AQ

N6636420

ELKRIDGE LANDING RD. LINTHICUM HEIGHTS, MD 21090

ATTN

DATE OF REQUEST 1997-12-29 02:38:47 pm

USER ID 2672

ORDER NUMBER 110357

ENCLOSED IS YOUR REQUEST FOR 1 HARDCOPY

TITLE **Manufacturing research at MSFC Research Achievements Review series no. 8**

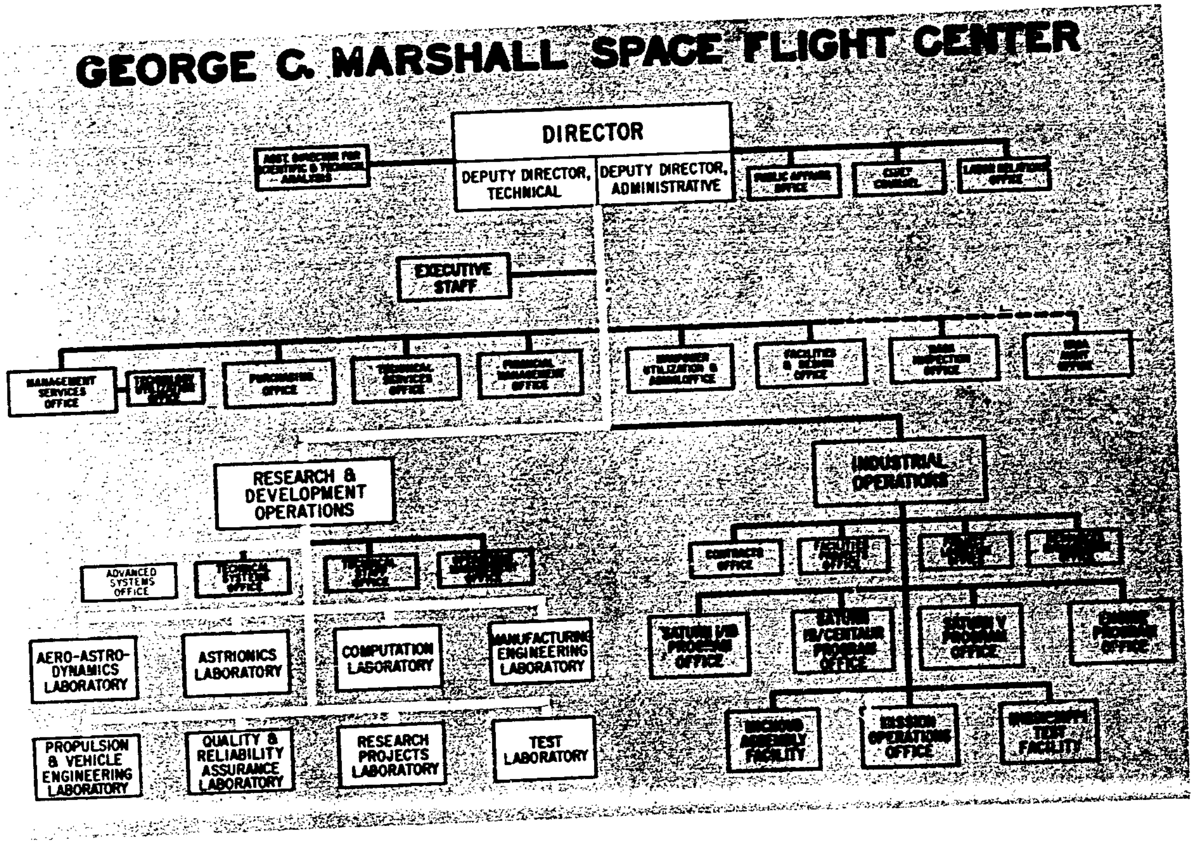
REPORT NUMBER **NASA-TM-X-53505**

DOCUMENT ID **19660027130**

DOCUMENT CLASSIFICATION **Unclassified**

DISTRIBUTION LIMITATION STATEMENT **Unrestricted - Publicly Available**

QUESTIONS CONCERNING THIS ORDER SHOULD BE DIRECTED TO DOCUMENT REQUEST SERVICES, NASA CENTER FOR AEROSPACE INFORMATION, (301) 621-0390.



RESEARCH ACHIEVEMENTS REVIEW SERIES INCLUDES THE FOLLOWING FIELDS OF RESEARCH

1. Radiation Physics
2. Thermophysics
3. Chemical Propulsion
4. Cryogenic Technology
5. Electronics
6. Control Systems
7. Materials
8. Manufacturing
9. Ground Testing
10. Quality Assurance and Checkout
11. Environmental and Aerodynamics
12. Atmospheric Dynamics
13. Instrumentation
14. Power Systems
15. Guidance Concepts
16. Astrodynamics
17. Advanced Tracking Systems
18. Communication Systems
19. Structures
20. Mathematics and Computation
21. Advanced Propulsion
22. Lunar and Meteoroid Physics

NASA TM X-53505

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C.

MANUFACTURING RESEARCH AT MSFC

RESEARCH ACHIEVEMENTS REVIEW
SERIES NO.8

RESEARCH AND DEVELOPMENT OPERATIONS
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

1965

PREFACE

In 1955, the team which has become the Marshall Space Flight Center (MSFC) began to organize a research program within its various laboratories and offices. The purpose of the program was two-fold: first, to support existing development projects by research studies and second, to prepare future development projects by advancing the state of the art of rockets and space flight. Funding for this program came from the Army, Air Force, and Advanced Research Projects Agency. The effort during the first year was modest and involved relatively few tasks. The communication of results was, therefore, comparatively easy.

Today, more than ten years later, the two-fold purpose of MSFC's research program remains unchanged, although funding now comes from NASA Program Offices. The present yearly effort represents major amounts of money and hundreds of tasks. The greater portion of the money goes to industry and universities for research contracts. However, a substantial research effort is conducted in house at the Marshall Center by all of the laboratories. The communication of the results from this impressive research program has become a serious problem by virtue of its very voluminous technical and scientific content.

The Research Projects Laboratory, which is the group responsible for management of the consolidated research program for the Center, initiated a plan to give better visibility to the achievements of research at Marshall in a form that would be more readily usable by specialists, by systems engineers, and by NASA Program Offices for management purposes.

This plan has taken the form of frequent Research Achievements Reviews, with each review covering one or two fields of research. These verbal reviews are documented in the Research Achievements Review Series.

Ernst Stuhlinger
Director, Research Projects Laboratory

These papers presented May 27, 1965

TABLE OF CONTENTS

INTRODUCTION TO MANUFACTURING RESEARCH AT MARSHALL SPACE FLIGHT CENTER

MANUFACTURING RESEARCH IN SUPPORT OF SATURN V

by James R. Williams

LIST OF ILLUSTRATIONS

TABLE OF CONTENTS (Cont'd)

ESTABLISHING A COMMON DENOMINATOR IN WELDING

by Gordon Parks

LIST OF ILLUSTRATIONS

TABLE OF CONTENTS (Cont'd)

RESEARCH IN SUPERPOWER LASERS AND INTENSE MAGNETIC FIELDS

by R. J. Schwinghamer

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

INTRODUCTION TO MANUFACTURING RESEARCH AT MARSHALL SPACE FLIGHT CENTER

By

H. F. Wuenscher

Research and development in manufacturing has gained importance with the advance of the space programs. In the Apollo program, the state of the art in manufacturing technology seemed to be extended to practical limits; consequently, in many instances new approaches had to be made available by more intensified manufacturing research activity. This manufacturing research activity has the following broad purposes:

1. To provide the scientific basis for manufacturing and to establish the principles for control of all variables and boundary conditions.

2. To develop new manufacturing concepts by application of existing and new scientific principles.

3. To verify the feasibility of advanced concepts in experimental manufacturing applications.

The major areas in which MSFC is doing in-house or contract-supporting manufacturing research and development in fulfillment of these general purposes are listed in Table I.

TABLE I. MANUFACTURING RESEARCH AND DEVELOPMENT AT MSFC

MANUFACTURING RESEARCH

Techniques

Welding
Brazing
Soldering
Mechanical joining

Bonding
Chemical processing
Electrical processing
Thermal treatment

Forming
Material removal
Material deposition
Sterilization

Concepts

Tooling
Handling and Cleaning
Metrology

EXPERIMENTAL MANUFACTURING

Element development for structures and systems
Configuration development for structures and systems
Space manufacturing for orbital and lunar operations

The three reports which follow cover research achievements such as welding, bonding, forming, and the use of intense magnetic fields and lasers for novel processing and tooling concepts. The status and results of MSFC research work in all the other areas are given in the supporting research and technology reports published in the semiannual progress reports issued by Research Projects Laboratory. Although this achievement review cannot give details of all Manufacturing Engineering research and development, some of the interesting projects which are not covered in detail in the reports which follow will be mentioned here.

Research and development contracts in the field of high-frequency welding and in diffusion bonding were started late in fiscal year 1965. This work will pioneer the "perfect" joining of metals to form large, one-piece ("unitized") structures. Beyond structural improvement for the present programs, such joining processes are important for possible manufacturing application in space vehicle programs.

In regard to tooling research, the modular tooling concepts in weld joining of large structures, new approaches in automation and measuring technology, and local environmental control concepts have gained basic importance for the present program.

Experimental manufacturing, which provides the only realistic test bed for large-scale verification of manufacturing research results, is subdivided under the categories of development of structural elements, configuration development, and manufacturing development for space programs.

One example of the development of structural elements is the 2.4-meter (8-foot)-long ultralightweight box beam series, in which similar beams are optimized in high-strength aluminum, titanium, beryllium, Lockalloy, magnesium-lithium alloy, and fiberglass. This work is being done to establish state-of-the-art limitations and to provide the necessary support in manufacturing process research to the point at which space vehicle application becomes feasible.

Another example is the insulation-systems development in the short-duration double seal and the long-duration multilayer radiation barrier superinsulation. Here the manufacturing feasibility for system elements such as penetrations by the supporting structure and fuel lines, and manhole cover closeouts and vacuum-sealed jackets, determine to a large extent the systems configuration. The research work in energy-absorbing elements should be mentioned, because the extruding tube mode, used for absorbing the Saturn V launch release shock loads, basically uses a manufacturing process. There is a very promising new mode under development in which wire rings are rolled over and over between telescoping tubes. This is a unique reusable energy absorber and is now under consideration for use on the Lunar Excursion Module and the Lunar Hopper.

The configuration development program consists of a number of common-dome conceptions such as the bonded strip seal and the all-welded face-sheet versions. Furthermore, a series of configuration developments for tanks 5 meters (200 inches) in diameter provide the basis for development and verification of many manufacturing research projects. As an example, the mangetomotive hammer principle was first used for the experimental multicell tank. Also, tack welding and subsequent automatic skate welding were first used at MSFC as a new modular concept for large space vehicle manufacture.

The second experimental tank, being assembled now, is a torus tank, made of a new type high-strength aluminum alloy, 7039, for which new forming processes, magnetomotive flaring processes, and advanced welding concepts are used. A third experimental tank of semitoroidal shape is in preparation.

Application of manufacturing processes in orbit and on the moon for maintenance, repair, modification, and even orbital assembly and lunar manufacturing, is entering the study phase within the Apollo Applications Program. MSFC is selecting manufacturing processes which could utilize the space environment to their advantage, and is looking for tooling concepts suitable for the given payload and power conditions. All this is in preparation for the planned activities in the fiscal year 1966 and beyond.

N66

36421

N66 36421

MANUFACTURING RESEARCH IN SUPPORT OF SATURN V

By

James R. Williams

SUMMARY

Research achievements applicable to the production of Saturn V components are described in this report.

Leakage at the mechanical connections in high-pressure lines has been minimized or eliminated through the use of precisely flared tubes. Flaring to close tolerance is done with an orbital flaring adapter, and the forming operation is precisely controlled with an electronic control console.

A technique of "aging" or heat-treatment hardening of aluminum materials has been used to form cylindrical-tank segments and double-contoured gore segments precisely, and to remove weld distortions.

The control of weld porosity has been improved as a result of research which demonstrated the close correlation between electrical energy input per inch of weld and weld porosity and metallurgical quality. Based on this information, the gas metallic arc method has been used successfully for two-pass welding, and thinner gage aluminum has been welded (LOX tunnel to fuel bulkhead) with an MSFC designed gas metallic arc unit.

Much research has been done in processing and assembly techniques as they apply to composite structures and materials. Using brackets and fasteners on Saturn wall structures as well as strengthening and repairing substandard tank structures have been made possible by the studies in adhesive formulation and application. Other investigations are concerned with the fabrication of double-curvature common bulkheads and with improvements in fabrication technology of other bulkhead structures.

Tooling costs have been reduced as a result of the development of skate-type tooling for S-IC gore-edge trimming. Research is continuing on self-regulating skate systems.

Control techniques for milling by chemical etching have been developed. As a consequence, chemical milling has been used extensively for Saturn V gore segments.

I. INTRODUCTION

This report reviews manufacturing research achievements which are being used today to assist in the production of Saturn V components. Manufacturing technology required for the Saturn V vehicle covers a broad range of requirements. The following, which are typical areas of research application, are discussed in detail:

1. High-pressure liquid and pneumatic ducting systems
2. Age forming and sizing
3. Welding research applications
4. Composite structures research applications
5. Tooling research and applications
6. Chemical milling.

These research applications reflect the cooperative effort of MSFC and the stage contractors in defining common problem areas, outlining research projects, and applying the gain of knowledge to the original problem.

II. HIGH-PRESSURE LIQUID AND PNEUMATIC DUCTING SYSTEMS

A problem which has been general for all organizations building Saturn hardware is manufacturing leak-tight liquid and pneumatic ducting systems for the vehicle. The defect is leakage at the mechanical connector of the higher pressure ducting systems, which operate at pressures up to 27.6 MN/m^2 (4000 psi). The connectors join the many subsystems throughout the Saturn vehicle. For example, the first stage alone of the Saturn V space launch vehicle required over 1000 flared-tube connectors of the design shown in Figure 1.

Component designers and fabrication research personnel are working to eliminate mechanical connections through welding and brazing. However, many mechanical connections are still required to permit effective use of subassembly and modular fabrication principles.

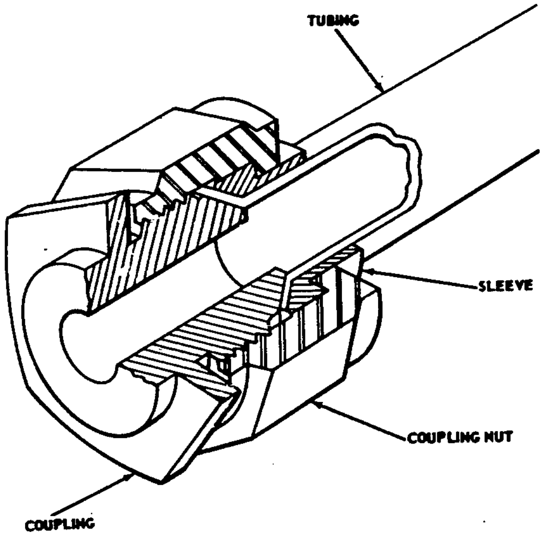


FIGURE 1. FLARED TUBE CONNECTOR USED ON THE S-IC STAGE, SATURN V

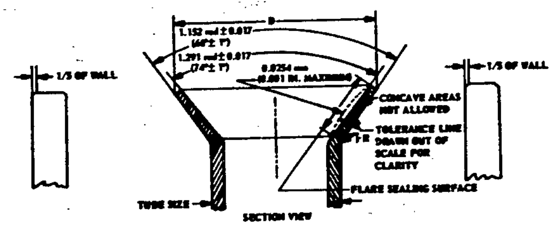
A typical installation using hundreds of these flared-tubing connections is the S-II stage (built by North American Aviation) shown in Figure 2. The majority of the flares are on tubes with a diameter of 25.4 mm (1 inch) or less.

The major deficiency of this type of connector has been the inconsistent configuration of the tube flare. Experience and testing indicated that if the flare could be formed to very close dimensions, the major leakage problem would be eliminated.

Research funding during the past three years has made it possible for Manufacturing Engineering Laboratory of MSFC to develop a unique technique of precision tube flaring which produces the characteristics required by tube flare design standard MC-146. These basic requirements are shown in Figure 3. The flared end of the tube must be round within 0.02 mm (0.0008 inch) TIR, the ID angle and OD angle each must be within ±0.0087 radian (±½ degree) of the basic 0.65 radian (37 degree) and 0.58 radian (33 degree) designation, respectively, and it is necessary to control the major diameter of the flare within 0.254 mm (0.010 inch). The roughness allowance of the sealing surfaces is 0.0004 mm (16 microinches) for stainless steel and 0.0008 mm (32 microinches) for aluminum tubing.

FIGURE 2. INSTALLATION WITH FLARED TUBING CONNECTIONS ON THE S-II STAGE, SATURN V

This dimensional quality is constantly reproducible by use of the orbital flaring adapter developed by MSFC (Fig. 4). The tool, which attaches to a standard Leonard 3CP flaring machine, exploits the principle of rolling the material on the



NOTE 2 DEBURR EDGES BEFORE FLARING.

NOTE 3 FLARE SEALING SURFACE TO BE CONCENTRIC WITH O.D. OF TUBE WITHIN 0.7620 mm (0.0030 IN.) TIR

NOTE 4 FLARE SEALING SURFACE TO BE ROUND WITHIN 0.0203 mm (0.0008 IN.) TIR.

NOTE 5 SEALING SURFACE NOT TO EXCEED 16 FOR STEEL AND 32 FOR ALUMINUM

NOTE 7 NO RADIAL SCRATCHES ON FLARE

TUBING OD mm	(IN.)	D, DIA mm	(IN.)	D, TOL mm	(IN.)
3.2	(1/8)	5.1	(.200)	+0.000 -0.254	(-0.010)
6.4	(1/4)	9.1	(.359)		
9.5	(3/8)	12.3	(.484)		
12.6	(1/2)	16.7	(.656)		
19.1	(3/4)	23.8	(.937)		
25.4	(1)	30.1	(1.187)	+0.000 -0.381	-0.015

FIGURE 3. BASIC REQUIREMENTS OUTLINED BY TUBE FLARE DESIGN STANDARD MC-146

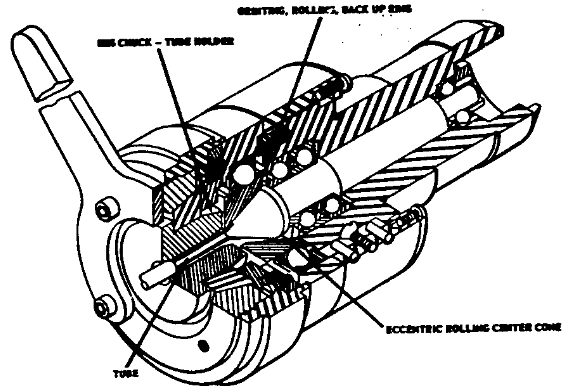


FIGURE 4. ORBITAL FLARING ADAPTER DEVELOPED BY MSFC

flared end of the tube from both sides simultaneously with an ID cone and an OD rolling die.

Precision control of the forming operation is obtained by use of an MSFC-developed electronic control console, shown in Figure 5. The electronic console provides the operator with precision control over important phases of the forming operation such as flaring pressure, machine speed, and the number of revolutions.

The results of this improved flaring capability are shown in Figure 6. Here a comparison is made of the spread of angular tolerance for seven different sizes of tubing produced by the new dual-rolling technique and by the split-die method.

Although efforts are currently underway to automate completely the flaring operation to improve the quality of the flare further, all of the required characteristics of the design specification MC-146 can now be produced with a high degree of consistency.

This development of the flaring tool and electronic control console is currently being introduced into manufacturing engineering shops. Many of the Saturn stage contractors are already using or are evaluating this new development for use in their programs.

III. AGE FORMING AND SIZING

An interesting research project using the "aging" or heat treatment hardening of aluminum resulted in precise forming of contours of the very large Saturn V first-stage cylindrical tank segments and the double contoured gore segments. The aging process consists very simply of restricting the oven-warm aluminum alloy material to a shape for a period of time until it conforms to the desired contour.

Aging, as related to type 2219 aluminum alloy, is the metallurgical process which is used to obtain the maximum strength from the material. Relatively soft 2219 aluminum alloy is heated to 436°K (325°F) for 24 hours. During this time there is rearrangement of the crystalline structure of the alloy, with the result that the material increases its strength approximately 40 percent.

Exploiting this phenomenon, Boeing Company and MSFC embarked on several research programs to determine whether the 2219 aluminum components of Saturn V could be formed or their contours corrected during this aging cycle. An MSFC-funded research program at Boeing proved that 2219 aluminum alloy would respond desirably to the age-forming techniques.

Figure 7 illustrates the practice now employed by Boeing to form the large cylindrical skin panels for the S-IC LOX (liquid oxygen) and fuel tanks. The flat machined parts are wrapped onto a ruggedly built contoured fixture and then placed in a furnace for the prescribed time and temperature. During this period, stresses are relieved and hardening takes place. A 25-percent springback allowance is compensated for in the design of the holding fixture. After release from the fixture, the part is perfectly contoured to the desired radius. The completed part in a contour inspection gage is shown in Figure 8.

FIGURE 5. ELECTRONIC CONTROL DEVELOPED BY MSFC FOR TUBE FLARING

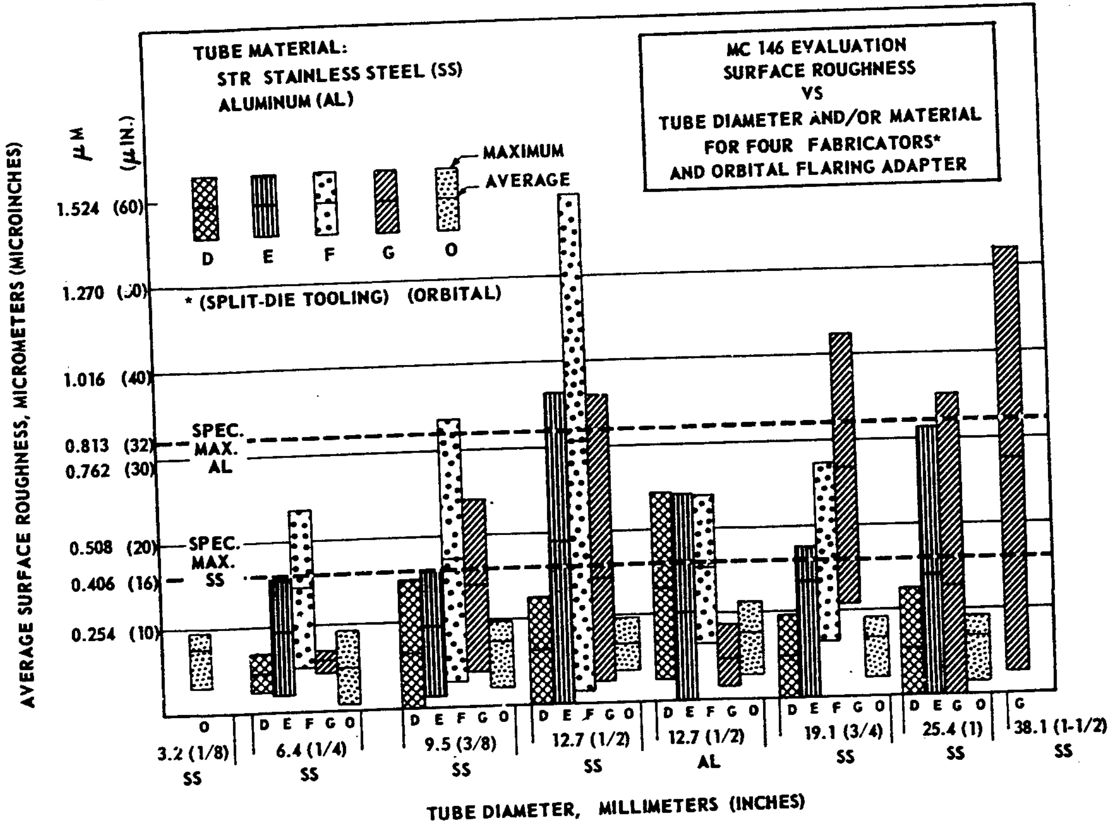


FIGURE 6. COMPARISON OF TUBE SURFACE ROUGHNESS, ORBITAL FLARING VERSUS SPLIT-DIE METHOD

MSFC engineers also exploited this age-hardening principle to remove weld distortion from the gore segment and fitting subassemblies. The gore segments for the LOX and fuel bulkheads are welded in the T-4 or semihard condition. Figure 9 shows a correct-contour fixture of the type provided for holding the distorted part to the desired contour during the aging cycle.

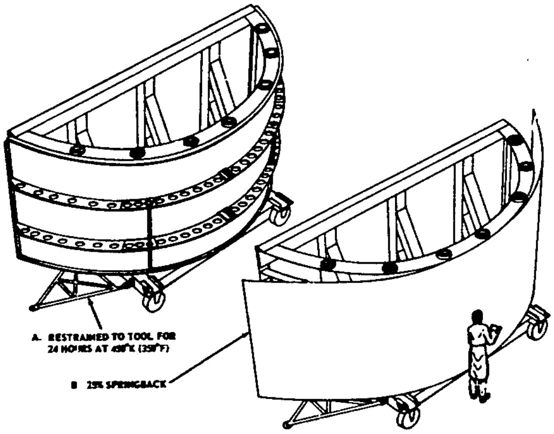


FIGURE 7. AGE FORMING THE LARGE SKIN PANELS FOR CYLINDRICAL S-IC LOX AND FUEL TANKS

After the part has been clamped to the fixture, it is subjected to furnace heat treatment for 24 hours at 436°K (Fig. 10). During this time, most of the weld stresses are relieved and the material becomes metallurgically stronger and more rigid, and after removal from the fixture it resists returning to its distorted contour.

North American Aviation has also adapted this age-sizing technique to improve the contour of the welded 2014 aluminum alloy gore segment subassemblies on the S-II stage.

The applications of the research project findings to full-scale hardware at MSFC, Boeing, and North American Aviation have resulted in reduced processing costs and improved quality of parts.

IV. WELDING RESEARCH APPLICATIONS

A major problem in welding type 2219 aluminum alloy is porosity control as related to the mechanical and metallurgical properties of the weld. During the past two years, several welding research projects were directed toward relating weld porosity and metallurgical quality to the electrical energy input per inch of weld. The research projects revealed a very distinct correlation for these factors in reference to aluminum alloys used on the Saturn

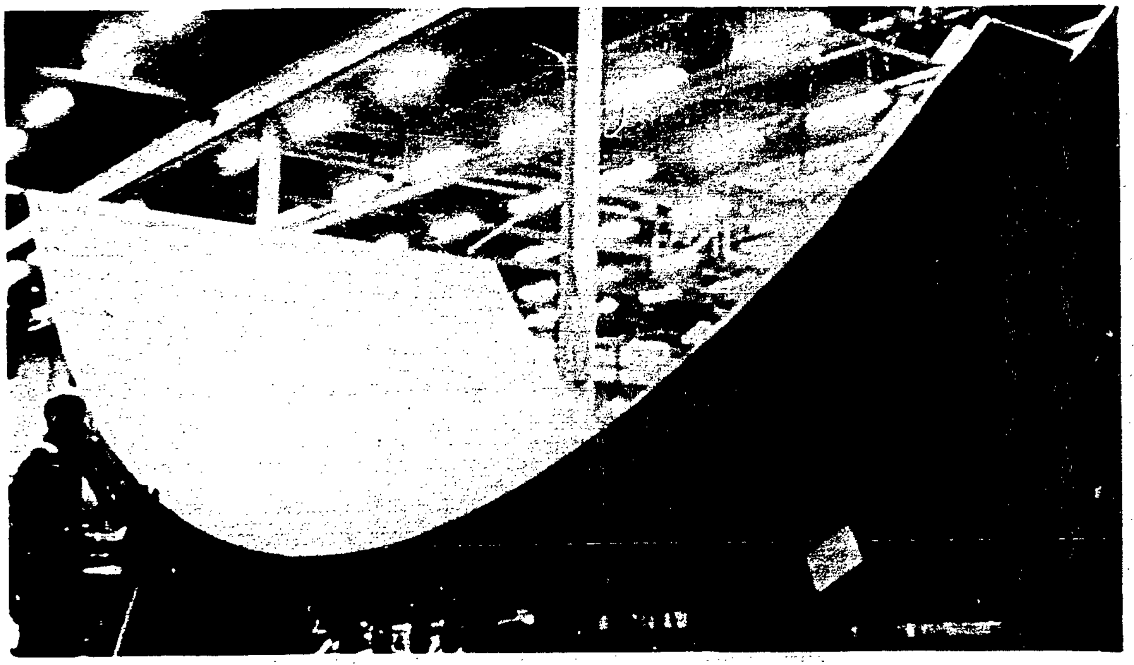


FIGURE 8. FORMED PART IN A CONTOUR INSPECTION GAGE

FIGURE 9. CONTOUR FIXTURE

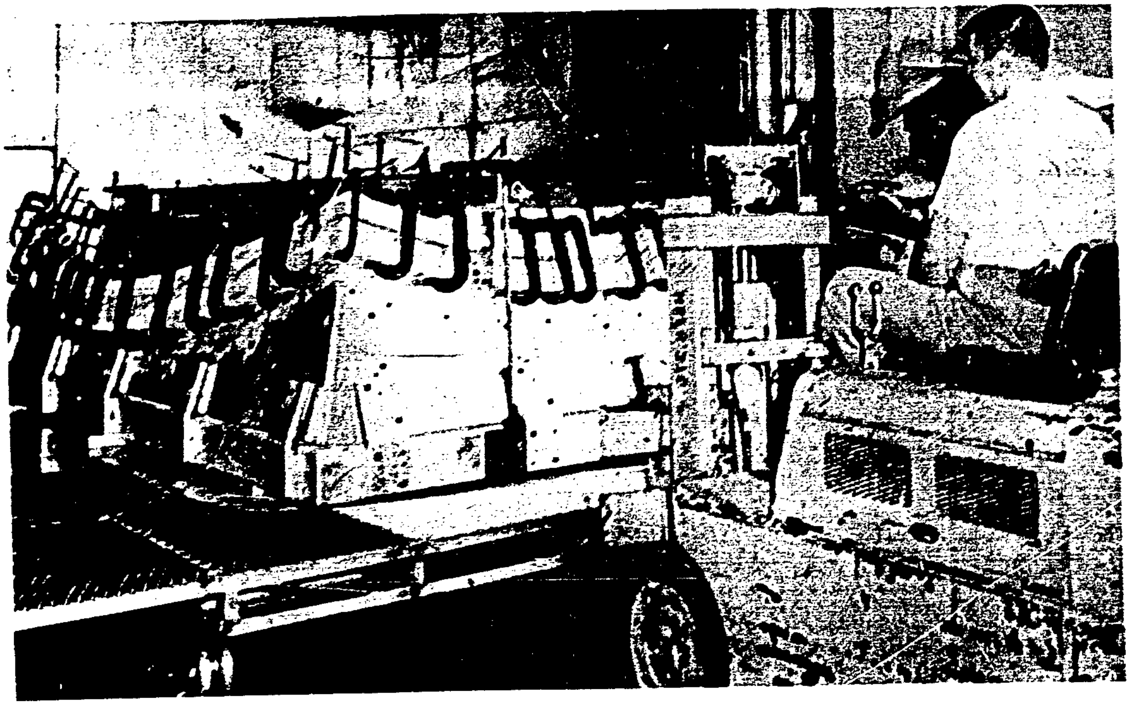


FIGURE 10. AGING FIXTURE

vehicle. Basically, as the energy input rate was lowered, porosity decreased and the mechanical and metallurgical properties improved.

The knowledge gained in this series of research projects is now used throughout the Saturn program and it also applies to material other than aluminum, such as the hardenable stainless steels.

The findings of the weld research program are particularly applicable in welding the thinner gages [6.35 to 25.4 mm ($\frac{1}{4}$ to 1 inch)] of 2219 aluminum alloy used on the Saturn S-IC tank structure.

Figure 11 illustrates the horizontal welding of the Y-shaped transition ring to the dome-shaped tank closure. Initially, MSFC used the gas tungsten arc (GTA) process on this 5.7 mm (0.224 inch)-thick joint, but the quantity of weld porosity was unacceptable.

Data obtained in MSFC research dictated the use of a lower-energy-level type of weld. The final selection was a two-pass weld with the gas metallic arc (GTA) process, which produced excellent results on the first effort.

Another recent application of this energy control technology was the welding of aluminum LOX tunnels into the fuel tank (Fig. 12). Previously MSFC had attempted to produce this horizontal circular weld by means of the GTA process, but the slow rate of deposition of the weld metal caused objectionable weld porosity and excessive distortion of the relatively thin walls of the 2219 aluminum alloy tube.

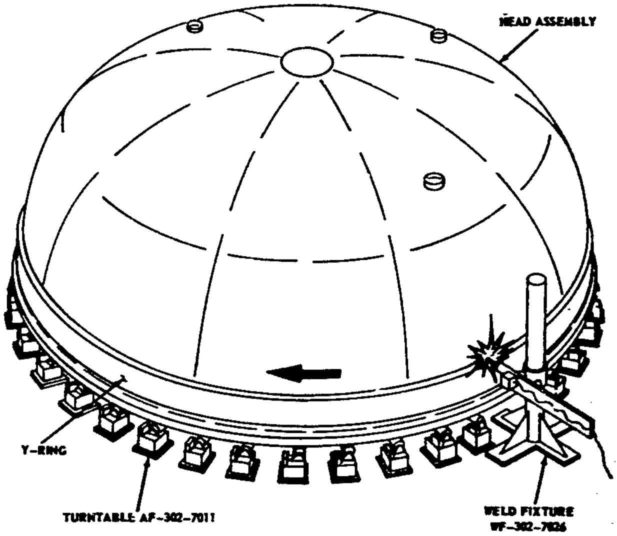


FIGURE 11. HORIZONTAL WELDING OF Y-SHAPED TRANSITION RING TO THE DOME-SHAPED TANK CLOSURE

Using research data and the knowledge gained by MSFC and Boeing in welding the thinner gage aluminum bulkheads by the high-speed GMA process, MSFC engineers designed and built a GMA mechanized unit for welding the LOX tunnel end to the lower bulkhead. Figure 13 is a diagrammatic illustration of the machine attached to the vehicle in position for welding.

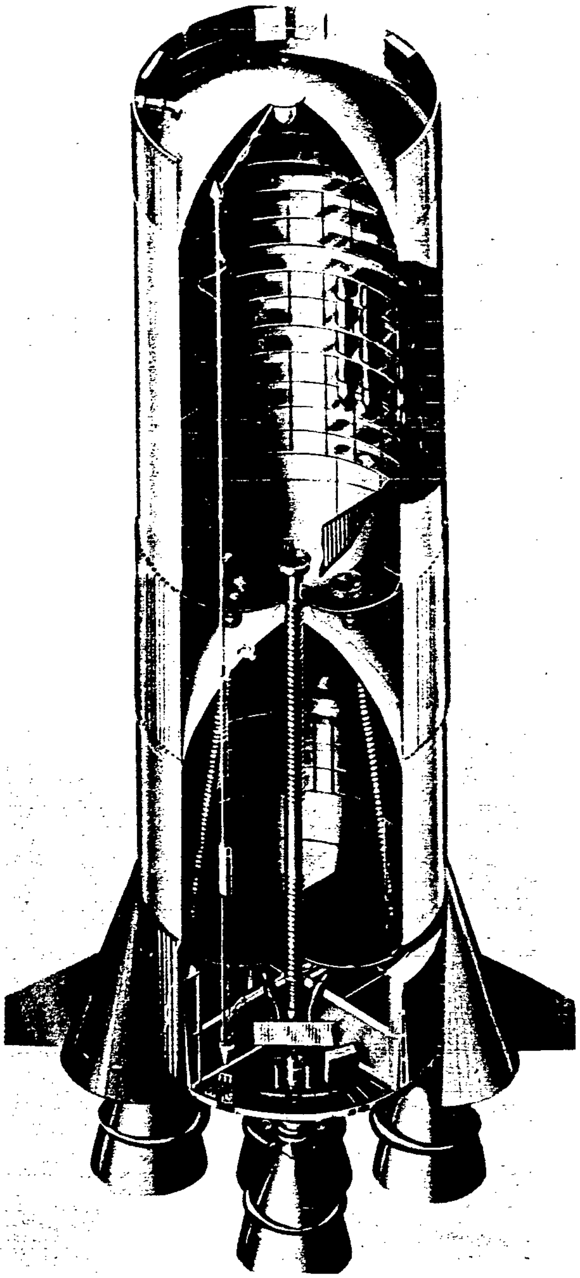


FIGURE 12. CUTAWAY VIEW OF LOX-TUNNEL WELD

The above-mentioned examples do not mean that GTA welding does not have its place within Saturn V welding requirements. On the contrary, it is particularly applicable to 2219 aluminum alloy in gages above 9.5 mm (3/8 inch) thickness. Shown in Figure 14 is a typical GTA welding setup. Electrical energy input rate, which must be considered, is determined by the ability of the thicker materials being welded to carry away excessive and damaging heat generated during welding.

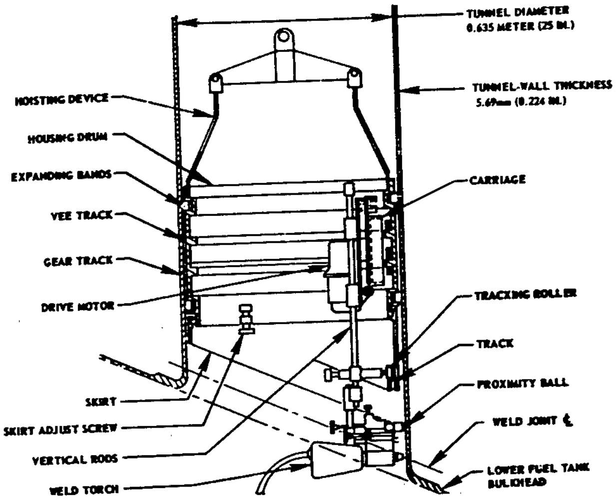


FIGURE 13. LOX-TUNNEL WELDING MACHINE

Energy control research has not provided answers to all MSFC welding problems, but it has provided experience and information which have become useful for determining the causes of many other Saturn V welding problems and for solving them.

V. COMPOSITE STRUCTURES RESEARCH APPLICATIONS

One of the newer areas of fabrication development applicable to Saturn hardware is the composite type of structure. A composite structure is defined as one composed of a variety of materials (e.g., aluminum, plastics, etc.) joined by adhesives, mechanical fasteners, welding, etc. This type of structure offers major advantages in weight savings and insulation characteristics, which are important

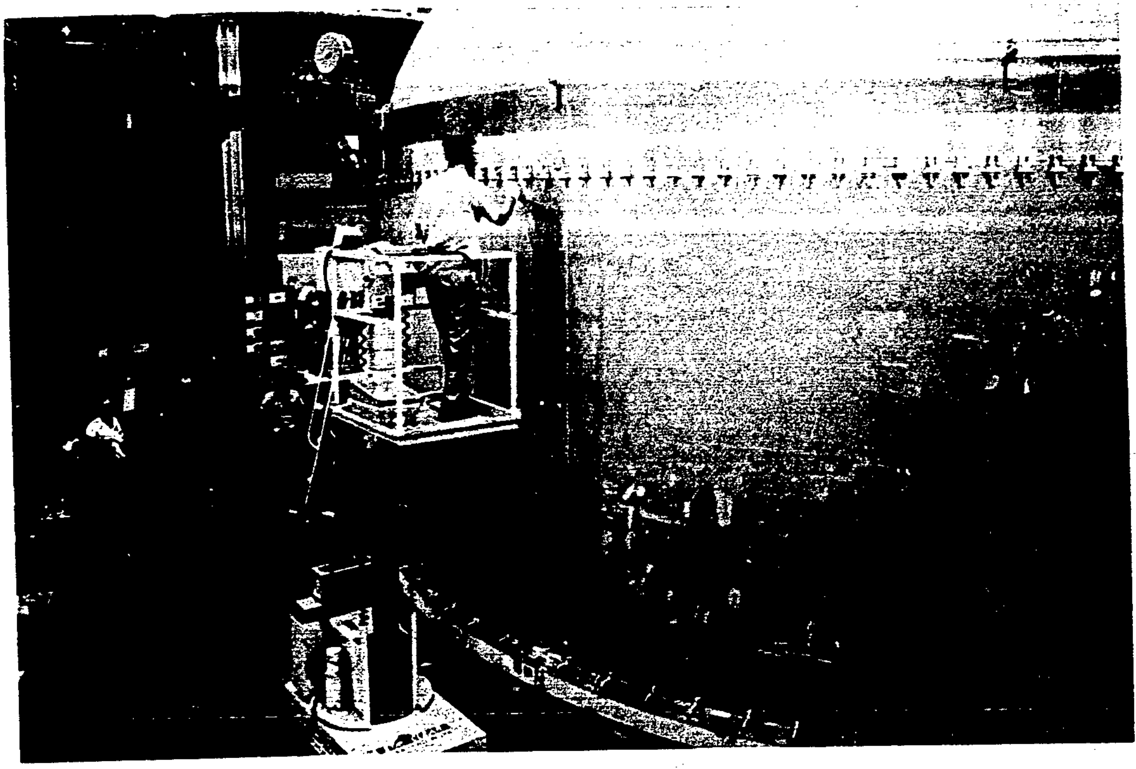


FIGURE 14. TYPICAL GTA WELDING SETUP

in producing a more efficient space vehicle. A typical composite structure is shown in Figure 15, and actual and potential applications are illustrated in Figure 16.

Manufacturing Engineering Laboratory has sponsored many research programs on composite structures. Because the advantage of the best of any material selection can easily be nullified by improper fabrication processes, the objective usually has been related to developing assembly and processing techniques for materials previously selected by the Propulsion and Vehicle Engineering Laboratory.

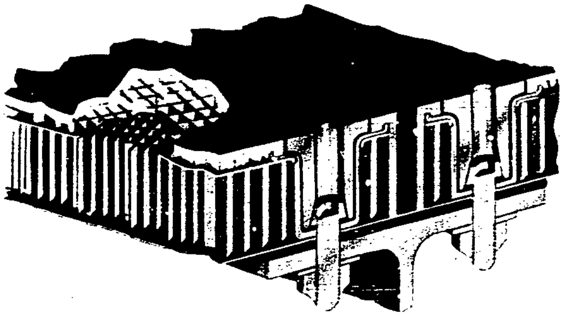


FIGURE 15. TYPICAL COMPOSITE STRUCTURE

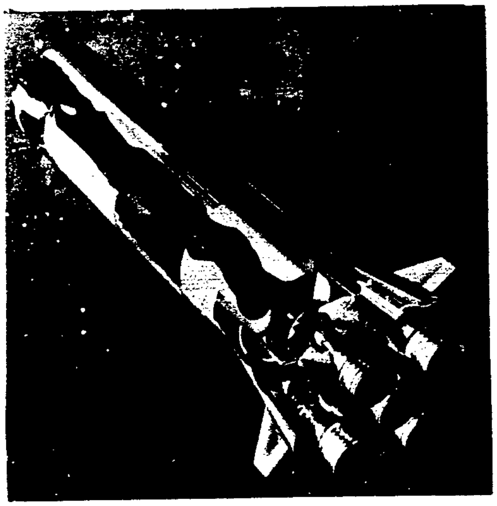


FIGURE 16. CURRENT AND POSSIBLE APPLICATIONS OF COMPOSITE STRUCTURE ON S-IC STAGE, SATURN V

Figure 17 shows the S-II test panels fabricated by Manufacturing Engineering Laboratory being fitted to an evaluation tank. The Laboratory's research in this project helped to define characteristics such as material preparation and cleaning, application techniques for the various adhesives, vacuum-bagging methods, development of time and temperatures to obtain desired properties from the adhesives, and the handling methods for the large insulation panels during all phases of fabrication.

Problems often reveal themselves during a phase of fabrication; an example is the cracking at the seal or doubler strips between the large subassembled panels. Numerous closeout configurations were considered, fabricated, and tested. Figure 18 illustrates a type of joint which can offer adequate flexibility and expansion characteristics to prevent cracking and thus maintain the gas-tight seal required for optimum insulation properties.

Adhesives developed through research in adhesive fabrication currently are being used to bond special bracketry and fastener on the tank walls of

FIGURE 17. S-II TEST PANELS BEING FITTED TO AN EVALUATION TANK

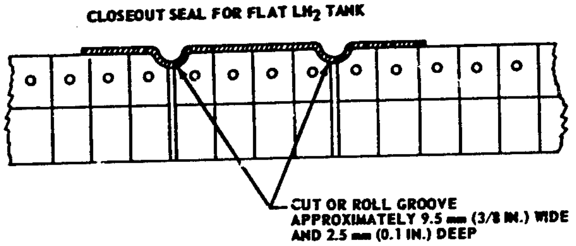


FIGURE 18. FLEXIBLE GAS-TIGHT SEAL

the Saturn structure. This bracketry is used for a variety of purposes, for example, holding special instruments in place and providing support points for flight electrical control cables. Adhesively bonded patches also have been successfully used to strengthen a damaged or substandard tank structure.

Another important composite fabrication problem under intensive investigation deals with the techniques for building common bulkheads or a structure of double curvature. A typical common bulkhead structure on the third stage of the Saturn vehicle is shown in Figure 19. Current research projects also are intended to improve fabrication technology and subsequent reliability of similar bulkhead structure for the Saturn V second stage.

VI. TOOLING RESEARCH AND APPLICATIONS

Tooling research as related to welding and routing skates is being done at MSFC in an attempt to lower tooling costs.

Figure 20 illustrates the principle of skate-type tooling. A track is attached to, or alined along, a weld seam or edge trim zone. A carriage carrying a weld head, or a router, skates along the track at a preset rate.

Figure 21 shows an application of skate research which involves the S-IC gore-edge trimming operation. The part is held in position against the polka-dot vacuum chuck and the skate travels along the arc-shaped track.

Figure 22 shows a similar application of surface trimming the honeycomb core during the manufacture of the S-II common bulkhead.

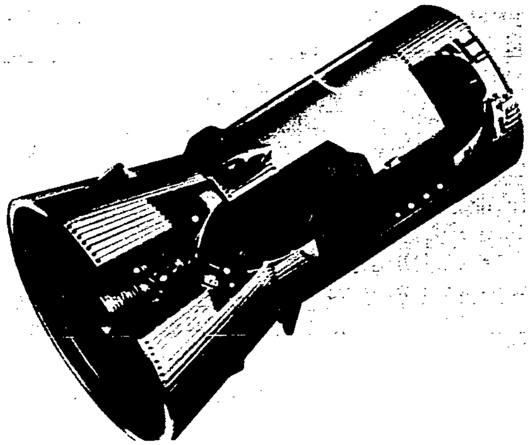


FIGURE 19. TYPICAL COMMON BULKHEAD STRUCTURE ON THIRD STAGE OF SATURN VEHICLE

Currently research work is underway on skate systems which are self-regulated through the use of various systems of arc guidance or analog computers, or both.

VII. CHEMICAL MILLING

The purpose of an important series of research projects on the chemical processing of types 2219 and 2014 aluminum alloy has been to determine the control techniques for chemically milling and surface treating these Saturn V materials. Chemical milling is the process of removing metal by chemical etching. Results of this process on the base and apex gore segments are shown in Figure 23.

Undesirable results of chemical milling included a wavy milled surface or one with a rough texture caused by an uneven rate of etching in recessed areas.

A series of research contracts was established with several commerical chemical companies to develop etchants and processes to avoid these defects. As a result of these contracts, hundreds of large gore segments used on all stages of the Saturn V vehicle have been chemically milled, with thickness and surface roughness successfully controlled.

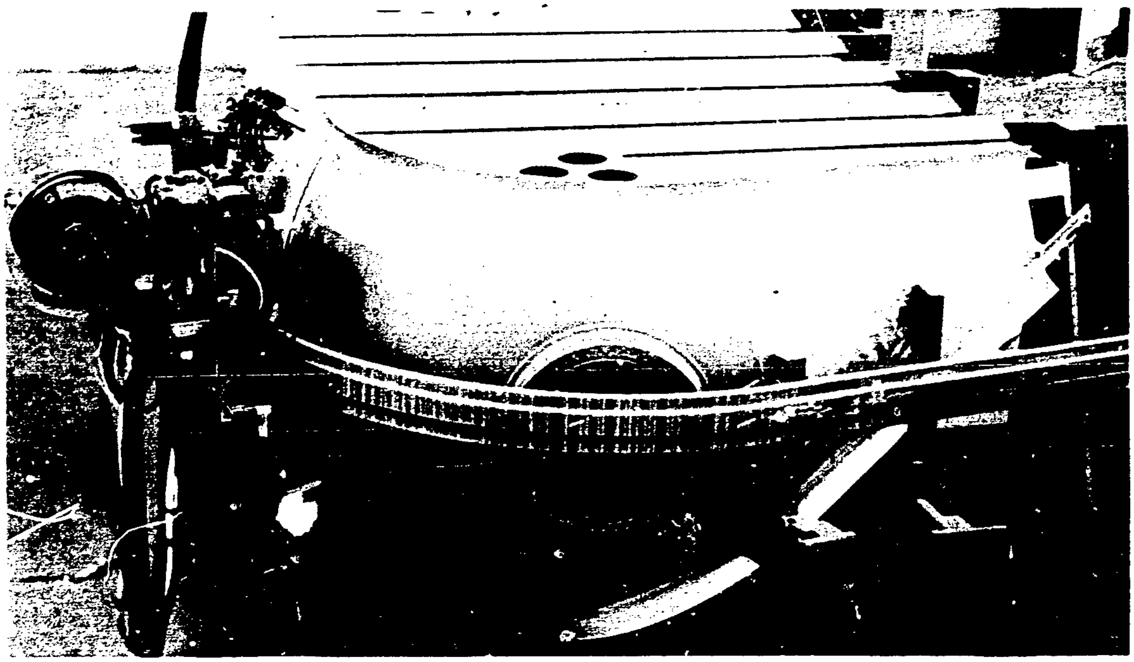


FIGURE 20. EXAMPLE OF SKATE-TYPE TOOLING

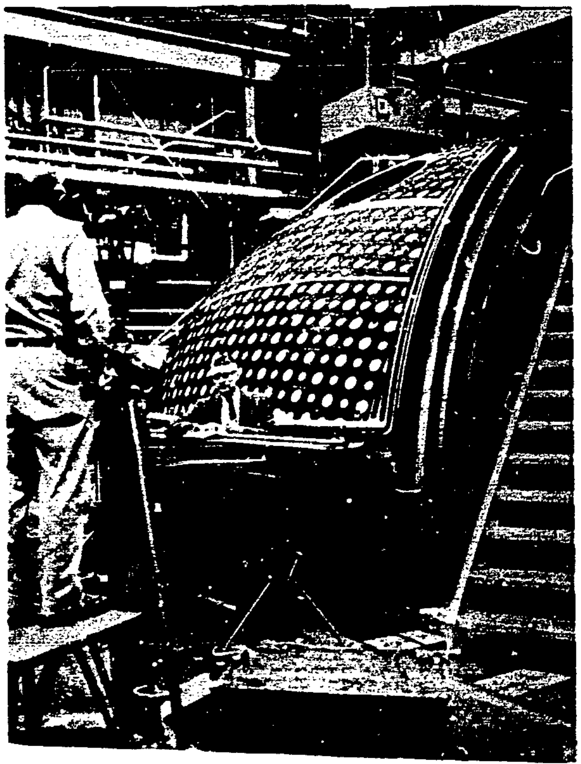


FIGURE 21. S-IC GORE-EDGE-TRIM OPERATION

FIGURE 22. S-II COMMON BULKHEAD HONEYCOMB-CORE-TRIM OPERATION

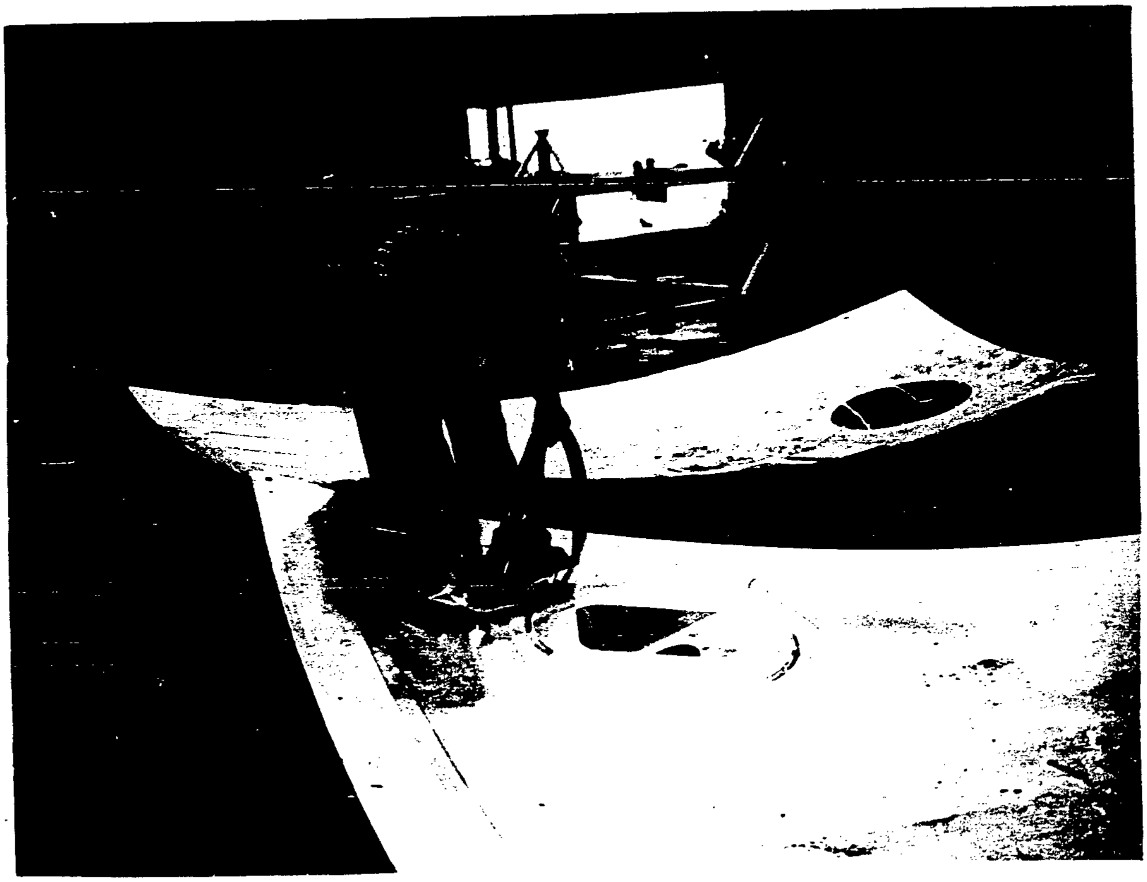


FIGURE 23. BASE AND APEX GORE SEGMENTS AND THE CHEMICALLY MILLED SURFACES

N66

36422

N66 36422

ESTABLISHING A COMMON DENOMINATOR IN WELDING

By

Gordon Parks

SUMMARY

The solutions to various welding problems ultimately depend upon the establishment of a more systematic and scientific basis for welding practices than has existed. One of the approaches to welding fundamentals undertaken at MSFC has been to relate all welding processes and materials to a common denominator of time-temperature relationship.

With this basic relationship applied to the various welding parameters, relationships can be drawn for better systemized information. For example, there may be optimum time-temperature curves for yield strength, ultimate tensile strength, elongation, porosity, distortion, material thickness, etc.

The efficiency of gas metallic arc and gas tungsten arc, the chief welding methods used in Saturn V manufacture, differs with the electric current used (AC or DC). A statistical study is being made to obtain quantitative measurements of the various responses in AC and DC welding.

Investigations on the very efficient and practical electron-beam technique are aimed at minimizing or removing the need for a vacuum welding environment. Three conceptions have been considered to achieve this aim. One is a split, or local, chamber method in which only the joint to be welded is in vacuum. The second is a plasma electron-beam system in which a hollow electron gun operates in a low vacuum provided by a mechanical pump. The third is a nonvacuum system in which the material to be welded is in a normal atmosphere and the vacuum is maintained within the electron gun.

I. INTRODUCTION

A weld may be defined as a continuous defect surrounded by sound metal. This is not meant to be facetious nor disparaging; rather it expresses an acceptance of a problem, and thus places the investigator in the favorable position of emotionally unhindered investigation. Two weld-development objectives may be postulated: (1) to minimize this total defect to the maximum extent possible and (2) to establish a high level of confidence in the reproduction of known weld quality.

Much of what must be considered in attaining these objectives is well delineated in the welding handbook chapter, "The Physics of Welding," published by the American Welding Society:

> "Welding involves more sciences and variables than any other industrial process, which may explain why most of those concerned are satisfied with a very crude understanding of its problems.
>
> "The principal sciences involved in welding are physics, chemistry and metallurgy. Of these, the physics problems are the ones most neglected and least understood, specifically from the quantitative point of view. These involve heat, mechanics, elasticity, plasticity, electricity and magnetism, as well as those very complicated and as yet little understood phenomena of the welding arc. Testing and research work in this field require a knowledge of optics, including polarized light, X-rays, X-ray diffraction, crystal theory, and the constitution of matter."

In reference to the present stage of welding theory and techniques, no common abstraction is found to which all processes and materials can be related. The absence of such an abstraction has made welding appear to be an art, consisting of isolated, unrelated modes and materials. Therefore, welding research at MSFC has involved: (1) the formulation of a common, unifying denominator or general index based on theory and experiments, (2) a program which will arrange the various elements of the welding complex into their proper, quantitative relationships, and (3) the methods and means of applying such knowledge to manufacturing of space vehicles.

II. THE COMMON DENOMINATOR

Realizing that energy, or heat, in some span of time results in degradation of material, one may go directly to the core of the problem and select time-temperature relationships as the common denominator to which welding processes and their effects on metals can be related. The time-temperature relationships are more clearly defined in Figure 1, in which the welding temperature gradient reflects the peak temperature, and the time above a subtemperature adversely affects the material. Such curves can be related to the responses, strength, and porosity, as shown in the chart below and in Figure 2. There will be an optimum curve for each response sought, for example, ultimate tensile strength, yield strength, elongation, distortion, and porosity. Thickness and material changes may require other time-temperature curves.

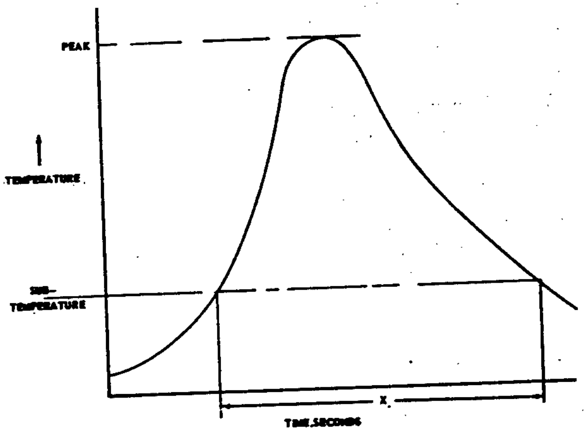


FIGURE 1. TIME-TEMPERATURE CHARACTERISTICS CURVE

$$Y_1 = f(X_1, X_2)$$
$$Y_2 = f(X_1, X_2)$$
$$Y_3 = f(X_1, X_2)$$

IN WHICH:

Y_1 = YIELD STRENGTH
Y_2 = ULTIMATE STRENGTH
Y_3 = ELONGATION
X_1 = MAXIMUM TEMPERATURE
X_2 = TIME ABOVE TEMPERATURE

Each welding process has its limits in the manipulation of variables that produce time-temperature curves; thus, processes can be located on a curve of time-temperature versus strength or other response (Fig. 3). Lowest in efficiency is the tungsten inert gas DCSP (straight polarity), and highest in efficiency is electron beam welding. In a similar manner, we can consider different materials, material thickness, mass, and joint geometry. With this general index of time-temperature relationships, a coherent, logical framework of the metals-joining complex may be formulated.

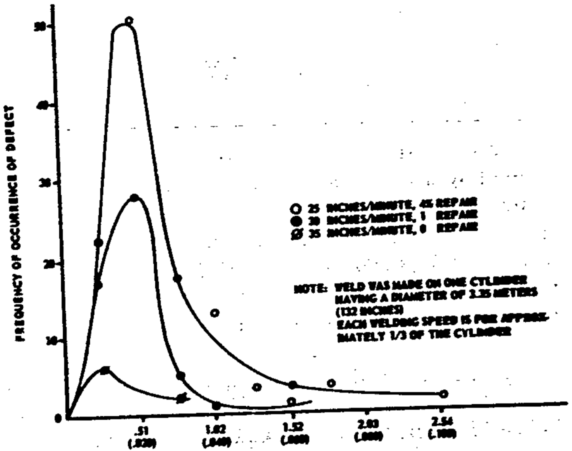


FIGURE 2. WELD DEFECTS, FREQUENCY OF OCCURRENCE VERSUS SIZE

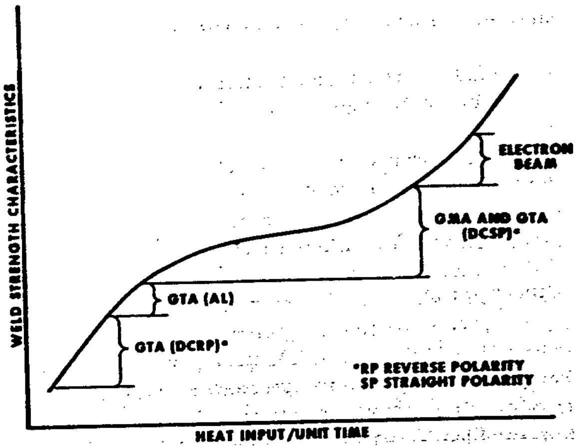
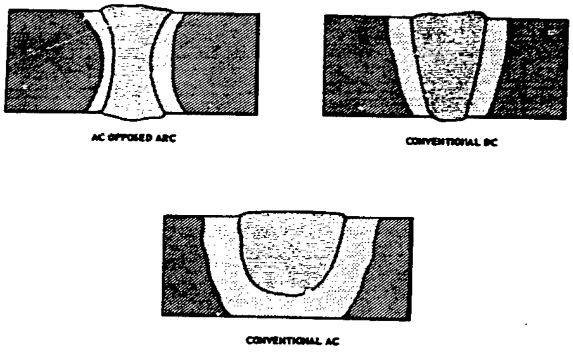


FIGURE 3. RELATIVE EFFECT OF PROCESS HEAT INPUT VERSUS WELD STRENGTH CHARACTERISTICS

III. PROCESS DEFINITION

A. INERT GAS ARC WELDING

Two welding processes are predominant in Saturn V manufacturing: consumable electrode, gas metallic arc (GMA), and nonconsumable electrode, gas tungsten arc (GTA). Efficiency differences in the processes using alternating current (AC) and direct current (DC) can readily be seen by a comparison of the melt areas shown in Figure 4. A narrower bead and deeper penetration are produced with DC than with AC. The GTA DCSP offers more potential of increasing the conventionial AC arc efficiency, while retaining the assumed advantages of cathodic cleaning and nugget structure refinement caused by the AC stirring of the molten puddle. On the other hand, when the AC cleaning and refinement potentials are not considered, two opposed DC arcs may have a still greater efficiency. A statistical study is being conducted to place quantitative measurements on these responses of AC and DC welding. The study will ultimately include all the processes, as shown in Figure 5.


AC OPPOSED ARC

CONVENTIONAL DC

CONVENTIONAL AC

FIGURE 4. MELT AREA COMPARISON

B. ELECTRON-BEAM WELDING

The most efficient and practical process related to the common denominator of time-temperature is electron-beam welding (EB). A GTA weld on 6.4 mm ($\frac{1}{4}$ inch)-thick plate through which an EB weld has been made is shown in Figure 5, and aptly illustrates the gain in efficiency. The EB process can be used to weld material 76 to 102 mm (3 to 4 inches) thick, whereas the GTA process is limited to materials approximately 19 mm (3/4 inch) thick. The lower time-temperature of EB welding results in higher strength and quality.

Electron beam welding has been limited in application because of its higher vacuum requirement (0.013 N/m^2 or 10^{-4} mm Hg). Three approaches have been made toward removing this limitation, and thus they make this most efficient process as versatile as the GTA and GMA modes. These approaches, in progression, are as follows:

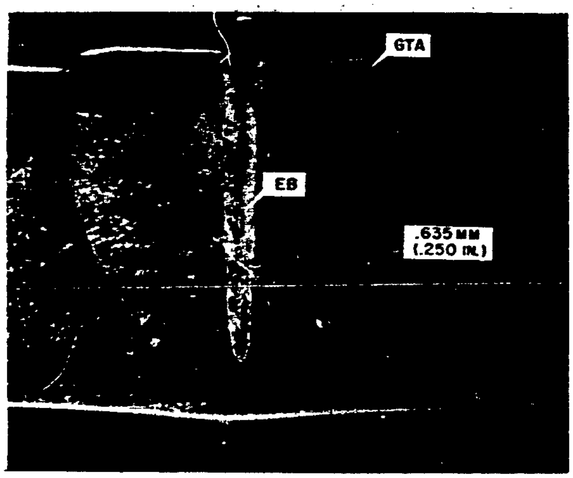


FIGURE 5. COMPARISON OF WELD ZONES, ELECTRON BEAM VERSUS GTA

1. Split, or Local, Chamber Concept. A conventional high-vacuum chamber is often impractical if large components must be completely enclosed. The split chamber, with adequate local sealing, reduces the vacuum chamber size to that necessary to encompass the joint to be welded. An example of this technique is shown in Figure 6. The welding of fittings into bulkhead gore segments by the low time-temperature EB process will eliminate the severe distortion and buckling which result from the high-energy TIG process, and the consequent shrinkage stresses.

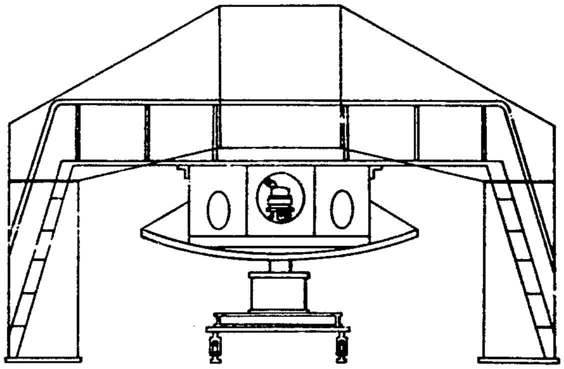


FIGURE 6. SPLIT-CHAMBER VACUUM SYSTEM

2. Plasma Electron-Beam Welding. As stated before, the conventional EB system requires a high vacuum and uses a complex and bulky gun. The plasma electron beam system (PEB), on the other hand, uses a simple, hollow electrode gun which will

function in a vacuum of 13.3 N/m^2 (0.1 mm Hg) provided by a mechanical pump (Fig. 7). The higher positive pressure of the system may permit the use of a simple, inexpensive ducting system rather than the complex, directly coupled, diffusion-pumped, high-vacuum system now being used. Developmental tests indicate that weld joint efficiencies will be equal to those produced by the high vacuum. In addition, the PEB system can be combined with the split-chamber method to increase the system's potential versatility.

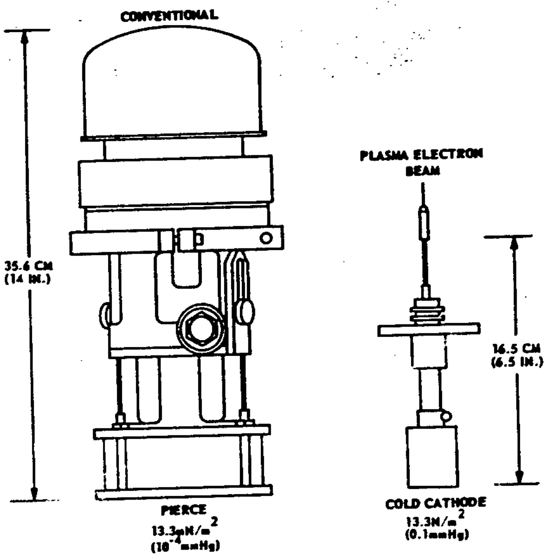


FIGURE 7. ELECTRON-BEAM WELDING DEVICES

3. Nonvacuum Electron-Beam System. The most direct approach toward versatility is to remove the vacuum requirement, i.e., to remove the material being welded from a vacuum. Such a system exists, and currently is being improved and refined for selected application studies. It eliminates the need for chambers and ducting systems. Figure 8 shows schematically a method of bringing the electron beam out of the chamber. The vacuum is maintained within the gun as the beam passes through a series of orifices which separate the differentially evacuated compartments. Helium gas is introduced outside the last orifice to minimize beam scatter. In welding 12.7 mm ($\frac{1}{2}$ inch) type 2219 aluminum alloy, the gun-to-work distance is approximately 9.5 mm (3/8 inch).

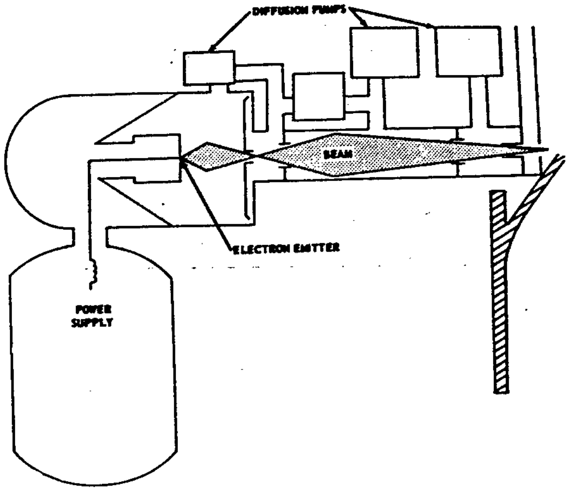


FIGURE 8. NONVACUUM ELECTRON-BEAM WELDER

Comparison of a two-pass tungsten arc weld with a nonvacuum EB weld is shown in Figure 9. The tungsten arc weld was made at 15 cm (6 inches) per minute, and the EB weld at 318 cm (125 inches) per minute, with an energy input about 90 percent less than the tungsten arc weld.

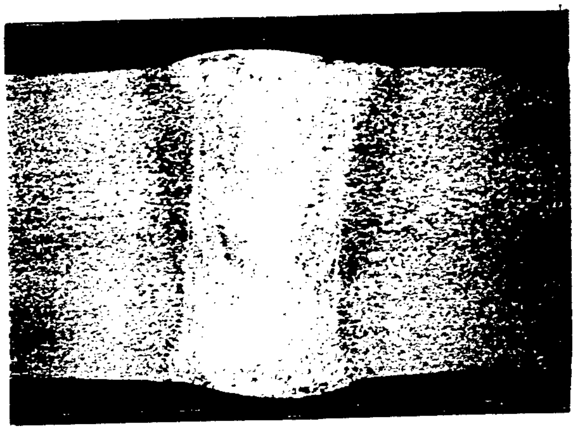
The present nonvacuum EB package has a mass of 102 kg (225 lbm). The equipment, shown in Figure 10, will be used at MSFC for application development.

4. Lightweight, Hand-Held EB Gun. The EB system is not necessarily earthbound. It has the intriguing potential of being usable in a space environment (in which a very high vacuum exists). Figure 11 shows conception of hand-held EB guns which would have a mass less than 20 kg (45 lbm). The gun on the right would be powered by self-contained, rechargeable batteries. The gun on the left would obtain power from an independent source.

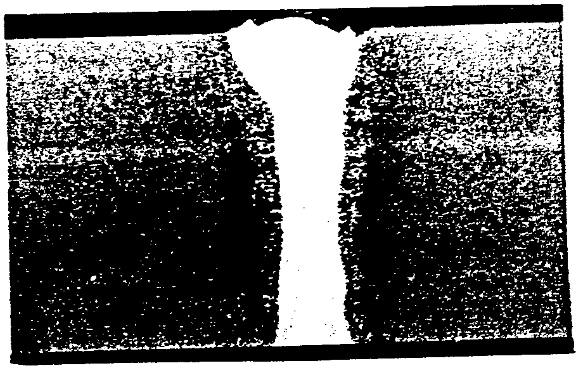
IV. DEVELOPMENT AND APPLICATION STUDIES

Our development effort, which can be represented as a welding development complex, is shown

TYPE 2219 ALUMINUM ALLOY
12.7 MM (.500 IN.)



TWO-PASS GTA



NONVACUUM EB

FIGURE 9. COMPARISON OF A TWO-PASS TUNGSTEN ARC WELD WITH A NONVACUUM ELECTRON-BEAM WELD

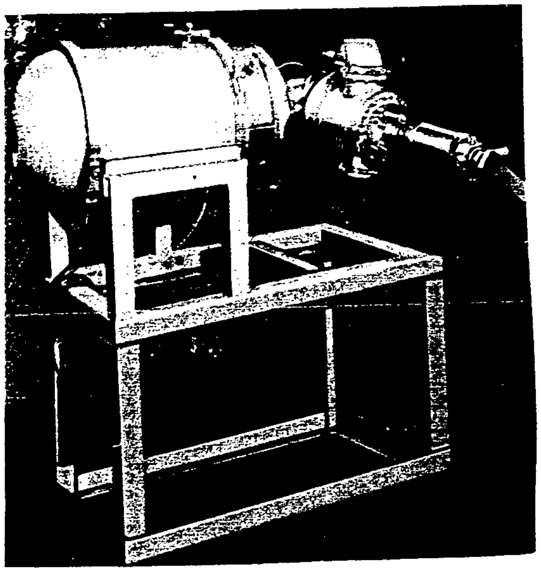


FIGURE 10. NONVACUUM ELECTRON-BEAM SYSTEM

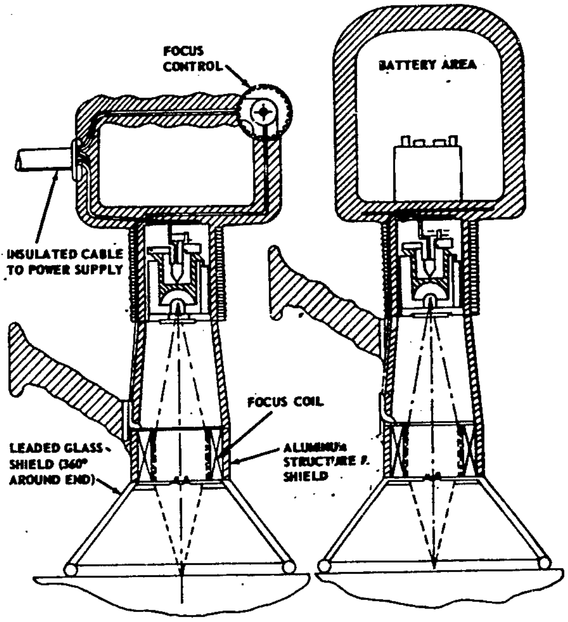


FIGURE 11. PORTABLE ELECTRON-BEAM WELDER

in Figure 12. The complex of projects constitutes an ordered and coherent program, each project being a logical step toward the goal of high joint performance and reliability. Thus, basic studies now being made are: base metal analysis at Battelle Memorial Institute to determine the weld defect potential in materials; mechanism of porosity at Douglas Aircraft; time-temperature effects at MSFC; means of controlling time-temperature at Harvey Aluminum; arc shaper, to increase process efficiency; electron beam studies; and so on to the industry/NASA verifications and application, specifically to the Apollo program, and to space vehicles in general.

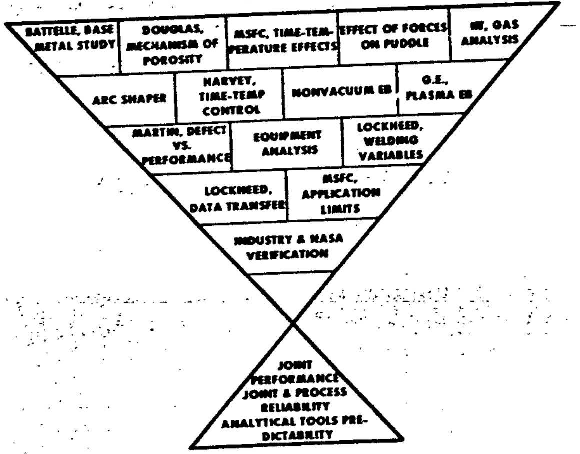


FIGURE 12. WELDING DEVELOPMENT COMPLEX

N66

36423

N66 36423

RESEARCH IN SUPER POWER LASERS AND INTENSE MAGNETIC FIELDS

By

R. J. Schwinghamer

SUMMARY

New tools and tooling concepts based upon MSFC research developments in superpower lasers and intense magnetic fields are discussed in this review.

Superpower lasers are being investigated for drilling and welding applications. One of the most promising lasers, a pink-ruby type in a coaxial gun, with a Cassegrainian focusing system, has an input power of 240 000 joules and an output of 2000 joules, sufficient for vaporizing any material. Since this welding system operates in a normal ambient pressure while its beam can be projected into vacuum to do work, it has potential for use in space as well as the laboratory and shop.

Research developments in intense transient magnetic fields are being successfully applied to many manufacturing problems. An electromagnetic constriction technique, employing high-intensity pulsed fields, is used to correct oversized metal tunnels (Saturn V LOX and others). Pneumatically clamped and hand-held magnetomotive hammers, based upon the same principle of pulsed magnetic fields, have been developed for removing weld distortions from Saturn V heavy skin sections, gore segments, and bulkheads. Other magnetic-field tools for manufacturing processes such as fastening, swaging, blanking, sizing, and coining are being developed and tested.

I. INTRODUCTION

New research developments in superpower lasers and magnetic fields are reported in this review, and some of their current and potential applications are discussed.

The very considerable potential of lasers is well recognized, as evidenced by the many research and development programs being conducted by numerous laboratories and agencies. The broad objective of such work by Manufacturing Engineering Laboratory is a laser tool which will be used in the shop, in the laboratory, and in space.

The Laboratory's work in intense magnetic fields also has a very practical objective. It has been based upon magnetic-field phenomena discovered at Harvard Cyclotron Laboratory in 1955, and these have led, at MSFC, to significant new tooling concepts.

II. SUPERPOWER LASERS

Manufacturing Engineering Laboratory has concentrated on doped-crystal lasers available. There are about five other basic types of lasers: gas discharge, semiconductor junction, liquid, plastic, and glass. The number of laser materials has increased very rapidly, so that it has become difficult to keep up with all the details of new developments.

For drilling and welding studies, Manufacturing Engineering Laboratory has considered both red and pink ruby (there are two kinds, depending on the amount of chromium dopant) and the glass lasers. While general agreement on their relative merit by no means exists even now, the pink ruby seems best suited for high-power drilling and welding studies because: (1) it has a very high thermal conductivity, (2) its emission wavelength is more suitable for welding because this laser is characterized by less reflection and more absorption (3) life of the crystal still is better than that of any other laser material because the crystal does not craze or solarize easily, and (4) the unfocused beam spread is very small, being approximately 0.15 mrad (30 seconds) of arc.

Subsequent events have verified the superiority of the choice made two years ago. Features of the superpower laser work are discussed briefly in the following paragraphs.

A. PINK RUBY LASER SYSTEM

Figure 1 shows a typical transition diagram for the so-called three-level ruby laser. The conventional excited chromium atom population inversion is shown by the solid lines; a less likely and rather unusual transition is shown by the dotted lines.

Transitions can be considered roughly as a shifting of electron orbits.

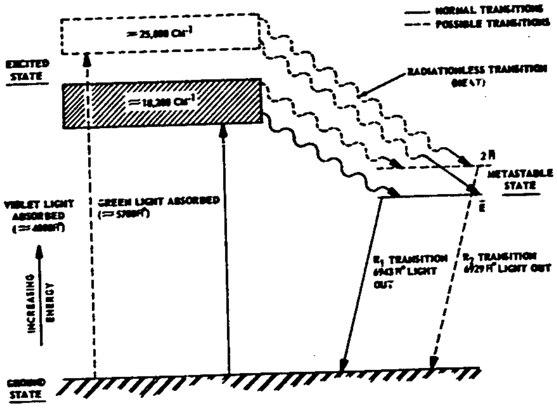


FIGURE 1. TRANSITION DIAGRAM FOR THREE-LEVEL RUBY LASERS

B. TYPICAL HIGH-POWERED LASER GUN DESIGNS

The laser gun is the next important system element. There are three basic high-powered gun designs which are shown in Figure 2. The coaxial design was selected primarily bacause this was, and still is, the only configuration able to handle the full 240 000-joule input that was available from the Medusa capacitor bank.

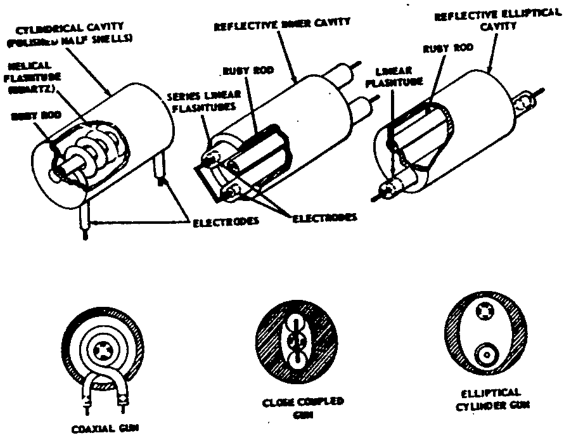


FIGURE 2. THREE BASIC HIGH-POWER GUN DESIGNS

Building such a gun required a flashtube of unprecedented size. The Kemlite Company of Chicago provided a special tube which is said to be the largest in the world.

C. LASER GUN WITH FLASHTUBE AND RUBY

Figure 3 shows the flashtube in the first version of a 240 000-joule gun. The top half of the reflector

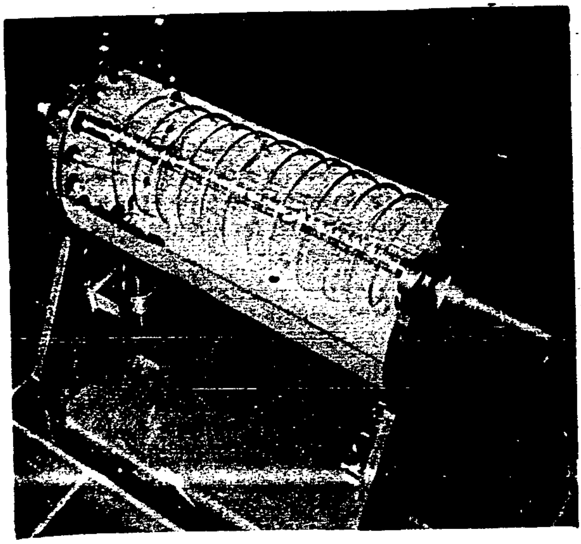


FIGURE 3. FLASHTUBE IN THE FIRST VERSION OF A 240 000-JOULE GUN

cavity has been removed. The flashtube helix is approximately 13 cm (5 inches) in diameter and 33 cm (13 inches) long, while the ruby is 1.6 cm (0.625 inch) in diameter and 30.5 cm (12 inches) long. The flashtube has very high light output, as can be seen by the graph in Figure 4.

D. XENON FLASHTUBE LIGHT OUTPUT VS. ENERGY INPUT

With full energy input of 240 000 joules to the system, the light output of the Xenon flashtube is a little over 7.8-billion candelas (8-billion horizontal candle power). Earlier in this research the question was raised as to what kind of energy

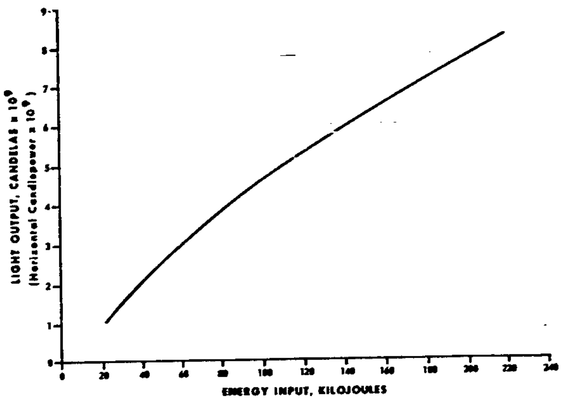


FIGURE 4. XENON FLASHTUBE LIGHT OUTPUT

density could be produced from this output so that it could be used for drilling and welding. A focusing system was considered as a basic requirement for obtaining an adequate energy density. The early efforts at focusing were frustrating because ordinary crown glass and composite lenses disintegrated. Finally some success with single quartz lenses was achieved, and later the Cassegrainian focusing system shown in Figure 5 was developed.

E. CASSEGRAINIAN FOCUSING SYSTEM

This system is basically of the astronomical telescope type except that it functions in reverse order. In the astronomical telescope the terminus is behind the large reflector, but in the laser system it is somewhat beyond the small reflector, and has a

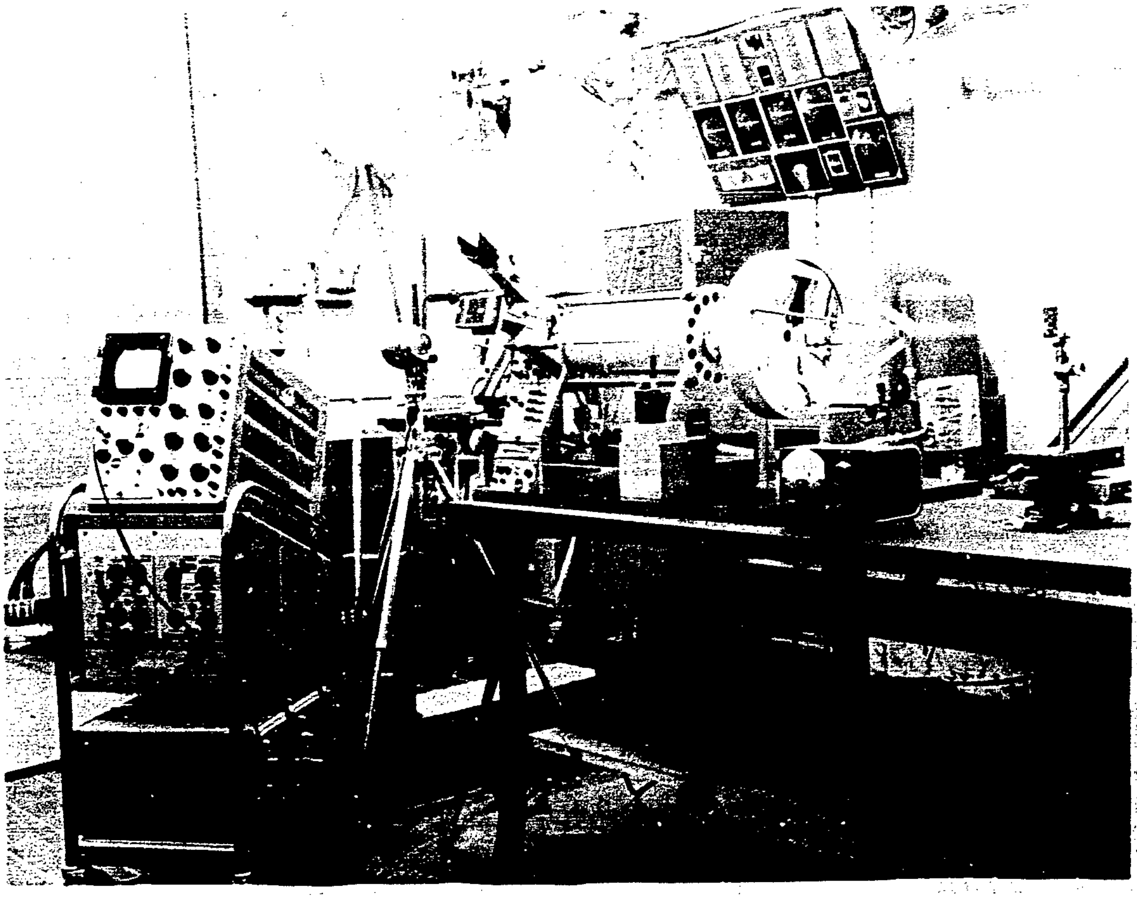


FIGURE 5. CASSEGRAINIAN FOCUSING SYSTEM

focal length of about 0.6 meter. The maximum power density attained to date has been on the order of 218-million watts per square centimeter, with an input energy of 240 000 joules and an output of about 2000 joules. This is sufficient to vaporize any material, even diamond. About 300 000 watts per square centimeter produces vaporization of the metals that the laser is being developed to drill and weld. The efficiency is almost 1 percent, which is commendable for the ruby laser.

F. WELDING WITH THE LASER

In 1962 a small, 4000-joule system was used to weld type 304 stainless steel 0.2 mm (0.008 inch) thick, and types 5086 and 2219 aluminum 0.127 mm (0.005 inch) thick. Stainless steel was easy to weld even in air, but the same technique was not suitable for aluminum. The short pulses were not as effective in preventing oxidation as had been expected. At that point, Manufacturing Engineering Laboratory demonstrated that a laser could be operated in a "shirt-sleeve environment," (i.e., a normal ambient pressure) and that the beam could be projected into vacuum to do work. The laser is the only welding device which can be operated in this manner, and this is one of its very advantageous features for space use. The aluminum welds made in vacuum were of good quality because of the absence of an oxidizing atmosphere. Figure 6 shows stainless steel welds being made by a repetitive pulsing technique, and Figure 7 shows one of these welds.

Although these studies conclusively proved the suitability of small lasers for microwelding applications, much more power was needed to handle the kind of materials in which Manufacturing Engineering Laboratory was interested. Inasmuch as the Medusa capacitor bank was already available, this led to the development of the 240 000-joule system.

Subsequent studies indicate that the quality of the large rubies varies over a wide range, and in some cases threshold (the point where lasing begins) varies between supposedly identical rubies by as much as 70 000 joules. This means that, at present, the individual characteristics of the rubies must be taken into account and, therefore, the rubies cannot be interchanged routinely in equipment.

G. MEASUREMENTS OF 240 000-JOULE LASER OUTPUTS

Figure 8 shows the diagnostics apparatus employed in making laser output measurements. It goes by the title of a rat's nest calorimeter because of the mass of fine wire used in its construction.

FIGURE 6. STAINLESS STEEL WELDS MADE BY A REPETITIVE PULSING TECHNIQUE

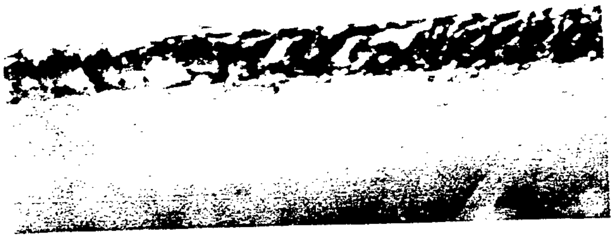


FIGURE 7. STAINLESS STEEL WELD

H. RUBY FILAMENTARY LASING MODE

Another phenomenon which caused concern, but which has not yet created much trouble, is the filamentary lasing mode of the ruby.

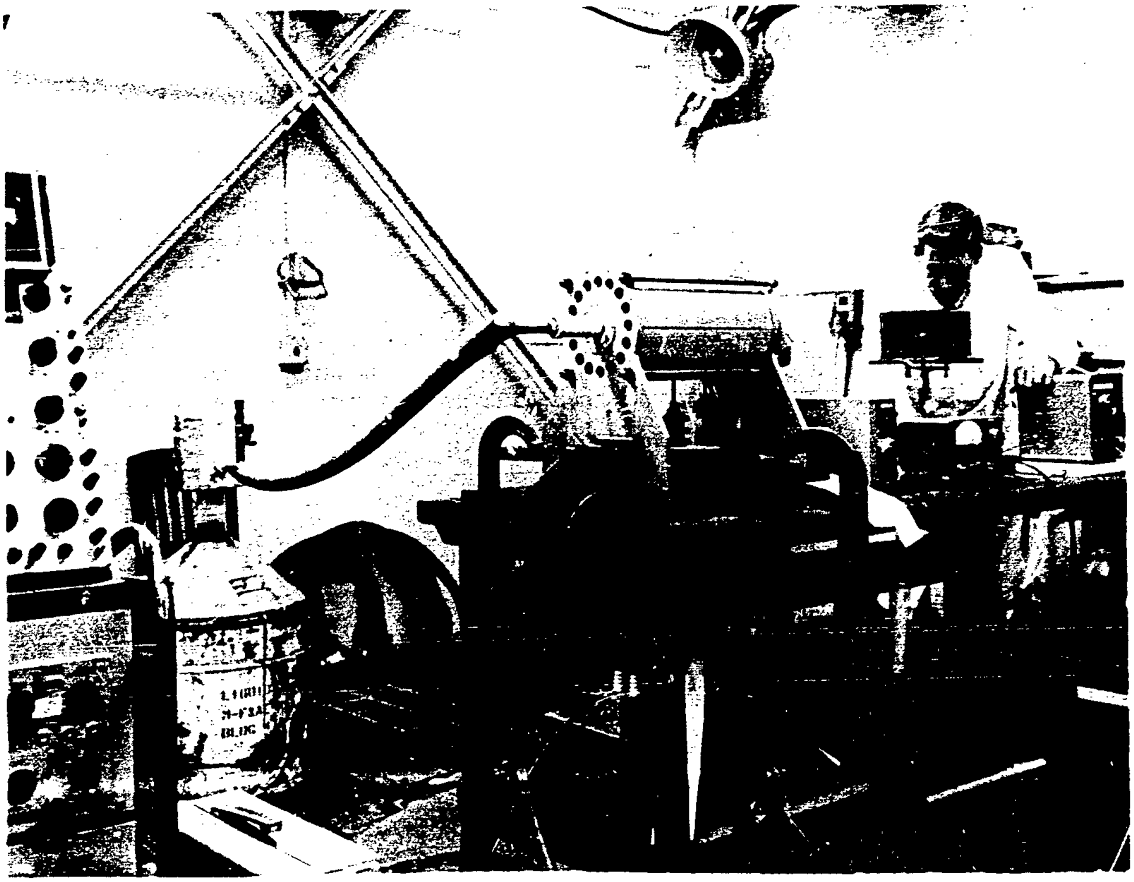


FIGURE 8. RAT'S NEST CALORIMETER

Figure 9 represents three separate laser shots. The three exposures of one shot at the left exhibit this filamentary lasing mode. The beam is random and pulsating across the cross-sectional area, but evidently does not cause much trouble after the beam is focused. It is doubtful whether anyone as yet completely understands this phenomenon. This photograph was made with a Space Technology Laboratory image converter camera focused into the eye of the laser gun at a low power level. Welding data recorded so far, in which the large system was used, indicate that the best welding results can be obtained by reducing spot density and increasing the pulse repetition rate. Studies by Newman at Ames Research Center, in which laser beams were used to simulate micrometeoroid impacts, tend to verify what has been observed experimentally on metals. Giant pulsing or Q-spoiling techniques have not been found good for welding, and now emphasis is being placed on focusing, flash-lamp waveform, and pulse repetition rate optimization. Mathematical analysis indicates that aluminum 3.2 to 6.4 mm (1/8 to 1/4 inch) thick can be welded at an equivalent rate of 127 mm (5 inches) per minute. So far, type

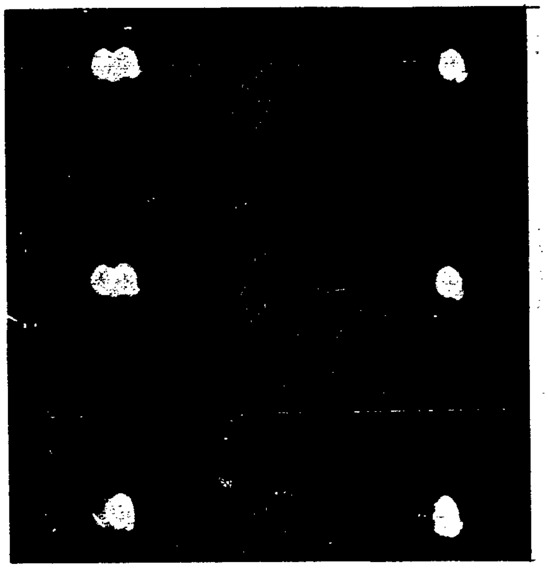


FIGURE 9. FILAMENTARY LASING MODE

2219 aluminum 3.2 mm thick has been drilled through easily, but the pulsed laser still cannot match the electron beam welders with respect to average power for continuous welding.

I. CONTINUOUS-WAVE ARGON LASER

Figure 10 shows a continuously emitting, or continuous-wave, laser being developed by Raytheon under an MSFC-supporting contract. Raytheon has operated this type of laser sporadically at 18 watts continuous wave. This could be the beginning of a new generation of laser welders that do not have to be pulsed and that can weld in a continuous manner.

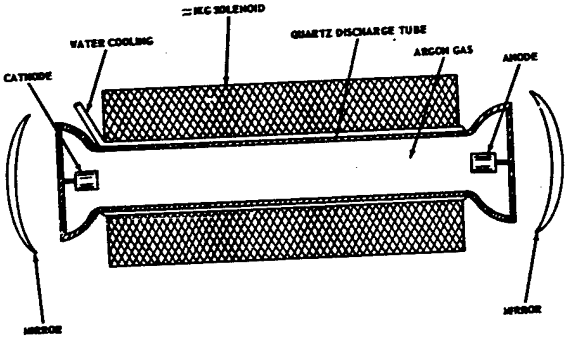


FIGURE 10. CONTINUOUS-WAVE ARGON LASER

III. INTENSE MAGNETIC FIELDS

The following commonplace magnetic fields are given as a frame of reference for this discussion of research in intense magnetic fields: the field of an ordinary toy bar magnet amounts to 0.2 or 0.3 tesla (2000 or 3000 gauss), and for an electromagnet it may be 6 teslas (60 000 gauss). Superconducting coils recently have been made to attain field strengths in excess of 10 teslas (100 000 gauss), and Montgomery at the National Magnet Laboratory (Massachusetts Institute of Technology) has reported fields slightly above 20 teslas (200 000 gauss). For much higher field strengths, the coil core must be eliminated, so that the magnetic field is produced in air or vacuum.

The use of magnetic fields is obvious in such mundane devices as electric motors, relays, and other electrical equipment. A newer, less obvious use was introduced through the discovery of unusual magnetic field phenomena by Furth and Waniek (1955, Harvard Cyclotron Laboratory). They found that with high enough transient magnetic fields they could work tough metal as though it were soft plastic, and could cause even the hardest steel to flow like water and sometimes to explode.

This discovery was incidental to their research on the determination of the charge and momentum of particles by their deflection in a high magnetic field region. This incidental, practical result and the results of work by Colgage at Livermore, a group at General Atomics, and MSFC, have proved utilitarian, and a new tooling concept has evolved as a consequence.

The manner in which intense transient fields are created is illustrated diagrammatically in Figure 11. Features of the pulsed magnetomotive power system and its practical applications are discussed in the subsequent paragraphs.

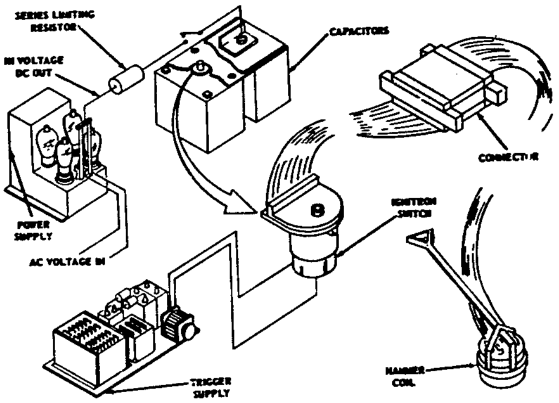


FIGURE 11. THE MANNER IN WHICH INTENSE TRANSIENT FIELDS ARE CREATED

A. MAGNETOMOTIVE PULSE POWER SYSTEM

This is the type of system needed to generate high-intensity pulsed fields. Static magnetic fields are not effective in forming metals, but pulsed or transient fields are.

Figure 12 is a pictorial representation of what takes place when a powerful transient current pulse is discharged through a coil with an electrically conductive workpiece in proximity. The coil current creates a magnetic field, and this field causes induced or eddy current to flow in the workpiece. The induced field associated with eddy current interacts with the initiating coil's magnetic field to create high magnetic field pressure between the coil and workpiece (the JXB force equation for a physicist, or the BLI relationship for the engineering force equation). If the coil is either physically or inertially stronger than the workpiece, the workpiece yields and is formed.

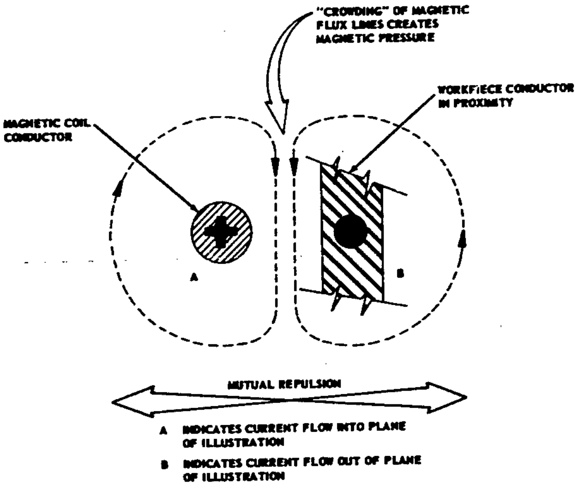


FIGURE 12. POWERFUL TRANSIENT CURRENT PULSE DISCHARGE THROUGH A COIL WITH AN ELECTRICALLY CONDUCTIVE WORKPIECE IN PROXIMITY

B. MAGNETOMOTIVE ENERGY RELATIONSHIPS

The pertinent energy relationships in the system are as follows: the electrical charge stored in the capacitors ($1/2\ CV^2$) is converted into magnetic field energy in the coil ($1/2\ LI^2$) which, in turn, creates magnetic field pressure proportional to the field strength squared over the volume V. The electrical discharge which accomplishes this is usually a damped oscillatory wave in the middle audiofrequency range.

C. ELECTROMAGNETIC PRECISION FORMING

Manufacturing Engineering Laboratory developed an electromagnetic technique for the precise forming of annular bulges in a metal cylinder. (The method is illustrated diagrammatically in Fig. 13.) In the spring of 1962 the Laboratory suggested this technique for use in stiffening Saturn V LOX tunnels. The idea could not be applied by the interested design group because its schedule commitments did not allow time for obtaining required test and design data. Three years later, however, this research development provided a successful solution to a serious manufacturing problem, described in the next paragraph.

D. SATURN V LOX TUNNEL CONSTRICTION

In February 1965 MSFC received Saturn V LOX tunnels that were oversize because of inherent difficulties in their manufacture. To deal with the important considerations of cost, reliability, and scheduling, an emergency program was begun to correct the tunnel defects. Manufacturing Engineering Laboratory, through its technique developed for precision bulging, was able to design, manufacture, and test a large magnetomotive coil to precisely size (constrict) the oversize tunnels. In this work, done in a 2 1/2- week crash program, the technique was converted to produce metal-tube constriction by fitting the magnetomotive coil over the outside of the tunnel. Since this application, the constriction method has been used to correct size defects in tunnels for Saturn facilities checkout and for "502" vehicles (Fig. 14).

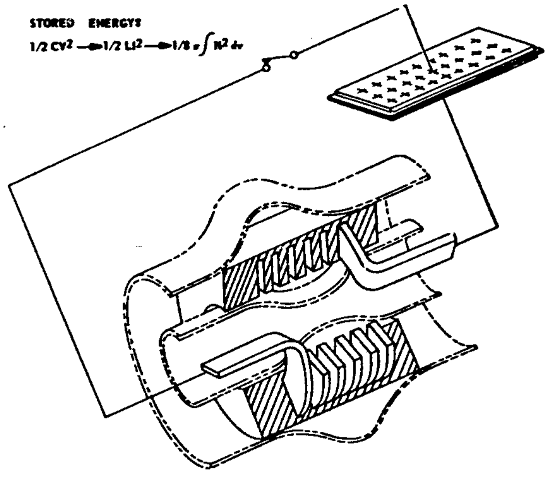


FIGURE 13. ELECTROMAGNETIC PRECISION FORMING

E. PNEUMATICALLY CLAMPED MAGNETOMOTIVE HAMMER

Until 1964, welding of heavy S-IC skin sections produced undesirable distortions. Manufacturing Engineering Laboratory developed a magnetomotive device which employed pneumatic clamping and delivered a powerful impulse. This device was then used to remove distortions. As shown in Figure 15, the device is not hand held. Its special advantages are: no surface marring results, the pressure is unique in that it is isodynamic (three-dimensional), and the strain rates are thousands of inches per inch per second.

F. HAND-HELD MAGNETOMOTIVE HAMMER

An outgrowth of the pneumatically clamped magnetomotive hammer is a hand-held magnetomotive hammer, developed by Manufacturing Engineering Laboratory (Fig. 16). It has been used to remove distortions from S-IC gore segments of

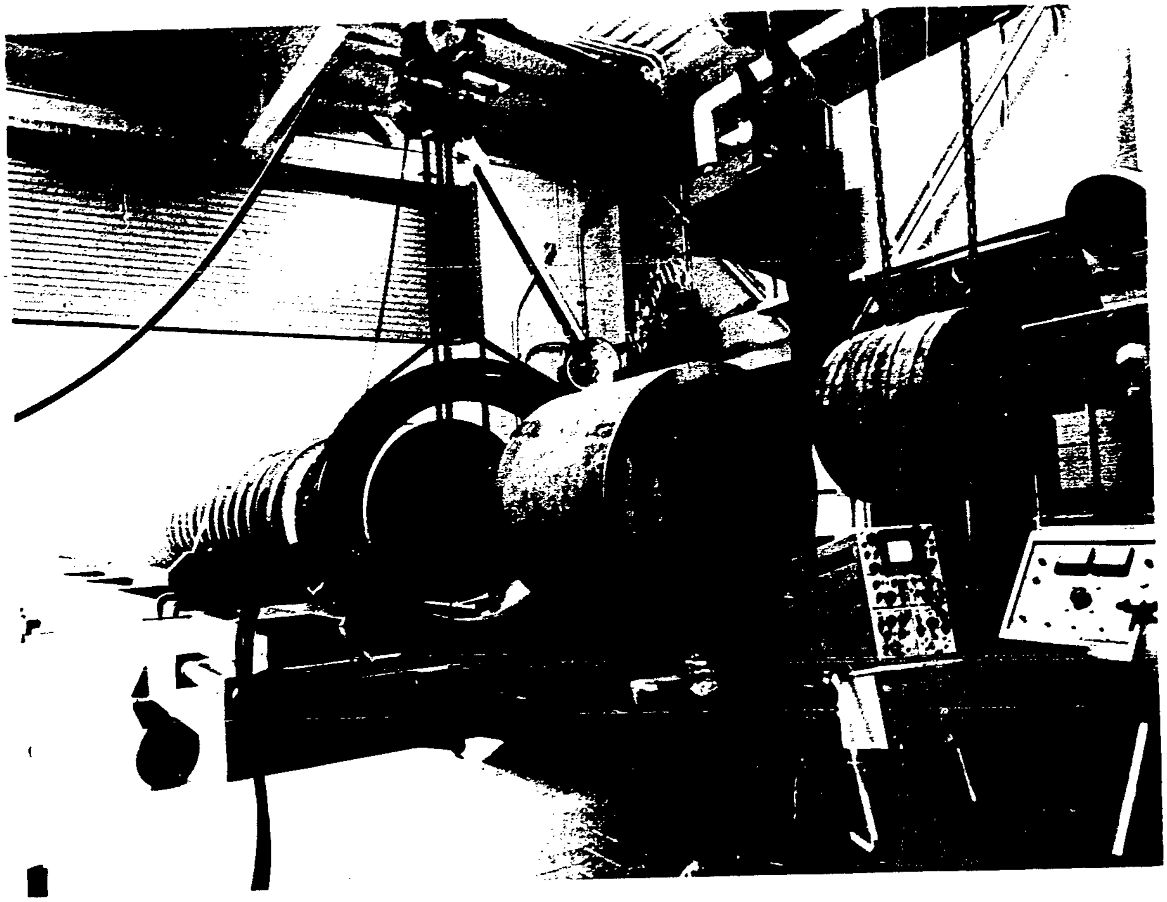


FIGURE 14. MAGNETOMOTIVE COIL FOR PRECISION SIZING LOX TUNNELS

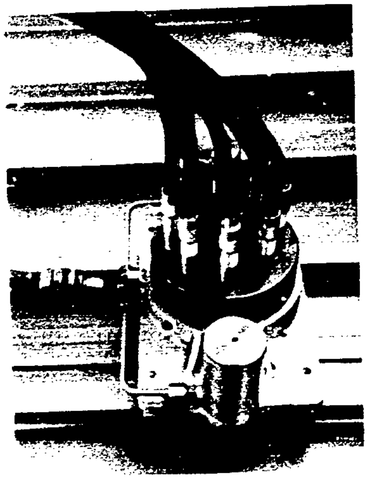


FIGURE 15. PNEUMATICALLY CLAMPED MAGNETOMOTIVE HAMMER

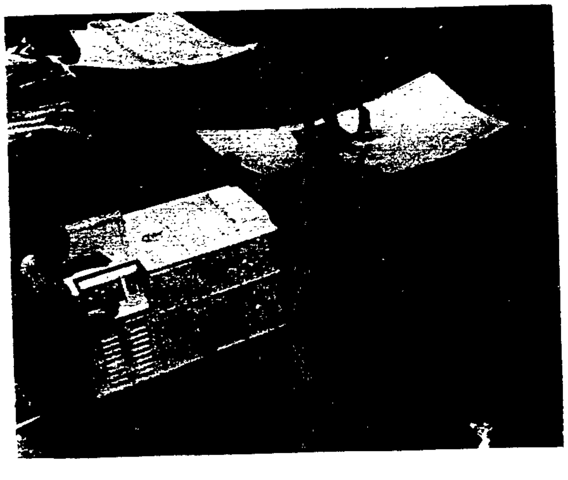


FIGURE 16. HAND-HELD MAGNETOMOTIVE HAMMER

the Saturn V (approximately 44 gore segments have been saved, up to May 1965). Similar prototype systems have been provided to MSFC prime contractors. They are being used for various purposes at Boeing's Michoud plant, North American's Seal Beach plant, and Douglas' Santa Monica plant. Boeing's Seattle plant will receive the next unit when it is completed. The new development data and results obtained at the various locations will be coordinated by MSFC.

G. DISTORTION REMOVAL FROM FINISHED SATURN BULKHEAD

Distortions of unprecedented magnitude have resulted from welding work on the very heavy sections in Saturn V. This is a serious problem because it gives rise to unknown stress conditions in the final configuration. Use of the magnetomotive hammer to correct these distortions has been very successful. Figure 17 shows precision-controlled sizing in operation on a Saturn V bulkhead. In one case, MSFC sent a crew to Michoud to demonstrate the technique on an early S-IC bulkhead so that now the Michoud plant itself can handle these problems.

H. TOOLS UNDER DEVELOPMENT AT MSFC

Manufacturing Engineering Laboratory also is developing and testing a wide variety of magnetic-field tools for potential applications to fastening, swaging, flaring, blanking, sizing, coining, compacting of metallurgical powders, etc. Some of the diagnostic apparatus and measuring techniques are second to none, so that MSFC in many respects is doing pioneer work in pulse power systems and magnetic field tools, and in their applications. Some of the tools and systems under development in the Manufacturing Engineering Laboratory are illustrated in Figure 18. In addition, Manufacturing Engineering Laboratory soon will have the largest known portable pulse power system. This is a 240 000-joule, completely portable system which will power lasers and large magnetic-field tools such as the tunnel-constricting coil.

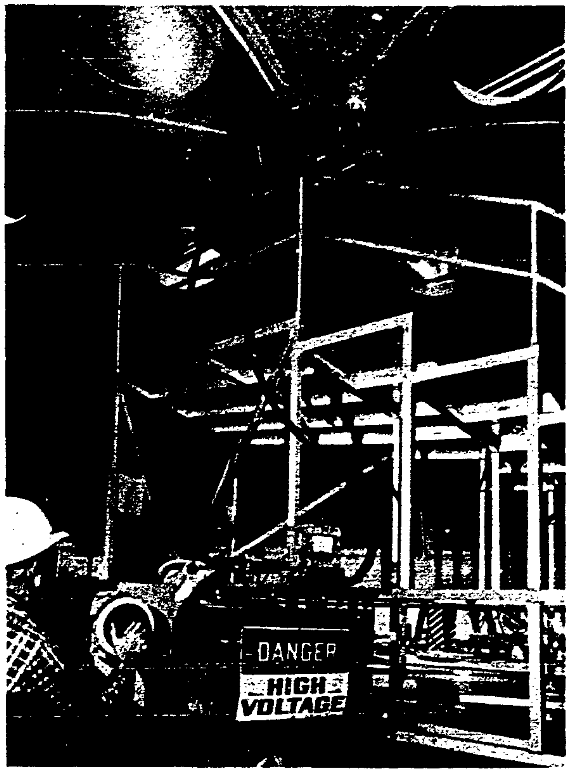


FIGURE 17. PRECISION CONTROLLED SIZING IN OPERATION ON A SATURN V BULKHEAD

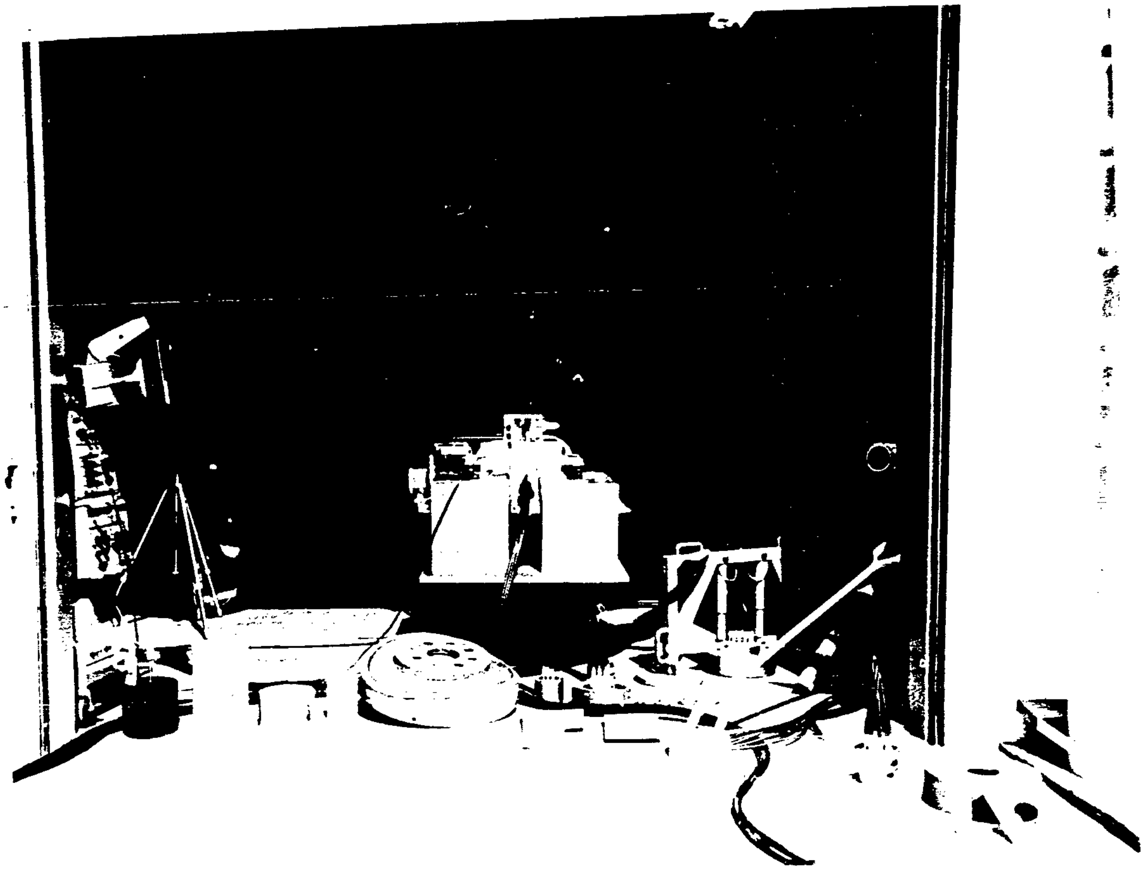


FIGURE 18. TOOLS AND SYSTEMS UNDER DEVELOPMENT IN MANUFACTURING ENGINEERING LABORATORY

APPROVAL

RESEARCH ACHIEVEMENTS REVIEW SERIES NO. 8

By H. F. Wuenscher, James R. Williams, Gordon Parks and R. J. Schwinghamer

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

for Hans F. Wuenscher

WERNER R. KUERS
Director, Manufacturing Engineering Laboratory

DISTRIBUTION

MSFC INTERNAL

DIR	1
DEP-T	1
DEP-A	1
AST-P	1
CC	1
CC-P	1
LR	1
MA-S	1
PA	2
E-DIR	6
F&D-CH	1
R-DIR	3
R-S	1
R-TS	1
R-AS	5
R-AERO (Through Branch Level)	30
R-AERO-T	9
R-ASTR	25
R-EO-R (Reserve)	50
R-COMP (Through Branch Level)	10
R-COMP-T	5
R-ME (Through Branch Level)	21
R-RP (Through Branch Level)	8
R-P&VE (Through Branch Level)	79
R-QUAL (Through Branch Level)	26
R-QUAL-T	8
R-TEST (Through Branch Level)	12

DISTRIBUTION (Continued)

MSFC INTERNAL (Cont'd)

LVO	2
I-DIR	1
I-I/IB-MGR (Through Branch Level)	10
I-V-MGR (Through Branch Level)	10
I-E-MGR	3
I-MICH-MGR	20
I-MT-MGR	2
MS-T	25
MS-IP	2
MS-IL	8
MS-I, Daniel Wise	1
Air Force Space Systems Division Huntsville, Alabama	1

NASA HEADQUARTERS

Dr. Mac C. Adams, Code R, Washington, D. C.	1
Mr. Milton B. Ames, Jr., Code RV, Washington, D. C.	1
Mr. Walter Beckwith, Code MTP, Washington, D. C.	1
Dr. Raymond L. Bisplinghoff, Code A, Washington, D. C.	1
Mr. Edmond C. Buckley, Code T, Washington, D. C.	1
Mr. Oliver Bungardner, Code MLT, Washington, D. C.	1
Mr. Roland H. Chase, Code RET, Washington, D. C.	1
Mr. Fred J. DeMeritte, Code RV-1, Washington, D. C.	1
Mr. Robert W. Dunning, Code RBA, Washington, D. C.	1
Dr. James B. Edson, Code R-1, Washington, D. C.	1
Mr. Albert J. Evans, Code RA, Washington, D. C.	1
Mr. Harold B. Finger, Code RN, Washington, D. C.	1
Mr. W. Foster, Code SM, Washington, D. C.	1
Mr. Robert Freitag, Code MC, Washington, D. C.	1
Mr. Edward Z. Gray, Code MT, Washington, D. C.	1
Dr. John Holloway, Code SC, Washington, D. C.	1
Maj. Gen. David M. Jones, Code MD-P, Washington, D. C.	1
Dr. Walton L. Jones, Code RB, Washington, D. C.	1
Dr. Hermann H. Kurzweg, Code RR, Washington, D. C.	1
Mr. William E. Lilly, Code MP, Washington, D. C.	1
Dr. Douglas R. Lord, Code MTS, Washington, D. C.	1
Mr. Ivan Mason, Code MAT, Washington, D. C.	1
Dr. George E. Mueller, Code M, Washington, D. C.	1

DISTRIBUTION (Continued)

NASA HEADQUARTERS (Cont'd)

Mr. Joseph L. Murphy, Code KR, Washington, D. C.	1
Mr. Boyd C. Myers, Code RD, Washington, D. C.	1
Dr. J. Naugle, Code SG, Washington, D. C.	1
Dr. Homer E. Newell, Code S, Washington, D. C.	1
Mr. E. O. Pearson, Jr., Code RV-1, Washington, D. C.	1
Maj. Gen. Samuel C. Phillips, Code MA, Washington, D. C.	1
Mr. Maurice J. Raffersperger, Code MTE, Washington, D. C.	1
Mr. Melvin G. Rosche, Code RV-2, Washington, D. C.	1
Mr. Charles T. D'Aiutolo, Code RV-1, Washington, D. C.	1
Mr. J. Warren Keller, Code RV-1, Washington, D. C.	1
Mr. J. L. Sloop, Code RC, Washington, D. C.	1
Mr. S. M. Smolensky, Code MCD, Washington, D. C.	1
Mr. Frank J. Sullivan, Code RE, Washington, D. C.	1
Mr. William B. Taylor, Code MT, Washington, D. C	1
Dr. M. Tepper, Code SF, Washington, D. C.	1
Mr. Adelbert Tischler, Code RP, Washington, D. C.	1
Mr. Theofolus Tsacoumis, Code RET, Washington, D. C.	1
Mr. Gene A. Vacca, Code REI, Washington, D. C.	1
Dr. John M. Walker, Code RET, Washington, D. C.	1

CENTERS

Mr. H. Julian Allen, Director NASA, Ames Research Center Moffett Field, California 94035	2
Dr. Kurt H. Debus, Director NASA, John F. Kennedy Space Center Kennedy Space Center, Florida 32899	2
Mr. Paul F. Bikle, Director NASA, Flight Research Center P. O. Box 273 Edwards, California 93523	2
Dr. John Clark, Acting Director NASA, Goddard Space Flight Center Greenbelt, Maryland 20771	1
Dr. William H. Pickering, Director NASA, Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103	2
Dr. Floyd L. Thompson, Director NASA, Langley Research Center Langley Station Hampton, Virginia 23365	2

DISTRIBUTION (Continued)

CENTERS (Cont'd)

Dr. Abe Silverstein, Director
NASA, Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135 2

Mr. Warren Gillespie
Code EA 5
NASA, Manned Spacecraft Center
Houston, Texas 77001 15

Mr. J. P. Claybourne, EDV-4
Chief, Future Studies Office
NASA, John F. Kennedy Space Center
Kennedy Space Center, Florida 32899 1

Dr. Winston E. Kock
NASA, Electronics Research Center
575 Technology Square
Cambridge, Massachusetts 02139 2

Mr. A. R. Lawrence
Management Analysis
NASA, Electronics Research Center
575 Technology Square
Cambridge, Massachusetts 02139 25

Mr. John Boyd, Technical Assistant
Office of Assistant Director for Astronautics
NASA, Ames Research Center
Moffett Field, California 94035 1

Mr. Chesley H. Looney, Jr., Ass't Chief
Advanced Development Division
NASA, Goddard Space Flight Center
Greenbelt, Maryland 20771 1

Mr. James F. Connors, Chief
Office of Research Plans and Programs
NASA, Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135 1

Mr. James E. Calkins
Office of Research and Advanced Development
NASA, Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103 1

Mr. A. R. Raffaelli
PR-2
NASA, John F. Kennedy Space Center
Kennedy Space Center, Florida 32899 1

DISTRIBUTION (Continued)

CENTERS (Cont'd)

Dr. A. H. Knothe
Code TEC
NASA, John F. Kennedy Space Center 1
Kennedy Space Center, Florida 32899

Mr. Robert Hinckley
NASA, Electronics Research Center
Room 323 B
575 Main Street 1
Cambridge, Massachusetts 02139

Dr. William G. Melbourne
Mail Stop 180-300
Jet Propulsion Laboratory
4800 Oak Grove Drive 1
Pasadena, California 91103

Scientific and Technical Information Facility
Attn: NASA Rep. (S-AK/ RKT)
P. O. Box 33 25
College Park, Maryland 20740

Mr. H. M. Drake, Chief
Advanced Planning Office
NASA, Flight Research Center
Edwards Air Force Base 1
Edwards, California 93523

DEPARTMENT OF DEFENSE

Dr. William W. Carter
Chief Scientist
U. S. Army Missile Command
Bldg. 5250 1
Redstone Arsenal, Alabama

Mr. John McDaniel
Technical Director
Research and Development Directorate
U. S. Army Missile Command
Bldg. 4505 12
Redstone Arsenal, Alabama

Lt. M. V. Vasilik
Arnold Air Force Base 30
Tullahoma, Tennessee 37389

DISTRIBUTION (Continued)

CONTRACTORS

The Boeing Company
Attn: Mr. John Pehrson
Huntsville Industrial Center
Huntsville, Alabama 5

Brown Engineering Company, Inc.
Mail Stop 5
300 Sparkman Drive, NW
Huntsville, Alabama 5

Chrysler Corporation
Attn: Mr. Howard Blood
1312 Meridian, North
Huntsville, Alabama 5

Douglas Aircraft
Holiday Office Center
Huntsville, Alabama 5

General Electric Company
Holiday Office Center
Huntsville, Alabama 5

Mr. Robert A. Hardesty
General Electric Company
Ordnance Department
100 Plastics Avenue
Room 1040
Pittsfield, Massachusetts 01201 5

Hayes International Corporation
204 Oakwood Avenue, NE
Huntsville, Alabama 5

IBM Corporation
150 Sparkman Drive, NW
Huntsville, Alabama 5

Lockheed Aircraft Corporation
Holiday Office Center
Huntsville, Alabama 5

North American Aviation, Inc.
Holiday Office Center
Huntsville, Alabama 5

Northrop Corporation
Holiday Office Center
Huntsville, Alabama 5

Mr. W. G. Calder
General Electric Co.
Suite 13
Holiday Office Center 1
Huntsville, Alabama

DISTRIBUTION (Continued)

CONTRACTORS (Cont'd)

Sperry Rand Corporation
8110 Memorial Parkway, SW 5
Huntsville, Alabama

Space Craft, Incorporated
8620 Memorial Parkway, SW 1
Huntsville, Alabama

Spaco, Incorporated
3022 University Drive, NW 5
Huntsville, Alabama

University of Alabama
4701 University Avenue, NW 5
Huntsville, Alabama

Vitro Corporation of America
Holiday Office Center 5
Huntsville, Alabama

Wyle Laboratories
Highway 20, West 5
Huntsville, Alabama

Mr. Robert A. Hardesty
General Electric Company
Ordinance Department 1
100 Plastics Avenue
Room 1040
Pittsfield, Massachusetts 01201

UNIVERSITIES AND COLLEGES

Alabama A& M College 1
Huntsville, Alabama

University of Alabama 1
Tuscaloosa, Alabama

Dr. Clyde Hull Cantrell, Director
Ralph Brown Draughon Library
Auburn University 4
Auburn, Alabama

University of California (UCLA) 1
Los Angeles, California

Carnegie Institute of Technology 1
Pittsburgh, Pennsylvania

Case Institute of Technology 1
Cleveland, Ohio

Clemson University
Celmson, South Carolina 1
Attn: Mr. J. W. Gourlay

DISTRIBUTION (Continued)

UNIVERSITIES AND COLLEGES (Cont'd)

Mr. S. G. Nicholas
Director of Engineering Research
Clemson University
Clemson, South Carolina 1

Columbia University
New York, New York 10027 1

Librarian
Columbia University
Nevis Laboratories
Irvington, New York 10533 1

University of Denver
Denver, Colorado 1

Director's Office
Denver Research Institute
University of Denver
Denver, Colorado 1

Department of Nuclear Engineering Sciences
University of Florida
Gainesville, Florida 32603 1

Mrs. J. Henley Crosland
Director, Libraries
Georgia Institute of Technology
Atlanta, Georgia 9

University of Georgia
Athens, Georgia 1

Louisiana State University
Baton Rouge, Louisiana 1

Massachusetts Institute of Technology
Cambridge, Massachusetts 1

University of Michigan
Ann Arbor, Michigan 1

Mississippi State University
State College, Mississippi 1

University of Mississippi
University, Mississippi 1

University of North Carolina
Chapel Hill, North Carolina 1

DISTRIBUTION (Continued)

UNIVERSITIES AND COLLEGES (Cont'd)

Northeast Louisiana College Monroe, Louisiana	1
Ohio State University Columbus, Ohio	1
Ohio University Athens, Ohio	1
Oklahoma State University Stillwater, Oklahoma	1
University of Pittsburgh Pittsburgh, Pennsylvania	1
Princeton University Princeton, New Jersey	1
Library School of Electrical Engineering Purdue University Lafayette, Indiana	1
Rev. R. J. Henle, S. J. Vice President for Academic Matters and Research Director Saint Louis Univeristy 221 N. Grand Blvd. St. Louis, Missouri	2
Stanford University Palo Alto, California	1
Syracuse University Syracuse, New York	1
University of Tennessee Knoxville, Tennessee	1
Cushing Memorial Library Texas A&M University College Station, Texas	1
Mr. Harry E. Whitmore, Head Space Technology Division Texas A&M University College Station, Texas	2
University of Texas Austin, Texas	1

DISTRIBUTION (Concluded)

UNIVERSITIES AND COLLEGES (Cont'd)

Science Librarian
Tulane University Library
New Orleans, Louisiana 70118 1

The Joint University Libraries
419-21st Avenue, South
Nashville, Tennessee 1

Science Library
Vanderbilt University
Box 1521, Station B
Nashville, Tennessee 1

Virginia Polytechnic Institute
Blacksburg, Virginia 1

Washington State
Pullman, Washington 1

Mr. H. W. Hsu
Associate Professor of Chemical Engineering
University of Tennessee
Knoxville, Tennessee 37916 1

Professor F. N. Peebles
Department of Engineering Mechanics
University of Tennessee
Knoxville, Tennessee 1

Mr. W. Byron Long
Director of Special Projects 1
Mississippi Research and Development Center
Jackson, Mississippi

Engineering Library
University of Arkansas 1
Fayetteville, Arkansas

UNITS OF MEASURE

In a prepared statement presented on August 5, 1965, to the U. S. House of Representatives Science and Astronautics Committee (chaired by George P. Miller of California), the position of the National Aeronautics and Space Administration on Units of Measure was stated by Dr. Alfred J. Eggers, Deputy Associate Administrator, Office of Advanced Research and Technology:

"In January of this year NASA directed that the international system of units should be considered the preferred system of units, and should be employed by the research centers as the primary system in all reports and publications of a technical nature, except where such use would reduce the usefulness of the report to the primary recipients. During the conversion period the use of customary units in parentheses following the SI units is permissible, but the parenthetical usage of conventional units will be discontinued as soon as it is judged that the normal users of the reports would not be particularly inconvenienced by the exclusive use of SI units."

The International System of Units (SI Units) has been adopted by the U. S. National Bureau of Standards (see NBS Technical News Bulletin, Vol. 48, No. 4, April 1964).

The International System of Units is defined in NASA SP-7012, "The International System of Units, Physical Constants, and Conversion Factors," which is available from the U. S. Government Printing Office, Washington, D. C. 20402.

SI Units are used preferentially in this series of research reports in accordance with NASA policy and following the practice of the National Bureau of Standards.