FURNACE BRAZING THE F-1 THRUST CHAMBER FOR APOLLO

by

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INTRODUCTION

The work described in this report was performed for the National Aeronautics and Space Administration under contract NASw-16.

Rocketdyne is now building the F-1 engine for the Apollo lunar mission. Five F-1 engines, each capable of developing 1-1/2 million pounds of thrust will power the first stage of the launch vehicle of Saturn V (Fig. 1). F-1, the free world's largest liquid rocket engine (Fig. 2), has a regeneratively cooled, tubular-walled, thrust chamber (Fig. 3) that consists of a tube bundle surrounded by a heavily jacketed combustion chamber, a series of bands around the nozzle, and two end rings. The chamber is constructed primarily of Inconel X-750, a high-temperature, heat-treatable, nickel base alloy.

The thrust chamber is approximately 11 feet in length and 9-1/2 feet in diameter at the aft end of the nozzle. The tubular construction of the chamber provides the regenerative cooling which maintains the operating temperatures of the tube walls below the melting temperatures of the tube material and the brazing alloy which joins the tubes. The thrust chamber with 178 primary tubes and 356 secondaries is furnace brazed in two operations and has over 3000 feet of brazed joint between the tubes. The brazed joints between the tubes serve primarily as a seal to contain the combustion gases within the chamber. Although the brazed joints provide

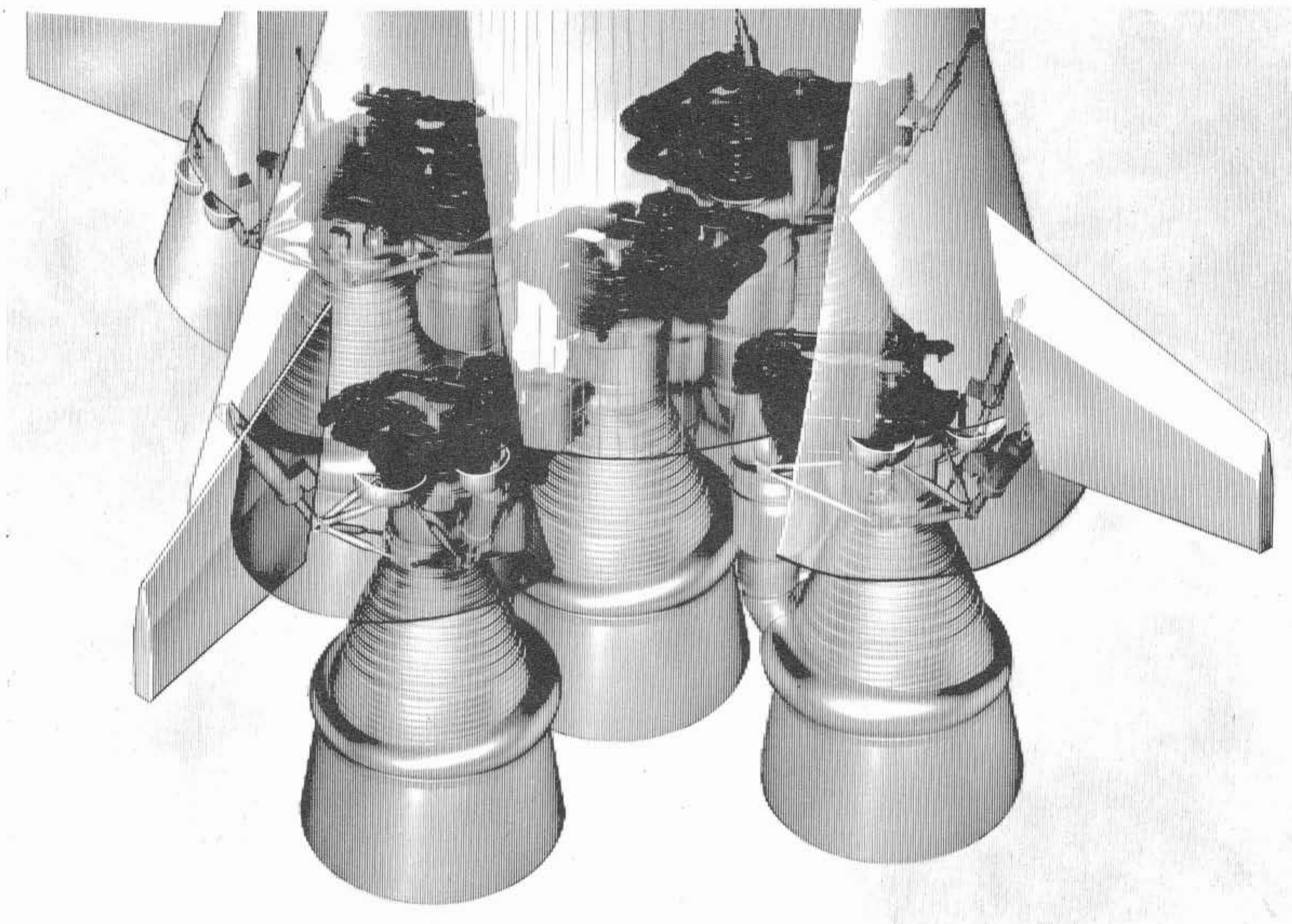

Figure 1. Saturn V Booster

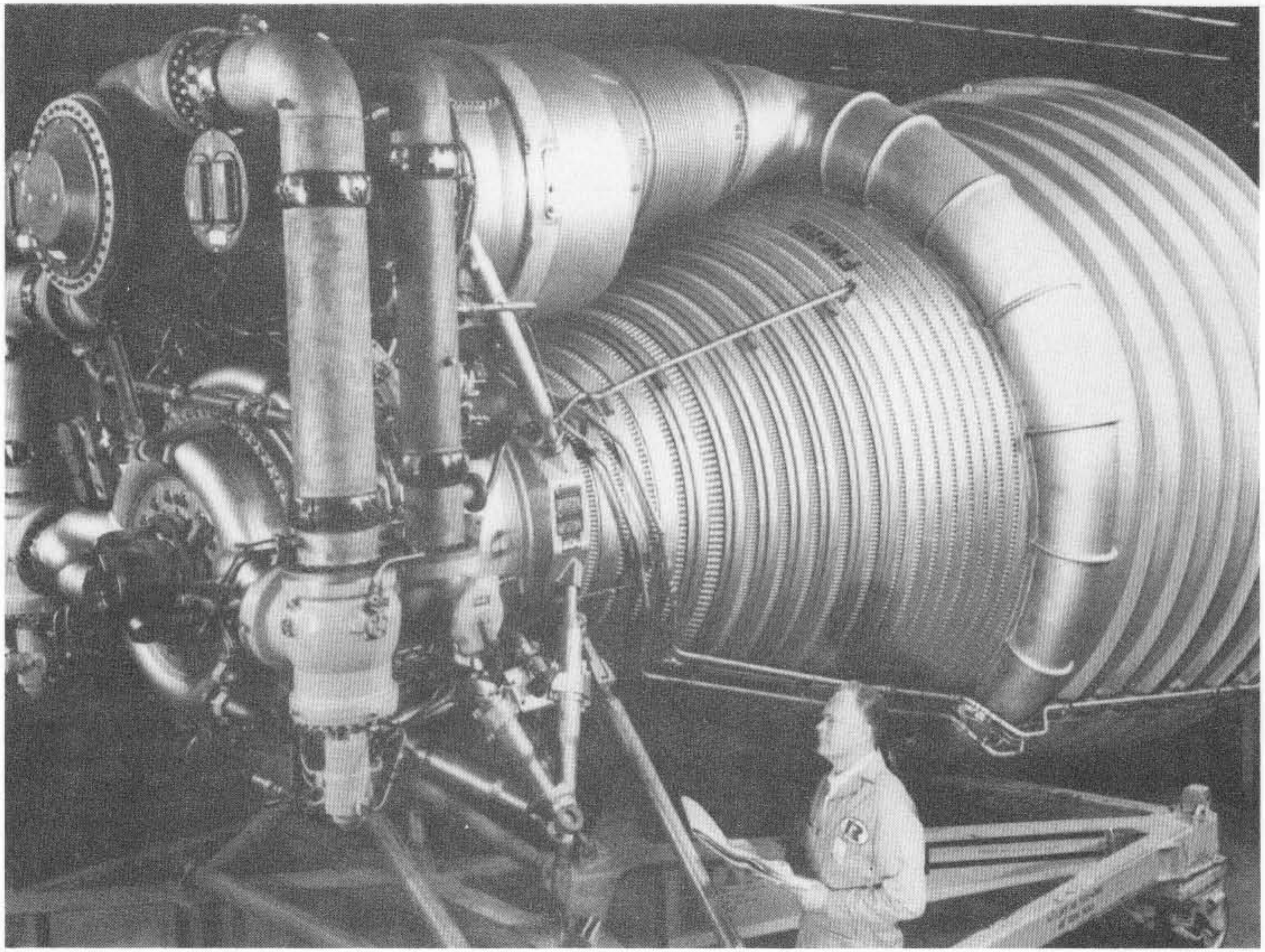

Figure 2. F-1 Engine

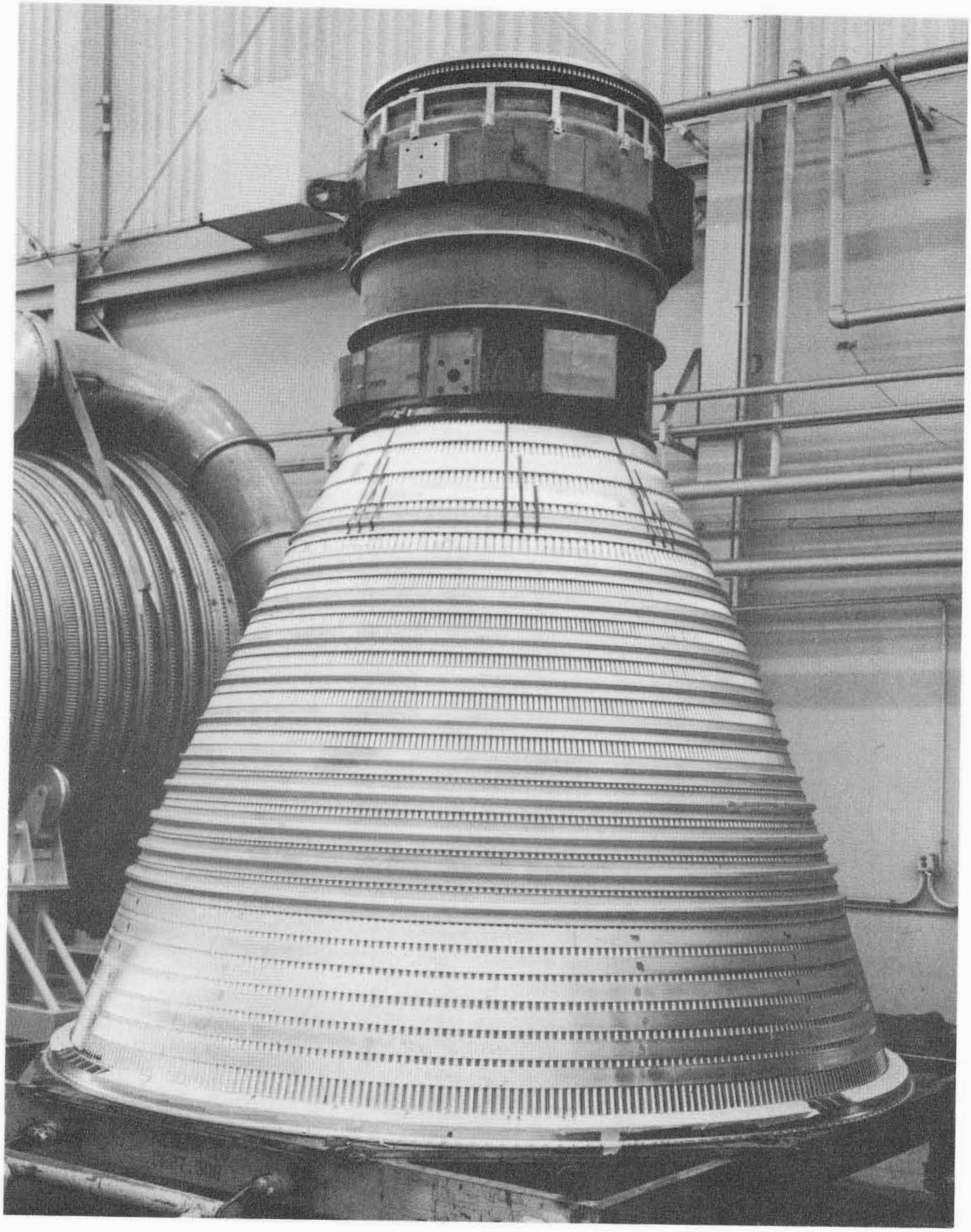

Figure 3. F-1 Thrust Chamber

some resistance to the separating forces generated by the internal gas pressure, the primary load is borne by the jacket and bands surrounding the tube bundle. In many respects the construction features described in the F-1 thrust chamber design concept are similar to those employed in earlier successful tubular-walled regeneratively cooled chambers, such as the Atlas booster and sustainer engines, and the H-1 engine which powers the first stage of Saturn I. However, the greatly increased power and high thrust-to-weight ratio imposed by the design requirements on the F-1 engine necessitated the application of more advanced joining methods than those previously used. The successful application of brazing, as a method of fabricating earlier thrust chambers at Rocketdyne, directed development toward this method of joining.

DISCUSSION

EVOLUTION OF FURNACE BRAZING

The first liquid rocket tubular-walled thrust chambers were fabricated by torch brazing, using low-melting silver-base brazing alloys. The tube material was high heat transfer pure nickel. For the thrust levels, operating temperatures, and pressures required, this material performed satisfactorily.

The F-1 engine with thrust requirements almost ten times greater than any free world engine then in existence required new design concepts, based upon more advanced materials and processes. The selection of Inconel X-750, although it provided the required high strength-to-weight ratios essential to a successful design, posed certain limitations on the brazing process. Initial development work on various joining processes established that, because of the characteristic low ductility of high-nickel alloys in the brazing range of most silver-base brazing alloys (1200 to 1500 F), the conventional torch brazing techniques used on pure nickel could not be used on Inconel X-750. The lower specimen in Fig. 4 illustrates a typical failure resulting from the liquid metal stress cracking on

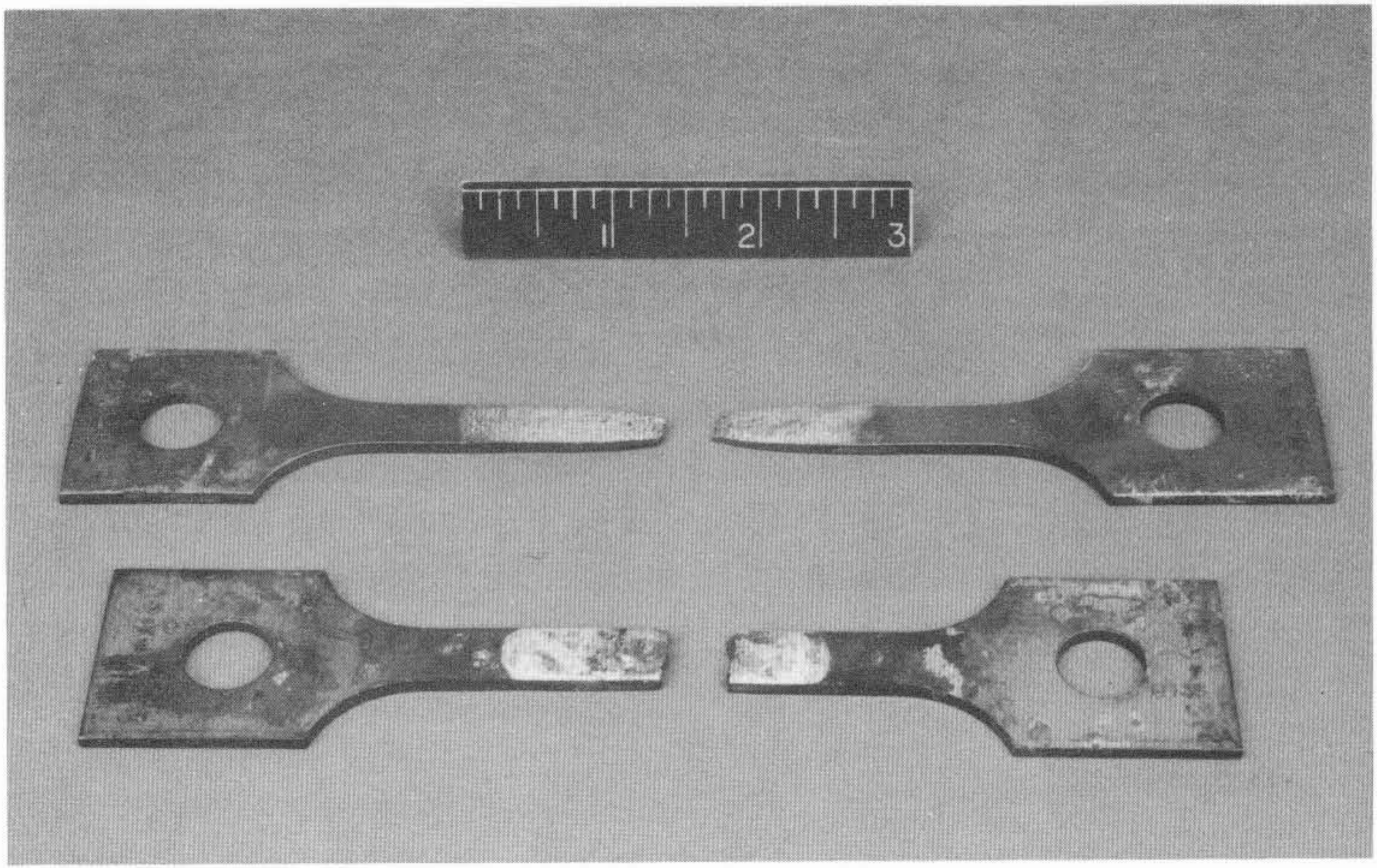

Figure 4. Liquid Metal Stress Cracking

Inconel X with a low-melting silver-base brazing alloy. In this test the alloy is applied while the test specimen is at brazing temperature and under load. The metallurgical phenomena of liquid metal stress cracking is associated with both the low ductility of the base metal in the melting range of the alloy and with the tendency of the alloy to rapidly penetrate the grain boundary. The upper specimen in Fig. 4 was brazed at a higher temperature and exhibits a typical ductile failure with good elongation. At the completion of the analysis of the liquid metal stress cracking problem, furnace brazing, using high temperature brazing alloys, was considered to be the only feasible method of joining the thrust chamber assembly. Inconel X-750, however, contains significant amounts of aluminum and titanium which tend to form refractory oxides with the result that the surface of the Inconel is not readily wet by most brazing alloys at elevated temperatures.

The diagram in Fig. 5 illustrates the wetting problem created by these oxides and the surface forces involved. The wetting angle between the surface of the Inconel X and the brazing alloy had to be reduced to some low value by reducing the surface tension at the brazing alloy-Inconel X-750 interface. This was accomplished by electrolytically depositing 0.0010 to 0.0014 inch of nickel on the surfaces of the Inconel X components and, hence, eliminating the formation of refractory oxides on the surfaces which were to be brazed. Pure nickel is readily wet in either an inert or reducing atmosphere because it has a relatively unstable oxide. The oxide equilibria diagram in Fig. 6 illustrates the relative instability of nickel oxide as a function of temperature and moisture in a hydrogen atmosphere.

Further evaluation of the furnace-brazing process indicated that this method of fabrication would provide certain additional advantages over torch brazing. These included:

1. Minimizing of thermal stresses resulting from differences in heating and expansion rates.

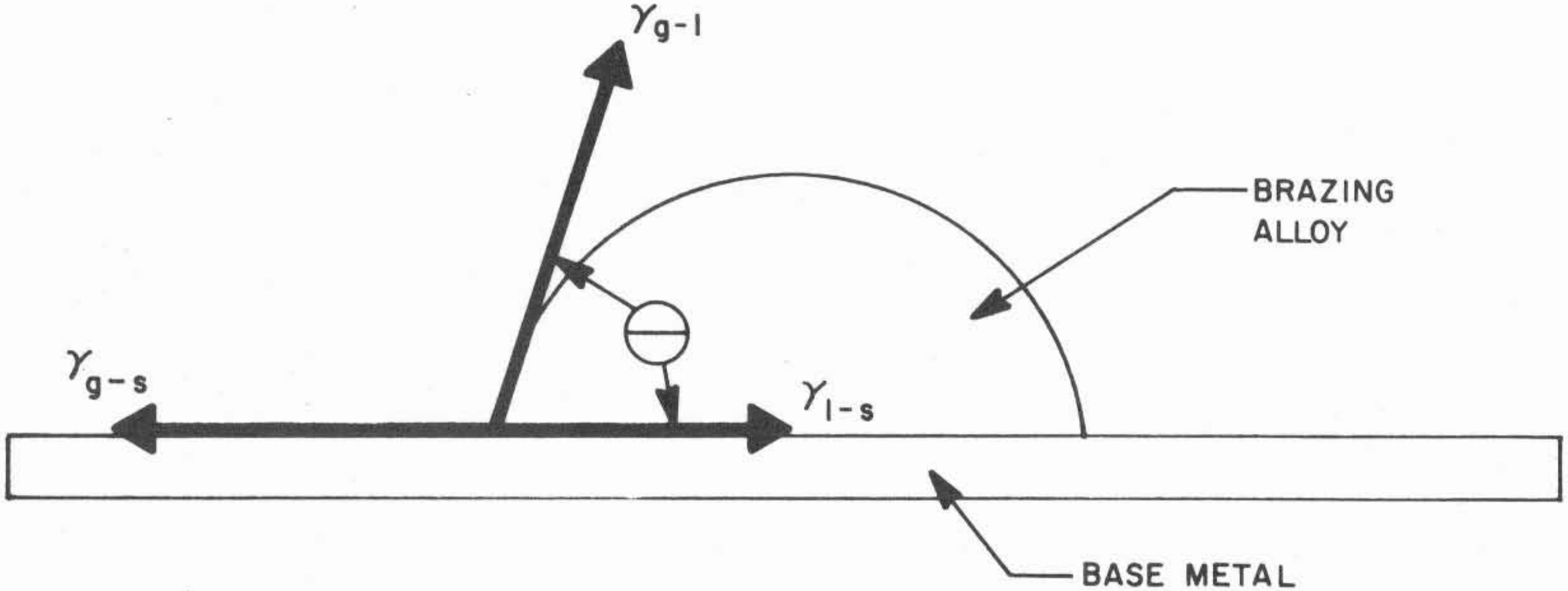

Figure 5. Wetting Diagram

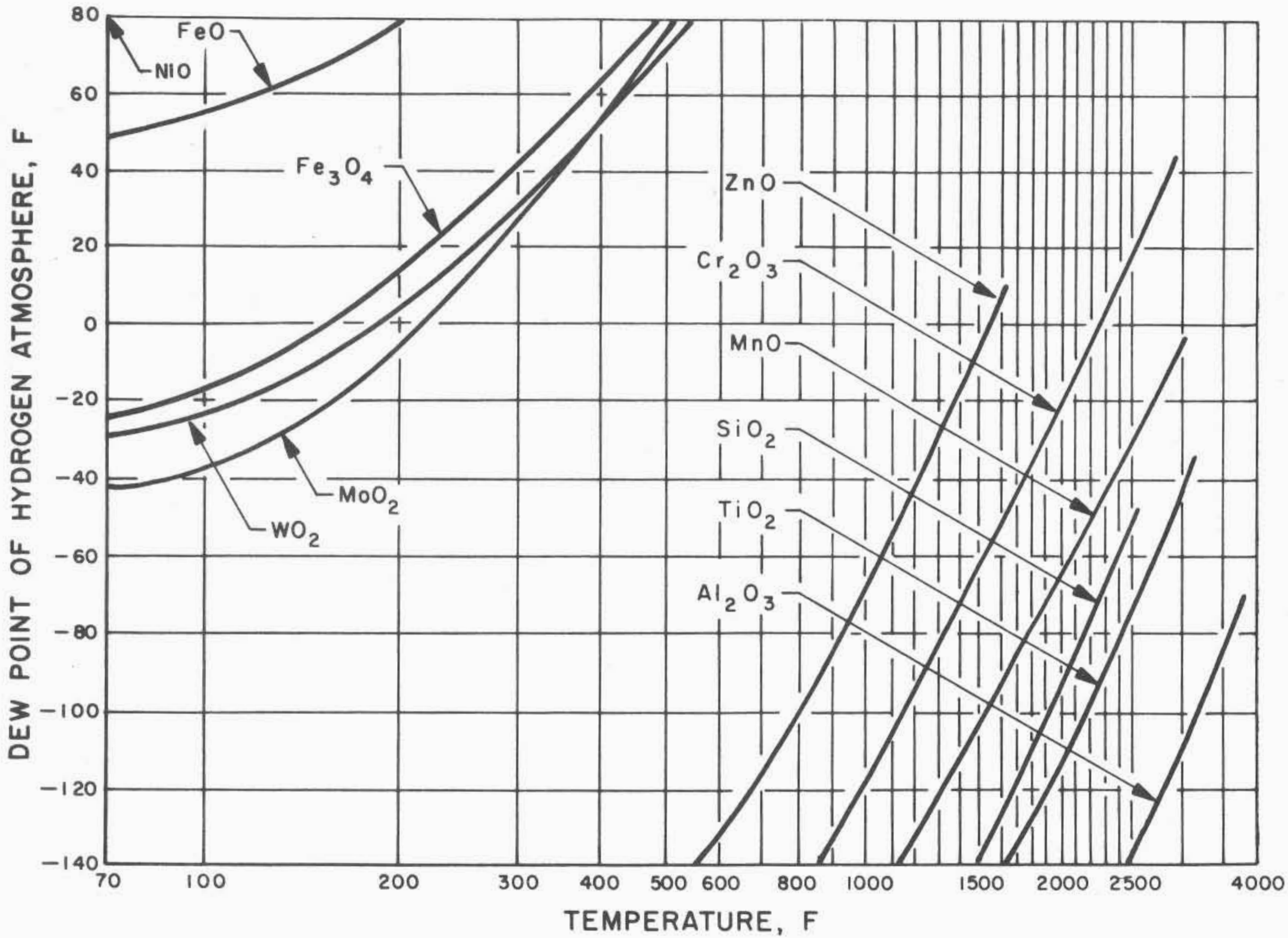

Figure 6. Metal/Metal Oxide Equilibria in Hydrogen Atmospheres

2. The opportunity to combine the age hardening of the Inconel X-750 with the brazing operation.

3. Improved reliability and uniformity by eliminating the operator variable.

SELECTION OF A THRUST CHAMBER BRAZING ALLOY SYSTEM

The selection of Inconel X-750 and the decision to proceed with furnace brazing as a primary joining process on the F-1 thrust chamber led to extensive evaluation of a series of potentially usable alloy systems. These included silver-, nickel-, and gold-base brazing alloy systems. An analysis of the thrust chamber brazed-joint reliability requirements resulted in a decision to employ a three-step brazing process.

In the first brazing operation, the two secondary thrust chamber tubes would be joined to the primary tube using induction heating. These detail parts would then become a subassembly to be subsequently stacked and furnace brazed as part of the total thrust chamber assembly.

In the second brazing operation, all of the thrust chamber components, including the primary-secondary tube subassemblies, the jacket, bands, and end rings would be joined in a primary furnace-brazing operation.

In the third brazing operation, the chamber would be partially realloyed in certain critical joint areas and exposed to a second furnace brazing operation.

To accomplish the three brazing operations with no remelting, required a minimum separation of 50 F between the melting ranges of each of the alloys selected. To prevent the Inconel X-750 base metal from being exposed to molten alloy in the low-ductility range, the lowest melting alloy in the system could not have a solidus temperature less than 1700 F. The alloy system requirements were then established by an upper temperature limit of 2250 F and a lower temperature limit of 1700 F. A 2100 F upper limit for furnace brazing was imposed by two limitations:

(1) impairment of base metal properties as a result of grain growth, and (2) furnace and brazing retort material operating temperature capability.

Working within the 2250 to 1700 F brazing envelope, three alloys were selected: (1) Au-27Pd-22Ni-10Cr, (2) Ag-20Pd-5Mn, and (3) Au-18Ni. The application of these alloys in the three-step brazing process is illustrated in Fig. 7. The alloys selected in addition to meeting the temperature requirements discussed also fulfill other important requirements: (1) good successive wetting and flow characteristics without the formation of low melting eutectics or brittle intermetallics, (2) minimum tendency to erode the base metal, (3) good oxidation and corrosion resistance, and (4) adequate strength and thermal conductivity at elevated temperatures.

DETAIL PART PREPARATION

Thrust chamber components, such as the jacket, injector ring, and exit ring, are all precision machined. The Inconel X-750 jacket of forged and welded construction is subjected to rigorous process and quality requirements during fabrication. Thrust chamber Inconel X-750 tubes are formed to precision tolerances and are then induction brazed, using the semi-automated process illustrated in Fig. 8. The bands that surround the chamber in the nozzle section are precision formed for maximum accuracy. Thus, the entire chamber assembly is capable of meeting the minimum clearances necessary to establish capillary joints and good brazing alloy flow. The next important step in manufacture after the detail components are machined, is their surface preparation.

The electrolytic nickel plating of the thrust chamber jacket and tube bundle, a critical process in the successful brazing of Inconel X-750, is controlled by specification. All thrust chamber components, in addition to those which are plated, are subjected to a succession of cleaning operations, including degreasing, alkaline cleaning, and a final rinse in deionized water to provide optimum brazing conditions. Thrust chamber components are then ready for assembly.

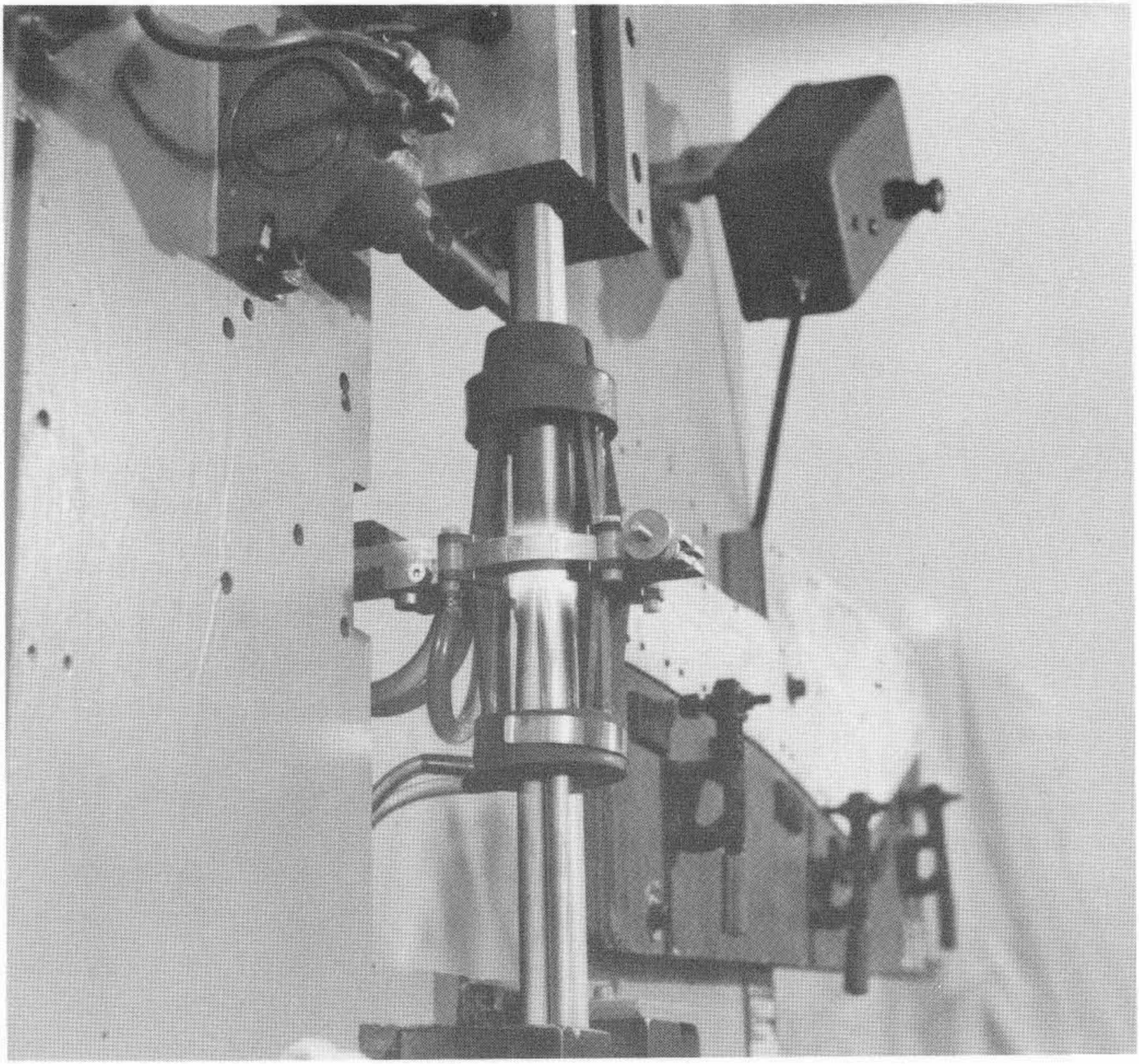

Figure 8. Induction Brazing Tube Assembly

ASSEMBLY AND ALLOYING FOR FURNACE BRAZING

The F-1 thrust chamber is assembled and alloyed for furnace brazing in a white room so that the chamber may meet the cleanliness requirements necessary for high-reliability brazing. The assembly of the chamber tube subassemblies into the jacket and end rings, referred to as the "stacking operation," is done in a stacking fixture. This tool establishes the initial alignment between the tube bundle, jacket, and end rings prior to alloy application.

As mentioned earlier, the thrust chamber as assembled for alloy application has approximately 3000 feet of tube-to-tube joint length to be sealed against combustion gas leakage. The containment of these high-pressure gases in the combustion zone at temperatures as high as 5000 F has been a significant accomplishment of the brazing process. The exterior of the thrust chamber also requires considerable brazing, with approximately 7000 tube-to-band joints to be bonded. Figure 9 illustrates thrust chamber tube-to-band joints as brazed.

The first-cycle brazing operation is performed, using brazing alloy in powder form. Application is accomplished by a spraying process developed at Rocketdyne and illustrated in Fig. 10. This process, as well as all phases of the thrust chamber furnace brazing process, are controlled by the company's F-1 Furnace Brazing Process Specification. In the spraying process, alloy is applied to the tube-to-tube joints on the interior and exterior of the thrust chamber. The chamber is now ready for assembly on the furnace braze tooling.

THE BRAZING RETORT AND HIGH TEMPERATURE PRESSURE BAG TOOLING

A primary requirement in the successful brazing of the thrust chamber is the ability of the tooling to support the interior of the thrust chamber tube stack at temperatures in excess of 2000 F. This is done

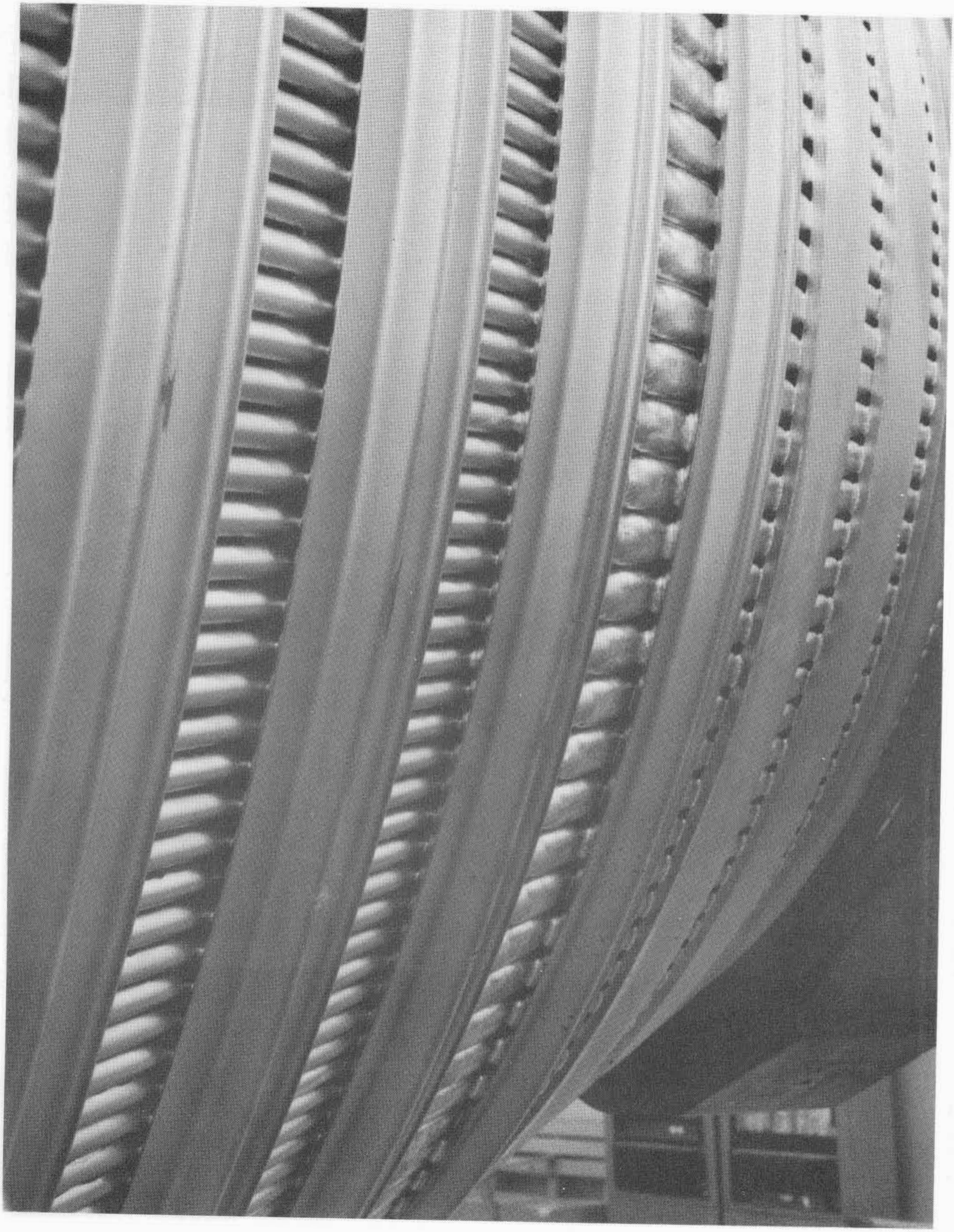

Figure 9. Thrust Chamber Tube-to-Band Joints

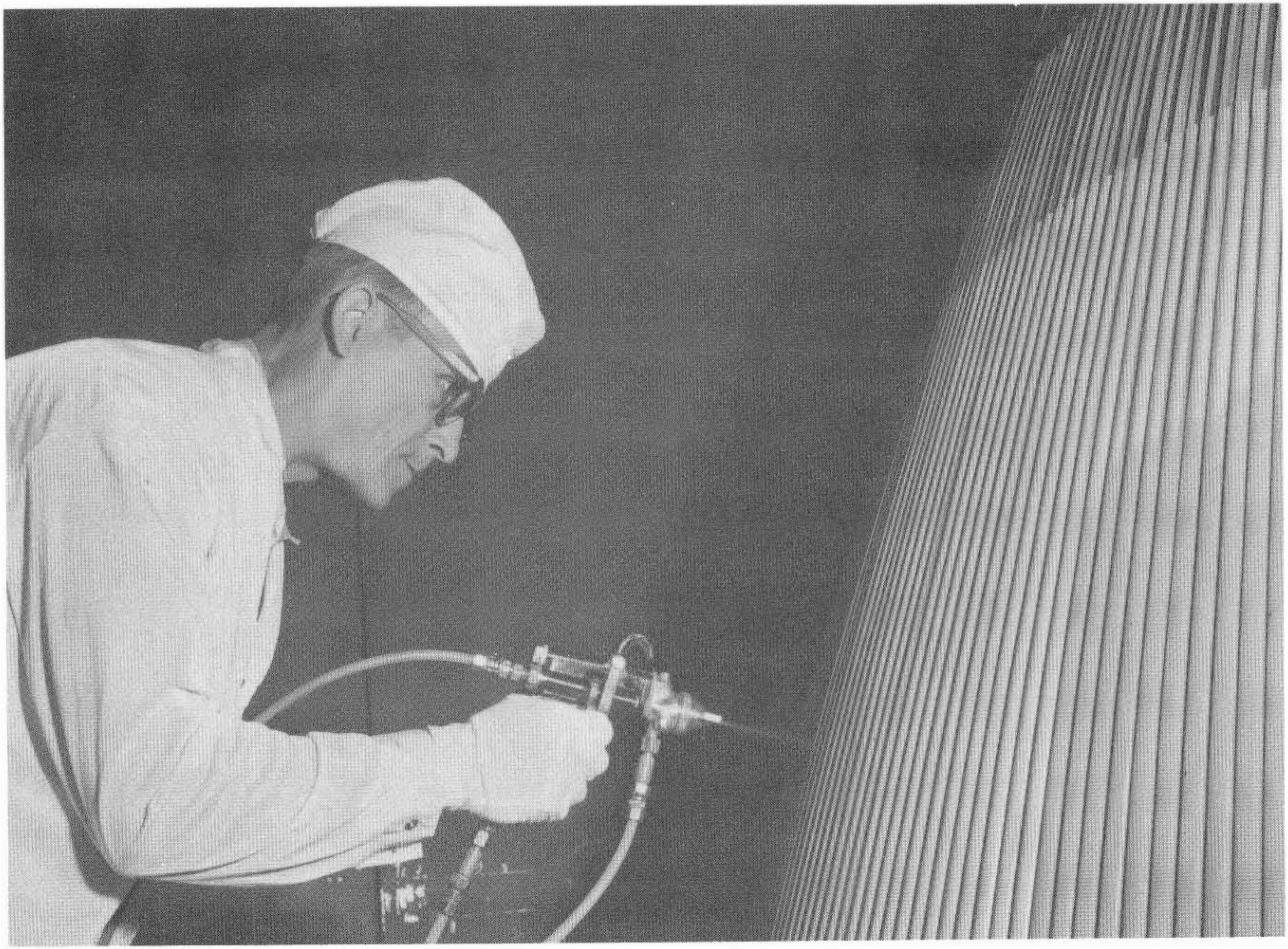

Figure 10. Braze Alloy Application

with a unique device called a "pressure bag" shown being assembled to the thrust chamber in Fig. 11. This device consists of a flexible heat-resisting alloy skin, shaped to the interior contour of the thrust chamber which, when pressured, supports the tube stack. The use of pressure bag tooling represents a significant departure from earlier support concepts which used a high-mass rigid mandrel of heat-resisting alloy construction. The low-mass and good internal support characteristics of the pressure bag tooling were primary factors in establishing a relatively rapid economically feasible furnace brazing cycle.

The brazing retort (Fig. 12) satisfies a second requirement in the furnace brazing operation--the elimination of oxygen from the atmosphere surrounding the brazed assembly. To exlude this oxygen requires the containment of a high-purity protective atmosphere around the thrust chamber. A retort, constructed of a high nickel-chromium-oxidiation-resistant stainless steel, is used for this purpose. Its construction is such that it provides a protective gas atmosphere around and within the thrust chamber throughout the brazing cycle. Atmosphere gas lines to the retort flow argon gas (with a specific gravity of 1.38) into the bottom of the retort and, by displacement purging, remove all the air prior to initiation of the heating cycle.

FURNACE BRAZING (FIRST CYCLE)

The furnace brazing operation represents a final step in which all the material, time, and resources expended in the fabrication of hundreds of thrust chamber parts and subassemblies are committed. In many respects it is similar to the launch of the vehicle itself, since failure of any one of many numerous controls exercised during the furnace brazing operation could result in a poorly brazed, unacceptable piece of hardware. Because of its critical nature, the entire process is a highly developed, closely controlled operation.

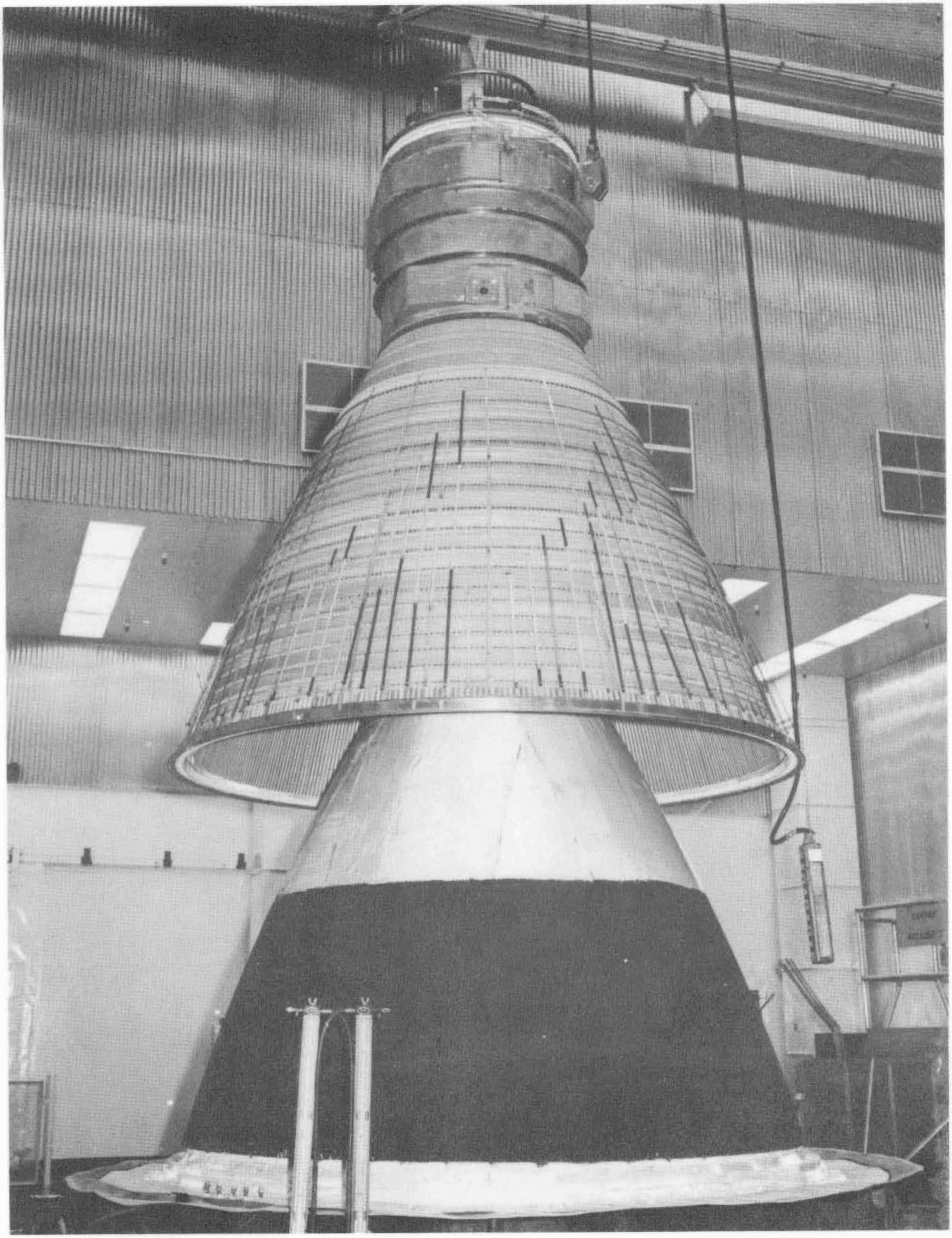

Figure 11. F-1 Pressure Bag

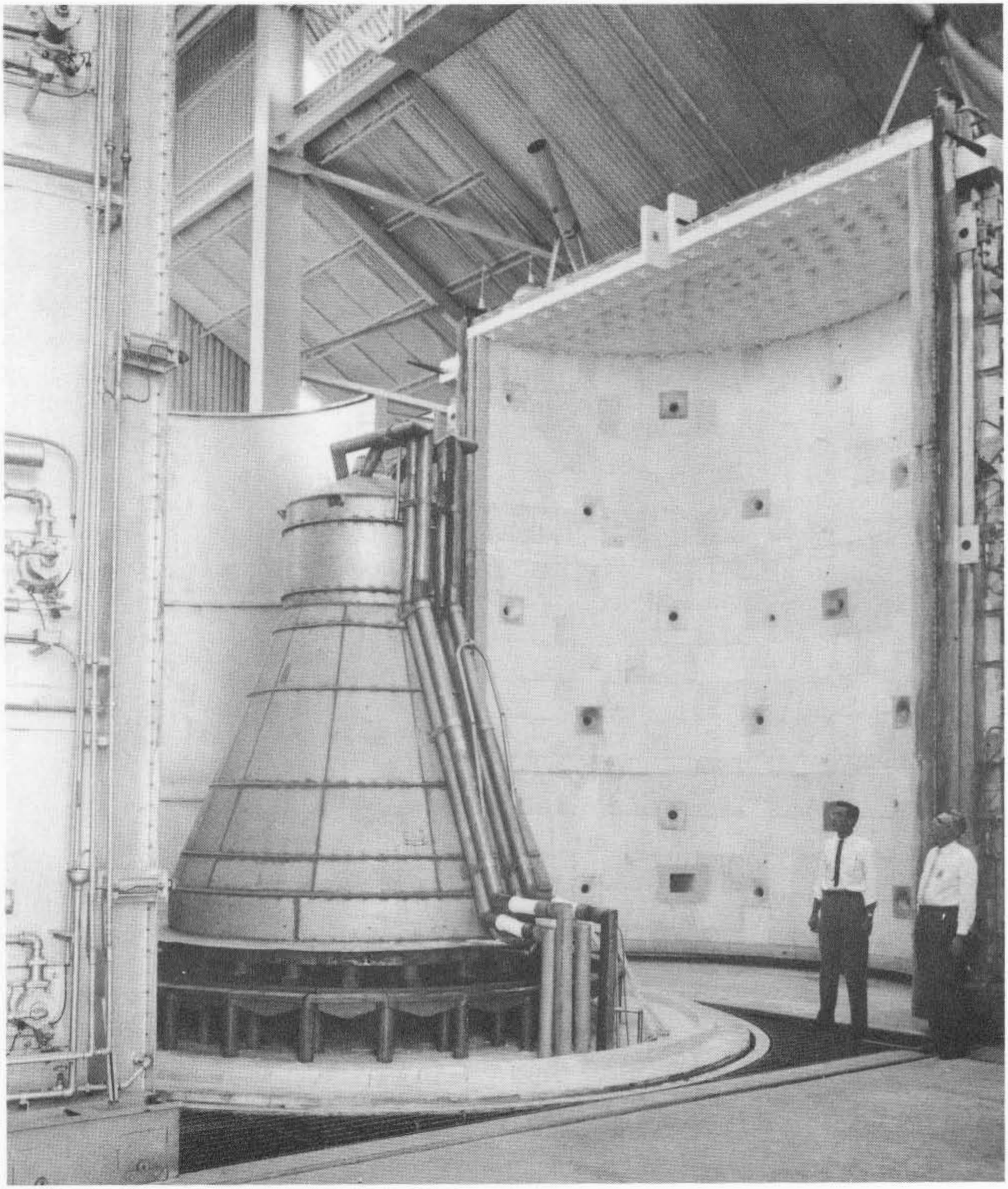

Figure 12. F-1 Brazing Furnace and Retort

The furnace designed specifically for the brazing of the F-1 and other thrust chambers, is unique in design and performance. Its high-energy-input, low-mass construction provides a design of minimum heat capacity and rapid response to thrust chamber heating requirements during the brazing cycle. Three zones of temperature control also contribute significantly to the ability of the furnace to provide uniform heating and rapid response. These performance characteristics make it possible to initiate the furnace brazing cycle with the furnace at room temperature. This factor minimizes the thermal shock to which the thrust chamber would ordinarily be subjected if suddenly exposed to a furnace at or near operating temperature. This cold start capability helps to keep thrust chamber temperature gradients below 150 F while heating to brazing temperature. Large temperature gradients in a poorly controlled furnace could produce extreme part dimensional variations and intolerable thermal stresses, since thrust chamber component wall thicknesses vary from a low of 0.020 inch in the tube wall to a high of 0.500 inch in portions of the jacket.

As the thrust chamber temperature increases, the 150 F maximum temperature gradient reduces to 25 F, which is the gradient at brazing temperature. Figure 13 illustrates the first furnace brazing cycle, time-temperature relationship for the F-1 thrust chamber. The heating rate (approximately 200 F per hour), as such, is not controlled, but rather is a result of limitations imposed by thrust chamber temperature gradients.

As the chamber temperature passes the solidus temperature and the brazing alloy begins to melt, heating of the alloy should be as rapid as possible to minimize liquation (separation of the low-melting from the high-melting phases of the alloy). This reaction is particularly significant on thrust chamber tube-to-tube joints which are vertically oriented. Since gravity tends to flow the low-melting constituents in the brazing alloy to the bottom of the chamber, there is a tendency to

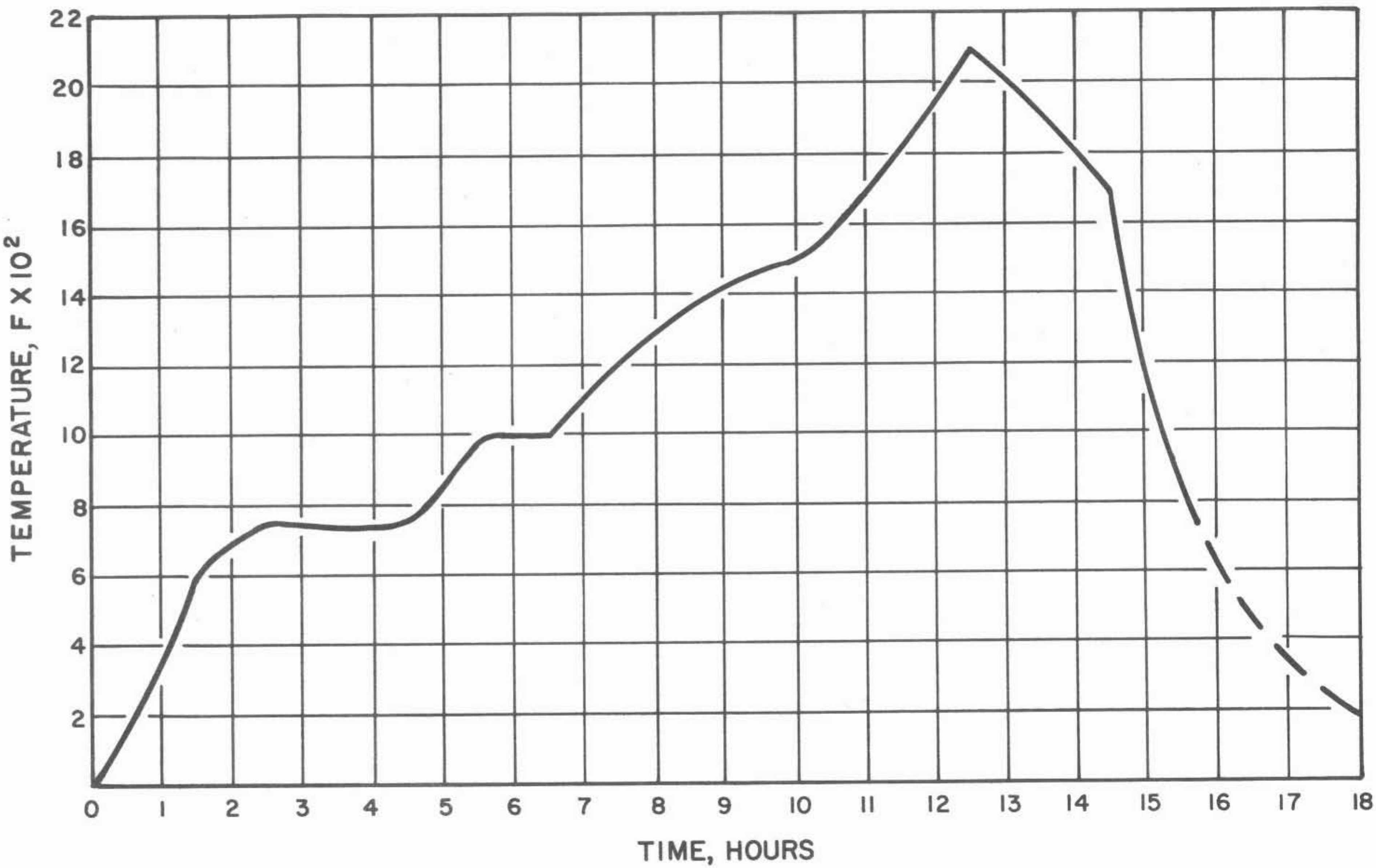

Figure 13. F-1 Furnace Braze (First Cycle)

leave a high melting skull at the location where the alloy is preplaced. The upper specimen in Fig. 14 is an example of liquation in a tube-to-tube joint. When this occurs the effectiveness of the brazing is significantly reduced. However, the spraying of the silver-palladium-manganese brazing alloy has essentially eliminated liquation or sculling as is evident in the lower specimen in Fig. 14. After the chamber has reached brazing temperature, the cooling rate is essentially determined by the maximum temperature gradient allowed.

TESTING FOR INCOMPLETE TUBE-TO-TUBE BRAZED JOINTS

Following the first furnace-brazing cycle, the chamber is prepared for its first tube-to-tube leak test. Incomplete joints located during leak testing or radiographic inspection are identified for realloying prior to second-cycle brazing.

CLEANING AND ALLOY APPLICATION FOR SECOND FURNACE BRAZING CYCLE

Prior to the return of the thrust chamber to the white room for second-cycle braze-alloy application, it is cleaned, scrubbed, and rinsed to remove binder residue, loose alloy particles, and stop-off*, and provide optimum second-cycle brazing conditions.

When the thrust chamber is returned to the white room, selected areas are realloyed. The second-cycle alloying process is accomplished, using a slurry of the Gold-18 Nickel second-cycle alloy, a paste flux, and alcohol. To optimize brazing alloy flow and sealing capability, the chamber is inverted with the jacket down during the second furnace-brazing cycle. Figure 15 illustrates the loading of the chamber into the retort prior to the second furnace-brazing operation.

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*A commercially available flow inhibitor that is usually a refractory oxide in a lacquer, acrylic, or alcohol vehicle, intentionally applied to limit brazing alloy flow.

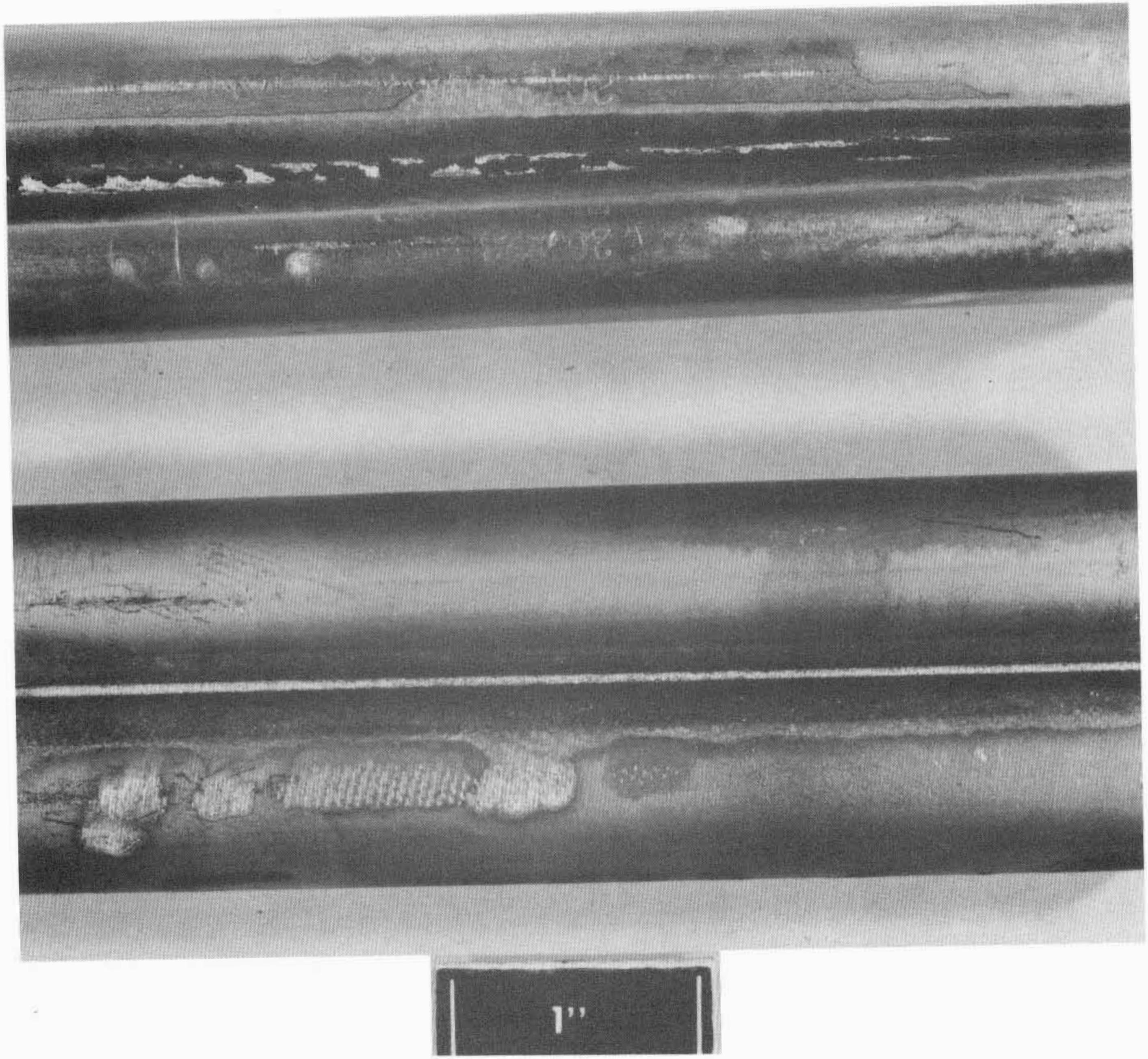

Figure 14. Brazing Alloy Liquation

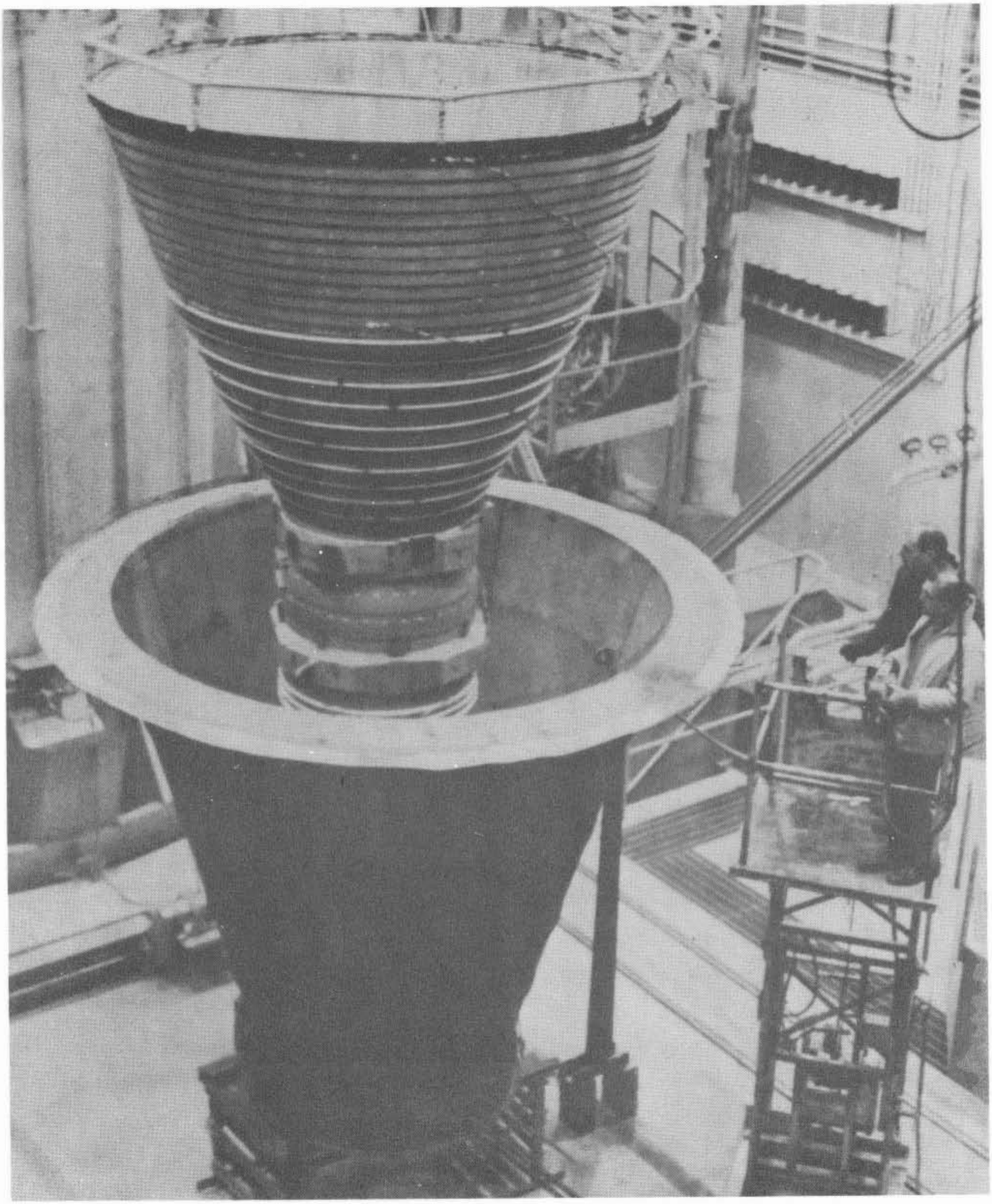

Figure 15. Chamber Being Loaded Into Retort (Prior to Second Furnace Brazing)

FURNACE BRAZING (SECOND CYCLE)

The second furnace-brazing cycle (Fig. 16) is similar to the first cycle, but with certain significant exceptions. These are:

1. No internal support tooling is required, since structurally the chamber is completely bonded and self-supporting.
2. The second cycle brazing temperature is now 1800 F, significantly less than the solidus temperature of the first cycle alloy. This avoids remelting or undermining of the joints initially brazed.
3. Aging of the Inconel X-750 is accomplished during the cooling cycle.

FURNACE-BRAZING INSTRUMENTATION

Thrust Chamber Temperature Measurement

Chromel-alumel thermocouples with calibrated check points are used throughout the chamber to monitor the temperature. Thermocouples are also placed at each location where section thickness or proximity to the furnace wall might cause a variation from the average chamber temperature. To maintain the required high-purity atmosphere in the brazing retort, thermocouple leads are fed through a line from the retort to a cool location at the bottom of the furnace where they are fed through a gas-tight seal to recording instruments.

Brazing Atmosphere Moisture Measurement

Water vapor in the atmosphere gas surrounding the thrust chamber is the most significant cause of surface oxidation and poor brazing. For this

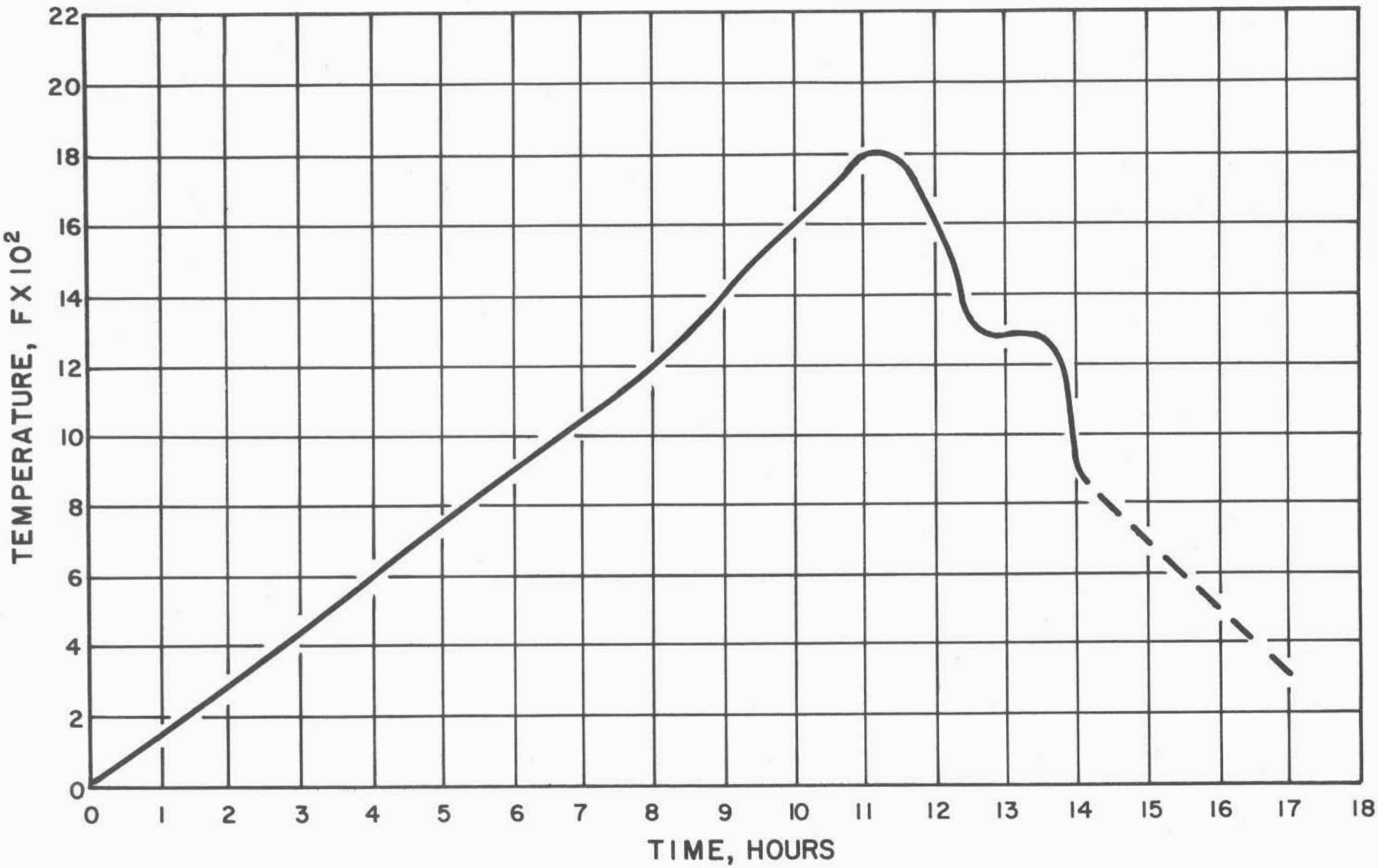

Figure 16. F-1 Furnace Braze (Second Cycle)

reason, the monitoring and control of moisture in the argon surrounding the thrust chamber is highly critical. Argon gas used for furnace brazing, is usually obtained from a liquid source (with $<$ 2 ppm of water vapor) or as a high-purity grade in gaseous form (with $<$ 4 ppm of water vapor).

In thrust chamber furnace brazing at Rocketdyne the liquid storage facility illustrated in Fig. 17 is used. During furnace brazing, moisture is monitored as it enters and leaves the retort. The electrolytic hygrometer, illustrated in Fig. 18, is an instrument which measures moisture as a function of the current required to disassociate a given amount of water. This instrument is used to measure the dew point of the argon entering the retort. A cold cup containing dry ice and acetone is used for determining exhaust atmosphere gas moisture levels. This device, although less sensitive than the electrolytic hygrometer, is simple and effective for dew point measurements as dry as -80 F. Above the binder burn-off and oxidation threshold (approximately 800 F), a dew point of -80 F ($<$ 8 ppm) or drier is required. Above 1700 F and through the melting range of the brazing alloy, a dew point of -90 F or drier is maintained.

Atmosphere Gas Flow Measurement

The flow meters illustrated in Fig. 19 measure argon flow through the retort purging system.

Gas Density and Oxygen Measurement

The retort atmosphere gas in addition to being monitored for moisture is also measured for both oxygen content and specific gravity. This ensures complete purging and the total absence of air prior to initiating the heating cycle.

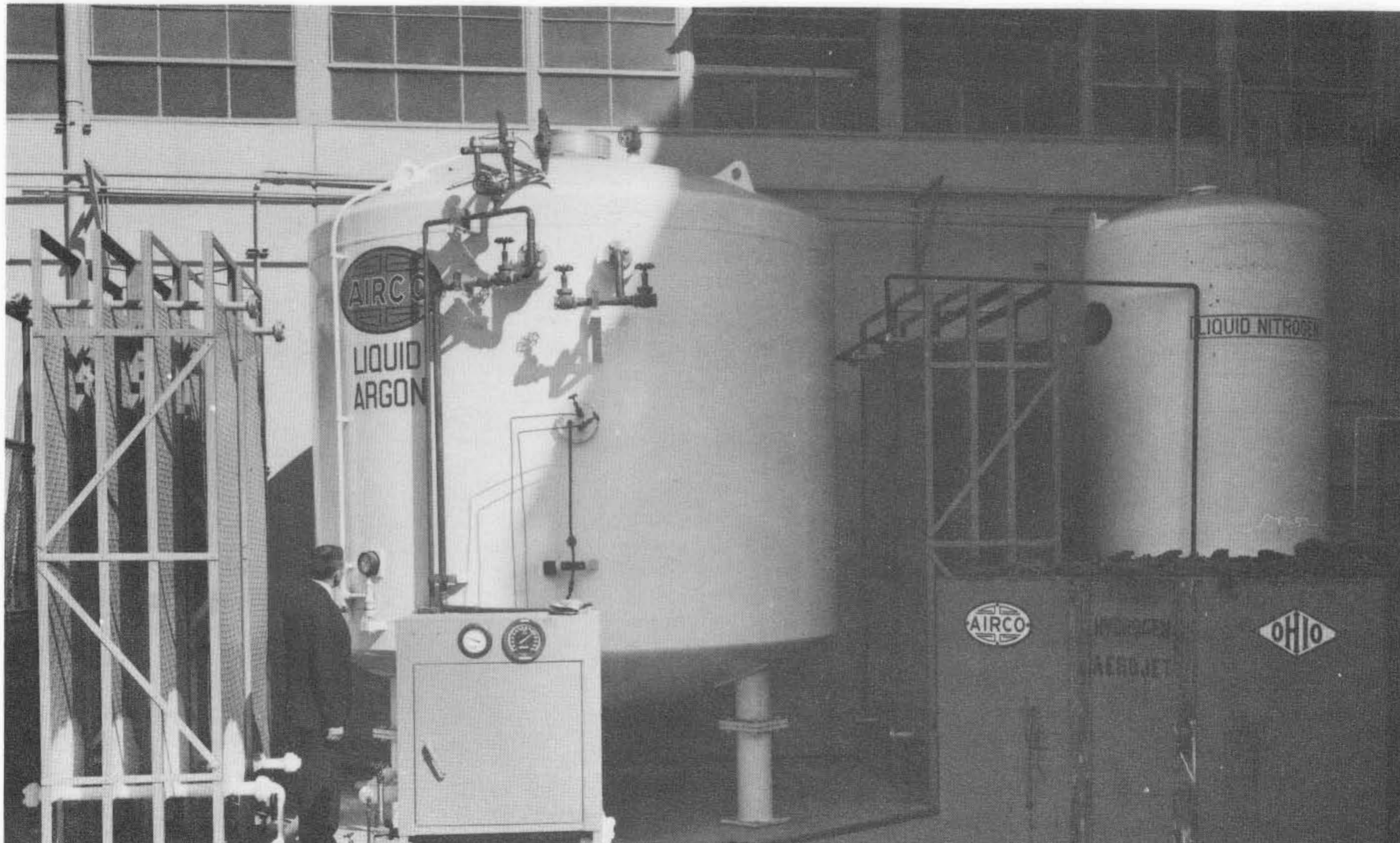

Figure 17. Liquid Argon Storage Facility

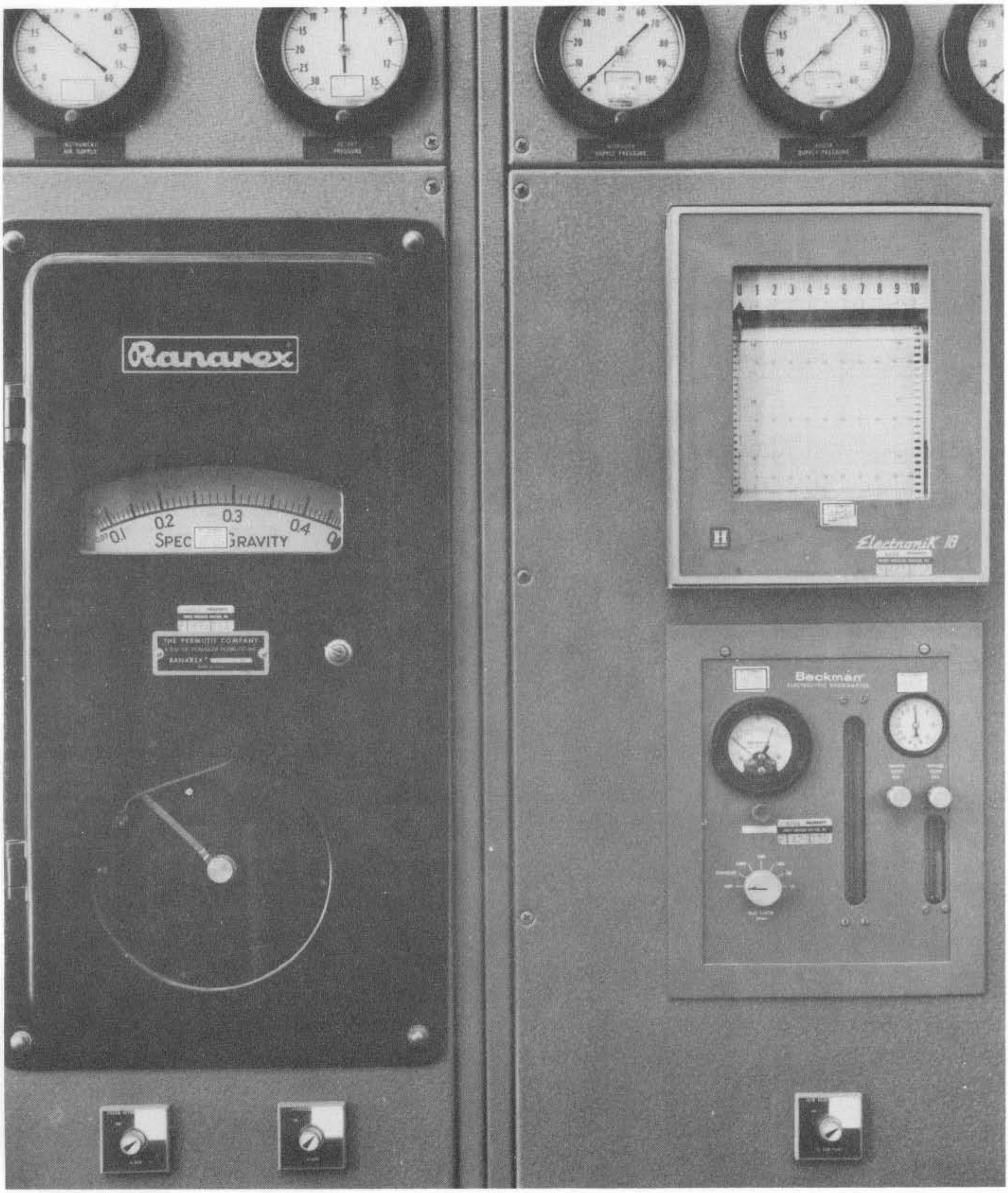

Figure 18. Electrolytic Hygrometer and Specific Gravity Instrument

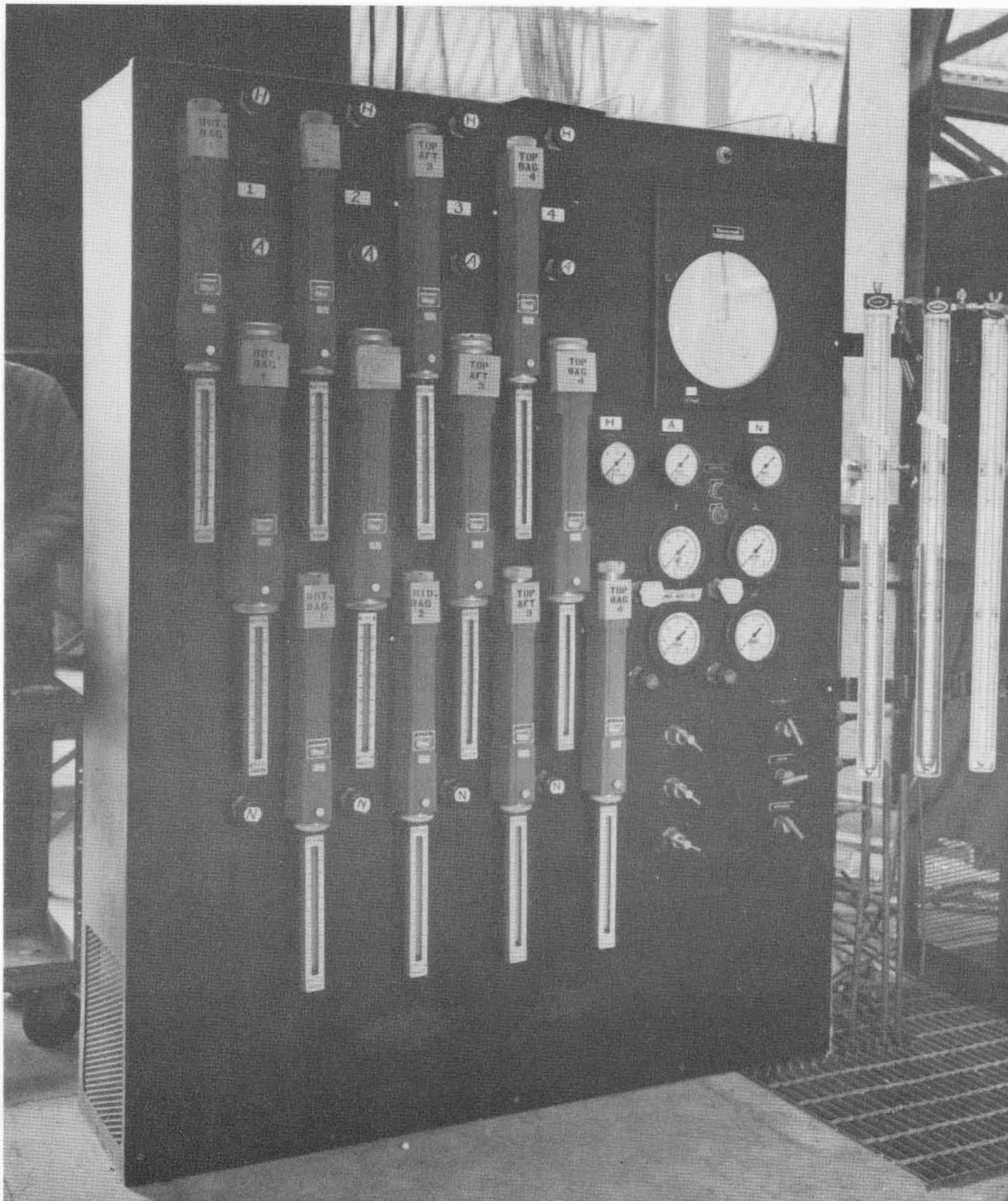

Figure 19. Retort Gas Flowmeters

POST BRAZING QUALITY ASSURANCE

Following the second furnace-brazing operation, the thrust chamber is subjected to a series of pressure, penetrant, and radiographic tests (Fig. 20). These tests determine that the thrust chamber brazed joints are totally free of hot gas and fuel leakage, and include:

1. Pressure test for tube-to-tube joint hot-gas leakage
2. Radiographic inspection of tube-to-tube joints in critical areas of the chamber
3. Penetrant tests of joints for fuel leakage
4. Static, hydraulic pressure test for fuel leakage

Any brazed joint leakage detected in these tests is repaired, using the Gold-18 Nickel as a repair alloy with an oxy-acetylene torch or tungsten inert-gas torch and then retested.

CONCLUSION

After months of F-1 thrust chamber furnace-brazing development, thrust chambers are now being manufactured for production engines. Behind the brazing of the first successful thrust chamber were the following major milestones:

1. The development and manufacture of precision Inconel X-750 sheet metal components to provide optimum brazing effectiveness
2. The development of a successful three-step brazing process and controlling process specification

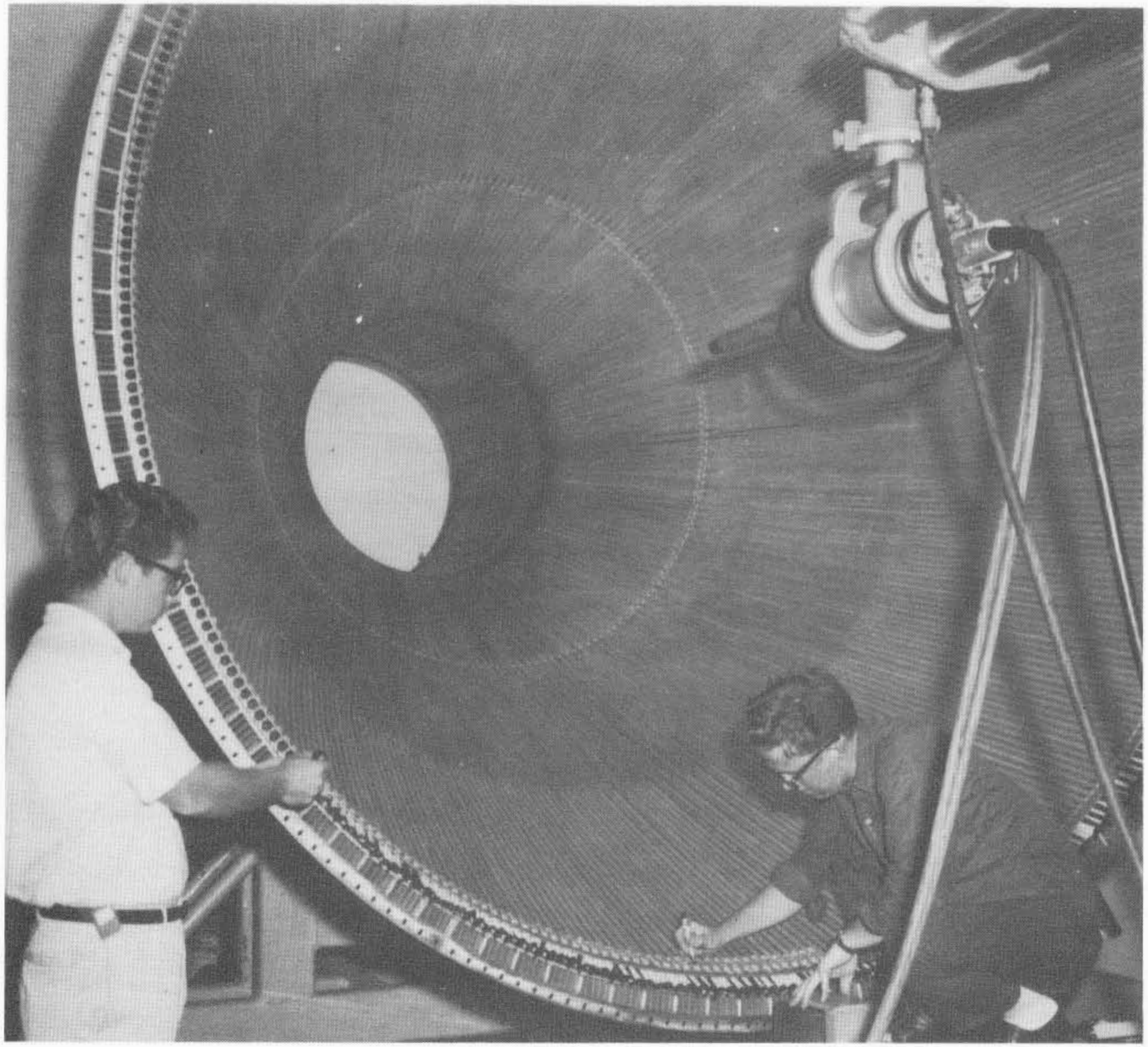

Figure 20. Radiographic Inspection of Tube Joints

3. The construction of a uniquely designed F-1 brazing furnace--the largest facility of its kind

4. The development and application of a lightweight, pressure-bag, furnace-brazing tooling concept

With the F-1 engine now in production, what will be the direction of future furnace brazing development?

This question can best be answered by consideration of future engine requirements and applications. A primary consideration here will be the manned-flight rating program which will require maximum emphasis upon reliability. At the same time, cost considerations will demand that the thrust chamber be produced as economically as possible.

In conclusion, the furnace-brazing process on the F-1 thrust chamber has passed many significant milestones. Hopefully, these successes will contribute toward a more significant one--the success of the Apollo Mission.

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