MANUFACTURING ENGINEERING RESEARCH AT MSFC

November 30, 1967

By

Robert T. van Aller
Frederick J. Beyerle
Charles R. Cooper
Robert V. Hoppes
Ronald L. Nichols
P. Gordon Parks
John R. Rasquin
Paul H. Schuerer
Douglas L. Stephens
William A. Wall, Jr.
Vaughn H. Yost

CONTENTS. . .

CONTAMINATION CONTROL

by Robert T. van Aller and Frederick J. Beyerle

LIST OF TABLES

LIST OF ILLUSTRATIONS

CLOSED CIRCUIT TV ARC GUIDANCE DEVELOPMENT FOR WELDING

by William A. Wall, Jr. and Douglas L. Stephens

CONTENTS (Continued)...

LIST OF TABLES

LIST OF ILLUSTRATIONS

CONTENTS (Continued) . . .

MECHANICAL DEVICES FOR ZERO GRAVITY SIMULATION

by Vaughn H. Yost

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LASERS USED IN MANUFACTURING

by John R. Rasquin

LIST OF ILLUSTRATIONS

NEUTRAL BUOYANCY SIMULATION

by Charles R. Cooper, Paul H. Schuerer, and Ronald L. Nichols

LIST OF ILLUSTRATIONS

ALUMINUM WELDING DEVELOPMENT COMPLEX

by Robert V. Hoppes

LIST OF TABLES

LIST OF ILLUSTRATIONS

EXPERIMENTAL ELECTRON BEAM WELDING IN SPACE

by P. Gordon Parks

CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

CONTAMINATION CONTROL

By

Robert T. van Aller and Frederick J. Beyerle

THE CONTAMINATION CONTROL PROGRAM

Contamination control cannot be effectively applied without an understanding of what constitutes contaminants and an analysis of their detrimental effects on environments in which they are found. Contamination comes in many forms: the metal chip in a pneumatic valve; the fiber which clogs a filter; and the loose nut, bolt, or washer in a fuel tank or in a spacecraft.

Many factors need to be considered in the evolution of a comprehensive contamination control program to make it as effective and as economical as possible. Consideration must first be given to the various types and levels of contamination that can be tolerated without adversely affecting the reliability of the product. Factors that must be carefully considered are (1) the processes and tools, (2) the facilities and their monitoring equipment, (3) the cleanliness verification methods, and (4) personnel training. Briefly the considerations for a contamination control program can be summarized as follows:

1. The need for contamination control.
2. Tolerance levels in contamination controlled products.
3. Relationship of processes, the product, contamination sources, and facilities.
4. The product cleaning.
5. Personnel factors.

SPECIFICATIONS AND PROCEDURES

To bridge the gap between theory and practice in the field of contamination control, MSFC embarked upon a program to develop the best methods to clean both intricate and large spacecraft parts to the levels required by NASA specifications. This program began in the Redstone days when there was only one specification, and it called out cleanliness levels to a degree that was quite difficult to meet and almost impossible to verify because of the lack of tools and knowledge in testing parts for contamination.

The R&D effort on space vehicles was accomplished on a priority basis with tight schedules. However, most, if not all, of the schedules were met, and although many problems occurred during the cleaning programs, the complex spacecraft parts cleaned inhouse met the specified requirements. Accomplishments in contamination control programs for the Redstone, Jupiter, Saturn I, and Saturn V vehicles will be summarized in this paper.

For the Saturn vehicles a method was developed for internal spray cleaning of large LOX and fuel tanks and lines to MSFC cleaning levels. This method is now being used by prime contractors such as Boeing, Douglas, Chrysler, and North American Rockwell to clean their launch vehicle tanks.

Figure 1 shows the fuel exclusion riser that was developed and successfully tested for use in the Saturn V S-IC fuel tank sump. Its purpose is to replace the heavier JP fuel in the sump area with urethane foam blocks for a large weight savings to the vehicle and to eliminate the need for excess fuel removal after static firing tests.

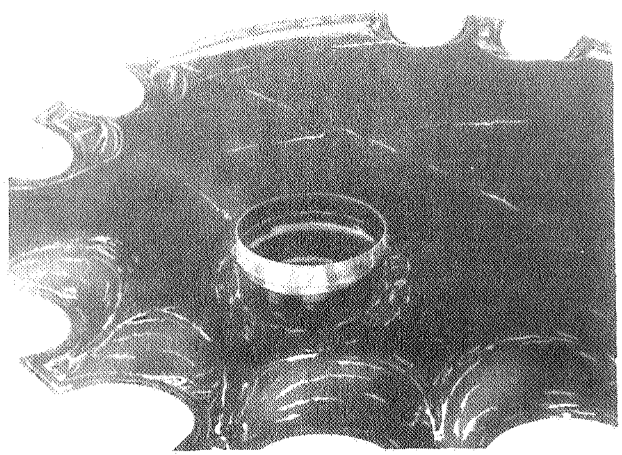


FIGURE 1. FUEL EXCLUSION RISER

About 100 procedures were written for use in MSFC contamination control programs during the development of the Redstone, Jupiter, Saturn I, and Saturn V vehicles. These procedures specified cleanliness levels for hardware such as (1) vehicle tanks, (2) valves and regulators, (3) stainless steel bellows and lines, (4) liquid oxygen gaskets (5) flared tubing, and (6) honeycomb parts. Specific cleaning procedures were developed for crucial or intricate items that included (1) gas-bearing parts in gyroscopes, (2) high pressure spherical tanks in the S-IB stage (3) heat exchangers on F-1 engines, (4) electrical connectors, (5) nonmetallic gaskets for LOX service, and (6) various hydraulic parts.

Some methods in corrosion protection specified (1) electropolishing small parts, (2) deoxidation and conversion coating of aluminum alloys, and (3) electroless nickel plating. A spray anodizing technique and equipment (Fig. 2) were developed under contract to Reynolds Metals Company, Richmond, Virginia. The technique involves applying an anodized coating to an aluminum seam, such as a weld area, after a space vehicle tank has been welded together. The present vehicle tanks are protected from atmospheric corrosion with a conversion coat during their manufacture and assembly operations. These coatings are easily and cheaply applied (compared to other coatings), but these coatings also are the least resistant to corrosion attack. The conversion coating was chosen because it was the only coating that could be applied feasibly to a weld area on large surfaces such as space vehicle tank surfaces. Now, however, with the development of the spray flush anodizing technique, it is possible to apply a coating with an electric current in a matter of seconds rather than the 30 to 60 min it formerly took. The anodized coating offers maximum protection to the areas most susceptible to corrosion.

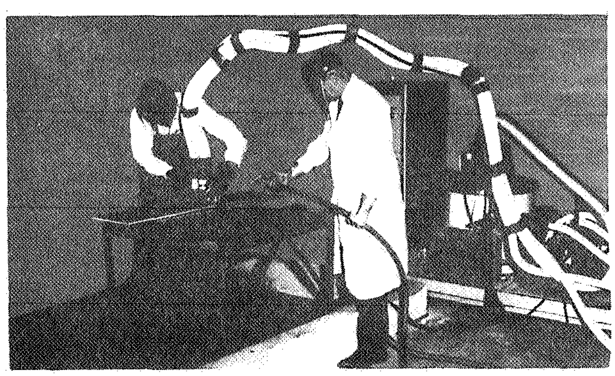


FIGURE 2. SPRAY ANODIZING EQUIPMENT

A contract was awarded to the Sandia Corporation, a prime contractor of AEC, to develop a handbook in contamination control to be used by designers and engineers working on contamination control programs. One document presently being released by the Office of Technology Utilization (OTU) of NASA Headquarters is entitled <u>Principles of Contamination Control</u>, which is the forerunner to the main document entitled <u>Handbook for Designers and Engineers in Contamination Control</u>. This last document will be available for release in August, 1968.

Table I shows a NASA contamination control panel initiated at Marshall Space Flight Center. One of the functions of the panel is to standardize documentation such as specifications, standards, and procedures in contamination control work. The Manned Spacecraft Center at Houston, the center at Cape Kennedy, and Marshall Space Flight Center are all jointly involved.

TABLE I. NASA CONTAMINATION CONTROL PANEL

CHAIRMAN	ALTERNATE
Frederick J. Beyerle	Mitch Pickard
MSFC R-ME-MM	MSFC R-QUAL-AA

CO-CHAIRMAN
Quintin Ussery
MSC NC-3

CO-CHAIRMAN
Dr. John Gayle
KSC SOP

FORMAT:

1. Sponsorship: NASA Headquarters
2. Meets once a month alternately at each center.
3. Each center visited chairs the panel.

SPACECRAFT STERILIZATION

Spacecraft sterilization is an important area in contamination control programs. One of the major goals of planetary exploration is to provide information about the existence of extraterrestrial life. Forerunners to manned exploration are automated biological laboratories designed to detect life on planetary surfaces with very sophisticated instruments. To assure the validity of information from these craft, it is absolutely essential that there be no life on the device when it lands. This is in itself justification for a spacecraft sterilization program, and is totally aside from any possible moral implications of infecting a planet with earth-type microbes that may be lethal to indigenous life. Present NASA policy stipulates three fundamental requirements that unmanned planetary landers must fulfill. They are as follows:

1. The lander will be assembled in clean rooms at specified levels of assembly. This is interpreted to mean biologically clean rooms in which the number of living organisms in the air is maintained at or below one organism/cu ft.

2. The landing assembly will be subjected to an approved sterilization procedure. Dry heat is currently the only approved method of sterilization; however, it is recognized that certain items not compatible with the dry heat sterilization cycle may require sterilization by other methods. Also, chemical decontamination may be used for biological load reduction prior to dry heat terminal sterilization.

3. The landing assembly will be enclosed in a bacteriological barrier.

Present NASA procedures call for 24.5 hr at 125°C for terminal dry heat sterilization. The conditions necessary for the decontamination of surfaces by using ethylene oxide (ETO) gas require not less than 300 mg of ethylene oxide per liter of space in the enclosure, a minimum exposure time of 4 hr, and an exposure temperature of not less than 21°C. Prior to ETO treatment, surfaces must be exposed to more than 35% relative humidity (RH) for 72 hr or longer. Proof that decontamination has been achieved may be obtained in each case by pre- and post-treatment culturing of representative parts from the group treated. ETO cannot be used for internal decontamination but might conceivably be used for terminal sterilization.

Design and manufacturing procedures must allow for these considerations and is the subject of a study conducted by the General Electric Company for the Manufacturing Engineering Laboratory. The information has been compiled in three volumes. Volume I considers Design Guidelines, Volume II deals with Manufacturing Procedures, and Volume III is a Biological Handbook for Engineers.

In Volume I, Design Guidelines, it is established that as a general rule the design for sterilizability does not invalidate established practices for good design. Particular attention must be paid, however, to a number of critical details. Very early in this study, it was determined that moist heat could not be used for spacecraft sterilization. At the temperatures required, air saturated with water vapor has a deleterious effect on most spacecraft components. On the basis of information gained from the study, the decision was made to use dry heat.

It was also found that parachutes present unique sterilization problems. Table II shows tensile strength variations of 3 parachute materials as a result of thermal sterilization. These types of nylon are degraded to a large extent and therefore should be excluded from this application.

TABLE II. TENSILE STRENGTHS OF SEVERAL PARACHUTE MATERIALS RESULTING FROM HEAT STERILIZATION

MATERIAL	CONTROL	COVERAGE STRENGTH AFTER EXPOSURE
Dacron Types 52 & 56	1	0.90
Nomex	1	0.99
Nylon Types 300 & 380	1	0.20

Most planetary spacecraft contain a number of explosively actuated devices. The Mariner flyby has approximately 30 explosive squibs. Heat sterilization creates a severe environment for these devices, and it must be recognized that the requirement for sterilization must be considered during the squib design and not as an afterthought. Table III shows special problems associated with some representative devices. Squib manufacturers are generally of the opinion that explosive mixtures capable of withstanding sterilization temperatures can be found for most applications.

TABLE III. TYPICAL EXPLOSIVELY ACTUATED DEVICES FOR PLANETARY SPACECRAFT

DEVICE	DESCRIPTION – TYPICAL USES	SPECIAL PROBLEMS
Valves	Valve closed or opened using explosive actuator. Used for disconnecting cooling loops, attitude control loops, propulsion lines.	Leaks – Increased pressure during sterilization may aggravate.
Pin Pullers	Gas pressure drives piston which retracts. Used for separating structural systems, jettison of stores, release of science experiments.	May utilize heat labile "O" rings.
Bolts	Frangible section of bolt is cut by charge. Used for separation of structural systems, band clamps, etc.	Fragmentation – Material properties may be changed by heat.
Cable Cutters	Explosively actuated piston and cutter impacts on anvil. One shot device used for cutting cables, electrical harness, chute lines.	
Nuts	Frangible nut enclosed in jacket which contains pieces after fracture. Used to release structural systems.	Fragmentation
Shaped Charges	Shaped charge uses "Monroe effect" to sever. Used for separation, jettison, or deployment release.	Fragmentation
Thrusters	Explosively actuated piston works like pin-puller in reverse. Used for separation, deployment, or jettison.	May utilize heat labile "O" rings.
Gas Generators	Provide sustained gas pressure. Used to inflate impact limiters. Deploy scientific payload devices.	

An initial study was made of the effect of ETO gas and heat on electronic components. Briefly, some transistors suffer a slight decrease in beta after exposure to ETO. Some resistors, such as carbon composite, metal film, and oxide film, show marked resistance drift and life loss after exposure to dry heat. Failure occurs in some transistors such as the 2N 559 GE Mesa transistor, and in polymeric wire insulations after the dry heat exposure. In general, the effects that may occur from dry heat and ETO gas sterilization treatment are shown in Table IV. The Design Guidelines manual also included a detailed discussion of structural and thermal analysis, materials selection, and canister design.

Volume II, Manufacturing Procedures, deals with the problems which arise from manufacturing and assembling a planetary lander which is to be sterilized. The currently preferred procedure for achieving a sterile planetary lander is assembly under closely controlled environmental conditions to achieve a low biological population, enclosure in a biological barrier, and dry heat sterilization. To avoid excessively long sterilization times which may adversely affect the reliability of critical lander systems, assembly of the lander with a low biological population is necessary. This requirement fundamentally affects all manufacturing and assembly operations. The maintenance of particulate and

TABLE IV. EFFECTS OF STERILIZATION TREATMENT

EFFECTS	TREATMENT	
	GASEOUS DECONTAMINATION	DRY HEAT STERILIZATION
Physical	Absorption or adsorption of the decontaminant or its constituent gasses.	Expansion, weakening, stress generation, stress relief, sublimation, outgassing, fractional distillation of volatiles. Rupture or fracture due to increased stress and loss of permanent magnetism.
Chemical	Reaction with decontaminant, polymerization of ETO on surfaces.	Decomposition, exo- or endothermic reaction within part, and reaction of part with contiguous materials.

biological cleanliness becomes as important as functional reliability. This manual gives detailed procedures for the manufacture and assembly of major components, subsystems, systems, and the complete spacecraft. It is recommended that piece parts be manufactured by conventional or non-bioclean methods, and that they be decontaminated or sterilized prior to their use in subassemblies. Subassemblies that should be manufactured by special procedures are listed in Table V. Final spacecraft assembly is to be performed in a clean room with bioclean controls.

TABLE V. SPACECRAFT SUBASSEMBLIES

ELECTRICAL SYSTEMS	THERMAL SYSTEMS
Electronic Cordwood Modules	Thermal Insulation
Printed Circuits	Thermal Coatings
Black Boxes	Heat Shield
Electrical Relays	MECHANICAL SYSTEMS
Electrical Harnesses	Structure
Photosensitive Tubes	Honeycomb
Magnetometers	Parachutes
Batteries	Pyrotechnic Devices
ELECTROMECHANICAL SYSTEMS	Solid Rocket Motors
Tape Recorders	
Gyroscopes	
Solar Arrays	
Antennas	

Volume II also contains sections on cleaning and decontamination, as well as parts packaging and special facilities such as laminar flow clean rooms and assembly/sterilizer rooms. A view of an assembly/sterilizer room is shown in Figure 3. This type of facility is proposed for use in final assembly after sterilization so that components sterilized by techniques other than heat can be introduced into the lander. The room is protected from microbial contamination from humans by enclosing the personnel in sealed, extendable suits.

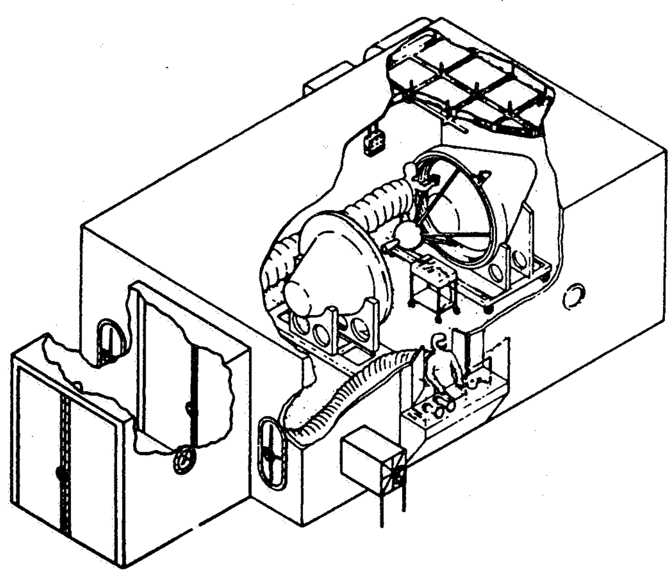


FIGURE 3. ARTIST'S SKETCH OF AN ASSEMBLY-STERILIZER

Volume III, the Biological Handbook for Engineers, provides microbiological background information useful to personnel who have had training and experience in the physical sciences but none in the life sciences. Subjects covered in Volume III are as follows:

1. Characteristics of microorganisms
2. Decontamination and sterilization procedures
3. Contamination control
4. Facilities
5. Bioassay
6. Effects of decontamination on materials

The first subject discussed, characteristics of microorganisms, provides basic information on microbiology required for a better understanding of the later sections of the handbook. The decontamination and sterilization section describes the techniques that may be employed in the manufacture and assembly of spacecraft that are to be sterilized. The section on contamination control describes sources of contamination, and the discussion of facilities describes clean rooms and personnel selection, motivation, and training. Bioassay describes the current approved methods of measuring bioloading on spacecraft and their components.

A serious problem in sterilization procedures is the need to remedy functional problems discovered after terminal sterilization (during prelaunch checkout). One approach is to use a heat sealable plastic envelope, which allows previously sterilized components to be inserted into a sealed spacecraft without breach of sterile integrity. This concept is shown in Figure 4. In each step shown, the sterile spacecraft is on the right and the sterile replacement item is contained in a plastic bag on the left. After the plastic bag is sealed to the plastic covered entry port on the spacecraft, the center is removed by cutting around the port through the middle of the 0.8 cm (5/16 in.) wide band of heat sealed plastic. Heat sealing and cutting are accomplished with tools included in the bag with the replacement item. After work on the spacecraft is completed, heat sealing a piece of replacement plastic to the entry port returns

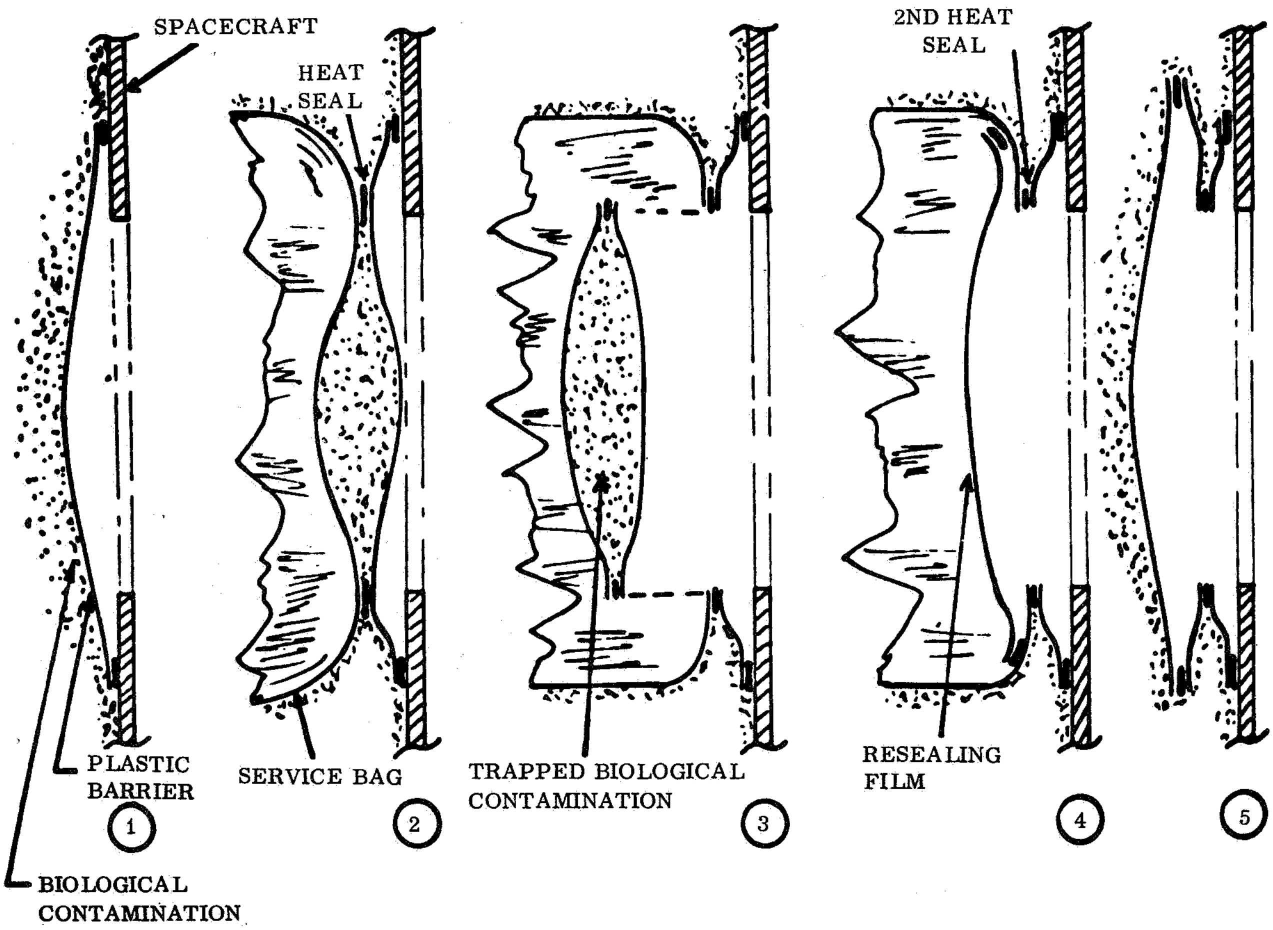


FIGURE 4. GENERAL CONCEPT FOR STERILE INSERTION

the craft to a flight readiness condition. The Manufacturing Engineering Laboratory has a contract with the Martin Company of Denver, Colorado, to investigate an initial phase of this plan. Any heat sealing and seam cutting processes used must not allow microorganisms trapped during heat sealing to be released from the cut seam into the sterile bag. It is essential to have perfect seals with no air pockets, and no live microorganisms should be exposed during cutting. The conditions of time, temperature, and pressure of sealing have been developed, which ensures strong seals and almost complete bacterial kill in the seam area. It has also been shown that the probability of release of organisms remaining viable after the heat sealing process is very remote.

Challenge System. It has been recognized that there will be certain components that probably cannot be heat sterilized in an assembled condition: that the parts will have to be sterilized before assembly and the component assembled in a sterile enclosure (Fig. 5). In a study conducted for the Manufacturing Engineering Laboratory by the McDonnell-Douglas Company, a particulate challenge system was developed and tested. This facility is shown in operation in Figure 6. The system consists of a double wall glove box with an aerosolized fluorescent dye contained between the double wall. The dye particles simulate bacteria. Within the inner wall is a very sensitive instrument for detecting any fluorescent dye particles which may be released through an accidental puncture in the inner wall. In this

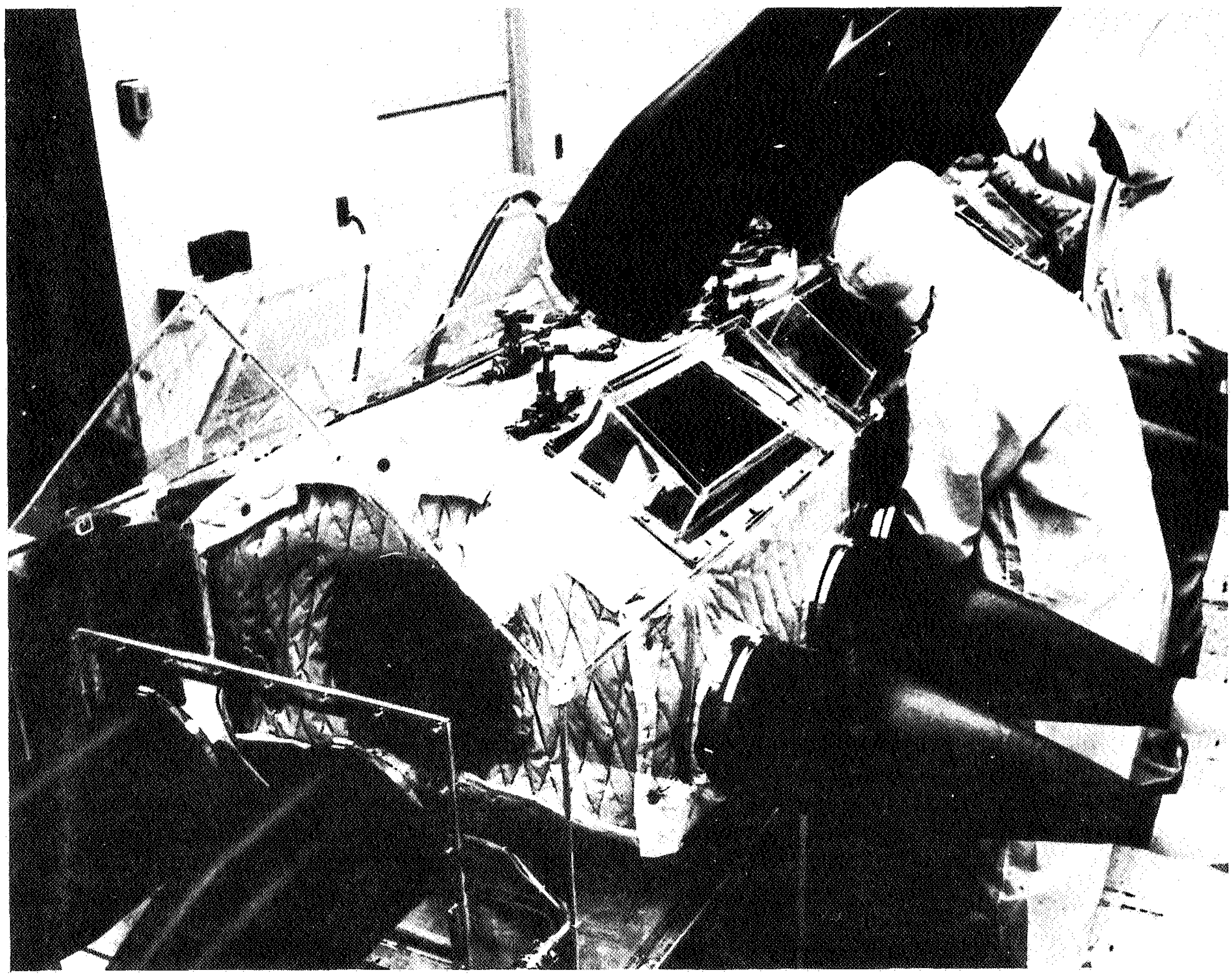


FIGURE 5. BIOLOGICAL CHALLENGE SYSTEM

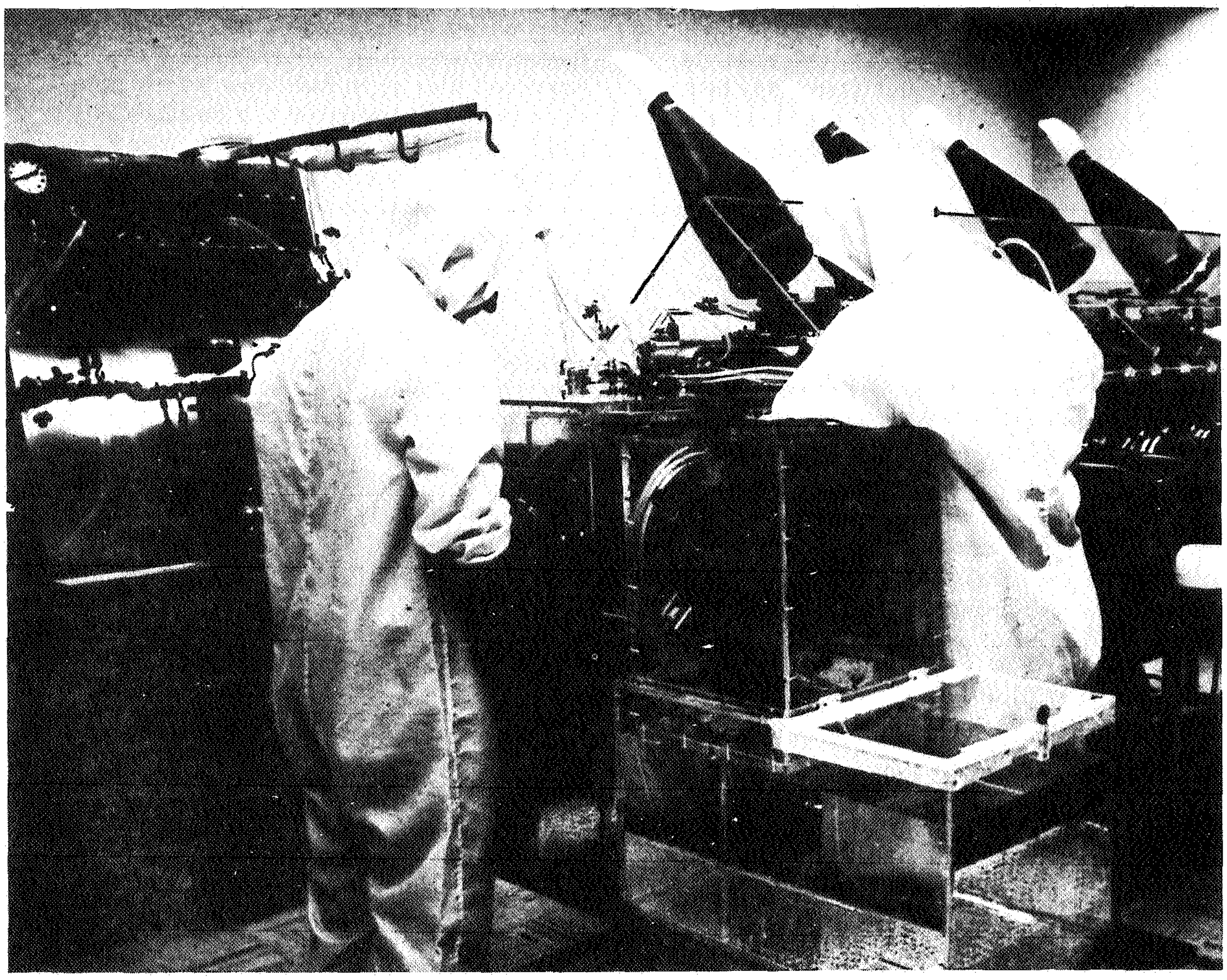


FIGURE 6. VIEW OF BIOLOGICAL CHALLENGE SYSTEM SHOWING DUNK BATH

manner, assurance of sterility is maintained during assembly

Information was also obtained concerning handling difficulties caused by the loss of tactile sensitivity when using the double rubber gloves. For example, it was found that assembly of tape recorders and pressure bottles in this sterile facility required approximately 12 times as many man hours as the same assembly on a conventional clean bench.

CLOSED CIRCUIT TV ARC GUIDANCE DEVELOPMENT FOR WELDING

By

William A. Wall, Jr. and Douglas L. Stephens

SUMMARY

Manufacturing engineers have long sought a reliable automatic arc guidance system for welding to simplify tooling and to perform remote welding. Several welding systems using automatic guidance techniques have been developed, but so far the results have been too limited for widespread industrial application. None of the systems were designed to track tack-welded joints. Tack welding aligns the weld components. Many complex parts are now tack welded prior to automatic welding, and this is when an automatic arc guidance system is really needed.

As a result, a program was initiated at MSFC to develop an automatic arc guidance system for welding. It was found that a closed circuit television (CCTV) signal furnished the data to permit the development of an automatic guidance system for the welding torch. This paper discusses the new CCTV system, its basic principles, and its scope of application. For system reliability, digital counting and logic techniques are used throughout the control circuitry.

The automatic video technique has shown considerable promise. Moreover, the creation of a new family of instrumentation can be achieved by using the same basic techniques developed for arc guidance control.

INTRODUCTION

Arc guidance may be defined as the means to accurately guide a welding torch along a weld joint. This function can be accomplished manually, mechanically, or automatically, with each mode having its unique application. The vast majority of space vehicle automatic welding uses mechanical tooling to maintain the required tracking accuracy of ± 0.75 mm (± 0.031 in.). Precision tooling is expensive, especially as parts increase in size and/or complexity. Automatic arc guidance could bring about a significant decrease in welding costs by minimizing the time required to assure that the torch and the joint are in perfect alignment. Moreover, there are some applications where the operator must, by necessity, be remote from the welding torch. Examples of this condition are the electron beam welding process and repair of radioactive parts. However, automatic guidance has not been widely used because there is no known commercially available sensing transducer that is sufficiently versatile.

PRIOR TECHNOLOGY

At least four general types of arc guidance sensors were evaluated, or considered for Saturn welding. These systems fall into the following major categories:

1. Electro-inductive.
2. Optical with photocell detectors.
3. Resistance of material.
4. Mechanical probes.

ELECTRO-INDUCTIVE TRANSDUCERS

The electro-inductive sensor [1] of Figure 1 operates on the principle of inducing eddy currents into the workpiece. Any shift in the weld joint will cause an unbalance in the reflected signal. The major advantages of this sensor are its compactness and ability to home in on the weld joint from a distance of at least 2.5 cm. Its major disadvantages are its susceptibility to stray electrical signals and other inherent problems listed in Table I.

TABLE I. RELATIVE MERIT RATING

AUTOMATIC ARC GUIDANCE MAJOR PROBLEM AREAS	RELATIVE TRACKING SYSTEM CHARACTERISTIC RATING*				
	ELECTRO-INDUCTIVE	OPTICAL WITH PHOTO CELL DETECTORS	RESISTIVE PROBE	MECHANICAL PROBE	CCTV ARC GUIDANCE
1. Type of material to be welded	Poor	Good	Poor	Excellent	Good to Excellent
2. Thickness of material to be welded	Poor to Good	Good to Excellent	Good to Excellent	Poor to Excellent	Good to Excellent
3. Symmetry of holddown tooling	Poor to Good	Excellent	Poor	Excellent	Excellent
4. Ferrous tooling metals	Poor	Excellent	Poor	Excellent	Excellent
5. Weld joint offset	Good	Good to Excellent	Good	Poor to Good	Poor to Good
6. Weld joint fitup	Excellent	Good to Excellent	Poor	Excellent	Good to Excellent
7. Distance changes from work to transducer (Proximity changes)	Poor to Good	Poor	Good	Good	Good to Excellent
8. Work surface finish	Excellent	Poor to Good	Poor	Excellent	Excellent
9. Welding arc light	Excellent	Good to Excellent	Excellent	Excellent	Good to Excellent
10. Welding arc heat	Poor	Excellent	Excellent	Good to Excellent	Excellent
11. Welding arc smoke	Excellent	Good	Excellent	Excellent	Good
12. Welding arc electromagnetic radiation	Poor	Good	Excellent	Excellent	Excellent
13. Stray electrical pickup interference	Poor	Poor	Good	Good to Excellent	Excellent
14. Electrical resistance of work material	Poor	Excellent	Poor	Excellent	Excellent
15. Weld joint special preparation required	Excellent	Poor	Good	Poor	Poor
16. Probe does not touch work	Excellent	Excellent	Poor	Poor	Excellent
17. Transducer field of view	Excellent	Poor	Excellent	Good	Excellent
18. System resolution of the field of view	Good	Excellent	Poor	Excellent	Excellent
19. Linearity of transducer signal over field of view	Poor	Poor	Good	Good	Excellent
20. Ability to track a tack-welded joint	Very Poor	Poor	Poor	Poor	Good to Excellent
21. Cost of system (Relative)	Good	Poor to Good	Excellent	Excellent	Good

* Excellent — Excellent system characteristic
Good — Had moderate bearing on performance
Poor — Had critical bearing on performance

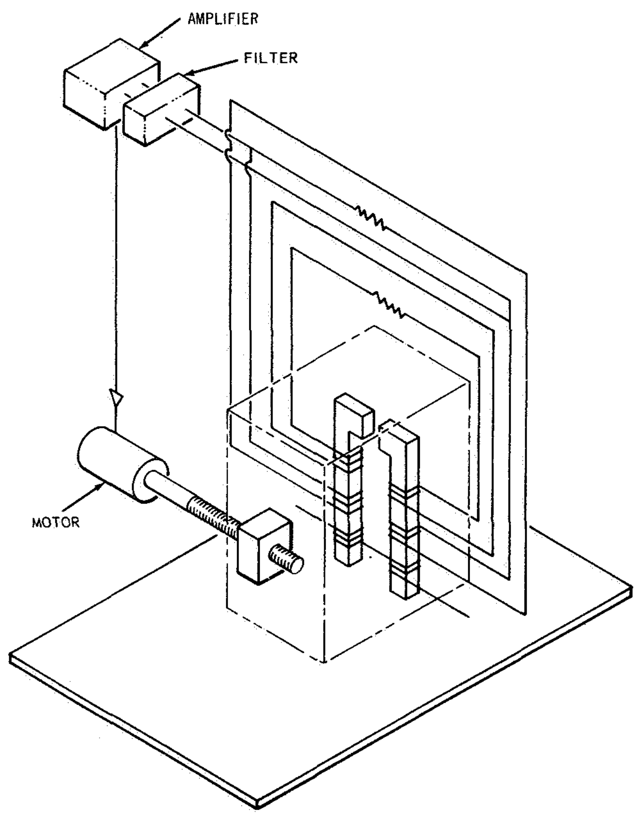


FIGURE 1. BASIC EDDY CURRENT ARC GUIDANCE

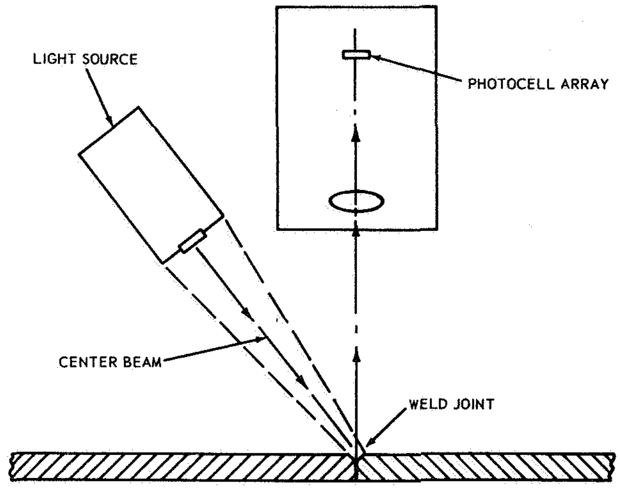


FIGURE 2. BASIC LIGHT BEAM ARC GUIDANCE

OPTICAL TRACKERS

Optical arc guidance trackers (Fig. 2) obtain their signal by focusing an intense light beam on a chamfered weld joint and sensing the reflected light amplitude on a photocell array. Setup of this equipment over the weld joint is very delicate; also, the sensor becomes completely lost if the light beam ever strays from the weld joint for any reason. This blindness is mainly a result of its very small field of view.

RESISTANCE OF MATERIAL TRACKERS

The resistance of material technique is implemented by two probes, one on either side of the weld joint. These two probes ride on the work surface and are take-off points for measuring the electrical resistance of the material for guidance purposes. Any resistive deviation from the initial setup condition would indicate a shift in the weld joint. This method was never successful on aluminum material because of the material's low electrical resistance.

MECHANICAL PROBES

The fourth method, or mechanical probe, is basically very simple. A mechanical probe attached to a delicate electromechanical transducer is dragged along a groove in the weld joint. In theory, any seam deviation is reflected as an electrical signal from the electromechanical sensor. For several reasons, this technique may not always be desirable. Weld joint offset can cause considerable error; in addition, a dragging probe can distribute minute particles of contaminates along the weld seam. This is serious because contamination has been established as the major cause of weld porosity. For this reason it has long been a welding requirement at MSFC that nothing touches the welding area after it has been cleaned.

SUMMARY

It is not the intent of this report to thoroughly discuss the merits and limitations of prior technology.

Rather, these welding techniques are briefly mentioned to stress the fact that there is good reason to pursue a more reliable system. Arc guidance was needed on the Saturn V S-IC bulkhead weld fixture, but early in the welding program it was determined that the weld joints must be tack welded [1] to maintain alignment of the large parts. Since none of the above mentioned systems would work on tack-welded joints, manual cross seam control was the only resort. Fortunately, this mode of operation was successful primarily because the welding process travel speed was very slow (7.5 - 30 cm/min). Following some promising preliminary feasibility tests, a project was initiated to take advantage of the visual aspects of closed circuit television (CCTV) to solve the problem of tracking tack-welded joints. As a result of this effort, such a system is fast emerging as a workable model (Figs. 3 and 4). Table I gives a relative rating of prior tracking systems and the CCTV guidance system when judged in light of the 21 major problem areas. A rating of excellent in all 21 categories would indeed indicate an ideal arc guidance

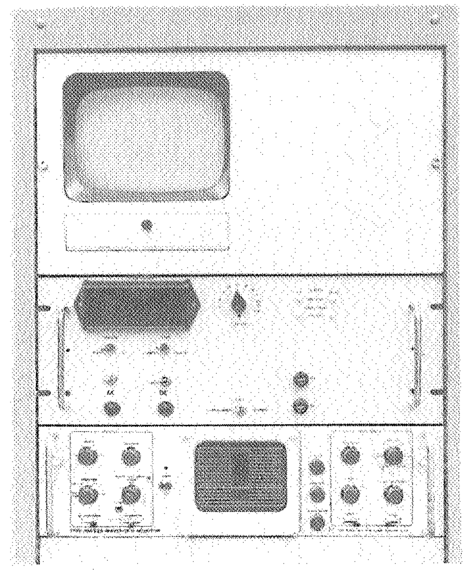


FIGURE 3. CCTV TRACKING ELECTRONIC CONTROL CABINET

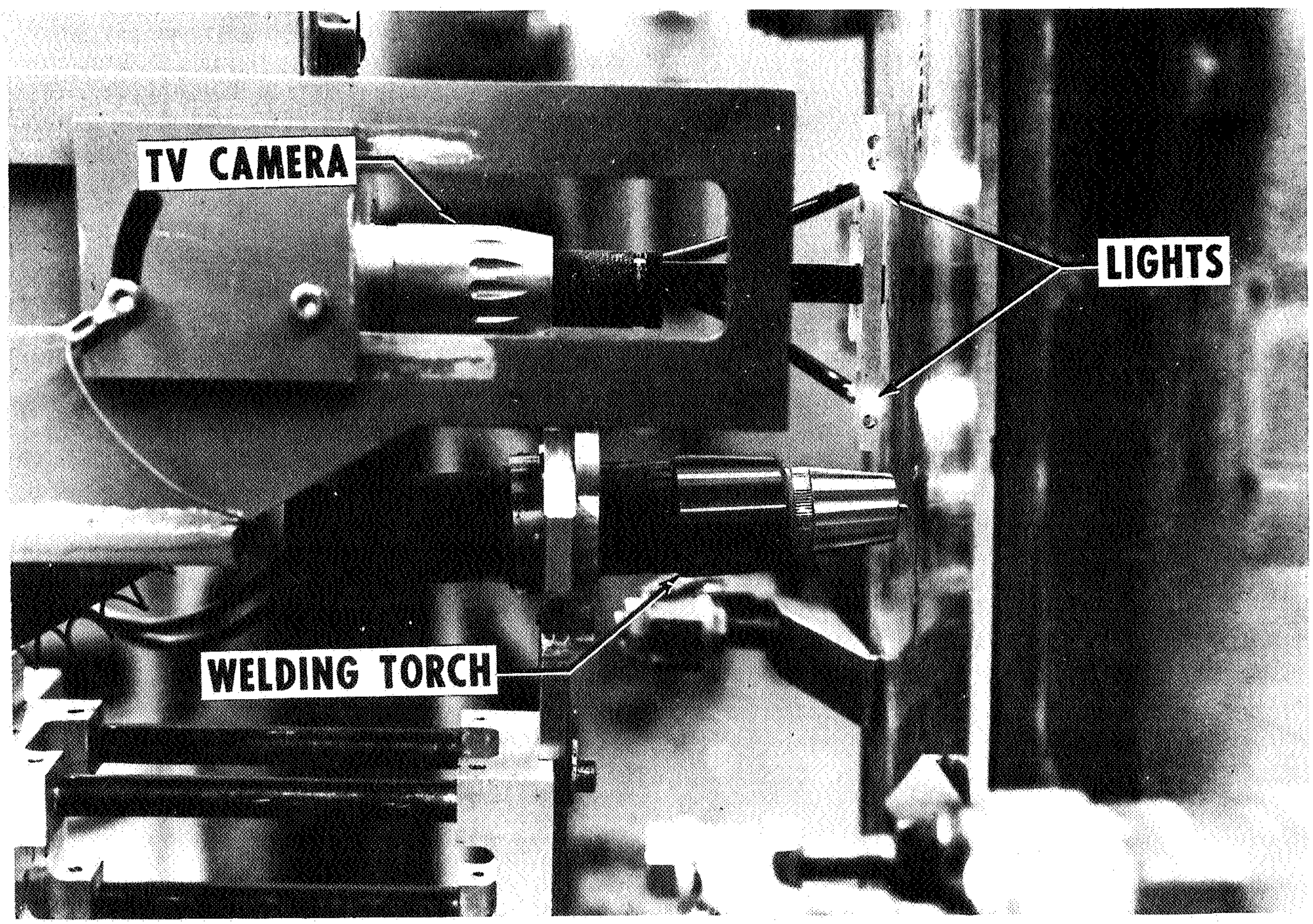


FIGURE 4. CCTV TRACKING WELDING HEAD

technique. A rating of poor in any category indicates that either special design or application precautions must be taken or that the system is inherently below par when compared with the ideal criteria.

CCTV ARC GUIDANCE

To better grasp how the CCTV arc guidance system functions, it may be helpful to review some of the basic principles of standard television equipment. The electronic equipment in a television camera systematically scans the scene that is to be reproduced and, by a photo-electronic means, produces a voltage proportional to the light intensity of the particular portion of the scene being scanned. Scanning has a certain pattern sequence and rate. As a scene is scanned by the electronics of the TV camera, it is simultaneously reproduced in the receiver. The rate of scan is rapid enough to give the appearance of motion as another scene appears. Figure 5 is a diagram of the pattern and sequence of scanning, which is termed the raster.

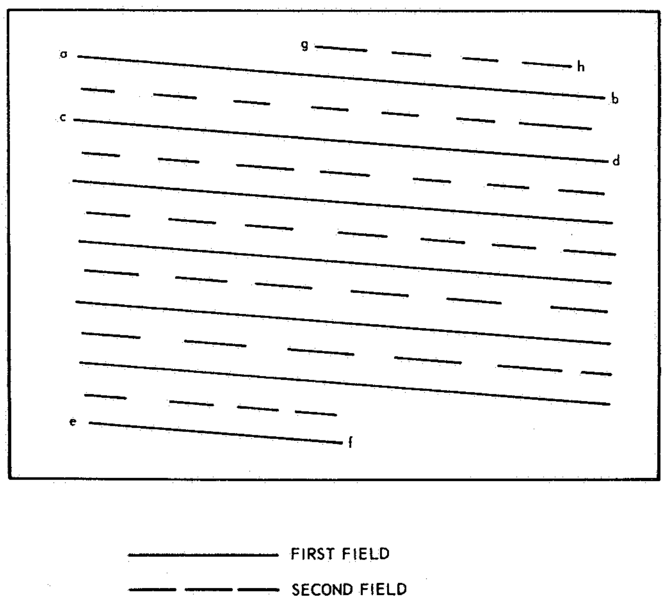


FIGURE 5. TV RASTER SCAN

TELEVISION RASTER SCAN

The scanning spot starts at point a and travels at a uniform rate to point b. When point b is reached, the scanning spot quickly returns to point c to start the second line cd. During return intervals, the spot is blanked out and is not shown in the figure. The standard television field is scanned from top to bottom and returned to the top in 1/60 sec. When the scan of the first field is completed, a second field is scanned and then interlaced between the lines scanned in the first field. The two fields make up one television picture frame. There are 525 scan lines in a frame, or 262.5 lines in each field.

The scan beginning at the top of each field and the start of each horizontal line must have a precise timing control. A voltage pulse is generated 60 times a second, which is recognized by the television circuitry as the beginning of a field scan. This is termed the vertical synchronization pulse. Another form of pulse is generated at a rate so that there are 525 pulses during the period of 2 fields, or 1 frame (1/30 sec). These pulses control the beginning of horizontal scan movement, which results in 262.5 lines per field. They are termed horizontal synchronization pulses.

One method of reproducing the video information in electrical form is to optically focus the scene on a photo sensitive surface in an electronic tube. The tube has an electron gun that emits a beam of electrons to strike the photo sensitive surface. The vertical and horizontal sync pulses control the electronic focusing circuits that guide the electron beam to strike the photo sensitive surface in the scanning pattern at a given instant of time; therefore, the beam will be striking the surface at a particular point. Because of the characteristics of the photo surface, the magnitude of the electron beam current will be proportional to the light level at any particular spot on the surface. Since the beam position is scanning or varying with time, the beam current will also vary with time. This current produces a voltage signal representative of the light variations along the scan path.

The varying voltage or video information from the camera is then formed into a composite signal, along with the vertical and horizontal timing pulses, before being transmitted to the receiver. A basic composite signal is shown in Figure 6. The video information is the upper portion of the composite signal, and its height is above the 0.5 V line. Amplitudes of the video information are proportional to the relative whiteness of the scan position on the screen. The part below the 0.5 V line on the composite signal is the timing information for use in the receiver that must reproduce the picture on its screen.

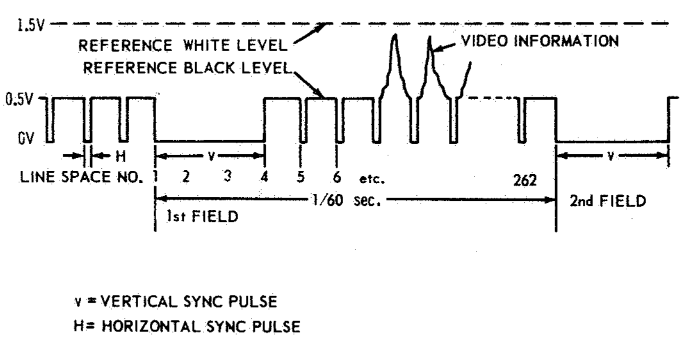


FIGURE 6. COMPOSITE VIDEO SIGNAL

The receiver screen is the face of a tube treated so that its area will glow in proportion to the electron density striking its surface. The receiver separates the video information from the timing pulses. Tube scanning is controlled by the signal pulses, and the receiver beam current is controlled by the video information level to reproduce the picture on the screen.

BASIC SYSTEM OPERATION

Figure 7 is a symbolic diagram of the operation of the basic video welding arc guidance system. The purpose of welding arc guidance is to maintain the welding arc on the weld seam as the area to be welded moves past the torch in the Y direction. A closed circuit television camera is assumed to be mounted in-line with the torch, and the camera is positioned so that the weld centerline runs horizontally, left to right, as viewed on a television monitor. Since the weld joint centerline is parallel to the horizontal lines of the television scan, the centerline image will mainly occupy only one scan line as viewed on a television monitor. Proper arrangement of lighting on the weld joint by two bright light sources will cause this video scan line to be much brighter than the remainder of the lines. This extra bright line in the video signal is easily separated from the composite video signal and is used for guidance purposes.

In operation, the composite video signal from the TV camera is first routed to video viewing and waveform monitors and then to a blanking circuit to remove unwanted portions of the signal. Next, the signal is amplified to raise its voltage and power to a level that can be used by the logic section. Logic circuits then separate the video information from the synchronizing pulses to control a binary counter. Because of the control in the logic circuit, the counter will begin counting at the top of the television field and will count each successive horizontal line (1, 2, 3, 4, 5. .) until the bright line caused by

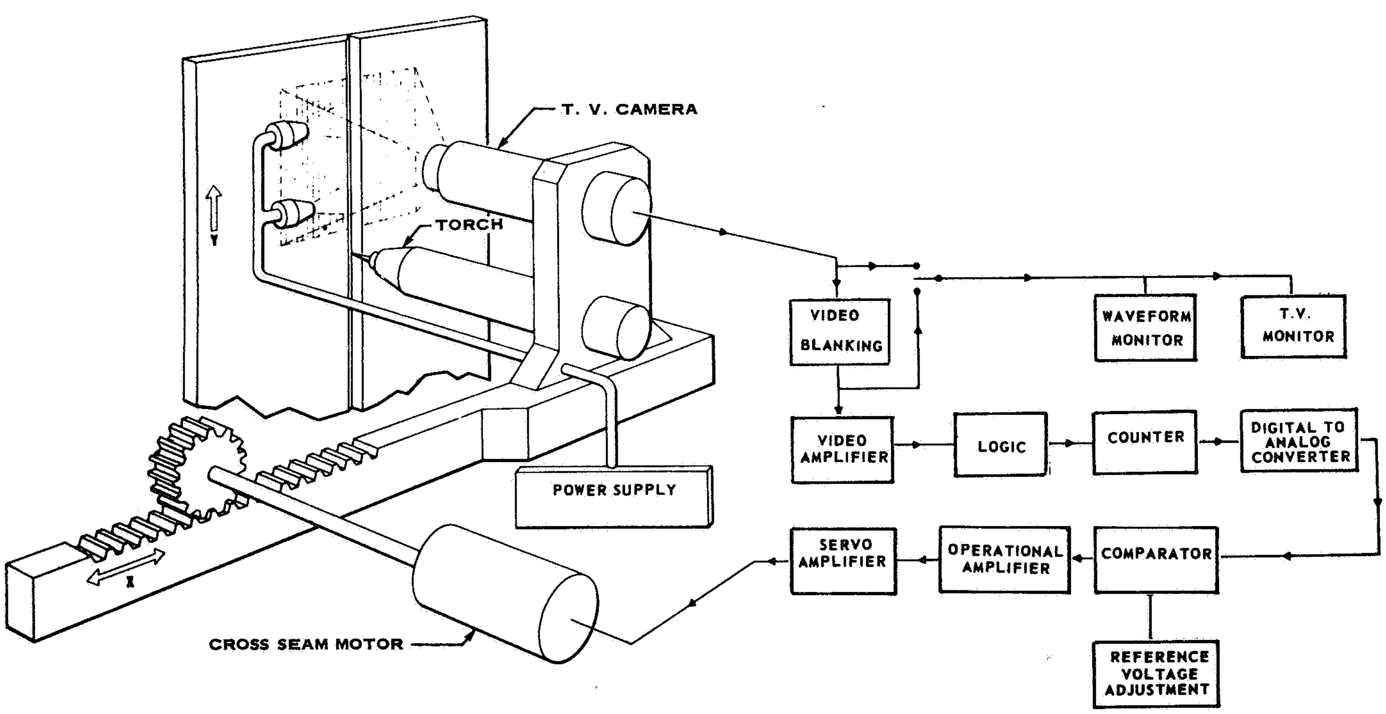


FIGURE 7. BASIC CCTV ARC GUIDANCE SYSTEM BLOCK DIAGRAM

the weld joint illumination is sensed. Appearance of the bright line stops the counter on that horizontal line number. This number is then stored in a flip-flop register and the counter is reset for operation during the next television field.

The stored horizontal line number in the register is next fed to a digital-to-analog (D-A) converter which converts the number to a proportional dc voltage. This dc voltage representation of the stored number is then algebraically summed with a reference voltage. The reference voltage can be set to a level corresponding to any scan line position desired, but it is usually set to a level near the center of the field of view. If the (D-A) output dc voltage level is either less than or greater than the reference dc voltage level, the difference between the two voltages will be a plus or minus dc error signal to the torch positioning servo amplifier.

An error signal to the servo amplifier causes it to drive the motor in a direction that will move the camera-torch carriage along the X axis. Polarity of the error signal to the servo amplifier determines the direction of the X axis movement until the error difference is nulled. New error information is received much more rapidly than the carriage can move because the counter is counting and supplying new tracking data each time a television field is scanned. Since the television field is scanned sixty times per second, the counter will supply new tracking data each 1/60th of a second. A continuous and rapid supply of position information allows the servo system to guide the welding arc on the weld centerline.

CAMERA AND LIGHT SOURCE POSITIONS

Figure 8 shows a typical arrangement of light projections and the relationship of the weld subject and camera for butt welding tack-welded joints. Two illumination devices containing projection lamps focus their intense light on the receiving end of two fiber-optic tubes. The emission ends of the fiber-optic tubes serve as illumination sources to project light as shown in Figure 8. In Figure 8-A, the path of light from the fiber-optic tube is shown reflecting from the chamfer of the weld joint into the camera. The angle of incidence, A, is equal to the angle of reflection, B, so that the light reflected from the chamfered surface is much brighter at the lens position than is any of the light received from other

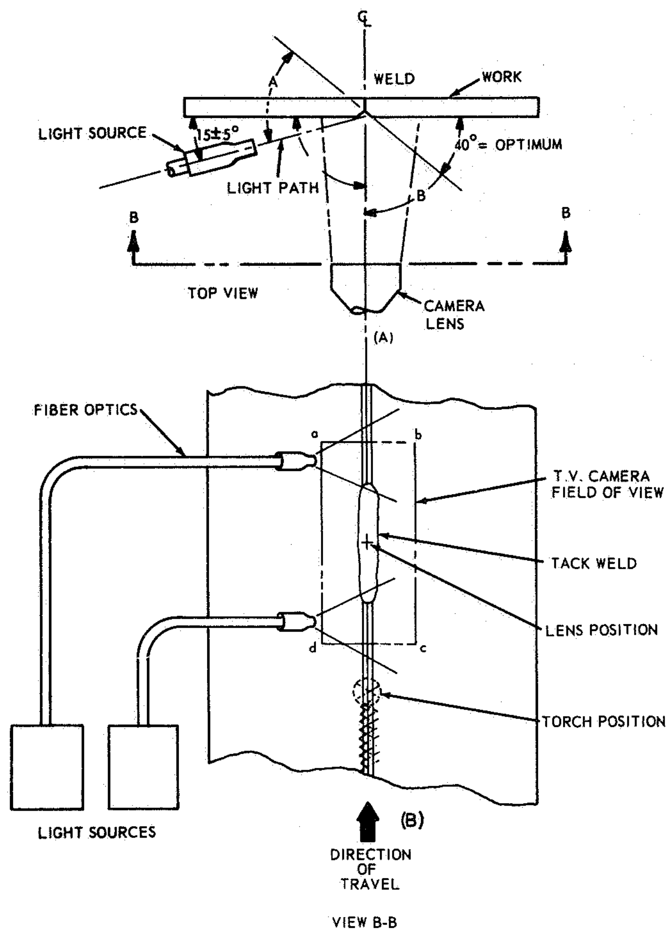


FIGURE 8. JOINT ILLUMINATION SCHEME

surfaces of the metal. This capability to obtain an extra bright image at the chamfered surface makes it useful as a reference of the true weld centerline position. The light beam sources and the camera may be mechanically attached so that they have a fixed physical relationship. When the weld joint appears near the top or bottom of the field of view, rather than the center of the field of view, the angle of reflection will change and cause the brightness of the chamfer image to diminish slightly. However, there is not sufficient loss of brightness to affect the tracking capability.

In Figure 8-B, area abcd will be the field of view displayed by the television monitor screen of Figure 9. The two light sources shown in Figure 8-B serve to provide the necessary illumination of the chamfered surface when a tack weld appears in any portion of the field of view. Tack welds must

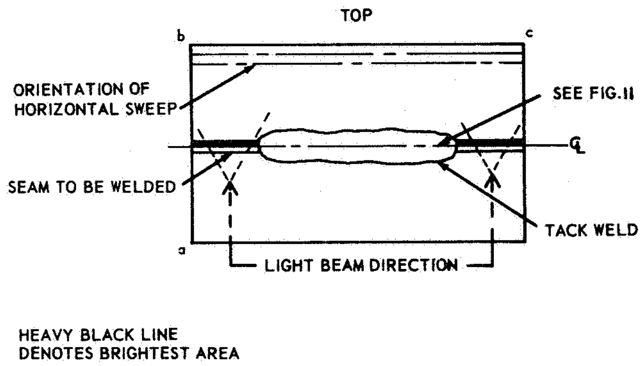


FIGURE 9. MONITOR SCREEN

be limited to less than the length (bc) of the field of view so that some part of the chamfered surface will always be visible to the camera.

VIDEO WAVEFORM

The shape of the TV waveform is important to the electronic tracking circuitry. Figure 10 is an

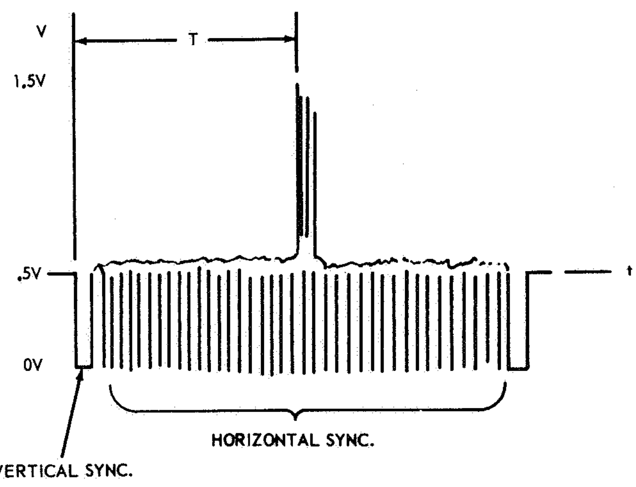


FIGURE 10. WAVEFORM OF VERTICAL FIELD

example of the necessary waveshape of the vertical sweep of the closed circuit television system. The high positive peak of this waveshape is caused by the bright reflection from the above described chamfered surface. This high peak is made up of the few horizontal television lines that are the brightest area of the monitor screen shown in Figure 9. The 0 to 0.5 V pulses of the waveshape are standard vertical and horizontal synchronization pulses of a composite television signal. Figure 11 shows the waveform of the brightest horizontal line sweep of the monitor screen.

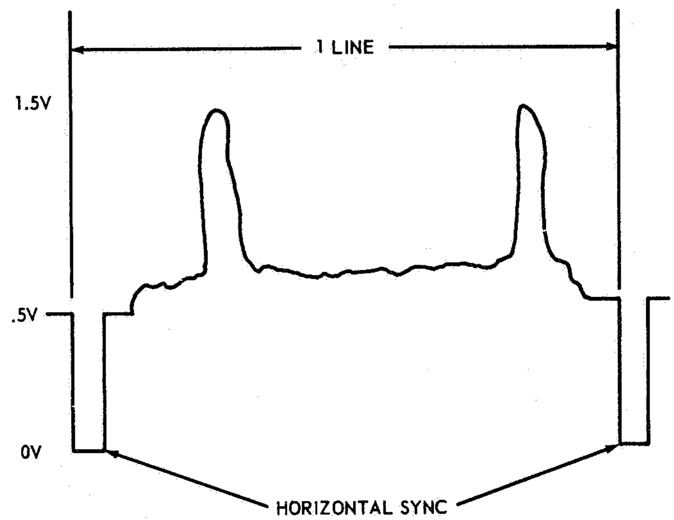


FIGURE 11. WAVEFORM OF HORIZONTAL LINE CONTAINING BRIGHTEST REFLECTIONS

VIDEO BLANKING

In most automatic tracking situations the horizontal line waveform of Figure 11 is the most desired form of tracking information. The high peaks on the left and right side of this waveshape are the only desired information; high peak information between these two peaks would only be caused by some unwanted reflection from a surface scratch or tack-weld edge. The video blanking circuit may be switched on to eliminate the effect of such reflections and is one of the video systems' means of discriminating true information from error information.

The video blanking circuit is timed by the horizontal synchronizing pulses. The blanking circuit operates by chopping out all video information in each horizontal line except at the left and right ends of the line or screen. The resulting video monitor appearance is shown by Figure 12. The effect is

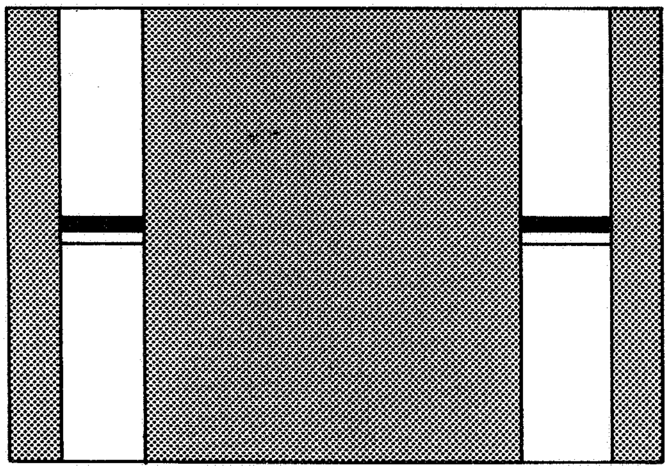


FIGURE 12. MONITOR SCREEN VIEW WITH BLANKED SIGNAL

that of masking off all except two strips of the viewing area of the subject, and any light reflections in the dark area of the picture will have no effect on the tracking. Of course, width and position of blanking are fully adjustable in the actual hardware.

In practice, use is made of the two light sources to track tack-welded joints. If the weld joint is not tack welded, only one light source is required. Although the one-light system is fairly straightforward, the technique used to track tack-welded joints warrants further explanation.

TRACKING TACK-WELDED WELD JOINTS

Two modes of tracking, "straight" and "curved," are available in the CCTV guidance system.

In the "straight" tracking mode, the seam to be followed must not deviate from a straight line more than the prescribed tolerance of ±0.75 mm (±1/32 in.) in 7.5 cm (3 in.). Although the seam must be straight, the angle of the seam with respect to direction of travel is not critical and the guidance can easily follow the constant offset. This mode is the simplest to set up and operate.

In the "curved" mode of operation, initial camera alignment is such that the seam can be followed when the seam varies from a straight line at a rate exceeding 75 mm in 2.5 cm. Analog computing and memory circuits are used in this mode and are not used in the "straight" tracking mode; therefore, the "straight" tracking mode should be used whenever possible to avoid tolerance buildup.

Straight Mode. Figure 13 points out the relation between the direction of travel, the arbitrary seam

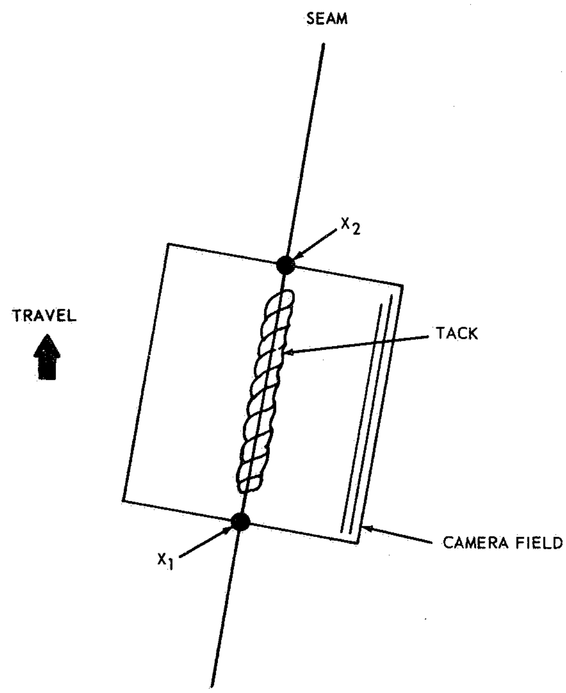


FIGURE 13. STRAIGHT SEAM OPERATION

angle, and the camera orientation. In Figure 13 the camera has been rotated so that the horizontal scan lines of the camera are parallel to the straight weld seam. This causes bright spots X_1 and X_2 to appear in the same scan line. Now, when the tack weld moves to blank out the X_1 bright spot, bright spot X_2 will still provide the information to indicate which scan line the weld seam occupies. A distinct advantage of this mode is that the tack weld does not have to be sensed in order to switch computing circuits.

Curved Mode. Figure 14 describes a possible curve tracking situation and points out the relation between the direction of travel, and the camera orientation and the variable seam. In Figure 14 the camera has been rotated so that the horizontal scan lines of the camera are parallel to the plane of travel. Bright spots X_1 and X_2 each have a video field line position dependent on the seam's angular relation to the planes of travel. As the tack weld moves to block out X_1, the circuits sense the tack weld and hold in memory the last true information giving the scan line positions of X_1 and X_2. The analog circuits are then switched into the circuit to use (1) the ΔS information supplied by the memory of X_1 and X_2 and (2) the known time Δt. This information is necessary to provide a computed path from X_1 to X_2 for the welding torch to follow during the loss of video information caused by the tack weld. At the end of the tack-weld period, the system switches back to X_1 to follow the seam.

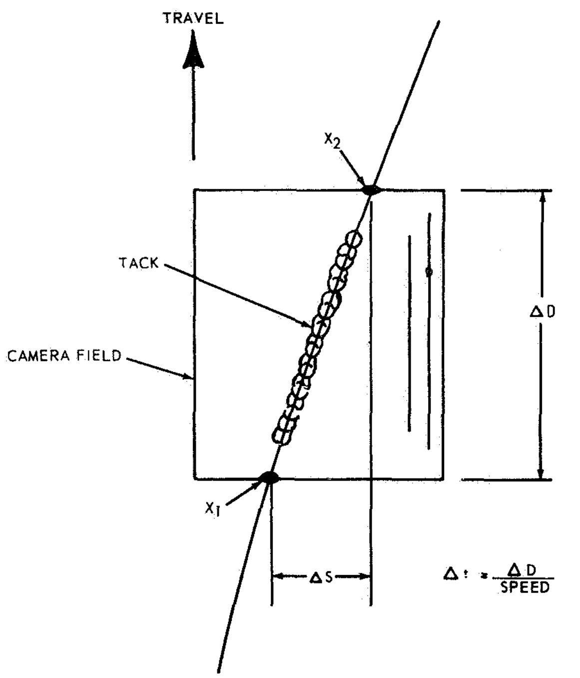


FIGURE 14. CURVED SEAM OPERATION

Since the camera normally follows a straight line from X_1 to X_2 over tack welds, it is desirable to place tack welds over a relatively straight portion of the weld joint. Error caused by following a straight line through a curved tack will depend on the degree of curvature. A higher order of computing could be added, if necessary, to produce a curved path from X_1 to X_2.

APPLICATION NOTES

The present equipment is being developed to track the following general types of weld joints:

1. Highly irregular weld joints without tack welds.
2. Moderately irregular weld joints with tack welds.
3. Butt joints, overlap joints, or tee joints.

In addition, the guidance equipment should operate equally well on a wide variety of metals including, but not restricted to, (1) aluminum, (2) steel, (3) stainless steel, (4) copper, (5) titanium, and (6) alloys of these metals. The surface condition of the work (bright, dull, painted, rusty, etc.) generally has no effect on the operation; however, some joint preparation is necessary to assure success. Examples of the typical joint preparation are shown in Figure 15. It should be pointed out that the required

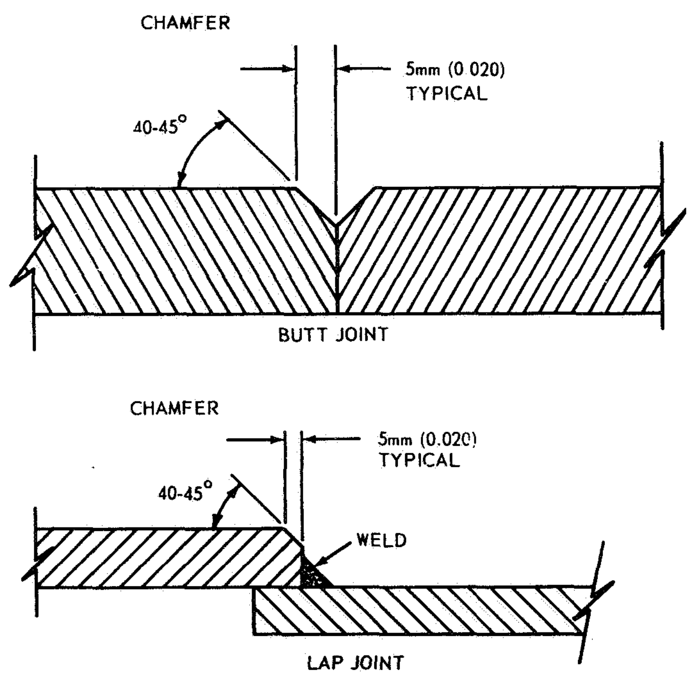


FIGURE 15. TYPICAL JOINT PREPARATION

joint preparation is a relative consideration. The amount and type of chamfer is only that necessary to get a good reflection. On a dull material, such as steel, simply breaking the edge with a file or router would probably suffice. As a general rule, the more precise the tracking requirement, the more precise the joint preparation.

As for camera location, one major advantage is that the CCTV system can operate almost equally well whether the camera is stationary mounted (Fig. 16) or integrally mounted with the welding torch cross seam positioning mechanism (Fig. 17). If necessary, generous use can be made of coherent fiber optics to pipe the light signals into the camera.

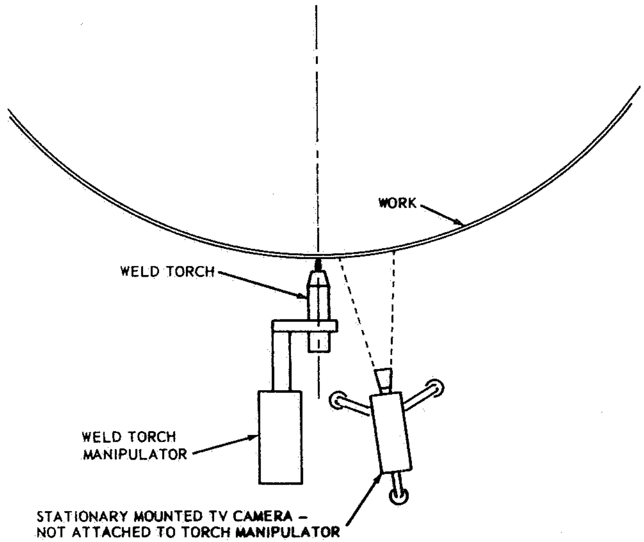


FIGURE 16. CCTV CAMERA MOUNTED REMOTE FROM TORCH

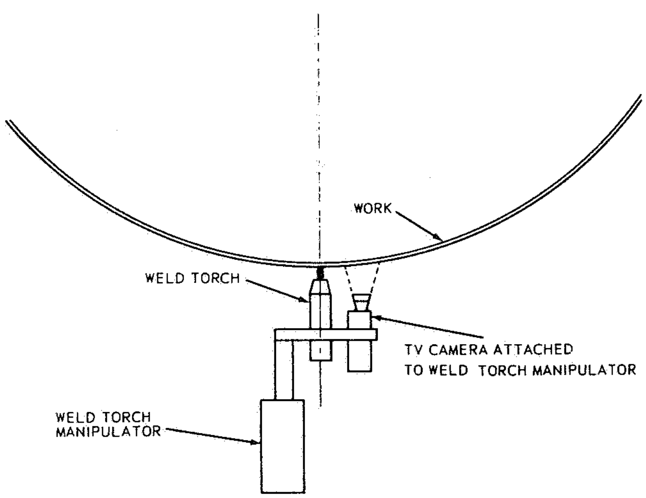


FIGURE 17. CCTV CAMERA MOUNTED WITH TORCH

Also included as an option is a dc signal time-delay unit. This module accepts the dc signal from the digital-to-analog converter and delays it for torch positioning a few seconds later. A delayed signal is needed when the joint varies at a rate exceeding ±0.75 mm (±0.031 in.) per every 5 cm (2 in.) of weld. If this delay were not used, the torch would not necessarily be located over the joint although the guidance intelligence is correct. Of course, this is because the intelligence is being sensed ahead of the torch. The closed circuit video equipment which may be used to view the joint is standard broadcast quality Vidicon apparatus. Generally, this means that the horizontal and vertical sync pulse generator outputs a signal meeting broadcast standards. This requirement assures steady, accurate tracking. CCTV equipment of this type is not necessarily expensive, and has been developed to a high degree of economy and reliability. Except for the blanking, the power amplifier, and the logic sections of the system block diagram, the equipment is, or could be, standard vendor's items. Packaging of all the electronic control equipment on the prototype model, Figure 3, is within a 48.26 x 137 cm (19 in. x 54 in.) rack space. This includes the time-delay module that was mentioned earlier.

UNIQUE ADVANTAGES OF CCTV ARC GUIDANCE

In brief, some of the major highlights of this welding arc guidance technique are as follows:

1. The sensor has the capability, like the eye, to look at a relatively large welding area. Yet the accuracy, or resolution, is as fine as the physical distance between two TV lines projected on the image plane. This resolution is a result of the video-digital technique used to extract the joint location. Accuracy, therefore, is a function of the vertical field of view, in centimeters (inches), at the image plane, divided by the number of TV lines of the system. For a 525 line system, the resolution is ±0.2 percent of the field of view.

2. The video system takes advantage of a digital technique to yield a go or no-go signal. Use of the sweep, or scan, technique of video allows the engineer unparalleled latitude in designing circuits to derive tracking information, time information, and electronic logic control.

3. One sensor, the TV camera, is all that is required to gather the welding arc guidance information even when tack welds are present on the work piece. This camera may be located reasonably remote from the joint.

4. The signal from the tracking circuit digital-to-analog converter is essentially linear; hence, the camera could be mounted stationary, if required, and the torch could be accurately guided. This feature would eliminate the need to keep the TV camera close to the welding torch if conditions were adverse in that area.

5. The tracking signal from the standard video camera is relatively large, usually 1 V or greater. This amount of signal is almost immune to most electrical noise problems when standard precautions are taken.

6. This system is engineered to track tack-welded joints as well as nontack-welded joints, and hence exceeds the capability of all known welding arc guidance equipment.

7. This system can track thin or thick metals with equal capability. Generally, weld tooling is no problem and stray light does not normally present a problem. The blanking circuit in this system can be adjusted prior to welding to electronically block all but the wanted signals from entering the tracking logic electronics. At the same time, the entire composite picture can be viewed by the weld operator on a conventional video monitor.

8. The mounting distance from the work to the TV camera (transducer) can vary from a few centimeters to meters. Variation of proximity distance, within the depth-of-field of the lens, does not affect tracking accuracy.

9. Offset of the welding joint edges (one side higher than the other) for square butt joints need not affect tracking accuracy since this trouble spot can be eliminated by proper design of the joint lighting system.

CONCLUSIONS

The CCTV arc guidance development is not a panacea, but it could well turn out to be the most versatile welding arc guidance system yet developed. Use of the scanning method, the vertical and horizontal sync timing pulses, and the digital electronic go or no-go logic circuits literally opens the door for the imaginative engineer. As a result, engineers have only begun to take advantage of the visual information available. Not only are major improvements to the CCTV guidance system possible, but also a completely new class of instrumentation could be created for alignment and recording purposes. Much work still remains to be done to qualify the necessary optical and mechanical hardware for practical application in the field. However, progress has been rapid, and there is every reason to believe that this technique will prove to be highly effective.

REFERENCE

1. Selected Welding Technique, NASA SP-501, Washington, D. C., April 1963.

MECHANICAL DEVICES FOR ZERO GRAVITY SIMULATION

By

Vaughn H. Yost

SUMMARY

Mechanical simulator development conducted in support of the Apollo Applications Program and in anticipation of future programs is summarized in this review. Mechanical simulators that have been developed are illustrated and their characteristics described. Results are reported on investigations of air bearing systems, air bearing cart thrust systems, and devices for supporting hand tools and the serpentuator. Applications of mechanical simulators are also illustrated.

INTRODUCTION

The Manufacturing Engineering Laboratory divides earth orbital weightless and lunar gravity simulation devices into two categories: mechanical and neutral buoyancy. Mechanical simulators include all those devices that do not use a liquid such as water to support the subject, workpiece, or tool.

Some of the objectives of mechanical simulation are evaluation of design concepts, evaluation of hardware, and determining the subject's capability for performing tasks.

Mechanical simulation offers certain advantages over neutral buoyancy simulation in that much less preparation time is required. It can be performed by a minimum of two people (a test subject and technician to balance him and operate the suit), and the simulators can be moved to the work site. The advantages of neutral buoyancy simulation over mechanical simulation are that complete tasks requiring vertical clearance or large changes in vertical elevation can be performed in one operation as opposed to breaking the task up into several part tasks so that it can be performed in a mechanical simulator.

The research and development efforts in the mechanical simulation category are discussed in this review under the divisions of mechanical simulators, air bearing systems, air bearing cart thrust system development, devices for supporting hand tools and serpentuator, and the use of mechanical simulators.

MECHANICAL SIMULATORS

FIVE-DEGREES-OF-FREEDOM SIMULATOR

1. General Information

The five-degrees-of-freedom simulator is an aluminum framework mounted on air-bearing pads. Yaw and horizontal translation in two directions are obtained by moving the entire simulator on its air-bearing pads. Pitch and roll motions are obtained through gimbals mounted with anti-friction bearings. Pitch is the only motion that is limited. This simulator was designed to be used with the Lunar Gravity and Earth Orbital Simulator that is described in this paper.

2. Technical Information

The five-degrees-of-freedom simulator consists of three major assemblies: a cradle or seat, roll yoke, and base (Fig. 1). The cradle, or seat, supports the subject in an erect position and contains provisions for adjusting the position of the subject relative to the roll and pitch axes of the simulator. The roll yoke supports the cradle at the pitch axis and permits 108 degrees of rotation in pitch between the cradle and the yoke. The yoke also contains a system for supplying ventilation, breathing, and pressurization gases to a subject in a space suit.

The "U"-shaped yoke is supported at the base of the "U" roll bearings that permit unlimited rotation around the roll axis. The base structure supports the roll bearings and distributes the total load of the simulator and subject to three air-bearing pads equally spaced around the nominal yaw axis.

The simulator has an onboard air supply which requires a 115 Vac, 5 A, 60 Hz (60 cps) power input.

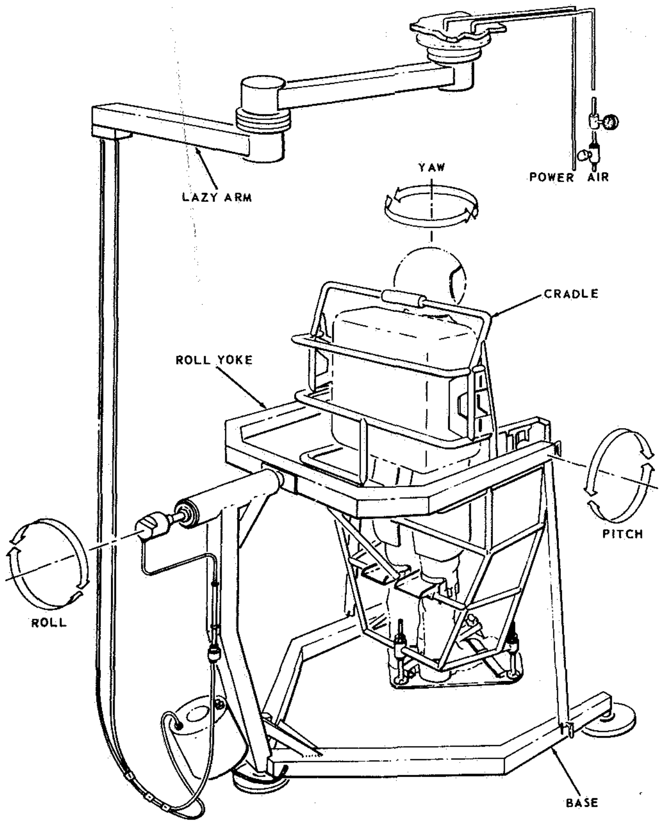


FIGURE 1. FIVE-DEGREES-OF-FREEDOM SIMULATOR

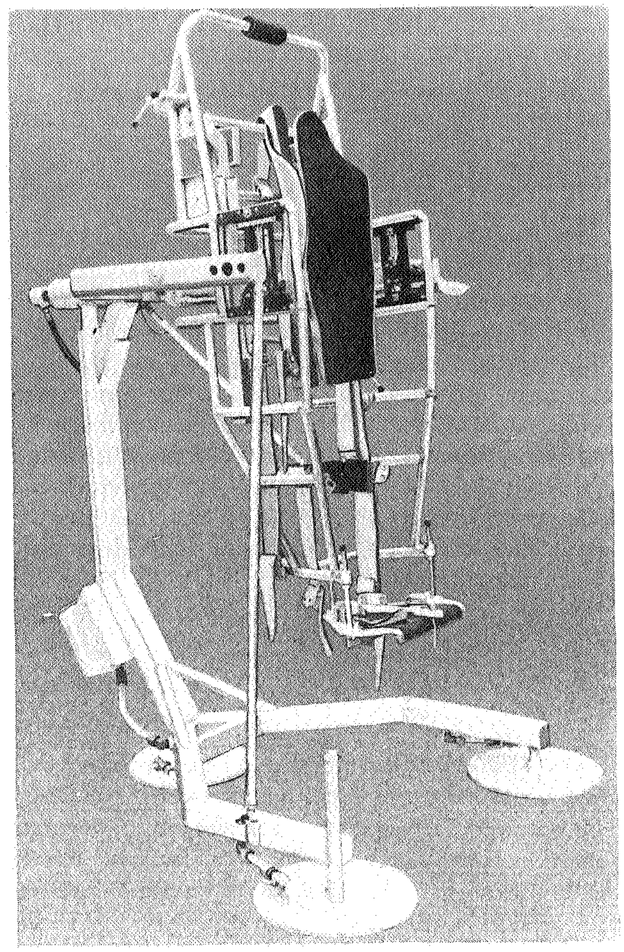


FIGURE 2. FIVE-DEGREES-OF-FREEDOM SIMULATOR WITH CRADLE ASSEMBLY ATTACHED

In addition, there are provisions for supplying 0.283 m^3/min (10 scfm) of breathing and suit pressurization air at 0.31 MN/m^2 (45 psig) through a hose to the subject.

A lazy arm may be used to minimize the hose and power cable drag by positioning the hose in an essentially constant vertical position. Air is fed through rotating unions so that each of the two sections of the lazy arm is capable of unlimited rotation.

Cradle Assembly. The cradle assembly consists of the supporting structure for subject and back pack; the subject's restraint system, consisting of the torso corset, leg supports, and restraining straps; and the vertical and fore and aft balancing adjustments and pitch axis ball bearings (Fig. 2).

The supporting structure is welded tubular aluminum with an aluminum foot plate supported by three adjustment screws. The adjustment screws permit raising or lowering of the subject's center of gravity (c.g.) over a 0.152 m (6 in.) range to place the c.g. within the range of the vertical balancing adjustment. The back pack supports are attached with machine screws fitted in slotted holes to permit vertical adjustment of the back pack position over a range of 0.076 m (3 in.). Right and left adjustment of the back pack position is accomplished by selective tightening or loosening of the back pack attachment screws. An angle on each side of the cradle is provided for attachment of the torso corset. These angles are located in the plane of the subject's back, and they establish the fore and aft positioning of the subject. The torso corset is attached to each angle at 4 points with 8 machine screws. Threaded screw holes are provided on 0.013 m (0.50 in.) centers over a range of 0.229 m (9 in.) and slotted holes in the corset attachment fitting permit locating the corset at any point within the extreme limits. A 0.203 m (8 in.)

section of tube is welded to the back of the structure, perpendicular to the vertical axis of this cradle. It is used for attachment of counterweights, if required, to bring the cradle and subject's c.g. within the range of the balancing mechanism.

The subject's restraint system confines his torso and legs while his head and arms remain free. The torso restraint consists of a two-piece fiberglass corset. The two pieces of the corset are supported by two 0.025 m (1 in.) diameter aluminum tubes bolted to the angles described above. The two pieces of the corset can be adjusted horizontally to move the subject right or left and to accommodate different torso widths. The sections are clamped into place on the tubes by the integral split ring clamps and bolts accessible from the front. Supplementing the corset are restraining straps located at the following positions: shoulders, pelvis, knees, and feet. The two shoulder straps are fastened to the corset at the approximate location of the shoulder blades. Each strap is brought over the shoulder, across the upper chest, and back under the opposite arm to attach to the cradle structure at waist level. These straps consist of two parts that are connected together with aircraft-type, quick-release, adjustable buckles located in the upper chest area. The pelvic strap is a one piece strap around the corset and subject at his hips. It is attached to one side of the corset to prevent slipping and has the same type buckle as the shoulder straps.

The legs are restrained at the knees by individual, sponge-rubber padded, contoured supports attached to the cradle structure. The supports may be adjusted side to side and fore and aft. Each support has a continuous strap held in place to prevent slipping and fastened on the outside of the knee with the adjustable quick-release buckle.

The foot plate is covered with corrugated rubber tread and is provided with semi-circular heel retainers and a foot strap. The heel retainers prevent the heels from slipping backward and the strap restrains the feet from forward or vertical movement. The strap is attached at both ends with adjustable strap restrainers and, normally, enough slack is left to permit insertion of both feet under the strap. After both feet are in place, a locking bar, pivoted at the back between the heels, is dropped into place between the feet and is secured by engaging a "J" hook with front edge of the foot plate. A screw handle permits tightening the "J" hook to apply tension to the foot strap.

The balancing adjustments (Fig. 3) are built into the right and left sides of the cradle to permit movement of the subject's c.g. 0.038 m (1.5 in.) vertically and fore or aft from the nominal c.g. position with

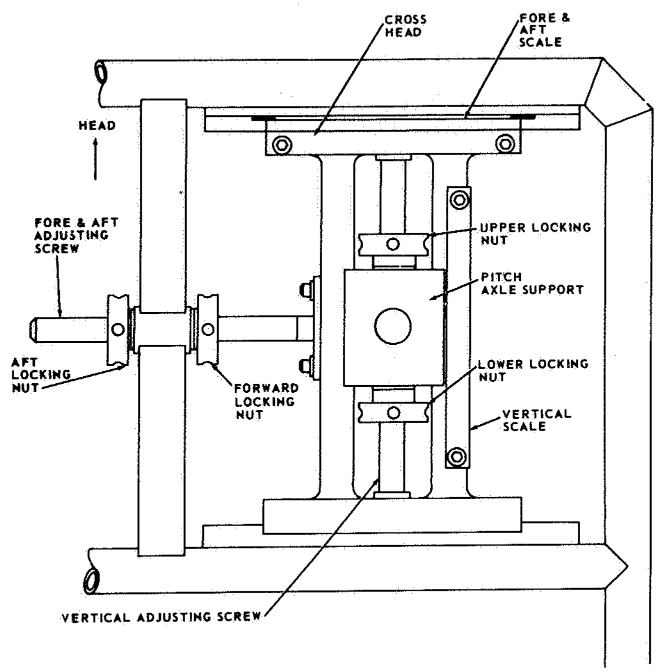


FIGURE 3. BALANCING ADJUSTMENT

respect to the pitch axis ball bearings. Each adjustment consists of a crosshead and adjustment screw that provides fore and aft motion of the cradle. The adjustment screw slides through a bushing and is locked in place by two adjusting nuts, one on each side of the bushing. The crosshead carries the pitch axle support and vertical adjusting screw. The pitch axle support slides on the crosshead, the adjusting screw passing through it. Two adjusting nuts, one on the top and one on the bottom, permit vertical adjustment and locking. The crosshead has two reference scales, one for vertical adjustment and one for horizontal. The cradle has a pointer for the horizontal scale and there is an index mark on the pitch axle support for vertical reference. The scales permit equal adjustment of both right and left sides. When a subject has been balanced previously, the balancing adjustments can be preset, thereby reducing the time required to accomplish this task.

The pitch axle fits into the bore of a self-aligning ball bearing mounted by two bolts to the roll yoke.

The axle has a threaded hole accessible from the outer edge. This can be used for attachment of instrumentation to obtain a readout on the pitch movement.

Seat Assembly. The seat assembly consists of the supporting structure for the subject; the subject restraint system consisting of the bicycle seat, back support, and restraint straps; and the cradle vertical and fore and aft balancing adjustments with pitch axis ball bearings (Fig. 4).

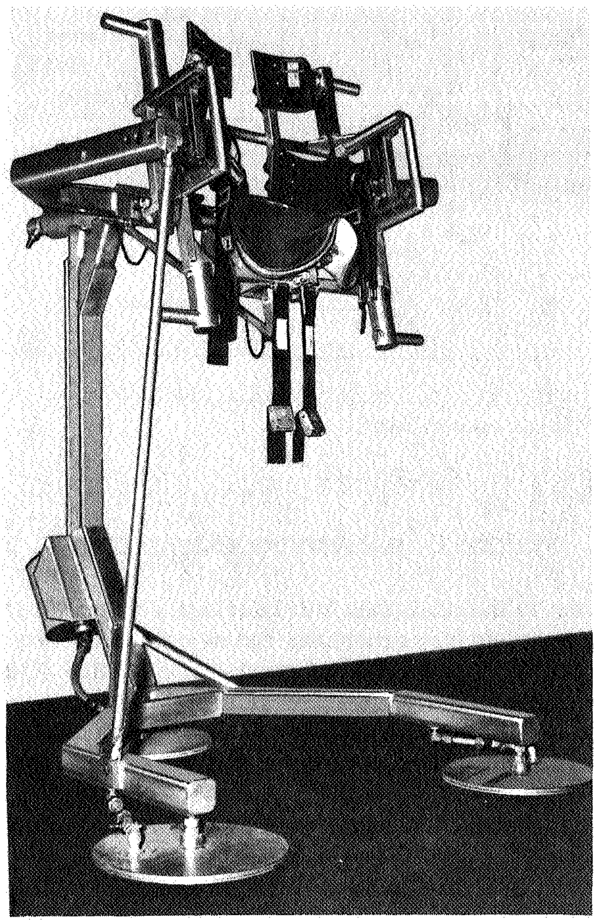


FIGURE 4. FIVE-DEGREES-OF-FREEDOM SIMULATOR WITH BICYCLE SEAT ASSEMBLY ATTACHED

The supporting structure is made of aluminum tubes welded together and a bicycle seat that is fastened in place with a set screw. The adjustment of the seat height permits raising and lowering the subject's c.g. over a 0.152 m (6 in.) range to place the c.g. within the range of the vertical balancing adjustment. The back supports are attached with machine screws fitted in slotted holes to permit horizontal adjustment. A 0.203 m (8 in.) section of tube is welded to the back of the structure, perpendicular to the vertical axis of seat. It is used for attachment of counterweights, if required, to bring the seat and subject's c.g. within the range of the balancing mechanism.

The subject's restraint system confines his torso while his head, arms, and legs remain free. The torso restraint consists of four curved-aluminum, sponge-rubber lined, back supports. The four back supports are supported by two 0.0254 m (1 in.) square aluminum tubes welded to the structure. The four back supports can be adjusted horizontally to move the subject right or left and to accommodate different torso widths. Supplementing the back supports are restraining straps for the torso and pelvis. The two straps are fastened to the upper back supports at the approximate location of the shoulder blades. Each strap is brought over the shoulder, across the upper chest and back under the opposite arm to another strap attached to the lower back support at waist level. These straps consist of two parts which are connected together with an aircraft-type quick-release adjustable buckle located in the upper chest area. The two parts of the pelvic strap are attached to the lower back supports. It has the same type of adjustable buckle as the shoulder straps.

The subject is held on the bicycle seat by two strap assemblies, one of which goes over each leg. The ends of each strap are attached to the frame below and behind the crotch and the lower back supports.

The seat uses the same balancing adjustment mechanism as the cradle.

Roll Yoke. The roll yoke supports the pitch bearings in a "U" shaped structure of welded 0.076 m (3 in.) square aluminum tubing attached to a hardened steel shaft. The yoke permits a pitch movement of 108 degrees with approximately equal pitch-up and pitch-down motion. The cradle has adjustable stops that strike rubber pads on the yoke to limit the cradle motion so that the subject does not strike the base during extreme motion in both pitch and roll.

The yoke also has two small tabs, one welded to the front of the right arm of the yoke and the other to the bottom at the rear center. These tabs are attachment points for locking bars. Locking the pitch movement is accomplished by attaching a 0.025 m (1 in.) diameter aluminum tube to the back tab and to the rear of the cradle at about the knees. A notch in each end of the bar slips over the tabs on the cradle and the yoke, and each end is held secure to the tab by a ball lock pin. Locking the roll movement is accomplished by attaching the roll locking bar between a tab on the base and the tab on the yoke arm. Locking of one axis does not restrict the motion of the other axis.

The roll axle fits through the roll yoke and the bearings. It is attached to the roll yoke from the front (inside the U) by two machine screws. The axle has a 0.013 m (0.50 in.) diameter passage which connects through standard pipe fittings to a Hansen 5000 series quick-disconnect fitting at the front end of the left arm. This is used to provide breathing and pressurization air to the subject in a space suit. The aft end of the axle has a Deublin model 20-8 rotating union to provide rotating freedom and a continuous air supply. The shaft of the rotating union extends completely through the union and may be drilled and tapped to provide a mounting for instrumenting the roll axis, if desired.

The vernier roll balance adjustment is located between the arms of the yoke to the rear of the cradle. It has a 1.36 kg (0.0933 slugs) lead mass mounted to slide freely on a threaded rod. Nuts on each side provide locking for the lead mass. The hole in the lead is positioned slightly off center so that it will hang at about a 50 degree angle from the vertical to clear the cradle in the extreme pitch-up position. The upper corner of the lead has been beveled and padded with rubber to minimize damage to the back pack in the event that contact does occur.

Base Assembly. The base is an aluminum square tube structure that provides support for the roll axle and the three air bearing pads. The vertical member of the base supports the roll axis approximately 1.59 m (62.5 in.) off the floor. It is designed to provide clearance for the cradle to permit unrestricted roll in any pitch attitude with the cradle foot plate in the lowest position.

The bottom tubular structure provides support for the air bearing pads that are equally spaced on a 0.635 m (25 in.) radius circle about the nominal yaw axis. One pad is directly under the vertical base member and the other two are forward and to the side to give stability.

The air bearing pads on 0.019 m (0.75 in.) threaded rods are screwed into fittings welded to the base.

The tubular base structure serves as a plenum chamber to equalize air flow to the pads and minimize line surges. The input to the base plenum is located on the right rear side.

Lazy Arm Assembly. The lazy arm provides for positioning the upper end of both the power cable and breathing and suit pressurization air hose at any point within a 3.66 m (12 ft) diameter circle (Fig. 1). The lazy arm consists of two 0.915 m (3 ft) sections that rotate on thrust bearings to provide minimal friction forces. The lazy arm mounting plate is bolted to the supporting structure and leveled. Suspended from the mounting plate is the inner arm, which rotates about the center on thrust bearings that are concentrically mounted around the rotating unions. The two unions are tandem-mounted on the rotating axis and are capable of unlimited rotation. There's a similar rotating joint between the inner and outer arms. The outer arm terminates in fittings for the attachment of the power cable and flexible hose leading to the simulator. Although the nominal restriction in the rotating union is 0.0063 m (0.25 in.) ID, larger diameter hoses have been provided to minimize functional losses in supply lines. Air is provided through a 0.0095 m (0.375 in.) ID hose.

A force of approximately 0.556 N (0.125 lbf) applied at the hose fittings is required to move the lazy arm when it is fully extended.

Basic Data. Figures 5 and 6 show detailed dimensions and operating clearances for the five-degrees-of-freedom simulator. The total mass of the

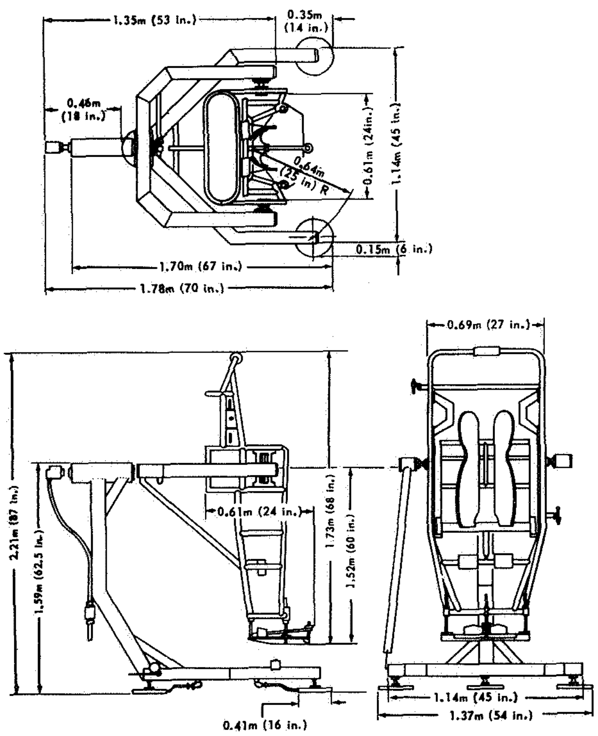


FIGURE 5. BASIC DATA

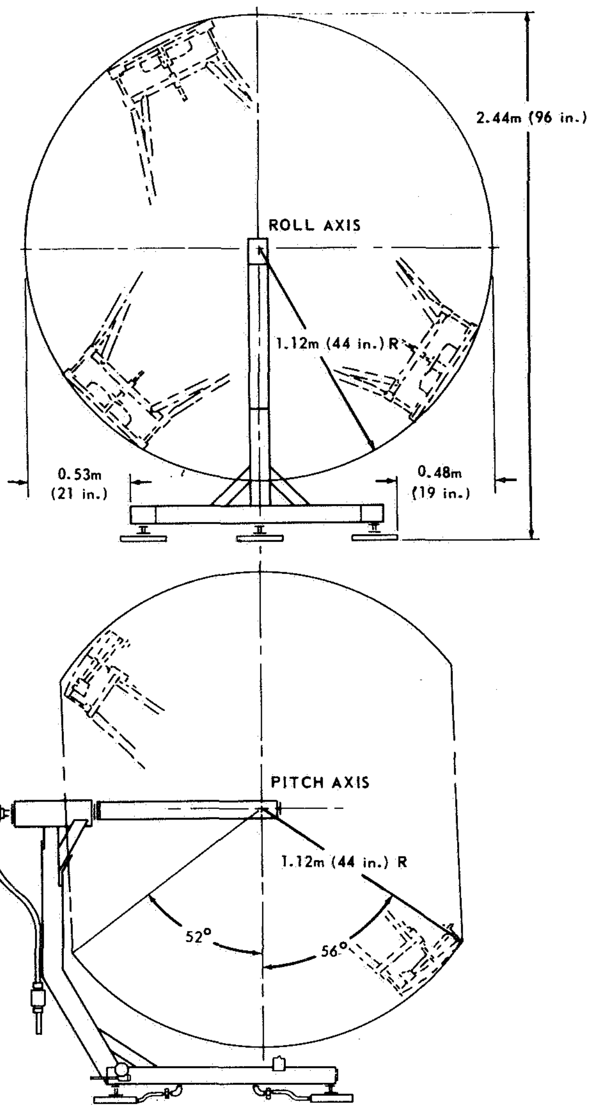


FIGURE 6. CLEARANCES REQUIRED FOR OPERATIONS

simulator with the cradle is 90 kg (6.15 slugs). The cradle has a mass of 28.6 kg (1.96 slugs) and the base and yoke 61.4 kg (4.20 slugs).

The torques required to overcome the static friction of the simulator are the following: pitch, 0.284 J (40 in. oz); roll, 0.494 J (70 in. oz); and yaw, 0.007 J (1 in. oz).

ACTION-REACTION FREE-FALL SIMULATOR

1. General Information

The action-reaction free-fall simulator or six-degrees-of-freedom simulator is a mechanical apparatus that allows the subject to react to any force as he would in space, except where the subject is required to translate over great distances (Fig. 7). This is accomplished by designing the experiment so that the desired test data are obtained.

Assume the following for the purpose of demonstrating that the subject can produce a translation acceleration just as he would in space by properly designing the experiment:

F_a = force applied to the object by the subject, assume 13.3 N (3 lbf)

F_s = force required to bend the pressure suit, given as 44.4 N (10 lbf) for 2.41×10^4 N/m^2 (3.5 psia) pressurization.

$F_c = F_a + F_s$

F_μ = force required to produce translation of the moving parts of the simulator, given as 0.58 N (0.13 lbf)

$F_T = F_a + F_s + F_\mu$

m_m = mass of the moving parts of the simulator, 114 kg (7.78 slugs) [a weight of 1110 N (250 lbf) at 1 g]

m_s = mass of subject and space suit, 91 kg (6.21 slugs) [a weight of 889.6 N (250 lbf) at 1 g]

g = acceleration, standard free fall, 9.80 m/sec^2 (32.16 ft/sec^2)

From Newton's Second Law of Motion, "The change of motion is proportional to the motive force impressed; and is made in the direction of the straight line in which force is impressed," we can determine the subject's acceleration in space.

$$F_c - F_s = ma$$

$$a = \frac{F_c - F_s}{m}$$

$$a = \frac{57.7 - 44.4}{91} = 0.146 \text{ m/sec}^2 \ (0.51 \text{ ft/sec}^2)$$

To produce the same acceleration in the simulator, it is necessary to change a parameter(s) that will produce the correct applied force, F_a, and not degrade the test data. Solving for the total force, F_T, we obtain

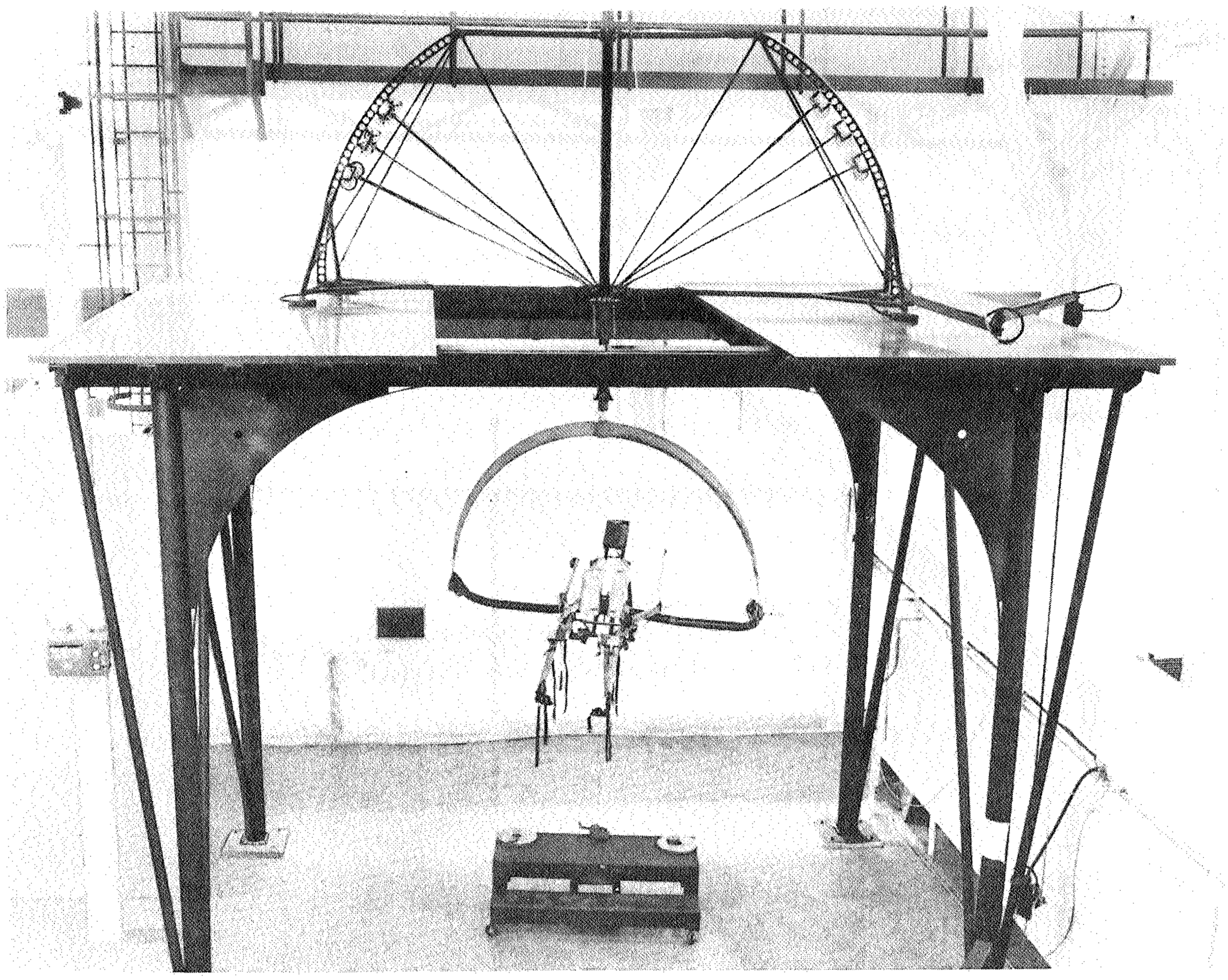


FIGURE 7. ACTION-REACTION FREE-FALL SIMULATOR

$$F_T = ma = (m_m + m_s)a$$

$$F_T = (114 + 91) \times 0.146 = 30 \text{ N } (6.75 \text{ lbf})$$

$$F_T = F_a + F_s + F_\mu$$

Since F_μ is an inherent characteristic of the simulator, it cannot be changed. Assume that the F_a is to be the same as it would be in space. This leaves only F_s which can be altered.

$$F_s = F_T - F_a - F_\mu$$

$$F_s = 30 - 13.3 - 0.58 = 16.12 \text{ N } (3.63 \text{ lbf})$$

A force of 16.12 N (3.63 lbf) to bend the suit can be obtained by reducing the suit pressure to 1.19×10^4 N/m^2 (1.74 psig).

The same analysis can be done for the other degrees-of-freedom for the action-reaction free-fall simulator.

2. Technical Information

The subject is strapped into a fiberglass harness that both positions him properly in the gimbal axis and adjusts to fit anyone between 1.65 and 1.86 m (65 and 73 in.) tall. The test subject is supported in such a way that he can rotate freely about any axis. He is capable of moving to either his left or right side, forward and backward, or up and down. (Fig. 8.) In other words this is a six-degrees-of-freedom simulator.

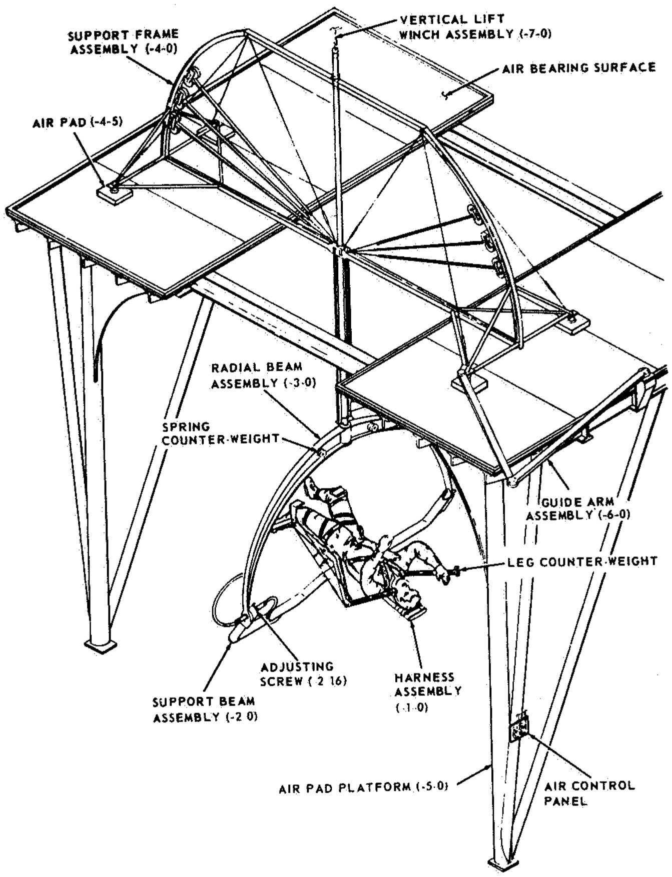


FIGURE 8. ACTION-REACTION, FREE-FALL SIMULATOR

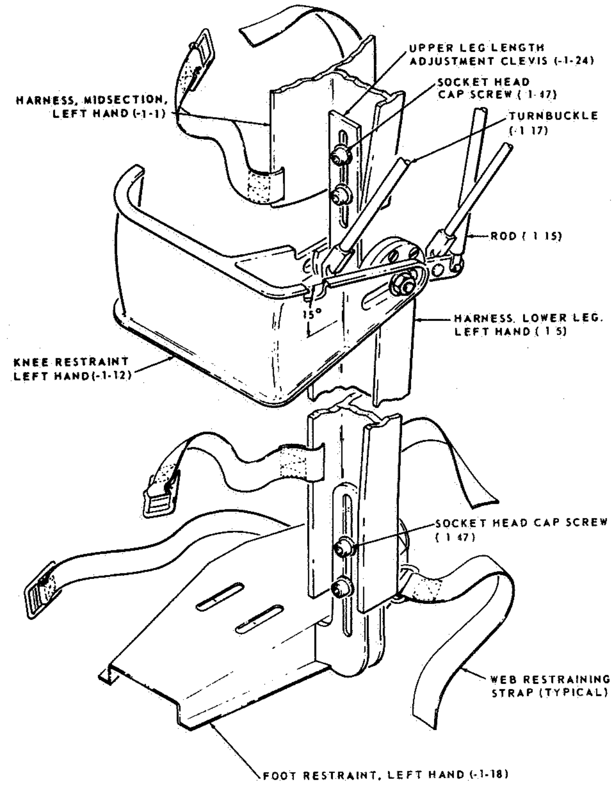


FIGURE 9. ADJUSTING HARNESS ASSEMBLY

The harness allows the astronaut free leg movements (Fig. 9), while counter-weighting them in any position, and keeping his center of gravity in the same place.(Fig. 10). The gimbal axis and harness have a built-in air line for breathing and space suit pressurization and cooling. This allows the subject to train for weightlessness either with or without his suit.

To allow the astronaut to move freely horizontally, the simulator is mounted on four almost frictionless air bearings. This, combined with the small mass of the simulator, less than 114 kg (9.33 slugs) gives almost no resistance to movement through its 1.83 × 3.66 m (6 × 12 ft) horizontal working envelope. Negator springs, which resemble a belt wound on a spool, are attached to the gimbal axis. By mounting sets of springs as shown in Figure 11, the springs can exert any constant force over their six feet of vertical travel.

Adjustments of the simulator can also be made to lift five-sixths or two-thirds of the test subject's mass. In this way, Lunar, Mars, and Venus gravity can be simulated.

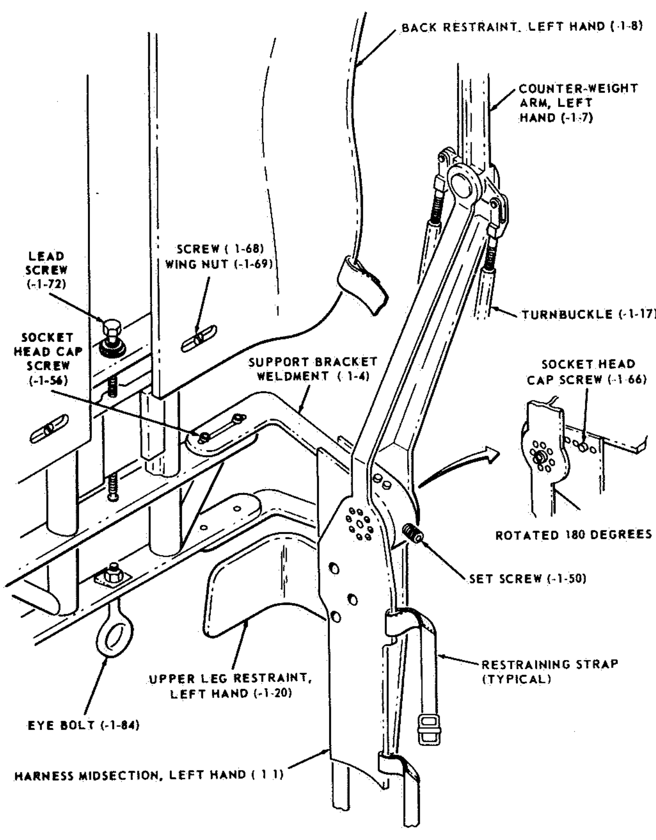


FIGURE 10. ADJUSTING HARNESS ASSEMBLY

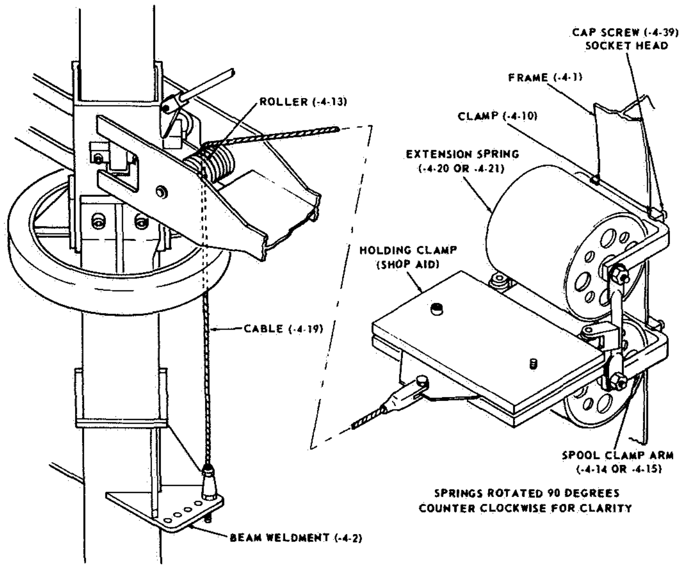


FIGURE 11. INSTALLATION OF EXTENSION SPRINGS

LUNAR GRAVITY AND EARTH ORBITAL SIMULATOR

1. General Information

This simulator was designed to be used with the five-degrees-of-freedom simulator (Fig. 12). The purpose of this simulator is to support the object the subject is working on. It provides four degrees-of-freedom for the workpiece. Vertical translation is produced by moving the work panel up and down. The remaining three degrees-of-freedom are in the horizontal plane. The simulator is supported by three air bearing pads which offer a minimum of resistance to horizontal translation.

For simulating lunar gravity, the subject stands on the semicircular platform (Fig. 12). A mass equal to one-sixth of the subject's mass is placed in the counterweight box. This added mass produces an upward force on the subject's feet which gives him the sensation of walking on the lunar surface.

In the earth orbital (zero gravity) mode, the semicircular platform is removed and sufficient mass is added to the weight box to bring it and the work panel into equilibrium.

2. Technical Information

The lunar gravity and earth orbital simulator consists of the following components: base and support structure, parallelogram arms, work panel assembly, platform assembly, counterweight assembly, and air bearing system (Fig. 13).

<u>Base and Support Structure</u>. The base structure consists of a welded triangular, tubular aluminum base that holds the air bearing pads and serves as a plenum for air supply. The support structure is a rectangular frame made of aluminum channel and welded to the base structure. The support structure supports the parallelogram and transmits all loads to the base.

<u>Parallelogram Arms</u>. The parallelogram arms are two welded aluminum channel assemblies that are supported near their centers on the support structure. Each arm is a lever connecting the work panel and platform assembly to the counterweight assembly. Each arm contains six self-aligning ball-bearing joints for vertical motion.

<u>Work Panel Assembly</u>. The work panel assembly, attached to the front of the parallelogram arms, provides a vertical mounting surface for work objects.

<u>Platform Assembly</u>. The detachable platform is provided for a walking or foot placement surface for experiments other than those performed in zero gravity. An aluminum lip around the edge of the platform is provided to permit gravel or simulated "moon dust" to be placed on the platform for more realistic testing. Folding legs on the platform can be extended for stability when setting up the experiments. These are folded out of the way during operation.

<u>Air Bearing System</u>. The air bearing system consists of a blower and variable transformer control, an air distribution system, and three air bearing pads. The base structure serves as a plenum chamber to prevent air pulses and consequent bearing instability. The front two air bearing lines are provided with bleed-off air valves. The rear pad uses a restriction type valve. The three valves and the variable transformer can be adjusted to provide an even lifting force to elevate the entire structure.

AIR BEARING CAPTURE AND TRANSFER SIMULATOR

1. General Information

This simulator was designed to provide the capability to investigate the following: docking, grappling mechanisms for capture and attachment to work surfaces, manipulators for handling and maneuvering of masses, and boom dynamics associated with mechanisms for capture, despin, respin, and insertion of cooperative and noncooperative objects in earth orbit.

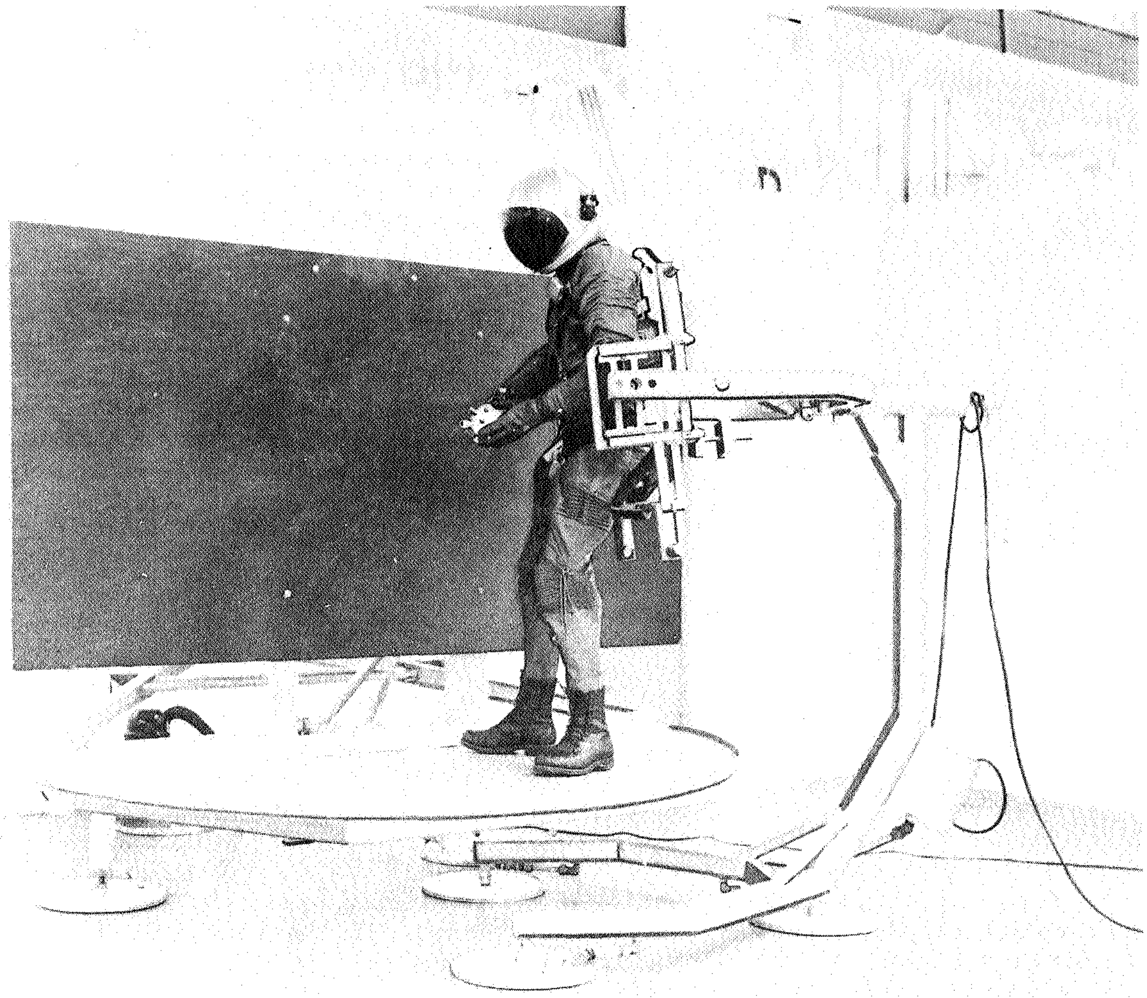


FIGURE 12. LUNAR GRAVITY AND EARTH ORBITAL SIMULATOR AND FIVE-DEGREES-OF-FREEDOM SIMULATOR BEING USED FOR LUNAR GRAVITY SIMULATION WORK

2. Technical Information

The air bearing capture and transfer simulator (Fig. 14) consists of the following major components: frame assembly, walking beam assembly, air bearing pads, air supply system for pads, thruster system (Fig. 15), thruster control electronics package and control stick assembly, transportation casters, and personnel seat assembly.

Frame Assembly. The frame 10 is rectangular in shape, made of square aluminum tubes welded together, and serves as a plenum for the pad air. The front air bearing pads are attached to it.

Walking Beam Assembly. The beam 35 is free to pivot in a plane perpendicular to the frame. This provides the simulator with the same leveling effect on an uneven floor as three air pads but with the load carrying capacity of four pads.

Air Bearing Pads. The pads like the one shown in Figure 16 are used on this simulator.

Air Supply System for Pads. A Black & Decker Manufacturing Company Model 820 EDA heavy-duty central cleaning system unit 12 is used on this simulator.

Thruster System. Six thrusters 60 are used with this system. A high pressure storage sphere 11, fill valve 44, regulator 46, ball valve 50, manifold 56, solenoid valves 57, and tubes 53 and 55 make up the other major components of the system (Fig. 15).

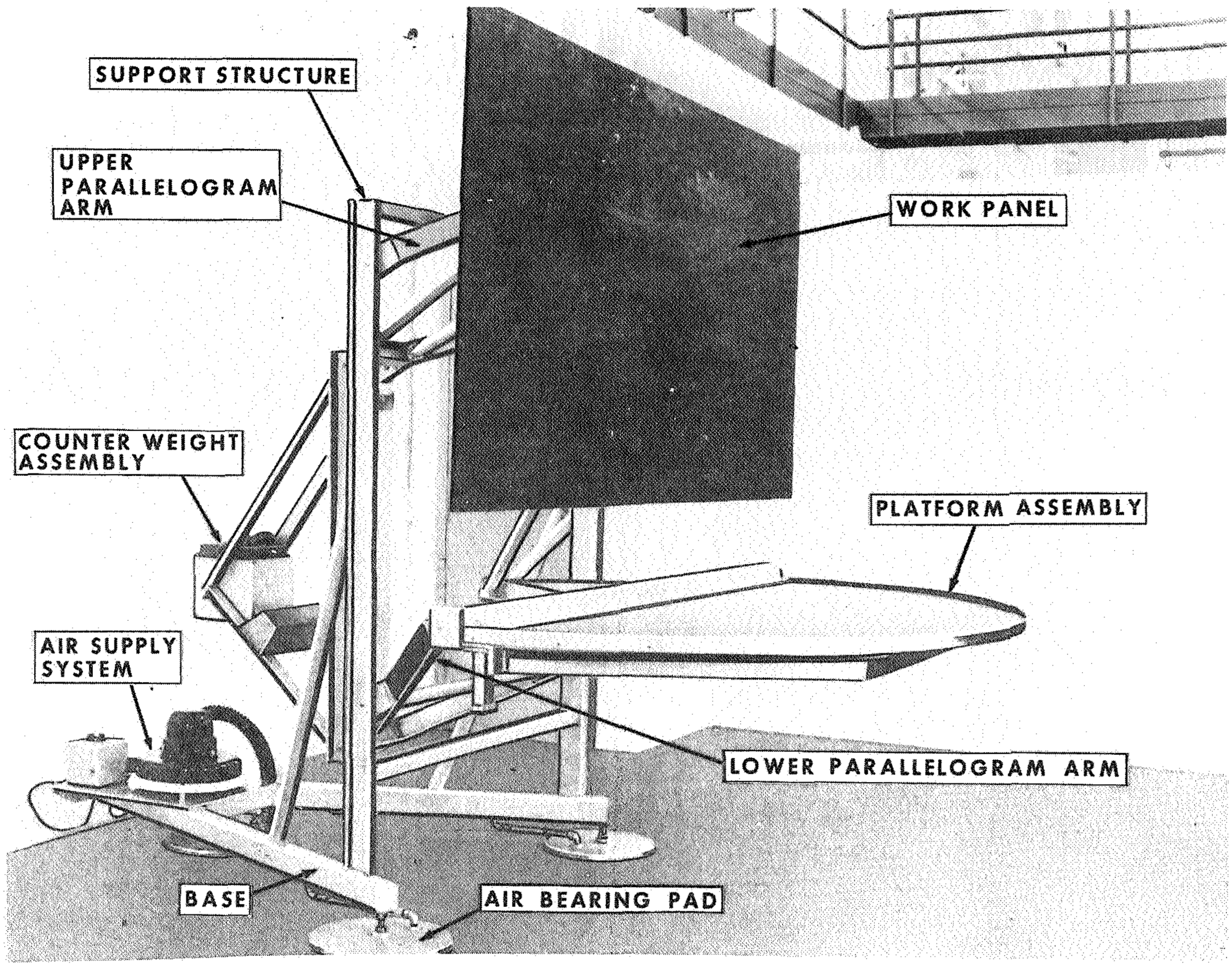


FIGURE 13. LUNAR GRAVITY AND EARTH ORBITAL SIMULATOR

Thruster Control Electronics Package and Control Stick. A military aircraft control stick SA/2-0 electrically actuates relays in the control electronics package, which in turn electrically actuates the solenoid valves 57.

Transportation Casters. These casters 1 provide a means of moving the simulator other than on its air bearing pads. When in use the pads do not touch the floor.

Personnel Seat. The seat support 28 provides a place to attach the air supply 12 as well as support the personnel seat 29.

3. Application.

A grappler developed for use as a means of attaching spacecraft to work surfaces is shown mounted on the simulator. When tests have been completed it can be removed and so the simulator can be used for other tests.

AIR BEARING SYSTEM DEVELOPMENT

MEDIUM INLET PRESSURE AIR BEARING SYSTEM

Air Bearing Pads. A Hovair air bearing pad made by the Inland Division of General Motors Corporation is shown in Figure 17. This pad will support various loads with the pressures and volumes of air described by the load map shown in Figure 18. Inlet pressures of approximately 0.62 MN/m^2 (90 psig) are used with this pad. For the purpose of this review, this is a medium inlet pressure.

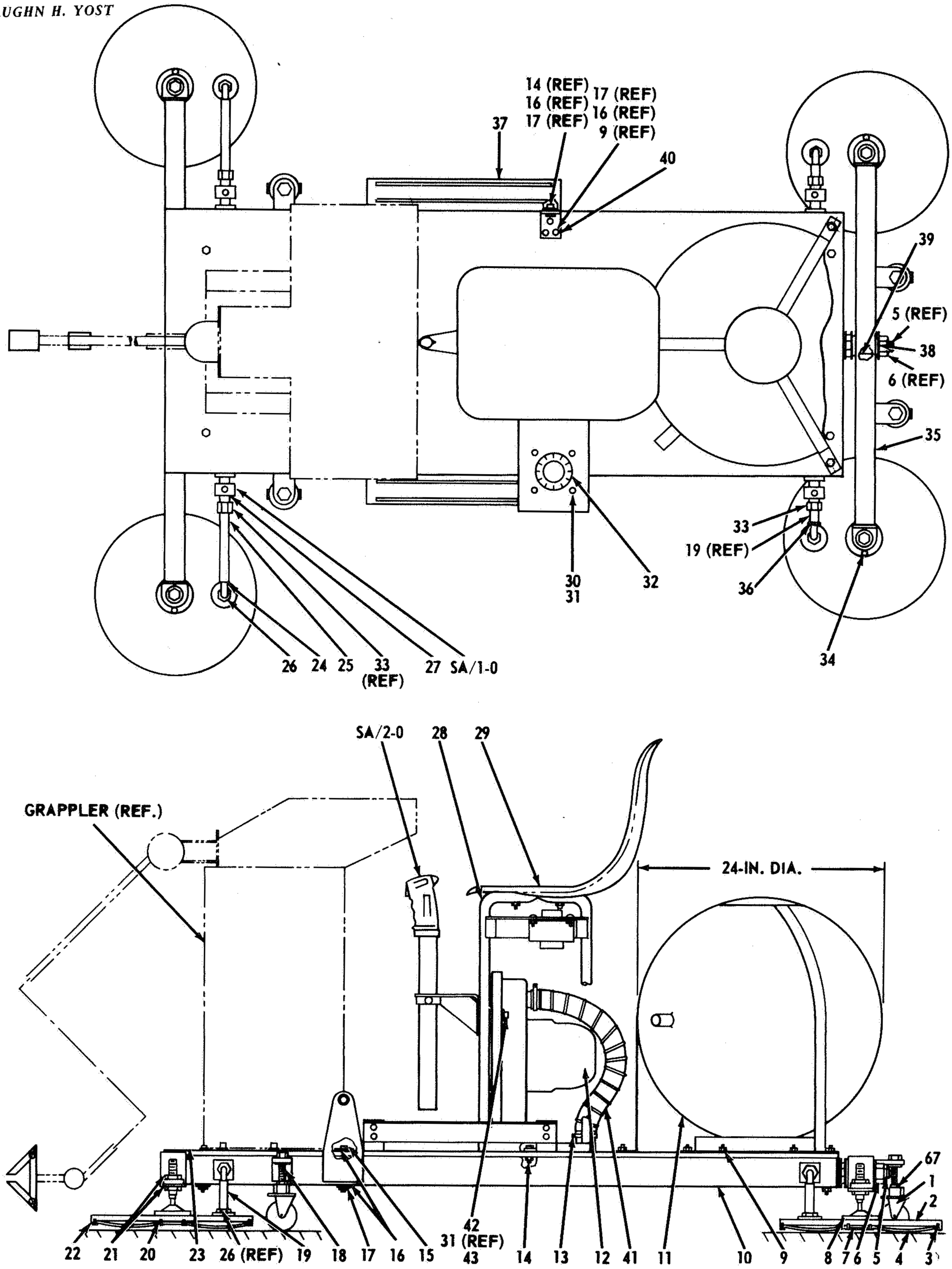


FIGURE 14. AIR BEARING CAPTURE AND TRANSFER SIMULATOR — TOP AND SIDE VIEW

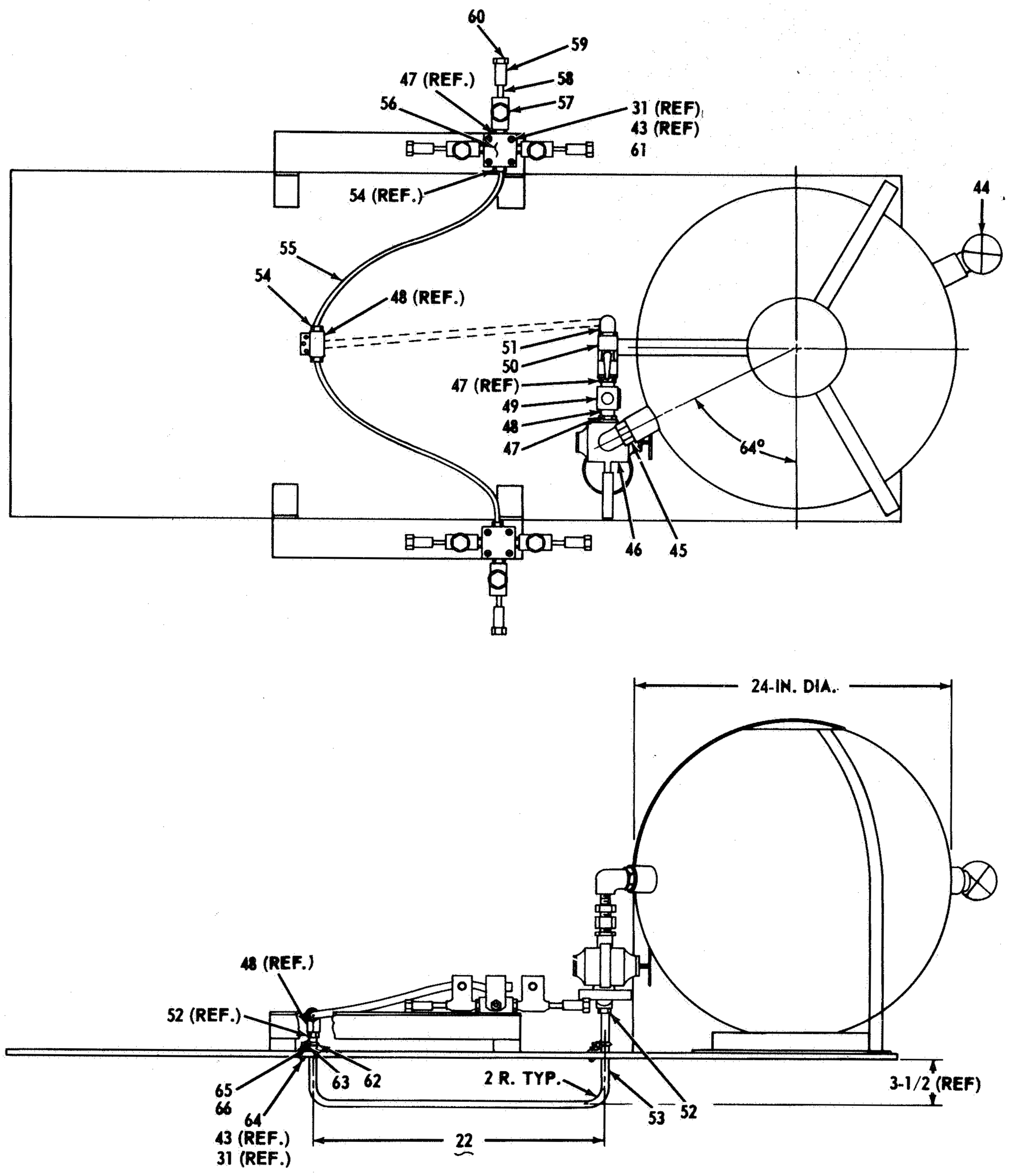


FIGURE 15. THRUSTER SYSTEM FOR AIR BEARING CAPTURE AND TRANSFER SIMULATOR

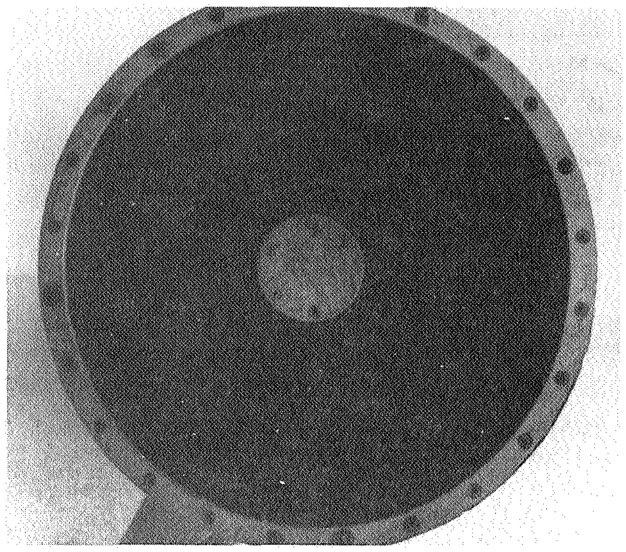


FIGURE 16. LOW INLET PRESSURE AIR BEARING PAD MADE BY MARTIN-MARIETTA CORPORATION

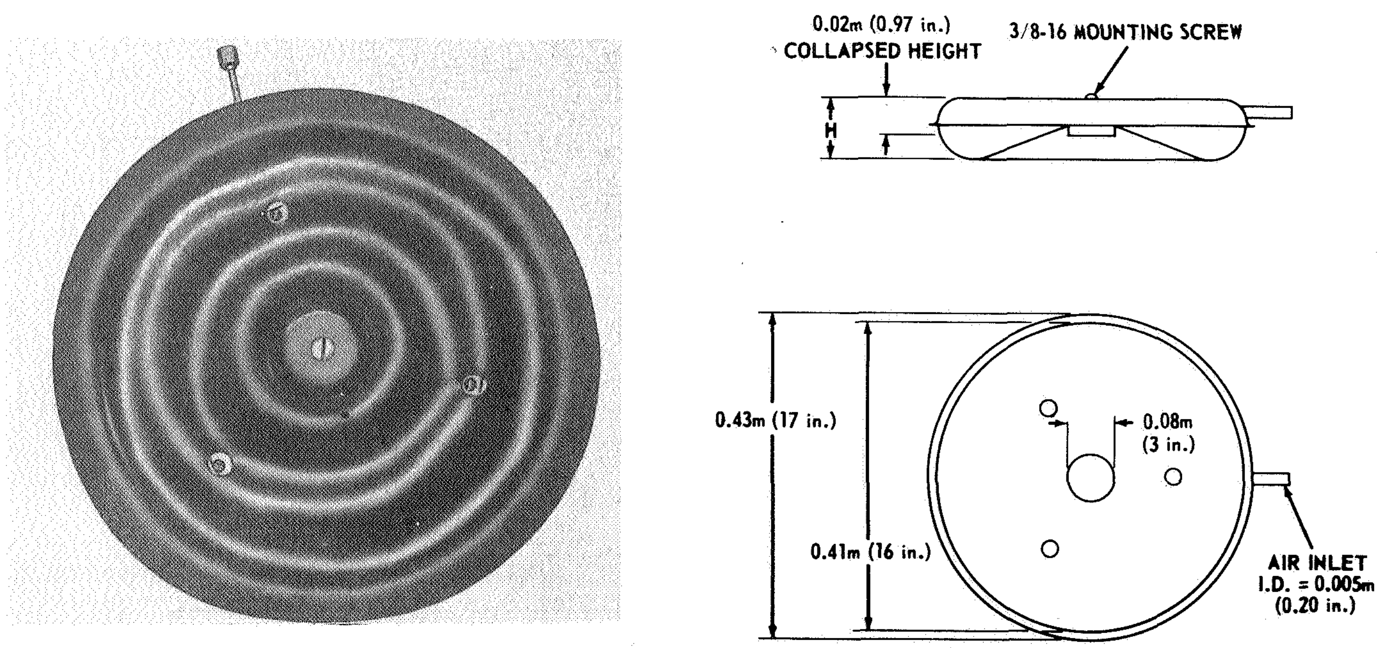
Air Supplies. There are at least three ways of supplying air at medium pressures. They are the following: mounting a high pressure {2063 N/cm^2 (3000 psig)} sphere and regulating equipment on the device, mounting an air compressor on the device, or attaching a medium pressure air line to the device.

LOW INLET PRESSURE AIR BEARING SYSTEM

Air Bearing Pads. A low inlet pressure pad designed by the Martin-Marietta Company, Baltimore Division, is shown in Figure 16. This cushion operates on inlet pressures and volumes of air obtainable with vacuum cleaner motors described in subsequent paragraphs.

Air Supplies. The two types of air supplies that have been used are described below.

Lamb Electric Model 115250. This is a two-stage direct air flow vacuum motor for domestic canister and tank type vacuum cleaners (Fig. 19). Since the motor is cooled by discharge of the vacuum air from the blower section, this type of unit is not suitable for use in applications where the air flow could be sealed



Specifications

Diaphragm Material	3032-50 Urethane	Support Area @ 5.2 psig	192 in.^{2}
Diaphragm Thickness	0.050 in. Nominal	Seal Perimeter @ 5.2 psig	4.10 ft
Top Plate Material	Steel	Air Inlet	1/4 in. Tubing
Top Plate Thickness	0.060 in.		

FIGURE 17. HOVAIR MEDIUM INLET PRESSURE AIR BEARING PAD MADE BY THE INLAND DIVISION OF GENERAL MOTORS CORPORATION

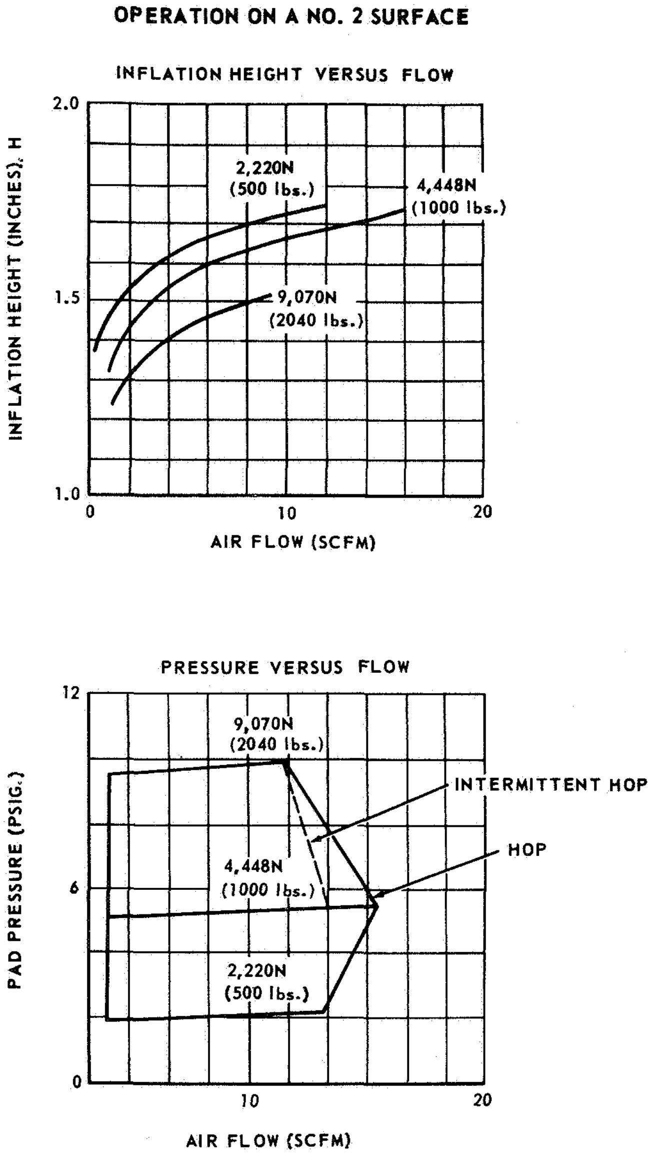


FIGURE 18. LOAD MAP FOR HOVAIR XD 16009 AIR BEARING PAD

off for an appreciable length of time. The motor performance curves are shown in Figure 20. Curve "A" shows the characteristics of a vacuum cleaner which was designed for Lamb's older Model 1S-14750 but has been replaced with Model 115250. Vacuum cleaners having the performance specified in Curve "B" draw the maximum amount of power allowable for #18 SV line cord when using Model 115250.

Black & Decker Manufacturing Company Model 820EDA. This is a heavy-duty central cleaning system 1680 W (2-1/4 h.p. maximum) unit, for medium size homes and apartments (Fig. 21). Since the motor is cooled separately, this type of unit is suitable for use in applications where the air flow could be sealed off.

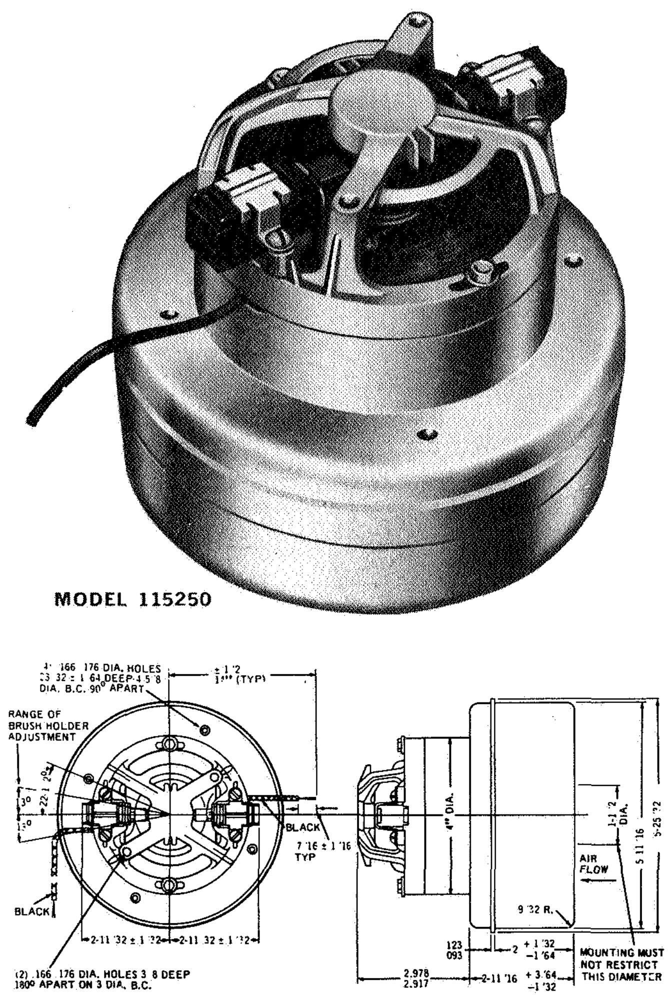


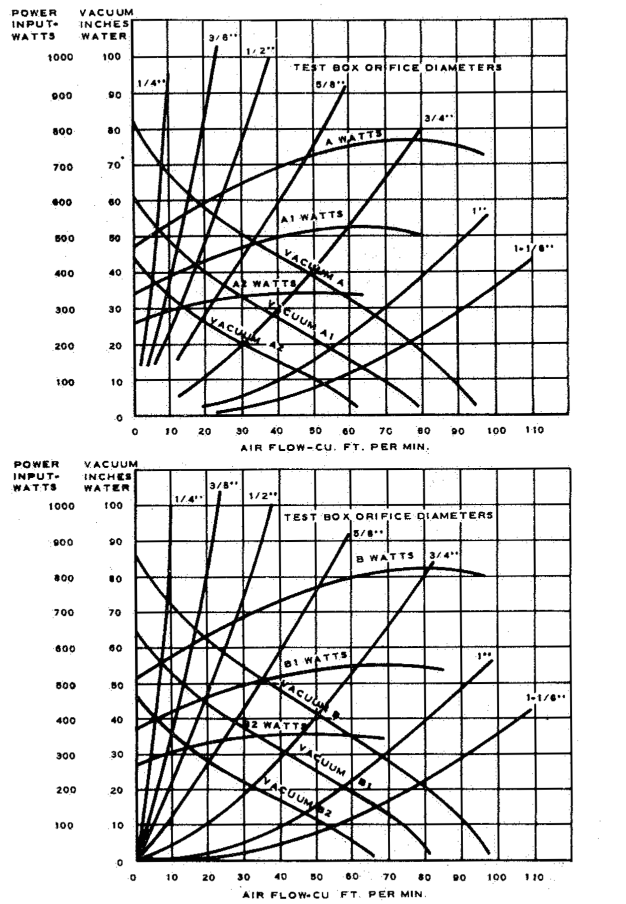
FIGURE 19. LAMB ELECTRIC MODEL 115250 TWO-STAGE DIRECT AIR FLOW VACUUM MOTOR FOR DOMESTIC CANISTER AND TANK TYPE VACUUM CLEANERS

COMPARISON OF MEDIUM AND LOW INLET PRESSURE AIR BEARING SYSTEMS

Mass. Assuming the air supply is mounted on the device, the mass of the low pressure system is lesser of the two. The lower the mass of simulator supporting the subject or work piece, the more accurate the simulation data will be.

Force. When medium pressure shop air lines are attached to the device, the forces required to produce translation are increased, thereby degrading it for simulation purposes.

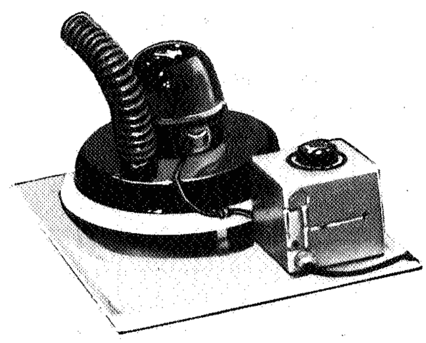
Floor Finish. A smoother floor is required for medium inlet pressure pads (Fig. 17) than for low inlet pressure pads (Fig. 16).



AVERAGE TEST DATA CORRECTED TO STANDARD BAROMETER OF 29.92 IN. HG. AND 68°F.

NOTE: CURVES MARKED WITH FRACTIONAL INCH DESIGNATIONS INDICATE AIR FLOW AND VACUUM THROUGH SHARP-EDGED THIN PLATE TEST ORIFICES OF DIAMETER INDICATED.

FIGURE 20. LAMB ELECTRIC MODEL 115250 VACUUM MOTOR PERFORMANCE CURVES



CENTRAL CLEANING SYSTEM UNIT

Horsepower Rating Max.	2 1/4
R.P.M. Rated	12,000
Amperage	10
Voltage	115
Current	AC
Cycles	50-60
Inches sealed water lift	72
Inches Mercury	5.32
C.F.M.	118
Fans	2 stage
Cooling System	by-pass

FIGURE 21. BLACK & DECKER MODEL 820 EDA HEAVY DUTY CENTRAL CLEANING SYSTEM VACUUM MOTOR AND VARIAC SPEED CONTROL

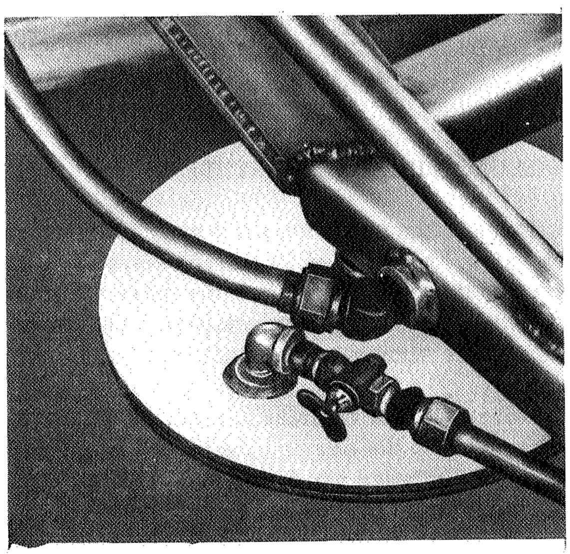


FIGURE 22. METAL TUBING AND FITTINGS USED WITH LOW OR MEDIUM INLET PRESSURE AIR SUPPLY (NOTE BALL VALVE)

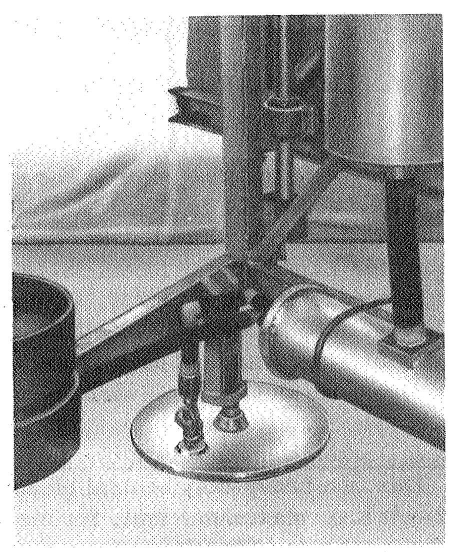


FIGURE 23. NONMETALLIC TUBING AND FITTINGS USED WITH LOW INLET PRESSURE AIR SUPPLY

Plumbing. The plumbing required for a medium inlet pressure system costs more than for a low inlet pressure system. Nonmetallic water pipe and fittings can be used with the latter system (compare Figs. 22 and 23).

MANIFOLD AND AIR SUPPLY RESERVOIRS

The frame of the device may be used for both medium and low pressure systems. This produces a significant weight savings.

REGULATION OF THE VOLUME OF AIR SUPPLIED TO EACH AIR BEARING PAD FOR MEDIUM AND LOW PRESSURE SYSTEMS

Ball Valves. Metallic and nonmetallic ball valves can be used with either system (Figs. 22 and 23).

Bleed Off Valve. See Figure 24.

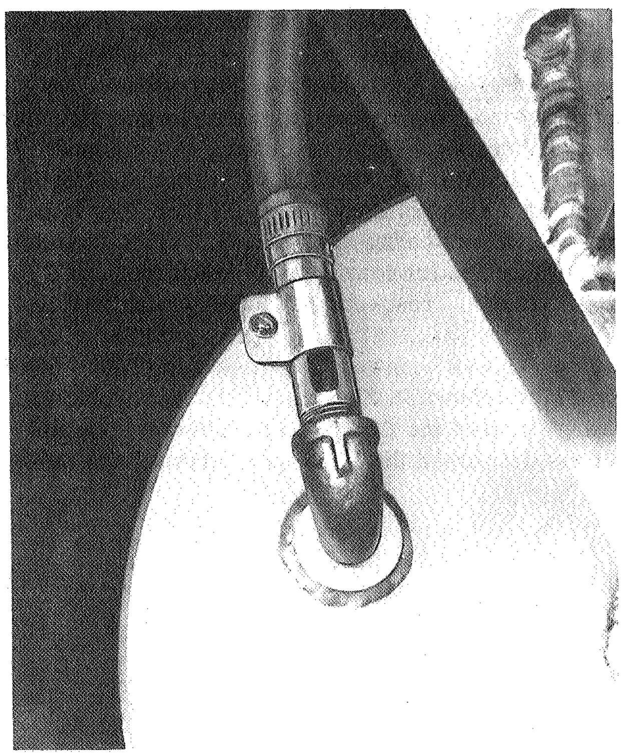


FIGURE 24. BLEED-OFF VALVE USED WITH AIR SUPPLY MOTORS THAT ARE COOLED BY DISCHARGE OF THE VACUUM AIR FROM THE BLOWER SECTION

Comparison of Ball and Bleed Off Valves. Commercially available ball valves generally cost less than the labor and materials required to make bleed off valves. Bleed off valves (Fig. 24) should be used with vacuum cleaner motors that are cooled by the air discharge from the blower section.

AIR BEARING CART THRUST SYSTEM DEVELOPMENT

1. General Information

The design criteria for this system were the following:

Cart Mass. The total mass of the cart less operator and item to be tested was estimated to be 168 kg (11.5 slugs). The masses of the operator and item to be tested were estimated to be 81.3 and 68.2 kg (5.60 and 4.66 slugs) respectively. A total mass of 318 kg (21.8 slugs) for the cart, operator and item to be tested was used for design purposes.

Velocity. The cart is to reach a velocity of at least 1.52 m/sec (5 ft/sec) in less than 6.1 m (20 ft).

Propellant. Select a propellant that has the best specific impulse for the following characteristics: easy to handle, readily available, inexpensive, requires no protective equipment for handling or use, and the exhaust products must not be toxic or nauseating.

Utilities. No propellant lines were to be attached to the cart during operation. One 120 Vac power cable could be attached to the cart during operation to run the vacuum cleaner motor, thruster control system, and item being tested.

Miscellaneous. Select inexpensive, lightweight, commercially available hardware and use it in such a manner as to produce a reliable minimum-maintenance system.

2. Technical Information

Test Setup. The apparatus shown in Figure 25 was designed to test different propellants. Its major components are a high pressure sphere 2, regulator 8, relief valve 23, ball valve 11, solenoid valve 17, and the candidate thruster 18. This apparatus was attached to a platform scale to determine thrust levels for different propellants and thruster designs. The

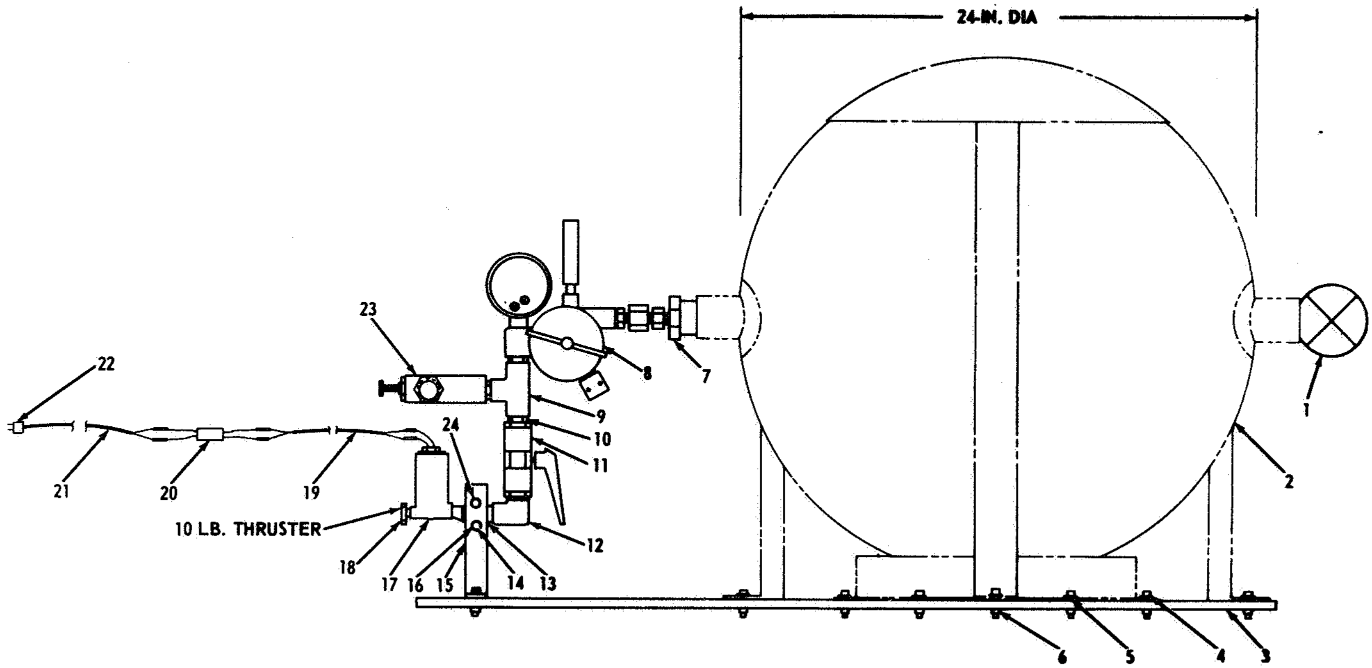


FIGURE 25. TEST SETUP USED FOR SELECTION OF PROPELLANT AND THRUSTER

center line of the thruster was perpendicular to the platform with the exit nozzle pointing upward. For determining the velocity and acceleration obtainable with each propellant, the apparatus was attached to a test cart (Fig. 26).

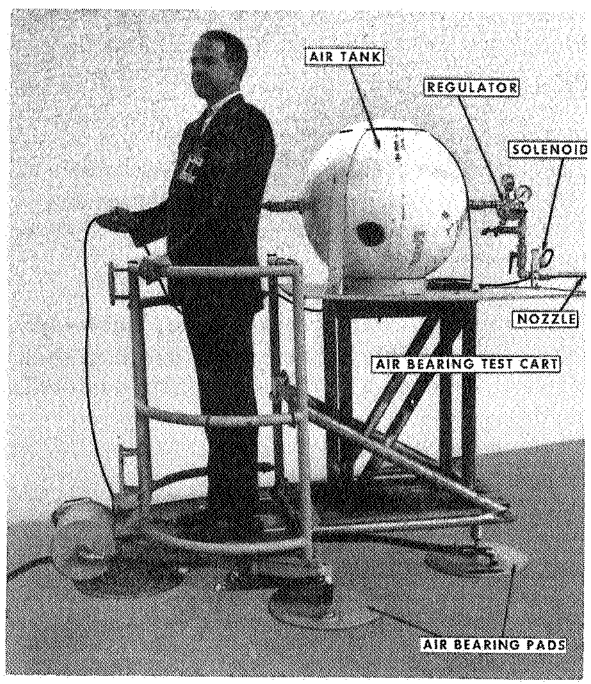


FIGURE 26. TEST SETUP USED TO DETERMINE VELOCITY AND ACCELERATION OBTAINABLE WITH EACH PROPELLANT AND THRUSTER

Test Results. Air was the first and only propellant tested. It produced the desired results after several thruster designs and tubing configurations were tried. The thruster shown in Figure 27 produced the maximum thrust once the flow into the inlet nozzle was changed to laminar. This thruster has inlet and outlet nozzle areas equal to 4 and 2 times the throat area, respectively. The throat area is 3.38×10^{-5} m^2 (0.0523 in.^{2}). In the earlier tests the thruster 18 was screwed into the outlet of the solenoid valve 17 as shown in Figure 25. The solenoid valve passage caused the flow to be turbulent. This turbulence decreased the maximum thrust of the thruster.

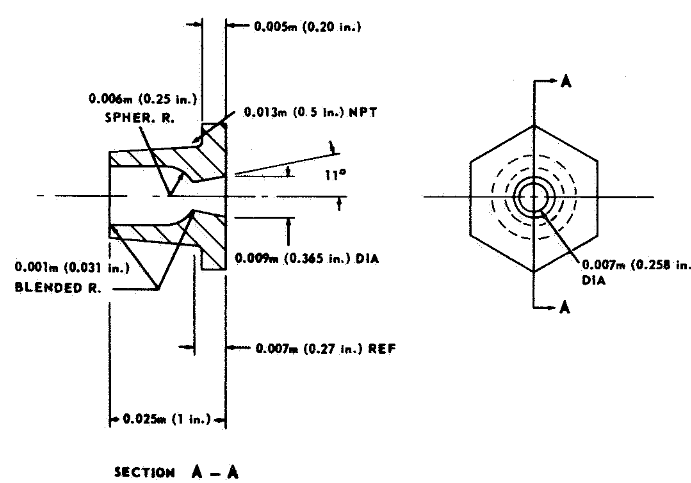


FIGURE 27. THRUSTER SELECTED FOR AIR PROPULSION SYSTEM

The flow into the inlet nozzle of the thruster was changed from turbulent to laminar by putting a pipe nipple 10 times the pipe diameter between the solenoid valve and thruster as shown in Figure 26. Table I data were obtained with the apparatus shown in Figure 25 mounted on the platform scale and a 0.127 m (5 in.) pipe nipple between the solenoid and thruster.

DEVICES TO SUPPORT EQUIPMENT FOR MECHANICAL SIMULATION

1. General Information

The weight of equipment, e.g., hand tools, which a subject uses to perform tasks, cannot be effectively balanced with a simulator balancing system because as soon as equipment is moved, the subject is out of balance. If the subject is balanced without the equipment and then handed the equipment he is out of balance too. To remedy this situation the equipment may be supported with a helium filled balloon. The balloon can be filled to produce a force equal to the weight of the equipment for earth orbital gravity simulation, or 5/6 its weight for lunar gravity simulation.

Equipment designed for earth orbital or lunar gravity work will not necessarily function in an earth gravity, one "g", environment because of its mass, deflections caused by cantilevered members, etc. One way of solving this problem is to support the equipment with a pedestal attached to the platform supported by air bearing pads. These devices are called Air Bearing Platforms.

2. Technical Information

Balloons. In Figure 28 an impact wrench is supported by a 1.83 m (6 ft) diameter weather balloon filled with sufficient helium to provide an upward force equal to the weight of the wrench.

The balloons presently used were made especially for simulation work by the G. T. Schjildahl Company, Northfield, Massachusetts. These balloons are 2.54 m (8 ft) in diameter consisting of 12 gores of two layers of 25.4 μm (0.001 in.) thick polyester bilaminate with 2 plastic inflation valves 180 degrees apart. These balloons will lift a mass up to 8.2 kg (0.56 slugs).

Air Bearing Platform. These platforms are designed to provide a stable base for simulating a near-frictionless environment by means of air bearing pads operating on a smooth level floor. Two configurations of the platform are presently being used: the manned

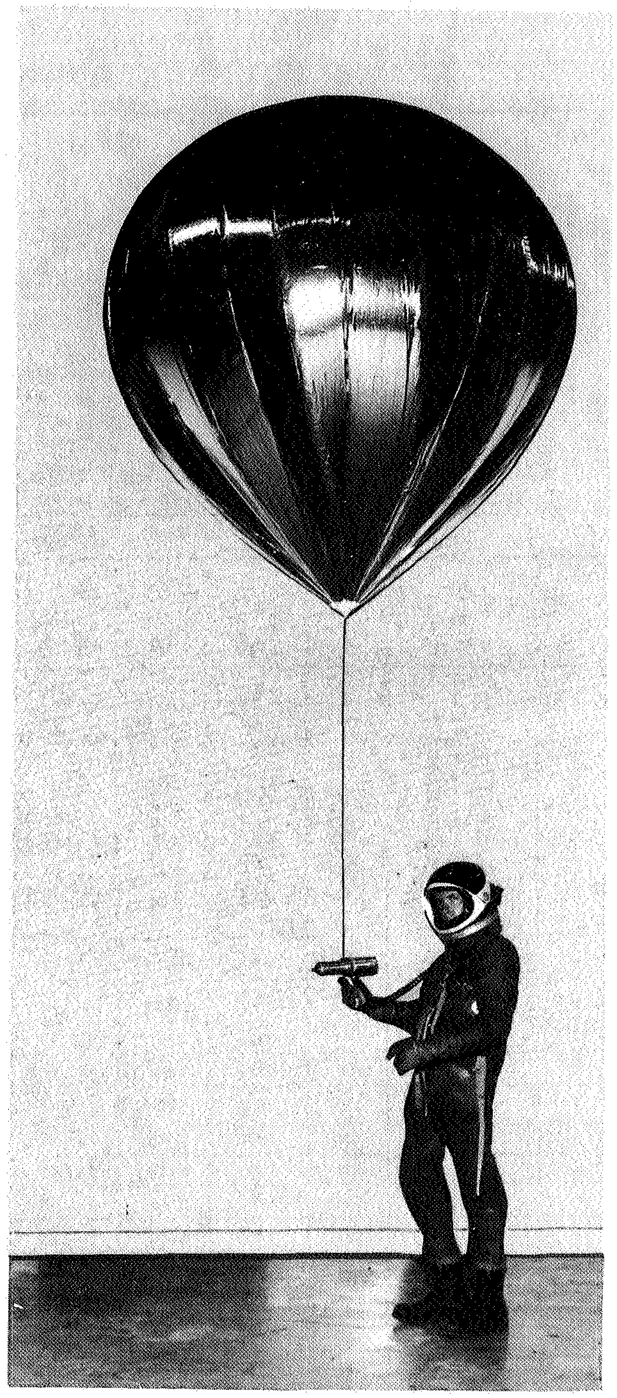


FIGURE 28. HELIUM FILLED WEATHER BALLOON SUPPORTING THE IMPACT WRENCH

version including a man-seat pedestal and serpentuator attach bracket (Fig. 29), and the unmanned version that includes the serpentuator support bracket (Fig. 30). The components that make up these configurations have the following masses: platform air bearing, 25 kg (1.71 slugs); serpentuator attach post and

TABLE I. AIR BEARING CART TEST THRUSTER ASSEMBLY THRUST TESTS

OCTOBER 13, 1967

TEST NUMBER	TIME CYCLE (sec)	SET REGULATOR AT 215 psi	DYNAMIC PRESSURE 150 psi TIMED	SPHERE PRESSURE PRIOR TO TEST	SPHERE PRESSURE AFTER TEST	INITIAL WEIGHT OF SPHERE PRIOR TO TEST (AT 1 g)	TOP READING OF BLAST TEST	BOTTOM READING OF BLAST TEST	THRUST AT TOP READING	THRUST AT BOTTOM READING	WEIGHT OF SPHERE AFTER TEST (AT 1 g)	ROOM TEMPERATURE
	sec	psi	psi	psi-N_2	psi-N_2	lbf	lbf	lbf	lbf	lbf	lbf	°F
1	7	215	150	2500	2400	179.50	188.00	187.50	8.50	8.00	178.50	68
2	10	215	150	2500	2375	179.50	188.00	186.75	8.50	6.75	178.00	69
3	12	215	150	2500	2350	179.25	188.00	186.50	8.75	7.25	177.75	70
4	15	215	150	2500	2325	179.50	188.00	186.00	8.50	6.50	177.25	73
5	5	215	150	2500	2450	178.50	188.00	187.50	8.75	8.25	178.50	72

OCTOBER 20, 1967

TIME START: 10:00 a.m. TIME END: 11:30 a.m.

TEST NUMBER	TIME CYCLE	SET REGULATOR AT 215 psi	DYNAMIC PRESSURE TIMED	SPHERE PRESSURE PRIOR TO TEST	SPHERE PRESSURE AFTER TEST	TOP READING OF BLAST TEST	BOTTOM OF BLAST TEST	THRUST AT TOP READING	THRUST AT BOTTOM READING	WEIGHT OF SPHERE BEFORE TEST (AT 1 g)	WEIGHT OF SPHERE AFTER TEST (AT 1 g)	ROOM TEMPERATURE	SPHERE TEMPERATURE	DATA RECORDING TIME
	sec	psi	psi	psi-N_2	psi-N_2	lbf	lbf	lbf	lbf	lbf	lbf	°F	°F	min
1	5	215	150	2500	2425	189.75	187.50	11.25	9.00	178.50	178.00	72.0	78.0	6
2	5	215	150	2425	2360	188.75	186.50	10.75	8.50	178.00	177.00	71.0	76.0	3
3	5	215	150	2360	2300	187.75	185.25	10.75	8.25	177.00	176.25	71.5	76.0	2
4	5	215	150	2300	2225	187.00	184.50	10.75	8.25	176.25	175.25	72.0	75.0	1
5	5	215	150	2225	2175	186.50	183.50	11.25	8.25	175.25	174.50	72.0	75.0	1
6	5	215	150	2175	2100	185.25	182.75	10.75	8.25	174.50	173.50	71.5	75.0	1
7	5	215	150	2100	2050	184.50	181.75	11.00	8.25	173.50	172.75	71.5	74.0	1
8	5	215	150	2050	2000	183.25	181.00	10.50	8.50	172.75	171.75	71.5	73.5	1
9	5	215	150	2000	1950	182.25	181.00	10.50	9.25	171.75	170.75	71.0	73.0	1
10	5	215	150	1950	1875	181.50	179.00	10.75	8.25	170.75	170.00	71.0	72.0	1
11	5	215	150	1875	1825	180.75	178.00	10.75	8.00	170.00	169.00	71.0	71.5	1
12	5	215	150	1825	1775	179.75	177.00	10.75	8.00	169.00	168.25	71.5	70.5	1
13	5	215	150	1775	1710	178.75	176.50	10.50	8.25	168.25	167.25	72.0	70.0	1
14	5	215	150	1710	1650	177.75	175.00	10.50	7.75	167.25	166.25	72.0	69.0	1
15	5	215	150	1650	1600	176.50	174.00	10.25	7.75	166.25	165.25	72.0	69.0	1
16	5	215	150	1600	1550	175.75	173.25	10.50	8.00	165.25	164.50	71.0	68.0	1
17	5	215	150	1550	1510	174.75	172.50	10.25	8.00	164.50	163.75	72.0	67.0	1
18	5	215	150	1510	1470	173.75	171.50	10.00	7.75	163.75	162.75	72.0	67.0	1
19	5	215	150	1470	1400	173.00	170.50	10.25	8.75	162.75	162.00	72.0	67.0	1

TABLE I. AIR BEARING CART TEST THRUSTER ASSEMBLY THRUST TESTS (Concluded)

TEST NUMBER	TIME CYCLE	SET REGULATOR AT 215 psi	DYNAMIC PRESSURE TIMED	SPHERE PRESSURE PRIOR TO TEST	SPHERE PRESSURE AFTER TEST	TOP READING OF BLAST TEST	BOTTOM OF BLAST TEST	THRUST AT TOP READING	THRUST AT BOTTOM READING	WEIGHT OF SPHERE BEFORE TEST (AT 1 g)	WEIGHT OF SPHERE AFTER TEST (AT 1 g)	ROOM TEMPERATURE	SPHERE TEMPERATURE	DATA RECORDING TIME
	sec	psi	psi	psi-N_2	psi-N_2	lbf	lbf	lbf	lbf	lbf	lbf	°F	°F	min
20*	5	215	149	1400	1375	172.25	169.75	10.25	7.75	162.00	161.00	72.0	65.0	1
21	5	215	149	1375	1310	171.25	169.00	10.25	8.00	161.00	160.00	72.0	75.0	1
22	5	215	148	1310	1280	170.50	168.00	10.50	8.00	160.00	159.25	72.0	64.0	1
23	5	215	148	1280	1210	169.50	167.00	10.25	7.75	159.25	158.25	72.0	64.0	1
24	5	215	147	1210	1200	168.50	166.00	10.25	7.75	158.25	157.50	72.0	63.0	1
25	5	215	147	1200	1150	167.75	165.25	10.25	7.75	157.50	156.50	72.0	73.0	1
26	5	215	146	1150	1100	167.00	164.50	10.50	8.00	156.50	155.75	72.0	62.0	1
27	5	215	145	1100	1050	165.75	163.50	10.00	7.75	155.75	155.00	72.0	61.0	1
28	5	215	144	1050	1010	165.00	162.50	10.00	7.25	155.00	154.00	72.0	60.0	1
29	5	215	144	1010	1000	164.00	161.75	10.00	7.75	154.00	153.25	72.0	59.0	2
30	5	215	143	1000	960	163.00	160.75	9.75	7.50	153.25	152.25	72.0	59.0	1
31	5	215	142	960	910	162.00	160.00	9.75	7.75	152.25	151.50	72.0	58.0	1
32	5	215	142	910	890	161.25	159.00	9.75	7.50	151.50	150.75	71.5	58.0	1
33	5	215	141	890	850	160.25	158.00	9.50	7.25	150.75	150.00	71.5	58.0	1
34	5	215	135	850	800	159.50	156.75	9.50	6.75	150.00	149.25	72.0	57.0	1
35	5	215	135	800	770	158.25	155.75	9.00	6.50	149.25	148.50	72.0	57.0	1
36	5	215	130	770	750	157.50	155.00	9.00	6.50	148.50	147.75	72.0	57.0	1
37	5	215	130	750	700	156.50	154.25	8.75	6.50	147.75	147.00	72.0	57.0	1
38	5	215	125	700	680	155.75	153.25	8.75	6.23	147.00	146.25	72.5	57.0	1
39	5	215	120	680	650	155.00	152.50	8.75	6.25	146.25	145.50	72.5	57.0	1
40	5	215	115	650	600	154.00	151.50	8.50	6.00	145.50	144.75	72.5	56.5	1
41	5	215	115	600	580	153.00	150.75	8.25	6.00	144.75	144.00	70.0	56.0	1
42	5	215	115	580	525	152.25	150.00	8.25	6.00	144.00	143.25	69.0	55.0	1
43	5	215	110	525	510	151.50	149.00	8.25	5.75	143.25	142.75	68.0	55.0	1
44	5	215	110	510	500	150.50	148.25	7.75	5.50	142.75	142.00	68.0	54.0	1
45	5	215	110	500	480	149.75	147.50	7.75	5.50	142.00	141.25	68.0	54.0	1
46	5	215	105	480	425	149.00	146.75	7.75	5.50	141.25	140.75	69.0	54.0	1
47	5	215	100	425	400	147.75	145.50	7.00	4.75	140.75	140.00	70.0	54.0	1
48	5	215	95	400	390	147.25	145.00	7.25	5.00	140.00	139.50	70.0	54.0	1
49	5	215	85	390	350	146.25	144.25	6.75	4.75	139.50	138.75	71.0	54.0	1
50	5	215	80	350	310	145.50	143.25	6.75	4.50	138.75	138.25	72.0	54.0	1
51	5	215	80	310	300	144.50	142.50	6.25	4.25	138.25	137.75	72.0	54.0	1
52	5	215	80	300	290	143.75	141.75	6.00	4.00	137.75	137.25	72.0	54.0	1
53	5	-	75	290	250	142.75	141.00	5.50	3.75	137.25	136.75	72.0	54.0	1
54	5	-	70	250	220	142.00	140.25	5.25	3.50	136.75	136.25	72.0	54.0	1
55	5	-	65	220	210	141.00	139.25	4.75	3.00	136.25	135.75	72.0	54.0	1
56	5	-	60	210	200	140.25	138.50	4.50	2.75	135.75	135.50	72.0	54.0	1

*Sphere started to frost up.

1 g weight of sphere was measured at AEC Oak Ridge Tenn. facility

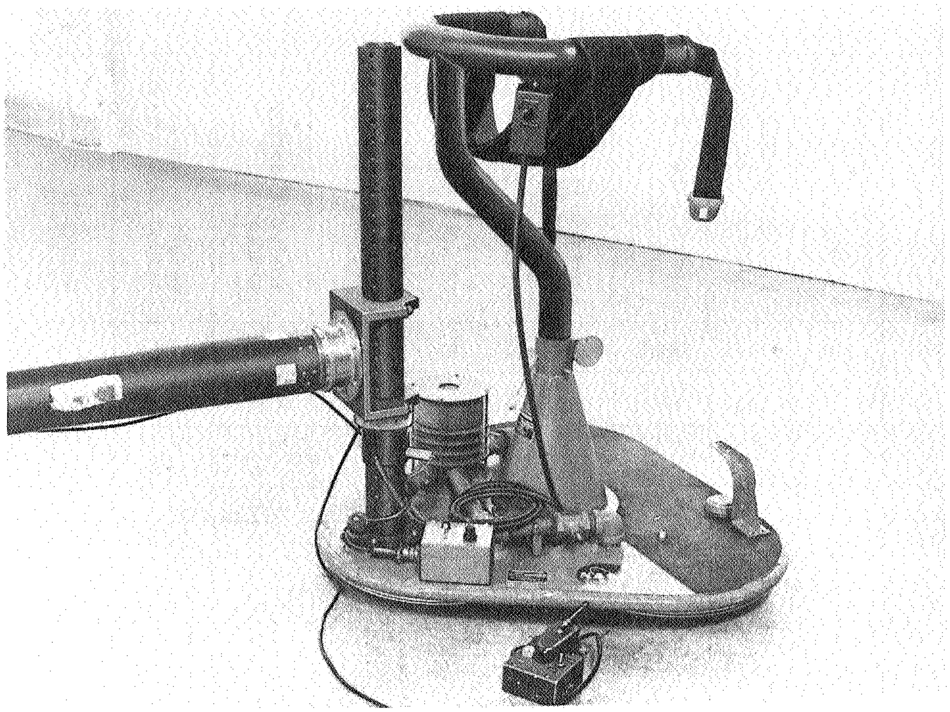


FIGURE 29. MANNED VERSION OF THE AIR BEARING PLATFORM

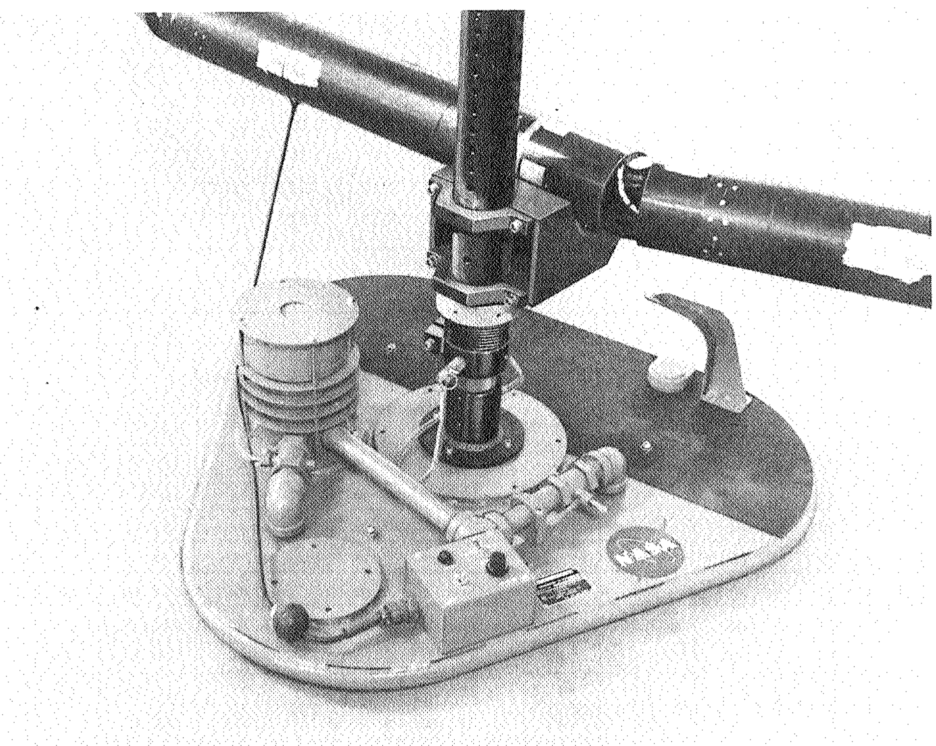


FIGURE 30. UNMANNED VERSION OF THE AIR BEARING PLATFORM

bracket, 4.45 kg (0.373 slugs); serpentuator support, post and bracket, 4.45 kg (0.373 slugs); and the operator's mast and safety yoke, 8.18 kg (0.56 slugs). Each platform will support a nominal load of 273 kg (18.7 slugs). The platform flotation lifting height can be adjusted by controlling the speed of the air supply motor. When unbalanced loads are supported by the platform, it can be leveled by manually adjusting valves which restrict the air flow delivered to each pad. The air supply motor is protected by a 10 A combination circuit breaker/toggle switch mounted in the electrical control box. The unmanned speed control is also contained in the electrical control box. On the manned version the air supply motor runs as long as the foot-treadle is depressed, and the air supply speed control is mounted on the operator's seat yoke. The air supply is capable of maintaining a plenum pressure of 17 220 N/m^2 (2.5 psig) for flows up to 0.438 standard m^3/min (15.5 scfm). The only power requirement is single phase 115 Vac 60 Hz (60 Cps) with maximum current of 10 A.

Application. In Figure 31 the serpentuator and operator are supported by the air bearing platforms described above.

FIGURE 31. AIR BEARING PLATFORMS SUPPORTING SERPENTUATOR AND OPERATOR

BIBLIOGRAPHY

1. Air Bearing Platform, T50-2, Final Report. Contract NAS8-20855, North American Rockwell Corporation, Space Division, Downey, California, October 31, 1967.

2. Bread-Boarded Thruster Assembly, TR SE-33-67, Contract NAS8-20083, Hayes International Corporation, Huntsville, Alabama, December 12, 1967; and Evaluation Test Plan for the Air Bearing Thrusted Scooter Assembly and LTV Grappler Module, December 21, 1967.

3. Design, Fabrication and Proof Testing of a Low Pressure, Air Bearingized Frictionless Parallelogram, Technical and Program Plan, and Progress Reports 1, 2 and 3; Operation and Maintenance Instruction Manual for Lunar Gravity and Earth Orbital Simulator. Contract NAS8-20821, Martin-Marietta Corporation, Baltimore Division, Baltimore, Maryland, May through October, 1967.

4. Evaluation of Six-Degree-of-Freedom Mechanical Simulator, TR SE-1-67. Contract NAS8-20083, Hayes International Corporation, Huntsville, Alabama, February 9, 1967.

5. Lunar Gravity and Earth Orbital Simulator (Parallelogram), TR SE-19-67. Contract NAS8-20083, Hayes International Corporation, Huntsville, Alabama, October 9, 1967.

6. Operation and Maintenance Instructions for the Frictionless Simulator. Contract NAS8-17264; Martin-Marietta Corporation, Baltimore Division, Middle River, Maryland, November 20, 1963.

7. Operation Plan for Action-Reaction Free-Fall Simulator, MIT-375-14529. Manufacturing Engineering Laboratory, MSFC, Huntsville, Alabama.

8. Upgraded Lunar Gravity Simulator, TR SE-26-67. Contract NAS8-20083, Hayes International Corporation, Huntsville, Alabama, November 6, 1967.

LASERS USED IN MANUFACTURING

By

John R. Rasquin

SUMMARY

The chief manufacturing uses for the laser are in the areas of welding, cutting, and hole punching. These uses are now leading to new manufacturing methods. The lasers used for these tasks can be classified into two types: the continuous wave laser and the pulsed laser. It has been the experience of this laboratory that the continuous wave (CW) laser is better for welding and that the pulsed laser is better for cutting and hole punching.

PULSED LASER

The use of a pulsed laser for welding, when the pulse repetition rate is slow enough so that the weld nugget does not remain molten, results in a series of spot welds, one on top of the other. This method usually does not produce a good weld because the odds of producing oxide inclusions, incomplete fusion, etc., are greatly increased. If the pulse repetition rate is high enough to keep the weld nugget molten, then there are the problems of crystal cooling and having a power supply large enough to charge this energy storage system rapidly enough.

The large capacitor bank used in the Manufacturing Engineering Laboratory has a capacity of 240,000 J and takes 15 sec to charge fully. A pulse repetition rate of four times a minute is relatively fast for an electrical apparatus of this size. Yet it is evident that even this rate will not suffice to maintain a weld crater. It is estimated that a repetition rate of at least four times a second is needed to maintain a molten crater. This makes the size of the power supply ridiculously large.

Figure 1 shows the interior of the 240 kJ ruby laser gun which has been used for welding, cutting, and hole punching. Figure 2 shows that a 0.635-cm (0.25-in.) thick aluminum sheet can be pierced quite easily using this laser. The ruby laser gun was developed and built in the Manufacturing Engineering Laboratory. Energy outputs as high as 2800 J have been measured.

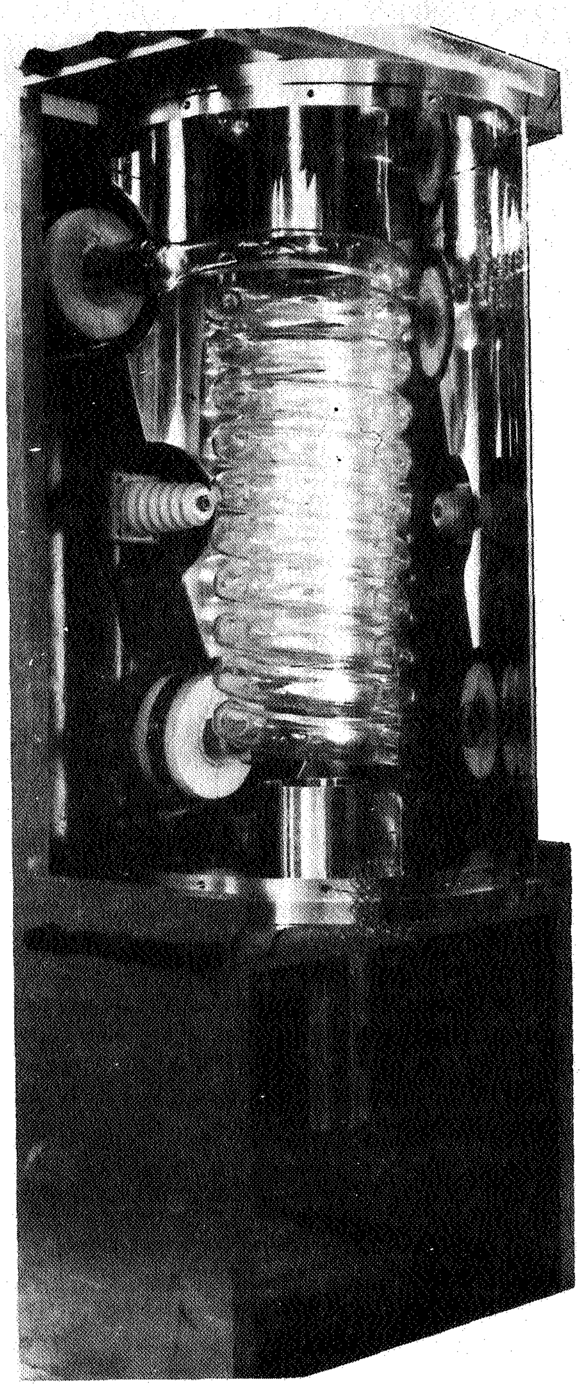


FIGURE 1. INTERIOR VIEW OF 240 kJ RUBY LASER GUN

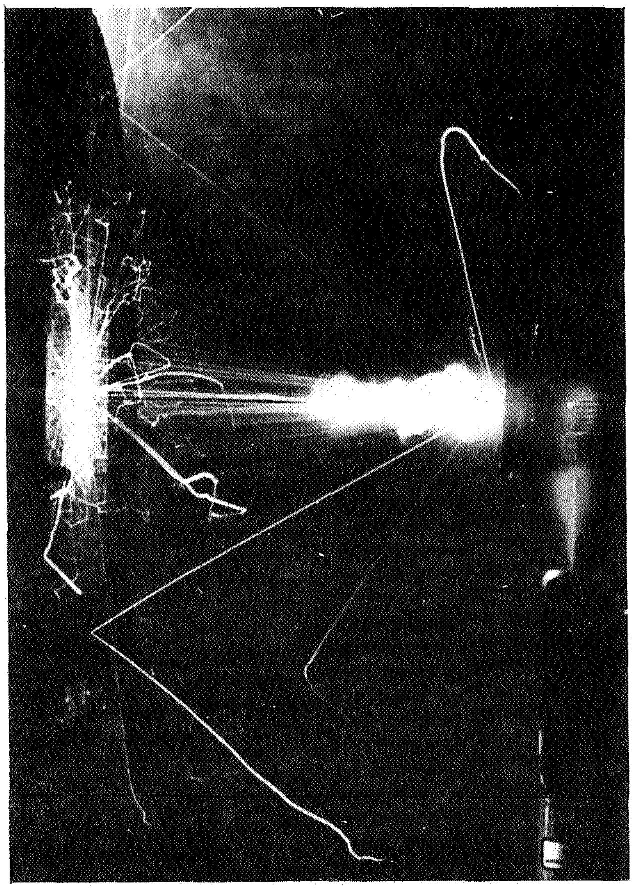


FIGURE 2. LASER PENETRATION OF 0.635-cm (0.25-in.) THICK ALUMINUM SHEET

Two problems that are annoying with rapid-pulse repetition rates are (1) radiation damage to the crystal by the intense ultraviolet (uv) output from the lamp, and (2) keeping the crystal cool enough so that the threshold for lasing remains reasonable. New Pyrex filters will stop almost all the uv radiation from reaching the crystal, but at high lamp intensities the Pyrex will solarize badly. Liquid nitrogen is used to cool the crystal, but it is relatively difficult to use and is somewhat hazardous.

Figure 3 shows the light output from our flash tube. When the radiation gets this high in the visible light region, it can be easily seen that the uv radiation is tremendous because when flash tubes are run at this level the uv output is greater than the light in the visible region.

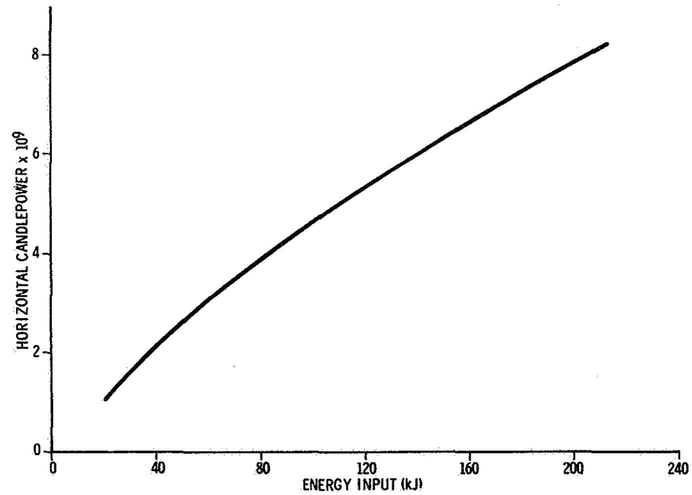


FIGURE 3. FLASH TUBE LIGHT OUTPUT

It is this laboratory's opinion that a liquid coolant is needed for the laser. This liquid coolant should have the following properties, listed in the order of their relative importance.

1. Excellent ultraviolet absorber.
2. Transparent in the pumping bands for ruby lasers.
3. Extremely low freezing point.
4. Liquid at ambient temperatures.
5. Large specific heat.
6. Inexpensive and readily available.
7. Nontoxic.

A contract was negotiated with Auburn University to investigate possible liquid coolants. This contract has not yet been concluded, but so far it has been found that a mixture of substances will probably be the best solution. The result will probably be a silicone oil because of its stability as a coolant when mixed with a uv absorber material.

Elements on the periodic chart that have unfilled inner electron orbits exhibit intense absorption bands. If it is possible to find an element with this property that absorbs at the proper wavelengths for the laser crystal, then this element will make a much better solute than any compound that absorbs energy between a bond of two atoms, because the absorption of tremendous amounts of radiation will destroy the bond and decompose the solute.

There are three primary groups of elements that have unfilled inner electron shells: the transition metals, the lanthanide series, and the actinide series. Absorption spectra have been run on a majority of the transition metals including manganese, iron, cobalt, nickel, and copper, chosen because of their low cost and availability. Of all these, copper is the only element that absorbs at the proper wavelengths to be an effective laser coolant solute.

The most suitable coolant will probably be a suspension of copper sulfate in a silicone oil. Since the silicone oils have an affinity for glass, the copper sulfate will probably be mixed in glass in the molten state. After cooling, the glass will be powdered and mixed in the oil.

Another contract has been awarded to the Linde Crystal Division of Union Carbide Corporation to investigate the damage done to ruby crystal by uv radiation. It is possible that the Cr^{+++} ion becomes Cr^{4+} or even Cr^{6+} from the radiation. Of course, Cr^{4+} and Cr^{6+} will not lase.

A sample of the original boules from 5 crystals was subjected to spectroscopic analysis. These 5 crystals were used by this laboratory until badly damaged by radiation and were then shipped to Linde Crystal Division where another sample was cut from the rod. Preliminary spectroscopic analysis of these samples shows that the crystal becomes absorbent at 6934 Å. It is hoped that with a better understanding of how degradation occurs in the crystal when it is exposed to radiation, it may be possible to make rods more radiation resistant.

When cutting and hole punching are done with a pulsed laser, the best cuts are made when the material is completely vaporized. This produces clean cuts and the absence of tears on the back of the material. The pulsed laser does a good job of vaporizing material, and is superior to the CW laser when used for this task.

CONTINUOUS WAVE LASER

An important consideration in the application of lasers in the welding field is efficiency. Generally the laser is simply not efficient. The most efficient laser with respect to power requirements is the CO_2 laser. This CW laser will operate at an efficiency as high as 15%. To weld metals of practical thickness, at least a 500 W input into the weld zone is needed. When considering 95% reflection at this wavelength in aluminum, the power requirement is increased to about 72 kW. In spite of this, the CO_2 laser is the most efficient laser for welding. The main drawback is the huge size of the laser; one meter of discharge tube is required for every 50 W of output. This means that a 500 W CO_2 laser would be roughly 10 m (30+ ft) long. Obviously any welding job done with this laser would have to be brought to the laser, instead of the laser being transported to the job. Otherwise a very expensive optical system would have to be made to guide the laser beam. Therefore this laboratory took the next best choice and decided upon the YAG laser. Here the lasing element is a small YAG crystal, and the welding head for this laser would not be so large as to be impractical. The acronym YAG means Ytterbium Aluminum Garnet.

Accordingly, a 100 kW argon vortex arc light pump (Fig. 4) was made for this laboratory on a contract with the Korad Division of Union Carbide. This equipment has been received and will be tested as soon as it can be hooked up. The output of this welding head should exceed 300 W at a wavelength of 1.06 μ.

Figure 5 shows a close-up view of the pressure control panel. These argon arc lamps are potentially explosive. The higher the gas pressure the more intense the light. Pressures of 7 MN (1000 psi) are not uncommon, although this lamp uses 2.1 MN (300 psi) gas pressure. A closeup of the electrical control panel is shown in Figure 6; and Figure 7 shows a close-up of the lamp assembly. This unit is small enough to fit on a Linde side-beam carriage so that no special fixture will have to be made to use it for welding. Also this unit was designed to operate from two standard electric welding machines for power supplies. This is a great saving of money in building this apparatus. If this machine is successful, it can weld sheet metal up to 0.635-cm (0.25-in.) thickness as easily as a tig (tungsten inert gas) or mig (metallic inert gas) welder can do the job. This ought to make the laser a practical tool for the shop.

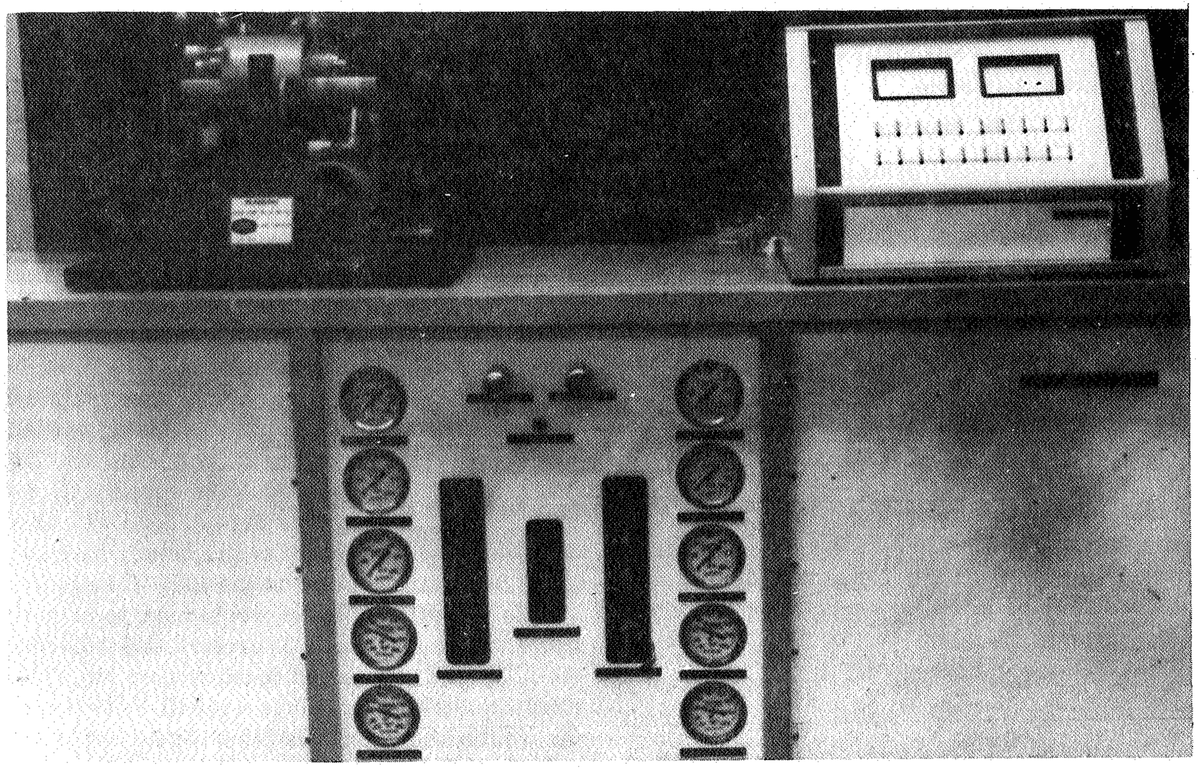


FIGURE 4. VIEW OF 100 kW VORTEX ARC PUMP

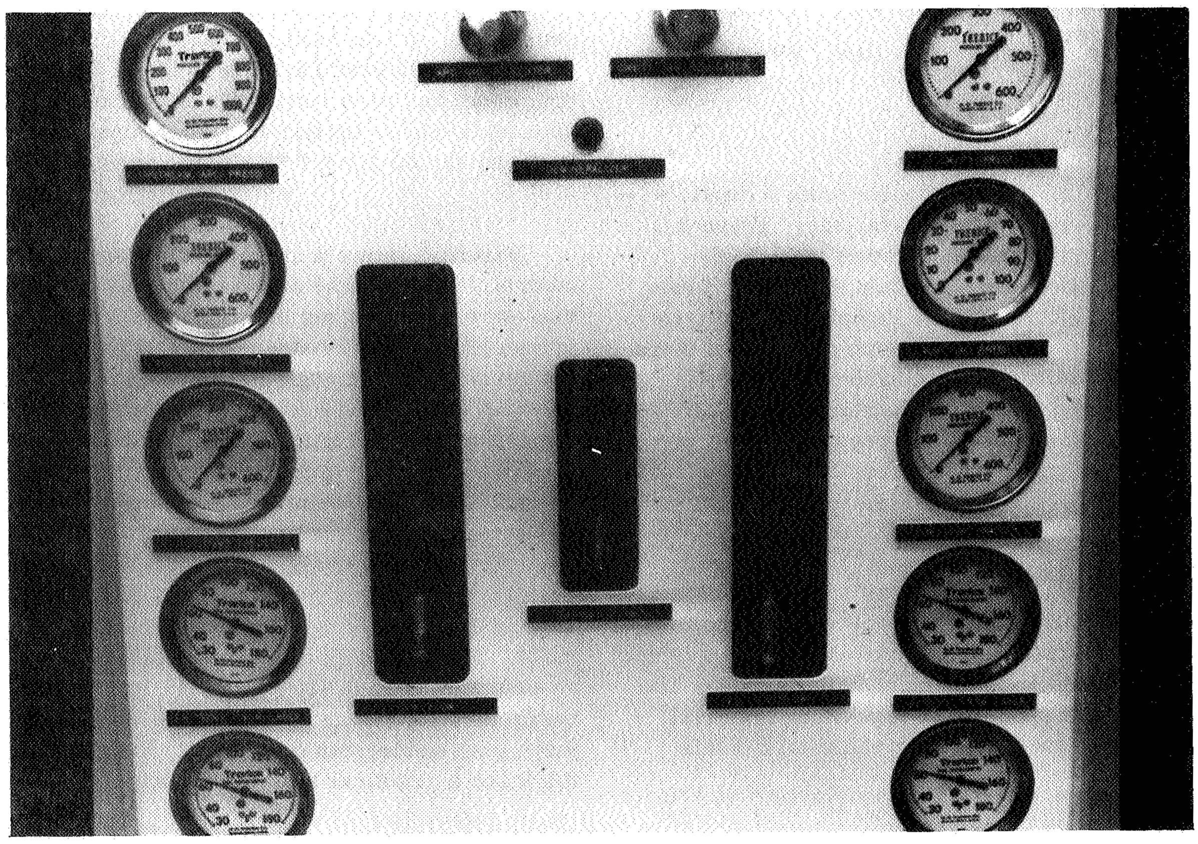


FIGURE 5. PRESSURE CONTROL PANEL

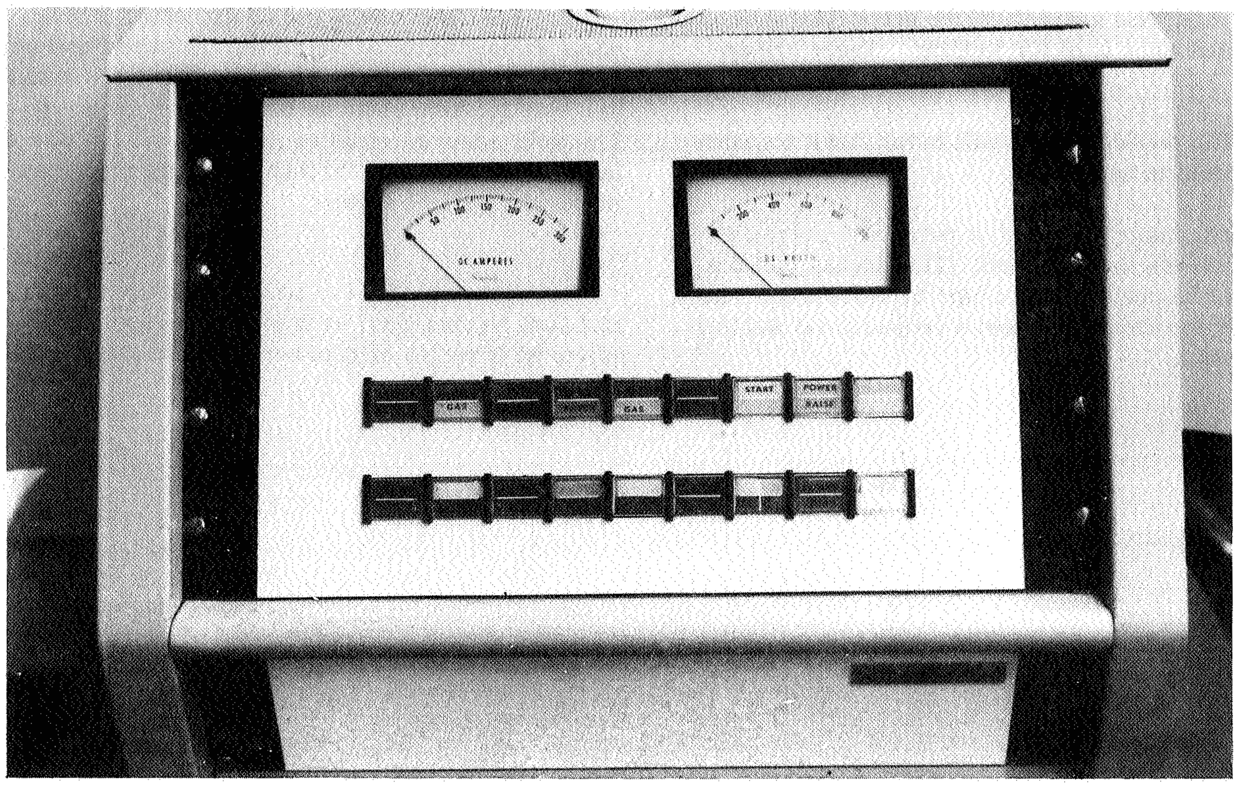


FIGURE 6. ELECTRICAL CONTROL PANEL

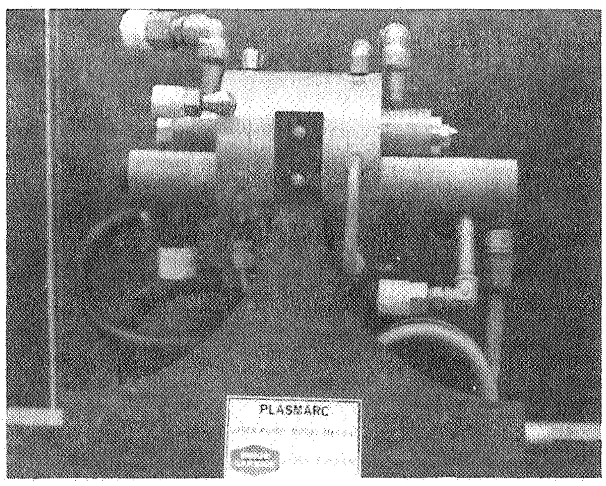


FIGURE 7. LAMP ASSEMBLY

Figure 8 shows the cracking and porosity that result when trying to weld with a pulsed laser in thick material. This laboratory favors the continuous wave laser approach to welding seams. The weld nugget shown is in 0.635-cm (0.25-in.) thick aluminum.

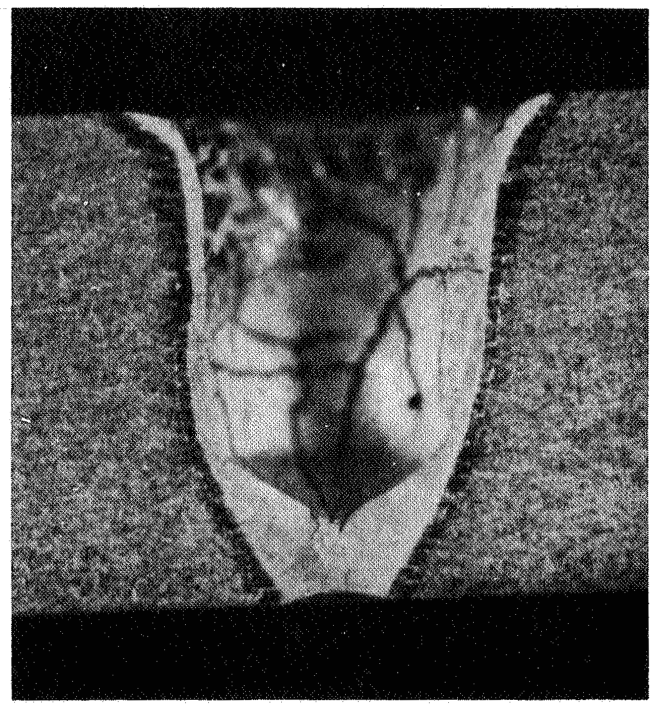


FIGURE 8. WELD CRACKING IN THICK MATERIALS (PULSED-LASER WELD)

The laser has several unique properties that can be exploited when used for welding. These are as follows:

1. The source of heat will not in itself contaminate the weld in any way.

2. The laser will weld at relatively great distances from the welding head. This means that the weld could be made inside a pipe or valve where the opening is too small to insert a conventional welding head or torch.

3. The laser beam can be projected through glass without harm to the glass. If a toxic material such as beryllium needs to be welded, a box vented to a safe location could be fitted with a glass top. The weld material could be placed in the box and the laser beam projected through the glass and a weld made with perfect safety.

4. If it is desired to bore extremely hard material such as diamond, or if extremely small holes are to be bored, a high powered pulsed laser is ideal.

NEUTRAL BUOYANCY SIMULATION

By

Charles R. Cooper, Paul H. Schuerer,
and Ronald L. Nichols

SUMMARY

With the advent of the Apollo Applications (AAP) Program, it became apparent that Marshall Space Flight Center (MSFC) would be called upon to develop hardware that would be man operated in a zero gravity environment. A capability for evaluating the hardware to be produced was urgently needed.

In 1966 a small electrohydraulic forming tank was converted for use as the first neutral buoyancy facility. This tank was 1.8 m (6 ft) in diameter and 2.4 m (8 ft) deep. The first task assignment was to evaluate a Marshall concept for the S-IVB Orbital Workshop hatch cover; and the tests were made with the diver wearing scuba gear.

In 1967 Marshall converted its explosive forming tanks into a neutral buoyancy facility; this facility and associated equipment will be described in this paper.

INTRODUCTION

MSFC is engaged in two types of zero gravity simulation testing: mechanical simulation and neutral buoyancy. Two distinct advantages of mechanical simulation are that (1) preparation times are short, and (2) the test environment is relatively free of hazards. However, mechanical simulation testing has limited application because of handicaps created by the equipment when conducting task studies. This limitation is one of the major reasons why MSFC decided to develop a capability in neutral buoyancy testing.

The three major objectives to be achieved through zero gravity simulation testing are as follows:

1. To provide information on spacecraft and component design concepts prior to freezing the design for production of test items.

2. To provide statistical data to the design engineers on the capabilities of men working under zero gravity conditions.

3. To be a method of evaluating hardware by testing under conditions that simulate zero gravity of the space environment in which the components will eventually function.

NEUTRAL BUOYANCY FACILITIES AND EQUIPMENT

The operational structure from which neutral buoyancy tests are conducted is shown in Figure 1. This structure possesses the highest degree of safety devices for conducting these tests. The entire operation is controlled by the Test Conductor who has overall responsibility during any test being performed.

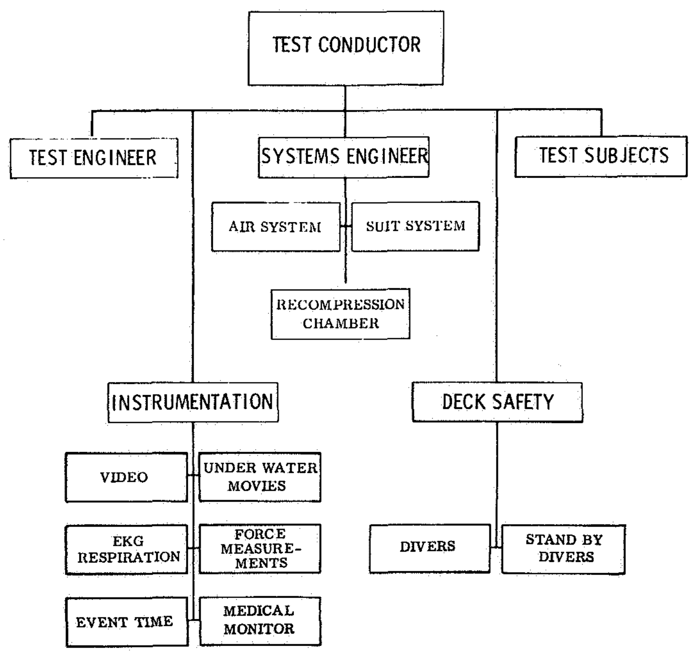


FIGURE 1. OPERATIONAL STRUCTURE

The Test Engineer's primary function is to explain to the diver the sequence of events to be accomplished in the tank. The Systems Engineer is responsible for the air system, suit system, and recompression chamber. Hopefully, the recompression chamber will never have to be used, but when working with underwater activities at depths and pressures being planned for future tests, it is a necessary piece of equipment. Skilled divers perform the underwater tests. The Deck Safety is also the above-water observer for the test. The Instrumentation Engineer is responsible to record all the data and to monitor the instruments while the test is being performed.

Figure 2 shows a schematic of the present facility. There are two tanks in the area: a small 4.6 m (15 ft) diameter, 3.1 m (10 ft) deep tank that is used in good weather, and a larger tank, 7.6 m (25 ft) in diameter and 4.6 m (15 ft) deep, in which most of the tests are currently performed. This larger tank is covered with an air structure containing the control panels (Fig. 3). The tank has one air lock for personnel and another air lock through which large mock-ups and equipment are transported (Fig. 4). The instrumentation (Fig. 5) and recompression chamber (Fig. 6) are housed in the structural area near the tank.

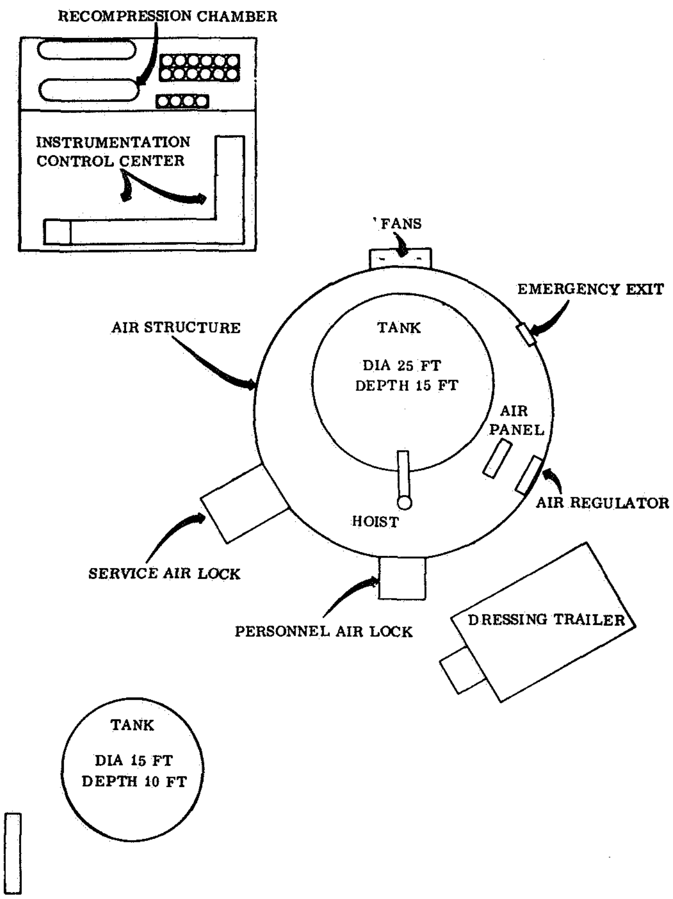


FIGURE 2. SCHEMATIC OF NEUTRAL BUOYANCY FACILITY

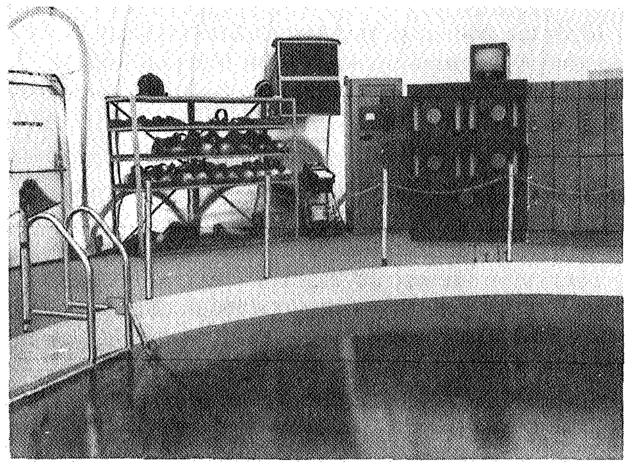


FIGURE 3. TANK WITH SUIT AND HELMET PRESSURE MONITORING EQUIPMENT

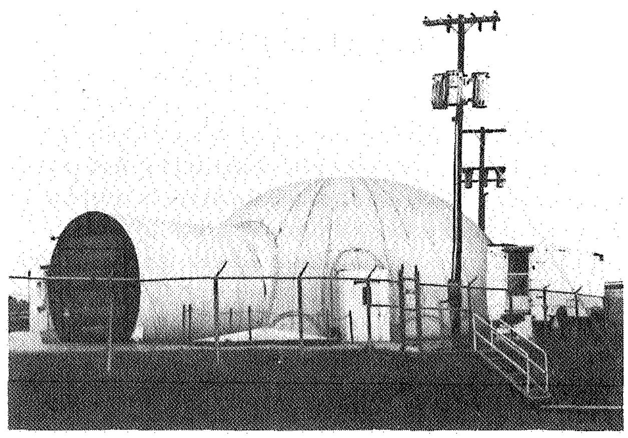


FIGURE 4. AIR STRUCTURE FOR NEUTRAL BUOYANCY FACILITY

When neutral buoyancy testing was initiated, divers had to use scuba gear instead of pressurized suits. One of the most significant advances since then is the introduction of pressure suit testing.

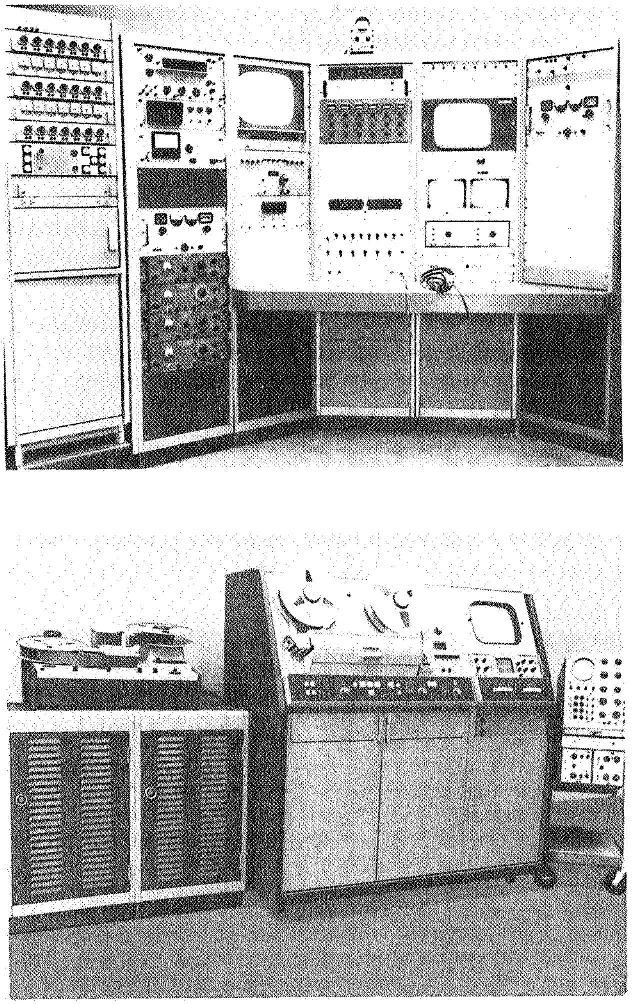


FIGURE 5. MONITORING AND RECORDING EQUIPMENT

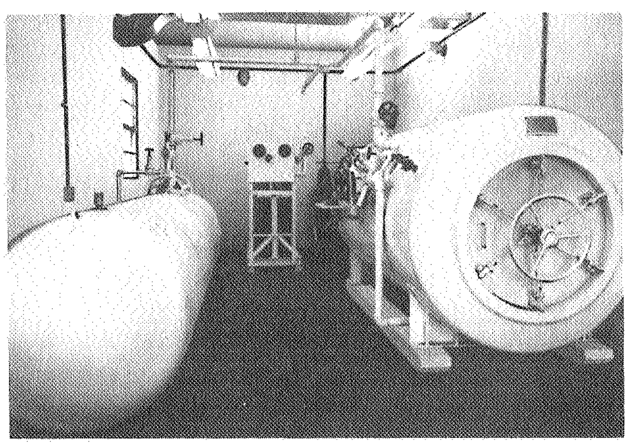


FIGURE 6. RECOMPRESSION CHAMBER

Figure 7 shows some of the types of instruments to record measurements. A continuation of these programs will allow expanding and improving the data acquired from these devices.

BIOMEDICAL, METABOLIC AND ENVIRONMENTAL

A. Six Channel Telemetry (Low Level)

1. EKG
2. Respiration
3. Internal Body Temperature
4. Skin Temperature
5. Differential Pressure
6. Absolute Pressure

B. Carbon Dioxide Monitor (2 Channels)

EXPERIMENT INSTRUMENTATION

A. Magnetic Tape Recorder (14 Channels)

B. Strip Chart Recorder (8 Channels)

C. Signal Conditioning and Amplifiers

D. Transducers

VIDEO EQUIPMENT

A. Ampex VR 2000 and VR 1500 Recorders

B. Underwater Cameras (3)

C. Above-Water Cameras

PHOTOGRAPHY

A. Underwater Movie Cameras (2) 16 mm

B. Underwater Still Cameras (2) 35 mm

C. Above-Water Movie and Still Cameras

FIGURE 7. INSTRUMENTATION

Telemetry equipment is used to measure EKG, respiration, internal body temperature, differential pressures, absolute pressure, and carbon dioxide concentration. Instruments to record the data include magnetic tape recorders, strip chart recorders, signal conditioning devices, amplifiers, and transducers for measuring forces in force measurement studies. Video equipment consists of Ampex VR 2000 and VR 1500 recorders, and underwater and above-water cameras.

NEUTRAL BUOYANCY TESTING

The Human Engineering Maintenance and Repair Study was a program to gather statistical data on the amount of force that could be applied by a diver wearing a pressure suit and working against various types of restraint systems. Variables in the program included (1) test subject, (2) type of suit pressurization, (3) restraint systems, and (4) orientation of the force measuring apparatus.

In Figure 8, the diver is performing activities in the Human Engineering Maintenance and Repair Study. He is wearing an Apollo State-of-the-Art pressure suit with a modified helmet having pressurization modes of water or air. This suit is air pressurized to 24 000 N/m^2 (3.5 psi). The diver is operating a force receiver that transmits data to a digital tape recorder.

The cue panel that the driver reads to obtain instructions is shown in Figure 9. The test engineer in the instrumentation control center has a cue panel that matches this one to instruct the diver orally and visually to perform an operation.

The translation study on the Apollo Telescope Mount (ATM) included developing a handrail that could be used by the astronaut to maneuver from the Lunar Excursion Module (LEM) work station of the ATM to the Sun work station on the opposite end. Figure 10 shows the evaluation of this translation device when attached to the exterior of the ATM. The diver is translating from the Lunar Module (LM) work station to the Sun work station with the assistance of this mobility aid, and is performing this test in a Mark IV full pressure suit.

Figure 11 shows a diver in scuba attire performing a mass transfer study of moving packages through

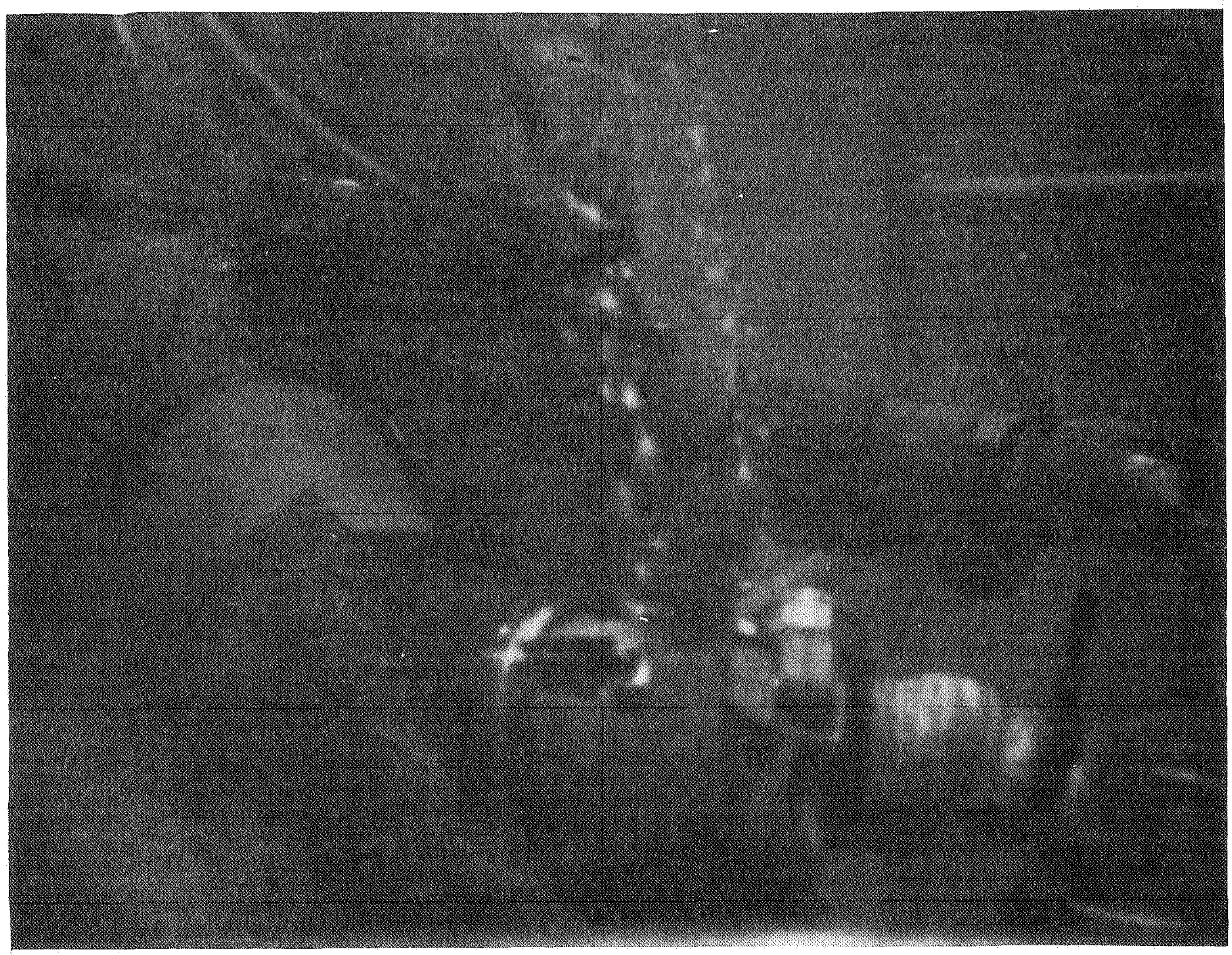


FIGURE 8. TEST BEING PERFORMED IN APOLLO PRESSURE SUIT

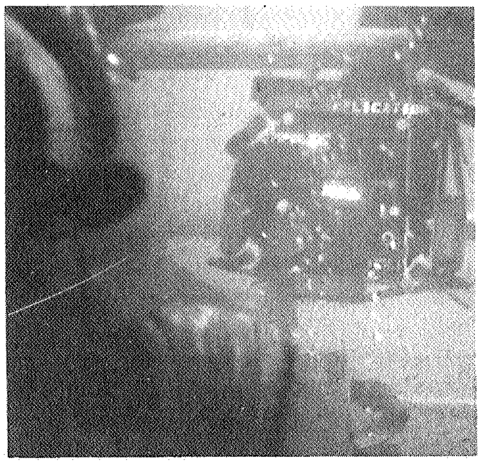


FIGURE 9. CUE PANEL ISSUING INSTRUCTIONS TO DIVER

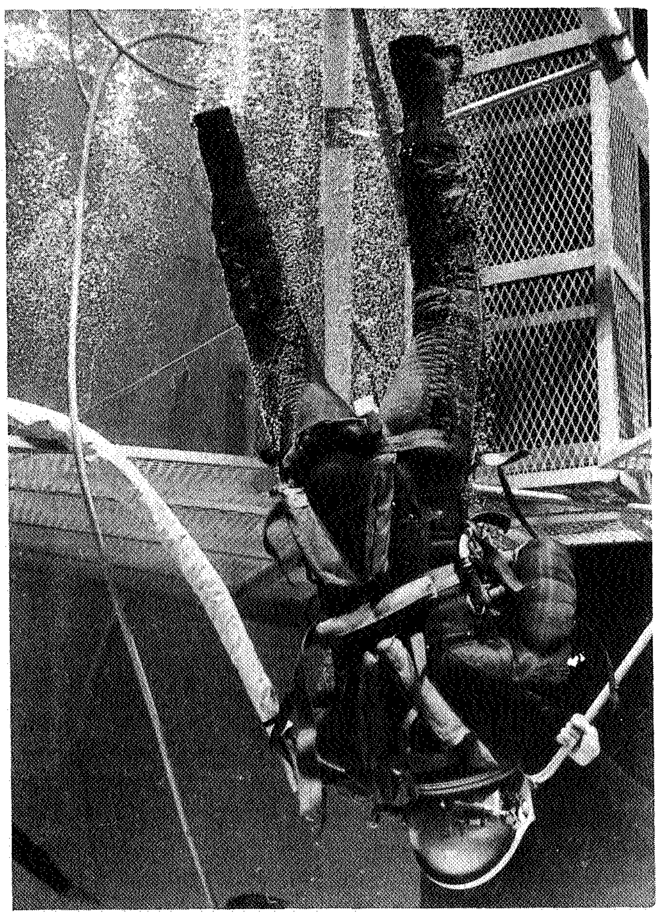


FIGURE 10. TRANSLATION DEVICE TEST IN MARK IV PRESSURE SUIT

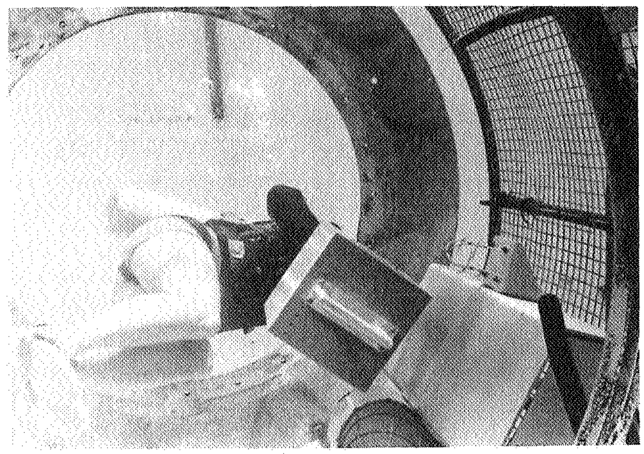


FIGURE 11. MOVEMENT OF EQUIPMENT INTO THE ORBITAL WORKSHOP

the airlock module into the Orbital Workshop. One of the preliminary Orbital Workshop evaluations was to determine if the floor grid would be useful as an aid in maneuvering throughout the Orbital Workshop crew quarters (Fig. 12). The diver was pressurized to 24 000 N/m^2 (3.5 psi) in the Mark IV suit and was wearing Apollo thermal gloves. The test program established that the floor grid was a mobility aid.

FIGURE 12. MOVEMENT OF EQUIPMENT ACROSS THE FLOOR GRID OF THE ORBITAL WORKSHOP

Prior to activating the S-IVB Workshop, it is necessary to double seal all penetrations through the tank wall. Under normal conditions, this would be accomplished in an unpressurized suit. Under Contingency Mode Conditions, however, it would be necessary to accomplish this task in a pressurized suit.

In Figure 13 the diver is performing one of the tasks required to seal all the penetrations in the aft

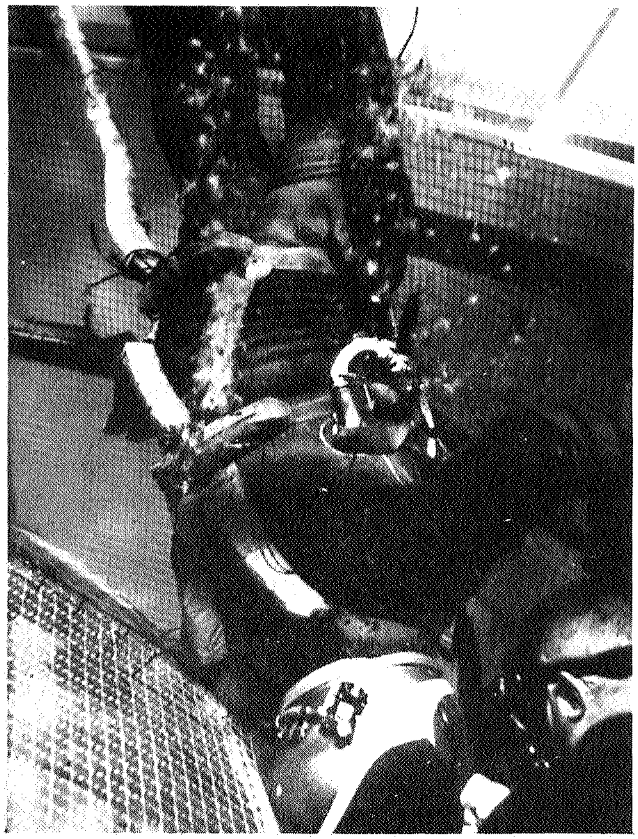


FIGURE 13. SEALING THE AFT DOME PENETRATION OF THE ORBITAL WORKSHOP

dome section of the Orbital Workshop. Although these penetrations are sealed by valves, mechanical seals will be installed as an additional safety measure to ensure that the module remains pressurized. Four sealing devices are required: the LH_2 chill pump seal, the LH_2 feed line plug, chill system return line seal, and the fill and drain line plug.

CONCLUSIONS

1. Neutral buoyancy provides the most realistic long time simulation of zero gravity conditions. Other simulation techniques are limited to either short test times of a maximum of 30 sec in the parabolic flight of the KC-135, or to localized work areas, as is the case with mechanical simulators. Zero gravity testing under neutrally buoyant conditions can be conducted over several hours and is restricted only by the physical capabilities of the man performing the test and the confines of the pool in which the test is being conducted.

2. Primary benefits are obtained when tests are conducted with the diver in a pressure suit. Most individuals possess an inherent knowledge of man's capability to perform work under zero gravity conditions if he is not restricted by a pressure suit. This may be related somewhat to experiences connected with swimming. This knowledge is not available, however, when a man must work in zero gravity while constrained by a pressure suit.

3. Probability of mission success can be significantly improved by both evaluating hardware and training personnel in its use under zero gravity conditions. Hardware must be tested in the environment in which it will be used to determine the best design and the amount of personnel training required.

4. Instrumentation and equipment must be improved and/or developed to more closely equate the water and space environments. Work to date indicates many areas in which further development is required. Medical monitoring systems need to be improved and expanded. Hopefully, hard wires can be eliminated between the test subject and surface mounted instruments so that eventually the diver will be completely free of outside attachments. This will require providing the diver with a miniaturized breathing apparatus, and alternate methods of data transmission must be found. Perhaps the use of liquid air would be another solution to this problem.

Improved systems for making the divers neutrally buoyant are required. The present system of weights is time consuming to employ, although it is effective.

New, neutrally buoyant, high-strength materials, from which more realistic mockup components can be produced, must also be found.

These are but a few of the many equipment and hardware developments needed. In the coming months improved mockups should be available of all AAP hardware for which MSFC has design or fabrication responsibility. Experience to date from MSFC and other personnel who have used the neutral buoyancy facility indicates the value of this type of zero gravity simulation testing and is an encouragement for its continued use in the AAP and follow-on programs.

ALUMINUM WELDING DEVELOPMENT COMPLEX

By

Robert V. Hoppes

SUMMARY

First, a description of the past welding situation and identification of the first group of studies are presented. Second, a review of technical data and how an analysis of such data have led to new studies are discussed. Finally, a summary of welding contributions to the Saturn V vehicle and to technology in general is described.

INTRODUCTION

In 1963 a survey of the aerospace industry was made to determine common aluminum welding problems, what was being done about these problems, and what areas still needed investigation. It was expected that the survey would find duplication of effort and redundancy, but this was not the case. Each company was either concentrating on a unique problem, or was employing a distinct approach. On the other hand, none of the companies was attempting to survey the whole area of fusion welding. It was decided that MSFC could most effectively function by compiling and analyzing the results from the many studies about fusion welding, and thus determine which future studies were needed to solve complex welding requirements.

In 1964 a symposium was held in which Marshall and industry representatives discussed common welding problems and postulated solutions. A general outline for a comprehensive welding development program was then formulated, and the first group of studies in this program included the following aspects of welding:

1. Defects (in particular, porosity)

2. Mechanical strength of weld joints

3. Transferability of welding parameters (process control)

4. Process and equipment improvement

During 1964 and 1965 several studies were initiated (Fig. 1). The area of porosity was broken into the subareas of (1) the source of porosity, in which shielding gas, material composition, and material surface were studied, (2) porosity formation, in which the mechanism of formation and porosity inhibitors were investigated, and (3) the effect of weld defects on joint performance.

Mechanical strength and processes and equipment were covered by studies of (1) welding energy effect on Al alloy strength, (2) new power sources with different wave shape combinations, (3) magnetic shaping of the Gas Tungsten Arc to increase its power density, (4) data transfer, that is, how to confidently transfer welding techniques and procedures from the laboratory to production, or from facility to facility, (5) development of plasma and nonvacuum electron beam systems, and (6) development of a solid state brazing generator.

TECHNOLOGICAL DEVELOPMENTS

Analysis of this generation of studies has made it possible to further define welding development needs and to concentrate on more significant areas. A summary of data from the 1964 through 1966 studies is discussed with respect to meeting these developments. From a quantitative study of contaminants in helium shielding gas, a tentative guide has been constructed for space vehicle fabrication (Fig. 2). The guide shows contamination levels where significant changes occur. Weld density begins to increase with 250 ppm of oxygen and to decrease with the same amount of hydrogen; porosity begins to occur with 350 ppm contamination; the welding arc begins to

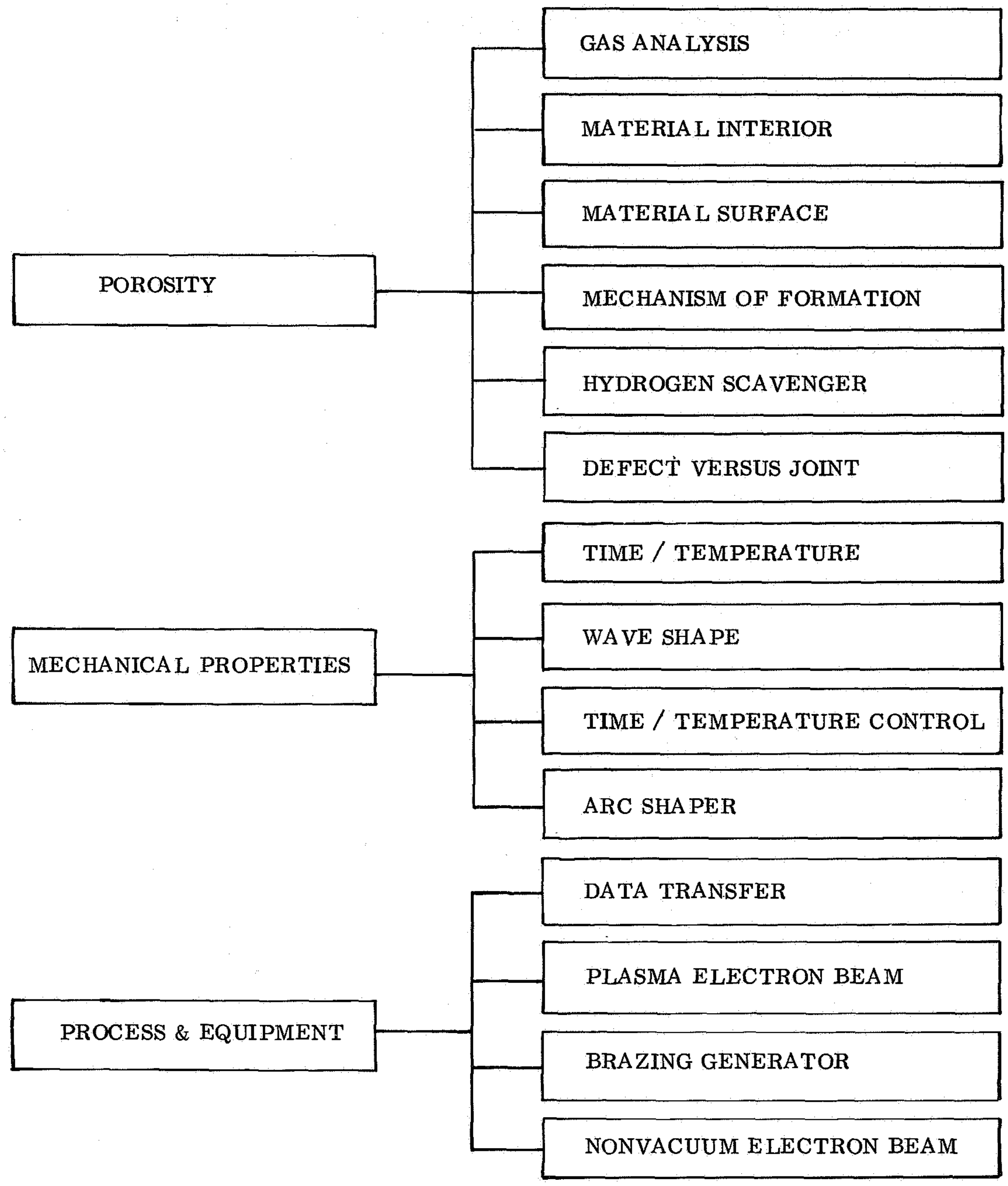


FIGURE 1. WELDING DEVELOPMENT COMPLEX (1964 - 1966)

waver at 800 ppm contamination, etc. More importantly, it is now known that the shielding gas purchased to the present MSFC specification is a minor source of weld porosity.

In a like manner, the weld defect potential of Al plate was examined with regard to the effect of chemical content, internal impurities, and hydrogen content (Table I). Although statistically there are

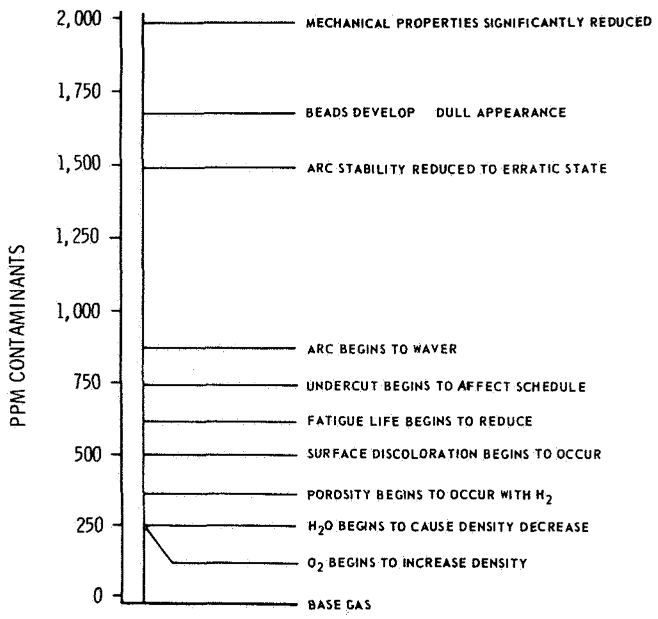


FIGURE 2. CONTAMINATION CONCENTRATION LEVELS AT WHICH SIGNIFICANT CHANGES OCCUR IN WELD QUALITY

TABLE I. VARIABLES VERSUS POROSITY
(In Order of Importance)

1.	Arc Shielding - Gas and Water Content
2.	Alloying Content
3.	Internal Impurities
4.	Internal Hydrogen Content

significant differences in the effect of these variables, it was again concluded that material composition is a secondary source of porosity. If materials were fabricated to the upper limits of current specifications, an increase in weld defects could be expected. However, this is not the case; aluminum companies control material fabrication to a remarkable degree of accuracy on the lower limits of specifications.

In the preceding studies there was convincing evidence that contaminants on the surface of the material might be the greatest source of porosity. The investigators calculated that an influx of 0.6% of air saturated with water vapor would result in 250 ppm of hydrogen in the shielding gas. Less than 0.16 mg/cm (1 mg/in) of hydrogen on the surface could generate 250 ppm of hydrogen, and a single fingerprint could cause a 750 ppm increase in hydrogen contaminants.

Laboratory analysis has now confirmed the conclusion that surface contaminants are a major source of porosity. The investigators have made a list of common cleaning procedures and their relative potential for producing defects in welds (Fig. 3). "As-machined surfaces result in defect-free welds. All other treatments induce some degree of weld impairment," the investigators stated. Surface treatments are listed as follows in increasing potential to produce defects in welds: chemically cleaned, chemically cleaned plus stored in water, degreased in benzene, anodized (according to time), and coated with silicon.

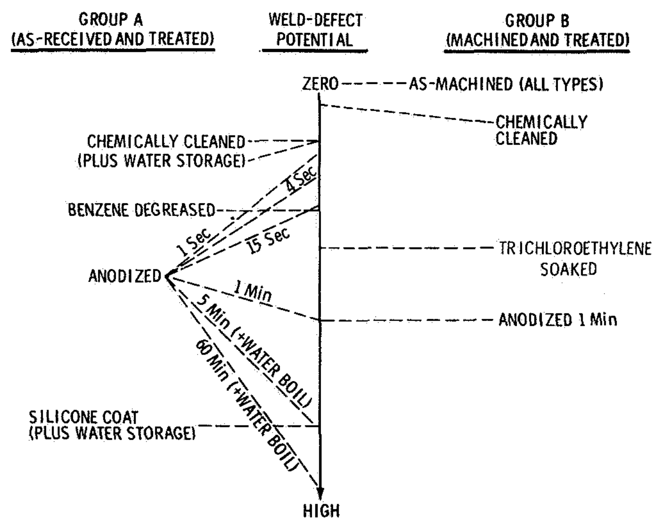


FIGURE 3. CLEANING PROCEDURES

The areas of mechanical properties were covered by an inhouse time-temperature study: a study of the effect of welding energy on the material's strength (Fig. 4). It was concluded that the use of low-energy produces welds with greater strength than those from high-energy welding. Welding energy is expressed as energy in joules of heat per unit length of travel divided by material thickness, or joules/cm^2. As the welding energy in joules decreased, the weld strength increased in 2219 Al weld joints and the peak weld strength of 393 MN/m^2 (57,000 psi) occurred at 1,550 J/cm^2 (10,000 J/in^2), made possible by the highly efficient electron beam welding process. The 2219-T87 Al base metal had a strength of 475 MN/m^2 (69,000 psi) of which about 69 MN/m^2 (10,000 psi) was a result of strain hardening. This metal in the unstrained condition, T6, is listed at 407 MN/m^2 (59,000 psi) weld strength, nearly reached in electron beam welds at 1,550 J/cm^2 (10,000 J/in^2).

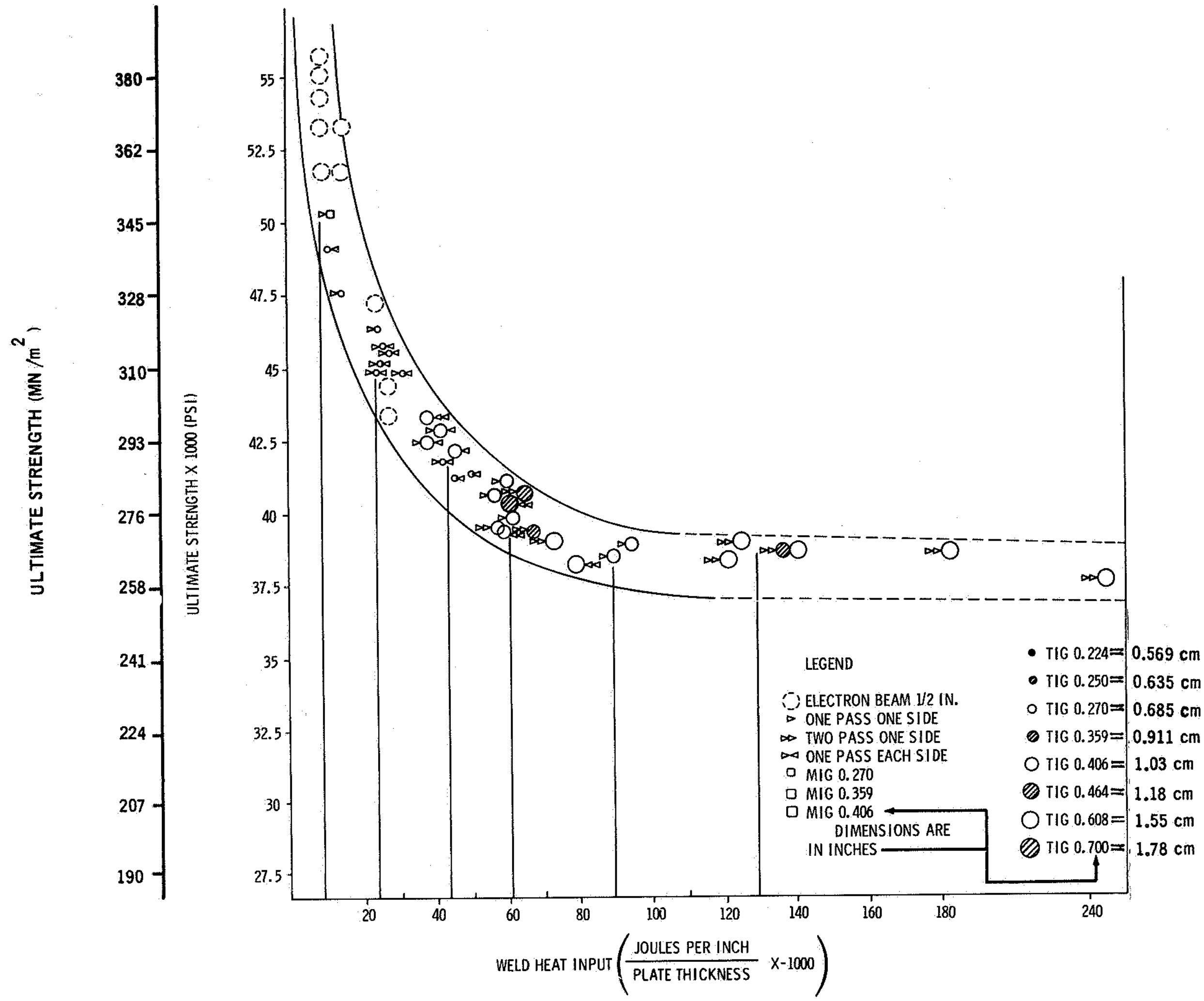


FIGURE 4. HEAT INPUT VERSUS ULTIMATE STRENGTH IN 2219-T87 AND T81 Al ALLOY

Growth of pores (porosity) also is affected by time-at-temperature ratios (Fig. 5). Heating for a long time-at-temperature allows gas to escape from the molten weld puddles; heating the weld area for a short time inhibits pore growth. Unfortunately, most welding is done at a travel speed and temperature that allows gas to expand but not to escape, thus forfeiting the significant increase in weld joint strength obtained in low-energy welding. Porosity frequency plotted against porosity size at different welding travel speeds also shows the effects of thermal gradients or solidification time on porosity formation (Fig. 6). At some level of decreased time-temperature, the formation of porosity should be almost entirely stopped, or at least so finely dispersed that it would not be discernible. Other responses, such as elongation, may require greater energy. In any case, knowledge of the thermal characteristics necessary for any given response allows for purposive, planned uses of welding processes.

Process Control. Some significant progress has been made in the area of process control. Process control is nearly impossible without an efficient system of measurements and records. In addition, records are static in that they represent events that have occurred, and are not influenced by events that are occurring. Keeping records should be preceded by a knowledge of what to measure and to what accuracy. In the past, miles of recording paper have been used, but the variations in the ink lines on the paper were

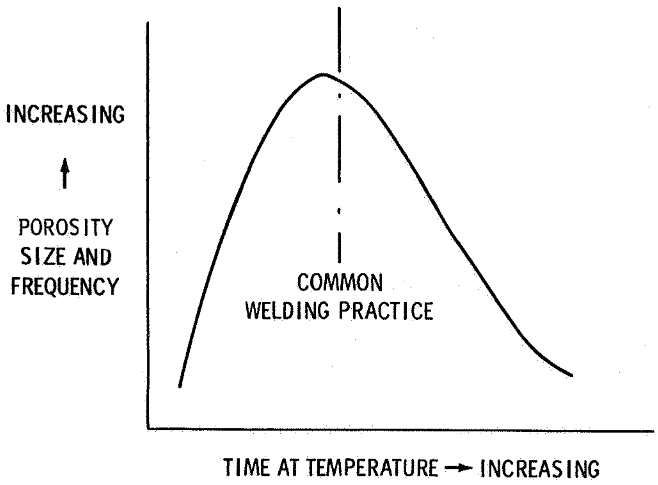


FIGURE 5. TIME-AT-TEMPERATURE RATIOS

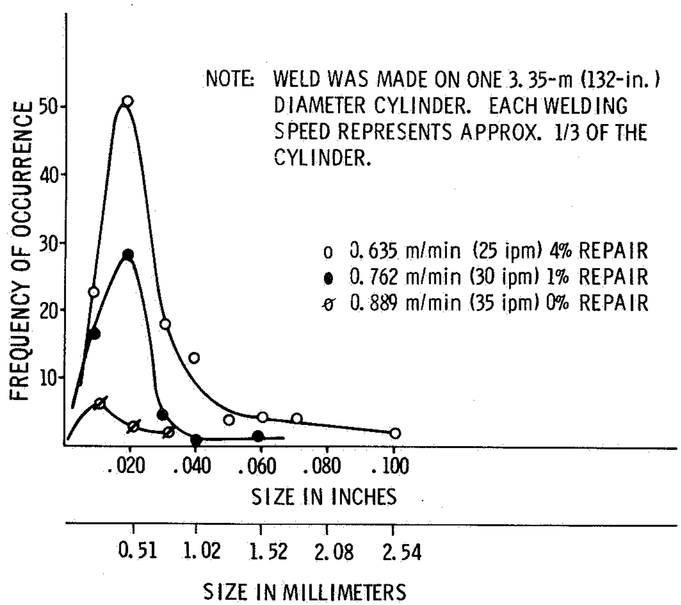


FIGURE 6. DEFECT SIZE VERSUS FREQUENCY IN 0.224-in. THICK 2219 Al MIG SINGLE WELD PASS

seldom used as a mode of inspection; the significance of deviations was not understood. Since 1964, emphasis has been placed on putting meaning into measurements. A welding study at Lockheed was made in two phases. First, an analysis was made of the interaction of several welding variables and combinations to determine their relative importance. Second, a practical measurement and recording system was formulated. Some results of these studies are described in the following paragraphs.

The tungsten electrode position was the most significant variable for controlling yield strength in two side 1.9 cm (3/4 in.) plate welds; it accounted for 41% of the variation measured in yield strength. This tungsten electrode position also appeared in six other regression equations as the second or third important variable.

To review the order of significance of the independent variables as they affect the dependent variables of the weld, it appears that the travel speed (T) is the most important; the electrode position (EP) is second, with the current (C) and voltage (V) being third and fourth, respectively (Fig. 7).

Dependent Variable	Independent Variable	% of Total Variation Explained
Ultimate Strength	T, EP	62.5%
Yield Strength	EP, T	54%
Elongation	T, EP	55.5%
Penetration	T, EP	64%
Area of Melt Zone	T, C, EP	76%

FIGURE 7. ORDER OF SIGNIFICANCE OF INDEPENDENT VARIABLES FOR EACH DEPENDENT VARIABLE

Computer data from the Lockheed program were quite voluminous. The Lockheed program manager proposed the following example of how such data might be applied as a potential process control. Assume that in two side tungsten welding of 1.9 cm (3/4 in.) 2219 aluminum plate it is desirable to control ultimate strength to 6.9 MN/m^2 (1,000 psi), and penetration depth to ±0.0813 cm (±0.032 in.) variation. If any one of the variables changes from an established welding program, the expected result will change as shown in Table II. Here then is the start of a welding process specification (a set of limits that will enable an inspector to put meaning into ink lines on recorder paper). With this information a decision can be made on the acceptability of a weld, and if and where repairs are necessary.

TABLE II. VARIABLES - CHANGES AND RESULTS

If Any Set-Up Parameter is Changed By:	We Can Expect a Change of:
T[0.561 cm/min (0.221 in./min)]	-6.9 MN/m^2 in Ultimate Strength
EP [0.032 cm (0.0126 in.)]	(-1000 psi in Ultimate Strength)
V [0.119 volt]	
GP [0.458 ppm x 100]	
T[2.64 cm/min (1.04 in./min)]	+0.0813 cm in Penetration
EP [0.0675 cm (0.0266 in.)]	(+0.032 in. in Penetration)
C [0.2377 amp x 100]	
D [0.0546 cm (0.0215 in.) dia.]	
GP[2.8318 ppm x 100]	
GP = Gas Purity	

The 1967 and 1968 development plan reflects the preceding negative and positive conclusions (Fig. 8). These studies are concentrated in the areas of porosity, metallurgy, power density; and later some problems related to stress were added.

With the assumption that removing metal is the most effective cleaning procedure, plans are being made to clean by machining and to develop instruments for obtaining a quantitative measure of cleanliness.

The inhouse time-temperature studies have shown that low-energy welding produces superior weld joints, but more basic data are needed on what happens to the material structure during the heating-cooling cycle of welding. Thus, engineers at MSFC are currently studying the microscopic disorganization and reorganization of material as affected by the welding energy.

Also involved in low-energy welding is the effort to develop the efficient nonvacuum and plasma electron beam systems; and proposals have been evaluated for a study to increase the power density of the tungsten electrode arc.

Three studies are in process in the area of stress analysis. One study is an empirical and mathematical look at metal movement during welding. Such movement often results in permanent mismatch and angular distortion of vehicle components. To date, computer programs have been developed for (1) prediction of welding isotherms based on energy input and welding speed and (2) prediction of dynamic stress patterns based on isotherms and changing yield strength of the material. From such data, designers may determine the critical rigidity of a component (that point at which buckling or metal movement will occur).

A second study is the reduction of dynamic stress by cryogenic cooling. An area of expanding metal caused by the heat from welding would be bordered by areas of shrinking metal, thus theoretically causing zero stress and consequently zero distortion (Fig. 9).

The third study is concerned with the ultrasonic measurement of residual stresses in weldments. This is particularly important in repair welding. Repeated local heating of the material creates unidentified complex stress patterns that can be detrimental to the performance of mechanical joints. This unknown residual stress lowers confidence in the reliability of the mechanical joint.

CONTRIBUTIONS TO SATURN V PROGRAM

Some principal contributions to the Saturn V program have come from this weld development survey.

First, the importance of material preparation has been established. A welding technique that includes metal removal as the optimum cleaning procedure was demonstrated. Second, data that stresses the benefits of discriminate use of energy (low-energy welding) was distributed.

Third, it was shown that (1) shielding gas and material composition are minor sources of porosity, (2) welds are not improved by arc shaping and exotic power sources, and (3) expensive humidity-controlled clean rooms will not in themselves ensure quality welds, but have limited use in preventing recontamination of carefully cleaned aluminum surfaces.

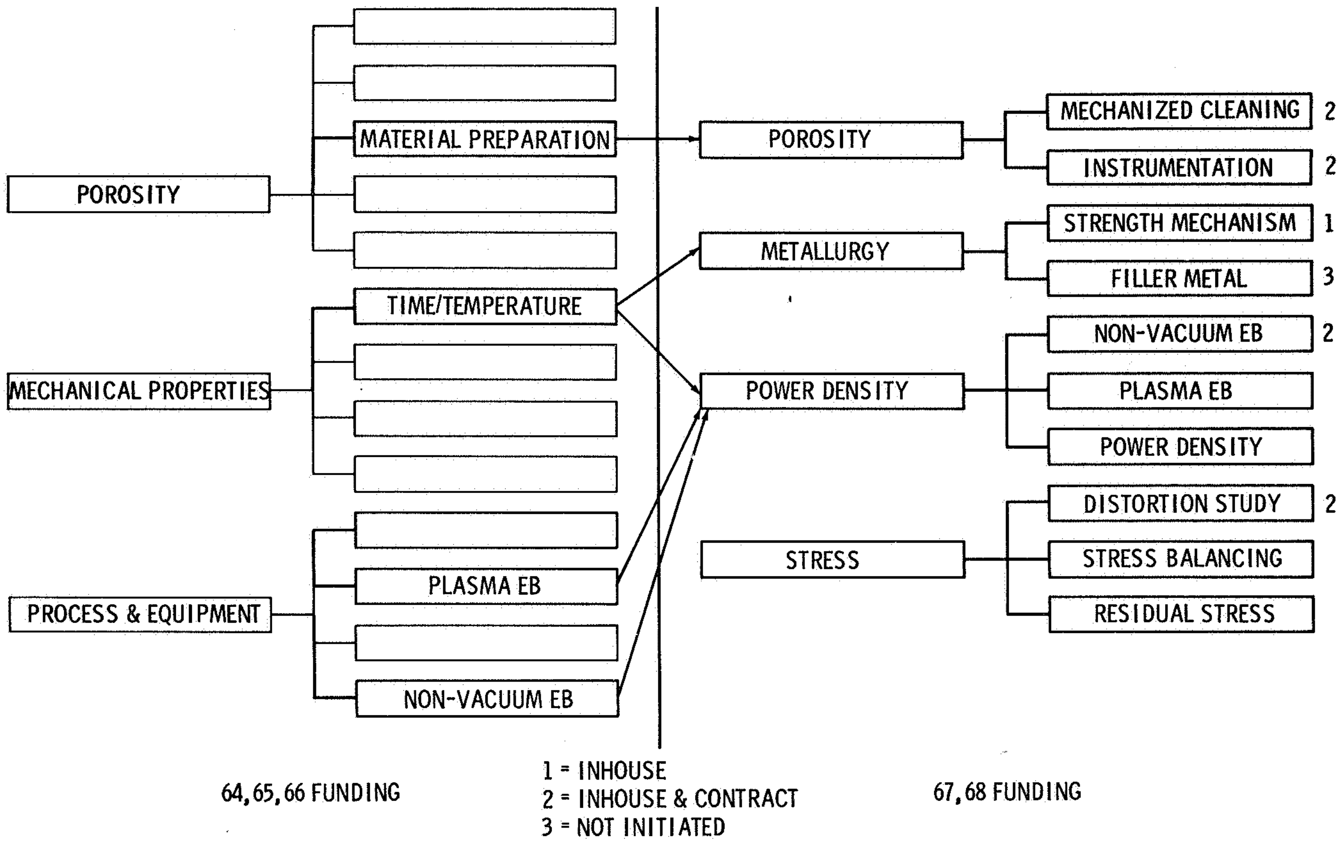


FIGURE 8. WELDING DEVELOPMENT COMPLEX (1967 - 1968)

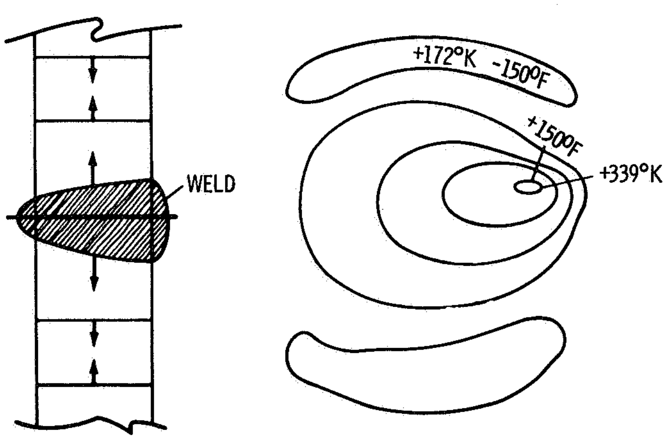


FIGURE 9. STRESS BALANCING

Fourth, the importance of a quantitative data analysis has been emphasized as a methodology in welding studies. The Lockheed-Marietta Corporation has now become so proficient and enthusiastic about quantitative analysis that it is a mandatory part of their welding development program, and has been applied to their Air Force contracts. Many welding engineers and management are pursuing weld development in a more systematic, engineering manner. The consequences, not immediately spectacular, will be solid, enduring advances in all areas of welding.

Finally, the welding process has been analyzed and identified as a dynamic whole, an entirety. It is a series of interrelated, interdependent events. Engineers are not yet able to analyze minutely the dynamic whole, but must arbitrarily select restricted areas for study, which might be considered fragments of the map of welding.

The time has come, however, when the fragments must be integrated and the whole map constructed before we can understand welding, achieve process control, and make full use of the data. The first nine studies on welding were compiled into a single report, now available through the Redstone Scientific Information Center and as announced in the NASA STAR. Each year all completed pertinent studies will be added to the report and it will be redistributed.

Engineers at MSFC intend to so analyze welding problems and avenues of solution that the welding development effort will be a logical, coherent system of meaningful studies.

EXPERIMENTAL ELECTRON BEAM WELDING IN SPACE

By

P. Gordon Parks

INTRODUCTION

During the Research Achievement Review, May 1965, it was announced that a lightweight, self-contained, electron beam (EB) welding system was being developed under contract with the Westinghouse Electric Corporation; if successful, the system could probably be used to weld objects located in the vacuum of space. This Saturn application unit, designed for limited weld fabrication, or weld repair within a portable vacuum chamber, was to be built to these six general specifications:

1. The mass of the complete unit — gun, power supply, and controls — would be no more than 34 kg (75 lb).

2. The unit would be capable of operating continuously for 2 min.

3. The maximum operating potential would be no more than 20 kV.

4. The unit must be operable in a pressure range of 1.3×10^{-2} N/m^2 (10^{-4} torr), or lower, down to 1.3×10^{-7} N/m (10^{-9} torr).

5. The unit would have a gun-to-work range from 0.64 to 3.8 cm (0.25 to 1.5 in.).

6. The beam diameter at the work piece would be no greater than 0.051 cm (0.020 in.).

THE SATURN APPLICATION UNIT

The Saturn application unit shown in Figure 1 more than met the six specifications. The Saturn application unit has a mass of 27.7 kg (61 lb), is 53.4 cm (21 in.) long, and 30.5 cm (12 in.) in diameter. The small end of the focus coil protrudes 25.4 cm (10 in.) below the body of the unit. It can be operated at 98 mA and 20 kV for as long as 5 min without battery drain. In addition, it can be operated

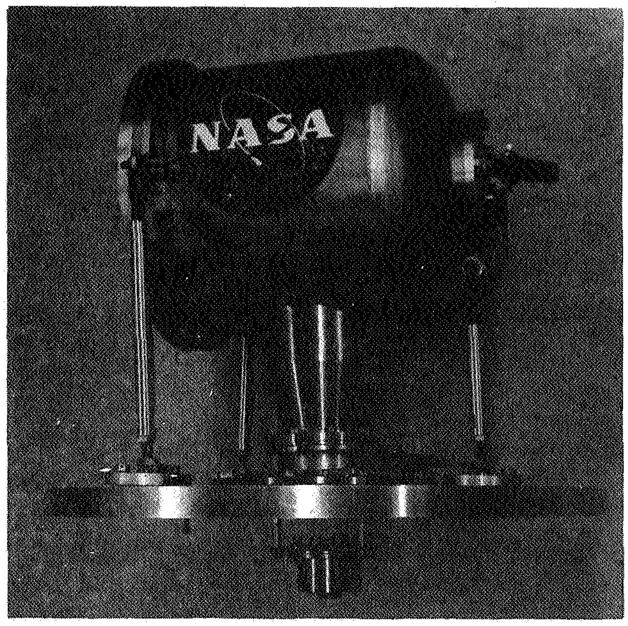


FIGURE 1. SATURN APPLICATION UNIT

independently of the battery power supply. This feature eliminates the dependency on batteries and increases its potential usefulness. A schematic of the unit is shown in Figure 2. This gun has welded aluminum and stainless steel 0.64 cm (0.25 in.) thick at speeds up to 1.0 m/min (40 in./min). The technical significance of this achievement is recognized by comparing the Saturn application unit with the conventional EB system shown in Figure 3. The conventional system, including the vacuum chamber, controls, and power supply, has a mass of approximately 6800 kg (15 000 lb) and requires 5.66 m^3 (200 ft^3) of space. Needless to say, it is not portable. Items to be welded must be brought to it. Physical capacity for welding is limited by the work chamber size.

With the successful development and functional use of the Saturn application unit (considering that the problems of bulk and mass of the power handling equipment have been overcome) it was proposed that the system be adapted for welding in the S-IVB orbital workshop.

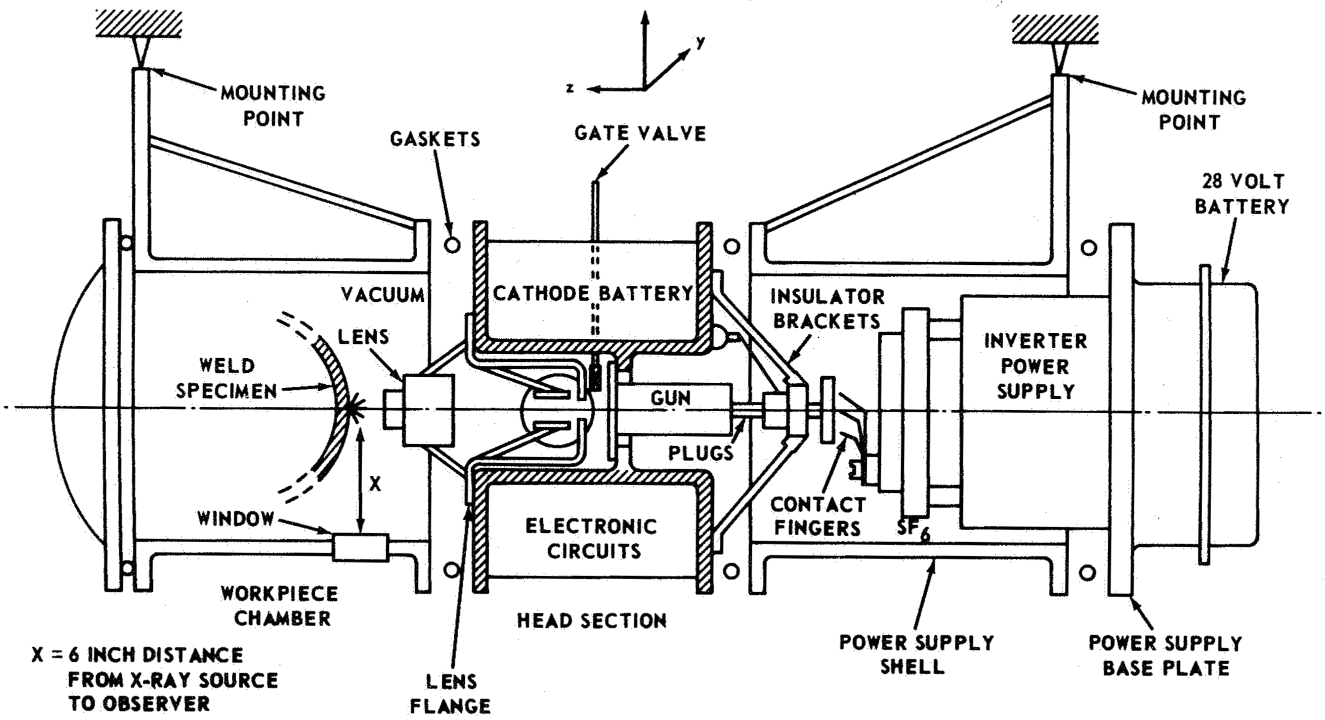


FIGURE 2. SCHEMATIC OF THE STRUCTURAL DESIGN OF THE BATTERY POWERED ELECTRON BEAM WELDER

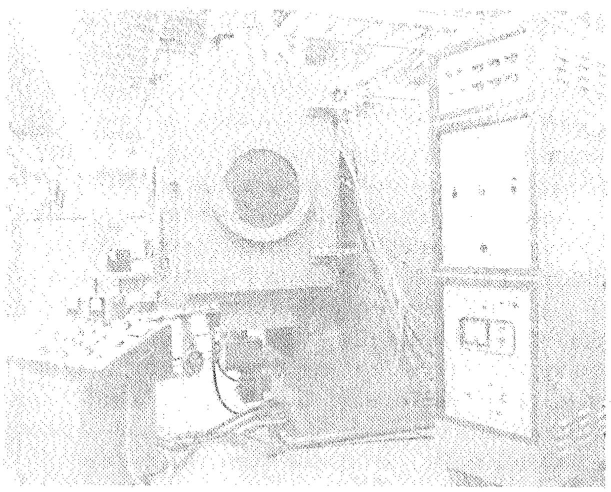


FIGURE 3. CONVENTIONAL ELECTRON BEAM WELDING UNIT

ELECTRON BEAM WELDING IN SPACE

The electron beam welding experiment under zero-gravity conditions in the S-IVB Orbital Workshop is described in the following paragraph. A battery-powered 2 kW, 20 kV electron beam system with a mass of approximately 45.4 kg (100 lb) has been built for this experiment. The weight increase was the result of integrating the control and the use of space-rated components. Battery, power conditioning circuits, electron gun and lens (Fig. 4) are mounted in a cylinder 76.2 cm (30 in.) long by 30.5 cm (12 in.) in diameter. The inverter in the center section of the case is insulated with sulfur hexafluoride (SF_6) at a pressure of 2.1×10^5 N/m^2 (30 psi) gauge. Design concepts used for the application unit and the advanced space welding electron beam unit, the work plan, and the experiment objectives are described.

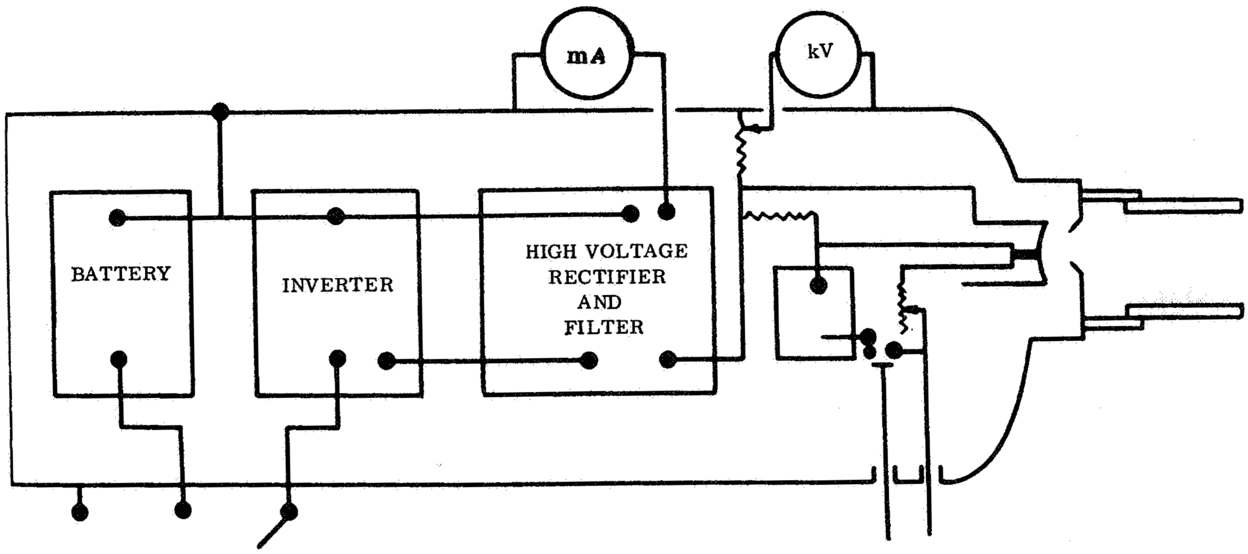


FIGURE 4. SCHEMATIC OF CONVENTIONAL ELECTRON BEAM WELDING UNIT

SPACE EB UNIT

Figure 5 shows the completely self-contained space electron beam unit that has been built and is undergoing advanced testing at the Westinghouse Research Laboratories. An identical unit will be used for the flight experiment in the S-IVB Orbital Workshop. The most obvious difference between the flight model and the laboratory model is the position of the gun relative to the power supply and battery pack. This in-line configuration is designed to be mechanically sturdier during launch and will be positioned so that the long axis is parallel to the direction of maximum acceleration.

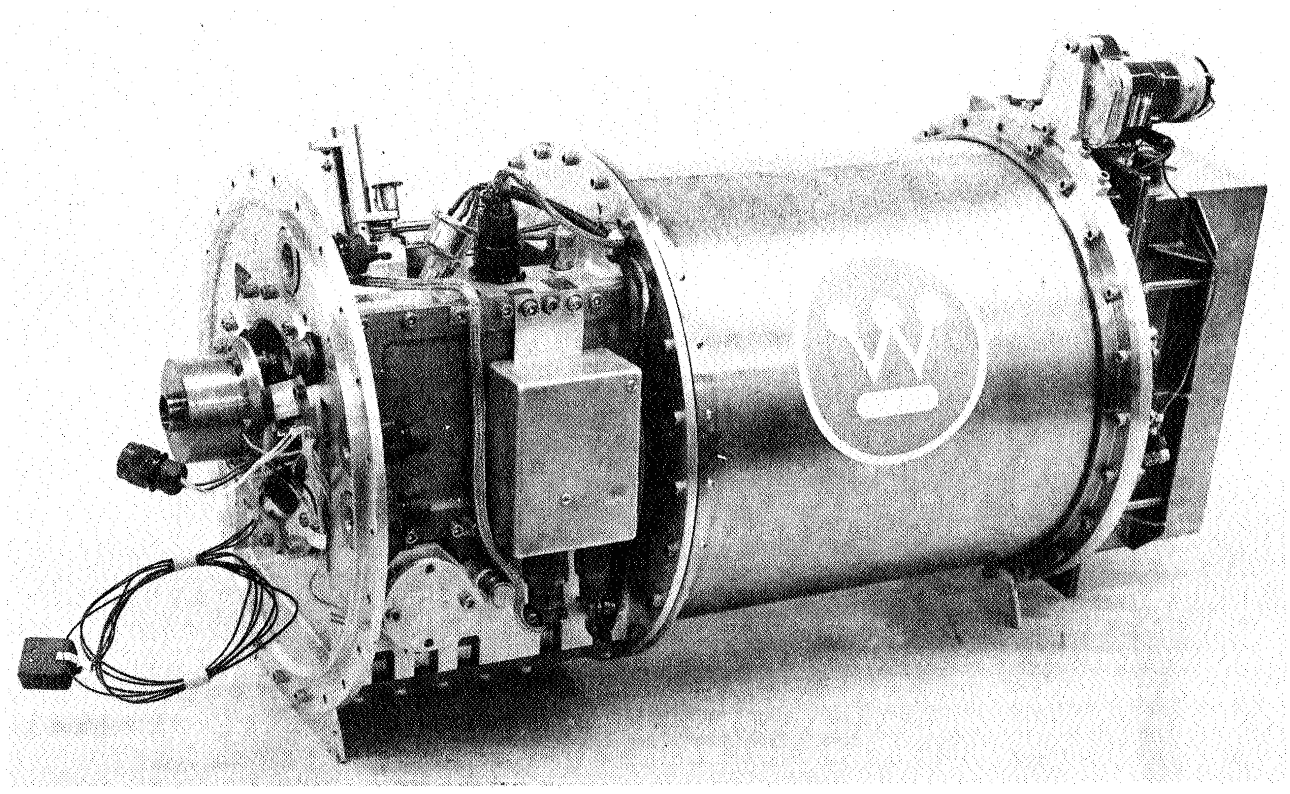


FIGURE 5. SELF-CONTAINED ELECTRON BEAM WELDING UNIT

Control Panel. Another obvious change is the integral control panel (Fig. 6). This panel contains all controls and meters required for the welding experiments. The astronaut will have direct control of beam current; he can also control lens current to optimize beam focus on the work pieces. The high voltage output of the inverter power supply is maintained at 20 kV, regulated to ± 400 V with no adjustments required. Meters monitor the beam voltage and current. Switches are provided for the high voltage power supply, the magnetic lens, the weld specimen drive motor, and the lights that are required for the two recording cameras.

Battery Package. For increased reliability, over that of the Saturn application gun, the original battery pack has been replaced with a Gemini-rated Yardney missile battery pack, which provides up to 100 A at a nominal 28 V for approximately 10 min, or two times the life of the original unit's batteries. Included in the battery capacity are the power requirements for lights, fixture drive, and camera operation.

Inverter Power Supply. The inverter power supply employs two stages: A saturable-inductor power oscillator and a 2 kW inverter consisting of two banks of silicon transistors. Each power transistor is separately fused so that failure of any one transistor will not cause additional failures.

Gun System. The gun consists of an anode, grid, and filament (Fig. 7). The anode is at ground potential; the filament and grid operate at a high negative voltage relative to the anode and are insulated from the anode by a glass envelope. The glass envelope also acts as a seal between the SF_6 pressurized power

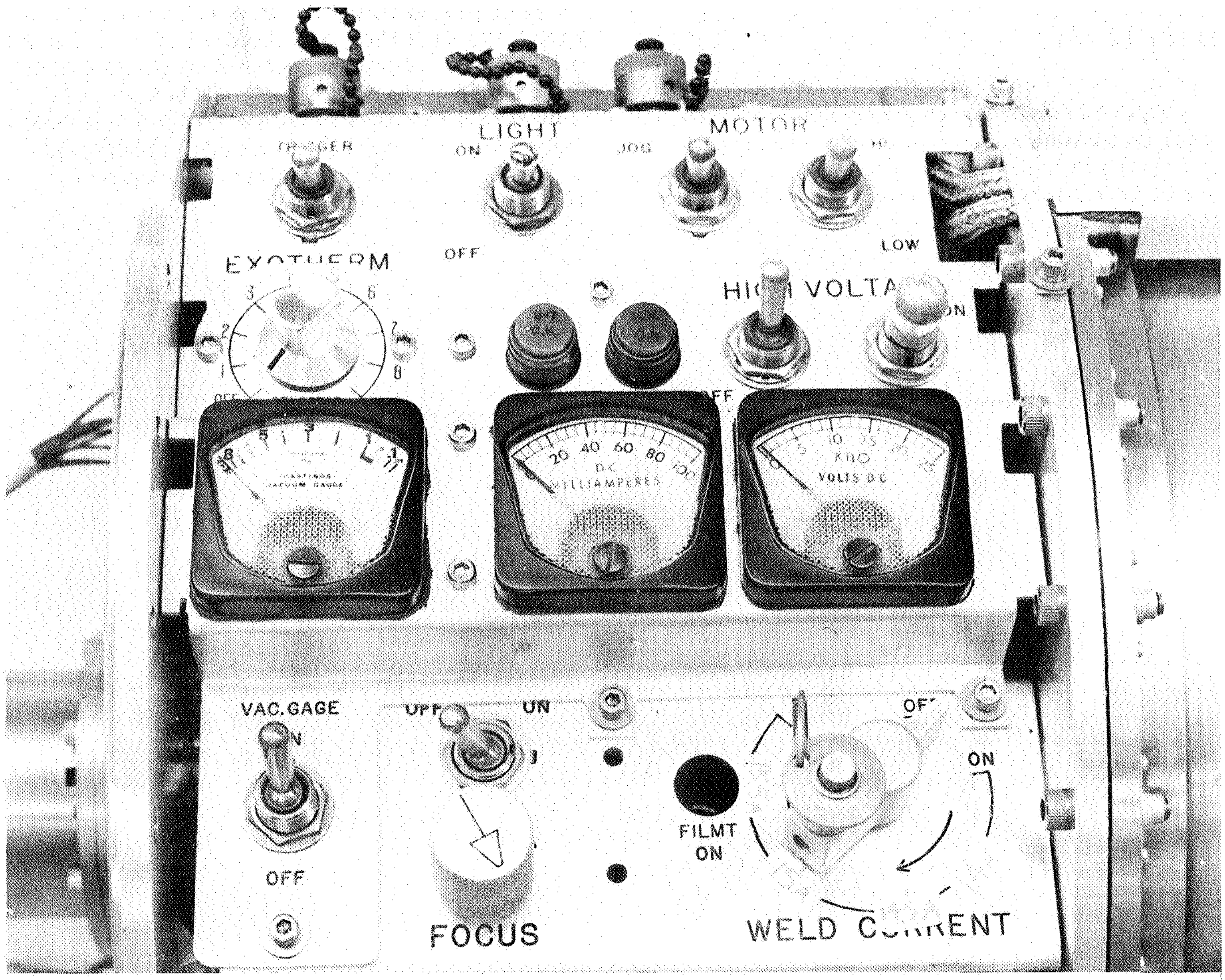


FIGURE 6. CONTROL PANEL FOR THE SATURN ELECTRON BEAM WELDING UNIT

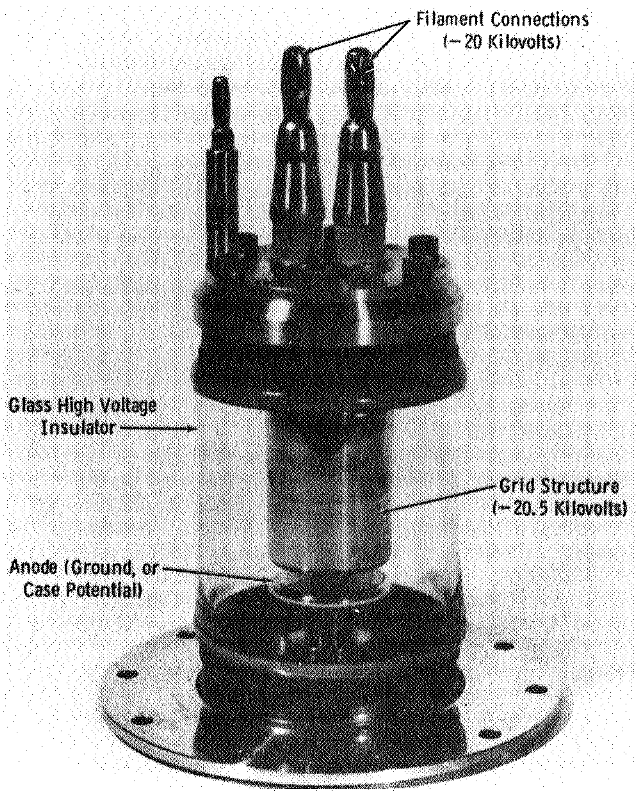


FIGURE 7. ELECTRON BEAM GUN FOR BATTERY POWERED WELDER

supply section and the hard vacuum required for the gun. The gun filament is a pure tungsten ribbon. The last section of the gun is the magnetic lens that is used to refocus the beam at the work piece. The beam is refocused approximately 5.1 cm (2 in.) from the center of the lens, or about 1.9 cm (0.75 in.) below the end shield. The axis of the lens has been moved about 1.9 cm (0.75 in.) from the axis of the electron beam gun and two electromagnetic deflection coils added to steer the beam from the former axis to the latter. This is required to reduce the possibility of damage by droplets of metal being ejected from the molten weld pool and floating into the gun elements.

DEVELOPMENT SCHEDULE

Figure 8 illustrates the work plan and the time schedule. As can be seen, there are five major work phases. The total effort involves four laboratories: Manufacturing Engineering, Astrionics, Propulsion and Vehicle Engineering, and Quality and Reliability Assurance, as well as the supporting effort of the Westinghouse Corporation. The MSFC effort involves approximately 80 people. The work phases are illustrated and explained as follows:

PHASE I — Application Model. This is the welding fixture in the bell jar (Fig. 9) where preliminary EB welding tests leading to a statistically designed experiment are conducted.

PHASE II — Dynamic Test Unit. This phase will cover the evaluation of the test package, which consists of the chamber, the valve, the EB unit, and the welding fixture, and will permit the study of simulated dynamic loads on the entire test package. Dynamic testing will include vibration tests, acceleration tests, and acoustical tests (Fig. 10). Later this unit will be sent to MSC at Houston for involved space simulation evaluation.

PHASE III — Mock-Up Unit. By the use of the mock-up unit (Fig. 11) in the neutral buoyancy tank, the astronaut will become familiar with the operation of the experiment. Involved will be the human engineering analysis of handling equipment and the motions required to conduct all operations.

PHASE IV — Qualification Model. The qualification model will be used to perform the statistically designed one-gravity reference experiment with the astronauts participating. In addition, it will be thoroughly retested and finally put into a "stand-by" position. Figure 12 is a model of the complete space package: the vacuum chamber, the welding fixture at the open end of the chamber, the controls, and the gun, as attached to the workshop wall. Not visible is the valve for exhausting the chamber and the gun system. The test weldment, a ring consisting of three alloys — stainless steel, aluminum, and titanium — is visible at the open end.

PHASE V — Flight Unit. The flight model which will be identical to the qualification unit, will receive limited preflight functional testing. It will be considered flightworthy on the detailed testing accomplished with the qualification model. However, it will receive astronaut performance checks, and finally, after installation in the flight vehicle, it will have fresh batteries installed and be subjected to final checkout.

Additional experiment requirements include spare parts (batteries, specimens, lights, etc.), GSE — electronics and vacuum test equipment, vacuum pump, and insulating gas. Documentation includes experiment plan, operating manuals, flight qualifications,

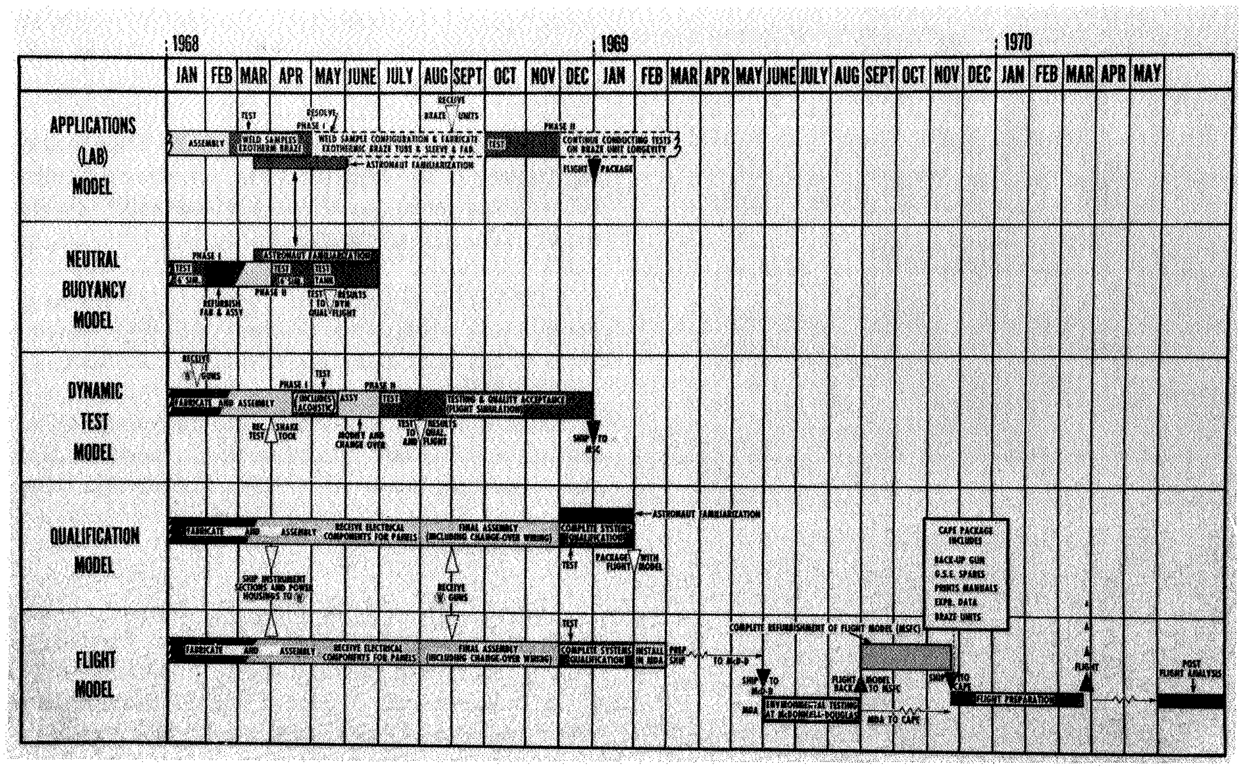


FIGURE 8. PRODUCTION AND APPLICATION SCHEDULES FOR EB UNITS

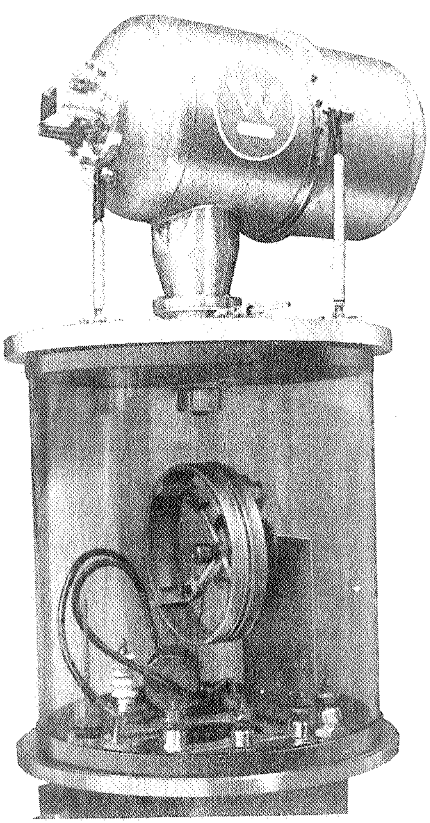


FIGURE 9. NEUTRAL BUOYANCY MOCKUP

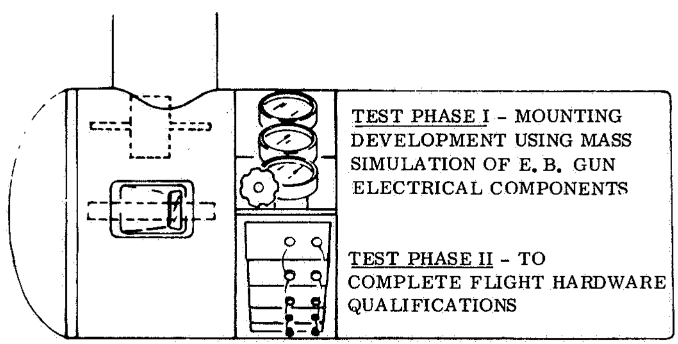


FIGURE 10. DYNAMIC TEST MODEL

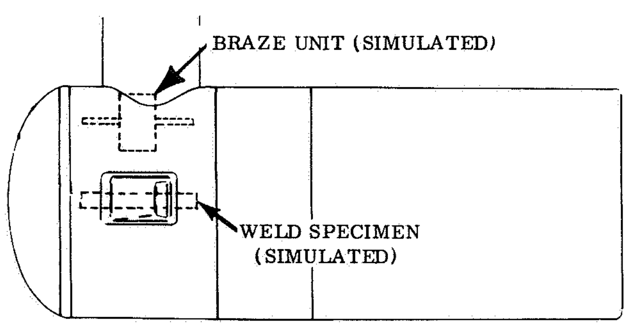


FIGURE 11. MOCKUP UNIT

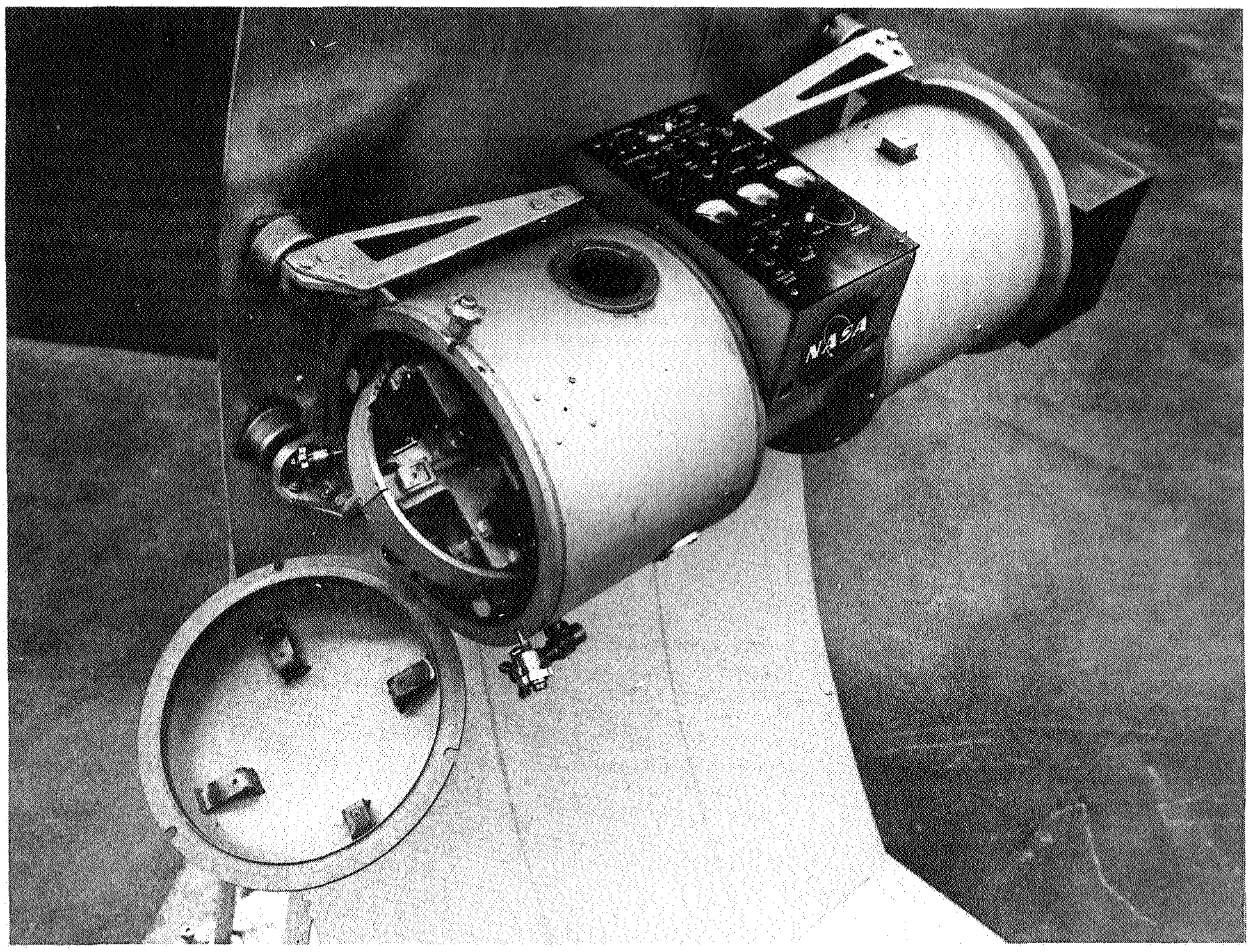


FIGURE 12. QUALIFICATION MODEL

experiment debriefing, and engineering drawings. Astronaut familiarization includes neutral buoyancy tank and functional welding using qualification model.

This is an outline of supporting equipment, documents, and the astronauts' part in attaining flight status and conducting the experiment in space.

EXPERIMENT OBJECTIVES

The experiment is designed to obtain as much useful information and data as is practical. All performance parameters (such as beam power and welding speed) and environmental conditions (such as temperature, vacuum, and radiation) will be established in preflight tests. The general objective of the experiment is to determine and to attempt to understand the effects of weightlessness on molten metal.

In conclusion, the experiment will accomplish these specific objectives:

1. Determine that the development of equipment, processes, and data at one gravity can be utilized at zero gravity.

2. Observe and record molten metal behavior considering:

   A. Metal surface tension

   B. Vaporization and sublimation

   C. Weld spatter and "floating"

3. Waste heat dissipation characteristics of gun system and weld specimen.

4. Retrieve space-made welds and photographic records of each weld for laboratory study and evaluation for comparison to the one-gravity weld data.