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FURNACE BRAZING OF LIQUID ROCKET THRUST CHAMBERS

By

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INTRODUCTION

Brazing as a technique for joining metal parts has been utilized for centuries. Industry, however, has only begun to use it on a wide scale in the last twenty years. The rapid growth of brazing has been a result of consumer and military demands for products of lighter weight, less expense, and higher performance. Today, brazing is one of the most widely used fabrication techniques in the production of liquid rockets, gas turbines, refrigerator and other types of heat exchangers, automobile parts, vacuum tubes, and many nuclear products.

In general, brazing is a process in which joining is accomplished by melting a filler metal into closely fitted joints between a number of metal parts. The term is further defined when the materials joined, equipment and/or atmosphere used, intended service temperatures, brazing alloys used, or other such details are given. The discussion in this paper is related to furnace brazing of liquid rocket thrust chambers. Although various furnace atmospheres, intended service temperatures, and brazing alloys will be discussed, their use as specific modifying conditions will be minimized.

Liquid rocket thrust chambers are of simple geometry, but are quite complex to braze. Although many types of construction have been attempted, the tubular-walled, fuel-cooled regenerative construction is most utilized today. This type of chamber consists of a fuel and oxidizer injector, combustion zone, throat and bell expansion nozzle, fuel regeneration tube wall, and external supports.

The materials used to fabricate these thrust chambers include pure nickel, nickel alloys, stainless steel, precipitation-hardening steel, copper, and light metals. The brazing filler metals used include nickel, silver, gold, and copper-base alloys. Furnace atmospheres include inert and reactive gases. All material and process variables must be correctly chosen and carefully controlled because the reliability of a nearly perfect piece of hardware is required to ensure mission capability.

This paper covers four of the many categories into which the furnace brazing of liquid-rocket thrust chambers can be divided. These categories are: (1) factors affecting the braze bond, (2) joint requirements, (3) brazing preparation process and equipment, and (4) resulting product.

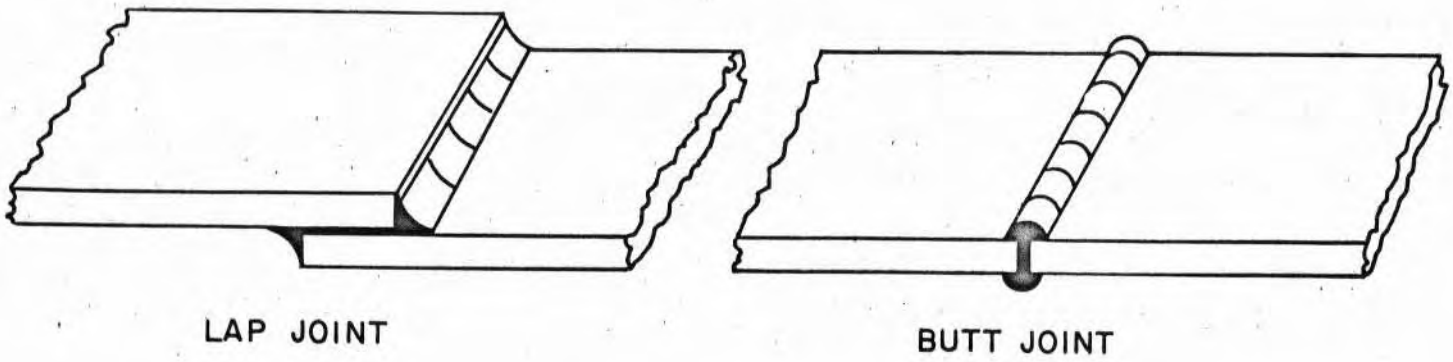
FACTORS AFFECTING THE BRAZE BOND

When considering the bond and resulting strength which is achieved in a brazed joint, the optimum conditions should be reviewed. The best condition, of course, would be the elimination of the joint. Because this is impossible, joining the parts with a filler metal equivalent in strength to the base metal should be considered. This can be accomplished by several well-developed welding techniques but not by brazing. If, however, cost considerations, complexity of the part, or service requirements are amenable to a brazing process, the practical factors which determine the bond obtained in a brazed joint must be considered by the design engineer.

The first consideration is braze joint geometry (Fig. 1), which may be classified as a butt, overlap, or fillet type. For each type, joint clearance is an extremely important factor. The clearances should vary with the base and filler metals being used to ensure ideal brazing conditions. Unfortunately, experimentation is generally necessary to determine the proper joint clearance for a particular base metal/filler metal combination. However, basic studies of wetting reactions, brazing alloy/base metal interface reactions, and processing conditions have greatly increased understanding of this phase of the brazing process.

A primary objective of brazing is obtaining a sound joint exclusive of voids or flux entrapment. This means that the brazing alloy must wet the base metal and flow into the joint. Wetting ability may be defined as the capacity of a molten brazing alloy to flow over a base metal surface while superficial elemental diffusion and alloying interactions are occurring. A diagram of the forces acting up on a molten droplet of brazing alloy, exclusive of gravity, is shown in Fig. 2. Thus, if γ g-s $> \gamma$ l-s+ γ g-l cos θ, conditions are favorable for good wetting. Conversely, if γ g-s $< \gamma$ l-s + γ g-l cos θ, poor wetting will occur. The factors affecting this force system are the brazing atmosphere, the cleanliness of the base metal, the compositions of the brazing alloy and base metal and their interdiffusion, the purity of the brazing alloy, the composition of the brazing alloy binder, and the brazing temperature.

The brazing atmosphere has the primary function of protecting the brazing alloy and base metal from oxidation during the brazing cycle. Dry inert gas and hydrogen have been the most successful atmospheres



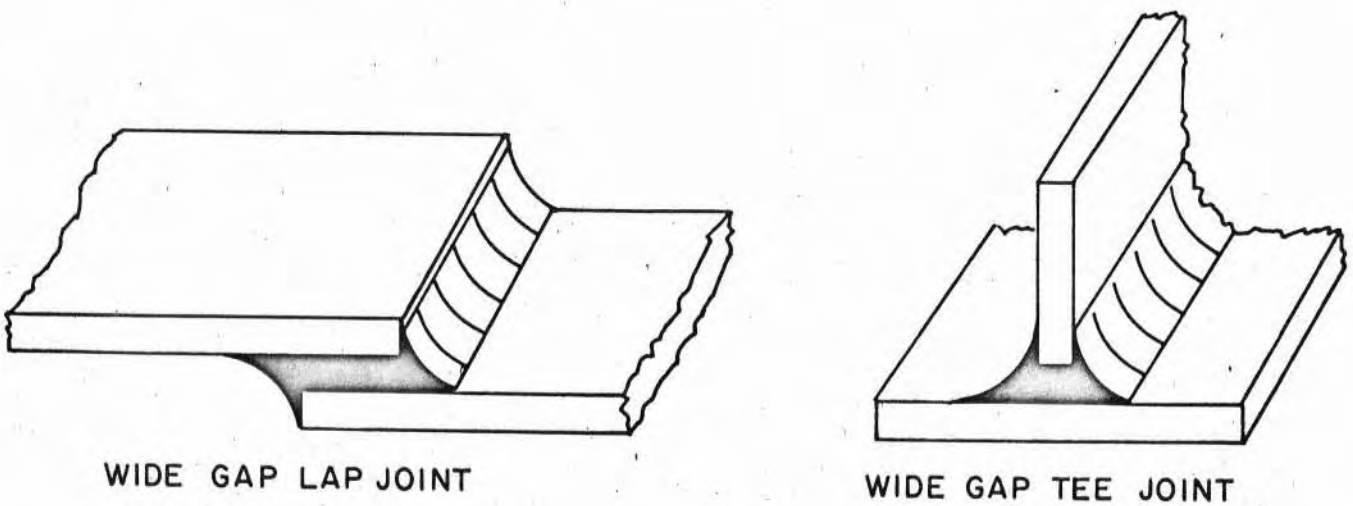


Figure 1 . Joint Types

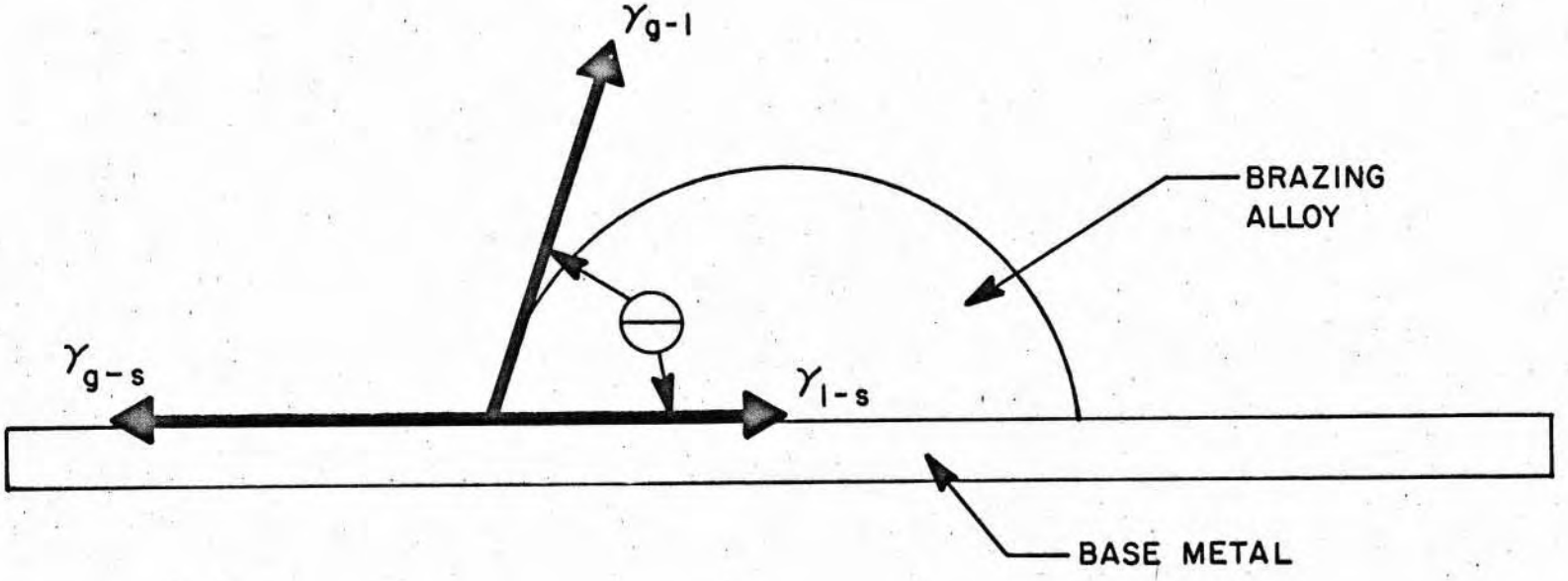


Figure 2 . Wetting Diagram

in thrust-chamber brazing. Other brazing and heat-treating atmospheres are usually unsatisfactory because of a high reactivity of elements in the base metals and brazing alloys. When a clean surface is produced or maintained, the surface tension of the solid surface, γ g-s, is high, promoting good flow. If a clean surface is not maintained, the brazing alloy may react with the contaminating film, increasing the surface tension of the liquid brazing alloy, γ g-l, and decreasing the surface tension of the solid surface, γ g-s. Poor wetting ability will result, and in some cases the brazing alloy will actually contract into a spherical shape after initially spreading over and reacting with the base metal surface film.

Most oxides of the alloying elements in commercial base metals and brazing alloys (except titanium and aluminum) can be reduced by dried hydrogen. The simple representation of the metal-to-metal oxide equilibria in hydrogen shown in Fig. 3 can be a valuable guide in furnace brazing. It shows readily how titanium and aluminum oxides can form during heating in a -60 F dew point hydrogen and cannot be reduced at a 2100 F brazing temperature. It does not, however, show how chromium oxide could remain after a 2100 F brazing temperature or how dried argon (theoretically always oxidizing) can prove to be a more effective brazing atmosphere than dried hydrogen. As an example, in the case of chromium in stainless steel and using a brazing temperature of 1900 F, a -60 F dew point hydrogen atmosphere would be oxidizing to the steel until 1500 F is reached. The amount of oxide formed on the surface would be proportional to the time at any temperature and to the net oxidation rate at that temperature. Unless heating is rapid in the 800 to 1400 F range, a heavy oxide will form. Though the atmosphere becomes reducing above 1500 F, sufficient time at any temperature may not be allowed to reduce the oxide formed upon heating.

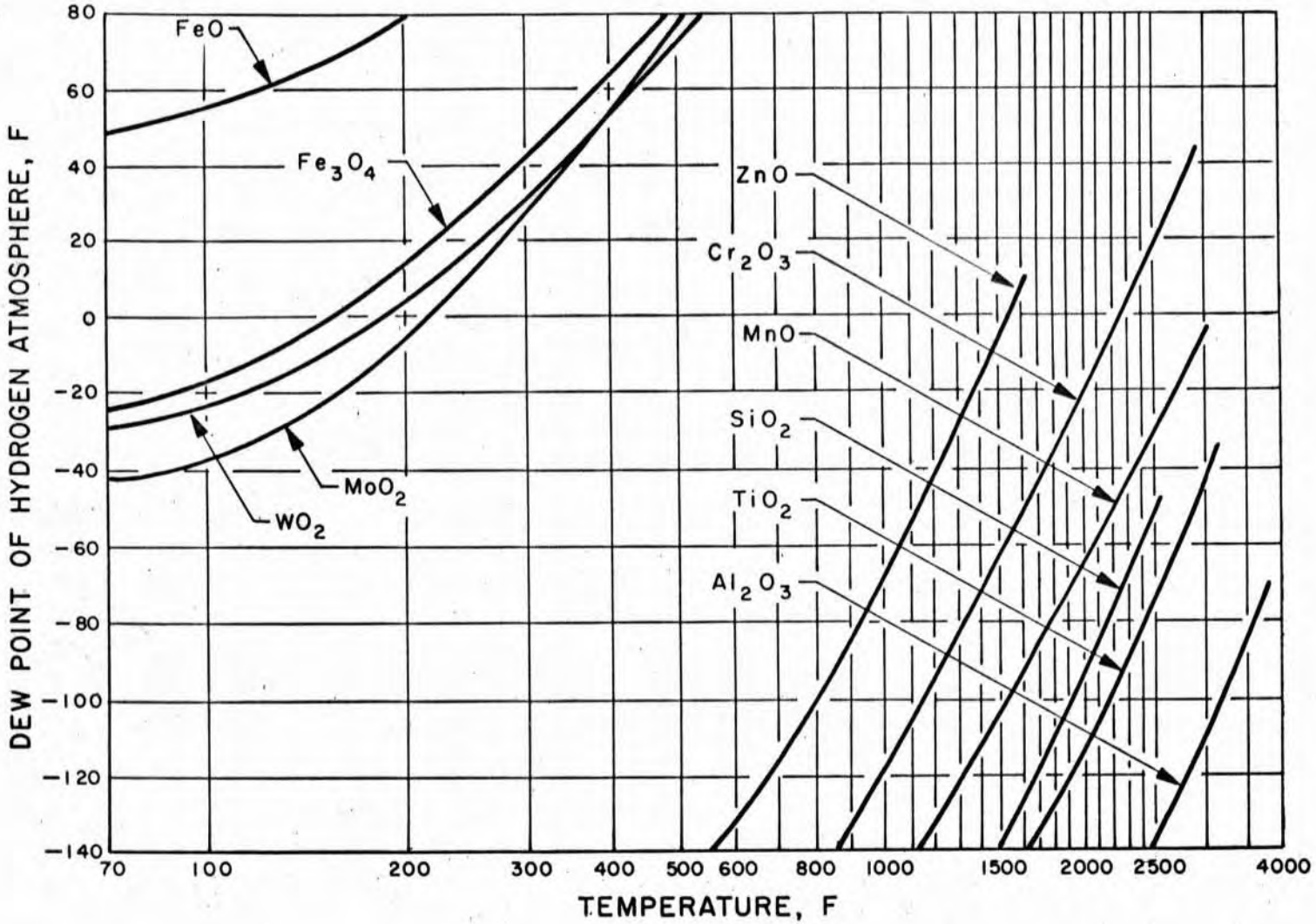


Figure 3 . Metal/Metal Oxide Equilibria in Hydrogen Atmospheres

At just above the 1500 F equilibria temperature, the rate of reduction is so slow that hours or even days might be necessary to clean the surface. Even at a 1900 F brazing temperature, a finite time would be required to reduce the oxide. In addition, the brazing alloy begins to melt below this brazing temperature and poor results can occur. In furnace brazing, the one-metal system does not exist. The addition of a second metal to the system makes the metal-to-metal oxide reactions more complex. If the second metal has an oxide which reduces at a lower temperature than chromium, the hydrogen will have a momentary increase in dew point (moisture content) and become more oxidizing to the chromium. As a result, oxidation will be accelerated and the reduction of chromium oxide will be more difficult at higher temperatures. Even more serious problems result when the second metal (lower metal-to-metal oxide equilibria temperature) is in a cooler region of the furnace than the braze joint area and reduction of its oxides takes place when a good dew point is required to provide maximum reduction in the joint area just below the melting temperature of the brazing filler.

The ability of hydrogen to transfer oxides and to have accelerated oxidation rates in relation to certain elements at lower temperatures has made it and other reactive atmospheres less effective than dried inert atmospheres in the furnace brazing of many base metals. An inert atmosphere is more readily dried and its purity maintained during handling and during its elevated temperature exposure to the part because it cannot reduce existing oxides with resulting moisture pickup. The net result can be a cleaner joint at the brazing temperature.

Another important factor which influences wetting ability during brazing is the composition of the base metal and brazing alloy. These compositions determine not only an acceptable brazing atmosphere, but the base metal/brazing alloy interactions which occur during the brazing operation.

The definition of wetting ability includes superficial elemental diffusion and alloying between the brazing alloy and base metal. If no alloying occurs, the interfacial tension between the liquid brazing alloy and solid base metal, γ l-s, is high, causing poor wetting. Lead, for example, has practically no solubility in iron, even when both metals are liquids. Consequently, lead does not wet iron. If the brazing alloy contains elements which are reactive, excessive alloying with the base metal may occur. The fluidity of the brazing alloy will also decrease by interdiffusion with base metal elements, which increases its flow temperature. In extreme cases, gross erosion of the base metal may occur which negates the entire brazing operation. The ideal brazing system, therefore, is one in which limited alloying occurs between the brazing alloy and base metal.

The effect of brazing temperature upon wetting ability must be considered in terms of heating rate as well as in terms of actual brazing temperature. In general, with the exception of pure or eutectic alloys, brazing alloys melt over a temperature range. If the heating rate is slow, liquation occurs, during which low-melting phases of the brazing alloy melt and flow out. These low-melting phases are generally most reactive with the base metal and wet it well. However, the flow temperature of the remainder of the brazing alloy, having now been increased, necessitates a higher brazing temperature. The heating rate in the melting range should be high enough to avoid excessive liquation, thus promoting adequate wetting ability and flow at the minimum brazing temperature.

The actual brazing temperature and its effect on wetting ability are subject to some popular misconceptions. One such misconception is the

thought that the brazing temperature must be increased to increase the wetting ability of the brazing alloy. In reality, increasing the brazing temperature generally will reduce wetting ability because of the increased reactivity of the brazing alloy with the base metal. The interfacial surface tension, γ l-s, is therefore increased, offsetting any decrease in the liquid brazing alloy surface tension. Raising the brazing temperature would be beneficial in only a few cases where the liquid brazing alloy does not react excessively at the superheated brazing temperature.

JOINT REQUIREMENTS

If the interdependent variables controlling wetting ability have been adequately regulated, a soundly brazed joint should result. Consideration must then be given to the strength and oxidation resistance of the resulting joint under service conditions. In addition, the effect of the brazing cycle up on the mechanical properties of the base metal should be determined.

The strength of a brazed joint is determined principally by joint design and by the inherent strength of the brazing alloy and base metal. Many authors have reported the effect of the amount of overlap on the tensile/shear strength of simple lap joints. It was noted that as the shear area becomes smaller, the indicated shear strength increases. This effect is caused by the bending moment which is present in tests of this type. Bending stresses applied to the thin base metal members cause the joint plane to rotate so that the loading axis is no longer parallel to the joint. This type of test is influenced by the base metal strength, base metal thickness, joint overlap,

strength of the brazing alloy, and ductility of both the base metal and brazing alloy. As a result, the single overlap has little value except to compare almost equal combinations.

Other standard mechanical tests, though less sensitive to some of the material and test conditions, still provide mainly comparative data and are of little value in design. Figure 4 gives the relative joint strengths of various chamber brazing alloys using the Miller-Peaslee single lap shear specimen. Theoretical calculations, past experience, simulated hardware testing, and large safety factors still remain the best design tools for brazed joint strength.

In addition to joint strength, joint integrity is very important in the brazing of liquid-rocket engine thrust chambers. Two conditions must be met: suitable heat transfer between joined members, and the rigidity always required of pressurized chambers. Such service failures as tube buckling, hot spots, chamber distortion, fuel entrapment and later explosion, and unstable combustion have all resulted from strong but not fully bonded brazed joints. Maximum joint coverage is usually the most important requirement for thrust chambers, and required joint strength is easily obtainable.

The effects of the brazing cycle up on the base metal properties and the interalloying with the brazing alloy must be considered. The effect of the brazing cycle up on the tensile strength of four superalloys is shown in Fig. 5 . No brazing alloy was presented in these experiments, so that only the effect of the brazing cycle was determined. The tensile strength of the superalloys after simulated brazing cycles was less than normally heat-treated material. This loss of

ULTIMATE SHEAR STRENGTH (PSI) OF BRAZED JOINTS AT VARIOUS TEMPERATURES*

TEST TEMPERATURE, F	PREMABRAZE 750 (75 Ag-20 Pd-5 Mn)	LITHOBRAZE 971 (97 Ag -3Li)	NIORO (82 Au-18 Ni)	COAST 52 (91.2 Ni-1.4 Fe-2.9 B-4.5 Si)	GE J-8590 (60 Cu-28 Ni-10 Mn-2 Si)
-320	46,900	25,030	81,460	48,400	60,030
AMBIENT	34,700	22,130	60,160	38,620	53,900
700	21,830	6,630	31,830	36,950	36,300
1500	7,530	**	9,770	16,450	8,483

**NO MEASURABLE LOAD BEFORE FAILURE.

*BRAZING CYCLES WERE SELECTED TO REPRODUCE F-1 THRUST CHAMBER FURNACE BRAZING CONDITIONS.

NOTES:
1. ARGON ATMOSPHERE USED FOR ALL FURNACE BRAZING.
2. JOINT GAP OF 0.002 IN. MAINTAINED ON ALL SPECIMENS.
3. MATERIAL THICKNESS = 0.080 IN.
4. SHEAR TEST SPECIMEN DESIGNED AS FOLLOWS: (SHADED AREA MACHINED AFTER BRAZING.)

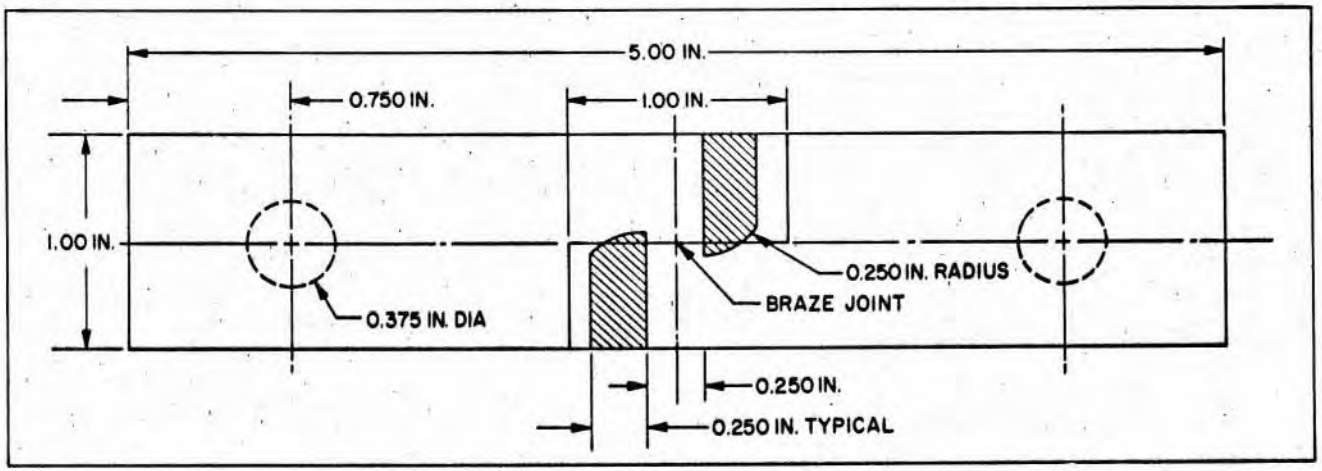


Figure 4. Miller-Peaslee Data

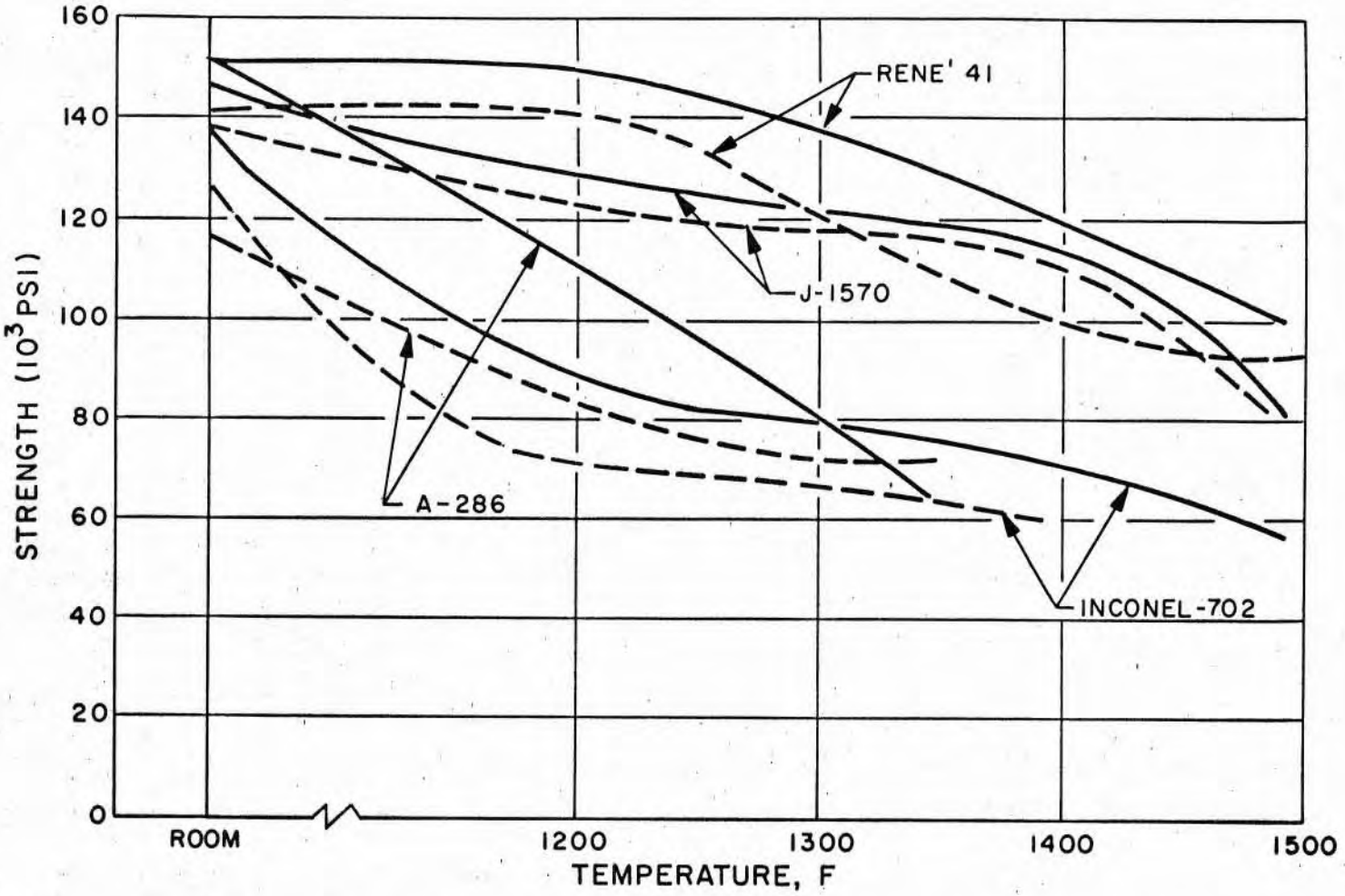


Figure 5 . Ultimate Strengths vs Temperature of Four Superalloys (Strengths obtained by aging following brazing cycle compared with those obtained by normal heat treatments)

mechanical strength can range from as little as 1 percent to as high as 50 percent for various other materials.

The joint strength is also influenced by brazing alloy/base metal interactions which occur during brazing and in subsequent service. When liquid brazing alloys contact the solid base metal, a diffusion couple exists because of the elemental concentration gradients between components of the system. The resultant structures will be dependent upon the relative reactivities of the elements in the brazing-alloy composition and upon the relative sizes of the atoms involved in the diffusion process. Several different diffusion reactions can occur during the brazing operation. In the first type of reaction, elements in the brazing alloy having relatively small atomic radii diffuse into the base metal along the grain boundaries. The interstitial elements, carbon and boron, will diffuse along the grain boundaries of nickel, iron, and cobalt-base alloys. Silicon, with a slightly larger atomic radius, diffuses along grain boundaries to a lesser extent. These diffusing elements either may form intermediate compounds with base metal elements or produce a solid solution by diffusing from the grain boundaries into the base metal lattice. In extreme cases of rapid grain-boundary diffusion, an "irrigation" effect may occur. Atoms of the brazing alloy migrate from the grain boundaries into the adjacent base metal structure where intermediate compounds form and coalesce. This behavior produces a "filling in" of the grain boundaries at some distance from the original joint interface, as in the upper portion of Fig 6 .

A second type of alloying reaction consists of volume diffusion between elements of the brazing alloy and base metal. This substitutional alloying occurs at a slower rate and generally involves all

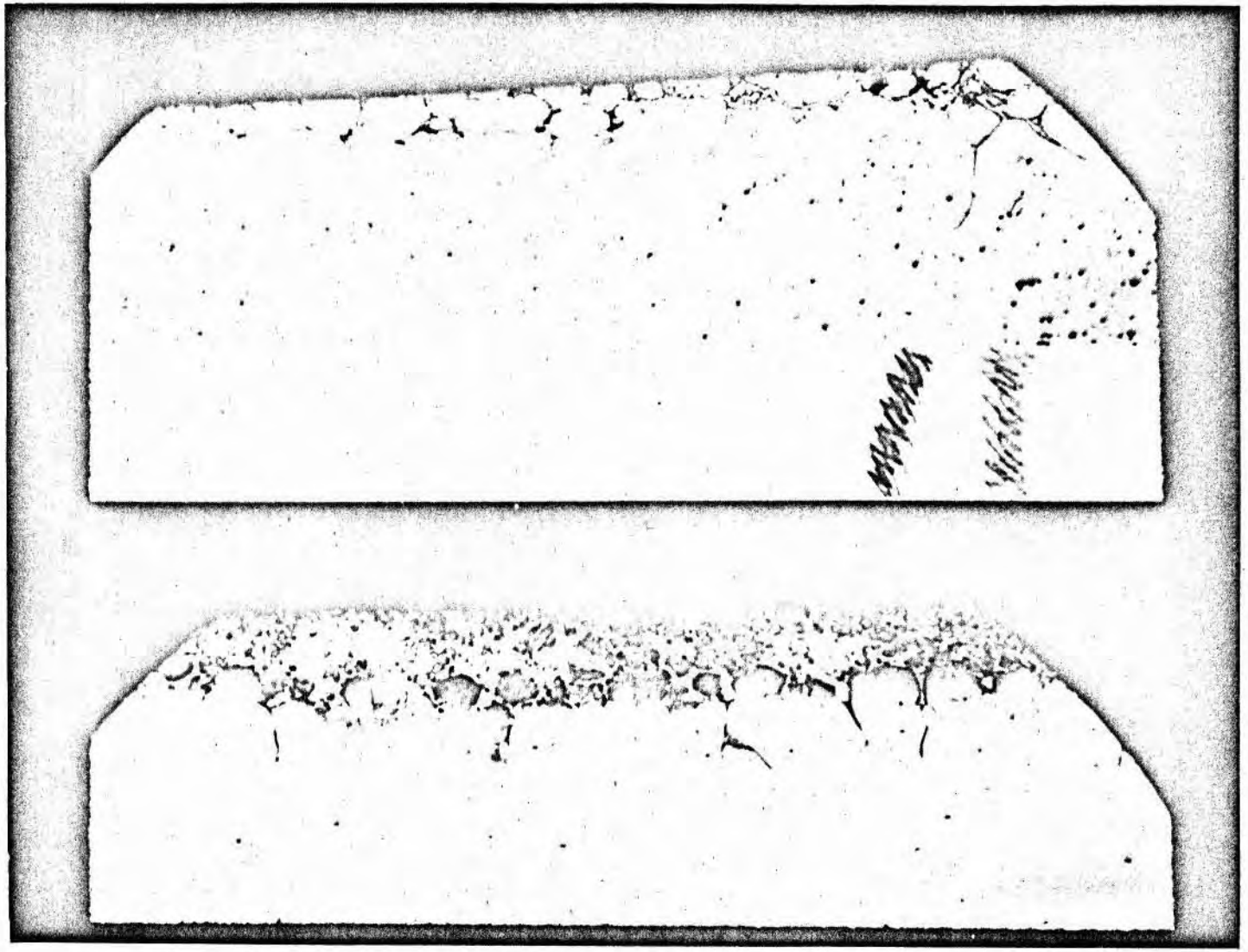


Figure 6. Intergranular Attack (Top) and Solution Attack (Bottom)

elements of the brazing alloy. The reaction generally occurs along the entire joint interface and results in the formation of complex solid solutions as shown in the lower portion of Fig. 6 or severe erosion as shown in Fig. 7 . Figure 8 shows a sound joint in which only very limited interalloying has occurred.

The products of these interactions have a pronounced effect up on the strength of the resulting joint. Although moderate diffusion is desirable to produce a sound metallurgical bond erosion and brittle eutectics or intermediate compounds which form may severely embrittle the base metal, reducing the joint serviceability.

BRAZING PREPARATION PROCESS AND EQUIPMENT

The brazing process for liquid-rocket engine thrust chambers is extremely intricate. Cleanliness, delicate assembly and handling, proper sequencing, and constant inspection and quality control are required. The placing of even the smallest prebrazing error in the furnace will produce a chamber which requires expensive and difficult repairs or may even result in the scrapping of a part that already has more than 75 percent of its cost built in. To avoid this problem, detailed preparation procedures and manufacturing checkoff books must be carefully followed as the chamber progresses through the shop.

Prebraze preparation of the chamber occurs in two major steps: braze alloy placement and fixturing. Because three basically different types of joint are encountered (tube-to-tube, tube-to-flat, and tube-to-header), more than one placement technique is usually used on a

Figure 7. Erosion

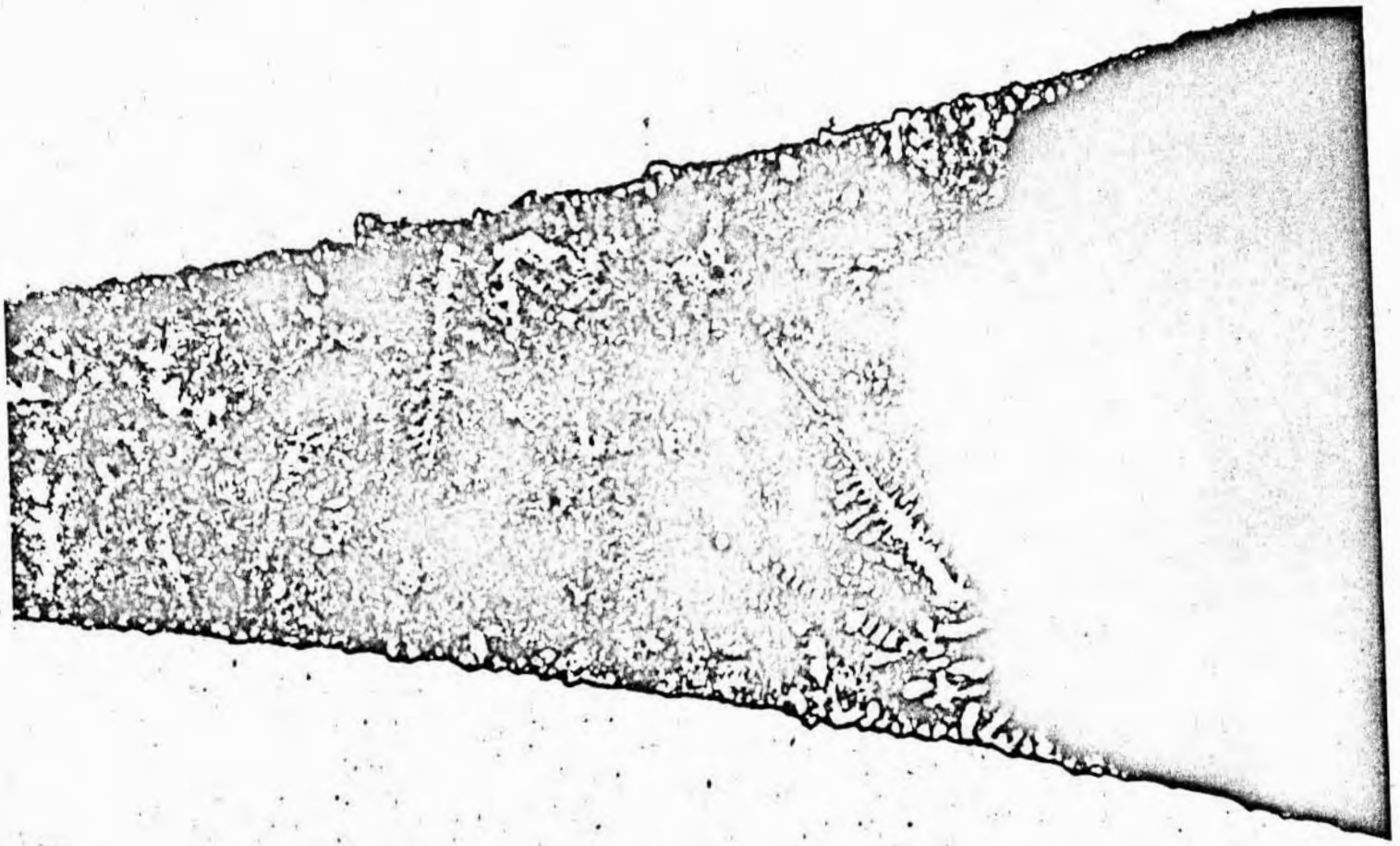


Figure 8. Good Tube-To-Tube Joint

specific chamber. Preplaced fillets, preplaced foil, spray coatings, and wire preforms are some of the methods used. Tube-to-tube joints are usually prepared by preplaced fillets or sprayed coatings or by a combination of both (Fig. 9 and 10). Tube-to-flat joints as in the bands and the jacket, are usually prepared by preplacing brazing alloy sheet on the mating surfaces and providing wire or powder feeding reservoirs (Fig. 11). Tube-to-header joints are prepared with preplaced fillets or braze alloy preforms (Fig. 12). The amount of alloy placed is carefully controlled to avoid excess weight, alloying with the base metal, and waste of expensive brazing alloy. Fillet size, coating thickness, and placement location are predetermined and become manufacturing and inspection control items.

Three methods of support fixturing are used either independently or in combination: (1) self-fixturing by tack welding, (2) internal mandrels, and (3) tooling rings and pressure bagging.

When tack welding for support (Fig. 13), the majority of the welds must be made between very-thin-walled tubes (as thin as 0.008 inch) and heavy bands (up to 1/8 inch thick). In addition, the tube and band alloys often have different thermal coefficients of expansion, resulting in relative movement during subsequent furnace brazing. The Tungsten Inert Gas (TIG) welding equipment used is fitted with a special small torch to help limit the tack size. The filler metal used is weak and ductile in comparison with the tube material, so that yielding or failure will occur in the tacks rather than in the thin tube wall (Fig. 14). Because the operation is tedious and costly, and because there is always a risk of tube-wall failures, the number of tacks used is usually reduced to a minimum by means of careful patterns or sequencing.

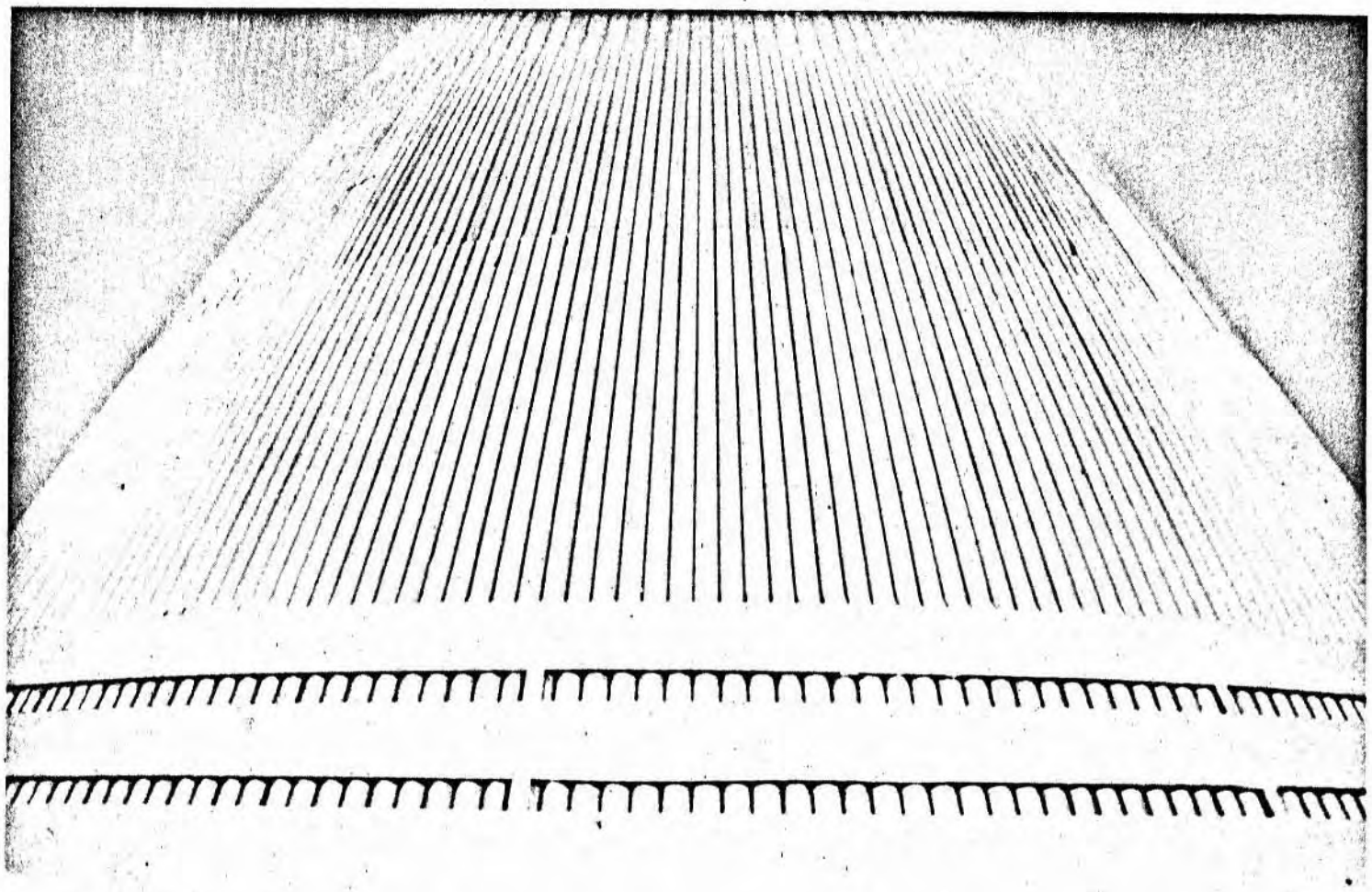


Figure 9. Brazing Alloy Placement (Tube-to-Tube Joint)

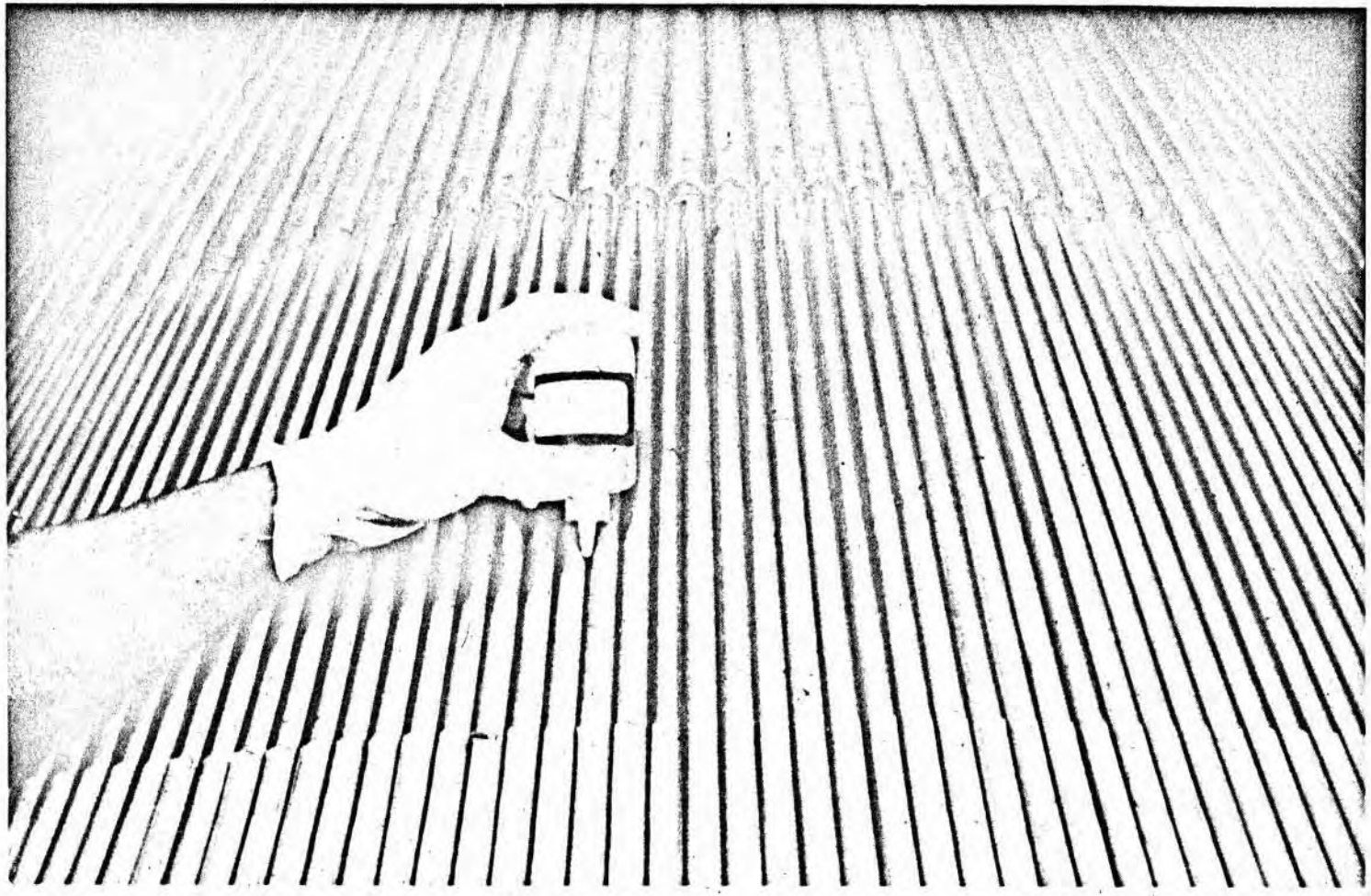


Figure 10. Tube-To-Tube Joint (Alloy Placed)

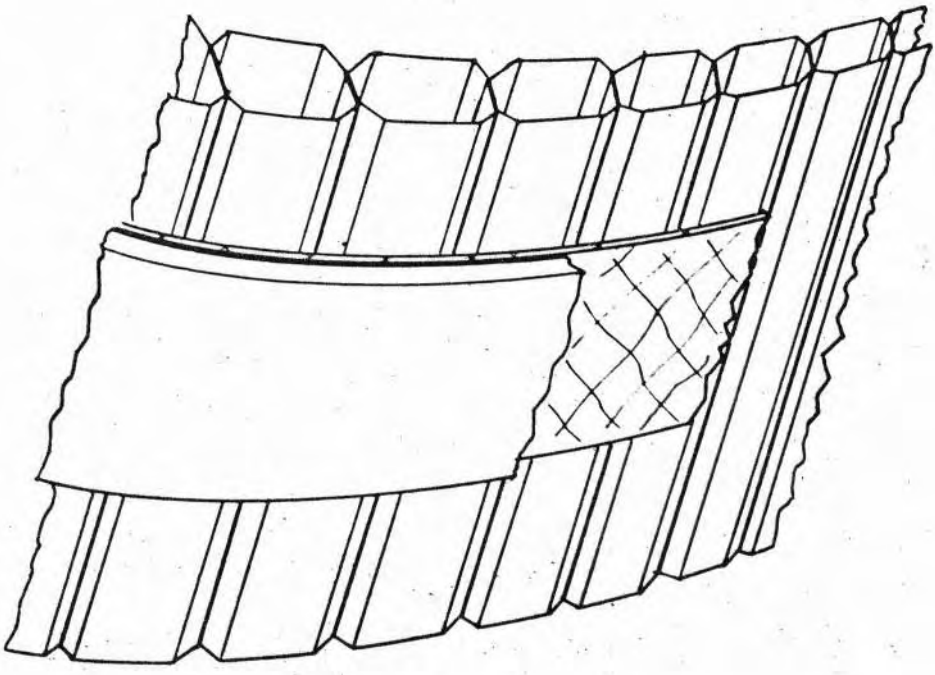


Figure 11. Sketch of Alloy Placement Tube to Band

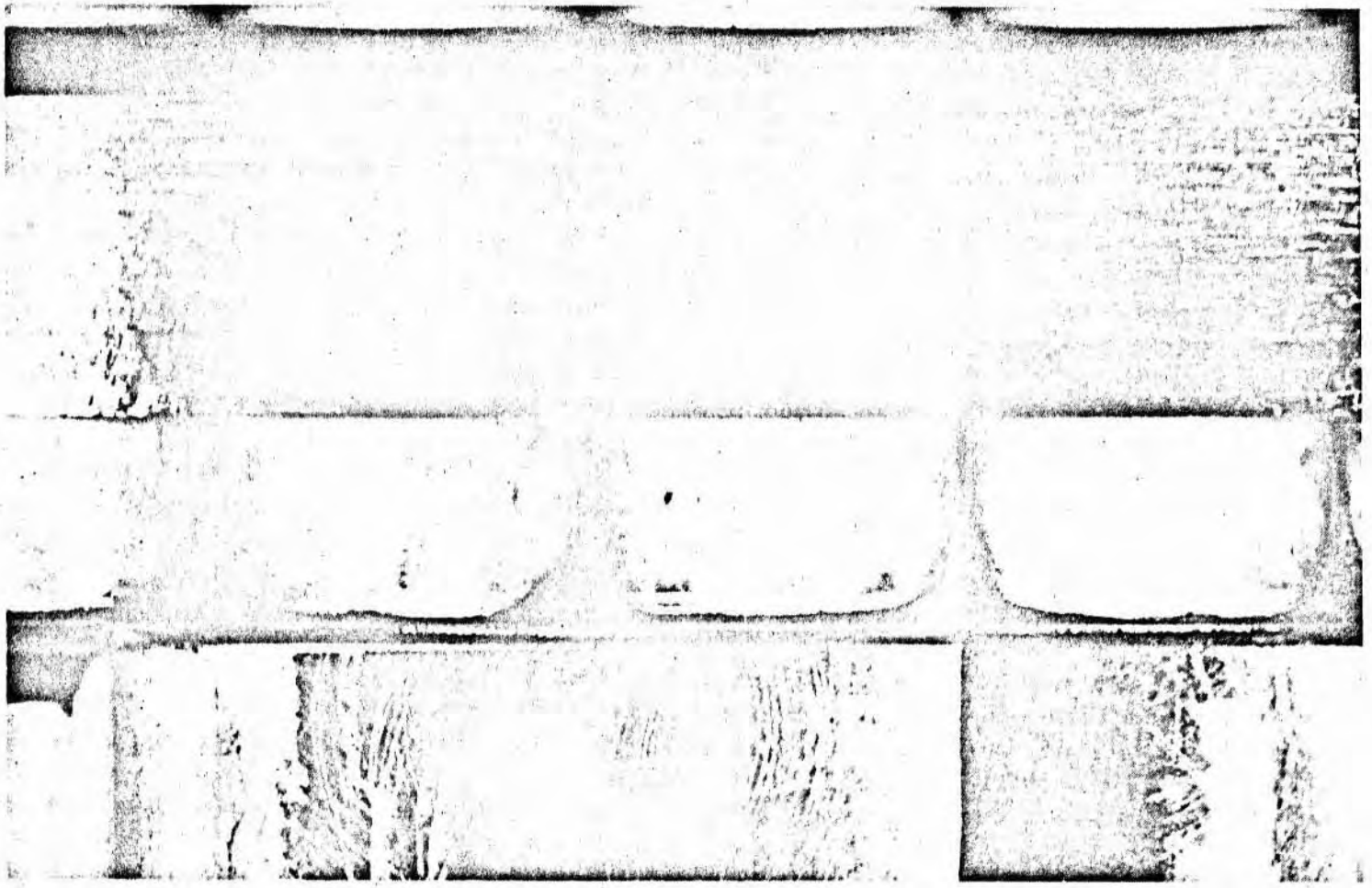


Figure 12. Tube-To-Ring Joint (Alloy-Placed)

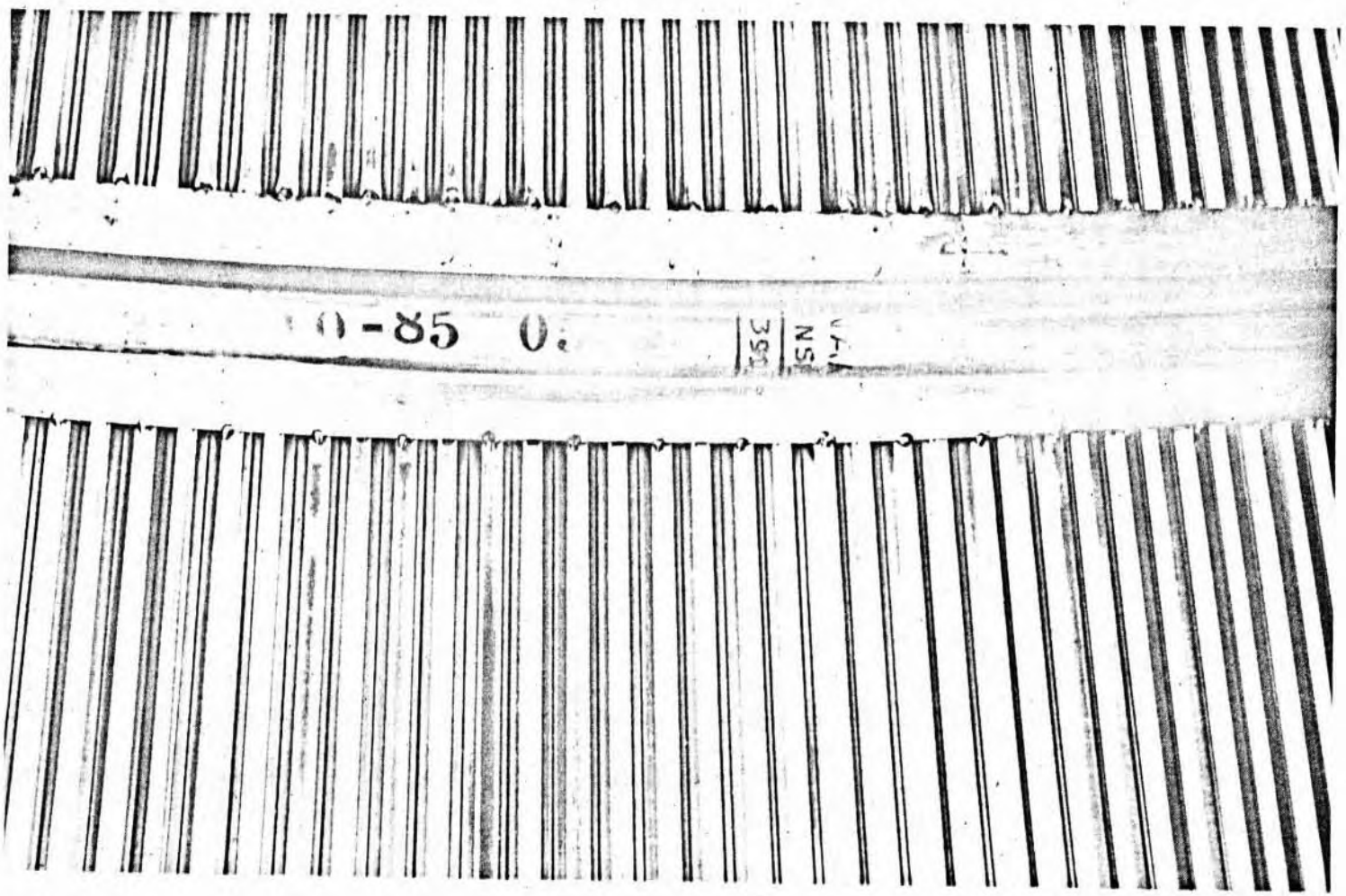


Figure 13. Tube-To-Band Tack Welds

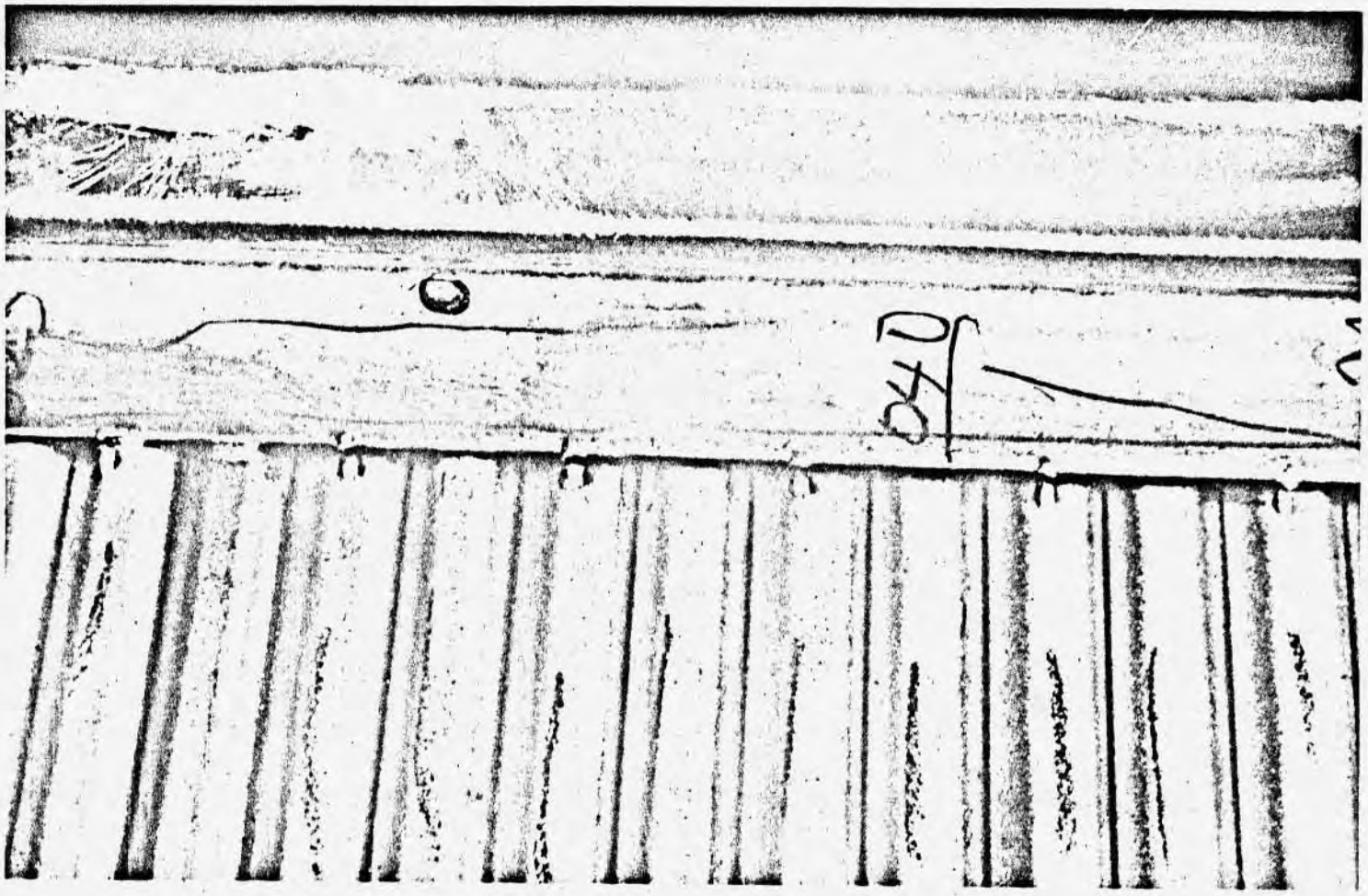


Figure 14. Tube-To-Band Tack Welds Pulled Loose

Internal mandrels, tooling rings, and/or pressure bags are often used to provide support during the furnace-brazing cycle. In addition to providing support, they are usually designed to expand a controlled amount and to force the tubes against the external bands and jacket providing proper location and braze-joint control

The furnace-brazing equipment used is for the most part standard in design. The thrust chamber is enclosed in a controlled-atmosphere retort which is heated by either an electric- or a gas-powered furnace. At Rocketdyne, smaller thrust chambers are brazed in an electric-resistance-heated furnace (Fig. 15). Larger thrust chambers are brazed in a gas-fired furnace of somewhat unique design and size (Fig. 16). The furnace is designed so that the two gas-fired half shells can be moved away from the retort after the brazing temperature is reached and two water-cooled half shells can be moved in from a 90-degree axis, providing a rapid and controlled cooling cycle.

The furnace-brazing cycles used vary with the brazing alloy and the materials used in the chambers. Very often heat treatment of the base materials is required during brazing, and will dictate the heating or cooling cycle to be used. Both the design and the control of currently used brazing cycles are not perfect. The product must be improved and its cost reduced. The earlier discussion of bonding and atmosphere/temperature relationships should be sufficient to increase the interest of the engineer in many of the areas in which constant efforts are being made to determine the right combination of brazing-cycle variables which will give optimum results.

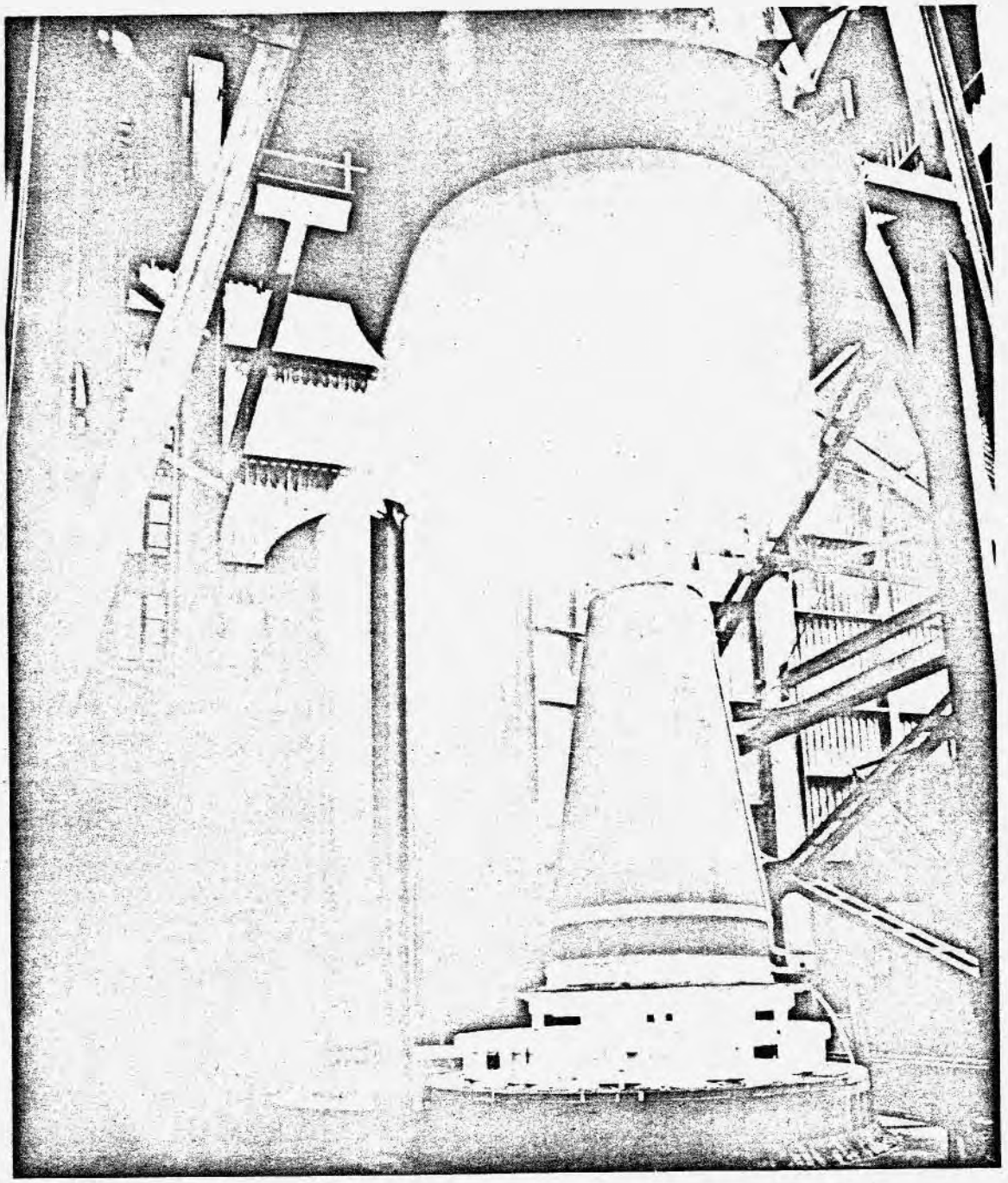


Figure 15. **Electric Furnace**

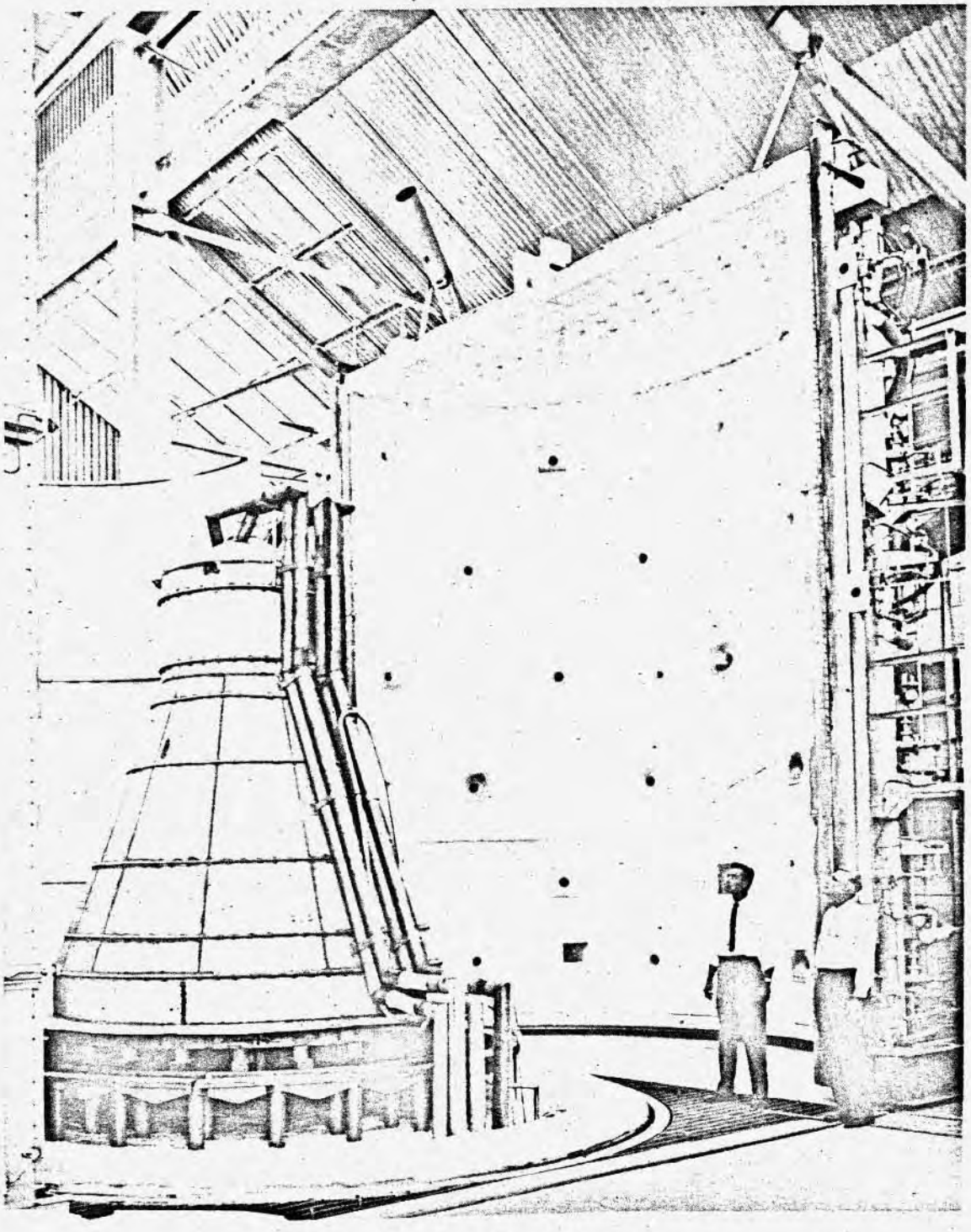


Figure 16. Gas-Fired Furnace

RESULTING PRODUCT

The product is, of course, a soundly brazed thrust chamber.. Figure 17 , 18 , 19 , 20, and 21 show four different chambers after brazing and in various stages processes of braze-bond inspection.

Figure 17 shows a Vanguard thrust chamber after brazing. This chamber was brazed in a hydrogen atmosphere furnace using a copper-base brazing filler metal. The major components are of 347 stainless steel.

Figure 18 shows an Atlas thrust chamber after brazing. This chamber was brazed in a hydrogen atmosphere furnace using a silver-base brazing filler metal. The major components for this chamber are of both 347 and 410 stainless steel.

Figures 19 and 20 show two chambers during ultrasonic inspection of the tube-to-jacket joints. This method, in conjunction with X-ray, is used both as a process development tool and as a quality inspection method.

Figure 21 shows the inspection of tube-to-tube joints to determine the areas in which brazing filler metal is to be preplaced for a second brazing cycle. Both hydrostatic and air pressure are also used to locate this type of tube-to-tube gap.

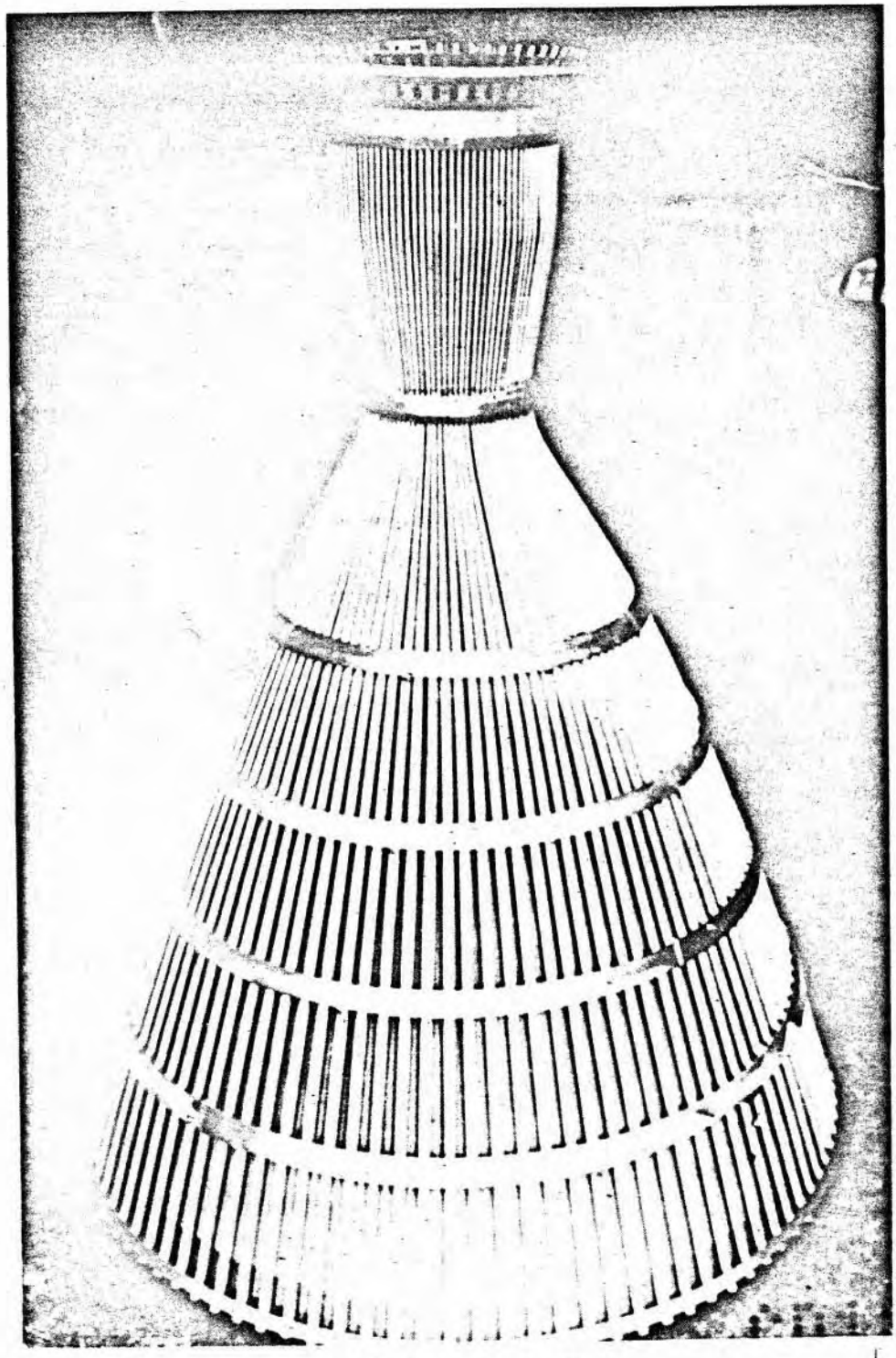


Figure 17. Vanguard Chamber

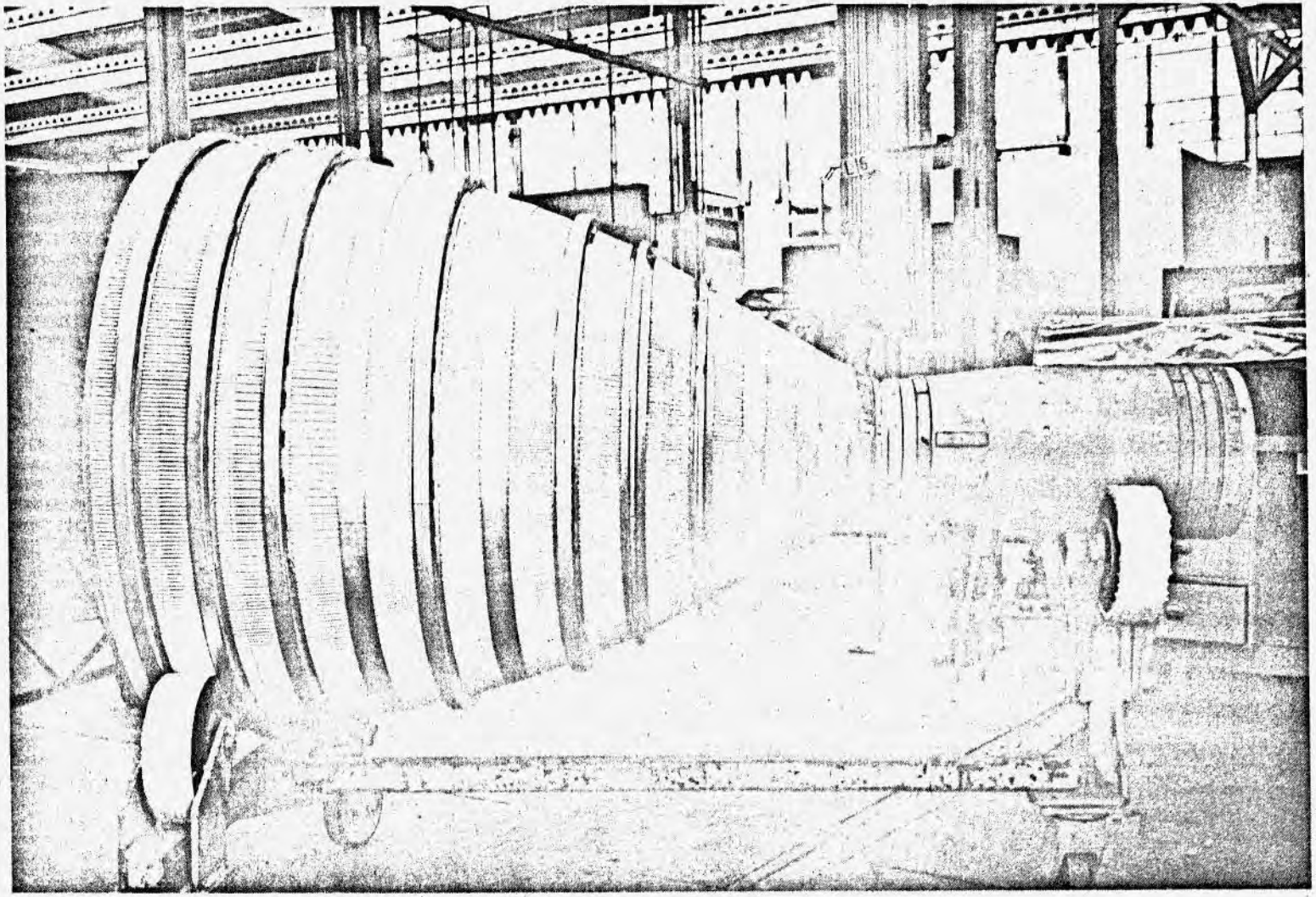


Figure 18. Atlas Chamber

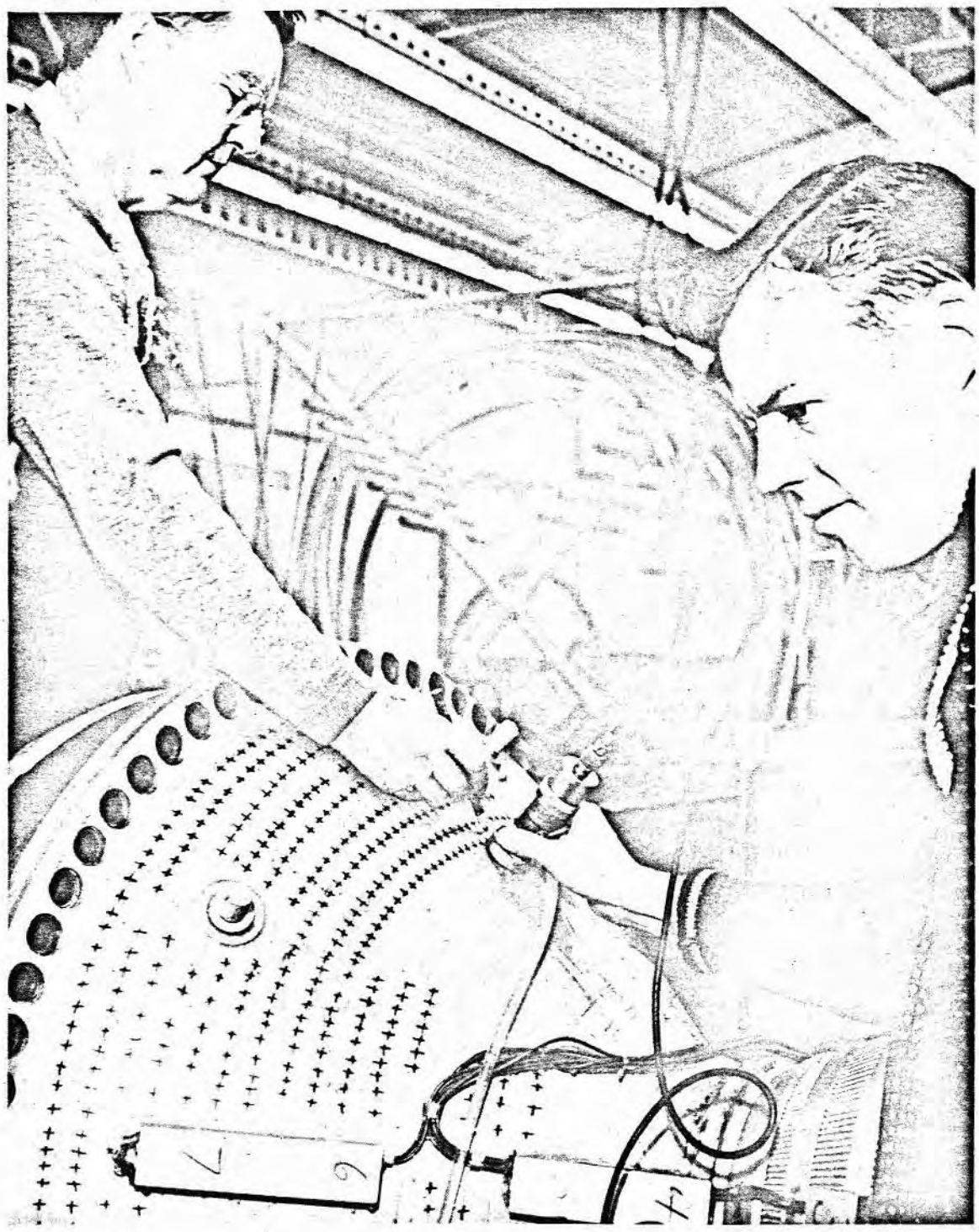


Figure 19. Ultrasonic Inpsection

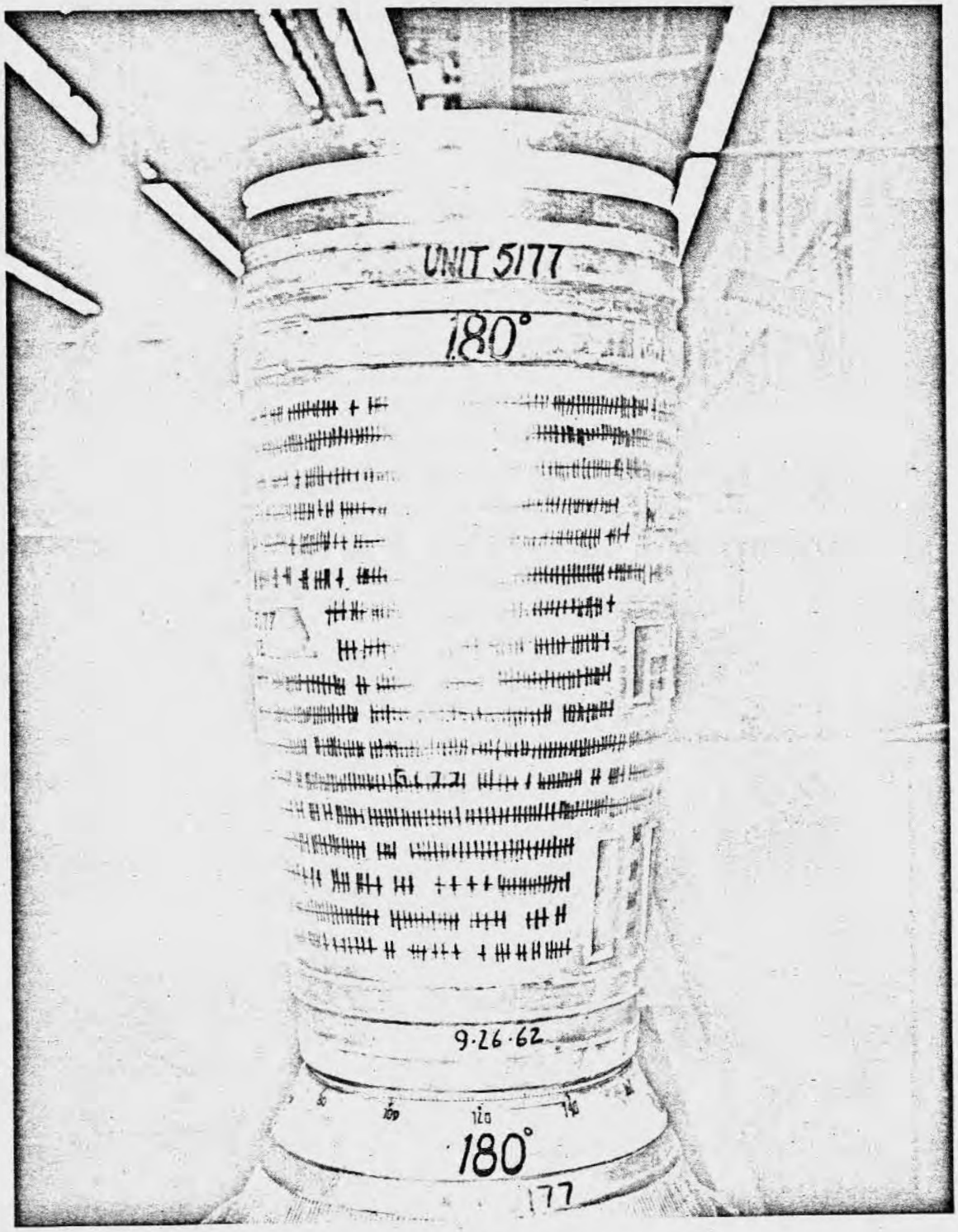


Figure 20. Ultrasonic Inspection Results

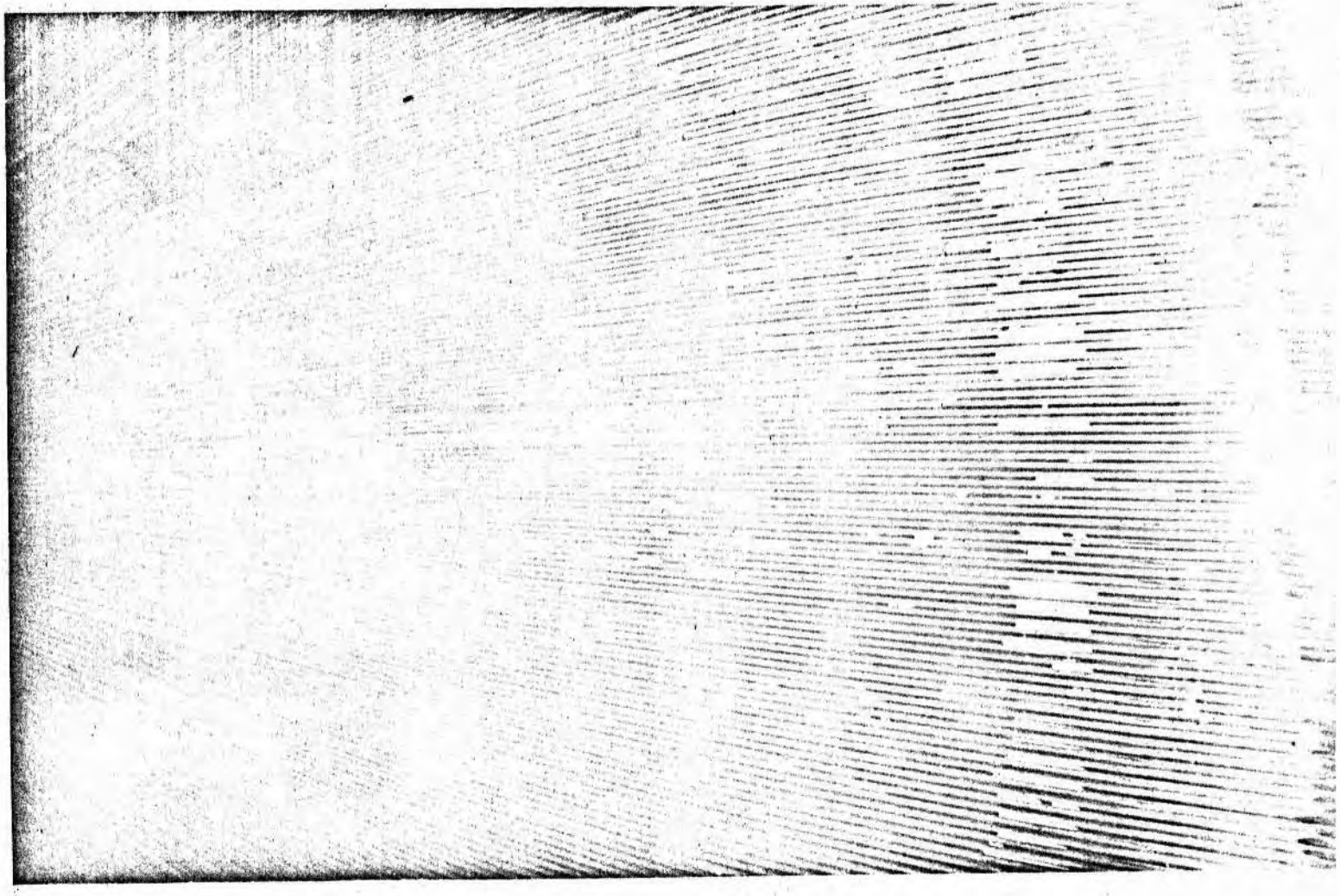


Figure 21. Light Source Inspection

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