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Refractomet Division

UNIVERSAL-CYCLOPS STEEL CORPORATION

Technical Report

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THE STATE-OF-THE ART OF
WELDING OF REFRACTORY METALS

Prepared Under Navy
Bureau of Weapons
Contract NOw 63-0043-c

Prepared By
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FOREWORD

This report covers the State-of-the-Art Survey of Refractory Metals welding. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the navy.

D. J. Seman of the Development Group, Refractomet Division, Universal-Cyclops Steel Corporation was the Engineer in charge. F. D. Seaman was the consultant representing the Astronuclear Department of the Westinghouse Electric Corporation.

Since the nature of this work is of interest to so many fields of endeavor, your comments are solicited as to the potential utilization of the information produced under this contract. In this manner, it is felt that a full realization of the resultant information will be accomplished.

PUBLICATION REVIEW

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ABSTRACT

Contract NOw 63-0043-c

This document includes a literature and industrial "State-of-the Art" Survey of Refractory Metal Welding. The report (1) summarizes the number and types of facilities engaged in refractory metal welding, (2) summarizes the nature of Refractory Metal Welding, and (3) projects the current methods and limitations in terms of future needs.

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I. INTRODUCTION

The survey reported in this document is one phase of a program aimed at establishing optimum production techniques for the welding of refractory metals such as columbium, tantalum, molybdenum, tungsten, or alloys of these metals. The scope of the survey included all methods of joining where the base metal is joined through fusion or through the use of forms of energy such as ultra-sound, friction, or explosion. The objectives of the survey can be stated as follows:

1. Determine what facilities currently constitute the refractory metals welding industry.
2. Determine what the industry produces, what methods the industry has adopted to carry out this production, and what limitations have evolved as the result of any special requirements associated with the fusion welding of refractory metals.
3. Project current abilities into the future and determine what effort must be put forth to assure that refractory metals welding capabilities will be adequate to meet future needs.
4. Evaluate progress to date and make recommendations for future efforts to assure that future capabilities will meet future needs.

This report has been prepared to determine what constitutes the refractory metals welding industry today and what factors may influence the industry in the future. With this information the reader may determine what resources are available to assist him. It is also possible for him to compare his approach and other approaches to, for example, quality control. Finally the report is aimed at pointing out the possibilities for welding refractory metals in terms of thicknesses, types of material that have been welded, processes that have been used (and some pitfalls associated with these processes), joints that have been designed, etc., in order to assist in the application of these materials to specific uses. No attempt has been made by the writers to comment on the correctness of any given approach.

In order to assist the reader in using the information the report has been divided into three independent parts as follows:

> <u>Part I</u> Determination of the number and type of facilities currently engaged in the welding of refractory metals. Facilities engaged in the systematic production of engineering data have been included as a part of the industry because much of the information required to meet the second objective (e.g., methods for welding these materials and the associated limitations) exists exclusively in the form of engineering data.
>
> <u>Part II</u> Analysis of the nature of work carried out by these facilities in such terms of equipment employed, metal thicknesses joined, form of base material, techniques, limitations methods of evaluating results, etc. Where possible, the analysis has been set forth in at least a semi-quantitative form. Since individuality appears to be a major characteristic of the industry, no attempt has been made to use the statistical data to produce a typical facility or production item.
>
> <u>Part III</u> Projection of current methods and limitations in terms of future needs to permit an evaluation of progress to date and recommendations for future efforts.

II PART I - FACILITIES ENGAGED IN REFRACTORY METAL WELDING

At least forty-nine industrial and research facilities are or have engaged in the welding of one or more of the refractory metals (tungsten, molybdenum, columbium and tantalum) or their alloys. This group does not include organizations in the electronics industry.

In eliminating the electronics industry, recognition was given to the pioneering efforts of this segment of industry in the welding and brazing of refractory metals to form such items of production as filaments, filament support, cathode devices. A limited amount of non-proprietary technical information has been successfully solicited from such sources as an aid to the experimental portion of this program. However, such techniques have become largely a matter of routine in, for example, the electric lamp industry and it was felt that current engineering effort could better be directed toward production improvement associated with welding in the more recent areas of application as represented by the analysis of the forty-nine company sample shown in Table I.

In proposing these forty-nine facilities as largely representing those facilities engaged in the welding of one or more refractory metals, the following sample procedure was used.

A gross sample of one hundred seventy-two (172) questionnaires was mailed. Recipients included twenty-seven (27) organizations associated with primary aerospace contracts. This included major air frame and engine manufacturers as well as organizations associated with solid and liquid rockets, ramjets and nuclear propulsion units. A second sample of sixteen (16) was directed at major subcontractors to the air frame and engine industry (particularly if they had engaged in a systematic,

TABLE I

ANALYSIS OF SURVEY SAMPLE WITH RESPECT TO APPLICATIONS

Class	Areas of Welding Application	No. of Facilities Involved
I	Air Frame Components and Weapons Systems	16
II	Engines (Power Sources)	5
III	High Temperature Testing Devices (Liquid Metal Loops, etc.)	8
IV	In addition, certain companies appear to be qualified as general fabricators of refractory metal components for any of above product-oriented contractors.	8
V	Equipment producers that have refractory metals welding experience for example, through application demonstrations or through the production of parts on their equipment.	7
VI	Research organizations engaged in systematic welding programs of refractory metals.	5

NOTE: In addition to the above listed facilities, nine other organizations (part of the 108 polled) provided information. Six of these were metals producers and three were electronic equipment producers. 43.5% of the organizations returned completed questionnaires. Another 21.3% indicated that they had no applicable experience. The remaining 35.2% did not reply.

documented technical program or had entered into significant production contracts). A third sample of twelve (12) was aimed at research facilities. Eleven (11) manufacturers of arc, electron beam, resistance, flash and ultrasonic welding equipment (as well as some manufacturers of welding chambers) were contacted and also asked to provide references to customers in the first category. Twenty-four (24) metal producing organizations (ten of which specialize in refractory metals production) were contacted and in turn asked for references to other organizations working with the welding of their materials. These above lists were made up of organizations that had exhibited an interest in refractory metal developments on at least two previous occasions and could, by nature of their products, be expected to have an interest in fusion welding. Finally, eighteen (18) organizations that had not been identified in the above categories were contacted. These included twelve (12) government agencies.

It was recognized that within large complex corporations several facilities might be closely enough associated with one of the categories I-VI (Table I) to possess pertinent information. Furthermore, such corporate facilities might exhibit significantly different viewpoints and capabilities. Therefore, as many persons or divisions as appeared applicable were polled in the larger corporations. Additionally, persons in staff positions were contacted and asked to refer the questionnaires within their respective organizations. This "shotgunning" in the interest of completeness resulted in a small amount of duplication within the 172 items mailed. This duplication has been recognized in the returns and is factored out of the above sub-samples, the classification of respondents and any other statistical references hereinafter referred to.

Unquestionably organizations with special capabilities in the field of welding refractory metals have been overlooked.

However, the number of such oversights is believed to be small. In all questionnaires a request for references to persons or corporations with refractory metal welding experience was made. In the course of analyzing fifty-nine (59) separate questionnaires forty-five (45) references were encountered. Thirty-eight (38) of these references had already been contacted. The remaining seven were contacted during the course of the investigation. Any organizations as yet unpolled would, therefore, presumably be unrecognized by a sample of eighty-six (86) persons* (respondees) directly associated with the field of refractory metals welding, design and materials production.

While the above discussion is concerned with the number of technical organizations potentially interested in any production studies, it does not consider the nature of current production. An understanding, at least semi-quantitative, of the nature of production is necessary to provide substance to any study that has as its objective, production improvement. Finally, it is necessary to consider future production as a source of direction. Studies of the nature of current production and a projection of the future needs of refractory metal welding constitute Parts II and III of this report.

Part I - Conclusions

1. At least forty-nine research and industrial facilities are or have engaged in the welding of refractory metals. This group does not include the electronics industry.

2. The forty-nine facilities represent a reasonably complete listing since they were identified by polling a group of eighty-six persons directly associated with the field of refractory metals welding, design and materials production.

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* Often a questionnaire would be answered by more than one person.

III PART II - NATURE OF CURRENT REFRACTORY METALS WELDING OPERATIONS

In reviewing the information obtained from the 49 facilities identified as comprising the refractory metals welding industry, attention has been directed to six major areas:

A. Materials used in current refractory metal weldments including findings related to the thicknesses welded, metals and alloys involved and dissimilar metal joining experiences.

B. Welding processes employed (both in production and in organized engineering efforts) and determination of the relationship between processes and products.

C. Reported combinations of materials and processes.

D. Size of refractory metal weldments (arc and resistance)

E. Techniques for welding refractory metals.

F. Methods for evaluating welds destructively and non-destructively.

A. Materials of Current Refractory Metal Weldments

1. Relative Welding Experience of the Four Major Refractory Metals: Columbium, Molybdenum, Tantalum and Tungsten

In reviewing reports from designers, metallurgists, and welding engineers it appears that there exists an appreciable amount of welding experience for each of the refractory metals and most of their alloys. These are shown according to frequency of reference in the Figure I. This tabulation shows that the welding of columbium and its alloys was referred to in the answers to the survey approximately twice as often as molybdenum or tantalum and their alloys. Columbium welding experience was noted

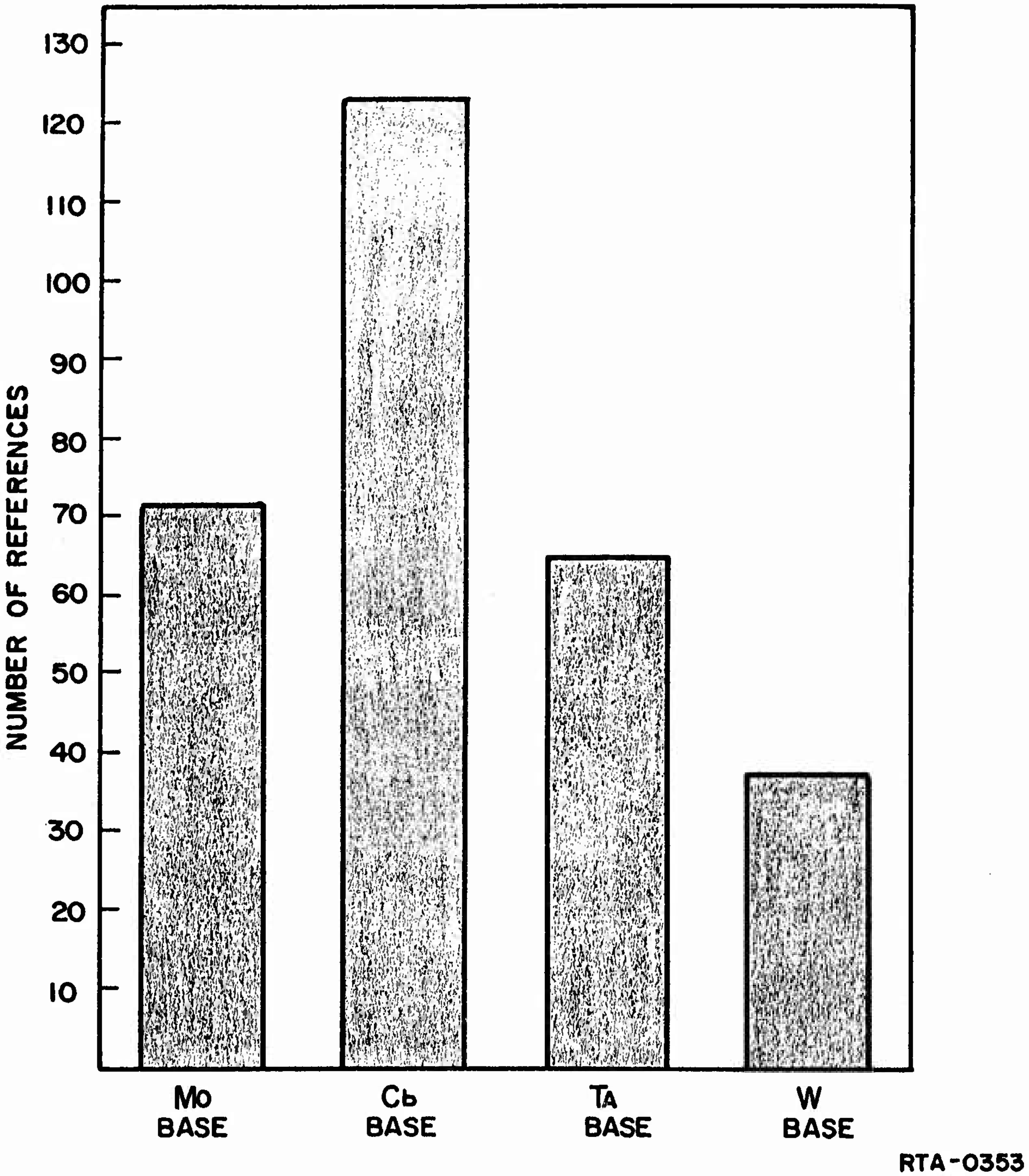

FIGURE I

RELATIVE WELDING EXPERIENCE OF THE FOUR REFRACTORY METALS AND ALLOYS AS EXPRESSED IN NUMBER OF REFERENCES three times for each reference to tungsten. Each reference, as used in this figure and the following figures in this section, related to a specific product, experimental application, or systematic welding program identified by welding engineers responding to the questionnaire. Each was, in the respondents mind, significant enough so that such details as thickness, type of joint, method and inches of weld involved could be set forth.

Using the same references, the data were reviewed to determine if there was a discrepancy between the number of times an alloy was used (as indicated above) and the actual welding experience in terms of inches of weld. The latter data had been reported by category, that is, respondents had been asked whether the referenced application involved less than 12 inches of weld; 12-24 inches of weld etc. In order to display the data each category was assigned a single value usually midway between the range. This technique was also used to display the information in the remaining figures of this section on materials.

From Figure 2 it appears that the relationship between the materials is the same when experience is stated in inches of weld as it was when experience is stated in terms of the number of products, programs, etc., to which the material has been applied. This relationship indicates that columbium and its alloys are most frequently welded while molybdenum or tantalum alloys have been welded about half as extensively. Tungsten welds total only about one third the length of the columbium welds.

The above values are relative and not absolute. One reason for emphasizing this point is the inclusion of one or more references to applications involving "over 200 inches of welding", in the data for each material. Recognizing that such applications might involve several thousand inches and thus change the

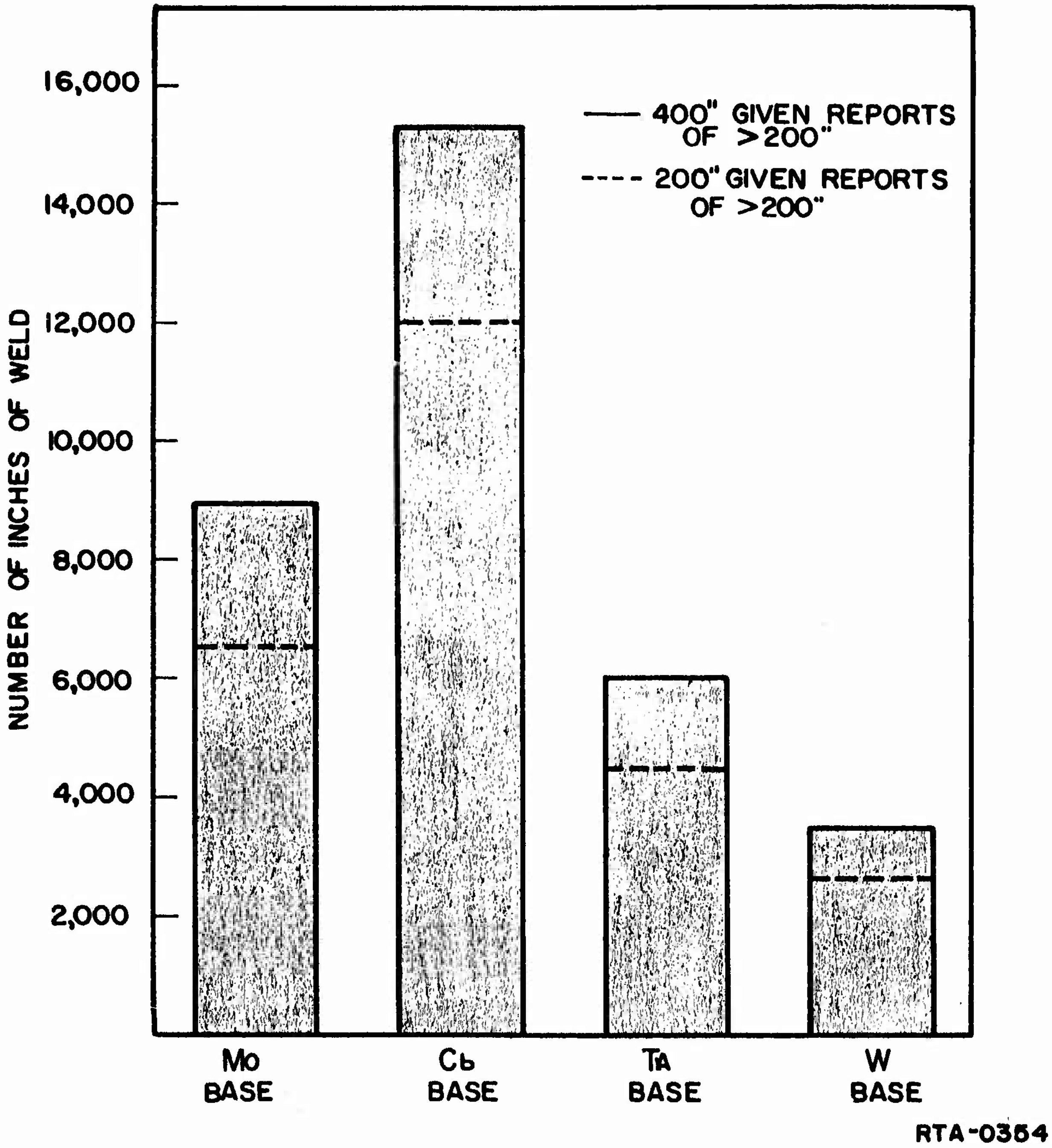

FIGURE 2

RELATIVE WELDING EXPERIENCE OF THE FOUR REFRACTORY METALS AND ALLOYS AS EXPRESSED BY TOTAL INCHES OF WELD REPORTED relationship where a particular metal had been subjected to a large proportion of such applications the data was re-examined. The dotted line was calculated using 200 inches when over 200 inches was indicated and the solid line 400 inches for over 200 inches. Behind this re-examination of the data lay recognition of the production welding that has been applied to tungsten rocket nozzle components. This particular application appeared to be the closest approach to production, as the term is commonly used, yet tungsten appeared to be the least welded of the four refractory metals.

Figure 2 indicates no significant change when the "over-200 inch" category was reweighed. This has been conservatively interpreted to mean that each material has a similar proportion fo "over 200 inch" applications to its credit.

The observation, from Figure 2, that each material involves a number of "over 200 inch" applications is in itself an important point for the following reason. As will be noted in other sections, components produced from refractory metals tend to be small involving only a few inches of welding per unit. However, the special nature of refractory metal welding is such that even the smallest welds require the application of a considerable amount of engineering skill. According to interviews, welds are often carried out under the supervision of engineers otherwise assigned to research or development programs. Special equipment (such as vacuum chambers, purged chambers and electron beam equipment) is often applied. Furthermore, as the care in selecting personnel and equipment might imply, the risk of something going wrong is still considered high. For example, nearly every respondent to the questionnaire specified a desire for greater shielding reliability. If something should go wrong, the value of the material involved may exceed the value of an equivalent component of a more common material such as aluminum by a factor of two-hundred. Therefore, if production improvement implies improvements in process reliability, simplifications, etc., then the potential for effecting an improvement in cost and delivery on even a few inches of weld is considered where refractory metals are involved.

In addition to the insight gained into the relative usage of the refractory metals and their alloys several instances were noted where the various metals and alloys were joined (by processes other than brazing or diffusion bonding) to dissimilar metals or alloys. These are listed, along with the joining method, in Table II. It is assumed that the joints were satisfactory for the intended application.

2. Properties of Refractory Metal Welds

While the above information has been generalized with respect to materials, the literature provides the means for obtaining specific documented information concerning the weldability of the various refractory metals and alloys. In many instances the specific properties of welded material will not be given since some of the data was fragmentary and in the reported results the variables of welding and testing were significantly different so that the results were not usually comparable.

a. Molybdenum

The major commercial molybdenum based metals are commercially pure molybdenum, Mo-0.50Ti and TZM. The nominal compositions and normal interstitial levels are shown in Table III.

The three molybdenum alloys have all been fusion welded. Difficulty is often encountered in producing sound, crack free, porosity free welds. These defects are caused by material

TABLE II

REPORTED DISSIMILAR METAL JOINTS

	No. of References	Thickness (Inches)	Method of Joining
Mo to Cb Alloy	2	.005 - .010	Resistance
		.030 - .050	TIG, EB, Resistance
		.050 - .100	TIG, EB
Mo to W	5	.005 - .010	Ultrasonic, Resistance, EB
		.010 - .030	TIG, EB, Ultrasonic
		.030 - .050	Resistance, TIG, EB
		.050 - .100	TIG
		.100 - .150	TIG, EB
		-<.250	TIG
Cb to Cb Alloy	1	.030 - .050	TIG, MIG
		.150 - .250	TIG, MIG
Cb to Ta	1	.250	TIG
Cb alloy to Ta	2	.010 - .030	TIG
		.030 - .050	TIG
		.050 - .100	EB
Cb alloy to Ta alloy	1	.010 - .030	TIG
		.030 - .050	TIG
Cb to W	1	.030 - .050	EB
Cb alloy to W	1	.005 - .010	Resistance
		.030 - .050	Resistance
Ta to Ta alloy	2	.005 - .010	EB
		.010 - .030	TIG
		.030 - .050	TIG
Ta to W	2	All thicknesses listed in the survey (<005 thru >.250)	TIG, EB

TABLE III

NOMINAL COMPOSITION AND INTERSTITIAL LEVEL OF COMMERCIAL MOLYBDENUM ALLOYS

ALLOY	Composition				
	O_2(ppm)	N_2(ppm)	C ppm	Ti(%)	Zr(%)
Molybdenum (Powder Met)	50	20	40	-	-
Molybdenum (Arc Cast)	10	5	200	-	-
Mo - 0.50 Ti	10	5	200	0.5	-
TZM	10	5	200	0.5	0.100

defects in some cases and by poor processes at other times. The process difficulties will be discussed in a later section.

The interstitial elements oxygen, carbon and nitrogen have a marked effect on weld ductility(1, 2, 3, 4) of molybdenum. The effects of these residuals in the molybdenum alloys should be similar to the parent metal. Welding of powder metallurgy molybdenum often shows centerbead cracking and porosity. These effects are blamed on the high gas content of powder metallurgy product(4) as shown in Table III. Generally, arc cast molybdenum contains a low enough gas content so that cracking and porosity is not as great a problem. Throughout the industrial survey no great difficulty was noticed in the welding of commercially pure arc cast molybdenum with respect to cracking and porosity. Some early welding reports show the difficulty,(1, 2) however, arc casting techniques have been developed such that the gas content is low enough so that porosity and cracking is not normally a problem.

The results of the investigations of the effects of interstitials on the weld ductility of molybdenum is shown in Figures 3, 4 and 5. The effects of these elements on cast molybdenum are shown in Figure 6. Some correlation should be able to be made between as welded and cast material. The results show some differences mainly in magnitude probably due to variances in base material grain size, grain shape, impurity distribution and testing procedures.

Oxygen in both cases seems to have the greatest effect on bend transition temperature with 0.009% raising the transition temperature from -150° to about 100°F (strain rate 0.003 "/"/min). The effect of nitrogen is somewhat less (0.12%) raising the transition temperature in a welded specimen from 0°F

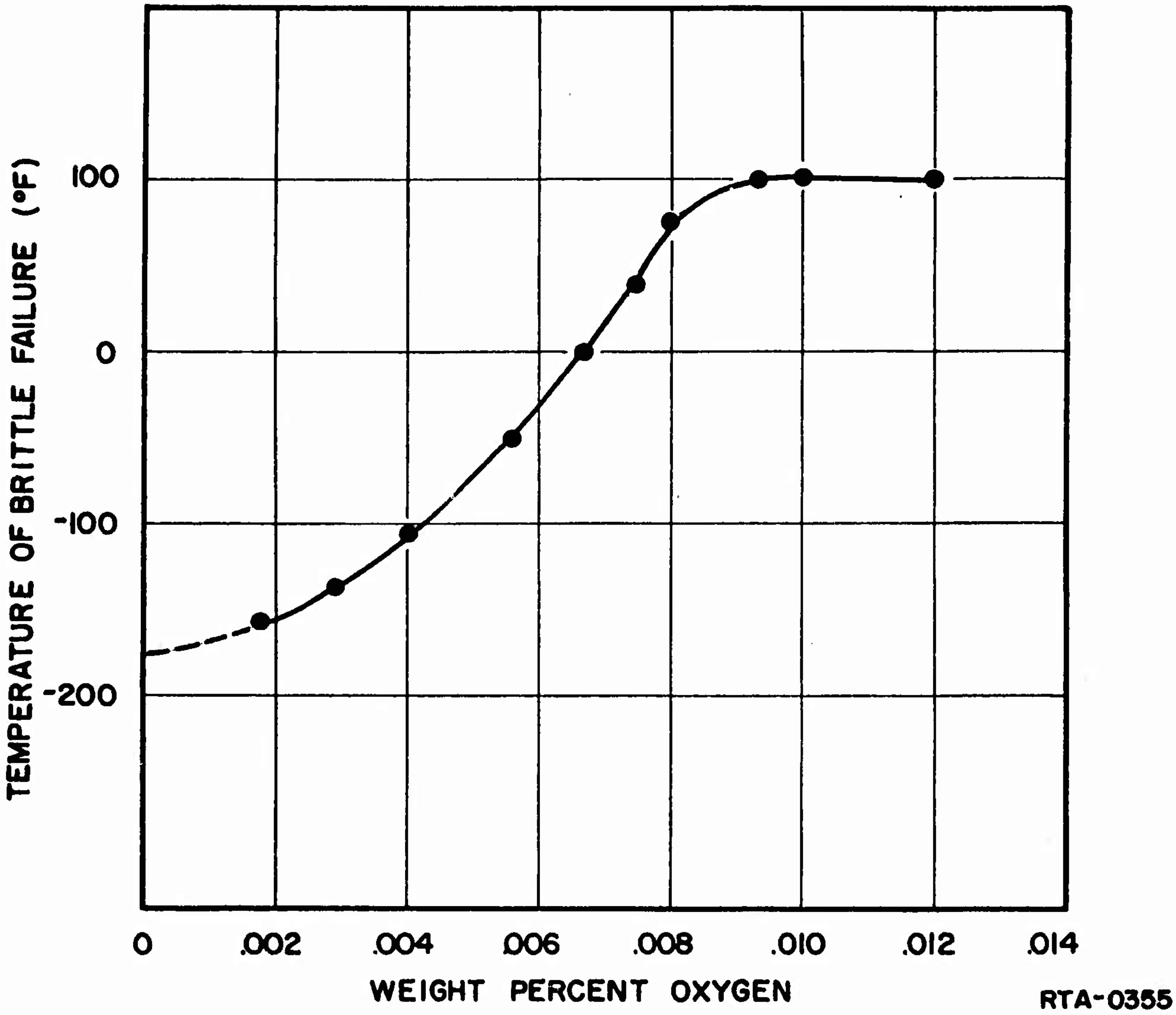

FIGURE 3

EFFECT OF OXYGEN IN THE WELD BEAD ON TEMPERATURE OF BRITTLE FAILURE (1)

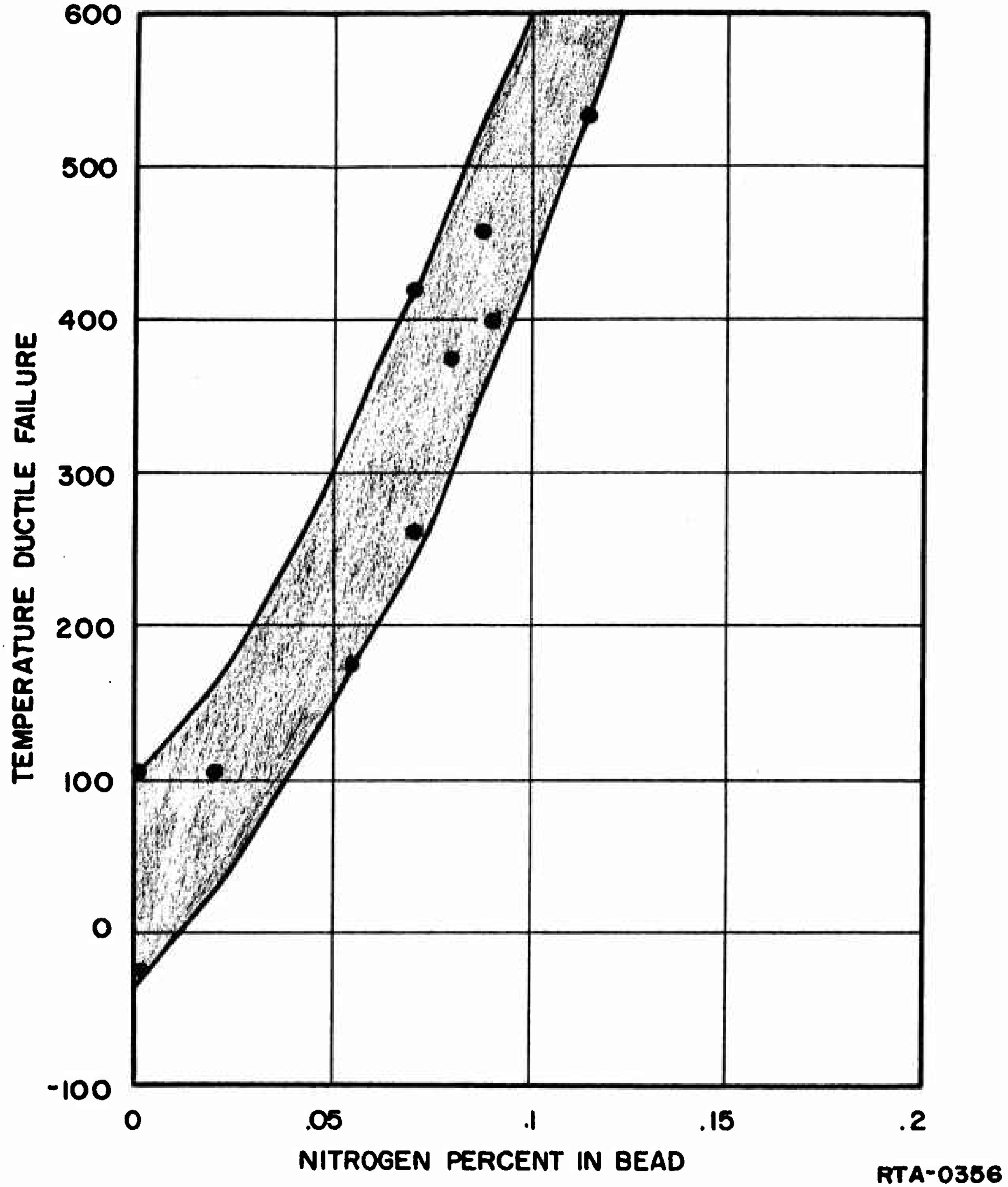

FIGURE 4

THE EFFECT OF NITROGEN IN THE WELD BEAD ON TEMPERATURE OF DUCTILE FAILURE

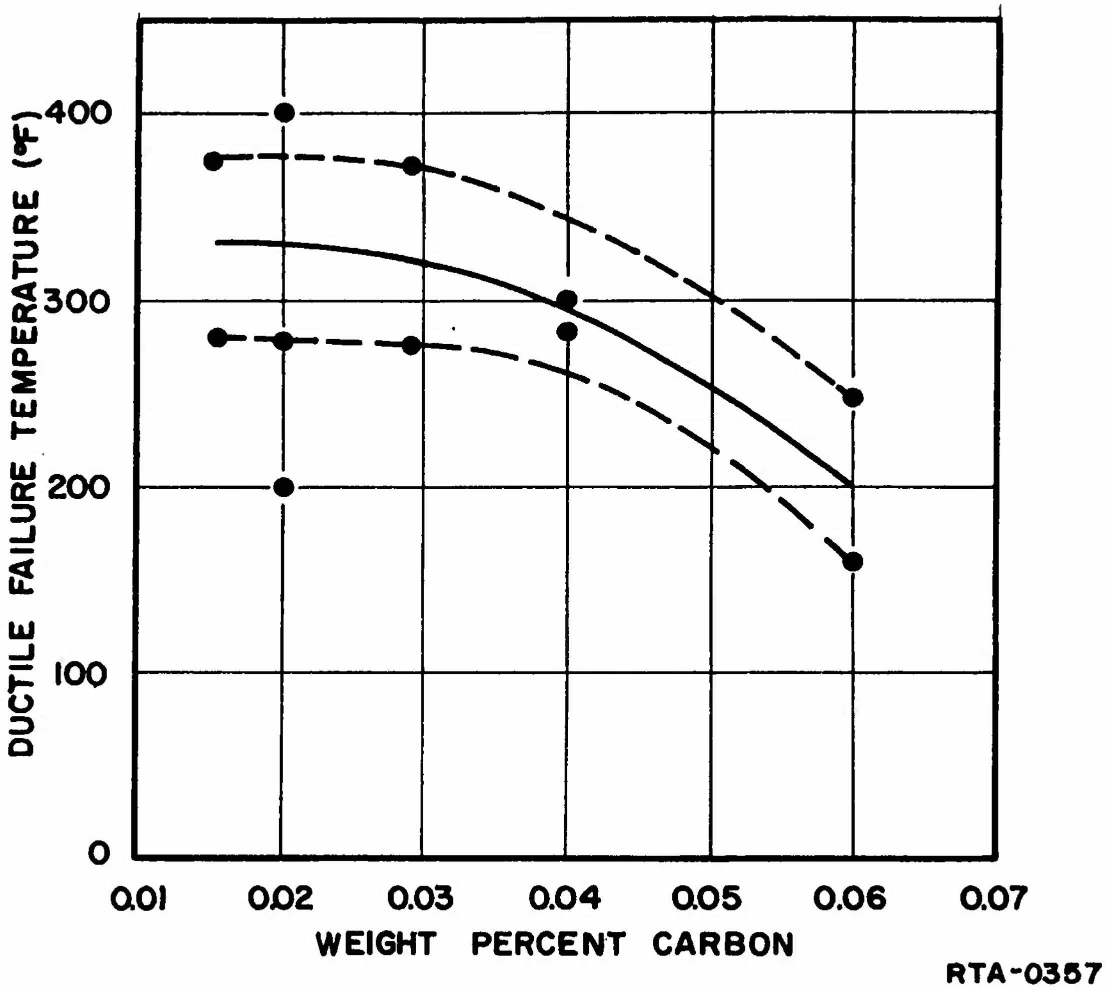

FIGURE 5

TEMPERATURE FOR DUCTILE FAILURE VS CARBON CONTENT

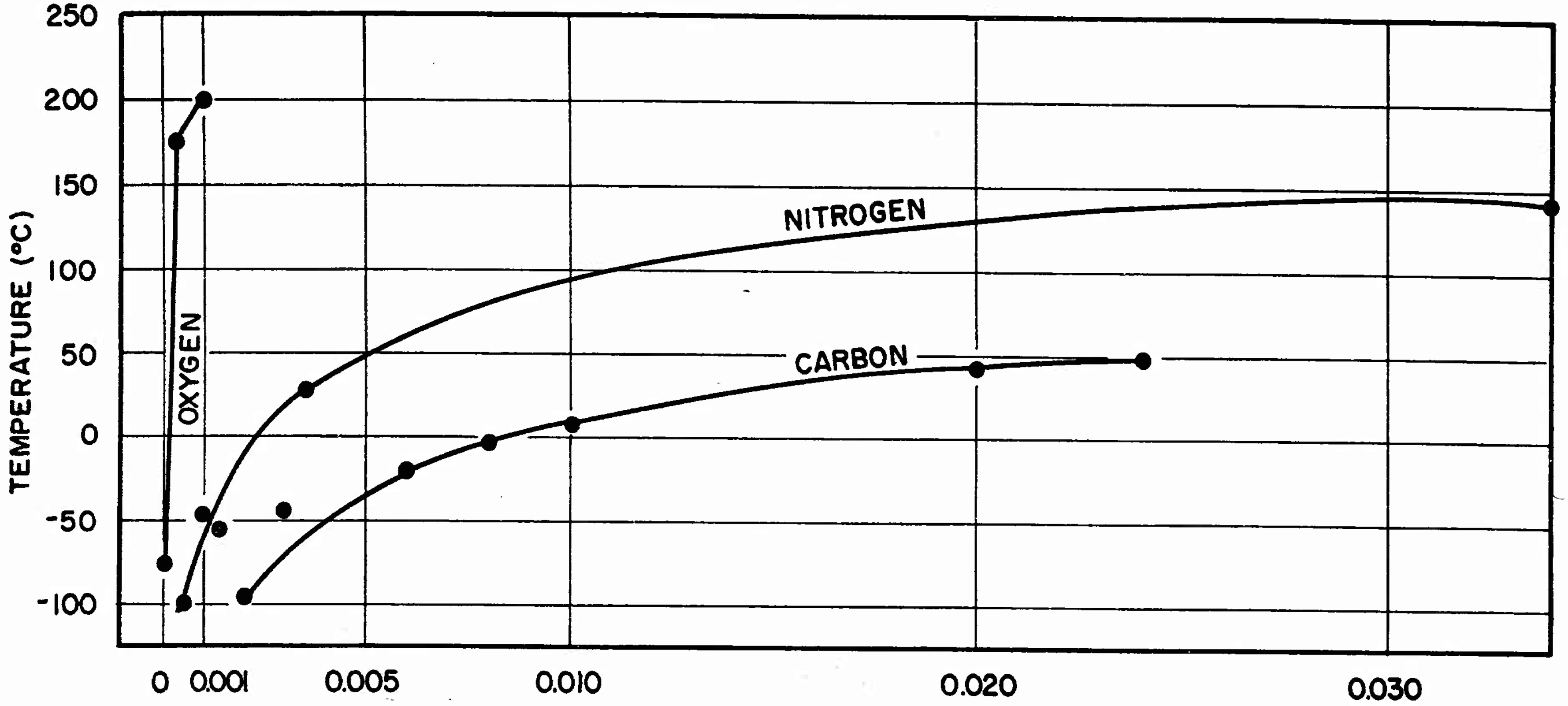

FIGURE 6

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EFFECTS OF OXYGEN, NITROGEN AND CARBON UPON BRITTLE TRANSITION TEMPERATURE OF CAST MOLYBDENUM to 500°F. The as cast study shows 0.01% nitrogen raising the transition temperature from -100°C (-148°F) to 100°C (212°F).

The effect of carbon on weld ductility is somewhat controversial. Figure 6 (as cast material) shows a detrimental effect of carbon from 0.001% to 0.025% while Figure 5 on welded materials shows a slight increase in weld ductility in the range 0.01 to 0.06. Monroe et al found a decrease in weld ductility with increase carbon(6) in the range 0.15% to 0.82%. The question of the effect of carbon on weld ductility is still unresolved.

Titanium in cast molybdenum shows an increase in ductility in amounts to about 1%.(6)

Mo-0.5Ti has also shown little difficulty in welding(8, 9) with respect to soundness. In the survey of the industry no great difficulty was encountered in producing sound welds using proper welding techniques.

Reference to the welding of TZM has not been found in the literature, however, in the Industrial Survey several organizations have indicated the ability to join TZM. Difficulty is sometimes encountered in cracking. Porosity is not generally a problem.

Mechanical properties of commercially pure and molybdenum alloy welds are generally reported in bend transition temperature and/or tensile properties. Bend transition temperatures are generally between 100° and 300°F, however, some references indicate transition temperatures as low as room temperature and as high as 400°F. The range of indicated transition temperature is not surprising when the great effect of the interstitial elements are considered. Small variations of starting material and in welding techniques could easily account for the range of reported data.

Tensile data on welds of molybdenum base materials have been presented by several authors.(8, 11, 15) Typical strength properties of the parent metal and of welds in Mo-0.50Ti are shown in Figure 7. This material was electron beam welded. Again it seems difficult to compare these results with other investigations both with respect to welding process and properties due to the testing being non-uniform and the starting materials being different.

b. Columbium

Formal investigations on the weldability of the commercial (or semi-commercial) columbium based alloys are shown in Table IV. Specific parameters of welding will not be given nor will all the data presented in the referenced material. The discussion is presented to indicate the relative properties and welding problems relative to the columbium alloys discussed in the literature.

Cb-1%Zr when welded in a controlled atmosphere chamber with TIG equipment showed capabilities of a 180° bend at room temperature.(13) No difficulty was reported in the Industrial Survey. Ductile, resistance spot welds have been made with this material.

FS82 is another columbium alloy which gives little difficulty in welding. Transition temperatures of -100°F have been achieved using TIG welding in a controlled atmosphere chamber. An overaging at 2000 to 2800°F improved weld ductility and prevented embrittlement on aging at 1800°F.(15) Electron beam welds showed a transition temperature of -280°F for this alloy. A second investigation also studied the weldability of FS82. Room temperature bends of 105° over a 4T radius were possible after a post heat treatment of 2200°F for 1 hour.(14) Spotwelds

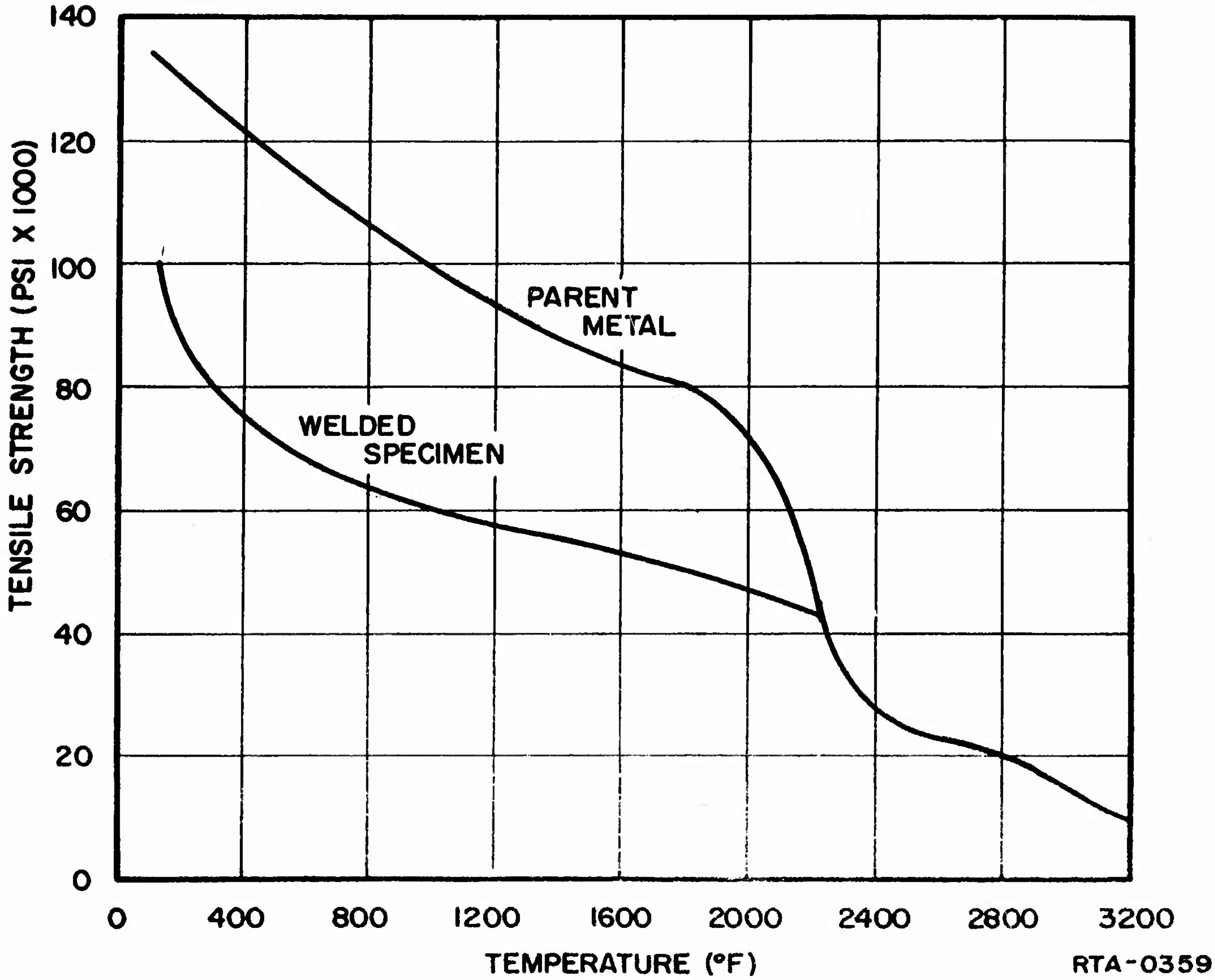

FIGURE 7

COMPARATIVE ULTIMATE TENSILE STRENGTH OF PARENT METAL AND ELECTRON BEAM WELDED Mo-.5% Ti SHEET

TABLE IV

COMMERCIAL COLUMBIUM ALLOYS INVESTIGATED FOR WELDABILITY

Commercial Designation	Nominal Composition
Cb-1Zr	1.0Zr
FS-82	33Ta - 0.7Zr
D-31	10Ti - 10Mo
F-48	15W - 5Mo - 1Zr
D-36	10Ti - 5Zr
Cb-752	10W - 5Zr
FS-85	27Ta - 12W - 0.6Zr
B-66	5V - 5Mo - 1Zr
X-110	1Zr - 10W

were formed and a heat treatment similar to the TIG treatment was necessary to restore ductility.(14, 15)

The alloys D31 and F48 reacted similarly to fusion welding. The transition temperature of D31 and F48 TIG welds was reported to be about 600°F. Transition temperatures of electron beam welds were somewhat lower at about 250°F. Post weld heat treatments and preheating reduces the transition temperature, however, the best set of conditions showed F48 TIG weld transition temperature at 350°F and D31 at 450°F.(14)

Both D31 and F48 have been resistance spot welded.(14, 15) Both have shown brittle welds at room temperature. Cracking is prevalent in the fused nugget type welds, therefore, the recrystallized type weld is generally preferred. Foil insets of titanium have shown some improvement in properties. Tensile shear properties were somewhat improved, however, brittle failure was still prevalent.

Cb752 has shown tungsten arc welds capable of a 180° bend over a 3T die at room temperature.(12)

The remaining alloys listed are at present being investigated.(16) Some of the preliminary results will be given.

D36 showed a bend transition temperature of -250°F for TIG welds while electron beam welds were ductile to -320°F. Some cracking was observed in the D36 welds at speeds at 15ipm. Higher or lower speeds eliminate the cracks.

FS85 electron beam welds showed a transition temperature of -200°F to -175°F.

Cb752 TIG welds gave a transition temperature of -140°F compared to -275°F for electron beam welds.

B66 gave electron beam welds with transition temperature range of -150 to -100°F. Center bead cracking was observed in TIG welds when the clamping pressure was high. Very light clamping pressure eliminated the cracking problem.

B66 was reported weldable with room temperature minimum bend radius of 2.5T.(17)

X-110 showed TIG welds with a transition temperature of -150°F and electron beam welds with a transition temperature of -150°F.

c. Tungsten

Ductile - brittle transition temperatures of welds in powder metallurgy tungsten have been reported in the range of 600° to 1100°F.(3, 18) Again the wide range of values can be assumed due to variations in starting material, testing techniques and welding techniques. Cracking is a problem and careful preheat and fixturing practices should be used. Porosity is sometimes a problem in the powder metallurgy product whether electron beam or TIG welding is used. Arc melted tungsten should eliminate most welding porosity, however, the mechanical properties should be similar. Tensile strength of welds in tungsten are generally lower than the base metal up to a temperature of 2800°F. Above these temperatures the strengths are comparable(12) to base material.

d. Tantalum

Welds of tantalum and Ta-10W can be bent at room temperatures to 180° bend over a 1T radius.(3) Tensile properties show the welded material somewhat lower strength than the base metal up to temperatures of 3000°F;at this temperature the tensile properties are similar.

All of the four major refractory metals, molybdenum, columbium, tungsten and tantalum and most of their alloys have been fusion welded. In all materials the necessity of an inert atmosphere is emphasized. In a future portion of this document a section is devoted to the impurity content of the welding chambers in use today.

3. Thicknesses of Refractory Metal Welds

Having reviewed the type of material involved in refractory metal weldments, the same data were re-evaluated to establish the thicknesses with which the refractory metal welding industry had at least some experience. Figures 8, 9, 10 and 11 set forth the findings for tantalum, columbium, molybdenum, and tungsten respectively in terms of both frequency of reference and the more quantitative value of reported inches of weld.

Tantalum, molybdenum and columbium show a marked predominance of experience in either the .010 - .030 inch or .030 - .050 inch thickness ranges. Columbium appears to be most often applied in the .030 - .050 inch range. All have been welded a significant amount in foil thicknesses and in thicknesses in the .150 - .250 inch range as well as in the catch-all range of over .250 inches. The trends in terms of relative length of weld parallel the number of reported applications in almost all instances leading to the observation that the number of welding experience per application is about uniform.

Tungsten does not exhibit a marked predominance of experience in any thickness range. Based on inches of welding experience, the tungsten weldments have been heavier than the other three materials with very slight peaks observed at .050 - .100 inches and in the over .250 inch categories (closely following the frequency of reference). In the .030 - .050 inch range only 250

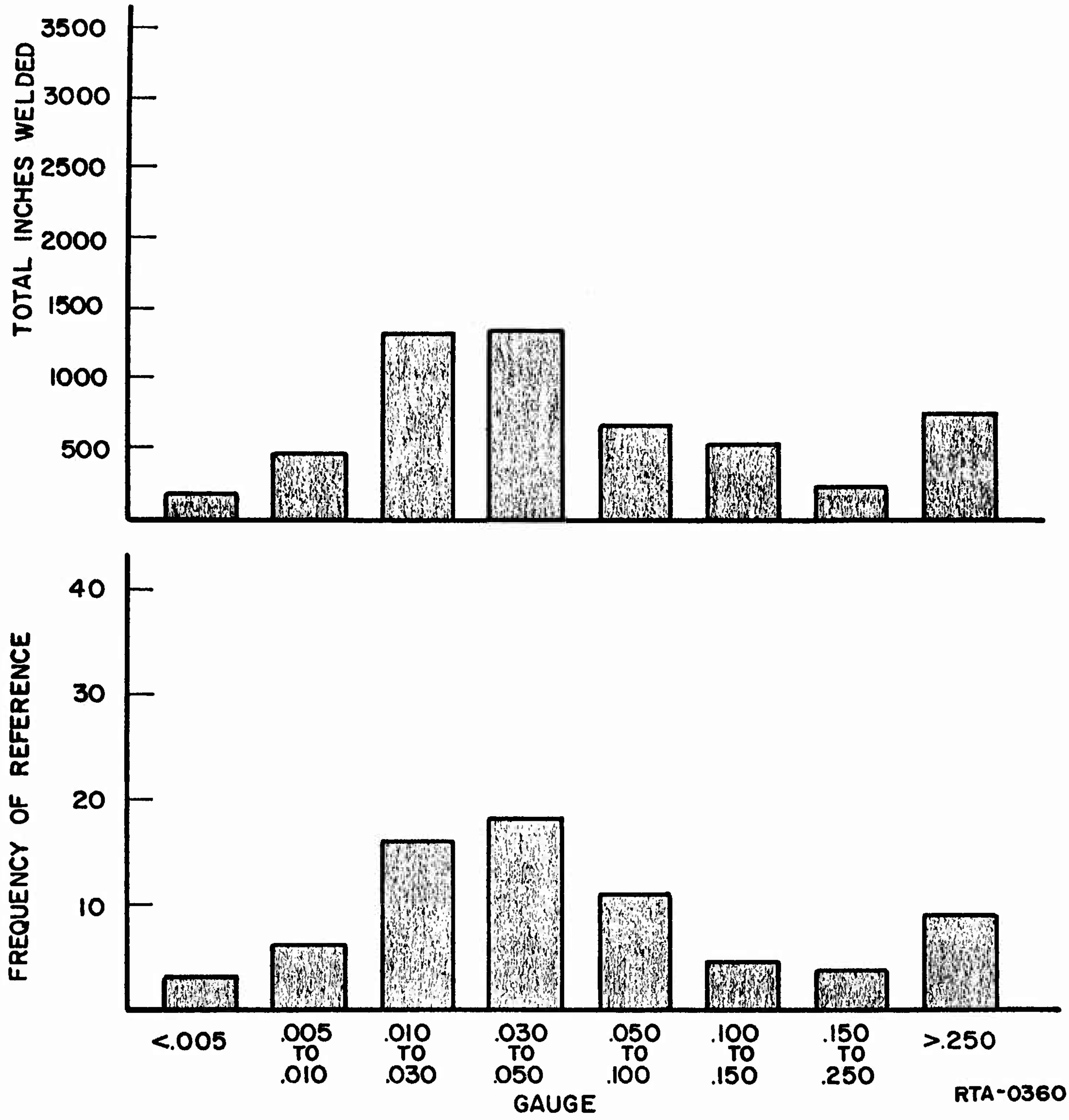

FIGURE 8
RELATIVE WELDING EXPERIENCE OF TANTALUM AND ALLOY VERSIS GAUGE

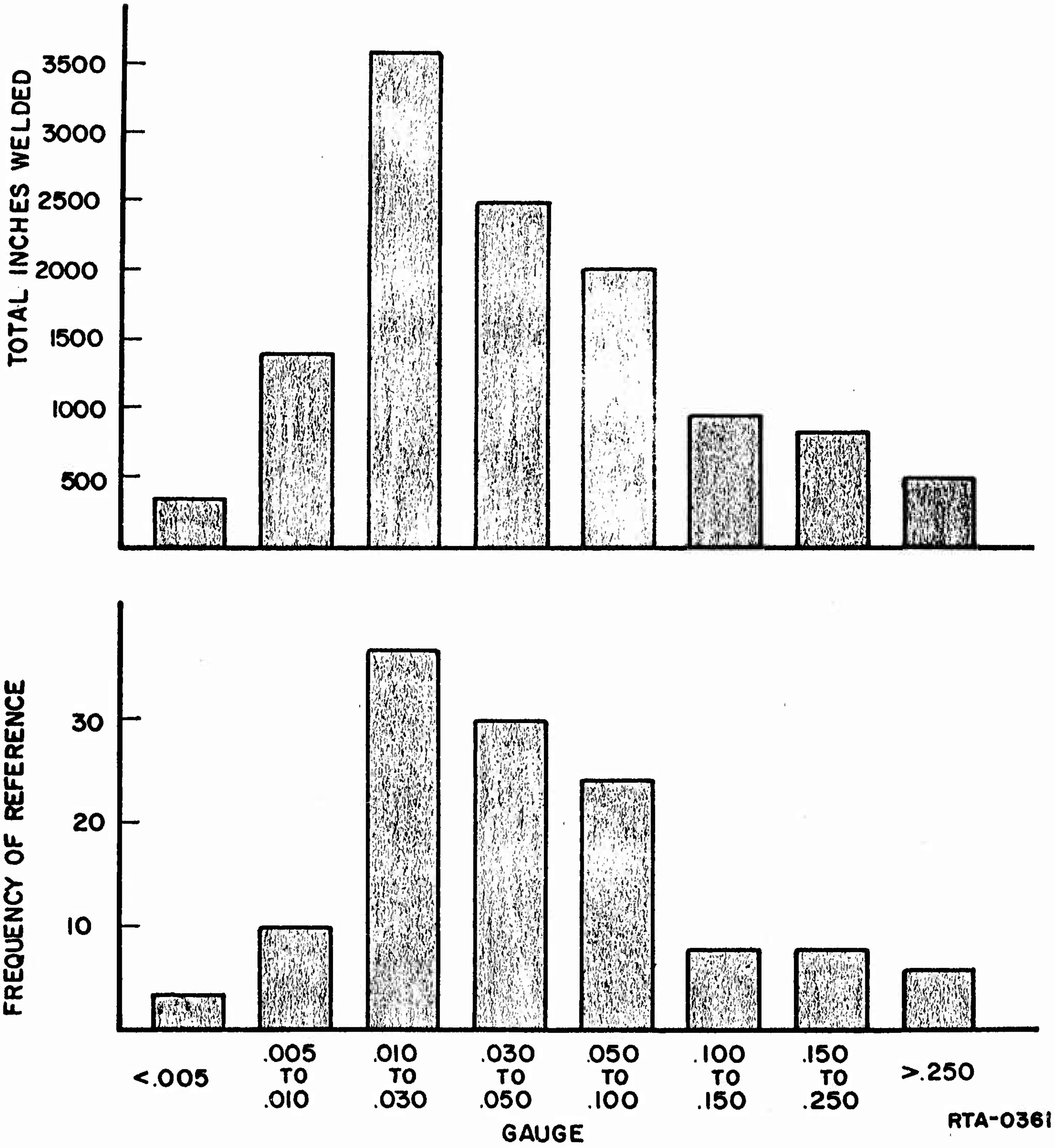

FIGURE 9

RELATIVE WELDING EXPERIENCE OF COLUMBIUM AND ALLOYS VERSIS GAUGE

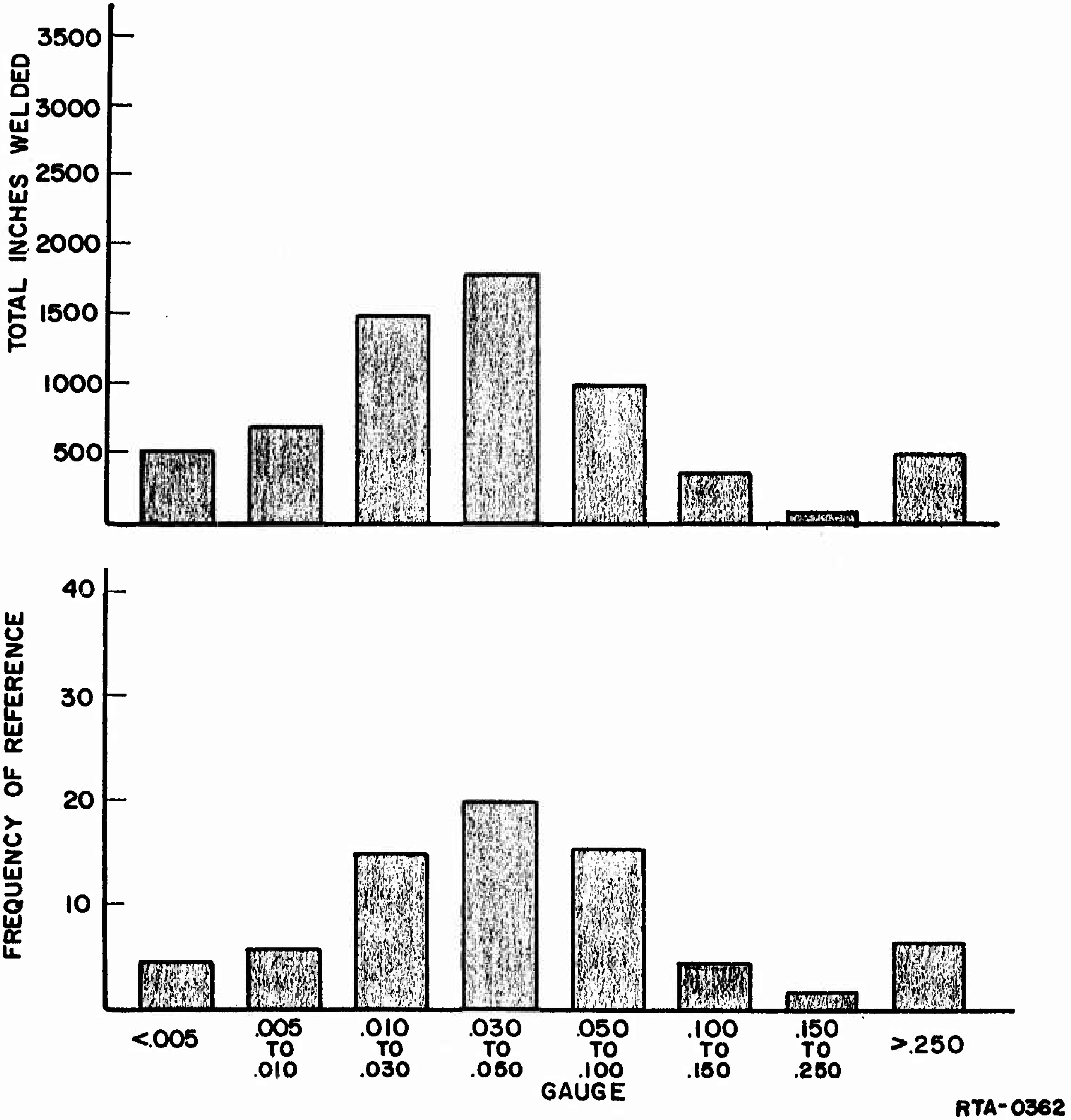

FIGURE 10

RELATIVE WELDING EXPERIENCE OF MOLYBDENUM AND ALLOY VERSIS GAUGE

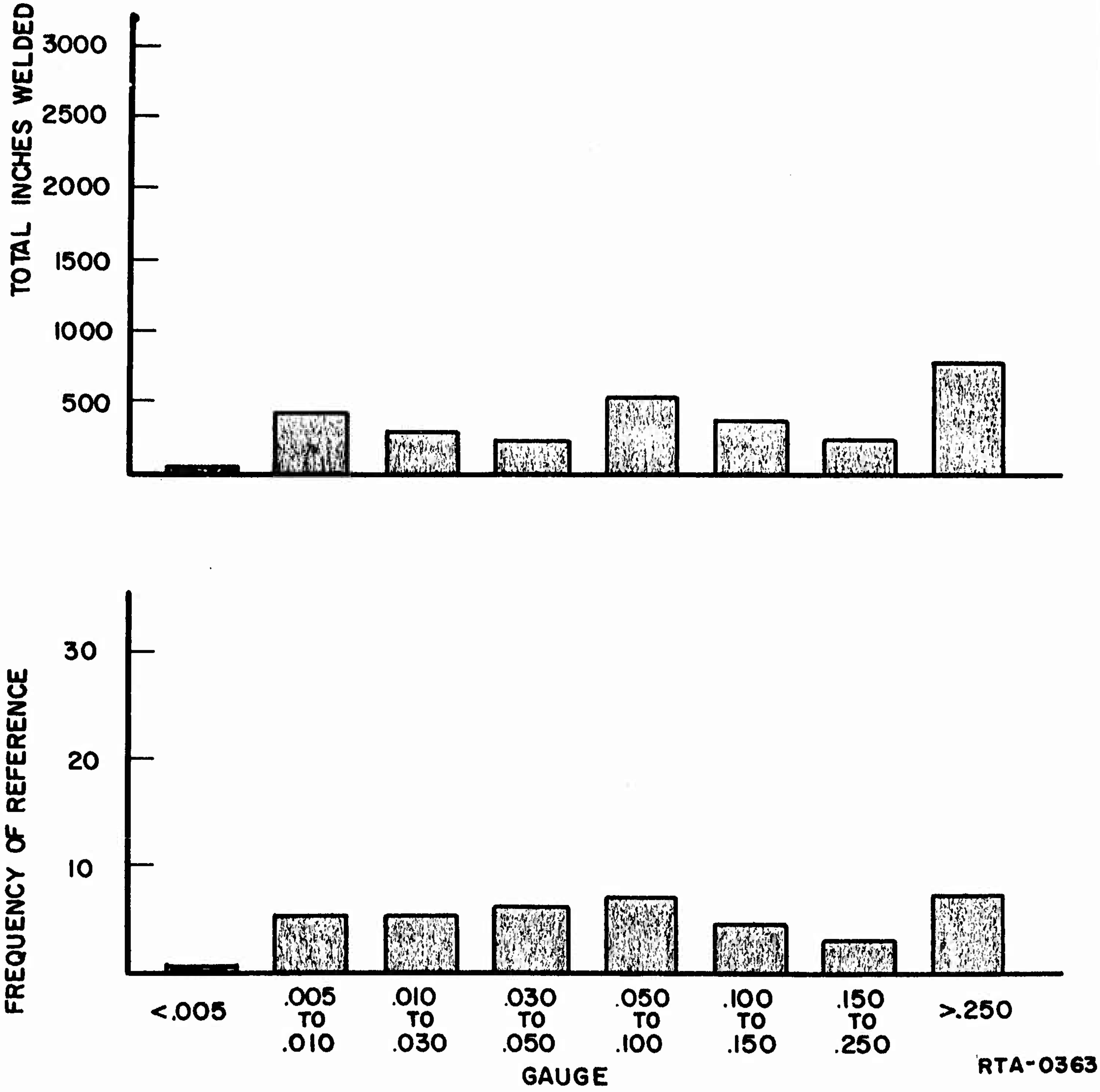

FIGURE 11
RELATIVE WELDING EXPERIENCE OF TUNGSTEN AND ALLOYS VERSIS GAUGE

inches (relative) of experience is reported. Thus it appears that the applications in this range involve significantly less welding experience per application than that encountered in other ranges.

The reported ability to weld heavy (over .250 inches) tungsten suggests the advanced nature of the welding skills that exist within the industry sample represented by this survey. Such welds involve immense heat input and generate very high welding stresses, while the welding technique, at the same time, must successfully accommodate the stresses generated by these welding conditions through sophisticated fixturing, careful alignment, preheating, etc. Furthermore all of this must be accomplished on a material that requires careful shielding and is extremely brittle up to temperatures approaching 800 - 1000°F.

B. Welding Processes

As noted in the introduction, this program is concerned with those processes wherein the individual base materials are joined directly. The scope, therefore, involves fusion welding but has been arbitrarily extended to cover joining under the influence of ultra-sound, or similar energy forms. Bonding, using extended time and temperature, or brazing through the addition of a third material to the joint, has not been considered. Table V, shows the frequency of reference to the various joining processes.

Non-consumable electrode inert gas welding (TIG) appears to be the most commonly used process in terms of frequency of reference in replies to the survey. However, of considerable significance is the indication that the refractory metals welding industry, as defined by this survey, has in its relatively short existence explored nearly every applicable welding process. That is, the refractory metals welding industry has attempted to apply nearly every process that appears to be capable of joining

TABLE V

JOINING PROCESSES SHOWING USAGE IN WELDMENTS-BY FREQUENCY OF REFERENCE

Process	Frequency of Reference
Arc, Inert Gas Non-Consumable Electrode	37
Arc, Inert Gas Consumable Electrode	6
Electron Beam	29
Resistance	19
Ultrasonic	3
Flash	4
Explosive	1
Laser	2

materials and still maintaining the metallurgical integrity of a material with the characteristics of brittleness and sensitivity to contamination exhibited by the refractory metals. This suggests that the level of technical sophistication is high and that the breadth of knowledge of the technical personnel associated with refractory metals joining is considerable.

One trend that was strongly evidenced in the survey is the close relationship between non-consumable electrode inert gas welding and electron beam welding. Of the 37 respondents that indicated experience with non-consumable electrode inert gas equipment, 20 also indicated experience with electron beam equipment. When asked during discussions to express an opinion regarding the relative advantage of each as applied to a given weldment, all facilities interviewed, that had both available, considered electron beam welding to be applicable only where their first choice, TIG welding, did not appear to meet all of the requirements. Several refinements over TIG are available through the application of electron beam welding. Two organizations apply electron beam welding to reduce stresses in the welding of complex shapes, one of these facilities emphasized the desirability of this approach when tungsten is involved. One other organization definitely felt that an improvement in the properties of columbium and its alloys could be achieved (if an improvement over the normally acceptable properties of properly produced TIG welds was required). Improved shielding reliability was cited by four facilities, but the improvement is a matter of degree and depends upon the TIG welding chamber that is available. In each case, however, electron beam welding was considered as capable of producing a process refinement that would not be achieved by TIG, which was in each case, the first process considered when fusion welds are indicated.

The need for very good fitup, tooling to permit remote manipulations and a vacuum quality chamber are limitations that are always present for electron beam application but are not always required for TIG. These limitations are not always of negative value since they force the facility to provide good fit and tooling (both of which are essential, for example, on complex tungsten weldments) when there might be a tendency to overlook these elements in the interest of cost or delivery. While the TIG-electron beam relationship was carefully probed in four interviews no attempt was made to evaluate the relative merits of high or low voltage electron beam equipment.

No similar relationships were observed for other processes. Currently other processes are applied on the basis of unique abilities or limitations. In the future the ability to produce spot welds between surfaces may require an evaluation of resistance and ultrasonic methods. Only two facilities were found actively working with both at present and the interest in spot welding is generally less than that encountered in arc welding so that a meaningful general statement could not be obtained.

C. Materials and Process Combinations for Reported Applications

A listing of the various weldments reported in the survey (Table VI) provides, perhaps, a better insight into the nature of the refractory metals welding industry than do the foregoing semi-quantitative statements regarding composition and thickness of the base material or a description of the equipment, since an intangible degree of complexity and reliability is implied by most of the weldment descriptions.

In reviewing the process-weldment relationships in Table VI the limited application of the electron beam process appears to refute the earlier statement made regarding the large number of

TABLE VI

SPECIFIC REFRACTORY METAL WELDMENTS REPORTED IN SURVEY

Description	Maximum Service Temperature	Material	Process Used
Exhaust System Components			
Rocket Nozzle & Nozzle Components			
Nozzle (Assembly)	4000°F	Tungsten	EB
Nozzle (Radiation Cooled)	3000°F	Molybdenum	Resistance
Nozzle (Uncooled skirt)	3000°F	Molybdenum	EB
Nozzle	-	Columbium	EB
Nozzle	-	Columbium Alloy	EB
Nozzle	4000°F	Tantalum	EB
Nozzle	3000°F	Tantalum	TIG
Nozzle (Liquid metal cooled)	2000°F	Mo-Mo Alloy-Ta	EB and TIG
Other Rocket Exhaust Components			
Hot Gas Valve	3000°F	Molybdenum	TIG
Manifold	5000°F	Tungsten	TIG
Elbow	5000°F	Tungsten	TIG
Blast Tube Inlet	5000°F	Tungsten	TIG
Components for Exhaust Systems in Other Type of Engines			
Vane	2000°F	Columbium Alloy	TIG
Sound Suppressor	3000°F	Molybdenum Alloy	EB and/or TIG
Structural Components for Aerospace Vehicles			
Leading Edge	4000°F	Tantalum Alloy	TIG
Leading Edge	3000°F	Columbium Alloy	TIG
Double Reversed Corrugated Panels	3000°F	Columbium Alloy	Resistance
Air Foil Surface	3000°F	Molybdenum	TIG
Corrugated Panel	2000°F	Molybdenum Alloy	Resistance
Honeycomb (Core)		Molybdenum Alloy	EB
Honeycomb (Core)		Columbium	Resistance
		Molybdenum	Resistance
		Tantalum	Resistance
Fitting	2000°F	Columbium Alloy	TIG
Heat Shield	3000°F	Columbium Alloy	TIG
Heat Shield	2000°F	Columbium Alloy	Resistance
Heat Shield	2000°F	Columbium Alloy	TIG (Spot)

TABLE VI (Con't)

SPECIFIC REFRACTORY METAL WELDMENTS REPORTED IN SURVEY

Liquid Metal Systems & Components

Loop	2000°F	Columbium Alloy	TIG
Loop	2000°F	Columbium Alloy	TIG
Loop (Small)	2000°F	Columbium Alloy	TIG
Loop (Large)	2000°F	Columbium Alloy	TIG
Loop, Sodium	2000°F	Columbium Alloy	TIG
Container-Liquid Metal	-	Columbium	TIG
Liquid Metal Pump	-	Columbium Alloy	TIG
Liquid Metal Sump	-	Columbium Alloy	TIG
Liquid Metal Pressure Vessel	-	Columbium Alloy	TIG
Connector Loop	2000°F	Molybdenum	TIG
Connector Loop	2000°F	Columbium Alloy	TIG
Heat Exchanger	2000°F	Molybdenum	TIG
Heat Exchanger	2000°F	Tantalum	TIG

Other Applications

Wave Guide	3000°F	Columbium Alloy	TIG
Pitot Tube	4000°F	-	TIG
Calorimeter	2000°F	Tantalum	EB
Thermionic Emitter	2000°F	Tantalum	EB
Thermocouples	3000°F	Tungsten-Tantalum	EB
Vessel Liner	under 1000°F*	Tantalum	TIG
Furnace Liner	3000°F	Tantalum	TIG
Heat Exchanger	under 1000°F*	Tantalum	TIG
Agitator	under 1000°F*	Tantalum	TIG

* Used in chemical industry

applications reported for this process. It appears from Table VI that electron beam welding has been largely confined to the geometrically simple welds associated with nozzles. The need to manipulate the workpiece very accurately may have limited the application of electron beam welding. When more complex shapes are involved, TIG appears to have been preferred. In some instances problems associated with fitup may have precluded the use of electron beam welding. Resistance welding seems to play a more important role than electron beam welding when actual components are considered.

Finally, it is believed that the relative use of the processes as reflected by Table VI is somewhat less current than the remainder of the information taken from the survey or from interviews since these refer to components already built and indicate past capabilities rather than present or future. In discussions with two major refractory metals welding subcontractors, emphasis was placed on the one-of-a-kind nature of the orders that they encounter. To illustrate the influence that the one-of-a-kind nature of the market has on process selection, one vendor cited a particular component that had been repeatedly fabricated by his organization but emphasized that a process such as MIG was still not attractive for this application because some variance was always encountered as a result of fabrication problems and engineering changes. A single TIG welding procedure accommodated these variations. Several MIG procedures would have been required in the workpiece. The joint thicknesses would have favored MIG over TIG under normal production conditions.

D. Size of Refractory Metal Weldments

The tendency to weld refractory materials in a chamber in order to achieve reliable shielding conditions suggested that the size of weldments might be important to any discussion of the current capabilities of the refractory metals welding industry. Tables VII and VIII show this relationship in arc and resistance welded structures.

Over half of all the applications reported appear to have dimensions less than one foot. This predominance of small weldments may be associated with the comment of many facilities that their output was largely in the form of test specimens or test assemblies since the environmental testing facilities for refractory materials rarely can accommodate full scale components. It also reflects the tendency for heat shields, a major item of prototype production as noted in Table VI, to be limited in size in order to minimize the effect of temperature gradients on the structure. Rocket exhaust system components with their current dependence upon tungsten may also contribute to the limited component size encountered by the industry since weldable (and formable) tungsten material is not available in large sizes. Liquid metal systems, one of the largest of the current refractory metal components are limited by the economics of environmental chambers. If one or more of the limiting situations suddenly changed (particularly in the area of rocket exhuast components or liquid metal systems), severe arc welding chamber limitations might result. The effect on resistance welds would be less noticeable providing processes were available to produce the welds in most thicknesses and without excessive electrode wear.

E. Techniques for Welding Refractory Metals

Having reported the materials, equipment and weldments involved in the welding of refractory materials, the survey in this section undertakes a discussion of how refractory metal welds are made for any given process. For the purpose of the survey, the term "technique" has been chosen to define all of the elements

TABLE VII

LARGEST WELDMENTS CURRENTLY PRODUCED BY ARC WELDING

	Number of Responses				
	<1 ft.	1-2 ft.	2-5 ft.	5-10 ft.	>10 ft.
Max. Length	15	4	6	2	1
Max. Width	17	6	0	0	0
Max. Depth	18	4	0	0	0
Max. Diameter	13	5	1	0	0

TABLE VIII

LARGEST WELDMENTS CURRENTLY PRODUCED BY RESISTANCE WELDING

	Number of Responses				
	< 1 ft.	1-2 ft.	2-5 ft.	5-10 ft.	> 10 ft.
Max. Length	4	4	3	0	0
Max. Width	4	5	0	0	0
Max. Depth	9	1	0	0	0
Max. Diameter	2	1	1	0	0

of equipment and tooling that may influence the final weld. Specific items of technique that were included in the questionnaire were:

- Shielding
    - Importance
    - Methods
    - Gas Purity Limitation
    - Methods of Monitoring Purity
- Power Supply
- Special Equipment Controls
- Underbead Chill
- Underbead Shielding
- Carriage Travel Requirement
- Tool Rigidity
- Clamping and Alignment Requirement for Fixtures
- Resistance Welding Electrode Materials
- Rating of Resistance Welding Equipment
- Material Control with regard to:
    - Surface Finish
    - Levels of Contamination

The survey approached the gathering of information regarding the importance of these items of welding technique from a comparative viewpoint. By determining where the techniques varied from some rather well-established basis of reference (both austenitic stainless steel and high temperature alloy welding practices were used) a dual purpose would be served. First, a semi-quantitative value could be provided (i.e., the importance of a particular parameter was higher or lower than that used to weld stainless steel) so that trends would be more readily and reliably established. Second, since changes in practice are one likely source of production limitations it was felt that comparison would best highlight potential problems. In short, the questionnaire was keyed to establishing the existence of any trends or variances from contemporary practice that might ultimately result in production limitations.

Actual procedures in terms of amperages and voltages were not solicited because:

a. This information would be difficult to correlate. the degree of optimization for a given procedure would not be known. Further such conditions as fit-up, chill etc., which vastly influence these parameters could not be easily classified. Proper clarification of conditions is essential when discussing parameters such as current.

b. Data of these types would not be apt to suggest limitations in production.

The techniques applied to and problems associated with each process are discussed in subsequent sections.

1. Fusion Arc Welding Techniques

Identified shielding methods include the use of auxiliary nozzles attached to the torch (19 to 39 responses from facilities working with TIG). In 27 of 39 answers, chambers were identified. Sixteen of the 27 facilities using chambers also used auxiliary shields without chambers in certain applications. Twelve respondents indicated that special welding parameters could also be used. Of the 27 facilities reporting the use of chambers, 12 were identified (or observed) to be of the type that could be evacuated and backfilled with inert gas. The report evacuation levels ranged between 1.5×10^{-3} mm and 1×10^{-6}. Where evacuation and backfilling is employed at least one facility also reported a systematic procedure for periodically checking on the leak rate under vacuum and also had applied specific techniques for rapidly backfilling -- both technqiues aimed at minimizing the introduction of contaminants during the low vacuum portion of the purging cycle. The diffusion of water directly through rubber gloves during welding was cited as a source of contamination. In three instances, double evacuation-refill cycles were employed. At least sixteen facilities that use chambers (including six that are known to use vacuum purging), also produce a weld on a reactive metal prior to initial production. Titanium is frequently used. The appearance (and, less frequently, bend behavior) of the scavenge weld are used to establish the purity of the chamber atmosphere.

The appearance of a weld in a reactive metal is frequently used in setting up auxiliary shielding equipment on welding torches that are not to be used in chambers.

Nine facilities of the 27 that commented on monitoring the shielding environment actually used instruments to analyze the chamber gas. Fourteen others relied on the certified purity of the gas in the container. Twenty-two specifically noted the use of weld appearance. Eight facilities (each with experience in all four refractory metals) were questioned regarding the use of open welding with auxiliary shielding versus the use of some type of chamber. In each case, satisfactory open welds had been made. In all but one case a welding chamber was preferred. Reliability was cited in each instance as the reason for preferring a chamber. There was general agreement that, in theory, at least moderately pure atmospheres could be obtained from an open torch equipped with properly designed auxiliary nozzles. However, process reliability is a big factor in the one-of-a-kind experience that characterizes the production welding of expensive refractory metal subassemblies. Estimates of the reliability of the open (non-chambered) torch with auxiliary shields ranged from good, for one application where the welding was in a deep trough-like configuration, to very difficult and expensive to achieve, in the case of outside corner welds where the gas could fall away from the joint causing a directional flow across the weld. Even under the best circumstances, the open torch does not permit monitoring and welding could not be discontinued in the event that the purity level started to drop during welding. Secondly the commonly used technique of using a scavenge and preweld observation in the same batch of gas that will be used during welding is not possible as it is in chamber welds.

In 22 instances, the facility had considered gas purity in sufficient detail to define it in the questionnaire. Table IX gives these results.

It appears that there is a wide divergence of limits for the individual contaminants. However, 13 out of 21 facilities in the above table indicated a preference for less than 50 ppm total impurities.

It should be noted that contamination effects both mechanical properties and corrosion resistance so that varying attitudes for different applications would be anticipated. Further the effect appears to be related to the amount of contamination so that different applications could tolerate different welding conditions. However, there does not yet appear to be a trend toward the establishment of common limits for a given segment of the industry (for example a common agreement among facilities building loops).

No data were reported for helium. Only twelve references were made to helium while at least 25 references were made to argon. This result is difficult to explain on a technical basis since helium provides greater penetration and, when processed, is capable of achieving less than 1 ppm total impurity levels. The

TABLE IX

REPORTED GAS (ARGON) PURITY LEVELS FOR 16 FACILITIES

Number & Type* of Facilities												
I	II	III	IV	V	VI	VII	O_2ppm	N_2ppm	H_2O**	$C_xH_x$ppm	H_2 ppm	Other ppm
		1					< 2.5	--	< 10ppm	--	--	--
		1					< 5	<10	2 g	< 2	--	< 5(carbon)
1							<10	<20	9 g	< 5	< 5	--
1		1					<10	<10	5 g	<10	<10	--
2		1		1		1	<10	<10	<10ppm	<10	<10	--
1	1	1					10/100	10/100	<10ppm	<10	<10	--
1				1			10/100	10/100	10/100ppm	10/100	10/100	--
1							-	--	<100ppm	--	--	--
	1						"Welding Grade Gas passed thru Molecular Sieve & Scavenged with Ti"					
		1					-	--	"-80°F"	--	--	--
1				1	1		"Bottle Gas"					

*I = Prime Contractor; II = Propulsion Contactors; III = Liquid Metal Loop Contractors; IV = Welding Equipment Vendors; V = Subcontractors; VI = Research Laboratories

** Water analysis was given in grains, parts per million, and dew point.

relative availability of the two shielding gasses may explain the higher number of argon applications. This situation may change with increased availability of helium.

Greater reliability with regard to gas shielding was identified by 27 of the 39 facilities that had worked with inert gas welding as being of benefit to present or future welded assemblies.

Table X lists the other parameters that were probed and suggests the uniformity of opinion regarding the importance of each.

It appears that control of the backup and chill is considered to be very important by the greatest portion of those facilities with welding experience involving refractory metals.

Individual discussions with three facilities that indicated considerable inert gas welding experience in the areas of (a) welding evaluation studies, (b) production tooling and, (c) the production of operation components provided some qualitative information regarding the reasons behind the importance associated with backup material and chills.

The facility engaged in welding evaluation studies noted that some of the heat treatable columbium alloys might exhibit metallurgical changes unless the temperature was dropped rapidly by proper chilling techniques. All facilities agreed that sudden changes in thermal conditions (including, in the case of tungsten, those associated with arc initiation or termination) could cause cracking. One facility that had studied the importance of chill on final weld configuration in complex production weldments had observed that as the thermal conductivity of materials increase chill becomes increasingly important. Under these circumstances it appeared that molybdenum and tungsten had approximately twice the

TABLE X

SPECIAL FEATURES REQUIRED FOR TIG WELDING REFRACTORY METALS

Feature	Identified as a special feature by*
Torch Construction	31%
Power Supply	18%
Arc Starting or Stopping	33%
Backup, Chill Bar, Materials or Design	62%
Rigidity, or Other Feature, in Fixtures	28%
Torch Travel (smoothness, special speed range)	33%

* % of the 39 facilities indicating experience with TIG equipment.

NOTE: Additionally a sample of 18 of the 39 facilities also indicated the relative importance of the following:

Wire feed - 27% indicated that it was important
Automatic Voltage Control - 65% indicated that it was important
Special Weld Cycles - 67% indicated that it was important

conductivity of more commonly welded materials such as steel. They felt that the complexity of the problem of backup design would further be increased. Furthermore, these refractory metals are not ductile, thus they will not easily conform to minor irregularities in the tooling or irregularities that might occur during preheating operations. Therefore not only are molybdenum and tungsten sensitive to changes in rate of heat extraction but it is difficult to assure that they will remain in uniform contact with the chill.

2. Resistance Welding Techniques

Of the 20 facilities that indicated resistance welding experience with the refractory metals, 15 stated that electrode life was shorter than that anticipated for stainless steel. The remaining five did not state one way or the other.

One vendor indicated the use of shielding gas with resistance welding of molybdenum but no value could be provided regarding the contamination level of the gas and only flowthru purging was involved. No effect was observed. However, several facilities (Table XI) apparently felt that it might improve the weld.

Six out of 14 facilities answering the questionnaire noted that welding pressures were higher while 6 noted that they were lower. One indicated that both higher and lower pressures had been encountered.

Twelve out of 17 facilities answering the questionnaire noted that weld cycles were shorter while 3 noted that they were longer. One noted that the welding times were similar to those used on stainless steel. One facility, the same as that listed above, felt that both longer and shorter cycles could be used.

TABLE XI

SPECIAL FEATURES FOR RESISTANCE WELDING EQUIPMENT USED TO JOIN REFRACTORY METALS

	% Indicating this Feature of special importance
Electrode Materials or Designs	93%
High Rate of Response	57%
Unusually Short or Long Cycle	64%
Forge Cycles, etc.	43%
Special Mechanical or Electrical Rating	14%
Inert Gas Blanketing	71%

Table XI indicates which of several features would be considered an important feature on equipment used particularly for resistance welding refractory metals.

Discussion with two facilities that had carried out resistance welding studies brought forth the reasoning behind the emphasis placed on electrode materials and also suggested some other limitations regarding resistance welding.

At present electrode wear rates of 6:1 and 10:1 have been reported. Except for high production applications such as the manufacture of honeycomb core, the major concern involves process control between electrode dressing and subsequent test coupon evaluations when rapid electrode deterioration is encountered.

Factors other than electrode wear confront most potential users of resistance welding. The problem of coating spot welded structures is one such problem. Additionally resistance welds in molybdenum have not exhibited either great strength or reproducibility. There is one report of a columbium alloy structure welded to the minimum standards of MIL-W-6858. Other investigators report chronic cracking problems associated with molybdenum welds. Methods of modifying the interface resistance of the base material and the use of extremely long welding times are under consideration in an attempt to reduce the effect of the sudden heating and cooling associated with resistance welding.

Columbium and its alloys are generally considered more amenable to spot welding. Honeycomb core which nearly met the minimum standards for cores of conventional materials have been reported (50% of the strength of an unwelded strip compared to 75% minimum required) and several resistance welded heat shields and corregated panels of columbium alloys are reported in Table VI in addition to the honeycomb application.

Resistance welding has been applied to tantalum honeycomb cores and while no quantitative values were provided, the strength of the spots was reported to be percentage wise only slightly less than that obtained for columbium.

3. Electron Beam Welding Techniques

The conditions characteristically associated with electron beam welding are such that the process is naturally compatible with the shielding and metallurgical requirements which characterize the welding of refractory metals. Therefore, the survey failed to uncover any requirements that could be labeled as "special" when compared to other electron beam applications. This survey, as noted earlier, did not attempt to arrive at generalizations regarding basic parameters such as current, voltage focusing etc., since they are closely tied to many other elements of the process such as tooling, component geometry, degree of overwelding, etc., that do not lend themselves to tabulation.

4. Flash Welding Techniques

Tungsten, columbium and molybdenum have been welded on production equipment. Power requirements are extremely high for tungsten and very low for columbium and columbium alloys. Welds have also been evaluted in molybdenum alloys.(19, 20, 21) Amount of upset was found to be a critical value. Brittleness was found in low and high upset values. In the low upset values brittleness was due to included oxides and porosity. In the high upset values the drop in ductility was attributed to transverse fibering. Some atmosphere flash welding of molybdenum was accomplished and results showed poorer ductility than in air. The lower properties were attributed to slower cooling in the inert atmosphere which caused a larger grain size and the precipitation of carbides in the grain boundary.(12)

5. Ultrasonic Welding Techniques

The development of ultrasonic welding for refractory metals components is being actively pursued in at least one instance - the fabrication of honeycomb core. Present equipment is limited to relatively thin gauges. Some materials and thicknesses that have been welded are listed in Table XII.

The above work has been accomplished on equipment providing up to 4 kilowatts of power. Twenty-five kilowatt equipment is being designed. It is anticipated that this equipment will weld .100 inch tungsten.

A major source of ultrasonic welding equipment noted that the relative power requirements of the various materials varies with the microhardness of the alloy according to the following emperically derived relationship:

$$\text{Power} \times \text{Time} = Kt^{3/2}h^{3/2}$$

K : is an efficiency factor for a given piece of equipment

t : is the thickness of the workpiece material against the ultrasonic transducer.

h : is the vickers microhardness

NOTE: Time cannot be substituted for power beyond certain limits established by the fatigue life of the workpiece and its thermal conductivity.

Various special practices have been observed when welding refractory metals. Surface etching improved weldability with certain lots of material. Super alloy tips reduce tip wear. The use of an inert gas had, on one easily oxidized (but non-refractory) material reduced the power requirement. Ultrasonic welding has been applied in chambers (for electronic applications) but the cladding of various materials had not been improved by carrying out the process in argon. Argon jets are used with some

TABLE XII

TENSILE-SHEAR STRENGTHS OF ULTRASONIC SPOT WELDS IN REFRACTORY METALS

Alloy	Gage in.	Interleaf	Ave. Weld Strength lb.
Mo, arc cast	.005-.010		120*
	.010		170
	.015		240
	.020		330
	.025		360
Mo, sintered	.005-.010		150
	.015		340
	.020		380
	.025		430
	.025	.0025 in. Ni	530
Mo-0.5Ti	.015		147**
	.017		250
	.017	.0045 in. Zr	300
	.017	.003 in. Ti	270
	.017	.0003 in. Mo	255
	.017	.0015 in. Mo	380
	.017		300
Nb-10Ti-10Mo	.0056		21
		.001 in. Ni	181
Nb-5V-5Mo-1Zr (B66)	.005		112
Ta, Stress-Relieved	.005-.010		90
and Annealed	.010		250
W, sintered and rolled	.005		91
	.010		57

* Stress-relieved and annealed.
** Parent metal failures.

refractory metal welds to improve surface appearance.

The performance of the generator or of a properly instrumented transducer can be monitored and, thru experimentation, related to weld quality. Cracks from improper welding are generally detectable. Cracks from overdriving extend through the sheet. Excessive pressure may crack the weld parallel to the interface but material is also visibly extruded. Random cracking has thus far been related to material defects propagated by the welding energy.

One facility has performed an ultrasonic weld through .010 inch molybdenum that had been precoated. The strengths of the joints compared favorably with the strength of uncoated material. The effect on the coating has not yet been evaluted.

6. Refractory Metals Welding Techniques for Other Potential Production Welding Processes

Welds using explosive force and laser energy were reported. The applications are primarily feasibility demonstrations. One facility is currently engaged in a program to produce a 10 joule laser unit.

Many other joining processes that could be classed under fusion welding have been used on refractory metals. These include submerged arc and atomic hydrogen. However, there was no indication that any of the 39 facilities listed in Part I were using or considering these methods. One electronic component manufacturer listed atomic H_2 and another has attempted submerged arc as a means for joining arc melting electrodes. Atmosphere electron beam welding is at present being developed.

F. Methods for Evaluating Welds in Refractory Metals

1. Evaluation of Fusion Welding

Of the 41 facilities reporting experience with fusion (arc or electron beam) welding, 37 indicated one or more methods of nondestructively evaluating welds. In several instances the nondestructive test had been conducted under several standards. The following methods were reported Table XIII.

Standards for evaluation are largely internal. One facility that had made extensive use of both penetrant and x-ray reported that the acceptability of an indication was based largely on two considerations.

a. If the indication was linear, it was rejected regardless of size. The low fracture toughness and high welding stresses associated with refractory metals was given as the reason for this policy--based largely on experience with tungsten.

b. If the indication was non-linear, rejection was based on the risk involved in repairing the weld (i.e., extent of rewelding, method to be used, etc.)

Bend tests involving both root and face bends were reported. In specific instances each had revealed desirable information according to one facility but the over-all superiority of one over the other had not been established. At least two facilities reported the use of both standard and cross bends (mandril 90° to joint). Prior experience dictates which is used in routine evaluation. However, for metallurgical engineering studies the cross bend was preferred by at least one facility because it permitted a comparative evaluation of both the weld metal and the metal adjacent to it. Rate of strain during bending was recognized by at least three facilities as important.

TABLE XIII

METHODS OF NON-DESTRUCTIVELY EVALUATING FUSION WELDS (ARC OR ELECTRON BEAM)

	Frequency of Reference		
Method	In House Standards	Government Standards	Industry Standards
X-ray	28	8	2
Penetrant	23	6	0
Bend (Periodic sample)	33	NA	NA

In spite of this recognition, rates have not been standardized and may vary from 0.05 to 10 inches per minutes (ram speed). The Materials Advisory Board, however, recommends a ram speed of 1 in. per minute.

Determination of service behavior using some form of destructive, mechanical test was reported by 35 of the 41 facilities indicating fusion (arc or electron beam) welding (arc or electron beam) welding experience. The preponderance of experience appears to involve tensile testing. (See Table XIV) The dependence on tensile testing does not appear justified in view of the service life reported for 82 refractory metal components as per Table XV.

Many of the above applications are reported to be test assemblies suggesting that much long-time performance data is being obtained only through simulated service and that basic principles of behavior are not being obtained in a more quantitative fashion.

Only 5 facilities reported having run chemical analyses on fusion welded joints. The results are shown in Table XVI.

Testing refractory materials for ability to withstand welding restraint was indicated by two organizations. Both indicated the use of the cross patch test using only bead on plate welding. No data were given.

2. Evaluation of Resistance Welding

Resistance welding experience was reported by 20 facilities. The methods of nondestructive evaluations are listed in Table XVII.

TABLE XIV

DESTRUCTIVE TESTS FOR EVALUATING SERVICE BEHAVIOR

Method	Frequency
Tensile	35
Fatigue	4
Creep	6
Stress Rupture	9

TABLE XV

REPORTED SERVICE LIFE FOR REFRACTORY METAL WELDMENTS

Service Life	Number of Applications
1 second	0
1 - 60 seconds	6
1 - 10 minutes	9
10 - 60 minutes	16
1 - 100 hours	19
over 100 hours	32

TABLE XVI

INTERSTITIAL ANALYSIS OF REFRACTORY METAL WELD JOINTS

Material	Welding Method	O_2 Joint	O_2 Base	N Joint	N Base	H Joint	H Base	C Joint	C Base
		Chemistry ppm							
Mo-0.50Ti	EB	35	4	10	2	-	-	-	-
Mo-0.50Ti	?	48	11	25	5	-	-	-	-
Cb-1Zr*	TIG	150	120	180	170	-	-	200	190
FS-82	TIG	159	59	27	16	17	6	-	-
Tantalum	TIG	40	25	-	-	-	-	-	-
Tungsten	EB	15	5	12	4	-	-	-	-

* Same ranges were noted for commercially pure columbium and Ta-10W.

TABLE XVII

NON-DESTRUCTIVE EVALUATION OF RESISTANCE WELDS

Method	Frequency
X-ray	10
Penetrant	4
Tensile (periodic)	11

Four facilities reported the use of Government standards and as noted under resistance welding at least one application of columbium alloys met MIL-W-6858. Thirteen, including the above four facilities, reported the use of in-house standards. Seven did not indicate any method of evaluating the weld.

The serviceability of resistance welds has been determined only for conditions of tension-tension shear. No fatigue, creep or stress rupture tests were reported.

3. Evaluation of Flash Welding

Flash welds of refractory metals are limited and have been subjected only to nondestructive (radiographic and penetrant) tests and metallography. Resistance-butt welding has been attempted in one instance. This method is commonly used to join tungsten wires for the electrical industry.

4. Evaluation of Ultrasonic Welding

Ultrasonic welds have been subject (in at least three cases) to tensile tests and metallography. In two applications (not on refractory materials) an energy monitoring approach to quality control is being applied.

G. Discussion of Part II Findings

In reviewing the nature of refractory metals weldments it appears that most of the welding is on a one-of-a-kind basis with only one area, rocket exhaust systems, exhibiting a degree of repetition suggestive of production. It appears, however, that even one-of-a-kind applications in refractory metals exhibit overtones of production when the amount of mechanization, tooling and monitoring are considered.

Under these circumstances production improvements would be most profitable if they increased the assurance of success of individual applications and at the same time retained (or preferably increased) the flexibility that appears to be required to accommodate present production. The above approach is in contrast to the more often encountered concept of production improvement where a narrowly-defined well-established production application is attached with the intention of improving the efficiency of one or more of its elements. The cost in time and money of welded refractory metal structures lies in tooling, establishing and monitoring the environment, preparing the work piece, establishing welding parameters etc. The actual welding operation seems to be a minor (in terms of time and money) portion of the total production cycle.

1. Increasing Assurance of Success in One-of-a-Kind Processing.

When there is no appreciable relationship from one part to the next on which to gain experience it is necessary to carry our considerable systematic engineering effort before welding is started on a given application. Two common sources of quantitative engineering data which might assist the welding engineer to approach a new application with maximum insurance are:

a. Standards

Standards that identify the undesirable conditions characterizing refractory metal weldments are required in order to permit the establishment of quality, price and delivery in the many one-of-a-kind or first-of-a-kind situations facing the welding engineer at present. Furthermore, several levels of quality must be identified for each condition, since the achievement of near perfection with regard to any given undesirable condition can only be accomplished, in most instances, by accepting the presence of a limited amount of some other condition.

Two factors influence the delineation of undesirable conditions for any given material. These are:

(1) The requirements of the product, or of each of several products, to which the material will be applied.

(2) The nature of refractory metals and refractory metal welds.

The nature of refractory metals weldments suggest that welding specifications for refractory metals would be concerned with many phenomena, (such as monitoring welding atmospheres to assure ductility and to control corrosion rates) that are not commonly encountered in welding standards for other materials (except, to a limited extent, titanium).

Becuase some compromise is always involved in the selection of acceptance criteria it is essential that the proposed standards be supported by test data showing the influence of the various conditions on weld behavior in service. Long time testing is indicated for the type of application most often reported in the survey and is not presently being carried out in proportion to the short time tests. It appears that the present emphasis is on the development of long time data as a byproduct of the service tests for which many of the components are being fabricated. The extrapolation of such data to other applications is difficult. Usually, the conditions of test are difficult to establish, and also welding and design are often conservative. This conservatism is adopted because the main purpose of the test is to obtain engineering data regarding the behavior of the component rather than establishing the conditions under which a weld will fail. Weld failures, however, are essential to any conclusions regarding weld performance.

b. Process Latitude Studies

Faced with any given set of standards it is equally important that the welding engineer know how closely the processing of the component (including tooling) must be controlled to achieve that standard. The special techniques identified in this survey (as an example, the shielding and chilling or preheating) suggest that new process - materials relationships exist which must be explored. The required level of gas purity associated with TIG is an example of an area where effort might be expended to determine what can be done to increase the tolerance of the weldment for contamination (e.g. through modification of such welding parameters as speed - the use of special filler materials etc.).

2. Increasing Flexibility of Equipment to Accommodate One-Of-A-Kind Production

While an across-the-board recommendation for standards or process latitude studies can be made, recommendations concerning the development of maximum flexibility must be related to each process in turn. This report confines its recommendations to production equipment and techniques. However, the need for development of more weldable materials and the achievement of a better understanding of the phenomena that are influencing the properties of welds in current materials is recognized as fundamental to increased use of refractory metals and weldments.

a. Recommendations for Butt and Fillet Welding Process Improvement

TIG welding is a very flexible tool for producing joints between the edges of two sheets or even plates up to 3/8" thick according to the finding of this survey. TIG, with filler, can also produce fillet welds to join members at an angle. When, however, a chamber is employed the complexity of operation is increased and flexibility decreased. Where manual operations are involved (e.g. where greatest flexibility exists) gloves must be used which, in turn, result in some contamination. Additionally, the problems of adopting chambers to provide access to a multitude of weldments with an infinite variety of shapes and sizes suggests that, while the chamber has not prohibited welding in any case identified in the survey it is the least flexible and reliable element of the process. At the same time the use of a stable, monitored, envelope of gas in a chamber does provide considerable assurance where the quantity of production of any one item rarely warrants the design and verification (under all possible conditions) of a trailing shield. Therefore, there is a need for methods of achieving the shielding and monitoring characteristics of the current welding chambers without the inflexibility associated with many of the present units.

Electron beam welding can be used for butt, and to a lesser extent fillet welding but is somewhat less flexible than TIG (manual). Flexibility is decreased from TIG (manual) to the extent that the process must be mechanized and better fitup is generally required. The need for a vacuum chamber does not increase comparative flexibility since TIG also often must be used in chambers that can be evacuated. Further, monitoring a level of vacuum is, in the minds of many, a simpler problem than monitoring the composition of an inert atmosphere. Improving the flexibility of the electron beam process, therefore, depends upon whether or not the process can be fundamentally modified to provide greater flexibility and whether flexibility would be achieved at the expense of some of the advantages currently claimed for the process. There are at least three current attempts to permit the use of electron beam equipment outside of a vacuum chamber but it is not possible to say what flexibility such a modification would ultimately provide or what with regard to weld properties might be sacrificial. There is no known systematic effort to provide, through operator control or the use of special parameters, a means of accommodating poor fitup or to weld irregular shapes with some of the flexibility associated with TIG. Wire feed devices are being developed[*] and will increase flexibility by permitting fillet welds to be made between plates formed at right angles.

A systematic study of the process with regard to relating primary parameters (speed, amperage, voltage) of secondary parameters (focus and pattern) to joint configuration, including some amount of irregularities is recommended to increase flexibility.

While flash welding does not have the potential flexibility that the above processes have for butt welding and is not adoptable to fillet welding, its development on a systematic basis is recommended. This recommendation considers the specialized role that flash welding has played in the joining of the rings and cylinders that are the building blocks of many aerospace structures. Further, the ability of the process to produce a weld without molten zone or with a minimum heat affected zone suggests that a possibility exists in this process for some basic improvement in refractory metal joints. Therefore, a systematic study to determine which parameters are critical and to establish the effect of environment during both welding and the associated stretching operation should be carried out. This is not inconsistent with the need for increased flexibility at this time in the refractory metals welding industry since it broadens the number of processes that the welding engineer can call upon.

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[*] Some prototype units are in use but there was no evidence that these have been applied exclusively to refractory metals.

b. Recommendations for Spot and Seam Welding Process Improvement

The value of resistance welding as a technique for producing spot and seam welds is limited by the poor qualities of the resulting weld rather than by a specific equipment deficiency. The resulting joint, particularly in molybdenum, exhibits very poor strength and it appears that little can be done as far as equipment is concerned to improve this. In the columbium materials the welds exhibit better properties but still are not as reliable as welds in more conventional materials.* Additionally neither pre-weld or post-weld coating techniques were reported to be comptabile with the columbium welds. In view of the complex inter-relationship between making a suitable weld, application of the weld to the design, and the coating problem, it does not appear desirable to recommend process development until a better understanding of the conditions of application can be derived. Electrode wear might prove to be limiting when the application picture becomes clearer. The rapid deterioration of electrodes reduces the reliability of the process and effects the surface of the material as well as creating a production problem.

Ultrasonic welding provides one means for avoiding the problems associated with the cast nugget. At present the flexibility of application is limited because only relatively thin materials can be welded. Development of welders that would

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* Reference is made here to conventional resistance welding (or even spot welding) wherein a fused nugget is produced. Methods wherein the actual spot is formed by a brazing or diffusion bonding technique have been developed and are reported to exhibit an improvement over conventional spots. However, these processes are not within the scope of this report.

encompass the most frequently encountered (approximately up through ,050") thicknesses would be compatible with the improvement of process flexibility (and is currently in progress). At present there is no clearly identified program associated with relating the affect of ultrasonic welding on the performance of a pre-weld or post-weld coating. Such a program should be carried out and need not await the development of more powerful equipment.

c. Recommendations for Other Processes

Other processes appear applicable to refractory metals. These include MIG processes, friction welding, explosive welding and even submerged arc welding. However, the special merit of each, high deposition rates with low heat input in the case of MIG for example, are achieved through a relatively careful organization of process parameters. In the case of friction and explosive welding workpiece configuration is also important. For this reason broad recommendations toward increased flexibility are not reasonable and the process must be adapted to each application on its own merit. For example, if all that is required for a given application is an arc weld of good quality then a general TIG procedure can provide this over a broad range of component shapes, sizes and materials. If, however, the special economic or mechanical characteristics of MIG are required a special procedure would be required for different materials, as a minimum, and very likely for different components of the same material.

Laser welding cannot be discussed in terms of production improvement studies unitl prototype welding equipment is available.

H. Conclusions of Part II Findings

The data submitted by the 49 facilities engaged in the welding of refractory metal components and in systematic engineering programs associated with refractory metal welding, permitted a number of quantitative conclusions to be drawn. Conclusions regarding the nature of the current refractory metals welding industry are as follows:

1. All four of the refractory metal systems (tungsten, tantalum, molybdenum and columbium and their alloys) are being joined by welding (although not all forms or alloys are weldable). The greatest amount of experience involves columbium alloys.
2. The refractory materials investigated have been welded in thicknesses ranging from less than .005 inches to over .250 inches. Columbium and its alloys were most frequently welded in the .030 - .050 inch thickness. Molybdenum and tantalum were most frequently welded in the .010 - .050 inch thicknesses.
3. Non-consumable electrode inert gas welding is most often used, but nearly every method that has the potential for maintaining the desired metallurgical characteristics has been applied including (in about 85% of the survey references) electron beam and resistance welding in order of usage.

The survey and subsequent discussions permitted some conclusions to be drawn regarding the processes themselves. The non-consumable electrode inert gas (TIG) process appears to be favored when simple fusion welds are to be made. General availability, flexibility and simplicity seem to be the basis for this attitude. Electron beam equipment apparently is becoming almost as available as TIG and is looked on as a means for achieving such added advantages as lower distortion and possibly better properties when the need for these are identified. Good alignment, fitup and mechanical manipulations are characteristic requirements of electron beam welding that are some times believed to limit the flexibility of the process. However, the clearly identified need for careful attention to these details may have provided some of the advantages attributed to the processes itself and, thus, should not necessarily be considered in a negative fashion.

4. Most current refractory metal weldments are small (less than one foot in any dimension) although components with lengths in excess of 10 feet have been arc welded.

5. Certain items of technique were considered of particular importance when any or all of the refractory metals were being welded. These are:

   a. Shielding During Arc Welding. A desire for a high degree of reliability was expressed. Most facilities that monitored shielding gas maintained impurities below 50 ppm but several insisted on levels as low as 10 ppm.

   b. Backup and Chill During Arc Welding: These elements of the welding technique can be used to minimize welding stresses and the effect of thermal shock. Metallurgical reactions can be controlled. Proper chill may be hard to achieve but is important to dimensional and penetration control for Mo and W.

c. <u>Reduced Electrode Life During Resistance Welding:</u> No means of reducing the 6:1* to 10:1* decrease in electrode life was reported.

6. Arc welds are most commonly evaluated by bending. Radiography and tensile testing are most common for spot welding processes. Company standards have been established or adopted to permit interpretation of the test results.

7. Although most applications listed were specified as having service lives greater than one hundred hours, only a very limited amount of long-time testing has been accomplished.

When the quantitative findings were reviewed with various facilities certain other quantitative conclusions could be drawn. Fabrication subcontractors noted that most orders involved one-of-a-kind production. Refractory metal welding is still carried out under the direction of the most competent technical personnel available to the facility - often in the R & D segment of the organization. The application of this type of personnel has resulted in a high level of technical sophistication throughout the industry. The one-of-a-kind production has resulted in a tendency to apply the simplest process that will do the job. Many of the one-of-a-kind weldments are aimed at service testing - not necessarily the testing of the welds.

The application of resistance welding to produce spot welds appears to be limited both by resulting weld characteristics (particularly in molybdenum and its alloys) and, by coating complexities. Ultrasonic welding is being evaluated. Present equipment is limited to thin materials (under .015") but heavier equipment is being built.

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* Compared to the welding of stainless steel.

Other welding processes are considered only when there is a unique requirement for one of their characteristic advantages such as high deposition rates, low heat input, etc. Many processes such as flash and explosive welding are limited with regard to workpiece geometry and this lack of versatility may have limited their application to date.

I. Recommendations From Part II Findings

The large amount of valuable technical time, complex equipment, and expensive base material involved in each inch of many welds in refractory metals assemblies suggests that studies aimed at reducing any of these would constitute a valuable production improvement. Effort directed toward the cataloguing of typical defects, their cause, and means of controlling processes to avoid them would constitute one means of reducing the time and effort associated with setting up and controlling processes used to join current refractory metals weldments. Such effort may constitute well over 80% of the manufacturing time applied to a welding application.

Further effort directed toward improving the flexibility of existing processes, or evaluating new processes to permit a more flexible application of joining processes would improve the ability of the present facilities to produce effectively in the one-of-a-kind production environment that exists today.

IV PART III - FUTURE REQUIREMENTS OF REFRACTORY METAL WELDING

The foregoing sections have identified the facilities engaged in joining refractory metals. The processes for producing refractory metal weldments and to some degree, the detailed techniques and practices have also been identified along with their relationship to materials and materials' thicknesses. In Part III the above current information is to be related to future requirements in such a manner that long range recommendations for improved equipment or production techniques can be identified.

A. Survey of the Size of Future Weldments

An increase in the size of future refractory metal weldments would affect the production capabilities of refractory metal welding facilities. The impact would be particularly severe for arc or electron beam applications requiring welding chambers. Table XVIII illustrates the anticipated trend.

A further insight into the size of future weldments can be obtained from the tabulation of estimated dimensions (Tables XIX and XX.)

It appears from Table XVIII that weldments will increase in size. Table XX suggests that the overall dimensions of over 50% of future components will be in the 2-5 foot or 5-10 foot range; whereas, over 50% of current components have dimensions less than one foot in any direction (Table XIX). There is a significant increase in the number of components that will be longer than 25 feet and also an increase in the number that will be 10-25 feet in either their width, depth or diameter. It was not possible to relate the need for large welding facilities to any specific segment of the industry. The need seems to be as pressing in the Class I facilities as in the Class II or III organizations.

TABLE XVIII

PREDICTED INCREASE IN WELDMENT SIZE

Prediction	Length			Width			Depth			Diameter		
	I*	II*	III*	I	II	III	I	II	III	I	II	III
No change	-	1	2	-	-	-	1	-	1	-	-	-
1-2X increase in size	1	-	-	-	-	-	-	-	-	-	-	-
2-3X "	1	1	2	-	-	3	1	-	2	-	-	1
3-4X "	3	-	-	2	1	-	1	1	-	2	-	-
4-5X "	-	-	-	-	-	1	-	-	-	-	-	-
5-10X "	2	-	-	2	-	-	1	-	1	2	-	2
10-20X "	1	-	1	1	-	-	-	-	-	-	-	-
20-30X "	-	-	-	-	-	-	1	-	-	-	-	-

* Number of Responses for Various Categories. I-Airframe Facilities II-Propulsion Systems Facilities III-Liquid Metal Loops Facilities

TABLE XIX

SIZE OF CURRENT WELDMENTS

	Length of Indicated Dimension				
	<2'	2-5'	5-10'	10-25'	25'
Maximum Length	15	4	6	2	1
Maximum Width	15	5	1	0	0
Maximum Depth	12	4	0	0	0
Maximum Diameter	13	5	1	0	0

* Number of references to a specific dimension.

TABLE XX

SIZE OF FUTURE WELDMENTS*

	Length of Indicated Dimension				
	2'	2-5'	5-10'	10-25'	25'
Maximum Length	0	7	6	5	4
Maximum Width	1	5	7	2	1
Maximum Depth	4	3	7	1	0
Maximum Diameter	1	5	6	1	2

* Number of references to a specific dimension.

B. Future Processes

Several questions were asked regarding the type and capability of the processes to be applied to future refractory metal weldments.

1. Arc Welding

Future increases in shielding reliability were sought by many cognizant personnel in the refractory metal welding field. One of the questions asked whether respondees felt that weldments produced in the future would benefit from greater reliability regarding protection from contamination. Of the 39 respondents indicating TIG or MIG welding experience, 27 indicated that greater shielding reliability would be desirable. Sixteen (16) of the same group of 39 respondents indicated that an ability to perform out-of-position welding would benefit future (or present) welded assemblies. One respondent indicated that he had an ability to weld out-of-position (horizontal but not vertical or overhead as indicated in a subsequent interview).

Design personnel felt that certain limitations currently associated with the arc welding of refractory metals were imposing restrictions on their designs. The need to provide shielding to weldments of refractory metals seems to be having the greatest effect. Of the 32 respondents who answered questions regarding the application of refractory metals to the design of arc welded structures, 10 indicated that if the same design had been produced in a material such as stainless steel, they would have used more arc welding. Six (6) affirmed that they would have used more out-of-position welds. Seventeen (17) responded that they would have had more freedom to design subassemblies without considering the limitations imposed by chambers or trailing shields.

2. Other Processes

Eleven (11) respondents noted that future designs would benefit from the application of a greater amount of flash welding. Ten (10) respondents indicated a similar benefit if greater amounts of resistance welding were employed. The sample with which these respondents must be compared consists of all persons answering any portion of the questionnaire (e.g. 49 respondents). Nine (9) of those desiring the application of more resistance welding were those who noted resistance welding experience. Three of those desiring more flash welding noted previous experience with the process. All of the above interested respondents are equipment users, not manufacturers of resistance or flash welding equipment.

C. The Need for Improved Processes

In another portion of the questionnaire, welding engineers were asked what their interest would be in certain processes if the process represented improvements over current practice. The results are tabulated below in Table XXI.

There appears to be general, though not unanimous, agreement that an advance in any of the processes would permit an extension of present abilities to design welded refractory metals structures. The most definite needs appear to relate to electron beam welding and to resistance welding (or to ultrasonic welding).

D. Limitations

In order to establish at least some of the process features that required improvement, a few specific areas were probed. Because of the nature of refractory metals (particularly the shielding requirements for arc welds), it was felt that limitations were most likely to exist in that area. Specifically, designers were asked if shielding requirements associated with the refractory metals had to be considered in the design of weldments that they

TABLE XXI

INTEREST IN IMPROVEMENTS IN CERTAIN PROCESSES

	Number of Facilities Responding as Follows:		
New or Improved Processes	Have Definite Application	Would Increase Design Flexibility	Can see no Advantage(1)
Arc Welding	5	12	8
Resistance Welding	8	13	4
Flash Welding	3	12	7
Electron Beam Welding	11	10	9
Friction Welding	2	10	7
Ultrasonic Welding	6	9	8

(1) or feel they are presently working with a process that could be considered to be advanced.

had described for the survey. Of the 33 respondents that described one or more weldments, 26 said they had considered some special requirements and 7 said they had not.

Additionally certain design limitations were listed and designers were asked if they had been required to modify designs to accommodate any of them. Their response is shown in Table XXII.

From these responses, it appears that the restrictions imposed by chambers (or even the more flexible auxiliary shield) is already influencing designs. This influence could be expected to increase as component size increase.

E. The Nature of Future Weldments

Undoubtedly many of the welded refractory metal components of the future will be advanced versions of the applications listed in Part II. An attempt to discuss refractory metal components that are not related to the contemporary weldments described in Part II would not provide useful information because of the technical complexities of describing components that have not yet reached a sufficiently advanced conceptual stage to be reflected even in the prototype weldments described in Part II. Strong proprietary interests also preclude the gathering of meaningful information about novel refractory metal structures of the future.

F. Discussion of Part III Findings

The identification of an effect upon designs as a result of current shielding capability limitations, coupled with a projected four-fold increase in the size of future components suggests a need for developing shielding techniques that do not impose a limitation on the size of weldments. The almost universal desire for shielding techniques that represent an increase in reliability over present methods must also be considered when such developments are considered.

TABLE XXII

MODIFICATIONS OF DESIGNS TO ACCOMMODATE REFRACTORY METAL WELDING LIMITATIONS

Limitations	References
Design Subassemblies to Permit Access of Torches with Shields or Nozzles	6
Adopted Designs to Fit Chambers	14

The identification of improved electron beam welding, resistance welding and ultrasonic welding processes, as having definite application on future weldments, suggests that any process or equipment improvement should be aimed at achieving one or the other of the following basic capabilities.

(1) The ability to reduce the volume of material involved in fusion welds; to minimize the detrimental effects (in terms of welding stresses and undesirable metallurgical phenomena) of whatever volume of metal is melted: or at least to provide a positive means for preventing contamination of the volume. These are the values principally assigned to electron beam process by welding engineers according to Part II of this report.

(2) The ability to join the surfaces of large sheets with a strong, tough oxidation resistant spot in the presence of an oxidation resistant coating.

G Conclusions from Part III Findings

Quantitative conclusions regarding the size of future weldments and some required process and/or equipment improvements can be drawn as follows:

(1) Components with lengths greater than 25 feet and with other dimensions in the 10-25 foot range will be much more common then they are in current production.

(2) An extension of shielding capabilities is needed both in terms of the workpiece size that can be shielded and the reliability of shielding techniques.

(3) Processes or equipment should be developed with the characteristics of electron beam welding and resistance welding.

H Recommendations From Part III Findings

In an effort to overcome shielding limitations on future, large assemblies:

(1) Problems associated with the accomplishment of fusion (arc) welding in extremely large (walk-in) chambers should be studied.

(2) The InFab* chamber should be used to accomplish the above by attempting to carry out qualification procedures on joints which are common in characteristically large components.

In an effort to improve the capability of equipment to produce more desirable fusion (arc) and spot welds:

(1) Proposals should be solicited from equipment vendors to develop equipment and techniques to meet the requirements identified under conclusions.

(2) During InFab qualification, emphasis should be placed on quantitatively and systematically reducing the amount of distortion and metallurgical change (specifically HAZ width, grain growth and increase in interstitial content) associated with TIG processes. These data are to be used as a base line for more fundamental improvements in the TIG process.

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* InFab is an inert atmosphere mill facility constructed and operated by Universal-Cyclops Steel Corporation for the Department of the Navy, Bureau of Naval Weapons under Contract Number NOa 55-006-c. The internal dimensions of InFab measure 42 feet wide, 97 feet long and 23 feet high.

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22. Thompson, E. G., Binder, H., and Collins, H., "Properties of Flash Welded Molybdenum IBID 26 (4), Research Supplement 160-s to 165-s 1961

APPENDIX A

Questionnaire Used in the Industrial Survey

SERIAL ________

QUESTIONNAIRE COMPLETED BY:

________________ Phone

________________ Phone

QUESTIONNAIRE NUMBER I - APPLICATION OF REFRACTORY METALS TO THE DESIGN OF WELDED STRUCTURES

SECTION A EXPERIENCE

A.1. Would you note your experience with welded designs that use tungsten, molybdenum, tantalum, columbium, or alloys of these materials?

___ Are (or have) worked with the design of refractory metal welded structures

___ Suggest you also contact:

________________ (name) of ________________ (company)

________________ (name) of ________________ (company)

A.2. How many welded refractory metal structures have been designed by you (or your organization)?

___One ___Two ___Three ___Four ___Five ___More than Five

A.3. Are you considering future applications of refractory metals to welded structures?

___ Yes ___ No

A.4. What welding processes have been involved (or will be involved):

___ Inert gas welding (tungsten arc)

___ Inert gas arc welding (consumable electrode)

___ Resistance

___ Other joining process (name ________________)

SECTION B DESCRIPTION OF TYPICAL APPLICATIONS

B.1. From the designs discussed above, would you select

___ (a) one or more of the weldments described in question A.2.

___ (b) one or more of your future designs from question A.3.

Would you describe these designs by checking the appropriate blanks in TABLE I on the following page.....

Open Folder for Next Question

TABLE I TYPICAL APPLI
REFRACTORY ME
(Note: Detailed or/exact informa
blank that comes closest to

	ESCRIPTION: Briefly escribe one or more f the applications eferred to in quesions A.2. and A.3.	MATERIAL: What metals were joined?									OPERATING TEMPERATURE: What is max?						OPERATING TIME: What is maximum?					
	lace name or escription of each pplication on one f the lines below	TUNGSTEN	TUNGSTEN ALLOYS	COLUMBIUM	COLUMBIUM ALLOYS	MOLYBDENUM	MOLYBDENUM ALLOYS	TANTALUM	TANTALUM ALLOYS	DISSIMILAR METALS	UNDER 1000°F.	1000°F. -	2000°F. -	3000°F. -	4000°F. -	OVER 4000°F.	UNDER 1 SECOND	1-60 SECONDS	1-10 MINUTES	10-60 MINUTES	1-100 HOURS	OVER 100 HOURS
1																						
2																						
3																						
4																						
5																						

SECTION C PROBLEMS IN ADOPTING REFRAC

C.1. Which of the TABLE I applications were fabricated by arc welding?

____#1 ____#2 ____#3 ____#4 ____#5 ____None

C.2. Was this welding carried out by:

___ Your Company (Direction of ______________________)

___ A Vendor (Name ________________________________)

C.3. What was the size of the largest single weldment involved:

TABLE II - SIZE OF ARC WELDED ASSEMBLIES

	<1 Ft.	1-2 Ft.	2-5 Ft.	5-10 Ft.	>10 Ft.
Length					
Width					
Depth					
Diameter					

C.4. Did any special welding practices or requirements associated with refractory metals have to be given consideration in designing the above weldments:

___ Yes No ___

___ Special practices not considered necessary for joining refractory metals.

ONS OF WELDING TO
STRUCTURES
is not necessary. Check the
ribing the application.)

ADS ote ype			ENVIRONMENT Type?				PURPOSE: Check the category that most nearly describes function								FEASIBILITY		
VIBRATION	CONTINUOUS	OTHER	LIQUID METAL	INERT GAS	VACUUM	AIR	CONDUCTING FLUIDS	SHIELDING FROM HEAT (e.g. RE ENTRY)	DIRECTING A FLOW OF GAS	ROTATING DEVICE (e.g. HINGE JOINT OR PUMP IMPELLOR)	VESSELL FOR CONTAINING GASSES OR FLUIDS	HEAT SINK	HEAT SOURCE	PORTION OF AN ELECTRONIC DEVICE	HAS BEEN SUCCESSFULLY PRODUCED	COULD BE PRODUCED WITH CURRENT SKILLS	HAS GREAT POTENTIAL IF COULD BE PRODUCED

METAL ASSEMBLIES FOR ARC WELDING

C.5. If you did adopt designs to accomodate special shielding requirements, did you:

____ adopt designs of sub assemblies to permit access of welding torches with special shields or nozzles

____ adopt designs of sub assemblies to fit welding chambers

____ consider that parts had to be designed so that they could be manipulated to avoid welding in other than the downhand position

C.6. If components identical to those described in TABLE I were being designed for fabrication from an austenitic stainless steel such as AISI 304, 321, etc., would you:

____ Use more arc welding

____ Use more out of position welds

____ Have more freedom in designing the sub assemblies since special shielding techniques such as chambers and trailing shields would not be required.

SECTION D PROBLEMS IN ADOPTING REFRACTORY METAL ASSEMBLIES TO RESISTANCE WELDING

D.1. Which of the TABLE I assemblies was fabricated by resistance

___#1 ___#2 ___#3 ___#4 ___#5 ___None

D.2. Was this welding carried out by:

___ Your Company (Direction of ______________________________)
___ A Vendor (Name ______________________________________)

D.3. What was the size of the largest single weldment involved:

TABLE III - SIZE OF RESISTANCE WELDED ASSEMBLIES

	<1 Ft.	1-2 Ft.	2-5 Ft.	5-10 Ft.	>10 Ft.
Length					
Width					
Depth					
Diameter					

D.4. Did any special requirements or practices associated with resistance welding of refractory metals have to be given consideration in finalizing the design of components for resistance welding:

___ Yes ___No—Special requirements for the welding of refractory metals not considered necessary

D.5. If you did modify the designs to recognize special resistance welding requirements or practices for refractory metals did you do so to:

___ Permit the use of special shielding
___ Offset the tendency for short electrode life
___ Recognize other special resistance welding requirements

SECTION E NEED FOR NEW OR IMPROVED WELDING PROCESSES

E.1. From your present knowledge of the requirements of your industry, what is the size of the largest design in the forseeable future:

TABLE IV - SIZE OF FUTURE WELDED ASSEMBLIES

	1 Ft.	1-2 Ft.	2-5 Ft.	5-10 Ft.	10 Ft.
Length					
Width					
Depth					
Diameter					

E.2. As a designer would you expect to be able to improve existing or contemplated designs using one of the processes listed in the left-hand column of Table V (on next page).

Turn to next page...

TABLE V - NEED FOR NEW OR IMPROVED WELDING PROCESSES

How would the introduction of these new or improved processes affect your design? (Check one column)

Some potential new (or improved) processes	Have Definite Application for Such a Process	Might Permit More Design Flexibility If Reliable	Can See No Particular Design Advantage From Such a Process	Presently Using Such a Process
Improved Arc Welding (e.g. Inert Gas Practice Similar To Stainless Steel)				
Improved Resistance Welding Welding Practice				
Flash Welding				
Electron Beam Welding				
Friction Welding				
Ultrasonic Welding				
Other Joining Processes				

Thank you for your co-operation.

(Did you sign at the top of page 1?)

SERIAL 255

QUESTIONNAIRE COMPLETED BY:

Phone

Phone

QUESTIONNAIRE NUMBER II - WELDING ENGINEERING AS APPLIED TO REFRACTORY METALS

SECTION A EXPERIENCE

A.1. Have you joined tungsten, molybdenum, tantalum, columbium, or their alloys by any or all of the following processes:

___TIG ___MIG ___Resistance(Spot) ___Flash

___Electron Beam ___Other(Describe ______________________)

A.2. Using the following check list would you please describe the joints which comprise your refractory metals welding experience or that of your organization. (Detailed information not required. Check space that you think comes closest to describing the joint.)

DESCRIBE TYPICAL JOINTS IN COLUMNS 1-9		#1	#2	#3	#4	#5	#6	#7	#8	#9
MATERIALS: What material(s) were involved in the joint (check more than one if for dissimilar metal joints)	TUNGSTEN									
	TUNGSTEN ALLOYS									
	COLUMBIUM									
	COLUMBIUM ALLOYS									
	MOLYBDENUM									
	MOLY ALLOYS									
	TANTALUM									
	TANTALUM ALLOYS									
	DISSIMILAR METALS									
JOINT CONFIGURATION: Describe the configuration of the finished joint	BUTT									
	FILLET									
	PLUG									
	LAP									
	EDGE									
	OTHER									
BASE MATERIAL CONFIGURATION: Describe form(s) of the components being joined	SHEET TO SHEET									
	BAR TO BAR									
	TUBE TO FITTING									
	TUBE TO TUBE									
	OTHER									
THICKNESS: Thickness of base material at the joint (check more than one for dissimilar metal thicknesses)	<005 INCHES									
	.005-.010 INCHES									
	.010-.030 INCHES									
	.030-.050 INCHES									
	.050-.100 INCHES									
	.100-.150 INCHES									
	.150-.250 INCHES									
	> .250 INCHES									
APPLICATION: Note whether joints have been produced for	MECHANICAL TESTING									
	TESTED IN SIMULATED ENVIRONMENT									
	SHIPPED AS A PRODUCT OF OUR COMPANY									
EXPERIENCE: Approximate number of inches of joints produced (for any purpose)	<SIX INCHES									
	6-12 INCHES									
	12-100 INCHES									
	100-200 INCHES									
	OVER 200 INCHES									

SECTION B INERT GAS ARC WELDING PROCEDURES FOR REFRACTORY METALS

B.1. Which of the above joints were made with TIG equipment?

___#1 ___#2 ___#3 ___#4 ___#5 ___#6 ___#7 ___#8 ___#9 ___None

B.2. Were any of the joints made with MIG equipment?

___#1 ___#2 ___#3 ___#4 ___#5 ___#6 ___#7 ___#8 ___#9 ___None

B.3. What methods were used to evaluate the quality of above joints:

___X-ray per in-house stds __, Govt Stds.___, Industry Stds.___.

___Penetrant per in-house stds __, Govt Stds.___, Industry Stds.___.

___Periodic bend, or other mechanical tests

B.4. Have you evaluated refractory metal welds by any of the following testing techniques

___Tensile tests ___Fatigue ___Creep ___Stress-rupture

B.5. Which of the following shielding practices have you used?

___ Chamber, or other enclosure, following size:

TABLE I - WELDING CHAMBER SIZE

	<1 Ft.	1-2 Ft.	2-5 Ft.	5-10 Ft.	>10 Ft.
Length					
Width					
Depth					
Diameter					

___ Special auxiliary nozzles or trailing shields

___ Special welding parameters (speed, etc.) normal nozzle

___ Limiting materials to those with minimum sensitivity to contamination

___ No special practices used to prevent contamination.

B.6. What limits do you require with regard to shielding gas impurities?

TABLE II - MAX PERMISSIBLE IMPURITY LEVELS

MATERIAL	W and Alloys			Mo and Alloys			Cb and Alloys			Ta and Alloys		
LIMIT(PPM)	<10	10-100	>100	<10	10-100	>100	<10	10-100	>100	<10	10-100	>100
OXYGEN												
NIGROGEN												
WATER*												
HYDROCARB												
HYDROGEN												
OTHER( )												

* May be reported in grains, if so, mark answer with "G".

B.7. How do you control these impurities?

___Through a chamber monitoring instrument

___Through analysis of the gas in its container

___By observation of the appearance or ductility of the resulting weld

B.8. Would you specify special gas shielding capability on equipment procured for refractory metal arc welding?

___Yes ___No

B.9. If you were buying a new piece of equipment or designing a fixture for refractory metal welding, would you look for any of the following?

___Special features in torch construction

___Special power supply characteristics

___Special arc starting or stopping features

___Special back-up, or chill-bar, materials or design

___Special rigidity or other features in fixture

___Special torch travel requirements (smoothness, special range, etc.)

___Other special features

___No features other than those required for any weld of equivalent quality

B.10. What size assembly have you welded and what size assembly do you feel will have to be welded in the future?

TABLE III - ESTIMATED SIZE OF CURRENT AND FUTURE WELDED ASSEMBLIES

	Current Welded Assemblies					Future Welded Assemplies				
SIZE IN FEET	<2	2-5	5-10	10-25	>25	<2	2-5	5-10	10-25	>25
Length										
Width										
Depth										
Diameter										

B.11. Would the welding of present or future assemblies benefit from

a. Ability to perform out-of-position welding

___Yes ___No

b. Greater reliability regarding protection from contamination

___Yes ___No

SECTION C WELDING REFRACTORY METALS WITH RESISTANCE AND/OR FLASH WELDING EQUIPMENT

C.1. Which of the joints listed on the first page were made with resistance welding equipment?

___#1 ___#2 ___#3 ___#4 ___#5 ___#6 ___#7 ___#8 ___#9 ___None

C.2. Was the resistance welding procedure characterized by:

Welding cycles that were (___longer, ___shorter) than conventional cycles

The use of forging cycles: ___Yes ___No

Pressures that are (___higher, ___lower) than conventional values

The use of low inertia pressure systems: ___Yes ___No

C.3. When resistance welding is used on refractory metal, is electrode life:

___Less than that encountered on stainless steel for a similar joint

___Equal to or better than that encountered with stainless steel

C.4. Which of the joints were made using flash welding equipment?

___#1 ___#2 ___#3 ___#4 ___#5 ___#6 ___#7 ___#8 ___#9 ___None

C.5. Was the flashwelding procedure characterized by:

___Welding cycles that were significantly different than those used to weld stainless steel

___Post or Pre-weld treatments different than those used for stainless steel

___Equipment or power supply requirements different from those used on stainless steel

C.6. What special shielding was used in conjunction with the above equipment:

Welded in chamber or enclosure: ___resistance ___flash

Shielding nozzle attached to machine: ___resistance ___flash

No shielding used: ___resistance ___flash

C.7. Would present or future designs be improved by application of?

A greater amount of resistance welding: ___Yes ___No

A greater amount of flash welding: ___Yes ___No

C.8. What methods were used to evaluate the quality of the above joints:

X-ray: ___Resistance, ___Flash

Penetrant: ___Resistance, ___Flash

Tensile: ___Resistance ___Flash

Fatigue: ___Resistance ___Flash

Creep: ___Resistance ___Flash

Stress-rupture: ___Resistance ___Flash

C.9. Have you standards for the above non-destructive tests

___Government

___Industry-wide standards used

___In-house standards used

___No quantitative standards used, acceptability based on quantitative judgement

ECTION D WELDING REFRACTORY METALS WITH ADVANCED WELDING TECHNIQUES

D.1. Were any of the welds described on the first page performed by any of the following advanced methods:

TABLE IV - APPLICATION OF ADVANCED WELDING PROCESSES TO REFRACTORY METALS

	#1	#2	#3	#4	#5	#6	#7	#8	#9	None
Electron Beam (low voltage)										
Electron Beam (high voltage)										
Friction Weld										
Ultrasonic										

D.2. If friction or ultrasonic welding was used, was an inert gas shield employed?

___Yes ___No

D.3. Are you aware of any welding development on any refractory metal alloy outside of your own organization involving any of the following types of equipment:

	Company	Contact
Electronbeam	___	Mr.___
Flash welding	___	Mr.___
Ultrasonic welding	___	Mr.___
Friction welding	___	Mr.___
Resistance welding	___	Mr.___
TIG or MIG welding	___	Mr.___

Thank you for your co-operation
(Did you sign at the top of page 1?)

SERIAL ________

QUESTIONNAIRE COMPLETED BY:

________________ Phone ________

________________ Phone ________

QUESTIONNAIRE NUMBER III - APPLICATION OF CAPITAL EQUIPMENT, TOOLS, AND FIXTURES TO REFRACTORY METAL WELDING

SECTION A EXPERIENCE

A.1. Has any of the equipment produced by your organization been applied to the welding of molybdenum, columbium, tantalum or tungsten or to alloys of these refractory metals?

___ Yes (on a laboratory basis)

___ Yes (on a production basis)

___ Not to our knowledge

A.2. Which of the following types of equipment are involved?

___ Tungsten inert gas welding (with or without wire feed)

___ Consumable electrode inert gas welding

___ Electron Beam Welding Equipment

___ Positioners and other tooling

___ Flash welding

___ Ultrasonic welding

___ Other (Please describe ________________________)

A.3. Where is the above equipment in use?

COMPANY	UNDER DIRECTION OF

SECTION B ARC WELDING EQUIPMENT, SPECIAL REQUIREMENTS WHEN APPLIED TO WELDING OF REFRACTORY METALS

B.1. If equipment were purchased primarily to join one or more of the refractory metals would you propose that it have some special features (compared to equipment purchased to join stainless steel or one of the super alloys to equivalent quality levels)?

___ Yes (Do recognize certain problems and would emphasize certain features perhaps even develop certain features especially for the job)

___ No (Would not place unusual emphasis on any feature)

B.2. In recommending the above special features, to which of the following portions of the equipment would they apply

- ___ Inert gas shielding
- ___ Power supply
- ___ Wire feed equipment
- ___ Controls
  - ___ Automatic arc voltage control
  - ___ Preset welding cycles
- ___ Carriage speed and smoothness of travel
- ___ Carriage alignment
- ___ Tools and fixtures
  - ___ Rigidity
  - ___ Clamping features
  - ___ Design of back-up fixtures

B.3. In providing equipment which you feel is particularly well suited to meet the special requirements of refractory metals, do you feel that your customer should, in turn, recognize special requirements

- ___ in the training of operators
- ___ in the establishment of quality standards
- ___ in the procurement of material to be welded
  - ___ with regard to O_2, N_2, C levels
  - ___ with regard to grain size
  - ___ other special requirements
- ___ with regard to joint design
- ___ with regard to joint preparation
- ___ with regard to special cleaning

SECTION C RESISTANCE WELDING EQUIPMENT, SPECIAL REQUIREMENTS WHEN APPLIED TO THE WELDING OF REFRACTORY METALS

C.1. If equipment were purchased primarily to join one or more of the refractory metals would you propose that it have some special features (compared to equipment purchased to join a material such as the age hardening nickel base high temperature alloys)?

- ___ Yes (Do recognize special problems and would emphasize certain features, perhaps even develop certain features especially for the job)
- ___ No (Would not place unusual emphasis on any feature)

C.2. In designing equipment to weld refractory metals would you consider the use of

___ special electrode materials or designs
___ very high rate of response in application of pressure during welding cycle
___ unusually short or long weld times
___ other special welding cycle features such as forge cycles, etc. (please describe ______________________)
___ special mechanical or electrical ratings on equipment
___ inert gas envelope blanketing the area being welded

C.3. In providing equipment which you feel is particularly well suited to meet the special requirements of refractory metals do you feel that your customer should, in turn, recognize special requirements

___ in the training of operators
___ in the establishment of quality standards
___ in the procurement of material
    ___ with regard to O_2, N_2, C level
    ___ with regard to surface finish
    ___ with regard to special pre-weld cleaning
___ with regard to overlap or other features of joint design

ECTION D WELDING POSITIONERS AND OTHER TOOLING, SPECIAL REQUIREMENTS WHEN USED IN CONJUNCTION WITH REFRACTORY METAL WELDING OPERATIONS

D.1. Would you incorporate special design features in positioners or tooling to join refractory metals such as molybdenum, columbium, etc. (as opposed, for example, to a similar design stainless steel or high temperature alloys)

___ Yes ___ No

D.2. Would special design features be aimed at

___ rigidity of the tooling
___ speed control or torch movement
____ underbead shielding
___ chilling
___ hold-down pressure
____ use of special clamping techniques
___ provision for extra inert gas shielding
___ other features such as ______________________________

Turn to Next Page

SECTION E WELDING EQUIPMENT OTHER THAN RESISTANCE OR ARC WELDING, SPECIAL REQUIREMENTS FOR APPLICATION TO REFRACTORY METAL

E.1. Did the application of refractory metals require some modification of the equipment (compared with equipment used on stainless steel or high temperature alloys)

___ Yes (Was necessary to emphasize certain equipment features and/or to actually modify certain features with or without some development)

___ No (Standard equipment was used and no need for special features observed)

Thank you for your co-operation.

(Did you sign at the top of page 1?)

SERIAL ________

QUESTIONNAIRE COMPLETED BY:

________ Phone ________

________ Phone ________

QUESTIONNAIRE NUMBER IV - MATERIAL ENGINEERING AS APPLIED TO REFRACTORY METAL JOINING

SECTION A GENERAL KNOWLEDGE OF REFRACTORY METAL JOINING

A.1. Have you or are you aware of any experience in joining any or all of the following refractory materials:

___ columbium and alloys

___ molybdenum and alloys

___ tungsten and alloys

___ tantalum and alloys

___ other (name ________________________________)

A.2. Suggest you also contact:

________________ (name) of ________________ (company)

________________ (name) of ________________ (company)

________________ (name) of ________________ (company)

ECTION B SPECIFIC EXPERIENCE

	State material used in joining in each specific experience. If dissimilar metal joint, state both.					Method of Join								
						Welding								
	Columbium Based	Molybdenum Based	Tungsten Based	Tantalum Based	Other	TIG	MIG	Electron Beam	Resistance	Ultrasonic	Other (name)	Riveting	Brazing	Other (name)
xperience # I														
xperience # II														
xperience # III														
xperience # IV														
xperience # V														

CTION C PROPERTIES OF JOINTS DESCRIBED IN B

C.1. What means of evaluating any or all of the joints in Question B were employed?

____ tensile test
____ bend test
____ bend transition test
____ dye penetrants
____ ultrasonics
____ radiography
____ metallorgraphy
____ other (name)

____

____

:mosphere Used			What type of chamber was used?	Atmosphere Purity Level Attainable (or Impurity Level)	Has this work been documented?		Where might a copy of the work be obtained?
Argon	Helium	Other (name)			YES	NO	

II - Tensile Properties of the Joints Described in B

	Exp. I		Exp. II		Exp. III		Exp. IV		Exp. V	
st mp. .	UTS	Efficiency	UTS	Efficiency	UTS	Efficiency	UTS	Efficiency	UTS	Efficiency
00										
00										
00										
00										
00										
00										
00										

III - Bend Test Results (Include Angle and Radius of Bend)

Test Temp. (°F.)	Exp. I	Exp. II	Exp. III	Exp. IV	Exp. V
-300					
-200					
-100					
0					
RT					
100					

IV. Describe the appearance of the joints in general. Include any of the remaining tests, i.e., dye penetrants, radiography, ultrasonics, metallography, etc.

Experience I	
Experience II	
Experience III	
Experience IV	
Experience V	

V Was the joint tested for contamination? ___ Yes ___ No

If yes, give means of analysis and results

Experience Number	Means of Analysis	Level of Impurity					
		O_2		N_2		C	
		Joint	Base	Joint	Base	Joint	Base
I							
II							
III							
IV							
V							

SECTION D SYNOPSIS OF THE STATUS OF REFRACTORY METALS AND ALLOYS

Check block (or blocks) which applies to the alloy in question

Metals or Alloys	is at present used for structural designs	has greatest potential for structural designs	shows little or no potential for structural material	presently used in welded structures	not satisfactorily weldable with present technology	would have great potential if weldable
Tungsten (AVC)						
Tungsten (Powder)						
Molybdenum						
TZM						
Mo+0.5%Ti						
TZC						
Tantalum						
Ta-10W						
Ta-30Cb-7.5V						
Columbium						
Cb-1Zr						
Cb-132						
66						
S 82						
48						
31						
36						
S 85						
110						
ther (name) __________ __________						

APPENDIX B

Distribution List for Questionnaire

Aerojet General Corporation
Azuza, California

Aerojet General Corporation +*(2)
Sacramento, California

Aeronca Manufacturing Company
Middletown, Ohio

Aeronutronic
Newport Beach, California

Aeroprojects Inc.*
West Chester, Pennsylvania

Air Reduction Sales Company
Union, New Jersey

Airesearch Manufacturing Company
Phoenix, Arizona

Allegheny Ludlum Steel Corporation
Watervliet, New York

Allegheny Ludlum Steel Corporation
Brackenridge, Pennsylvania

Alloyd Research Corporation
Watertown, Massachusetts

Aluminum Company of America
Pittsburgh, Pennsylvania

American Welding & Manufacturing Co.*
Warren, Ohio

Armour Research Foundation
Chicago 16, Illinois

Argonne National Laboratory
Argonne, Illinois

Argonne National Laboratory
Fermont, Illinois

Arthur D. Little, Inc.
Cambridge, Massachusetts

Atlantic Research Corporation
Alexandria, Virginia

Atomic Energy Commission
Oak Ridge, Tennessee

Atomic Energy Commission
Germantown, Maryland

Atomics International
Canoga Park, California

AVCO Corporation
Wilmington, Massachusetts

Babcock & Wilcox Company
New York 17, New York

Ballistic Missiles Center
Los Angeles 45, California

Battelle Memorial Institute*(3)
Columbus 1, Ohio

Bell Aerospace Corporation
Fort Worth 1, Texas

Bell Aircraft Company
Buffalo 1, New York

Bendix Corporation
Elmira, New York

Bendix Aviation Corporation
South Bend, Indiana

Boeing Airplane Company
Wichita, Kansas

Boeing Airplane Company (3)*
Seattle, Washington

\+ Numerals in parentheses indicate the number of questionnaires sent to the corporation.

* Indicates personal contact with the corporation.

Budd Company
Philadelphia, Pennsylvania

Clevite Research Center
Cleveland, Ohio

Climax Molybdenum Company
of Michigan
Detroit, Mighigan

Crucible Steel Company of America
Pittsburgh 13, Pennsylvania

Cornell Aeronautical Laboratories
Buffalo 21, New York

Curtiss-Wright Corporation (3)*
Woodridge, New Jersey

Curtiss-Wright Corporation
Quehanna, Pennsylvania

Curtiss-Wright Corporation
Caldwell, New Jersey

Curtiss-Wright Corporation
Buffalo 15, New York

Denver Research Institute
Denver 10, Colorado

Douglas Aircraft Company, Inc.
Santa Monica, California

Douglas Aircraft Company, Inc.
Long Beach 8, California

Dow Chemical Company
Midland, Michigan

Dresser Products Incorporated
Oveat Barrington, Massachusetts

E. I. duPont deNemours & Company
Wilmington, Delaware

Fansteel Metallurgical Corporation
North Chicago, Illinois

Federal Machine and Welders
Warren, Ohio

Firth Sterling, Incorporated
Pittsburgh 30, Pennsylvania

General Dynamics Corporation
Pomona, California

General Dynamics Corporation(4)*
San Diego, California

General Dynamics Corporation(2)*
Fort Worth, Texas

General Electric Laboratories(3)
Cincinnati 15, Ohio

General Electric Company
Schenectady, New York

General Motors Corporation
Indianapolis, Indiana

General Telephone & Electronics
Bayside, Long Island, New York

Grumman Aircraft Engineering
Corporation (2)
Bethpage, Long Island, New York

Harvey Aluminum, Inc.
Torrance, California

Union Carbide Stellite Corp.
Kokomo, Indiana

Hexcel Products
Berkeley 10, California

Hughes Tool Company
Culver City, California

Iowa State University
Ames, Iowa

Jet Propulsion Laboratory (2)*
Pasadena 3, California

Johns Hopkins University
Silver Springs, Maryland

Kaiser Aluminum & Chemical Corp.
Dayton, Ohio

Kentucky Metal Products
Louisville 13, Kentucky

Ladish Company
Cudahy, Wisconsin

Linde Company
Newark, New Jersey

Lindy Corporation
Indianapolis, Indiana

Link Chance Vought Corporation (4)*
Dallas, Texas

Lawrence Radiation Laboratory
Livermore, California

Lockheed Aircraft Corporation
Marietta, Georgia

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