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DEVELOPMENT OF TECHNIQUES FOR CONTROLLING WARPAGE AND RESIDUAL STRESSES IN WELDED STRUCTURES

Prepared under Contract No. NAS 8-21174 by
Donald Q. Cole

HARVEY ENGINEERING LABORATORIES

For

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

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ABSTRACT

This document is the final report of a series of experimental studies performed to determine the feasibility of alleviating warpage and residual stresses in welded aluminum structures applicable to the Saturn program. The studies were performed by altering the thermal pattern during the welding operation using local applications of cryogenic liquids and auxiliary heat to counterbalance thermal stresses produced by welding. Results of the work have definitely demonstrated that such control is possible. For some welded samples, warpage has been reduced to zero, and residual stresses have been reduced to values as low as 5 percent of those present in conventionally welded samples. Sufficient data has not yet been accumulated for establishing optimum thermal patterns for specific weldments, but it is indicated that such patterns can be established empirically in relatively short time.

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I. INTRODUCTION AND SUMMARY

Distortion and high residual stresses caused by welding of Saturn V booster tanks are serious problems. Either condition could result in stress concentrations and cause premature failure of the structure, especially when flaws are present and the structure is stressed in low temperature environments. When normal welding techniques are used, both distortion and high residual stresses are probable.

The objective of this project was to determine the feasibility of applying a new and novel technique proposed by Harvey Aluminum for controlling both distortion and residual stresses in aluminum weldments typical of those in the Saturn V booster tanks. The concept involves the use of cryogenic liquids and auxiliary heat sources to produce contraction and expansion of metal in the vicinity of the weld in such a manner as to counterbalance expansion and contraction caused by welding. By properly altering the thermal pattern of the weldment, it will be possible to control warpage and residual stresses.

Work performed under Contract NAS8-11930 during 1966 and 1967 indicated that the tensile strength of welds in 2219-T87 and 2014-T6 plate can be increased approximately 10 percent by using liquid carbon dioxide to extract heat to shorten the time-temperature cycle for the weldment. It was also observed that warpage appeared to be reduced as compared to unchilled welds.

In the initial phase of the current contract, an analytical study was performed to establish a theoretical thermal pattern which would counterbalance expansion and contraction due to welding. This selected target thermal pattern consisted of confining the heated portion of the plate to a 2-inch diameter circle around the welding torch with a surrounding 8-inch diameter ring at a temperature of approximately -100 deg. F.

The experimental portion of the program was performed in two phases. The first phase consisted of tests on small samples to determine basic data on the feasibility of counterbalancing weld expansion and contraction by using liquid cryogenics. This work produced definite evidence that such counterbalancing is possible thus verifying the fundamental concept. The second phase consisted of development of beneficial thermal patterns in 12 x 48 x 5/16-inch 2014-T6 welded panels by application of the concept. Results of this work demonstrated conclusively that the concept can be successfully applied for controlling warpage and residual stresses in larger weldments. Some patterns actually reversed the normal warpage while other patterns reduced residual tensile stresses to less than five percent of those present in conventionally welded panels.

In order to apply the concept to specific hardware, it is recommended that further work be performed on simulated parts.

The author wishes to acknowledge the significant technical assistance afforded throughout the program by Harvey Engineering Laboratories Director, Mr. P.E. Anderson, and Research Administrator, Mr. L.W. Davis. Also, appreciation is expressed to Mr. A.H. Malinovszky for important laboratory work, to Messrs. J.R. Johnson and M.R. Ransom for instrumentation, and to Mr. A.J. Goulding for assistance in preparing this report.

II. PROGRAM OBJECTIVE

The objective of the program was to demonstrate the feasibility of controlling warpage and residual stresses in aluminum weldments by altering the thermal pattern of the weldment during the welding process. It was proposed that alteration of the thermal pattern be accomplished by using local application of liquid carbon dioxide in the vicinity of the weld with the addition of auxiliary heat, if necessary, to cause sufficient contraction and expansion in material adjacent to the weld to counterbalance the expansion and shrinkage normally produced during welding. It was also proposed that the welding be accomplished by techniques similar to those used for welding the aluminum tankage for Saturn V.

III. PROGRAM PLAN

The program consisted of four principal tasks: (1) an analytical study to determine theoretically beneficial thermal patterns, (2) set-up of equipment and instrumentation, (3) development of basic experimental data, and (4) development of controls for warpage and residual stresses.

The analytical study was completed during the first program month. Performance of the other three tasks was delayed approximately two months due to unexpected difficulties in obtaining materials and execution of instrumentation for measuring thermal patterns during welding.

Four major systems for changing the thermal pattern of the weld, with a total of thirty variations of these systems, were experimentally investigated during the course of the program. One hundred 12 x 48-inch weld panels were produced. Approximately 20 percent of these were unchilled; 45 percent were chilled from the front side; 20 percent were chilled from the back side, and 15 percent were chilled from the front side with the application of auxiliary heat. More than 50 panels were instrumented for measurement of temperature and warpage. Residual stresses were determined for 30 panels, requiring placement of over 200 strain gages and 100 trepanning or slicing operations. X-rays, macrosections and tensile tests were performed for 15 panels.

IV. ANALYTICAL STUDY

A study was made to establish mathematically the feasibility of accomplishing sufficient contraction and expansion of metal adjacent to the weld to counterbalance that produced by the welding operation. This study was concerned with heat extraction by means of liquid CO_2 to produce elastic deformation equivalent to the thermal expansion and contraction as well as the weld shrinkage (liquid-to-solid) which occurs during welding. The calculations were based on parameters observed during the performance of Contract NAS8-11930 for producing liquid CO_2 chilled weld panels 12 x 48 x 5/16-inch thick in 2014-T6 aluminum alloy.

Results of the mathematical study indicated that the thermal stresses would be counterbalanced if the portion of the plate heated by the arc could be contained within a 2-inch diameter circle with this circle surrounded by an area of approximately 45 square inches cooled to -100 deg. F. It was estimated that approximately 0.8-lb. of liquid CO_2 per inch of weld, in addition to that dissipated by the heat of welding in formation of the weld, would be required.

Calculations are shown in Appendix A.

V. DEVELOPMENT OF CONTROLS FOR WARPAGE AND RESIDUAL STRESSES

General

The experimental work to develop controls for warpage and residual stresses consisted of the following principal efforts: (1) procurement and preparation of materials, (2) set-up of welding equipment with instrumentation, (3) development of chilling systems and techniques, (4) development of techniques for measurement of temperatures and residual stresses, (5) development of basic data on thermal stresses, and (6) development of thermal patterns for controlling warpage and residual stresses.

Four major systems were developed for altering the thermal pattern during welding. All employed jet spraying of liquid CO_2 with or without the application of auxiliary heat. The basic systems included the following:

1. V-shaped cryogenic jet systems for cooling the front side of the weld.

2. Trailing cryogenic jet systems for cooling the front side of the weld.

3. Circular cryogenic jet systems for cooling the back side of the weld.

4. Auxiliary heating with trailing cryogenic jet systems for cooling the front side of the weld.

Results of this work conclusively demonstrated the feasibility of controlling warpage and residual stress by altering the thermal pattern of the weldment during the welding process. By application of combinations of chilling with auxiliary heating, it was possible to reverse normal warpage which indicated that with the optimum thermal pattern, warpage can be eliminated. Combined chilling and auxiliary heating also reduced residual stresses by as much as 95 percent. Tensile tests indicated that strength was not impaired by altering the thermal patterns; in fact, it may actually be improved.

The following paragraphs describe the experimental procedures used and the results obtained:

Experimental Procedure

Material

Aluminum plate.- All plate material used for experimental welding consisted of 5/16-in. thick 2014-T651 aluminum plate. This plate was cut into 6 x 48-in. pieces with both edges machined straight and square within a tolerance of ± 0.010-in. with 60 rms finish. Immediately preceding welding, the plates were chemically cleaned using standard practices adopted by the aerospace industry, and the mating edges were mechanically scraped to remove remaining contaminants.

Welding wire.- Aluminum alloy 2319 welding wire of 3/64-in. diameter was used for all welding. This wire was level-wound on standard spools and specially packaged to prevent oxidation during storage.

Liquid carbon dioxide.- Liquid carbon dioxide was received in 250-lb. tanks under pressure of approximately 300 psig.

Helium.- Welding grade helium was used for all welding operations.

Welding Equipment and Instrumentation.- Equipment for performing the welding operation consisted of a 600/1200 amp. d-c rectifier with imposed high frequency. Straight polarity was used for all welding. The fixture for welding in the horizontal position is adjustable for alignment and is suitable for imposing low and high degrees of restraint. Figure 1 shows the welding fixture with accessories in operation for application of liquid CO_2 during welding.

Principal instrumentation consisted of the following: (1) voltmeter and ammeter for measuring welding current, (2) platinum resistance thermometers with 6-channel recorder

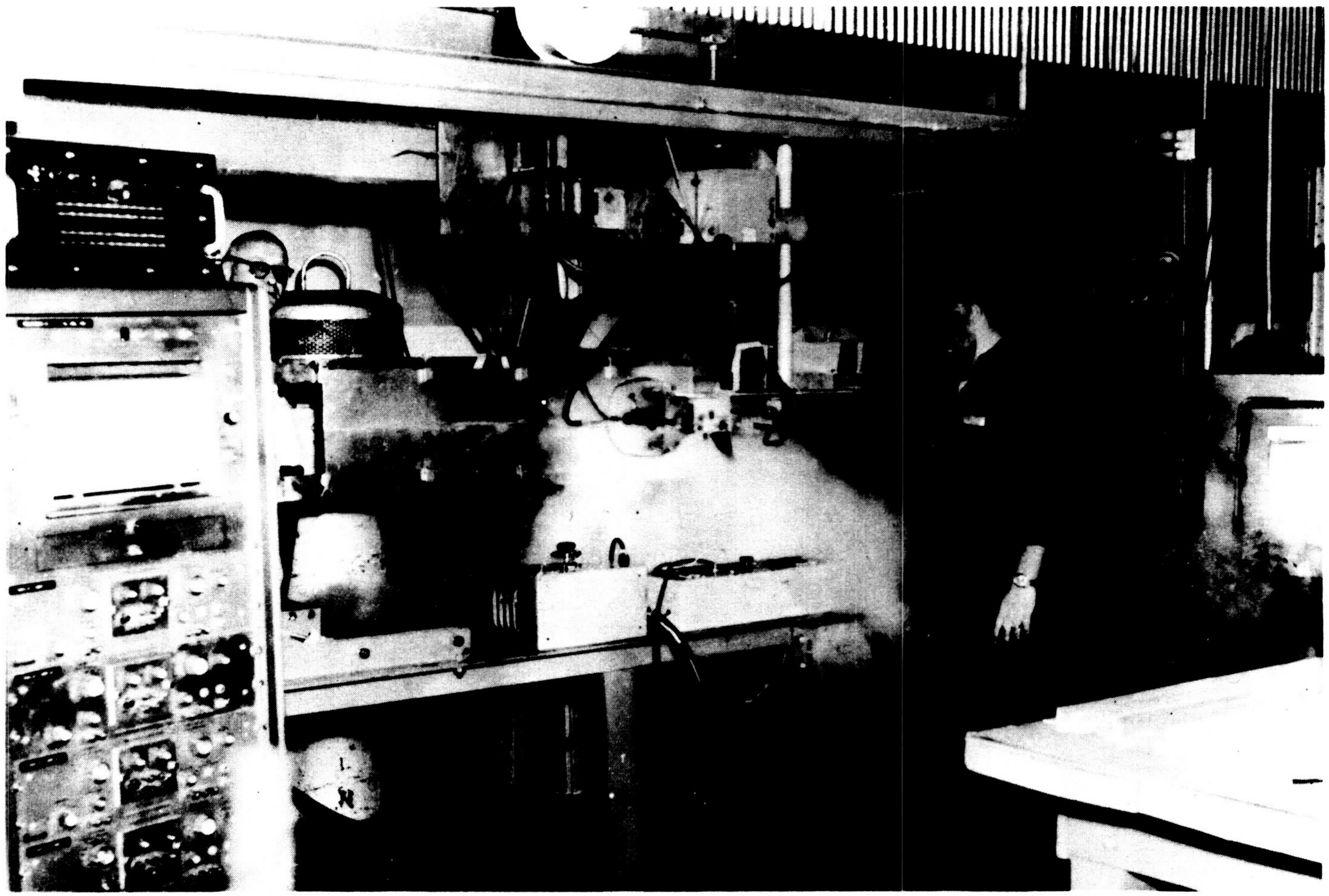


Figure 1. **Using Cryogenic Liquids to Control Thermal Stresses During Welding**

for measuring temperatures (figure 2), (3) dial micrometers for measuring deflection, (4) platform scales for measuring liquid CO_2 usage, and (5) wire or foil strain gages with strain indicator for measuring residual stresses.

Details concerning equipment and instrumentation are contained in Appendix B.

Chilling Systems.- Three types of chilling systems were devised during the course of the program. A V-shaped system was designed to concentrate the chilling around the welding torch on the front side of the panel. A circular system was designed for concentrating the chilling around the molten puddle on the back side of the panel. A trailing system was designed for use on the front side (but could be used on either side) with the chilling at various distances behind the welding torch. As shown in Appendix II, thirty variations of these systems were used during the experimental welding program.

V-shaped chilling systems.- This system is illustrated in Figures 3 and 4. As can be seen in the bottom views, the single manifold is fitted with 14 jet-nozzles, and the double manifold contains a total of 34 jet-nozzles. Each of these nozzles can be positioned to direct the CO_2 jet as desired. For varying the chilling pattern, nozzles of various orifice sizes are easily interchangeable or the nozzle may be plugged. Height of the nozzles above the weld panel surface is also adjustable. It is extremely important that CO_2 be prevented from entering the atmosphere surrounding the arc as CO_2 in the welding arc causes severe voltage fluctuations and contamination of the weld. For this purpose, a double seal, consisting of stainless steel-wool supported by a fine stainless steel brush, was used.

NOTE

For purpose of illustration, the photographs used for Figure 4 have been rotated to the flat welding position; however, the horizontal position was used for the actual panel welding operation.

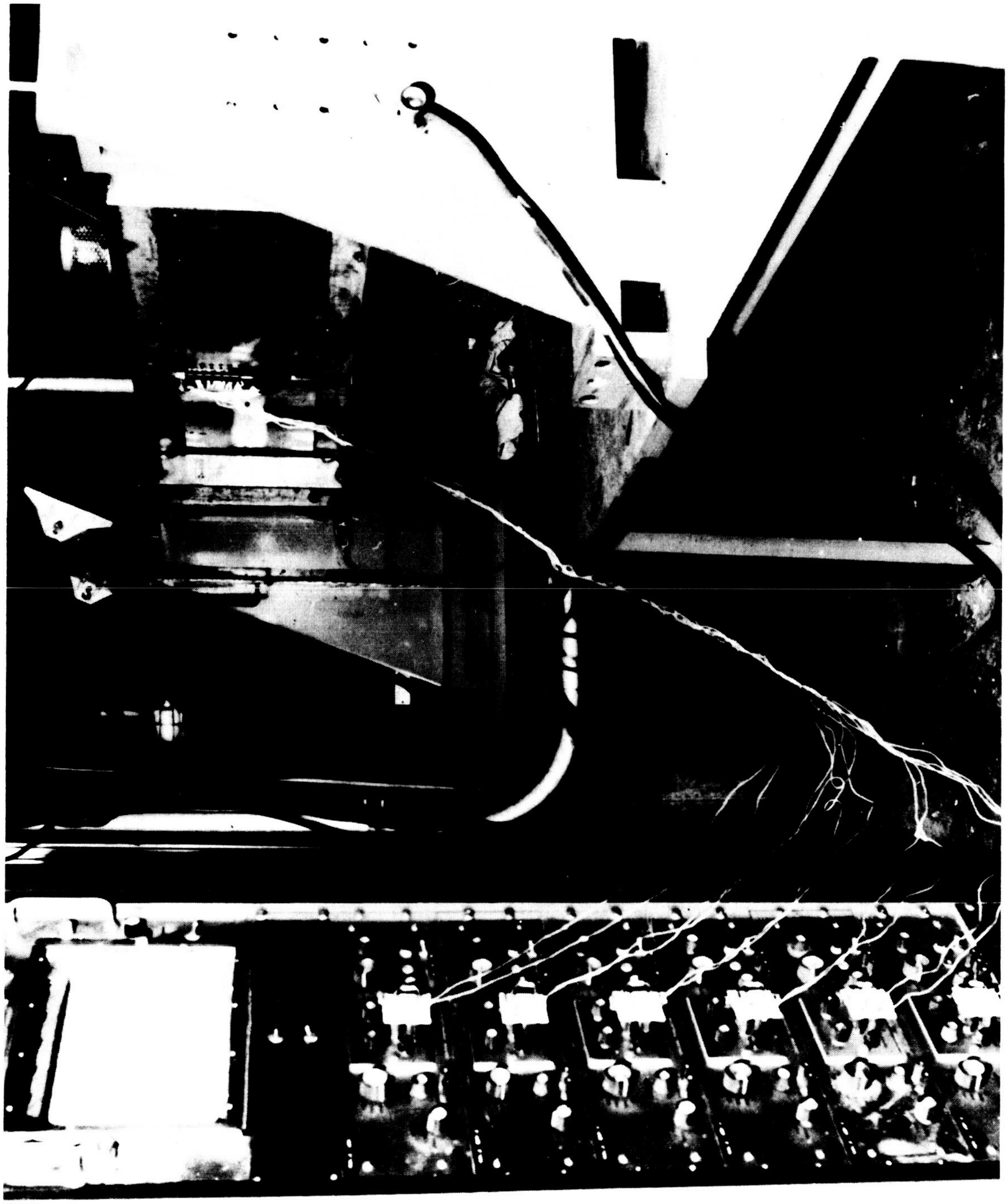
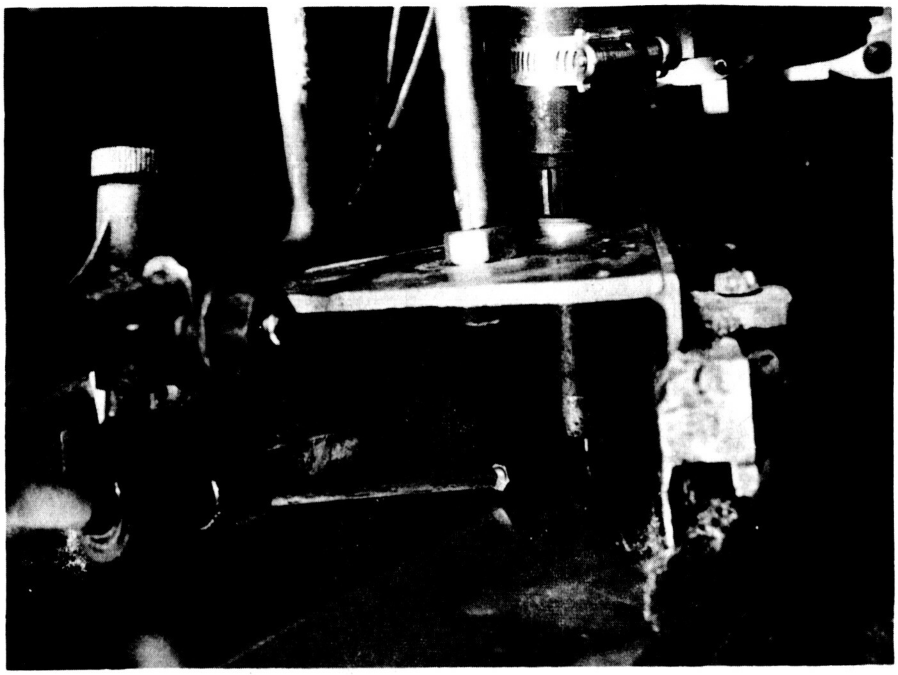


Figure 2. **Instrumentation for Measuring Temperatures During Welding**

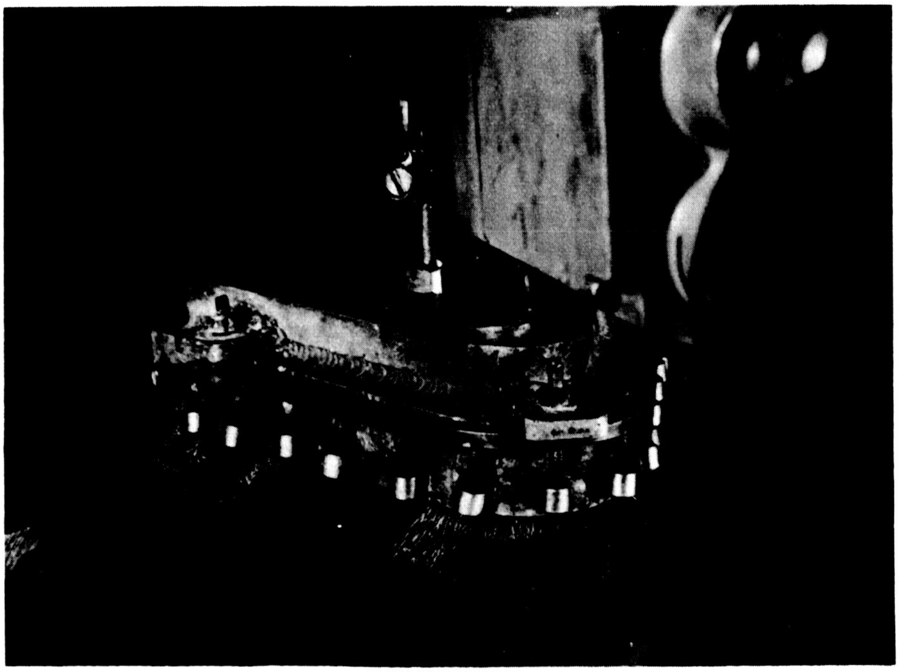
a. Single manifold with brush seal (bottom view)

b. Double manifold with brush seal (bottom view)

Figure 3. V–shaped Cryogenic Jet Systems for Cooling Front Side of Weld



a. Front view



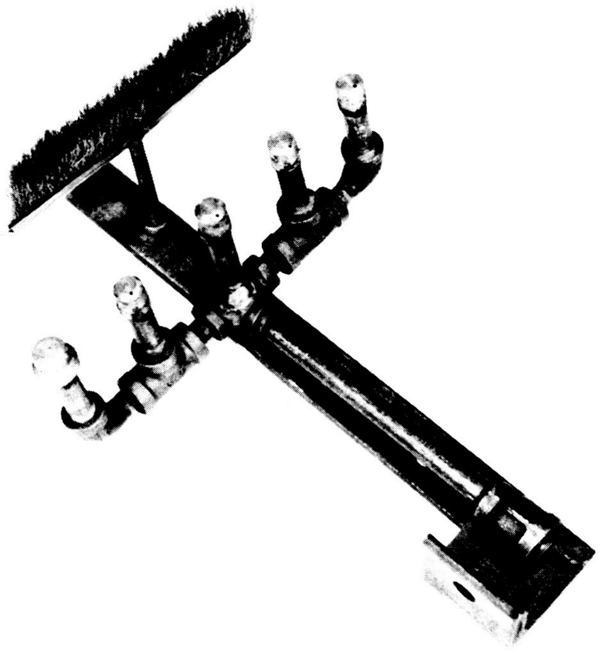
b. Rear view

Figure 4. Installed V–shaped Cryogenic Jet System for Cooling Front Side of Weld

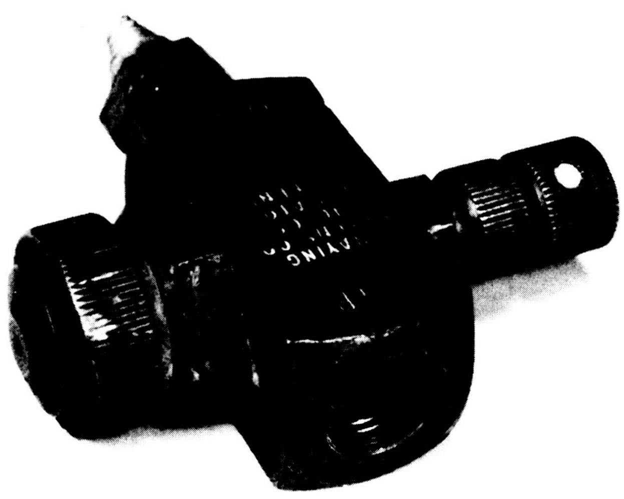
Trailing chilling systems.- Two types of nozzles were used for the trailing systems as shown in Figure 5. The five-jet system operates in a manner similar to the V-shaped system in that the nozzles can be positioned and orifice sizes can be changed. The DeVilbiss nozzle does not have this flexibility; consequently, it proved to be less useful than the manifold systems. Figure 6 shows the five-jet trailing manifold mounted behind the welding torch. Unless the distance from the jets to the torch is more than 12 inches, it is necessary to use a shield around the torch to keep the CO_2 out of the welding arc. As shown in Figure 6a, the steel-wool and wire brush seal designed for the V-shaped systems was used for this purpose. The distance between the jets and the welding torch can be adjusted by lengthening or shortening the attachment bracket (not shown).

Circular chilling system.- It was not possible to successfully develop a system for chilling the weld panel ahead of the torch by applying CO_2 to the front side of the panel. The systems investigated either interfered with the welding operation or could not be sealed sufficiently to prevent CO_2 from leaking into the arc. For this reason, the system shown in Figure 7 was fabricated. This system employs a circular manifold with eight nozzles which are adjustable and interchangeable in the same manner as those used in the V-shaped and 5-jet trailing systems. The seal consists of stainless steel-wool packed into a circular channel between the jets and the back side of the molten puddle. The axial channel, also packed with steel-wool, was designed to prevent CO_2 from getting into the unwelded joint ahead of the torch as well as to keep the CO_2 from contaminating the hot metal immediately behind the arc.

<u>Welding Techniques</u>.- All welding was performed with the panels in horizontal position; the TIG process was used with d-c straight polarity. Arc voltage was controlled by a "proximity control." The control automatically adjusts the distance between the electrode and the work piece so that a preselected voltage will be maintained. The amperage and travel speed used for accomplishing the weld was selected by trail, and each was varied directly with the type of

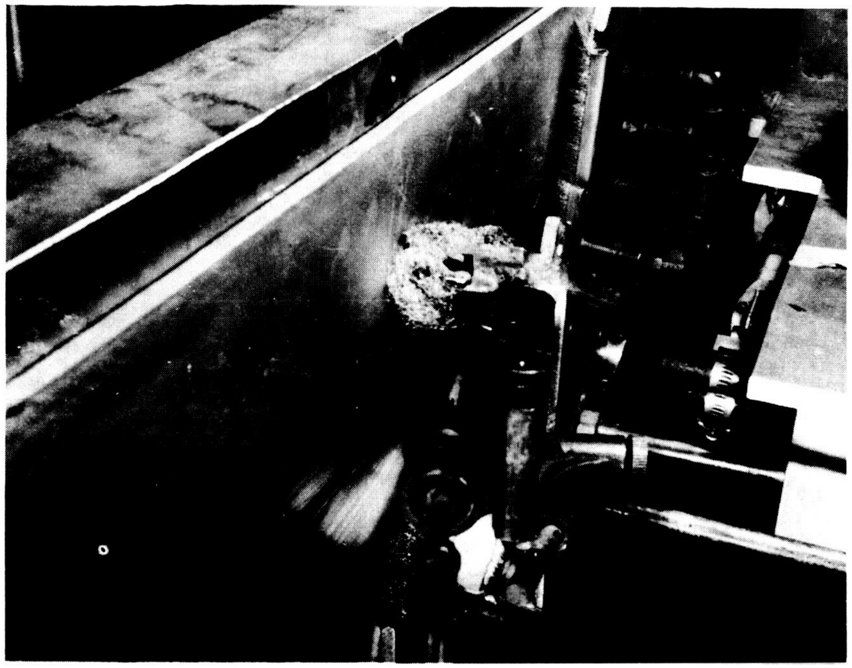


a. Five-jet manifold

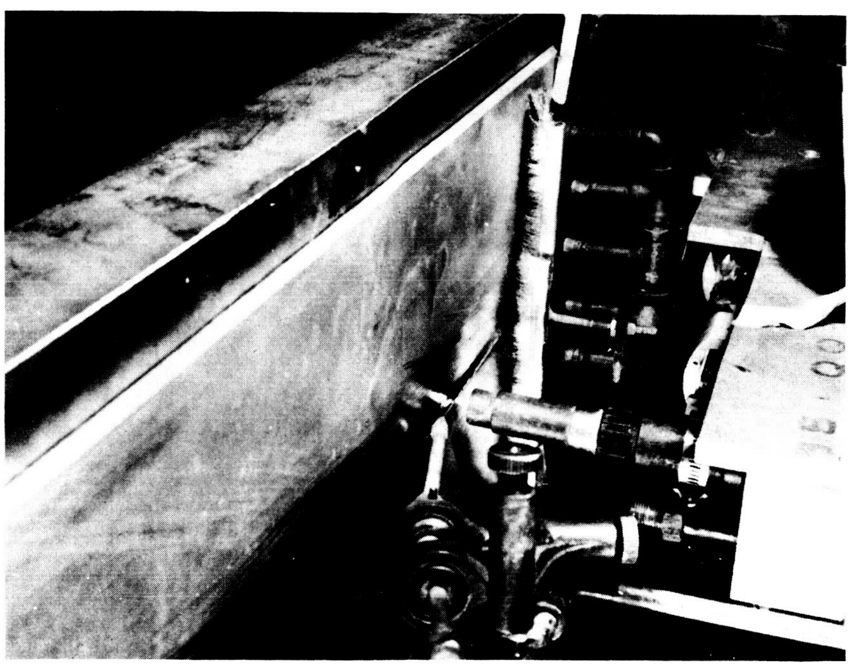


b. De Vilbiss nozzle

Figure 5. Trailing Cryogenic Jet Systems for Cooling Front Side of Weld (bottom views)

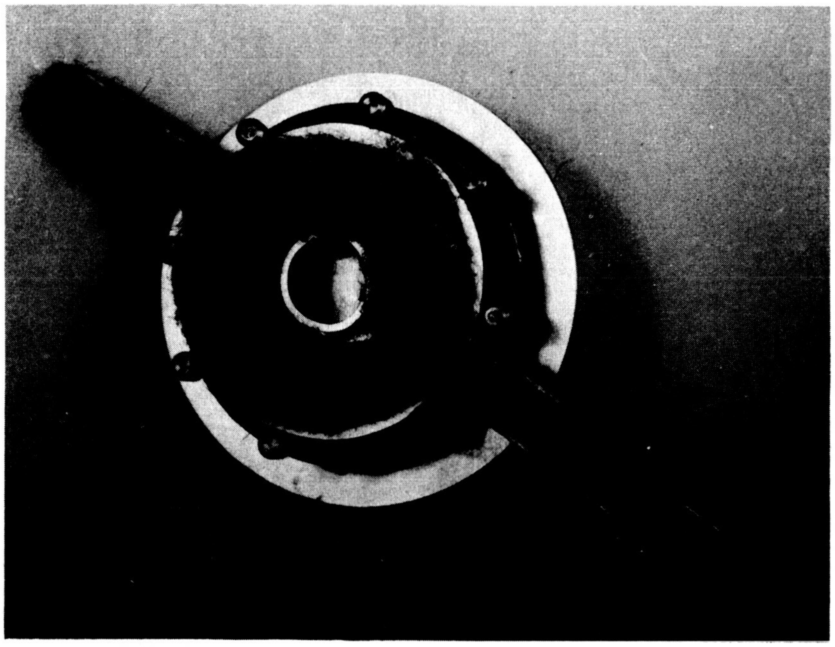


a. Using auxiliary torch shield

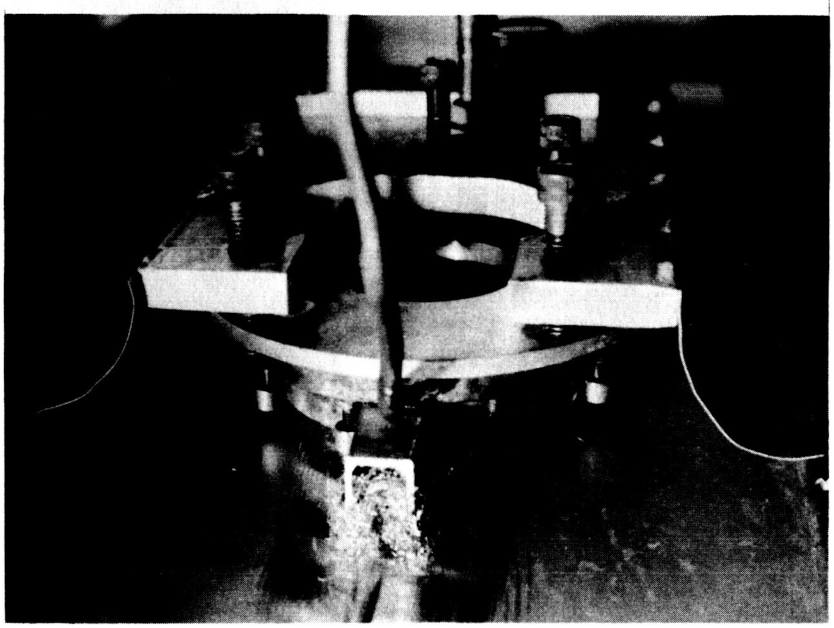


b. Without torch shield

Figure 6. Trailing Cryogenic Jet System Installed for Cooling Front Side of Weld



a. Bottom view



b. Installed rear view

Figure 7. Circular Cryogenic Jet System for Cooling Back Side of Weld

chilling used. In most cases, welds were made at 250 amperes with the travel speed adjusted from 5 to 14 inches per minute as needed to effect optimum penetration.

Temperature Measurement.- Six platinum resistance thermometers were held by spring wire clips against the surface of the weld panel so that air gaps between panel and thermometers could not occur in the event of panel warpage. The thermometers were connected to a six-channel Brush recorder using a Wheatstone Bridge arrangement to produce the proper range of needle deflection in accordance with the resistance changes produced by expected temperature changes. Prior to making each experimental weld, the recordings were calibrated against a standard resistance.

Placement of the thermometers was generally near the center of the length of the panel with thermometers spaced approximately one-half inch apart and outward from the weld centerline. Chart deflections produced by each thermometer were then measured and converted to temperature by using the calibration deflection as a reference.

Warpage Measurement.- Warpage was measured using the center at the top of the panel as the reference point. Linear measurements were converted to angular units for convenience.

Residual Stress Measurement.- Two techniques were used for measuring residual stresses. Both involved the use of wire or foil strain gages in conjunction with a manually-operated strain indicator. Standard techniques were used for preparing the panel surface and laying the strain gages. Mechanical trepanning, with CO_2 coolant to prevent overheating, was initially used for relaxing the residual stress. The equipment for trepanning as shown in Figure 8, and the trepanned sections are shown in Figure 9. However, there was some indication that this technique affected the actual residual stress slightly. Therefore, the slicing technique illustrated in Figure 10 was used for most residual stress measurements.

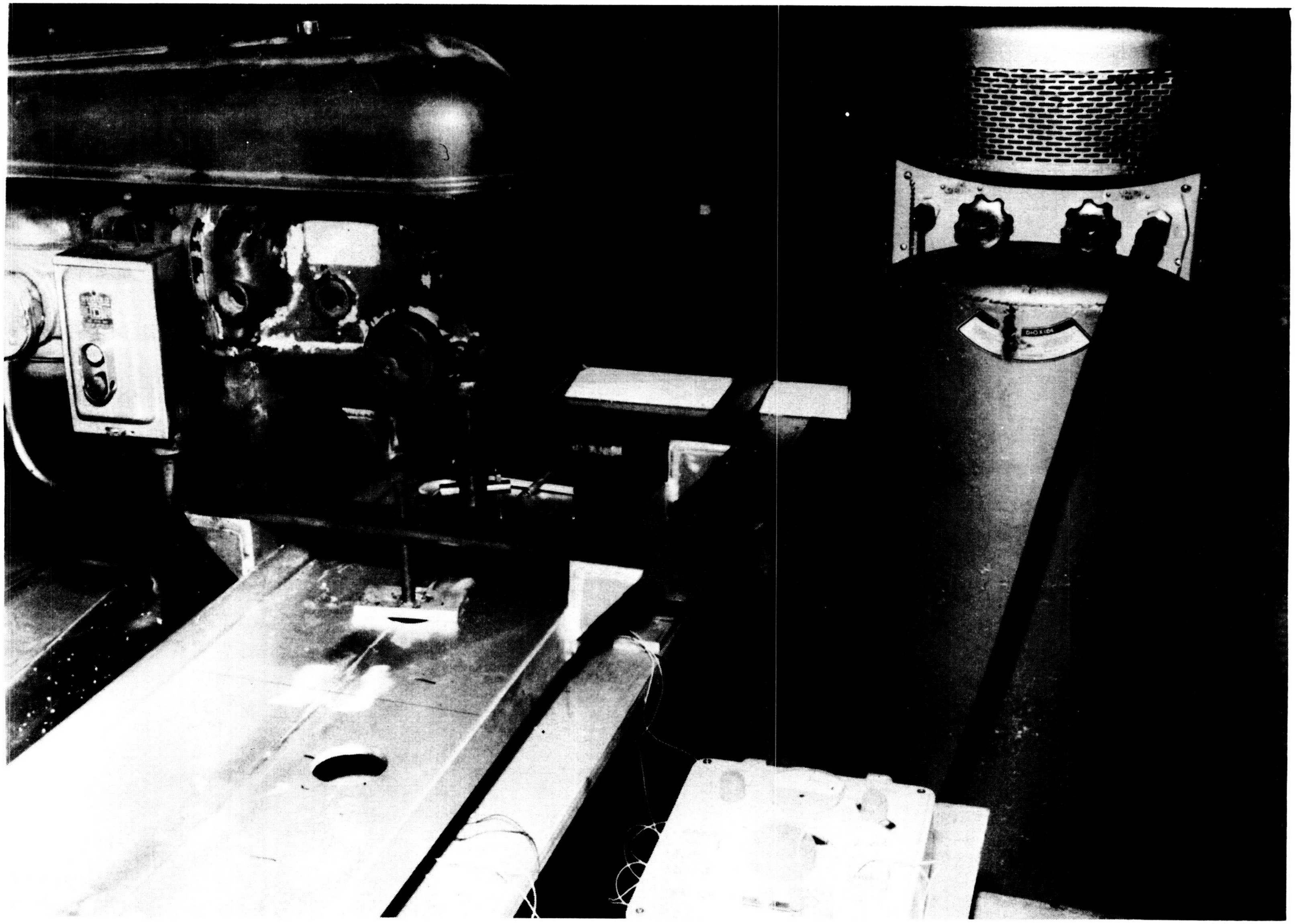


Figure 8. **Equipment for Measurement of Residual Stresses by Trepanning**

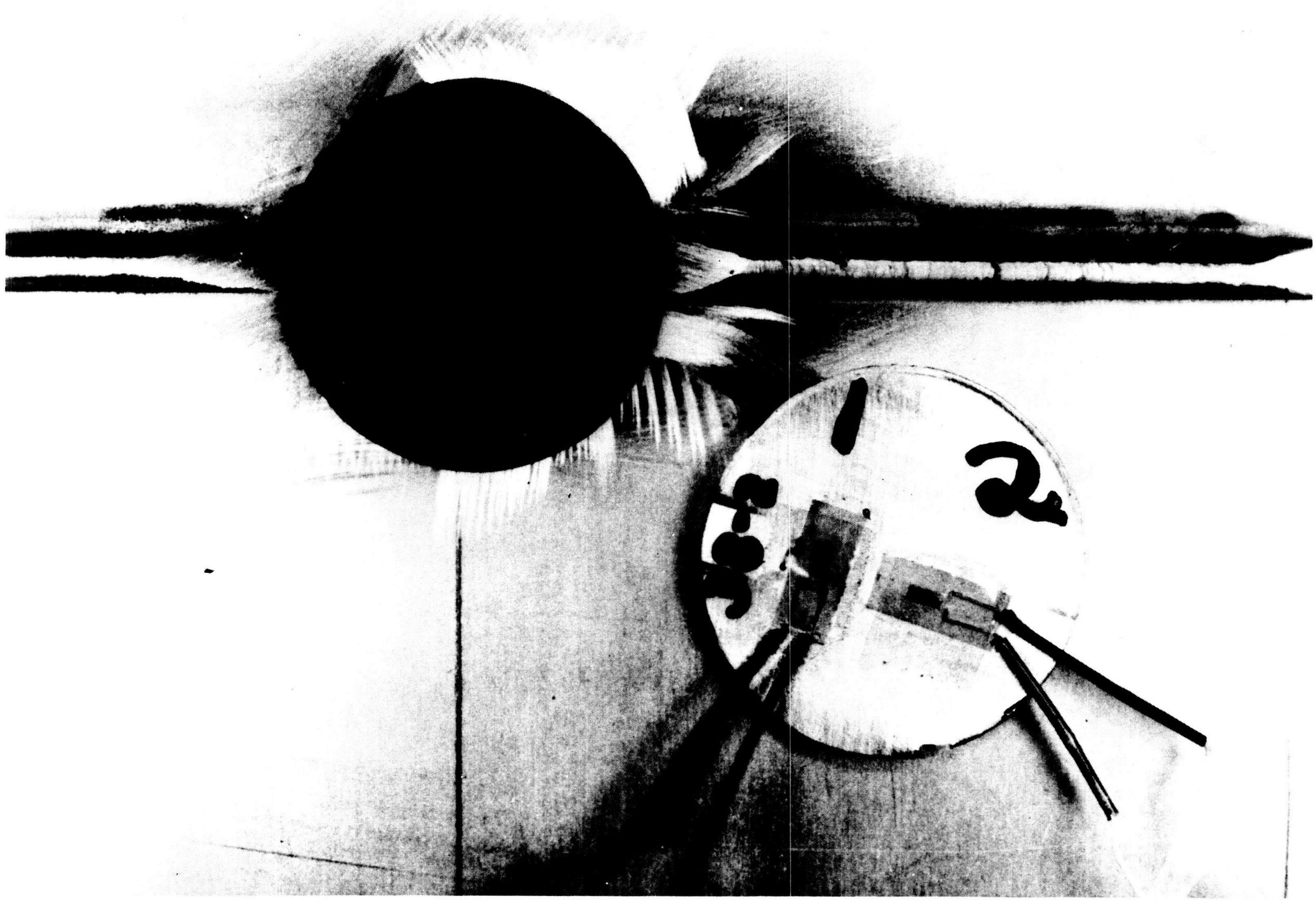
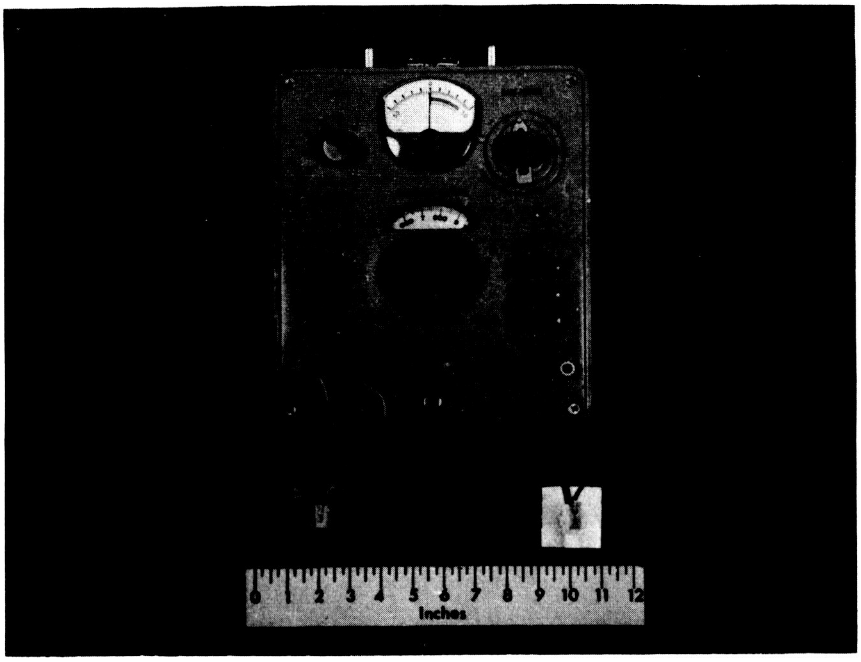
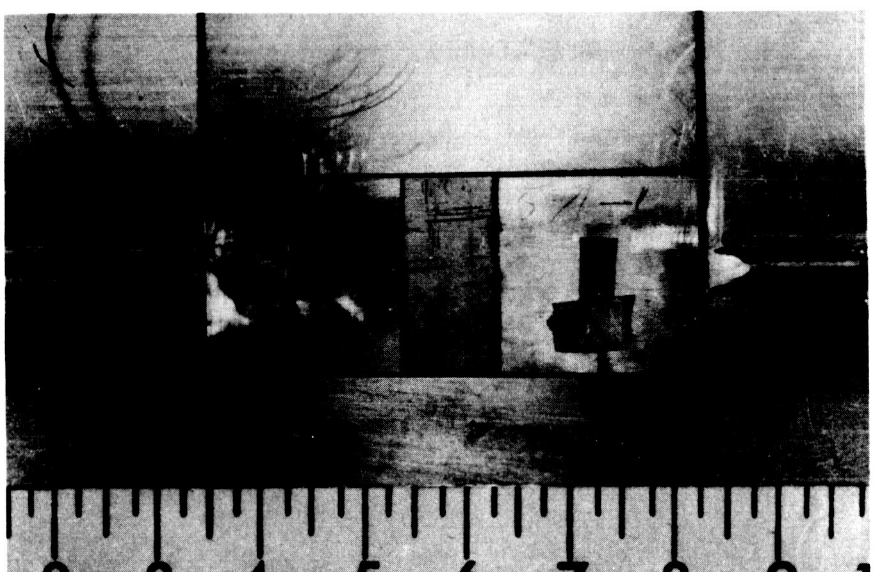


Figure 9. **Trepanned Portion of a Welded Panel Showing Strain Gages for Measuring Residual Stresses**



a. Strain gages (ref. gage on right) connected to strain indicator



b. Blocks with strain gages reassembled in weld panel to show location

Figure 10. Measurement of Residual Stresses Using The Slicing Technique

Although strain gages were placed in various portions of the weld panel, it was determined that the most significant measurements for evaluating effect of thermal patterns were those made directly on the cast weld with the axis of one strain gage parallel to the longitudinal axis of the weld and another transverse to the longitudinal axis. In order to obtain a flat surface upon which to place the strain gages, and to obtain uniform relaxation of the stresses upon cutting, the weld reinforcement was ground off. Extreme care was taken to avoid raising the temperature of the weld over 150 deg. F. during the grinding operation.

X-Ray Examination.- Standard techniques were used for determining weld quality by X-ray.

Macrosectioning.- Macrosections were prepared by cutting samples 3 in. long x ½-in. thick of the weld transverse to the longitudinal axis. These samples were polished and etched for macroscopic examination of the weld and heat affected zones.

Tensile Testing.- Strips 12 x 3/4-in. were cut transverse to the longitudinal axis of the weld. Weld reinforcements was not removed. Tensile tests, using standard testing techniques, were performed within one week after the panel was welded.

Experimental Results

Development of Basic Experimental Data.- A limited test series was performed to determine the effect of weld heat on expansion and contraction of 5/16-in. 2014-T6 plate and to establish the practicality of applying sufficient liquid CO_2 adjacent to the weld to counteract the thermal effects of welding. These tests were performed upon small samples supported in such a manner that deflections of the edge of the plate could be measured by means of dial micrometers.

Welding consisted of spot, slot, and seam. Cooling was accomplished by means of a stationary manifold specially constructed for this purpose.

Results of these tests demonstrated that the deflection can be reduced to zero and that residual stresses can be reduced substantially. In some cases, the deflection was reversed by application of excessive quantities of liquid CO_2.

Details of the tests are contained in Appendix D.

Development of Optimum Thermal Patterns

General.- Summaries of experimental data on this portion of the program are presented in the following pages. Detailed data are contained in Appendix C.

Typical Thermal Patterns

Unchilled weld panels.- In order to establish a basis for comparison, several 48 x 12-in. panels were welded without chilling. Measurements of warpage, residual stress and tensile properties indicated that warpage is extremely sensitive to the time-temperature cycle, degree of restraint, and shape of the cast weld structure. A typical thermal pattern for unchilled weld panels is shown in Figure 11.

Front-side chilling.- Various chilling patterns were used in an effort to select those that would produce the most beneficial effects on warpage and residual stresses. As shown in the sketches contained in Appendix B (Equipment and Instrumentation), a total of 14 variations of the V-shaped systems were used to weld 48 x 12-in. panels. Fourteen variations of the trailing systems were also used to weld 48 x 12-in. panels. A total of more than 50 panels were welded to investigate the 28 variations of the front side chilling systems. Typical thermal patterns for weld panels chilled from the front side with the V-shaped and trailing manifold systems are shown in Figures 12 and 13.

Back-side chilling systems.- During the course of the experimental work with the front side chilling systems, a cursory stress analysis was made in an effort to determine the reason these systems did not effect more pronounced reductions in warpage and residual stresses.

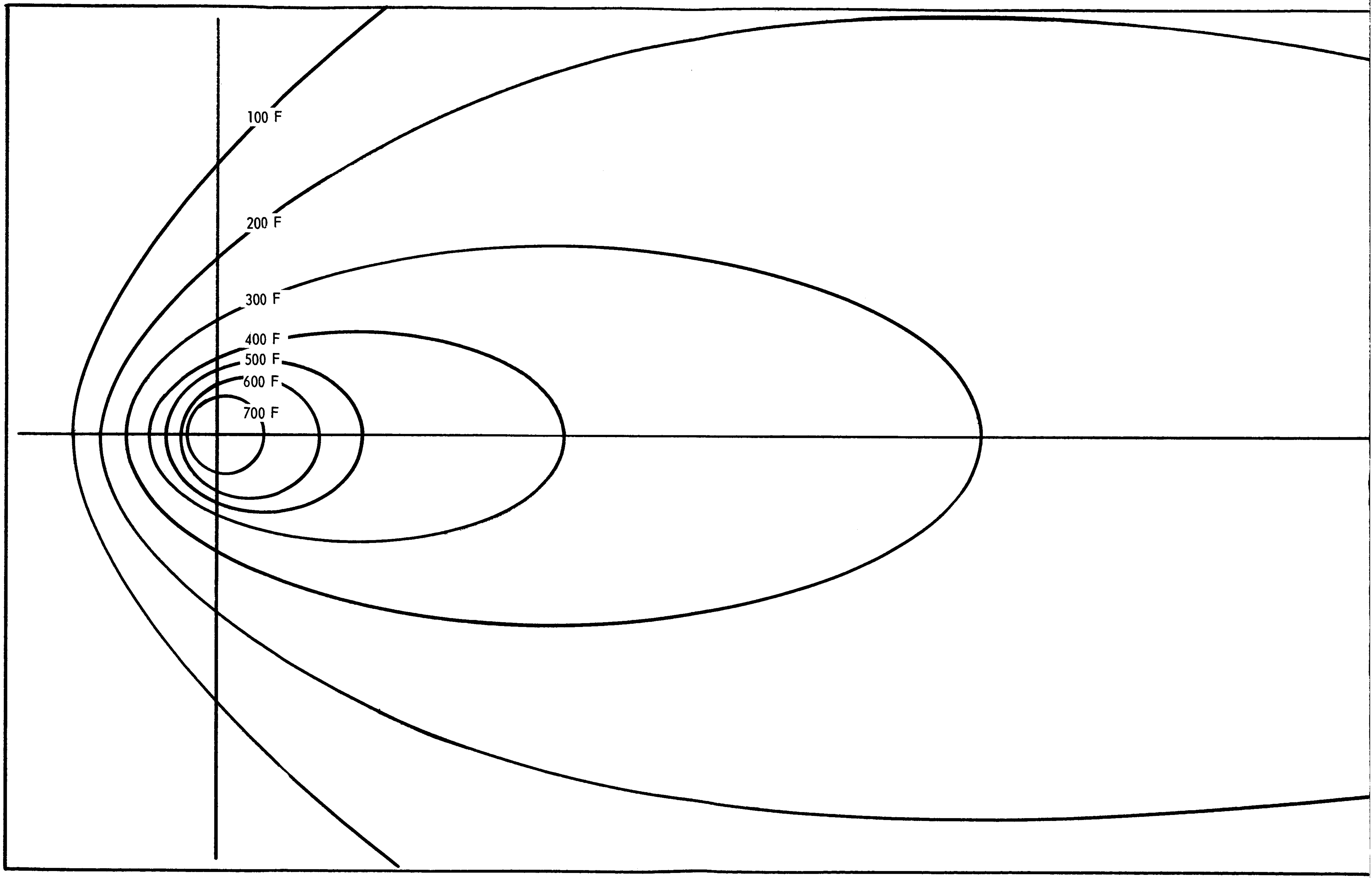


Figure 11. Typical Thermal Pattern for Unchilled Weld Panels

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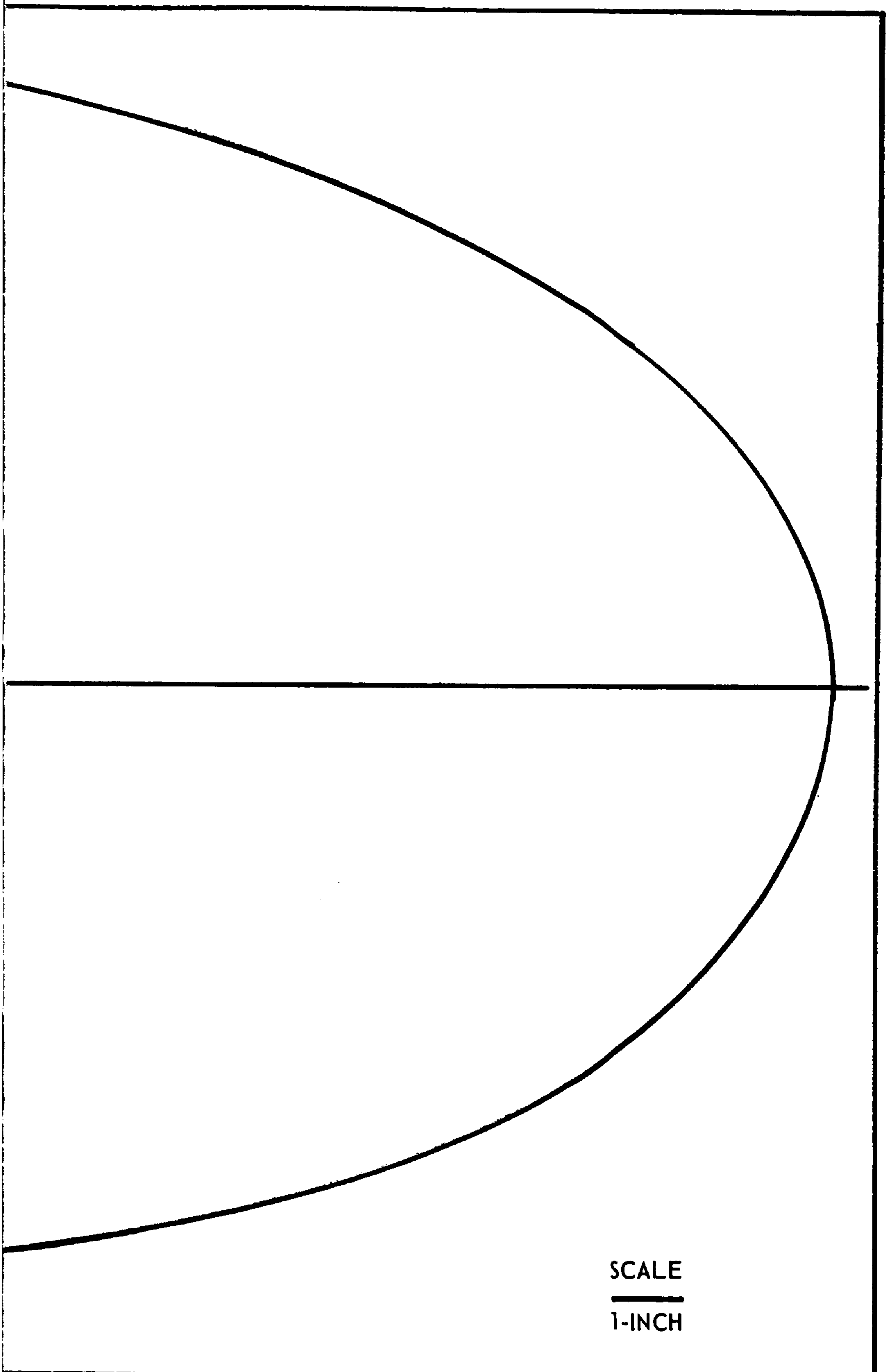

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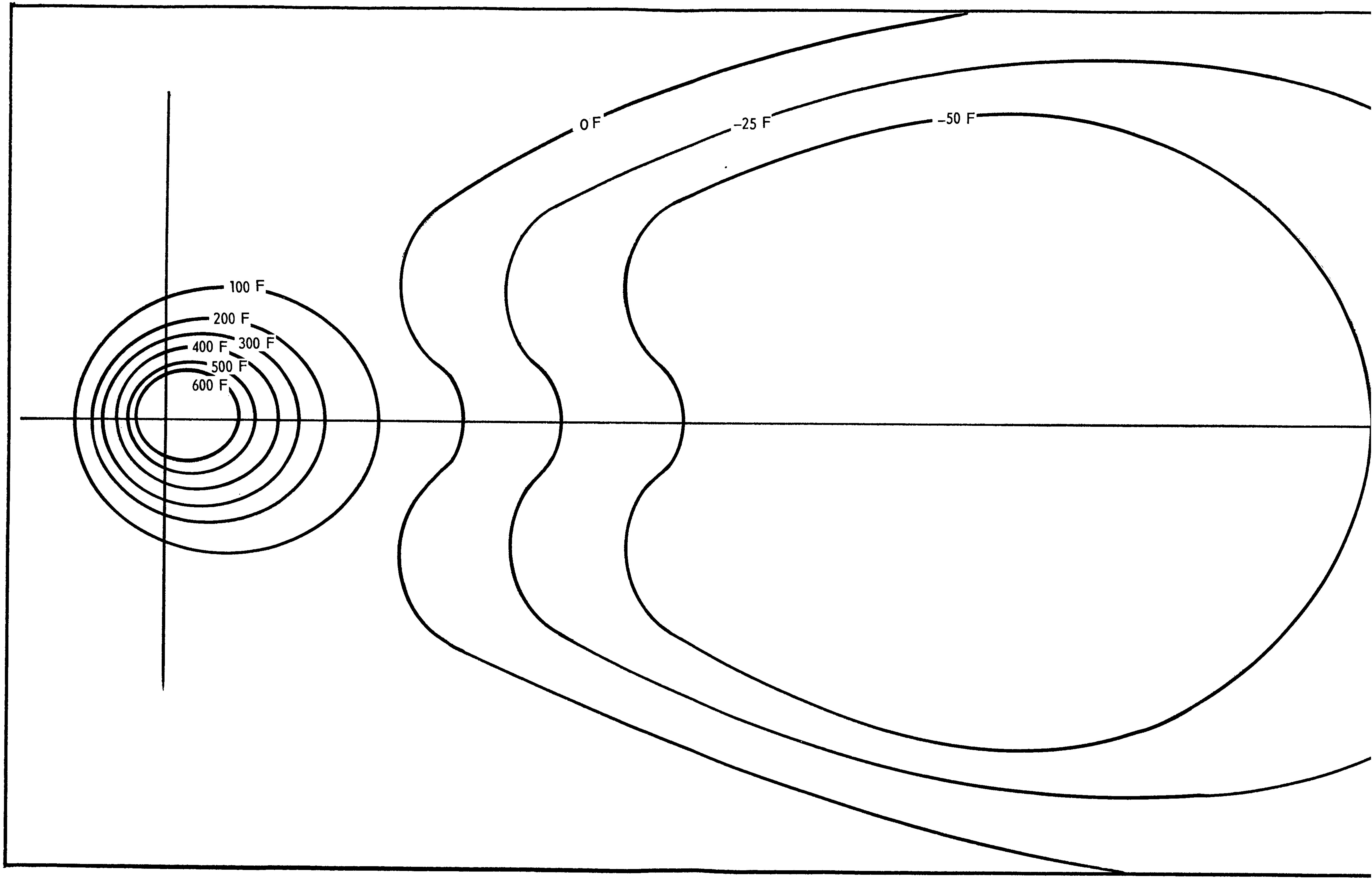

Figure 12. Typical Thermal Pattern for Panels Welded with V-shaped CO_2 Chilling System

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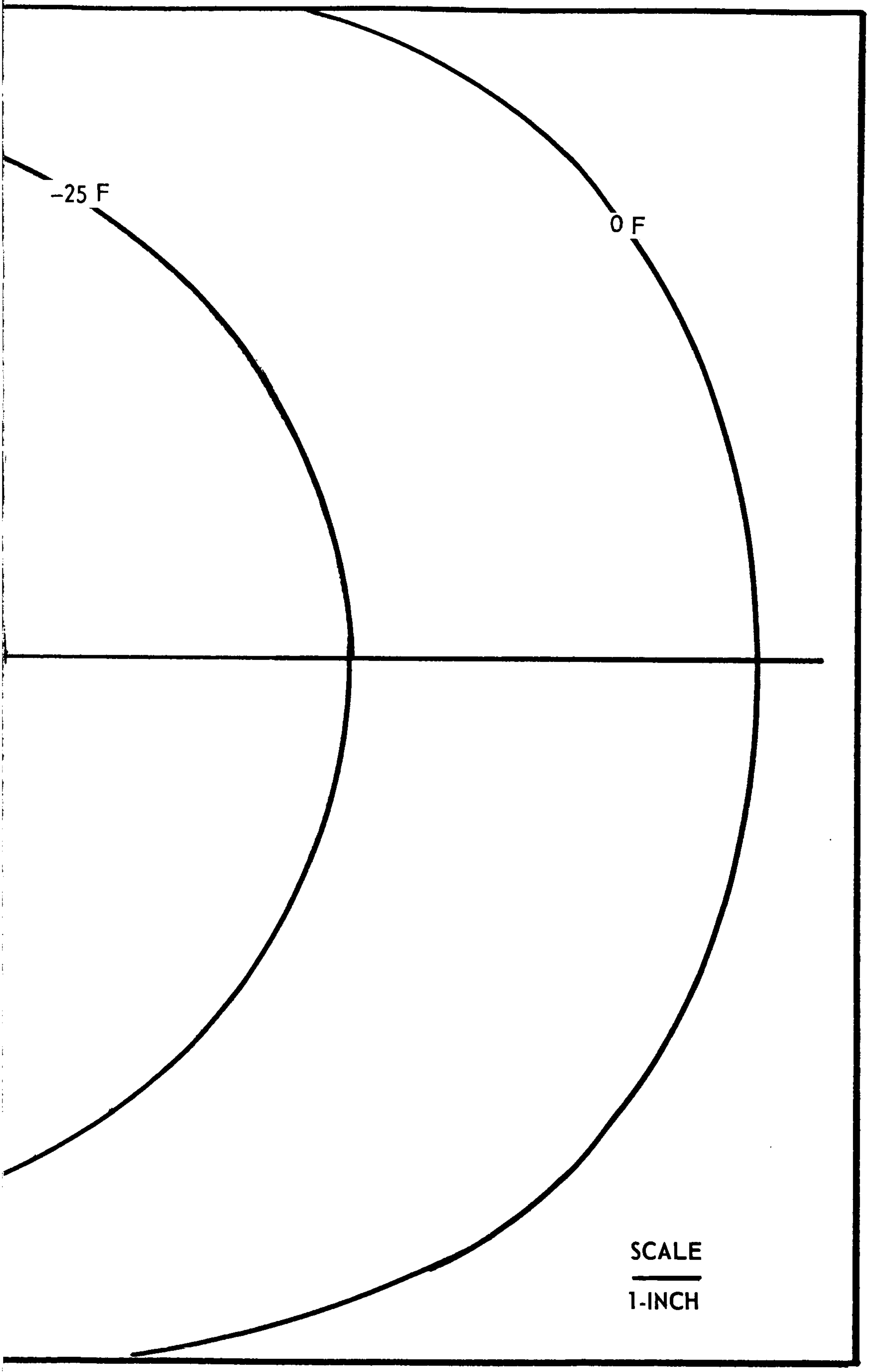

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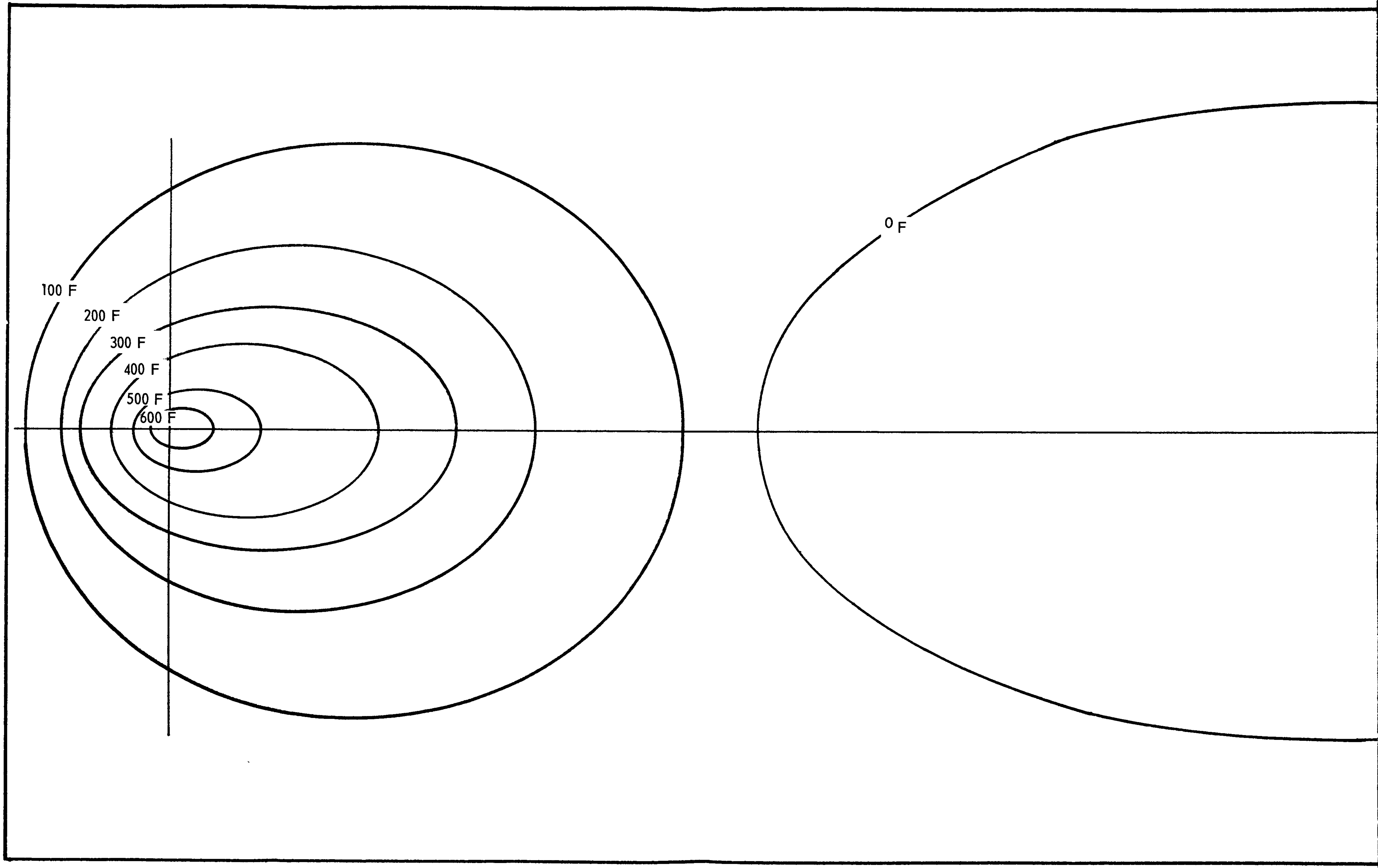

Figure 13. Typical Thermal Pattern for Panels Welded with Trailing CO_2 Chilling System

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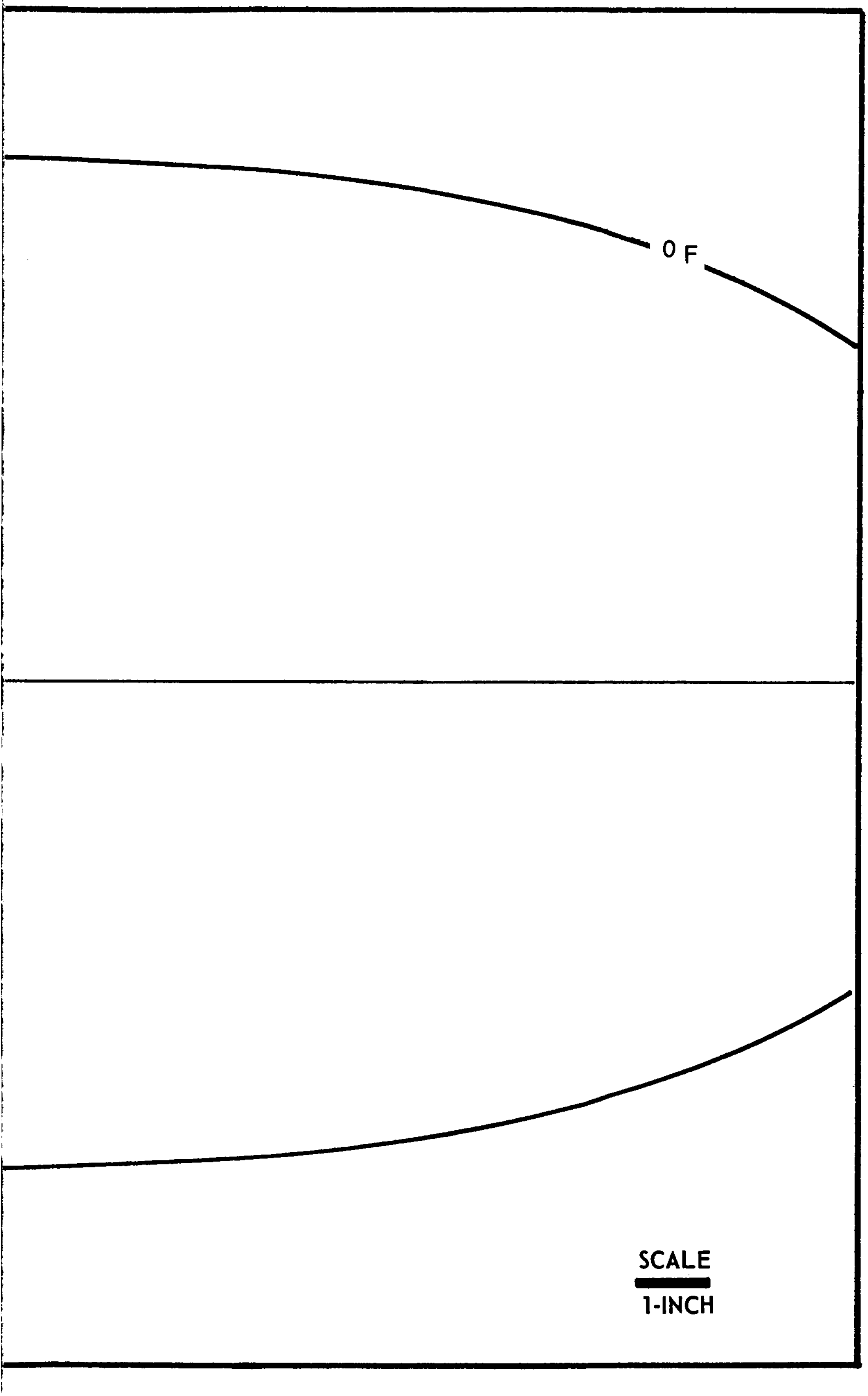

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The result of this analysis indicated that thermal contraction was nonuniform since liquid CO_2 could not be applied to the plate ahead of the welding torch without interfering with the welding operation. On this basis, a system was designed and fabricated for chilling in a circular pattern.

The first system was designed for use on the front side but failed to keep CO_2 out of the arc and was therefore abandoned. The second system was designed for use on the back side and was effective in producing the desired chilling pattern. A typical thermal pattern is shown in Figure 14. However, this system caused excessive porosity in the weld.

It is believed that the porosity resulted from water condensed on the cold aluminum becoming trapped between the butting edges ahead of the arc. Inasmuch as this system also did not effect the desired degree of warpage or residual stress reduction, it was postulated that the necessary elastic-plastic relationships were not being produced by chilling alone as the expansion after chilling takes place too slowly to be effective. In order to cause the proper relationship to take place, it would be necessary to use auxiliary heat.

Combined Chilling and Auxiliary Heating Systems._ The first system utilized one of the front side trailing manifolds for chilling and an acetylene flame behind the chilling manifold to cause more rapid expansion. This system caused the warpage to reverse from normal, but the acetylene flame was difficult to control. Therefore, in the remaining experiments, the flame was positioned manually. It was found that the most effective combined system was a general preheat of the plate of 200 deg. F. with approximately 1.5 pounds of CO_2 per inch of weld impinged on the weld seam 10 inches behind the torch. A typical thermal pattern for this system is shown in Figure 15. This pattern repeatedly produced panels with low warpage and with longitudinal residual stresses of less than one-third of the normal. Work for further refinement of this combined system could not be accomplished within the limits on this project.

Effect of Thermal Pattern on Warpage.- As shown in Table I, it was possible to produce unwarped panels either with or without the use of any of the systems for changing the thermal pattern; however, repeatability was extremely low for all except the combined chilling and heating systems as indicated by the variation from maximum to minimum. It is concluded that the degree of warpage is extremely sensitive to minor variations in welding parameters, and in order to "de-sensitize," it is necessary to distribute plastic yielding over a wider area of the weldment by spreading the isotherms around the weld puddle while creating elastic strains in such locations as to counteract the thermal strains created by the welding operation.

Effect of Thermal Pattern on Residual Stresses.- All of the systems for altering the thermal pattern were effective to some degree in reducing the residual stresses as compared to those present in unchilled weld panels. However, chilling alone produced a maximum of 50 percent reduction in the longitudinal residual stress, while chilling combined with auxiliary heating reduced these stresses as much as 95 percent as shown in Table II.

Effect of Thermal Pattern on Tensile Properties.- Although only limited testing was performed, it was indicated that tensile yield strengths were improved through chilling by amounts ranging between 10 and 20 percent. This is in agreement with the findings of work performed under Contract NAS8-11930. Typical properties are shown in Table III.

Effect of Auxiliary Heating on Metallurgical Structure of Chilled Welds.- As shown in Figure 16, there are no noticeable adverse effects caused by preheating of the panel during the welding operation. This, in conjunction with the improved tensile properties, indicates the auxiliary heat actually causes a favorable metallurgical condition.

Effect on Chilling on Porosity.- Except for welds chilled from the back side with the circular manifold system, there was no evidence that altering the thermal pattern affects porosity adversely. Some chilled welds contained small amounts of fine porosity but this was

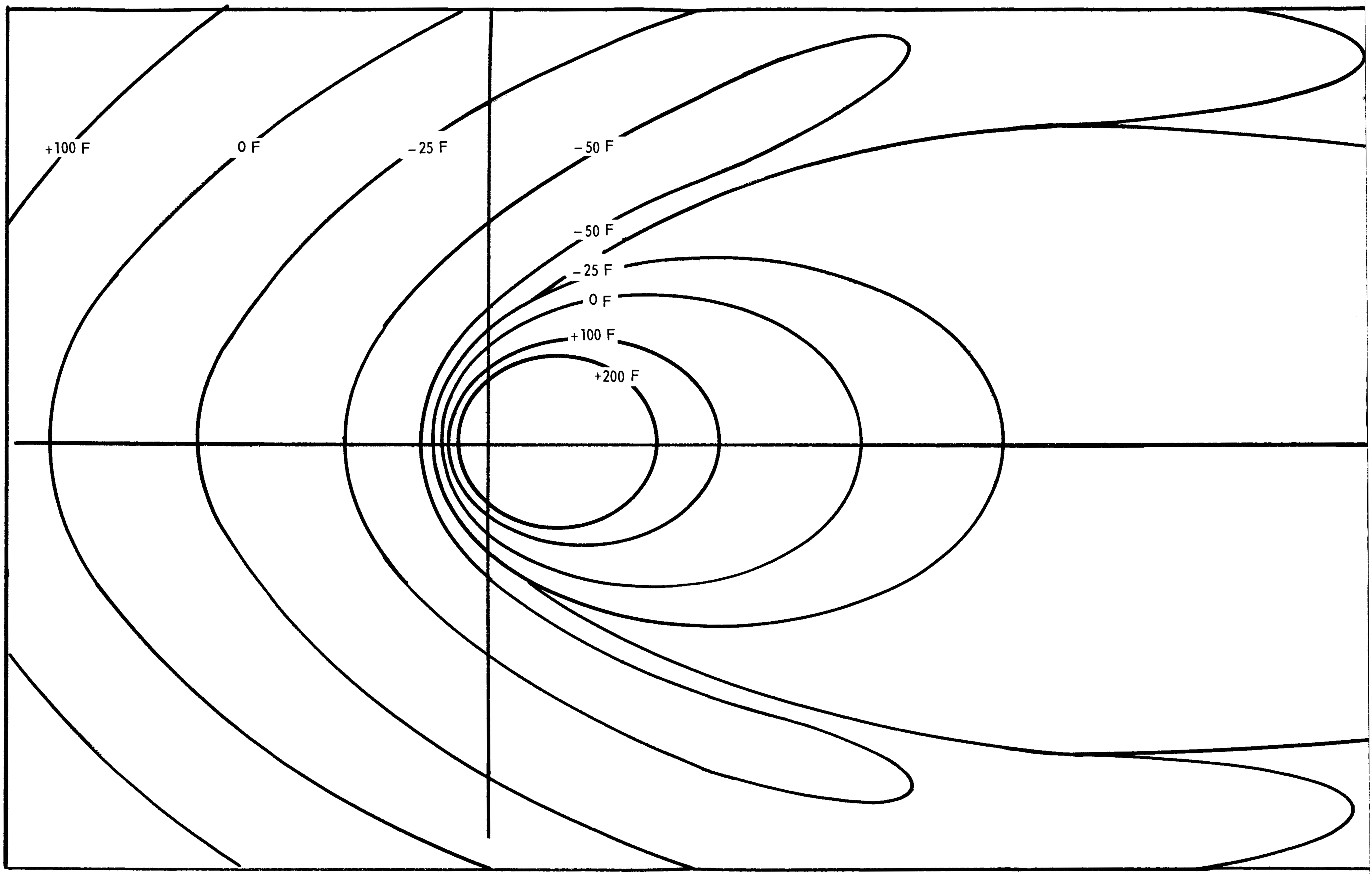

Figure 14. Typical Thermal Pattern for Panels Welded with Circular CO_2 Chilling System

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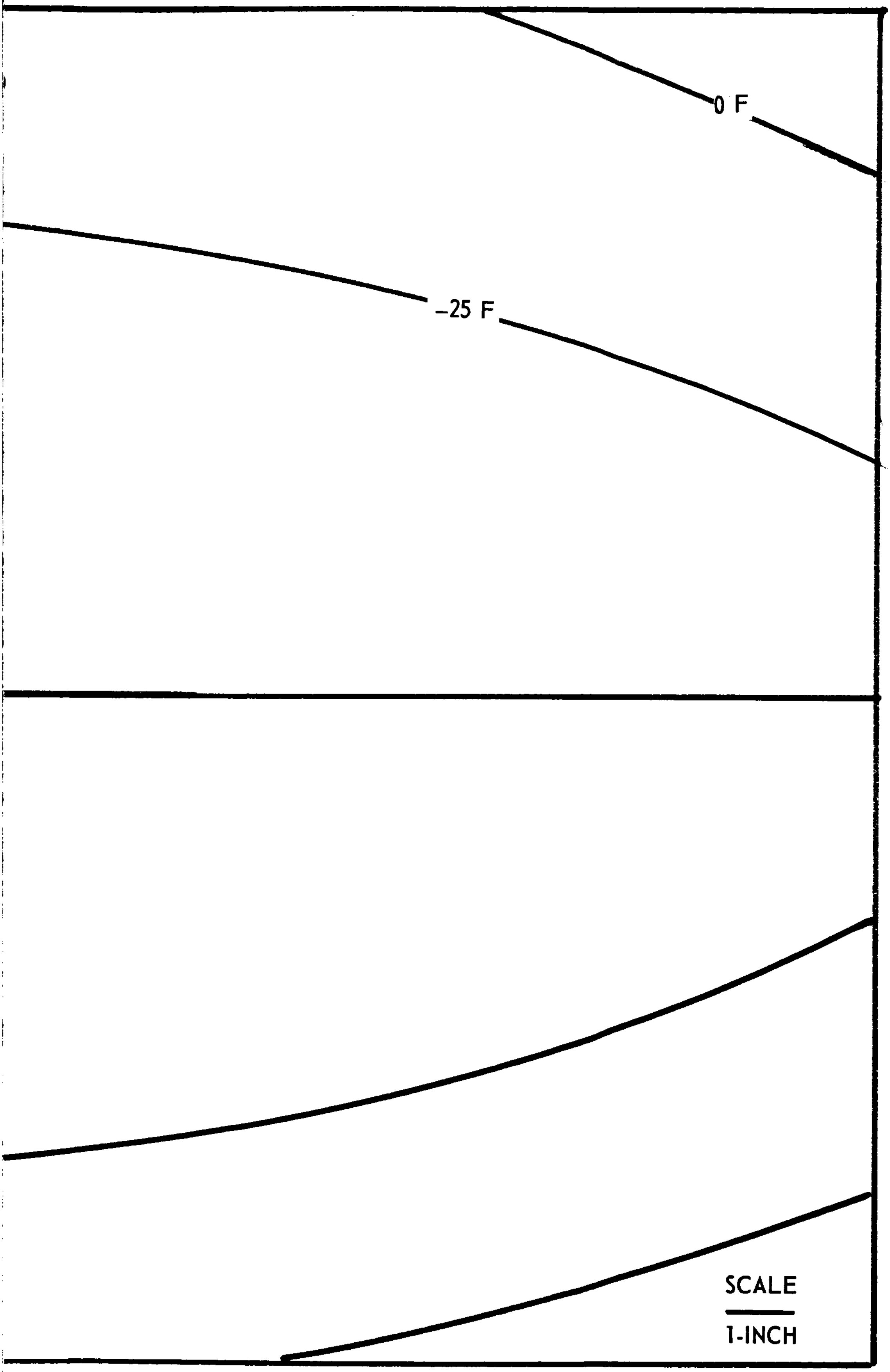

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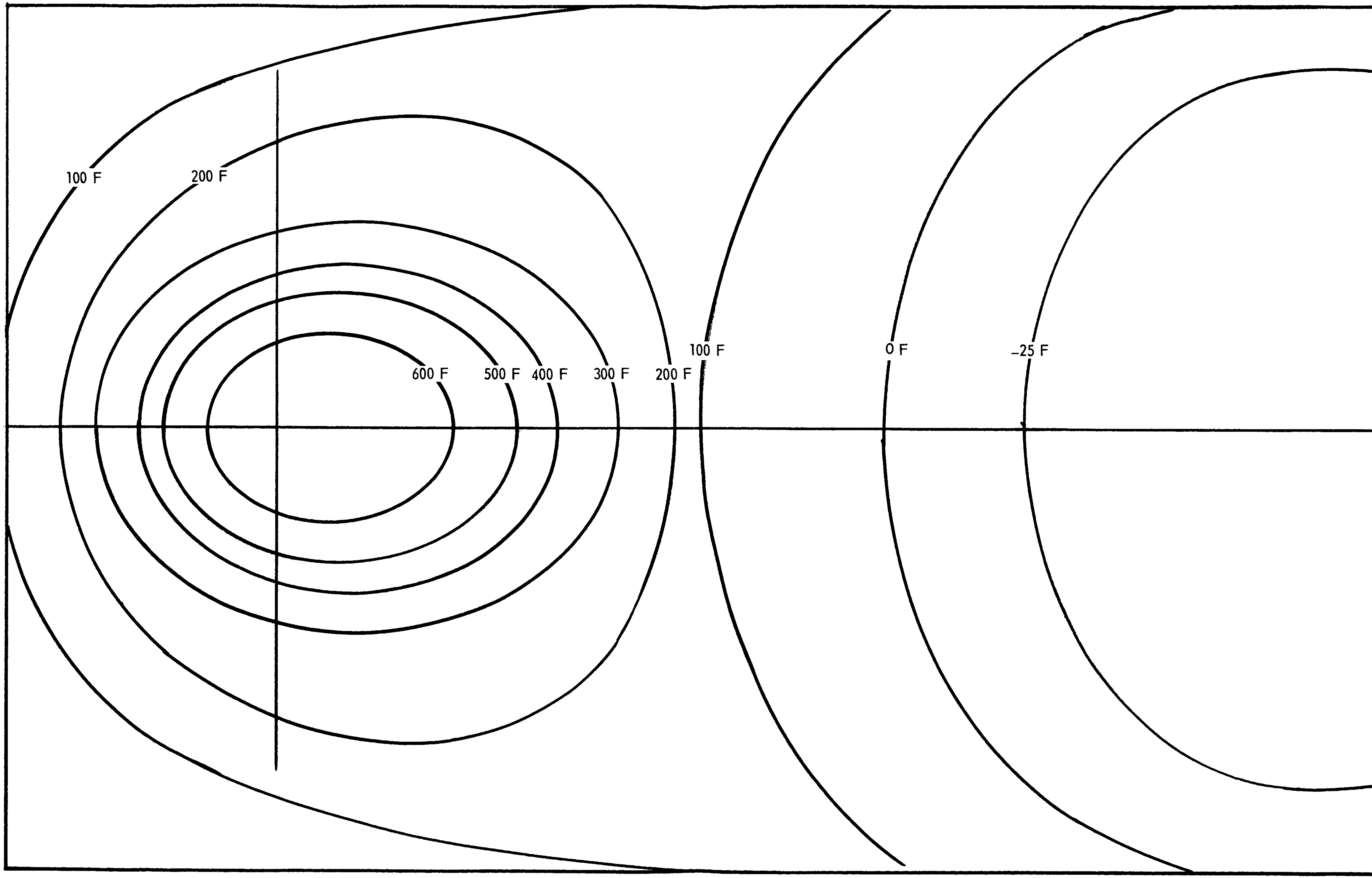

Figure 15. Typical Thermal Pattern for Panels Welded with Trailing CO_2 Chilling System and Auxiliary Heat

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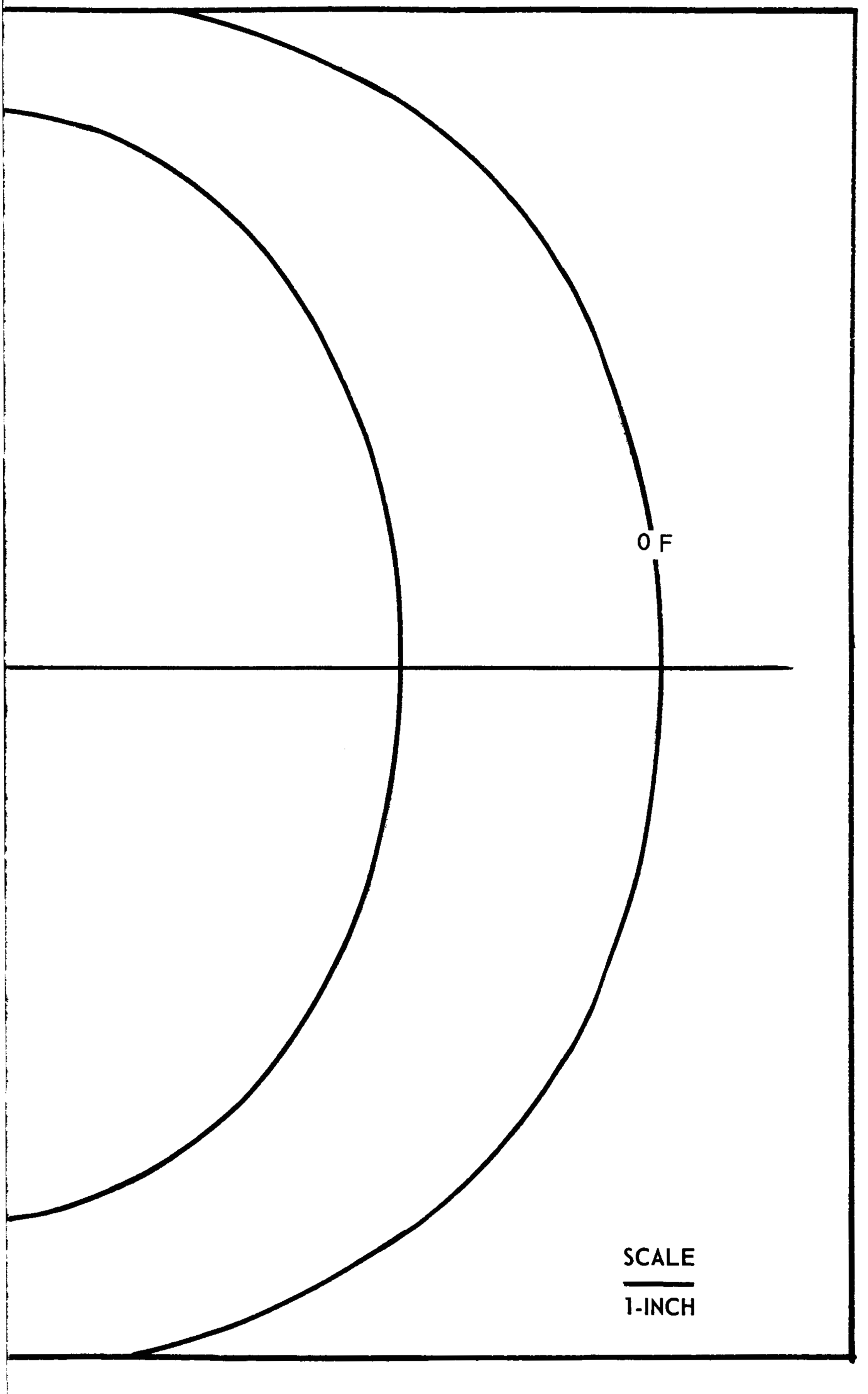

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TABLE I. Effect of Thermal Pattern on Warpage

Principal Factors Producing Thermal Pattern	Warpage in Degrees (1)					
	Maximum		Minimum		Typical	
	Bow	Peak	Bow	Peak	Bow	Peak
Unchilled	-.08	+1.6	0	0	-0.4	+1.2
Chilled Only-Front Side	-1.2	+3.5	0	0	-0.8	+1.2
Chilled Only - Back Side	-0.8	+0.6	0	0	-0.8	+0.6
Chilled and Auxiliary Heat	+0.3	-0.3	0	0	+0.2	0

NOTE

1. Minus sign (-) indicates direction of bow or peak is away from face of weld; plus sign (+) indicates bow or peak is toward face of weld. Note that the bow is reversed when combined cooling and auxiliary heating are used to change thermal pattern.

TABLE II. Effect of Thermal Pattern on Residual Stresses

Principal Thrm. Patt. Factors	Residual Stress (psi) (1)					
	Maximum		Minimum		Typical	
	Long.	Trans.	Long.	Trans.	Long.	Trans.
Unchilled	+22,500	-12,300	+17,600	-3,000	+21,000	-7,000
Chilled Only-Front Side	+20,500	- 8,000	+12,200	-1,600	+12,000	-7,500
Chilled Only-Back Side	+20,300	- 7,800	+11,900	-4,000	+15,000	-5,000
Chilled and Auxiliary Heat	+ 9,200	-12,600	+ 1,100	+ 800	+ 3,000	-2,000

NOTE

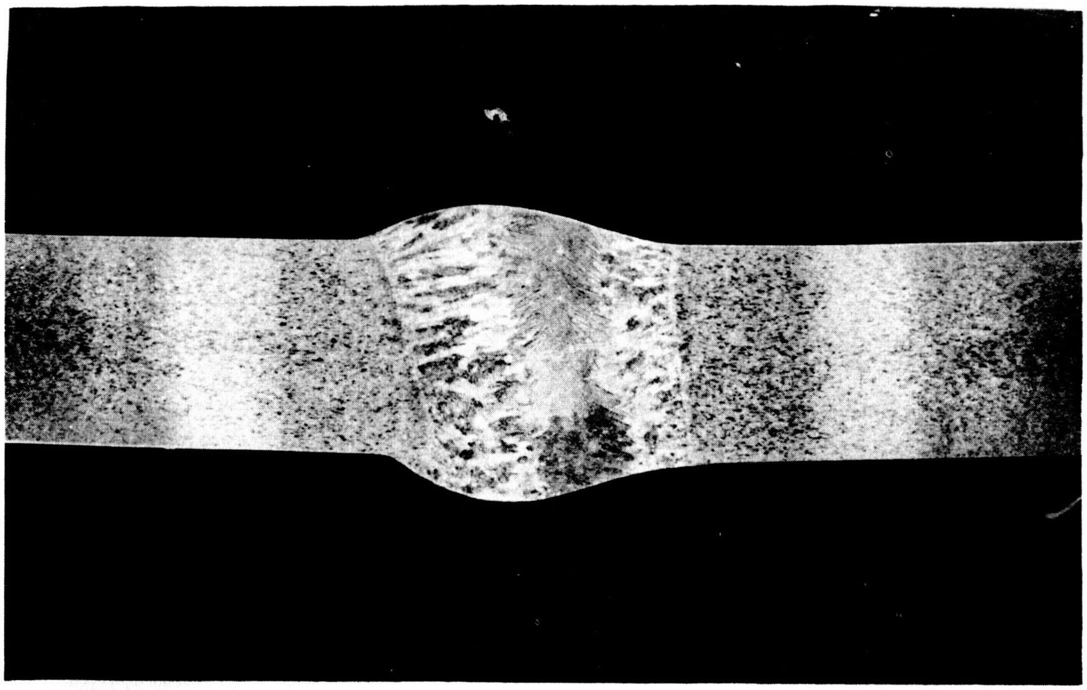
1. Plus sign (+) indicates residual stress in tension; minus sign (-) indicates residual stress in compression. Strain gages placed in the center of the weld seam.

TABLE III. Effect of Thermal Pattern on Tensile Properties

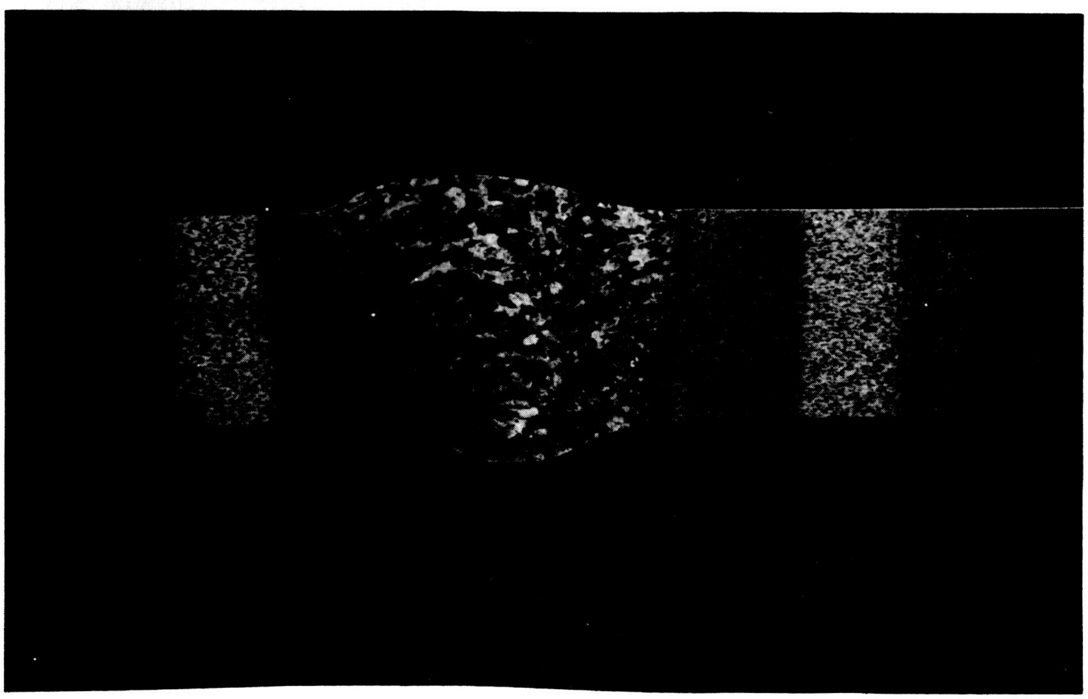
Chilling System	Auxiliary Heating	Typical Tensile Properties		
		Yield (psi)	Ultimate (psi)	Percent Elongation (1)
None	None	27,900	42,100	5.0
None	Preheat	26,300	42,100	5.0
Front-V-shaped	None	35,300	45,500	5.0
Front-Trailing	None	30,000	42,150	4.0
Front-Trailing	Preheat	34,400	56,000	4.0
Back-Circular	None	31,100	34,000 (2)	3.5

NOTES

1. Two-inch gage length.
2. Gross porosity in weld.



a. CO_2-chilled only during welding



b. Preheated and CO_2-chilled during welding

Figure 16. Macrosections Showing Effect of Auxiliary Heating on CO_2-chilled Welds

attributed to contaminants on the surface of the welding wire as porosity appeared in both chilled and unchilled welds made during the same interval. In general, porosity in chilled welds was smaller in quantity and size than that in unchilled welds.

Effect of Restraint

A limited study was made to determine the effect of restraint on warpage and residual stresses. As shown in Table IV, residual stress is apparently inversely proportioned to the amount of restraint imposed. There is also definite evidence that the degree of warpage is reduced by restraint; which of course, agrees with conventional welding practice. In an effort to simulate Saturn welding conditions, an intermediate degree of restraint was selected for performance of the final experimental work in this program (combined chilling and auxiliary heating).

TABLE IV. Effect of Restraint on Warpage and Residual Stress

Restraint	Type of Chilling System	Warpage (Deg.)		Residual Stress (typ) (psi) (1)	
		Bow	Peak	Long.	Trans.
None	Unchilled	-0.6	+1.0	+23,000	-7,000
2 Sides		0	0	+21,000	-7,000
4 Sides		0	0	+17,000	-6,000
None	Front-Trailing	-0.3	+0.2	+14,000	-3,000
2 Sides		-0.1	0	+12,000	-7,500
None	Back-Circular	0	0	+19,000	-4,000
2 Sides		+0.1	0	+15,000	-5,000

NOTE

1. Plus sign (+) indicates tensile stress; minus sign (-) indicates compressive stress. Strain gages placed in center of weld seam.

VI. DISCUSSION OF RESULTS

The elastic-plastic strain relationships during welding are extremely complex inasmuch as they are influenced by a great many variables, most of which are dependent. In spite of this complexity, the results of the work performed under this contract definitely proved the feasibility of applying the concept of balancing thermal stresses during welding to control distortion and residual stresses. The optimum thermal pattern for a specific weldment can be developed through a combination of theoretical and empirical methods. Undoubtedly, after sufficient empirical data have been generated, it will be possible to establish a pattern for a proposed weldment entirely upon the basis of mathematical formulae. However, in the meantime, it will be necessary to establish these patterns for important weldments on the basis of analysis of patterns developed experimentally on simulated parts.

It is also necessary that further work be performed to improve the mechanical means of altering thermal patterns even though the systems developed during this program can be used with a fair degree of reliability and repeatability.

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APPENDIX A. ANALYTICAL STUDY OF THEORETICAL PATTERNS

Selection of Approach

The approach adopted for Phase I of the program was to use empirical data developed under Contract NAS8-11930 as the starting point for calculation of the thermal patterns in Phases II and III.

Selection of Empirical Data

Data developed for two weld panels made under Contract NAS8-11930 were selected as the basis for calculation. These weld panels were fabricated by joining two pieces of 48 x 6 x 5/16-inch 2014-T6 aluminum plate in the horizontal position using the DC-SP TIG welding process. Both panels were welded in one pass adding 3/64-inch diameter 2319 filler wire. Minimum restraint was used during welding. One panel was welded without chilling and the other panel was locally chilled by impingement of liquid CO_2 jets on the front side of the weldment during the welding operation. Welding parameters, chilling data and flatness measurements are shown in Table A-I and the thermal patterns are depicted in Figure A-1.

Calculation of Target Thermal Pattern

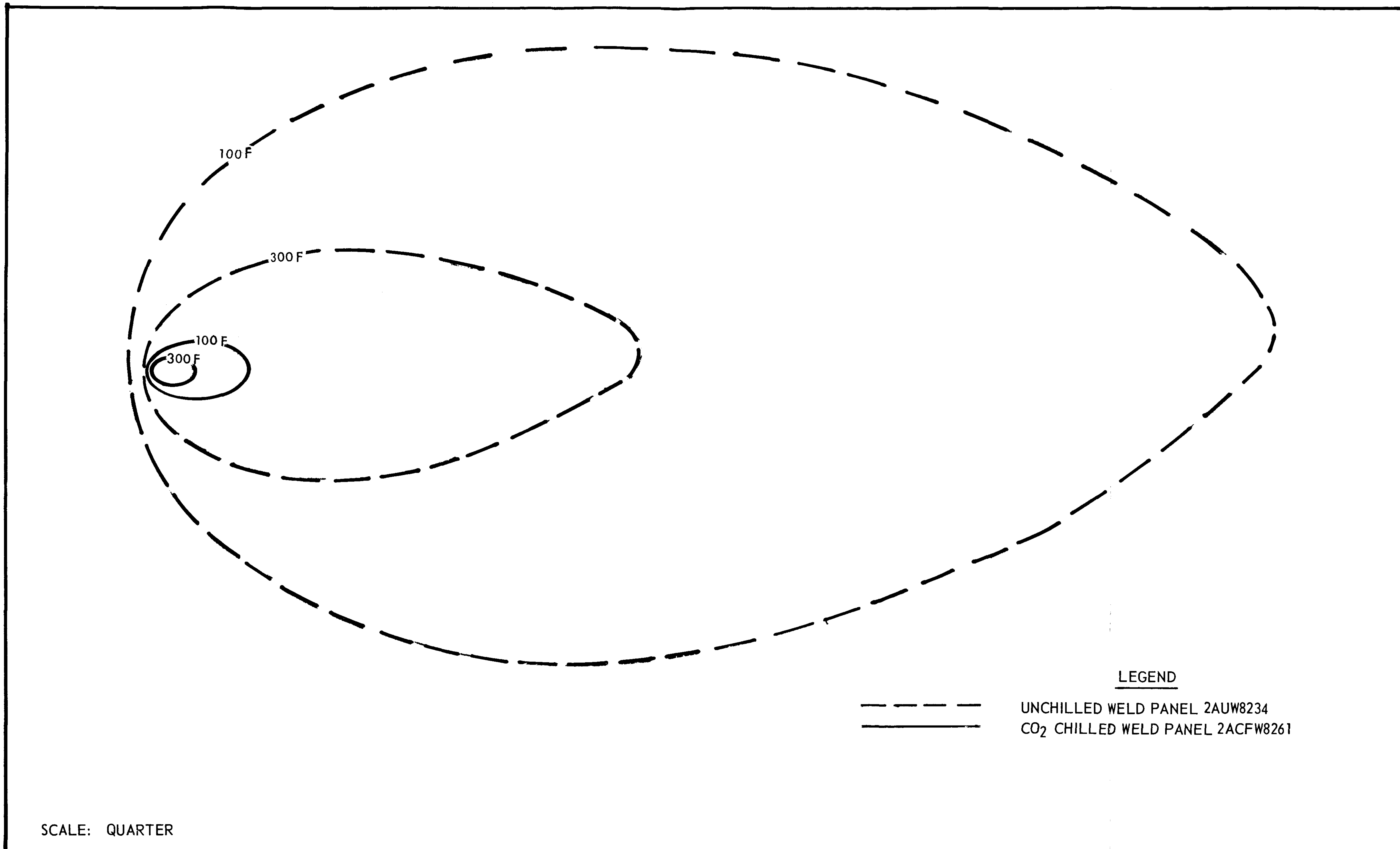
Approach.- By using the data from the welds depicted in Table A-I, heat flow constants pertaining to the specific setup to be used for welding experimental panels were established empirically pending further work to permit mathematical determination through computer analysis after sufficient additional data can be obtained.

The first thermal pattern to be used for experimental work was based on alteration of heat extraction attained for weld panel 2ACFW8261. Additional amounts of liquid CO_2 were used to reduce the area of metal heated to a temperature above 100 deg. F. to the minimum permitted by the physical dimensions of the shielding device and to lower

TABLE A-I. Welding Parameters

	2AUW8234 (unchilled)	2ACFW8261 (chilled)
Amperage	210	215
Voltage	12.5	12.0
Welding Speed	11.0 in./min.	7.0 in./min.
Wire Feed Speed	80.0 in./min.	80.0 in./min.
CO_2 Jet System	---	No. 19
Lb. CO_2/in. of Weld	---	1.27 lb/in.
Longitudinal Bow (in./48inches)	5/8	0
Peaking (degrees)	2.3	0.5
Lateral Shrinkage (in 1-in. across weld seam)	1/64-in.	1/64-in.

sufficient areas of the weld panel to a temperature of -100 deg. F. In this way, shrinkage due to weld metal solidification and thermal contraction could be counter-bananced by subsequent expansion of the chilled areas to reduce stresses to zero. Figure A-2 shows the pattern obtained for weldment 2ACFW8261 superimposed on the area in which chilling below 100 deg. F. is not possible due to the physical limitations of the shielding device (2-in. center of the weld puddle). While it may not be possible to produce this pattern in the exact proportions shown, previous work indicated that zero degree temperatures at a distance of 3/4-in. from the weld centerline are obtainable.



FOLDOUT FRAME 1

Figure A-1. Comparison of Thermal Patterns for Unchilled Weld and CO_2 Chilled Welds (Jet System No. 19) in 5/16-in. Thick Aluminum Plate

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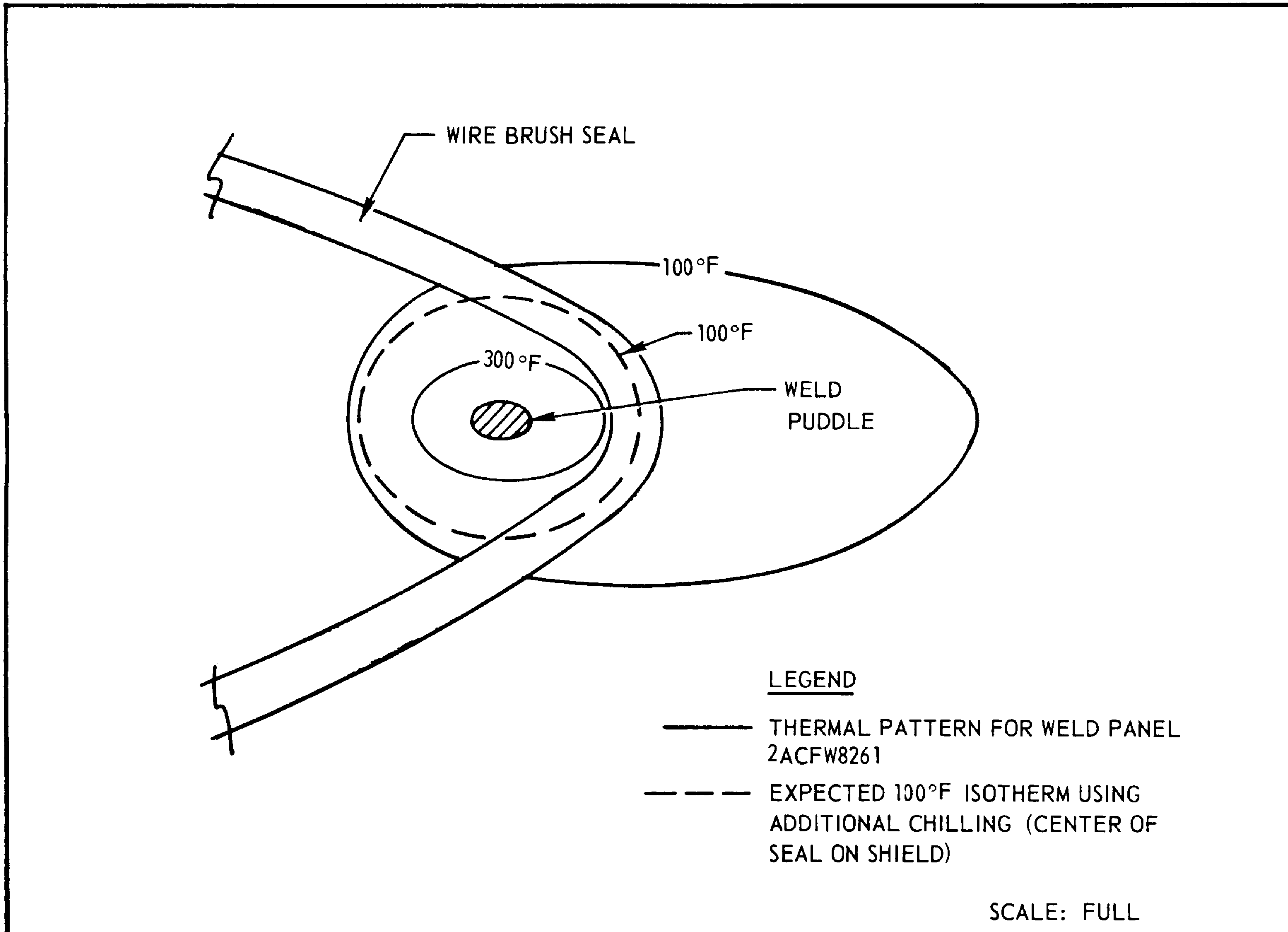


Figure A-2. Proposed Alteration of Thermal Pattern of Weld Panel 2ACFW8261 to Obtain Zero Warpage and Residual Stress

Using this proposed pattern, the additional amount of liquid CO_2 cooling required to counterbalance shrinkage is calculated as shown in the following paragraphs:

Formulas

$$CO_2 = \frac{PCVT}{HE} \quad (1)$$

CO_2 = lb. of liquid CO_2 required per in. of weld.

P = density of aluminum plate = 0.090 lb/in.^{3}

C = specific heat of plate = 0.025 Btu/lb.

V = volume of metal to be chilled to -100°F.

T = temperature change = 200°F. (100°F. to -100°F.)

H = sensible heat of liquid CO_2 = 139 Btu/lb.

E = chilling efficiency of liquid CO_2 jet system = 50%

$$V = (L_t + L_l)\, t \quad (2)$$

V = volume of metal chilled to -100°F.

L_t = length of plate 2-in. wide chilled to -100°F. to counteract transverse shrinkage.

L_l = length of plate 2-in. wide chilled to -100°F. to counteract longitudinal shrinkage.

t = thickness of plate

$$Le = \frac{S}{2\, a_l\, (T_l - T_0)} \quad (3)$$

Le = length of plate 2-in. wide chilled to -100°F. to counteract transverse or longitudinal shrinkage.

a_1 = coefficient of thermal expansion of plate in the range of -100°F. to +100°F.

= 12 x 10-6 in. per in. per deg. F.

= total linear shrinkage of the plate portion heated during welding.

$T_0 - T_1$ = available temperature change = 200°F.

T_1 = temperature to which area is to be chilled -100°F.

T_0 = temperature of area before applying additional chilling = +100°F.

$$S_w = X_1 s \qquad (4)$$

S_w = shrinkage of weld metal in changing from liquid to solid at room temperature.

X_1 = width or length of weld puddle

s = coefficient of linear shrinkage - 0.05

$$S_p = X_2\, a_2\, (T_a - T_0) \qquad (5)$$

S_p = shrinkage of aluminum plate in cooling from temperature attained during welding to 100°F.

a_2 = coefficient of thermal expansion of plate the range of T_a to T_0.

X_2 = length of 2-in. wide strip to plate cooled from T_a to T_0.

T_a = average temperature of heated area of plate.

T_0 = final temperature of plate = +100°F.

$S_r = X_3 a_3 (T_b - T_0)$ (6)

a_3 = coefficient of thermal expansion of plate cooled from T_b to T_0.

X_3 = length of 2-in. wide strip of plate to be cooled from T_b to T_0.

T_b = average temperature of heated area of plate = 300^oF.

T_0 = final temperature of plate = 100^oF.

$S = S_w + S_p + S_r$ (7)

S = total linear shrinkage of the portion of plate heated during welding.

Calculations for Balancing Transverse Shrinkage

Total Linear Shrinkage.-

$S = S_w + S_p + S_r$ (7)

$= X_1 s + X_2 a_2 (T_a - T_0)$ (4) + (5)

$X_1 = 0.25$ in.

$S = 0.05$

$X_2 = 2.0$ in.

$a_2 = 14 \times 10\text{-}6$ in. per in. per deg. F.

$T_a = 1000^oF$.

$T_0 = 100^oF$.

$S_r = 0$

$= 0.250 \times 0.05 + 2.0 \times 14 \times 10\text{-}6 \times 900$

$= 0.0125 + 0.0252 = 0.0377$ in. total linear shrinkage transverse to the weld.

Area to be Chilled to -100°F. to Counteract Transverse Shrinkage.-

$$Le = 2 \frac{S}{a_1 (T_0 - T_1)}$$

$a_1 = 12 \times 10\text{-}6$ in. per in. per deg. F.

$S = 0.0377$ in.

$T_0 = +100°F.$

$T_1 = -100°F.$

$$Le = \frac{0.0377}{2 \times 12 \times 10\text{-}6 \times 200} = 8\text{-in. long strip}$$

2-in. wide (or 4 inches on each side of the weld).

CO_2 Required.-

$$CO_2 = \frac{PCVT}{HE}$$

$$= \frac{0.090 \times 0.25 \times 8 \times 2 \times 0.312 \times 200}{139 \times 0.5}$$

= 0.33 lb./per in. of weld required to counterbalance transverse shrinkage.

Calculations for Balancing Longitudinal Shrinkage

Total Linear Shrinkage.-

$$S = S_w + S_p + S_r \qquad (7)$$

$$= X_1 \, s + X_2 \, a_2 \, (T_a - T_0) + X_3 \, a_3 \, (T_b - T_0) \qquad (4), (5) \; \& \; (6)$$

$X_1 = 0.5$ | $x_2 = 2.0$ in.

$s = 0.05$ | $a_2 = 14 \times 10\text{-}6$ in. per in. per deg. F.

$X_3 = 2.5$ in.

$a_3 = 12.5 \times 10\text{-}6$ in. per in. per deg. F. | $T_a = 1000^{\circ}$F.

$T_b = 300^{\circ}$ F.

$T_0 = 100^{\circ}$ F.

$$= 0.5 \times 0.05 + 2.0 \times 14 \times 10\text{-}6 \times (1000 - 100) + 2.5 \times 12.5 \times 10\text{-}6 \; (300 - 100)$$

$= 0.025 + 0.0252 + 0.006 = 0.056$-in. total longitudinal shrinkage.

<u>Area to be Chilled to -100°F. to Counteract Longitudinal Shrinkage</u>.-

$$Le = \frac{S}{2a_1 \; (T_0 - T_1)} \qquad (3)$$

$S = 0.056$-in.

$a_1 = 12 \times 10\text{-}6$ in. per in. per deg. F.

$T_0 = +100^{\circ}$F.

$T_1 = -100^{\circ}$F.

$$= \frac{0.056}{2 \times 12 \times 10\text{-}6 \times 111.1} = \text{12 in. long strip 2-in. wide}$$

CO_2 Required

$$CO_2 = \frac{PCVT}{HE}$$

$$= \underline{0.090 \times 0.25 \times 12 \times 2 \times 0.312 \times 111.1}$$

= 0.49-lb. per inch of weld to counterbalance longitudinal shrinkage.

Chilling System Design

Based on calculations shown under preceding "CO_2 Required," the jet system used to produce weld panel 2ACFW8261 was modified in accordance with the schematic drawing shown in Figure A-3. This jet system would provide chilling to the front side of the weld using a fine wire brush as a sliding shield to keep CO_2 out of the arc. Actual design of the new jet system and shielding device included provisions for making adjustments to change the thermal pattern as required to accomplish the objectives of the program. Redesign for stability during operation and reproducibility of chilling parameters was also performed.

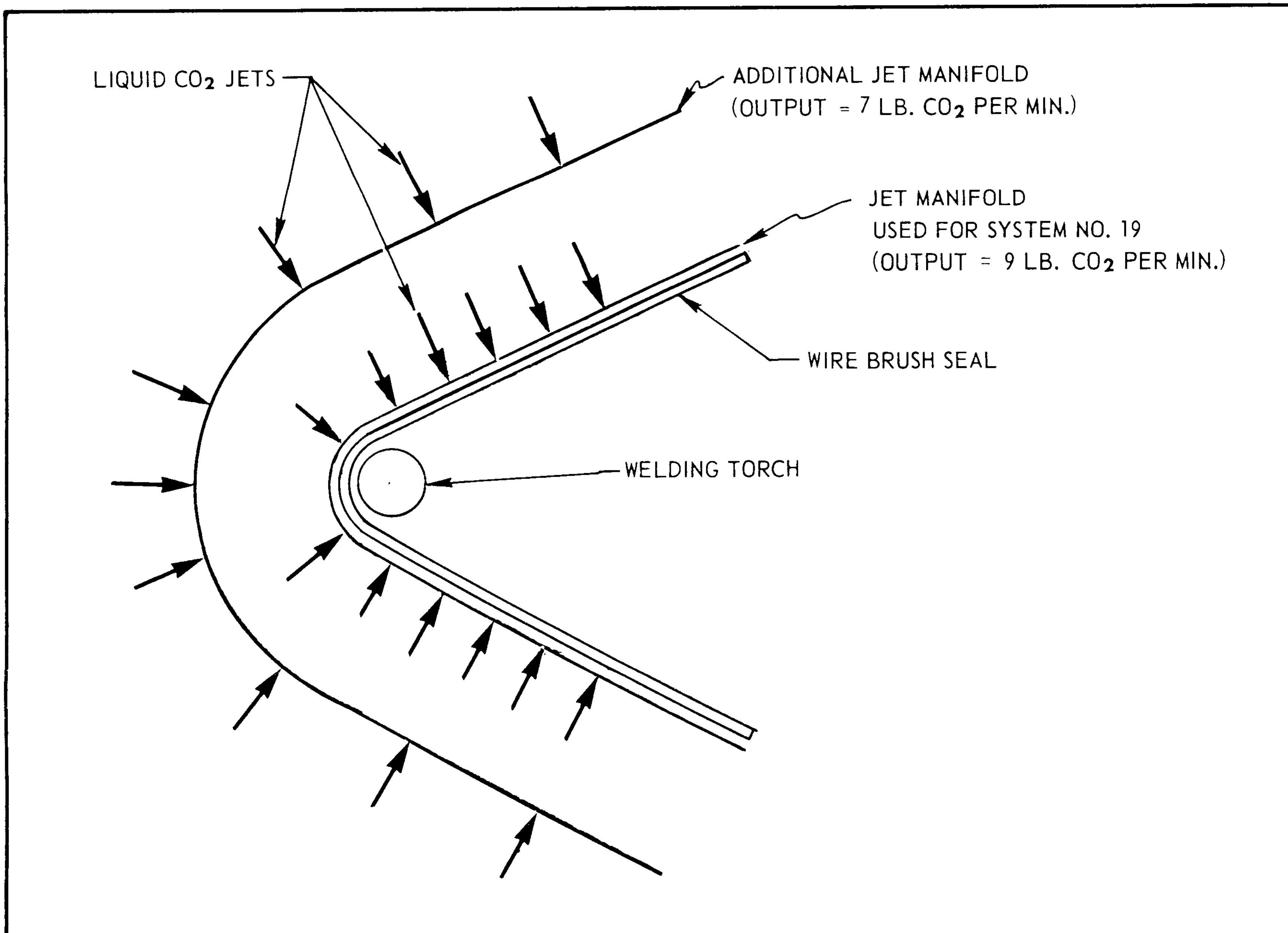


Figure A-3. Proposed Modification of Jet System No. 19.

APPENDIX B. EQUIPMENT AND INSTRUMENTATION

Equipment

Existing equipment was modified for welding test panels from one side in the horizontal position. The basic equipment consisted of a Miller Model 600/1200 Power Supply, a Miller High Frequency Unit, a Berkeley-Davis Side Beam and Carriage System, an Airco TIG Welding Torch and Wire Feed System (with mounting brackets), a fixture for 48-in. x 12-in. weld panels, a cryogenic jet spray system with suitable brackets and attachments for mounting the chilling systems.

Welding Power Supply.- A Miller Duplex Welder, Model No. 600/1200 (d-c rectifier-type), with superimposed high frequency, was used to supply the welding current.

Side Beam and Carriage System.- A 12-ft. Berkeley-Davis System Model No. TC4 was mounted on a rectangular support frame which was anchored to the floor. Side beam carriage speed was controlled by an Electronic Governor (Model EG-3) for travel speeds ranging from 4.4 to 72.01 inches per minute.

Welding Torch.- An Airco Proximity Control, Model HMH-F Heliweld Unit, with metallic nozzles of 5/8-in. and 1/2-in. orifices, was adapted for semi-automatic welding using 5/32 and 3/16-in. two-percent thoriated tungsten electrodes.

Wire Feed.- An Airco filler wire feed with wire positioner was installed on the carriage system and fitted for 3/64 and 1/16-in. wire.

Panel Fixture.- The fixture for positioning the weld panels in the horizontal position consisted of a frame fabricated from 3 x 3 x 1/4-in. stainless steel angle iron with a "free" area of 4 inches on each side of the weld centerline. The panels were clamped to the fixture by means of angle clamps for "unrestrained" welding; or they were bolted to the stainless steel frame to provide restraint. The frame was held in side mounts which are independently adjustable to enable precise alignment of the weld seam.

Chilling Systems and Heating Systems.- Figures B-1 through B-4 show the variations of the chilling and heating systems used for the experimental work. Jets of various orifice size, flexible hose, and liquid CO_2 in 250-lb. tanks were used in conjunction with these systems. An attachment bracket for positioning the jets was mounted on the weld carriage system for use on either the front or back side of the weld. The location and number of jets were adjustable.

Instrumentation

Welding Speed.- An optical tachometer, utilizing light reflections from the carriage drive motor shaft, was used to monitor welding speed. The reflected light is directed into a photocell from which a signal is converted into revolutions per minute by a Hewlett-Packard Frequency Meter, Model 500C. This motor speed is then calibrated in terms of travel speed in inches per minute.

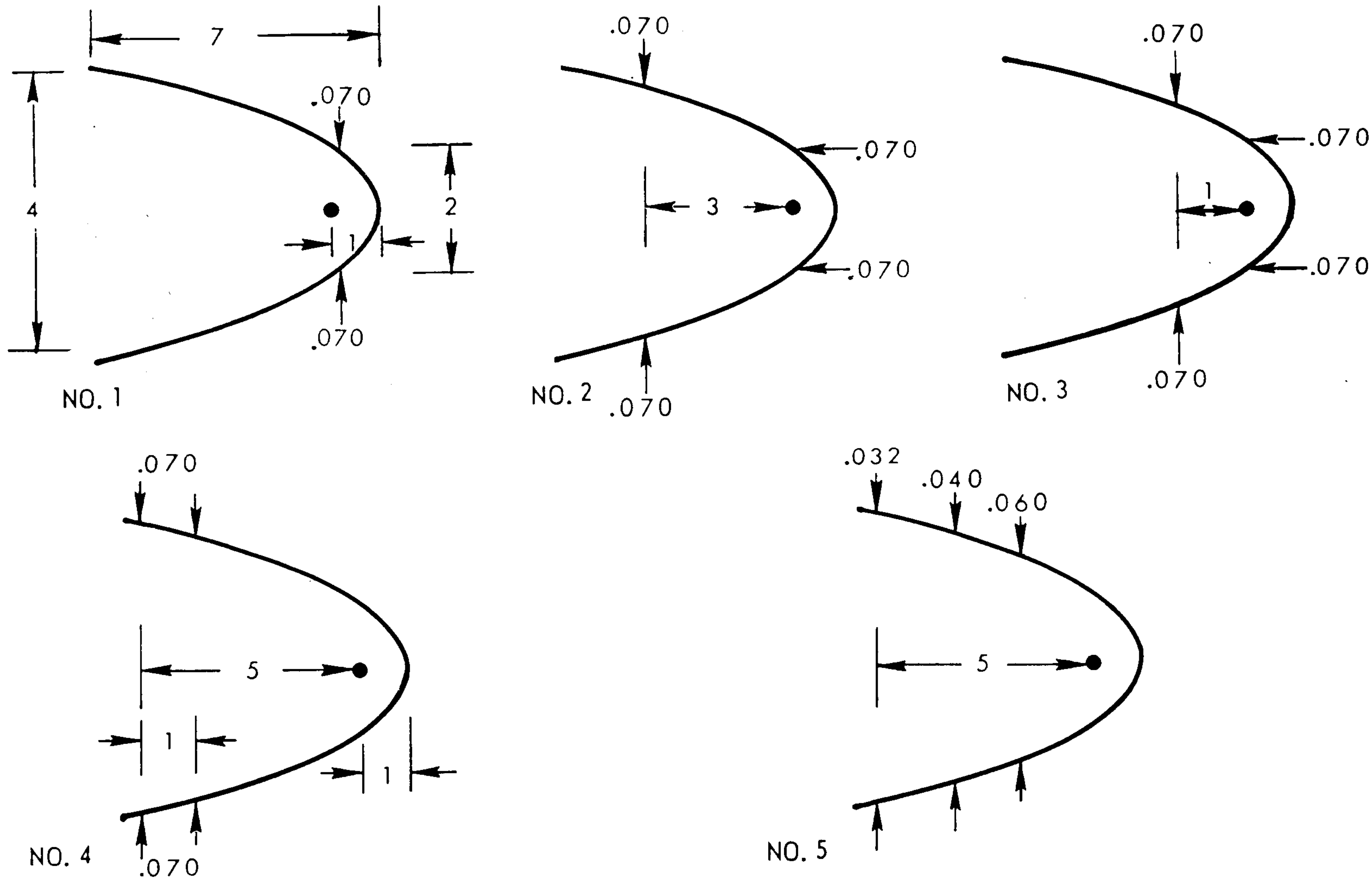
Welding Current.- A Weston D-C Ammeter, Model 1, with a 750-amp. shunt was installed in the workpiece ground lead, which, in conjunction with a Weston D-C Voltmeter Model 1, monitors the welding current.

Six-Channel Recorder.- A Model RA-1152-60 Six-channel Brush Recorder was used for recording weld panel temperatures. The Brush Recorder is composed of one Model RD-2662-00 Chart Recorder, six Model RD-5612-00 Amplifiers and six Model RA-5212-00 Input Boxes.

Resistance Thermometers.- BLH Electronics' Type RTPW-28-5 Platinum Resistance Thermometers were used in conjunction with the Brush Recorder for measuring weld panel temperatures.

Strain Indicator.- A BLH Electronics Type N Strain Indicator was used in conjunction with strain gages for measuring residual stresses.

Strain Gages.- BLH Electronics SR-4, Type A-7, Strain Gages were used for the major portion of the work. During the latter part of the program, the adhesive-backed Budd Type C12-142B Metalfilm Strain Gages were used inasmuch as the adhesive could be successfully cured in a very short time.



NOTES: 1. UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE INCHES.
2. UNLESS OTHERWISE SPECIFIED, ALL JETS ARE SPACED 1-IN. APART.
3. UNLESS OTHERWISE SPECIFIED, RADIUS OF BASE OF INNER PARABOLA IS 1-IN.; RADIUS OF BASE OF OUTER PARABOLA IS 2-IN.

Figure B-1 Chilling Systems - V-shaped (contd)

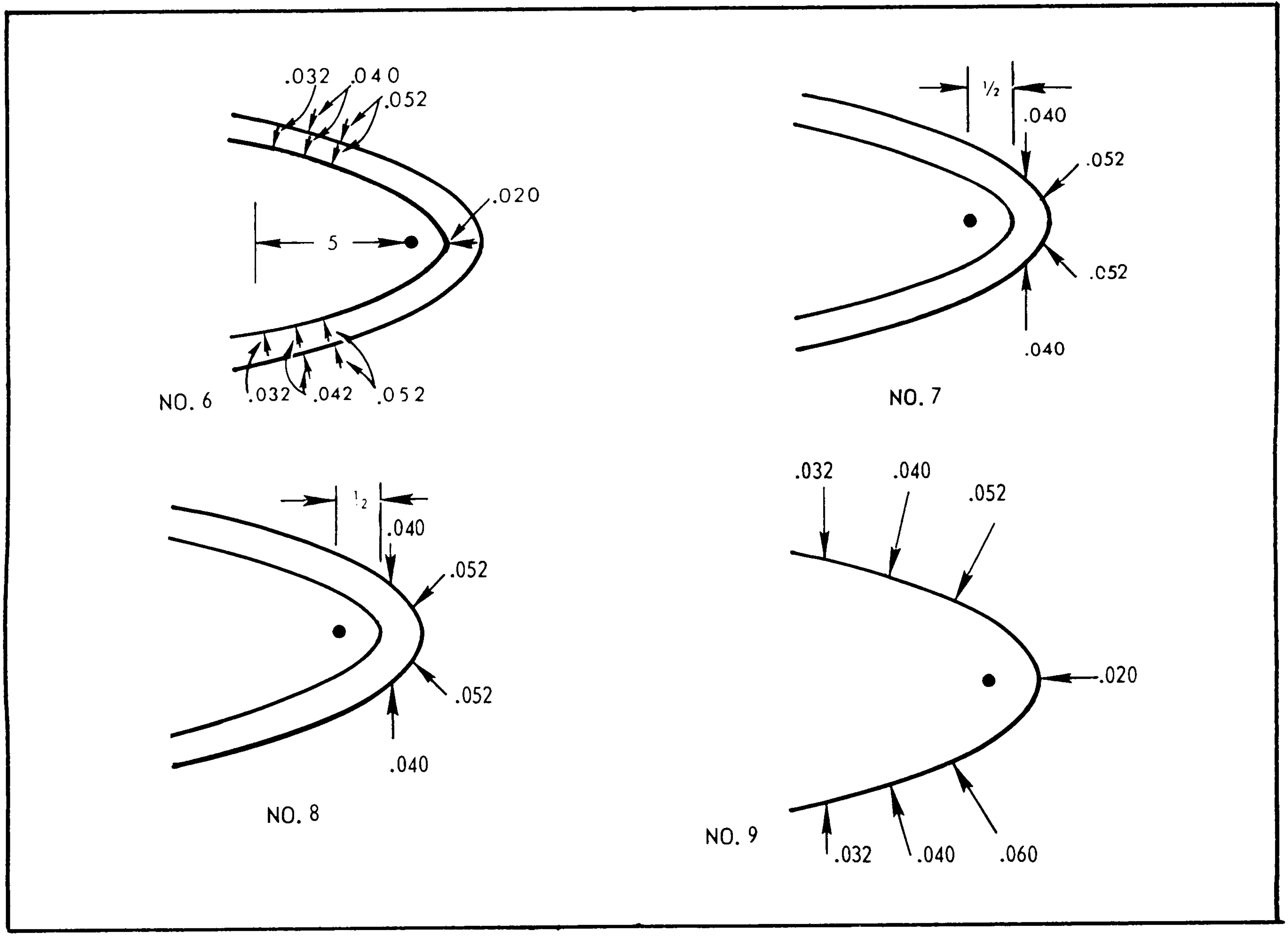


Figure B-1 (contd)

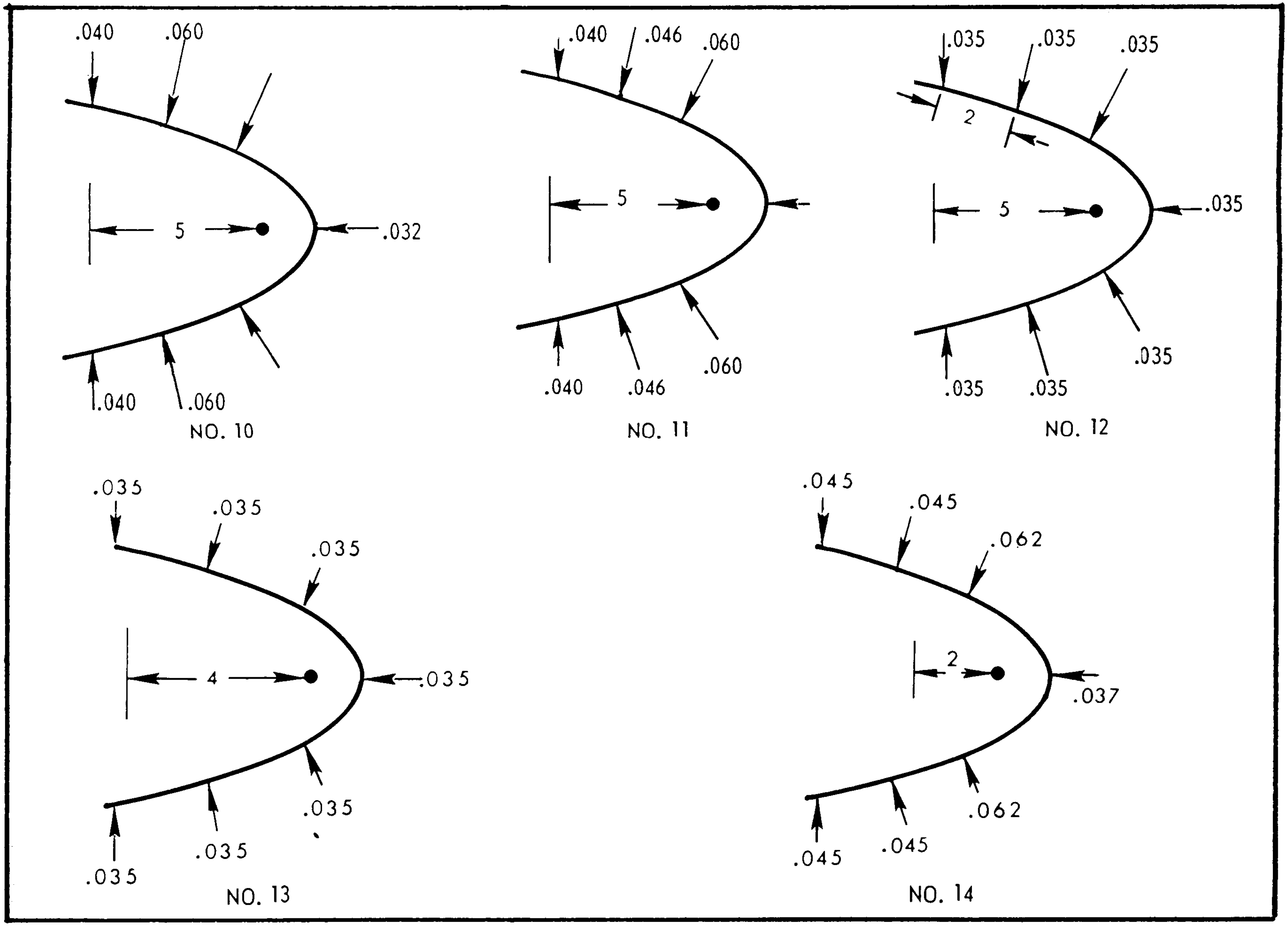
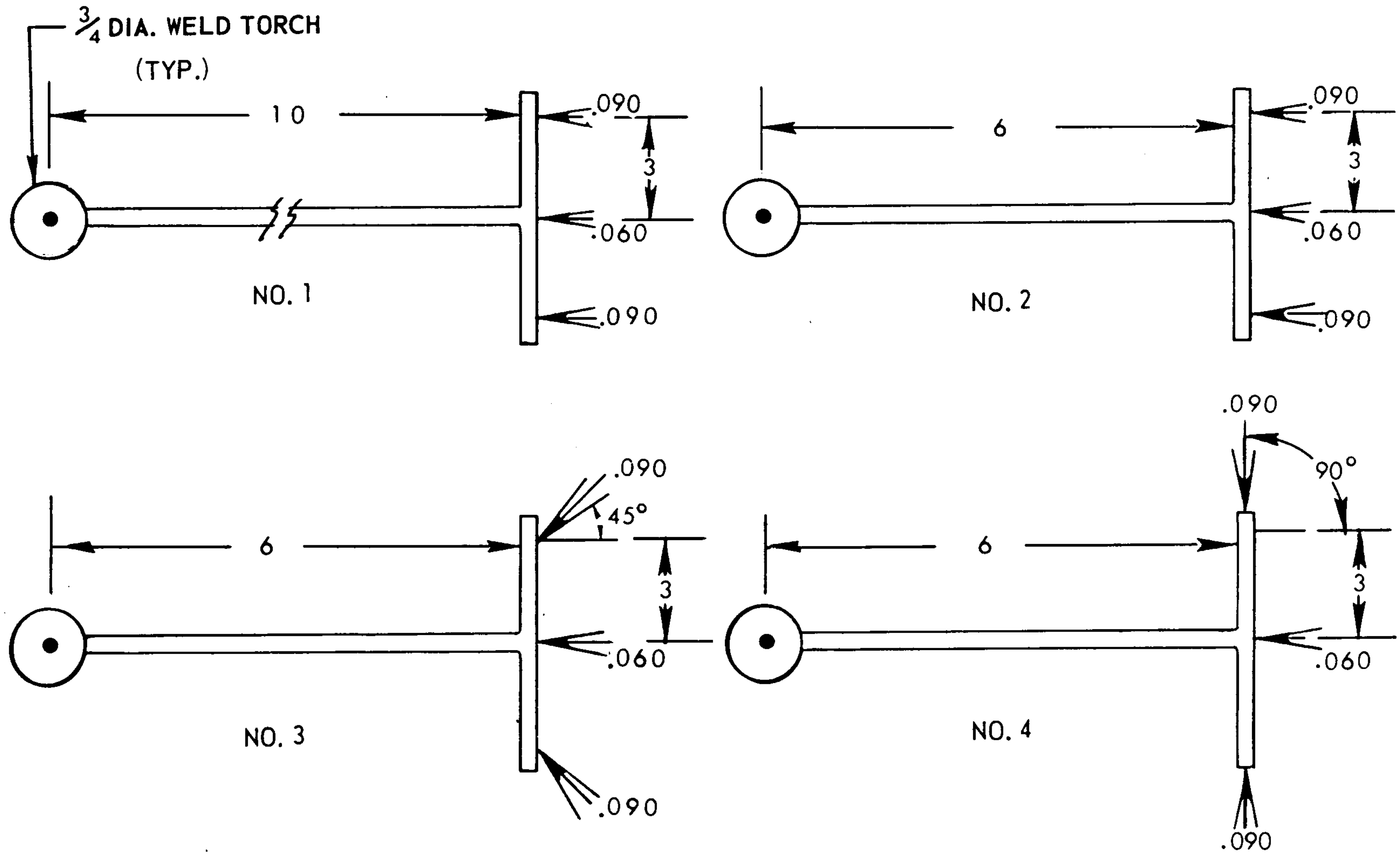


Figure B-1 (concluded)



NOTES: 1. UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE INCHES.
2. UNLESS OTHERWISE SPECIFIED, ALL JETS ARE SPACED 1-IN. APART.

Figure B-2. Chilling Systems - Trailing (contd)

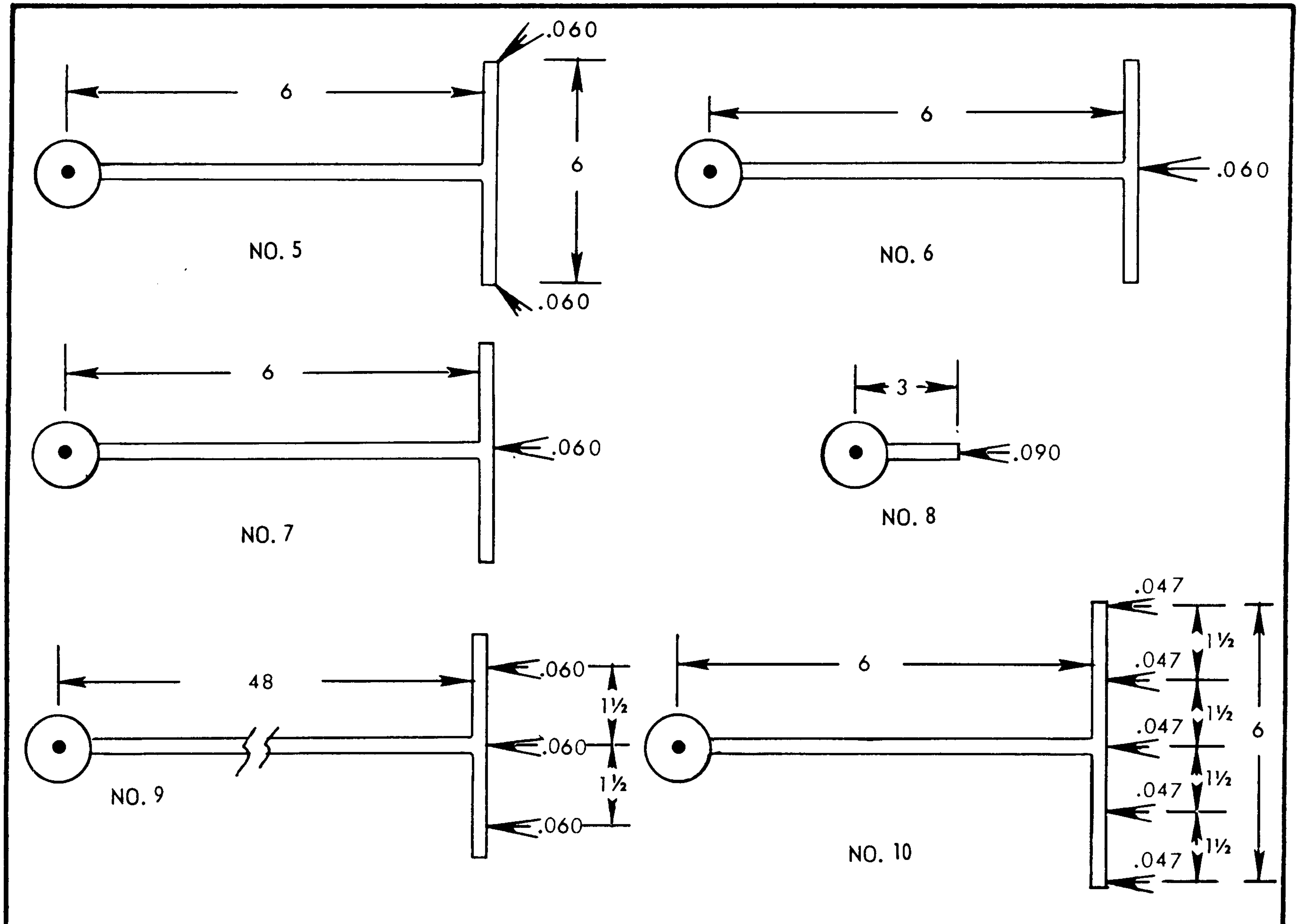


Figure B-2 (contd)

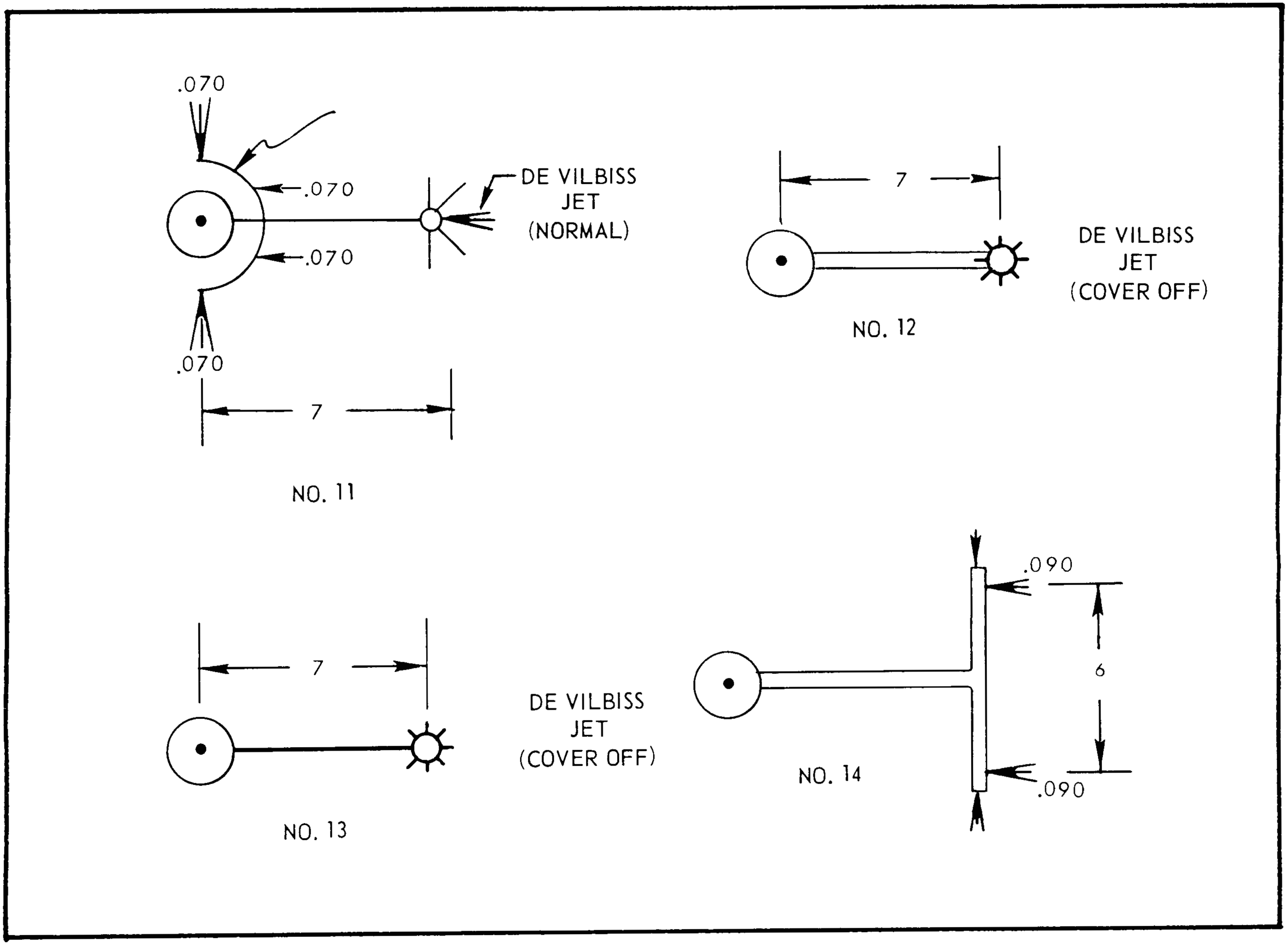
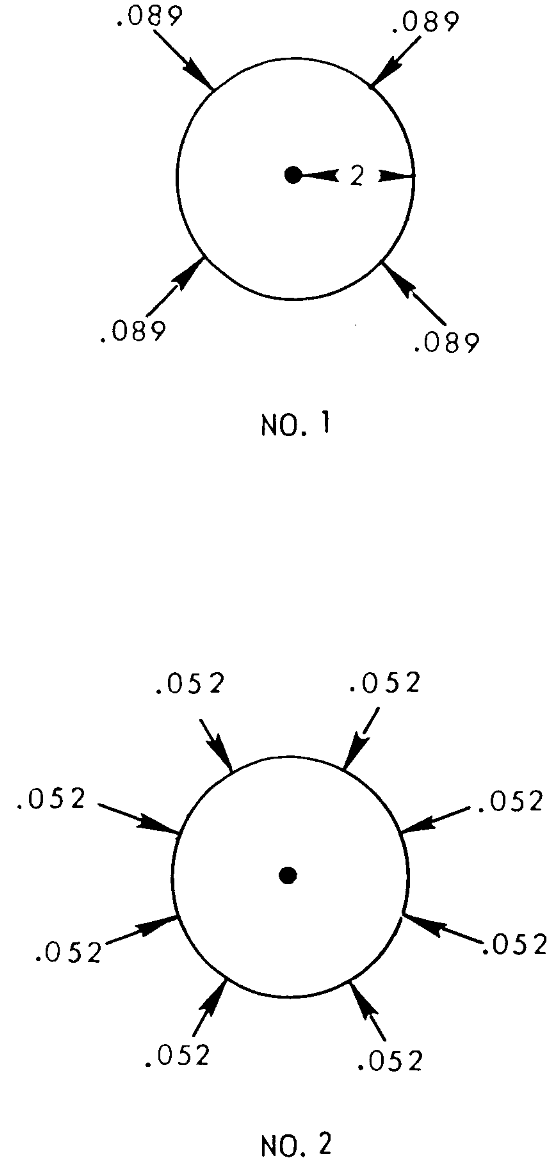


Figure B-2 (concluded)



NOTES: 1. UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE INCHES.
2. UNLESS OTHERWISE SPECIFIED, ALL JETS ARE SPACED 1-IN. APART.

Figure B-3. Chilling Systems - Circular

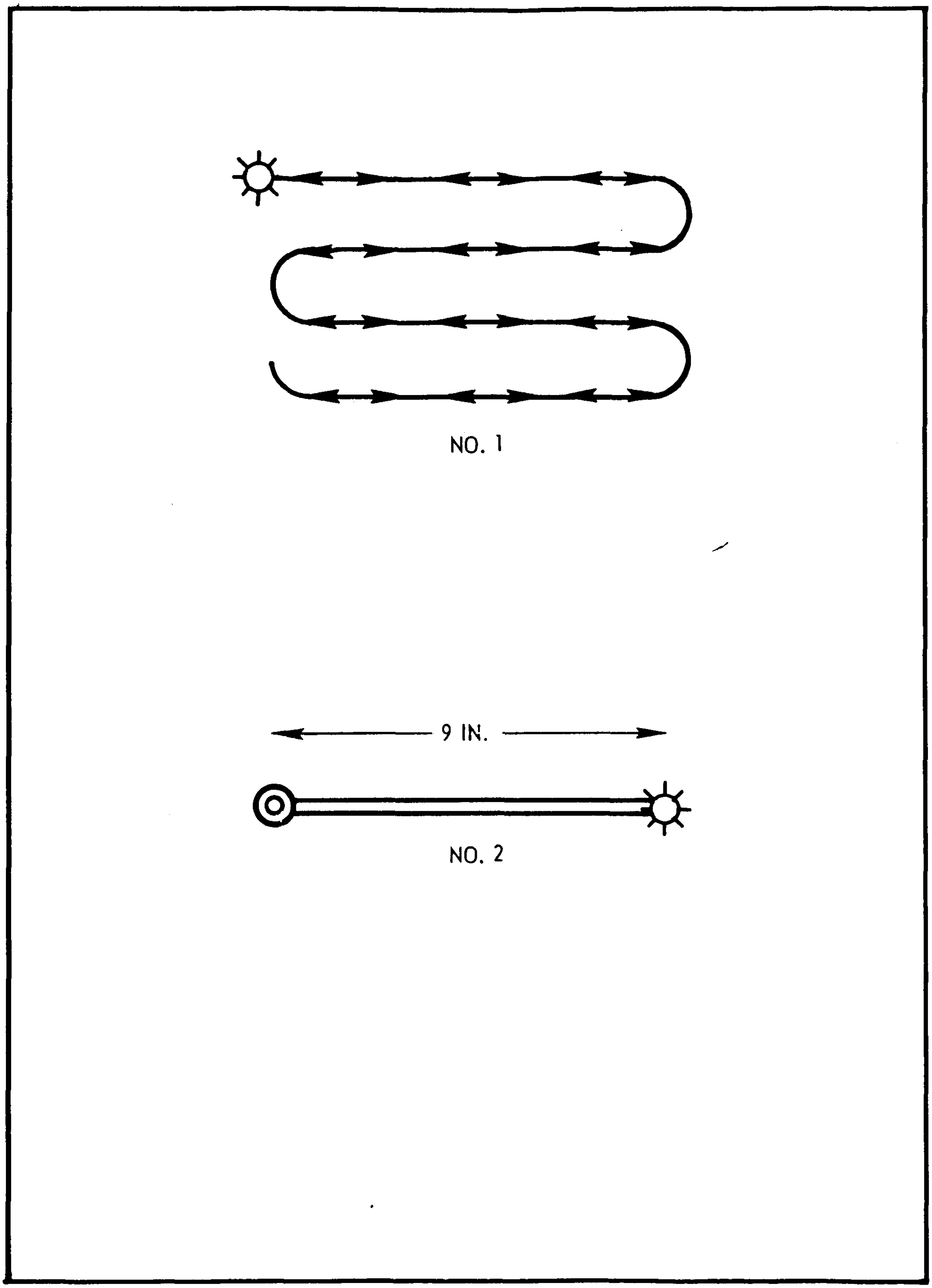


Figure B-4. Auxiliary Heating Systems

APPENDIX C

EXPERIMENTAL DATA

TABLE C-1. Warpage of Unchilled Panels

Weld Panel Parameters									Experimental Results	
Panel No.	Amps	Volts	Travel(1) Speed	Restraint(2) System	Chilling		Heating		Warpage (6)	
					System (3)	CO_2 (4)	System (3)	Temp.(5)	Bow	Peak
56-2	225	14.0	11.3	2 Sides	None	– – –	Preheat	200	– 0.8	0.0
51-1	225	14.5	9.6	2 Sides	None	– – –	None	– – –	– 0.4	+ 1.6
38-3	250	13.0	9.6	4 Sides	None	– – –	None	– – –	0.0	0.0
38-2	250	13.0	9.3	2 Sides	None	– – –	None	– – –	0.0	0.0
38-1	250	13.0	9.3	None	None	– – –	None	– – –	– 0.2	0.0
228-2	200	13.0	6.2	None	None	– – –	None	– – –	– 0.4	+ 1.2
228-1	200	13.0	6.2	None	None	– – –	None	– – –	– 0.4	+ 1.2
226-2	250	13.5	9.0	None	None	– – –	None	– – –	– 0.4	+ 1.2
222-4	235	14.0	6.0	None	None	– – –	None	– – –	– 0.8	+ 1.2
216-3	250	12.5	10.2	None	None	– – –	None	– – –	– 0.8	+ 1.2

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Angles in degrees. Plus sign (+) indicates bowing or peaking toward front side of front weld; minus sign (–) indicates bowing or peaking away from front of weld.

TABLE C-II. Residual Stress in Unchilled Panels

Weld Panel Parameters									Experimental Results (6)	
Panel No.	Amps	Volts	Travel Speed (1)	Restraint System (2)	Chilling		Heating		Long.	Transv.
					System (3)	CO_2 (4)	System (3)	Temp. (5)		
56-2	225	14.0	11.3	2 Sides	None	– – –	Preheat	200	+22,500	–12,300
51-1	225	14.5	9.6	2 Sides		– – –	None	– – –	+18,200	–11,300
38-3	250	13.0	9.6	4 Sides		– – –	None	– – –	+17,600	– 7,000
38-2	250	13.0	9.3	2 Sides		– – –	None	– – –	+21,600	– 7,300
38-1	250	13.0	9.3	None		– – –	None	– – –	+20,600	– 6,000
228-1	200	13.0	6.2	None		– – –	None	– – –	+20,000	– 3,000
226-2	250	13.5	9.0	None		– – –	None	– – –	+23,000	– 7,300

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahreheit.
6. Pounds per square inch. Plus sign (+) indicates stress in tension; minus sign (–) indicates stress on compression.

TABLE C-III. Warpage of Panels Chilled from Front Side

Weld Panel Parameters									Experimental Results	
Panel No.	Amps	Volts	Travel Speed (1)	Restraint System (2)	Chilling System (3)	Chilling CO_2 (4)	Heating System (3)	Heating Temp. (5)	Warpage (6) Bow	Warpage (6) Peak
56-1	220	15	10.5	2 Sides	Trail. #1	75	None	---	-1.0	+2.0
319-1	250	13	9.6	None	Trail. #5	---	None	---	0.0	0.0
318-3	250	13	8.7	None	Trail. #6	70	None	---	-1.0	+1.0
318-2	250	13	7.0	None	Trail. #7	45	None	---	-1.0	+1.0
318-1	250	13	8.0	None	Trail. #8	131	None	---	-0.2	+0.6
315-1	250	13	9.6	None	Trail. #9	---	None	---	0.0	0.0
314-1	250	12.5	10.3	None	Trail. #9	---	None	---	0.0	0.0
313-1	245	13	9.6	None	Trail. #10	85	None	---	-0.1	0.0
37-1	250	13.5	7.0	None	Trail. #11	131	None	---	-0.1	+0.3
36-4	245	13	8.7	None	V #1	31	None	---	-0.2	+0.8
36-3	245	13	8.7	None	V #2	61	None	---	-0.2	+0.8
36-2	250	13	7.8	None	V #3	63	None	---	-0.2	+1.1
36-1	245	14	7.4	None	V #4	85	None	---	-0.8	+0.6
35-2	235	14	8.0	None	Trail. #12	105	None	---	-0.4	+0.9
35-1A	245	13.5	8.3	None	Trail. #13	30	None	---	-0.1	+0.3
226-1	250	14	8.0	2 Sides	V #5	64	None	---	-0.4	+0.6
222-5	245	13	8.0	None	V #5	55	None	---	-0.8	+0.6
223-3	240	13	5.8	None	V #6	101	None	---	-0.9	+1.2
222-2	235	13	5.1	None	V #7	30	None	---	-0.8	+1.6
222-1	245	13	5.1	None	V #8	165	None	---	-1.2	+3.5
220-4	248	14	6.7	None	V #9	61	None	---	-1.2	+1.2
220-3	240	13.5	5.1	None	V #10	64	None	---	-0.9	+1.2
220-2	250	12.5	7.4	None	V #5	41	None	---	-0.8	+0.6
220-1	245	12.5	8.0	None	V #11	58	None	---	-0.9	+1.2
216-2	225	13.5	6.4	None	V #12	103	None	---	-1.2	+1.2
215-1	245	13.5	9.6	None	V #13	---	None	---	-0.8	+2.4
818-1	220	12.5	9.6	None	V #14	74	None	---	0.0	0.0

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Angles in degrees. Plus sign (+) indicates bowing or peaking toward front side of front of weld; minus sign (-) indicates bowing or peaking away from front of weld.

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FOLDOUT FRAME

FOLDOUT FRAME 2

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TABLE C-IV. Residual Stresses in Panels Chilled from Front Side

Weld Panel Parameters									Experimental Results (6)	
Panel No.	Amps	Volts	Travel Speed (1)	Restraint (2) System	Chilling System (3)	Chilling CO_2 (4)	Heating System (3)	Heating Temp. (5)	Long.	Transv.
56-1	220	15	10.5	2 Sides	Trail. #1	75	None	- - -	+15,000	-10,000
319-1	250	13	9.6	None	Trail. #5	- - -	None	- - -	+16,700	- 5,800
318-3	250	13	8.7	None	Trail. #6	70	None	- - -	+17,400	- 2,400
318-2	250	13	7.0	None	Trail. #7	45	None	- - -	+16,100	- 1,800
318-1	250	13	8.0	None	Trail. #8	131	None	- - -	+14,600	- 2,900
315-1	250	13	9.6	None	Trail. #9	- - -	None	- - -	+16,200	- 1,600
314-1	250	13.5	10.3	None	Trail. #9	- - -	None	- - -	+17,900	- 8,000
313-1	245	13	9.6	None	Trail. #10	85	None	- - -	+12,200	- 7,600
37-1	250	13.5	7.0	None	Trail. #11	131	None	- - -	+20,500	- 3,100
35-2	235	14	8.0	None	Trail. #12	105	None	- - -	+19,700	- 2,900
35-1A	245	13.5	8.3	None	Trail. #13	30	None	- - -	+16,800	- 3,600

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Pounds per square inch. Plus sign (+) indicates stress in tension; minus sign (−) indicates stress in compression.

TABLE C-V. Warpage of Panels Chilled from Back Side

Weld Panel Parameters									Experimental Results	
Panel			Travel (1)	Restraint (2)	Chilling		Heating		Warpage (6)	
No.	Amps	Volts	Speed	System	System (3)	CO_2 (4)	System (3)	Temp. (5)	Bow	Peak
429-2	300	16.0	13.2	None	Circ. #1	76	None	- - -	-0.8	+0.6
429-1	325	15.0	13.7	None	Circ. #1	80	None	- - -	0.0	0.0
223-2	250	12.5	8.2	None	V #5	41	None	- - -	-0.8	+0.6

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Angles in degrees. Plus sign (+) indicates bowing or peaking toward front side of front weld, minus sign (−) indicates bowing or peaking away from front of weld.

TABLE C-VI. Residual Stresses in Panels Chilled from Back Side

Weld Panel Parameters									Experimental Results	
Panel No.	Amps	Volts	Travel Speed (1)	Restraint (2) System	Chilling		Heating		Residual Stresses (6)	
					System (3)	CO_2 (4)	System (3)	Temp. (5)	Long.	Transv.
429-2	300	16.0	13.2	None	Circ. #1	76	None	---	+20,300	---
429-1	325	15.0	13.7	None	Circ. #1	80	None	---	+19,760	-4,000
423-4	250	14.0	8.0	2 Sides	Circ. #1	---	None	---	+15,000	---
423-3	250	14.0	5.3	None	Circ. #2	195	None	---	+15,600	-4,700
422-1	250	13.0	9.6	None	Circ. #3	34	None	---	+11,900	-7,800

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Pounds per square inch. Plus sign (+) indicates stress in tension; minus sign (−) indicates stress in compression.

TABLE C-VII. Warpage of Panels Chilled from Front Side with Auxiliary Heating

Weld Panel Parameters									Experimental Results	
					Chilling		Heating		Warpage (6)	
Panel No.	Amps	Volts	Travel Speed (1)	Restraint System (2)	System (3)	CO_2 (4)	System (3)	Temp. (5)	Bow	Peak
514-1	250	14	9.6	2 Sides	Trail #1	90	Front #1	250	- 0.1	+0.1
57-1	225	15	10.7	2 Sides	Trail. #1	64	Front #1	200	0.0	-0.3
53-2	225	15	11.0	2 Sides	Trail. #1	69	Back #1	200	+ 0.3	0.0
53-1	225	15	10.0	2 Sides	Trail. #2	74	Back #1	200	+ 0.2	0.0
52-3	225	15	9.6	2 Sides	Trail. #3	75	Back #1	200	-10.1	0.0
52-2	210	15	9.6	2 Sides	Trail. #4	88	Back #1	200	- 0.9	+1.2
52-1	250	14	11.0	2 Sides	Trail. #4	85	Back #1	200	+ 0.9	-0.6
425-2	250	14	- - -	None	Trail. #4	85	Front #2	- - -	+ 0.8	-0.6

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Angles in degrees. Plus sign (+) indicates bowing or peaking toward front side of front weld; minus sign (-) indicates bowing or peaking away from front of weld.

TABLE C-VIII. Residual Stresses in Panels Chilled from Front Side with Auxiliary Heating

Weld Panel Parameters									Experimental Results	
Panel No.	Amps	Volts	Travel (1) Speed	Restraint(2) System	Chilling		Heating		Residual Stresses (6)	
					System(3)	CO_2 (4)	System(3)	Temp.(5)	Long.	Transv.
514-1	250	14	9.6	2 Sides	Trail. #1	90	Front #1	250	+2,300	- 100
57-1	225	15	10.7	2 Sides	Trail. #1	64	Front #1	200	+1,100	-2,100
53-2	225	15	11.0	2 Sides	Trail. #1	69	Back #1	200	+3,400	- 800
53-1	225	15	10.0	2 Sides	Trail. #2	74	Back #1	200	+1,900	+ 800
52-3	225	15	9.6	2 Sides	Trail. #3	75	Back #1	200	+9,200	-12,600
52-1	250	14	11.0	2 Sides	Trail. #4	85	Back #1	200	+6,000	-1,500

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch long weld.
5. Degrees Fahrenheit.
6. Pounds per square inch. Plus sign (+) indicates stress in tension; minus sign (−) indicates stress in compression.

TABLE C-IX. Tensile Properties

Weld Panel Parameters									Experimental Results		
			Travel (1)	Restraint (2)	Chilling		Heating		Tensile Properties		
Panel No.	Amps	Volts	Speed	System	Syst. (3)	CO_2 (4)	Syst. (3)	Temp. (5)	ys (6)	UTS (6)	e (7)
56-2	225	14	11.3	2 Sides	None	---	Preheat	200	26,600	42,100	5.5
228-1	200	13	6.2	None	None	---	None	---	27,400	43,100	6.0
226-2	250	13.5	9.0	None	None	---	None	---	28,500	41,200	4.0
Panels Chilled from Front Side											
56-1	220	15	10.5	2 Sides	Trail. #1	75	None	---	29,900	42,100	4.0
35-2	235	14	8.0	None	Trail. #12	105	None	---	34,500	45,200	5.0
35-1A	245	13.5	8.3	None	Trail. #13	30	None	---	36,600	40,400	5.0
215-1	245	13.5	9.6	None	V #13	---	None	---	35,500	45,500	6.0
Panels Chilled from Back Side											
423-3	250	14	5.3	None	Circ. #2	195	None	---	31,100	34,200	3.0
57-1	225	15	10.7	2 Sides	Trail. #1	64	Front #1	200	29,500	43,600	4.0
53-2	225	15	11.0	2 Sides	Trail. #1	69	Back #1	200	29,800	42,200	4.0
53-1	225	15	10.0	2 Sides	Trail. #2	74	Back #1	200	31,600	43,100	---
52-3	225	15	9.6	2 Sides	Trail. #3	75	Back #1	200	30,200	44,400	4.0
52-1	250	14	11.0	2 Sides	Trail. #4	85	Back #1	200	34,400	56,000	4.0

NOTES

1. Inches per minute.
2. Restrained by bolting to positioning frame.
3. See Appendix B.
4. Total number of pounds used on a 48-inch weld.
5. Degrees Fahrenheit.
6. Pounds per square inch.
7. Percent in a two-inch gage length.

APPENDIX D. BASIC STUDIES OF THE EFFECTS OF CO_2 CHILLING ON THERMAL STRAINS CAUSED BY TIG WELDING

Series 1

A limited number of tests were performed using the experimental configuration shown in Figure D-1. Purpose of these tests was to determine if practical cryogenic cooling could overcome thermal expansion produced by TIG welding.

Procedure.- Spotweld heat input was started simultaneously with adjacent liquid CO_2 flow. Dial indications were noted, and a positive indication signified more thermal contraction than expansion near the bottom edge; negative indication meant more expansion than contraction.

It was noted that deflections could be controlled by regulating the CO_2 flow adjacent to the heated area.

Series 2

A second series of tests using the experimental setup shown in Figure D-2 were conducted in an attempt to overcome transverse weld contraction by adjacent simultaneous cooling with liquid CO_2. The amount of weld contraction was assumed to be directly related to residual stress and warpage.

Procedure.- Welding the one-inch length (as shown in figure D-2) was accomplished simultaneously with adjacent cooling. The dial was set at zero before the weld operation. A positive dial reading after the weld cooled to ambient temperature indicated contraction of the weld.

Table D-I shows results of the basic tests of Series 2. It appears from these results that there is considerable benefit to be gained from contracting the plate adjacent to the weld thermal expansion.

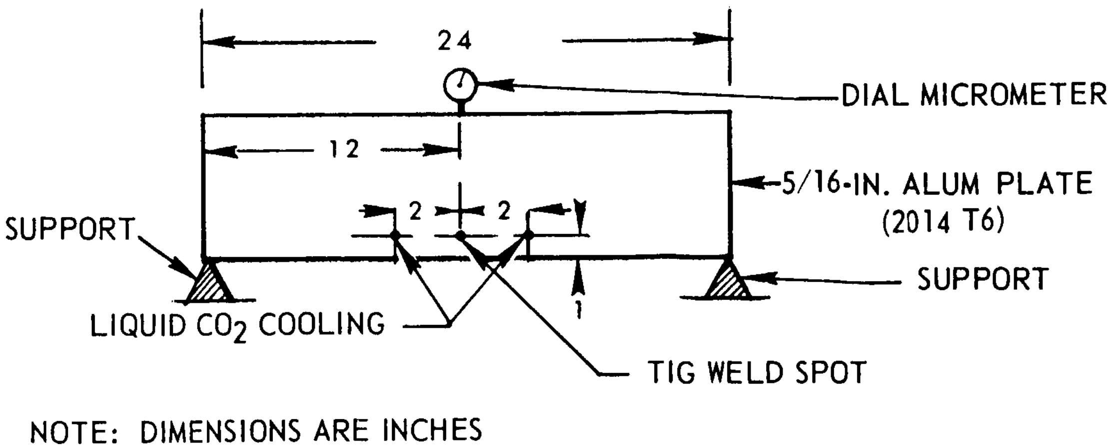

Figure D-1. Experimental Configuration for Series 1 Tests

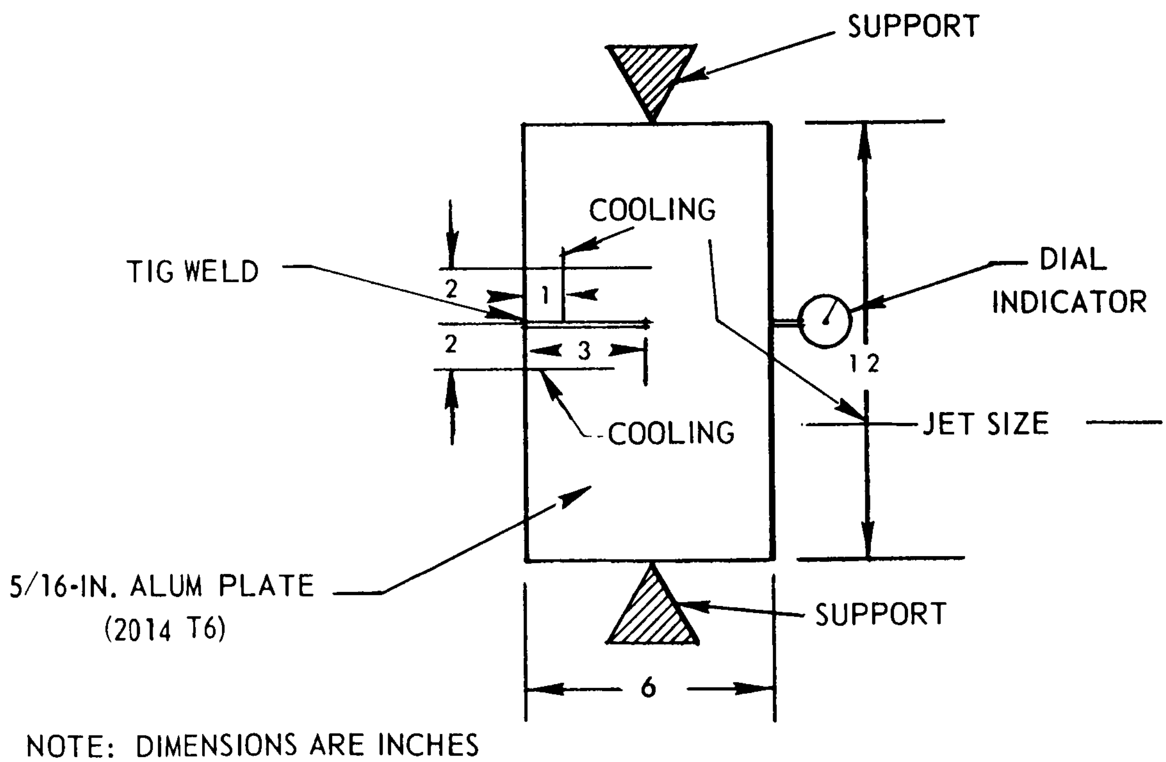

Figure D-2. Experimental Setup for Series 2 Tests

TABLE D-I. Results of Series 2 Tests

Test	Deflection	Remarks
3-28-1	+ .013	Uncooled
3-28-2	+ .003	Uncooled
3-28-3	+ .007	Uncooled
3-29-1	- .001	Cooled (filler wire-pulled plate)
3-29-2	- .005	Cooled (front side)
3-29-3	Void	Filler Wire Hung
3-29-4	- .008	Cooled (back side)
3-29-5	+ .009	Uncooled

Series 3

On the basis of other favorable indications, the experimental setup shown in Figure D-3 was devised in an attempt to accomplish larger scale reduction in weld contraction reactions. A more controlled system of liquid CO_2 handling was created for this experiment.

Procedure.- The plates were bolted to the stainless steel frame (figure D-3). Simultaneous with CO_2 cooling on either side of the weld, the TIG welding was performed semi-automatically. The top bolt was released which allowed the plate to expand or contract. Reactions were indicated on the dial micrometer. SR-4 strain gages were applied to some samples in the transverse direction and a 2 x 2-in. square cutout was made to determine residual stress present in this direction.

Conclusions.- Although variances in the data obtained from this experiment were substantial in some cases, again, a reduction in contraction was indicated during the latter phase of the test when an increased area was cooled. See Table D-II.

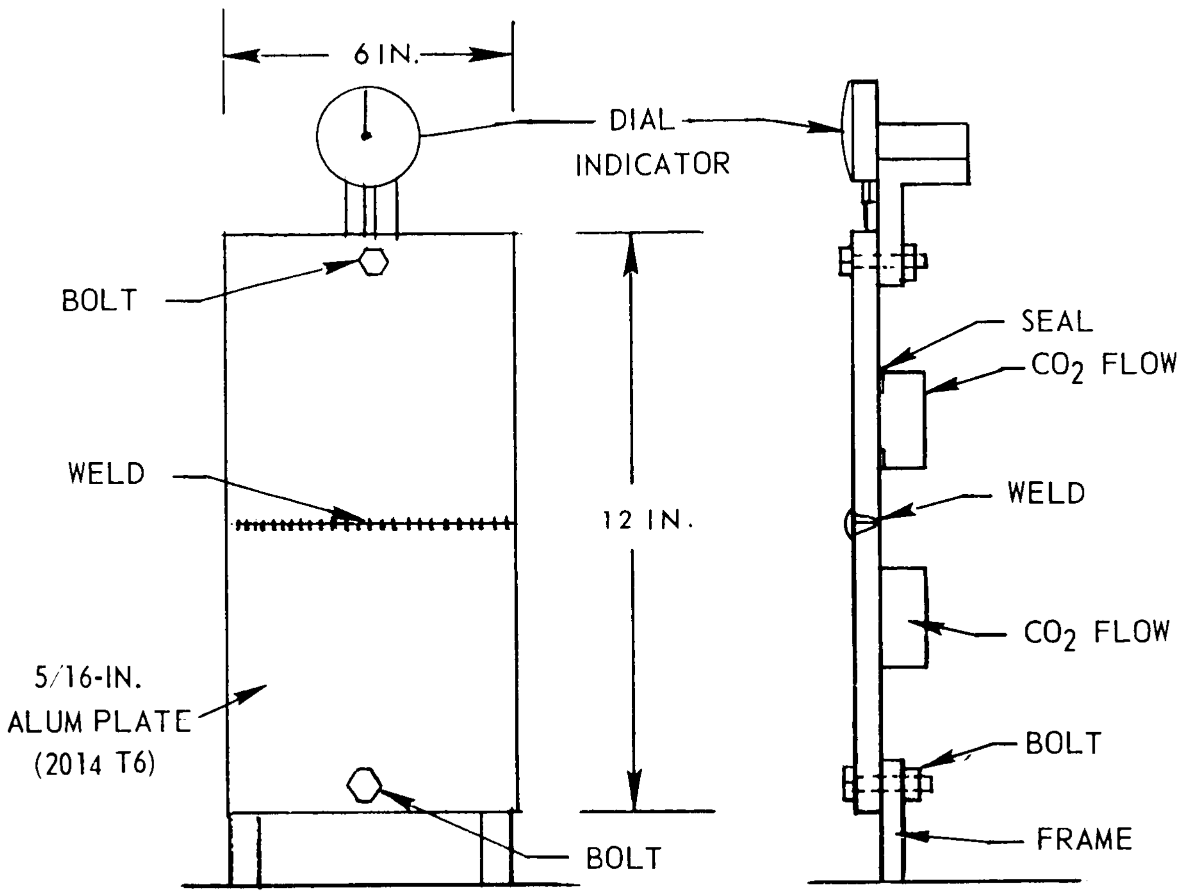

Figure D-3. Test Setup for Series 3.

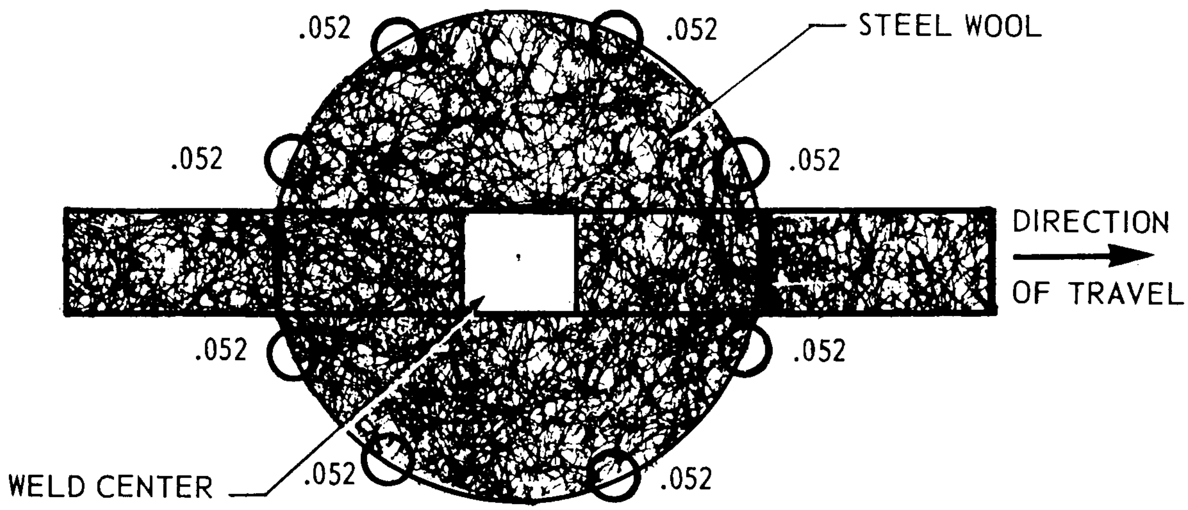

Figure D-4. Jet Pattern of Six-inch Diameter Manifold Back of Plate Cooling

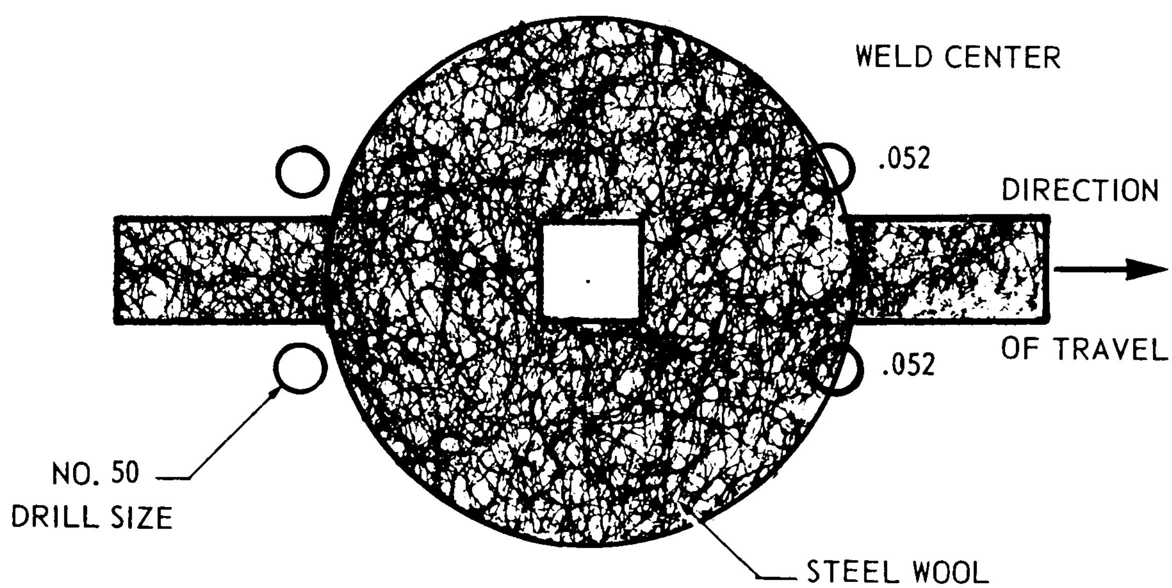

Figure D-5. Modified Manifold with Orifice Blocked Off

TABLE D-II. Data Obtained from Test Series 3

Test	Method	Deflection	Grain Direction	Residual Stress	Remarks
4-4-1	Cooled	---	---	---	Cooling Manifold Check (-91°F.)
4-2-2	Uncooled	---	Perp.	-5,600 psi	Unrestrained Uncooled
4-8-2	Cooled	- .022	Perp.	---	Unrestrained
4-8-3	Slight Precool	- .025	Perp.	-2,100	Unrestrained
4-8-4	Cooled	- .020	Perp.	-1,300	Restrained
4-9-1	Cooled	- .019	Perp.	---	Restrained
4-9-2	Slight Cooling	- .013	Par.	---	Restrained
4-9-3	None	- .021	Perp.	-2,000	Restrained
4-9-4	None	- .023	Par.	-1,150	Restrained
4-10-1	Cooled	- .026	Par.	-3,350	Restrained
4-10-2	Cooled	- .022	Par.	-2,800	Restrained
4-10-3	Cooled	- .016	Par.	---	Restrained (poor weld)
4-10-4	None	- .022	Perp.	---	Restrained
4-10-5	Cooled	- .003	Perp.	-2,700	Restrained(1)
4-10-6	Cooled	- .011	---	---	Restrained(1)

NOTE

1. Manifold modified to increase cooled area.

Series 4

This series was conducted in an attempt to apply, to larger scale applications, those factors which produced favorable indications in past tests. The cooling manifolds used for back side cryogenic cooling are shown in Figures D-4 and D-5. Figure D-4 shows the manifold rigged with orifices encircling the area to be heated by the torch. Figure D-5 is a modification of the manifold shown in Figure D-4 with four orifices blanked off. The steel-wool surrounding the weld center was necessary to prevent the CO_2 from interfering with the welding process. Half-size (24-in. long) plates were TIG welded together in one pass while cooling was applied to the rear side of the plate.

Procedure.- Two 2014-T6 aluminum plates 5/16-in. thick were TIG welded together in a single pass while liquid CO_2 jets were applied to the back side of the plates. Front side cooling proved to be impractical due to CO_2 interference with the weld. SR-4 resistance strain gages were applied to some weldments in both longitudinal and transverse directions to obtain a record of the effects of cooling upon weld residual stresses. The gages were centered and then cut out in two-inch squares, and second readings were taken. Table D-III presents the results of these experiments.

Although repeatability was low, residual stresses in the transverse direction appeared to be radically affected by the cooling. Longitudinal residual stresses appeared to be relatively unaffected by the amount of cooling used in these tests. Cooling before and after the welding process apparently reduced the tendency of the plate to bow away from the weld with a resultant fracture of the tacks that secured the plates together. Cooling also reduced warpage of the plates; although, no explanation for this factor can be forthcoming at this time. However, there is the possibility that a relationship exists with the increased transverse residual stresses in excess of one-half of longitudinal stresses when cooling is applied immediately before and after the welding process. It is postulated that the difference in magnitude between longitudinal and transverse stresses bears directly upon warpage in welded plates.

TABLE D-III. Results of Test Series 4

Specimen No.	Method	Grain	Residual Stresses	Remarks
4-17-1 Long. #1 Transv. #2	Full "0" Cool. 250-lb. CO_2	Par.	13,600 psi 200 psi	High warpage (tack weld fractured as weld approached)
4-17-2 Long. #1 Transv. #2	Cooled Before and After Weld. 22 lb. CO_2	Par.	12,550 psi 7,860 psi	Low Warpage (tacks held)
4-17-3 Long. #1 Transv. #2	Cooled Before and After Weld. 40 lb. CO_2	Par.	6,050 psi 3,080 psi	Low Warpage Poor Weld (tacks held)
4-18-2 Long. #1 Transv. #2	Cooled Before and After Weld. 40 lb. CO_2	Par.	18,900 psi 12,400 psi	Low Warpage Good Weld (tacks held)
4-18-4 Long. #1 Transv. #2	No Cool	Par.	20,800 psi 3,400 psi	High Warpage (tack weld fractured as weld approached)