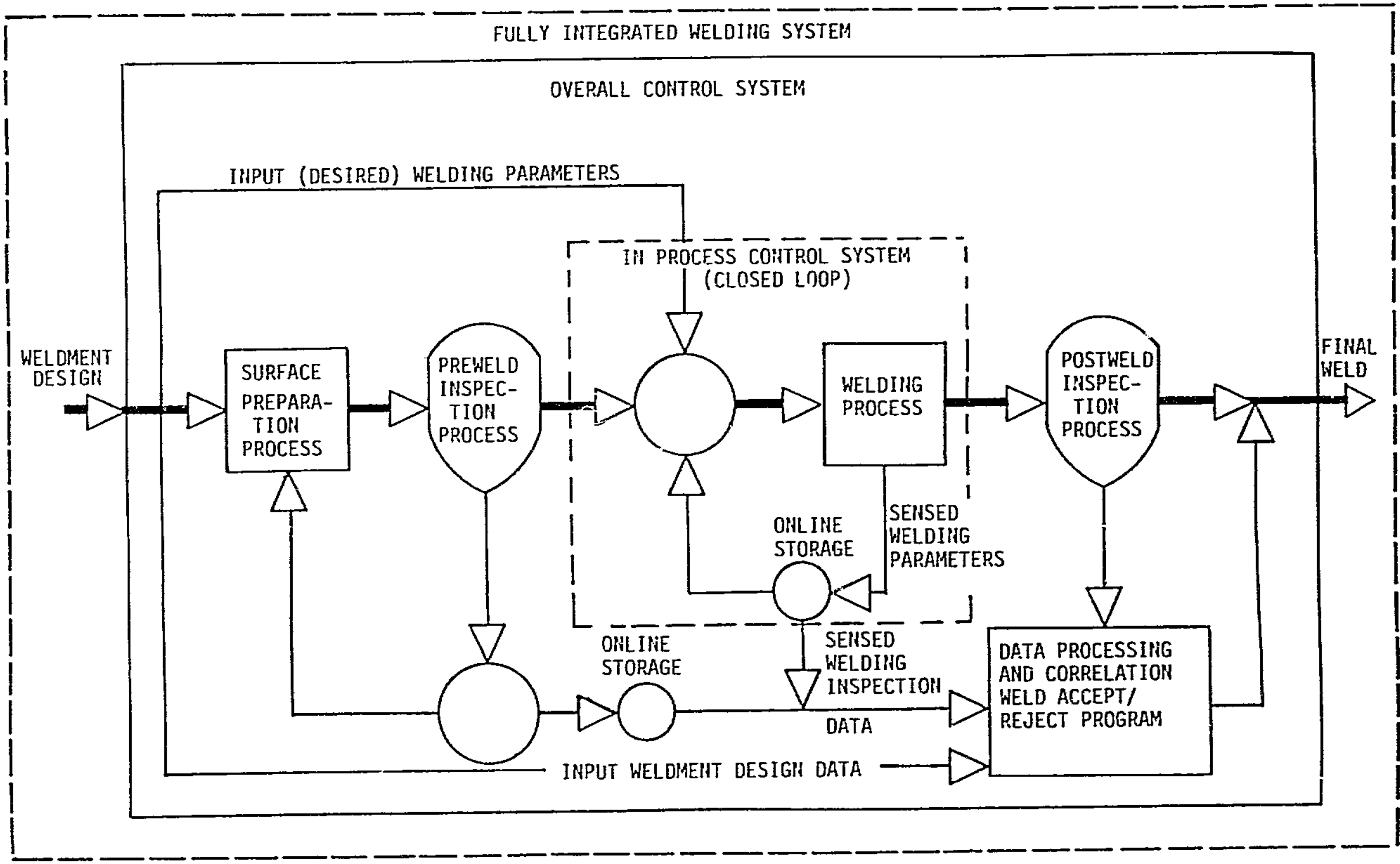


FIGURE 5-2 Control system for a fully integrated welding system

(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 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 in Figure 5-2.

The final product of Phase 1 will include:

(a) Experimental data on stud welding of various materials in a vacuum,

(b) Information on suitable stud materials and optimum welding conditions for stud welding selected 2000 series aluminum alloys,

(c) Design of an initial hardware system which will be constructed and tested in Phase 2. The system, which is called the first generation space stud welding system, will include some portions of the completely integrated space stud welding system which we plan to develop during the entire research program.

5.1.2. Phase 2: Development and Laboratory Testing of the First Generation Space Stud Welding Systems. The objective of Phase 2 is to construct and perform laboratory tests of the first generation space stud welding systems which will include some parts of an integrated space stud welding system. Phase 2, which will be completed in two years, will consist of the following steps:

Step 2-1: Construction and testing of the first generation hardware

Step 2-2: Improvements of the first generation hardware and further testing

Step 2-3: Development of designs of integrated space stud welding systems.

The objectives of Step 2-1 will be to construct the first generation hardware of the space stud welding system based on the design which will be developed during Step 1-3 and perform laboratory testing of the hardware. During the tests important experimental data useful for future improvements will be generated, and we will gain experience which will be invaluable in future development work.

The objectives of Step 2-2 will be to improve the first generation hardware and conduct further tests using improved systems. We will try to incorporate increasing number of sybsystems as the research progresses.

At the end of Phase 2, which will be the end of Step 2-3 as well, designs of an integrated space stud welding system will be developed.

5.1.3. Phase 3: Simulated Zero Gravity Testing of Systems Developed in Phase 2.

The objective of Phase 3 is to conduct testing of systems which will be developed in Phase 2 under simulated zero-gravity conditions obtained in an aircraft during a prescribed flight path. A close coordination with NASA representatives are needed to make necessary arrangements for such in-flight experiments. The most logical arrangement will be to have the 1-1/2 years long Phase 3 start six months after the initiation of Phase 2, as illustrated in Figure 5-1. It would be very helpful if flight tests can be made two different times as follows:

(1) The first series of in-flight tests on the first generation hardware developed in Step 2-1 to be performed around the end of the first year of Phase 2 or the beginning of the second year

(2) The second series of in-flight tests on the improved hardware around the end of the second year of Phase 2.

The experimental data and the experience which will be obtained in Phase 3 will be used in the research efforts in later stages.

5.1.4. Phase 4: Development and Laboratory Testing of Integrated Space Stud Welding Systems.

The objective of Phase 4 is to construct and perform laboratory testing of integrated space stud welding systems. Phase 4, which will be completed in two years, will consist of the following steps:

Step 4-1: Construction and testing of the first generation integrated space stud welding system

Step 4-2: Construction and testing of the improved integrated space stud welding systems.

The objective of Step 4-1 will be to construct the first generation integrated space stud welding system based upon the design which will be developed during Step 2-3 and perform laboratory tests on the system.

The objective of Step 4-2 will be to further improve the system developed in Step 4-1. It is hoped that the final system which will be developed after the completion of Step 4-2 will be complete enough to be used, perhaps with minor modifications, for actual uses in space.

5.1.5. Phase 5: Simulated Zero Gravity Testing of Integrated Space Stud Welding Systems Developed in Phase 4.

Phase 5 will be similar to Phase 3 except that in-flight testing will be made on integrated space stud welding systems developed in Phase 4. Again, the most logical arrangement will be to have a 1-1/2 year long Phase 5 start six months after the initiation of Phase 4. It would be most helpful if flight tests can be performed in at least two series.

5.1.6. Phase 6: Testing in Space of the Integrated Space Stud Welding Systems.

Phase 6 will be to perform testing in space of the integrated space stud welding systems developed in Phase 4 and tested in Phase 5. The tests in space may be performed aboard the Space Shuttle or the Space Station. It would be ideal if an arrangement could be made so that tests can be made during more than one flight. By using the results which will be obtained in the first flight test in space, we may find it necessary or advisable to make some modifications on the stud welding systems. Our goals are:

(a) In six years, to develop integrated space stud welding systems which will be ready for testing in space, and

(b) In eight years, to improve the systems so that they will be routinely operational in space.

5.2 Research Program #2: Development of "Instamatic® " GTAW Systems for Space Applications which can be Operated by an Astronaut with no Welding Training.

It is recommended that a research program be carried out with the objective of developing "instamatic® " 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 as follows (see Figure 5-3):

Phase 1: Identification of several types of "instamatic® " welding systems for space applications and development of initial designs (1 year)

Phase 2: Construction and laboratory testing of some prototype models and development of detailed plans for later phases (2 years)

If the results of the above two phases are positive, the research program should be continued to cover the following phases (see Figure 5-3):

Phase 3: Construction and laboratory testing of the first generation integrated "instamatic® " welding systems for space applications (2 years)

Phase 4: Simulated zero gravity testing of systems developed in Phase 3 (Concurrently with Phase 2)

Phase 5: Construction and laboratory testing of integrated "instamatic® " welding systems for space applications (2 years)

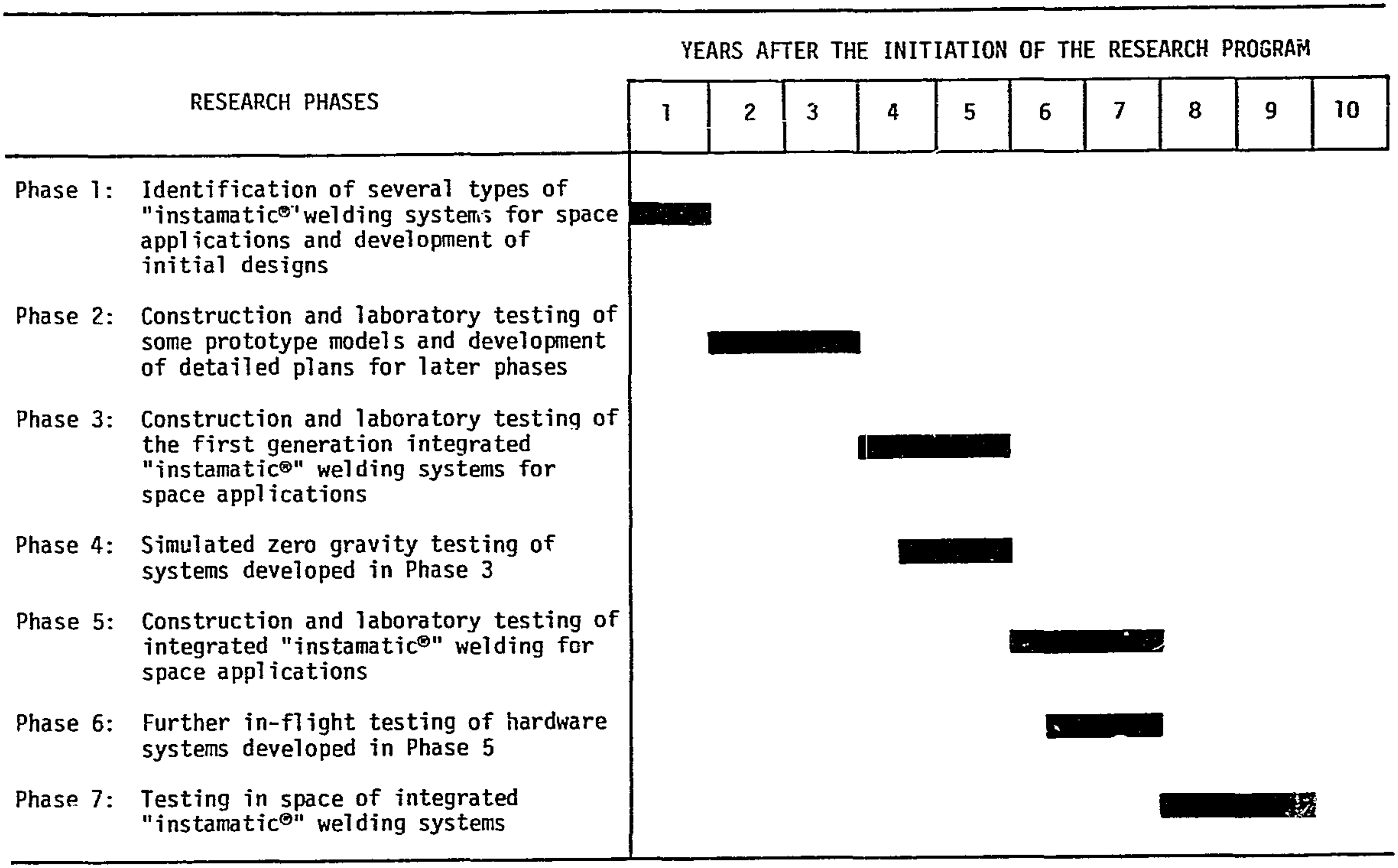


FIGURE 5-3 Phases which will be included in the Research Program #2: Development of "instamatic®" GTAW welding systems for space applications which can be operated by an astronaut with no welding training

Phase 6: Further in-flight tests of hardware systems developed in Phase 5 (Concurrently with Phase 5)

Phase 7: Testing in space of integrated "instamatic®" welding systems (2 years).

Details of Phases 3 through 7 will be greatly affected by the outcome of Phases 1 and 2; therefore, discussions on Phases 3 through 7 in this report are very brief.

5.2.1. Phase 1: Identification of Several Types of "Instamatic®" Welding Systems for Space Applications and Development of Initial Designs.

The objectives of Phase 1 of the 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 the 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 and 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 are very 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.

Discussions on four types of joints which are likely to be selected are given below. They represent different types of joints with different levels of complexity required for developing "instamatic®" welding.

Joint Type No. 1: Fillet Weld. As we envision, the system of joining a flat plate to a flat plate by fillet welding, as shown in Figure 2-3c, will probably be selected as the first choice, because:

(1) A fillet weld is not only one of basic joint types but also it is very extensively used, and

(2) M.I.T. researchers have already constructed and tested a system to be used on earth.

Figure B-2 in APPENDIX B shows the M.I.T. developed system that uses flux-shielded process for welding steel. The system which will be developed in Phase 1 for space applications will use GTAW process, and the primary materials to be investigated will be aluminum alloys.

Joint Type No. 2: Circular Cover Plate: A good candidate for the second joint type to be studied is a system to lap weld a circular cover plate over a flat plate, as shown in Figure 2-3e, because:

(1) Attaching a patch by lap welding, as shown in Figure 2-6, is very useful in many applications.

(2) M.I.T. researchers have already constructed and tested a system to be used on earth.

Figure B-3 shows the M.I.T. developed system that uses GMAW process for welding steel. The system which will be developed in Phase 1 for space applications will use GTAW process, and the primary materials to be investigated will be aluminum alloys.

Joint Type No. 3: Seal Welding along a Cylinder: A good candidate for the third type of joint to be studied is a system to perform seal welding along a girth joint between two cylinders mechanically fastened, as shown in Figure 2-6, because:

(1) Girth welding of a pipe is one of basic types of joints which have extensive applications

(2) Since the original design of the mechanical joint has been developed at M.I.T., we expect good communications within M.I.T.

Joint Type No. 4: Replacing a Section of a Pipe: The fourth joint type which may be studied is replacing a section of a pipe, as shown in Figure 2-3f. This joint is considerably more complex than the above three joint types, since:

(1) The old pipe must be cut first. When the section is cut, mismatch between the two sections may occur. Therefore, it may become necessary to hold the two separate portions of the pipe in place until joining.

(2) There are two girth joints to be welded.

Efforts will be made to identify other types of joints suitable for developing "instamatic® " welding systems. Designs of these "instamatic® " welding systems will be developed. Then several "instamatic® " welding systems will be selected for further development in later phases, considering (1) probabilities of successful construction of necessary hardwares, and (2) potential uses of these systems.

5.2.2. Phase 2: Construction and Laboratory Testing of Some Prototype Models and Development of Detailed Plans for Later Phases.

The objectives of Phase 2 are (1) to construct and test some prototype models of "instamatic® " welding systems based on the designs which will be developed in Phase 1, and (2) to develop detailed plans for phase phases. Efforts in Phase 2 will include construction and laboratory testing of some important welding subsystems in order to find out possibilities and limitations of "instamatic® " welding systems as applied to space fabrication. Phase 2, which will be completed in two years, will consist of the following steps:

Step 2-1: Construction and testing of some prototype models
Step 2-2: Development of detailed designs of some promising "instamatic® " welding systems for space applications
Step 2-3: Development of detailed plans for later phases.

The objective of Step 2-1 will be to construct and test some prototype models based on the initial designs which will be developed in Phase 1. The emphasis of the study will be placed on welding subsystems to find out whether these systems can successfully weld the joints for which they are designed. During the tests, important experimental data useful for future improvements will be generated, and we will also gain experience invaluable in future development work.

The objective of Step 2-2 will be to develop detailed designs of some promising "instamatic®" welding systems for space applications.

By the time Phase 1 and Steps 2-1 and 2-2 of Phase 2 are completed, we should know whether or not it is indeed appropriate to develop "instamatic®" welding systems for space applications, and if so, what types of welding systems should be developed. The objective of Step 2-3 will be to develop detailed plans for later phases.

The final product which will be generated after the completion of Phases 1 and 2 will include the following:

(1) A list of joining tasks in space on which "instamatic®" welding systems may be developed.
(2) Initial designs of various "instamatic®" welding systems for space applications.
(3) Hardwares of some welding subsystems and experimental data.
(4) Detailed designs of some promising "instamatic®" GTAW systems.
(5) Detailed plans for later phases of Research Program #2.

5.2.3. Phase 3: Construction and Laboratory Testing of the First Generation Integrated "Instamatic®" Welding Systems for Space Applications.

The objectives of Phase 3 will be to construct and test the first generation "instamatic®" welding systems for space applications, designs for which will be developed in Phase 2. An integrated welding system will have various subsystems, some of which are as follows:

1. Subsystem for cutting and forming
2. Subsystem for assembly of parts
3. Subsystem for surface cleaning
4. Subsystem for welding with or without closed-loop control
5. Subsystem for weld inspection.

An integrated "instamatic®" welding system may or may not contain some of the above subsystems.

It is envisioned that hardwares which will be developed in Phase 3 will probably not include all of the above subsystems. The hardware systems will be gradually improved during the two years.

5.2.4 Phase 4: Simulated Zero Gravity Testing of Systems Developed in Phase 3.

The objective of Phase 4 is to conduct testing of systems which will be developed in Phase 3 under simulated zero-gravity conditions obtained in an aircraft during a prescribed flight path.

5.2.5. Phase 5: Construction and Laboratory Testing of Integrated "Instamatic®" Welding Systems for Space Applications.

The objectives of Phase 5 will be to further improve the first generation "instamatic®" welding systems which will be developed in Phase 3, and to test these systems. At the end of Phase 5, which will be completed in two years, the systems will be developed enough to be eventually used in space.

5.2.6. Phase 6: Further In-Flight Tests of Hardware Systems Developed in Phase 5.

Phase 6 will be similar to Phase 4 except that in-flight testing will be made on integrated hardware systems which will be developed in Phase 5.

5.2.7. Phase 7: Initial Testing in Space, Either in the Space Shuttle or in the Space Station.

Phase 7 will be to perform the initial testing of the hardware systems which will be developed in Phase 5, either in the Space Shuttle or in the Space Station.

5.3 Research Program #3: Development of Flexible Space Welding Systems

It is recommended that a research program be initiated immediately. The program's objective will be the development of flexible systems capable of performing space welding with the necessary guidance and assistance from a command station.

Based on the results of Research Programs #1 and #2, it will become possible to perform certain simple welding tasks in space without the presence of a skilled welder. However, the flexibility of the developed package welding systems will be minimal since they handle only a certain welding geometry and configuration. The objective of this program is to extend our capabilities for general welding fabrication that will permit welding of a variety of joints with a single unit. Again, this should optimally be accomplished without having to send a welder or welding engineer to space. In addition to welding, per se, all other operations involved in welding fabrication (such as plate cutting and forming, plate assembly, surface cleaning, and weld inspection) should be effectively handled by the overall fabrication system. This will influence the design of the proposed welding systems.

The selection of the appropriate welding processes for the proposed systems will depend upon the exact task requirements, and possibly on the [illegible]s of Research Programs #1 and #2. However, at this point we believe that Gas Tungsten Arc Welding (GTAW) is the more likely candidate for the reasons examined in section 2.3.1. of this report.

Another important issue is the desired amount of flexibility. An increase in the flexibility of the system will be accompanied by an increase in the level of complexity. The level of flexibility (complexity) will be determined by such factors as cost, amount of time invested in research, and current levels of technology. It should also be noted that more complex systems will require a higher level of maintenance, as these systems tend to break down more often.

Detailed research plans for this program cannot be completed at this point. Therefore, it is recommended that the research effort be initiated by the following three phases (see Figure 5-4):

Phase 1: Identification of possible welding tasks.

Phase 2: Preliminary feasibility study and determination of design strategies.

Phase 3: Development of initial designs of flexible welding systems, and plans for later phases.

5.3.1. Phase 1: Identification of Possible Welding Tasks.

The objective of Phase 1 of the Research Program #3 is to identify several welding tasks for which flexible welding systems can and need to be developed for space applications.

Phase 1 is extremely important for the success of the Research Program #3, because we must select welding tasks which are (a) simple enough so that the proposed systems can be developed within the time and budget available, and (b) important for activities using the Space Station. Close coordination among M.I.T. researchers, representatives from NASA, and people in the space industry are very important in identifying the examples to be investigated. Attempts will also 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 at present are given below (see Figure 5-5). 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 5-5a, is perhaps the most fundamental welding task. Therefore, any flexible system able to perform useful welding tasks ought to be able to perform this one 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,

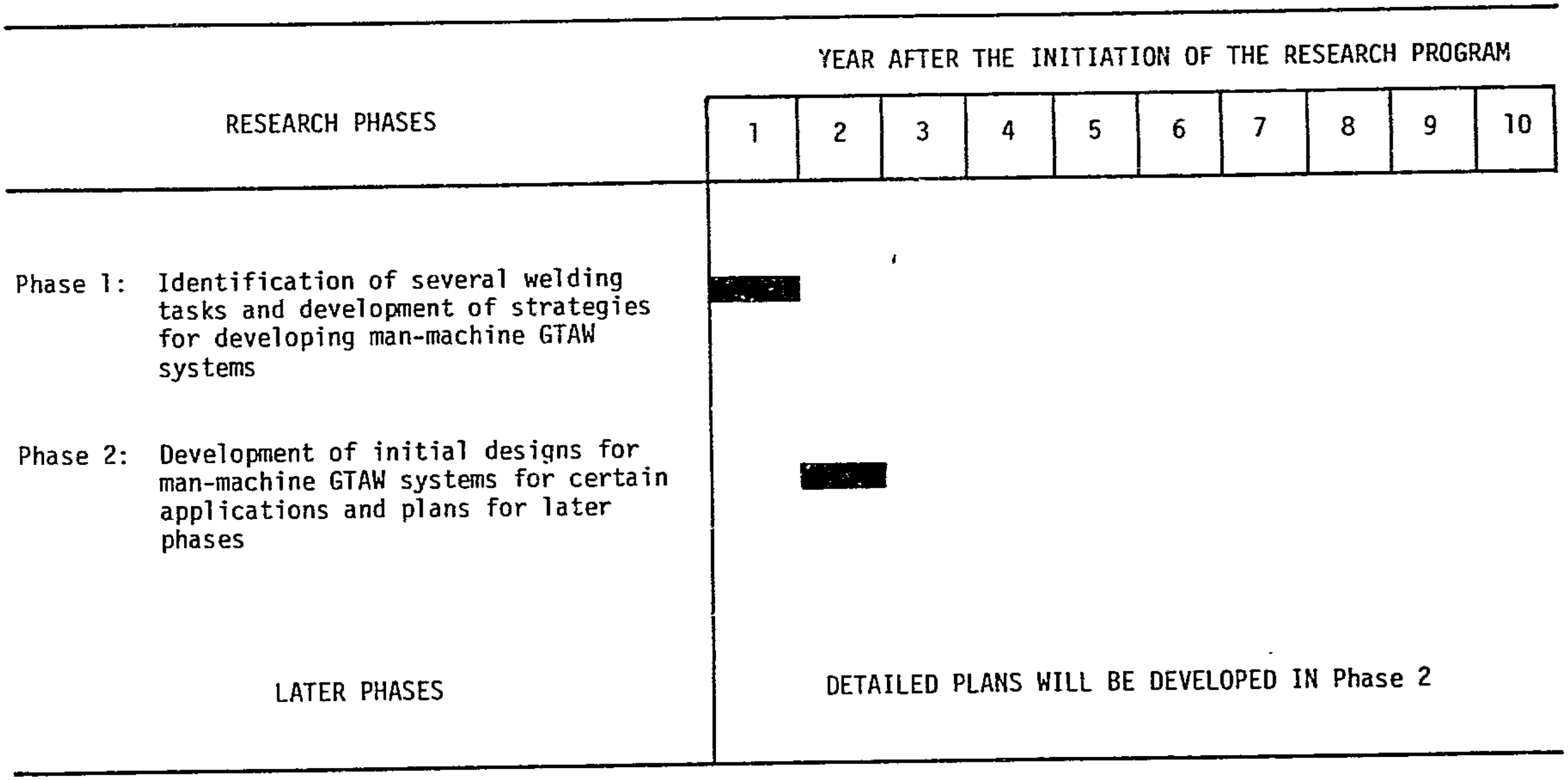
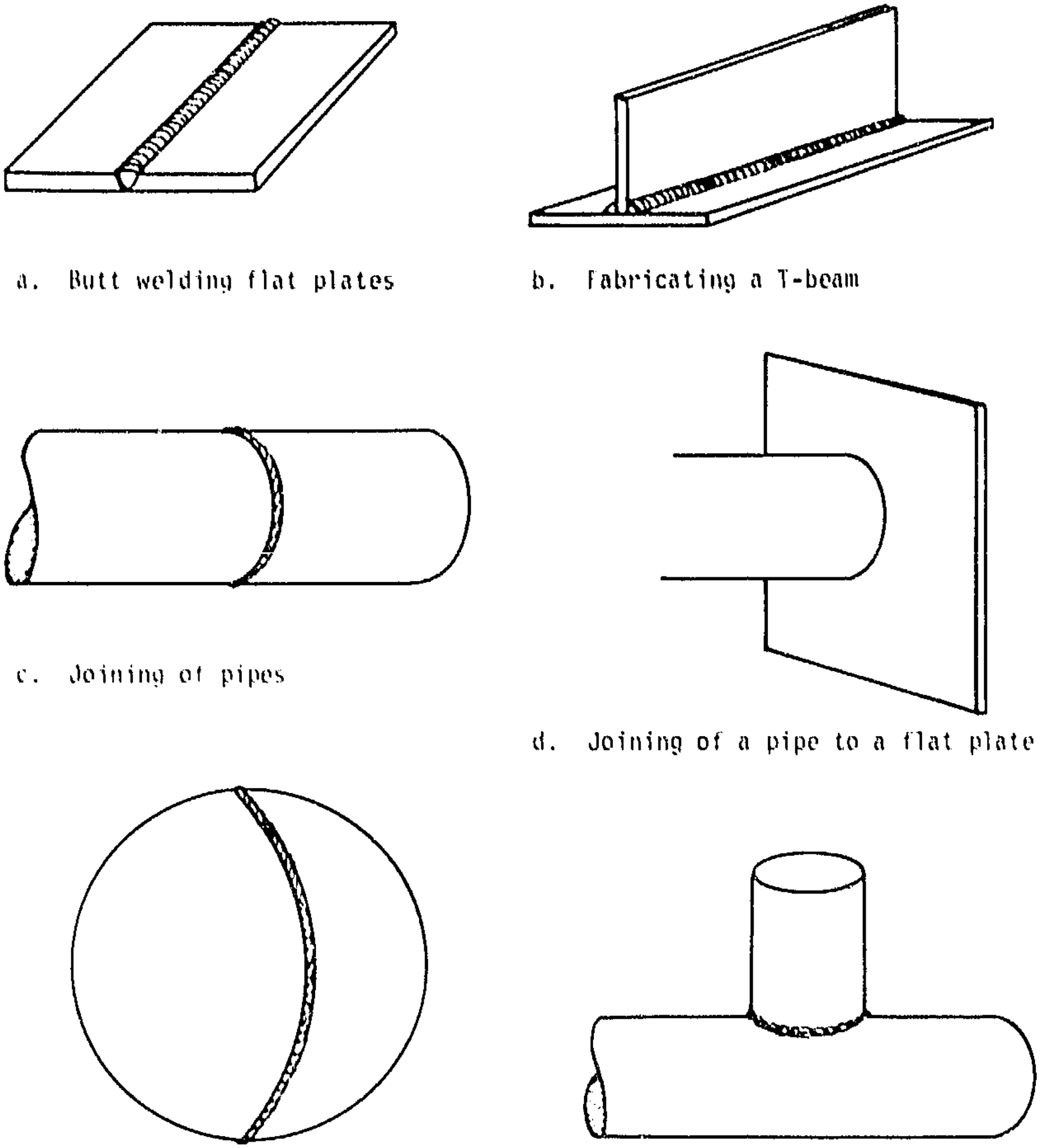


FIGURE 5-4 Phases which will be included in the Research Program #3: Development of man-machine GTAW systems for performing certain welding jobs through proper guidances and assistances from the command station on earth



a. Butt welding flat plates

b. Fabricating a T-beam

c. Joining of pipes

d. Joining of a pipe to a flat plate

d. Joining of two semi-spherical shells

f. Joining of two intersecting pipes

FIGURE 5-5 Welding tasks being considered in Research Program #3 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.

Welding Task No. 2: Fabricating a T-Beam. Fabricating a T-beam by joining two flat plates by fillet welding, as shown in Figure 5-5b, is also a basic welding task. 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 may be more economical to simply transport the metal pieces and join them in space.

Welding Task No. 3: Joining of Pipes. Joining of pipes, as shown in Figure 5-5c, is another basic welding task. Joining of pipes in a fixed dimension, 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.

It is interesting to note that the welding of pipes in space is easier than on earth, in at least one respect. In welding pipes on earth, welding conditions must be changed in order to accommodate the effect of gravity. Welding processes and welding positions may need to be changed on earth, whereas no such adjustment is needed in space welding. Automatic welding machines used in space may thus have simpler process control devices than those required by similar machines used on earth.

Welding Task No. 4: Joining of a Pipe to a Flat Plate. The joining of a pipe to a flat plate, as shown in Figure 5-5d, is another basic welding task.

Welding Task No. 5: Joining Two Semispherical Shells. The joining of two semispherical shells to form a spherical hull, as shown in Figure 5-5e, is another important and difficult fabrication problem. Guiding the welding torch along the weld line could be done by a properly designed automated welding system. However, we may have difficulties in finding ways to securely hold the pieces to be welded during welding, due to distortion. If joint mismatch is caused during welding due to thermal stresses, satisfactory welding may not be achieved. If one could successfully perform this task by use of a developed system, this would demonstrate that many other complex structures could be fabricated in space with this welding system.

Welding Task No. 6: Joining of Two Intersecting Pipes. The joining of intersecting pipes, as shown in Figure 5-5f, is very common in the fabrication of tubular structures and pressure vessels. This task is again cited to test the limit of the technical capabilities of any developed welding systems. If this task is accomplished, this would mean that many more space structures could be fabricated successfully on site.

5.3.2. Preliminary Feasibility Study and Determination of Design Strategies.

As was mentioned above, the objective of Research Program #3 is to develop systems that are flexible enough to weld different joint geometries. This flexibility is most likely to be achieved by using a mechanical (robotic) arm for the tool manipulation. As was detailed in Section 3, the control of the manipulator should be shared between a computer and a human operator. This operator can be either located on site (concept of a manned remote work section), or on earth (where other experts are also readily available). It should be stressed at this point that the development of such flexible, remotely manipulated welding systems cannot be accomplished by merely attaching a welding tool on the end effector of a mechanical manipulator, since welding is far more than simple path tracking. As was detailed in Section 3, the welding conditions and schedules must be determined (using the expertise of a welding engineer), the process must be continuously controlled, and the resulting joint must be inspected. All these steps must be given serious consideration during the design of the proposed systems.

Phase 2 will consist of the following two steps:

Step 2-1: Preliminary feasibility study.

Step 2-2: Determination of design strategies.

The objective of Step 2-1 will be to find answers to questions such as:

1. Can systems with the needed flexibility be developed at this time?

2. If not, what technological advances are necessary in order to make these flexible systems possible?
3. What will be the trade-offs between flexibility (complexity), cost, weight, and other factors?

The objective of Step 2-2 is to determine strategies for developing these systems which will be able to perform tasks selected in Phase 1, given the limitations found in Step 2-1. We must therefore find solutions to a number of questions, some of which are listed below:

1. Should we develop one system capable of performing all of the welding tasks identified in Phase 1? Or should we develop several types of systems for families of generic welding systems, etc.?
2. How do we deal with many operations involved in welding fabrication, including plate cutting and forming, assembly of parts to be welded, preweld preparation, welding, and post weld inspection?
3. Should we use some "instamatic®" welding packages which will be developed in Research Program #2 as parts of these systems?
4. What should be the relative roles of the human operator and the machine? (Supervisory controlled system)
5. How should be expertise of earth-based experts be utilized?

5.3.3. Phase 3: Development of Initial Designs of Flexible Welding Systems and Plans for Later Phases.

Phase 3 will consist of the following steps:

Step 3-1: Development of initial designs of flexible systems.

Step 3-2: Development of plans for later phases.

In Step 3-1, efforts will be made to develop initial designs of the proposed systems based on the strategies which will be developed in Step 2-2. Further elaboration of this step is not possible at this time because it relies on the results of the previous phases.

In Step 3-2, detailed plans of later phases of Research Program #3 will be developed. By the time when Step 3-1 is completed, we should have definite ideas about the hardware and software requirements, and about how long it would take to construct and test proposed welding systems.

An important outcome of Step 3-2 will be a proposal for Phase 4 and other later phases.

5.4 Research Program #4: Research on Space Welding Using GMAW, EBW, and LBW Processes.

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. The systems which will be developed in these programs can do certain welding jobs, but there are many other jobs which cannot be successfully performed or which can be more effectively performed by other processes.

Since space structures are primarily built of light components made of thin plates and materials with high strength-to-weight-ratios, gas tungsten arc welding (GTAW) process is a good process to join these materials. However, when thick plates are used, gas tungsten arc welding (GMAW) would be more suitable than GTAW.

Electron beam welding (EBW) and laser beam welding (LBW) processes are also quite attractive for welding in space. In fact, if we think about joining techniques extensively used in space in a distant future, say 2025 or 2050, EBW and LBW are the more likely candidates.

It is recommended that a systematic research program be established for developing space welding fabrication technologies using GMAW, EBW, and LBW processes. Before embarking a long-term research program, however, we recommend that an initial Phase 1 study be conducted for a period of one year. The best time to conduct Phase 1 study will be during the second year of the Space Welding Fabrication Research, as shown in Figure 5-6.

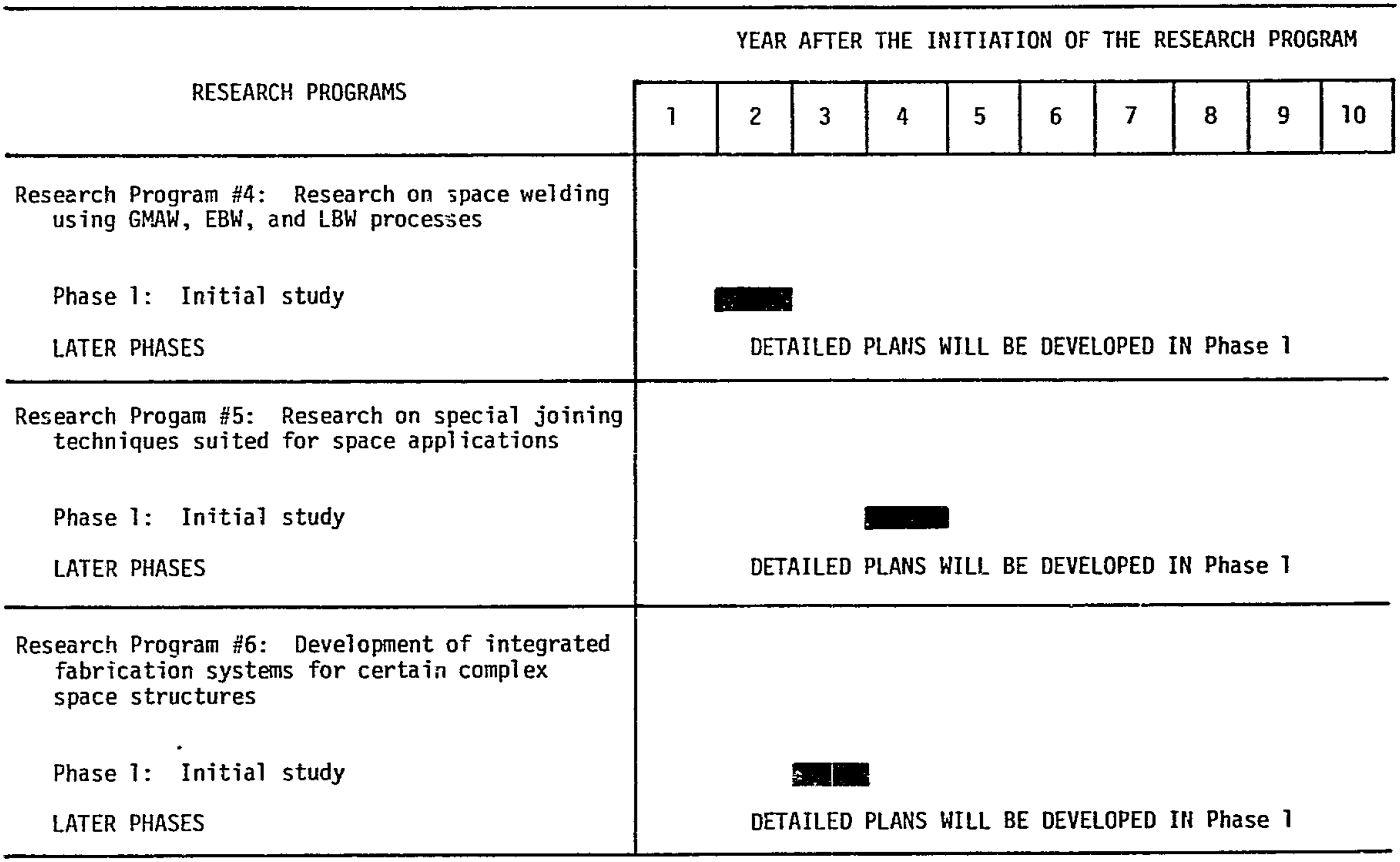


FIGURE 5-6 Schedules of Research Programs #4, #5, and #6

Phase 1: Initial Study will consist of the following steps:

Step 1-1: Identification of potential uses of GMAW, EBW, and LBW processes in space.

Step 1-2: Identification of potential problems with GMAW, EBW, and LBW processes and possible solutions.

Step 1-3: Development of plans for future research phases.

The objective Step 1-1 will be to identify potential uses of GMAW, EBW, and LBW processes in space.

The objectives of Step 1-2 will be (1) to identify potential problems with GMAW, EBW, and LBW processes when they are used for space fabrication and (2) to suggest solutions, if possible. Examples of potential problems are:

(a) Accurate joint fit-up. EBW and LBW processes require accurate joint fit-up. How can we achieve the accurate joint fit-up in space?

(b) Safety Problems. How to protect astronauts from X-rays emitted by the EBW equipment? How to protect an astronaut from laser beam?

(c) Maintenance Problems. Are there any problems with maintenance of EBW and LBW equipment?

These and many other issues will be examined in Step 1-2.

In Step 1-3, plans for future research phases will be developed.

The final product of Phase 1 will include:

(1) Information on potential uses of GMAW, EBW, and LBW processes in space fabrication.

(2) Discussions on potential problems with these processes when they are used in space and possible solutions.

(3) Plans for future research phases.

5.5 Research Program #5: Research on Special Joining Techniques Suited for Space Applications

Today there are almost 100 welding and allied processes, as shown in Figure 2-1, which are used for various applications on earth. Some of these processes and perhaps others will be uniquely suited for some applications under space environments. For example, joining by solar energy may be a good idea in space. During the Skylab experiments, feasibility of using exothermic brazing for joining tubes was studied. An attractive feature of the exothermic process is that it requires no additional energy to perform joining, except a small amount of energy to activate the exothermic reaction. Some investigators have already studied possible uses in space of several processes including cold welding, diffusion bonding, and explosive welding, as discussed in both 2.1.1 and 2.1.2. There may be other joining processes which are suited for uses in space.

It is recommended that a research program be carried out to identify joining processes which are suited for uses in space and their possible applications. It is estimated that this initial Phase 1 research will be completed in one year, perhaps during the fourth year of the Space Welding Fabrication Research, as shown in Figure 5-6. If we find some processes which have good prospects, further research may be recommended.

5.6 Research Program #6: Development of Integrated Fabrication Systems for Certain Complex Space Structures.

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, since

(1) Already many joining processes have been developed and used on earth

(2) Differences in joining mechanisms on land and in space are relatively minor.

This second approach can be very effective if welding systems are incorporated as parts of an integrated fabrication system. In such a case welding systems may be completely automated.

It is recommended that a research program be carried out to look at welding problems from the viewpoint of the structures being fabricated. We recommend an initial Phase 1 research, which will be composed of the following steps:

Step 1-1: Identification step

Step 1-2: Development of suggested future plans.

The objective of Step 1-1 will be to identify space structures being planned, to which introductions of new concepts in welding may make significant effects. For example, fabrication cost may be significantly reduced by introducing new ideas on welding fabrication. In some cases, proper uses of welding technologies may be essential for fabricating certain structures beyond certain lengths or sizes. After these structures are identified, efforts will be made to develop new fabrication methods useful for these structures.

The objective of Step 1-2 will be to develop future plans of further research and development work.

It is estimated that Phase 1 will be completed in one year, perhaps during the third year of the Space Welding Fabrication Research, as shown in Figure 5-6.

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APPENDIX A

REVIEW AND ANALYSIS OF THE SPACE ENVIRONMENT AND PREVIOUS SPACE WELDING EXPERIMENTS

A.1. INTRODUCTION

This appendix is written in three parts. The first part discusses the differences between the environment on Earth and in space, and how these differences may affect the various welding processes. Experiments pertaining to welding that were performed aboard Soyuz 6 and Skylab are then reviewed. Included at the end is an annotated bibliography on space welding and related subjects.

A.2 Environment of Space

Before reviewing the studies done on welding in space, it is beneficial to examine the differences between the space and the terrestrial environments, and see how these differences might affect welding and its related phenomena. For example, the nature, magnitude and direction of physical forces control the liquid dynamics of the molten metals, which in turn affect melting and solidification of the metals. Since these forces differ in space and on Earth, we expect the weld pool to behave differently, so melting and solidification should differ also. By understanding the predominant forces out in space, insight into tbe potential benefits and problems associated with welding in space can be obtained.

In space, the differing conditions that may substantially affect the processes taking place during welding are:

- Weightlessness
- High Vacuum
- Drastic Temperature Changes

Of these factors, the long exposure to a virtually zero-gravity environment is a truly unique situation that cannot be duplicated or even approximated for any length of time on Earth. In the low Earth orbit (LEO) of the Space Shuttle and planned space station, the gravitational acceleration is approximately 10^{-4} g_e (g_e = gravitational acceleration on Earth's surface = 9.8 m/sec^2). This extremely low gravity condition is termed microgravity.

In welding, the effect of gravity is most important in determining the properties of the solidified material. Although gravity has no direct effect on grain structure or other microstructural properties (these are determined by crystallization kinetics, which in turn are controlled by short range inter-molecular forces), it can, however, indirectly affect solidification through its effect on fluid motion. On Earth, the major indirect effects of gravity on solidification are:[7404]

- Sedimentation and buoyancy
- Buoyancy induced convection
- Hydrostatic pressure

In LEO under microgravity, it can be assumed that these indirect effects of gravity can be neglected. With no sedimentation, the result of welding will most likely be a more uniform composition of the solidified metal with a more uniform grain size. However, separations provided by buoyancy such as the removal of unwanted gas bubbles will not occur, so the potential for voids and porosity in space welded specimens is higher than that of similar welds made on Earth.

In terrestrial process, gravity is also the primary driving force for the convection of contained fluids subjected to thermal or concentration gradients. This fluid motion could alter solidification rate and the final grain structure. The elimination of gravity-driven convection may have the effect of substantially reducing or possibly eliminating macro- and micro-segregation from the solidified welds.[7406] Also, microstructure and weld pool shape are affected by fluid flow, so these can be expected to be different in space.

This is not to say that in the absence of gravity there will be no fluid flow. Possible physical forces that could induce flow while welding in space are:[7404]

- Lorentz Force - Electromagnetic forces induced by passage of current through specimen.
- Electrostriction - Stresses induced when electrical permittivity changes with density.

- Magnetostriction - Stresses induced when permeability changes with density.
- Electrostatic Force - Caused by presence of excess electrical charge.
- Surface Tension - Tangential stresses at vapor-liquid or liquid-liquid interfaces can be induced if surface tension depends on temperature and/or concentration. Surface tension will also cause pressure gradients across curved interfaces.
- Density differences accompanying phase changes.
- Beam Force - Impinging electrons give up their momentum.
- Thermal Expansion - Dilation and compression of fluids whose density changes appreciably with temperature can induce fluid flow.

While these forces also exist in a gravitational field, gravity induced convection is dominant so the effect of these other forces are masked. A dimensional analysis of the equations governing fluid flow reveals that surface tension forces are most likely the driving force for fluid flow in the absence of gravity.

In the absence of hydrostatic pressure, the molten metal will not deform under its own weight. Thus, the liquid drop will take a shape that tends to minimize surface energy. Because of this, the weld bead shape will be determined solely by surface tension. Also, wetting and spreading characteristics will differ under microgravity.

The lack of gravity will also affect the rate of metal transfer in certain welding processes. In consumable electrode arc welding, especially in the down-hand position, gravity plays an important role in drop detachment from the electrode. However, in the absence of gravity, the drop must be detached by the electromagnetic pinch effect. As a result, the drop will be larger and will remain on the electrode longer, unless the pinch effect is increased by increasing the current. Alternatively, a short-circuit type transfer may be used.

Although the high vacuum of infinite pumping power is as prevalent a space condition as microgravity, its potential to vary the welding process is not as severe. High vacuums can be created on Earth, so experiments to determine the proper welding parameters for different welding processes performed in vacuum can be designed. Also, there are welding techniques that require a vacuum (i.e., electron beam welding), so this condition in space will not affect their performance in any way.

The ultrahigh vacuum could prove beneficial for cold welding. It is known that the strength of cold welded bonds increases as the vacuum in which the weld is made increases. Also, the absence of gaseous particles will prevent oxides from forming on the bonding surfaces, which also results in a stronger bond. The only disadvantages to this method are that it requires careful edge preparation and fit-up, as well as large specific pressures.

The absence of gaseous particles will be detrimental when trying to perform any welding with an arc. A flow of electrons is necessary to maintain an arc, and usually the electrons are supplied by a shielding gas or the atmosphere itself. While it is possible to obtain the needed electrons from the electrode itself (thermionic emission), this requires more power and usually results in a less stable arc.

The vacuum of space, along with the extreme temperature conditions, will greatly affect the cooling rate of the weld, and this will be an important factor in determining the microstructure and other physical properties of the finished weld. Because there is no atmosphere to protect structures from direct sunlight, they may become extremely hot, which will slow down their cooling rate. On the other hand, if a structure remains in the shadow of the Earth or another orbiting structure, it has the potential to get very cold.

The lack of an atmosphere also eliminates convection as a means of cooling down the weld. This must be accomplished by conduction to cooler parts of the weldment and by radiation losses. This means a much different cooling rate than on Earth.

It should be emphasized that most of these environmental differences need only be taken into consideration if the welding is actually done outside the spacecraft. In the Space Shuttle, for example, there is an atmosphere and the temperature is controlled. Thus, if welding was to be done inside the Shuttle, the effect of the vacuum of space and of the drastic temperature conditions would be of no consequence. When welding is done inside a spacecraft with atmospheric and temperature controls, the basic difference from terrestrial processes is the lack of gravity.

A.3 Space Welding Experiments

The majority of space welding experiments have been carried out by the United States and the USSR. The experiments were performed in specially designed apparatus based on-board a plane, flown through a Keplerian trajectory to achieve dynamic weightlessness. Also, welding was performed aboard orbiting laboratories. It should be pointed out that both the USSR and United States experiments were designed to study the feasibility of different welding techniques in space. No specific welding task was evaluated.

A.3.1. USSR Experiments.* The orbiting USSR space welding experiments were performed aboard Soyuz 6 in October 1969. The welding processes examined were:

- Electron Beam Welding (EBW)
- Plasma-Arc Welding
- Consumable Electrode-Arc Welding

Reasons given for examining these processes were reliability, versatility in application, and ease of automation. In addition to these welding processes, resistance spot welding was also examined in a condition of dynamic weightlessness. Metals investigated were:

*Compiled from [7102], [7201], [7410], [8001].

- 1X18H9T Stainless Steel (equivalent to AISI 321 Stainless Steel)
- AM-6 Aluminum Alloy (a 2000 series Al alloy)
- BT-1 Titanium Alloy (U.S. equivalent A-55 Titanium)

The Russians also discussed the possibility of testing methods that required no metal melting, such as:

- Diffusion Bonding
- Cold Welding
- Explosive Welding

Because no metal is melted, these processes would not be affected by the lack of gravity. In addition, these must be done in a vacuum. However, since these methods require careful edge preparation and fit up, as well as large specific pressures, they were deemed not suitable for space. Also, friction welding was dismissed due to its limited range of applications and considerable power capacity required.

The results of the Russian experiments are discussed below:

Electron Beam: Welding and cutting of the various metals was performed at a constant beam power of 1 kw, beam current of 70 ma, and welding (cutting) speed of 30 m/hr. Film taken of the welding and cutting showed that the processes are stable, and the necessary conditions for normal welded joint formation are provided. No differences as compared to similar operations under conventional conditions on Earth were observed.

In the welded samples, both terrestrial and space specimens had similar weld shape and degree of penetration. However, the aluminum alloy showed more porosity when welded in the weightless condition. A possible explanation is that the gas bubbles have difficulty in getting free of the liquid weld pool.

The cutting of the metals was also achieved using EB. Although the metal beadings of the cut samples differed slightly in location when compared to samples EB cut on Earth, the results were similar.

The completed tests showed that it is possible to obtain sound welded joints of various metals and alloys with EB welding. EB cutting also performed with little change compared to routine conditions on Earth.

Plasma-Arc: For these experiments, a non-cooled torch was used. The cathode was designed for fixing to a vacuum inlet, and also to isolate a cathode region of arc discharge from the evacuated volume. The arc discharge was performed in an argon atmosphere. Other special equipment was used to excite the arc discharge when the experiment was performed in a vacuum. Arc power was obtained from a storage battery. The welding parameters were arc current 43-50 amps, voltage 26-27 volts, and nominal arc length 5 mm. The welding chamber could be open to space through a hatch.

The tests indicated that the amount of vacuum substantially affects the character of arc ignition, arc stability, and focus of the anode spot. When vented into space, the high-speed gas evacuation through the hatch makes the process of arc constriction difficult.

The plasma-arc process was tested on thin specimens, and since the dimensions of the weld pool in this case are small, the effect of gravity is not great. In both terrestrial and space samples, the weld formation is determined mainly by the forces of surface tension. As such, visual observation shows no difference between the two.

Examination of the welded specimens showed no porosity in the stainless steel sample. In the titanium alloy, porosity was observed, mainly along the fusion line. In general, though, sound welded joints were obtained using this process.

Consumable Electrode Arc Welding: The experiments on consumable electrode arc welding were performed in a controlled atmosphere chamber and in a vacuum chamber. Changes of arc current were made by varying the wire feed speed, and the arc voltage was adjusted by changing the open-circuit voltage of a storage battery. In all cases, the arc power did not exceed 1 kw. The metal samples were all 1 mm thick.

The biggest difference noted between the Earth and space welded samples were in metal melting and transfer. After arc ignition, a drop of liquid metal forms at the electrode tip. Drop size is basically determined by the relationship of surface tension, electromagnetic force, and length of arc gap. As stated before, in the absence of gravity, it is the electromagnetic pinch effect that detaches the molten drop from the electrode.

At low current values the drop grew to a very large size, sometimes exceeding the electrode diameter. Random impulses were used to bring the drop into contact with the workpiece, which resulted in a sharp increase in current value and electromagnetic force, causing the drop to detach. When the random impulses were absent, the drop remained at the electrode tip for a long period of time, sometimes more than three seconds.

As the drop grew, the current density decreased in the active spot of the electrode and stability of the arc discharge was reduced. The arc spots were disorderly, moving along the surface of the drop and pool. The depth of base metal penetration decreased, and weld penetration got worse.

An increase of the electrode feed speed increased the current value, resulting in a reduced arc gap. Thus, the free growth of the drop became difficult, and drop size was reduced. Increasing the welding current from 50 to 70 amps, when welding stainless steel, resulted in an increase of drop frequency from 15 to 33 drops/sec.

In the absence of gravity, the surface tension forces drew the melted metal together, away from the weld edges. This caused the weld to bulge slightly in the center. Although the shape of the bead remained satisfactory, the depth of penetration was somewhat reduced.

In consumable electrode arc welding in a vacuum, the kinetics of gas liberation off the welding pool change, and a necessity for stabilization of the arc discharge arises. These studies on the arc process also showed that, in spite of an increase in diffusion of neutral and charged particles out of the arc gap and an increase of speed of deionization of the arc discharge plasma, it is possible to obtain long-term, stable arc discharge in the vapor of electrode material.

<u>Spot Welding</u>: Experiments with spot welding were performed only on board a plane flying a planned trajectory. The tongs for the spot welder were made with a built-in 1 kw transformer weighing only 1.5 kg. Space conditions did not seem to affect the spot welding process.

A.3.3. <u>United States Experiments</u> *. Welding experiments in space were carried out by the United States aboard Skylab in 1973. Of the 18 experiments devoted to materials science and manufacturing processes, 3 experiments were related to welding in space. These were:

- M551 Metals Melting
- M552 Exothermic Brazing
- M553 Sphere Forming

<u>M551, Metals Melting Experiment</u>: This experiment used an EB to study cutting and welding in space. The experimental procedure is described briefly as follows:

> Three sample disks, each composed of a test metal of varying thicknesses, were rotated automatically at a speed of 2.5 rpm under an EB gun such that an EB weld seam was produced in the metal specimen at a radius of 6 cm. During the continuous weld portion of each disk, both full and partial penetration of the disk was achieved by having a constant power input but varying the disk thickness. For each disk, the continuous weld was followed by a dwell portion. In the dwell portion of the weld, the disk remained stationary while the EB impinged on a thick section of the disk, thus creating a large molten pool. The EB was then shut off, and the pool allowed to solidify.

The EB operated at 20 kV and 50-80 ma. The vacuum was created by venting the experimental chamber directly into space. The three metals investigated were:

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*Compiled from [7304], [7412], [7404], [7702], [7710]

- 304L Stainless Steel
- 2219-T87 Aluminum Alloy
- Commercially Pure Tantalum

Flights made in an Air Force KC-135 aircraft flying ballistic trajectories to achieve low gravity were made with the apparatus mounted and specimens installed to simulate operations in Skylab. However, the low gravity was achieved for only 15-25 seconds at a time, not enough time to complete a cycle of melting and solidifying. Hence, no useful metallographic studies of low gravity solidification were obtained from this phase of the study. Samples similar to the Skylab specimens were processed exactly the same way on Earth for comparison.

The gravity effects appear to be small in weld nugget configuration and puddle control of all three materials. In all cases there was greater puddle sagging in the groundbase specimen when compared to the Skylab specimen. Frequency of surface ripple, beading, and weld spatter appeared to be somewhat related to gravity. All of these were slightly reduced in the Skylab specimens.

When examining the microstructures of the Earth and Skylab specimens, the groundbased melts showed the familiar large grains often seen in weldments, with columnar grain growth oriented perpendicular to the solidification front. It also shows heavy banding, the fine, equiax-grained chill zone, and the grain growth of the unmelted HAZ.

By contrast, the Skylab specimens show a major reduction in large, elongated grains; an increased width of the finer-grained chill zone and almost no banding. This can be explained by a reduction in thermal convection (as predicted) which is accompanied by a greater temperature differential at the solidifying interface. In addition, the reduced convection would provide less mixing and greater constitutional super cooling which would produce nucleation of many more but smaller grains of varying composition. Instability of the freezing interface results in sub-grain micro-segregation which breaks up the banding.

Basically, the experiments indicate that molten metal surface tension is the predominant force controlling the weld puddle. In low gravity, the welds are more symmetrical. No difference was detected in the micro-hardness of the Earth and Skylab samples. Hence, the feasibility of cutting and welding in space using EB was demonstrated.

M552, Exothermic Brazing Experiment: The procedure for M552 is as follows:

> A cylindrical sleeve with machined grooves for preplaced braze alloy was positioned concentric with a 19.1 mm inner tube. The sleeve was surrounded by an electrically fired exothermic material which heated the sample to brazing temperatures, where the preplaced braze alloy melted and flowed into the narrow gap between the tube and sleeve. The experiment was performed in a vacuum chamber.

Four specimens were used, each specimen possessing a different clearance gap between the tube and sleeve. Two of the four specimens contained pure nickel tubes and sleeves. The other two tubes and sleeves were type 304L stainless steel with the tube partially slit through the center cross section to simulate a butt joint. Sample identification material and gap clearances between the sleeves and tubes are listed in Table A-1.

Table A-1 M552 Brazing specimen specifications

Material	Gap Dimensions	Identification
304L	0.13 mm (0.005 in.)	SLS1
Ni	0.25 mm (0.010 in.)	SLN2
304L	0.50 mm (0.020 in.)	SLS3
Ni	0-0.75 mm (0-0.030 in)	SLN4

The braze alloy for all specimens was composed of 71.8 wt. % silver, 28.0 wt. % copper, and 0.2 wt. % lithium. The alloy's melting temperature was 760°C (1410°F).

Many specimens of flight configuration were brazed at Marshall Space Flight Center prior to the flight experiment. These specimens were brazed under conditions simulating the Skylab experiment, except for gravity. These brazed specimens served as references for comparison with the specimens brazed during the Skylab flight.

SLS-1 exhibited a near perfect braze joint, except for one minor shrinkage defect adjacent to a ring groove. The braze alloy had completely spread to the outermost ends of the sleeve. In contrast, the groundbased samples all exhibited voids adjacent to ring grooves and a much higher frequency of small defects throughout the solidified braze zone. It should be noted that a 0.13 mm gap exceeds normal design specifications for braze joints in 1-g applications. Normal design clearance in 1-g is approximately 0.05 mm (0.002 in.).

SLN-2 was very similar to the groundbased equivalent. In these specimens, the gap volume is about equal to the volume of braze alloy. Both specimens retained some braze metal in the ring groove. This would indicate equalizing forces between the ring groove to retain the molten metal and the gap zone to draw the metal into it. Both Skylab and ground samples exhibited void areas in the braze gap zone.

The SLS-3 specimen was designed to represent a starved braze joint, possessing only about 50% enough alloy to fill the gap. In the ground sample all the braze metal pooled at the bottom section and gravity forces had completely drained the ring grooves. In the Skylab sample, a small quantity of braze alloy was retained as fillets in both ring grooves and most braze alloy had bridged the gap between the tube and sleeve. This contrast is due to the absence of gravity in the Skylab sample, where surface energy is the dominant force. Had adequate braze alloy been present, the 0.50 mm gap most likely would have completely filled.

The braze quality of SLN-4 was very good and much better than any ground based sample. Nearly all the braze alloy was drawn from the ring groove at the narrow end of the gap. In both specimens, braze alloy was retained in the ring groove adjacent to the wide gap end. Radioactive tracing on the Skylab sample indicate alloy spreading the full length of the sleeve.

In general, all the Skylab samples had braze gaps filled to at least the same extent as the ground samples. The absence of gravity greatly extends the scope of brazing, and, thereby, the applicability of brazing to fabrication in space. In zero gravity, the surface tension forces driving capillary flow predominate, while on Earth these forces must complete with gravity. Study of braze alloy distribution in Skylab specimens clearly indicates that dimensional tolerances, especially braze gap clearances, are far less critical to joining operations in space.

<u>M553, Sphere Forming Experiment</u>: M553 was performed in the same facility as M551 and M552. The procedure was as follows:

> Twenty-eight 6.35 mm diameter spherical specimens were cast using the electron beam gun as a heat source. The specimens were initially supported on two wheels by a string. After melting was completed, the spheres were separated from their strings and allowed to solidify while free-floating in the vacuum chamber.

The metals studied were:

- Pure Ni
- Ni with 1 wt % Ag
- Ni with 12 wt % Sn
- Ni with 30 wt % Cu

For ground based samples, the sphericity value (R_{max}/R_{min}) was typically around 1.28. For Skylab samples the value was between 1.01 to 1.04, a substantial enhancement due to the reduction in gravity. However, surface morphology of both terrestrial and flight samples were similar.

One interesting feature was the formation of internal voids during the Skylab processing of the Ni-Ag and Ni-Sn samples. Due to the low pressure (10^{-5} mm Hg) and microgravity, metallic gas evolution probably occurred as a phase reaction within both systems on cooling. This reduced pressure reaction is suppressed within the ground based samples due to the hydrostatic pressure head within the liquid itself.

In conclusion, this experiment confirmed the ability to form near perfect spheres from liquid melts free-floating in zero gravity. The reason a sphericity value of 1.00 was not achieved was probably due to insufficient internal damping of the molten metals. Either the EB itself or the release of the molten drop can cause vibrations in the melt, and the drops solidify before these vibrations can be completely dampened.

A.3.3. Analysis of Space Welding Experimental Results. From experiments performed in space by the USSR and the United States, it is obvious that welding is a viable technique for metal joining in space. It is interesting to note that both countries examined the use of electron beams to cut and weld. There are a number of factors responsible for the considerable interest shown this process:[7102]

- The high (up to 80%) efficiency of the transformation of electric power into thermal power for heating and melting metal.
- The high energy density of a focused EB. This means that for the same thickness of metal less power is required for welding than with other heat sources.
- EB welds have small heat affected zones, with a high depth to width ratio, leading to good physical and mechanical properties.
- EB is the most successful method of treating metals in a vacuum so far discovered.
- With EB, there are practically no reactive forces.

However, for welding in space an EB apparatus must be safe, highly reliable, maneuverable, and must weigh as little as possible. Also, a high degree of accuracy in need for joint fit-up. Because of these restrictions, the days when EB welding will be done routinely in space seem a long way off. Although this method has great promise in the long range outlook, the first practical uses of welding in space will most probably be done by other means.

In regards to the arc processes experimented with in Soyuz 6, these seem to have limited applicability. These processes will most likely find use in small repair and construction jobs performed inside spacecrafts, due to the availability of an atmosphere there. The Russian experiments indicate that although an arc can be maintained in a vacuum, these arcs are not very stable. Such an unreliable process cannot be expected to be used in structure construction that must be performed in space.

This is not to say that the use of these arc processes in space are not important. In a space station or other structure that is expected to remain in orbit for a long time, it is inevitable that some minor repair will be needed. Also, the construction of a small experimental apparatus or similar device may be needed. As these arc processes are well developed on Earth, and experimentation shows that the microgravitational effects can be dealt with, it is not unrealistic to visualize an "emergency welding kit" which utilizes an arc process.

As far as brazing goes, the experiments performed indicate that this is a very good technique for use in space. Although its applications seem limited, it has the advantage over welding in its minimal energy requirements and the ability to finalize the entire set-up on the ground. Also, the fit-up requirements are not as strict.

Overall, it is clear that no one welding process will be adequate to perform all the possible welding tasks in space. As different specific tasks are identified, the selection of the proper joining technique can be made. This selection must include ability of the process to perform the task, research and development needed to adapt the process to the space environment, and amount of training the person actually performing the welding will need.

A.4 Annotated Bibliography on Space Welding and Related Subjects

This is an annotated bibliography on space welding and related subjects. Experiments performed in space or in conditions simulating a space environment, along with papers describing the influence of space conditions on various welding phenomena and processes are presented. Related subjects include possible equipment to perform welding in space and construction in space using welding. The use of robots and other remote control devices to perform welding in space are also listed.

This bibliography was compiled by performing a computer literature search using the following data bases:

- NASA
- NTIS
- Compendex
- WeldaSearch

Descriptive words used included:

- Space welding
- Space Fabrication
- Space Manufacturing
- Space Environment
- Remote Manipulation in Space

This initial search resulted in hundreds of articles relating to the descriptives mentioned above. The information contained in the literature search was then screened by a few individuals to see which articles were actually related to the study at hand. These selected articles were then compared to each other to check for duplicity. The remaining articles, along with others found by alternative means during the preparation of this report, comprise the annotated bibliography.

References have been designated by a four-digit number. The first two digits of the number indicate the year of publication. The remaining digits are assigned consecutively to all items within a year. This system of numbering makes it easy to expand the bibliography without changing numbers. Any new reference is merely assigned the next available number within its year of publications.

1966

6601 Lawrence, G. S., Schollhammer, F. R., "Hand Held Electron Beam Gun and External Power Supply". Report under contract NAS9-4501 to Hamilton Standard Div., United Aircraft Corporation, Windsor Locks, CT.

The design, development, and evaluation of an operable, prototype hand-held electron gun capable of joining space-age materials in a high vacuum environment are described. The electron optics and power (Watts) required to weld typical aerospace materials of representative thickness are defined on the basis of a study which indicated that most in-space fabrication tasks would involve joining predominantly stainless steel, aluminum or titanium alloys of approximately 0.75 inch thickness. A detailed description is given of the systematic development tests and the results obtained for each major component prior to its integration into the complete gun assembly. Weld penetration capabilities of the prototype gun are given for various typical aerospace materials. For all materials investigated, the simulated in-space electron beam welds exhibit greater depth-to-width ratios and smaller grain sizes than those obtained in conventional fusion welding of similar specimens. The reliability and safety of the hand-held device are demonstrated in the results of man-rated space chamber tests which completed the evaluation.

1967

6701 Schollhammer, F. R., "Status of Electron Beam Welding for In-Space Applications". Record of IEE 9th Annual Symposium on Electron, Ion, and Laser Beam Technology, Berkeley, CA, May 9-11, 1967, p. 215-238.

Description of some operational considerations for in-space welding and subsequent equipment development. Results achieved at Hamilton Standard for gravity-free and atmosphere-free welding of thin materials are given.

1968

6801 Schwarz, H., "Present Knowledge of Fundamental Processes of Electron Beams as Material Working Tools". Electron and Ion Beam Set and Technology, 3rd International Conference, Boston, MA, May 5-8, 1968, p. 301-317.

A critical survey of recent studies in thermal electron beam processes is given. Emphasis is on experimental results and interpretation with attempt to clarify basic processes of so-called "deep penetration effect". Cutting and welding in a non-vacuum environment are discussed, along with electron beam welding in outer space and special problems associated with non-gravitational conditions.

6802 Kohn, M. L., "Materials Joining Tool". Under contract F33615-67-C-1424 to Hamilton Standard, Windsor Locks, CT.

The use of nonthermionic cathodes was investigated as a heat-energy source for welding in space. This program included the design, manufacture, and performance of welding tests on two tools. One tool, using an annular cathode, was designed to weld tubing up to 3/8-inch outside diameter and wires and rods as large as 1/8-inch diameter. The second tool, with a linear cathode, was designed to produce linear welds of variable length. The tools were built and tested.

6803 Blackmer, R. H., "Remote Manipulators and Mass Transfer Study". Under contract F33615-67-C-1322 to General Electric Co., Schenectady, NY.

This report provides a summary and review of pertinent manipulator technology, assessment of space task capabilities, preliminary specifications and design for a general purpose manipulator, and a program plan for developing operational capabilities.

1969

6901 Houldcraft, P. T., "Welding in Space". New Scientist, V. 44, n. 12, Dec. 1969, p. 502-504.

The suitability of plasma welding, electron beam welding, cold pressure welding, resistance welding, vacuum diffusion bonding, and brazing for use in outer space is discussed. In connection with the Russian Soyuz 6, 7, and 8 missions.

6902 Anon., "Which Welding Process for Space?". Metalworking Production, V. 113, n. 43, Oct. 1969, p. 7.

Discussion of the suitability of the four welding processes - diffusion welding, electron beam welding, plasma welding, consumable electrode arc welding - which appear to have been experimented with in the Soviet space capsule, Soyuz 6.

6903 Houldcraft, P. T., "Cold Welding a Space Station-Probable Russian Method." Metal Construction and British Welding J., V. 1, n. 11, Nov. 1969, p. 526.

Although Russian reports indicate that electron beam, plasma, consumable electrode arc, and cold pressure welding have been tried out in their recent space program, this article suggests that the latter process is the most likely one to have been used.

6904 Conrad, H., Rice, L., "A Basic Study of Cold Welding in Ultrahigh Vacuum". Under contract NONR-4825/00/ to Franklin Institute, Philadelphia, PA.

The cohesion of the FCC metals Ag, Al, Cu, and Ni under ultrahigh vacuum was investigated by cold welding specimens previously fractured in the vacuum. The effects of the compressive load, heat treatment, alloying, and exposure to contaminating gases are discussed.

6905 Frankel, H. E., "Effect of Vacuum on Materials". Report no. NASA-TM-X-61789.

Most of the parameters of the space environment are the same as those of terrestrial environments, except that the former are generally more severe. However, in space a new condition is imposed: a vacuum. The degradative effects of this alien condition on metals, alloys, lubricants, ceramics, coatings, thin films, and polymeric systems are discussed. In some instances a vacuum environment can be extremely beneficial to systems, so that a component can be designed to take advantage of the environment. Methods of prevention of premature failure in space environment, as well as proper testing, are also presented.

6906 Wall, W. A., Stephens, D. L., "Automatic Closed Circuit Television. Electrode Guidance for Welding". Welding J., V. 48, n. 9, Sept. 1969, p. 713-720.

The development of a closed circuit television tracking system for welding was developed during the Saturn V prototype program. This new system is unique since it is designed to track both tack welded or nontack welded joints. Furthermore, the system utilizes a digital, or pulse, technique which results in a large 'go-no-go' tracking signal. This system can be used on a variety of joint types and metals. An added advantage is that almost any modern 525-line Vidicon T.V. camera is electrically compatible and satisfactory as the tracking sensor. The heart of the system is a special blanking and logic circuit which culminates in a binary coded decimal output signal.

6907 "A Study of Application of Remote Manipulation to Satellite Maintenance". Under contract NAS2-5072 to General Electric Co., Philadelphia, Pa.

Volume 1: Summary Report

Feasibility of design, development, operation, and costs was studied for a remote manipulator spacecraft to be used for in-orbit repair and maintenance of a satellite. The concept was applied in the study of four satellite systems representing a cross section of satellite designs and characteristics. Standard satellite design practices were identified which could simplify in-orbit maintenance. The design constraints were minimum cost, simplicity, ground control link only, and use of the spacecraft for one mission only. Portions of the maintenance missions were simulated in a setup that included M-8 mechanical bilateral manipulators and a remote television display. Such characteristics as manipulator force, torque, reach requirements, mission duration, weight of the package containing the maintenance parts, thrust requirements, special tools, and docking equipment were determined. Development, recurring, and sustaining portions of the costs were specified for spacecraft operation, ground station, and factory test equipment. The study shows that a remote manipulator spacecraft system is feasible with only minimum modifications of existing hardware or designs.

Volume 2: Technical Report

This volume contains the detailed data, illustrations, and descriptions of the remote manipulator spacecraft feasibility study. In addition to details concerning mission analyses, laboratory simulations, and design recommendations as specified in abstract N69-35657, this volume presents information on manipulator tools, reliability and failure modes, design of subsystems, rendezvous requirements, time delay, and development schedules.

1970

7001 Buness, G., Weisner, P., "Welding in Space, (Schweissen in Kosmos)". Schweisstechnik, V. 20, n. 2, Feb. 1970, p. 56-58. (In German)

The welding experiments conducted in the spaceship Soyuz 6 are described, with a discussion of the space conditions which influence welding results. Besides the weldments carried out with the Vulkan welding apparatus, other welding processes suitable for space conditions are reported. The space welding experiments have a great significance for welding on ground, and for the assembly and repair of orbiting stations.

7002 Paton, B. E., "Experiment on the Welding of Metals in Space". Translated into English from Visn. Akad. Nauk Ukr. RSR (Kiev), n. 6, 1970, p. 37-44.

A complex of equipment was constructed to test welding methods and instruments aboard a spaceborne laboratory under conditions of vacuum and weightlessness. The equipment included a vacuum chamber, mechanical preevacuation and getter-ion pumps, recording system, control apparatus, and instruments for welding by an electron beam, low-pressure plasma arc, and a fusible electrode. The principal electrical parameters of welding and chamber pressures for each region of flight were recorded with an oscillograph, and the liquid-drop phenomenon was filmed with SKS-IM camera. In electron-beam welding and cutting, the fused metal was held back in the bath or in vacuum cutting only by the force of surface tension, which was reduced with elevation of the metal temperature. Low-pressure plasma-arc welding and cutting gave analogous results. When arc welding with a fused electrode in weightlessness, surface tension force and metal moistening were of basic importance in the formation and transport of electrode metal. Long-arc and short-arc methods of stabilizing arc welding with a fusible electrode were investigated.

7003 Dmitriev, V. B., "Three Welding Methods Tested in Space". Translation of Khimiya; Zhizn (USSR), V. 6, n. 2, Feb. 1970, p. 17-20.

The article describes the use of an automatic welding machine for electron beam, consumable electrode and compressed arc welding in space.

7004 Weisner, P., "Soyuz 6 and Welding". Zis-Mitt., V. 12, n. 1, Jan. 1970, p. 54-57. (In German)

Describes the working conditions in space, and welding tests carried out during the flight of Soyuz 6. The equipment used is described, as well as welding with plasma, electron beam, and consumable electrode. Influence of weightlessness on these processes is discussed. Possibilities regarding the use of diffusion, laser, and cold pressure welding mentioned.

7005 Fartushnyi, V. G., Lapchinskii, V. F. "Welding - a New Element of Astronautics". Edited translation from Sovetskaya Rossiya, Oct. 1969, p. 2.

The article discusses welding under the high vacuum and weightlessness conditions of outer space. It briefly summarizes the advantages of welding over other joining methods in outer space.

7006 Mallory, Jr., K. M., Malone, T. B., Saenger, E. L., "Selection of Systems to Perform Extravehicular Activities, Man and Manipulator. Volume 2 - Final Report". Report no. NASA-CR-102765, Matrix Corp., Alexandria, Va.

The EVA problem is described, and the EVA functions are listed with associated task and performance requirements. The currently available methods for satisfying these requirements are discussed. Task, performance, and equipment requirements and capabilities are presented for manual EVA and for remote manipulator systems. Tradeoff and workbook methodologies are also discussed.

1971

7101 Paton, B. E., "Electron Beam Welder for Space". Translation from Avtomaticheskaya Svarka (USSR), n. 3, 1971, p. 3-8.

The article describes research to develop processes and create maneuverable, highly reliable, safe equipment for electron beam welding and cutting of thin-sheet materials under conditions of terrestrial outer space.

7102 Paton, B. E., "Special Features of Electron Beam Welding and Cutting Apparatus and Processes for Use in Space". Automatic Welding, V. 24, n. 3, March 1971, p. 3-8.

The article describes small electron beam apparatus for welding and cutting sheet metal in space. The special features of the electron beam welding and cutting of metals have been studied under conditions simulating weightlessness, and also in flight in the spaceship Soyuz 6.

7103 Paton, B. E., "Characteristics of Methods and Equipment for Electron Beam Welding and Cutting in Space". Schweisstechnik, V. 21, n. 10, Oct. 1971, p. 440-443. (In German)

The advantages of the electron beam process for both welding and cutting in space are discussed and development work on the determination of the best installation parameters for electron beam welding in space is described. The requirements of such welding apparatus, with regard to safety, reliability, and mobility, are stressed and the development of such equipment at the E.O. Paton Institute in Kiev is described. Welding and cutting trials aboard a Russian spacecraft are described. These involved the flange butt welding of stainless steel and Al alloy, lap joint Ti alloys, and cutting thin specimens of these metals.

7104 Paton, B. E., Kubasov, V. N., "Welding Experiments in Space, (Schweissversuche in Weltall)". Zentralinst Schweisstech, V. 13, n. 2, Feb. 1971, p. 199-210. (In German)

The welding test in space, performed by Soviet astronauts, is seen as a new important step in the development of space technology. For the first time in world experience a technical process was accomplished which had to do with the heating and melting of metals. The results obtained in electron beam, plasma, and electric arc welding with consumable electrodes are analyzed.

1972

7201 Paton, B. E., "Welding in Space". Welding Eng., V. 57, n. 1, Jan. 1972, p. 25-29.

Soviet Soyuz 6 experiments have proven that welding in space is practical. Instead of exotic diffusion or other cold welding as supposed by many, the processes studied were gas shielded consumable arc, microplasma-arc, and electron beam, with a considerable portion of the research devoted to determining the physics of metal transfer through an arc in the weightless vacuum of space.

7202 Frantsevich, I. N., et. al., "Investigation of the Possibility of Using Radiant Solar Energy for Welding and Soldering of Materials". Paper presented at the 23rd IAF International Astronautical Congress, Vienna, Austria, Oct. 8-15, 1972.

Description of solar-furnace equipment and test results in a simulation study of the feasibility of using solar energy for welding, soldering, and heat treatment of metals in space. Solar energy was concentrated by a parabolic reflector (2 m. diameter) providing a flux density of about 20,000 cal/sq.cm per minute in a focal point 8 mm in diameter at normal solar irradiation. The flux was focused on samples held in a vacuum chamber with a quartz window. Energy losses in the quartz window and in the atmosphere are evaluated and test data are given for welds in tubular samples of steel and titanium alloy. Overall results demonstrate the feasibility of solar welding both in space and on the Earth surface.

7203 Kleinwaechter, H., Weinss, W., "Remotely Controlled Manipulator for Maintenance of Spacecraft in Orbit, (Ferngesteuerter Manipulator Zur Wartung von Raumfahrzeugen im Orbit)". Presented at the 5th Dglr. Ann. Meeting, Berlin, Oct. 4-6, 1972. (In German)

A synchronous remotely controlled manipulator for space maintenance is described. The most important information transmission system is the binocular stereo television camera. Force is transmitted by strain gages, and 7 degrees of freedom are available for manipulation.

1973

7301 Pisarenko, G. S., "Space Studies in the Ukraine". Translation of "Kosmicheskiye Issledovaniya na Ukraine", Kiev, 1973.

Number 1: Space Materials Studies and Technology

The results are presented of studies of the physical and mechanical properties of constructional materials in vacuum at low and high temperatures. The peculiarities of the processes of friction and wear and metal failure, under short-term static and long-term alternating loads in conditions similar to those of space, are examined. Equipment is described which makes it possible to carry out the technological operations of metal melting welding, brazing, and vacuum deposition under conditions simulating space. The problems of unsteady heat transport and heat transfer for bodies of different shape in space are solved.

7302 Paton, B. E., Nazarenko, O. K., "Electron Beam Welding in Various Space Positions and in Weightlessness". Preprints from the 4th Internal Conference on Vacuum Metallurgy, Tokyo, Japan, June 4-8, 1973.

Difficulties in on-site welding by the electron beam method occur not only because of the complexities of equipment maintenance and control, but also because of changes in the joint formation for various positions (vertical, overhead, etc.). A method of welding sheet materials under conditions of weightlessness has therefore been developed. The method and equipment are described, and the mathematics of pressure, surface tension, and volume relationships are explained.

7303 Baker, D., "Skylab - A Spaceborne Materials Laboratory". Engineering, V. 213, n. 11, Nov. 1973, p. 810-813.

The Skylab space laboratory contains 54 experiments of which 18 are devoted to materials science and manufacturing processes. The manufacture of items in space for use on Earth is being considered. The facility for carrying out metal joining by electron beam and external heat sources is described with details of experiments on welding and exothermic brazing. Other experiments: sphere forming by solidification of metals, semiconductor crystal growth, flammability in space, experiments in a multipurpose furnace.

7304 Monroe, R. E., "Characterization of Metals Melting Discs: Skylab Experiment M551". Under contract NAS8-28725 to Battelle Labs, Columbus, Ohio.

Information developed to characterize flight and ground based samples from the metals melting experiment is detailed in this report. Included are the characteristics determined by non-destructive examination, visual observation, metallographic examination and posttest measurements. Comparisons of the flight and ground based discs showed that an electron beam heat source can be used successfully in zero gravity for cutting, welding, or melting. Few differences were observed that could be attributed to the absence of gravity in these operations.

7305 Muraki, T., Masubuchi, K., "Final Report on Thermal Analysis of M551 Experiment for Materials Processing in Space". Under contract NAS8-28732 to M.I.T., Cambridge, Ma.

Heat flow in a disc due to moving heat generated by electron beam was studied analytically. Computer programs based on the finite-element method were developed for the analysis of two-and three-dimensional mathematical models. The limited experimental data were compared with the analytical results and various factors which had influence on heat flow in the disc were studied. Among various factors radiation seemed to be important for the analysis of the disc which was stored in a chamber. The computer programs were modified to consider the effects of metal melting and solidification as well as of radiation. Temperature dependency of thermophysical properties was also considered in the program.

7306 Muraki, T., Masubuchi, K., "Final Report on Thermal Analysis of M552 Experiment for Materials Processing in Space". Under contract NAS8-28732 to M.I.T., Cambridge, Ma.

Heat flow analyses as well as experiments were conducted on the exothermic brazing unit. Emphasis of the analysis was placed on studying the temperature distribution of the tube and the sleeve. Therefore various unknown factors on heat supplied to the sleeve and the tube were reduced to the rate and the distribution of the heat supplied to the outer wall of the sleeve. Experimental results were used to improve the analytical model. As far as the heat flow analysis of the tube and the sleeve was concerned, fairly accurate results were obtained by the analytical models adopted.

7307 Holl, H., "The 'Aeros' Satellite-A Welded Construction in Space". Schweissen und Schneiden, V. 25, n. 9, Sept. 1973, p. 433-435.

The welding problems arising in the production of the outer shell (874mm diameter, 558mm height) for the research satellite "Aeros", weighing 125kg are dealt with. The walls were of X10 crniti 18 90.5mm thick, and were welded together and to the bottom flange by micro-plasma. Difficulties during welding in consequence of minor inaccuracies at the butts were dealt with by lengthening the arc from normally 2.5mm to 6mm. All welds were defect free.

7308 Bement, L. J., "Totally Confined Explosive Welding". Patent 4 106 687, U.S. Government.

The undesirable by-products of explosive welding are confined and the association noise is reduced by the use of a simple enclosure into which the explosive is placed and in which the explosion occurs. An infrangible enclosure is removably attached to one of the members to be bonded at the point directly opposite the bond area. An explosive is completely confined within the enclosure at a point in close proximity to the member to be bonded and a detonating means is attached to the explosive. The balance of the enclosure, not occupied by explosive, is filled with a shaped material which directs the explosive pressure toward the bond area. A detonator adaptor controls the expansion of the enclosure by the explosive force so that the enclosure at no point experiences a discontinuity in expansion which causes rupture. The use of the technique is practical in the restricted area of a space station.

7309 "Photovoltaic Power and Its Application in Space and on Earth". International Congress on the Sun in the Service of Man, Paris, France, July 2-6, 1973.

Recent advances in silicon and Cu25 solar cells are reported in papers dealing with improved device fabrication processes, factors participating in degradation mechanisms, design details of spacecraft solar cell arrays, and prospects of economically justified terrestrial applications. Some particular topics include details of integrated solar cell panels, design feature of flexible and deployable large arrays, fabrication methods for thin-film solar cell structures, and the performance of protective coating materials. Individual items are announced in this issue.

1974

7401 Naumann, E., "Welding and Brazing with Sunrays, (Schweissen und Loeten mit Sonnenstrahlen)". Zis Mitt., V. 16, n. 1, Jan. 1974, p. 63-69. (In German)

A review and description is given of welding and brazing experiments carried out by Soviet scientists with the aid of focused sunbeams. It is shown that with suitable reflectors, sufficiently high intensity of solar radiation, and an adequate shielding of the welding location (a vacuum chamber) promising results can be obtained. The method is particularly important to welding applications in space.

7402 Paton, B. E., "Space Technology and Its Contribution to Science and Engineering". Akademiia Nauk USSR, Vestnik, April 1974, p. 48-54. (In Russian)

The significance, to general science and technology, of experiments in molten metal treatment under spacecraft conditions of weightlessness unreproduceable on earth is noted. Soviet and American experiments in metal welding on spacecraft are credited with the initiation of a new branch of technology. The oncoming trends in this field are visualized as experiments with single-phase and two-phase liquid metal systems involving crystallization, phase separation, surface tensions and wettability; maintenance and installation activities on spacecraft; and production of industrial materials and items such as reinforced alloy composites, single crystals for radio equipment, and cast pieces. Some typical low-weight small-size equipment designed for these purposes is described.

7403 Beliakov, I. T., Borisov, U. D., "Technology in Space". Izdatel'stvo Mashinostroenie, Moscow, 1974. (In Russian)

The present work is devoted mainly to a general explanation of the various problems associated with the prospective use of outer space for industrial and manufacturing purposes. First, the physical characteristics of space are considered in order to provide a basis for discussing space as an environment for performing technological processes. Methods of modeling the effects of space on materials and equipment are explained. The behavior of materials under space conditions are discussed. The major part of the book is devoted to technological processes for producing materials, semifinished products, and finished products in space, and to the technology of assembly and construction work. Attention is given to the systems needed for manned operations and some problems of organizing manufacturing in space.

7404 Bourgeois, S. V., "Physical Forces Influencing Skylab Experiments M551, M552, and M553". Under contract NAS8-27015 to Lockheed Missles and Space Co., Huntsville, Ala.

The forces concerned with metals melting, exothermic brazing, and sphere forming experiments on Skylab 1 mission are reported. The conclusions reached are that no significant practical differences exist between terrestrial and microgravity electron beam melting, and braze gap clearances are far less critical to joining operations in space than on earth. Altered microstructures, increased grain refinement, and the appearance of a single, large interior shrinkage pore were found in the Skylab specimens.

7405 Tobin, J. M., "Research Study on Materials Processing in Space-Adhesion-Cohesion Phenomena Under Weightlessness". Under contract NAS8-28730 to Westinghouse Electrc Corp., Pittsburgh, Pa.

Conclusions of the team of specialists can be generalized as: (1) Brazing and welding of metal structures in an orbital near zero gravity condition are quite feasible. (2) Design of joints for fabrication in zero gravity will place less emphasis on the tolerances and proximity of the adjacent structures than on the quantity of liquid metal available. (3) Brazing of metallic joints has many advantages over electron beam welding for practical reasons: simplicity, lauch weight, development costs, joint design tolerances, remotization, etc. (4) No evidence of different physical or mechanical properties of liquid metals in zero gravity was observed. However, many differences in liquid behavior were observed. Many of these effects have been called adhesion-cohesion phenomena.

7406 Garland, J. G., McKeown, D., "Metallographic Assessment of Skylab Experiment M551". Proceeding of Processing and Manufacturing in Space Symposium, Frascati, March 25-27, 1974, p. 45-64.

Electron beam welds made with 3 materials under conditions of zero gravity were compared with similar welds produced on Earth. Full and partial penetration welds in 2219-T87 Al alloy, AlSl 304 stainless steel, and pure tantalum were examined. Metallographic techniques were developed during the program which facilitated observations of the solidification and segregation structures of the materials, including the use of the scanning electron microscope and electron-probe micro-analyser. The differences in structure between welds made with and without gravity were small. Further work proposed for Skylab is designed to amplify the role of convection in weld-pool motion. Relevance to advances in welding techniques on Earth is outlined.

7407 Malone, T. B., Micocci, A. J., "Study of Roles of Remote Manipulator Systems and EVA for Shuttle Mission Support". Under contract NAS9-13710 to Essex Corp., Alexandria, Va.

Alternate extravehicular activity (EVA) and remote manipulator system (RMS) configurations were examined for their relative effectiveness in performing an array of representative shuttle and payload support tasks. Initially a comprehensive analysis was performed of payload and shuttle support missions required to be conducted exterior to a pressurized inclosure. A set of task selection criteria was established, and study tasks were identified. The EVA and RMS modes were evaluated according to their applicability for each task and task condition. The results are summarized in tabular form, showing the modes which are chosen as most effective or as feasible for each task/condition. Conclusions concerning the requirements and recommendations for each mode are presented.

7408 Ryklin, N. N., "Energy Sources Used for Welding". Welding in the World, V. 12, n. 9-10, p. 227-248.

The energy problems in welding are outlined, and the characteristics of concentrated energy sources are described. Detailed attention is then given to the individual sources i.e., gas flame, arc discharge, arc plasma jet, electron beam, radiation fluxes (including solar radiation), and laser beam.

7409 Akhmedov, A. R., "Use of Concentrated Solar Energy for Welding Metals". Welding Production, V. 21, n. 2, Feb. 1974, p. 20-23.

A device has been developed by means of which it is possible to weld metals with the aid of concentrated solar energy. Welding technology for 1.5, 2, and 3 mm thick stainless steel sheets has also been developed.

7410 Paton, B. E., et. al., "Stand for Studying Technological Processes Under Conditions Simulating Space". Translated from "Kosmicheskiye Issledovaniya na Ukraine, Vypusk 1", p. 5-9.

A test stand for conducting processing experiments under conditions simulating space is described. The most important units of the stand are discussed. Tests of the stand and research studies using the stand demonstrated that it is a reliable and universal research facility which makes it possible to study processes such as metal melting, welding, and deposition.

7411 Beck, R., et. al., "Assessment of the Results of the Skylab Space Processing Experiments with Respect to Their Scientific-Technical

Significance". Under contract ESA-SC-43-RQ to Battell Inst., Frankfurt am Main.

The Skylab experiments (series M512 and M518) were assessed on the basis of information available in various publications as well as through consultation with experts in the fields of materials science and space processing. Conclusions and recommendations are given for metals and alloys (melting, exothermic brazing, sphere forming, immiscible alloy compositions), composite materials (whiskers in metal matrix, pores in metal matrix, aligned eutectics), and the growth of single crystals.

7412 "Proceedings of the Third Space Processing Symposium - Skylab Results", April 30 - May 1, 1974, Marshall Space Flight Center, Ala.

This publication contains the presentations from the Third Space Processing Symposium. These papers cover the results of Materials Processing Experiments conducted on NASA's Skylab flights and several related research activities for Materials Processing in Space beyond Skylab.

1975

7501 Naumann, E., "Technology in Space - The Present Situation and Future Prospects as Regards Welding". Zis Mitteilungen, V. 17, n. 1, Jan. 1975, p. 61-67. (In German)

A summary is presented of Soviet and American research programs in space with particular attention to welding and allied processes. Experiments in Soyuz 6 and Skylab included plasma welding and cutting, electron beam welding, and arc welding. Planned work includes production and processing of novel materials, and experiments concerning crystal growth and remelting. Prospects for new technology and industrial processes are mentioned.

7502 Shoultz, M. B., McClurken, Jr., E. W., "Bibliography of the Space Processing Program. Volume 1". Under contract NAS8-31349 to Universities Space Research Assoc., Charlottesville, Va.

A compilation of NASA research efforts in the area of space environmental effects on materials and processes is presented. Topics considered are: (1) fluid mechanics and heat transfer; (2) crystal growth and containerless melts; (3) acoustics; (4) glass and ceramics; (5) electrophoresis; (6) welding; and (7) exobiology.

7503 Paton, B. E., "Space Technology, Its Influence on Science and Engineering". Translated from Avaiat Kosmonavt, n. 11, Nov. 1974, p. 34-36.

Basic directions in the development of space technology are defined. These directions are the scientific tests, technology for making repairs in space, and production of various materials and components in space. Practical examples of these directions are discussed.

7504 Ehricke, K. A., "On the Threshold of the Industrial Space Age". Schweissen und Schneiden, V. 27, n. 12, Dec. 1975, p. 479-487. (In German)

The themes dealt with are: Space for processing and space for living, exo-industry, sensor information, Earth-oriented teleoperations, production in orbits close to the Earth, light in space, space energy, industry on the moon, space transporters, the assembly of large plants, and welding technology.

7505 Paton, B. E., et. al., "Trainer for Simulating Welding Operations in Space". Kosmicheskie Issledovaniia na Ukraine, n. 6, 1975, p. 18-21. (In Russian)

The trainer described was developed to assist in designing various welding equipments for use in a space environment and for training personnel in operating them. The principal components of the trainer are a working chamber; a pre-evacuation pump; a high-vacuum evacuation system; a system for supplying the chamber with working gas; and recording, measuring, and control systems.

7506 Popov, Y. P., "Robot Manipulators". Translation of "Roboty - Manipulyatory", Znaniye Press, Moscow, 1974.

The general use of robot manipulators is explained and the basics of their design and operation are described for the average reader. Several pages of the first chapter include a discussion on the use of robot manipulators in space. Possibilities for fully and partially automatic robots, robot manipulator and information robots for space shuttles, space stations, and planetary exploration are outlined. The only example given of robots actually used in space is a mention of the Soviet Lunokhod, which is characterized as the initial stage of planetary robot development. A short list of references is included.

7507 McDermitt, J. H., Ruff, R. C., "Solar Concentrators for Space Processing Applications". AIAA Paper 75-698, presented at the 10th AIAA Thermophysics Conference, Denver, Colorado, May 27-29, 1975.

A study on the technological feasibility of using solar concentrators for crystal growth and zone refining in space has been performed. Previous studies related to the many aspects of the problem are reviewed. It was concluded from this effort that the technology for fabricating, orbiting, and deploying large solar concentrators has been developed. It was also concluded that the technological feasibility of space processing materials in the focal region of a solar concentrator depends primarily on two factors: (1) the ability of a solar concentrator to provide sufficient thermal energy for the process and (2) the ability of a solar concentrator to provide a thermal environment that is conducive to the processes of interest. The study indicates that solar concentrators of reasonable dimensions can satisfactorily provide both of these factors. This study also indicates that solar concentrators are attractive for space processing from the viewpoint of system specific power and system flexibility.

1976

7601 Ternovoi, E. G., et. al., "Some Aspects of the Electron Beam Weldability of Aluminum Alloys Under Conditions of Weightlessness". Kosmicheskie Issledovaniia na Ukraine, n. 9, 1976, p. 5-11. (In Russian)

The experiments described were carried out with the A-1084 electron-beam welding facility onboard a TU-104A aircraft. The bilaterally flanged specimens, prepared from AMg6 and D20 alloys, were 185 x 50 x 5 mm. Chemically etched and polished specimens were assembled, varying the clearance from 0 to 1.0 mm and the off-set from 1.2 to 2.5 mm. Micrographs of the macrostructure of welds prepared under terrestrial and zero-gravity conditions are compared. A comparative analysis of the content of alloying elements in terrestrial and zero-gravity welds showed that losses by evaporation are practically the same in the presence and absence of gravity. Weightlessness was found to have a positive effect in the sense of reducing the danger of arc-over, and a negative effect characterized by a substantially higher porosity of the welds, in particular for AMg6 alloy.

7602 Naumann, E., "Materials Research and the Working of Materials in Space Stations". Zis Mitt., V. 18, n. 8, Aug. 1976, p. 833-842. (In German)

The phenomenon of weightlessness is outlined and brief details are given of some experiments, including welding, melting, and brazing experiments carried out on board Soviet and American spacecraft. Possible future research goals and activities are described.

7603 Siewert, T. A., "A Study of Brazing in Skylab II". Ph. D. Thesis, University of Wisconsin - Madison, May 1976.

An investigation was made of exothermic brazing in space. Specimens consisted of pairs of concentric rings with a brazing filler positioned in grooves on the inside of the outer tube. An exothermic material was placed around the sleeve and ignited to bring the specimen to brazing temperature. Specimens were brazed in space and on the ground, and results are compared. It is concluded that the process is most acceptable for construction in space.

7604 Li, C. H., Busch, G., Creter, C., "M551 Metals Melting Experiment --Space Manufacturing of Aluminum Alloys, Tantalum Alloys, Stainless Steels". Under contract NAS8-28728 to Grumman Aerospace Corp., Bethpage, N.Y.

Results are presented which support the concept that the major difference between ground base and Skylab samples (i.e., large elongated grains in ground base samples versus nearly equiaxed and equal sized grains in Skylab samples) can be explained on the basis of constitutional supercooling, and not on the basis of surface phenomena. Microstructural observations on the weld samples and present explanations for some of these observations are examined. In particular, ripples and their implications to weld solidification were studied. Evidence of pronounced copper segregation in the Skylab Al weld samples, and the tantalum samples studied, indicates a weld microhardness (and hence strength) that is uniformly higher than the ground base results, which is in agreement with previous predictions. Photographs are shown of the microstructure of the various alloys.

7605 "Space Fabrication Techniques". Under contract NAS8-31876 to Grumman Aerospace Corp., Bethpage, N.Y.

A structural building block was designed for the construction of large area space structures for space manufacturing. The building block is lightweight and includes a roll formed aluminum alloy truss, 1 meter deep by 40 meters long, with vertical braces spaced every 1½ meters and interconnected by diagonal members. It can be fabricated in orbit by an automated facility consisting of three rolling mills used to roll form the three truss caps, and six magazines which carry ground fabricated shear bracing into orbit for assembly with the caps. Processes are synchronized using feedback control systems.

7606 Passaglia, E., Parker, R. L., "NBS Space Processing Research". Under contract NASA-W-13475 to National Bureau of Standards, Washington D.C.

This report describes NBS work for NASA in support of NASA's Space Processing Program covering the period November 1, 1974 to December 31, 1975. The objectives of the NBS program are to perform ground-based studies (and, where appropriate, space-based studies) of those aspects of space that could possibly provide a unique environment for making materials more perfect or more pure. The approach taken deals primarily with experimental and theoretical studies of the possible effects of the absence of gravitational forces on those materials preparation processes where the presence of gravity may be important in reducing perfection or purity.

1977

7701 Bogs, H., Sahm, P. R., Hesse, P., "Investigation of the Solidification Behavior of Electron Beam Welds Under Microgravitational Conditions". Brown, Boveri und Cie, Heidelberg. (In German)

A survey of the literature was made in order to define a technique for the visualization of convection currents in an electron beam melt-channel and to identify the gravity dependent components of this convection phenomenon. Preliminary experiments with different steels were also conducted in order to show the influence of convection on microstructure and mechanical properties. Results are summarized in three proposals for further experimentation. These are electron beam welding of a transparent medium, i.e. quartz glass, to directly visualize convection phenomena, utilization of larger than 1 g values in order to extrapolate back to zero g behavior, and controlled experiments with Cr steels to measure the effect of convection on the mechanical properties and microstucture (quantitative metallography).

7702 Siewert, T. A., Heine, R. W., Adams, C. M., Willaims, J. R., "The Skylab Brazing Experiment". Welding J., V. 56, n. 10, Oct. 1977, p. 2915-3005.

Four specimens from the exothermic brazing experiment processed aboard Skylab in June 1973 have been compared with identical specimens processed in the same conditions on Earth, the only difference being the presence of a gravitational field. Skylab samples had a generally lower concentration of defects and voids. A detailed description is given of the experimental package.

7703 Okhotim, A. S., Laptchinsky, V. F., Shonin, G. S., "Some results of Studies in Space Technology in the U.S.S.R.". Progress in Astronautics and Aeronautics, V. 52, 1977, p. 355-362.

Studies in space technology in the U.S.S.R. are discussed. Topics include experimental results of welding in weightlessness, development of suitable welding equipment, studies of the spacecraft (micro) atmosphere and its effect on processes, and the effect of controlled external disturbances on the crystallization of multiphase media and eutectic alloys under various gravitational conditions. Prospects are outlined.

7704 Greger, G., "Utilization of Space Laboratories for Materials Research and Processing Technology". Werkstatt im Weltraum, n. 391, 1977, p. 4-21. (In German)

Emphasis on possible economic advantages arising from prospects of increased knowledge, new materials and improved technologies in zero gravity conditions are considered in a general summary of German participation in the European Space Agency (ESA), and a survey of 400 scientific experiments suggested by various German research institutions. Theoretical possibilities for improvements or new discoveries relating to metals, composite materials, measuring and engineering assembly techniques, e.g. electron beam welding, are listed.

7705 Weiss, H., "Physical Conditions for Materials Manufacture in Zero Gravity". Werkstatt im Weltraum, n. 391, 1977, p. 22-27. (In German)

The idea o´ spacecraft assembly in space from component structures requires a thorough study of welding and soldering feasibility in weightless conditions. Comparisons are made of various welding methods, containerless melts, crystal growth methods, etc., in space conditions and on the ground. Proposed experiments with Zn-Sb, Al-In, Al-Pb liquid-phase systems are mentioned and thermal convection effects are compared, including the Marangoni effect.

7706 Grodzke, P. G., "Space Processing Applications of Ion Beam Technology". Under contract NAS3-20095 to Lockheed Missles and Space Co., Huntsville, Ala.

Ion thruster engines for spacecraft propulsion can serve as ion beam sources for potential space processing applications. The advantages of space vacuum environments and the possible gravity effects on thruster ion beam materials operations such as thin film growth, ion milling, and surface texturing were investigated. The direct gravity effect on sputter deposition and vapor deposition processes are discussed as well as techniques for cold and warm welding.

7707 "Space Fabrication Technique". Under contract NAS8-31876 to Grumman Aerospace Corp., Bethpage, N.Y.

A structural building block was designed for the construction of large area space structures for space manufacturing. The building block is lightweight and includes a roll formed aluminum alloy truss, 1 meter deep by 40 meters long, with vertical braces spaced every 1½ meters and interconnected by diagonal members. It can be fabricated in orbit by an automated facility consisting of three rolling mils used to roll form the three truss caps, and six magazines which carry ground fabricated shear bracing into orbit for assembly with the caps. Processes are synchronized using feedback control systems.

7708 "Space Fabrication Demonstration System'. Under contract NAS8-31876 to Grumman Aerospace Corp., Bethpage, N.Y.

Progress on fabrication facility (beam builder) support structure control, clamp/weld block, and welding and truss cut off is discussed. The brace attachment design was changed and the design of the weld mechanism was modified which achieved the following system benefits: (1) simplified weld electrode life; (2) reduced weld power requirements; and (3) simplified brace attachment mechanisms. Static and fatigue characteristics of spot welded 2024T3 aluminum joints are evaluated.

7709 Paton, B. E., Balitskii, V. M., Samilov, V. N., "Transforming Welded Shells for Space Systems". 28th IAF International Astronautical Congress, Prague, Czechoslovakia, Sept. 25-Oct. 1, 1977.

Regular isometric transformation of welded thin metal shells is studied, with the aim of facilitating the construction of metal assemblies in space. Laws for isometric surface transformation, based on the differential Codazzi-Gauss equations, are discussed, and processes involving a series of regular isometric folds to create an overall transformation with no shell deformtion are considered. Examples of the processes, including the construction of multicone shells from planar disks or the transformation of a toroidal shell into a compact roll, are given.

7710 Busch, G., "M551 Metals Melting Experiment". Under contract NAS8-28728 to Grumman Aerospace Corp., Bethpage, N.Y.

Electron beam welding studies were conducted in the Skylab M551 metals melting experiment, on three different materials; namely 2219-T87 aluminum alloy, 304L stainless steel, and commercially pure tantalum (0.5 wt % columbium). Welds were made in both one gravity and zero gravity (Skylab) environments. Segments from each of the welds were investigated by microhardness, optical microscopy, scanning microscopy, and electron probe techniques. In the 2219-T87 aluminum alloy samples, macroscopic banding and the presence of an eutectic phase in the grain boundaries of the heat affected zone were observed. The stainless steel samples exhibited a sharp weld interface and macroscopic bands. The primary microstructural features found in the tantalum were the presence of either columnar grains (ground base) or equiaxed grains (Skylab). The factors contributing to these effects are discussed and the role of reduced gravity in welding is considered.

7711 Vykukal, H. C., King, R. F., Vallotton, W. C., "Antropomorphic Master/Slave Manipulator System". Patent-4 046 262, to the United States Government.

An anthropomorphic master/slave manipulator system including master arm apparatus with a plurality of master tubular articulated portions is outlined. Objectives of this investigation were to provide a system that accurately and smoothly simulates human limb movement at a remote location. The system has a high frequency response, a high structural stiffness and a design that protects the components of the slave mechanism. Simulation of human movements is possible in outer space, underwater, and in a hazardous environment such as in a high radiation area. The equivalent ability, dexterity, and strength of a human arm are simulated.

7712 Henson, H. K., Drexler, K. E., "Vapor-Phase Fabrication of Massive Structures in Space". AIAA Paper 77-542, presented at the AIAA 3rd Conference on Space Manufacturing Facilities, Princeton, N.J., May 9-12, 1977.

Vapor deposition may be an economical approach to processing and fabricating metals (especially aluminum) in space. This method, which uses to advantage the sunlight, vacuum, and zero gravity conditions of space, is found to have advantages when considered from metallurgical, physical and cost viewpoints. A design for a large scale (230 ton) solar powered deposition apparatus with a throughput rate of 10 kg/second and the associated physical and chemical material problems are described in detail. Strength and fracture mechanics considerations may favor silica fiber reinforcement of seamless aluminum pressure vessels vapor deposited on inflated forms for space habitats.

7713 Woodcock, G. R., "Large-Scale Space Operations for Solar Power Satellites". AIAA Paper 77-1031, presented at the AIAA, EEI, and IEEE Conference on New Options in Energy Technology, San Francisco, Calif., Aug. 2-4, 1977.

Analogies with industrial development and with the Saturn, Shuttle, and Skylab programs demonstrate the feasibility of Solar Power Satellites (SPS) that require space lauch rates countable in flights per day, systems with very large mass and size, and large-scale construction techniques in orbit. SPS energy production is estimated to equal 400,000 barrels of oil per day throughout an SPS operational life of 30 years or more; low transport costs to low earth orbit and on to geosynchronous orbit are projected as a result of: reusability of vehicles; high traffic volume; relatively rapid ground turnaround; and large payload capacity. Construction procedures and installation of reflector systems are discussed, and diagrams of fabrication methods and devices are presented. About 10 manhours would be needed to erect one ton of material, and a workforce of 500 to

700, working 10-hour shifts 6 days a week during a 90-day orbiting period, is projected.

1978

7801 Lorant, M., "Electron Beam Welder for Use in Space". Welding and Metal Fabrication, V. 46, n. 6, June 1978, p. 365.

The development of electron beam welding equipment for use in space is reported. It is designed for test welding in an orbiting workshop, and is capable of producing a 20kw, 100ma tightly focused beam for five minutes at a time from a 2kw battery power source. Various design features and peformance tests are mentioned.

7802 "Space Fabrication Demonstration System". Under contract NAS8-32472 to Grumman Aerospace Corp., Bethpage, N.Y.

The completion of assembly of the beam builder and its first automatic production of truss is discussed. A four bay, hand assembled, roll formed members truss was built and tested to ultimate load. Detail design of the fabrication facility (beam builder) was completed and designs for subsystem debugging are discussed. Many one bay truss specimens were produced to demonstrate subsystem operation and to detect problem areas.

7803 Browning, D. L., "On-Orbit Fabrication and Assembly of Composite Structures". AIAA Conference on Large Space Platforms, Los Angeles, Calif., Sept. 27-29, 1978.

An investigation is conducted regarding the merits and the feasibility of on-orbit fabrication of composites for space applications. It is found that for reasons of economics, reliability, and structural efficiency, on-orbit beam fabrication with composite materials will be the principal mode of basic-member construction for the very large space systems of the future. The most significant current issue, then, is not so much why on-orbit fabrication as when. Clearly the system-functional technologies of future large space systems must first be developed and demonstrated, perhaps, in orbit., then integrated into larger spacecraft serving as prototypes to provide proof-of-concept for the yet larger operational systems. Similarly, cost-effective construction technology must be available when needed and the very high reliability required for mass production must exist.

7804 Fleisig, R., "Shuttle Demonstration of Large Space Structure Fabrication and Assembly". 29th IAF International Astronautical Congress, Dubrovnik, Yugoslavia, Oct. 1-8, 1978.

This paper describes a program aimed at the early on-orbit demonstration of a large-space-structure fabrication and assembly capability. Requirements for the demonstration concept have been formulated. The concept selected to meet these requirements is a Large Space Structure Platform consisting of a triangular prism of 31.5 m length. Sensors can be mounted on this platform to perform earth-observation measurements from space. Structural elements of the platform are fabricated using an automated beam builder in the Shuttle Orbiter payload bay. Special fixtures are designed to assemble the structure with the aid of the remote manipulator system and two astroworkers in an EVA mode. Results of the platform preliminary design are presented in terms of a design layout with related structural, thermal, mass-properties, and control-dynamics data. The assembly scenario is described. Estimates of the total construction time and Orbiter support requirements are also presented.

7805 Garibotti, J. F., Curertny, A. J., Johnson, R., "On-Orbit Fabrication and Assembly of Large Space Structural Subsystems". 29th IAF International Astronautical Congress, Dubrovnik, Yugoslavia, Oct. 1-8, 1978.

Future large space systems are examined with respect to on-orbit fabrication, and the role, design, and testing of generic structures are considered. The feasibility of on-orbit fabrication of a selected generic structure, a tetrahedral truss, is indicated and preliminary planning for integration of a beam machine and associated fabrication equipment with the Orbiter is reported. The development of large structural subsystems and their evaluation are discussed.

7806 Vontiesenhausen, G. F., "Nonterrestrial Materials Processing and Manufacturing of Large Space Systems". Report no. NASA-TA-78207, Marshall Space Flight Center, Huntsville, Ala.

An attempt is made to provide pertinent and readily usable information on the extraterrestrial processing of materials and manufacturing of components and elements of these planned large space systems from preprocessed lunar materials which are made available at a processing and manufacturing site in space. Required facilities, equipment, machinery, energy and manpower are defined.

7807 Disher, J. H., "Planning for Large Construction Projects in Space". In Using Space - Today and Tomorrow, Proceeding of the 28th International Astronautical Congress, Prague, Czechoslovakia, Sept. 25-Oct. 1 1977, Pergamon Press Ltd., Oxford, Eng., 1978, p. 79-123.

The paper discusses briefly some broad plans for developing the technology needed for large construction projects in space ranging from orbiting solar power stations to large communications antennas. Space construction classes include assembly of modules, deployment of compacted structures, assembly of passive preformed pieces, and fabrication of structures from sheet stock. Technological areas related to structural concepts include (1) analyses for prediction of structural behavior, structural/control interaction, electromagnetic and control performance, and integrated design development; (2) electronics for signal conditioning and data acquisition, power distribution, and signal channel interference and multipaction; (3) concepts for shape control, attitude/pointing control, and orbital transfer and station keeping; and (4) materials and techniques for 30-year dimensional stable composites, thermal control, thin-lightweight structural alloys, and material joining in space. The concept of a power module for the construction operations is discussed along with a concept for a habitability module.

7808 Davis, E. E., Miller, K. H., "Construction of a 10GWe Solar Power Satellite". 13th Intersociety Energy Conservation Engineering Conference, San Diego, Calif., Aug. 20-25, 1978. Proceedings, V. 1, p. 189-194.

This paper describes the major systems and operations associated with the construction of a 10 GWe photovoltaic power satellite. Eight satellite modules and two antennas are constructed at a LEO earth orbit construction base. Structure for the satellite is fabricated in orbit while solar arrays, power distribution and microwave units are fabricated on Earth and only require installation.

7809 Muench, W. K., "Automatic Fabrication of Large Space Structures - The Next Step". AIAA paper 78-1651.

An outline is presented of a plan which will lead to the establishment of an operational five giga watt solar power satellite in space. A detailed description is presented of the first stage of this plan. This stage is concerned with the development of a machine that is to be employed to produce the basic building block beams in space, which are used in the assembly of the large space structures required. A ground demonstration version of this machine has already been completed. After the feasibility of automatically producing beams has been successfully demonstrated, questions arise concerning the next step which has to be taken. One possible answer to this question is discussed, taking into account the development of a special end effector for the Space Shuttle's remote manipulator system.

7810 Spynu, G. A., Timoshenko, V. G., Antonenko, V. T., "Automation of Welding Production. Robots, (Avtomatizatsiya Svarochnogo Proizvodstva. Roboty)". Itogi Nauki I Tekhniki Svarka, V. 10, 1978. (In Russian)

This is a review of USSR and non-USSR literature on the use of robots for automating welding processes. The technology and automation of resistance, arc, and electron beam welding processes are discussed. Control systems, including group control, for line robots are discussed. Welding robots in space and underwater are considered.

7811 Paton, B. E., "Welding in the USSR: Technology and Production". Welding and Metal Fabrication, V. 46, n. 3, April 1978, p. 201-207.

The current status of welding technology in the USSR is reviewed. Recent developments are considered and prospects for the next five year plan are outlined, including a gradual conversion to mechanized and automated welding. The main subjects under discussion include: arc welding, electrslag welding, resistance welding, thermo-compression bonding, welding in space, and electron beam welding.

7812 Covault, C., "Structure Assembly Demonstration Slated--For Large Space Structures in Low Orbit". Aviation Week and Space Technology, V. 108, June 1978, p. 49-53.

A proposal to test the large structures fabrication capability of the STS is presented with reference to a 10 x 30 meter structure that could be deployed as early as 1983 with a science/applications payload, or remain attached to the Shuttle. Attention is given to the prospect of deploying large antennas in both LEO and GEO, the first of which would be powered by a 25 kw module. The use of aluminum rolls, which could be processed into beams once in space, is viewed as the most likely approach to the problem of large structure fabrication.

1979

7901 Philippovich, N., Frieler, K., Bathke, W., Stukler, R., "Brazing Under Microgravity - Texus II Experiment". Proceedings of Material Sciences in Space Conference, Grenoble, France, April 24-27, 1979, p. 95-100.

To evaluate the effects of low gravity on vacuum brazing and the phenomena involved (i.e. flow of braze metal, joint filling, microstructure), an experiment was performed in the isothermal heating furnace of the Texus II sounding rocket. The sample, consisting of four Ni cylinders inserted one inside the other to form a 200 micrometre cylindrical gap and a 0-2000 micrometre sickle-shaped gap was brazed with a near eutectic Ag-Cu alloy. This brazing alloy contained a small amount of Li to promote spreading (58%Ag-39%Cu-3%Li wt.) and radioactive 110 Ag as tracer metal. The sample was evaluated by autoradiography and metallographic techniques.

7902 Stokes, J. W., Pruett, E. C., "Structural Assembly in Space". Langley Research Center Large Space Systems Technology, 1979, p. 263-285.

A cost algorithm for predicting assembly costs for large space structures is given. Assembly scenarios are summarized which describe the erection, deployment, and fabrication tasks for five large space structures. The major activities that impact total costs for structure assembly from launch through deployment and assembly to scientific instrument installation and checkout are described. Individual cost elements such as assembly fixtures, handrails, or remote minipulators are also presented.

7903 Bloom, K. A., "Space Construction and Utility Distribution." Langley Research Center Large Space Systems Technology, 1979, p. 287-301.

Technology advancement to effect an orderly development program leading to construction of space platforms was defined, in a program that utilized a viable platform and service module concept with concise OSS/OAST mission and payload models. Consideration was given to concepts for alternate platform servicing of the payloads described in the model. Using the baseline configuration, issues pertinent to platform development as well as orbit emplacement and operation and on orbit construction methodology were analyzed. These analyses provided the following data: (1) payload definitions and installation options; (2) identified structural and subsystems options; (3) developed integrated platform system concepts; and (4) identified technology deficiencies and recommended technology development timelines.

7904 Kumagai, J. Y., Freeman, V. L., "Design and In-Orbit Operation of a Geodetic Beam Builder". In Enigma of the Eighties: Environment, Economics, Energy. Proceeding of the 24th National Symposium and Exhibition, San Francisco, Calif., May 8-10, 1979, p. 300-310.

Design and operation of a geodetic beam builder intended as the basis for an in-orbit fabrication demonstration of space structure is described. The machine automatically fabricates 426 ft. long by 5.07 ft diameter beams, with 36 helices and 36 longitudinal graphite-thermoplastic rods of 0.067 in. square cross-section. The machine construction and its prelaunch and in-orbit operations are discussed, noting that only ultrasonic welding and cutting of the rods will be done in orbit. The beam builder energy consumption, beam straightness, joining and cutting operations, and earth fabrication of rod stock and end closeouts are considered, and it is concluded that low-cost pultrusion of graphite-thermoplastic rods and their ultrasonic welding require further development.

7905 Jenkins, L. M., Browning, D. L., "Space Fabrication: Graphite Composite Truss Welding and Cap Forming Subsystem". Langley Research Center Large Space Systems, 1979, p. 247-261.

An automated beam builder for the fabrication of space structures is described. The beam builder forms a triangular truss 1.3 meters on a side. Flat strips of preconsolidated graphite fiber fabric in a polysulfone matrix are coiled in a storage canister. Heaters raise the material to forming temperature then the structural cap section is formed by a series of rollers. After cooling, cross members and diagonal tension cords are ultrasonically welded in place to complete the truss. The stability of fabricated structures and composite materials is also examined.

7906 Heer, E., "The Role of Robots and Automation in Space". Under contract NAS7-100 to Jet Propulsion Lab., Pasadena, Calif.

Advanced space transportation systems based on the shuttle and interim upper stage will open the way to the use of large-scale industrial nd commercial systems in space. The role of robot and automation technology in the cost-effective implementation and operation of such systems in the next two decades is discussed. Planning studies initiated by NASA are described as applied to space exploration, global services, and space industrialization, and a forecast of potential missions in each category is presented. The appendix lists highlights of space robot technology from 1967 to the present.

7907 "Space Construction Automated Fabrication Experiment Definition Study". Report NAS-CR-160345, General Dynamics/Convair, San Diego, Calif.

The concept of automated construction in a space environment of a triangular beam made from laminated graphite/glass composite strip is considered. Use of ultrasonic welding is mentioned, as are the use of external surface coatings, and cost aspects.

7908 "Manned Remote Work Station Development Artcle". Under contract NAS9-15507 to Grumman Aerospace Corp., Bethpage, N.Y.

The mission requirements for the manned remote work station (MRWS) flight article and the manned remote work station open cherry picker development test article is defined. Considerations are given for the near, mid, and far term use of the MRWS with emphasis on its ultimate application: constructing the Solar Power Satellite.

7909 Bement, L. J., "Totally Confined Explosive Welding". Report N79-13364/1SL, NASA Langley Research Center.

An explosive is placed inside a removable explosive-proof enclosure, attached to one of the members to be bonded directly opposite the bonding area. A detonator is attached to the explosive and the empty part of the enclosure is balanced by a shaped filler material, which directs the explosive pressure towards the area to be bonded. The expansion of the enclosure is controlled by a detonator adaptor, so that rupture cannot occur by expansion discontinuity. The undesirable by-products of explosive welding are confined and the noise reduced by the enclosure, providing a safe and practical technique for use in the restricted area of a space station.

7910 Paton, B. E., "Welding in the USSR". Welding J., V. 58, n. 2, Feb. 1979, p. 15-26.

Areas of welding applications reviewed include manufacture of steam/gas turbine rotors, electroslag surfacing, submerged arc and electroslag welding of titanium, pressure vessel welding, gas pipeline construction, nuclear power reactor construction, resistance/flash welding applications, space and underwater welding. Automation of welding and auxiliary processes is given high priority in the USSR.

1980

8001 Paton, B. E, et. al., "A Study of Electrode Melting and Metal Transfer in Welding Under Conditions of Variable Gravitational Forces". Proceedings of the International Conference on Arc Physics and Weld Pool Behavior, London, Eng., May 8-12, 1980. Volume 1, Session 2, Paper 37.

Experiments are reported on the welding of 18-8 stainless steel, aluminum, and titanium alloys (1 mm thick) under conditions of zero gravity during flights on board a flying laboratory in the Keplerian trajectory. Welding by conventional consumable electrode arc was carried out in a sealed chamber filled with argon. Electrode melting and metal transfer were studied with a high speed camera. Results are presented on: droplet formation; effect of current on transfer of droplets; effect of current pulsing. Procedures which stabilize welding under these conditions are proposed.

8002 Hoffmeister, H., Ruediger, J., "Investigations on the Influence of Gravity on Joining Processes with Liquid Melts, and of Brazing and Welding Experiments Under Weightlessness". Report no. BMFT-FB-W-81-024, Hochschule der Bundeswehe, Hamburg, Ger. (In German)

Physical mechanisms in welding and brazing likely to be affected by space conditions are considered and the literature on actual space experiments is reviewed. Proposed Spacelab test experiments and complementary testing on Earth are described. Further development needs are identified in arc welding. It is proposed to analyze the influence of gravity on material transfer, on the shape and structure of seam, and on the segregation of the phases by: (1) taking advantage of rotary motions on Earth in order to raise the g level or to create short time weightlessness; (2) working in an aircraft or rocket under longer microgravity conditions; and (3) performing arc-spot welding in a vacuum so as to develop this process for use in space.

8003 Derby, B., Wallace, E. R., "Joining Methods in Space: A Theoretical Model for Diffusion Bonding". Acta Astronautica, V. 7, 1980, p. 685-698.

In the near future it will be necessary to join metal components in space, for either construction or repair purposes. Potential joining techniques are briefly considered in terms of their suitability for bonding the likely materials to be used, aluminum and/or titanium alloys. One technique, diffusion bonding, is of considerable promise but the bonding mechanisms are not fully understood. Thus the paper describes a computer model which is being developed to gain sufficient understanding that diffusion bonding can be more fully and efficiently developed and thus exploited.

8004 Svoboda, T., et. al., "PERUN-Space Shuttle External Tank Used as a Space Station". Acta Astronautica, V. 7, 1980, p. 699-717.

This paper describes the results of a study project which has been conducted by a Student Working Group for Astonautics of the Planetarium of Praha. It deals with the possibility of converting an expended Space Shuttle External Tank into a space station, a permanently manned orbital facility. The space station was designed economically by using much off-shelf hardware developed for earlier space projects. It is compatible with the Space Transportation System which will operate in the 1980s. It is proposed that mission dependent experimental equipment be carried aboard Spacelab modules which should be exchanged during periodic revisits by the Space Shuttle.

8005 Savage, M., Hagler, T., "Space Fabriction - Th Key to Future Large Space Systems". 31st IAF International Astronautical Congress, Tokyo, Japan, Sept. 22-28, 1980.

Construction techniques for large space structures are discussed. It is pointed out that in contrast to assembly in orbit and the deployment technique space fabrication offers favorable densities (transporting structural materials on reels) and can be adapted to automated construction. A space fabrication machine containing reels of flat sheet material and sets of rollers or dies is described, as is a machine for fabricating composite material (which must be heated for forming and then cooled to achieve structural strength). The use of fabrication machines to build such structures as space platforms, microwave radiometers, and satellite power systems is discussed.

8006 Avduyevsky, V., Grishin, S., Savitchev, V., "Technological Experiments Aboard 'Salyut-5'". Acta Astronautica, V. 7, 1980, p. 867-876.

During the flight of the Soviet orbital space complex "Salyut-5" -- "Soyuz" the experiments on the space technology and materials production had been conducted amongst the versatility of various scientific research. The experiment "Diffusiya" was aimed at investigating the features of mass transfer under near-zero-gravity conditions. The experimental results had been compared with those obtained under terrestrial conditions and theoretical calculations. The experiment "Potok" was aimed at studying the gas inclusions motion dynamics in the liquid. The crystal growth from solutions was fulfilled with the aid of the "Crystal" instrument. The experiment "Sphera" had an objective to study the solidification of multicomponent metal sample with a free surface. When soldering the pipe junctions use was made of the "Reaktsiya" instrument. The experimental results contributed greatly to the creation of scientific foundation of space technology and material production.

8007 Weldon, W. F., "A Study of the Applicability/Compatibility of Inertial Energy Storage Systems to Future Space Missions". Report NASA-CR-163584.

The applicability of homopolar generators and compensated pulse alternators to future space mission, and to other applications, including welding, are discussed.

8008 Pruett, E. C., Loughead, T. E., Robertson, K., "Structural Attachments for Large Space Structures". Under contract NAS8-33599 to Essex Corp., Huntsville, Ala.

The feasibility of fabricating beams in space and using them as components of a large, crew assembled structure, was investigated. Two projects were undertaken: (1) design and development of a ground version of an automated beam builder capable of producing triangular cross section aluminum beams; and (2) design and fabrication of lap joints to connect the beams orthogonally and centroidal end caps to connect beams end to end at any desired angle. The first project produced a beam building machine which fabricates aluminum beams suitable for neutral buoyancy evaluation. The second project produced concepts for the lap joint and end cap. However, neither of these joint concepts was suitable for use by a pressure suited crew member in a zero gravity environment. It is concluded that before the beams can be evaluated the joint designs need to be completed and sufficient joints produced to allow assembly of a complex structure.

8009 Muench, W. K., "Automated Beam Builder". Proceedings of the 14th Aerospace Mechanics Symposium, p. 247-265.

Requirements for the space fabrication of large space structures are considered with emphasis on the design, development, manufacture, and testing of a machine which automatically produces a basic building block aluminum beam. Particular problems discussed include those associated with beam cap forming: brace storage, dispensing, and transporting; beam component fastening; and beam cut-off. Various critical process tests conducted to develop technology for a machine to produce composite beams are also discussed.

8010 Jenkins, L. M., "Construction Assembly and Overview - Large Space Structures". Langley Research Center Large Space Systems Technology, v. 1, 1980, p. 217-228.

The graphite composite forming and welding technologies for the beam builder concept are discussed. Testing of the prototype truss segment and requirements for orbiter based construction equipment concepts are briefly addressed.

8011 "Space Fabrication Demonstration System. Quarterly Progress Report, January 1980". Report NASA-CR-161704, Grumman Aerospace Corp., Bethpage, N.Y.

Various aspects of the development of this system are detailed from the point of view of meeting cost and schedule requirements. Also discussed are the continuing tests of the LARC prototype induction welder which shows that the interface screening must be well impregnated with resin to ensure proper flow when bonding graphite-acrylic lap shear samples, and the preparation of specimens from 0.030 in (0.76 mm) thick graphite-polyethersulphone for future induction fastening evaluation.

8012 "Advanced Automation for Space Missions: Technical Summary". Under contract NGR-05-017-998 to Santa Clara Univ., Calif.

Several representative missions which would require extensive applications of machine intelligence were identified and analyzed. The technologies which must be developed to accomplish these types of missions are discussed. These technologies include man-machine communication. space manufacturing, teleoperators, and robot systems.

1981

8101 Lapchinski, V. F., "Welding in Space". Welding in the USSR, V. 2, 1981, p. 487-493. (In Russian)

Experience with welding operations performed on Soviet space flights is reviewed. Particular consideration is given to space welding simulation experiments, and to the development of space welding equipment (e.g., welding guns) and techniques.

8102 Okhotin, A. S., "Basic Trends and Problems of Industrialized Processes in Space". In Problems of Space Studies, Mezhdunarodnyi Tsentr Nauchnoi i Tekhnicheskoi Informatsii, 1981, p. 60-72. (In Russian)

A number of physical and chemical phenomena occurring under conditions of weightlessness and deep vacuum are examined, including diffusion, heat transfer, and surface tension. Two basic trends in the development of industrial processes in space are considered: (1) manufacturing methods involving crystal growth; and (2) such industrial processes as the welding, soldering, and joining of structures, which are pertinent to the construction and operation of long-term space stations.

8103 "Space Construction Experiment Definition Study". Under contract NAS9-16303 to General Dynamics/Convair, San Diego, Calif.

Part 1, V. 1, Executive Summary:

Definition was completed on a basic flight experiment which will provide data on the construction of large space systems from the orbiter which could not be practicably obtained from ground tests. Dynamic behaivor of a representative large structure was predicted. On-orbit construction operations were studied. Orbiter control during and after construction was investigated. Evolutionary or supplmental flight experiments for the development of augmentation of a basic flight experiment were identified and defined.

Part 1, V. 2, Study Results:

A basic Space Shuttle flight experiment which will provide needed data on the construction of large space systems from the Orbiter was defined. The predicted dynamic behavior of a representative large structure, on-orbit construction operations, and Orbiter control during and after construction were studied. Evolutionary or supplemental flight experiments for the development or augmentation of a basic flight experiment were identified and defined. The study was divided into six major tasks with appropriate sub-tasks noted.

8104 Shen, C. N., "Data Acquisition and Analysis of Range-Finding Systems for Space Construction". Report on NASA-CR-164643, Rensselaer Polytechnic Institute, Troy, N.Y.

For space missions of future, completely autonomous robotic machines will be required to free astroanuts from routine chores of equipment maintenance, servicing of faulty systems, etc. and to extend human capabilities in hazardous environments full of cosmic and other harmful radiations. In places of high radiation and uncontrollable ambient illuminations, T.V. camera based vision systems cannot work effectively. However, a vision system utilizing directly measured range information with a time of flight laser rangefinder, can successfully operate under these environments. Such a system will be independent of proper illumination conditions and the interfering effects of intense radiation of all kinds will be eliminated by the tuned input of the laser instrument. Processing the range data according to certain decision, stochastic estimation and heuristic schemes, the laser based vision system will recognize known objects and thus provide sufficient information to the robot's control system which can develop strategies for various objectives.

8105 Cliff, R. A., "An Hierarchical System Architecture for Automated Design, Fabrication, and Repair". Proceedings of the 5th Space Manufacturing Conference, Princeton, N.J., May 18-21, 1981, p. 121-126.

The architecture of an automated system which has the following properties is described: (1) if it is presented with a final product specification (within its capabilities) it will do the detailed design (all the way down to the raw materials if need be) and then produce that product; (2) if a faulty final product is presented to the system, it will repair it. Interesting extensions of this architecture would be the ability to add fabricator nodes when required and the ability to add entire ranks when required. This sort of system would be a useful component of a self-replicating system (used in space exploration).

8106 Bondarev, A. A., et. al., "Welding of aluminum Alloy 1201 by Solar Radiant Energy". Kosmicheskie Issledovaniia na Ukraine, n. 15, p. 34-37. (In Russian)

The feasibility of welding aluminum alloys by employing concentrated radiant energy of the sun has been investigated experimentally using a 2000-mm diameter concentrator with a focal length of 864 mm and an aperture angle of 120 deg. Short welds of uniform quality were obtained for aluminum specimens up to 2 mm thick at a welding speed of not more than 4 m/hr. However, the quality of longer welds was unsatisfactory. In all cases, the mechanical properties of the weld metal were significantly lower than those of the base metal. Although the use of solar radiant energy for welding aluminum alloys is shown to be possible in principle, the need for further research is emphasized.

8107 Freitas, R. A., Zachary, W. B., "A Self-Replicating, Growing Lunar Factory". In Space Manufacturing 4: Proceedings of the 5th Conference, Princeton, N.J., May 18-21, 1981, p. 109-119.

The proposed growing lunar manufacturing facility (LMF) demonstrating self-replicating system unit growth is intended as a fully automatic general-purpose factory which expands to some predetermined adult size starting from a relatively tiny (100 ton) 'seed' initially deposited on the lunar surface. This seed, once deployed on the moon, is circular in shape, thus providing the smallest possible perimeter/surface area ratio and minimizing interior transport distances. The LMF platform is divided into two identical halves, each consisting of three major production subsystems: the chemical processing sector accepts raw lunar materials, extracts needed elements, and prepares process chemicals and refractories for factory use; the fabrication sector converts these substances into manufactured parts, tools, and electronics components, and the assembly sector assembles fabricated parts into complex working machines or useful products of any conceivable design. A mission scenario, operational phases, and productivity of the facility are briefly considered, and quantitative materials closure in the baseline lunar replicating design is briefly discussed.

1982

8201 Hoffmeister, H., Rudiger, J., "Welding Under Space Conditions - The Existing State of Knowledge, (Schweissen unter Weltraumbedingungen)". Schweissen und Schneiden, V. 34, n. 9, Sept. 1982, p. 441-445 (English translation of text p. E171-E172).

Possible ways of welding under space conditions are discussed with reference to the existing state of knowledge. The effect of very low gravitation (micrograviation) on molten phases during welding is considered, in particular its effect on the stability of the weld pool and on metal transfer during arc welding. The directions to be followed by future work are indicated.

8202 Bathke, W., Siegfried, E., "Brazing Under Reduced Gravity as Part of the Spacelab Utilization Program Space Shuttle - Spacelab and the Aims of the Experiments, (Loten under Verminderter Schwerkraft...)". Schweissen und Schneiden, V. 34, n. 5, May 1982, p. 249-251 (English translation of text p. E99-E100).

The authors review the Space Shuttle/Spacelab space flight system and the targets set for brazing experiments under low gravity. The results of these experiments can be expected to yield further information on the processes which actually take place during brazing.

8203 Bathke, W., Siegfried, E., "Brazing Under Reduced Gravity as Part of the Spacelab Utilization Program - Brazing Experiments for the First Spacelab Mission, (Loten un Verminderter Schwerkraft...)". Schweissen und Schneider, V. 34, n. 7, July 1982, p. 336-337 (English translation of text p. E135).

After a review of the aims of the brazing trials to be carried out as part of the Spacelab program, the specimens and the work which is currently going on are described. The parent metal is nickel and the brazing metal an alloy of silver and copper. Measurements being taken in experiments are intended to provide information on the characteristics of the heat source used. They will also be used as a basis for deciding on the parameters for the automatic temperature control.

8204 Bathke, W., Siegfried, E., "Brazing Under Reduced Gravity as Part of the Spacelab Utilization Progam-Brazing During a Rocket Flight, (Loten unter Verminderter Schwerkraft...)". Schweissen und Schneiden, V. 34, n. 8, Aug. 1982, p. 385-387 (English translation of text p. E151-E152).

Trials of the brazing of nickel tubes during a ballistic rocket flight, and the results obtained, are reported. The test demonstrated the suitability of brazing for use in a resistance-heated apparatus under micro-gravitation. Also, the capillary brazing of tubes with a crescent-shaped annular gap showed that a very wide gap could be filled.

8205 Blankenship, C. P., Tenney, D. R., "Materials Technology for Large Space Structures". Proceedings of the AFSOR Special Conference on Prime-Power for High Energy Space Systems, V. 2.

Several of the key material technology needs that were identified for large space structures are outlined. They include lightweight structural materials, materials durability in the space environment, and some special aspects of materials fabrication technology. Examples of current materials research directed toward large space structures are described. Additional research needs and opportunities are noted. A short bibliography is included of selected references that describe large space structural concepts and related technology needs in detail.

8206 "Space Fabrication Demonstration System Composite Beam Cap Fabricator (Final Report)". Under contract NAS8-32472 to Grumman Aerospace Corp., Bethpage, N.Y.

A detailed design for a prototype, composite beam cap fabricator was established. Inputs to this design included functional tests and system operating requirements. All required materials were procured, detail parts were fabricated, and one composite beam cap forming machine was assembled. The machine was demonstrated as a stand-alone system. Two 12-foot-long beam gap members were fabricated from laminates graphite/polysulfane or an equivalent material. One of these members, which as structurally tested in axial compression, failed at 490 pounds.

8207 Meintel, A. J., Schappell, R. T., "Remote Orbital Servicing System Concept". In NASA Johnson Space Center Satellite Service Workshop, V. 2, p. 104-119.

Increased applications of automation technology identified as necessary for NASA to carry out its missions within the constraints of future funding and available physical resources are described. A concept for a Remote Orbital Servicing System (ROSS) based on present teleoperator and robotics technology is presented. A single servicer design compatible with three specified spacecraft capable of performing service to the same extent as manned extravehicular activity, controlled from a ground control station, and using currently available technology is conceptualized.

8208 Miller, R. H., Minsky, M. L., Smith, D. B. S., "Space Applications of Automation, Robotics, and Machine Intelligence Systems (ARAMIS)". Under contract NAS8-34381 to MIT Space Systems Laboratory, Cambridge, Ma.

Volume 1, Executive Summary:

Potential applications of automation, robotics, and machine intelligence systems (ARAMIS) to space activities, and to their related ground support functions are explored. The specific tasks which will be required by future space projects are identified. ARAMIS options which are candidates for those space project tasks and the relative merits of these options are defined and evaluated. Promising applications of ARAMIS and specific areas for further research are identified. The ARAMIS options defined and researched by the study group span the range from fully human to fully machine, including a number of intermediate options (e.g., humans assisted by computers, and various levels of teleoperation). By including this spectrum, the study searches for the optimum mix of humans and machines for space project tasks.

Volume 2, Space Projects Overview:

Applications of automation, robotics, and machine intelligence systems (ARAMIS) to space activities, and their related ground support functions are studied so that informed decisions can be made on which aspects of ARAMIS to develop. The space project breakdowns, which are used to identify tasks ('functional elements'), are described. The study method concentrates on the production of a matrix relating space project tasks to pieces of ARAMIS.

Volume 3, ARAMIS Overview:

An overview of automation, robotics, and machine intelligence systems (ARAMIS) is provided. Man-machine interfaces, classification, and capabilities are considered.

Volume 4, Application of ARAMIS Capabilities to Space Project Functional Elements:

Applications of automation, robotics, and machine intelligence systems (ARAMIS) to space activities and their related ground support functions are studied, so that informed decisions can be made on which aspects of ARAMIS to develop. The specific tasks which will be required by future space project tasks are identified and the relative merits of these options are evaluated. The ARAMIS options defined and researched span the range from fully human to fully machine, including a number of intermediate options (e.g., humans assisted by computers, and various levels of teleoperation). By including this spectrum, the study searches for the optimum mix of humans and machines for space project tasks.

Volume 4, Supplement, Appendix 4.3: Candidate ARAMIS Capabilities:

Potential applications of automation, robotics, and machine intelligence systems (ARAMIS) to space activities, and to their related ground support functions, in the years 1985-2000, so that NASA may make informed decisions on which aspects of ARAMIS to develop. The study first identifies the specific tasks which will be required by future space projects. It then defines ARAMIS options which are candidates for those space project tasks, and evaluates the relative merits of these options. Finally, the study identifies promising applications of ARAMIS. and recommends specific areas for further research. The ARAMIS options defined and researched by the study group span the range from fully human to fully machine, including a number oi intermediate options (e.g., humans assisted by computers, and various levels of teleoperation). By including this spectrum, the study searches for the optimum mix of humans and machines for space project tasks.

APPENDIX B

PRESENT STATUS OF THE DEVELOPMENT OF "INSTAMATIC®" WELDING SYSTEMS

B.1 CURRENT DEVELOPMENTS ON "INSTAMATIC® " WELDING SYSTEMS

Most of the M.I.T. research on "instamatic®" welding systems has been directed toward marine applications under dry and wet conditions. Research on underwater welding at M.I.T. began in 1968, when Professor Masubuchi joined the faculty. The research effort has been to meet the growing demand for reliable techniques for construction, maintenance and repair of marine structures, especially offshore oil drilling rigs. In 1962, there were only 62 offshore oil drilling rigs in the world. By 1978, that number had increased to 470. There is a trend toward building an increasing number of different types of offshore structures in deeper and deeper waters.

Most of the underwater welding research at M.I.T. has been supported by the Office of Sea Grant, National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce, through the M.I.T. Sea Grant College Program. The research effort has been carried out under the following projects:

#1 "Fundamental Research on Underwater Welding and Cutting", July 1971 through June 1974

#2 "Development of New, Improved Techniques of Underwater Welding", July 1974 through December 1976

#3 "Development of Joining and Cutting Techniques for Deep-Sea Applications", July 1976 through June 1980

#4 "Development of Fully Automated and Integrated ("Instamatic® ") Welding Systems for Marine Applications", July 1980 through June 1982

#5 "Underwater Welding and Cutting by Remote Manipulation Techniques", a three-year program which started in July 1982.

Results obtained in these projects have been published in a number of theses, reports, and papers. A total of 23 theses and students reports have been prepared; they are listed in Section B.4 of this APPENDIX as

(T1) through (T23). Also, 26 publications have been presented listed in Section B.5 as (P1) through (P26). Two U.S. patents (P11, P15) have been granted, and another patent application has been filed (P21). Details of the results obtained in the four projects that were completed, are presented in (P9), (P13), (P19), and (P25).

The original idea of "instamatic® " welding was developed during the research project (#3) on joining and cutting techniques for deep-sea applications. The effort was continued during the next project (#4) to develop "instamatic® " welding systems for marine applications under both dry and wet conditions. Under the current research project (#5), efforts are being made to develop techniques for underwater welding and cutting by remote manipulation. The research efforts to date can be classified into the following two groups:

(1) Development of underwater stud welding systems

(2) Development of "instamatic® " arc welding systems.

B.2 DEVELOPMENT OF UNDERWATER STUD WELDING SYSTEMS

Conventional stud welding equipment consists of a stud gun, an electric controller, and a D.C. power source. To make a weld, the operator selects welding parameters, loads a stud into the gun, presses it against the work surface, and pulls the trigger. the electric controller then controls the sequence of the welding process according to pre-determined settings. Further details of stud welding and its possible uses in space are described in APPENDIX C.

Because of the simplicity of this process, M.I.T. researchers have been interested in underwater applications of stud welding since 1974. The first underwater experiments of stud welding were performed by Zanca (T8) using a capacitor-discharge stud welding. A U.S. patent on an underwater stud welding gun was granted to Masubuchi and Kutsuna (P11). All later experiments performed by Chiba (T6), Kataoka (T17), Scheckter (T18), and Schloerb (T20) have used arc stud welding in order to weld large-diameter studs up to 19 mm (3/4 inch) in diameter. All experiments have been performed on steel studs. A paper presented at the 1983 Offshore Technology Conference (P25) discusses results obtained by Schloerb, who designed and built a diver-operated underwater stud welding system. Efforts are currently being made (Project #5) to further develop stud welding systems which could be remotely operated from an underwater vehicle.

Figure B-1 is a schematic diagram of the final design by Schloerb (T20), showing key features of the gun. A diesel stud welding generator, a controller, and a trigger switch which activates the welding operation, are located above water. The switch is incorporated in a knife switch, which assures that electric power to the stud gun is only on when a weld is actually being made. The knife switch is operated by the diver's tender on command from the diver. An electrical umbilical connects the surface equipment to the submersible arc stud welding gun.

The heart of the stud gun is the stud lifting mechanism. This mechanism lifts the stud a predetermined distance in order to produce a

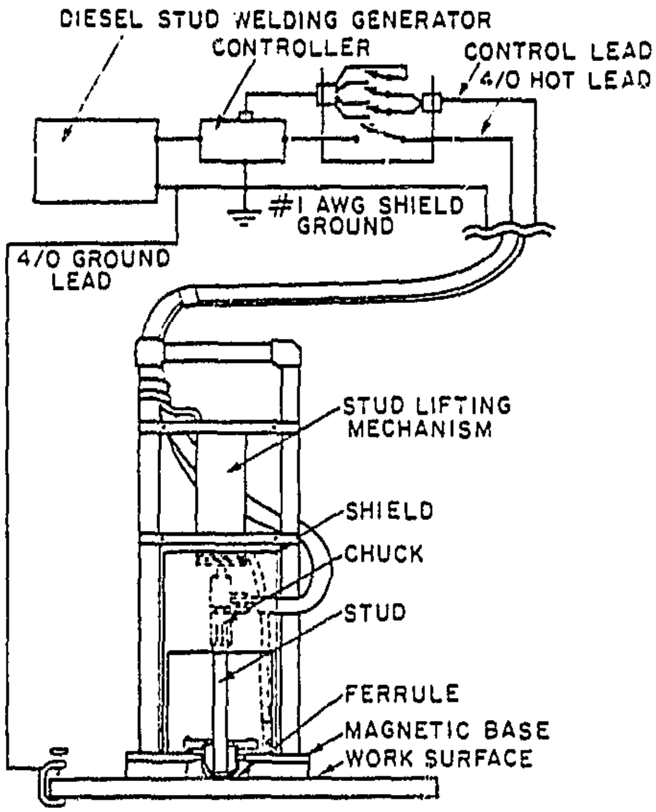

FIGURE B-1 Diver-operated underwater arc stud system developed by Schloerb precise arc gap between the end of the stud and the surface of the workpiece. The force to lift the stud is generated by a solenoid which is activated by the control unit. The control unit initiates the welding arc at the same time as the stud is lifted. The end of the stud and a portion of the work surface melt due to the intense heat of the arc. After a pre-determined time, the control unit stops the arc and de-energizes the solenoid. At this point, a spring forces the stud back against the work surface. A disposable ceramic collar, called the ferrule, is held in place around the base of the stud to prevent weld splatter. The molten metal solidifies quickly leaving the stud welded to the work surface. In order to successfully achieve stud welding, the stud must be securely held in place in the direction perpendicular to the work surface. In order to accomplish this in water, a system of magnets which can be electrically activated is used.

The machine developed by Schloerb worked satisfactorily under both dry and wet conditions.

B.3 DEVELOPMENT OF "INSTAMATIC® " ARC WELDING SYSTEMS

So far, two "instamatic® " arc welding systems have been built and tested. The one which can join a flat plate to a flat plate by fillet welding (Type 3 joint shown in Figure 2-3c) uses flux-shielded arc process. The other, which can perform lap welding a cover plate to a flat plate (Type 5 joint shown in Figure 2-3e), uses gas metal arc process. Both systems performed satisfactorily in laboratory conditions.

Lombardi (T19), who studied an improved method for underwater welding, developed an enclosed unit for joining a flat plate to a flat plate by fillet welding using the flux-shielded process. The original idea of using the submerged arc process for underwater welding was developed by Tsai (T13), who studied methods for preventing rapid quenching of underwater welds. Masubuchi and Tsai (P15) obtained a U.S. patent on underwater submerged arc welding. Figure B-2 is a conceptual design developed by Lombardi of an underwater welding box which may be used under either wet or dry conditions. The device has been built and tested under dry conditions. No tests under wet conditions have yet been made.

The welding box shown in Figure B-2 contains a welding machine consisting of a motorized carriage which simultaneously provides the consumable electrodes fed into two torches. These electrodes are connected via cables to the power supply which is not shown here. A plate to be welded is placed securely between the torches, parallel to the line of travel. Stainless steel foil molded at the base of the plate holds the shielding flux and keeps it dry. The mechanical parts of the machine are enclosed by a bottomless metal frame. The rim of the open face of the frame is lined with a thick rubber strip to provide a means of attachment to a steel surface.

Operation of the machine is simple. The motor and torches are activated by merely pushing one button. The arc, being of high temperature, will burn through the foil and can be maintained within the

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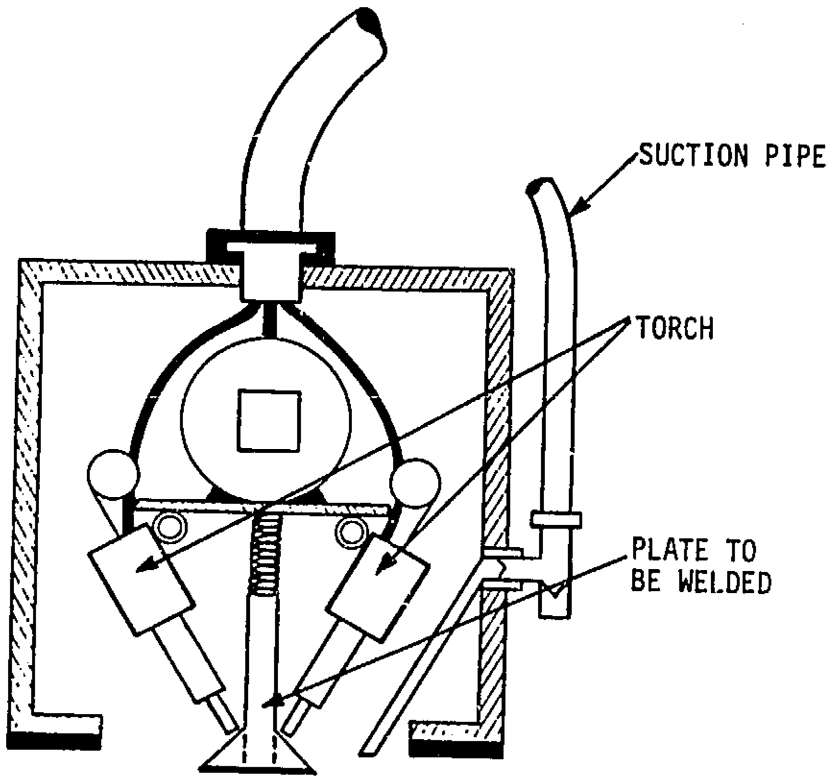

FIGURE B-2 Conceptual design of an automatic underwater welding machine developed by Lombardi

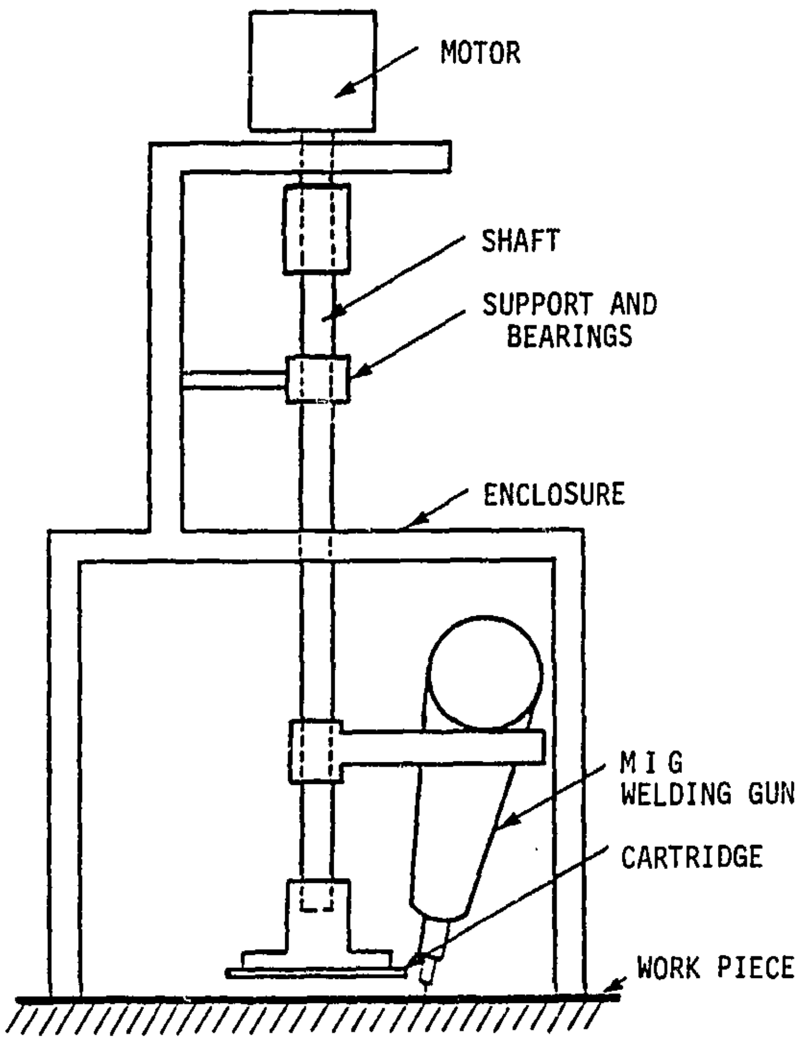

FIGURE B-3 Sketch of an automatic welding system developed by Gustin capable of joining a circular patch to a flat plate shielding flux. As the torches pass along the intersections of the two plates, a double fillet weld is produced. The cartridge automatically stops after the full length of the plate has been traveled. After welding is completed, the frame is removed from the workpiece. The plate is left welded to the workpiece.

Gustin (T21) continued the work started by Lombardi. However, Gustin's work differs from that of Lombardi in the following ways:

(1) Gustin's work is primarily directed toward developing a machine to be used in air, while Lombardi's work was aimed at developing a machine to be used underwater;

(2) Gustin decided to use gas metal arc welding (GMAW) process which is easier to control than flux-shielded process; and,

(3) Regarding the joint design, Gustin decided to work on lap welding of a circular plate to a flat plate.

Gustin designed and constructed a device capable of welding a circular "cartridge" of low-carbon steel to a base plate of similar material. Figure B-3 shows the schematic of the design which can be summarized as follows:

(a) A GMAW gun is mounted on a shaft so that rotation of the shaft causes the gun to transverse the desired circular path.

(b) A cartridge holder is mounted concentrically on the shaft. The cartridge holder accepts the patch to be welded and mechanically positions the patch against the workpiece. A bearing component of the cartridge holder allows the shaft to rotate without requiring holder rotation.

(c) The enclosure shown provides structural support for the other components.

B.4 M.I.T. THESES AND STUDENT REPORTS ON UNDERWATER WELDING

(T1) Staub, J.A., "Temperature Distribution in Thin Plate Welded Underwater," M.S. Thesis, M.I.T., Department of Naval Architecture and Marine Engineering, June 1971.

(T2) Brown, A.J., "Methods of Research in Underwater Welding", B.S. Thesis, M.I.T., Department of Naval Architecture and Marine Engineering, June 1971.

(T3) Anderssen, A.H., "Underwater Application of Exothermic Welding," M.S. and Ocean Engineer Thesis, M.I.T., Department of Ocean Engineering, June 1972.

(T4) Meloney, M.D., "The Properties of Underwater Welded Mild Steel and High-Strength Steel Joints," M.S. and Ocean Engineer Thesis, M.I.T., Department of Ocean Engineering, June 1973.

(T5) Brown, R.T., "Current Underwater Welding Technologies," M.S. Thesis, M.I.T., Department of Ocean Engineering, June 1974.

(T6) Renneker, S.L., "An Investigation of Underwater Welded HY-80 Steel," M.S. and Ocean Engineer Thesis, M.I.T., Department of Ocean Engineering, June 1974.

(T7) Moore, A.P., "Metals Joining in the Deep Ocean," M.S. and Ocean Engineer Thesis, M.I.T., Department of Ocean Engineering, June 1975.

(T8) Zanca, L.M., "Underwater Stud Welding," M.S. Thesis, M.I.T., Department of Ocean Engineering, August 1975.

(T9) Dalvi, C.M., "Mechanical Properties of Underwater Weld," M.S. Thesis, M.I.T., Department of Ocean Engineering, May 1976.

(T10) Naiman, J., "Effect of Coated Electrode Type on Hydrogen Cracking in Underwater Welds," B.S. Thesis, M.I.T., Department of Materials Science and Engineering, May 1976.

(T11) Metha, A.R., "Underwater Welding - An Investigation on Differential Heat Loss in the Shielded Metal Arc Process," M.S. Thesis, M.I.T., Department of Ocean Engineering, February 1977.

(T12) Chica, J., "Fundamental Study of Underwater Arc Stud Welding", M.S. Thesis, M.I.T., Department of Ocean Engineering, May 1977.

(T13) Tsai, C.L., "Parametric Study of Cooling Phenomena in Underwater Welding," Ph.D. Thesis, M.I.T., Department of Ocean Engineering, September 1977.

(T14) Prasad, S., "Development of Techniques for Deep-Sea Welding Simulations and Study," M.S. Thesis, M.I.T., Department of Ocean Engineering, February 1978.

(T15) Erickson, D.P., "Underwater Welding in Deep Sea," M.S. and Ocean Engineer Thesis, M.I.T., Department of Ocean Engineering, June 1978.

(T16) Iimura, O., "Underwater Fabrication and Constuction Systems," M.S. Thesis, M.I.T., Department of Ocean Engineering, June 1978.

(T17) Kataoka, T., "Applications of Arc Stud Welding for Deep-Sea Salvage Operations," M.S. Thesis, M.I.T., Department of Ocean Engineering, June 1978.

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APPENDIX C

A PRELIMINARY INVESTIGATION OF THE FEASIBILITY OF USING STUD WELDING IN SPACE

C.1 INTRODUCTION

The stud welding process was originally developed for the shipbuilding industry in the late 1930's, as a means of joining wooden planks to the steel deck plates of a ship.[C1] The major benefits of the then novel joining process was an increase in productivity, and the development of a joining process which did not require a through-hull penetrator to fasten wooden planking to the deck of newly constructed ships. The preservation of the watertight integrity, and the development of a reliable structural joint proved to be a great advantage in maintaining the seaworthiness of ships.

The stud welding systems commercially available are completely automated. After specific adjustments have been made to the stud gun, the only thing that an operator must do to weld a stud is to hold the gun perpendicularly to the workpiece and pull the rigger. All other operations necessary to achieve a quality weld are performed by a control box.

Today, stud welding is used in many different applications, from automobiles to various types of appliances, bridges, and railroad cars. In the offshore industry, stud welding has been used to attach anodes for cathodic protection to undersea structures. Researchers at M.I.T. have been studying underwater uses of stud welding. They are currently working on a research project which has the objective of developing an underwater stud welding system which may be operated remotely.

M.I.T. researchers believe that stud welding can be successfully used in space with minimal additional research and development. In fact, they believe that it is possible to develop completely integrated and automated stud welding systems which can be either remotely manipulated or operated by an astronaut with no welding skill.

C.2 STUD WELDING PROCESSES

Stud welding is a general term for joining a metal stud or similar part to a workpiece, according to the Welding Handbook.[C2] Welding can be achieved by a number of processes including arc, resistance, friction, and percussion. Of these processes, stud arc welding is the most widely used.

In stud arc welding, an electric arc is produced between the end of a stud and the workpiece. When the surfaces to be joined are properly heated, they are brought together under pressure. The stud arc welding can be classified into two types, depending upon the power supply used. In arc stud welding, D.C. power sources similar to those used for shielded metal arc welding are used. In the capacitor-discharge stud welding, a capacitor storage bank is used to supply the arc power.

Arc stud welding is suited for welding large-diameter studs up to approximately 32 mm in diameter, while capacitor-discharge stud welding is suited for welding small-diameter studs up to approximately 10 mm in diameter to thin sheets. We believe that most applications of space stud welding will be to weld small-diameter studs to thin sheets because:

(1) Most space structures will be fabricated with thin sheets of light metals, and

(2) Because of the extremely low-gravity in space, loads which will be applied to the stud welded joints will be small.

Therefore, it has been decided that discussions here should cover primarily capacitor-discharge stud welding. The basic technology discussed here, however, can be applicable to arc stud welding.

C.2.1. Capacitor-Discharge Stud Welding.[C3]

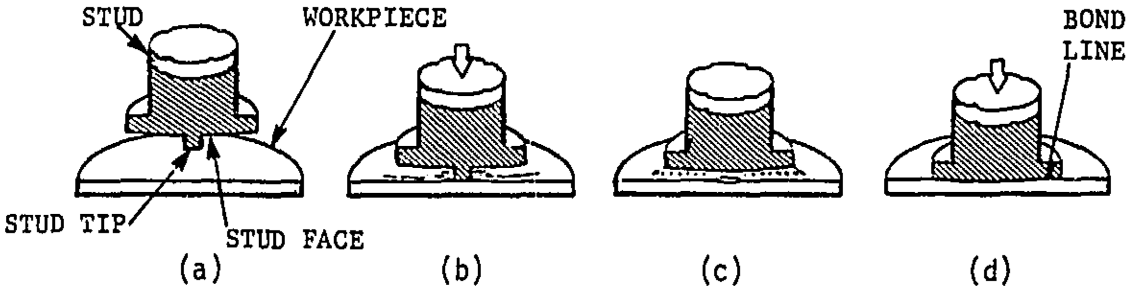
Capacitor-discharge stud welding uses the heat from an arc produced by the rapid discharge of a capacitor. A thin film of molten metal is formed on the end of the stud and on the workpiece adjacent to the stud. The stud is then forced into the molten puddle of metal, which extinguishes the arc and completes the weld. Flux is not needed in welding steel; argon shielding sometimes is used in welding aluminum alloys by the drawn-arc method. The welding system consists of a capacitor discharge stud welding gun, a control box, a capacitor bank, and a suitable weld cable and ground leads.

There are three methods of capacitor-discharge stud welding: the initial-gap, initial-contact, and drawn-arc methods. Figures C-1 through C-3 show sequences and steps in these three methods.[C3] Further detailed descriptions of these methods may be obtained in several publications including the Welding Handbook[C2] and the Metals Handbook.[C3]

The initial-gap and initial-contact methods have a weld time of 3 to 6 milliseconds, which prevents heat build up and permits welding of fasteners about 4 mm in diameter to a steel base metal as thin as 0.8 mm. Teflon coating on the inner surface of 1 mm-thick aluminum pans is not damaged when studs are welded to the outer surface. Small fastener-component cups made of low-carbon steel, stainless steel, aluminum alloy, or copper alloy have been welded to various base metals.

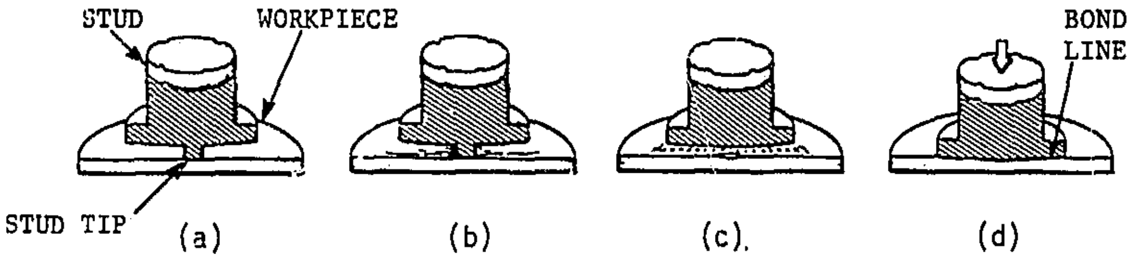
The drawn-arc method uses an arc time of 6 to 12 milliseconds, which is longer than those of the initial-gap and initial-contacts methods. The drawn-arc method is better suited for base metals that have rust, mill scale, or surface irregularities, than the initial-contact or initial-gap method.

Welding currents used in these methods also differ. The drawn-arc capacitor-discharge method uses 600 to 3,000 amperes, while the initial-gap and initial-contact methods use 2,500 to 20,000 amperes. Weld base diameter dictates the actual desired current flow with current densities on the order of 450 amp/mm^2 (300,000 amp/in^2) required for aluminum studs. The primary advantages of the capacitor-discharge stud welding over the arc stud welding, are low energy input (115 Volts A.C.) and shallow penetration of the base metal.



(a) The stud is initially positioned above the workpiece.
(b) When the unit is triggered, the stud holder is released and plunges the stud to the workpiece with the capacitor-discharge voltage impressed on the stud. When the stud tip contacts the workpiece, welding current starts to slow and an arc is formed.
(c) The tip disintegrates when it contacts the workpiece. Arcing between the stud and the workpiece melts the face of the stud and the workpiece surface opposite the stud face to a very shallow depth.
(d) The stud is plunged into the puddle of molten metal, to complete the weld.

FIGURE C-1 Sequence of steps in initial-gap capacitor-discharge stud welding (Metals Handbook[C3])



(a) The stud is initially in contact with the workpiece.
(b) When the welding current is turned on, the tip softens and disintegrates, and the arc is initiated.
(c) Arcing between the stud and the workpiece melts the face of the stud and the workpiece surface opposite the stud face to a very shallow depth.
(d) The stud is plunged into the puddle of molten metal, by spring pressure, to complete the weld.

FIGURE C-2 Sequence of steps in initial-contact capacitor-discharge stud welding (Metals Handbook[C3])

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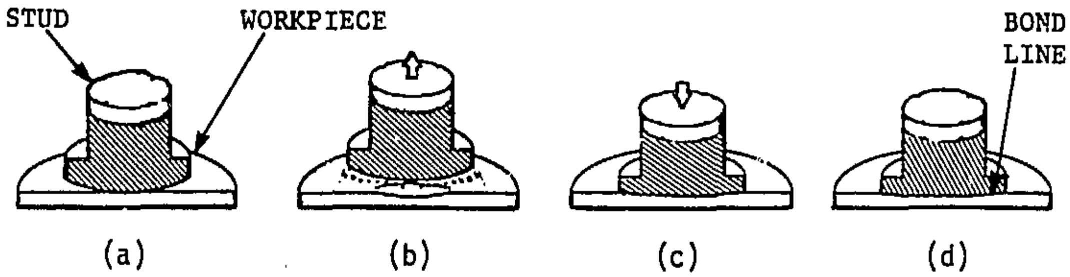
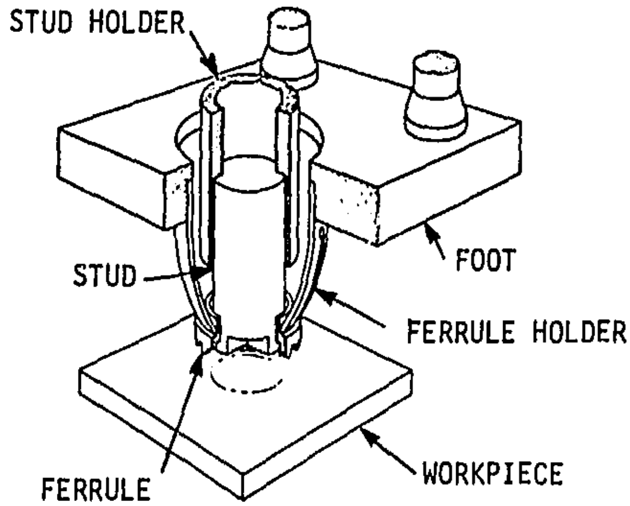


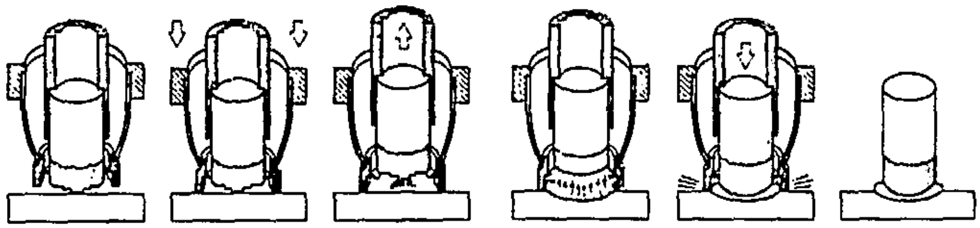
(a) The stud is initially in contact with the workpiece.
(b) When the current is turned on the current surges into the stud tip, and the stud is then immediately raised, to draw the arc The heat of the arc melts the face of the stud and the workpiece surface opposite the stud face to a very shallow depth.
(c) When the welding current is turned off, the solenoid in the gun is de-energized and the stud plunges into the puddle of molten metal.
(d) Finished weld, with little or no fillet.

FIGURE C-3 Sequence of steps in drawn-arc capacitor-discharge stud welding (Metals Handbook[C3])

C.2.2 Arc Stud Welding[C3].

Figure C-4 shows the sequence of steps in arc stud welding. The arc stud welding process is fundamentally the same as the drawn-arc capacitor-discharge method. Both processes require that an arc be drawn from an initial contact with the workpiece. After arc initiation, the form of energy input is different between the two processes. The arc stud process uses a lower voltage and much lower current density than those used in the capacitor-discharge process. For example, 30-35 volts and 3,000 amperes may be used for welding aluminum alloy studs 12.5 mm (1/2 in.) in diameter, while the capacitor-discharge method is limited to aluminum studs of 6.4 mm (1/4 in.) or less in diameter. Because the rate of energy discharge in arc stud welding is less than that in capacitor-discharge stud welding, welding periods used in arc stud welding are much longer than those used in capacitor-discharge stud welding. For example, welding periods of 0.25 to 0.7 second may be used for welding aluminum studs.





(a) First, the stud is located on the workpiece.
(b) Force is applied so that the spring within the gun is compressed until the ferrule is seated firmly on the workpiece.
(c) When the welding current is turned on, the solenoid in the welding gun is energized, the stud is automatically lifted, and an arc between the face of the stud and the workpiece is initiated.
(d) With the stud in the lifted position, arcing spreads across the face of the stud and the heat of the arc melts an area on the workpiece and produces a weld puddle under the stud, and also melts a small portion of the face of the stud.
(e) When the welding current is stopped, the solenoid is de-energized and the face of the stud is plunged, by spring pressure, into the weld puddle.
(f) Finished weld; note shape of fillet formed by the ferrule.

FIGURE C-4 Sequence of steps in arc stud welding

C.4 POSSIBLE APPLICABILITY OF STUD WELDING IN SPACE

We believe that among the many welding processes which may be considered for use in space, stud welding is one of most promising, in terms of potential for developing in a short time a workable hardware system which can be remotely manipulated or operated by an astronaut with little or no welding training. To accomplish this, however, we must develop answers to various questions, some of which are listed below:

(1) Is it really possible to perform stud welding in space with no air, no gravity, and a possibility of extreme temperatures?

(2) Can a stud welding process be delivered which can successfully weld 2000 series aluminum alloys at an acceptable confidence level?

(3) May the necessary electrical power for stud welding be obtained from existing or planned power sources, or new means of power generation necessary to perform stud welding in space?

(4) Which method of stud welding should be used for space applications?

These and a few other subjects which are important in developing space stud welding systems are discussed in the following pages.

C.4.1. Stud Welding in Space Environment.

Table 4 in the main part of this report compares differences in environments between space welding and ordinary welding on earth. The environments in space welding arc characterized by:

(1) Zero gravity,

(2) Lack of air, unless welding is performed inside a space station or a specially designed habitat (Case 3 in Table 4), and

(3) Extreme temperatures, when welding is performed outside a space station (Case 1).

C.4.1.1. Effects of Zero Gravity on Stud Welding. Although there has been no published record of stud welding under zero gravity, there sould be no difficulty in performing it. During stud welding there is practically no metal transfer between the electrode (stud) and the base metal. Therefore, the mechanisms of stud welding would be little affected by the presence, or lack, of gravity, especially when capacitor-discharge process is used. The Soviets have already found that spot welding is little affected by gravity.[7201] Experiments aboard an aircraft descending at a high speed should prove whether or not it is possible to perform stud welding under zero gravity.

C.4.1.2. Stud Welding in Vacuum. There has been no publication which discusses whether or not it is possible to perform stud welding in vacuum. Although we are optimistic about performing stud welding in vacuum, this subject needs experimental verification.

Fortunately, the Department of Ocean Engineering has a pressure tank which was originally designed to perform welding experiments, including those of stud welding, under high pressure simulating hyperbaric welding underwater. This experimental set-up can be easily used for stud welding in a vacuum. In fact we have already found that a vacuum of 1×10^{-1} Torr (13.33 N/m^2) can be established.

Figure C-5 is a diagram of a proposed experimental set-up for studying the effects of a partial vacuum and low pressure inert gas environment on the various stud welding methods. The intent of the system is to simulate the environment of space, disregarding the effects of gravity and extreme temperature.

This set-up includes: A vacuum chamber in which the stud gun and base metal are placed in a ready to weld position, the power supply and control box to supply energy and vary the welding parameters, an interfacing system to condition the signals chosen for data acquisition for input to the laboratory computer, and the laboratory computer for data storage, analysis, and potential control of the welding processes.

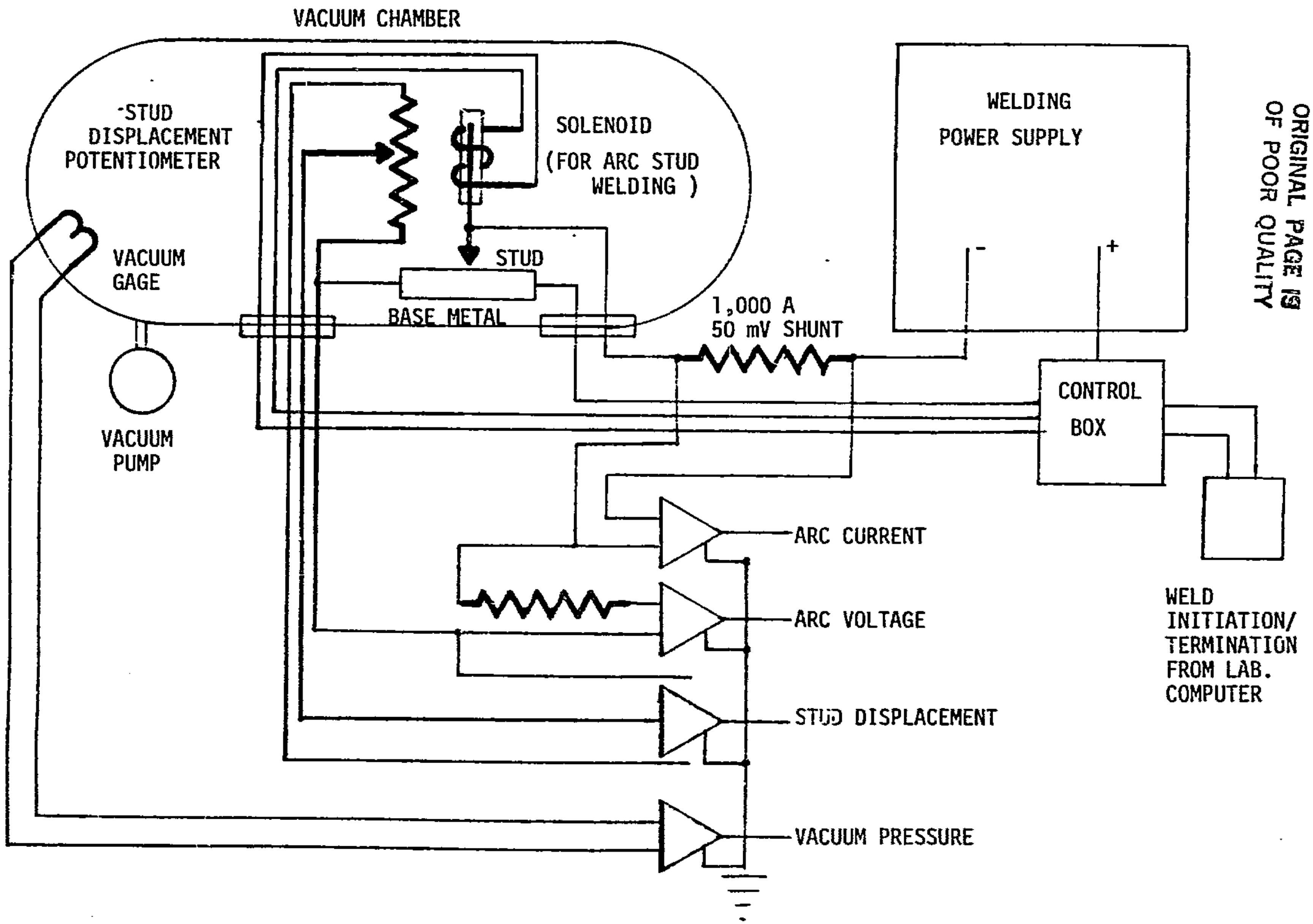


FIGURE C-5 Experimental set-up for studying the effects of a partial vacuum inert gas environment on the Stud Welding Process

We may find that the existence of a small amount of gas or a mixture of gases facilitate initiation and maintenance of an arc necessary to perform stud welding in a hard vacuum. If so, a simple device may be developed to supply the needed gas. For example, the gas may be stored in a small metal container, and the wall of the container may be puncturedjust before welding, to supply the gas near the weld.

It is recommended that a research program be established with the following objectives:

(1) Study whether or not it is possible to perform stud welding in vacuum,

(2) If it is difficult to establish an arc in a hard vacuum, study whether or not the existence of a small amount of gas or a mixture of gases would facilitate initiation and maintenance of the arc necessary to perform stud welding,

(3) If the above study is affirmative, study means to supply the needed gas to the weld area when needed.

C.4.1.3. Stud Welding at Low Temperatures. Performing stud welding at extremely low temperatures would not pose a serious problem, especially when welding aluminum, unless metal surfaces are contaminated by condensation of water vapor. Preheating of the workpiece, perhaps by means of electric resistance heating, may be useful for obtaining good-quality welds.

C.4.2. Development of Suitable Stud Materials and Welding Conditions for Stud Welding 2000 Series Aluminum Alloys.

Materials which are most likely to be used extensively in space structures are aluminum alloys, especially 2000 series alloys. Consequently, in order for stud welding to play any significant roles in the construction, maintenance, and repair of a space station we must be able to successfully perform stud welding of 2000 series aluminum alloys. On the basis of the currently available information, stud welding can be successfully performed on various types of aluminum alloys. However, 2000 series aluminum alloys are difficult to join by the stud welding processes. It is recommended that a research program be established with the following objectives:

(1) Develop alloy materials suitable for stud welding 2219 and several other aluminum alloys likely to be extensively used for space structures, and

(2) then develop optimum welding conditions for stud welding these aluminum alloys.

The experimental set-up shown in Figure C-5 may also be used to perform this research.

C.4.3. Power Requirements and Selection of Stud Welding Methods.

One of the major potential problems in the adaptation of stud welding in space is how to obtain the large instantaneous electric power needed for stud welding. For example, if we were to weld an aluminum stud 12 mm in diameter, we would have to use the arc stud process using approximately 640 amperes and 35 volts or 22,400 watts. However, the actual energy consumed is approximately 15,000 joules, since the welding time is about 0.67 seconds. The power and energy requirements are less for welding smaller-diameter studs.

It is recommended that the initial research effort be directed toward welding small studs using the capacitor-discharge stud welding process, which is capable of welding aluminum studs up to 6.4 mm (1/4 in.) in diameter using a light weight power supply of which approximate average characteristics are:

Capacitance: 40,000 Microfarad
Peak voltage: 200 volts
Weight: 30 kg.

In this research, no special effort has been made to determine exact methods of obtaining the needed electric power. It is assumed that the above mentioned power can be made available, perhaps by a system of solar batteries.

From the standpoint of operational simplicity, size, weight, and required energy input, the initial-contact capacitor-discharge method is believed to be the best choice for initial studies of stud welding in space. This method would provide us with workable hardware systems in space with minimum time and cost for development. The gun utilized in this system is the simplest of all the stud welding methods, and does not require power to operate a solenoid which is needed in the drawn arc stud welding. This further simplifies the control system. In addition, the initial-contact method does not require shielding gas when welding aluminum alloys.

However, we may find it advantageous in later stages to switch to the drawn-arc capacitor-discharge method, when it become necessary to perform stud welding in actual field conditions, in which metal surfaces may be rough. Although the drawn arc method utilizes a welding gun with a solenoid requiring a larger and heavier gun and a more complex control system, the versatility of the gun is much greater.

C.4.4. Importance of Surface Preparation in Stud Welding.

In order to successfully perform stud welding, it is very important to have both the surface of the stud and the surface of the workpiece clean and free of various foreign materials, including oxide films on the metal surface, dust, moisture, grease, etc. The surface cleanliness is especially critical in welding aluminum, because:

(1) An aluminum weld tends to have porosity, when hydrogen exists in areas near the weld, and
(2) An aluminum plate is normally covered with a thin film of aluminum oxides which is difficult to remove either mechanically or chemically.

It has been well established that porosity due to hydrogen is the major problem in welding aluminum alloys, as discussed in 2.5.2. of the main part of this report. During the fabrication of the huge fuel and oxidizer tanks installed in the Saturn V space vehicles, extensive studies were made on porosity in aluminum welds, especially those made with the GTAW and the GMAW processes. It was found that the major sources of hydrogen that caused weld porosity were contaminants on the metal surface, rather than hydrogen in the shielding gas and hydrogen contained in the filler metal and the base metal. A study was made to find the best method of removing surface contaminants covering various methods including wire brushing, and rinsing with different cleaning agents. It was found that the best method was to remove by machining a thin layer of the metal surface before welding.

As opposed to arc welding processes, in which the welding arc travels as welding is completed, stud welding is stationary. Therefore, it should be relatively easy to make sure that all potential sources of hydrogen are removed from the weld area in stud welding. Since stud welding is completed in a very short time, it is important to make sure that surfaces to be joined are absolutely clean before welding operation starts. We believe that the best method is to mechanically remove very thin layers from both the stud and the base plate in areas near the weld zone.

C.4.5. Control Systems for Stud Welding.

Today, control systems have become an indispensable part of modern manufacturing, industrial, and construction processes. This fact is a result of the considerable increase in reliability obtainable through the successful implementation of a properly designed control system. The majority of conventional stud welding systems utilize very simple but nonetheless effective open loop control systems. There has been little demand or motivation to further the development of these systems because the range of weld quality which is acceptable for normal usage is so wide.

Initial investigations performed during this research, however, have revealed that even though existing systems are quite reliable, further development of control systems beyond existing levels may significantly improve the reliability of the completed weld. Operational constraints, procedural mandates, and environmental factors imposed on various stud welding methods envisioned for use in space will demand the development of a more sophisticated control system in order to achieve required levels of confidence. Such systems may be designed and implemented using existing laboratory equipment and personnel at M.I.T. Later, after successful laboratory testing has been completed, the systems should be developed and packaged for field trials.

C.4.5.1. Control System Overview. Figure C-6 is a block diagram of a control process for a fully integrated welding system. The basic concept shown in this figure is applicable to any welding process, although the emphasis of the discussion presented here is placed on stud welding, especially capacitor-discharge stud welding.

The heavy horizontal lines show the progression of welding tasks which take place during the overall welding cycle. The lighter lines depict the flow of information input to the system from the weldment design tasks as well as information sensed during different tasks in the overall control process. At the heart of the overall control system is the in-process control system. The closed-loop welding process control system can be effectively used in such processes as arc welding which are relatively slow.

However, in the case of capacity-discharge stud welding process in which the welding time is only several milliseconds, it is not technically feasible to implement a practical closed-loop, in-process control system. This fact has motivated the development of the various in-process sensing systems shown in Figure C-6 to increase confidence levels in the reliability of the final weld. The success of the overall control system is dependent upon the processing of information sensed during the pre-weld inspection, welding, and post-weld inspection processes. This information, which is stored in the memory banks of the computer- or microprocessor-based system during each process, is then correlated with experimental data, also contained in memory, which is known to have produced consistent reliable welds under identical conditions. Comparative information formulated in this manner is then analyzed and used to predict weldment reliability with a high level of confidence. Such a system may be developed for any of the stud welding

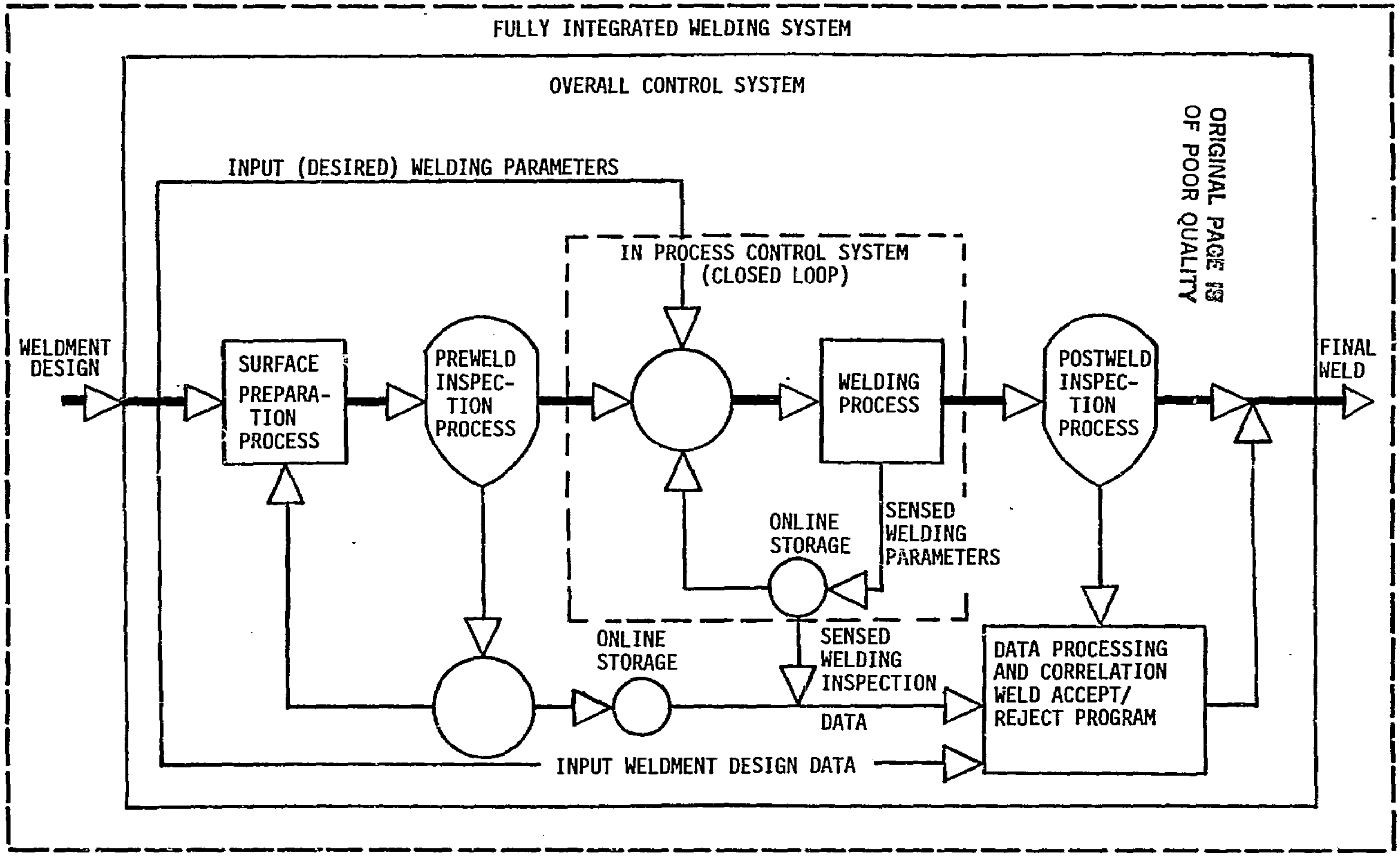


Figure C-6 Control system for a fully integrated welding system methods; this system may then be operated remotely, without human intervention. Additional research work must be performed to substantiate this thesis and to develop the necessary data base needed to implement the proposed system.

The goal of the overall control system is to prevent a defective weld from being placed in service. This objective is not intended to obscure the importance of high reliability in the actual welding process, but to place primary importance on the prevention of an in-service failure. A system of this design imposes a level of control on the welding process which does not prevent the production of a bad weld, an occurrence which is uncontrollable, but ensures that such a weld is detected and never placed in service, an occurrence which is controllable.

C.4.5.2. <u>In-Process Control System</u>. Analysis of potential control factors for the various stud welding processes has shown that:

(1) Control of welding time is the only viable means of closed-loop, in-process control,

(2) Weld energy input is the most important welding parameter to control, and

(3) The development of a closed-loop control system is only practical for the drawn arc stud welding method, and is not feasible for any of the capacitive discharge methods.

Figure C-7 depicts one segment of a closed-loop control system proposed for arc stud welding, of which welding time of 0.25 to 0.7 second may be long enough to exercise in-process control. The essential thoughts behind the control process are described below. By sampling arc voltage and arc current at a known rate of approximately one sample per millisecond, weld input energy may be computed for each sampling period. By equating accumulated weld energy with a required, predetermined weld energy input at the end of each sampling period, closed-loop control of weld energy input may be achieved. Minor fluctuations of voltage and current detected during the welding process are then compensated for by varying the actual welding time within established limits.

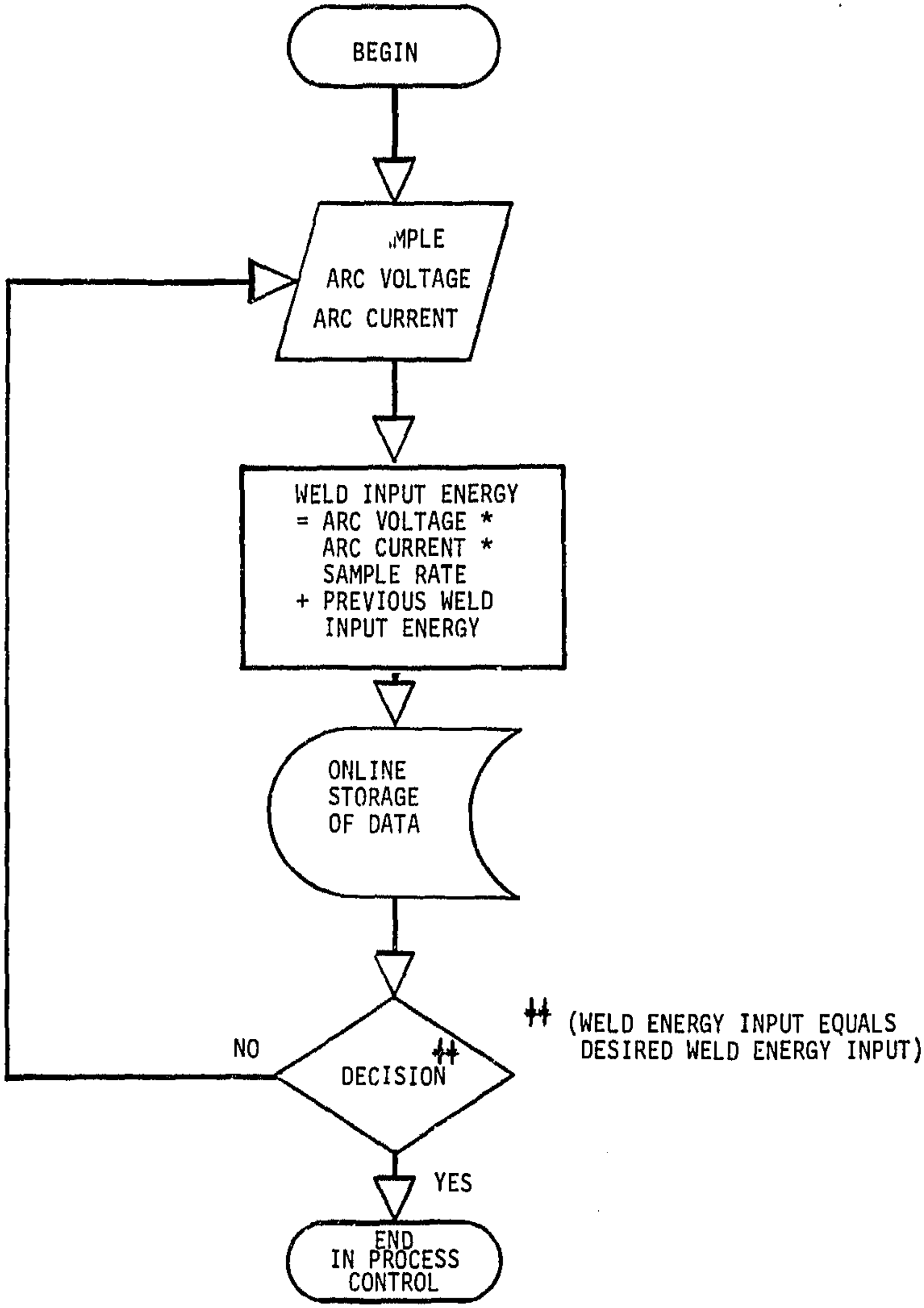


FIGURE C-7 In-process control system for arc stud welding system

It is possible to implement and test this control process in simulated space conditions utilizing existing equipment at M.I.T. The actual system could then be developed for field applications.

C.4.5.3. In-Process Sensing Systems. Initial investigation of the various stud welding methods has shown that closed-loop, in-process control is not a practical control method for all stud welding processes. As a result, various methods of in-process sensing and control are proposed and developed here.

As stated previously, weld energy input is thought to be the most important welding parameter to control during the welding process. In addition to this parameter, stud displacement, or the movement of the stud during the welding cycle, plays an equally important role in determining weld reliability. Stud displacement has two important effects during the welding cycle. It affects arc voltage during the arcing of the weld, and it shows the penetration of the stud into the base metal when the stud is forced into the workpiece at the end of the cycle. It is our belief that the most promising means of predicting weldment reliability from in-process information is through a correlation of weld energy input and stud displacement with known, predetermined experimental data. Weld energy input does not have to be controlled in-process for this approach to be valid.

The importance of surface conditions has been discussed in Section C.4.4. of this appendix. A cause and effect relationship is clear, in that surface conditions can affect the characteristics of the welding arc and hence the energy input and final weld. In addition, unfavorable foreign materials may be entrained into the molten metal which may reduce weld quality. It may be possible to sense unfavorable surface conditions before the welding process occurs. If unfavorable conditions are found, the weld cycle would be terminated, and additional surface preparation would be performed. It is felt that most unfavorable surface conditions will tend to increase the ohmic contact resistance between the stud and the base plate. If this thesis can be substantiated through experimentation, then a system can be developed and integrated into our overall welding system, increasing the reliability of the final weld and reducing the probability of producing an inferior quality weld.

The most important information about the final weld reliability is gained from the post-weld inspection process. Some possible methods of post-weld inspection are ultrasonic, acoustic emission, and tensile loading of the completed weld. Results of a post-weld inspection task such as tensile loading would form the basis for an accept/reject decision on the weld. It is felt that the tensile loading test offers the greatest promise because:

(1) It may be integrated into a properly designed gun, maintaining the simplicity of the operation, and
(2) Tensile loading of an aluminum stud will tend to increase the fatigue strength of the joint, enhancing weld quality.

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C4. "Nelson Stud Welding", by TRW Nelson Division

C5. Welding Kaiser Aluminum, First Edition, Kaiser Aluminum and Chemical Sales, Inc., 1867.

APPENDIX D

EXPERIMENTAL STUDY ON THE PERFORMANCE OF REMOTELY MANIPULATED SPACE WELDING

D.1 INTRODUCTION

The capability for remote unmanned construction and repair is a prerequisite for large scale human utilization of outer space or deep ocean. It also becomes necessary in such unconventional applications as the repair of highly contaminated nuclear reactor components, or work in other hazardous industrial environments. Furthermore, unmanned fabrication will become a necessity in the automated production lines in the "factories of the future".

Remote fabrication or repair of large structures is a very complex task, which requires significant advancements of the state of the art in a number of different areas. In this study, however, we focus on remotely manipulated metal joining technology in general, and welding in particular. Welding is a relatively complicated manufacturing process but it is preferred over alternative joining techniques--such as mechanical fastening or adhesive bonding--due to the excellent mechanical properties, high joining efficiency and air tightness that it can offer.

One of the objectives of this NASA study is to identify the fundamental components of various joining tasks and to examine which can or should be automated. The tasks that are more difficult to be effectively performed remotely and that disappropriately increase the total completion time are more likely to be passed to a machine. However, the current state of the art limits the extent of such automation and thus there will still be some tasks that have to be performed manually. Such sharing--and possibly trading--of control with the computer is the fundamental characteristic of a supervisory controlled system, as described by Sheridan in (D1).

As detailed previously in this study, welding fabrication usually involves three basic steps:

(i) Preparation
(ii) Actual Welding Process Execution
(iii) Inspection

The most fundamental subtasks involved in these steps are:

(a) Manipulation of welding, cutting, grasping, or inspection tools
(b) Selection of the process type and parameters
(c) Process Control
(d) Evaluation of joint quality

Different levels of automation are currently attainable for any of the above mentioned subtasks depending on the nature of the process, availability of information about the task, and capability of sensing and actuation. In addition, remote operation imposes further problems, such as limited sensing and/or manipulation capabilities, and inflexibility of the man-machine interface. These limitations are inherent in most telemanipulation applications. However, especially for the case of remote telemanipulation in space, the additional problem of transmission delay is introduced, due to the large distances involved.

This round trip time delay is composed of the time needed for a control command to travel to the teleoperator and for the first indication of response to travel back. This will be twice the distance divided by the speed of propagation. The effects of a transmission delay on teleoperation performance have been studied by various investigators. At M.I.T. in particular, fundamental work in the area has been performed by Sheridan and Ferrel (D2). They generally concluded that even complex tasks could be accomplished by adopting a simple "move-and-wait" strategy and observed no evidence of unstable motions or delay-induced emotional stress.

The human performance during remote operation of some of the elementary tasks involved in welding fabrication was investigated in this study. In the confines of this initial investigation, however, only the tool manipulation tasks were experimentally examined. Process control, or evaluation of the joint quality have to be shared to an extent with a machine and are inherently more difficult to be performed remotely.

As was detailed in chapter 3 of this report, tool manipulation is an important part of all the steps of remote fabrication (preparation, actual process, and inspection) and can be further broken down to:

- Positioning of a tool at an arbitrary position and orientation in space.
- Tracking of a two- or three-dimensional path at a constant speed while keeping a constant distance and orientation to an arbitrary surface.

Both remotely manipulated positioning and tracking were simulated, and details and results of the performed experiments are presented in the following sections of this appendix.

D.2 EXPERIMENTAL STUDY

D.2.1. Experimental Setup and Equipment.

The remote manipulation simulation experiments reported here were performed at the Man-Machine Systems Laboratory of the Mechanical Engineering Department at M.I.T. The equipment used in the experiments basically consisted of:

1. Manipulator system

   - A Modified ANL E2 master/slave manipulator unit. Master and slave arms are identical and have seven degrees of freedom (six rotating joints plus grasping). A detailed description of this system is given by Brooks.[D3]

   - A PDP-11 3/4 computer running under the RSX operating system. The computer was used both for the control of the manipulator and for timing and data acquisition operations. The computer control software and the man-machine interface were developed by Yoerger and are described in detail in D4.

2. T.V. System

   - Panasonic WV-1050 black and white TV camera fitted with a 12.5 mm lens.

   - Panasonic CT-1900M Color TV monitor.

   - ADAC System 1000 computer fitted with the QVC-120 and QAF-120 DATACUBE video graphics cards. This system is capable of controlling frame rate gray levels and resolution of the picture.

D.2.2. Simulation Considerations.

One of the major factors examined in this initial study was transmission delay. Transmission delay exists in both the feedforward and the feedback transmission paths. However, for simplicity in the simulation, we can lump the total delay in the forward path only, as can be readily seen in Figure D-1. These two situations are absolutely equivalent, as far as the human operator is concerned.

In our experiments, the transmission delay is simulated by the computer. The manipulator system is essentially under computer control, but the positions commanded by the computer for the slave arm are actually the positions where the master has been some time ago. Initial experiments with the system revealed some potential problems when master/slave manipulation is performed in the presence of transmission delay.

Specifically, there is a possibility of asking the slave to move in a position not permitted by the constraints of the remote site. This can happen because the operator receives information about collision with an obstacle long after he had commanded the slave to move even further "inside" the obstacle. In that case, the slave will not be able to follow the master, even if the operator retreats, since it will first have to complete the previously commanded moves. The positioning error at the joints of the manipulator will then become very high and will eventually blow the fuses of the servo controller.

To remedy this problem, a special strategy was included in the delay simulation software. Specifically when the positioning error exceeded some prespecifiable threshold, the computer would signal to the operator a "hit" (by two beeps) and would take over for two seconds. At this point the slave would be commanded by the computer to backtrack until the error was reduced to acceptable limits and then the master would be brought in the same position as the slave. The operator would finally be notified that the system had recovered (by four beeps).

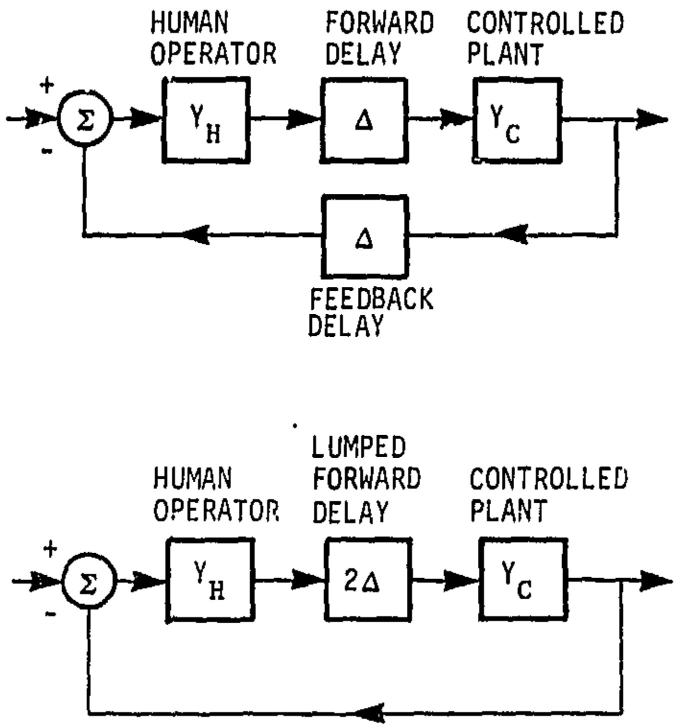


FIGURE D-1 Delayed manual control systems

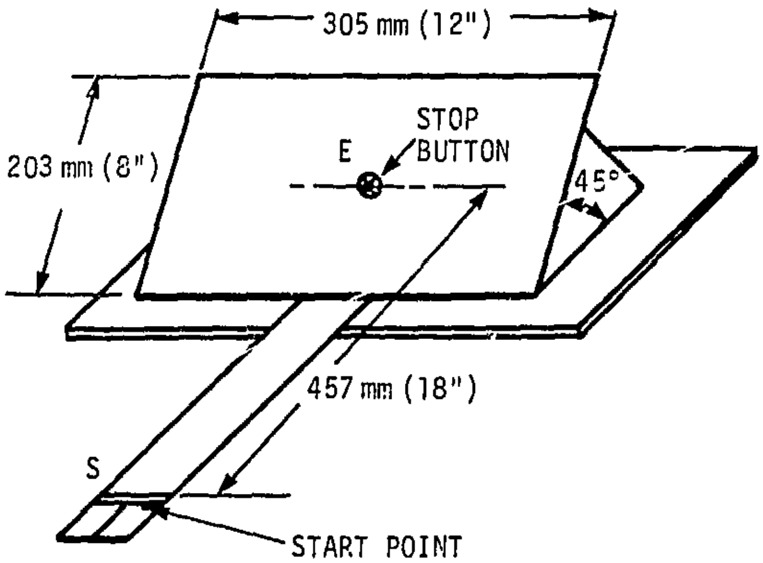


FIGURE D-2 The positioning task

D.2.3. <u>Experimental Procedures</u>.

D.2.3.1. <u>Positioning Task</u>.

For the simulation of the positioning task, the device shown in Figure D-2 was built. At a "START" signal, the subject was asked to move the end effector of the slave, from point S to point E [a distance of 457 mm (1.5 feet)], and press the "STOP" button there. Three different buttons sizes were used [19 mm (3/4 inch), 25.4 mm (1 inch) and 44.5 mm (1 3/4 inch) in diameter] to examine the effect of positioning tolerance. The time required for the move (between "START" and "STOP") was recorded by the computer.

Subjects would view the task site through a television with the camera and monitor positions fixed. The actual arrangement is shown in Figure D-3. It should be noted that the TV monitor was positioned parallel to the camera so that the subject would be better oriented. The viewing distance and the pan and tilt of the camera was preselected so that the subject would have a complete view of the task site.

D.2.3.2. <u>Path Tracking Task</u>.

For the simulation of the path tracking task, the test weld of Figure D-4 as originally developed by Yoerger (D4) was used initially. The subjects had to traverse the path keeping the end of the slave at a prespecified distance from the weld and pointed directly at the weld bead. The task was timed but performance was to be judged by the ability of the operator to keep a constant speed and a constant distance from the weld while continuously pointing at it. However, these performance specifications, shown in Figure D-5, were not directly comparable with the simple time measure available for the positioning task. Furthermore, time by itself would not be a reliable measure because then the subjects would have to make an unspecifiable trade-off between completion time and accuracy. To avoid these problems, only a limited number of experiments were performed with this test weld. Instead, a new path tracking task was developed. This latter

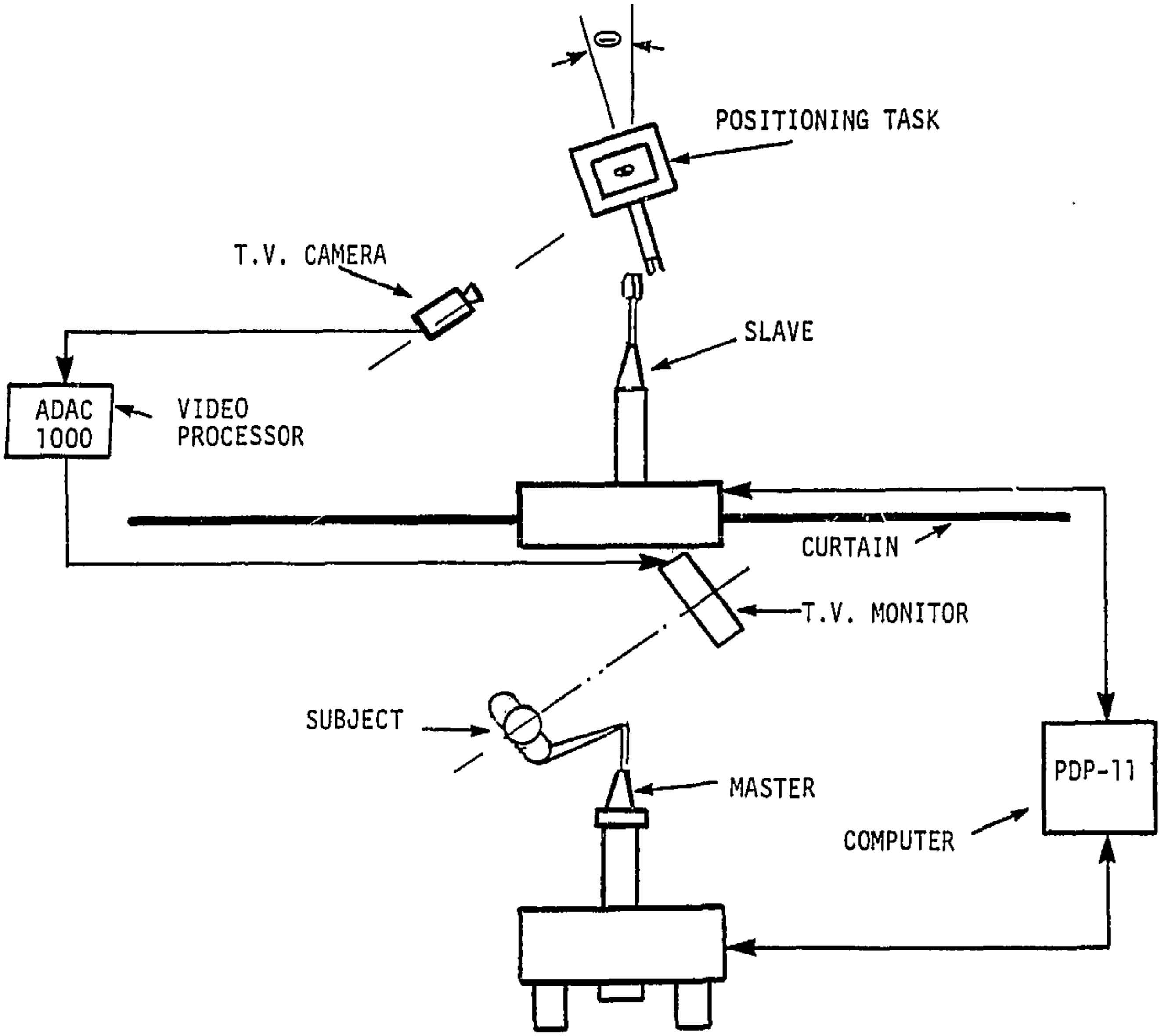


FIGURE D-3 Experimental setup in the M.M.S.L.

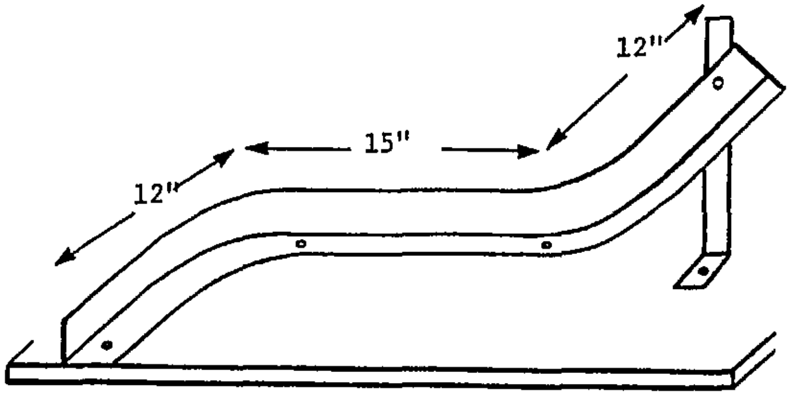


FIGURE D-4 Yoerger's test weld(D4)

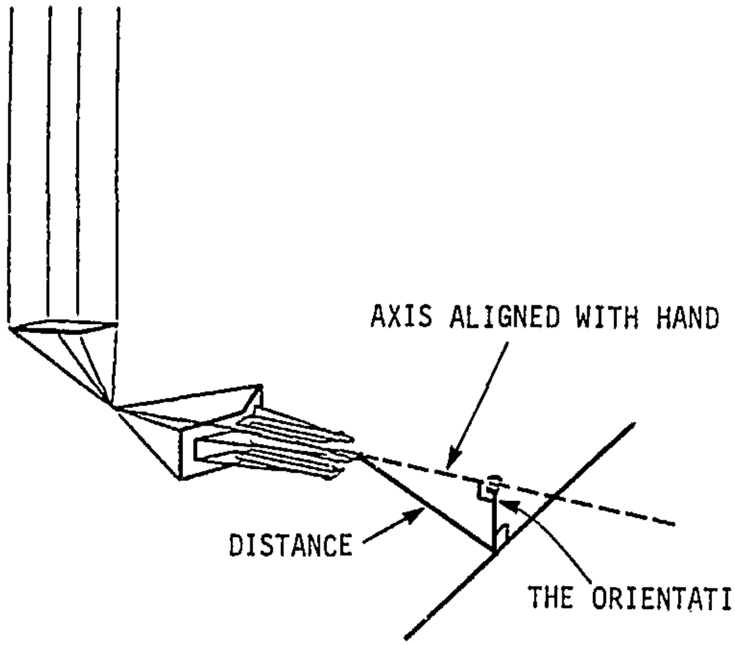


FIGURE D-5 Performance criteria. The distance criterion was the shortest distance between the tip of the tool and the weld bead. The orientation criterion was the shortest distance between the axis aligned with the hand and the weld bead(D4) task would impose prespecified accuracy tolerances both in position and orientation. Completion time would again be the only performance measure.

The device schematically depicted in Figure D-6 was developed as a more realistic simulation of a path tracking task for the case of welding or cutting. The operation of the device is rather simple. When the "torch" is directly over the slit of the table (Photo D-1), light from the lamp will reach the phototransistor (Photo D-2) of the light sensor, which in turn will activate the motor.* To keep the motor running,the subject has to follow the moving light sensor. If he fails to do so or if he deviates outside a permissible lateral tolerance, the motor will stop and the counter will count one error.

The tolerance can be varied by changing the size of the slit and the diameter of the aperture in the torch. The optics of the torch are designed to project a constant diameter beam of light. In this way, the path deviation tolerance is kept the same, irrespective of the torch-to-sensor distance. The motor speed can also be varied. The subject is, therefore, forced to follow a path with a prespecified tolerance and at a constant speed. Only the completion time is measured as the single performance criterion. Errors will simply increase the completion time, much in the same way as in the positioning task. Nevertheless both of the previously mentioned distance and angle performance criteria can still be measured.

Finally, it should be mentioned that the developed path tracking task is a better simulation of welding or cutting because it imposes a specified constant tracking speed to the operator. This is very similar to what really happens during cutting or welding, where the speed of tracking is dictated by the thickness of the metal (in cutting) and the welding conditions (in welding). If the torch is moved at a higher speed than actually required, cutting will not be completed

*The circuit details are given in Figure D-7.

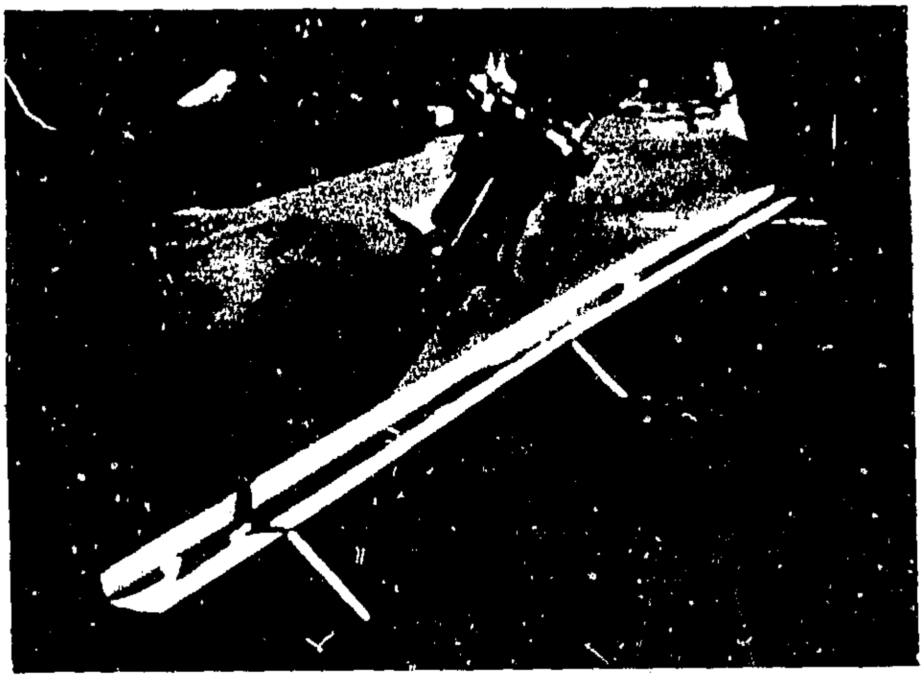


PHOTO D-1

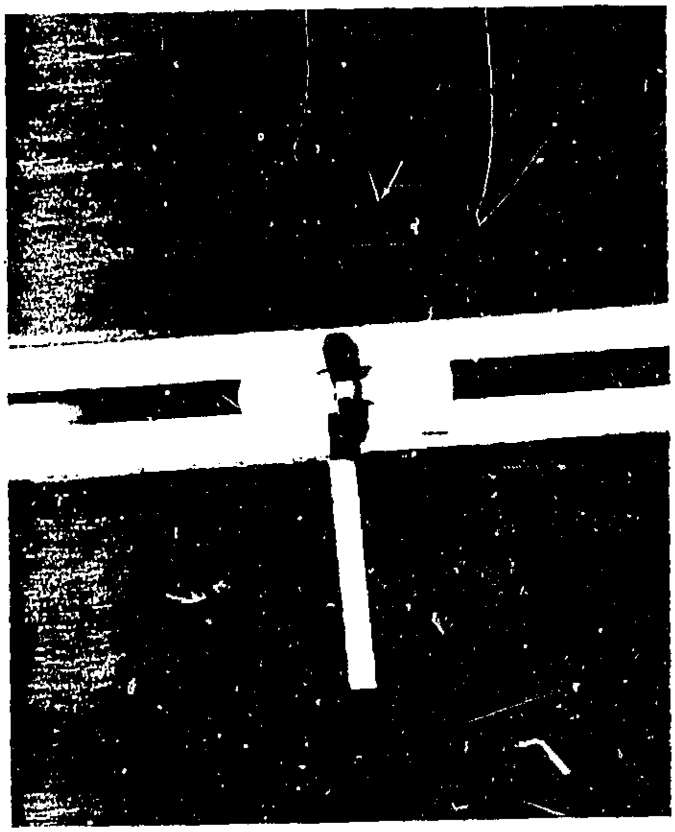
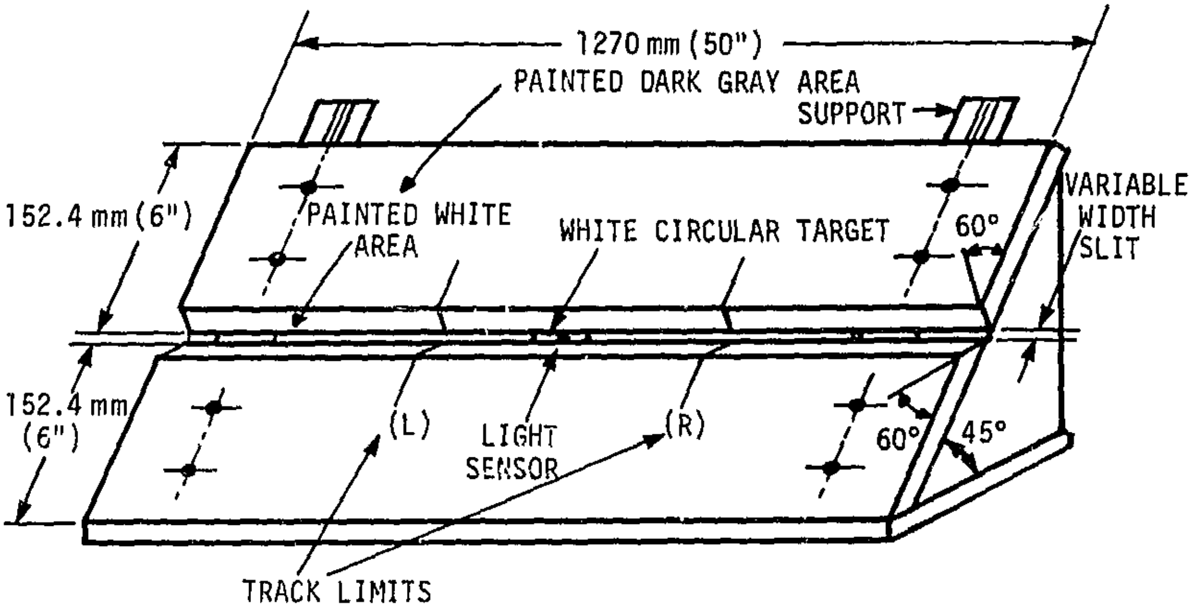
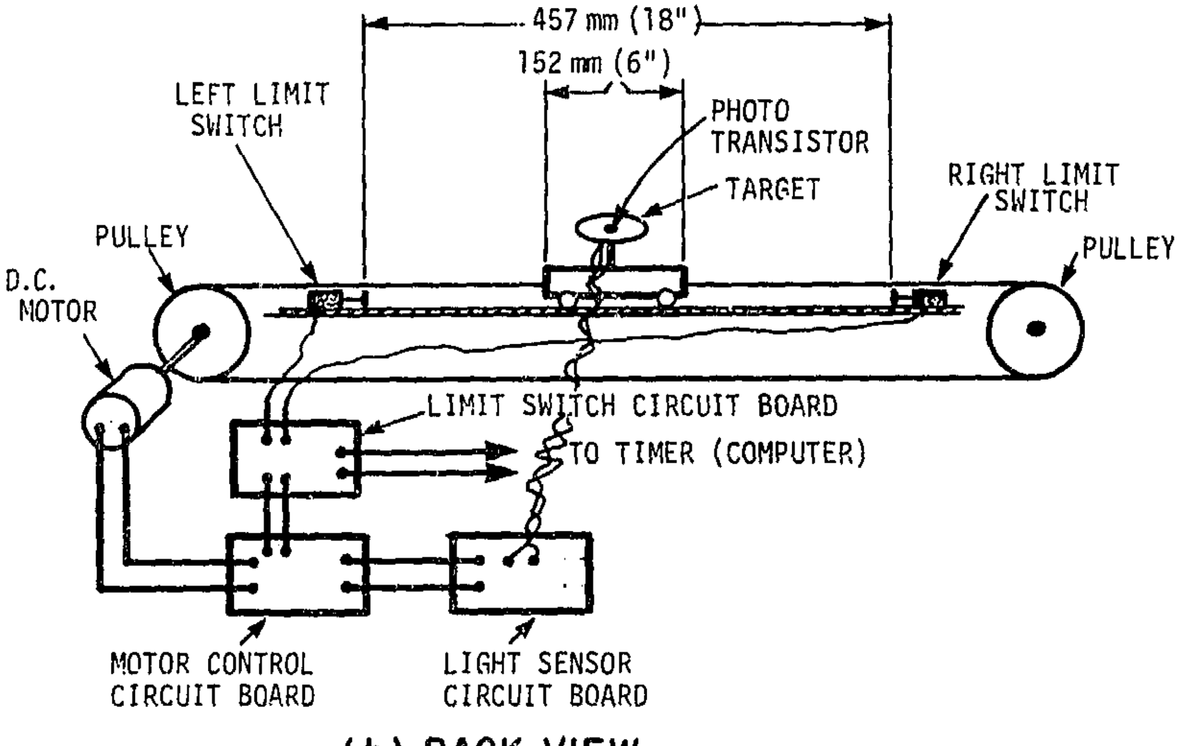


PHOTO D-2



(a) FRONT VIEW



(b) BACK VIEW

FIGURE D-6 The developed weld tracking task

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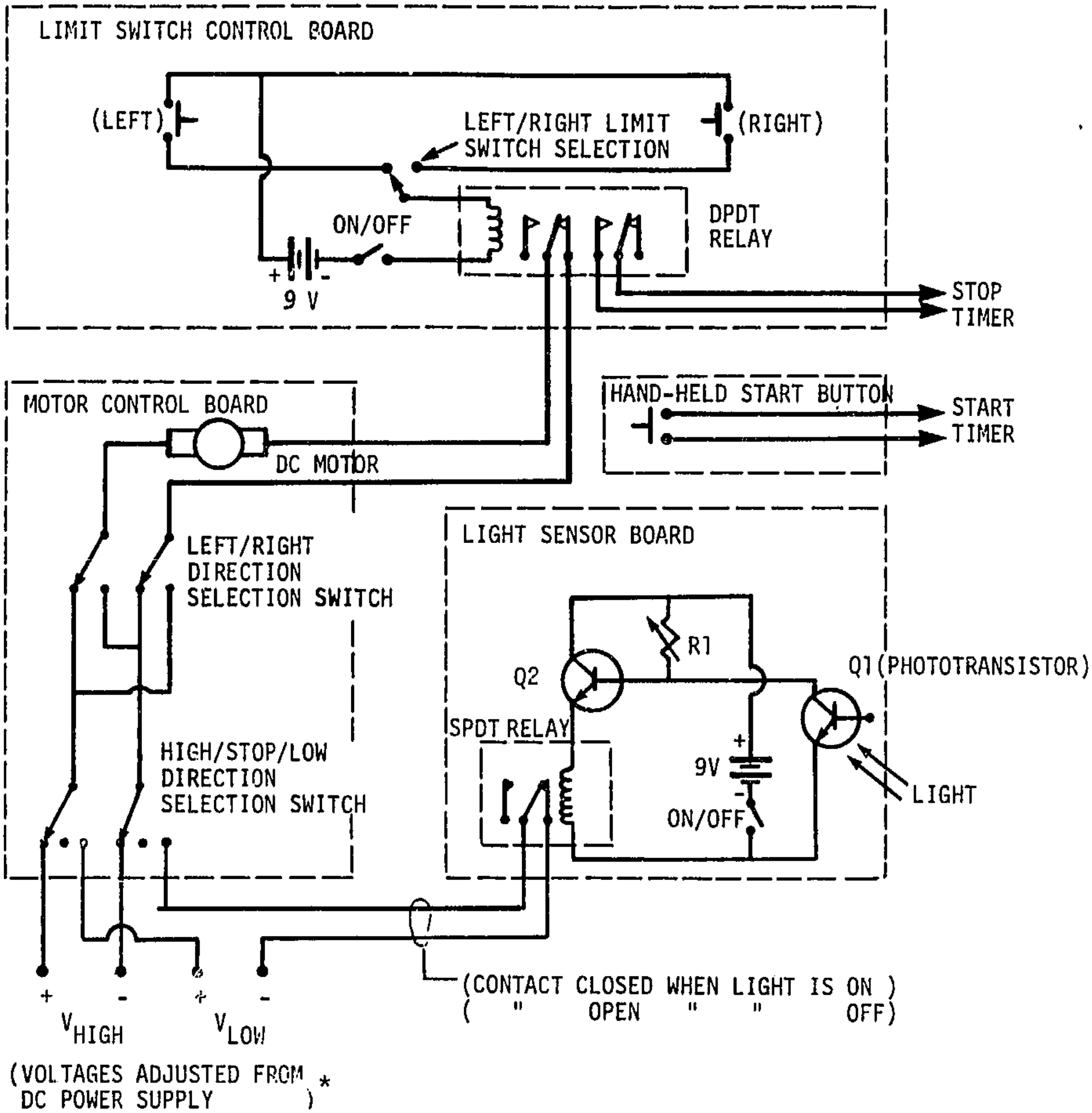

* Only the V_{low} voltage is controllable by the light.
V_{high} is used for a quick return to the starting position.

FIGURE D-7 Circuit details for the developed path tracking task through the thickness of the material, or insufficient metal deposition will result. If, on the other hand, a lower speed is used, an oversized weld bead or a wider cut will result. In either case, the operator will have to correct his tracking speed in order to get acceptable results. In a very similar manner, during simulation the operator will have to track at a constant speed in order to keep the target moving.

D.2.4. Experimental Design.

D.2.4.1. Positioning Task.

Two complete experiments were performed with the positioning task. Both were class IV experimental designs[D6] run with the same subjects. Due to the length of the experiments, only three subjects were tested -

(a) The first experiment was performed with the subjects directly viewing the task (no TV involved). Two factors were studied:

(A) Transmission delay as simulated by the computer in the feed forward path. Four levels of this factor were tested (0.0, 1.0, 2.0, and 3.0 seconds of delay).

(B) Positioning tolerance, varied by the size of the "STOP" button. Three different levels of this factor were tested (3/4", 1",and 1 and 3/4" diameter targets).

All subjects were exposed at all levels of all the factors (SxAxB design). To eliminate learning and carry-over effects, the order in which the treatments were presented to the subjects was randomized. The actual order for each subject is shown in Table D-2 (Numbered chips drawn off a bag were used for random number generation). All subjects were male, right handed, engineering graduate students with perfect vision. Before starting the experiments, they were briefed about the operation of the manipulator and the details of the simulation. They were permitted to practice at all the combinations of delay times and target sizes for about an hour.

Table D-1 Treatment numbering for Positioning Experiment #1

TARGET DIA. (inches)	DELAY TIME (seconds)			
	0.	1.	2.	3.
3/4	1	4	7	10
1	2	5	8	11
1 3/4	3	6	9	12

Table D-2 Order of treatment presentation to each subject for Positioning Experiment #1

ORDER	SUBJECT		
	S1 (K.I.)	S2 (U.D.)	S3 (A.D.)
1	10	9	2
2	9	3	6
3	1	2	12
4	2	12	8
5	6	1	7
6	11	4	5
7	3	10	9
8	12	7	4
9	5	5	3
10	4	11	11
11	7	8	10
12	8	6	1

During the actual experiment, each combination of the two factors was repeatedly tested 10 times. The first five were practice runs whereas the final five were averaged to give a single score for the treatment. It should be noted at this point that during each repetition the device of Figure D-2 was slightly reoriented to prevent the task from becoming rote. Several short rest periods were allowed throughout the experiment.

(b) <u>The second positioning experiment</u> was performed with the subjects viewing the task site through the TV monitor. The best possible TV picture was used. Direct sight was blocked by a black curtain as shown in Figure D-3. In this experiment only a single factor, the transmission delay, was studied. The positioning tolerance was kept constant by using only the 1" diameter target. To get more data points, seven levels of the single factor were now tested (0.0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 seconds). Again, in order to eliminate learning and carry over effects, the order in which the treatments were presented to the subjects was randomized. Table D-4 gives the order for each subject. All subjects were tested at all the levels of the single factor (SxA design). Ten repetitions at each level were performed, and again only the final five were averaged to give a single score.

An actual remote manipulation task would be necessarily performed with TV viewing. Therefore the second experiment is undoubtedly more realistic for the purposes of our study. The first experiment, however, (lasting about 3 to 4 hours for each subject) had to be performed so that the subjects would reach a consistently high level of experience with the manipulator. This was considered necessary since further experiments (with other remote manipulation tasks) were to be performed with the same subjects.

Table D-3 Treatment numbering for Positioning Experiment #2

TARGET DIA. (inches)	DELAY TIME (SECONDS)						
	0.0	0.5	1.0	1.5	2.0	2.5	3.0
1"	1	2	3	4	5	6	7

Table D-4 Order of treatment presentation for Positioning Experiment #2

ORDER	SUBJECT		
	SI (K.I.)	S2 (U.D.)	S3 (A.DeB)
1	3	1	5
2	6	7	3
3	2	3	7
4	7	4	1
5	5	2	4
6	1	6	6
7	4	5	2

D.2.4.2. Path Tracking Task.

(a) As was already mentioned, only an incomplete experiment was run with the initial path tracking task. Only subject S1 (K.I.) was used. Four levels of delay (0.0, 1.0, 2.0, 3.0 seconds) were tested, and the subject was asked to trace the test weld of Figure D-5 as accurately as possible in terms of speed, distance and orientation. The errors were recorded as well as the completion time.

(b) A complete set of experiments was planned with the developed path tracking task. The subjects were again viewing the task site through the TV monitor as in Figure D-3. A typical such TV view can be seen in Photo D-1.

Two factors were studied in this experiment (SxAxB experimental design):

(A) Transmission delay simulated by the computer in the feed forward path. Four levels of this factor were tested (0.0, 0.5, 1.0, 2.0 seconds of delay).

(B) Path tracking speed. Two levels of this factor were tested, 381 mm/min (15 inches/min) and 762 mm/min (30 inches/min). These two speeds were representative of typical manual welding or cutting speeds.

The developed welding simulation task permits selection of a tracking tolerance (by varying the aperture of the beam projection optics). However, initial experimentation suggested that if the tolerance was made very small, it would become necessary to increase the magnification of the TV camera (by using a zoom lens or several cameras) and would complicate these initial experiments. It was therefore decided to keep the tolerance constant using a light beam of 6.3 mm (0.25 inches) in diameter.

As in the previous experiments, the order of treatment presentation was randomized so as to avoid learning effects. Tables D-5 and D-6 give the actual treatment numbering and order of presentation. The experiment was again planned as an SxAxB design. Ten repetitions at each level were performed and only the final five were used for scoring purposes.

Table D-5 Treatment numbering for Path Tracking Experiment

TRACKING SPEED	DELAY TIME (SECONDS)			
	0.	0.5	1.	2.
(15 in./min)	1	2	3	4
(30 in./min)	5	6	7	8

Table D-6 Order of treatment presentation to each subject for Path Tracking Experiment

ORDER	SUBJECT	
	S1 (K.I.)	S2 (A.D.)
1	1	7
2	2	6
3	8	5
4	3	2
5	4	3
6	5	4
7	7	1
8	6	8

D.3 RESULTS AND DISCUSSION

D.3.1. Positioning Experiments.

The mean and the standard deviation of the completion times, over the final five repetitions, at each treatment and for each subject, are given in Table D-7 for experiment #1 and in Table D-8 for experiment #2. The mean will be used as the single score in our design.

For experiment #1, these scores are plotted in Figures D-8, D-9 and D-10, for the subjects S1, S2 and S3 respectively. For experiment #2, all the results are summarized in Figure D-11. For comparison purposes the average completion times in experiment #1, for the 1" diameter target only, are plotted for all subjects in Figure D-12.

From these figures, it can be readily seen that the effect of delay is very significant. In order to quantify our conclusions, however, analysis of variance was performed using the program ANOVA developed by I.B.M.[D5]. The obtained results are summarized in Tables D-9 and D-10. Using standard tables of the F-distribution[D6] we can readily conclude that:

(a) In both Experiments (1 and 2) the effect of delay is highly significant ($p<0.001$).

(b) In the case of Experiment 1, where both delay and positioning tolerance are studied, we see both a significant effect of tolerance itself ($p<0.05$) as well as a significant delay-tolerance interaction ($p<0.01$).

The latter effect may be attributed to the fact that tighter tolerances make the task disappropriately more difficult at the higher delay times. This can be supported by the observation that the subjects usually missed the smaller targets more often. When missing the target the arm was usually "locked" and the subjects had to backtrack and try the final approach again. This usually took longer at the higher delay times.

Table D-7 Results of Positioning Experiment 1

SUBJECT 1 (K.I.)

	B1 (3/4")		B2 (1")		B3 (1 3/4")	
	AVG	S.D.	AVG	S.D.	AVG	S.D.
A1 0	2.56	0.63	2.40	0.15	2.21	0.13
A2 1	14.03	2.51	12.69	0.92	15.78	1.41
A3 2	27.09	8.54	15.00	4.11	20.49	3.18
A4 3	40.12	16.98	32.34	8.18	23.67	2.86

SUBJECT 2 (U.D.)

	B1 (3/4")		B2 (1")		B3 (1 3/4")	
	AVG	S.D.	AVG	S.D.	AVG	S.D.
A1 0	2.59	0.40	1.86	0.68	2.06	0.42
A2 1	13.92	7.58	12.40	5.14	17.55	5.58
A3 2	23.40	6.36	22.32	7.02	22.37	9.23
A4 3	33.98	19.367	30.25	11.55	20.04	5.22

SUBJECT 3 (A. De B.)

	B1 (3/4")		B2 (1")		B3 (1 3/4")	
	AVG	S.D.	AVG	S.D.	AVG	S.D.
A1 0	1.93	0.60	1.61	0.33	1.35	0.14
A2 1	16.82	7.89	11.79	1.04	13.76	2.67
A3 2	21.26	7.50	24.92	9.80	25.36	10.95
A4 3	44.76	20.32	34.92	11.78	33.26	9.82

Table D-8 Results of Positioning Experiment 2

	S1 (K.I.)		S2 (U.D.)		S3 (A. De B.)	
DELAY	AVG	S.D.	AVG	S.D.	AVG	S.D.
0.0	4.55	1.18	4.88	1.78	3.00	0.63
0.5	17.61	7.47	13.11	4.76	13.93	7.61
1.0	28.99	4.93	24.36	9.8	19.85	6.80
1.5	36.72	14.81	30.98	15.16	17.73	10.71
2.0	45.81	7.43	25.28	4.68	47.74	32.93
2.5	44.56	23.13	23.38	4.148	43.12	29.72
3.0	51.69	25.91	51.31	10.41	47.38	13.51

Table D-9 Analysis of variance calculations for Experiment #1

LEVELS OF FACTORS

A	4
B	3
S	3

GRAND MEAN = 17.85695

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F-RATIOS
A	4504.63086	3	1501.54358	79.08
B	100.12605	2	50.06302	12.44
AB	227.28711	6	37.88118	5.07
S	39.42203	2	19.71102	
AS	113.92599	6	18.98767	
BS	16.10316	4	4.02579	
ABS	89.69079	12	7.47423	
TOTAL	5091.18555	35		

Table D-10 Analysis of variance calculations for Experiment #2

LEVELS OF FACTORS

A	7
S	3

GRAND MEAN = 28.38000

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F-RATIOS
A	4377.31787	6	729.55298	14.36
S	236.55296	2	118.27648	
AS	609.81848	12	50.81821	
TOTAL	5223.68896	20		

Table D-11 Developed Path Tracking Experiment

SUBJECT 1 (K.I.)

	SPEED LOW		SPEED HI	
	AVG	S.D.	AVG	S.D.
A1 0	57.384	2.824	30.479	2.196
A2 5	68.217	8.253	43.84	3.726
A3 1	79.821	10.790	52.341	8.385
A4 2	113.324	28.382	101.487	21.706

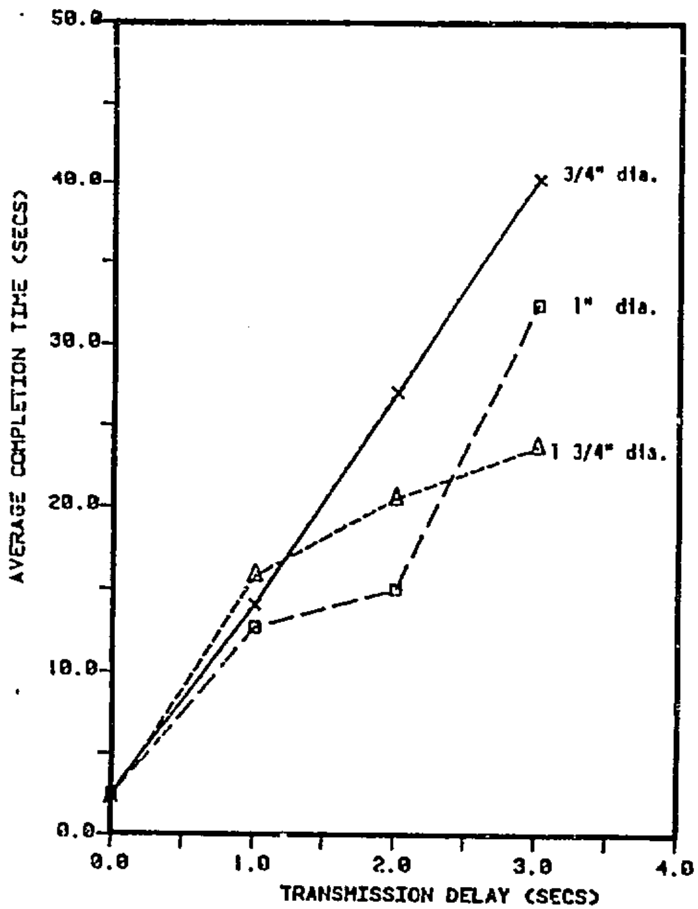

FIGURE D-8 Positioning Experiment #1

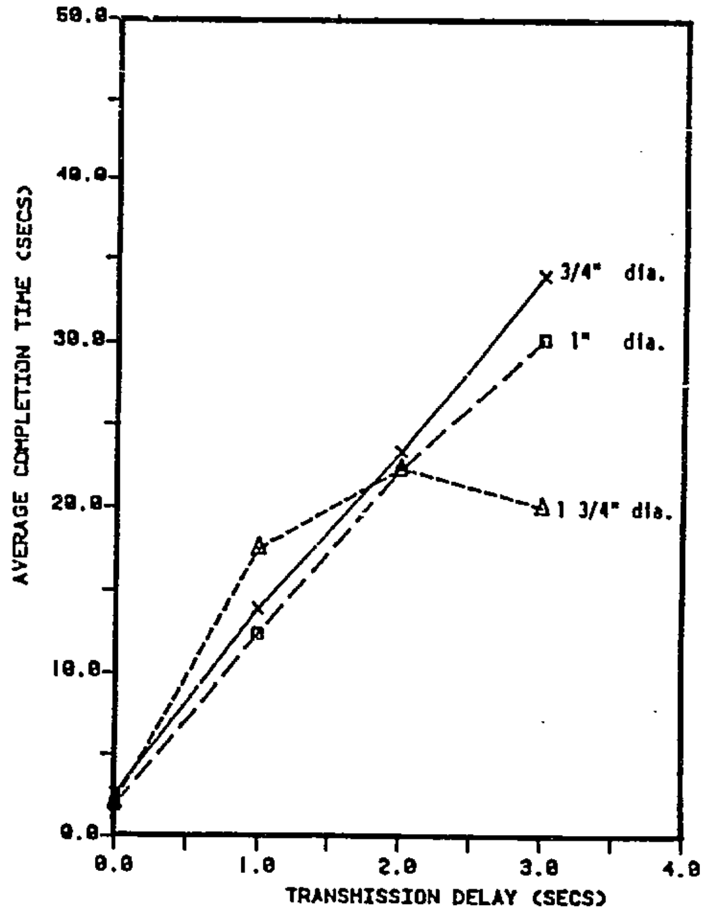

FIGURE D-9 Positioning Experiment #1

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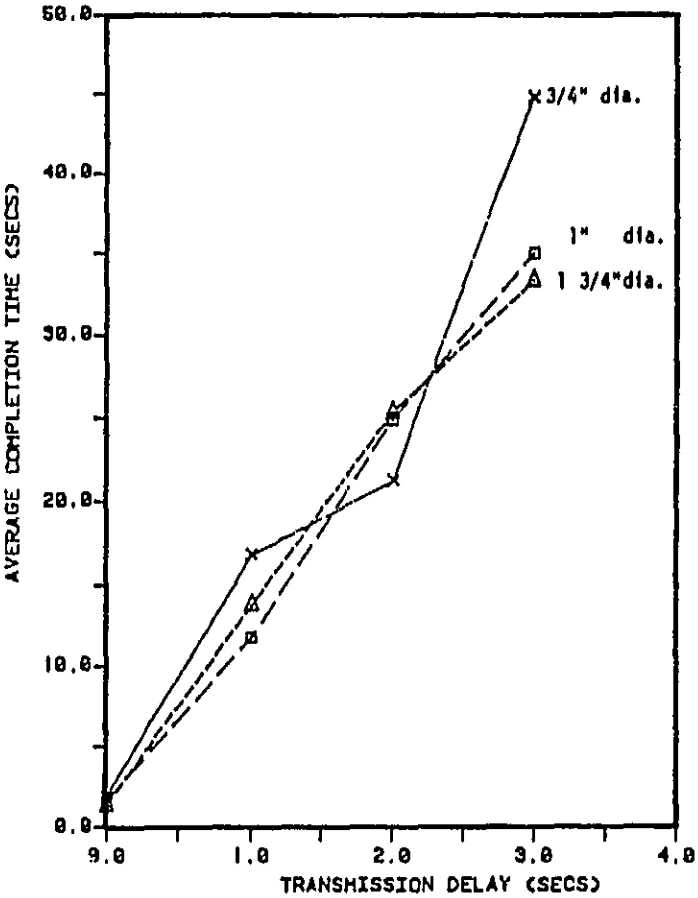

FIGURE D-10 Positioning Experiment #1

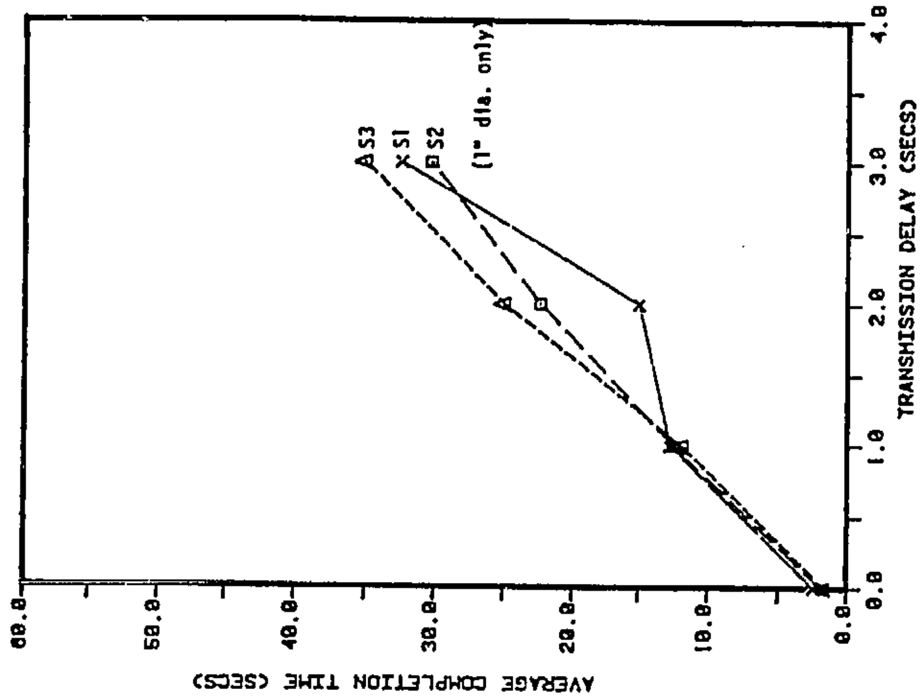

FIGURE D-12 Positioning Experiment #1

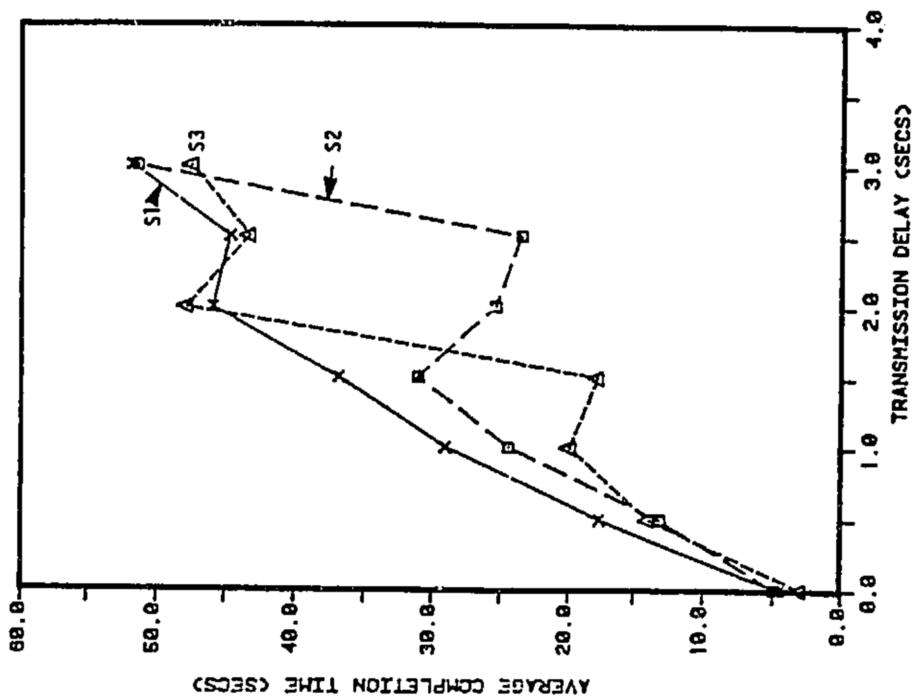

FIGURE D-11 Positioning Experiment #2

It should also be noted at this point that the subjects almost invariably used the same "golf player's" approach to the positioning task. Specifically, they all would first come to the closer area of the target with a continuous relatively fast move and then they would employ a much slower "move and wait" strategy for the fine positioning. This was especially true with the higher delay times. It is also interesting to note that when the TV was used, all subjects found the shadows cast by the manipulator very useful in giving them a depth perception.

D.3.2. <u>Path Tracking Experiments</u>.

The distance and orientation errors during the initial path tracking run with the first subject are shown in Figures D-13 and D-14, for delays of 0.0 and 2.0 seconds respectively. The performance of the subject seems to be better during the delayed mode operation. This can be attributed to the previously mentioned trade-off between completion time and accuracy. Furthermore, during the delayed mode the manipulator is under computer control, and according to the subjects felt somewhat more "stiff" and easier to keep at a given position and orientation.

As was already mentioned, no statistical analysis was performed, due to the lack of a single measure of performance comparable to the completion time of the positioning experiments. Instead, further complete experiments were designed using the developed path tracking task.

The complete set of experiments planned with the developed path tracking task is not yet finished. Only one subject has been completely tested and the current experimental results are summarized in Table D-11 and Figure 15. Very similar results were also obtained in the practice sessions performed with the other subjects. Experimentation will continue and further results will be included in (D7).

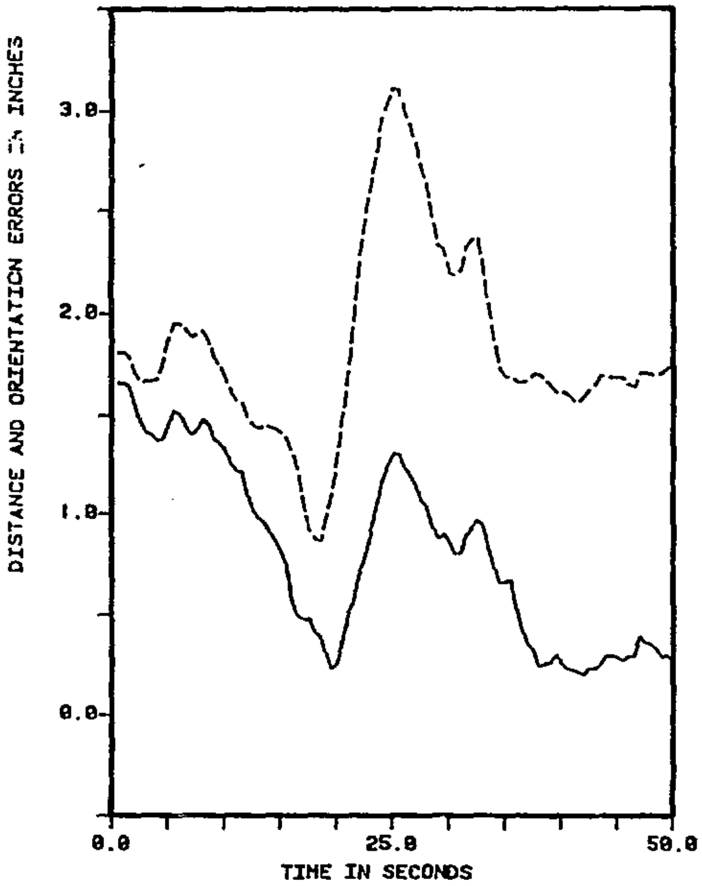

FIGURE D-13 Tracking Experiment #1
No delay

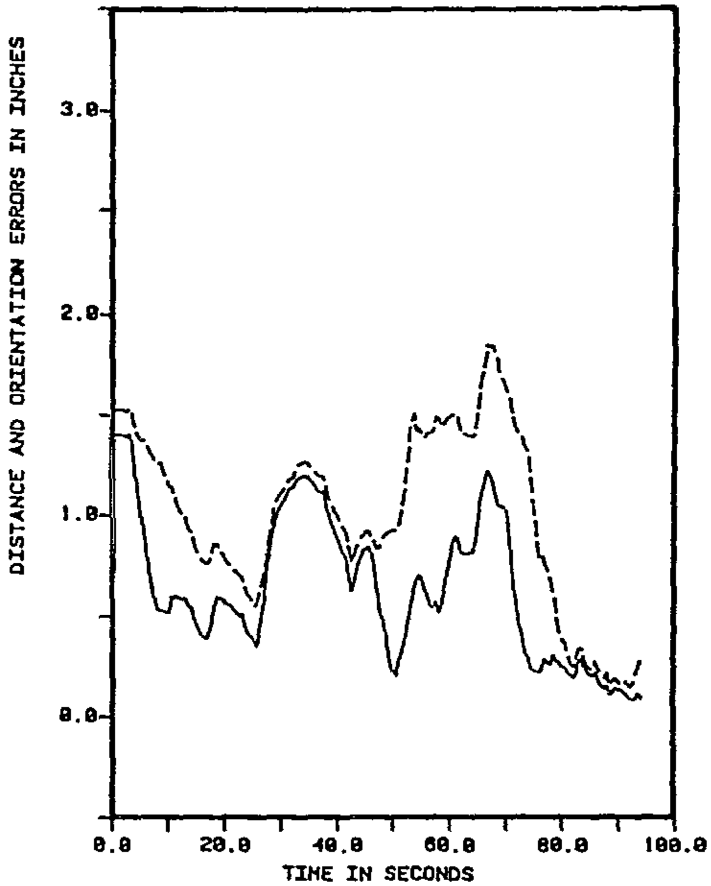

FIGURE D-14 Tracking Experiment #1
Delay of 2 seconds

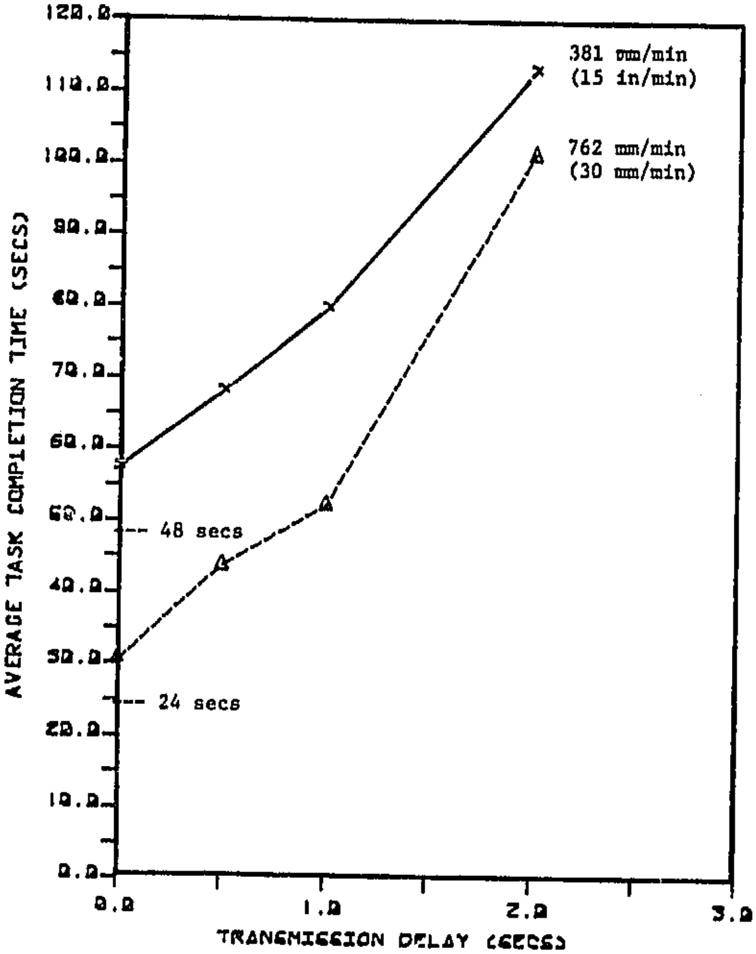

FIGURE D-15 Developed path tracking task

Although a complete statistical analysis cannot be performed at this point, it seems as if the effects of delay are not so pronounced in this case. This is mainly due to the fact that the task did not require any contact between the end effector of the manipulator and the "remote" site. This way, all the problems associated with "locking" of the arm are avoided and the proportionate increase of the task completion time is not as great as during positioning. The extra time is usually due to loosing the moving target and having to start tracking it again. This was happening more often at the higher tracking speeds and with the longer delay times, as can be verified from our raw data and observations during the experiment.

However, welding is more than following a moving target. Therefore, unless some means of avoiding spatter and wandering of the arc during the frequent starts and stops of the process are provided, it is rather difficult to perform actual high quality welding under these conditions. The required "wait-and-see" strategy may be acceptable for the case of assembly operations but is definitely undesirable during welding.

Therefore, it seems that the necessary continuity of path tracking, desirable for high quality welding, is difficult to achieve during remote manipulation, and computer controlled motion along a pretaught path is probably the best alternative.

REFERENCES TO APPENDIX D

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