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PERMANENT TUBE JOINT TECHNOLOGY

INTERIM REPORT NO. 1

W. D. Padian, R. Rohrberg, P. Sidbeck, et al

Technical Report AFRPL-TR-66-225

September 1966

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AIR FORCE ROCKET PROPULSION LABORATORY

RESEARCH AND TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

EDWARDS, CALIFORNIA

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PERMANENT TUBE JOINT TECHNOLOGY

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W. D. Padian, R. Rohrberg, P. Sidbeck, et al
North American Aviation, Inc.
Los Angeles Division

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FOREWORD

This interim report was prepared by North American Aviation, Inc., Los Angeles Division under Air Force Contract No. AF 04(611)-11203. The contract is sponsored by the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, Edwards, California. It is established under Air Force Program Structure No. 750G, AFSC Project No. 6753, AFSC Task No. 675304, with Captain John L. Feldman of the Air Force Rocket Propulsion Laboratory as the USAF Project Engineer.

This report constitutes the first report prepared under the subject contract, describing results of research conducted during the period 1 December 1965 through 30 June 1966.

The subject program is being conducted by the Materials and Productibility Department of the Los Angeles Division of North American Aviation Inc., Los Angeles, California. Work described in this report was performed under the direction of Mr. W. D. Padian, Program Manager. Personnel participating in the research described and assisting in preparation of the report include R. Rohrberg, Design Specialist; P. Sidbeck and J. Lambase, Senior Research Engineers-Welding; D. Weinstein, Senior Research Engineer-Electrical Engineering; and J. Riordan, Research Specialist. The performance of the program is under the general direction of Mr. N. Klimmek, Manager, Materials and Producibility Department, and Mr. R. Robelotto, Supervisor, Welding.

Some items compared in this report were commercial items which were not specifically developed or manufactured to meet Government specification, to withstand the tests to which they were subjected, or to operate as applied during research studies. Any failure to meet the objectives of this study is no reflection on the commercial items or the manufacturer discussed herein.

This report is filed in the contractor's file as NAA Report NA-66-836.

The subject report was prepared for information purposes only, and is subject to change or revision. Publication does not constitute Air Force approval of reported results or conclusions.

John L. Feldman
Captain, USAF
Project Engineer

ABSTRACT

A design evaluation study was conducted to establish requisites for tube-weld tool and electrical equipment design. Design criteria were formulated and operating parameters were delineated, based on tests performed to determine power and performance requirements. Clamping, and driving forces, milling cutter loads, tracking, and driving power requirements were established. A weld current servo-control unit to be incorporated in the weld programmer was designed and evaluated. Three commercial electrical power supplies, and related equipment were used in conducting tests to determine equipment adaptibility and performance under different operating conditions. Welding studies were conducted to determine the effect of arc voltage, gap, electrode configuration, and shield gas on the weld bead, and to establish joint design requirements and welding techniques for thick wall tubing. Material studies were conducted to select candidate materials typical of advanced liquid rocket systems, for use in tests which will be conducted with present and developed tool designs. The candidate materials selected include aluminum, titanium, nickel- and iron-base alloys.

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Section I

INTRODUCTION

A basic requirement for any operational system is the continuing evaluation of its operating characteristics in order to obtain the most effective utilization of its capabilities. This end may be accomplished by increasing system operational reliability and/or performance capability along with a commensurate adjustment in total system cost. Conventional aircraft-type fittings currently being used for tubing connections in liquid rocket propulsion fluid systems have proven inadequate on the bases of leakage, weight, fatigue life and corrosion resistance. These factors result in decreased reliability and overall performance of the systems, costly maintainance, extensive hold periods during launch, and delays in accomplishing missions. These problems have led to Air Force-sponsored investigations aimed at providing new technology for making reliable, permanent and semipermanent tubing connections for liquid rocket systems. The permanent connector studies are being conducted by NAA/LAD while the semipermanent connector work is being conducted by Battelle Memorial Institute, Columbus, Ohio.

The objective of the work conducted by NAA/LAD to date has been the development of a permanent tube joint connection system based on the automatic tungsten-inert-gas welding process (TIG). Previous to this program it has been demonstrated, by qualification testing, that welded tube connections will meet rocket fluid system design requirements for a wide range of tubing materials and environments. Additional studies have resulted in the development of prototype tooling and electrical control equipment and procedures for in-place parting, machining, and welding of tubing. The tooling, equipment, and procedures have been subjected to simulated field use and have been documented in a proposed Technical Order.

The primary purpose of the present program is to complete the technology development required to accomplish all-welded permanent connections in liquid rocket systems. The program objectives are as follow:

1. Finalize the design of all tooling and associated electrical control equipment.

2. Demonstrate by fabrication and performance testing that the design objectives have been accomplished.

3. Finalize the development of tube parting, machining, and welding procedures for AISI 347 stainless steel and 6061-T6 aluminum tubing in the 1/8-to 16-inch diameter range.

4. Extend the development of welding and machining procedures to include additional stainless steel and aluminum alloys, and titanium

and nickel-base superalloy tubing in the 1/4-to 3-inch diameter range.

This report is concerned with five major areas: (1) testing and analysis of previous prototype equipment, (2) determination of final design requirements, (3) description of final design configurations and testing of breadboard systems, (4) welding studies, and (5) advanced tubing alloy evaluation and selection.

Section II

SUMMARY

This report describes the work accomplished to date on a research program being conducted to finalize development of a system of equipment and procedures designed to accomplish installation of permanent connectors in rocket fluid tubing systems. The operating characteristics of prototype tools developed under a previous contract, AF04(611)-9892, have been reviewed and required design changes have been identified. Tool sizing and finalized concepts for parting tools, in the tube size range from 1/8-to 16-inches in diameter and 0.010-to 0.500-inch in wall thickness have been prepared. It was determined that the tooling requirements could be divided into two basic areas: 1/8-to 3-inch OD range tubing with wall thickness up to 0.093-inches, and 1-to 16-inch OD range tubing with wall thickness in the 0.050-to 0.500-inch range.

The finalized tooling concept for the 1/8-to 3-inch OD range thin wall tubing is predicated on the orbit arc enclosed tool approach, and as such, will provide facility for machining and welding tube sizes which utilize in-place filler material. The finalized tooling concept for the 1-to 16-inch OD range tool is predicated on the use of a series of carriages, based on diameter range, utilizing separate and interchangeable welding and machining heads which can be adapted to any of the carriages.

Methods of improving system performance from the electrical standpoint have been investigated and included review of the existing weld variable programmer performance, evaluation and testing of commercially available welding power supplies, and evaluation and selection of motors for the finalized tools. Initial evaluation of a breadboard weld current-servo control has proven successful, and following further testing, will be incorporated in the final weld variable programmer design. This unit will simplify operation of the weld current programmer and will make the unit self-regulating. Automatic arc voltage control was determined to be unsatisfactory for this particular application and will not be pursued further.

A system for slaving the wire feed to the arc voltage has been devised which permits filler pass buildup within 0.020-inch. A welding power supply considered to be acceptable for this program has been selected and purchased.

Welding studies conducted on aluminum and stainless steel tubing have indicated the effect of welding variables including current, inert gas shielding type, and electrode configuration on weld bead contour and penetration. Development of final joint designs for multipass welds in thick wall aluminum tubing was initiated, and included evaluation of Vee, U, and modified U grooves. Techniques were developed which permit satisfactory root and filler passes.

An investigation of aluminum, iron, nickel, and titanium-base tubing for use in advanced liquid rocket tubing systems was conducted. The following tubing alloys were selected for further machining and welding tests: 2219 aluminum, 6Al-4V titanium, commercially pure titanium, Inconel 718 nickel base, and 21Cr-6Mo-9Mn iron base.

Section III

DESIGN EVALUATION STUDY

OBJECTIVE

The objective of this study was to enhance fabrication capability through improved tool design. To achieve this objective, a design evaluation study was performed to establish the related design criteria. In light of the subsequent findings, the present system was evaluated for design improvements and/or redesign to fulfill program requirements.

The fundamental mechanical design requirements employed were based upon the engineering design application of welded fittings in liquid rocket propulsion systems. The design application information was based upon data received from the AFRPL, and from a study of the experience of the various North American Aviation divisions in the application of welded fittings in aerospace vehicles.

DESIGN EVALUATION SYSTEM

The system of evaluation employed on the program is known as the Total Design Concept. This method of evaluation entails consideration of four principal functions, namely: (1) Product Design Engineering, (2) Process Engineering, (3) Mechanical Design, and (4) Production Manufacturing. The focal point of these functions is called Total Design, as shown pictorially in figure 1. Viewing the requirements of the four functions from the unbiased vantage point of total design provides a natural tendency to achieve proper balance in the overall analysis for a process supporting mechanism such as the subject welding tools.

In the total design concept, the requirements from each of the four functions are analyzed and modified by a twofold evaluation involving: (1) an analysis of the function itself, and (2) an analysis of each function with respect to the other functions. This step ensures that the proper perspective is maintained in achievement of total design, precluding the possibility of an imbalance which may have undue influence on design results.

Each of the four functions entails a set of requisites which are predicated by the design application. These requisites may be defined as the basic factors which must be achieved to gain any significant value from that particular function. Subsequently, it is necessary to delineate the subordinate values, or modifiers, which determine the extent to which the requisite must be met.

By compiling a list of the requisites and modifiers for each of the four functions, all pertinent factors relating to the total design concept are displayed. Delineation of all factors in this manner provides

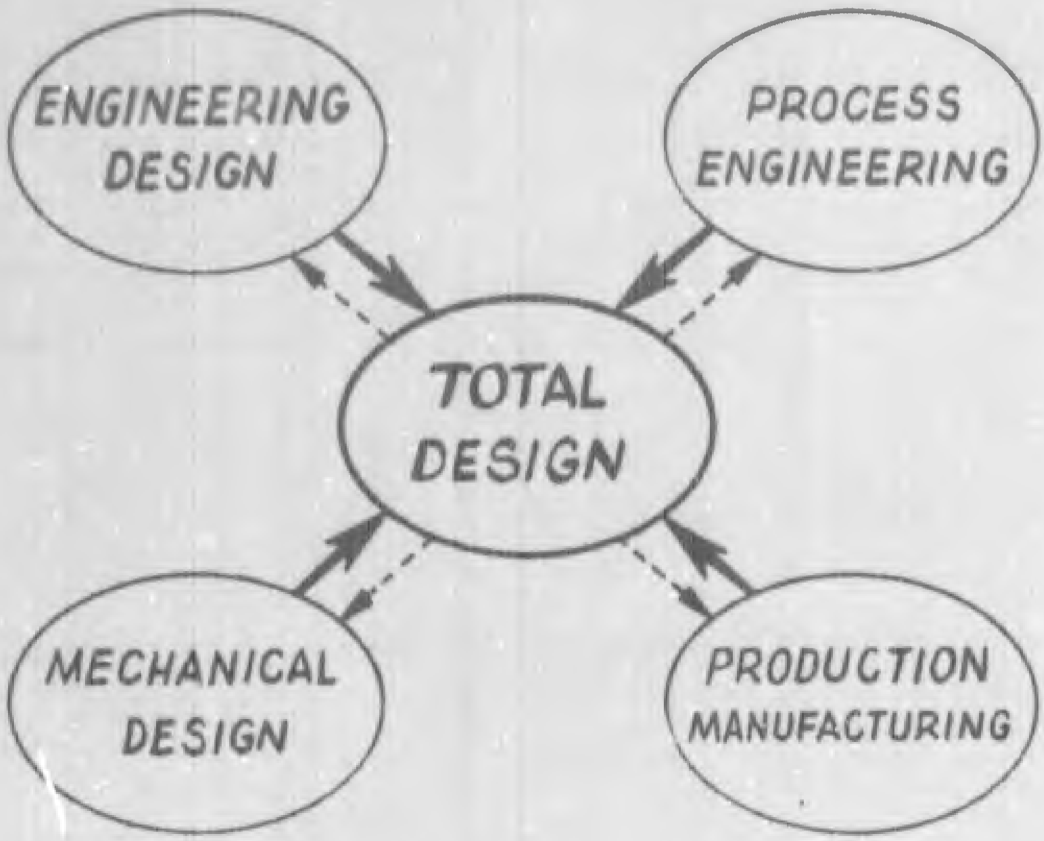


Figure 1. Sketch of the Total Design System of Evaluation Concept

the visibility necessary to achieve an internal balance in each function. By presenting the true requirements of each, compatibility of all design functions is achieved without redundancy or inherent weakness in the final design.

The Total Design Concept was utilized in evaluating the subject program requirements. The requisites and related modifiers were established for each function (Table I) to permit unbiased system evaluation. These factors were subsequently used in evaluating existing and conceptual designs to determine the total design concept.

DESIGN EVALUATION

The welding capability necessary to support the program must be based upon the engineering design application requirements. The design configuration of the weld joint is based upon the design loads, the materials, and the design function. The joints must be welded to a prescribed quality. Cleanness, line restriction, strength, and appearance factors must be considered under design quality. The welding must be performed within structural configurations which impose envelope restrictions upon the welding package, and also under certain logistical conditions such as field installations which pose various physical and environmental consideration.

The tubular materials, diameters, and wall thicknesses required for the program are tabulated in Table II. The joint designs calculated for application with these tubes are shown in figure 2.

The joint designs will require no filler material for some conditions, preplaced filler material for others, and the thicker wall thicknesses will require the addition of filler material. The joint designs, therefore, logically breakdown into thick versus thin wall configurations tempered by diametrical considerations. The weld joint will require some physical means for preparing the edges for welding, therefore a machining capability will be required.

The design evaluation suggests that the types of mechanisms required for the program may be broken down as shown in Table III. The required capability for welding, with the accompanying ability to prepare the joint for welding, may be graphically described as shown in figure 3.

The tubular welding equipment should permit the Design Engineer to employ any of the joint designs shown in figure 2. The Design Engineer will choose the proper design based upon the structural loads, the material, the quality and the design function for the particular joint under consideration. Joint design, therefore, will be considered a production design function; the ability to produce these joint designs under field conditions is the basic requirement for this program.

Table I

REQUISITES FOR TOTAL DESIGN CONCEPT FUNCTIONS

Function	Requisites	Modifiers
Engineering Design	Joint Design	Design Loads Materials Design Function
	Design Quality	Cleanness Line Restriction Strength Appearance
	Fabrication Envelope	Design Configuration Structure
	Fabrication Logistics	Fixturing Requirements Safety Assembly Procedure Field Application
Production Fabrication	Performance	Operating Time Handling Ease Set Up Time Quality
	Application	Weight Flexibility Envelope Safety
	Maintenance	Service Life Repair Procurement Supporting Tools
Total Design	System Integration	Engineering Design Process Engineering Mechanical Design Production Fabrication
	Value	Standardization Cost Producibility Esthetics

Table I (Continued)

Function	Requisites	Modifers
	Welding Specification	
Process Engineering Requirements	Electrical Power	Amperage Voltage Cooling Insulation
	Inert Gas	EnvelopeControl Flow Rate Adjustments
	Arc Control (Mechanical)	Oscillation Arc Voltage Tracking Electrode Reqmts Adjustments
	Drive System	Speed Control Adjustments
	Filler Metal	Wire Diameter Feed Rate Controls
	Machining Specification	
	Drive System	Feed Controls Adjustments
	Cutter Control	Speed Tracking Cut Depth Joint Design Diameter Tooth Design
Mechanical Design	Structural Geometry	Fabrication Methods Materials Loads Configuration Comparison Commercial Hardware Envelope Stability

Table I (Continued)

Function	Requisites	Modifiers
Mechanical Design	Servo Systems Principle Auxiliary	Loads Torque Horse Power Speed Drive Methods
	Welding Power System	Amperage Voltage Inert Gas Insulation Safety

Table II

ALUMINUM AND STAINLESS STEEL TUBE SIZES

Outside Diameter	6061-T6 Aluminum (In. Wall Thk.)	Type 347 SS (In. Wall Thk.)
1/8	NA *	.010 .020
1/4	.016 .028 .035	.012 .020 .035
1/2	.020 .035 NA	.010 .020 .083
1	.025 .065 .083 .125 .250	.010 .035 .065 .188 .250
3	.049 .083 .125 .188 .250	.035 .065 .250 NA NA
4	.125 .375	.375
6	.250	.500
8	.060	NA
8	NA	.250
12	NA	.060
16	.125 .250	.125 .250

* Not Applicable

Table III

TYPES OF MECHANISMS

Function	Tube Diameter (In. OD)	Wall Thickness (In.)
Welding		
Thin Wall	1/8 through 3	.010 through .093
Thick Wall	1 through 16	.100 through Up
	*(Over 3 in.)	*(.050 through .093)
Edge Preparation		
Slitting		
Forming	1/8 through 3	.040 (Stl.) .065 (Al.)
Sizing		
Milling Plus		.035 (Stl.)
Slitting Adaptor	1 through 16	.050 (Al.)

* For tube diameters greater than 3-inch, the number of tube sizes with wall thicknesses less than .093 inch is not sufficient to warrant a separate enclosed tool. For the specific tube sizes to be studied under the contract it is believed that the thick wall welding tool will prove adequate.

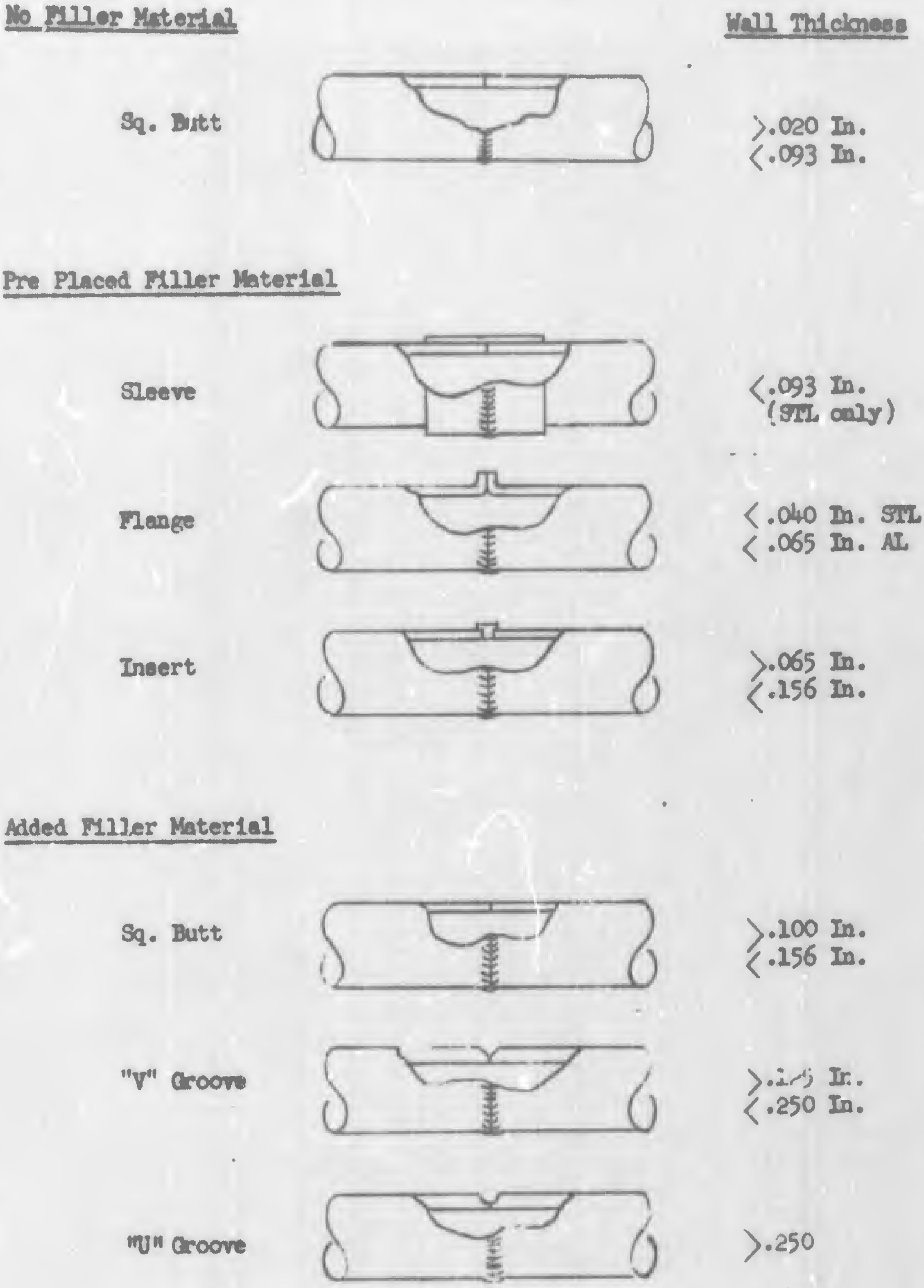


Figure 2. Tube Weld Joint Design

NOTE: THIS CHART IS BASED UPON THE ENGINEERING DESIGN APPLICATION REQUIREMENTS

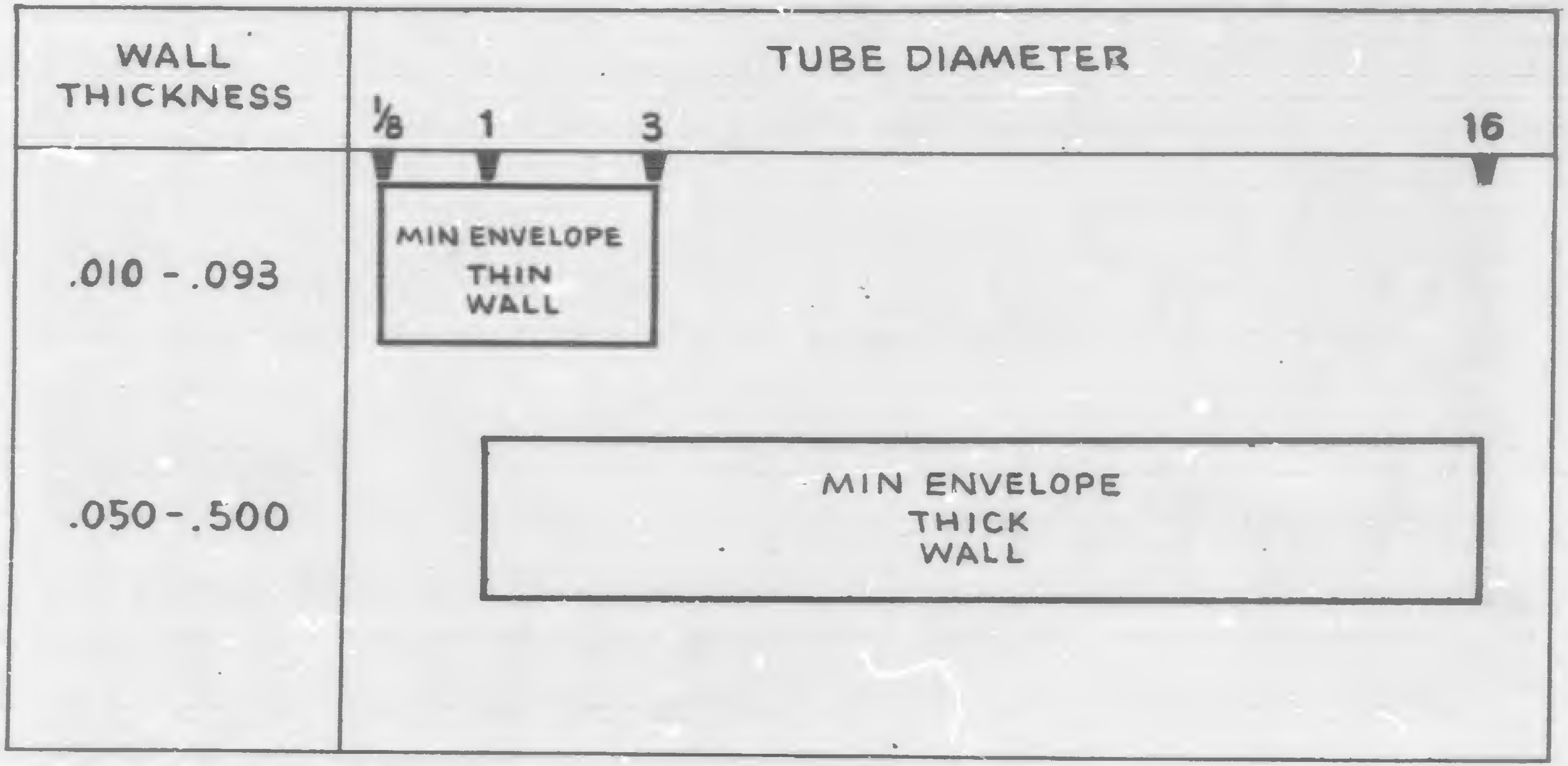


Figure 3. Tube Weld and Weld Preparation System Requirements

The fabrication envelope which appears to be most conducive to fulfill the design requirements for thick wall applications is shown in figure 4. This envelope will be employed from 1-inch through 16-inch

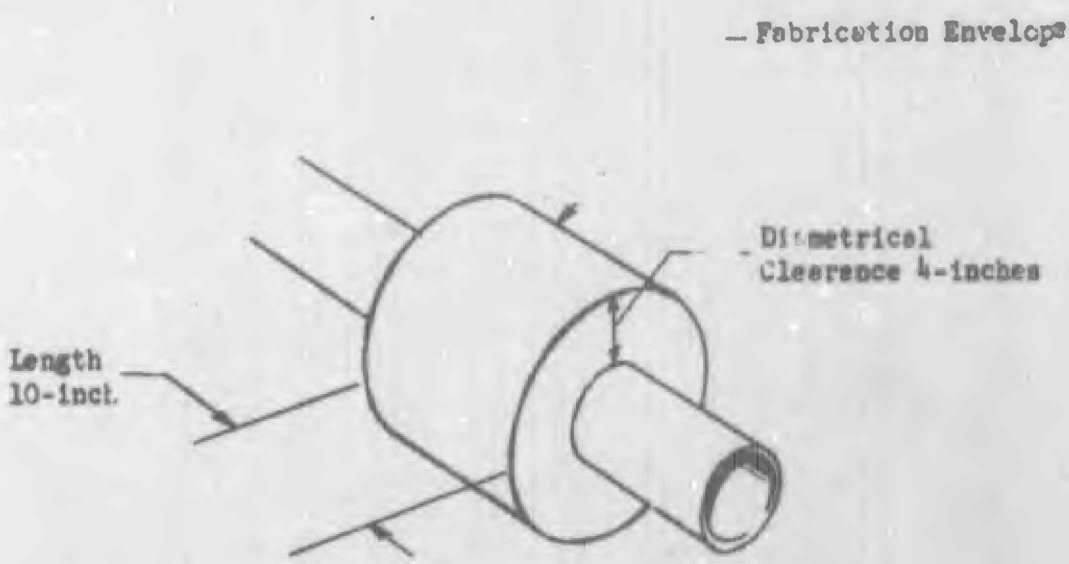


Figure 4. Envelope Requirements
Thick Wall Tubing
1-inch Through 16-inch Diameters

in diameter tubing. The commercially available orbit arc welding head envelope will be used for the thin wall small diameter configurations. Logistics will require that the mechanical design of the equipment have the following capability.

1. Perform in all welding positions on the bench or in the field.

2. Facility to perform at distances up to 100 feet from the power supply.

3. Operate in the field when exposed to various weather conditions.

4. Safety features for both operator and fellow workmen.

5. Portable.

Aside from design engineering, the requirements for Process, Mechanical Design, and Production Fabrication are all handled according to the total design concept. Each function being weighed against the other, to achieve an overall balance.

DESIGN EVALUATION TESTING

Certain physical tests were necessary to establish basic mechanical requirements such as loads, temperatures, and speeds. These tests were conducted on a limited basis to establish working values. These tests and related results are described in the following paragraphs.

TRACKING CONCENTRICITY

The ability of the rotating tool to position the welding electrode and the milling cutter accurately to the tube surface is critical. The platform with cam rollers used in the test is illustrated in figure 5-A. Its performance was compared with that of the chain mounted tool designed earlier in the tube welding program. The dial indicator was mounted on each of the tools and rotated around the tube. Readings were taken of maximum deflection. The chain mounted tool allowed variations in the indicator reading of as much as 0.023-inch while the platform with cam rollers held the variations to a maximum of 0.003-inch.

LONGITUDINAL DRIFT

In preparing the beveled ends of thick wall tubing and pipe for welding, a single angle milling cutter will be used. The cutter configuration will impose a longitudinal load on the milling head tending to move the head toward the end of the tube. This load has been estimated to be approximately 30 lb. To test for this effect, the setup shown in figure 5-B was used. A longitudinal load of 30 lb was applied to the platform with cam rollers as illustrated while it was rotated around the tube. Measurements, taken before and after the rotation, showed no appreciable longitudinal drift of the platform.

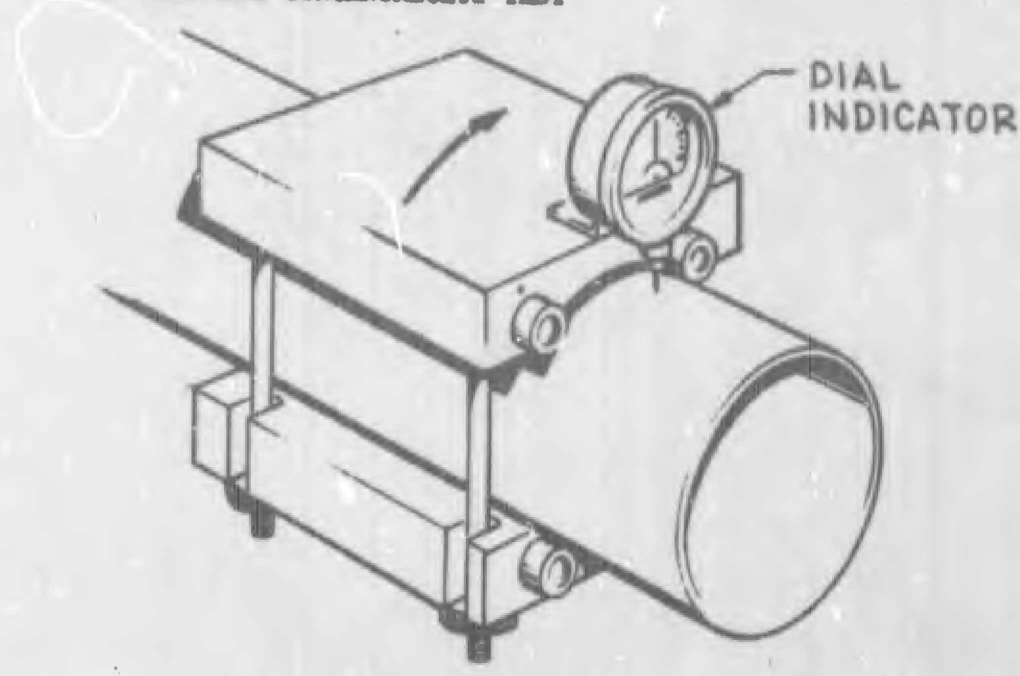
FRICTION TEST

The drive rollers must overcome a load of 300 lb to rotate the orbital carriage around a tube. To obtain adequate traction between the rollers and the tube surface, an intermediate material offering a high coefficient of friction is required. Viton, a flourinated elastomer, was chosen as a candidate material because of its high heat resistance. To determine its static coefficient of friction, the basic test shown in figure 5-C was used. A load of sufficient magnitude was applied to the spring scale, to cause the preloaded Viton patch to break static contact with the steel plate. The test results established a coefficient of friction of 0.75.

TUBE DEFLECTION TESTS

The orbital carriage design concept shows four rollers contacting the tube circumference at points approximately equally spaced. To prevent slippage, circumferentially and/or longitudinally, the rollers have to be forced against the tube surface with a 200 lb maximum load, as

A. TRACKING CONCENTRICITY TEST



B. LONGITUDINAL DRIFT TEST

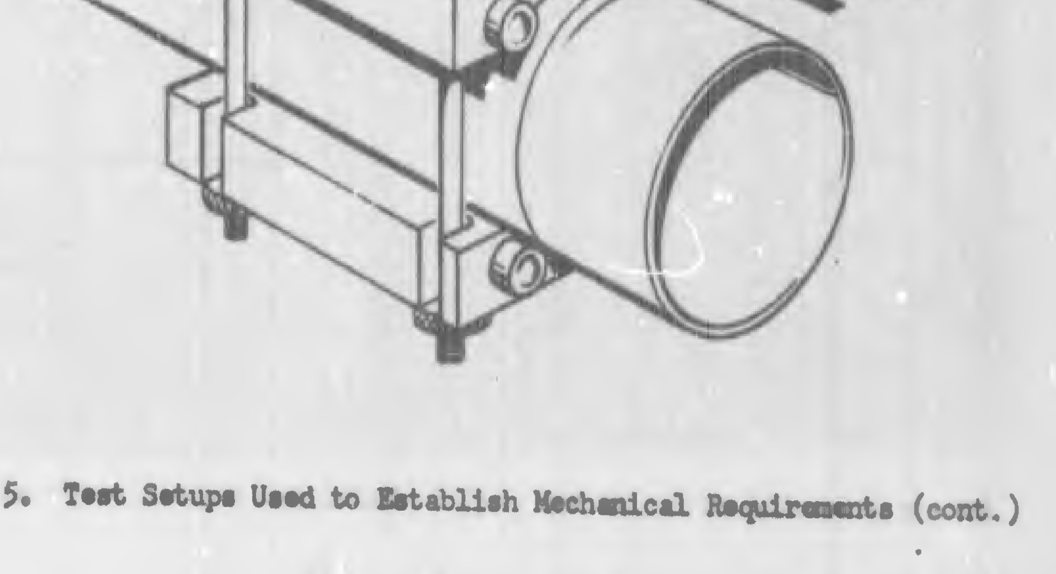
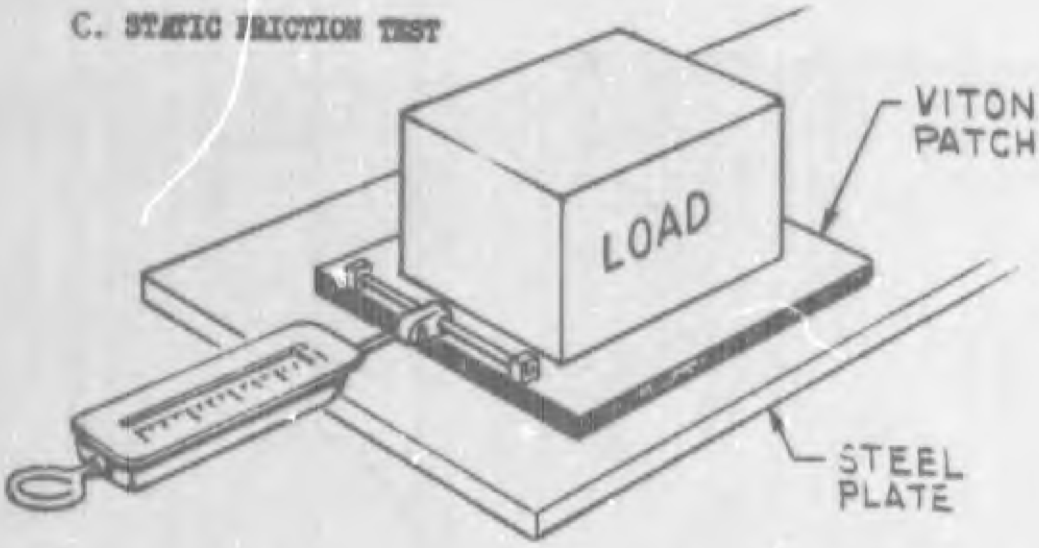


Figure 5. Test Setups Used to Establish Mechanical Requirements (cont.)

C. STATIC FRICTION TEST



D. TUBE DEFLECTION TEST

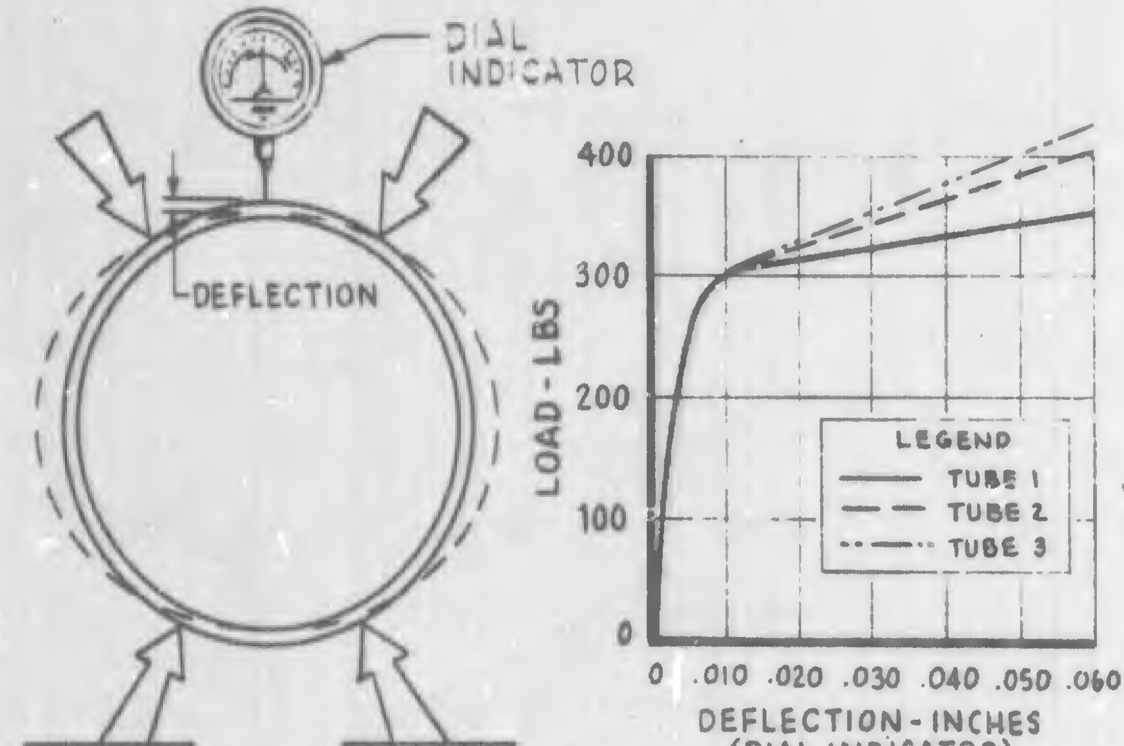


Figure 5 (cont.) Test Setups Used to Establish Mechanical Requirements determined in previous tests. The test setup illustrated in figure 5-D was used to determine if such a force would deflect the tube appreciably since the milling cutter and arc length settings may be affected by distortion of the tubing. The following three tube sizes were tested:

1. 1/8-inch wall by 16-inch diameter 6061-T6 Aluminum
2. 1/16-inch wall by 12-inch diameter Type 321 CRES
3. 1/16-inch wall by 8-inch diameter 6061-T6 Aluminum

The plotted test results indicate that a force of 200 lb will not deflect the tubes more than 0.003-inch. This is not considered to be of sufficient magnitude to affect operation of the tool.

MILLING CUTTER TORQUE TEST

The milling cutter loads required for stainless steel material will be the governing factor in determining the power requirements for the orbital drive and cutter drive systems. The power requirements were determined using the test setup shown in figure 5-E. The milling head was mounted on a cam roller platform to simulate actual operating conditions. A 3-inch diameter, 3/32-inch wide, 32 tooth slitting saw with side tooth chip clearance was operated at approximately 40 rpm, producing a cutter tooth speed of 32 fpm. The rotating cutter was set to a 1/8-inch depth of cut, and the tube rotated with the torque wrench at a speed commensurate with a chip load of 0.002-inch per tooth. An average value of 20 ft-lb was recorded on the torque wrench when performing cutting tests on a 4-inch tubular diameter. The 20 ft-lb torque results in a tangential load of 120 pounds at the tube surface. The required cutter motor horsepower is calculated as follows:

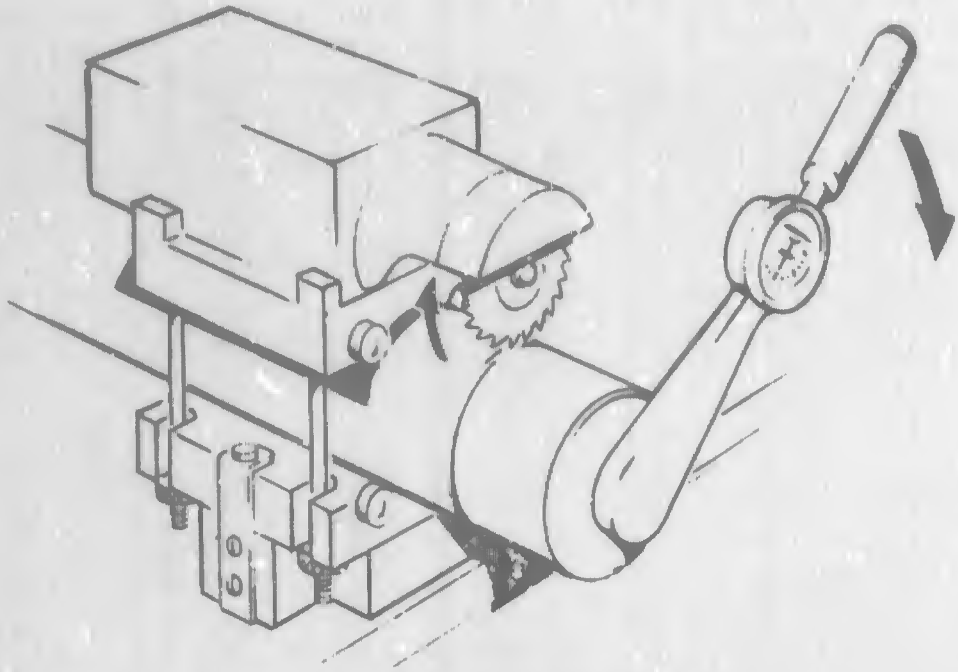
$$\text{Horsepower} = \frac{\text{Load (lb)} \times \text{Cutter Radius (ft)} \times \text{No. Revolutions per min}}{5252}$$

$$\text{Horsepower} = \frac{120 \text{ pounds} \times .125 \text{ ft} \times 40}{5252} = .114$$

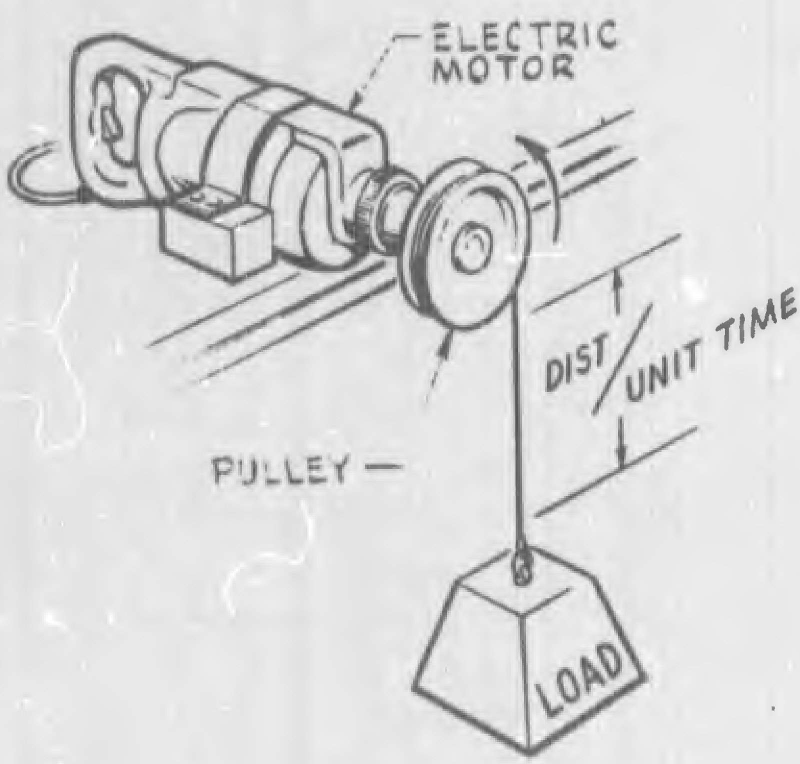
Assuming a safety factor of two, this resulted in the establishment of a 1/4 horsepower requirement.

ELECTRIC MOTOR HORSEPOWER TESTS

The milling cutter drive motor with its relatively high power requirements, coupled with its small packaging requirements, posed a major problem. It was decided to evaluate electric motors because of certain inherent problems in air motor systems, such as lack of adequate speed control, envelop dimensions, comparative inflexibility of air lines, lines, and lack of compressed air at some field sites. By measuring the time required to raise a given weight a given distance (figure 5-F), the output horsepower of the 1/2 inch electric drill motor selected was verified. A tangential load of 173 pounds applied on a 3-inch diameter pulley at 47.5 rpm produced a calculated horsepower of .196 and drew the full 5.4 ampere motor rating. Assuming 75 percent efficiency for the gearbox used to reduce the pulley rpm, a calculated horsepower of .26 would be obtained.



E. MILLING CUTTER TORQUE TEST



F. ELECTRIC MOTOR HORSEPOWER TEST

Figure 5, (cont.) Test Setups Used to Establish Mechanical Requirements

WELDING TEMPERATURE DETERMINATION

The carriage rollers are to be coated with Viton, an organic elastomer material. Viton will withstand 400°F temperatures for extended time periods and higher temperatures (600°F+) for short periods. For platform stability, the design requirements place the foreward ends of the four rollers approximately 1-inch from the tube joint centerline. The time/temperature gradient during the welding cycle on a 3-inch diameter by 1/4-inch wall aluminum tube joint was established using thermocouples. The results are shown in figure 6-A. Aluminum will present the maximum temperature conditions due to its high coefficient of thermal conductivity. The results indicate that the Viton material will be satisfactory for multipass welding.

POWER REQUIREMENTS DETERMINATION

The test data obtained from the milling cutter torque test and the Viton drive roller coating friction test were utilized to determine the orbital drive power and clamping forces required. The calculated loads are as follows:

1. Milling cutter torque: 20 ft-lb on a 4-inch diameter tube

   ∴ Tangential load produced by cutter teeth:

   $$\frac{20 \times 12}{2} = 120 \text{ lb}$$

   ∴ Tangential load with a safety factor of 2-1/2: 300 lb

2. Coefficient of friction, drive roller to tube: 0.75

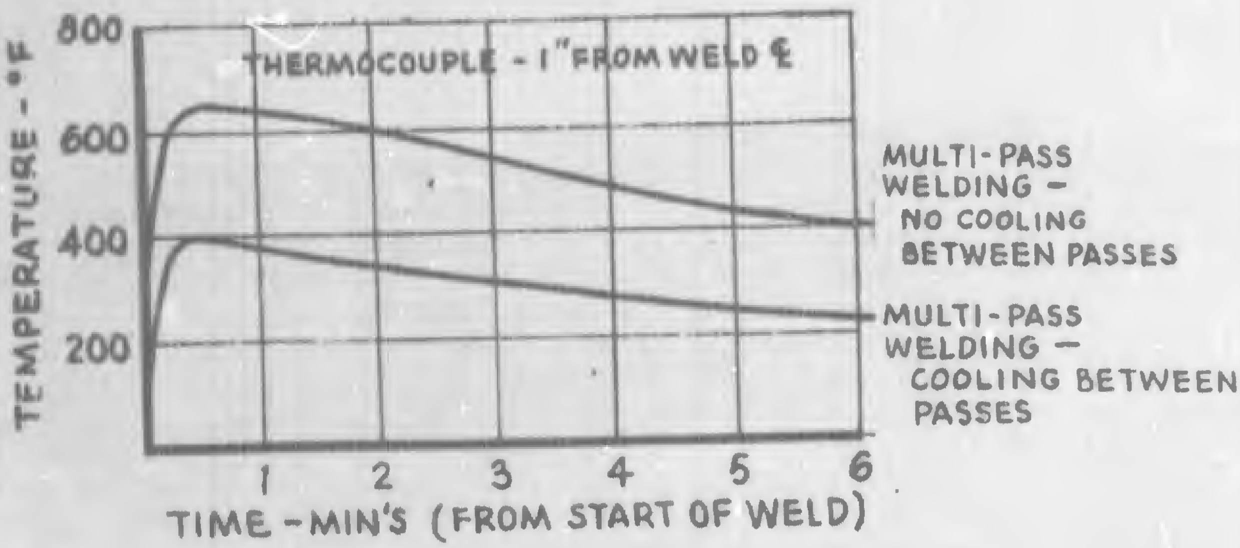
   ∴ Tractive effort requires a clamping force of 300/0.75 = 400 lb, or 200 lb per drive roller to react the milling cutter load.

Forces involved during tube slitting operations are illustrated in figure 6-B.

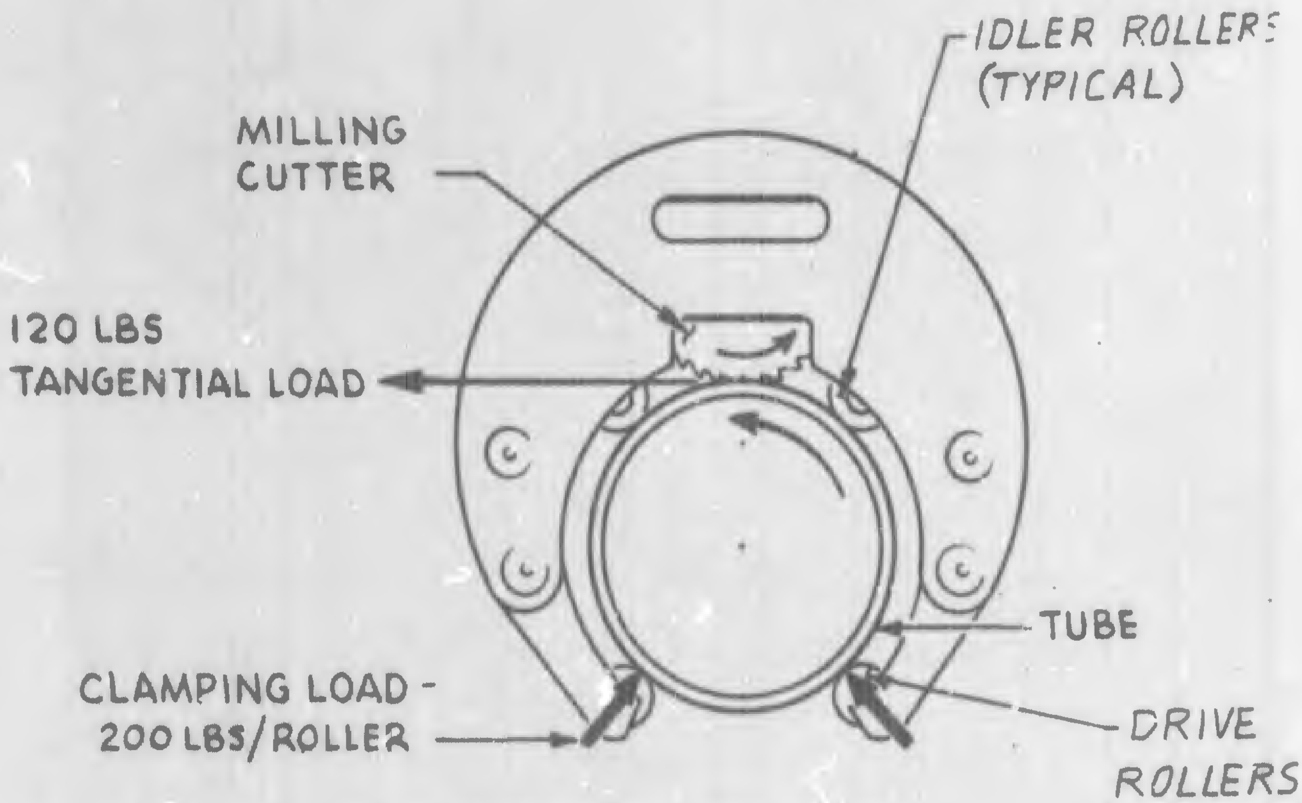
PROPOSED DESIGN CONCEPT

Specific welding tests have been conducted in this program, to establish the effect of arc gap on weld bead puddle control and penetration. Arc gap is defined as the distance between the tip of the electrode and the surface of the material being welded.

The results of these tests indicate that the variations in arc length should be held within a tolerance of ±0.010-inch. The magnitude of the amperage, the type of inert shielding gas, the shape of the tungsten electrode, and the type of material being welded have a definite effect upon arc length requirements.



A. WELDING TEMPERATURE TEST RESULTS



B. POWER REQUIREMENTS TEST RESULTS

Figure 6. Welding Temperature and Power Requirements Test Results

The milling cutter depth control is also an important consideration but of a lesser magnitude than the arc length requirements. Milling cutter stability, vibration, and the force required to hold the cutter in place are factors to be considered.

As a result of the tests, it was established that, mechanically, the welding electrode and the milling cutter must be supported by a stable platform. The platform would also provide a fixed datum plane from which the electrode and the cutter may be properly indexed to the work piece.

Precise tracking is a basic requirement in both milling and welding operations. Therefore, the platform support mechanism must provide an adequate tracking capability, preventing undesirable drift with respect to a plane perpendicular to the longitudinal axis of the tube, while the platform is orbiting the tube. The maximum drift considered permissible is approximately ±0.005-inch.

The method of attaching the platform to the tube must exhibit adequate structural capability to withstand the forces imposed upon it from clamping loads, orbiting forces, and milling cutter loads. The milling cutter loads are by far of greater magnitude than those imposed during the welding operation. Structural deflection of the platform with respect to the point of index on the tube must not exceed the ±0.010-inch tolerance established earlier.

Another consideration is the ability of the operator to work with the tool. Handling ease is of paramount importance to good workmanship, thus size, weight and configuration of the tool are elements relating to operator use.

Envelope requirements must be considered in the light of both tool application and the working mechanisms to be housed within it. The production design application potential of the tool is dependent upon the space required for tool operation.

The foregoing basic requirements provide a basis for analyzing the present tooling, and for projecting design changes directed toward achieving program objectives.

CONFIGURATION COMPARISON

A configuration comparison was made between the conceptual design and existing designs, using design evaluation data to ensure equitable comparison. The purpose of the comparison was to determine the feasibility of improving existing designs as opposed to the conceptual design.

As platform stability is a basic requisite to efficient operation of both machining and welding operations, related factors such as clamping, driving and mechanism mounting were compared. Through comparison of the respective approaches to clamping the tool on the work piece, it was determined that the chain tool could be clamped in place by a

180-degree segment of chain, in place of a 360-degree segment. By so doing, the platform could be oriented, with respect to the tube, by a pair of cam rollers. While this approach effects an improvement in the chain tool, it still entails the operations required to position fasten, and tension the chain. By comparison, the conceptual system, which also includes cam rollers, provides simplified installation while retaining the basic stability requirement.

Tracking characteristics were also compared, with consideration of operator requirements and the degree to which component wear may effect equipment performance. It was concluded that the 7-inch long cam rollers incorporated in the conceptual design will provide both a high degree of efficiency and long-term dependability, due to their configuration, application and reduced number of wear points. Since it was also possible to use two of the rollers as carriage drive members, the proposed design concept offered several significant advantages.

Factors relating to the configuration comparison are summarized in Table IV. These evidence the evolution of the original system to the present concept, through the design evaluation effort.

SYSTEM DESIGN

The design mechanics are based upon the platform stability requirements for the welding and machining processes. The operational mechanics were achieved through an integration of the various system functional requirements.

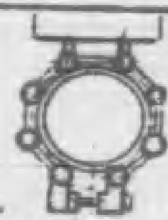
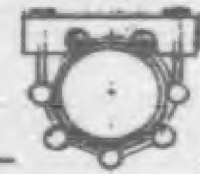
Platform Stability

The tests conducted under the design evaluation phase of the program established the basic requirement for a mechanically stable platform to be used as a datum plane for systematic reference to the tubular joint being welded or machined. The tests conducted to determine the arc length control requirements indicated that a tolerance control of 0.010-inch would be required to maintain proper weld puddle geometry. The mechanical design provides this control through the use of longitudinal rollers employed in the capacity of cams. These rollers automatically adjust to the various tube diameters and establish an indexing capability between the electrode and tube. The machining head mounts on the same platform and the milling cutter cutting depth control, therefore, employs the same reference plane as the weld head.

The carriage grasps the tube through two actuating arms. These arms contain the drive mechanisms and drive rollers. The drive rollers clamp the tube between themselves and the cam rollers. The cam rollers are linked mechanically to the drive rollers providing automatic diameter adjustment for different tube diameters. A simple worm screw adjusts the actuating arms for clamping and release.

Table IV

CONFIGURATION COMPARISON OF THREE TOOL CONCEPTS

Mechanical Design Requirement	Chain Concept 	Modified Chain Concept 	Integral Carriage 
Platform Stability	• Many Parts To Handle - and Misplace	• Ditto	• All Parts Packaged In One Assembly
Arc Length Control	• Must Add Or Remove Chain Links For Change In Tube Diameter	• Ditto	• Integral Adjustments For Change In Tube Diameter
Cutter Depth Control	• Requires Seperate Drive System	• Ditto	• Integral Drive
Tracking	• Clamping Geometry Not Positive - Allows Platform Instability	• Clamping Geometry Improved	• Stable Clamping Geometry - Any Position
Load Handling	• Tracking Is Not Positive - Particularly in Vertical Position	• Tracking May Be Improved	• Cam Roller Configuration Ensures Positive Tracking
Handling Ease	• Must Reach Around Tube To Install	• Ditto	• Install From One Side Of Tube Only.
		• Requires Upper Roller Position Change For Change In Tube Diameter Improved Stability	• Integral Adjustments
	• Platform Not Stable Enough For Cutter Loads On Stainless Steel		• Designed For Cutting 1/2 Wall S.S. Tubing

The cam and drive rollers are approximately seven inches long. They are held parallel to each other in a direction perpendicular to the forward and aft faces of the carriage. This roller system, coupled with the clamping mechanism, should afford good tracking capability.

The structural mechanics of the carriage are designed to withstand the milling cutter loads established during the design evaluation. The clamping forces are subsequently employed to provide the tractive effort required for orbital drive of the carriage. The orbital drive loads are those established by test which are required to feed the milling cutter around the tubular work piece.

Proposed Mechanisms; Thick Wall Tubing Systems

As a result of the design evaluation, the adjustable clamping arm platform carriage concept with an integrated mechanical system was selected for further study. This system advances the welding and machining capability for thick wall tubular shapes ranging in thickness from 0.050- to 0.500 inches, and diameters from 1 through 16 inches. The system concept provides both welding and edge preparation capability within the same basic unit.

The proposed concept includes a common platform (orbital carriage) designed to support both the welding head and milling head assemblies. The carriage will be structurally designed and powered to provide either the machining or welding capability by mounting either the machining or welding head assembly on the platform, at the discretion of the operator.

The system application requirement to include a 1- through 16-inch tubing diameter capability necessitates, for practical mechanical considerations a series of carriages in graduated sizes. A total of five carriages are planned, ranging in size to provide a 1- to 3-inch, 3- to 6-inch, 6- to 9-inch, 9- to 12-inch, and 12- to 16-inch diameter tubing size capability.

The welding and machining heads will be common to all five carriages as shown in figures 7 and 8. Figure 9 illustrates the overall proposed system, including the power supply, programmer, and remote control pendant in relationship with the proposed welding devices. The orbital carriage and interchangeable heads are shown in figures 10 and 11. A comparison of present versus proposed systems is shown in figure 12.

Proposed Mechanisms; Thin Wall Tubing Systems

The design evaluation established the need for welding a group of thin wall tubular shapes. This group ranges in wall thickness from 0.010- through 0.093-inch, and in diameter from 1/8 to 3 inches.

The orbit arc tubular welding heads have been chosen as the mechanism for welding the tubing in the thin wall category. These welding

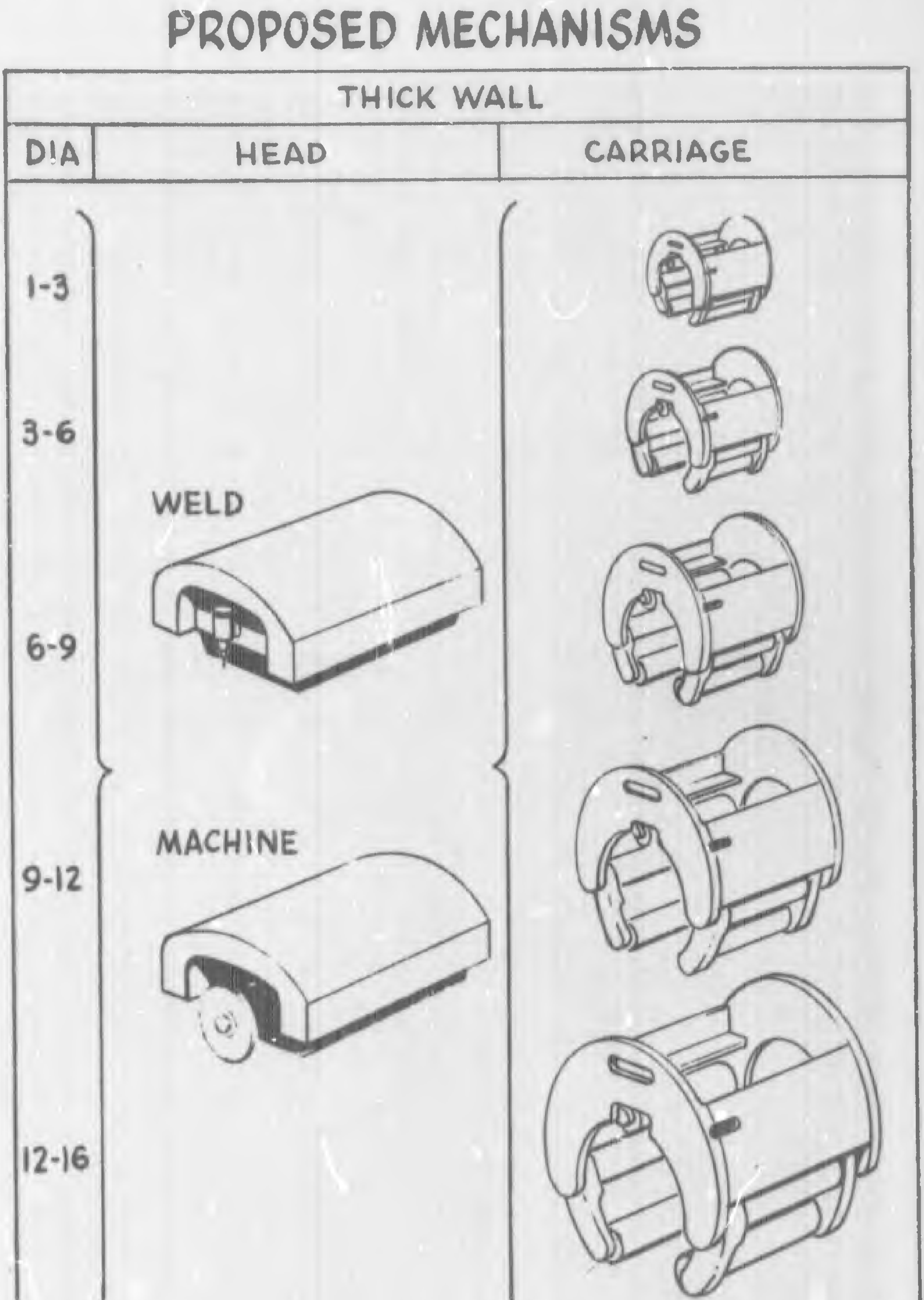


Figure 7. Proposed Mechanisms for 1-Inch to 16-Inch Diameter Tubing

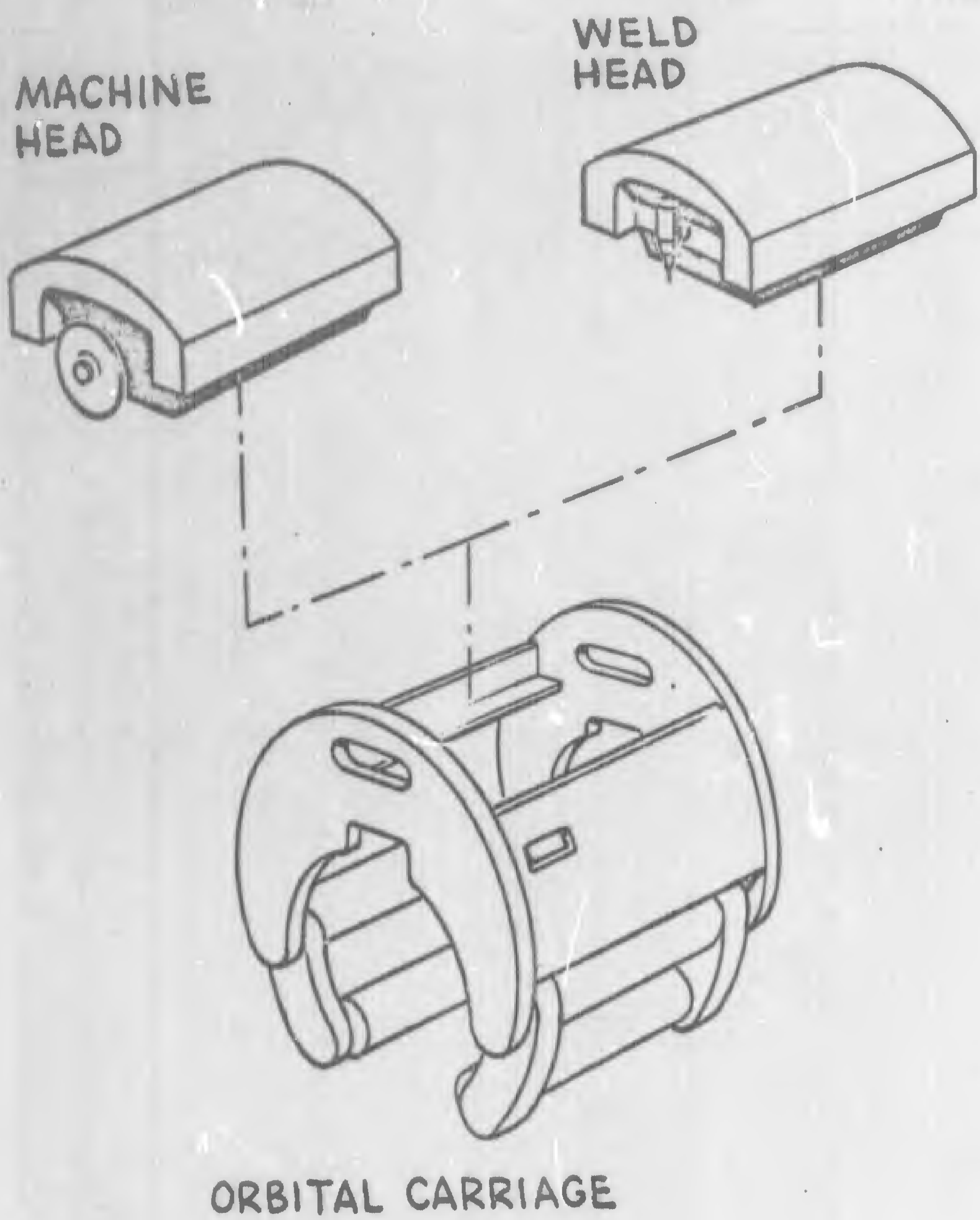


Figure 8. Basic Components of Proposed Mechanisms

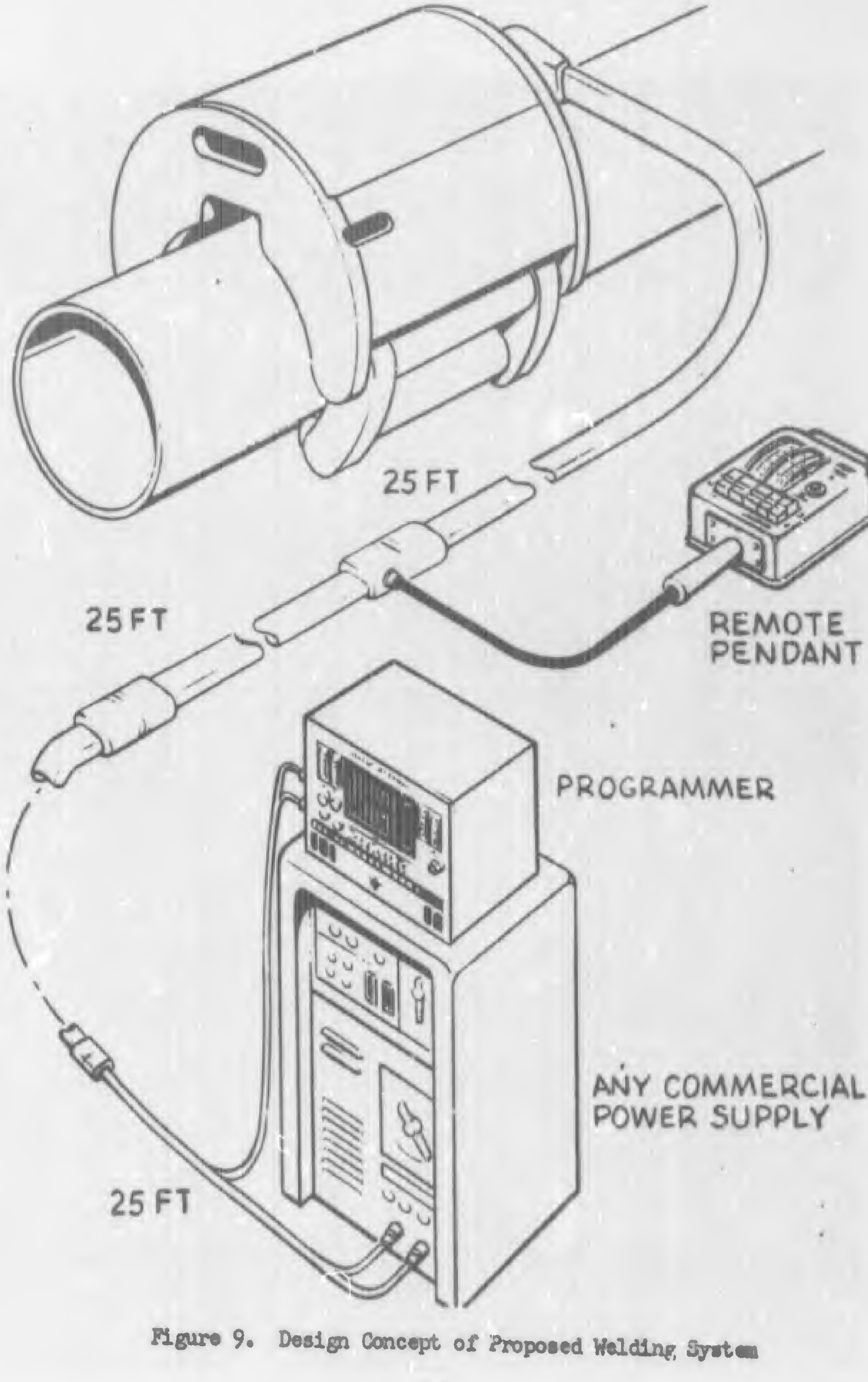


Figure 9. Design Concept of Proposed Welding System

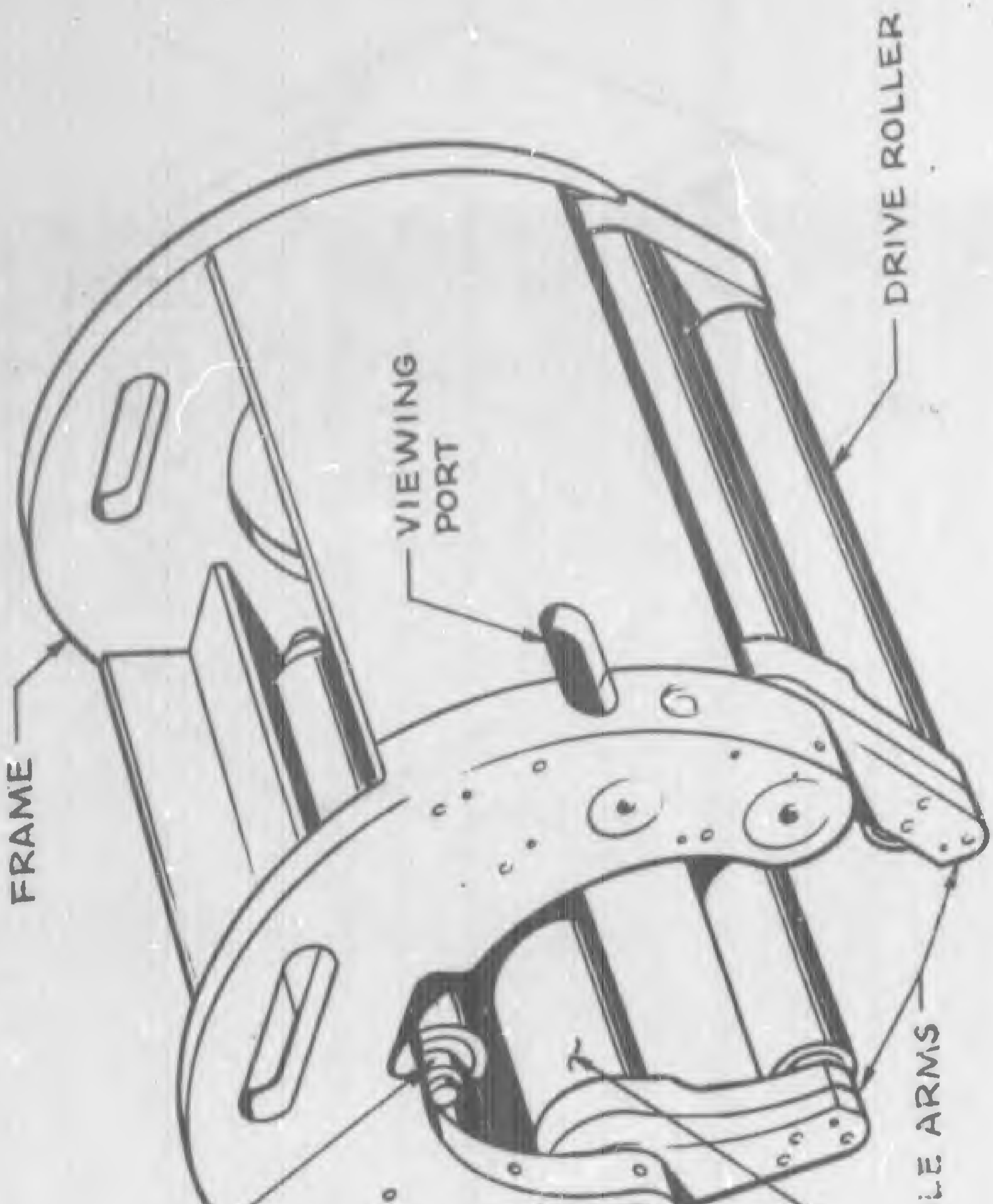


Figure 10. Typical Orbital Carriage

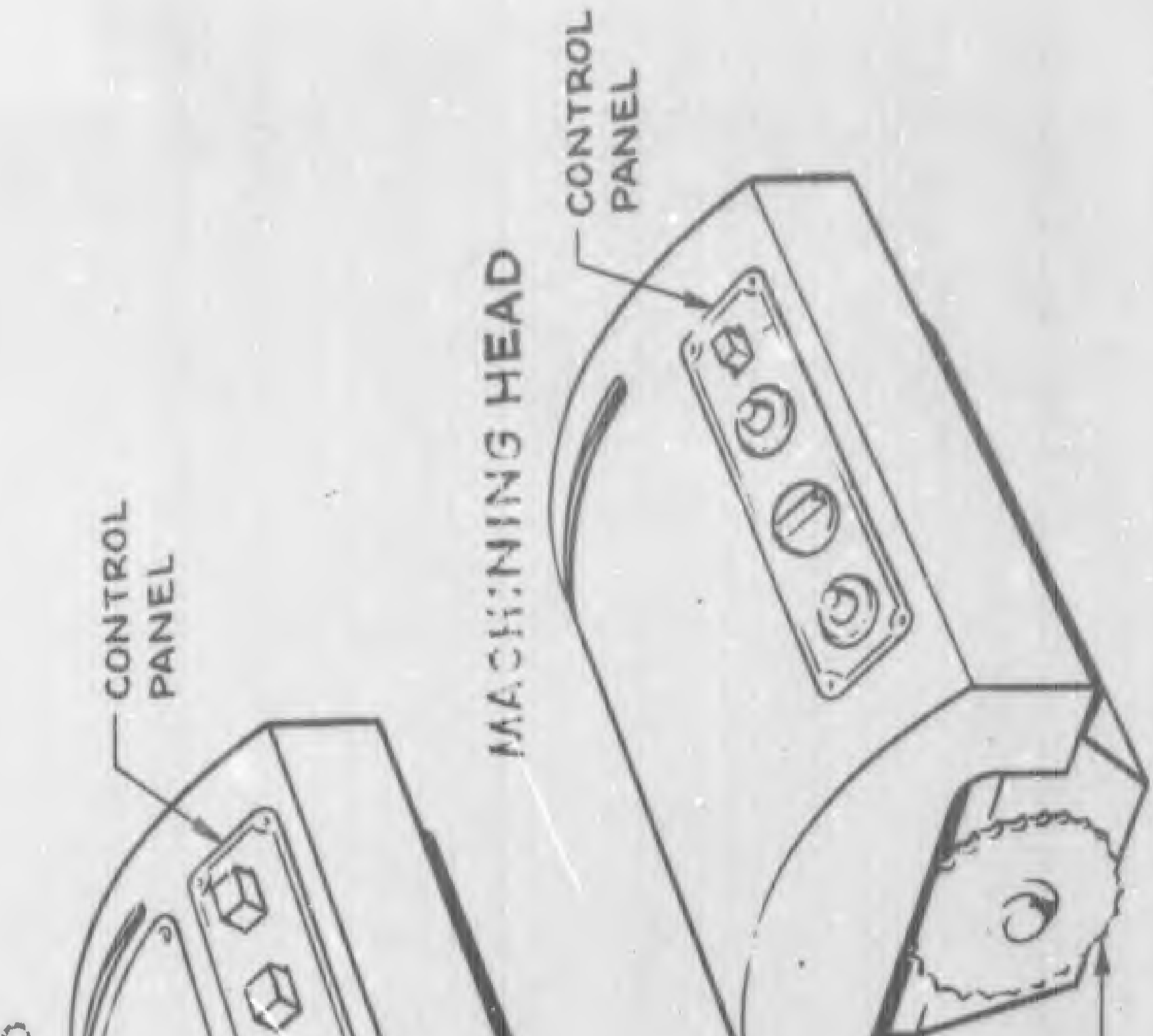


Figure 11. Interchangeable Heads for Orbital Carriage

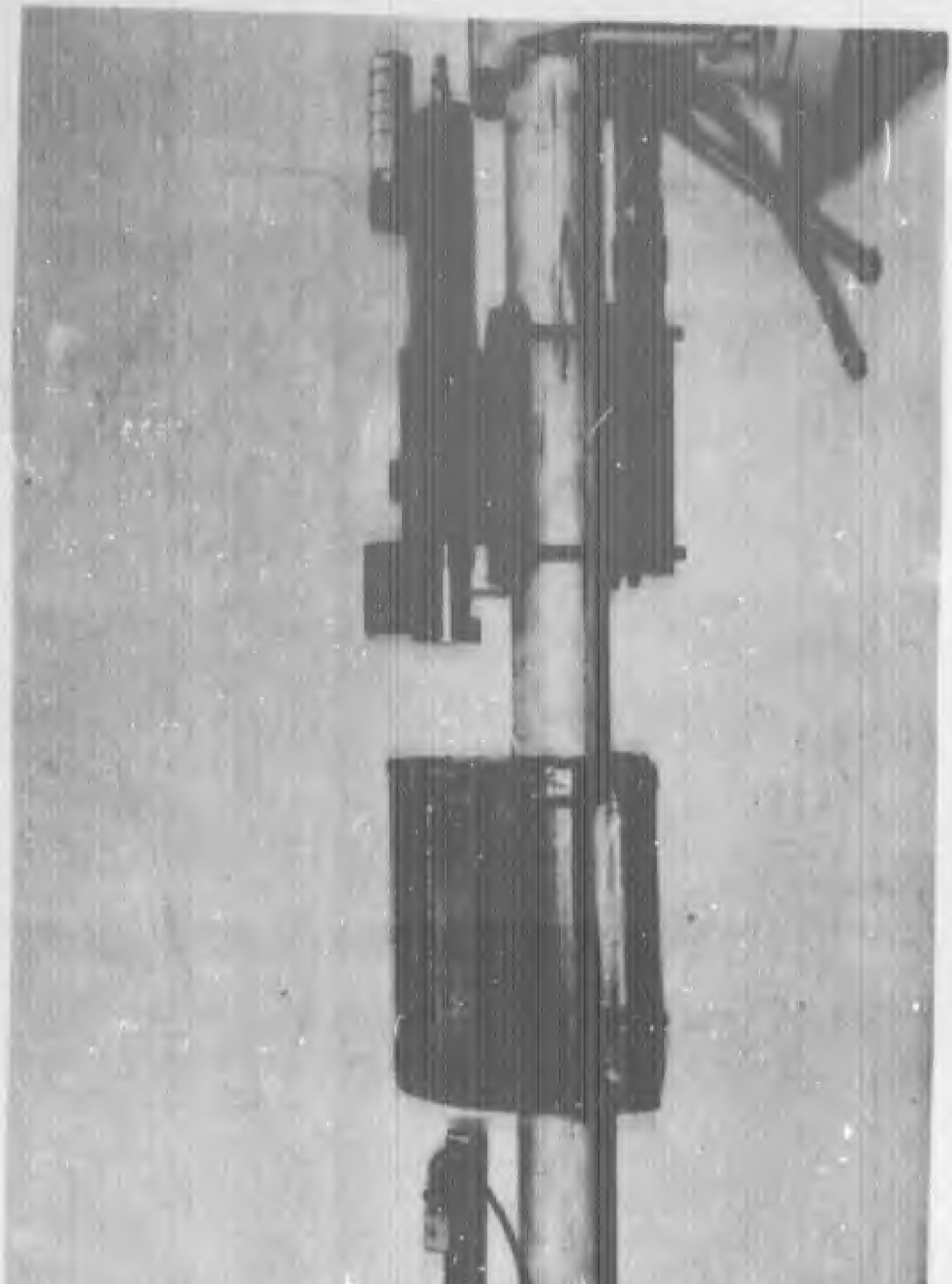


Figure 12. Present and Proposed Tool Concepts

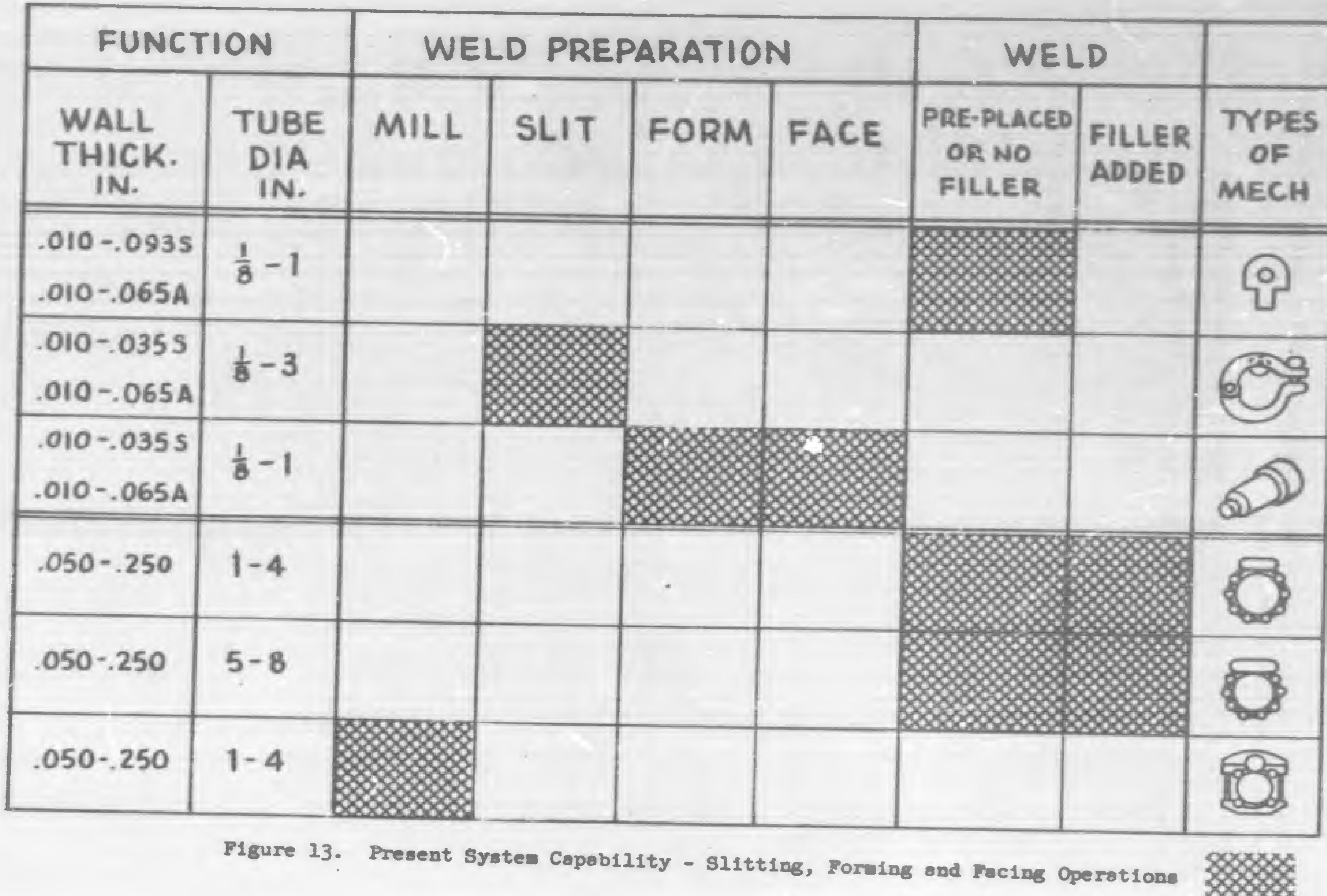
heads fulfill the requirements established in the design evaluation and are available commercially.

The evaluation effort for the thin wall system, therefore, was concentrated on the edge preparation mechanisms. The present and proposed system capability for slitting, forming, and facing operations in the thin wall tubing size ranges is shown in figures 13, 14, and 15 respectively.

Slitting the thin wall tubing, for example, the 0.010-inch wall, 1-inch diameter size, presents some problems in practical relationship between the wall thickness and diameter. For example, a 0.020-inch wall, 1/2-inch diameter tube may be quite stable, but a 3-inch diameter tube having the same wall thickness may be quite unstable when subjected to external loads. The unstable configuration does not cut satisfactorily with present hand powered slitting wheels as it is easily deformed during the cutting operation. The hand powered slitting tool requires a high slitting wheel load in order to make the cut in a reasonable time period. Therefore, the less stable configurations deflect and the edges turn in at the parting line unless extreme care is exercised during the slitting operation.

It is, therefore, planned to use the dynamic forces available in the orbit arc head to achieve satisfactory slitting results. By turning the rotor at high speed, perhaps 100 rpm, for example, the load on the slitting wheel may be reduced to the extent that slitting can be accomplished without deformation of the tubing. A new drive handle would be required for this operation, to facilitate tool control. This handle (figure 16) would attach to the present orbit arc head. The handle would house the same drive motor used in the machining head for the thick wall tubing. In the proposed application, the added power would be required to drive the slitting wheel rotor.

The present facing and flanging tool has capabilities in the range from 1/8- to 1-inch tubing diameters. Extending this concept into the 3-inch range capability would require a large, bulky, and heavy mechanism that would be difficult to use. It is, therefore, planned that a rotor device such as that shown in figure 17 will be designed to adapt to the same orbit arc head case as the slitting wheel. These rotors would be interchangeable, using the new power handle to provide the driving force. These changes would provide an integrated thin wall slitting-flanging-machining-welding system for thin wall tubing.



FUNCTION		WELD PREPARATION				WELD		
WALL THICK. IN.	TUBE DIA IN.	MILL	SLIT	FORM	FACE	PRE-PLACED OR NO FILLER	FILLER ADDED	TYPES OF MECH
.010-.093S .010-.065A	$\frac{1}{8}$ - 1							
.010-.035S .010-.065A	$\frac{1}{8}$ - 3							
.010-.035S .010-.065A	$\frac{1}{8}$ - 1							
.050-.250	1-4							
.050-.250	5-8							
.050-.250	1-4							

Figure 13. Present System Capability - Slitting, Forming and Facing Operations

FUNCTION		EDGE PREPARATION				WELD		
WALL THICK.	TUBE DIA	MILL	SLIT	FORM	FACE	PRE-PLACED OR NO FILLER	FILLER ADDED	TYPES OF MECH
.010-.093	$\frac{1}{8}-\frac{1}{2}$							
	$\frac{1}{2}-1$							"
	1-2							"
	2-3							"
.050-.500	1-3							
	3-6							"
	6-9							"
	9-12							"
	12-16							"

Figure 14. Proposed System Capability

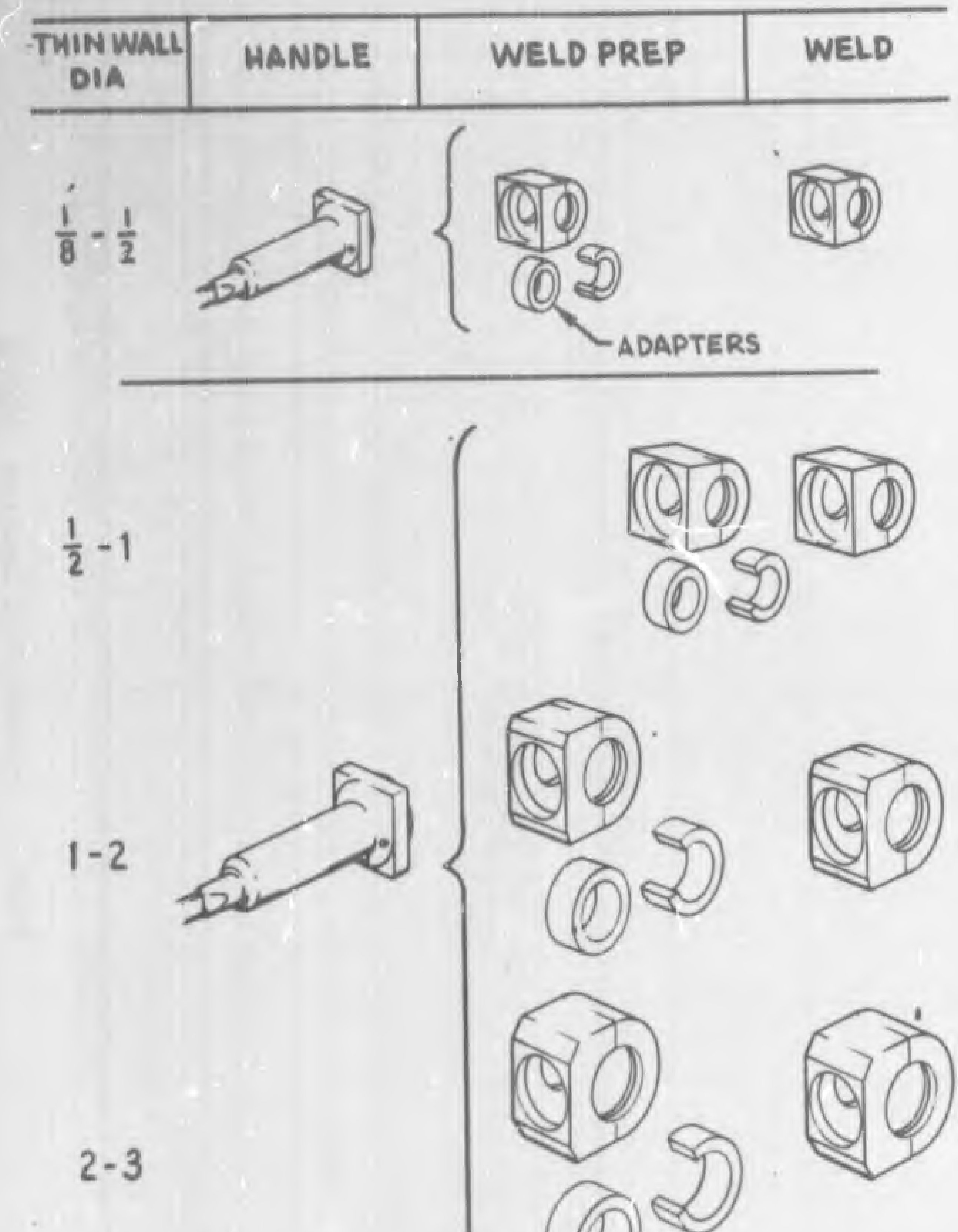


Figure 15. Proposed Mechanisms for Small Diameter Thin Wall Tubing Systems

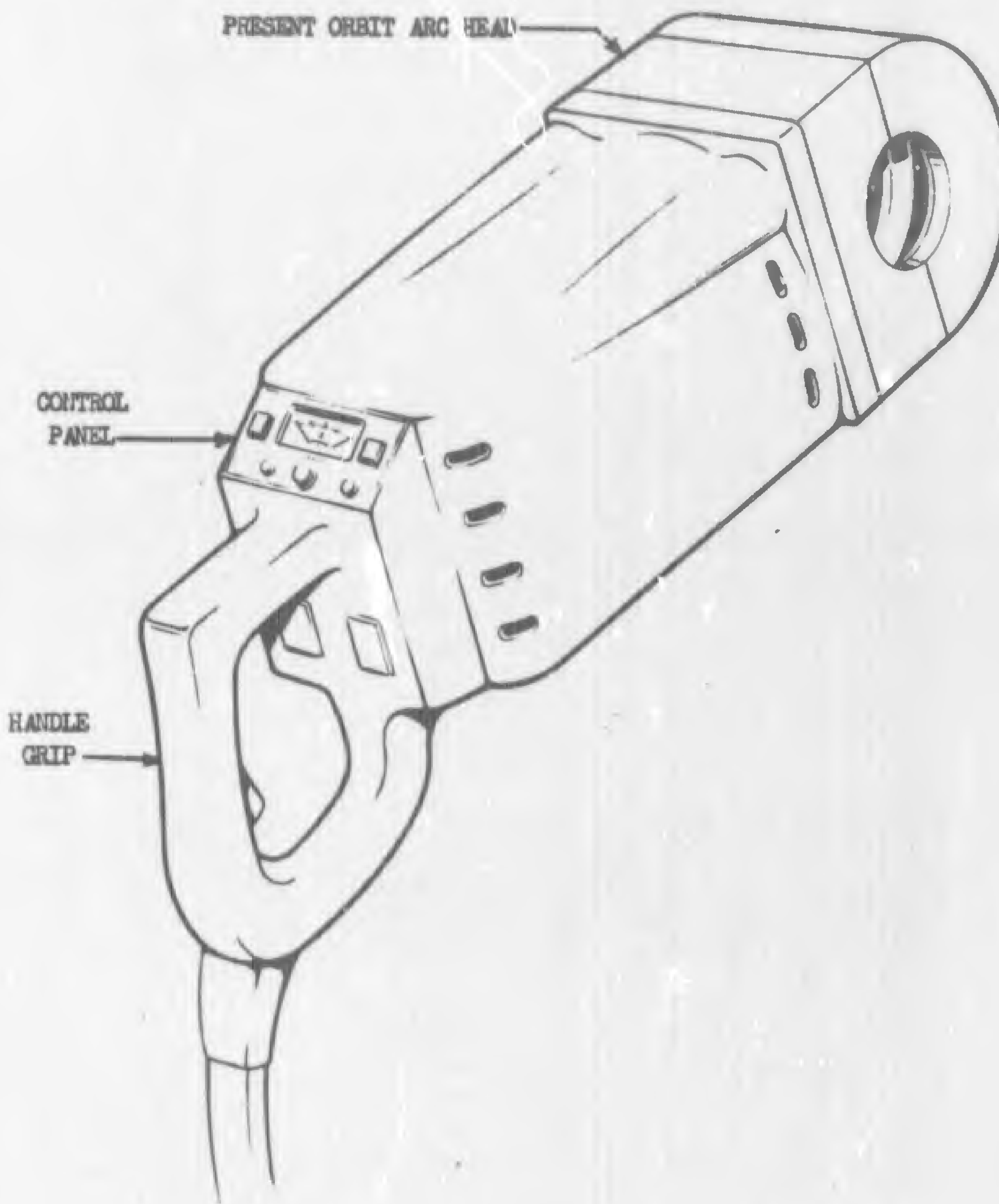
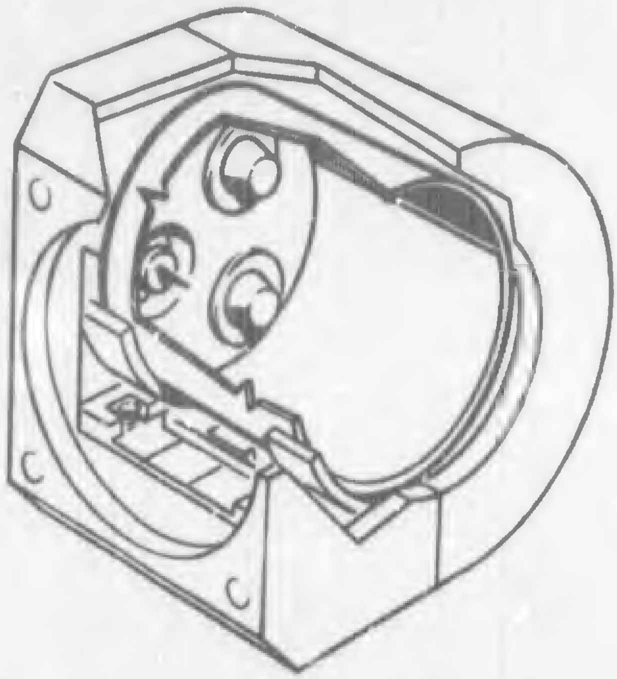
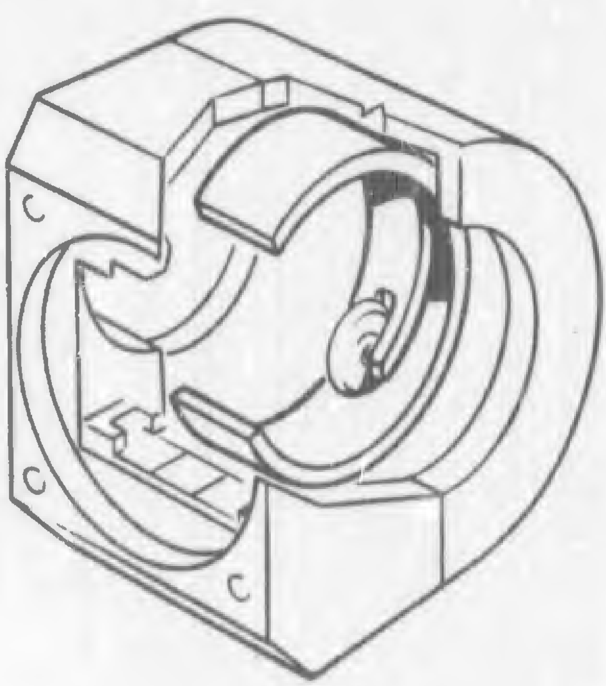


Figure 16. Proposed Drive Handle



FORMING-FACING
HEAD



SLITTING HEAD

Figure 17. Proposed Edge Preparation Heads

Section IV

ELECTRICAL EQUIPMENT STUDIES

The studies conducted in this area were aimed at obtaining the most efficient functional and operating characteristics for the tungsten-inert gas (TIG) tube joining system being designed, from the electrical standpoint. The studies were divided into three areas: (1) the weld programming and control equipment, (2) evaluation of welding power supplies, and (3) determination of the various drive motors and electrical connections required for the machining and welding tools. Of primary interest was the determination of electrical control and programming requirements for tube welding with the object of obtaining maximum simplicity of operation and reproducibility of results.

The control and thereby the reproducibility of the welding operation can be broken down into three major areas exclusive of the particular tool employed. These are as follows: (1) weld programming and control equipment, (2) welding power supply, and (3) the selection of welding variables which influence arc plasma shape and temperature. The purpose of the weld programmer is to provide a simple means of in-process control and sequencing of the weld variables. The most critical variables from the standpoint of reproducibility are those which influence energy input to the weld, i.e., current, voltage, and travel speed. The control of travel speed is relatively straightforward whereas the control of welding current and arc voltage are dependent both on the welding power supply utilized and on the selection of arc gap, shield gas, and electrode type and configuration, all of which significantly affect the shape and temperature of the arc plasma. Studies conducted to obtain improvements in the programmer operation and available functions, and to evaluate welding power supplies, are subsequently described, while the effects of weld variables on weld bead shape are described in Section V.

WELDING PROGRAMMER MODIFICATIONS AND IMPROVEMENTS

The Model 6294A tube welding programmer and remote control pendant (figures 18 and 19) have been used over a 6-month period. During this time, this equipment has been used with the 1-to 4-inch OD range chain weld tool, the 4-to 8-inch OD range chain weld tool, and the 1/8-to 1-inch range orbit arc weld tools. The current controls have been operated with Lincoln, Miller, P&H, NAVAN, Birdsell, Western Arctronics, and Vickers Welding Power Supplies. Welds have been made on a wide variety of tube and pipe materials and sizes, both with and without filler wire and/or oscillation, using both ac and dc power. During this operating period, problems requiring modifications and improvements were identified.

WELDING CURRENT CONTROL SERVOSYSTEM

The weld current programming system (vernistat control) in the existing weld programmers is not self-compensating with respect to in-process variations in the external circuit, such as line voltage or arc length. This can result in weld current fluctuations sufficient to produce undesirable weld

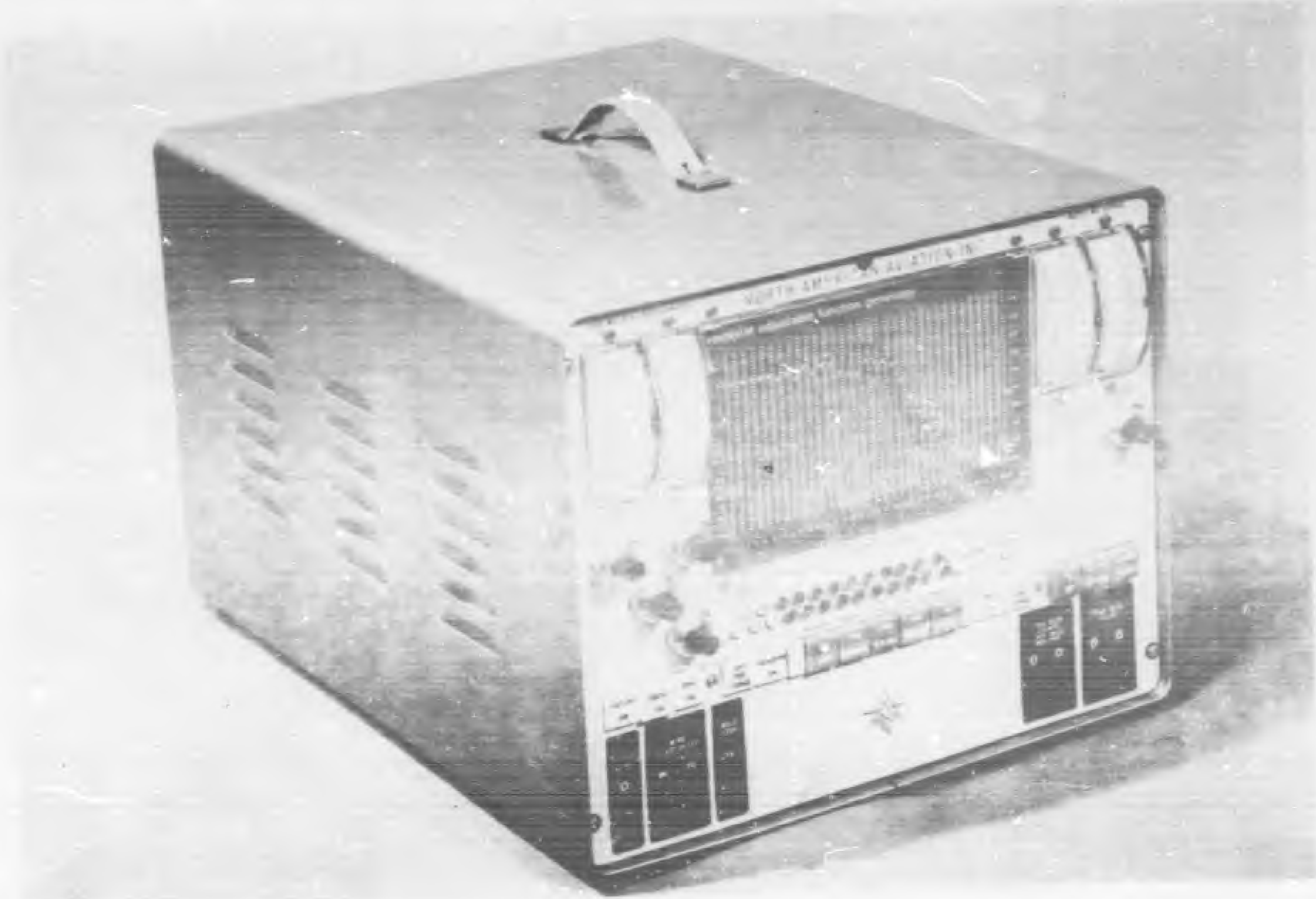


Figure 18. Tube Welding Programmer

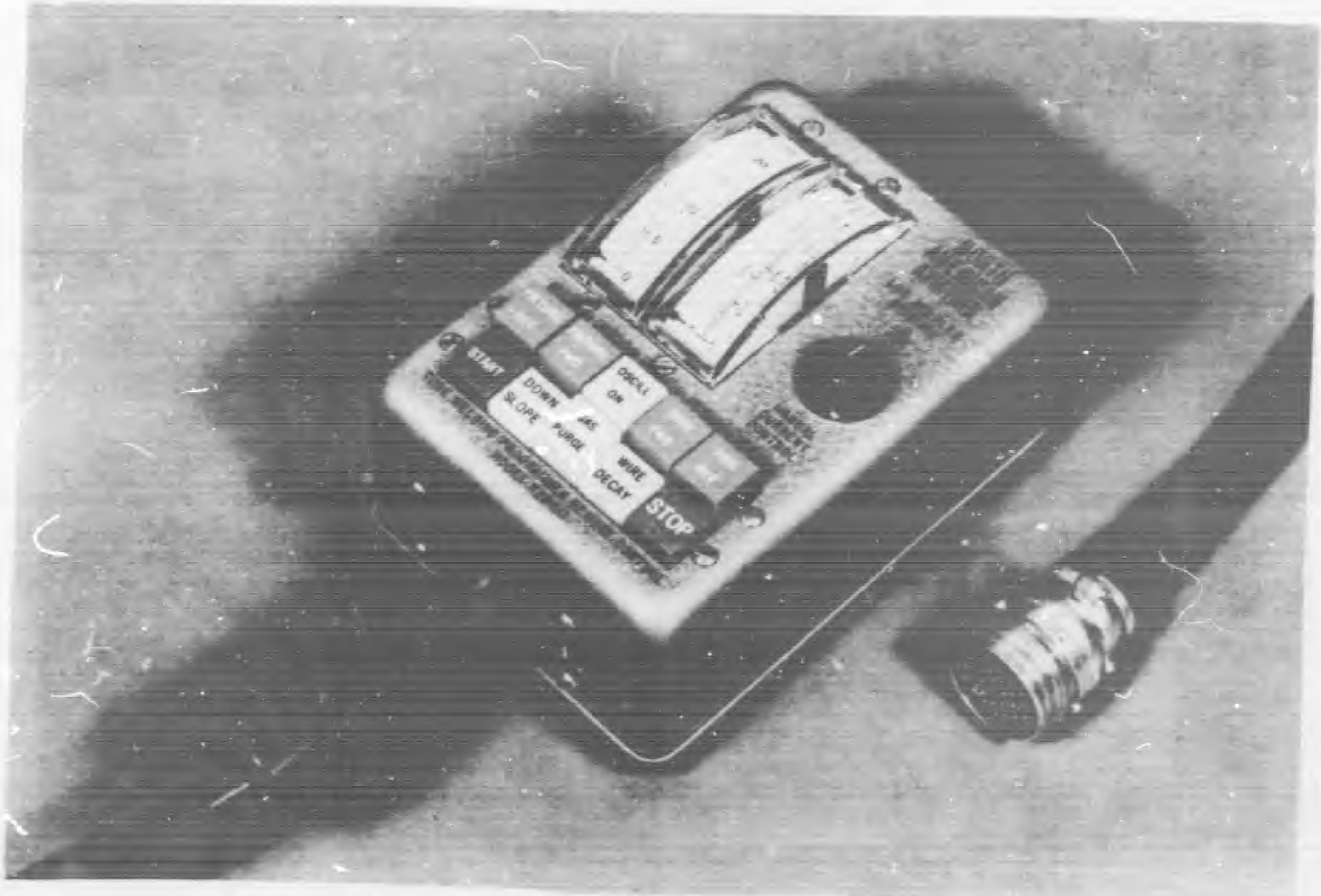


Figure 19. Remote Control Pendant

quality. A second deficiency in the existing current programmer is the nonlinear relationship between slider position and welding current. Further, this relationship can change from power supply to power supply, and from range to range on a particular supply thereby giving rise to a requirement for multiple calibration curves and complicated setup of the programmer.

An investigation has been conducted to determine whether a weld current servosystem could be devised which would: (1) minimize weld current variations due to variations in the external circuit, and (2) linearize and standardize the relationship between the programmer sliders and the welding current. Since the Lincoln Electric Company welding power supply was determined to offer the best combination of characteristics for this program it was used, together with a breadboard servo-current control and the Model 6294A-1 programmer, to conduct initial tests. The actual welding current was used as a feedback signal by comparing it with the programmer current command (vernistat) signal and feeding an amplified correction signal to the welding power supply current control circuits. The power supply was operated on the 2-to 37-ampere dc range, both with and without servo-control. Welding current and arc voltage were monitored with a recording oscillograph. The arc length was deliberately varied to produce arc voltages from 8-to 14-volts. Without the servo control, the welding current changed approximately ± 5 percent. With the servo control, the current change was reduced to less than ±1 percent. The preliminary testing demonstrated the feasibility of this method of servo-controlling welding current.

After purchase of the Lincoln welding power supply, a transistorized reactor control current amplifier was installed within the welder (figure 20). The prototype servo current control (figure 20) is presently being operated and evaluated with the welding power supply in order to refine and modify its circuitry and features as dictated by actual operation. This system has been operated with the Lincoln welder on all dc output ranges and has performed in a satisfactory manner to linearly control welding current during actual welding under varying arc length conditions. These tests will be continued on the ac ranges. The following controls are presently being utilized on this system: a switch for selecting either a 50-or 150-ampere operating range, a servo gain control to adjust for maximum performance without oscillation, and a feedback gain control to set maximum welder output current. The current servo control system is being designed to be compatible with a variety of welding power supplies and, as such, will be packaged in the weld programmer.

ARC VOLTAGE CONTROLLED WIRE FEED SYSTEM

It has been extremely difficult to ensure uniform weld buildup during multiple filler weld passes. A system for controlling filler wire feed rate as a function of arc voltage has been devised to ensure uniform weld buildup during filler passes. With this system, if, due to gravity effects, the weld puddle moves toward the

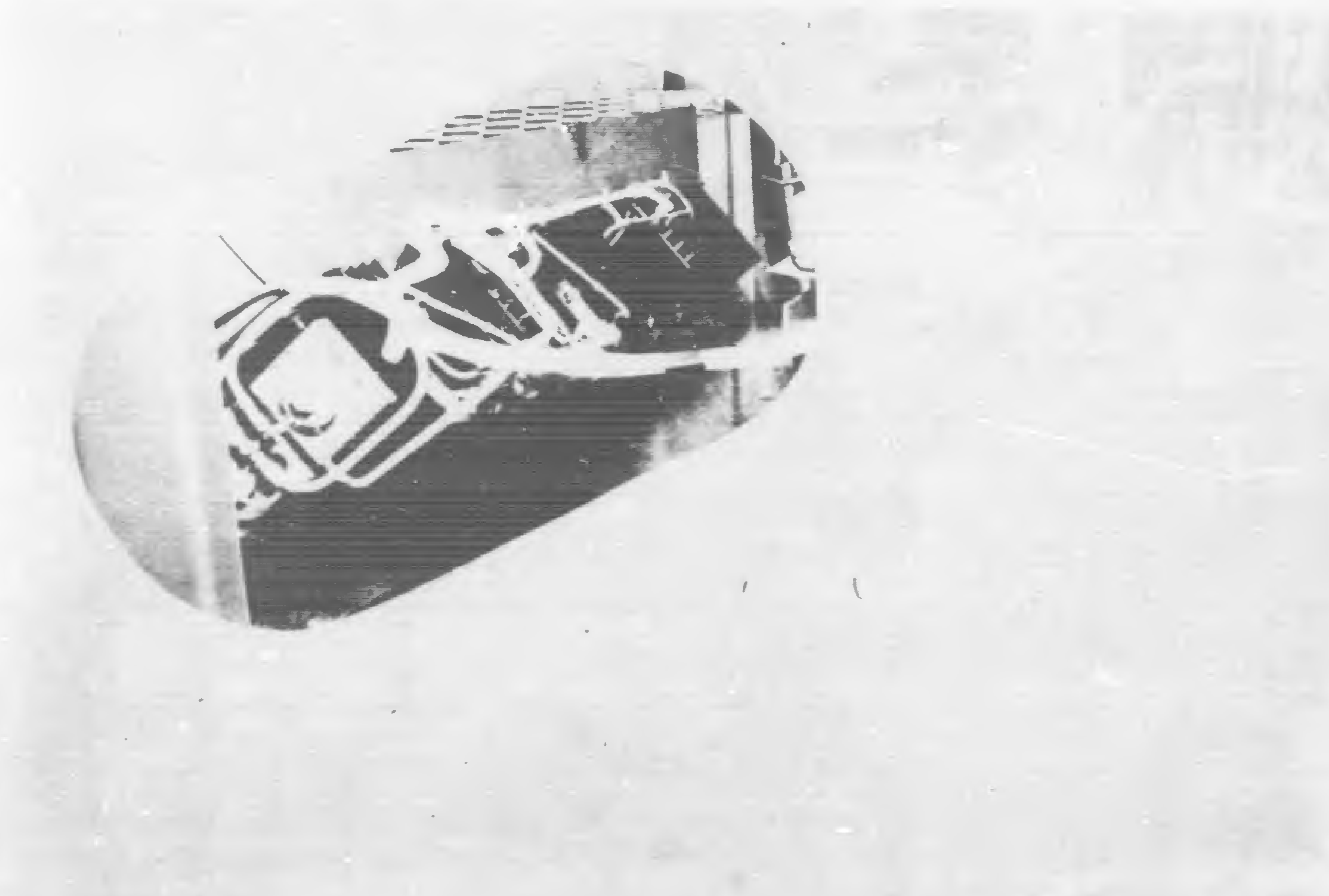


Figure 20. Transistorized Reactor Control

electrode, arc length and arc voltage decrease. A signal is then generated to decrease wire feed speed. It the weld puddle moves away from the electrode the situation is reversed. A more complete description of the operation of this unit is included in Section V .

The electronic circuitry for controlling the wire feed is relatively simple and very little modification of the existing wire feed circuits is necessary. This system will be further operated and evaluated with various operational modifications and improvements. The present system includes a transistorized converter/comparator which converts the arc voltage signal to a standard polarity and compares it with a preset voltage reference. The resultant signal controls the input to the wire feed amplifier to produce the desired wire feed rate. A variable arc voltage control and on/off switch are provided. A gain control is internally accessible for adjustments.

MISCELLANEOUS OPERATIONAL IMPROVEMENTS

Setting up the required weld time base has been a difficult and time consuming process for two reasons: the fixture speed meter is not directly calibrated in inches/minute, and the weld time can only be set in even multiples of the time base. To simplify this setup, the fixture and wire speed motors will be directly calibrated in inches per minute, and the weld time will be controlled by a multiturn potentiometer to provide any increment of time desired.

The ammeter and servo control ranges will be 0 to 50 amperes and 0 to 200 amperes. The arc voltage meter will have a 0 to 30-volt range. All multi-turn potentiometers will have illuminated digital dials to permit easier setup.

It is planned to have a single, multifunction cable running from the programmer (and welding power supply) to the various welding/machining tools and remote control pendant.

The remote control pendant will incorporate a number of changes. The controls will be repackaged in a smaller, lighter, more rugged case with better protection for the controls against handling damage. The pendant cable will be smaller, of more flexible construction, and will plug into and become a part of the main cable running to the programmer. The controls will be rearranged for easier operation and to preclude the possibility of actuating the wrong button. The wire decay function will be deleted. The necessary controls on the small welding/machining tool and the large welding/machining tool are somewhat different. Therefore, consideration is being given to the possibility of either having two separate pendants or incorporating all pendant functions into the handle of the small tool, and providing a separate pendant for the larger tool.

POWER SUPPLY EVALUATION

Because of the wide variety of tube sizes and material types being considered under this program, the welding power supply requirements vary considerably.

Small diameter, thin wall tubing particularly aluminum alloys in the range of 1/8-to 1-inch diameter, 0.010-to 0.030-inch wall, require: (1) low initial and final currents, (2) very accurate control of weld current, and (3) rapid response to changing current requirements. In the wall thicknesses of 0.030-inch and above, less stringent requirements apply.

A series of investigations was conducted to determine: (1) specific welding power supply requirements for ferrous and nonferrous tubing in the 1/8-to 16-inch diameters, 0.010-to 0.500-inch wall thickness range; and (2) to evaluate and, if possible, select a commercially available unit for use on this program. Alternatively it was planned to design and build a special welding power supply if no commercially available supply proved to be suitable. Based on a survey of welding power supply manufacturer's literature, three ac/dc units were selected for final evaluation and testing. These units were as follow: the Lincoln Electric Co. Model TIG-300/300-K-1175; the Miller Electric Mfg Co. Model 300-A/BP (with special low range); and the P&H, Harnischfeger Model DAR-200-HFGW (with special low range). These units were procured on loan and each was evaluated on the following bases: current control range, current upslope and downslope response time; arc initiation capability; output current stability particularly on the low ranges; ability to be integrated with the weld programmer; size; weight; cost; and general operating, service, and constructional details. In addition, it was required that the selected power supply (or supplies) should be suitable for incorporation of a servosystem to permit monitoring and control of the current during welding, to automatically compensate for fluctuations in weld current due to changes in the external system. The selected units were operated with the Model 6294A1 programmer in laboratory evaluation (figures 21, 22). All electrical tests were monitored with a direct writing oscillograph which displayed welding current, arc voltage, fixture and wire feed speed, and programmer command signals, as a function of time.

The Miller power supply control circuitry is directly compatible with the programmer circuitry. The P&H welder remote current control circuits operate on ac internal power; because of this it was necessary to modify the welder circuitry to permit operation on dc internal power in order to use the programmer. The Lincoln welder current control system uses a magnetic amplifier to drive the main control reactor. It was necessary to bypass the magnetic amplifier and drive the main control reactor directly in order to use the programmer. This was required since the control dc power supply in the welder was insufficient to supply the current programmer and also because the magnetic amplifier response speed was slower than desired.

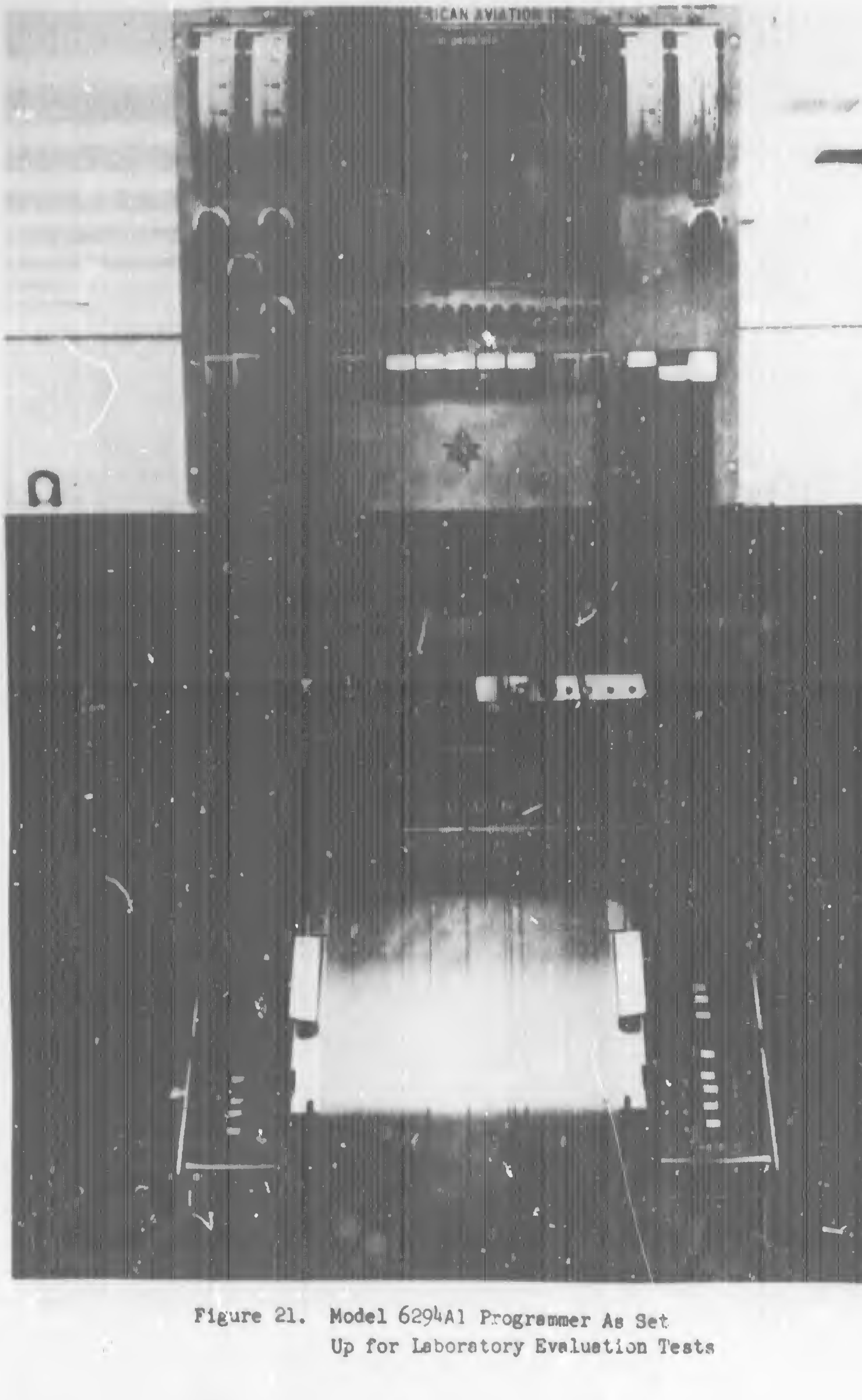


Figure 21. Model 6294A1 Programmer As Set Up for Laboratory Evaluation Tests

Figure 22. Selected Units Used for Laboratory Evaluation Tests

A wide span of maximum to minimum output current for each output range is highly desirable. Additionally, wide overlap of the various welding ranges is necessary in order to be able to choose the optimum range for a given weld. Each welding power supply was therefore operated to produce its full output range (from maximum to minimum) on each ac and dc power supply range. These tests were performed with the power supply alone. In this area the Lincoln power supply exhibits the best characteristics (figure 23).

Using the programmer to control the power supply, each supply was commanded to step from minimum output to maximum output and then to step back to the minimum output on each output range to obtain data on response speed to changing commands. These tests indicated that both the P&H and the Miller welders increase from minimum to maximum output in from 0.2 to 0.6 second, depending on output range. These units reduce from maximum to minimum output in from 0.4 to 1 second, depending on output range. The Lincoln power supply has a rise time of 0.5 to 0.8 second, and a fall time of 1.0 to 1.2 seconds. While the Lincoln is somewhat slower in responding to changing commands, the difference was not considered significant.

When welding small diameter, thin wall tubing with ac or dc, it is mandatory that very low welding currents be used. Because of this, power supply arc starting characteristics, minimum usable output current, and low current output stability are extremely important. Arc initiation capability and output current stability were demonstrated by programming the power supplies to strike the arc at maximum output and gradually step to minimum output on each output range. During this test series, the maximum output commanded was reduced in steps down to approximately twice the minimum output available. Adequate arc initiation capability was demonstrated on all ranges by the Lincoln and P&H supplies. The Miller supply had adequate arc initiation except on the 1 to 10 ampere ac/dc ranges where starting and output current stability are erratic. The Lincoln unit has the greatest output current stability. The P&H has very satisfactory stability, also. Generally, better output current stability is obtained when the power supply open circuit voltage is high, and the Lincoln welder has significantly higher open circuit voltage than the other units. Additional tests were conducted to determine output current stability with changes in arc length. In this area, the three units are roughly equivalent, with the Lincoln and P&H welders slightly better.

The Lincoln and the Miller units have overload protection for both the main transformer and the rectifier; the P&H unit has no overload protection. The Lincoln incorporates a main line contactor, with pushbutton controls, as well as an output contactor. The Lincoln and the P&H units provide auxiliary 115v ac power for operating accessory units (such as the programmer or weld joint machining tools). All machines are rated at 60 percent duty cycle (6 minutes on, 4 minutes off). The Lincoln is rated at 300 amps at 40 volts, the Miller 200 amps at 40 volts, and the P&H at 200 amps at 28 volts. General convenience features and workmanship are

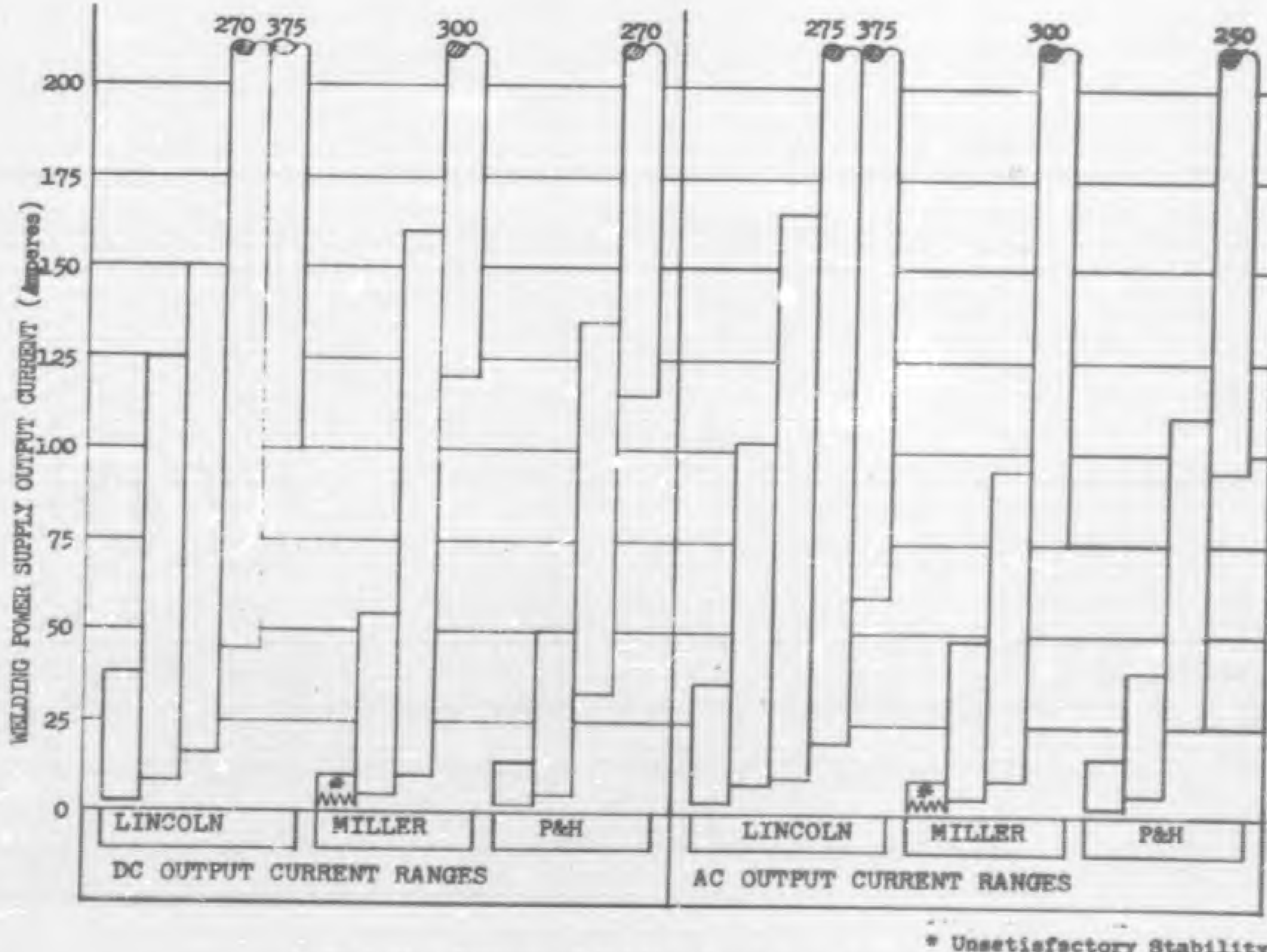


Figure 23. Summary of Welding Power Supply Current Ranges

considered satisfactory on all machines. The Lincoln unit is slightly smaller than the other units. The approximate weights are: P&H - 640 lb, Lincoln - 670 lb, and Miller - 760 lb. The prices of the three units are comparable.

Of the three supplies evaluated, the Lincoln Electric Company Model TIG-300/300 K-1175HC, ac/dc unit was found to be the most suitable for use on this program, particularly from the standpoints of range selection and low current arc stability. It is believed that the other two units evaluated are also suitable for this application but that the Lincoln power supply offers the widest latitude and, as such, will be utilized for this program. Based on the results of these studies, it has been concluded that no requirement exists for design and development of a special low amperage power supply.

DRIVE MOTOR INVESTIGATION AND EVALUATION

As part of the Design Evaluation Study, various types of electric motors, gear motors, and solenoids were investigated to determine the optimum types for operating the various mechanical functions of the welding and machining tools. Some of the factors considered were size, weight, power, electrical compatibility with the programmer; mechanical compatibility with the tool and its function; speed control and range, life, and relative cost. The types of motors and solenoids investigated were as follow:

1. Series motors (ac, dc, and universal)
2. Shunt motors (ac and dc)
3. Permanent magnet field motors
4. DC torque motors
5. Two-phase ac motors
6. Slow speed synchronous motors
7. Digital stepping motors (permanent magnet and variable reluctance)
8. Solenoids (rotary and linear)

Electric motors have been determined to be satisfactory for use on the machining tool to replace the air motors presently being employed. Electric motor advantages are quieter operation, elimination of the requirement for controlled air pressure supply, lower motor cost, simpler adaptation to the physical design, and more accurate speed control. After determination of actual cutter motor and fixture drive motor loads, through torque testing, standard fractional horsepower motors were evaluated for these tasks.

A nominal 1/2 hp electric drill motor was selected, obtained, and coupled, through a drive train to the 1-to 4-inch OD range milling tool, to determine operating characteristics under actual working conditions. The electric motor handled the cutting loads in an acceptable manner. A milling tool drive motor speed control was designed, breadboarded, and tested. The control can vary speed from one-half to full speed under normal cutting loads. It is planned to package the speed control within the milling cutter drive package.

Since fixture drive motor requirements were in excess of the capabilities of the present permanent magnet field drive motor, it was decided to use two motors, (similar to the present units) in tandem, to supply the required drive power. One of these motors will incorporate a tachometer to provide a signal for the speed control servosystem. The existing motor speed control system will be modified, as required, to control both motors.

The wire feed and the cross seam torch oscillator will use essentially the same motors as are presently being used for these functions.

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Section V

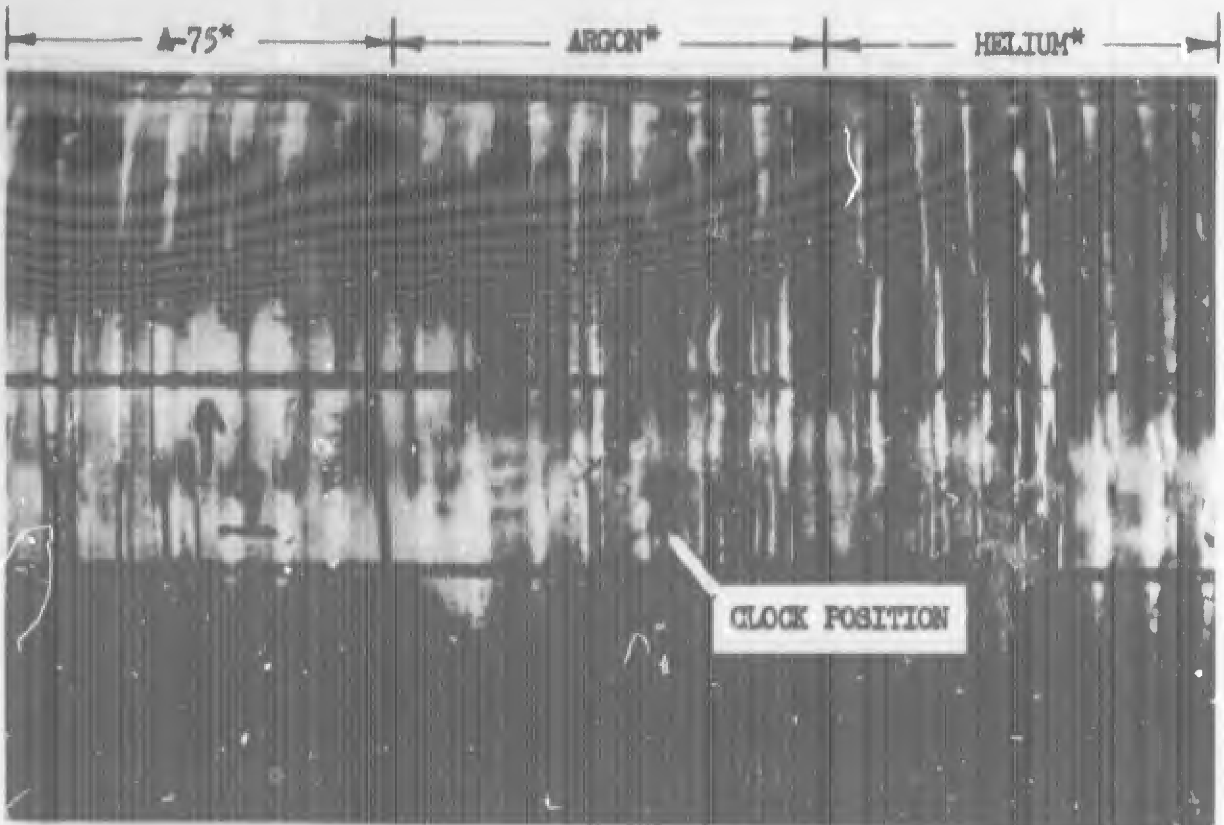
WELDING STUDIES

Welding studies were conducted in three major areas, the basic objective of each being increased understanding of the effects of the variables involved in tungsten inert gas (TIG) welding of tubing, as they effect the ability to maintain reproducible bead shape. The data obtained was used to support final design of the tooling and electrical equipment, and to simplify development of final weld joint designs and weld schedules. Data were obtained in the following areas: (1) the effects of inert shield gas type, arc gap, energy input, electrode configuration, and weld position on weld bead shape in stainless steel and aluminum, (2) the usefulness of automatic arc voltage control for this application, and (3) development of finalized joint designs for thick wall aluminum tubing.

SHIELDING GAS STUDIES

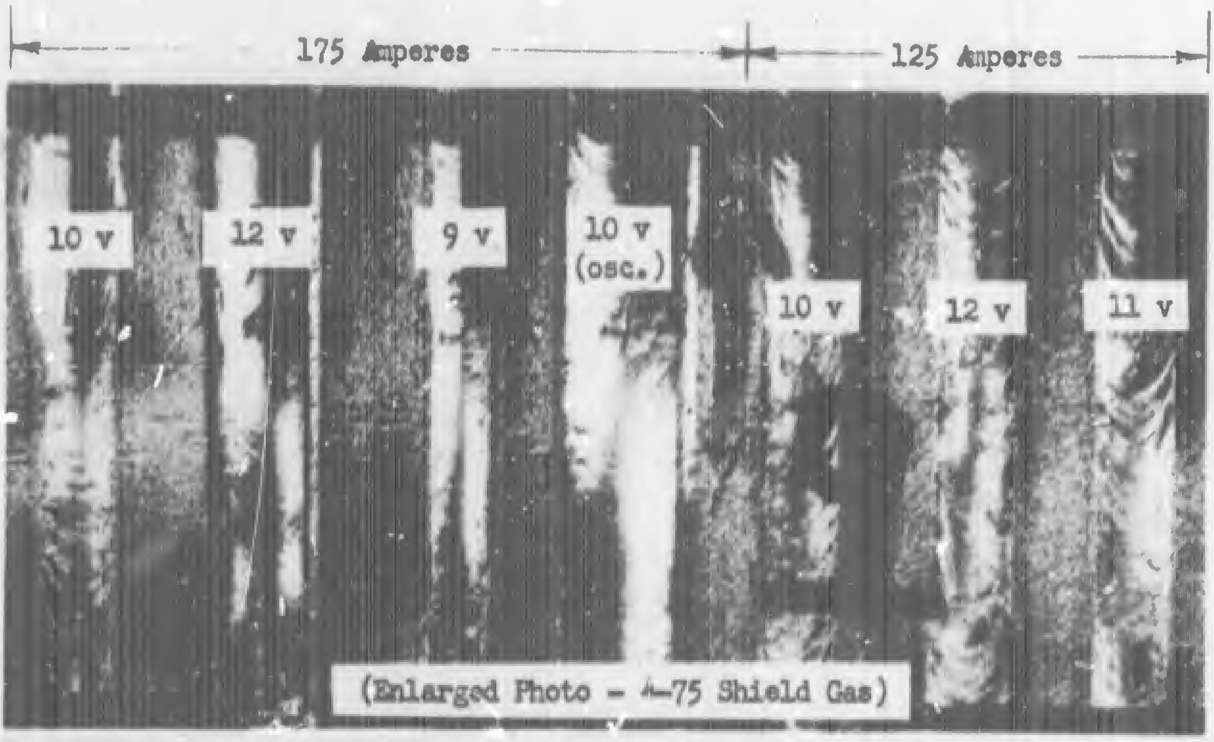
In welding tubing wherein the position is continously varying, it becomes extremely important to more fully evaluate the effects of shielding gases and weld position on control of weld contour and penetration. Inert shielding gas selection affects the weld shape and penetration. The use of argon shielding gas results in welds having less width and penetration than welds made using helium gas; mixtures of the two gases yield results ranging between the two.

Bead-on-plate fusion passes were made on 3-inch OD by 0.250-inch wall Type 347 stainless steel to establish the effects of shielding gas on bead contour and penetration as a function of weld position. The shielding gases investigated were Aircomatic 75 (25 percent argon/75 percent helium), argon, and helium. All welds were made with the tube in the horizontal position using a weld travel speed of 4 inches per minute. Two amperages (175 and 125 amp) were used and maintained constant throughout each run for each gas. Three arc voltages were used for each gas, however, the particular arc voltages selected for the individual gases were not identical due to differences in ionization potential. One weld was also made with each gas using cross-seam torch oscillation. An overall view of the welds is shown in figure 24A. Closeup views at the 9 o'clock position of the welds for each shielding gas are shown in figures 24B , 24C , and 24D. These photographs indicate that (1) with increased amperage and voltage, excessive puddle fluidity results, causing peaking of the weld bead which results in lack of fill at sides of the joint, and (2) for similar weld currents the puddle fluidity is greatest for helium and least for argon. The main point to be observed from the data is that as the weld torch rotates around the tube, the weld puddle shape varies considerably due to gravity, preheat, and puddle fluidity effects. This variation indicates the need for close control of the variables as the welding head rotates through the 360 degree weld path.



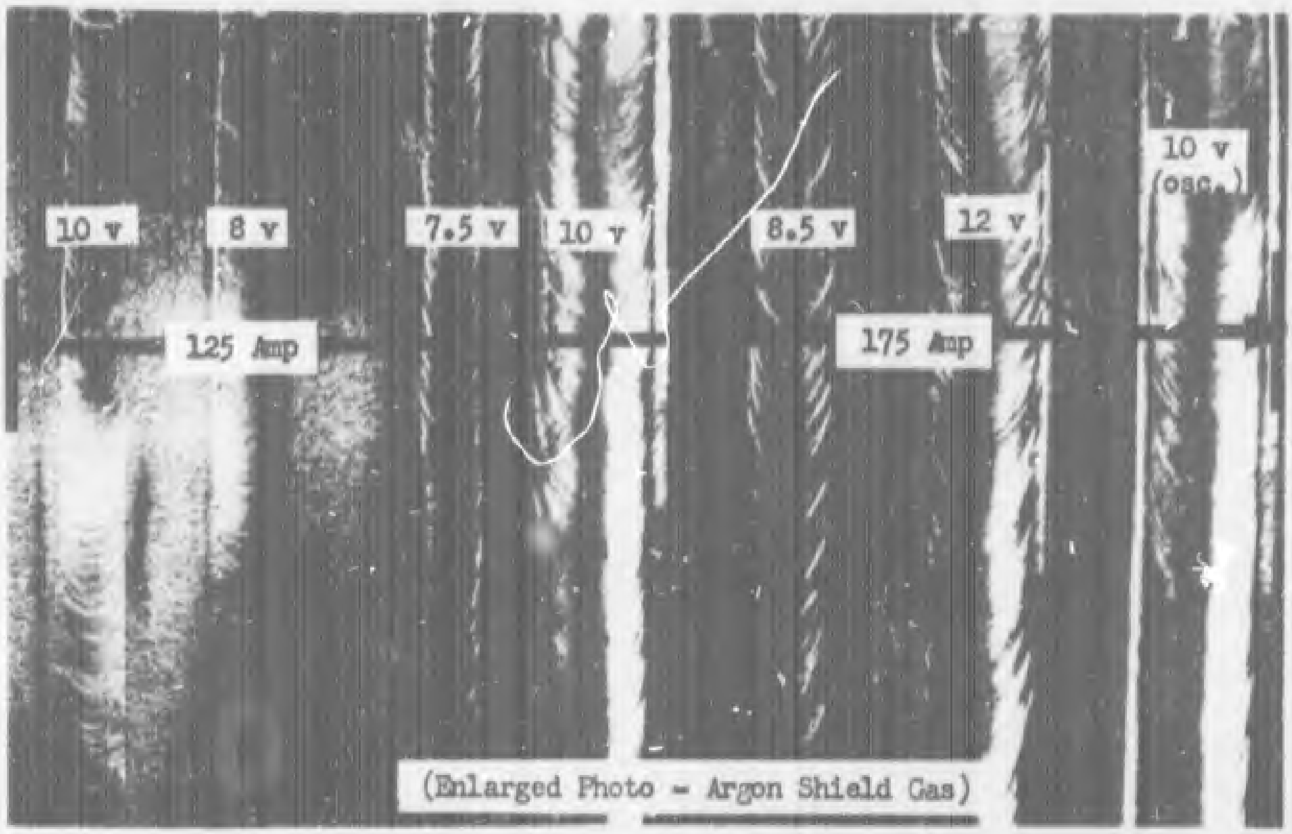
A.

* Shield gas used

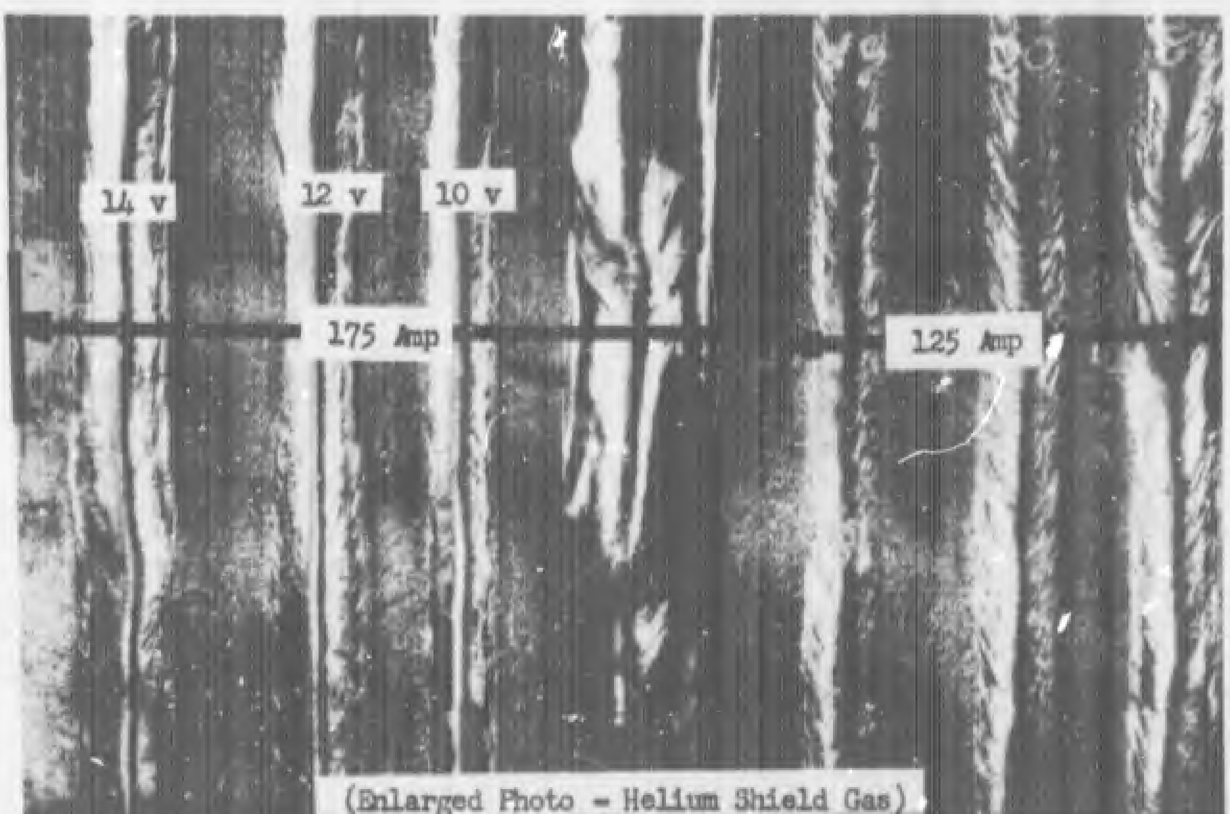


B

Figure 24 Effect of Shield Gas and Position on Weld Bead Control



C



D

Figure 24 Effect of Shield Gas and Position on Weld Bead Control, (cont.)

Studies were also conducted to establish the relationships between arc gap (the distance between the end of the electrode and the weld), arc voltage, and penetration for each gas. Figure 25 illustrates variation in arc length as a function of arc voltage for helium, argon, and Aircomatic 75 shielding gases. One set of data for each gas was obtained by setting the arc gap prior to initiation of the arc (fixed arc gap) while the second set of data for each gas was obtained by adjusting the arc length after arc initiation to obtain a particular voltage, then turning off the power and measuring the arc gap. The two sets of data for each gas correlate very well. In the case of argon shielding gas, small changes in arc voltage caused relatively large changes in arc gap while the reverse was the case for helium; Aircomatic 75 fell between the two. Based upon this data, it could be concluded that argon is optimum for use in fixed arc length welding where sensitivity of voltage with arc length is not desirable since some variation in arc length will probably always occur. However, the effect of arc gap on penetration for the various shield gases, as shown in figure 26, must also be considered. These curves indicate that the use of argon gas also results in a greater variation of penetration with variation in arc voltage, whereas helium shielding gas results in more uniform control of penetration.

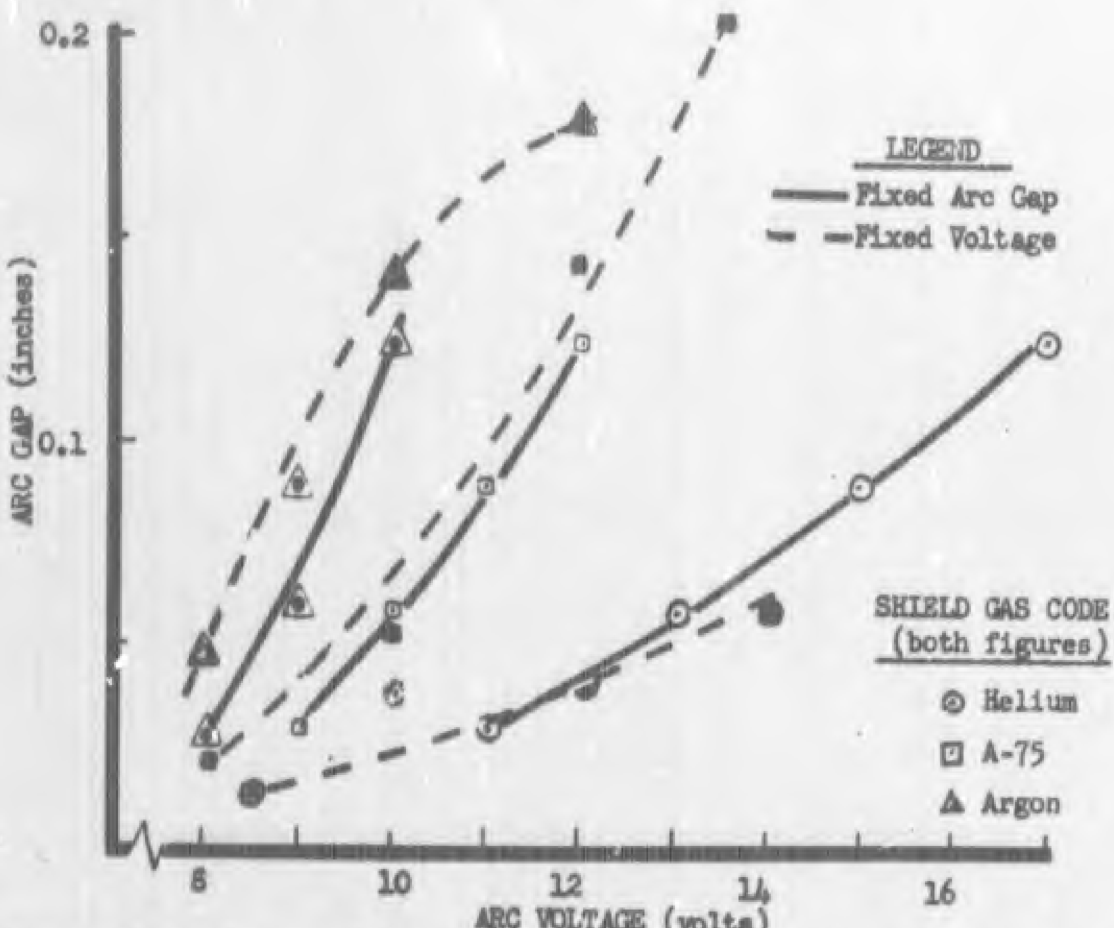


Figure 25 Arc Gap vs. Voltage at 100 Amperes, 0.250-inch Thick Type 347 SS

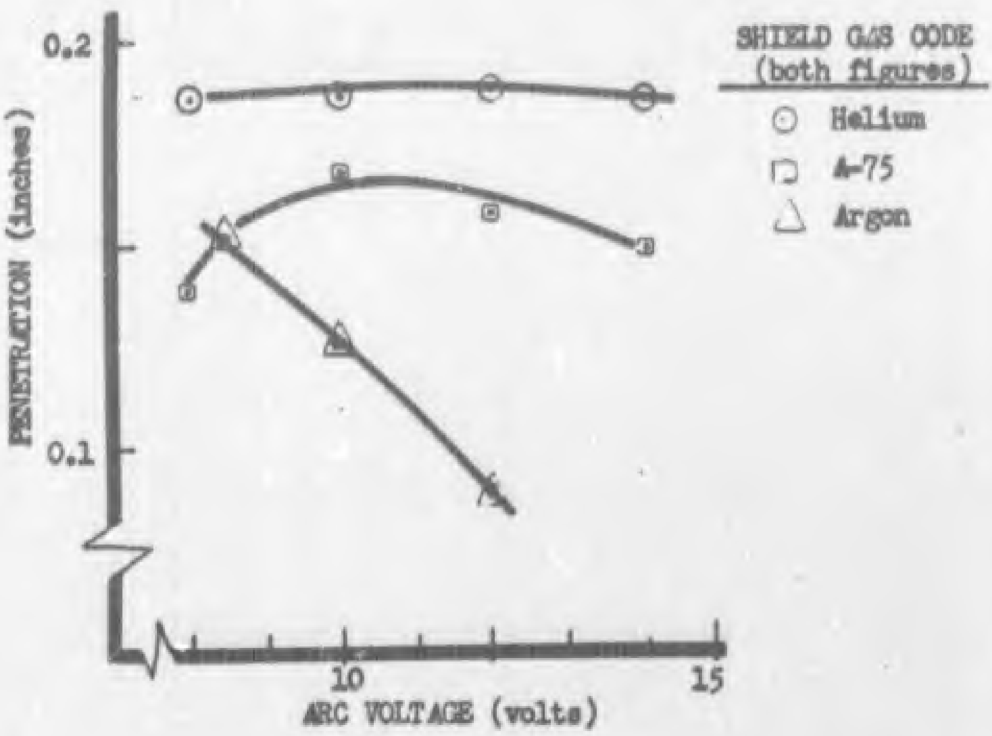


Figure 26. Weld Penetration vs. Voltage at 150 Amperes, 0.250-inch Thick Type 347 Stainless Steel

ELECTRODE CONFIGURATION STUDIES

Tests were conducted to identify the effect of electrode configuration on weld bead contour and effective arc length. Electrode preparation was varied from a pointed electrode with a 30 degree included angle through a blunt (flat) tip. Down hand bead-on-plate welds were made using both fixed arc length and automatic arc voltage control (AVC) while maintaining constant weld current and travel speed. The results indicated that arc length or arc voltage for a particular combination of inert gas, weld current, and electrode configuration is defined by the required emitting area on the tungsten electrode. Assuming the same diameter electrode, using a pointed electrode as opposed to a blunt electrode, results in less available emitting area at the tip of the electrode. Under AVC, or constant arc voltage conditions (floating head), the pointed electrode will seek a shorter arc gap than the blunt electrode and will move towards the weld puddle until the required emitting area is obtained. This can occur to the extent that the electrode actually dips into the weld puddle. In a fixed arc length situation (AVC disabled), since the electrode cannot move to provide the required emitting area for the particular weld current, the arc voltage increases. A blunt or beveled electrode designed to provide the majority of the emitting area at the tip of the electrode appears to be most desireable from a weld bead control standpoint, particularly when welding in a prepared groove.

The effect of varying the electrode included angle on arc voltage in a fixed arc length situation is shown in Table V for a variety of electrode diameters and weld currents in argon and helium inert shielding gases. In each case the pointed electrode required greater arc voltage with the effect being most pronounced under helium shielding gas. As shown in figure 27A, variations in arc voltage as a result of electrode preparation can result in considerable differences in weld bead contour. The magnitude of this effect was further demonstrated by a second series of tests conducted under constant arc voltage control conditions (Table VI). As shown in figure 27B, although the energy input was maintained constant, the shape and penetration of the weld obtained varied considerably with the angle of electrode taper. As the angle of taper was decreased, the AVC system drew the electrode towards the weld puddle until it actually dipped below the surface. Penetration increased from 50 percent through the thickness with a blunt electrode, to full penetration with a 30 degree included angle due to the closer proximity of the arc plasma to the workpiece.

The data indicate that variation in penetration, weld bead width, and the weld puddle control as a funtion of electrode preparation can occur under either constant arc voltage or constant arc length conditions. Automatic welding of tubing therefore, will require precise control of electrode contour to make the application of previously qualified welding parameters feasible. Any shaping of the tungsten tip will require a precision grinding operation to insure reproducible results.

AUTOMATIC ARC VOLTAGE CONTROL STUDIES

Automatic arc voltage control (AVC) was evaluated to determine whether it might be used to compensate for the root pass bead contour and penetration

Table V

CONSTANT ARC GAP CONTROL

0.250 Thick 6061-T6 Aluminum, Travel Speed 6 IPM

Shielding Gas	Arc Gap (In.)	Tungsten Diameter (In.)	Weld Current (Amp)	Electrode Included Angle (Degrees)	Arc Voltage (Volts)
Argon	.050	.040	70	Blunt	11.5 - 12
				30	12 - 15
		.060	135	Blunt	11.5
				30	12 - 13
		.090	225	Blunt	11
				30	13.5
Helium		.040	60	Blunt	18
				30	21 - 25
		.060	90	Blunt	15
				30	19.5
		.090	210	Blunt	13.5
				30	20

Shown in Figure 27A .

Table VI

CONSTANT ARC VOLTAGE (AVC) CONTROL

0.250 Inch Thick 6061-T6 Aluminum, Travel Speed 6 IPM

Shielding Gas	Tungsten Diameter (In.)	Amps	Volts	Electrode Included Angle (Degrees)
Helium	.040	60	18	Blunt
				90
				60
				30
	.060	90	15	Blunt
				90
				60
				30
	.090	210		Blunt
				90
				60
				30

Shown in Figure 27B.

Electrode Included Angle 30° Blunt (Flat)

A.

WELD BEADS USING CONSTANT ARC GAP (Note variations in penetration and bead contour as a result of variation in arc voltage due to electrode contour change.)

(See Table VII for welding parameters)

B.

WELD BEADS USING CONSTANT ENERGY INPUT AND AVC WELDING HEAD (Note variation in penetration as a function of electrode taper.)

Electrode Included Angle 90° Blunt (Flat) 60° 30°

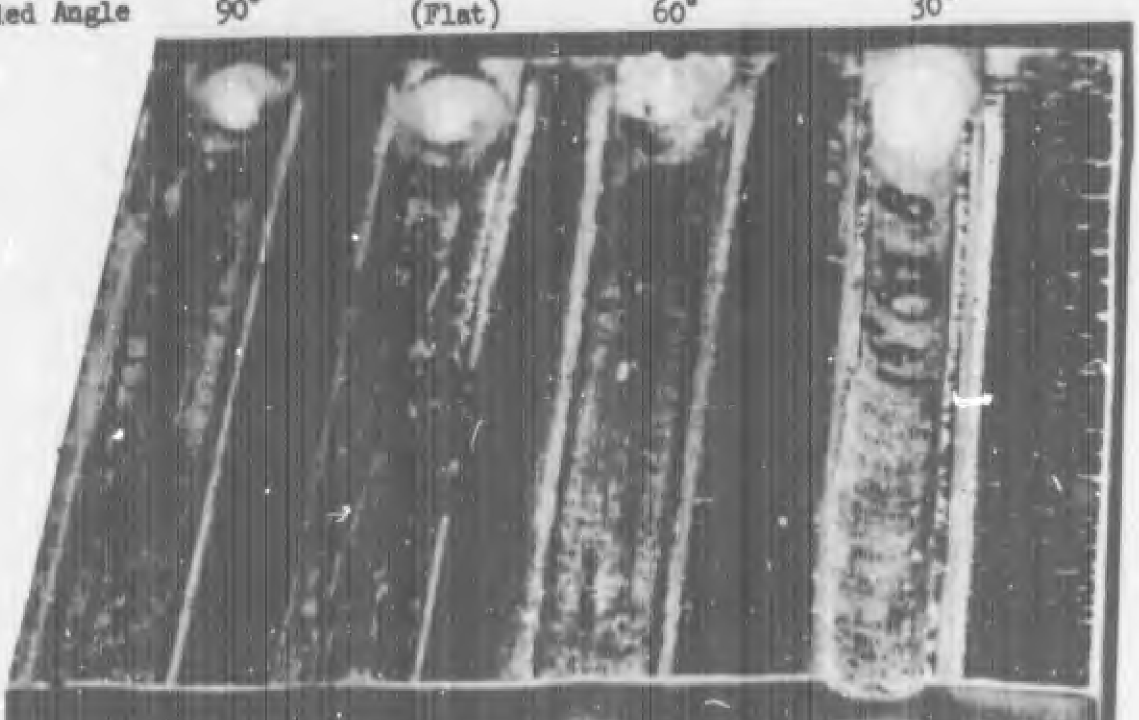


Figure 27 Bead-On-Plate Welds, 0.250-in.-thick 6061-T6 Aluminum, Showing Variations in Penetration and Bead Contour With Varying Conditions

problems encountered in tube welding as a result of gravity effects. A welding head including an AVC unit was attached to a rotating positioner in such a manner as to create a welding condition similar to that of a welding head traversing a pipe with AVC capabilities. Studies were conducted on both stainless and aluminum tubing. The reactions of the various shielding gases were similar to those obtained with a fixed arc length. The voltage with argon shielding gas was not sensitive enough to changes in arc length to permit the necessary corrections as the weld head traversed the pipe. The reactions on both materials were similar, with the aluminum arc voltage being of a lesser magnitude.

The net result with argon was that the weld head would traverse the pipe under varying arc gaps without being reflected as a significant voltage change and, therefore, go uncorrected with the AVC control unit. Since penetration is more sensitive to arc length under argon shielding gas, lack of penetration resulted as the weld progressed.

With helium, a change of arc length was quickly reflected as a voltage change which consequently caused the AVC controls to compensate for the change in arc length. The net result, using helium shielding gas, was to cause the welding head to hunt for the proper arc length in the vertical positions as the weld puddle ran away from the center of the electrode, and to move away from the pipe in the overhead position as the puddle sagged toward the electrode. The resulting welds were wide, concave, and had excessive penetration in the vertical positions and crowning of the puddle in the overhead positions.

The use of AVC to facilitate machine welding of tubing in itself is not considered to be worthwhile. The standard operating mode of AVC actually aggravates the problems caused by gravity effects on the weld puddle, rather than alleviating them. It is concluded to be more important to maintain a controlled arc length and program the weld current for root passes and wire feed rate for filler passes, to compensate for changes in welding postion and heat buildup in the tube.

JOINT DESIGN STUDIES

JOINT DESIGN

Development of optimum design parameters and welding procedures for single Vee and U - groove type joints is currently being pursued using 3-inch diameter aluminum and stainless steel tubing having a 0.250-inch wall thickness, prepared using both types of joints with a variety of land thicknesses and joint openings. The three major areas of concern are minimizing joint opening, developing techniques for obtaining root passes with smooth uniform penetration, and developing techniques for depositing filler passes with smooth bead contour. Weld development is being concentrated on developing current programming procedures and filler metal addition techniques for the penetration and filler passes. The solutions obtained in these areas will be directly applicable to all of the tube sizes requiring automatic addition of filler material. The results obtained on the evaluation of weld joint designs for the 3-inch OD by 0.250-inch wall thickness 6061-T6 tubing are summarized in Table VII. The test joint designs are shown in figure 28.

The basic problem in welding tubing in-place is puddle control. Excessive penetration occurs in the down hand position, and suckback occurs in the overhead position. This problem is more severe in aluminum but occurs to a lesser degree in all materials. The phenomena is apparently created by the inability of the molten weld puddle to sustain its own weight and is aggravated in thicker material due to the requirement for a higher energy input to overcome the heat sink created by the adjacent material. Because the problem is more severe in aluminum, the initial investigations were confined to this alloy, with the solutions considered to be directly applicable to the other alloys.

ROOT PASS WELDING

The root pass welding current requirements, for each series of joints, was established by manually controlling the current to maintain satisfactory visual penetration for the initial joint. The parameters were recorded on a light sensitive tracing paper and used to set the welding control programmer for all subsequent welds. Minor changes were made in the manual program in order to correct any weld bead contour discrepancies occurring during the operation.

Economy of preparation made joints A and B, (figure 28), the most desirable; initial evaluations were made on these Vee-groove configurations. In no case was it possible to maintain consistent weld penetration without suckback in the 6 o'clock position. Variations in weld speed, starting location, and current programming resulted in varying amounts of suckback but in no case was the problem completely eliminated. In general, lower energy input, short arc lengths, and faster wire feeds produced the best results.

Evaluations on U-groove joint types C and D produced results similar to those for types A and B. As with the Vee-joints, it was still not possible to consistently make a weld root pass completely free of suckback. Visual observation of the drop through in conjunction with manual adjustments of current and arc length resulted in acceptable penetration, however, this is not a practical approach since in most installations the inside of the tubing could not be seen, and the success of this technique depends upon operator skill. In summary, it was not possible to obtain root passes in either the standard U or Vee type grooves which were consistently free of suckback in the overhead position. The range of weld parameters used was as follows:

1. Travel speed, 3-to 1[illegible]-inches per minute

2. Filler wire speed, [illegible] to 30-inches per minute

3. Wire diameter, 0.045-and 0.063-inch

4. Arc voltage, 1[illegible]-15 volts (arc length 0.040 to 0.070-inch)

Table VII

SUMMARY OF WELD JOINT DESIGN STUDIES

3-Inch OD by 0.250-Inch Wall 6061-T6 Aluminum Tubing

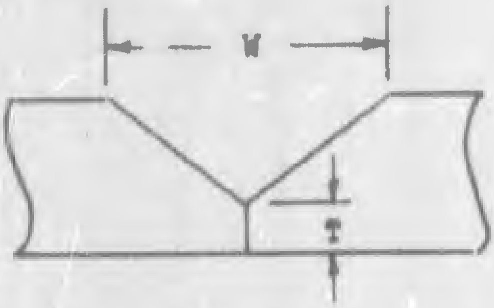
Joint Type **	Joint Opening (In.)	Land Width (In.)	Root Radius (In.)	Slope Degrees	Land Thickness (In.)									
					.040		.060		.080		.100		.125	
					Root	Fill	Root	Fill	Root	Fill	Root	Fill	Root	Fill
A	.400	DNA*	DNA	50°					3	1				
				46°			3	1						
B	.300	DNA	DNA	50°									3	1
				45°							3	1		
				41°					3	1				
				38°			3	1						
				35°	3	2								
C	.400	DNA	.156	55°									3	1
				49°							3	1		
				45°					2	1				
				41°			2	1						
D	.300	DNA	.125	37°									3	1
				33°							3	1		
				31°					2	1				
				27°			2	1						
E	.375	.125	DNA	34°					2	1				
				37°			1	1						
F		.250	DNA	21°			1	3						

*DNA - Does Not Apply
**See Figure 28.

Joint Visual Quality Rating

1. Good
2. Acceptable
3. Poor

JOINT CONFIGURATION	DIMENSIONS

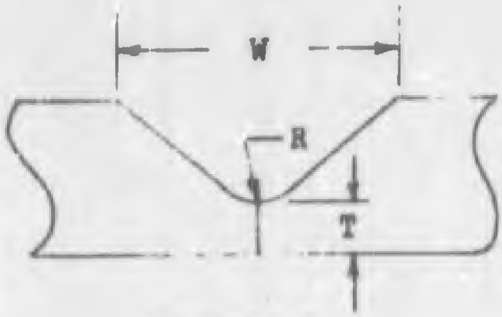


Types A & B

Joint Type A: W = 0.400-inch

Joint Type B: W = 0.300-inch

Land Thickness (T) - See Table VII



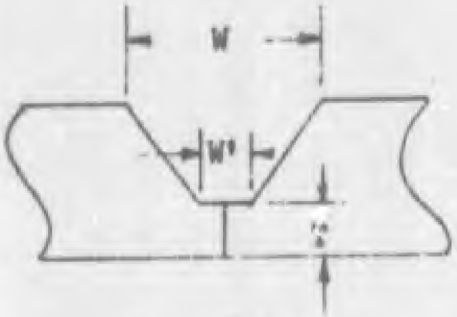
Types C & D

Joint Type C: W = 0.400-inch

Joint Type D: W = 0.300-inch

Land Thickness (T) See Table VII

Root Radius (R) - See Table VII



Types E & F

Joint Type E: W = 0.375-inch
W' = 0.125-inch

Joint Type F: W = 0.375-inch
W' = 0.250-inch

Land Thickness (T) - See Table VII

Figure 28. Welding Joint Configurations for Evaluation Studies

Elimination of suckback on the root pass was finally attained using a modified U-groove type joint design, (types E and F), with oscillation of the welding torch at about 1-1/2 cycles per second. Filler wire 1/16-inch in diameter was added at the rate of 28-inches per minute at a travel speed of 7 inches per minute. A land thickness was selected with sufficient width to permit transverse oscillation of the weld torch, similar to a manual welder welding in an "out-of-position" location. The land thickness selected was 1/16-inch and the land widths were 1/8-inch and 1/4-inch. In both cases transverse oscillation at about 1-1/2 cycles/second was used. The width of oscillation was equivalent to the width of the land. For both land configurations it was possible to obtain satisfactory root pass penetration. The narrower land resulted in better side wall fusion of the root pass. Apparently the torch oscillation is sufficient to allow the weld puddle to freeze and hold the position. A constant taper of 10 to 15 amperes in the welding current was made from the start to the completion of the weld pass. It is believed that the cross seam oscillation technique will also produce satisfactory root pass quality on certain of the standard U-groove weld joint designs. Welding parameters for these joints are shown in Table VIII.

FILLER PASS WELDING

All of the joint designs, with the exception of the 0.250-inch wide land modified U-groove, resulted in satisfactory sidewall and underbead fusion without undercut. Satisfactory filler passes were made with and without cross seam oscillation depending on the width of the groove.

A problem encountered in Vee type joints is the accurate tracking required to remain precisely centered in the joint. As the side walls of the joint become steeper, additional current is required to maintain a molten weld puddle thereby requiring precise tracking. Side wall slope, with the exception of joint type B with the .040 inch land, was adequate to permit good side wall fusion for the fill passes. The 0.400-inch wide joint, however, was impossible to fill without torch oscillation or parallel weld fill passes. Tracking on the standard and modified U-grooves was considerably simpler.

The primary problem encountered during the filler passes was nonuniform weld buildup at different positions. The groove filled faster in the overhead positions, the problem being additive with each subsequent weld pass. The net result was that when the overhead portion of the weld was completed, 1/16-to 3/32-inch concavity remained in the downhand position. This problem was resolved by making the wire feed speed sensitive to changes in arc voltage. If the puddle moves towards the electrode, the arc length and arc voltage are decreased and a signal is generated to decrease wire feed speed. If the weld puddle moves away from the electrode, the situation is reversed. Using this system for making filler passes it has been possible to maintain uniformity of buildup within 0.015 to 0.020-inch. As can be seen in Table VIII, the remaining fill, i.e., amount of joint left to be welded after each pass, is evened out considerably by using this device for filler pass welding. A difference of 0.040-to 0.050-inch in buildup after the root pass was, in each case, brought to within 0.015-inch prior to the last filler pass.

Table VIII

SUMMARY OF WELD PARAMETERS FOR SATISFACTORY JOINT DESIGNS

Joint Design	Travel Speed Inches/Minute	Clock Poisition At Start	Wire Feed (2) Rate Inches/Minute	Weld Pass	Description of Data Obtained	Clock Position 12	3	6	9	12
E (1)	7.1	12	28	Root Pass	WC (3)	117	117	112	96	92
					DT (4)	Full Penetration				
					RF (5)	.145	.120	.105	.105	
		6	Automatic Wire Feed To	Filler Pass #1	WC	92	92	92	92	92
			Maintain 15 Volts		RF	.095	.088	.083	.075	
		9		Filler Pass #2	WC	92	92	92	92	92
					RF	.055	.057	.060	.049	
		3		Filler Pass #3	WC	102	102	102	102	102
					RF	.040	.040	.040	.025	
		9		Filler Pass #4	WC	102	102	102	102	102
					RF	Build Up				
F (1)	7.1	12	28	Root Pass	WC	112	104	84	70	70
					DT	Full Penetration				
					RF	.180	.158	.138	.157	
		6	Automatic Wire Feed To	Filler Pass #1	WC	84	84	84	84	84
			Maintain 13 Volts		RF	.116	.105	.115	.104	
		12		Filler Pass #2	WC	84	84	84	84	
					RF	Build Up				

NOTE:

(1) Reference Figure 28 .

(2) Arc Gap 0.090-Inch, Helium Shield Gas CFH, Blunt Tungsten Electrode

(3) WC - Weld Current

(4) RF - Remaining Fill

(5) DT - Drop Through

In addition, it can be seen that joint type F was filled up in a total of three passes versus a total of five passes for joint type E, in spite of the larger opening. This was accomplished by decreasing the control arc voltage while utilizing the same initial arc gap, thereby increasing the rate of wire feed.

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Section VI

ADVANCED MATERIAL SELECTION

The use of advanced materials for tankage in future liquid rocket systems pose the requirement that similar materials be used in the connecting tubing systems in order to obtain the requisite compatibility of material properties. The analytical study described in this report was conducted to select tubing materials which might be used for advanced liquid rocket systems.

The study was directed toward four basic categories of tubing alloys, i.e., aluminum, titanium, nickel-base and iron-base alloys, with the objective of identifying the most promising alloy in each category for use in welded fitting applications.

Available data on the compatibility of liquid rocket propellants and oxidizers with various materials were reviewed. Compatibility information for the more advanced materials, such as the alloys selected for evaluation, was found to be either incomplete or nonexistent. Consequently, valid comparisons of the candidate alloys within a material category could not be made on the basis of chemical compatibility; therefore, this criterion was not used in the detailed evaluation.

Structural properties data for the candidate alloys were compiled and evaluated. Tensile properties were compiled within the anticipated applicable service temperature ranges, and structural efficiencies were determined and examined. Notch-strength properties were evaluated to determine the susceptibility to embrittlement of the candidate alloys at cryogenic temperatures.

The indicated welding and machining characteristics of the candidate alloys were examined. Weldability was evaluated and compared on the basis of the indicated capability of the material to be satisfactorily joined by the TIG fusion welding process. Relative machinability was evaluated on the basis of comparison with a free-machining steel.

On the basis of the evaluations performed, the alloy selected as being the most attractive candidate in each of the four material categories was as follows:

Aluminum:	Alloy 2219
Titanium:	Ti-6Al-4V
Nickel-Base:	Inconel 718
Iron-Base:	21Cr-6Ni-9Mn

An industry survey of tubing suppliers was conducted to determine the availability and cost of the candidate alloys. There is a material availability problem, however, with the procurement of Ti-6Al-4V. As the present availability of Ti-6Al-4V tubing is limited, it was recommended that commercially pure titanium tubing be procured for use in the development of welding techniques, and that Ti-6Al-4V tubing be used only for verification of the techniques developed. A summary of the tubing alloys and sizes to be procured for this program is shown in Table IX.

Table IX

TUBING MATERIALS PROCUREMENT LIST

Material	Diameter (Inches)	Wall (Inches)	Length (Feet)
Aluminum Alloy 2219	1/4 1/2 1 2-1/2	.035 .058 .055 .120	50 50 50 50
Titanium 6Al-4V	1	.055	50
Ti 40 or Ti 55	1/4 1/2 1 2-1/2	.035 .058 .055 .120	50 50 50 50
Inconel 718	1/4 1/2 1 2-5/8	.035 .058 .055 .125	50 50 50 50
Iron-Base Alloy 21Cr-6Ni-9Mn	1/4 1/2 1 3	.035 .058 .055 .125	50 50 50 50

CRITERIA FOR MATERIALS EVALUATION

Aluminum, titanium, nickel-base and iron-base alloys were screened with regard to their potential applicability for the tubing systems displayed in Table X , and candidate alloys were selected for evaluation studies. The principal criteria which were considered in the selection and evaluation of the candidate alloys are described in the following paragraphs.

CHEMICAL COMPATIBILITY

A primary requirement for a tubing material which is to be used in liquid rocket systems is that it be chemically compatible with the fluids which will be contained and transported during anticipated service. The fluid must not attack the tubing or otherwise degrade its mechanical material properties, nor the tubing material cause any change in the composition of the fluid, either by direct or catalytic reaction. During previous studies (Reference 1) the fluids listed in Table XI were established as being representative of future liquid systems; consequently, these fluids were used for the chemical compatibility considerations.

STRUCTURAL PROPERTIES

The structural properties of a liquid rocket system tubing material are extremely important because of the requirement in these systems for minimum weight consistent with structural integrity. The strength-to-weight and stiffness-to-weight ratios within the anticipated system operating temperature range are the properties generally used for evaluation of these materials. The susceptibility of a material to embrittlement within the temperature range of anticipated service is also evaluated. Other structural properties of a tubing material which may be evaluated include the fatigue characteristics, for applications where repeated stress cycling or vibration will be encountered; and the creep strength, for applications involving significant periods of time at elevated temperatures.

WELDING CHARACTERISTICS

It is axiomatic that a tubing material for use in welded fitting applications should be capable of being satisfactorily joined by the TIG fusion welding process. The designation "satisfactory welding characteristics" signifies that good quality weldments can be consistently produced in the material, and that the strength properties of the weldment will, as a minimum, approximate those of the material in the annealed condition.

MACHINING CHARACTERISTICS

The requirement for "in-place" joint preparation in the fabrication of welded fittings makes the machining characteristics of the tubing material an important consideration. Machinability is, in general, a function of the strength, strain hardening, and abrasive characteristics of a material. An indication of the machining characteristics of a material can be obtained from an overall machinability rating. This rating is derived experimentally

Table X

CLASSIFICATION OF TUBING SYSTEMS *

Service	System Operating Pressure Range	System Operating Temperature Range	System Tubing Dimensional Range
Propellant	0 to 2500 psig	-423°F to 200°F	½ to 2 inches in 1/4-inch increments 2 to 3 inches in 1/2-inch increments 3 to 5 inches in 1-inch increments 6 to 16 inches in 2-inch increments
Pneumatic	0 to 3000 psig	-320°F to 200°F	1/8 to 1/4 inch in 1/16-inch increments
	0 to 1000 psig	-320°F to 200°F	5/16 to 1 inch in 1/16-inch increments
	0 to 10,000 psig	-320°F to 600°F	1/8 to 1 inch in 1/16-inch increments
	0 to 4000 psig	-320°F to 1500°F	

* Established under Contract No. AF04(611)-8177 as being typical of future liquid rocket systems.

Table XI

LIQUID ROCKET SYSTEM FLUIDS

Tubing Service Classification	Fluid-Type Classification	Description of Rocket System Fluid
Propellant	Storable Propellants	(a) UDMH-Hydrazine Blends (0 to 100 percent N_2H_4) (b) Hydrogen Peroxide (c) Nitrogen Tetroxide (d) Chlorine Trifluoride (e) Pentaborane (f) Red Fuming Nitric Acid (g) White Fuming Nitric Acid (h) RP-1 (i) MMH (j) N_2F_4
	Cryogenic Propellants	(k) Liquid Oxygen (l) Liquid Hydrogen (m) Liquid Fluorine (n) OF_2 (o) ClO_3F
Pneumatic	Ambient Temperature Gases	(p) Gaseous Oxygen (q) Gaseous Hydrogen (r) Gaseous Nitrogen (s) Gaseous Helium
	Elevated Temperature Gases	(t) High Temperature Hydrogen Gas (u) High Temperature Helium Gas (v) High Temperature Combustion Products Associated with solid and Liquid Propellants Reactions (Flow rates of the order of 2 pounds per second)

by the force and power required to remove an assigned amount of material within an assigned interval of time by various machining methods. The ratings are based on a comparison with a free-machining grade of steel which is assigned an arbitrary value of 100.

AVAILABILITY AND COST

The consideration of a material for application in a tubing system implies that the material can be fabricated into tubing and made available for procurement within reasonable delivery and cost schedules. The majority of tubular shapes are produced by either drawing or seam-welding fabrication processes. Thus, the availability and the cost of a material in the form of tubing are dependent principally upon three factors: (1) the workability of the material, i.e., the relative ease with which the material can be fabricated into tubing; (2) the availability and cost of the material, itself, in the form of the required raw stock; and (3) the dimensional size and quantity of tubing ordered. Nonstandard sizes are difficult to obtain, and the cost of special dies is prohibitive for anything less than large quantity orders.

ALLOYS SELECTED FOR EVALUATION

Currently available alloys in each of the designated material categories were screened for their compatibility with the requirements of future liquid rocket systems. Twenty-three alloys displaying potential applicability were selected for more detailed study, the list being as follows:

Aluminum Alloys	Titanium Alloys	Nickel-Base Alloys	Iron-Base Alloys
2219	5Al-2.5Sn	Inconel 625	21Cr-6Ni-9Mn
5083	6Al-4V	Inconel X	19-9DL
6061	8Al-1Mo-1V	Inconel 718	A-286
7039	13V-11Cr-3Al	René 41	N-155
		Waspaloy	Carpenter "Custom 455"
		Hastelloy R-235	AM-350
		Hastelloy X	SS Type 304L
			SS Type 347

Several of the alloys selected for study had been evaluated during a previous, related program (Reference 1) but were included in the current study for comparison purposes. A brief description of the alloys and their characteristics is presented in the following paragraphs.

ALUMINUM ALLOYS

The four aluminum alloys selected for evaluation were 2219, 5083, 7039, and 6061, the latter being an alloy which was evaluated during a previous programs (Reference 1, 14). The nominal composition of each of these alloys is listed in Table XII; pertinent characteristics are summarized in Table XIII.

Table XII

NOMINAL COMPOSITIONS OF CANDIDATE ALUMINUM ALLOYS

Alloy	Composition, Percent						
	Cu	Mn	Mg	Zn	Si	Cr	Al
2219	6.3	0.3	--	--	--	--	Bal
5083	--	0.6	4.5	--	--	0.15	Bal
7039	--	0.3	2.8	4.0	--	0.20	Bal
6061	0.3	--	1.0	--	0.6	0.25	Bal

Table XIII

CHARACTERISTICS OF CANDIDATE ALUMINUM ALLOYS

Alloy	Type	Characteristics	Weldability	Strength
2219	Al-Cu	Elevated temp. applications	Good	Superior
5083	Al-Mg	Good corrosion resistance	Good	Moderate
7039	Al-Zn-Mg	High strength-toughness properties	Good	Good
6061	Al-Mg-Si	Good forming/corrosion resistance	Good	Moderate

All four alloys selected are suitable for use at cryogenic temperatures. Alloy 2219 exhibits good fusion welding characteristics and mechanical properties as compared to other heat-treatable aluminum alloys of similar strength. Alloy 5083 is the only alloy of the four which is not heat treatable, and is strengthened by cold working. Alloy 7039 is a recently developed material which offers the desirable combination of high strength and toughness properties, good weldability, and good stress corrosion resistance, making it well suited for applications involving cryogenic temperatures. Alloy 6061 was included in the selection as it is currently the most common alloy found in liquid propellant systems.

TITANIUM ALLOYS

The nominal composition of the titanium alloys selected for evaluation is listed in Table XIV, and pertinent characteristics are summarized in Table XV. The general corrosion resistance of all four titanium alloys is listed as excellent. The extra low interstitial grade of 5Al-2Sn alloy is well suited for applications at cryogenic temperatures. Strength properties of this alloy are not increased by thermal treatment.

The 8Al-1Mo-1V alloy offers the highest elastic modulus and lowest density of any commercially available titanium alloy. While welding characteristics are excellent in the duplex annealed condition, they are marginal in the mill annealed condition. This alloy is normally used in the duplex annealed condition to provide toughness properties.

The 6Al-4V alloy is widely used in the aerospace industry. It provides good strength properties in the annealed condition and can be further strengthened by solution and aging thermal treatments.

Beta-type alloy 13V-11Cr-3Al possesses the best formability properties of all the titanium alloys. It has good strength properties in the solution treated condition. [illegible] hardening will produce high strength levels, but results in a marked r[illegible]ction in toughness properties.

NICKEL-BASE ALLOYS

Nominal composition and general characteristics of the nickel-base alloys selected for evaluation are shown in Tables XVI and XVII, respectively. The corrosion and oxidation resistance of these alloys ranges from good to excellent. Of these alloys, Inconel 625 is a newly developed, nonheat-treatable nickel-chronium alloy which is solution strengthened by substantial additions of molybdenum and columbium. This alloy possesses excellent oxidation resistance at temperatures up to 1800°F, and good general corrosion resistance.

Inconel X is a well established age-hardenable alloy which offers good strength properties at temperatures up to 1200°F. The heat treatability of the alloy is due to additions of titanium, columbium, and aluminum. While the welding characteristics are satisfactory, the alloy is susceptible to strain age cracking.

Table XIV

NOMINAL COMPOSITIONS OF CANDIDATE TITANIUM ALLOYS

Alloy	Composition, Percent								
	Al	Sn	Mo	V	Cr	C*	N*	H*	Ti
5Al-2.5Sn	4.0-6.0	2-3	--	--	--	0.08	0.05	0.175	Bal.
8Al-1Mo-1V	7.5-8.5	--	0.75-1.25	0.75-1.25	--	0.08	0.05	0.015	Bal.
6Al-4V	5.75-6.75	--	--	3.5-4.5	--	0.08	0.05	0.015	Bal
13V-11Cr-3Al	2.5-3.5	--	--	12.5-14.5	10.0-11.0	0.05	0.08	0.025	Bal.

* Maximum

Table XV

CHARACTERISTICS OF TITANIUM ALLOYS

Alloy	Type	Characteristics	Weldability	Strength
5Al-2.5 Sn	Alpha	Good strength	Satisfactory	Good
8Al-1Mo-1V	Alpha-Beta	High elastic modulus, low density	Good *	Good
6Al-4V	Alpha-Beta	Broad base application;	Good	Good
13V-11Cr-3Al	Beta	Excellent formability	Satisfactory	Good

* In duplex annealed condition

Table XVI

NOMINAL COMPOSITIONS OF CANDIDATE NICKEL-BASE ALLOYS

Alloy	Composition, Percent										
	C	Cr	Mo	W	Al	Ti	Cb	Co	B	Fe	Ni
Inconel X	0.05	15.5	--	--	0.7	2.5	0.9	--	--	7.0	70
Inconel 625	0.05	22.0	9.0	--	--	--	4.0	--	--	3.0	61
Inconel 718	0.05	18.0	3.0	--	0.4	0.8	5.0	--	--	20.0	52
René 41	0.06	19.0	10.0	--	1.5	3.2	--	11.0	0.005	3.0	51
Waspaloy	0.05	19.0	4.0	--	1.2	3.0	--	13.0	0.005	1.0	57
Hastelloy R-235	0.08	16.0	5.5	--	2.0	2.5	--	--	--	10.0	62
Hastelloy X	0.10	22.0	9.0	0.6	--	--	--	1.5	--	18.5	47

Table XVII

CHARACTERISTICS OF NICKEL-BASE ALLOYS

Alloy	Type	Characteristic	Weldability	Strength
Inconel 625	Ni-Cr	Nonheat-treatable, good formability	Excellent	Good
Inconel X	Ni-Cr	Age-hardenable, heat-treatable	Satisfactory *	Good up to 1200°F
Inconel 718	Ni-Cr-Fe	Precipitation hardening with slow diffusion rate	Good	High strength and formability
René 41	Ni-Cr-Mo	Precipitation hardenable	Poor *	Superior to 1600°F
Waspaloy	Ni-Cr-Co	Precipitation Hardenable	Poor *	Good up to 1600°F
Hastelloy X	Ni-Cr-Fe	Nonheat-treatable solution strengthened	Excellent	Good

* Susceptible to strain age cracking

Inconel 718 is a precipitation-hardening alloy which combines high strength properties with good weldability. The slow diffusion rate of the precipitation hardening elements results in a sluggish hardening reaction which is beneficial to welding and forming processes. The alloy is readily welded in either the annealed or hardened condition.

René 41, Waspaloy and Hastelloy R-235 are also precipitation hardenable alloys possessing good strength/oxidation/corrosion resistance properties at temperatures up to 1600°F. However, these alloys are susceptible to strain-age cracking which makes welding difficult and limits the usefulness of the alloys for welded fitting applications.

Hastelloy X is a nonheat-treatable, solution strengthened alloy possessing excellent oxidation resistance at temperatures up to 2200°F. Like other solution strengthened nickel-base alloys, Hastelloy X offers good welding characteristics.

IRON-BASE ALLOYS

The composition and general characteristics of the iron-base alloys selected for evaluation are listed in Tables XVIII and XIX, respectively. Of these, the AM-350 and Type 304L, -347 stainless steel alloys were among those evaluated during previous studies (Reference 1). However, these alloys were included in the present evaluation for purpose of comparison.

All alloys in this group offer good oxidation and corrosion resistance, with some variation in the maximum temperature range. Weldability is, in general, good for all alloys in this group, although some alloys are susceptible to intergranular cracking in the heat affected zone unless the weldment is heat treated after welding. Pertinent factors and the attendant differences are shown in Table XIX.

Armco 21-6-9 is a nonheat-treatable austenitic stainless steel which is designed for use in applications requiring a combination of high strength and corrosion resistance. Its mechanical properites in the annealed condition are consideratly higher than those of the conventional Type 300 series of stainless steels. A combination of high strength and toughness at subzero temperatures makes this alloy an excellent candidate for cryogenic applications.

The corrosion resistance of AM-350 and Custom 455 alloys is inferior to the Type 300 series of stainless steels. Weldability of Type 304L and 347 stainless steel is excellent as neither of the alloys are susceptible to intergranular corrosion in the weld heat-affected zone.

Table XVIII

NOMINAL COMPOSITIONS OF CANDIDATE IRON-BASE ALLOYS

Alloy	Composition, Percent												
	C	Mn	Cr	Ni	Mo	Cb	Ti	W	Cu	Co	V	N	Fe
21-6-9	0.03	9.0	20.0	6.5	--	--	--	--	--	--	--	0.3	64
19-9DL	0.30	1.0	19.5	10.0	1.5	0.5	0.2	1.5	--	--	--	--	65
N-155	0.15	1.5	21.0	20.0	3.0	1.0	--	2.5	--	20.0	--	--	30
A-286	0.05	1.5	15.0	26.0	1.3	--	2.2	--	--	--	0.2	--	52
Custom 455	0.02	0.25	12.0	8.5	--	0.4	1.1	--	2.0	--	--	--	75
AM-350	0.10	1.0	16.5	4.5	2.8	--	--	--	--	--	--	0.1	75
347	0.05	1.0	18.0	10.5	--	0.8	--	--	--	--	--	--	69
304L	0.02	1.0	19.0	10.5	--	--	--	--	--	--	--	--	69

Table XIX

CHARACTERISTICS OF IRON-BASE ALLOYS

Alloy	Type	Characteristic	Oxidation Resistance*	Weldability	Strength
21-6-9	Austenitic SS	Nonheat-treatable	High	Excellent	Good
19-9DL	Austenitic SS	Nonheat-treatable	1500°F	Excellent (1)	Good
N-155	Austenitic	Solution strengthened	1600°F	Good	Good
A-286	Cr-Ni Austenitic	Age-hardening	1500°F	Satisfactory (2)	Superior
AM-350	Semiaustenitic SS	Age-hardening	1400°F	Good (3)	Superior
Custom 455	Martensitic SS	Precipitation hardened	1200°F	Good	Superior
304L	Austenitic SS	Low-carbon	1500°F	Excellent	Moderate
347	Austenitic SS	Columbium stabilized	1500°F	Excellent	Moderate

(1) Susceptible to intergranular corrosion in weld zone unless solution annealed after welding.

(2) Susceptible to hot cracking in multipass welds

(3) Susceptible to intergranular corrosion in weld zone unless heat treated after welding.

CANDIDATE ALLOY EVALUATION

COMPATIBILITY WITH ROCKET SYSTEM FLUIDS

The compatibility of materials with rocket propellants and oxidizers has been the subject of many investigations; for example, Reference 2 , which summarizes the available information on the compatibility of liquid rocket propellants with various materials of construction, lists 302 reference sources. A review of these data and the information obtained and reported by NAA during a previous program (Reference 1) disclosed:

1. The majority of the data reported are based on compatibility with the well-established materials of construction.

2. The compatibility data are concerned principally with comparisons between material categories rather than with alloys within a particular material category.

3. Compatibility data for more advanced materials, such as the alloys selected for the subject evaluation studies, are limited, incomplete, and, in many instances, nonexistent.

The objective of the subject program was to identify the most promising alloy within each of the four material categories rather than to perform comparisons between the material categories. However, due to the present unavailability of data, a detailed, evaluation could not be made on the alloys within each category (although some general conclusions regarding chemical compatibility could be made, e.g., aluminum alloys 5083 and 6061 will display overall superiority to the high copper-bearing alloy 2219 with regard to compatibility with rocket system fluids). Consequently, chemical compatibility criteria were not a prominent factor in the selection of the most attractive candidate alloy in each of the four material categories.

STRUCTURAL PROPERTIES

Properties data considered significant for the evaluation of potential tubing alloys were compiled for the candidate aluminum, titanium, nickel-base, and iron-base alloys. The properties data compiled include the following: tensile ultimate strength (F_{tu}), tensile yield strength (F_{ty}), modulus of elasticity (E), mean coefficient of thermal expansion (Alpha), and density. The tensile properties were compiled within the anticipated service temperature range considered applicable for each of the material categories as follows:

1. -423°F to 300°F for the aluminum alloys

2. -423°F to 1000°F for the titanium alloys

3. -423°F to 1400°F for the iron-base alloys

4. -423°F to 1600°F for the nickel-base alloys

Tables XX, XXI, XXII, and XXIII list the typical properties for the aluminum, titanium, and nickel-base, and iron-base alloys, respectively. From these data, the structural efficiencies of the candidate alloys were calculated and are listed in Tables XXIV through XXVI. Additional compilations were made of those data available regarding the notch-strength ratios (Notch strength/unnotch strength) of the candidate alloys: these data are listed in Table XVII and plotted in figures 24-32. The various sources which were used in the compilation of the properties data are listed in References 3 through 14.

As indicated in Tables XX through XXIII, the properties listed for each of the alloys is representative of either an annealed (solution treated) or a heat treated (solution treated and aged) condition. The properties of those alloys that can be strengthened only by cold working, or which display their optimum properties in this condition, are listed in the annealed condition; the properties of those alloys that can be strengthened by heat treatment, and which are normally used in this condition, are listed in the heat treated condition. This is a factor which has to be considered in the evaluation of alloys for welded fitting applications since the strengthening resulting from heat treatment will be eliminated in the fusion and heat-affected zones during the welding process.

Aluminum Alloys

From the structural efficiency data displayed in Tables XXIV and XXV, it is apparent that 2219-T81 and 7039-T6 display strength efficiencies which are superior to those of the other two alloys. Figure 29 shows the low-temperature notch strength ratios for three of the alloys. The 6061-T6 and 2219-T81 appear to be slightly superior to 7039-T6 at cryogenic temperatures.

Titanium Alloys

The structural efficiencies data in Tables XXIV and XXV show that from a strength standpoint, the 6Al-4V, 8Al-Mo-IV, and 13V-11Cr-3Al alloys are comparable at temperatures up to 800°F; the 8Al-1Mo-IV, however, is superior on the stiffness criterion. The notch tensile ratios for three of the candidate alloys are plotted in figure 30. It is apparent from the data that Ti 13V-11Cr-3Al is embrittled by exposure to cryogenic temperatures. Also, the beneficial effect upon the low temperature notch-strength characteristics of titanium alloys resulting from a reduction in the interstitial content should be noted by reference to the 5Al-2.5Sn(ELI) plots in comparison to the plots for conventional 5Al-25Sn.

Nickel-Base Alloys

Based on the structural efficiencies of the candidate nickel-base alloys displayed in Tables XXIV and XXV, Inconel 718, René 41, Waspaloy, and Hastelloy R235 are comparable at temperatures up to 1000°F; above 1000°F, René 41 displays the superior efficiencies. The notch tensile ratios for four of the nickel-base alloys at low temperatures are shown in figure 31; it is apparent that each of these alloys has good notch strength characteristics at cryogenic temperatures.

Table XX

TYPICAL PROPERTIES OF CANDIDATE ALUMINUM ALLOYS

Alloy	Density lb/in³	Property	Temperature, °F						
			-423	-320	-110	0	70	200	300
2219 (Heat Treated, T81 Temper)	0.102	F_{tu}, ksi	95	80	69	66	65	59	54
		F_{ty}, ksi	65	60	53	52	50	48	45
		E, 10^6 psi	12.5	11.9	11.1	10.7	10.6	10.3	9.9
		Alpha, 10^6 in/in/°F				(70°F-212°F)		12.4	
5083 (Annealed, O Temper)	0.096	F_{tu}, ksi	65	63	51	47	42	44	30
		F_{ty}, ksi	25	22	20	21	21	22	19
		E, 10^6 psi	11.3	11.1	10.7	10.5	10.3	10.1	9.8
		Alpha, 10^6 in/in/°F				(70°F-212°F)		13.2	
7039 (Heat Treated, T6 Temper)	0.099	F_{tu}, ksi	95	82	69	66	65	55	48
		F_{ty}, ksi	74	68	60	59	58	51	45
		E, 10^6 psi	12.1	11.5	10.6	10.3	10.2	10.0	9.7
		Alpha, 10^6 in/in/°F				(70°F-212°F)		13.3	
6061 (Heat Treated, T6 Temper)	0.098	F_{tu}, ksi	75	62	50	47	45	41	34
		F_{ty}, ksi	53	48	42	40	37	37	28
		E, 10^6 psi	10.9	10.5	10.2	10.1	10.0	9.8	9.5
		Alpha, 10^6 in/in/°F				(70°F-212°F)		13.0	

Table XXI

TYPICAL PROPERTIES OF CANDIDATE TITANIUM ALLOYS

Alloy	Density lb/in^3	Property	Temperature, °F									
			-423	-320	-110	0	70	200	400	600	800	1000
5Al-2.5Sn (Annealed)	0.162	F_{tu}, ksi	250	200	150	135	125	111	92	79	72	62
		F_{ty}, ksi	230	182	138	124	115	102	83	67	57	51
		E, 10^6 psi	18.6	17.7	16.4	15.8	15.5	15.2	14.7	13.7	12.4	9.9
		Alpha, 10^6 in/in/°F					(70°F to 1000°F)					5.3
8Al-1Mo-1V (Duplex Annealed)	0.158	F_{tu}, ksi	240	210	162	145	140	125	105	98	84	73
		F_{ty}, ksi	210	190	150	135	130		101	94	81	70
		E, 10^6 psi	21.5	18.8	18.0	17.6	17.5	16.9	16.1	15.5	14.0	11.0
		Alpha, 10^6 in/in/°F					(70°F to 1000°F)					5.6
6Al-4V (Annealed)	0.160	F_{tu}, ksi	240	210	160	140	135	123	108	101	90	73
		F_{ty}, ksi	225	195	145	130	125	111	93	84	77	55
		E, 10^6 psi	18.9	17.4	16.5	16.3	16.0	15.4	14.2	13.1	12.0	8.0
		Alpha, 10^6 in/in/°F					(70°F to 1000°F)					5.3
13V-11Cr-3Al (Solution Treated)	0.174	F_{tu}, ksi	--	275	175	150	140	126	119	116	112	84
		F_{ty}, ksi	--	260	170	140	130	113	107	100	95	75
		E, 10^6 psi	--	--	--	--	14.5	14.4	13.9	13.1	12.2	10.5
		Alpha, 10^6 in/in/°F					(70°F to 1000°F)					5.9

Table XXII

TYPICAL PROPERTIES OF CANDIDATE NICKEL-BASE ALLOYS

Alloy	Density lb/in^3	Property	Temperature, °F -423	-320	-110	0	70	400	600	800	1000	1200	1400	1600
Inconel X (Solution Treated-Aged)	0.300	F_{tu}, ksi	210	207	187	168	165	155	147	139	124	102	72	36
		F_{ty}, ksi	130	118	115	108	102	93	91	86	75	62	45	32
		E, 10^6 psi	32	31.5	31	31	31	29	28	27	26	24	—	—
		Alpha, 10^6 in/in/°F					(70°F to 1600°F)							9.2
Inconel 625 (Annealed)	0.305	F_{tu}, ksi	—	165	145	140	135	125	120	118	118	115	70	42
		F_{ty}, ksi	—	76	68	66	65	52	48	45	45	45	45	41
		E, 10^6 psi	—	—	—	—	30	29	28	27	26	25	23	—
		Alpha, 10^6 in/in/°F					(70 F° to 1600°F)							8.8
Inconel 718 (Solution Treated-Aged)	0.297	F_{tu}, ksi	275	230	215	200	190	170	163	160	160	150	100	40
		F_{ty}, ksi	205	185	170	160	155	130	128	125	125	120	90	30
		E, 10^6 psi	—	—	—	—	30	29	28	27	26	25	23	18
		Alpha, 10^6 in/in/°F					(70°F to 1600°F)							9.6
René 41 (Solution Treated-Aged)	0.296	F_{tu}, ksi	205	195	185	182	180	168	162	162	164	167	144	97
		F_{ty}, ksi	180	162	150	145	140	133	129	125	127	129	112	75
		E, 10^6 psi	—	—	—	—	32	30	29	28	27	26	25	24
		Alpha, 10^6 in/in/°F					(70°F to 1600°F)							8.7
Waspaloy (Solution Treated-Aged)	0.296	F_{tu}, ksi	—	—	—	—	180	178	176	172	170	153	120	76
		F_{ty}, ksi	—	—	—	—	115	113	110	108	106	103	94	75
		E, 10^6 psi	—	—	—	—	31	29	28	27	26	25	23	20
		Alpha, 10^6 in/in/°F					(70°F to 1600°F)							9.0
Hastelloy R-235 (Solution Treated-Aged)	0.296	F_{tu}, ksi	190	190	185	175	170	163	160	158	152	141	119	71
		F_{ty}, ksi	145	135	125	122	118	115	110	107	113	111	105	58
		E, 10^6 psi	—	—	—	—	31	29	28	27	26	25	22	19
		Alpha, 10^6 in/in/°F					(70°F to 1600°F)							8.9
Hastelloy X (Annealed)	0.297	F_{tu}, ksi	—	—	—	—	110	102	100	98	90	85	70	35
		F_{ty}, ksi	—	—	—	—	50	47	45	42	41	40	37	30
		E, 10^6 psi	—	—	—	—	30	28	27	25	24	22	21	19
		Alpha, 10^6 in/in/°F					(70°F to 1600°F)							9.0

Table XXIII

TYPICAL PROPERTIES OF CANDIDATE IRON-BASE ALLOYS

Alloy	Density lb/in³	Property	Temperature, °F -423	-320	-110	0	70	400	600	800	1000	1200	1400
21-6-9 (Annealed)	0.280	F_{tu}, ksi	245	203	134	119	111	90	82	78	71	60	—
		F_{ty}, ksi	196	150	87	74	66	43	38	32	29	27	—
		E, 10^6 psi	—	—	—	—	29	27	26	25	24	22	—
		Alpha, 10^6 in/in/°F					(70°F to 1400°F)						10.4
19-9DL (Annealed)	0.287	F_{tu}, ksi	---	---	---	---	115	95	90	82	70	50	35
		F_{ty}, ksi	---	---	---	---	60	55	53	50	45	40	30
		E, 10^6 psi	---	---	---	---	29	27	26	25	24	22	20
		Alpha, 10^6 in/in/°F	---	---	---	---	(70°F to 1400°F)						10.1
N-155 (Solution Treated)	0.298	F_{tu}, ksi	---	---	---	---	118	102	99	95	91	82	59
		F_{ty}, ksi	---	---	---	---	58	46	41	37	34	31	28
		E, 10^6 psi	---	---	---	---	29	25	23	22	21	20	18
		Alpha, 10^6 in/in/°F	---	---	---	---	(70°F to 1400°F)						9.7
A-286 (Solution Treated-Aged)	0.286	F_{tu}, ksi	225	200	170	155	150	138	135	132	123	102	57
		F_{ty}, ksi	140	125	108	100	95	85	82	80	77	62	40
		E, 10^6 psi	32	31	30	29	29	26	25	25	24	22	20
		Alpha, 10^6 in/in/°F					(70°F to 1400°F)						10.3

Table XXIII - Continued

TYPICAL PROPERTIES OF CANDIDATE IRON-BASE ALLOYS

Alloy	Density lb/in^3	Property	Temperature, °F -423	-320	-110	0	70	400	600	800	1000	1200	1400
"Custom 455" (Maraged)	0.282	F_{tu}, ksi	—	255	227	217	212	192	177	160	130	—	—
		F_{ty}, ksi	—	—	—	—	198	180	167	150	120	—	—
		E, 10^6 psi	—	—	—	—	27						
		Alpha, 10^6 in/in/°F					(70°F to 1000°F)				6.9		
AM-350 (SCT)	0.282	F_{tu}, ksi	270	260	225	215	210	200	195	185	140	—	—
		F_{ty}, ksi	—	240	190	170	160	150	140	125	90	—	—
		E, 10^6 psi	—	31	30	29	29	27	26	24	23	—	—
		Alpha, 10^6 in/in/°F					(70°F to 1000°F)				7.2		
304L (Annealed)	0.286	F_{tu}, ksi	220	190	125	100	80	65	60	57	52	43	28
		F_{ty}, ksi	35	35	30	25	20	18	18	15	14	12	10
		E, 10^6 psi	31	30	29	28	28	27	25	24	23	22	20
		Alpha, 10^6 in/in/°F					(70°F to 1400°F)						10.5
347 (Annealed)	0.286	F_{tu}, ksi	225	190	125	100	90	75	70	65	60	50	35
		F_{ty}, ksi	60	50	45	40	35	30	25	22	21	20	18
		E, 10^6 psi	31	30	29	28	28	27	25	24	23	22	20
		Alpha, 10^6 in/in/°F					(70°F to 1400°F)						10.7

Table XXIV

TENSILE ULTIMATE STRENGTH EFFICIENCY OF CANDIDATE ALLOYS

Material	Candidate Alloys	Ultimate Tensile Strength/Density, 10^4 Inch													
		-423	-320	-110	0	70	+200	+300	+400	+500	+800	+1000	+1200	+1400	+1600
Aluminum Alloys	2219-T81	93	78	68	65	64	58	53	---	---	---	---	---	---	---
	5083-O	89	66	53	49	44	46	31	---	---	---	---	---	---	---
	7039	96	83	70	67	66	55	48	---	---	---	---	---	---	---
	6061-T6	77	63	51	48	46	42	35	---	---	---	---	---	---	---
Titanium Alloys	8Al-1Mo-1V	152	133	102	92	89	79	---	66	62	53	46	---	---	---
	5Al-2.5Sn	154	123	93	83	77	68	---	55	49	44	38	---	---	---
	6Al-4V	150	131	100	88	84	77	---	67	63	56	46	---	---	---
	13V-11Cr-3Al	---	158	100	86	81	72	---	67	67	64	48	---	---	---
Nickel-Base Alloys	Inconel X	70	69	62	61	60	---	---	52	49	46	41	34	24	12
	Inconel 625	---	55	48	47	45	---	---	42	40	39	39	38	23	14
	Inconel 718	98	78	73	67	64	---	---	57	55	54	54	51	34	13
	Rene' 41	69	66	62	61	60	---	---	56	54	54	55	56	48	33
	Waspaloy	---	---	---	---	61	---	---	60	59	58	57	52	41	26
	Hastelloy R235	64	64	62	59	57	---	---	55	54	53	51	48	40	24
	Hastelloy X	---	---	---	---	37	---	---	34	34	33	30	26	24	12
Iron-Base Alloys	21-6-9	88	72	48	43	40	---	---	32	29	28	25	21	---	---
	19-9DL	---	---	---	---	40	---	---	33	31	29	24	17	12	---
	N-155	---	---	---	---	40	---	---	34	33	32	31	27	20	---
	A-286	79	70	60	54	52	---	---	48	47	46	43	36	20	---
	Custom 455	---	90	83	77	75	---	---	68	63	57	46	---	---	---
	AM-350	96	92	80	76	74	---	---	71	69	66	50	---	---	---
	304L	77	66	44	35	28	---	---	23	21	20	18	15	10	---
	347	79	66	44	35	31	---	---	26	24	23	21	18	12	---

Table XXV

TENSILE YIELD STRENGTH EFFICIENCY OF CANDIDATE ALLOYS

Material	Temperature Of Alloys	Tensile Yield Strength/Density, 10^4 Inch													
		-423	-320	-110	0	+70	+200	+300	+400	+600	+800	+1000	+200	+1400	+1600
Aluminum Alloys	2219-T81	64	59	52	51	49	47	44	—	—	—	—	—	—	—
	5083-O	26	23	21	22	22	23	20	—	—	—	—	—	—	—
	7039-T6	75	69	61	60	59	51	45	—	—	—	—	—	—	—
	6061-T6	54	49	43	41	38	38	29	—	—	—	—	—	—	—
Titanium Alloys	5Al-2.5Sn	142	112	85	77	71	63	—	51	41	35	31	—	—	—
	8Al-1Mo-1V	133	120	95	85	82	72	—	64	59	51	44	—	—	—
	6Al-4V	140	122	91	81	78	69	—	58	53	48	34	—	—	—
	13V-11Cr-3Al	—	149	98	80	75	65	—	61	57	55	43	—	—	—
Nickel-Base	Inconel X	43	39	38	36	34	—	—	31	30	29	25	21	15	11
	Inconel 625	—	25	23	22	22	—	—	17	16	15	15	15	15	14
	Inconel 718	69	62	57	54	52	—	—	44	43	42	42	40	30	10
	René 41	60	54	50	49	47	—	—	45	43	42	43	43	38	25
	Waspaloy	—	—	—	—	39	—	—	38	37	36	36	35	32	25
	Hastelloy R235	49	46	42	41	40	—	—	39	37	36	38	37	36	20
	Hastelloy X	—	—	—	—	17	—	—	16	15	14	14	13	12	10
Iron-Base Alloys	21-6-9	70	54	31	26	24	—	—	15	14	11	10	9	—	—
	19-9DL	—	—	—	—	21	—	—	19	18	17	16	14	10	—
	N-155	—	—	—	—	19	—	—	15	14	12	11	10	9	—
	A-286	49	44	38	35	33	—	—	30	29	28	27	22	14	—
	Custom 455	—	—	—	—	70	—	—	64	59	53	42	—	—	—
	AM-350	—	85	67	60	57	—	—	53	50	44	32	—	—	—
	304L	12	12	10	9	17	—	—	6	6	5	5	4	4	—
	347	21	17	16	14	12	—	—	10	9	8	7	7	6	—

Table XXVI

ELASTIC MODULUS EFFICIENCY OF CANDIDATE ALLOYS

Material	Temperature Of Candidate Alloys	Elastic Modulus/Density, 10^5 Inch													
		-423	-320	-110	0	+70	+200	+300	+400	+600	+800	+1000	+1200	+1400	+1600
Aluminum Alloys	2219-T81	122	117	109	105	104	101	97	—	—	—	—	—	—	—
	5083-0	118	116	111	99	107	105	102	—	—	—	—	—	—	—
	7039-T6	122	116	107	104	103	101	98	—	—	—	—	—	—	—
	6061-T6	111	107	105	103	102	100	97	—	—	—	—	—	—	—
Titanium Alloys	5Al-2.5Sn	115	109	101	98	96	94	—	91	85	77	61	—	—	—
	8Al-1Mo-1V	136	119	114	111	111	107	—	102	98	88	70	—	—	—
	6Al-4V	118	109	103	102	100	96	—	89	82	75	50	—	—	—
	13V-11Cr-3Al	—	—	—	—	83	83	—	80	75	70	60	—	—	—
Nickel-Base Alloys	Inconel X	107	105	103	103	103	—	—	97	93	90	87	80	—	—
	Inconel 625	—	—	—	—	100	—	—	97	93	90	87	83	77	—
	Inconel 718	—	—	—	—	101	—	—	98	94	91	88	84	78	60
	René 41	—	—	—	—	107	—	—	101	97	94	91	87	84	80
	Waspaloy	—	—	—	—	105	—	—	98	95	91	88	84	78	68
	Hastelloy R235	—	—	—	—	105	—	—	101	95	91	88	84	74	65
	Hastelloy X	—	—	—	—	101	—	—	94	91	84	81	74	71	64
Iron-Base Alloys	21-6-9	—	—	—	—	104	—	—	97	93	89	86	79	—	—
	19-9DL	—	—	—	—	101	—	—	94	91	87	84	77	70	—
	N-155	—	—	—	—	97	—	—	84	77	74	71	67	60	—
	A-286	112	108	105	101	101	—	—	91	87	87	84	77	70	—
	Custom 455	—	—	—	—	96	—	—	—	—	—	—	—	—	—
	AM-350	—	110	106	103	103	—	—	96	92	85	82	—	—	—
	304L	108	105	101	98	98	—	—	95	87	84	80	77	70	—
	347	108	105	101	98	98	—	—	95	87	84	80	77	70	—

Table XXVII

NOTCH STRENGTH RATIOS OF CANDIDATE ALLOYS AT SUBZERO TEMPERATURES

Material	Candidate Alloy	Notch Concentration Factor	Temperature, °F				
			-423	-320	-110	0	+70
Aluminum Alloys	2219-T81	$K_T = 7.2$ $K_T > 18$	0.90 0.72	0.92 0.74	0.93 0.73	0.95 0.75	0.96 0.82
	7039-T6	$K_T = 7.2$	0.80	0.83	0.98	1.02	1.04
	6061-T6	$K_T = 7.2$ $K_T > 18$	0.90 0.75	1.00 0.91	1.04 1.00	1.05 1.02	1.05 1.03
Titanium	5Al-2.5Sn	$K_T = 7.2$ $K_T > 18$	0.60 0.50	0.85 0.75	1.07 1.00	1.15 1.02	1.22 1.02
	5Al-2.5Sn(ELI)	$K_T = 7.2$ $K_T > 18$	0.95 0.60	1.15 0.95	1.22 1.03	1.30 1.03	1.32 1.03
	8Al-1Mo-1V	$K_T = 7.2$	0.65	0.82	1.05	1.10	1.12
	6Al-4V	$K_T = 7.2$	0.70	0.95	1.10	1.15	1.15
	13V-11Cr-3Al	$K_T = 7.2$	---	0.55	0.80	1.00	1.20
Nickel-Base Alloys	Inconel X	$K_T = 7.2$	0.86	0.87	0.92	0.94	0.97
	Inconel 625 (20% C Rolled)	$K_T > 18$	---	0.85	0.91	0.88	0.87
	Inconel 718	$K_T = 7.2$	0.98	0.95	1.03	1.04	1.05
	René 41	$K_T = 7.2$ $K_T > 18$	0.87 0.74	0.85 0.73	0.87 0.76	0.88 0.78	0.90 0.80
Iron-Base Alloys	A-286	$K_T = 7.2$	0.87	0.88	0.92	0.96	0.98
	Custom 455	$K_T = 10$	---	1.08	1.46	1.47	1.48
	AM-350	$K_T = 3.0$	0.45	0.95	1.00	1.02	1.00

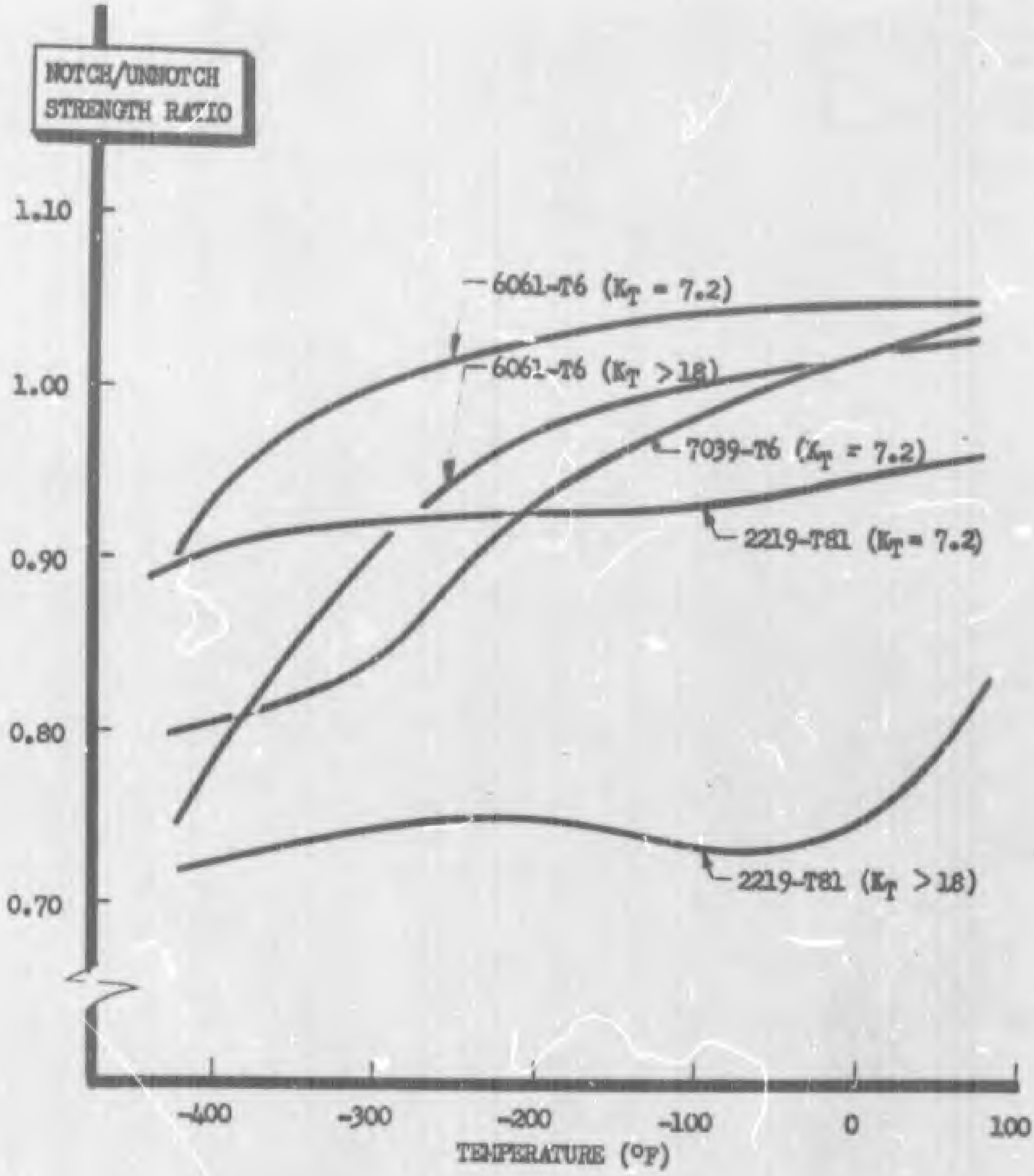

Figure 29. Notch Strength Ratios of Candidate Aluminum Alloys

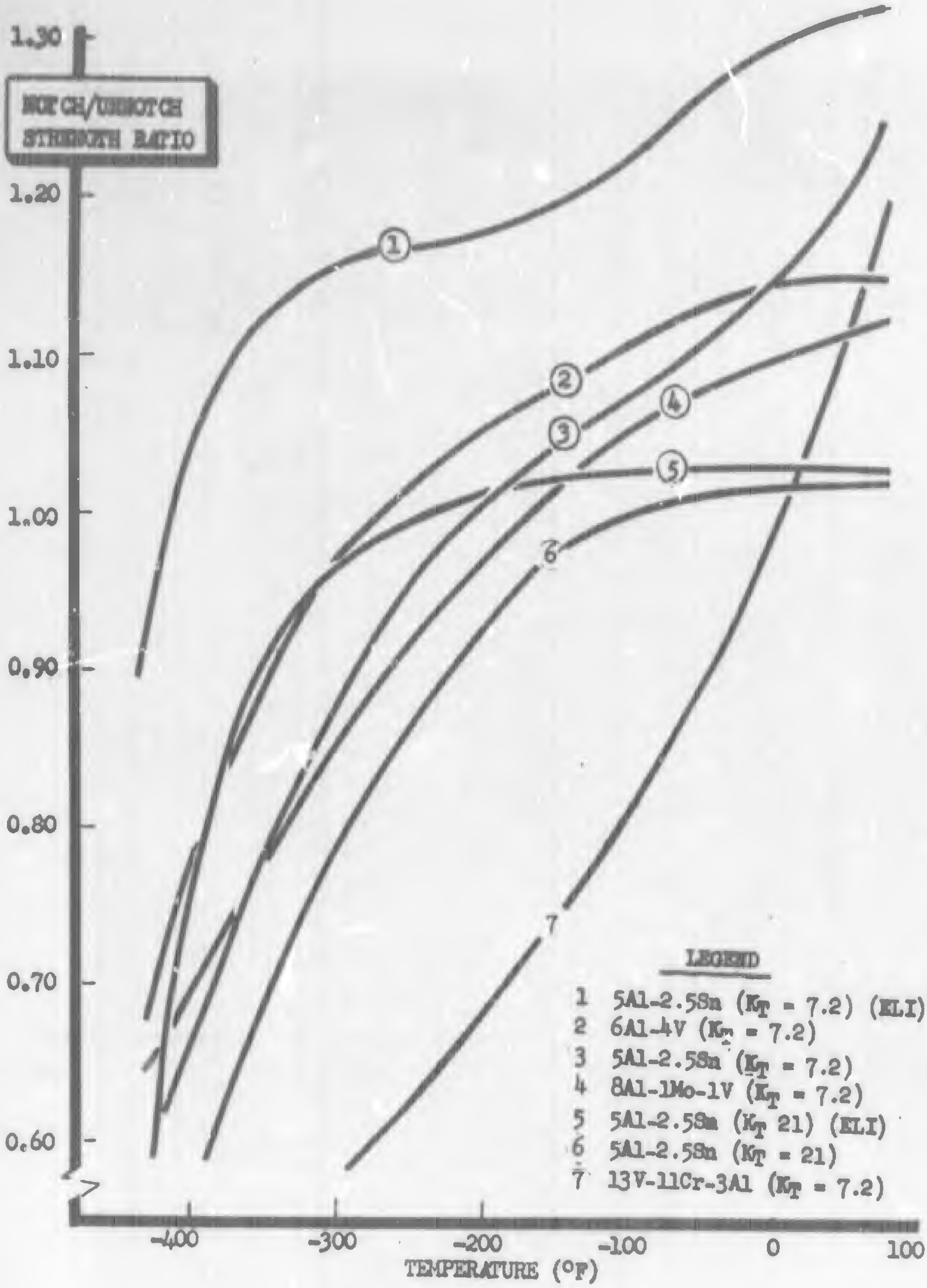

Figure 30. Notch Strength Ratios of Candidate Titanium Alloys

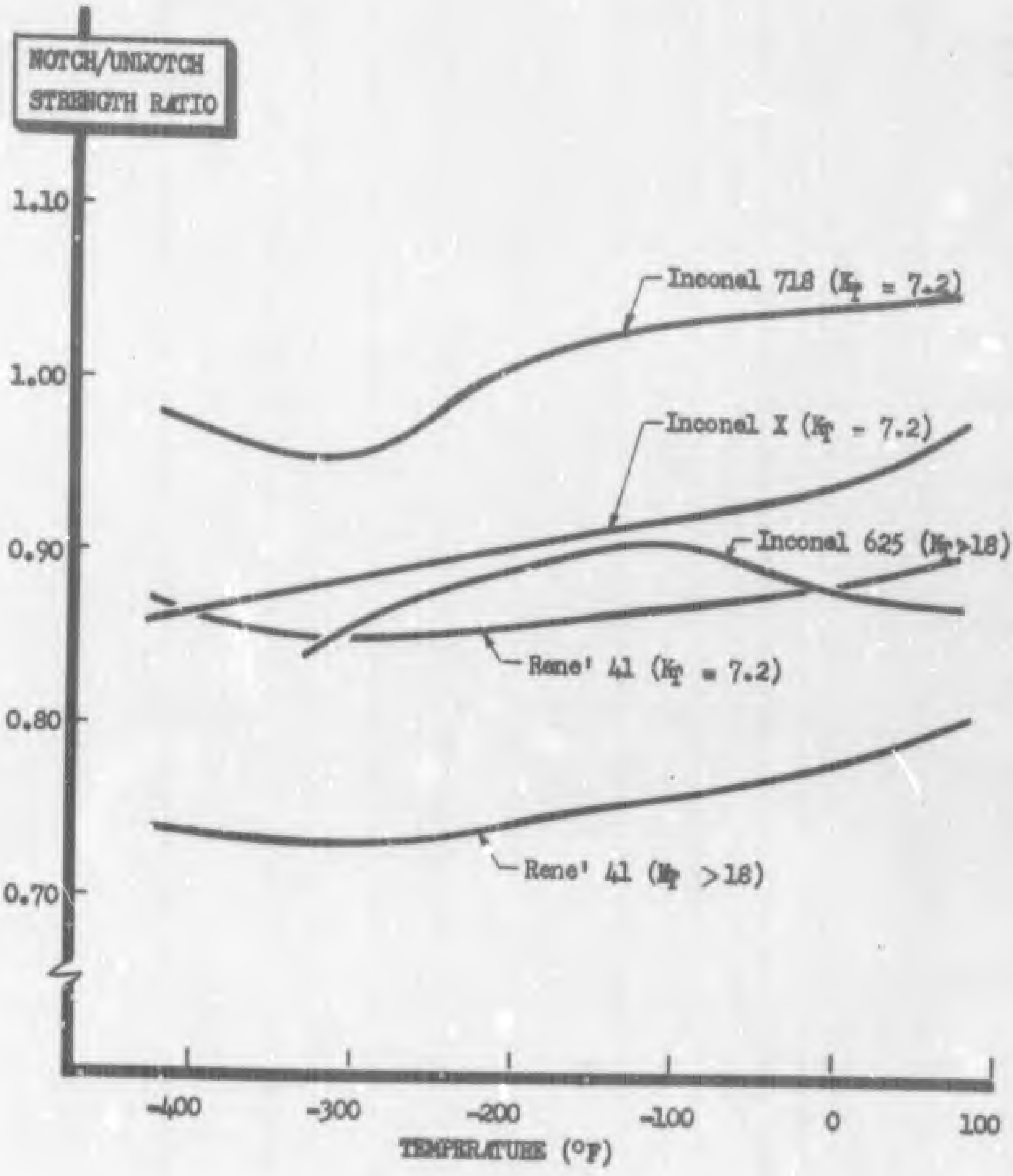

Figure 31. Notch Strength Ratios of Candidate Nickel-Base Alloys

Iron-Base Alloys

The structural efficiencies of the iron-base alloys, displayed in Tables XXIV and XXV show a superiority for the heat-treated alloys (AM-350, "Custom 455," and A-286) in comparison to the annealed alloys. In figure 32, notch-strength ratios are plotted for three of the alloys at subzero temperatures. No notch-tensile properties data were found for the 21-6-9 alloy, however, this alloy apparently possess excellent notch-toughness properties at cryogenic temperatures as evidenced by Charpy V-Notch Impact values of 53 foot-pounds at -423°F which have been obtained on specimens tested in the transverse direction from thick sections of 21-6-9.

WELDING CHARACTERISTICS

Aluminum Alloys

Four outstanding factors concerning the weldability of aluminum are: (1) a low melting point (2) the presence of an oxide film, (3) low strength at high temperatures, and (4) the fact that aluminum displays no color even at temperatures up to the melting point. Each of the candidate aluminum alloys has good TIG, fusion welding characteristics and good quality weldments can be consistently produced in these alloys.

Titanium Alloys

Each of the four candidate titanium alloys can be satisfactorily joined by the TIG fusion welding process. Good quality weldments can be consistently produced if the special weld shielding precautions necessary in the fusion welding of titanium alloys are observed. Titanium alloy fusion weldments are subject to embrittlement unless carefully shielded from contamination by the gaseous elements of the atmosphere during the welding process.

Nickel-Base Alloys

The weldability characteristics of the seven candidate nickel-base alloys vary considerably, although each can be welded by the TIG process. The two solution strengthened alloys, Inconel 625 and Hastelloy X, possess excellent weldability. Inconel 718 displays good weldability, despite being a precipitation-hardening alloy. The slow aging response of Inconel 718, as compared to many of the precipitation-hardening nickel-base alloys, minimizes the cracking problems generally associated with the fusion welding of these alloys. The remaining four alloys-Inconel X, Waspaloy, Hastelloy R-235, and René 41- have diminishing weldability characteristics in the order listed. Each of these alloys is subject to "strain-age" cracking when being welded under physical restraint.

Iron-Base Alloys

All of the candidate iron-base alloys can be welded satisfactorily by the TIG fusion welding process. Types 347 and 304 stainless steel, 21-6-9,

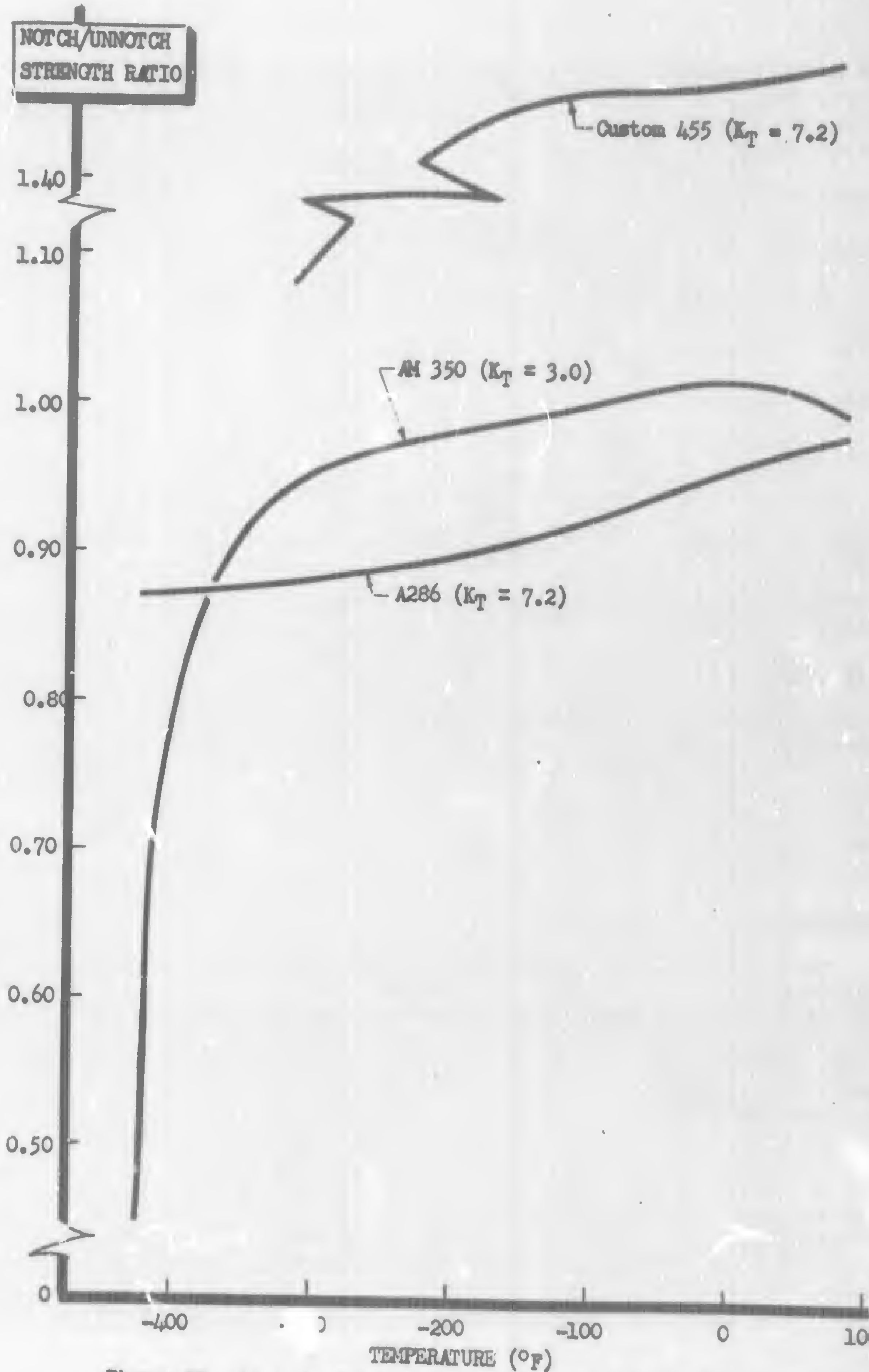

Figure 32. Notch Strength Ratios of Candidate Iron-Base Alloys

and 19-9DL have excellent weldability characteristics. N-155, AM-350, and "Custom 455" have good weldability. The weldability of A-286 is satisfactory, although this alloy is subject to underbead cracking when multipass welds are employed.

MACHINING CHARACTERISTICS

Aluminum Alloys

Aluminum alloys, are in general, rated as having outstanding machining characteristics, the relative machinability rating being 100 to 200 for these alloys. Each of the four candidate alloys has excellent machinability, with the two higher strength, heat-treated alloys--2219 and 7039--having the best characteristics.

Titanium Alloys

Titanium alloys display satisfactory machining characteristics with a relative machinability ratio of 30 to 60. Proper techniques must be employed during machining, however, to attain satisfactory results. Three of the candidate alloys--Ti5Al-2.5Sn, 6Al-4V and 8Al-1Ml-1V--are considered to have comparable machining characteristics, with the 13V-11Cr-3Al alloy being somewhat more difficult to machine.

Nickel-Base Alloys

Nickel-base alloys are generally difficult to machine due to their work hardening propensity the relative machinability rating for these alloys being 20 to 40. Through the use of good machining practices, however, the nickel-base alloys can be machined satisfactorily. Considering the seven candidate alloys, Hastelloy X and Inconel 625 are rated as having the best machining characteristics, followed by Inconel X and Inconel 718, and with Hastelloy R235, Waspaloy, and René 41 possessing the poorest machinability.

Iron-Base Alloys

The austenitic and age-hardenable iron-base alloys, such as the eight candidate alloys, have satisfactory machining characteristics with a relative machinability rating of 40 to 50. Of the eight candidate alloys, Types 347 and 304L have the best machinability, followed in order by 19-9DL, 21-6-9, A-286, and N-155, and then by the two alloys that are the least machinable, AM-350 and "Custom 455."

COMMERCIAL AVAILABILITY

An industry survey was made of the specialty tubing suppliers to determine the potential commercial availability of the candidate alloys in the form of tubing. The results of the survey are summarized in Table XXVIII, and are discussed in the following paragraphs under the appropriate material categories.

Table XXVIII

AVAILABILITY OF CANDIDATE ALLOYS

Material	Alloy	Availability As Tubing	Range of Sizes Available (Inches): OD (Min.)	Wall (Min.)	Wall (Max.)	OD (Max.)	Wall (Min.)	Wall (Max.)
Aluminum Alloys	2219	Yes	1/8	.015	.049	9	.406	.421
	5083	Yes	1/8	.015	.049	9	.406	.421
	7039	No	---	---	---	---	---	---
	6061	Yes	1/8	.015	.049	9	.015	.049
Titanium Alloys	5Al-2.5Sn	No	---	---	---	---	---	---
	8Al-1Mo-1V	No	---	---	---	---	---	---
	6Al-4V	Yes	3/4	.035	.083	1-1/2	.049	.203
	13V-11Cr-3Al	No	---	---	---	---	---	---
Nickel-Base Alloys	Inconel X	Yes	1/4	.016	.049	2-5/8 *	.125	.220
	Inconel 625	Yes	1/4	.016	.049	2-5/8 *	.125	.220
	Inconel 718	Yes	1/4	.016	.049	2-5/8 *	.125	.220
	René 41	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	Waspaloy	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	Hastelloy R-235	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	Hastelloy X	Yes	1/4	.016	.049	1-1/2 *	.035	.095
Iron-Base Alloys	21-6-9	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	19-9DL	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	N-155	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	A-286	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	Custom 455	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	AM-350	Yes	1/4	.016	.049	1-1/2 *	.035	.095
	304L	Yes	1/16	.010	.020	4 *	.035	.156
	347	Yes	1/16	.010	.020	4 *	.035	.156

* Maximum OD for drawn tubing; however, welded tube sizes to 10 in. diameter and 0.10 in. to 0.125 in. wall are available.

Aluminum Alloys

Three of the candidate aluminum alloys are commercially available as tubing; the fourth alloy, 7039, cannot be procured as tubing at the present time. Alloys 6061 and 5083 are generally available from warehouse stock in a wide range of tubing sizes. Tubing of Alloy 2219 is not generally available form warehouse stock, but is fabricated to order. Extruded tubing of Alloy 2219 is subject to a minimum procurement of 2000 pounds; drawn tubing, while more expensive than extruded tubing, is not subject to a minimum procurement.

Titanium Alloys

At the present time, Ti6Al-4V is the only candidate titanium alloy that is being produced as quality seamless tubing. Also, there presently is but a single source for Ti6Al-4V quality tubing. This supplier is Wolverine Tube, Allen Park, Michigan. The current delivery schedule for Ti6Al-4V tubing is 26 weeks.

Nickel-Base Alloys

The industrial survey results indicate that each of the nickel-base alloys is available as tubing on a commercial basis. This conclusion is valid for Inconel X, Inconel 625, Inconel 718, and Hastelloy X. However, based on previous NAA experience and the consensus of replies from the suppliers, the conclusion must be qualified with regard to René 41, Waspaloy, and Hastelloy R-235. In the past, these alloys have been difficult to procure as tubing. The majority of the suppliers would not presently accept orders to produce tubing from these alloys.

Iron-Base Alloys

All of the iron-base alloys are available commercially as tubing.

SELECTION OF CANDIDATE ALLOYS

ALUMINUM ALLOY

Aluminum Alloy 2219 is recommended for detailed welding development studies. Selection of 2219 in preference to the other aluminum alloys which were evaluated is based on: (1) the commercial availability of 2219 tubing as compared to the present nonavailability of 7039 tubing, (2) the superior structural properties displayed by 2219 in comparison to those possessed by alloys 5083 and 6061.

TITANIUM ALLOY

Ti6Al-4V is recommended for additional welding development studies. Recommendation of this alloy is based not only on the fact that it is the only high-strength titanium alloy which is commercially available as tubing, but also upon the broad base of production experience with Ti6Al-4V in the aerospace industry.

Due to the limited availability of Ti6Al-4V tubing, however, it is recommended that an unalloyed grade of titanium (e.g., Ti55) tubing be selected for use in the detailed welding development studies, and that Ti6Al-4V tubing be used for confirmation of the welding and machining techniques developed.

NICKEL-BASE ALLOY

The nickel-base alloy recommended is Inconel 718. Selection of Inconel 718 is based on the following considerations:

1. Inconel 718 has superior welding characteristics in comparison to the other high-strength, precipitation-hardening nickel-base alloys (René 41, Waspaloy, Hastelloy R-235, and Inconel X). The superior weldability of Inconel 718 would seem to more than compensate for any structural advantage that any of these other alloys display at temperatures in excess of 1200°F.

2. The structural properties of Inconel 718 are excellent at cryogenic temperatures and at elevated temperatures up to 1200°F.

3. Inconel 718 displays a structural properties advantage over the lower strength, nonheat-treatable alloys such as Inconel 625 and Hastelloy X.

IRON-BASE ALLOY

It is recommended that 21-6-9 be selected as the iron-base alloy for welding development studies. The advantages of this alloy are as follows:

1. Alloy 21-6-9 displays excellent structural characteristics at cryogenic temperatures, and has good strength properties at elevated temperatures to 1200°F.

2. The general corrosion resistance of 21-6-9 is much superior to the corrosion resistance displayed by the lower chromium-content, precipitation hardening alloys AM-350 and Custom 455.

3. Alloy 21-6-9 has excellent welding characteristics which are considerably superior to those displayed by A-286. In addition, weldments of 21-6-9 are not susceptible to intergranular corrosion in the heat-affected zone; this is an advantage for 21-6-9 compared to 19-9DL and AM-350 which are susceptible to this type of attack after welding.

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Section VII

CONCLUSIONS AND RECOMMENDATIONS

1. Finalized weld joint preparation and weld tool requirements have been established and are divided into two areas: First, a series of enclosed tools, based on the orbit arc concept, will be used in the 1/8-to 3-inch OD range combining slitting, flanging, machining, and welding capability. Second, a series of partially enclosed tools will be used in the 1-to 16-inch OD range utilizing separate weld and machining heads which mount on common orbital carriages sized as follows: 1 to 3, 3 to 6, 6 to 9, 9 to 12, and 12 to 16-inch ranges of outside diameters.

2. The basic weld programmer configuration has been determined to be satisfactory.

3. Operation of the weld programmer has indicated that a servo current control unit and an arc voltage sensitive wire feed control should be added to the unit. Testing has indicated feasibile approaches to both of these requirements.

4. Standard automatic arc voltage control (AVC) has been determined to be unsuitable for this application.

5. Standard welding power supplies were found to be satisfactory for this application.

6. For fixed arc length tube welding, particularly in thick wall tubing, the best weld penetration control was obtained using helium inert shielding gas.

7. Under fixed arc length conditions arc voltage was determined to vary considerably with electrode configuration. The most satisfactory configuration for controlling the arc voltage - arc gap relationship was a blunt or flat tip.

8. The most satisfactory weld joint design for thick wall aluminum tubing was found to be a modified U-groove. It was necessary to program sloping weld current and utilize cross-seam oscillation to obtain satisfactory root pass penetration.

9. A significant problem encountered in fixed arc length automatic welding of tubing was uneven buildup which occurs as a function of weld position. A satisfactory method of compensating for this problem has been devised which entails the use of an arc voltage sensitive wire feed unit with which the weld build-up can be maintained within 0.020 inch. Also, although very limited studies have been conducted on the use of this system for controlling drop-through of root passes, it is believed that the new wire feed control system may facilitate root pass penetration control with or without torch oscillation.

10. The most promising candidates for use in advanced liquid rocket tubing systems in each of the noted categories are as follow: 2219 aluminum alloy, 6Al-4V titanium alloy, inconel 718 nickel-base alloy and 21Cr-6Mo-9Mn iron-base alloy.

Section VIII

FUTURE WORK

The design of the twin-armed orbital carriages through 16-inches in diameter, the thick wall machining and welding heads, and the thin wall slitting and flaring tools will be completed. The tools will be fabricated and performance tested to demonstrate that the design objectives have been attained. The design of the weld programmer, including the finalized servo current control unit, will be completed, fabricated, and performance tested.

Development of joint design criteria and root and filler pass techniques for thick wall tubing will be continued using existing tooling. Using the finalized tooling and programming equipment, optimum joint preparation and welding procedures will be established for in-place joining of 6061-T6 aluminum and Type 347 stainless steel tubing in the 1/8-to 16-inch OD range. Using these techniques, developed under conditions of optimum tube end fit-up, the maximum allowable tolerances on end-to-end fitup and tube end misalignment will be established. Tube weld joint preparation and welding procedures will also be developed for 2219 aluminum alloy, 6Al-4V titanium alloy, commercially pure titanium, inconel 718 nickel-base alloy, and 21Cr-6Mo-9Mn iron-base alloy in the 1/4-to 3-inch OD range.

The data obtained pertaining to equipment and procedures will be prepared in technical order, military specification, and equipment manual format.

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13. ABSTRACT

A design evaluation study was conducted to establish requisites for tool design. Design criteria were formulated and operating parameters were delineated, based on tests performed to determine power and performance requirements. Clamping, and driving forces, milling cutter loads, tracking, and driving power requirements were established. A basic design concept for a basic tool carriage incorporating interchangeable cutting and welding heads was subsequently established. Welding studies were conducted to determine the effect of arc voltage, gap, electrode configuration, and shield gas on the weld bead. Three commercial electrical power supplies, and related equipment, were used in conducting tests to determine equipment adaptibility and performance under different operating conditions. Material studies were conducted to selected candidate materials typical of advanced liquid rocket systems, for use in tests which will be conducted with present and developed tool designs. The candidate materials selected include aluminum, titanium, nickel- and iron-base alloys.

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