

**DEVELOPMENT OF PARTIALLY VOLATILE BRAZING FILLER
ALLOYS FOR HIGH-TEMPERATURE APPLICATION
AND RESISTANCE TO OXIDATION**

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FOREWORD

This report was prepared by the Metals Research Division, Armour Research Foundation, Chicago, Illinois, under Contract No. AF33(616)-6882. The contract was initiated under Project No. 7351, "Metallic Materials," Task No. 73516, "Welding and Brazing of Metals." The work was administered under the direction of the Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, with L/Col. E. M. Kennedy and P. L. Hendricks acting as project engineers.

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ABSTRACT

The mechanical properties and the resistance to oxidation of 304 stainless steel joints brazed with the following four experimental filler alloys, containing volatile constituents, have been determined:

Alloy A: 61% Ni-39% In
Alloy C: 65% Ni-17% Cr-9% In-9% Si
Alloy I: 33% Ni-33% Cr-17% In-17% Ge
Alloy N: 35% Ni-24% Cr-26% In-15% Ge

A special brazing technique was developed for brazing these joints. The special technique involved: (1) a method of preparation of the alloy so that a homogeneous and desired composition was available to fill the joint capillary and (2) a method of volatilizing the melting point depressant which avoided the difficulty of "boiling," while still obtaining sufficient volatilization to provide the required higher remelt temperature and good high-temperature properties.

Miller-Peaslee type specimens brazed by this technique were used for the determination of joint strength at room temperature and elevated temperatures up to 1900° F.

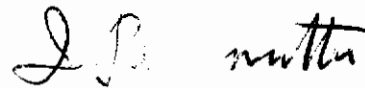
The highest shear strength of all four alloys was exhibited by the 65% Ni-17% Cr-9% In-9% Si alloy.

The oxidation resistance of all joints brazed with the four experimental filler alloys was excellent. Some of the joints brazed with the 61% Ni-39% In alloy showed considerable signs of oxidation after exposure to the open air for 500 hours at 1600° F.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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Contrails
TABLE OF CONTENTS

	<u>Page</u>
I INTRODUCTION	1
II BRAZING PROCEDURES AND OBSERVATIONS	2
A. General Procedure	2
B. Particle Size	3
C. Volatilization Behavior	3
1. Brazing in Vacuum	4
2. Brazing in Helium	5
D. Brazing in a Duplex Cycle of Flowing Helium Followed by Vacuum	7
III ELEVATED TEMPERATURE SHEAR STRENGTHS	7
A. The Miller-Peaslee Specimen	7
B. Shear Strength Results	8
C. Oxidation Evaluation	9
IV CONCLUSIONS	9
V BIBLIOGRAPHY	11
APPENDIX I - PLOTTED SHEAR STRENGTH DATA	33

Contrails

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Time-Temperature (Dotted Line) and Time-Pressure (Solid Line) Plots for a Vacuum Brazing Cycle with Alloy A (61% Ni-39% In)	12
2	Time-Temperature (Dotted Line) and Time-Pressure (Solid Line) Plots for a Vacuum Brazing Cycle with Alloy N (35% Ni-24% Cr-26% In-15% Ge)	13
3	Brazing Time - Shear Strength Relationship for Alloy A	14
4	Brazing Time - Shear Strength Relationship for Alloy I	15
5	Brazing Time - Shear Strength Relationship for Alloy N	16
6	Brazing Time - Shear Strength Relationship for Alloy C	17
7	Schematic Sketch of the Ni-Rich Section of the Ni-In Phase Diagram. (Ref. 2)	18
8	Photomicrographs of a 304 Stainless Steel Joint Brazed with the 61% Ni-39% In Alloy (Alloy A). The Joint was Removed from the Furnace as Soon as the Temperature Reached 1900°F	19
9	Photomicrographs of a 304 Stainless Steel Joint Brazed with the 61% Ni-39% In Alloy (Alloy A). The Joint was Removed from the Furnace as Soon as the Temperature Reached 1950°F	20
10	Photomicrograph of a 304 Stainless Steel Joint Brazed with the 61% Ni-39% In Alloy (Alloy A) for 15 minutes at 1950°F	21
11	Miller-Peaslee Coupon	22
12	Finished Shear Test Specimen After Brazing and Slotting	23
13	Shear Strength of 304 Stainless Steel Joints Brazed with Alloy A (61% Ni-39% In) at the Indicated Test Temperatures	24
14	Shear Strength of 304 Stainless Steel Joints Brazed with Alloy C (65% Ni-17% Cr-9% Si-9% In) at the Indicated Test Temperatures	25

Contrails

LIST OF ILLUSTRATIONS (continued)

<u>Figure</u>		<u>Page</u>
15	Shear Strength of 304 Stainless Steel Joints Brazed with Alloy I (33% Ni-33% Cr-17% In-17% Ge) at the Indicated Test Temperatures	26
16	Shear Strength of 304 Stainless Steel Joints Brazed with Alloy N (35% Ni-24% Cr-26% In-15% Ge) at the Indicated Test Temperatures	27
17	Shear Strength of 304 Stainless Steel Joints Brazed with the Designated Alloys (Brazing Temperature 1950°F) at the Indicated Test Temperatures	28
18	Enlarged Photograph of Cross-Section of a 304 Stainless Steel Joint Brazed for 60 Minutes at 2150°F with the 61% Ni-39% In Alloy (Alloy A) and Subsequently Oxidized in Air for 500 Hours at 1600°F	29
19	The Oxidation Groove Shown in Figure 18, Magnified 150 Times	30
20	Photomicrograph of a 304 Stainless Steel Joint Brazed for 60 Minutes at 1950°F with the 61% Ni-39% In Alloy (Alloy A), and Subsequently Oxidized in Air for 500 Hours at 1600°F	31
21	Shear Strength at Room Temperature Versus Overlap Distance for Joints Brazed with Alloy A	34
22	Shear Strength at 1000°F Versus Overlap Distance for Joints Brazed with Alloy A	35
23	Shear Strength at 1300°F Versus Overlap Distance for Joints Brazed with Alloy A	36
24	Shear Strength at 1600°F Versus Overlap Distance for Joints Brazed with Alloy A	37
25	Shear Strength at 1900°F Versus Overlap Distance for Joints Brazed with Alloy A	38
26	Shear Strength at Room Temperature Versus Overlap Distance for Joints Brazed with Alloy C	39
27	Shear Strength at 1000°F Versus Overlap Distance for Joints Brazed with Alloy C	40
28	Shear Strength at 1300°F Versus Overlap Distance for Joints Brazed with Alloy C	41

LIST OF ILLUSTRATIONS (continued)

<u>Figure</u>		<u>Page</u>
29	Shear Strength at 1600°F Versus Overlap Distance for Joints Brazed with Alloy C	42
30	Shear Strength at 1900°F Versus Overlap Distance for Joints Brazed with Alloy C	43
31	Shear Strength at Room Temperature Versus Overlap Distance for Joints Brazed with Alloy I.	44
32	Shear Strength at 1000°F Versus Overlap Distance for Joints Brazed with Alloy I	45
33	Shear Strength at 1300°F Versus Overlap Distance for Joints Brazed with Alloy I	46
34	Shear Strength at 1600°F Versus Overlap Distance for Joints Brazed with Alloy I	47
35	Shear Strength at 1900°F Versus Overlap Distance for Joints Brazed with Alloy I	48
36	Shear Strength at Room Temperature Versus Overlap Distance for Joints Brazed with Alloy N	49
37	Shear Strength at 1000°F Versus Overlap Distance for Joints Brazed with Alloy N	50
38	Shear Strength at 1300°F Versus Overlap Distance for Joints Brazed with Alloy N	51
39	Shear Strength at 1600°F Versus Overlap Distance for Joints Brazed with Alloy N	52
40	Shear Strength at 1900°F Versus Overlap Distance for Joints Brazed with Alloy N	53

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Shear Strength of 304 Stainless Steel, Miller-Peaslee Type Specimens Brazed at 1950°F Under Various Conditions	32

Contrails

I. INTRODUCTION

This program was a continuation of the alloy development work conducted at the Armour Research Foundation under Contracts No. AF33(600)-33406, Task No. 73022, "Development of Oxidation and Liquid Sodium Resistant Alloys" (1)*; and No. AF33(616)-5654, Task No. 73516, "Development of Partially Volatile Brazing Filler Alloys for High-Temperature Application and Resistance to Oxidation" (2).

In the course of the first study, indium and lithium were added to nickel-, iron-, and chromium-base alloys as brazing temperature depressants and aids-to-flow when used in a hydrogen atmosphere on Inconel-stainless brazements. Alloy compositions were shown that flowed between 1750° and 1900°F. Larger amounts of indium, however, which might have given lower melting alloys, resulted in a loss of oxidation resistance. It was recognized that the desirable flow and temperature depressant properties of indium could be utilized to its full extent if a means was established for the elimination of indium after flow has occurred. Oxidation resistance and high-temperature strength, after indium removal, should be that of the residual Ni-Cr-Ge or Ni-Cr-Si alloys. It was postulated that due to the relatively high vapor pressure of indium, this element could be eliminated from the brazed joints by volatilization in vacuum or in a flowing helium atmosphere.

Accordingly, in the next year's work it was attempted to develop brazing filler alloys containing indium, and some other volatile constituents which could then be volatilized during the brazing of stainless steel leaving joints of high remelt temperature. This work resulted in a series of brazing alloys which exhibited considerable increase in remelt temperature after brazing.

In the year's work reported here, four of these alloys:

Alloy A: 61% Ni-39% In
Alloy C: 65% Ni-17% Cr-9% In-9% Si
Alloy I: 33% Ni-33% Cr-17% In-17% Ge
Alloy N: 35% Ni-24% Cr-26% In-15% Ge

* Numbers in parentheses pertain to literature references listed at the end of this report.

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plus the Ni-Cr-In ternary eutectic, were selected for an investigation of the oxidation resistance and the high-temperature shear strength of 304 stainless steel joints. However, the composition of the Ni-Cr-In ternary eutectic was found to be essentially that of the composition of the Ni-In binary eutectic (alloy A); the Ni-Cr-In ternary eutectic was therefore eliminated from the experimental program.

The Miller-Peaslee specimen was chosen as the principal means of determination of the high-temperature shear strength. Brazing was performed in vacuum and in flowing helium at atmospheric pressure at 1950° and 2150°F. The shear strengths were determined at room temperature, 1000°, 1300°, 1600° and 1900°F. Oxidation was evaluated at 1000°, 1300°, and 1600°F for times of 100, 300, and 500 hours.

II. BRAZING PROCEDURES AND OBSERVATIONS

A. General Procedure

Since procedure development as such was not one of the planned major portions of this program, it would not ordinarily contribute heavily to the observations or conclusions of this report. However, experience with the brazing philosophy of volatilizing a melting point depressant is rather limited; and several problems were encountered in the preparation of braze specimens, the understanding and solution of which provided observations which were important in their own right. These "procedure" observations are reported in the following paragraphs.

Heats, weighing 225 grams, of the four subject filler alloys (A, C, I and N) were prepared by melting in a tungsten arc furnace under helium atmosphere. The prepared alloys were too brittle for extrusion, hot rolling, or cold rolling, and were applied to the joints in powder form (150-mesh). Each powder was mixed with Nicrobraz cement to a thin slurry, and the slurry was used for filling the capillary gaps. Various filling techniques were examined for filling the gaps: (1) filling with the slurry applied on one side of the gap, (2) filling from both sides of the gap, and (3) preplacing the slurry and squeezing the excess out of the gap by applying slight pressure. The best results were attained with the first filling method.

In the course of the brazing experiments it was observed that the brazing characteristics of the alloys were dependent on the crushing procedure, and on the size of the particles obtained, as well as on the atmosphere of the chamber.

B. Particle Size

The effect of particle size was first encountered in a brazing experiment in which alloy C (which has an expected melting point of $1885 \pm 10^{\circ}\text{F}$) did not melt even at 2050°F under flowing helium, when the alloy was introduced in powder form (150 mesh). When the experiment was repeated with the coarse particle fractions, the alloy not only melted but wet and flowed satisfactorily, giving acceptable shear strengths. Similar particle size comparisons were made with the other three alloys (A, I, and N) and again the coarse particle fractions gave better brazes in terms of strength and reduced porosity. Strength was improved on the order of 50 to 100%. The reasons for the dependence of brazing characteristics on particle size are not definitely known; however, the following possibilities exist:

1. Segregation of phases of the filler alloy during crushing, grinding, or ball milling (brittle phases are more friable than ductile phases).
2. Oxidation during crushing, grinding, or ball milling.
3. Loss of the melting point depressant by volatilization either (a) during crushing, or (b) during the early (pre-flow) stages of brazing.

Chemical analyses of the powdered fractions do not show a great departure from the design analyses; therefore, possibilities "1" and "3(a)" are evidently eliminated.

As a result of this observation, coarse alloy particles (1 to 2 mm) were used for the greater part of all subsequent work. These particles were preplaced and cemented in place near the joint.

C. Volatilization Behavior

The volatile element (indium) of the brazing filler alloy can be volatilized during the brazing operation if its partial pressure over the brazement can be kept lower than its vapor pressure. This lowering of partial pressure can be obtained by either surrounding the material with a pure inert gas, such as helium (either flowing or static, as discussed previously (2)) or by evacuating the chamber. The practical difference between the two methods is one of rate of volatilization, since the evaporating material creates a back pressure by its presence outside the solid. In helium, the rate of the process is evidently controlled by the rate of diffusion of indium through the surrounding envelope of helium, or, with flowing helium, by the rate of helium replacement; while in a vacuum the indium atoms are removed from the surface more rapidly, i. e., gaseous indium atoms would be expected to move more rapidly through a vacuum than through helium unless the flow-rate of helium is quite high.

Contrails

A second practical difference between pure helium and vacuum is that boiling, which is undesirable because it causes porosity, occurs when the vapor pressure exceeds the total pressure; thus boiling is more difficult under atmospheric helium than under vacuum. These considerations bear on the following experiments.

1. Brazing in Vacuum

Miller-Peaslee specimens were brazed with powdered alloys A and N (this experiment was performed prior to adopting the coarse alloy particles) by heating to 1950°F for 15 minutes, under a vacuum of 0.3 micron. With alloy A, the pressure in the retort, upon heating, increased spontaneously from 0.3 to 30 microns as soon as the solidus temperature, 1675°F, of the alloy was attained (the time-temperature and time-pressure curves are shown in Figure 1). This volatilization effect was also observed, to a lesser extent--from 0.3 to 18 microns--upon heating with alloy N (see Figure 2).

All the joints brazed by this method with alloys A and N were quite brittle; most of the specimens broke upon fastening them in the grips of the tensile machine, and some of them broke in filing off the tack-weld fasteners. Only one specimen of eight brazed with alloy A was ductile enough to perform a shear test. This specimen exhibited a shear strength of 3850 psi at an overlap of about 2 in.

Metallographic investigation of the cross-sectioned joints brazed in vacuum with alloy A revealed that the filler alloy only partially filled the capillary gap, and only at a few places were fragments of the metallic bond left which eventually could provide some strength to these joints. This non-filling could have been due either to a "boiling out" action after the capillary had been filled, or to the reduction in fluidity (due to loss of indium) being so rapid that the joint was never filled.

Miller-Peaslee specimens were also brazed with "coarse particles" (rather than powder) of alloys A, C, I, and N for 15 minutes at 1950°F, under a vacuum of 0.1 to 0.3 microns. Examination of these specimens after brazing revealed that only alloy A produced good wettability and sufficient penetration of the capillary gaps. The alloys C, I, and N did not penetrate into the capillary gaps at all. The edges of the chunks of these three alloys were rounded only slightly, indicating that the bulk of these chunks did not melt. Although the chunks were bonded quite strongly to the steel plates after brazing, the spreading of the low-melting, liquid phase on the surface of the steel surrounding these chunks was nevertheless quite negligible. It was rather obvious that the low-melting, liquid phase solidified before it could reach the capillary gap. This suggests that the rate of indium loss--hence, the rate of increase of melting point--is too high, in vacuum, for practical brazing applications. This is true both in the case of preplaced alloy (powdered alloy) and in the case where flow to and into a capillary is required (coarse particle alloy). The exception to this rule is alloy A, which must lose an appreciable amount of indium before an increase in solidus temperature is experienced.

2. Brazing in Helium

The above practical difficulties owing to the rapid loss of indium during brazing in vacuum suggest that brazing in helium might be a useful means of slowing the volatilization, thus allowing more flow before solidification. In order to alter the effect of volatilization, brazing temperature and time was varied. The following six series of specimens were brazed with powdered alloy A:

Series 1: Four specimens were brazed in a static helium atmosphere by heating them rapidly to 1775°F. In order to avoid the volatilization effect as much as possible, these specimens were removed from the hot zone of the retort as soon as the temperature of the specimens attained 1775°F. These specimens broke when the tack-welded fasteners were filed off. Metallographic examination revealed very poor wettability of the steel surfaces and almost no penetration of the capillary gaps by the molten filler metal.

Series 2: Four specimens were brazed in flowing helium atmosphere by heating them rapidly to 1900°F, and immediately removing them from the hot zone of the retort as soon as the temperature of the specimens attained 1900°F. The wettability and the penetration of the capillary gaps by the molten filler alloy were considerably better than in static helium. However, the shear strength of these specimens could not be determined since they all broke in the machining process.

Series 3: Four specimens were brazed in a flowing helium atmosphere by heating them rapidly to 1950°F and immediately removing them from the hot zone of the retort as soon as this temperature was reached. One specimen was cross-sectioned for metallographic investigation, and the other three were subjected to shear testing. All three specimens exhibited some shear strength.

Series 4, 5, and 6: In order to investigate the influence of the brazing time on the shear strength of the joints, the three remaining four-specimen series were brazed in a flowing helium atmosphere at 1950°F with brazing times of 15, 30, and 60 minutes, respectively. From each series one specimen was cross-sectioned for metallographic observation, and the other three were tested in shear. The shear results are presented in Figure 3 (powdered alloys).

These results show a gradual strength increase with increasing brazing time. All of these gaps were filled, and the strength improvement must therefore be due to loss of indium during holding time at the brazing temperature. This loss is probably due to both diffusion and volatilization mechanisms.

The determination of the brazing time-shear strength relationship was repeated for powdered alloys C, I, and N in flowing helium at 1950°F.

The brazing time-shear strength data which were obtained are plotted (for alloys I and N) in Figures 4 and 5. (Alloy C did not flow in this experiment.)

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The above experiment demonstrating the effect of brazing time, at 1950°F in flowing helium, on joint shear strength was repeated with the brazing alloy being applied in the coarse particle form. The results, are also presented in Figures 3, 4, and 5, with the now successful alloy C brazement shown in Figure 6. These data substantiate the previous observation that shear strength increases with increasing brazing time. Comparing the coarse particle filler alloys with the powdered alloys, the coarse particle brazements had considerably fewer voids and inclusions and higher strengths, as reported under the paragraph on particle size.

In order to understand the dependence of shear strength on brazing time-temperature, the following discussion is offered. The discussion is given, for the sake of simplicity, in terms of the binary eutectic alloy A, but the principles illustrated will be applicable to the more complex alloys C, I, and N.

As soon as the melting point of the eutectic is reached (1667°F), the alloy melts and flows into the joint. The molten brazing filler alloy dissolves only a slight amount of the base metal; and if the alloy freezes and cools immediately, the braze joint is filled with the Ni-In eutectic alloy, which does not have desirable properties. If the alloy and parent joint remains at this temperature for some time, or is further heated, indium escapes by volatilization. According to the Ni-In phase diagram (Figure 7), which may be referred to for a generalized mechanistic discussion, the loss of indium causes the precipitation of the proeutectic crystals of solid solution indium in nickel. As time-temperature is increased and additional indium is lost, the relative amount of "eutectic" which is present on solidification decreases, and the composition of the proeutectic nickel phase becomes leaner in indium. For example, at the brazing temperature of 1950°F the equilibrium composition of the proeutectic phase is 82.5% Ni, 17.5% In. Figure 8 shows a joint which has been heated only to 1900°F and immediately cooled. Evidently this high temperature excursion was too short to allow appreciable depletion of indium, because the gray "indium-rich constituent" is continuous throughout the joint. The brittleness of this gray phase is shown by the gross crack on the left (X 100) and by the many small cracks on the right hand (X 1000) photograph. This joint was too weak to be machined.

Figures 8, 9, and 10 provide a sequence of decreasing indium content, or of decreasing "gray constituent," with increasing time-temperature of brazing. As the temperature of 1950°F was just reached, the nickel-rich phase has bridged the capillary gap, reducing the "gray indium constituent" to islands (Figure 9). Further volatilization diffusion of indium after holding at 1950°F for 15 minutes has markedly reduced the size of these islands (Figure 10). These last two joints exhibited useful shear strength. Further changes in microstructure were observed as the holding time was increased to 30 and to 60 minutes. The latter microstructure contained only a small amount of "gray constituent." It is interesting to note that the quantity of "gray constituent" was still further reduced during the high-temperature oxidation evaluation which is reported below. After exposure of the 60-minute joint to air at 1600°F for 500 hours, the "gray constituent" was almost eliminated (see Figure 20).

Similar microstructural changes--that is, the loss of indium-rich gray constituent with time at temperature--were also observed with the other alloys (C, I, and N); but the presence of Ge, Cr, and Si complicated the structures, and their interpretation was more difficult.

D. Brazing in a Duplex Cycle of Flowing Helium Followed by Vacuum

The observation of the brazing behavior under vacuum showed that the loss of indium tends to be so rapid that flow of the alloy to the joint is limited. However, after the joint has been accomplished, a vacuum might be advantageous in increasing the rate of indium loss by a diffusion-volatilization mechanism. Therefore, the different behavior of the three alloys C, I, and N in high vacuum and in helium atmosphere could be utilized for obtaining sounder and stronger joints by modifying the brazing process so that the capillaries would be filled under helium atmosphere, after which the indium would be volatilized in high vacuum. In order to prove this postulation, three series of Miller-Peaslee type specimens were brazed with the coarse particle fractions of alloys C, I, and N for 10 minutes at 1950°F in helium atmosphere. Subsequently, the retort was evacuated to 0.1 to 0.3 micron's helium pressure and the joints kept in the high vacuum atmosphere at 1950°F for an additional 25 minutes. Another series of specimens was brazed by the two-step method at the same temperature as in the previous tests (1950°F) but at a less severe vacuum (5 to 10 mm and 100 mm Hg) in the second step of the brazing process.

In Table I the average shear strength of the joints brazed by the two-step process is compared with the average shear strength of comparable joints which were not given additional volatilization in vacuum. This comparison shows that the additional volatilization in partial vacuum does not contribute to the increase of the average shear strength of the joints brazed with alloy C, and results only in a slight increase of the average shear strength of the joints brazed with alloy I. Considering the difficulties which would be encountered in practical application of a complex, two-step brazing method, and especially considering the fact that the joints brazed by this method did not yield a considerable increase (in one case it was even a decrease) of the average shear strength, it was decided to abandon the two-step brazing experiments in favor of the flowing-helium (one-step) method.

III. ELEVATED TEMPERATURE SHEAR STRENGTHS

A. The Miller-Peaslee Specimen

Since a brazed joint is almost always designed to be loaded in shear, it is reasonable that its strength should be evaluated in shear. However, an evaluation of the shear strength of a brazing alloy is always complicated by the eccentricity and non-uniformity of shear stressing which is inherent in a brazed shear joint. The measured strength, in a shear test, is a complex

function of the relative stress-strain behavior of the parent metal and filler metal, and of the overlap and other specimen geometry considerations. The Miller-Peaslee test is not exempt from those objections, but was adopted for this program because of its low cost and simplicity. A description of, and a discussion of, the test appear in the literature (3); it suffices to point out that complete representation of strength properties of a given alloy requires shear strength measurements over a range of overlap distances.

The Miller-Peaslee shear specimen components were machined from 1 x 1/8 inch, 304 stainless steel strips, as shown in Figure 11. Figure 12 shows the finished shear test specimen (after brazing and cutting the slots). The spacing of the slots determines the overlap distance, which was varied from 0.1 to 1.8 inch in this program.

B. Shear Strength Results

Specimens were brazed for shear strength evaluation with the procedure which was found, by experiments described in the foregoing paragraphs, to give the best joint quality. This procedure included (1) use of the coarse particle fractions of the brazing alloy, (2) holding the brazement at temperature for 60 minutes, and (3) performing the braze under a flowing helium atmosphere. Two brazing temperatures were used (1950° and 2150°F) for each of the four alloys (A, C, I, and N). Overlap on the Miller-Peaslee specimen was 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.25, 1.5 and 1.8 inches, and shear strength data were obtained for room temperature, 1000, 1300, 1600, and 1900°F. These 4 parameters (brazing temperature and alloy, testing temperature, and overlap distance) and the measured variable, shear strength, can be plotted in a number of ways. Figures 13, 14, 15, and 16 present the shear strength versus overlap distance for alloys A, C, I, and N, respectively, plotted for five different testing temperatures after two brazing temperatures. (The same plots, with data points, appear for reference in Appendix A.) These curves show, as expected, that shear strength decreases with increasing test temperature; however, all of the alloys still exhibit some strength (~ 1000 psi) at as high as 1900°F, which is an encouraging demonstration of the practicality of volatilization and/or diffusion of indium as a means of altering the post-braze characteristics.

The "apparent" shear strength also decreases with increasing overlap distance, a mechanical effect which is expected.

In general, the strengths of the 2150°F brazements are greater, for comparable alloys and test temperatures, than the 1950°F brazements. This is probably due to greater loss of indium by volatilization and diffusion during brazing at the higher temperature. However, this strength increase may not be worth the extra 200°F brazing temperature, except for cases where such increase is imperative.

The order of strength of the four alloys--generalizing for all overlap distances, brazing temperatures, and testing temperatures--is C, A, I, and N. This order is illustrated by a partial re-plot of the data in Figure 17.

Contrails

Since the shear strength of the brazed joints is determined by many factors, it is rather difficult at this point to submit a complete explanation of the factors which cause this particular order of alloy strengths. However, one conclusion is indicated: additions of Ge (in alloys I and N) definitely decrease the shear strength of the joints at all test temperatures.

C. Oxidation Evaluation

The resistance to oxidation of joints in 304 stainless steel brazed with the four experimental alloys was determined by microstructural observation after exposure to 1000°, 1300°, and 1600°F air for 100, 300, and 500 hours. These experiments were conducted on joints brazed at both temperatures (1950° and 2150°F).

This metallographic study revealed definite signs of oxidation on some of the specimens subjected to 1600°F for 500 hours. The form of oxidation, which could be damaging, was the development of "oxidation grooves" from the outer surface of the specimen into the capillary gap as shown in Figure 18. The deepest "grooves" appeared with alloy A (0.01 inch deep) in a specimen which had been brazed at 2150°F for 60 minutes. However, it is interesting to note that the specimen which was brazed with the same alloy A at 1950°F, and subjected to the same oxidation procedure (500 hours at 1000°F), did not show any signs of oxidation (see Figure 20). A second micrograph of this specimen is shown at higher magnification in Figure 19.

In addition to the development of oxidation grooves, all the specimens exposed to 1600°F for 300 and 500 hours, show almost complete elimination of the gray indium-rich constituent from the region of the brazed joint. For example, in the photomicrographs presented in Figures 19 and 20, it is rather difficult to discern the traces of the original joint.

The shear strength of the oxidized joints was not determined. However, the metallographic investigation of these joints indicates that any loss of mechanical strength caused by the oxidation grooves might be more than compensated for by the increased integrity of the joint due to the elimination of the brittle, indium-rich constituent from the joint itself. Thus, it is quite possible that prolonged heating in air at higher temperatures might even result in the increase of the high-temperature strength of the joints brazed with these alloys.

IV. CONCLUSIONS

1. The high-temperature shear strength of the 304 stainless steel joints brazed with the four experimental filler alloys containing volatile constituents was measured at various test temperatures as a function of (1) brazing temperature and (2) overlap distance in the Miller-Peaslee type

Conclusions

specimen. These determinations have shown that all joints have a considerable shear strength at temperatures up to 1900°F. Furthermore, all the joints brazed at 1950°F exhibited only a slightly lower shear strength than the joints brazed at 2150°F. These observations indicate the great potential advantage of filler alloys containing volatile constituents--namely, the feasibility to attain appreciable high-temperature strength in joints brazed at considerably lower brazing temperatures than are possible with most of the other commercial high-temperature brazing alloys.

2. Alloy C (65% Ni-17% Cr-9% Si-9% In) has the highest strength at all five test temperatures. With 1.0 inch overlap it yields 3900 psi at 1600°F and 1300 psi at 1900°F.

3. Alloy N (35% Ni-24% Cr-26% In-15% Ge) had the lowest shear strength at all five test temperatures. With an overlap of 1.0 inch it yields 1000 psi at 1600°F, and 1300 psi at 1900°F.

4. The oxidation resistance of all the joints brazed with the four experimental filler alloys, and exposed to air for 100, 300, and 500 hours at 1000°, 1300°, and 1600°F, respectively, was excellent, except that some of the joints brazed with alloy A (61% Ni-39% In) exhibited large oxidation grooves after exposure to the air for 500 hours at 1600°F. The results of the metallographic investigation of the cross-sections of the oxidized specimens indicate that the mechanical strength of the joints heated at higher temperatures might be higher after heating than before, because of an improvement in the quality of the joint. This apparent improvement is due to the elimination of the brittle, indium-rich constituent in the process of prolonged heating.

V. BIBLIOGRAPHY

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2. W. M. Lehrer and H. Schwartzbart, "Development of Partially Volatile Brazing Filler Alloys for High-Temperature Application and Resistance to Oxidation," WADC Technical Report No. 59-404, December 1959.
3. F. M. Miller and R. L. Peaslee, "Proposed Procedure for Testing Shear Strength of Brazed Joints," The Welding Journal, Res. Suppl., Vol. 37, April 1958, pp. 144-s to 150-s.
4. Discussion, W. Lehrer and H. Schwartzbart, The Welding Journal, Res. Suppl., Vol. 39, Oct. 1960, p. 462-s.

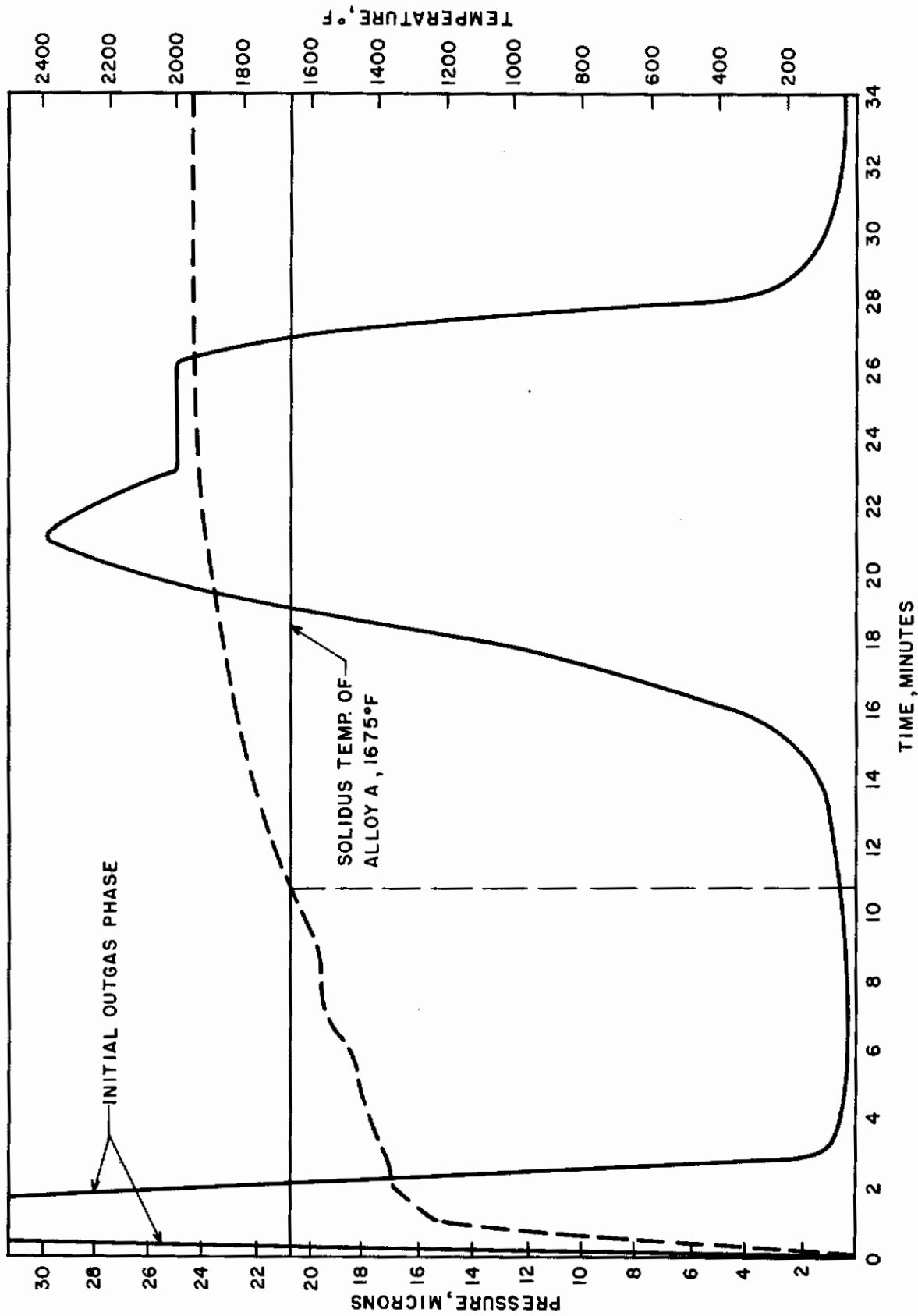


FIGURE 1. TIME-TEMPERATURE (DOTTED LINE) AND TIME-PRESSURE (SOLID LINE) PLOTS FOR A VACUUM BRAZING CYCLE WITH ALLOY A (61% Ni-39% In).

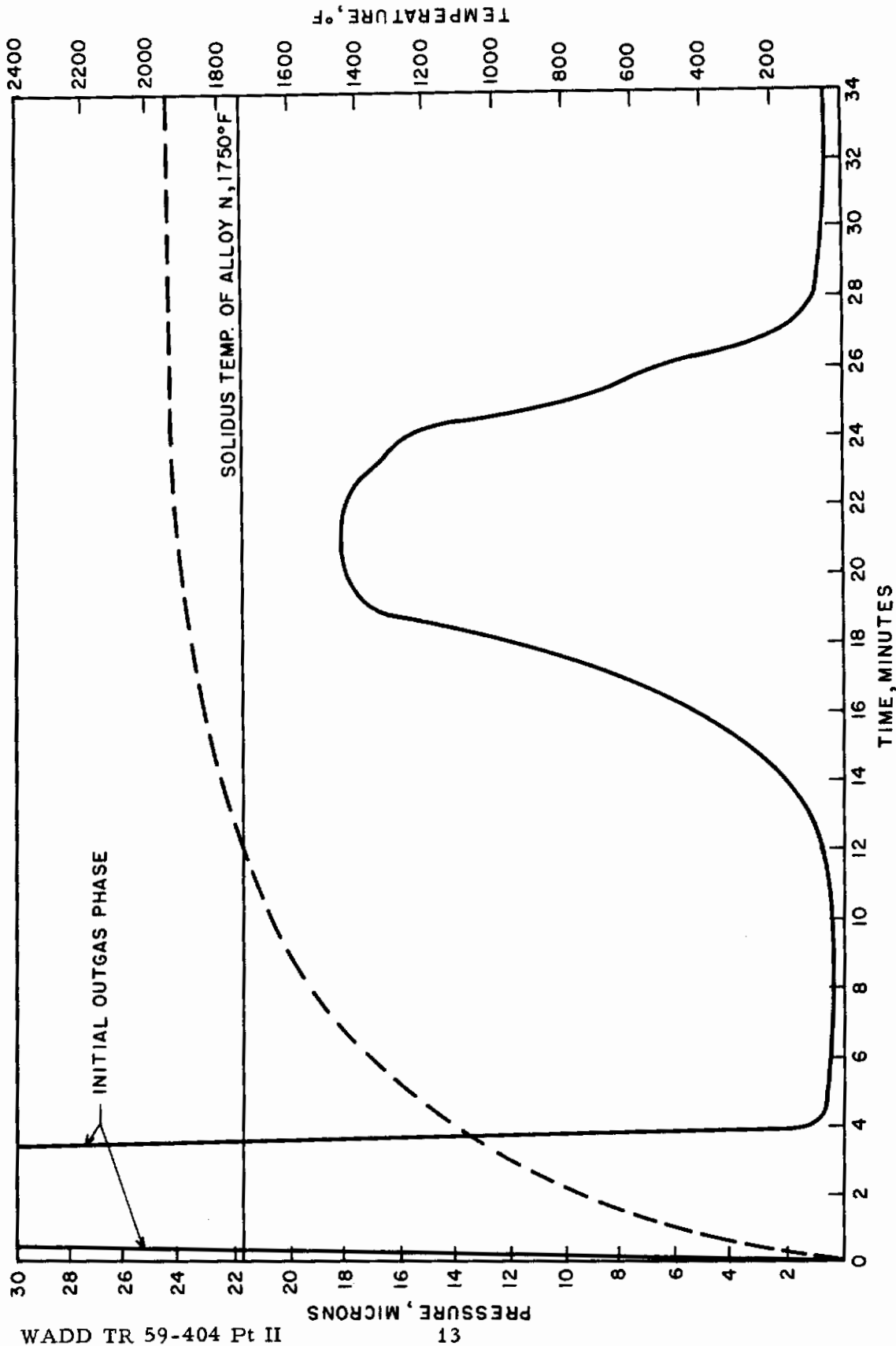


FIGURE 2. TIME-TEMPERATURE (DOTTED LINE) AND TIME-PRESSURE (SOLID LINE) PLOTS FOR A VACUUM BRAZING CYCLE WITH ALLOY N (35% Ni-24% Cr-26% In-15% Ge).

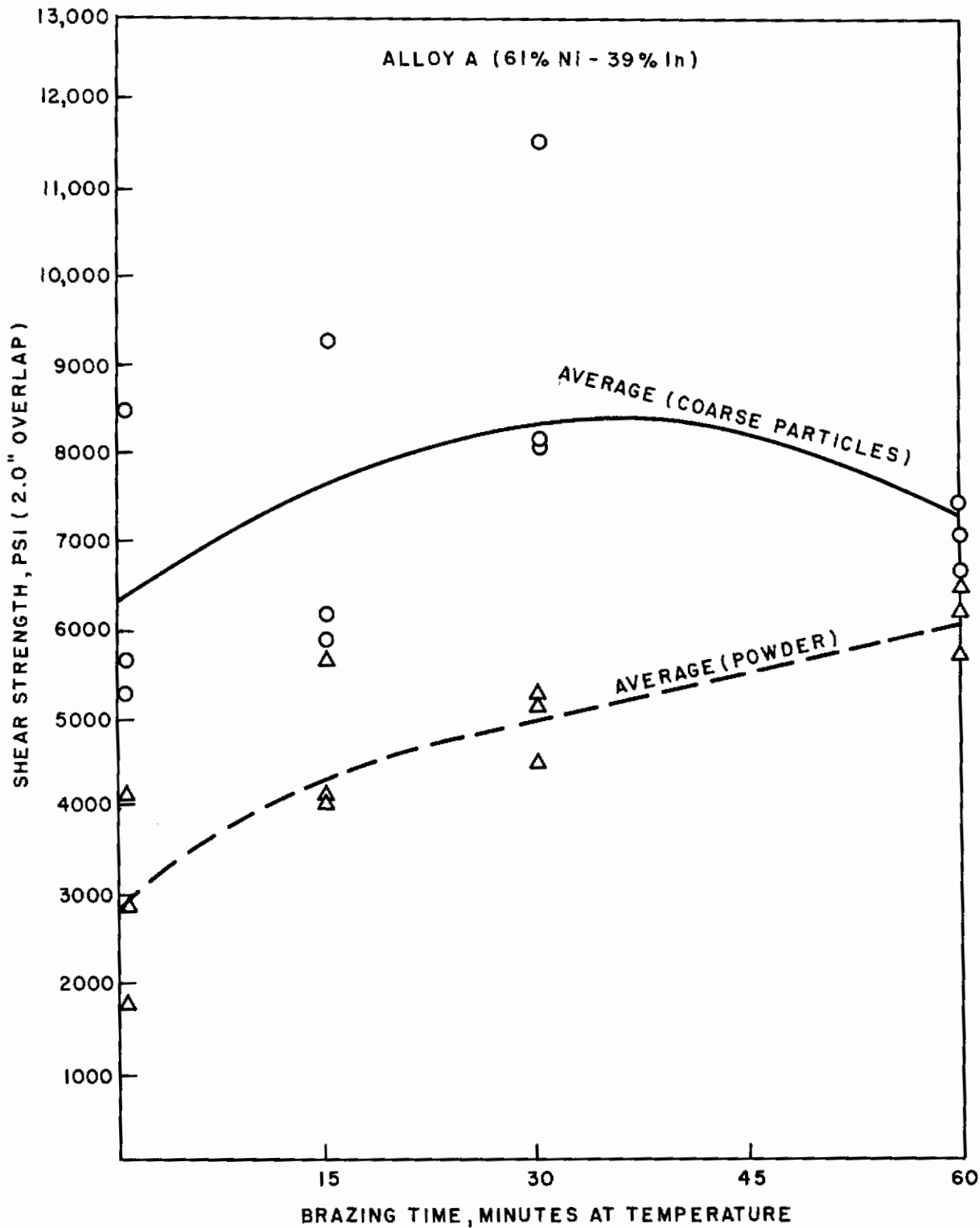


FIGURE 3. BRAZING TIME - SHEAR STRENGTH RELATIONSHIP FOR ALLOY A. 304 STAINLESS STEEL, MILLER-PEASLEE TYPE SPECIMENS BRAZED AT 1950°F IN FLOWING HELIUM ATMOSPHERE.

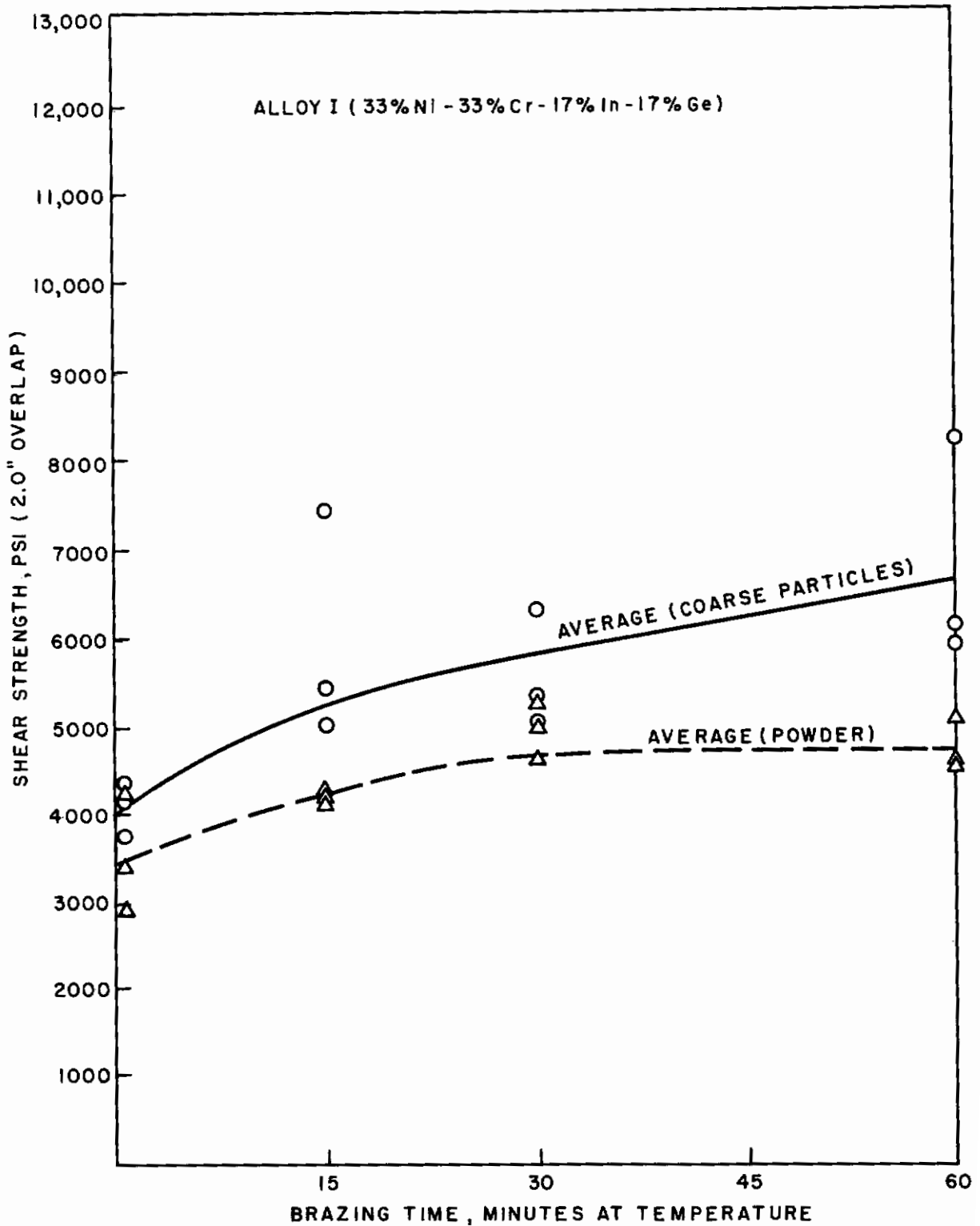


FIGURE 4. BRAZING TIME - SHEAR STRENGTH RELATIONSHIP FOR ALLOY I. 304 STAINLESS STEEL, MILLER-PEASLEE TYPE SPECIMENS BRAZED AT 1950°F IN FLOWING HELIUM ATMOSPHERE.

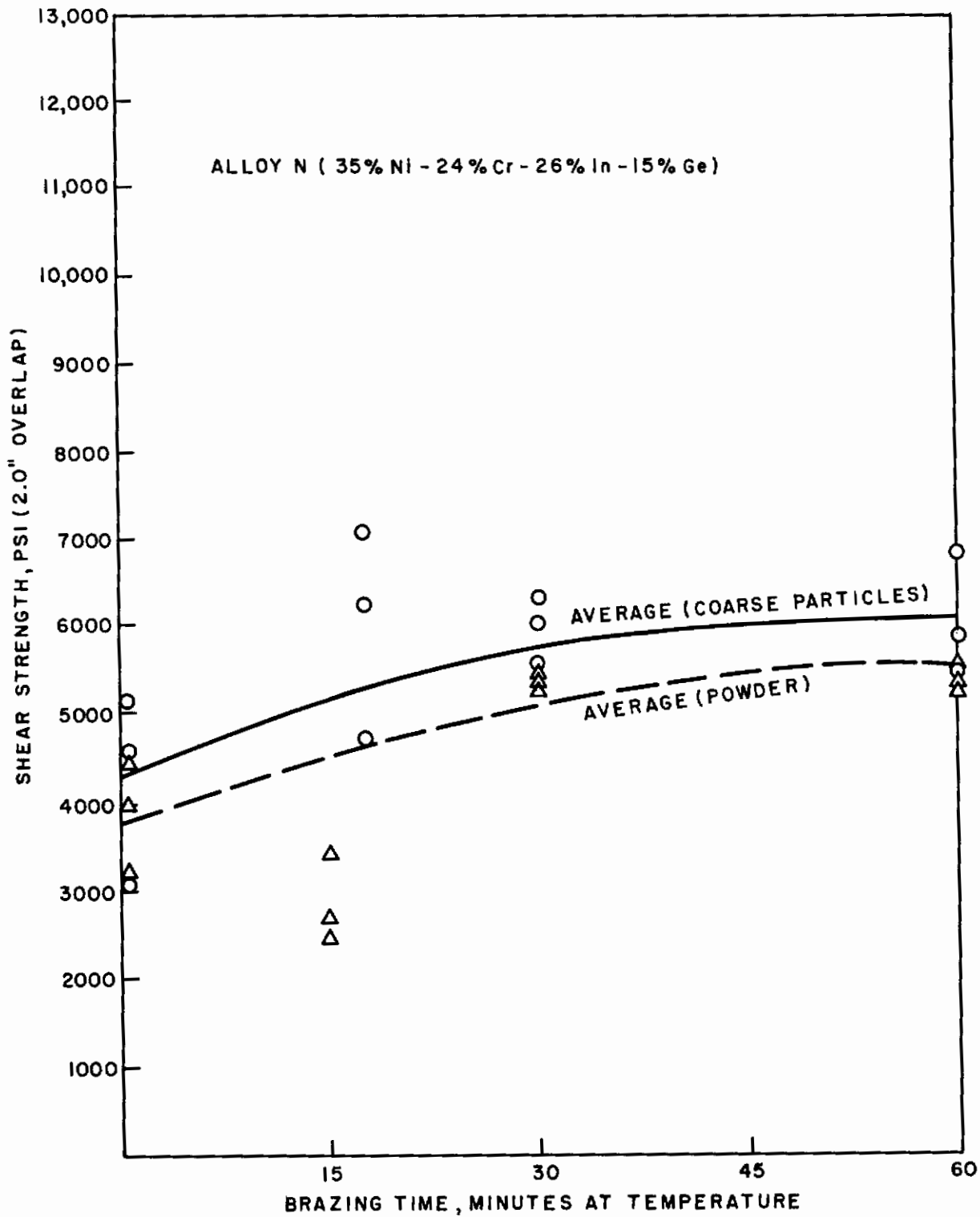


FIGURE 5. BRAZING TIME - SHEAR STRENGTH RELATIONSHIP FOR ALLOY N. 304 STAINLESS STEEL, MILLER-PEASLEE TYPE SPECIMENS BRAZED AT 1950°F IN FLOWING HELIUM ATMOSPHERE.

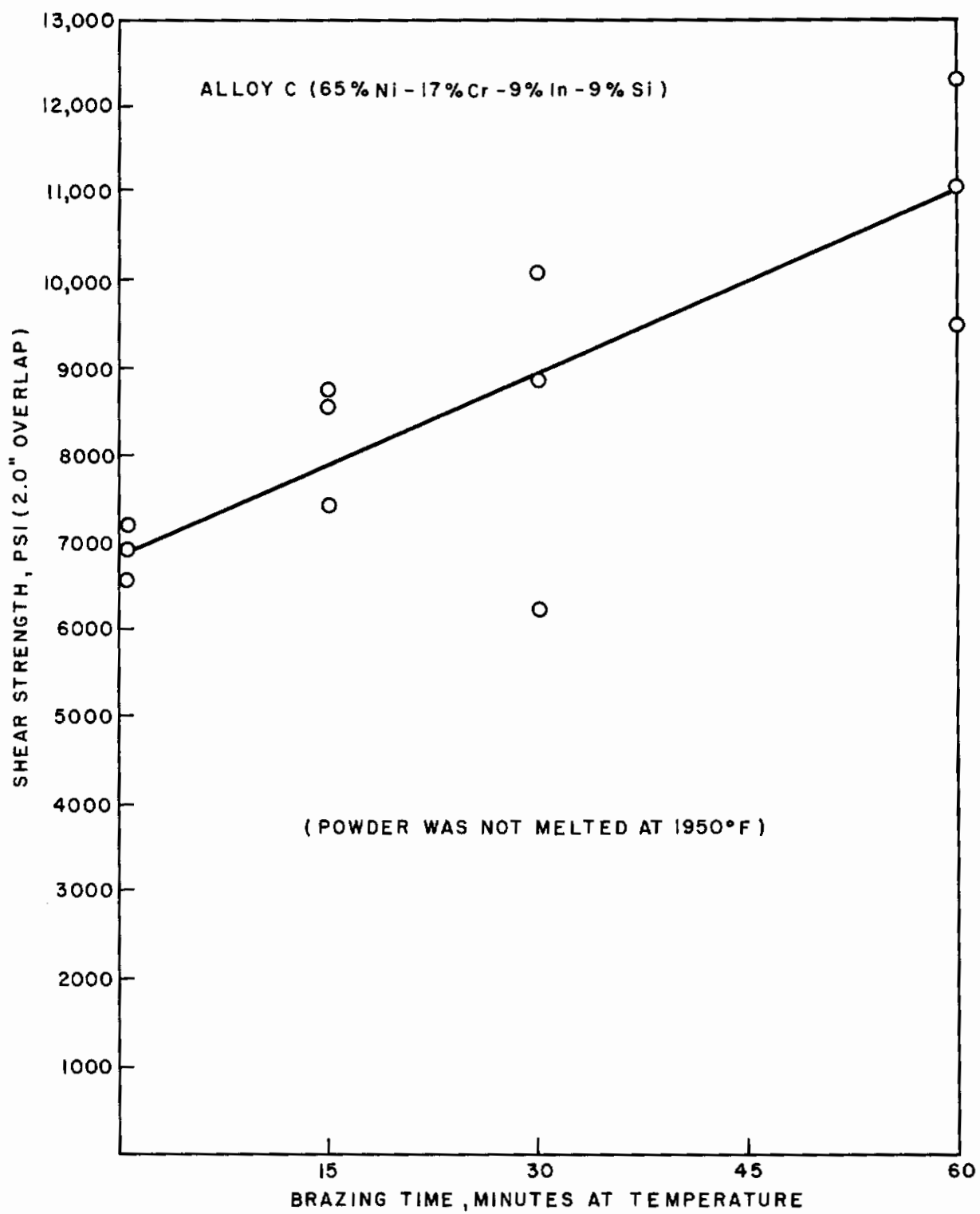


FIGURE 6. BRAZING TIME - SHEAR STRENGTH RELATIONSHIP FOR ALLOY C. 304 STAINLESS STEEL, MILLER-PEASLEE TYPE SPECIMENS BRAZED AT 1950°F IN FLOWING HELIUM ATMOSPHERE.

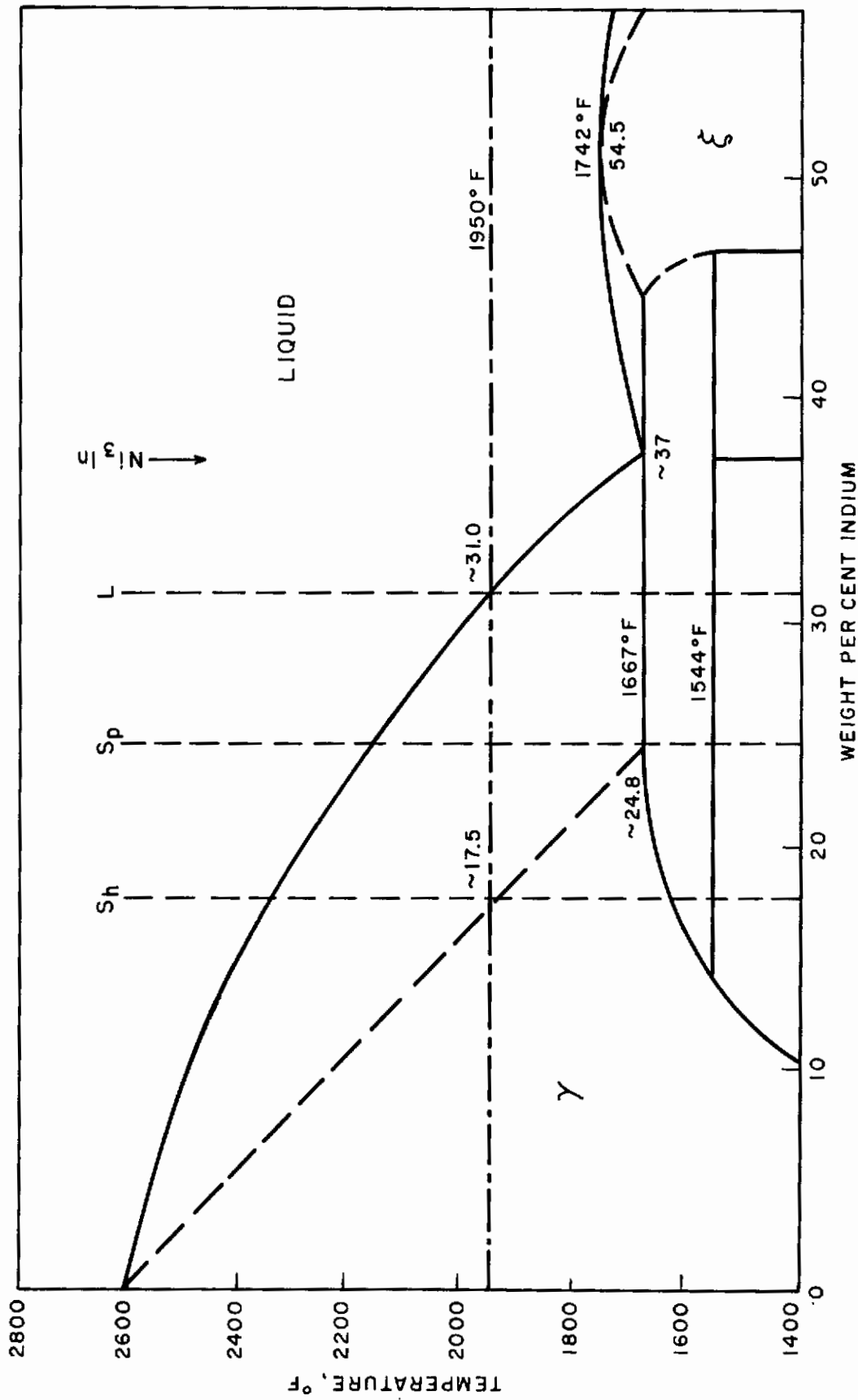


FIGURE 7. SCHEMATIC SKETCH OF THE Ni-RICH SECTION OF THE Ni-In PHASE DIAGRAM. (REF. 2).

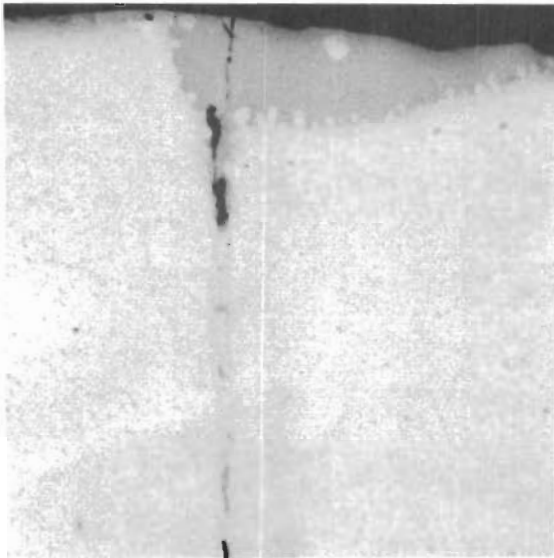


Neg. No. 19876 Mag. X 100
Unetched



Neg. No. 19877 Mag. X 1000
Unetched

Figure 8. Photomicrographs of a 304 stainless steel joint brazed with the 61% Ni-39% In alloy (alloy A). The joint was removed from the furnace as soon as the temperature reached 1900°F. A large crack propagated through the entire cross-section.



Neg. No. 19880
Unetched

Mag. X 200



Neg. No. 19879
Unetched

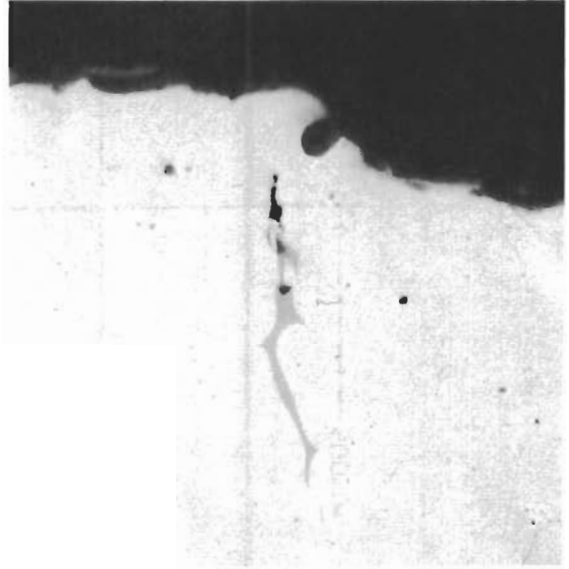
Mag. X 500

Figure 9. Photomicrographs of a 304 stainless steel joint brazed with the 61% Ni-39% In alloy (alloy A). The joint was removed from the furnace as soon as the temperature reached 1950°F. At some places of the capillary gap the white primary dendrites of the Ni-rich phase reach each other closing locally the capillary gap, and entrapping pockets of the gray In-rich constituent; a black gas-escape gap is clearly visible in the upper part of the photomicrographs.



Neg. No. 19888
Unetched

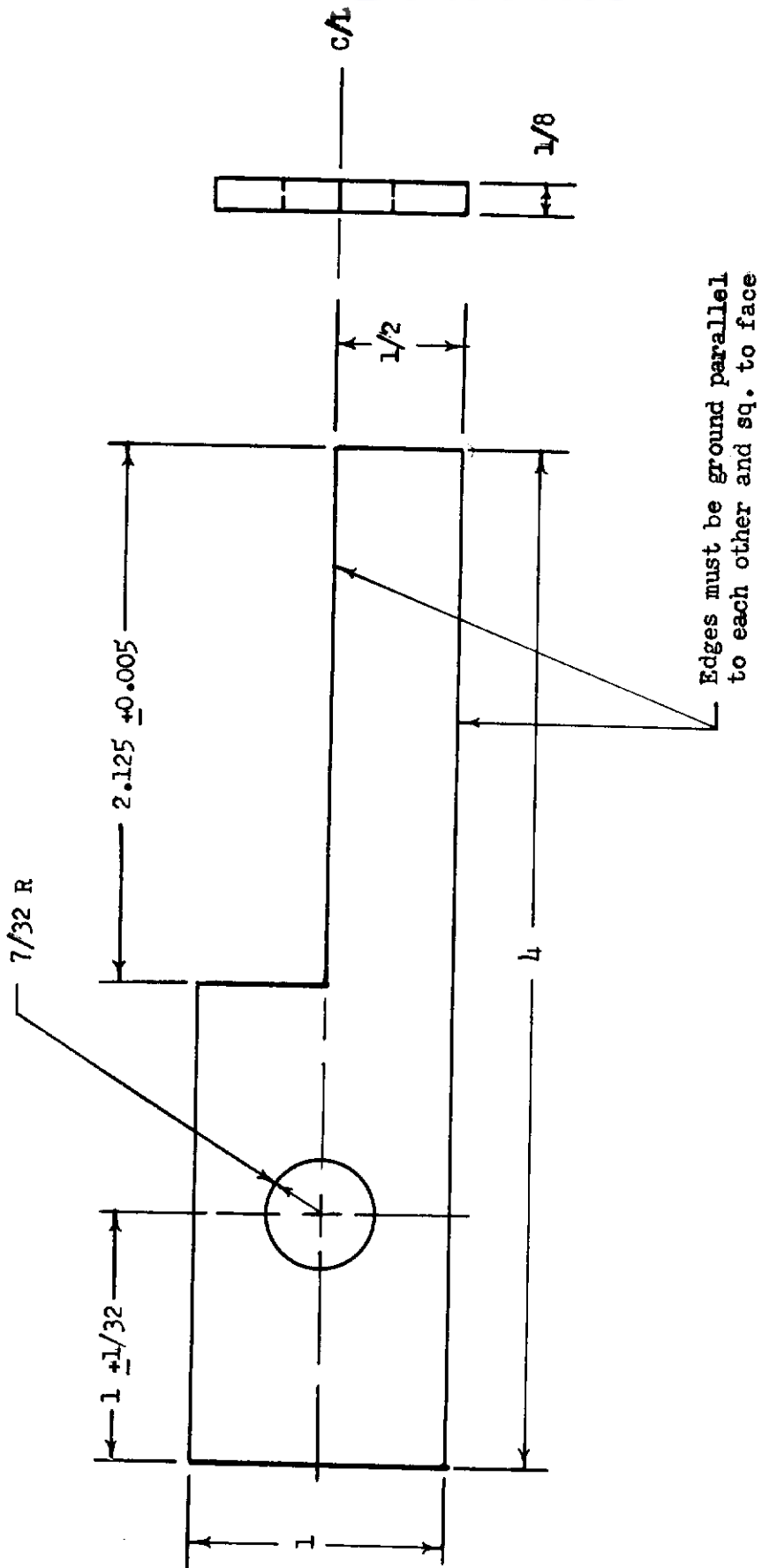
Mag. X 100



Neg. No. 19882
Unetched

Mag. X 500

Figure 10. Photomicrograph of a 304 stainless steel joint brazed with the 61% Ni-39% In alloy (alloy A) for 15 minutes at 1950°F. The amounts of the gray In-rich constituent are quite small.



Notes:

- 1. All corners to be "as ground"
- 2. Two outer edges to be ground until cleaned up.

FIGURE 11. MILLER-PEASLEE COUPON.

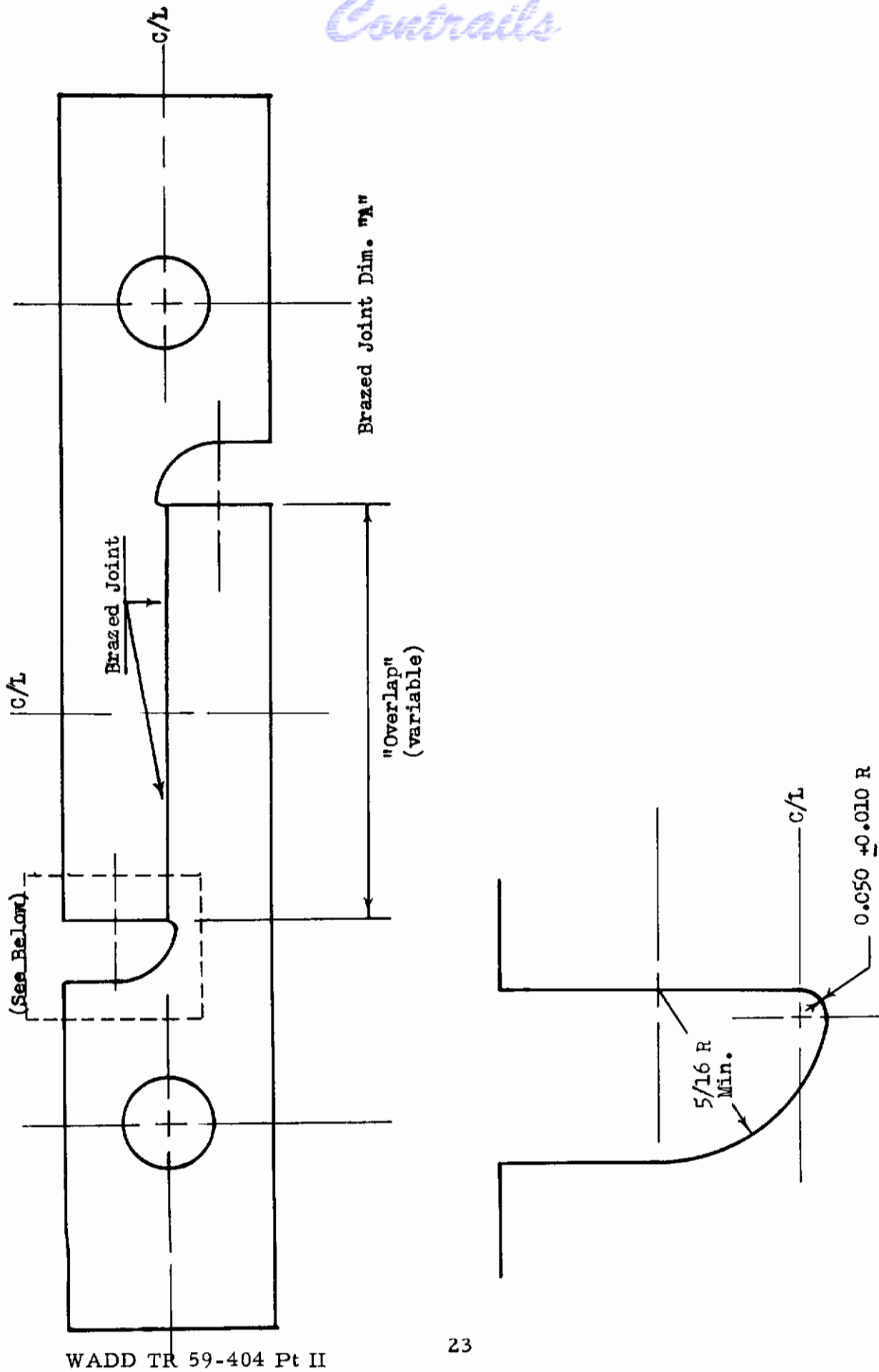


FIGURE 12. FINISHED SHEAR TEST SPECIMEN AFTER BRAZING AND SLOTTING.

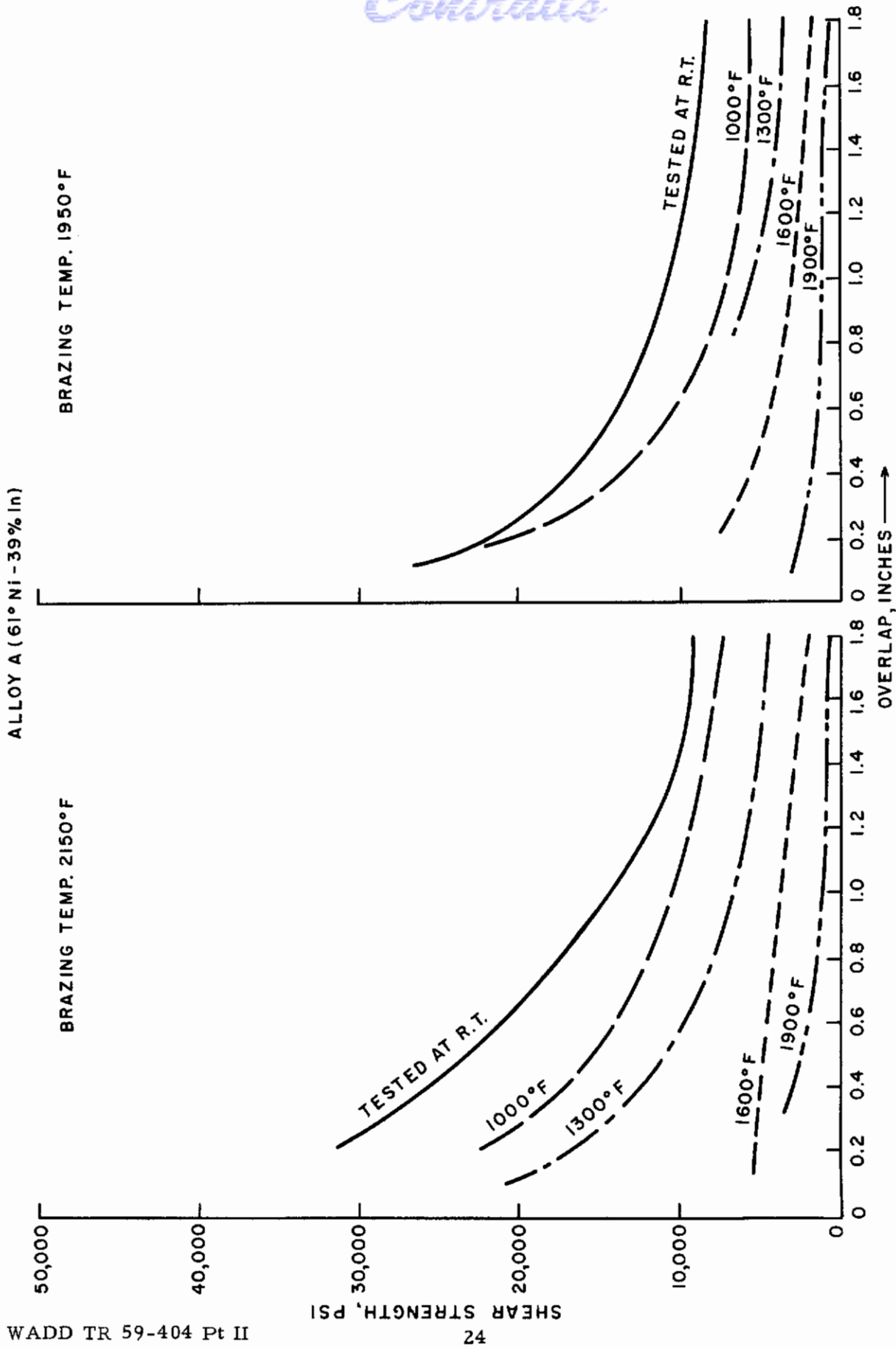


FIGURE 13. SHEAR STRENGTH OF 304 STAINLESS STEEL JOINTS BRAZED WITH ALLOY A (61% Ni-39% In) AT THE INDICATED TEST TEMPERATURES.

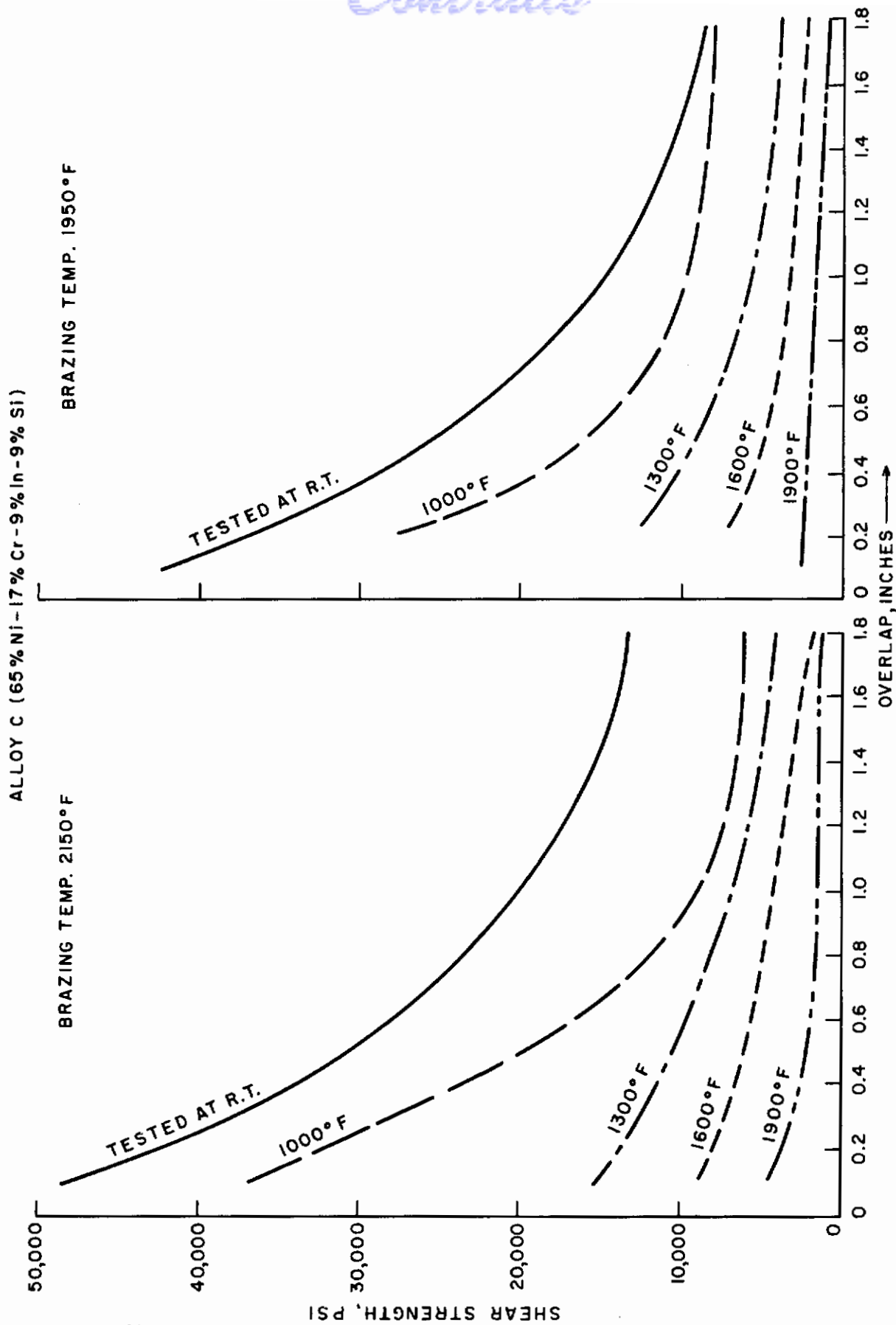


FIGURE 14. SHEAR STRENGTH OF 304 STAINLESS STEEL JOINTS BRAZED WITH ALLOY C (65% Ni-17% Cr-9% Si-9% In) AT THE INDICATED TEST TEMPERATURES.

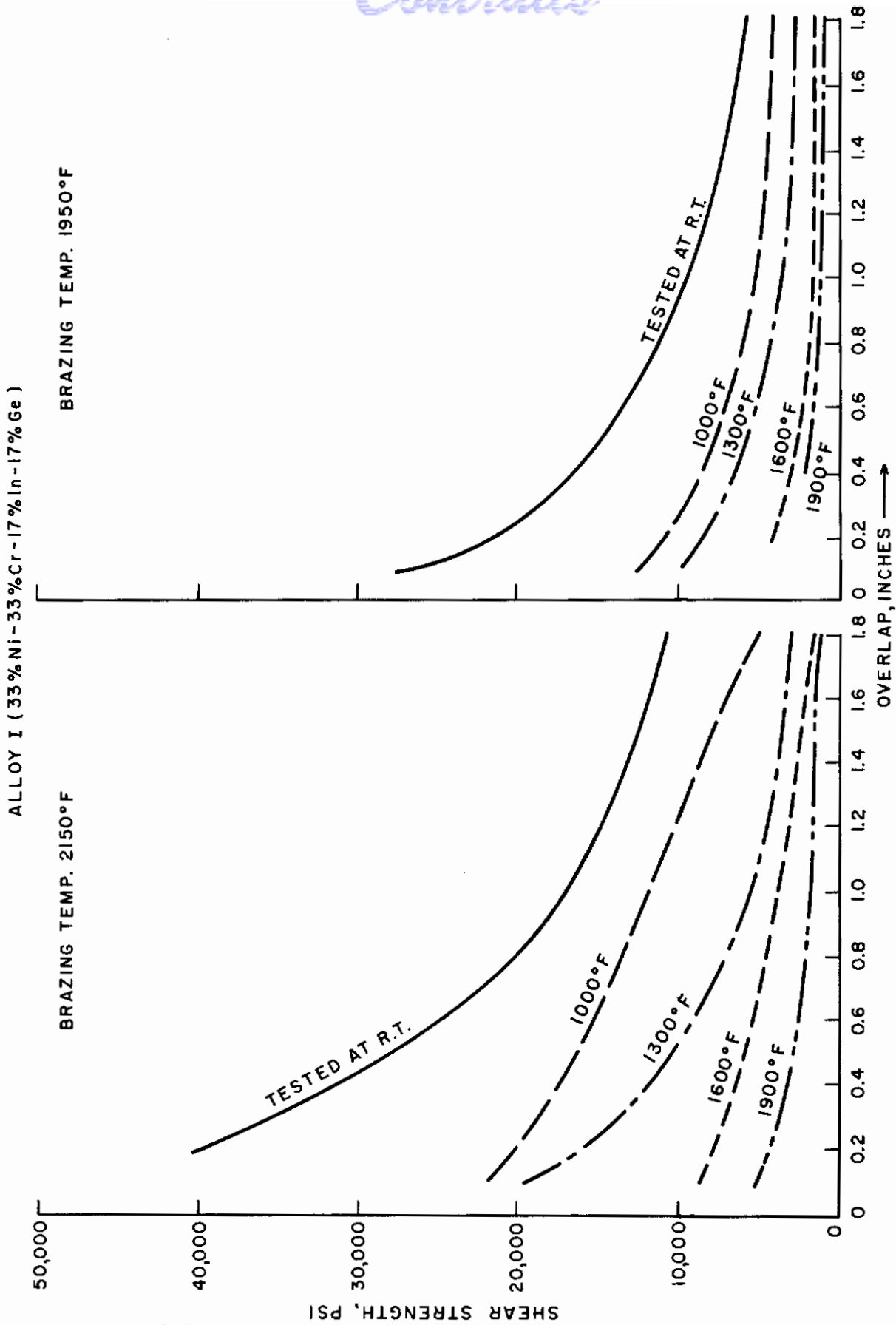


FIGURE 15. SHEAR STRENGTH OF 304 STAINLESS STEEL JOINTS BRAZED WITH ALLOY I (33% Ni-33% Cr-17% In-17% Ge) AT THE INDICATED TEST TEMPERATURES.

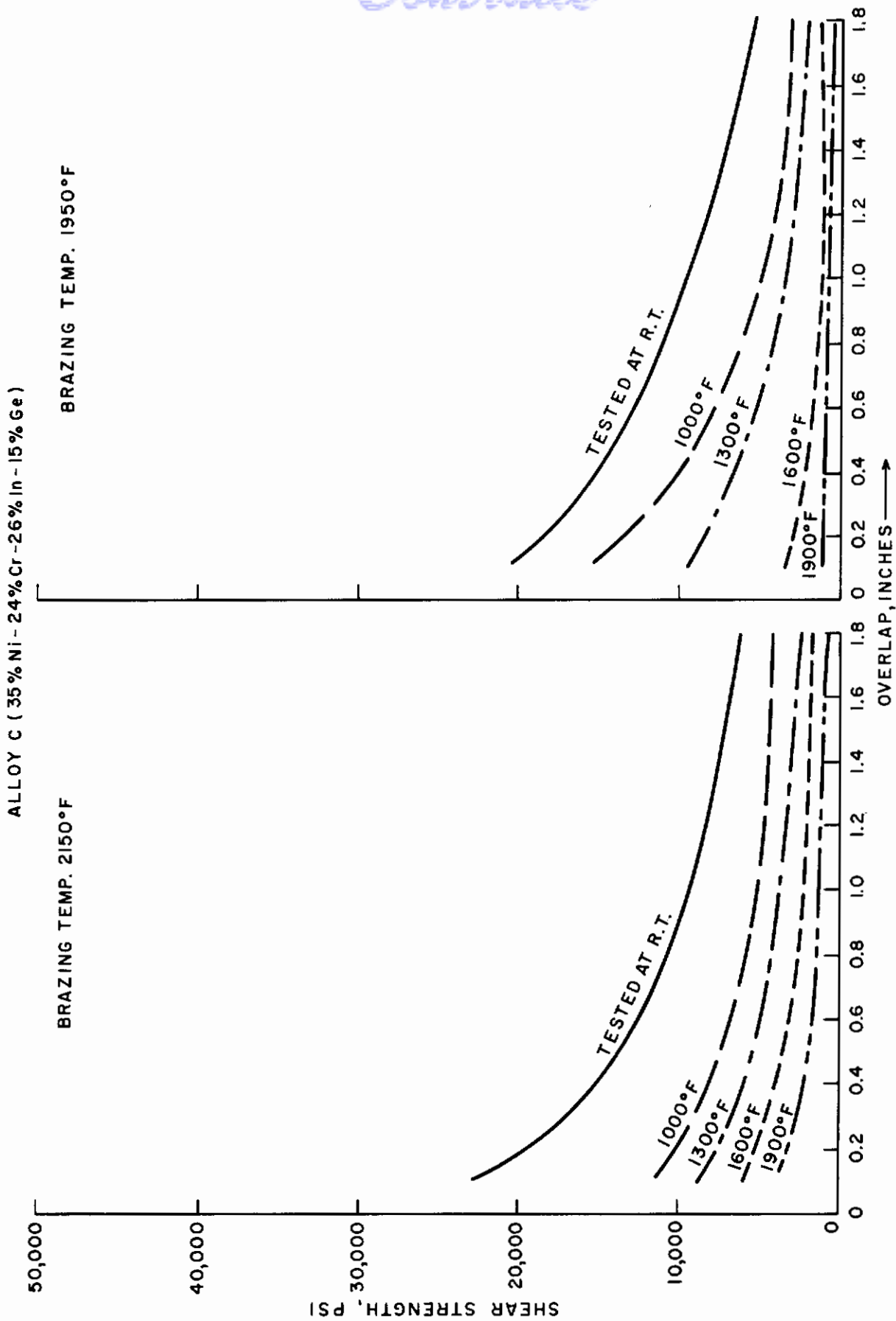


FIGURE 16. SHEAR STRENGTH OF 304 STAINLESS STEEL JOINTS BRAZED WITH ALLOY N (35% Ni-24% Cr-26% In-15% Ge) AT THE INDICATED TEST TEMPERATURES.

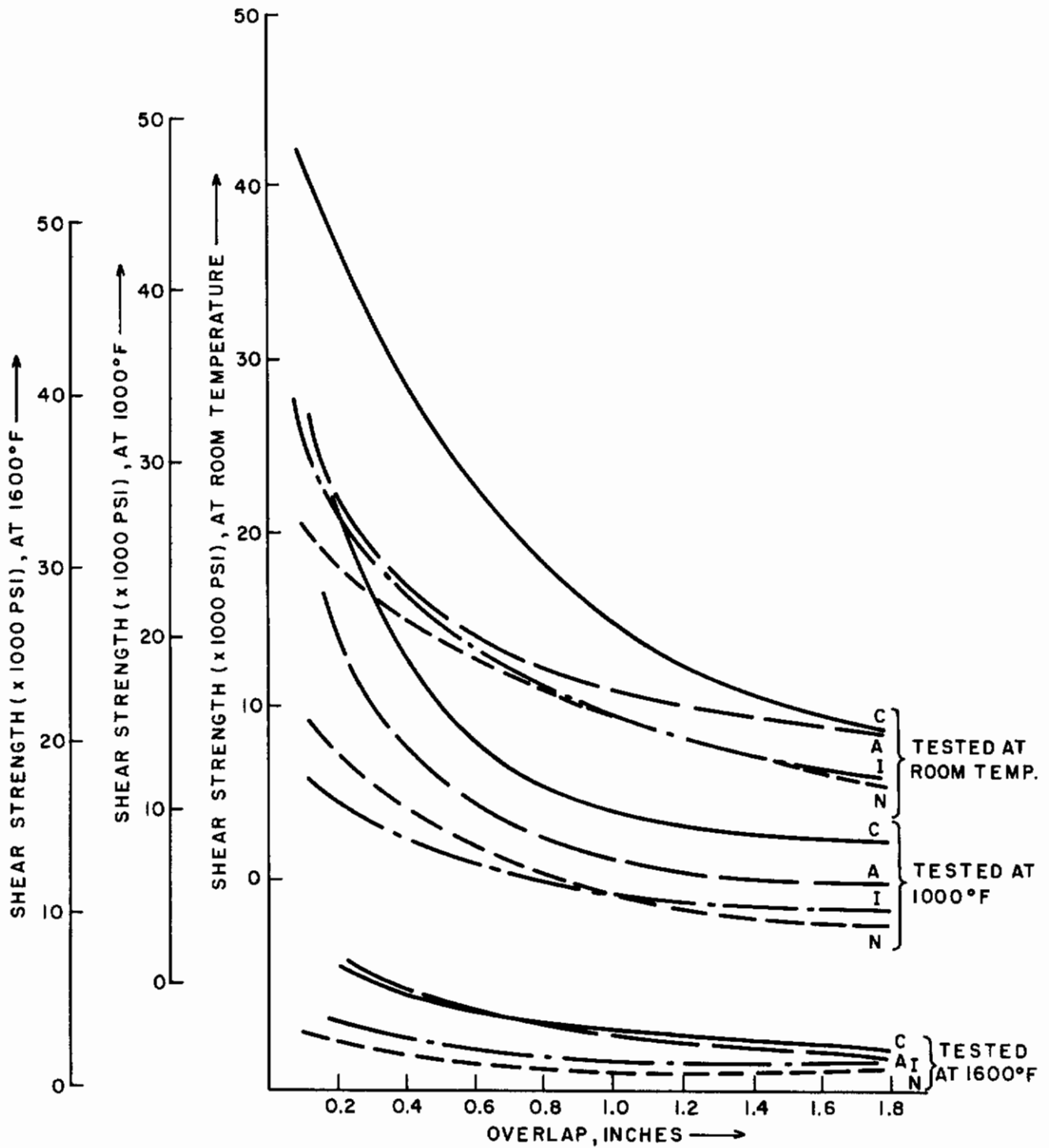
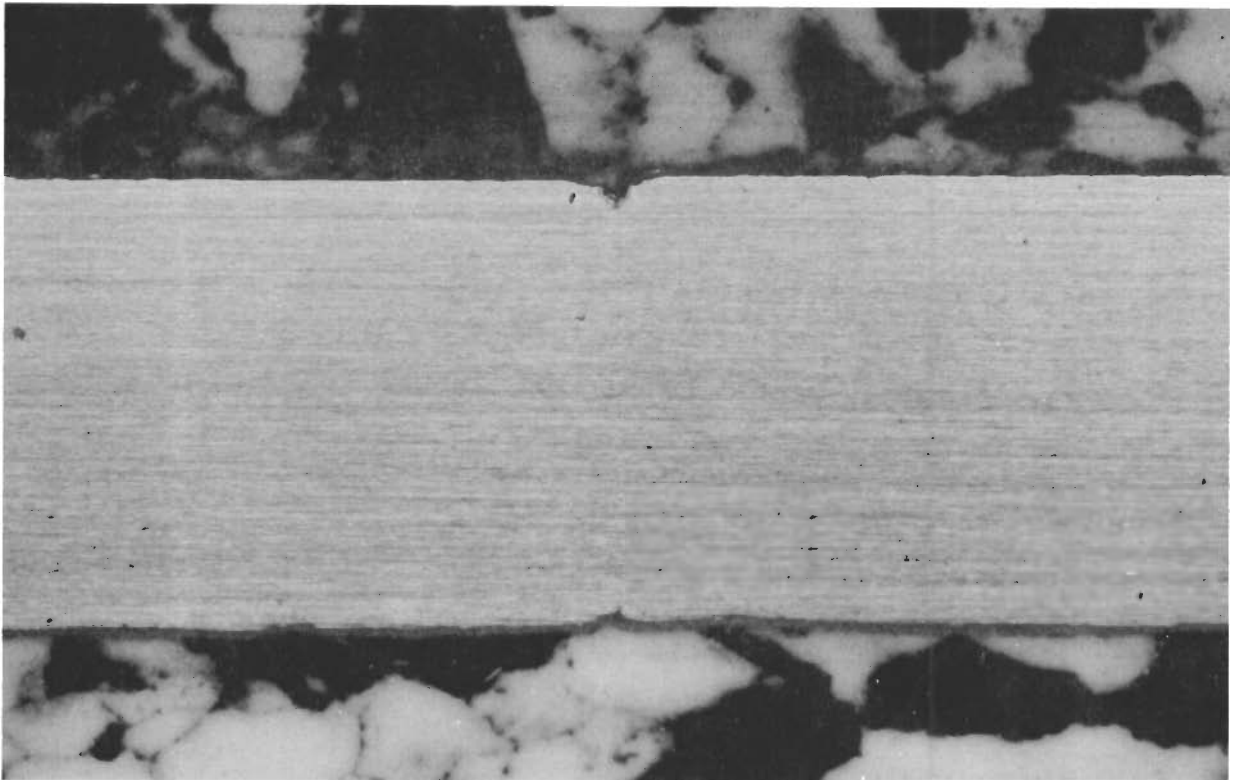


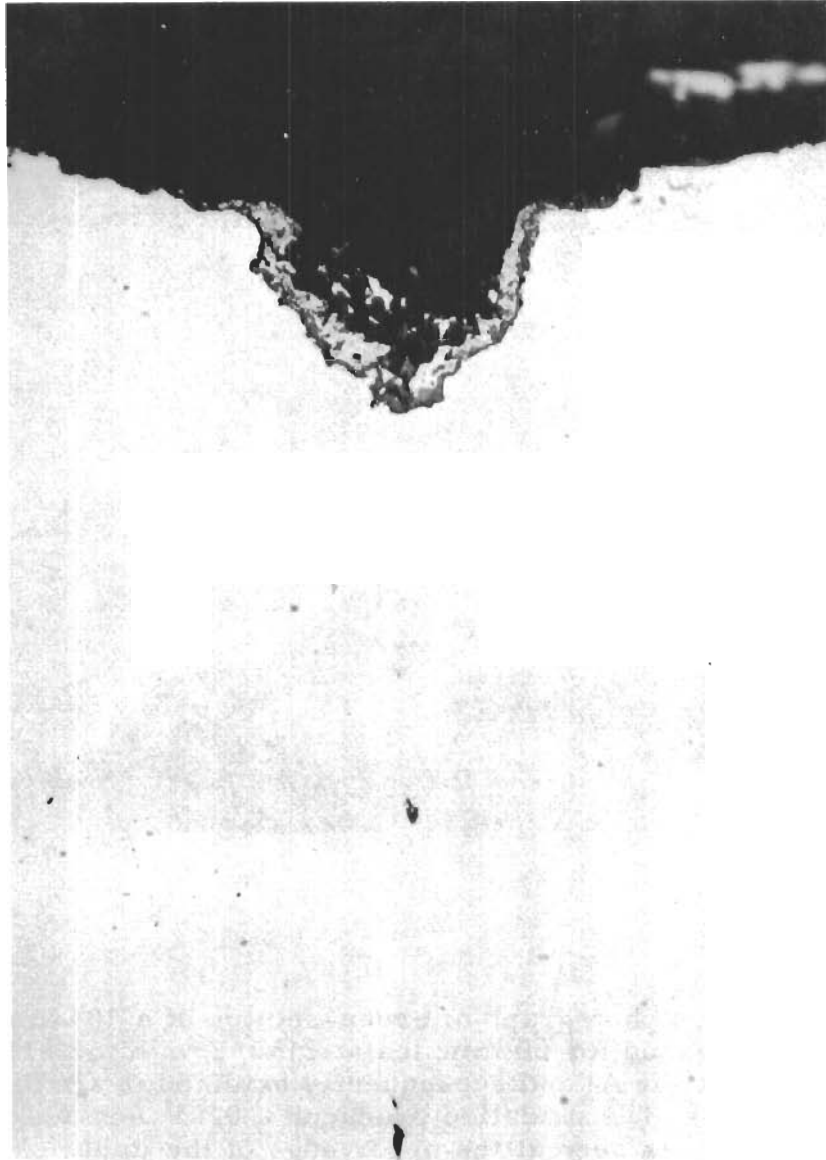
FIGURE 17. SHEAR STRENGTH OF 304 STAINLESS STEEL JOINTS BRAZED WITH THE DESIGNATED ALLOYS (BRAZING TEMPERATURE 1950°F) AT THE INDICATED TEST TEMPERATURES.



Neg. No. 20624
Unetched

Mag. X 18

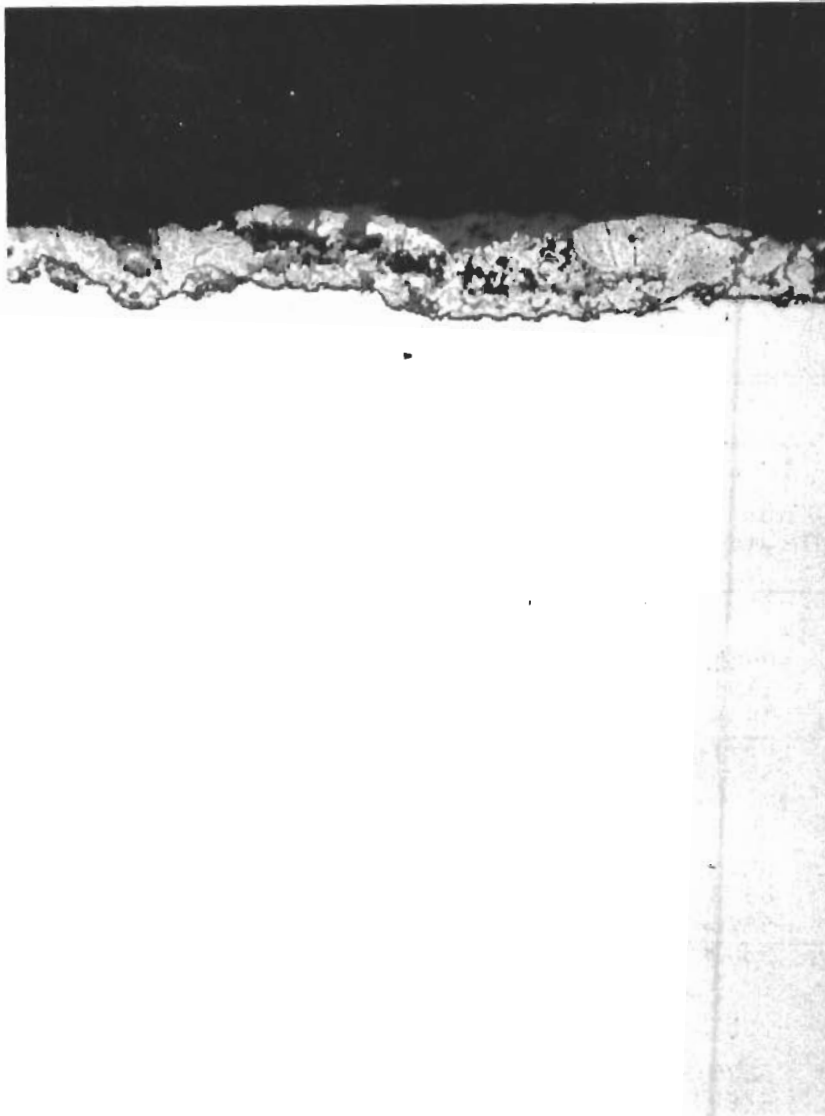
Figure 18. Enlarged photograph of cross-section of a 304 stainless steel joint brazed for 60 minutes at 2150°F with the 61% Ni-39% In alloy (alloy A) and subsequently oxidized in air for 500 hours at 1600°F. The oxidation produced a 0.01 inch deep oxidation groove, as seen at the upper edge of the joint.



Neg. No. 20637
Unetched

Mag. X 150

Figure 19. The oxidation groove shown in Figure 18, magnified 150 times. It is interesting to note that the prolonged heating (500 hr at 1600°F) resulted in a complete elimination of the gray In-rich phase from the brazed joint.



Neg. No. 20638
Unetched

Mag. X 100

Figure 20. Photomicrograph of a 304 stainless steel joint brazed for 60 minutes at 1950°F with the 61% Ni-39% In alloy (alloy A), and subsequently oxidized in air for 500 hours at 1600°F. The prolonged heating resulted in a complete elimination of the gray In-rich phase from the joint. Some traces of this phase are discernible in the lower section of the micrograph. A thick layer of the filler metal on the top of the specimen protected the joint from oxidation.

TABLE I

SHEAR STRENGTH OF 304 STAINLESS STEEL, MILLER-PEASLEE
TYPE SPECIMENS BRAZED AT 1950°F UNDER VARIOUS CONDITIONS

(2.0 in. Overlap)

Brazing Alloy	Shear Strength (psi) for Brazing Conditions			
	1 30 min in He atm	2 10 min in He plus 25 min in 0.1-0.3 μ vacuum	3 10 min in He plus 25 min in 5-10 mm vacuum	4 10 min in He plus 35 min in 100 mm vacuum
C		8900	9044	9125
	10085	8240	7180	4953
	6204	7200	8691	8013
	8883	7233	7615	6796
	avg. 8391	avg. 7908	avg. 8133	avg. 7229
I		6786	6792	6551
	5058	7040	8541	6775
	6393	7317	6304	6026
	5326	5100	5256	7601
	avg. 5592	avg. 6561	avg. 6723	avg. 6738
N		4400	4616	5089
	5573	5440	4694	4918
	5480	7355	5627	4764
	6248	9325	5221	5213
	avg. 5767	avg. 6630	avg. 5040	avg. 4996

APPENDIX I

PLOTTED SHEAR STRENGTH DATA

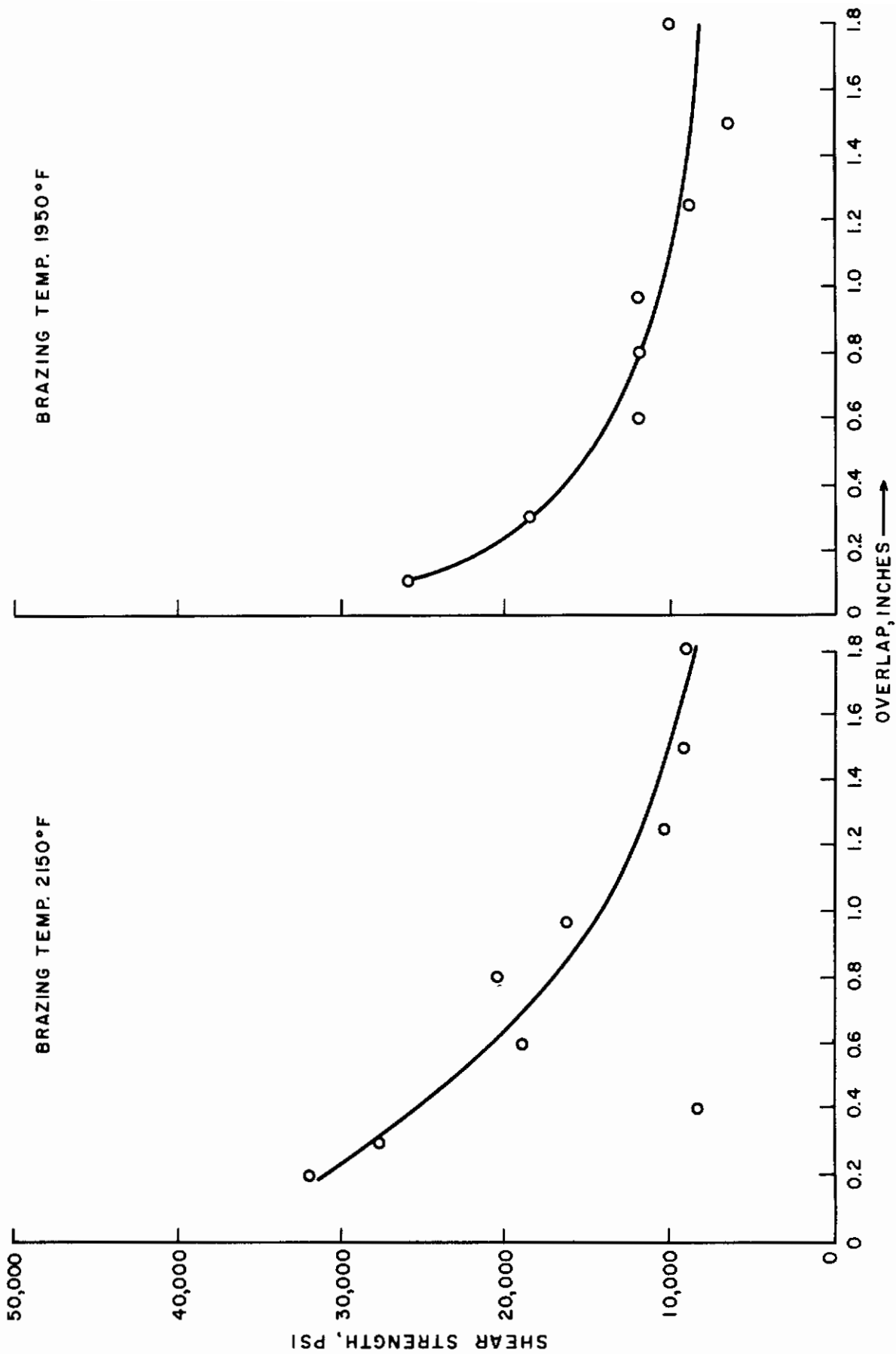


FIGURE 21. SHEAR STRENGTH AT ROOM TEMPERATURE VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY A.

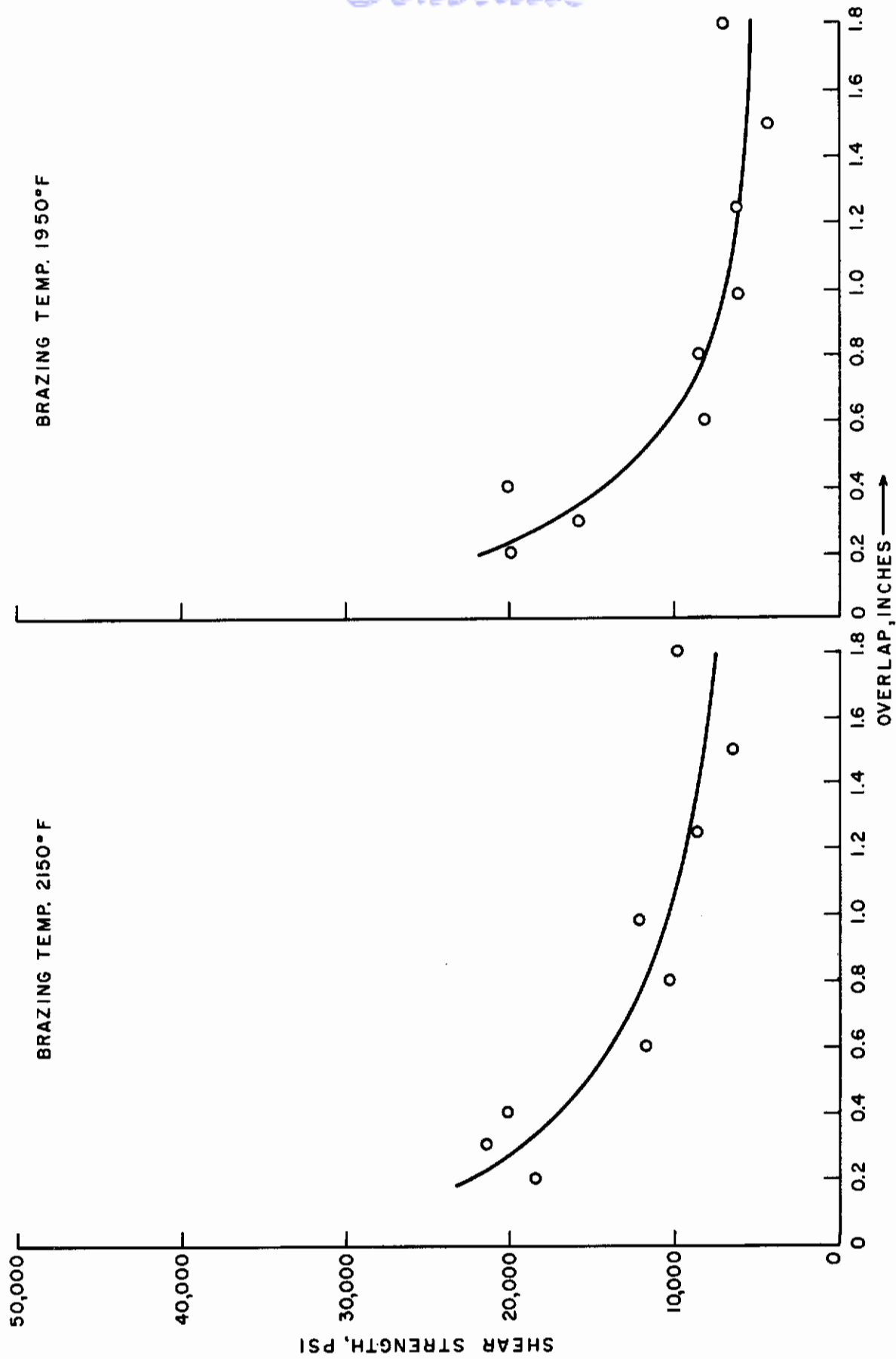


FIGURE 22. SHEAR STRENGTH AT 1000°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY A.

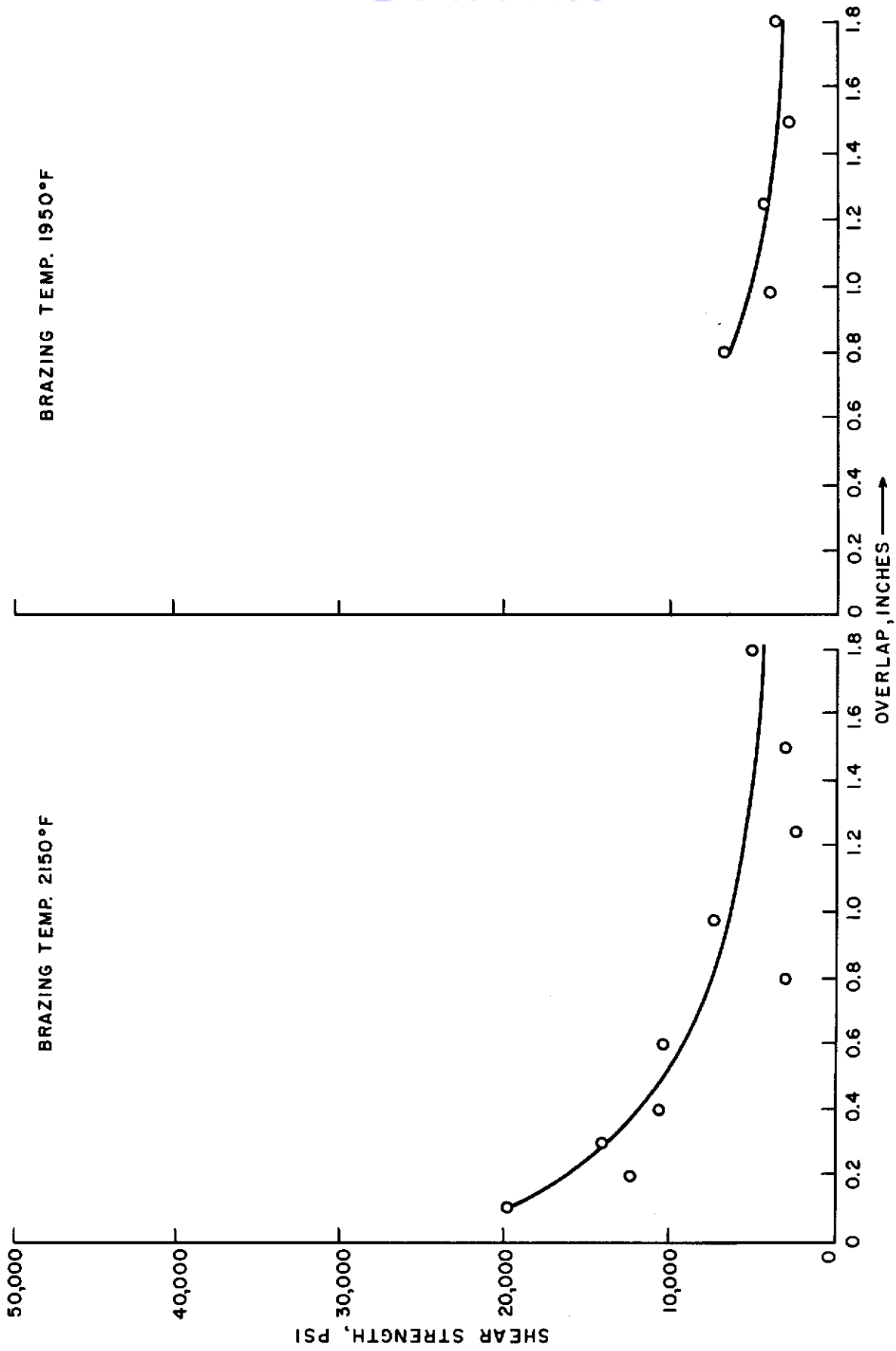


FIGURE 23. SHEAR STRENGTH AT 1300°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY A.

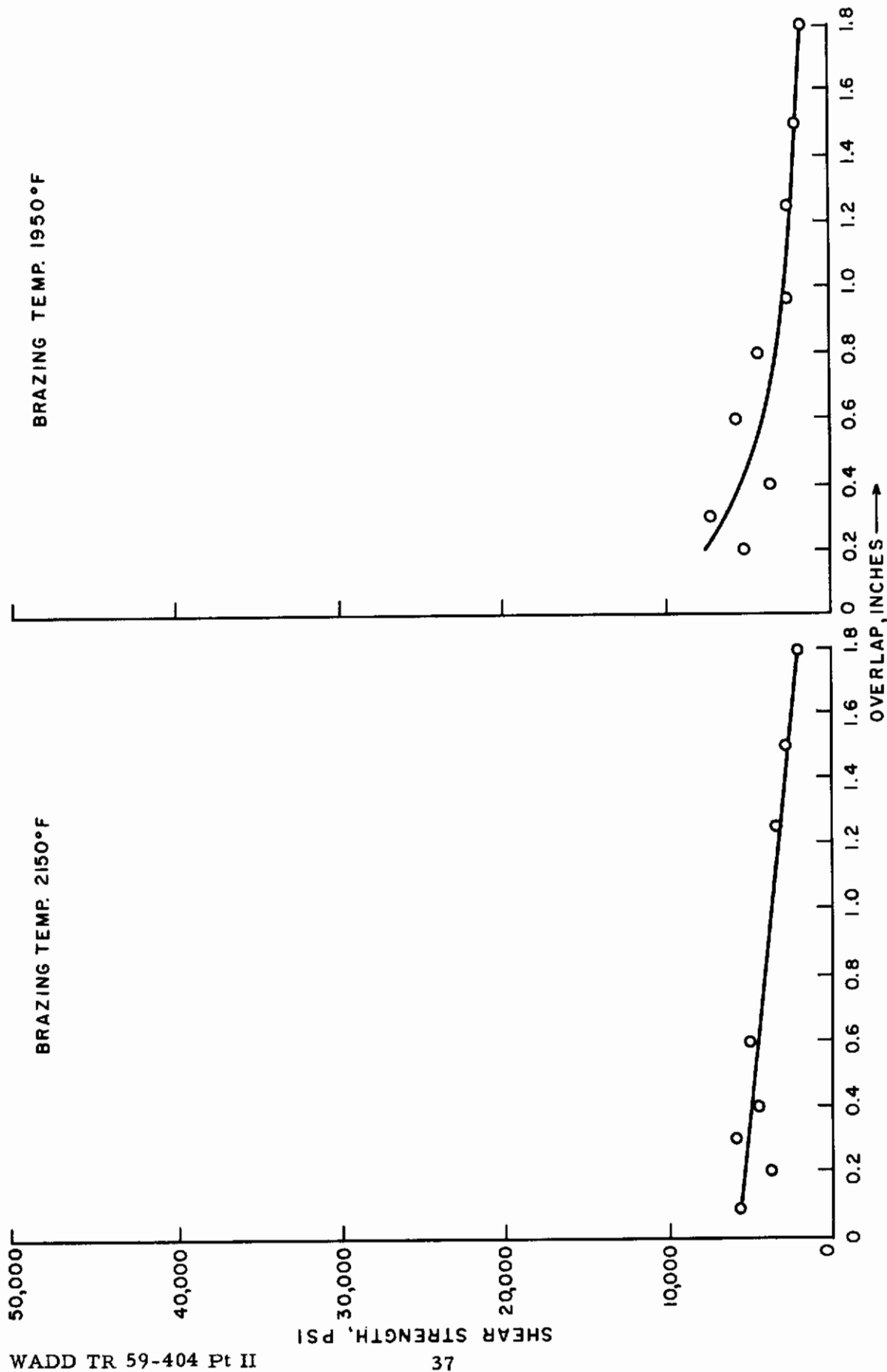


FIGURE 24. SHEAR STRENGTH AT 1600°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY A.

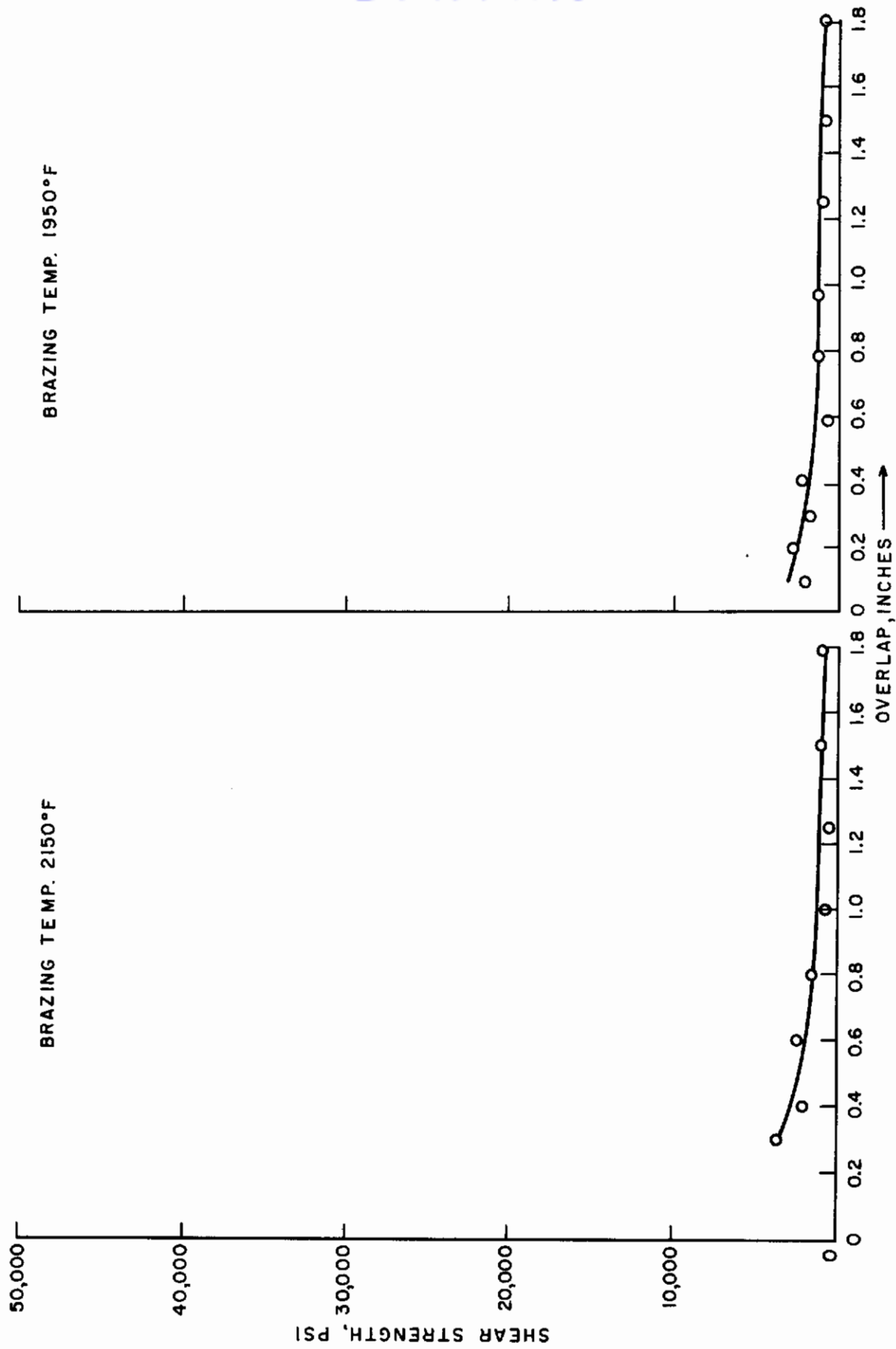


FIGURE 25. SHEAR STRENGTH AT 1900°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY A.

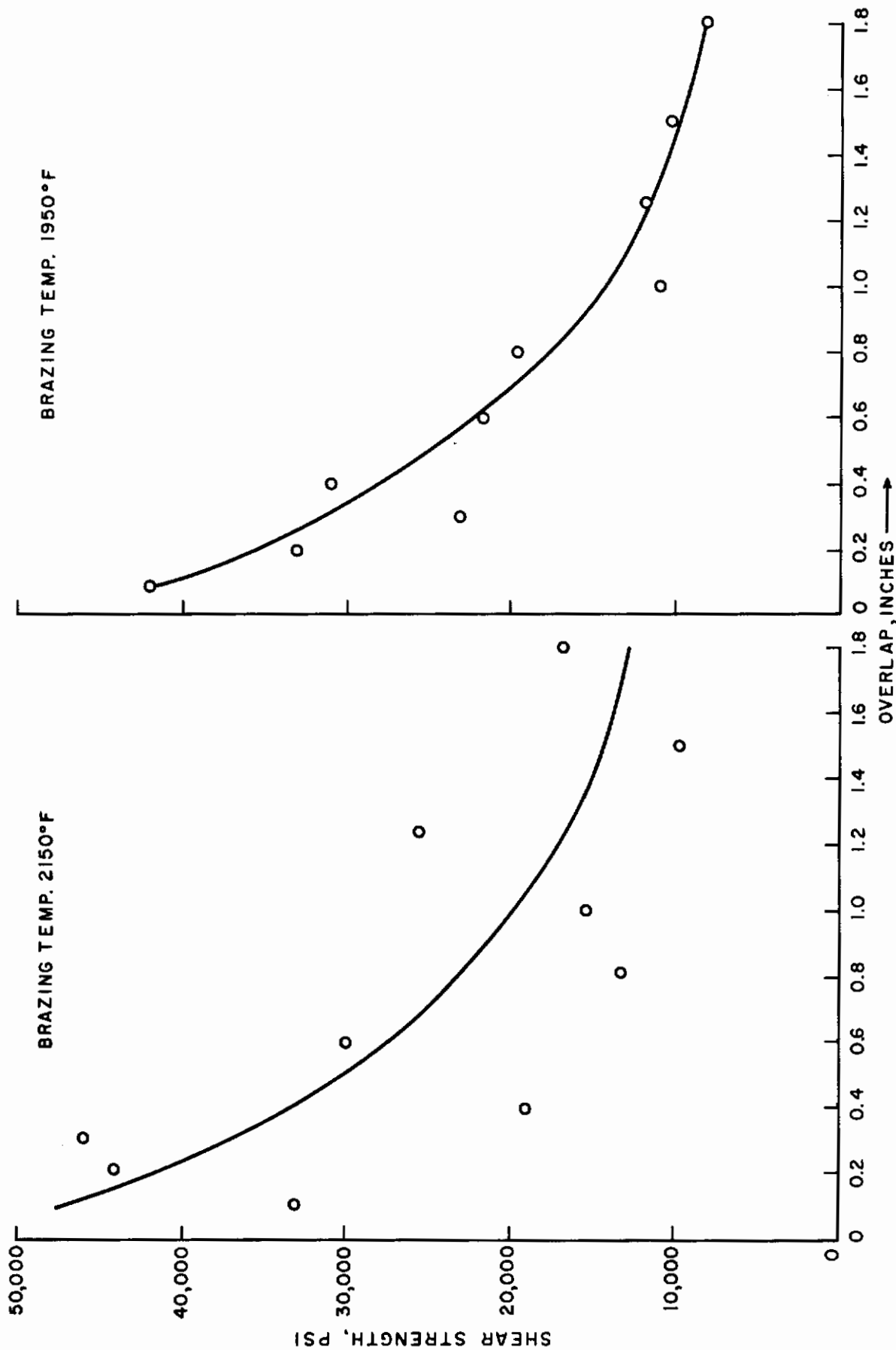


FIGURE 26. SHEAR STRENGTH AT ROOM TEMPERATURE VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY C.

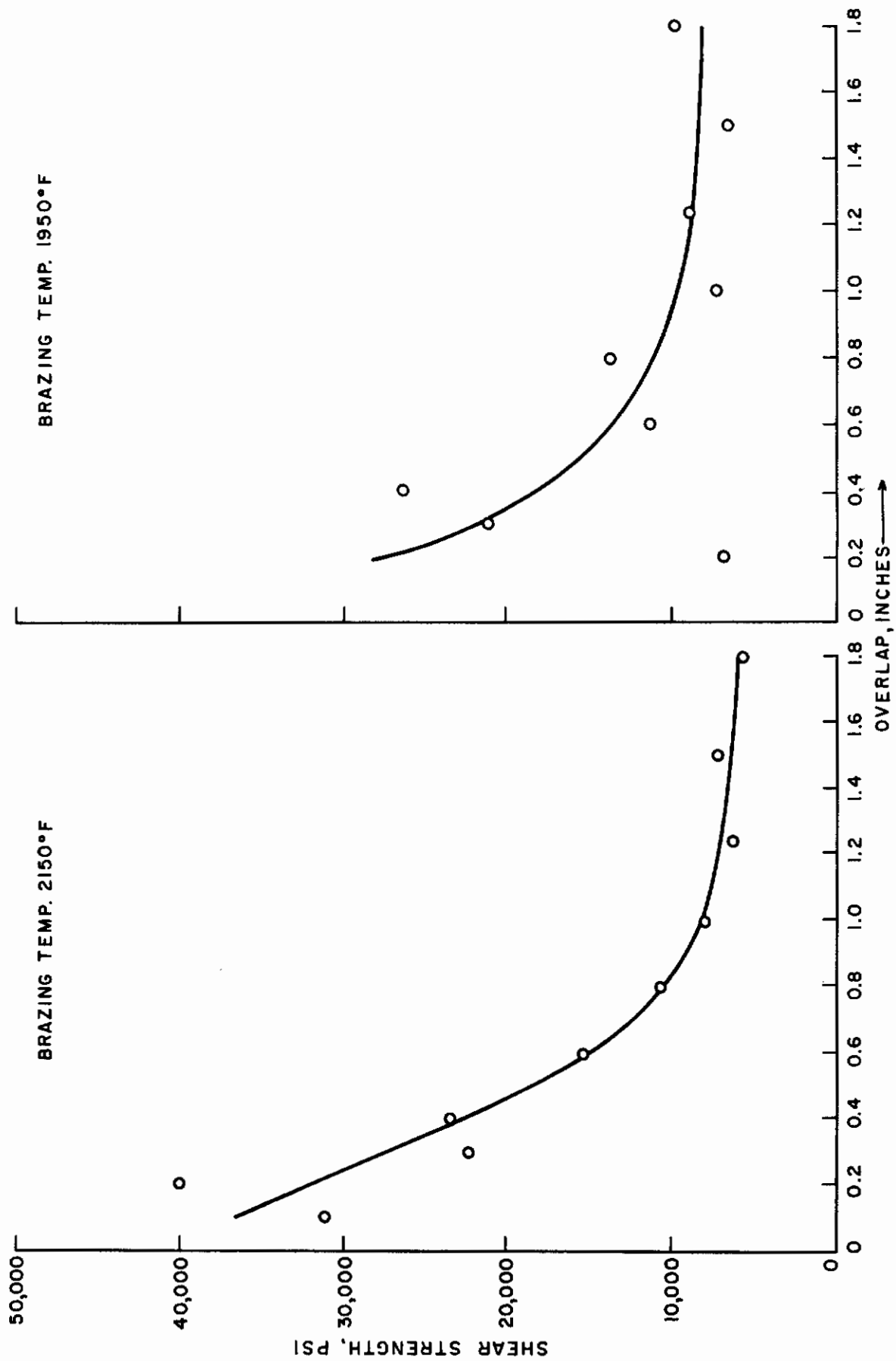


FIGURE 27. SHEAR STRENGTH AT 1000°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY C.

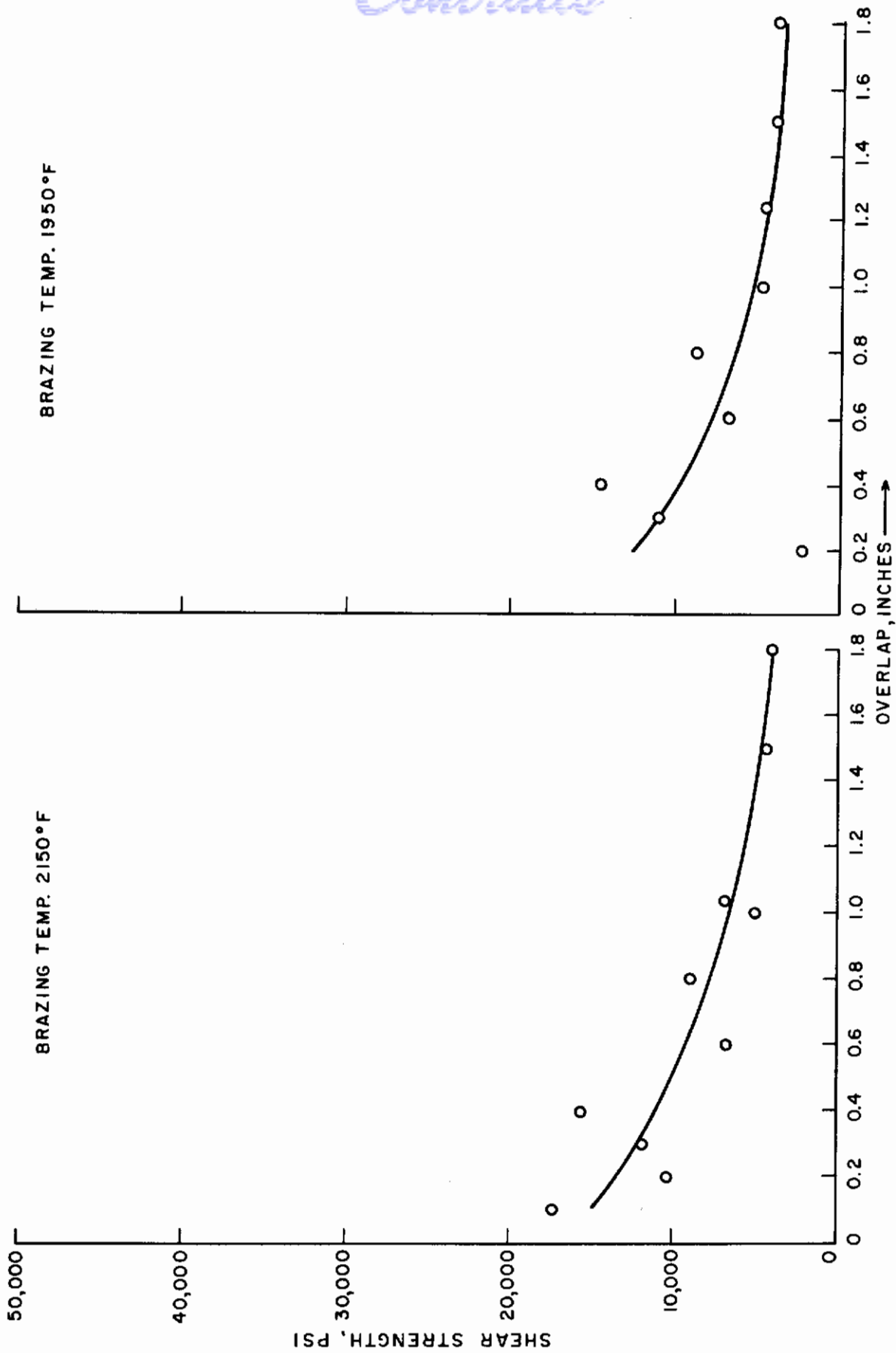


FIGURE 28. SHEAR STRENGTH AT 1300°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY C.

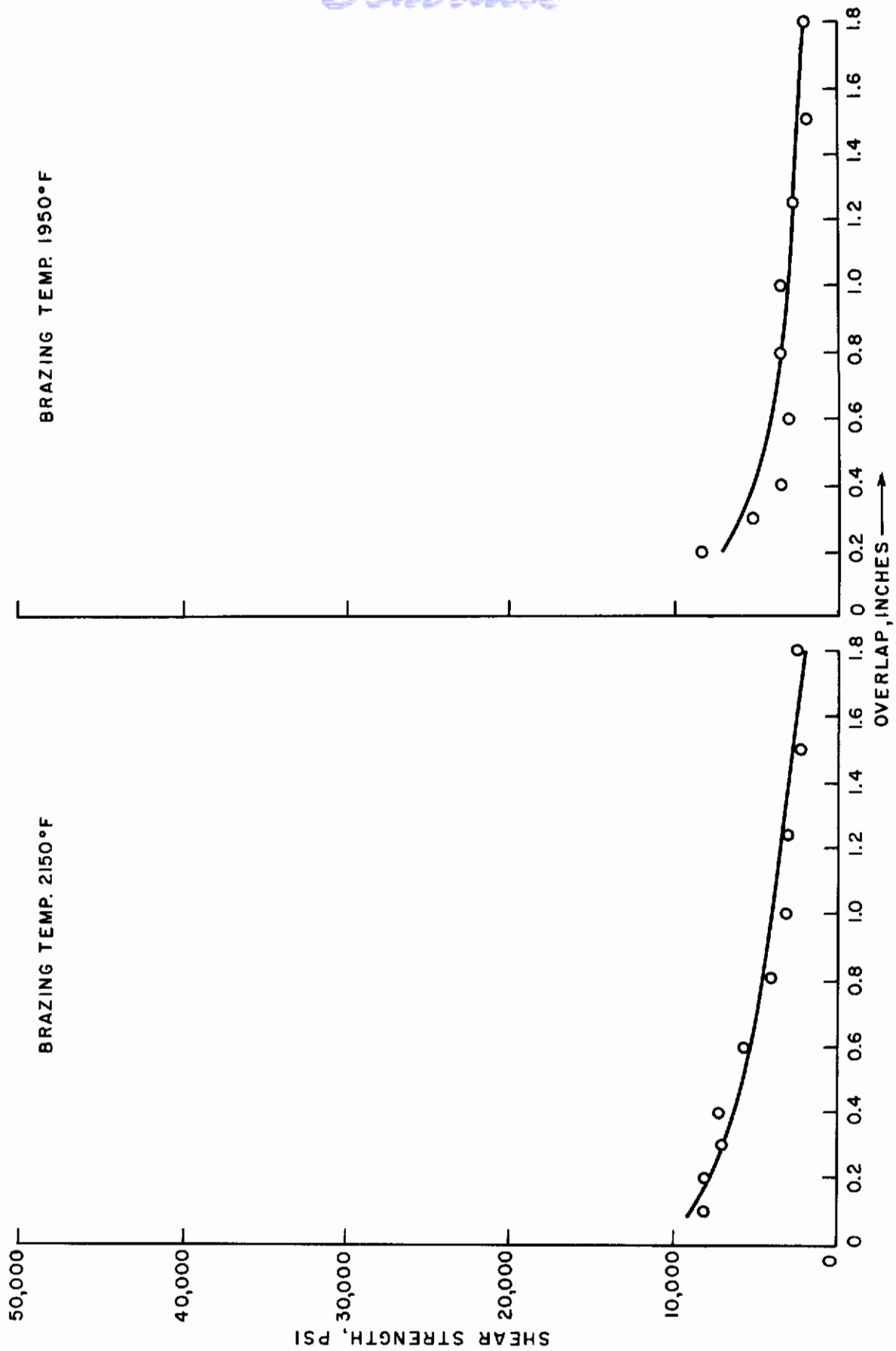


FIGURE 29. SHEAR STRENGTH AT 1600°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY C.

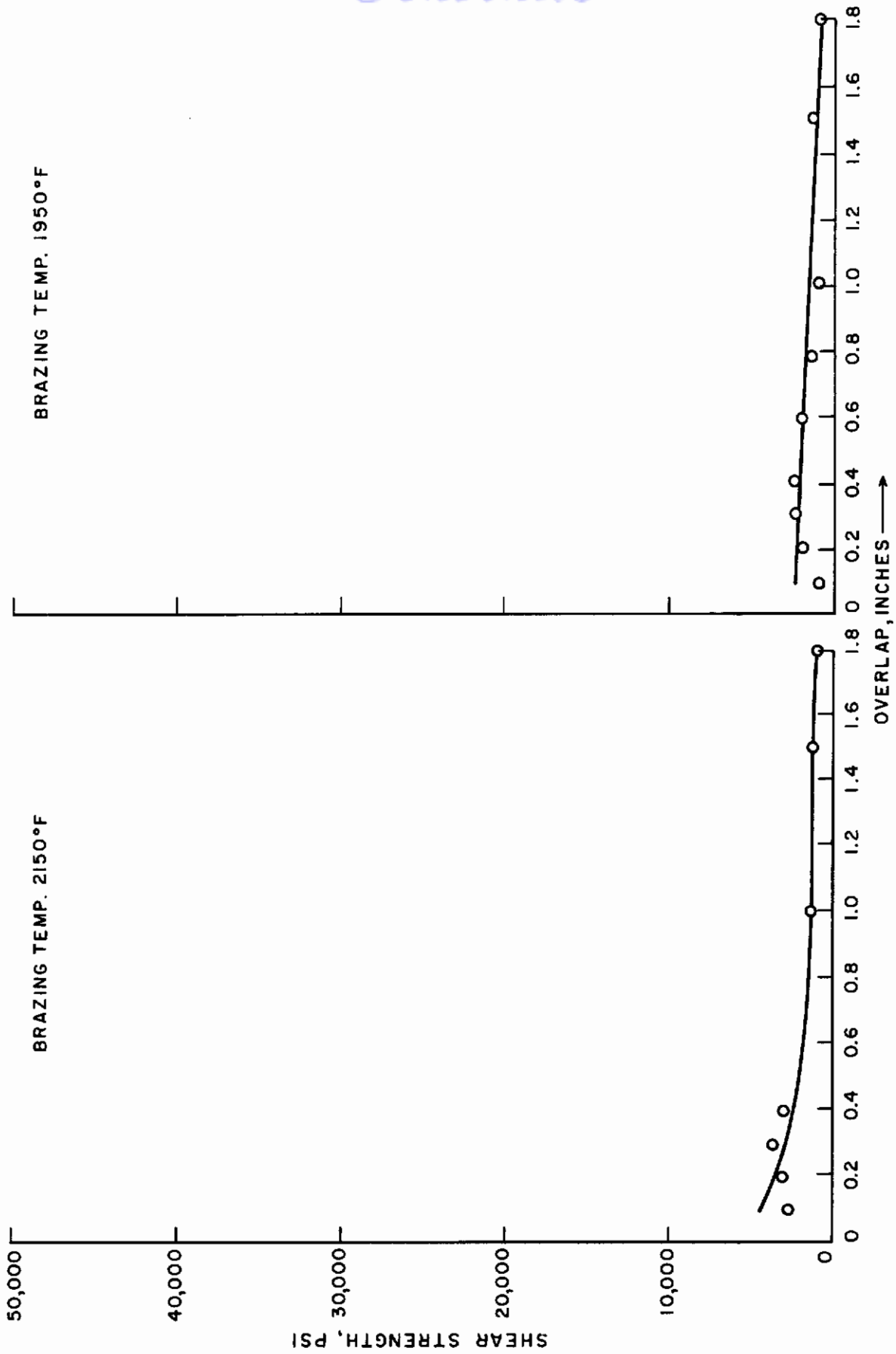


FIGURE 30. SHEAR STRENGTH AT 1900°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY C.

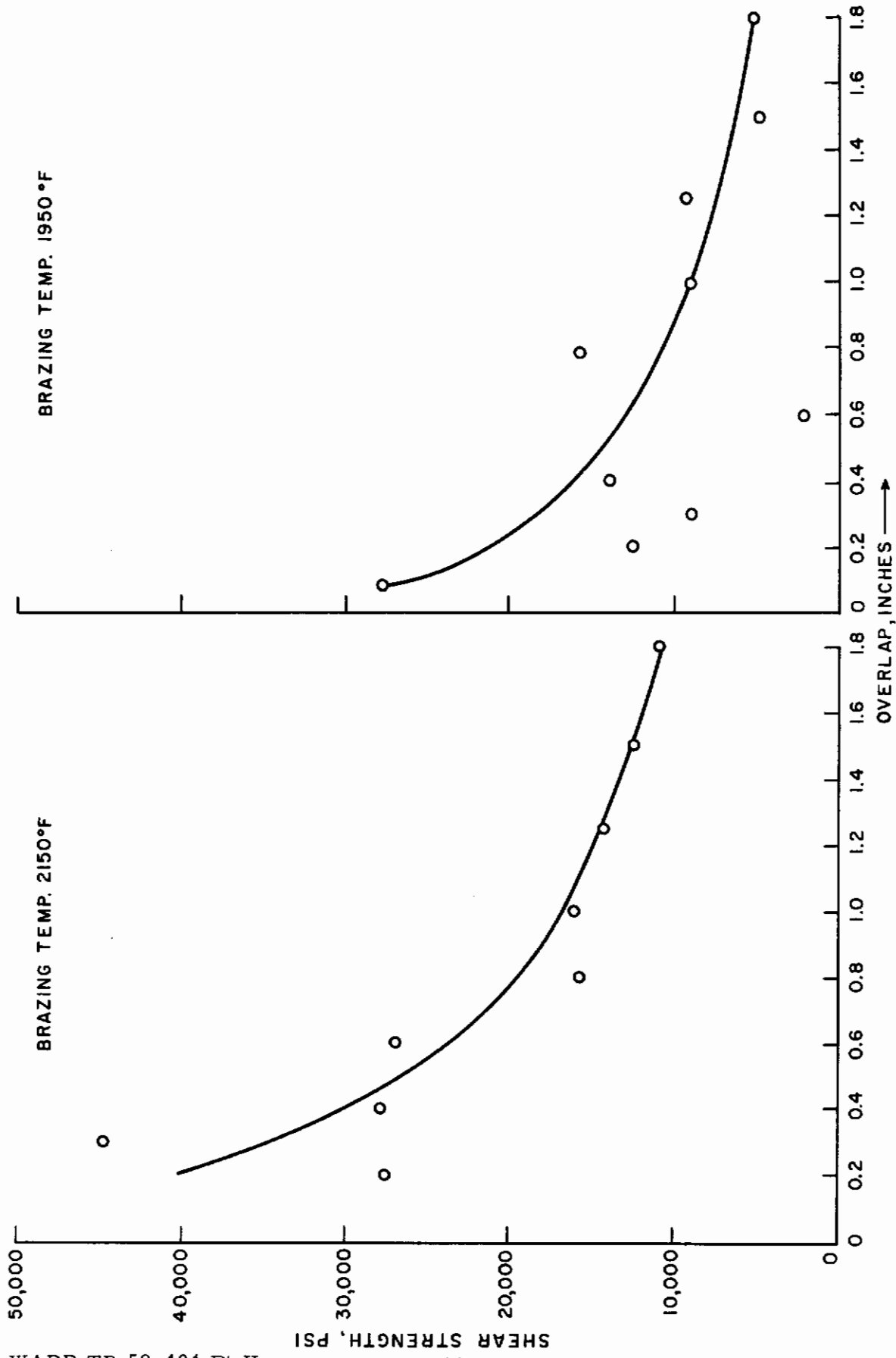


FIGURE 31. SHEAR STRENGTH AT ROOM TEMPERATURE VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY I.

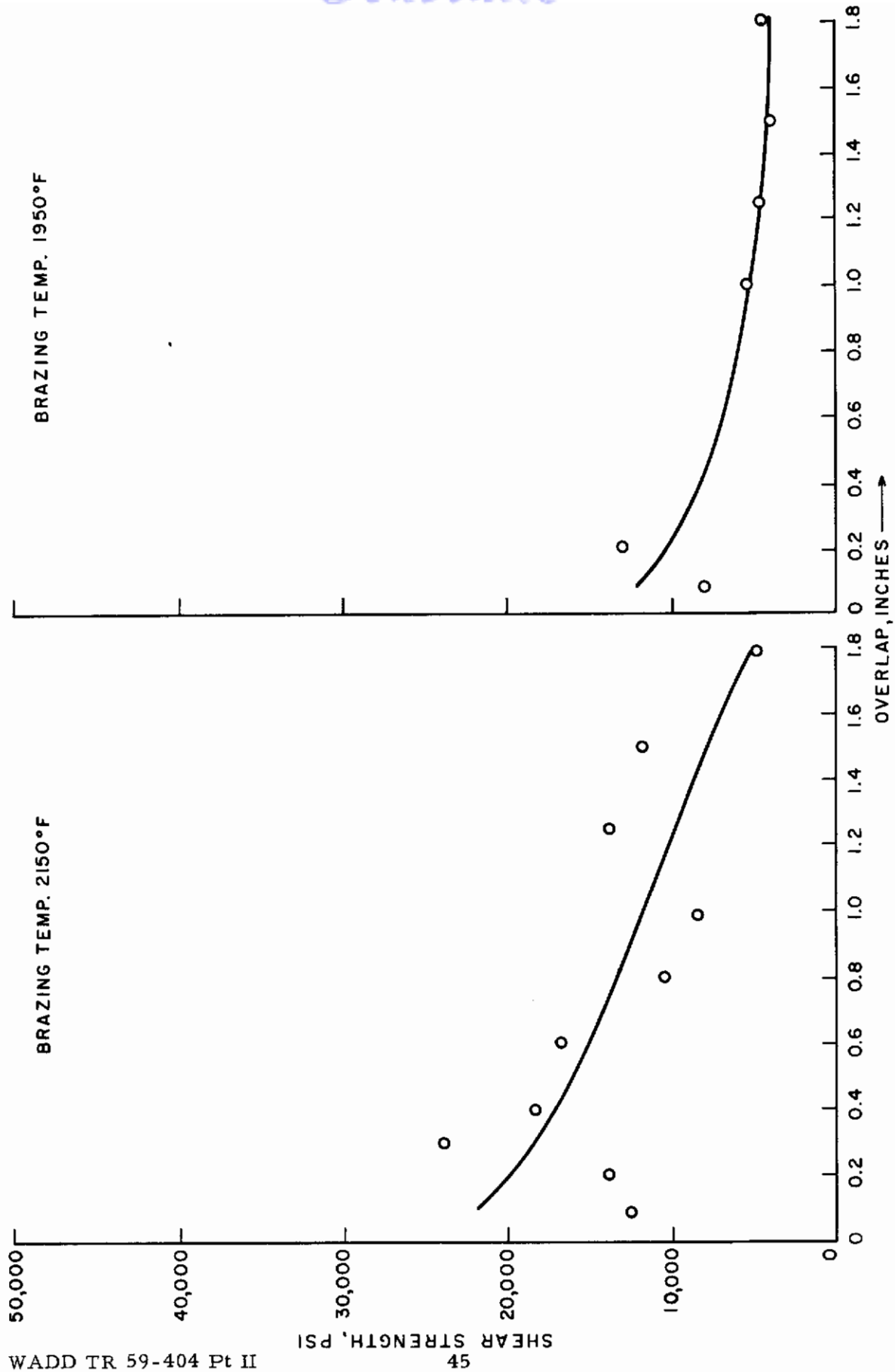


FIGURE 32. SHEAR STRENGTH AT 1000°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY I.

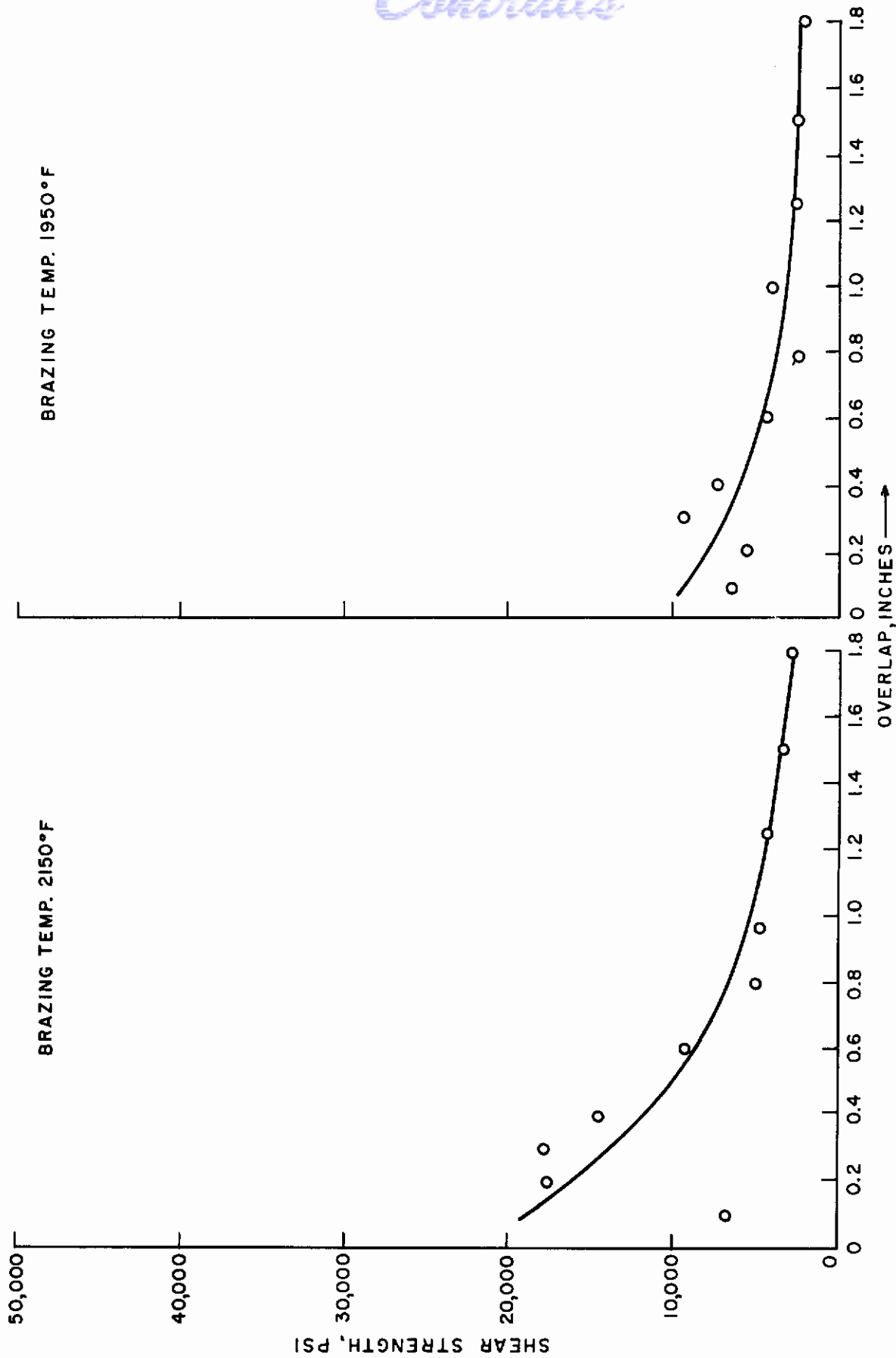


FIGURE 33. SHEAR STRENGTH AT 1300°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY I.

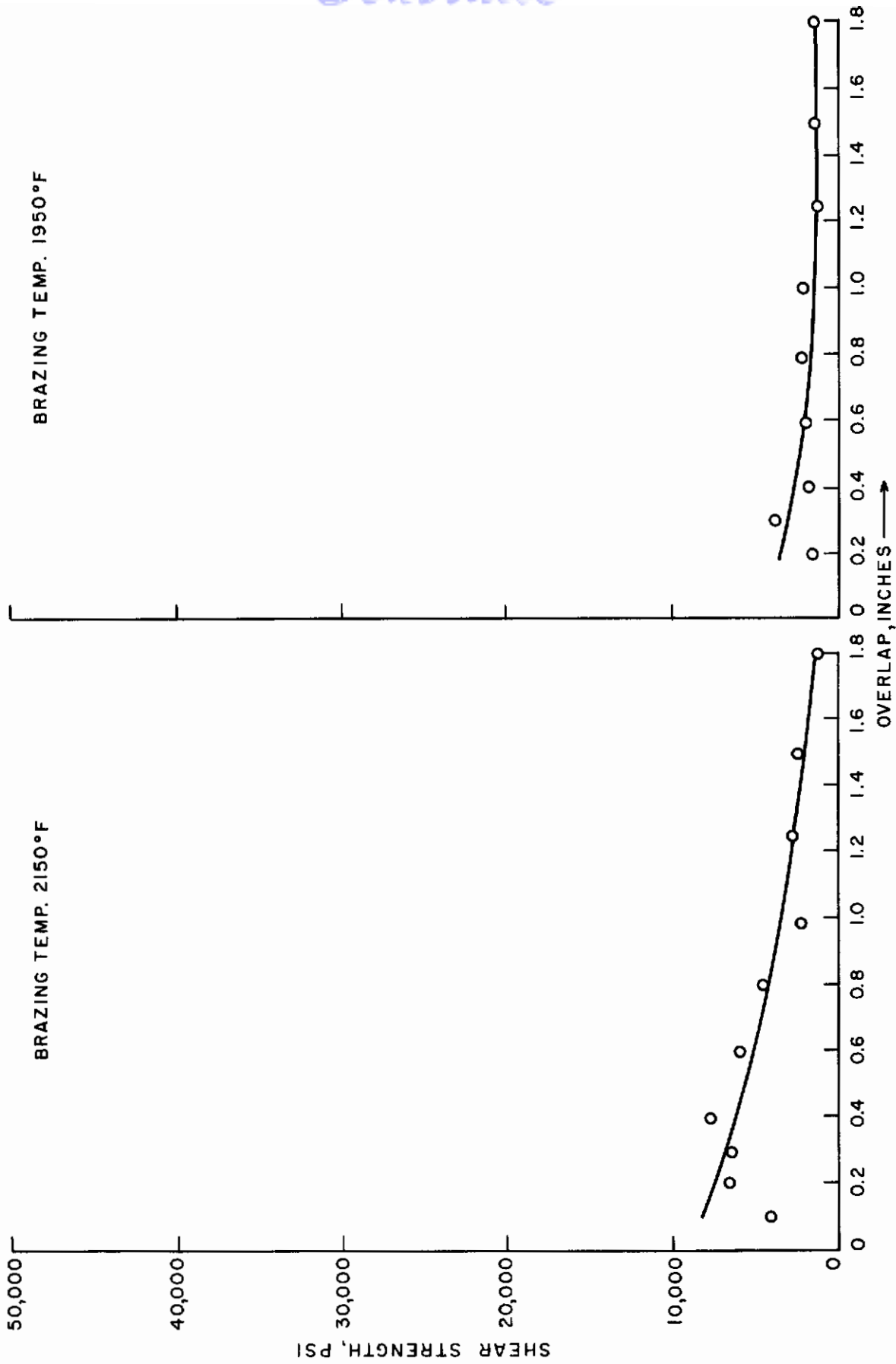


FIGURE 34. SHEAR STRENGTH AT 1600°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY I.

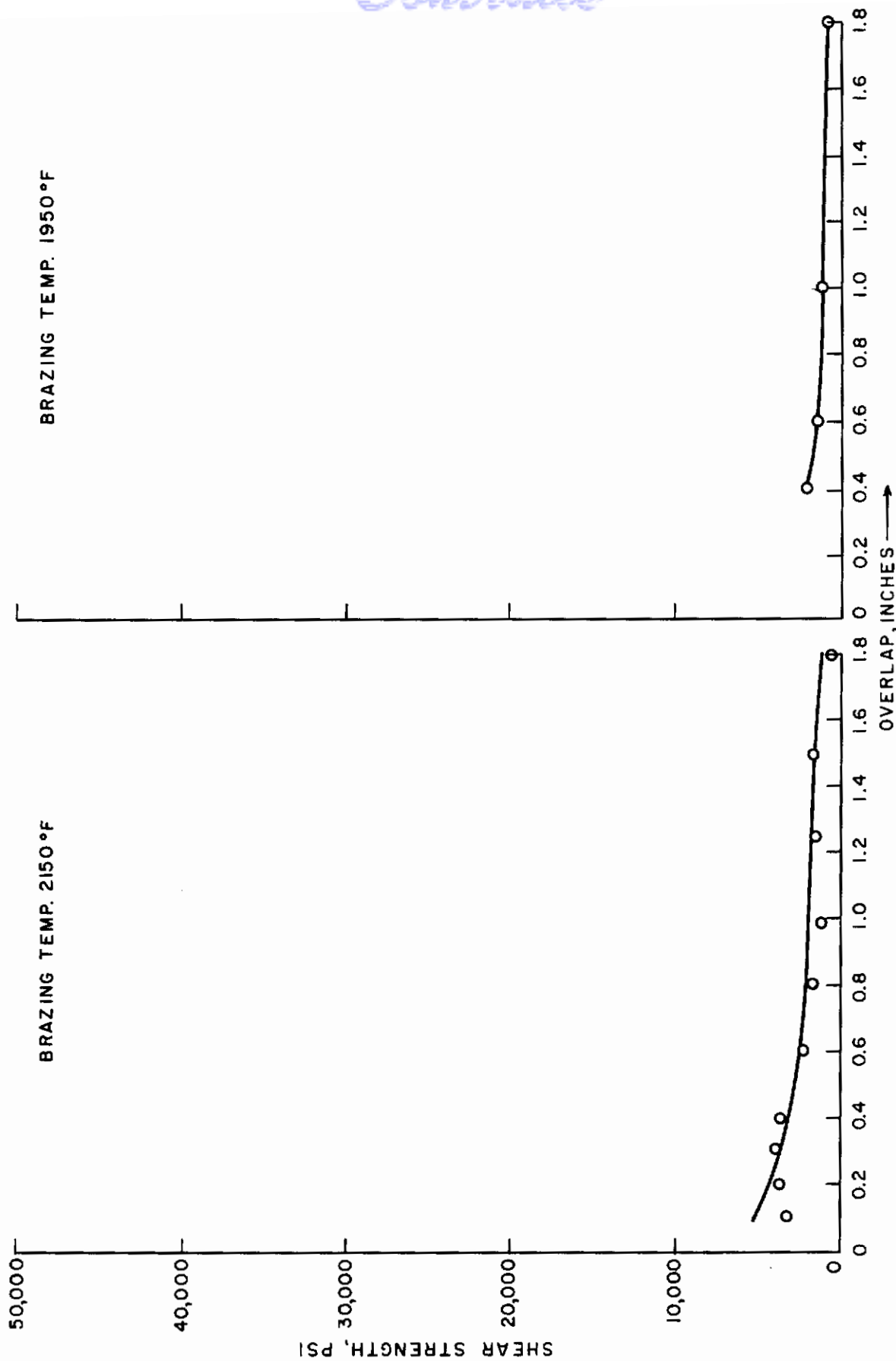


FIGURE 35. SHEAR STRENGTH AT 1900°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY I.

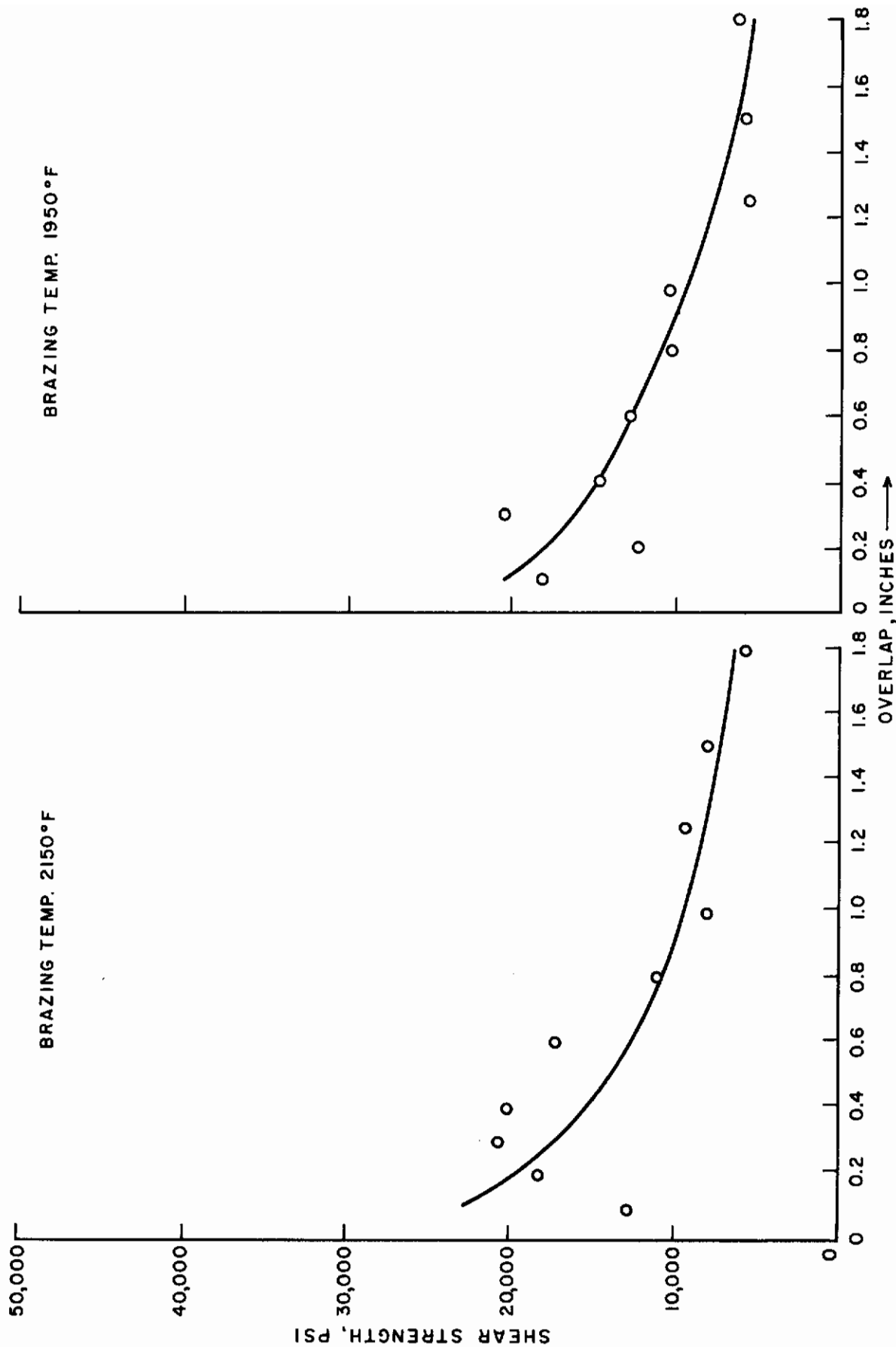


FIGURE 36. SHEAR STRENGTH AT ROOM TEMPERATURE VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY N.

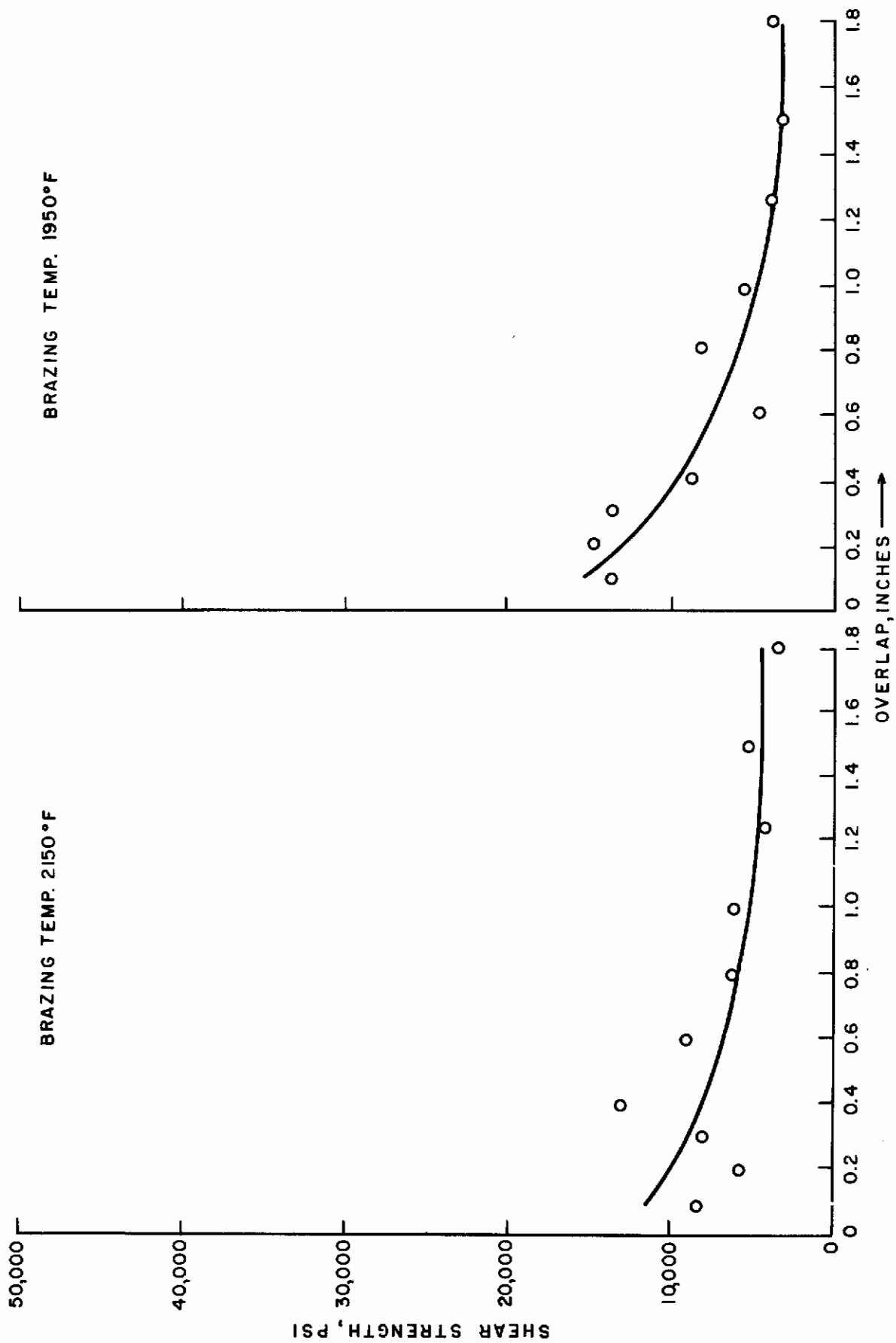


FIGURE 37. SHEAR STRENGTH AT 1000°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY N.

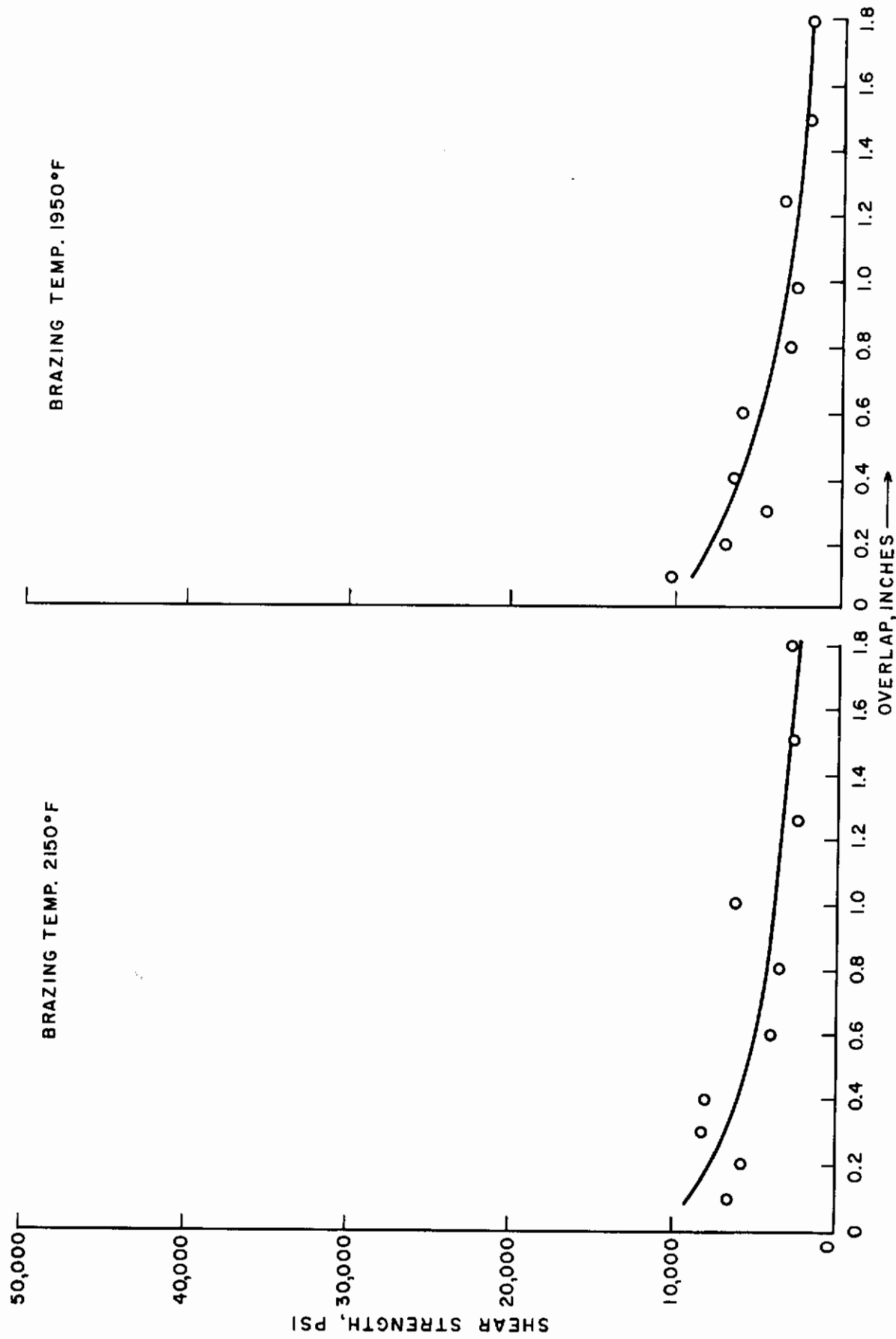


FIGURE 38. SHEAR STRENGTH AT 1300°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY N.

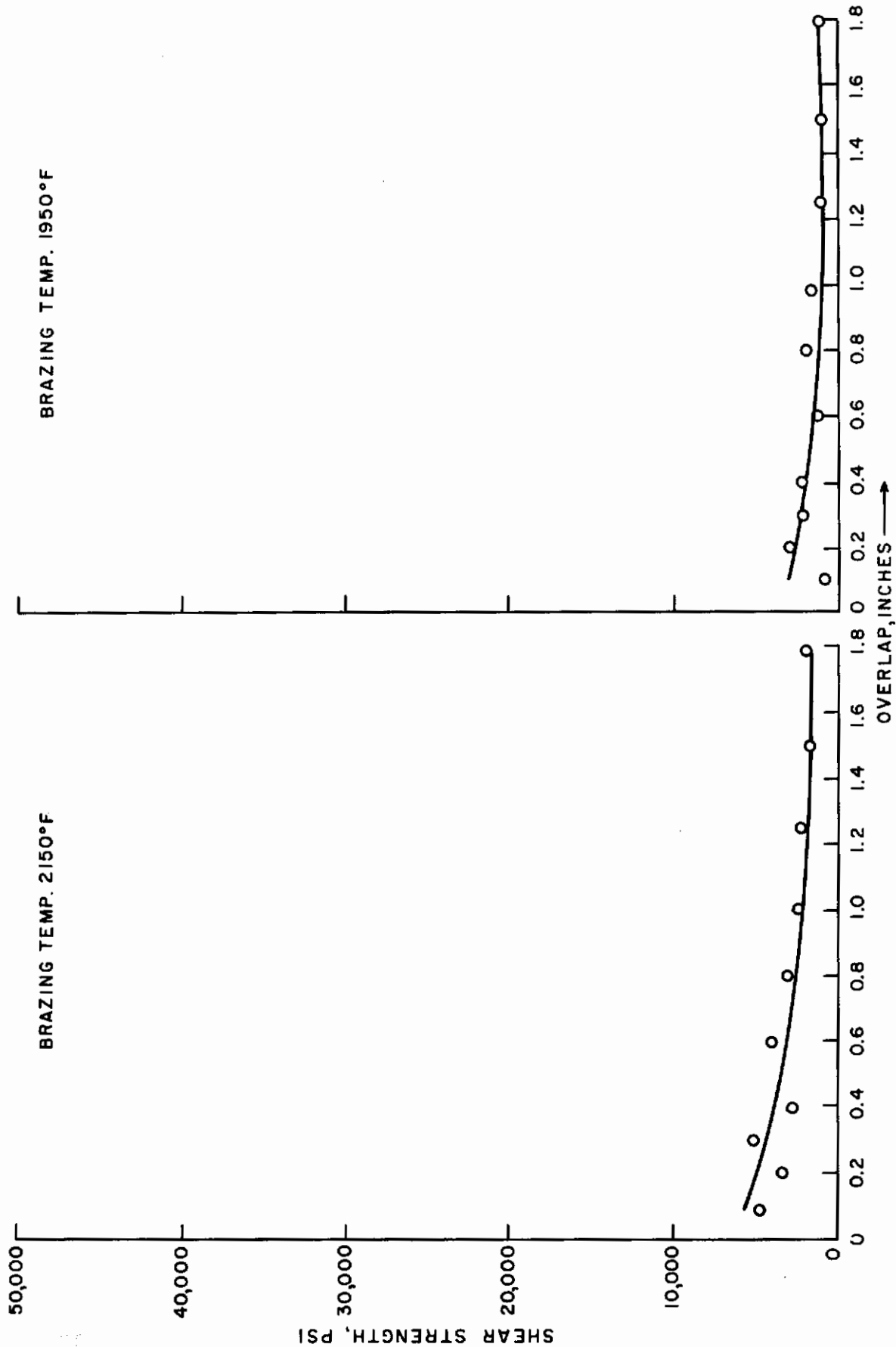


FIGURE 39. SHEAR STRENGTH AT 1600°F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY N.

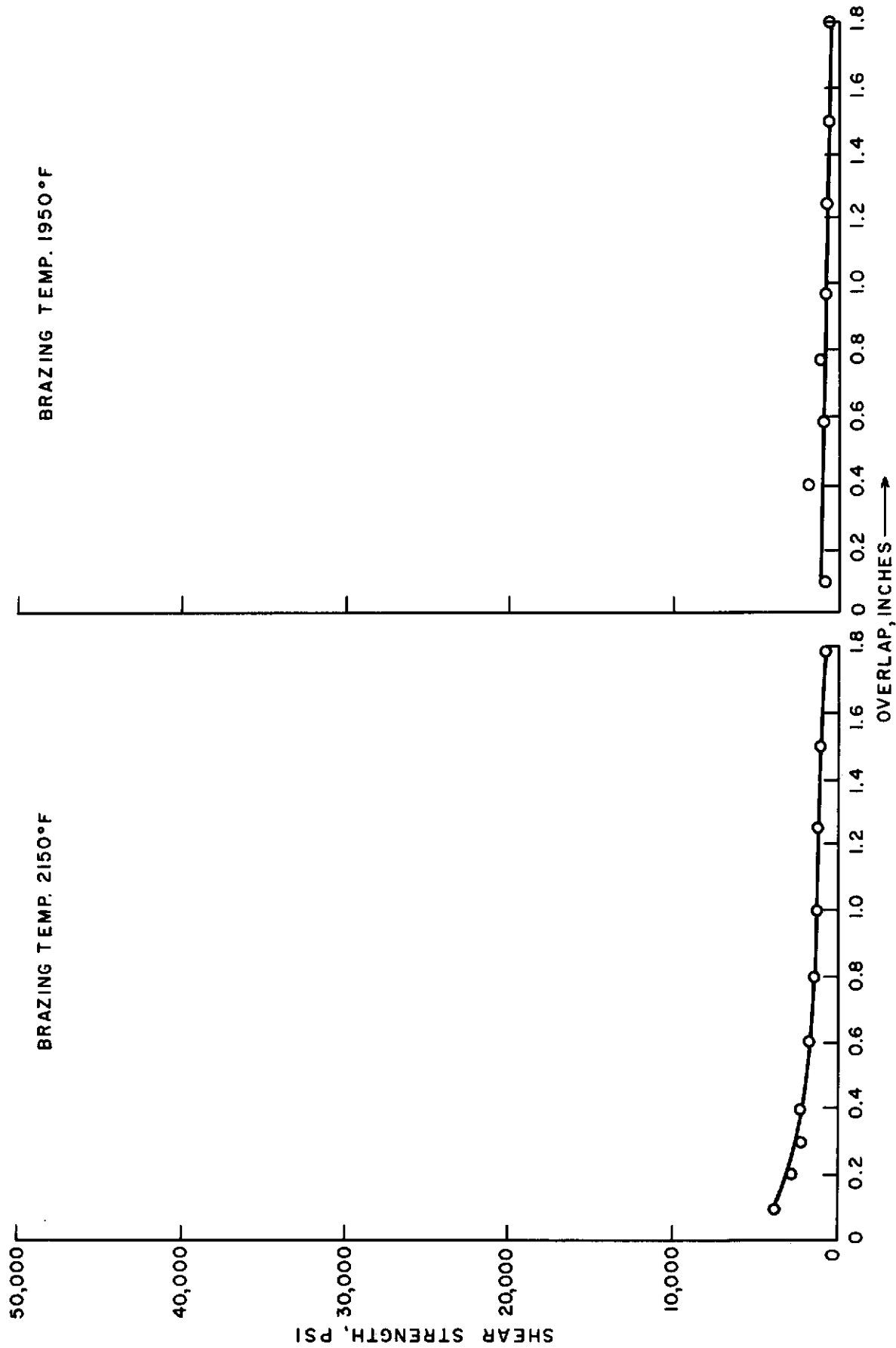


FIGURE 40. SHEAR STRENGTH AT 1900 °F VERSUS OVERLAP DISTANCE FOR JOINTS BRAZED WITH ALLOY N.

Contrails