REPORT NO. P66-127
HAC REF. NO. A6439

NASA CR 65402

CONTRACT NAS 9—4548

STUDY OF SPACE ENVIRONMENT FABRICATION AND REPAIR TECHNIQUES

[redacted]

FEASIBILITY REPORT

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MAY 1966

FACILITY FORM 602

N66 29077	
(ACCESSION NUMBER)	(THRU)
52	1
(PAGES)	(CODE)
CR-65402	15
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

AEROSPACE GROUP

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .50

Study of Space Environment Fabrication and Repair Techniques

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Feasibility Report

Contract NAS 9-4548

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ABSTRACT

The various joining systems that have been evaluated for potential application for fabrication of structures in an extraterrestrial environment are presented below in the ranking of the degree of their probable success:

1. Electron beam welding
2. Resistance welding or resistance brazing
3. Thermochemical brazing
4. Adhesive bonding
5. Solid state joining (diffusion bonding, pressure welding, and explosive bonding)
6. Gas fusion welding or brazing
7. Arc welding
8. Focused sunlight joining
9. Laser welding

A thorough evaluation of these candidate systems has been conducted utilizing laboratory and state-of-the-art investigations to determine the two systems that provide the highest potential. The joining systems that have been chosen are resistance welding and electron beam welding. In addition to collation of all data pertinent to the choice of these two joining systems, this report presents an evaluation of the available energy sources that may be exploited for application in a space environment. These energy systems are: 1) Solar cell/battery systems, 2) Fuel cell systems, and 3) Nuclear reactor systems.

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INTRODUCTION

This summary report presents the collation and analysis of all work performed through the month of April 1966 on the "Space Environment Fabrication and Repair Techniques" program, Contract NAS 9-4548.

The objective of this program is to study a broad spectrum of joining methods which might be applied to the repair and/or fabrication of spacecraft or other structures in a space environment. The two most promising methods, resistance welding and electron beam welding were selected on the basis of materials, design philosophies, logistics of currently contemplated missions and the abilities of astronauts to operate such systems. A feasibility demonstration of these two systems will be performed and reliability tests will be conducted in a simulated space environment. This report is organized into four basic sections covering: 1) Definition of System Requirements, 2) Joining System Analysis, 3) Evaluation of Energy Systems, 4) Recommendation of Two Processes for Feasibility Demonstration.

I. DEFINITION OF SYSTEM REQUIREMENTS

OPERATING CONDITIONS

Spacecraft Cabin and Lunar Environments

The atmosphere and temperature of the spacecraft cabin has been proposed as one similar to that experienced by man on earth. Thus the artificial cabin atmosphere would consist of 100 percent oxygen at 5 psia or 50 percent oxygen, 50 percent nitrogen at 10 psia. Temperature aboard the spacecraft should approximate 70°F. Consequently, it is anticipated joining problems would be encountered where the materials and combustion gases, employed in generation of heat would react with the cabin atmosphere. Another environmental factor relevant to development of successful joining techniques is the gravitational force within the spacecraft which can vary from nearly zero to one g. The critical disadvantage of a low gravitational force field concerns "levitation" effects on molten weld metal causing it to "ball-up" and literally float away during welding.

The environment postulated for the lunar surface is assumed to consist of an atmospheric pressure ranging from 10^{-6} to 10^{-9} Torr, or less, and temperatures from -250°F to +250°F. Temperature is anticipated to be a minor factor influencing the achievement of successful welding methods, but could have profound effects on joint reliability due to stresses induced by thermal cycling. However, a "hard" vacuum environment may result in problems of molten weld metal sublimation. Additionally, a low atmospheric pressure involves problems related to control of joining temperatures and waste heat dissipation. These joining problems may be minimized by steep thermal gradients, and small melting zones as may be achieved by electron beam welding. Resistance welding also provides an attractive feature of protecting the molten metal zone from vacuum during welding. Employing either welding method, the lunar vacuum provides volatilization of surface oxide films and elimination of re-contamination of cleaned surfaces. Welding problems associated with zero gravity, as previously described for the spacecraft cabin environment, also apply to the lunar environment.

Human Factors

In addition to basing the choice of a space joining method on metallurgical and environmental factors, pertinent human factors must be given consideration. Consequently, the candidate space fabrication techniques must be evaluated regarding their degree of practicality for operation in a space cabin or extraterrestrial environment. The following are salient features which influence the choice of potential joining techniques and the associated equipment:

1) Ease of utilization by astronaut (degree of complexity of the operation).
2) Mass and geometery of joining equipment.
3) Application to joining various structural geometries.
4) Reliability of weldments performed.
5) Maintenance and repairability of equipment.
6) Operator safety

The initial factor, ease of utilization, is of major significance since the astronaut may be limited in his degree of manual dexterity due to his cumbersome space suit and associated equipment. Additionally, it may be assumed the astronaut has developed only limited expertness and judgement in the operation of the joining equipment. Therefore the operation of the joining equipment should be aimed at a degree of simplification equivalent to "pushing a button".

Because of weight, storage and transference limitations of equipment deployed in space applications, the mass and geometry of joining equipment must be minimized. Fabrication of space vehicles may involve varying and complex geometries requiring joining equipment capable of following the various contours described by the space structure designs.

It is of a highly critical nature that the fabricated space vehicles be free of joining defects which would imperil their functioning. Hence a high degree of reliability must be incorporated into the joining process to prevent vehicle failure that would jeopardize the success of the space mission.

Low maintenance of the joining equipment is highly desirable since facilities for repair would not be available.

Of highest importance in the final analysis is the safety of the operator. Joining equipment must be chosen which will minimize danger to the operator, e.g. no usage of spontaneously combustible fuels for generation of heat energy, or liberation of gases that would "poison" the cabin atmosphere, minimization of shock and radiation hazards, etc.

MATERIALS AND GAGES

Materials for space environment fabrication have been chosen on the basis of their meeting three basic requirements. The first is their ability to be exposed to a space environment without incurring severe damage from corpuscular radiation, particle bombardment, and temperature ranging from approximately +250°F to -250°F. A second factor is their high strength-to-weight ratio and low bulk density. A final factor concerns their ability to be joined in space cabin and lunar surface environments. Based on these criteria, 2014 aluminum, 6Al-4V titanium, Inconel 718, and AZ80 magnesium have been chosen for investigation in this program. These materials and the range of gages to be joined are presented in Table I.

MATERIAL COMBINATIONS	GAGE, inches
2014-T6 Al-2014-T6 Al	0.012 to 0.032
6Al-4V Ti-6Al-4V Ti	0.030 to 0.090
Inconel 718 - Inconel 718	0.040 to 0.125
6Al-4V Ti-Inconel 718	0.030 to 0.090
AZ80A Mg-AZ80A Mg	0.060 to 0.080
AZ31 Mg-AZ31 Mg	0.060 to 0.080

Table I

II. JOINING SYSTEM ANALYSIS

ELECTRON BEAM WELDING

This process has probably the highest potential for use in an extra-terrestrial environment of all the joining methods evaluated in this study. The technology is fairly well understood, the process can be readily automated to simplify operator control, it is applicable to a broad range of materials including all of those involved in this study and because of the steep thermal gradients resulting from the high energy densities used, it is probably the most efficient process possible from the standpoint of energy utilization. The chief drawback is the bulk and mass of the power handling equipment required but this problem is under scrutiny by other contractors and should be resolvable.

Some of our early studies showed energy utilization efficiencies to be as high as 90 percent. This factor varies as a function of the thermal diffusivity of the material, in all probability. It also appears to vary in proportion with the specific energy input, that is, high specific energy input welding is more efficient than lower energy welding. Work is still being performed to verify these hypotheses. Some additional work is also being performed to evaluate the relationship between accelerating voltage and the depth of penetration of fusion in various metals. This subject is particularly confusing because of the complex interrelationships of power, speed of welding and focus. Extensive effort has been directed toward this problem in an attempt to resolve these relationships so that a clear definition of the lowest possible voltage, power and focus current necessary to make satisfactory welds in the requisite metals and gages can be determined. The net effect of this effort is to minimize the mass of the system from the standpoint of insulation, transformer size, weight, etc.

Tests have been performed to determine the factors of gun geometry that significantly control the power output of the electron gun. This study was done to obtain a means of controlling the gun to produce both constant power and constant specific energy.

Other tests have been directed toward the determination of the relationship of focus coil current and accelerating voltage. Preliminary work showed this to be an essentially linear relationship. Additional study is still being made.

It is believed that the potential universal applicability of electron beam welding, its simplicity of operation and high efficiency make it one of the most practical processes for further development.

RESISTANCE WELDING

Resistance welding is a joining method that functions by fusion or diffusion bonding of the metals to be joined utilizing the thermal energy generated by their resistance to the conductance of electricity. This process has a high potential for application to space joining due to two desirable characteristics. One factor pertains to the very short welding energy pulse times that are employed, thus minimizing the time during which hot metal might be exposed to the space vacuum. The second advantage is that the fusion zone is generated in an area which is virtually surrounded by solid metal. This effect thus shields the molten metal from the vacuum. The net effect of these two characteristics is the prevention of problems related to reduced gravity and vacuum and the maximization of thermal efficiency.

Resistance welding for space fabrication is further enhanced by employing a precision dynamically controlled microwelder marketed by Hughes Aircraft Company. The system, set up for opposed electrode spotwelding utilizes an 800 ampere battery pack to achieve square wave rise and decay at a constant welding voltage pulse. Additionally, the Hughes MCW-550 microwelder weighs 65 pounds, complete. A flight model system with the same power output could probably be built to a weight of 30 to 40 pounds. The weight probably could be reduced below 25 pounds for a system utilizing the spacecraft's batteries and charging system. Hughes is presently developing a 2000 ampere system which might significantly enhance the capability of this joining method. The disadvantages of this process are that the faying surfaces must be free of oxides and other contamination, fabrication is restricted to lap joints, and a clamping force must be applied to both sides of the joint or from one side against a rigid backup.

Investigations were initiated in January to evaluate the potential of resistance welding as a joining method for space environment fabrication. All work was conducted with the Hughes MCW-550 microwelder which utilizes a battery pack as the source of pure direct current energy. The unique characteristic of the welder is that it provides constant voltage rather than constant current and thus eliminates overheating during welding which causes metal vaporization (blowouts) and associated detrimental effects. The welder can deliver up to 800 amperes at 1.99 volts which can result in a 16 Kilojoule pulse at the 10,000 millisecond pulse duration.

The first phase of the investigation was to achieve spot welds in the metals of interest to this program. Spot welds were successfully achieved in 321 CRES stainless steel, 6 Al-4V Titanium and René 41 with gages ranging between 0.016 and 0.032 inches. In all instances the weldments were characterized by "nugget" shapes formed from solidification of a "molten plug". Both AZ31 magnesium and 2014 aluminum specimens were sandwiched between two pieces of 304L stainless steel during welding. The effect of this practice was to liberate heat in the two pieces of stainless steel because of their high resisitivity. The metals sandwiched between these sheets were heated by conduction from the steel until their resistance became high enough to generate a significant amount of heat by themselves to achieve fusion. Aluminum welded by this technique resulted in weld-metal expulsion and surface cracking. To develop metallurgically sound joints with aluminum, zinc or an aluminum - 13 wt. percent silicon alloy rolled to 0.003-inch gage were employed as a filler metal. Resistance brazed joints were successful with both filler metals; however, the aluminum alloy provides the advantages of achieving higher joint strength at ambient and elevated temperatures and will not volatilize in the vacuum of outer space. Overlapping resistance spotwelds were similarly achieved for the aforementioned metals employing the same joining techniques. The electrodes employed in the majority of this work were copper or copper-beryllium.

Seam welding was conducted by modification of the equipment to provide for two revolving, cylindrical, copper electrodes. Initial seam welding efforts were conducted on 0.010, 0.020, and 0.030-inch gage 4130 steel sheet. Although most attempts were successful in achieving weldments, they were often characterized by intermittent weld-spots along the surface. It was presumed that this effect was caused by either the copper wheels sticking to the steel sheet or because of discontinuous transmission of current. A 0.001-inch thickness of chromium was plated to the copper wheel contact surfaces to prevent plastic deformation of the copper which had caused it to stick to the base metals. Although this innovation has reduced the intermittent seam welding effect, it has since occurred when chromium plated wheels were employed. Various weld schedules have been attempted to reduce or eliminate intermittent seam weldments. Those schedules that were most successful were with a clamping force ranging from 16 to 20 pounds for most metals welded.

The latest seam weldments were accomplished with 0.020-inch 2014 aluminum, 0.016-inch AZ31 magnesium, 0.020-inch René 41, and 0.020-inch 6Al-4V titanium sheet. Photomacrographs of the weld surface, revealing the seam weld characteristics, and photomicrographs of weld cross sections are presented with the weld schedules employed in Figures 1 through 4. Although the 2014 aluminum weldments were successfully achieved with the 87 wt. percent Al-13 wt. percent Si filler alloy, AZ31 magnesium weldments employing this filler alloy were extremely brittle. Consequently, subsequent magnesium weldments did not utilize the aluminum filler alloy, but were, nonetheless, highly successful as revealed in Figure 2b. Welding of 6Al-4V titanium sheet resulted in incomplete fusion across the joint interface. Because of aluminum's solid solubility in titanium, the aluminum-silicon filler alloy (0.003-inch gage) was employed as a braze alloy. As shown in Figure 3b the joint appears to be successfully brazed. Although the René 41 specimens appeared welded from the surface characteristics, the cross-sections revealed incomplete fusion as illustrated in Figure 4b. It is believed that this problem will be eliminated by increasing the clamping force from 12 pounds to 20 pounds. Due to the continuing success achieved with resistance welding of the candidate materials, this

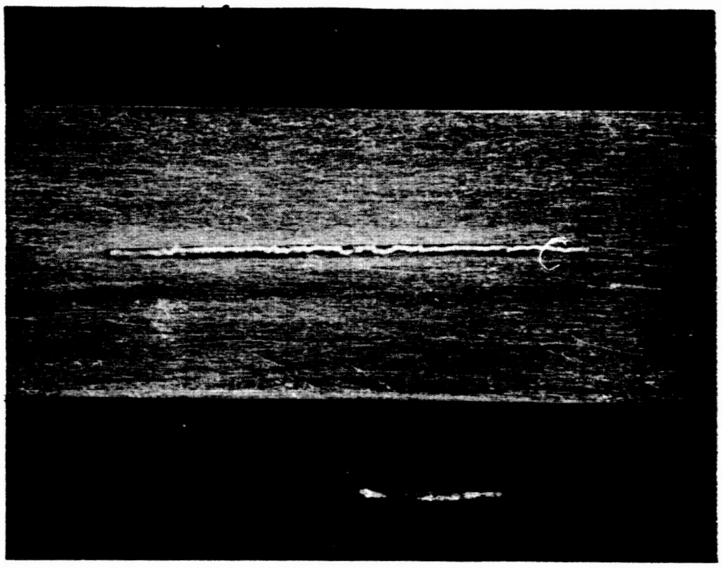


Figure 1a. Seam weld on surface of 2014 Aluminum. Weld schedule: 1.99 volts, 20 lbs. pressure, 30 inches/minute speed. 1.4X

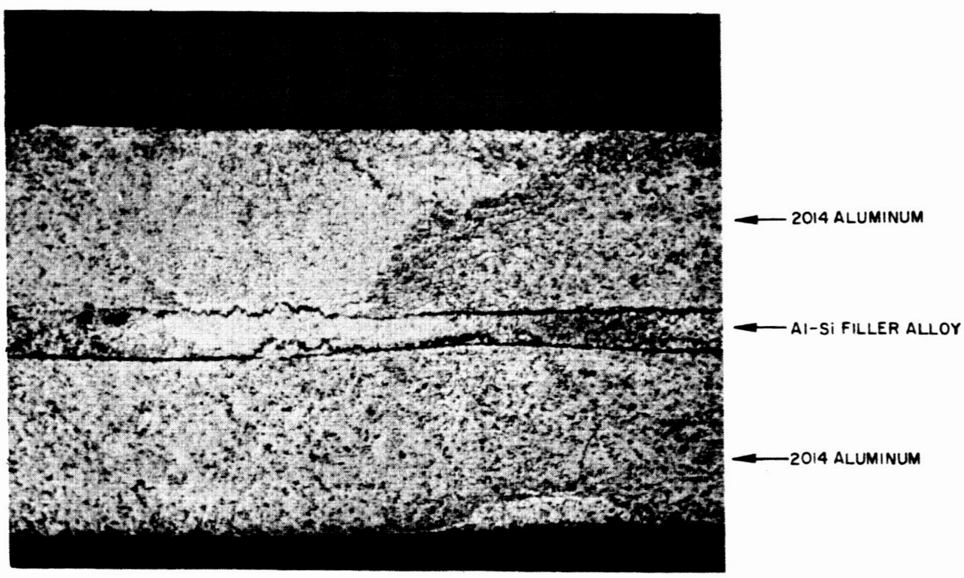


Figure 1b. Photomicrograph of cross-section of 2014 weldment revealing Al-Si Filler Metal brazed to parent metal Etchant: Keller's 50X

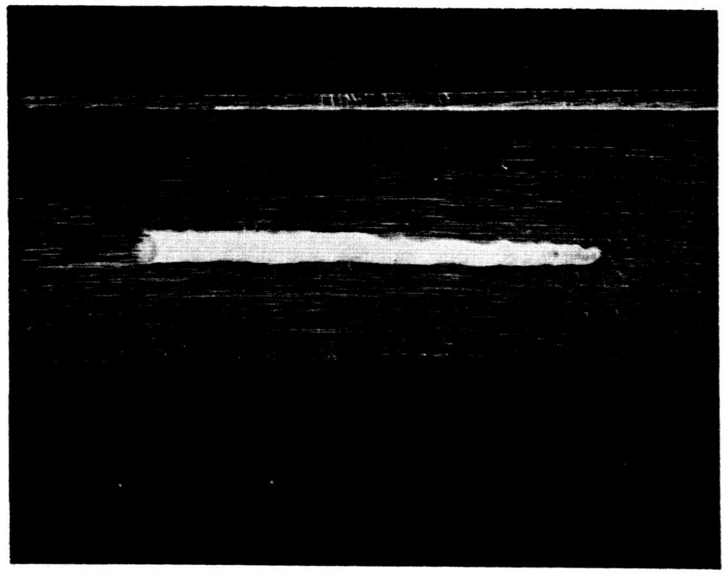


Figure 2a. Photomacrograph of AZ31 Magnesium seam weld. Weld schedule: 1.99 volts, 20 lbs. pressure, 30 inches/minute speed.
1.4X

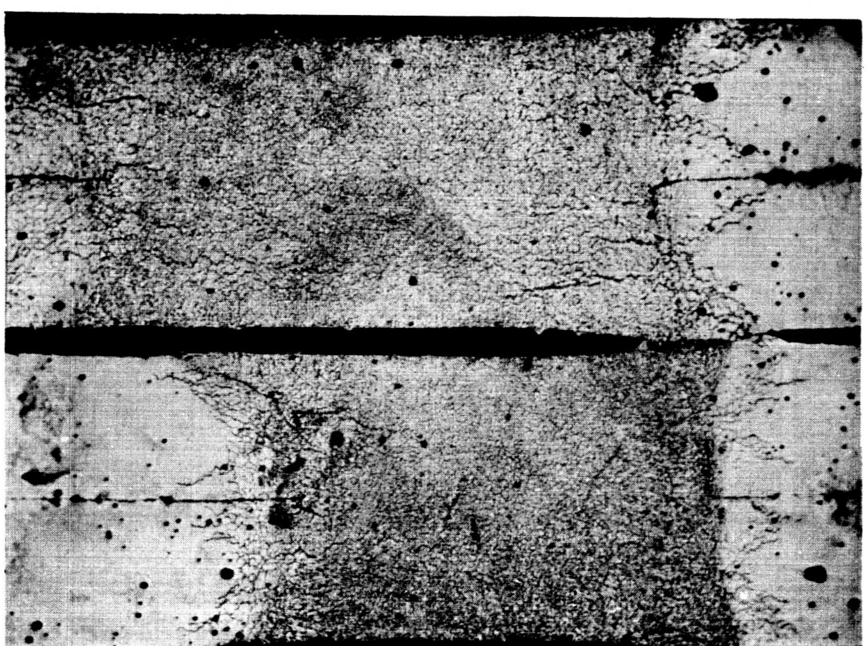


Figure 2b. Photomicrograph of cross-section of AZ31 Magnesium Welds. 10 percent tartaric acid etchant.
50X

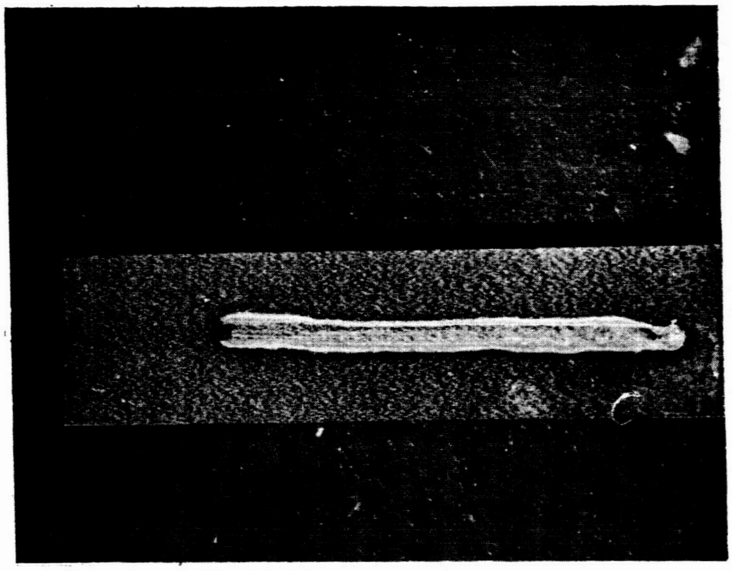


Figure 3a. Photomacrograph of 6Al-4V Titanium seam weld. Weld schedule: 1.99 volts, 20 lbs. pressure, 30 inches/minute speed. 1.4X

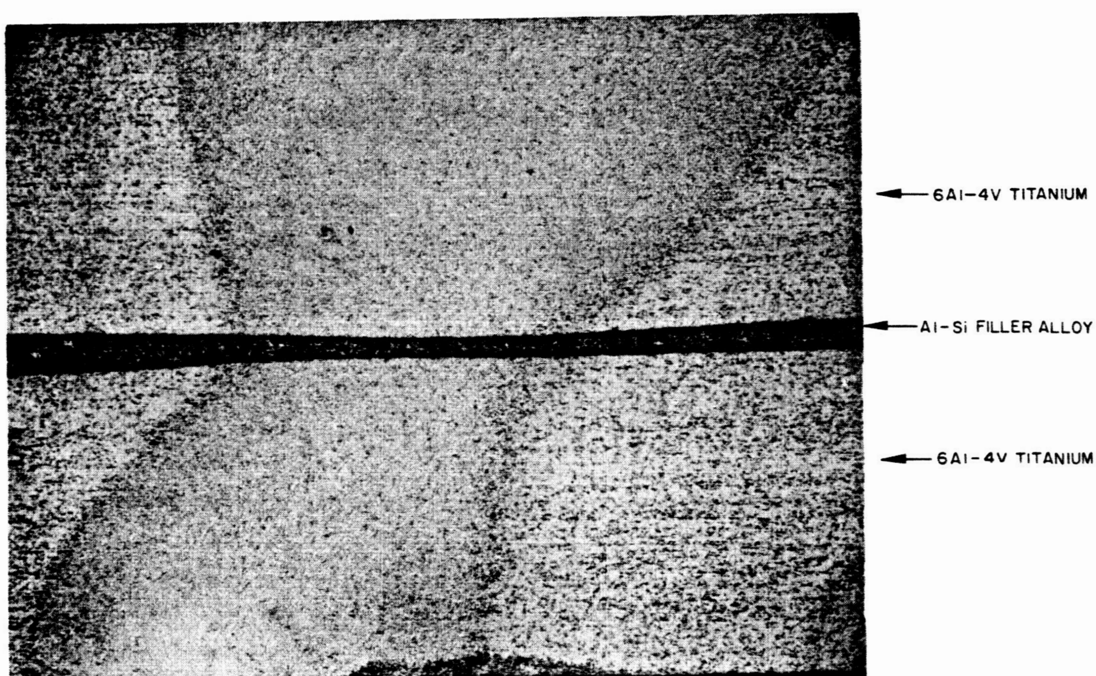


Figure 3b. Photomicrograph of cross-section of 6Al-4V Titanium joint with Al-Si Filler alloy brazed to Titanium. Etchant: 3 percent HF-6 percent HNO_3 bal. H_2O. 80X

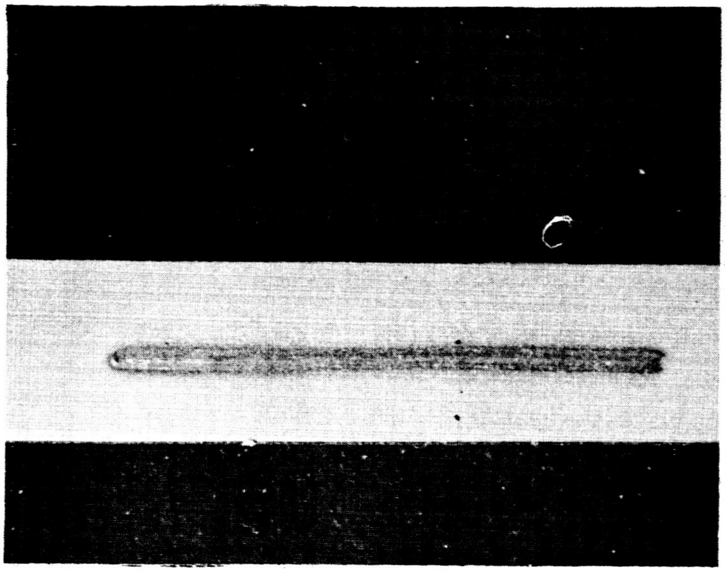


Figure 4a. Photomacrograph revealing Rene' 41 seam weld. Weld schedule: 1.99 volts, 12 lbs. pressure, 30 inches/minute speed. 1X

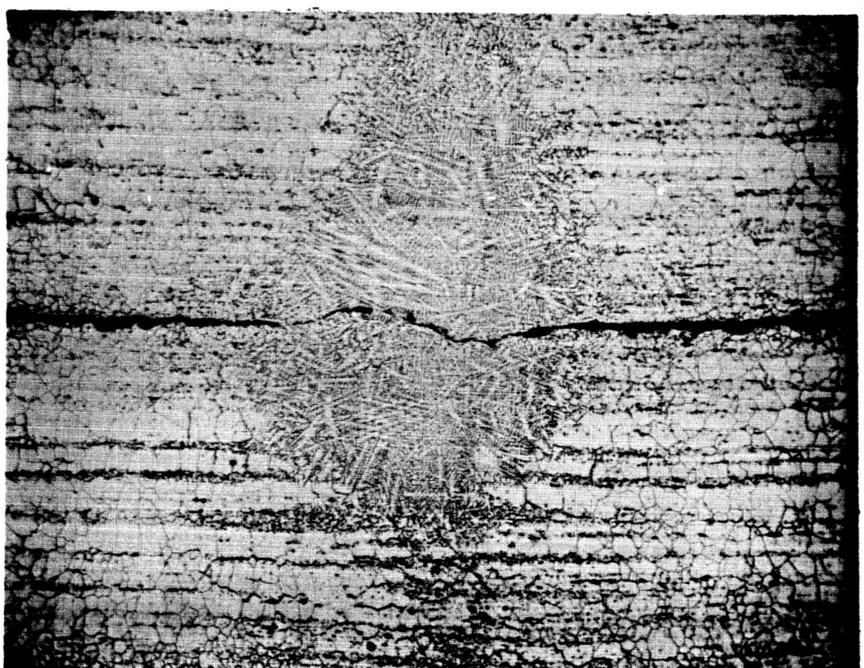


Figure 4b. Photomicrograph of cross-section of Rene' 41 weld, (Note incomplete fusion of the "nugget" across the joint). 10 percent tartaric electrolytic etch. Etchant: Electrolytic, 10 percent tartaric. 80X

fabrication method has been chosen as one of the two joining techniques for engineering development and test under simulated space conditions. Future work on resistance seam welding shall be directed to seam welding of the candidate materials in heavier gages with reduced welding speeds to maximize the quantity of energy available for welding.

THERMOCHEMICAL BRAZING

Thermochemical brazing is a joining method which employs exothermic reactants to provide sufficient heat to melt braze filler metal and cause it to wet and bond the adjoining surfaces. Exothermic reactants often are a thermit type composition composed of a metal oxide and a more active metallic reductant such as vanadium pentoxide and boron respectively. The reactants are pre-placed in a position adjacent to the metals to be brazed and ignited by a resistance wire. Often the products of the exothermic reaction can act as a brazing flux when properly placed. Although there are a broad range of reactants available for use in air at ambient pressure, there is only one system that has proven successful in a vacuum. This system utilizes boron and vanadium pentoxide. It is generally blended with some aluminum which attenuates the violence of the reaction but is itself fully oxidized in the process. The reactants are used only to liberate heat. Usually they are isolated from the braze joint and filler alloy by some form of a metal barrier shield which also serves to locate the pieces to be brazed. Cleanliness and tolerance requirements for fit of the components to be joined are as critical for exothermic brazing as for any other brazing process.

From the foregoing information, it is easy to see that exothermic brazing systems must be completely pre-engineered. The reactant blend, quantity of reactants, joint design and fit-up tolerances must all be determined in advance so that field fabrication becomes merely a job of erection, assembly and firing of the exotherm. This would not particularly tax the work capability of an astronaut except if any of the parts were damaged in transit or did not fit exactly. This is a distinct possibility. Further, it would be extremely difficult to engineer a repair kit that would be suitable for all types of damage that are conceivable.

Essentially, the need for thorough pre-engineering means that the system does not allow a sufficient degree of field versatility which would be highly desirable.

The exotherm material is compacted as wafers, discs or pellets which must be heated to a temperature of 800-1000°F by a resistance heated bridgewire before they will ignite. This assures a degree of safety for cabin storage during transit. Because of the nature of the redox reaction involved, there are virtually no fumes, vapors or toxic compounds evolved. About the only vapor emitted during the firing of an exothermic brazing kit is water vapor which comes from water adsorbed on the surface of the pellets and the insulator. This is harmless and can be controlled to some extent by proper vacuum drying and bagging techniques.

No work has been done to evaluate the effect of highly oxidizing atmospheres such as a spacecraft cabin atmosphere upon the ignition, propagation rate and violence or extent of completion of the redox reaction. This area should be investigated if additional work is to be done on exothermic brazing.

Another problem area is the lack of suitable brazing alloys for magnesium or aluminum. No work has been done with exothermic brazing of magnesium either in ambient air or a vacuum. A limited amount of work has been done with some zinc base aluminum brazing alloys with very limited success. NARMCO suggests the use of exothermically cured adhesive systems for these metals.

None of the systems tested have been fired in very hard vacuums. To date, firings have been made at a pre-firing chamber pressure of 10^{-6} torr. The rate of propagation of the reaction at lower pressures would have to be evaluated.

Several tooling concepts were proposed in the NARMCO report. The most promising of these involves a "piano hinge" sort of design. In this design, the sheets to be joined fit together like a piano hinge and a hollow rod containing the exotherm with a braze alloy coating on its outside is inserted as a hinge pin. Firing the exotherm liberates heat which is conducted through the tubing wall and melts the braze alloy, causing it to flow into the hinge joint surrounding it. The concept is reasonable except that it restricts the design of structures and could generate problems with vapor loss of the braze alloy, improper wetting, etc.

NARMCO made a demonstration firing of a tube joint package. Two pieces of 1/2 inch OD stainless tubing were brazed using a close fitting shroud to locate the tubing, hold the brazing alloy and isolate it from the exotherm. An acceptable, leak tight joint was produced although metallographic examination revealed some holidays in the braze.

From the information collated and evaluated on thermochemical brazing it has been determined that this joining technique does not presently provide a high potential for universal application in a space environment for joining of the metals considered in this program. Therefore, further consideration shall not be given to this joining method.

TUNGSTEN ARC WELDING

Arc welding is a fusion welding process where heat is provided by an electric arc and the materials to be welded may be protected from oxidation by an inert gas. Tungsten arc welding was chosen as a joining technique to be investigated for space fabrication because of its minimal requirements for specialized equipment, low weight and volume. Because of the limited information available on metal-arc welding under reduced environmental pressures, initial work was directed to operation of a tungsten arc in vacuum. It was anticipated that at low pressures a "swelling of the arc" would occur causing the power in the arc to dissipate and the heat input to the workpiece to spread, making the formation of a molten pool difficult.

Laboratory testing was conducted employing a 1/2 cubic foot vacuum chamber, and a Miller Model SR-15GHC DC power cupply with a 1/16 inch diameter tungsten electrode. Vacuum chamber pressures of less than one-inch of mercury were achieved with a large mechanical pump while a DC reverse polarity arc was drawn on the test piece for known periods of time. The objective of these tests was to determine whether a stable arc could be maintained for a long enough period of time to achieve any significant degree of fusion of the base metal. Fifteen to twenty spot weldments were made in AISI Type 304 stainless steel, titanium and aluminum. Measurements of the electrical parameters of the arc, i.e. voltage, current and time were used to calculate total energy input. The theoretical energy required to achieve the observed amount of fusion was determined by measuring the volume of the fusion zone. The thermal coupling efficiency was then established by determining the ratio of the input energy to that utilized to achieve the weld. The results of this investigation revealed very poor energy utilization and unsatisfactory metallurgical quality of the fused weld spots. These results lead to the conclusion that tungsten arc welding has a low potential for space fabrication applications and future work shall not be conducted.

ADHESIVE BONDING

Adhesive bonding provides some attractive features for potential application for outerspace and space cabin environment fabrication. These features include:

a) Fitup tolerances at mating surfaces may be liberal.
b) Dissimilar materials including non-metallics can be joined.
c) Energy sources available in a space environment may be utilized to supply heat for curing or processing bonded joints, e.g. concentrated solar energy.

However, a further evaluation of adhesive bonding has revealed some unattractive features that may limit its application in a space environment. The most serious problem of adhesive bonding for fabrication of space structures involves long curing cycles that may require large quantities of energy. Up to 40-50 kilojoules per inch of bonded joint length may be required to compensate for conductive heat loss in metal structures. Curing cycles may vary from 24 hours at 75°F to one hour at 300°F. The heat sources considered to supply the required heat for curing are solar collectors, electric or thermoelectric sources, and thermal energy from gaseous combustion. Although electric and gaseous combustion do provide a sufficient and continuous supply of energy, solar collectors do not. Solar collectors may provide thermal energy only for periods of time when the bonded structure is exposed to sunlight. Thus the curing time would be limited with solar collector heating. Additionally, rather large, collectors and complex sun tracking equipment may be required to provide enough heat to achieve bonding. A second problem is related to the space vacuum causing outgassing of plasticizers and short chain polymers which could damage adjacent optical equipment and passive thermal control surfaces. Another difficulty that may be anticipated is damage of adhesive bonds by changes in temperature ranging from +250^{o}F to -250^{o}F which would be experienced when the bonded structure was exposed, alternately, to direct sunlight and the darkness of space. Such thermal cycling could cause bond failure from stresses introduced by the differences in thermal expansion of the adhesive and bonded metals.

A final consideration of adhesive bonding pertains to their exposure to temperatures in excess of 500^{o}F. Most adhesive bonds retain reasonable strengths up to this temperature. Consequently only those materials that see service below this temperature can be considered for adhesive bonding fabrication, e.g. aluminum, magnesium and titanium. Inconel 718 is to be employed for applications over a temperature range of 600^{o}F-1300^{o}F thus precluding the use of adhesive bonding for fabrication of structures composed of this material.

The aforementioned limitations of adhesive bonding for space structure fabrication indicate a need for further development directed specifically at application in a space environment before it may be considered competitive with alternate joining methods.

EXPLOSIVE WELDING

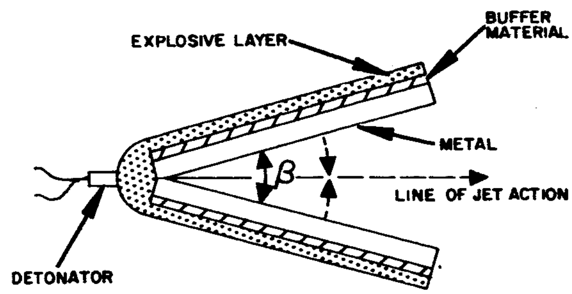
Explosive welding may be defined as a solid state joining technique where welding is accomplished by plastic flow at the mating surfaces. Metallic bonding is achieved by atom-to-atom contact of the plastically deformed surfaces. The majority of explosive bonding technology has been applied to joining flat plate. Plastic deformation employed to produce bonding is achieved by igniting explosive materials placed on opposite sides of the plates to be joined which creates a high energy shock wave that causes the faying surfaces to be joined under high impact. As illustrated in Figures 5 and 6, the relative positions of the flat specimens to be joined assume an angle to enable surface films to be extruded in front of the bonding surfaces during welding. Because of this feature, pre-bonding surface cleanliness is not of major significance in attaining metallic bonding. The specific advantages of explosive bonding are: 1) brittle welds between dissimilar metals caused by formation of intermetallic compounds may be eliminated, 2) there is no heat affected zone which would also degrade the material properties. In addition to these advantages, explosive bonding is unique in that the weight penalty versus energy for joining is exceptionally attractive. However, for application in a space cabin or outer space environment, explosive bonding has the disadvantage that weldments other than a flat geometery would probably require rather extensive tooling resulting in an over-all weight penalty. A second and more critical problem is the possibility that the products of combustion would jeopardize the space cabin life support system due to the large quantity of CO_2 that is liberated upon ignition of the explosive. It appears that the disadvantages of the process outweigh its merits.

DIFFUSION BONDING AND PRESSURE WELDING

Diffusion bonding may be defined as a solid state joining technique achieved by simultaneous application of heat and pressure to two well-cleaned metal surfaces. This must be done over a period of time sufficient for atom movement to form a reasonably continuous crystal lattice across the joint interface. Pressure welding is similar to diffusion bonding except that the applied pressure is sufficient to cause plastic flow at the mating surfaces. The plastic flow is sufficient to remove oxide films and allow atomic relocation to vacant lattice sites resulting in the formation of an atomic metal bond to form across the interfaces.

Although these solid state joining processes present attractive features for terrestrial applications, there are serious shortcomings for application to space environment fabrication. One limitation pertains to

Figure 5. Schematic of angular arrangement of components for explosive welding together flat plate.



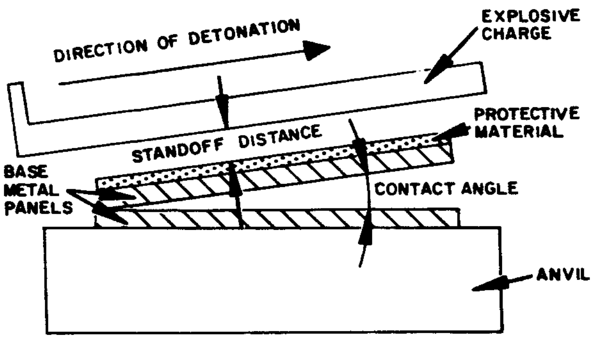


Figure 6. Components of explosive welding setup.

the requirements for bulky and complex tooling to be employed in space to attain the required pressures for bonding. A second consideration to be scrutinized is the relatively large quantity of heat required to achieve bonding of metals such as titanium and nickel base alloys. These thermal requirements may necessitate large and cumbersome power equipment. A final and important limitation to diffusion bonding in space is that the joints that may be achieved are severely geometry-limited. The majority of bonds accomplished on earth have involved the joining of flat plates; however, tube-to-sleeve joints may be achieved by shrink-fits caused by differences in thermal expansion of the metals employed. Because of the aforementioned problems associated with diffusion bonding and pressure welding for fabrication in a space environment, the joining methods shall not be further investigated.

GAS WELDING

Both fusion welding and brazing may be achieved by the heat of combustion released by burning oxygen and hydrogen. The combustible gases might be obtained from an electrolytic dissociation of water. Combustion can be sustained in a simple oxy-hydrogen gas torch. The chief advantages of this system for space fabrication are its simplicity, and its thermal efficiency realized by 85-90 percent utilization of the electrical energy input as thermal energy available for welding. The water required for generating the fuel gases could be obtained from urine purification. The major space joining problems associated with this system are the fairly high degree of skill and dexterity required for successful welding and the low weld coupling efficiency. Although torch brazing does not require a high degree of skill, problems associated with flux volitization and balling-up of the filler metal may be caused by the extra-terrestrial environment. Preliminary vacuum stability tests of an oxy-hydrogen flame revealed only a lengthening of the flame rather than fanning-out or flaring out.

Initially, a brief research study was conducted to determine the characteristics of an oxy-hydrogen flame in a low pressure environment. Eight combinations of gas pressure and mixture ratios were tested in two replicates. In all tests, flame extinction occurred at a pressure of approximately 2-1/4 to 3-1/4 psia. A literature search determined that for the oxygen-hydrogen system, the minimum ambient pressure which will sustain combustion is about 2 psia. This information correlated well with the experimental results. Subsequent efforts were conducted with a torch design that permitted combustion in a confined chamber at 15 psia and consumed approximately 0.01 standard cubic feet of gas per second.

Design details of the experimental torch which was fabricated for a demonstration of the feasibility of space welding using oxygen and hydrogen gases are shown in Figure 7, a reproduction of HAC drawing number X3031058.

The head consists of a 2.0 inch diameter copper bar with a 0.215 inch diameter hole drilled through it. Two 0.050 inch diameter holes drilled at 45° angles to the 0.215 inch hole are used for feeding oxygen and hydrogen gases into the combustion chamber. A 1/8 inch diameter copper tube was brazed into each of the feed holes to permit coupling to the gas feed system.

Five torch tips were made from standard AN815-4S fittings. Each tip was fitted with an insert made of 347 CRES. The tip inserts varied in size from 0.032 to 0.125 inch diameter.

Ignition of the gases was accomplished by use of a V24-1 miniature spark plug. Power to the spark plug is supplied by a 110 V A.C. transformer.

A 2-1/2 ft x 2 ft x 2 ft vacuum chamber was fabricated for testing the torch. Hydrogen and oxygen gases were supplied from separate "K" bottles. Gases flowed through two calibrated 0-3- PSIG gages. A Brooks flowmeter was placed downstream of the gages but testing showed the flowmeters were unable to accommodate the required volume of the gases. Two Skinner 110 V.A.C. solenoid valves were used as the fire valves. To allow for visual inspection of testing, two plexiglass windows were installed, one at the top and one on the side of the test chamber.

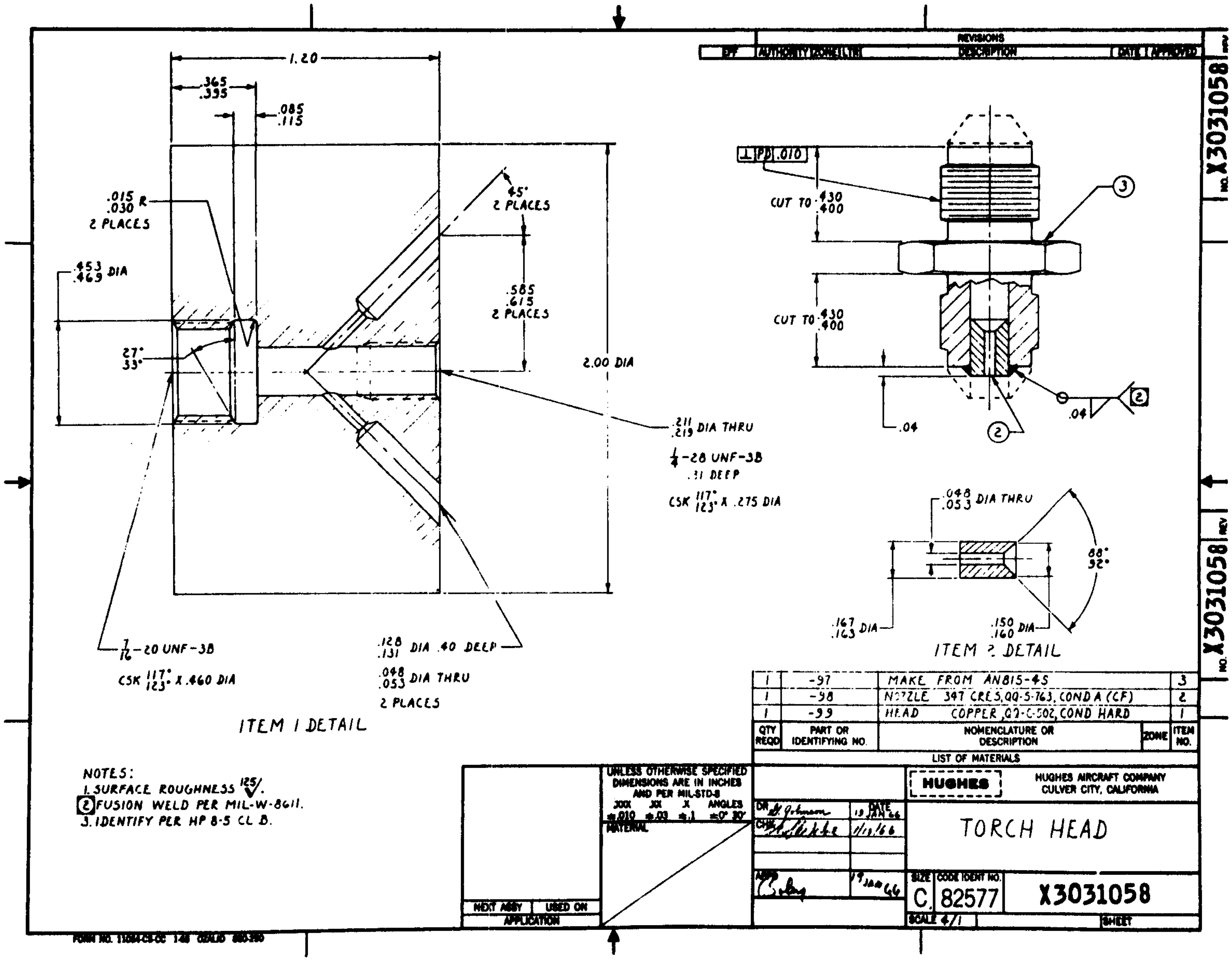


Figure 7. Torch head used for vacuum torch welding studies.

Maximum altitude used for all tests was 100,000 feet, which corresponds to a pressure of about 1/4 psi.

Testing was performed on 2014-T6 and 2219 aluminum sheets. The 2014-T6 sheets were 0.040 inch and 0.250 inch thick. The 2219 was 0.040 inch thick. All targets were approximately 3 in. x 3 in.

Attempts were made at cutting these plates using an 0.050 inch diameter nozzle tip. However, it was determined that not enough heat was liberated to efficiently cut the materials involved. Tests were then performed using tip diameters of 0.078; 0.101 and 0.125 inch. All of these diameters were efficient at cutting all of the materials.

Gas pressures ranged from approximately 0.5 to 10 PSIG for both hydrogen and oxygen. Mixture ratios ranged from 2:1 to approximately 12:1 with 8:1 being the stoichiometric proportion for these gases. All gases, mixtures and pressures ignited without fail with best efficiency obtained using a 0.101 inch or 0.125 inch diameter tip with hydrogen pressure of 3-4 PSIG and oxygen pressure of 0.5-1.5 PSIG. Torch tip to target distances were varied from 1/8 inch to 1 inch. Naturally, the closer the target, the faster was the cutting rate.

Attempts were made at penetration welding various stacks of plates with poor results. Butt welds were obtained with fair fusion. It was believed the inability to successfully weld was caused by extremely high velocity of the exhaust gases. The high exhaust velocity tended to blow the filler rod and the melted parent metal away from the weld zone before they could solidify and achieve the weld. In an effort to decrease the exhaust velocity, an existing torch nozzle was modified to incorporate a shock plate at the nozzle exit plane.

Attempts were made at welding, using various feed pressures and mixture ratios. Various sized holes, ranging from 0.088 inch to 0.140 inch, were drilled in the shock plate in an attempt to obtain optimum exhaust velocity and heating rates. Under all conditions the exhaust velocity was still too great to permit welding. In order to decrease the exhaust velocity the required amount, a further nozzle expansion downstream of the shock plate would be required. However, the expansion required would be too great to allow a suitably localized flame point for welding.

Platinum black was than deposited on a porous, sintered stainless steel disc approximately 2.5 inches in diameter. The platinum black acted as a catalytic ignition source in place of the previously used spark plug. Platinum black was then deposited on 3 porous sintered nickel plugs 0.5 inch in diameter. These were tested to ascertain their ability to act as a velocity decreasing device and as partial flame retainers.

Gas pressures ranged from 3-20 psig for both hydrogen and oxygen with volumetric mixture ratios ranging from 2:1 to 8:1. Of the three plugs tested, two failed to cause ignition under any circumstances. The remaining plug caused ignition after approximately 30 seconds of gas flow and gas pressures of 20 psig oxygen and 10 psig hydrogen. The upstream side of the plug was burned and the downstream side indicated a very slight erosion had started due, perhaps, to the flame stabilizing on the face of the plug.

The platinum black was deposited on the porous plugs in various degrees of thickness. Both the thickest and thinnest deposited surfaces failed to cause ignition, whereas the medium thickness surface deposits did allow ignition to occur. The thin surface was probably not sufficiently active and the thick surface may have blinded the porous plug.

Extensive effort would be required to develop and test an efficient catalyst system which could also be used as an exhaust velocity depressant. Because of this problem, and the high degree of operator skill required, this joining technique shall not be further pursued.

FOCUSED SUNLIGHT JOINING

Because of the availability of solar energy in outer space, focused sunlight as a space fabrication technique has been given serious consideration. To achieve maximum utilization of solar energy for joining, primary transducers may be used to concentrate solar energy into a beam for direct heating. The type, size and shape of the solar concentrator chosen would require a trade-off between total energy required and the area of the material to be heated. As the aperature of the concentrator is increased, the size of the region being heated is increased for a given f-ratio. Solar concentrators provide the advantage of being light and portable but are best suited for use external to the spacecraft. Although there is no convenient way to design a truly portable system for fabrication within the spacecraft, a solar concentrator might be affixed to the exterior of the vehicle with a window provided to accomplish benchwork inside the cabin.

Diffusion bonding and fusion welding of aluminum or magnesium may be accomplished with a 50X solar concentrator if the metal surfaces are given a thermal control coating having a minimum α/ϵ ratio of 10. Brazing, conducted with solar energy, would be feasible where the concentrator was capable of supplying sufficient energy to melt the filler alloy. Consequently, solar energy brazing of aluminum and magnesium would be feasible since sufficient energy would be available to to melt the braze alloys employed. However, temperature control problems could be anticipated. Titanium and nickel base alloys would not be as amenable to solar energy brazing due to the much higher energy required to melt their braze alloys.

Solar concentrators could be used for adhesive bonding where the solar energy may be utilized to cure one part epoxy adhesive systems through the use of controlled absorptivity material coated tapes. As an example, precoated faying surfaces could be brought together, clamped in position and cured by solar heat induced by a highly absorptive tape. The tape could be removed or left in place after the adhesive has cured.

The primary disadvantage of the utilization of solar energy for this joining system is that sunlight will not be available for extended periods of time to meet curing time requirements. Consequently, for solar energy to be adopted to supply heat for relatively long periods of time would involve methods of "tracking" the sun during fabrication of the space vehicle. Development of such a "solar tracking system" may prove to be very complicated.

Although focused sunlight joining for space environment fabrication does possess potential, (particularly for adhesive bonding), difficulty would be encountered in metallurgical joining of metals and alloys with high melting points. Since other fabrication methods being explored, e.g., electron beam and resistance welding, possess over-all higher potential for joining of metals in space, solar energy joining has received less attention in this program and will not be further evaluated.

LASER WELDING

Extensive research in the field of laser welding has been performed at Hughes. Most of this work has been directed toward achieving an understanding of the fundamental principles underlying the transfer of energy from the light wave emitted by the laser to the surface of the target workpiece in which thermal work is performed.

In general, there are several major drawbacks to the use of laser welding as a space repair and fabrication technique. First of all, laser systems with a sufficiently high power output to do useful metallurgical work are all pulsed output devices. It has been found at Hughes that short pulse lengths tend to vaporize the target rather than melt it. The pulse must be stretched out to at least 2-1/2 - 3 milliseconds duration if successful penetration of fusion is to be obtained. The longer the pulse duration is, the better the weld. If high power can be coupled with a long pulse, then defocussed beams can be used to make fairly good welds of a useful size and depth of penetration. Unfortunately, the conditions of long pulse duration and high optical power output are not easily attainable and certainly are not consistent with lightweight flight type hardware.

To obtain a long pulse, an inductive-capacitive pulse forming network must be used. Unfortunately, as the pulse length is stretched beyond, say, six or eight milliseconds, the inductive reactance in the power supply circuit begins to get high enough to severely limit the power output and cause severe heat dissipation problems in the power supply. Obviously, the power supply becomes very heavy and bulky.

This brings up the second significant problem. The pulsed laser is basically an inefficient device from an electrical energy utilization standpoint. Excellent thermal coupling is readily obtained. That is, a very high proportion of the energy in the optical beam emitted by the laser is converted to useful metallurgical work. However, there are high dissipation losses in the best power supplies available and an enormously inefficient optical coupling between the pumping source (usually a Xenon flash lamp) and the resonant cavity (the ruby rod). The reason for this is that the ruby is excited only by a particular wavelength of the "noisy" white light used for pumping. The remainder of the optical energy represented by the rest of the spectral wavelengths must be dissipated as heat in the reflector system in which the resonator is mounted. Unfortunately, the problem becomes even worse because the efficiency of the resonator drops off sharply as its temperature increases. External cooling with dry nitrogen gas, water or liquid nitrogen may be used to alleviate this problem but the best efficiency obtained is still of the order of magnitude of a few hundredths to perhaps a few tenths of a percent.

The third major problem involves the basic physical properties of the metals to be welded. The best results have been obtained with metals having a high thermal diffusivity, such as copper and aluminum. Metals such as stainless steel and titanium tend to confine or restrict the flow of heat thereby increasing the likelihood of vaporizing rather than merely melting.

Associated with these problem areas and further complicating the potential applications of laser welding is the fact that seams must be welded by the overlapping spot technique. This requires, perhaps twenty-five to seventy-five spots per lineal inch of seam. It is, therefore, a slow and tedious process and requires high precision tracking equipment to locate the overlaps accurately. Furthermore, if any one of the spots accidentally burns through the stock, salvage repair would be extremely difficult.

There is some hope for the future of laser welding. The Hughes Research Laboratories and Bell Laboratories have both succeeded in making a ruby laser operate in a continuous mode but at very low power levels. Recent developments indicate the possibility exists of developing a continuous operating gas laser with an output of the order of magnitude of hundreds of watts. This type of device will make laser welding a reality. Unfortunately such a development cannot be anticipated within the time period allowed for this research program. It is therefore recommended that no work be performed and no further consideration be given to laser welding.

III. EVALUATION OF ENERGY SYSTEMS

Upon the choice of a joining method for space environment fabrication, the power requirements for its successful utilization must be determined. Consequently, those power systems that seem to provide capability for adaptation to the chosen joining method shall be evaluated. As a result of preliminary studies, the following candidate energy systems are presently being given further consideration:

NUCLEAR REACTOR SYSTEMS

Nuclear fission represents an excellent source of energy, and a large amount of effort is being spent by other contractors in developing space power systems using compact fission reactors as heat sources. In order to minimize shielding weight, however, shadow shields are almost always specified in such power systems. While shadow shielding may be quite adequate for inanimate payloads, its use is highly questionable for operations involving men engaged in building a structure in space or on the moon. It appears, therefore, that nuclear reactor power systems for manned operations in space will require much more shielding than is usually allowed in their designs.

Nuclear power systems will afford a high flexibility in power management including high peak demand and overall power. However, development of such systems is not far enough along that they can be considered as practical power sources within the immediately forseeable future.

SOLAR CELL/BATTERY SYSTEMS

Solar energy has the attractive features of providing a high power flux density (the solar constant of one AU is 0.14 watts/cm^2) and of having been successfully exploited. It is one of the most attractive sources of power for space operations. Figure 8 illustrates a block diagram of suitable solar energy conversion systems.

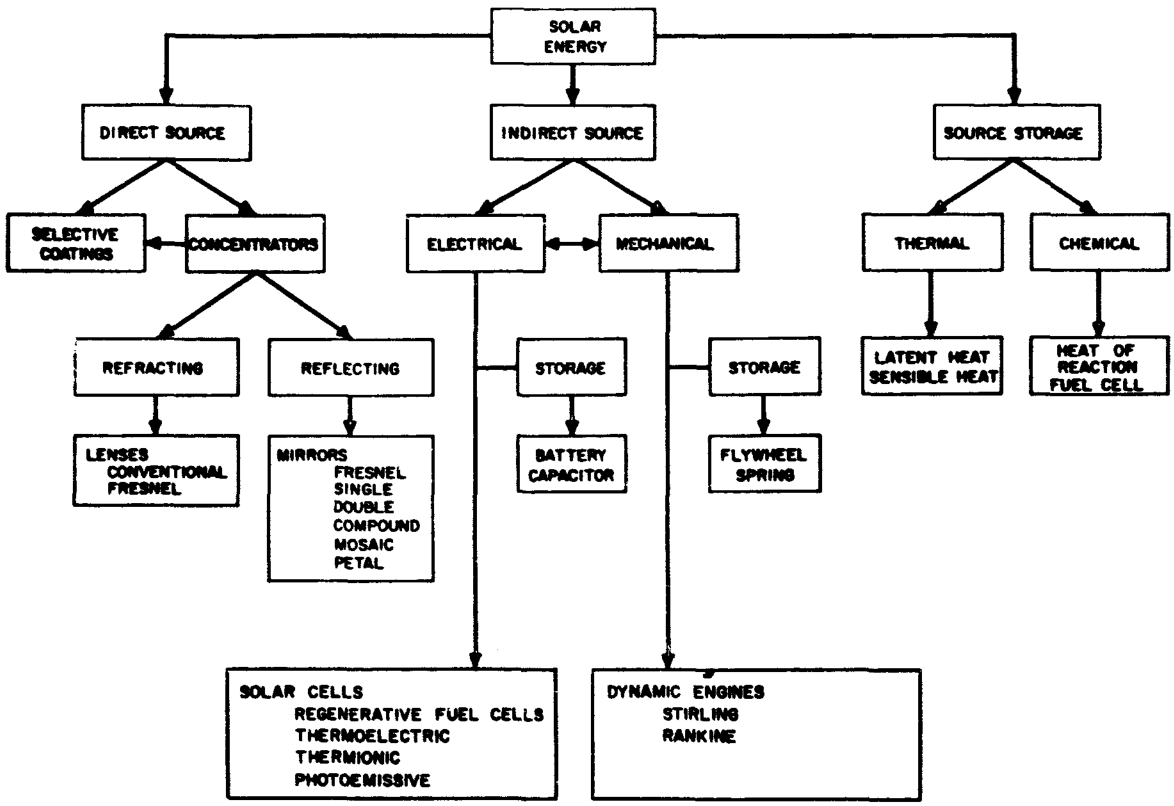


Figure 8. Solar Systems Diagram

A direct thermal system may consist of several transducers, depending on heating requirements. The unconcentrated solar flux at 1 AU will raise the temperature of an aluminum sphere to a value no higher than about 200°F (equilibrium, assuming a uniform temperature). If higher temperatures are desired, then either a selective surface coating or a concentrator may be used. A selective coating of α/ϵ equal to 10 would raise the temperature to a value no higher than 500°F. A solar concentrator which increases the solar constant by a factor of 50 would melt the aforementioned aluminum sphere, provided the hot spot covered the exposed side of the sphere completely. If the size of the hot spot is small relative to the dimensions of the work being heated, then the heat losses due to conduction and radiation will tend to limit the maximum temperatures attainable. Solar concentrators may be the most versatile transducer for joining methods requiring direct heating to temperatures below the melting point of aluminum. Thus, they would be desirable for melting soft solders or curing adhesives. The various types of refracting and reflecting solar concentrators which could be used are shown in Figure 9.

One of the major disadvantages of direct solar systems is the necessity of maintaining a direct line of sight between the solar collector, the sun and the workpiece. This imposes a requirement for a solar tracking system and limits the time during which work can be performed to those periods when the sun is in a favorable orientation.

The use of solar cells and batteries minimizes the problem of sun-orientation but has the disadvantage of the additional weight imposed by the energy storage system. While batteries are heavy, they do have the advantage of providing pure d c power and possess a known reliability.

FUEL CELL SYSTEMS

Chemical storage derives its feasibility from the fact that electromagnetic energy or heat may trigger or accelerate certain chemical reactions. Once the source is removed, the reaction may proceed in the other direction giving back heat or electricity. A good example of the latter is the regenerative fuel cell.

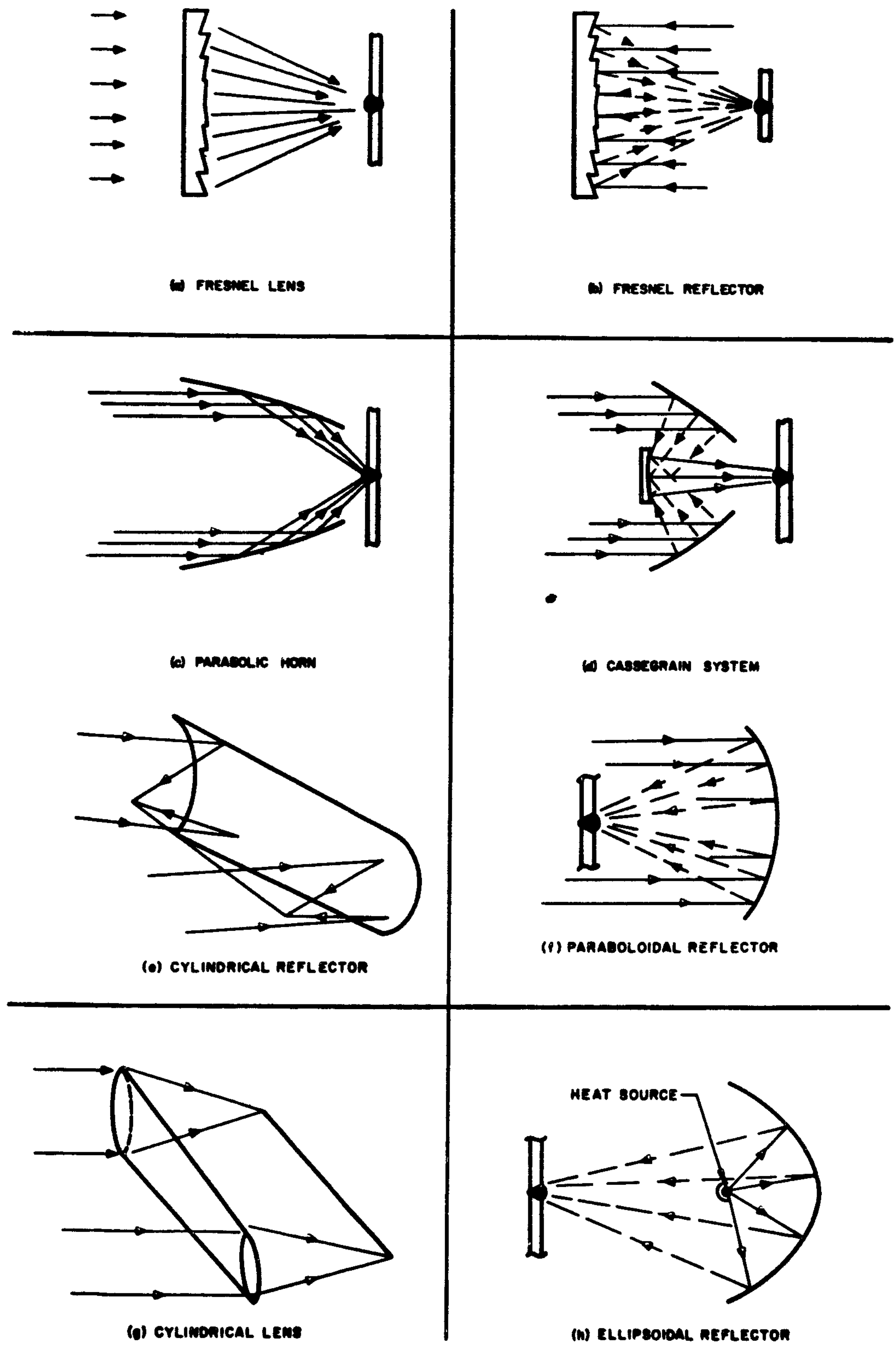


Figure 9. Types of solar concentrators.

A fuel cell may be defined as an electrochemical conversion device which delivers direct current as the result of oxidation of a flowing fuel. As such, the fuel cell differs from the conventional battery only in the manner in which the chemical energy source is introduced. As indicated in Figure 10, fuel cell systems are capable of more energy storage per pound than conventional batteries. For high performance applications, the hydrogen-oxygen family of fuel cells appears to be the most promising type. The electrolysis of water through the aid of photovoltaic cells and subsequent use of the hydrogen and oxygen in a regenerative fuel cell has been suggested.

A typical fuel cell power pack being developed for field use weighs 30 pounds and produces 200 watts for 14 hours on a 6-pound canister of fuel (hydrogen from decomposition of a metal hydride). The oxidizer is oxygen from the life support system. This unit exemplifies the feasibility of fuel cells as a convenient portable energy source. For operation outside a habitable atmosphere, of course, the oxygen would also have to be supplied.

For high power levels (megawatts), fuel cell systems tend to become rather bulky as well as heavy, although they are efficient devices for energy conversion.

Another characteristic of fuel cells is the relatively inflexible current density available from a given cell. This tends to limit their usefulness in applications requiring occasional surges in power supply. Conventional batteries are more flexible in this respect than fuel cells.

It is our understanding that fuel cell power systems similar to those in the Gemini vehicles will be used in Apollo and other contemplated programs in which metal joining equipment may be used. Power demand for a joining system may be of the order of magnitude of 1.5 to 2.0 kw. It is assumed that the voltage-current characteristics of fuel cell systems could be adjusted with appropriate switchgear to make the appropriate series or parallel interconnections of cells that may be required.

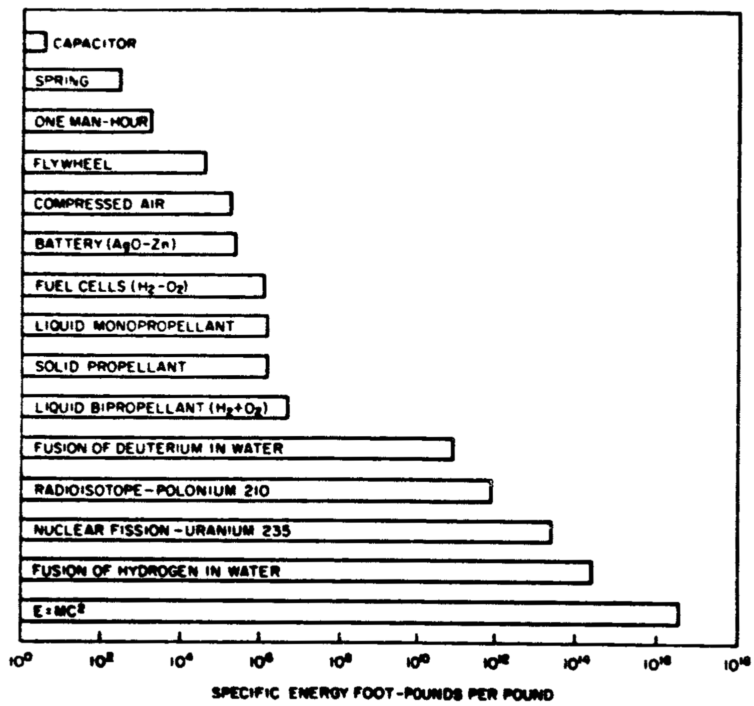


Figure 10. Performance characteristics of 5-cell series solar module.

IV. RECOMMENDATION OF TWO PROCESSES FOR FEASIBILITY DEMONSTRATION

It is recommended that resistance and electron beam welding be developed as joining processes for extraterrestrial fabrication and repair of space vehicles. Examination of Table II reveals that these joining processes provide the largest number of advantages for application in a space environment. Resistance welding has the best potential as realized by such pertinent factors as its operational simplicity, reliability, minimum joint preparation and tooling, and safety. Electron beam welding also exhibits attractive features for space joining which include excellent joint strength and reliability, minimal operator skills, and a high natural adaptability to the space environment, e.g. zero gravity, and low pressures. The only pertinent disadvantage of resistance welding is the thickness limitation of weldments achieved with 6Al-4V titanium and Inconel 718. A possible solution to this problem would be the use of low melting filler materials. The disadvantages related to electron beam welding for space fabrication are realized in relatively complex tooling, close tolerances, volume and weight requirements associated with high power source requirements, and possible safety hazards.

A test program will be conducted under simulated space conditions to prove the feasibility of the recommended joining processes. To accomplish these objectives, engineering effort will be applied in the following areas:

1) Adaptation of equipment for demonstration of the process under simulated space conditions.
2) Design, fabrication, and testing of specimens.

ADAPTATION OF EQUIPMENT

To date, effort in this work has not been initiated because the choice of the two final candidates was only recently decided. Electron beam welding fabrication is anticipated to be simply conducted with conventional equipment. However, resistance welding will require a remotely operated roll-seam welding set-up with suitable electrical and mechanical controls.

DESIGN, FABRICATION, AND TESTING OF SPECIMENS

The primary objective of this test program is to determine the mechanical strength, reliability, and metallurgical quality of joints fabricated in an extraterrestrial environment between the following alloy combinations:

2014 Aluminum-to-2014 Aluminum
Titanium 6Al-4V-to-Titanium 6Al-4V
Inconel 718-to-Inconel 718
Titanium 6Al-4V-to-Inconel 718
AZ80A Magnesium-to-AZ80 Magnesium
*AZ31 Magnesium-to-AZ31 Magnesium

The initial stage of this program shall be the static mechanical testing of welded joints conducted at temperatures ranging from -250°F to +250°F. Specimens have been designed to accommodate several joining methods. Various sheet panel lots and gages shall be employed for test specimens to evaluate joint strength reproducibility. Subsequent to static testing, leak check and pressurization testing of pressure vessel specimens shall be conducted before and after thermal cycling from -250°F to +250°F. Measurement of weld distortion and metallurgical evaluation will be carried out on representative static and leak-pressurization test specimens.

Presented in Table III is a program description which includes material combinations, fabrication methods and number and types of tests to be conducted. A program schedule is presented in Table IV.

TESTING METHODS AND PROCEDURES

Static mechanical testing of weld specimens shall be conducted at -250°F, -100°F, +70°F, and +250°F to determine ultimate strength and elongation. Test specimens shall be of a butt-type design (Figure 11)

*Used for fabrication of static test specimens due to unavailability of AZ80A magnesium alloy.

	Joint Characteristics						Reliability		
Joining Process	Thickness Limitation	Joint Configuration	Filler Required	Material Limitation	Strength/ Unit Length of Joint	Leak Tight	Joint Strength Consistency	Operator Skills Required	Required/ Unit Length of Joint
1) Gas Welding	No	Butts, Laps, Fillets	Probably	No	Poor	?	Poor to Fair	Yes, High	? (High but packs well
2) Electron Beam Welding	No	Butts, Laps	No	No	Very good, 60-100% of parent metal	Yes	Very Good	No (can be highly auto-mated)	Dependent on mate-rial, orde of magni-tude in 1-10 K_j/ in. range
3) Arc Welding	No	Butts, Fillets	In some cases	No	Fair to Good	Yes	Fair to Good	Yes, Fairly High	Dependent on mate-rial, orde of magni-tude 2-20 K_j/in.
4) Laser Welding	Yes very light gage (0.01-0.02)	Butts best, some Fillets	No	Yes, not good on on highly reflective or low cond.	Probably Good?	? Probably No	?	No	Very high
5) Resistance Welding	(?) Yes, light to med. gages 0.060 "max."	Laps only	In some cases	No (use filler with Al, Mg)	Probably Good	Yes	Probably Good	No	Medium depends on material 1-5 K_j/in.
6) Diffusion Bonding	No	Most likely Laps or Tees, maybe Butts	No per-haps in rare cases	Perhaps. Works best with soft duc-tile metals	Fair to Good	Probably Yes	Poor to Fair	No - but high order of planning and judge-ment req'd	Moderate to high
7) Explosive or Pressure Welding	No	Laps, Tees maybe Butts	Gener-ally No	Perhaps. Works best with soft duc-tile metals	Probably only Fair	Probably Yes	Poor to Fair	No - but high order of planning and judge-ment req'd	? (High but packs well
8) Adhesive Bonding	No	Laps	Yes (The adhesive)	Yes - Dependent primarily on service tempera-ture	Low	Perhaps	Fair	Minimal	Could be high (due to conduc-tive heat losses)
9) Focused Sunlight Joining	Probably	Laps, Fillets	In most cases	Not if Filler used	Probably only Fair	Probably Yes	Fair to Good	Yes, Orienta-tion of reflector critical	Low
10) Thermo-chemical Brazing	No	Laps	Yes	Yes - Not good for Al, Mg	Fair to Good	Probably Yes	Fair to Good	No	Low
11) Cold Molecular Welding	No	Butts, Laps, Tees	No	Perhaps. Works best with soft, duc-tile metals	Poor	Probably Yes	Poor to Fair	No - but high order of planning judge-ment req'd	Low to moderate

Power Requirements						Joint Preparation				System Characte		
Type of Power				System Efficiency	Demand/ Unit Time	Cleaning Required	Tooling Required	Tolerances Required	Set-up Problems	Total Volume	Total Weight	Develop-ment Cost
Elec-trical	Mechan-ical	Gas	Sunlight									
		√		Low	-	-	Minimal	Minimal Required	No	Low	Low	Low
√				High	KW range	Yes	High	Close, 0.001 to 0.005" fit-up	Yes, tool-ing and auto-head alignment	High sev-eral ft^3	High sev-eral cwt	High
√				Poor to Fair	KW range	Yes	Fair to High	Fair 0.010" to 0.020" fit-up	No (Tool-ing)	Low	Low	High
√				Very Poor	? Watt range	Probably No	High	Close, 0.001 to 0.005 fit-up	Yes, tracking difficulties envisioned	Very high	Very high	Very higł
√				Good	Low KW range	Minimal	Minimal	Reasonable fit-up OK (Laps)	Minimal	Low	Low	Low
Second-dary √	Primary √	Second-dary √	Second-dary √	Low	Low	Must be carefully cleaned	Very High	Fair Dependson joint	Yes, Tool-ing	High tool-ing volume	High tooling weight	Low
	Chemical			-	-	No	Fair to High	Moderate	Yes, Tool-ing	Tooling high, explosive low	Tooling high, explosive low	Moderate
Possi-bly √		Possi-bly √	Possi-bly √	Probably Low	Probably Low	Yes	Fair to High	Moderate	Yes, Tool-ing	Tooling could be high	Tooling could be heavy	Low
			√	-	-	Probably Yes	Fair to High	Close, 0.001 - 0.003" fit-up	Yes, Tool-ing	Probably High	Probably Heavy	High
√				Good	Negligible	No	? Simple to complex	Close, 0.001 - 0.003" fit-up	Possible tooling problems	Dependent primarily on tooling	Dependent primarily on tooling	Moderate (except for Al and Mg)
	√			-	-	Must be carefully cleaned	High	Depends on joint design	Yes, Tool-ing	Fair to High	Probably High	Moderate

istics		Space Environmental Requirements					Human Factors				
Production Cost	Logistic Problems	Metal Loss in Vacuum	Metal Oxication in Spacecraft	Suitable for Zero Gravity	Thrust Prob-lems	Torque Prob-lems	Radiation Hazard	Shock Hazard	Explosion Hazard	Operational Simplicity	Thrust Reaction
Low	Minimal	Yes, Dependent on skill	Yes, Hazardous	No	Yes	No	No	No	Yes	Low (com-plex)	Yes
High	High power required	Minimized by high welding speed	Possible hazard	Yes	No	No	Maybe X-ray	Yes	No	Fair to Good	No
Low	High power required	Yes	Yes Harardous	No (Depen-dent on Tooling)	No	No	Some UV	Moder-ate	No	Low (skill dependent)	No
Medium	Power required ?	Minimal	Minimal	Yes	No	No	Not Parti-cularly	Possi-bly	No	Poor	No
Low	Minimal	None	None	Yes	No	Some	No	Minimal	No	Very Good	No
Depends on tooling (could be high)	Minimal	None	None	Yes	No	Yes	No	No	No	Good-requires planning and judgement	No
Depends on tooling	Minimal	None	None	Yes	Yes	No	No	No	Extreme	Good	Yes
Depends on tooling	Could be high power required	None	None	Yes	No	No	No	No	No	Fair	No
Moderate to high dependent on tooling	Minimal	None	Minimal	Yes	No	No	Some UV	No	No	Low to Fair	No
Moderate	Minimal	None	None	Yes	No	No	No	No	Maybe?	Fair to Good (dep (depends on tooling)	No
Depends on tooling	Minimal	None	None	Yes	No	Some	No	No	No	Fair	No

Table II. Summary sheet, joining process characteristics.

Material Combination	Candidate Welding Techniques: Electron Beam	Candidate Welding Techniques: Resistance	Specimen Gages (in) (Approximate)	Tensile Test — No. of Specimens of Each Gage to be Tested at -250°F, -100°F, 70°F, 250°F: Butt	Tensile Test: Lap	Leak Test — No. of Pressure Vessel Specimens of Each Gage to be Cycled from -250°F to 250°F: Butt	Leak Test: Lap
2014Al-to-2014Al	X		0.012, 0.020, 0.025	3		3	
		X			3		3
Ti6Al-4V-to-Ti6Al-4V	X		0.030, 0.060, 0.090	3		3	
		X			3		3
Inco 718-to-Inco 718	X		0.040, 0.080, 0.120	3		3	
		X			3		3
Ti6Al-4V-to-Inco 718	X		0.030, 0.060, 0.090	3		3	
		X			3		3
AZ80AMg-to-AZ80AMg	X		0.060, 0.070, 0.080			3	
		X					3
AZ31Mg-to-AZ31Mg	X		0.060, 0.070, 0.080	3		3	
		X			3		

Table III. Test Program Description

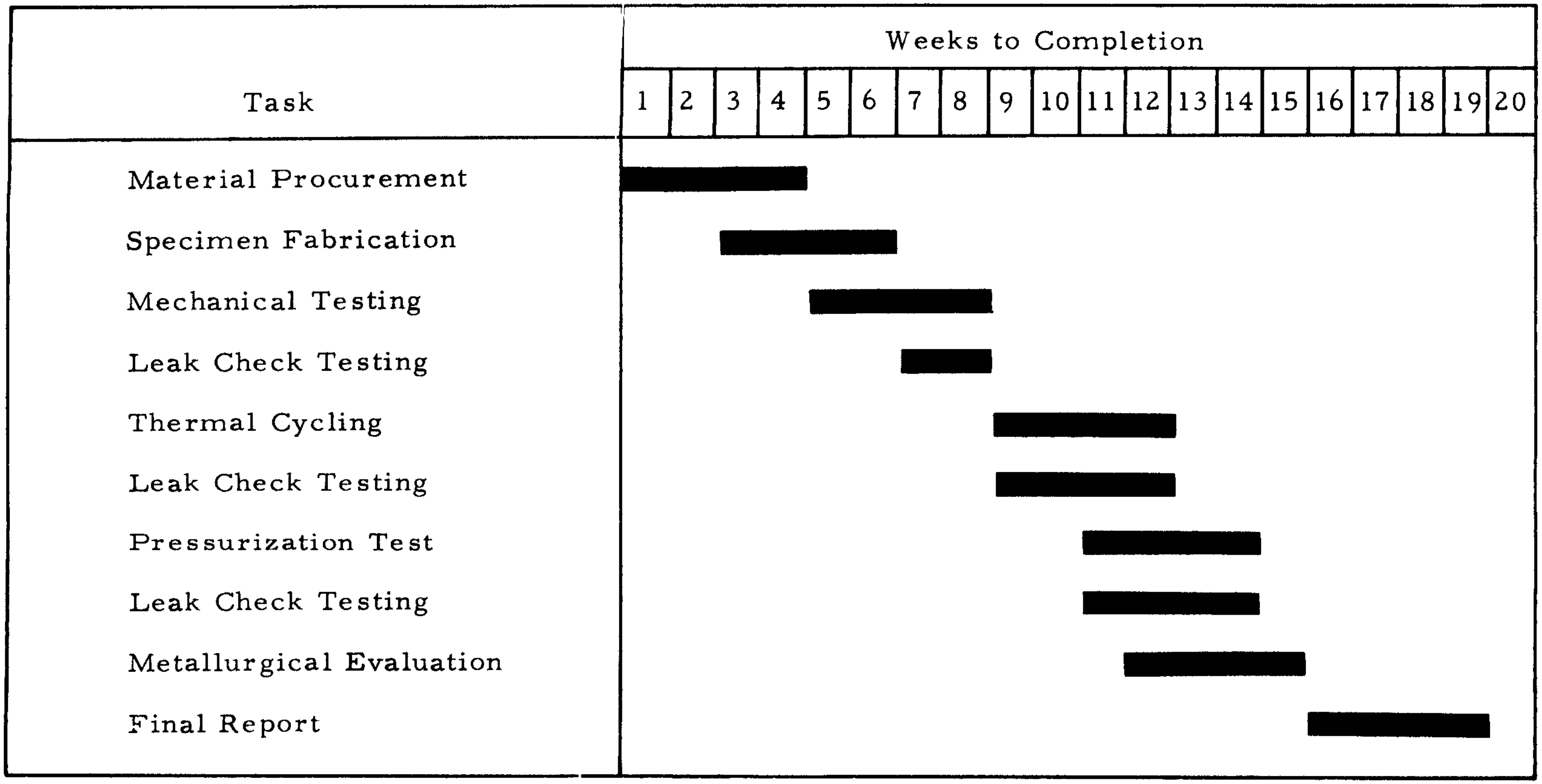


Table IV. Program schedule.

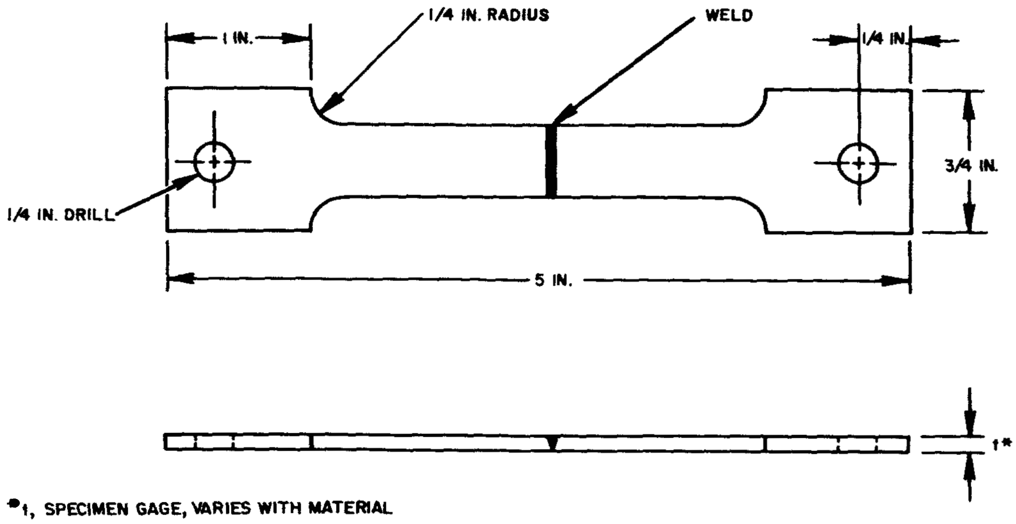


Figure 11. Butt-type tensile specimen.

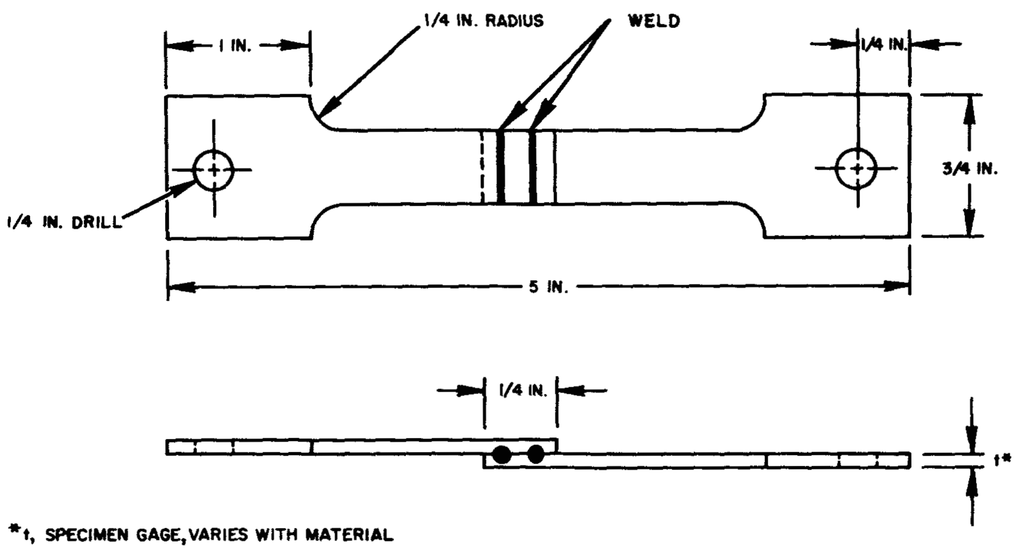


Figure 12. Lap-shear tensile specimen.

consistent with Federal Test Method 151 specifications or a lap-type specimen design (Figure 12) for joining processes requiring such a design. Three sheet lots of each material in three different gages shall be employed for each material combination fabricated. Testing shall be in triplicate.

Pressure vessel specimens illustrated in Figures 13 and 14 shall be fabricated employing the material combinations previously stated. Similar to the mechanical tests, the specimens shall be fabricated with three different gages for each material combination and tested in triplicate. The pressure vessel specimens (either cylindrical or rectangular in design) shall initially be leak tested under an internal pressurization of one atmosphere of helium in a vacuum of 10^{-6} Torr. Specimen leakage shall be detected andmeasured by a mass spectrometer connected to the vacuum chamber. After leak testing, the specimens shall be thermally cycled 100 times from -250°F to +250°F and again helium leak checked. Subsequently, the specimens shall be pressurized to various proof levels determined from mechanical testing and given a final helium leak test.

A metallurgical evaluation shall be conducted on: 1) mechanical specimens fabricated from each gage and material combination, 2) representative pressure vessel specimens that have completed leak and pressure testing. The evaluation shall consist of an examination of weld fusion characteristics, microstructure, weld penetration, and any detrimental effects, e.g., cracking, voids, and inclusions.

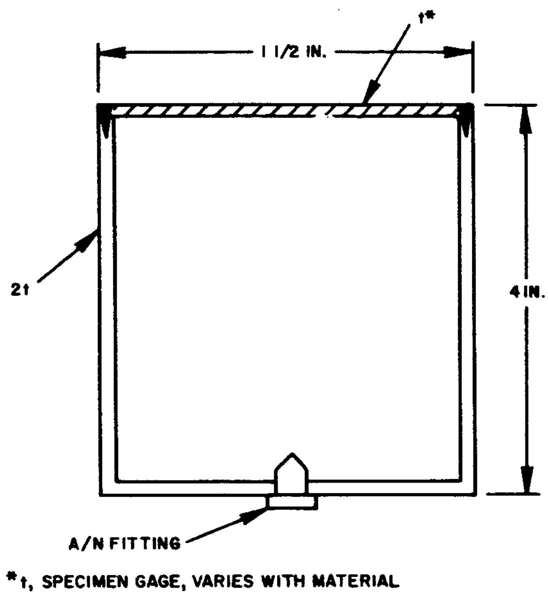


Figure 13. Cross-section of pressure vessel design suitable for welding.

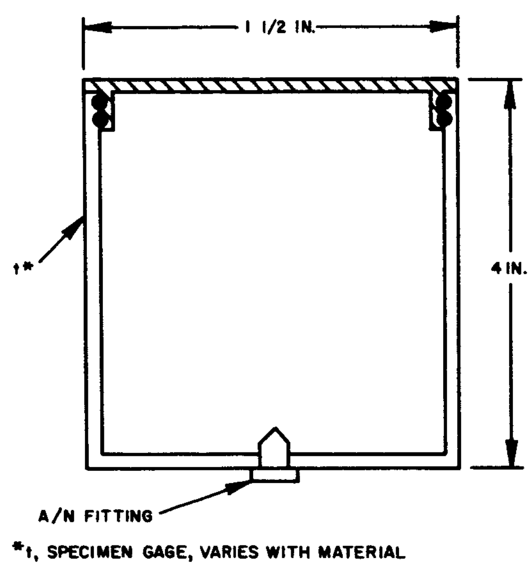


Figure 14. Cross-section of pressure vessel design suitable for resistance welding, brazing or bonding.