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WELDING AND BRAZING OF HIGH-TEMPERATURE RADIATORS AND HEAT EXCHANGERS

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ABSTRACT

Procedures were successfully developed for fabricating high-performance radiators and heat exchangers for the Aircraft Nuclear Propulsion (ANP) Program. These components, which contain multitudes of tube-to-tube sheet and tube-to-fin joints, are similar in design to those under consideration for a variety of space vehicle applications.

In order to ensure reliability of the tube-to-tube sheet joints, techniques producing welds of extremely high quality were used and back brazing of the welds with a suitable alloy was incorporated. High-temperature brazing was also incorporated to attach high-conductivity fins to Inconel tubes in the radiators.

The selection of a suitable brazing alloy for these applications was dependent upon several factors, including corrosion and oxidation resistance, flow point, and mechanical properties. A nickel-silicon-boron alloy was found to be adequate from all these considerations. Special brazing procedures were developed to obtain satisfactory flowability of this brazing alloy on tube-to-fin joints.

The suitability of these fabrication procedures for the very stringent service conditions to which the radiators and heat exchangers were subjected was demonstrated by testing full-size components under operating conditions.

INTRODUCTION

The Oak Ridge National Laboratory (ORNL) Metallurgy Division has conducted extensive developmental studies to determine satisfactory procedures for fabricating high-performance radiators and heat exchangers for the Aircraft Nuclear Propulsion (ANP) Program.[1] Since high-performance reactor systems under consideration for space applications may utilize liquid metals and have similar heat transfer problems, it appears appropriate at this time to review the developments which were accomplished on this program.

The liquid metal-to-air radiators and molten salt-to-liquid metal heat exchangers were extremely compact and contained multitudes of thin-walled, small-diameter, Inconel tubes. Figure 1 is a sketch of a typical 0.5 Mw radiator with closely spaced, stainless steel-clad copper, high-conductivity fins. A sketch of a typical 1.5 Mw heat exchanger which contains one hundred 1/2-in-OD x 0.025-in.-wall tubes is shown in Fig. 2. The major problems associated with the welding and brazing of components of these general types will be discussed in this paper, with emphasis being placed on the production of sound, high-quality tube-to-header and tube-to-fin joints.

WELDING AND BRAZING

Tube-to-Header Joints

One of the most important joints in any heat exchanger or radiator is that used to produce a leak-tight seal between the tube and tube sheet. Because of the special corrosion and fire hazard problems associated with liquid-metal systems, the welded tube-to-header joint, with its increased reliability, is preferred. The joint design generally used for such applications is one of the three types shown in Fig. 3. The design illustrated in Fig. 3A is suitable for applications where the tubes are of sufficient size and wall thickness to permit the addition of filler metal by the metallic-arc or inert-arc processes. Figure 3B

[1]R. E. MacPherson and M. M. Yarosh, Development Testing and Performance Evaluation of Liquid Metal and Molten Salt Heat Exchanger, ORNL CF-60-3-164 (March 17, 1960).

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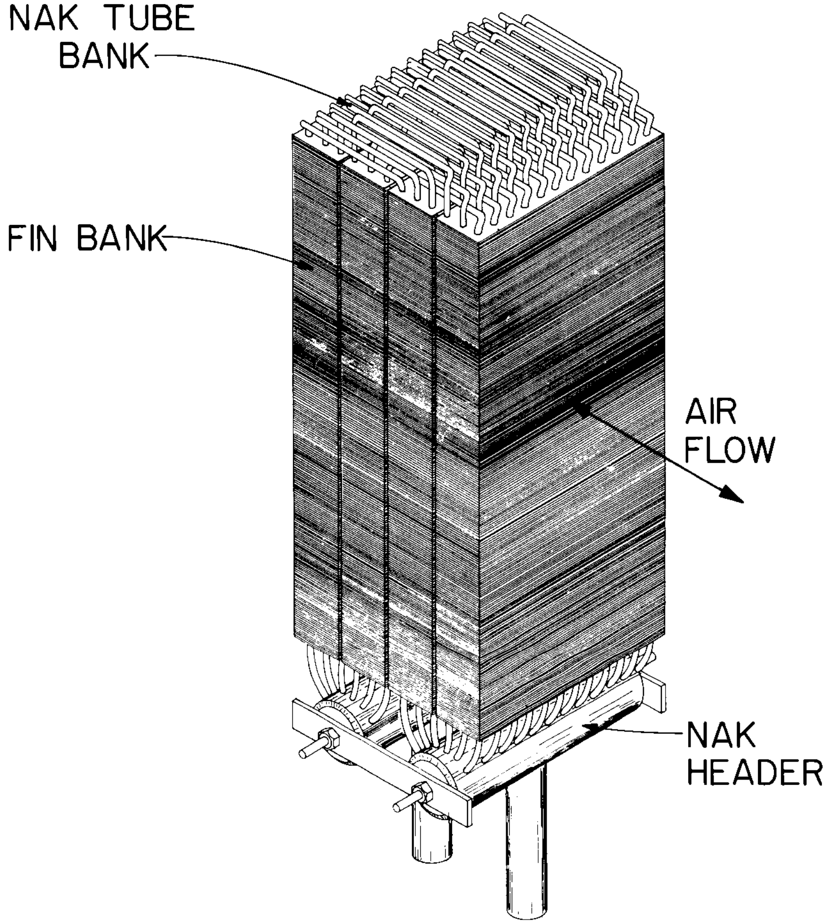

Fig. 1. Sketch of an 0.5 Mw Liquid Metal-to-Air Radiator.

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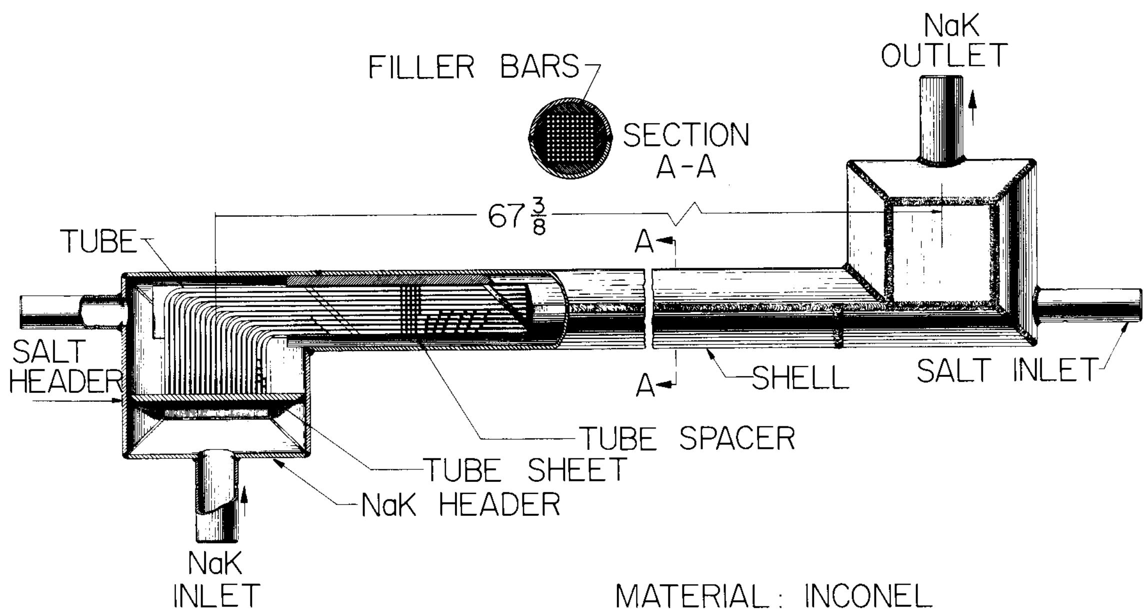

Fig. 2. Sketch of a 1.5 Mw Fused Salt-to-Liquid Metal Heat Exchanger.

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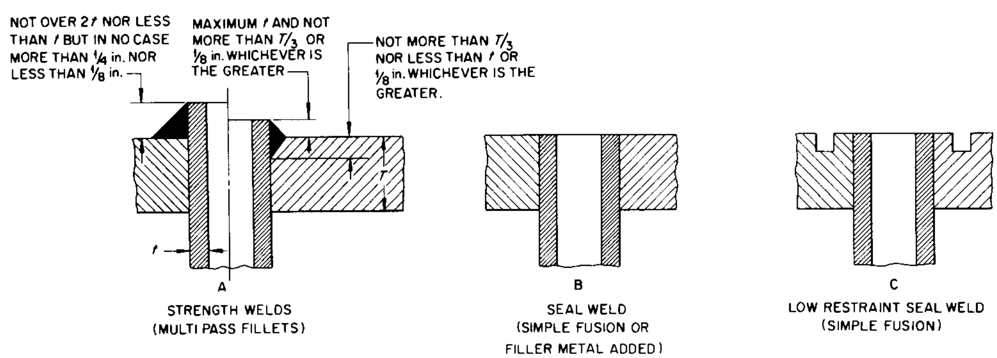

Fig. 3. Basic Joint Designs for Tube-to-Tube Sheet Welding.

is a joint design suitable for seal welds and utilizes simple fusion of the tube and header. A modification of this joint, shown in Fig. 3C, incorporates a trepan and is used where the welds are subject to cracking when made under conditions of restraint. A trepanned joint is inherently expensive to machine, and the ligament length between tubes is a governing factor in the use of such a joint. Therefore, in view of the small diameters of the tubes used in these components, the compactness desired, and the observed freedom from microfissuring, the simple seal-weld design shown in Fig. 3B was utilized in the construction of all heat exchangers and radiators.

Although highly skilled craftsmen can be trained to fabricate tube-to-tube sheet joints of the required quality, the reduction of the human element in such critical applications is considered advisable if the occasional gross flaw is to be avoided. Semiautomatic apparatus was therefore assembled for producing the tube-to-header welds in both the radiators and heat exchangers. A commercially available inert-arc welding torch was mounted on a modified contour oxygen-cutting apparatus. An eccentric was machined and attached to a variable-speed drive assembly in order to provide the correct diameter of rotation for a given tube diameter.

The welding power supply was a motor generator, and a welding contactor permitted push-button control of arc-starting. A high-frequency oscillator permitted starting of the arc without the need for contacting the tungsten electrode to the work.

Using suitable combinations of welding current, travel speed, and rotational diameter, welds with no porosity or root cracks were readily made and excellent penetration was achieved. Typical welding conditions were: arc current — 70 amp; arc distance — 0.050 in.; electrode travel speed — 6 rpm. A weld overlap of approximately one-half revolution was used after the complete peripheral weld had been made in order to permit a current taper to prevent arc craters.

However, as has been reported,[2] joints of this type, although initially sound, are subject to cracking during cyclic service at high temperatures. A performance testing program in which heat exchanger components were subjected to very severe steady-state and cyclic-temperature service was terminated prematurely as a result of the failure of several tube-to-tube sheet joints. Peripheral cracks such as those noted in Fig. 4 were observed in these welds. A metallographic section of a typical fracture is shown in Fig. 5. Further examination of a number of welds which had not leaked revealed other cracks in various stages of propagation. Since no microfissures had been observed during the metallographic examination of a large number of as-welded joints, it was concluded that the initiation and propagation of the cracks occurred during thermal cycling. It appeared that these cracks originated at the unavoidable notch at the root of the weld.

One means for circumventing this problem would be to back braze and thereby eliminate the notch in the manner shown in Fig. 6. The location of the major stress is removed from the weld and relocated to a more favorable area. In Fig. 6 is shown an Inconel tube-to-header joint that has been back brazed with a nickel-base, high-temperature, brazing alloy, thereby filling the annulus between the tube and tube sheet. It is evident that back brazing also provides supplementary functions in that it reinforces welds containing undetected flaws. A striking example of such a difficult to detect but very serious defect is shown in Fig. 7. Without back brazing, the existence of such severe porosity would result in premature failure since only 0.002 in. of sound metal remains as a corrosion barrier.

Resistance to its environment is one of the major considerations in selecting a brazing alloy for a particular application.[3] Adequate oxidation and corrosion resistance of the proposed brazed joints were demonstrated by the exposure of the joint for extended periods of time in the

[2]P. Patriarca, G. M. Slaughter, and W. D. Manly, "Heat Exchanger Fabrication," Welding J. 36(12), 1172–78 (1957).

[3]G. M. Slaughter et al., "Sodium Corrosion and Oxidation Resistance of High-Temperature Brazing Alloys," Welding J. 36(5), 217s–25s (1957).

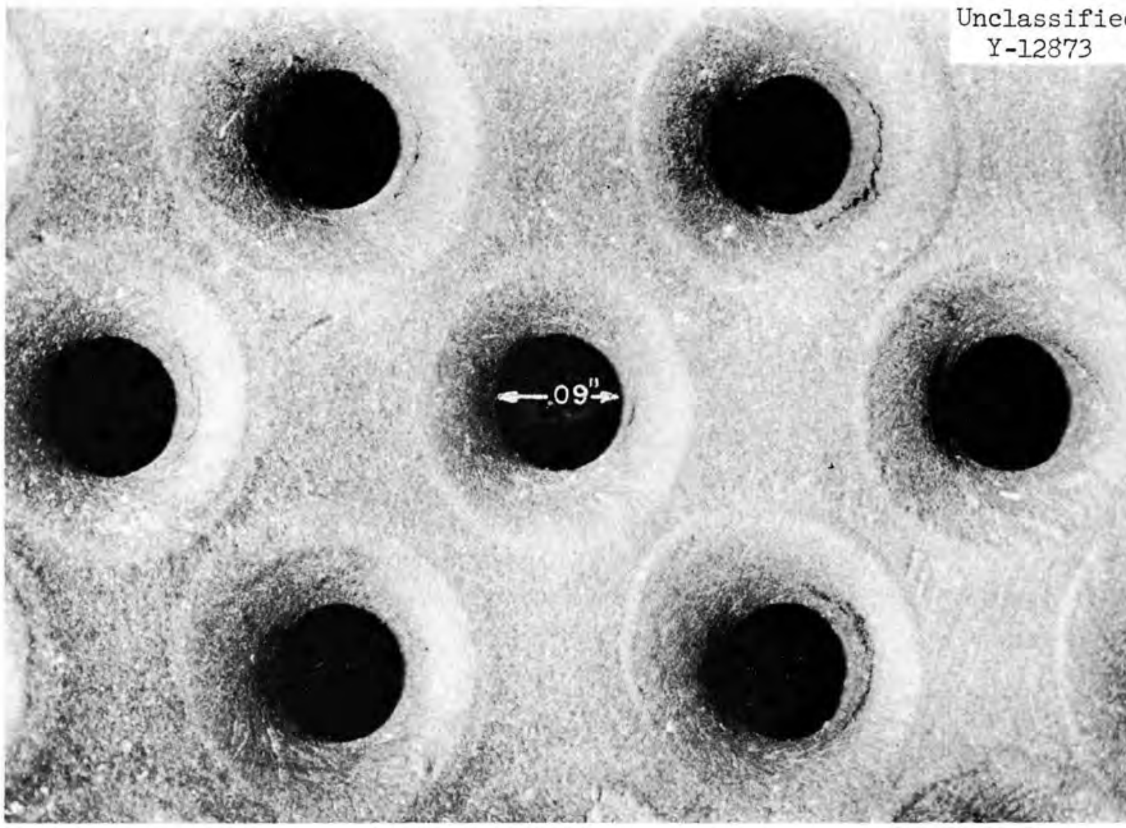

Fig. 4. Peripheral Cracking of the Tube-to-Tube Sheet Welds Observed After Performance Testing.

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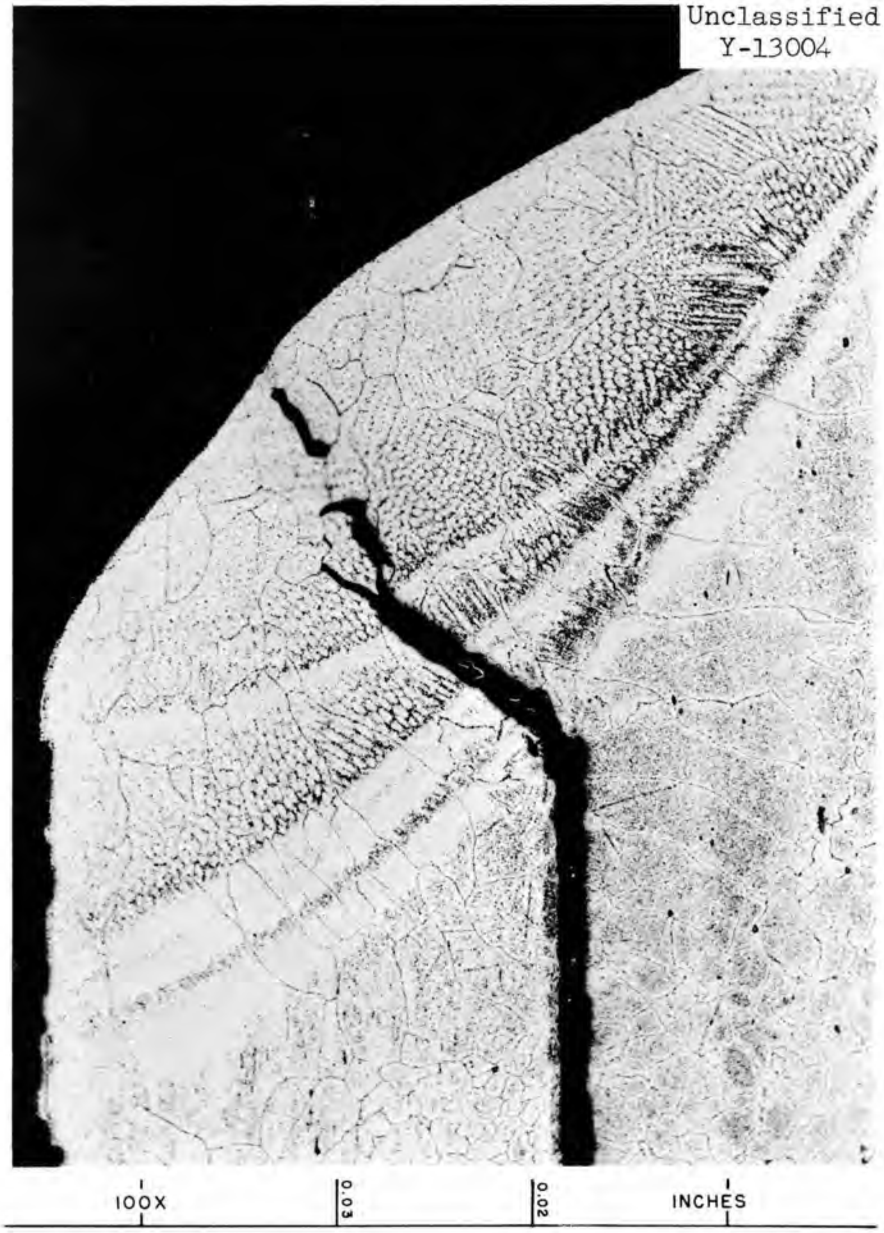

Fig. 5. Photomicrograph of Cracked Tube-to-Tube Sheet Weld After Performance Testing. It can be seen that the crack propagated from the notch and penetrated the weld. Etchant: 10% Oxalic acid-electrolytic.

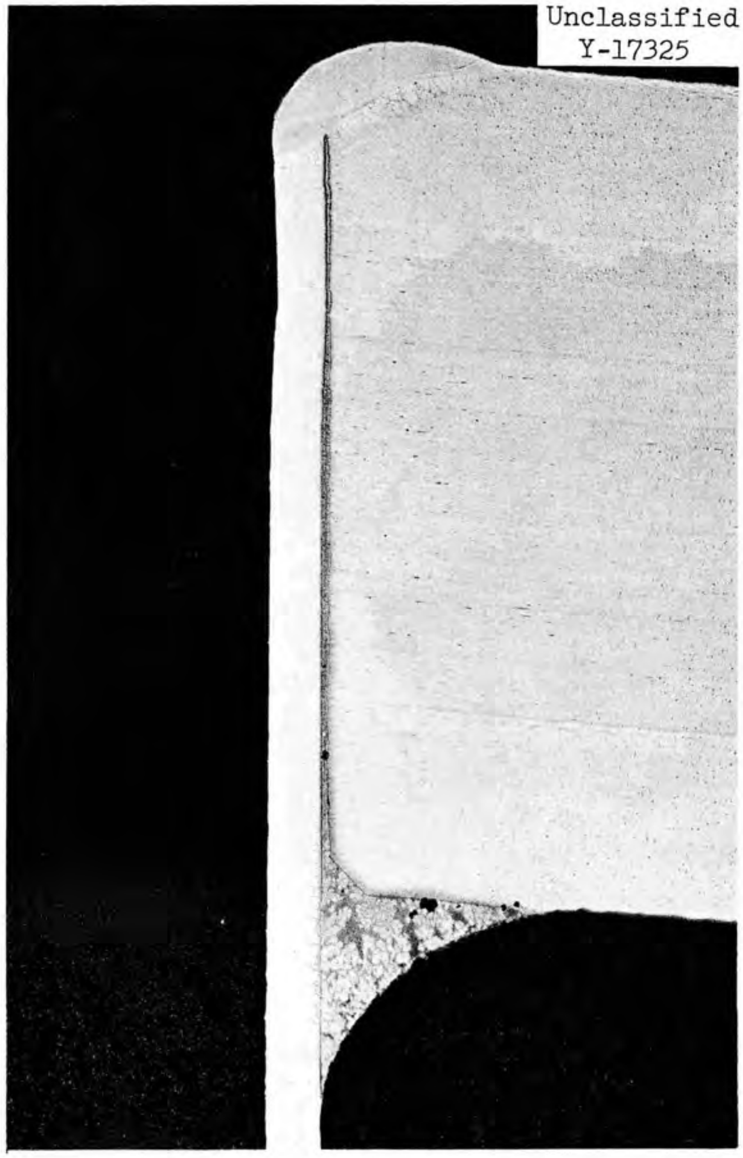

Fig. 6. Inconel Tube-to-Tube Sheet Joint Back Brazed with Nickel-Boron-Silicon Alloy. Etchant: 10% Oxalic acid-electrolytic. 12X.

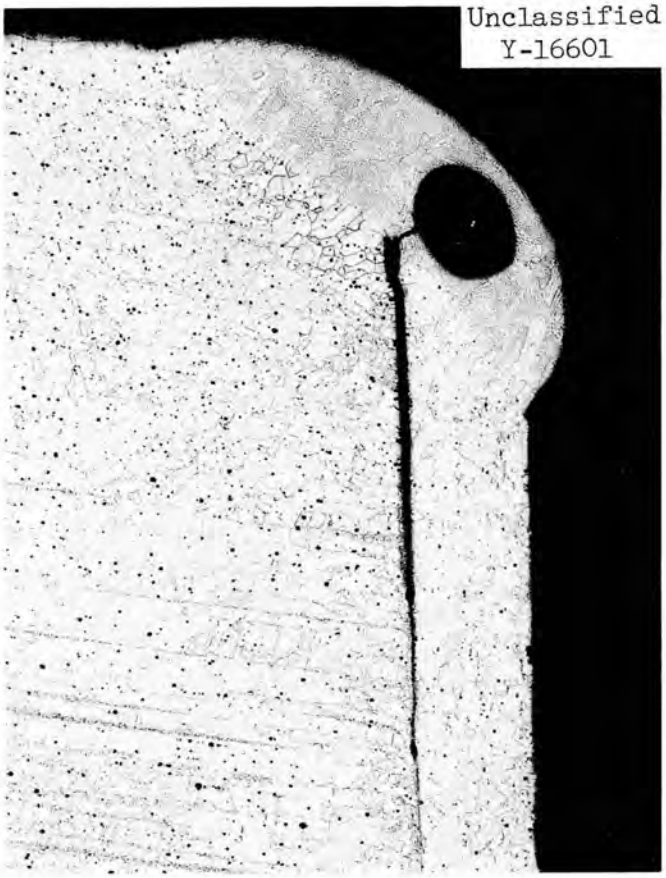

Fig. 7. Gross Porosity in Inconel Tube-to-Header Weld. Etchant: Oxalic acid-electrolytic. 24X.

environments of interest and at the desired operating temperature. An inverted T-joint flowability test is prepared from two strips 1/2 in. wide x 6 in. long which are inert-arc tack welded or wired together and a small amount of brazing alloy is placed at one end. After brazing at a suitable temperature, the specimen is cut into 1/2-in.-long segments and corrosion or oxidation tested. Weight change measurements and metallographic examination of the specimen after test reveal the extent of attack. Figure 8 is a composite showing the general appearance of a specimen before test and a photomicrograph of an acceptable braze after test.

As a result of the brazing alloy evaluation program, the nickel-silicon-boron alloy corresponding to AMS-4778 (ref 4) was selected for back brazing the tube-to-header joints. The alloy possessed good flowability on Inconel and the austenitic stainless steels in the temperature range of 1880–1920°F. The oxidation resistance of the alloy was found to be adequate, as can be seen in Fig. 8, and, in addition, it exhibited good corrosion resistance to liquid NaK and molten fluoride salts.[5] Although the ductility of this type of brazing alloy is low, it is possible to design brazed joints possessing adequate high-temperature properties.[6,7] The joints were therefore used on this basis since oxidation- and corrosion-resistant brazing alloys with better ductilities had not been developed.

These fabrication techniques were used successfully in the construction of several prototype heat exchangers at ORNL and were then utilized in the fabrication of similar, but larger, units by industrial concerns. A photograph of such an assembly is shown in Fig. 9. The curvature of this unit was designed to fit around the contour of a spherical reactor pressure vessel.

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[4]Aeronautical Material Specification-4778, Brazing Alloy – Nickel Base–4.5 Si–2.9 B.

[5]E. E. Hoffman et al., An Evaluation of the Corrosion and Oxidation Resistance of High-Temperature Brazing Alloys, ORNL-1934 (Oct. 23, 1956).

[6]R. L. Peaslee and W. M. Boam, "Design Properties of Brazed Joints for High-Temperature Applications," Welding J. 31(8), 651–62 (1952).

[7]W. H. Chang, "Basic Characteristics of Some Heat-Resisting Brazing Filler Metals," Welding J. 35(9), 431s–43s (1956).

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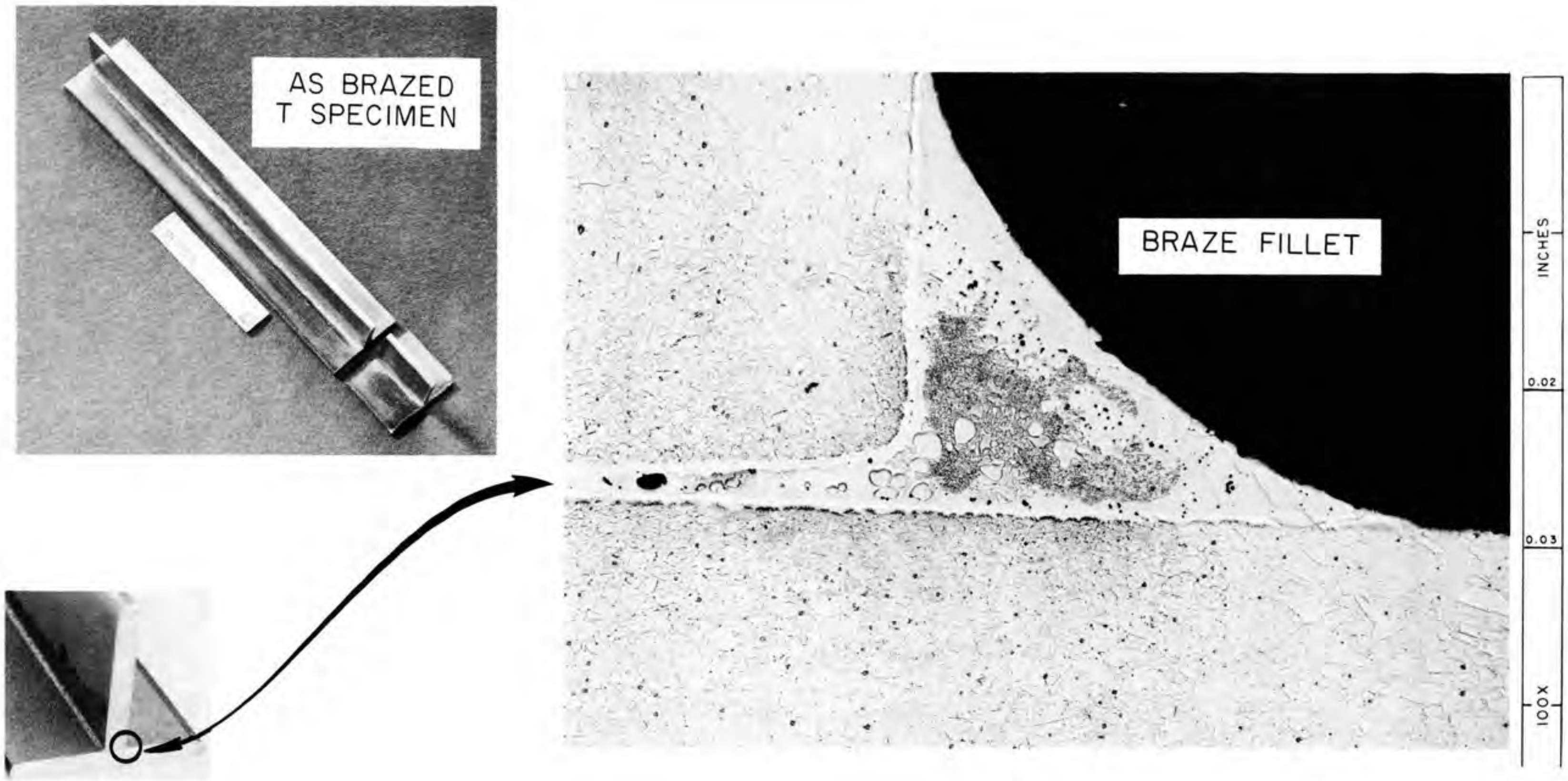

Fig. 8. Composite Showing the General Appearance of a Specimen Before Test and a Photomicrograph of a Braze After Test. This particular sample was an Inconel T-joint brazed with nickel-silicon-boron alloy and tested in air for 500 hr at 1500°F.

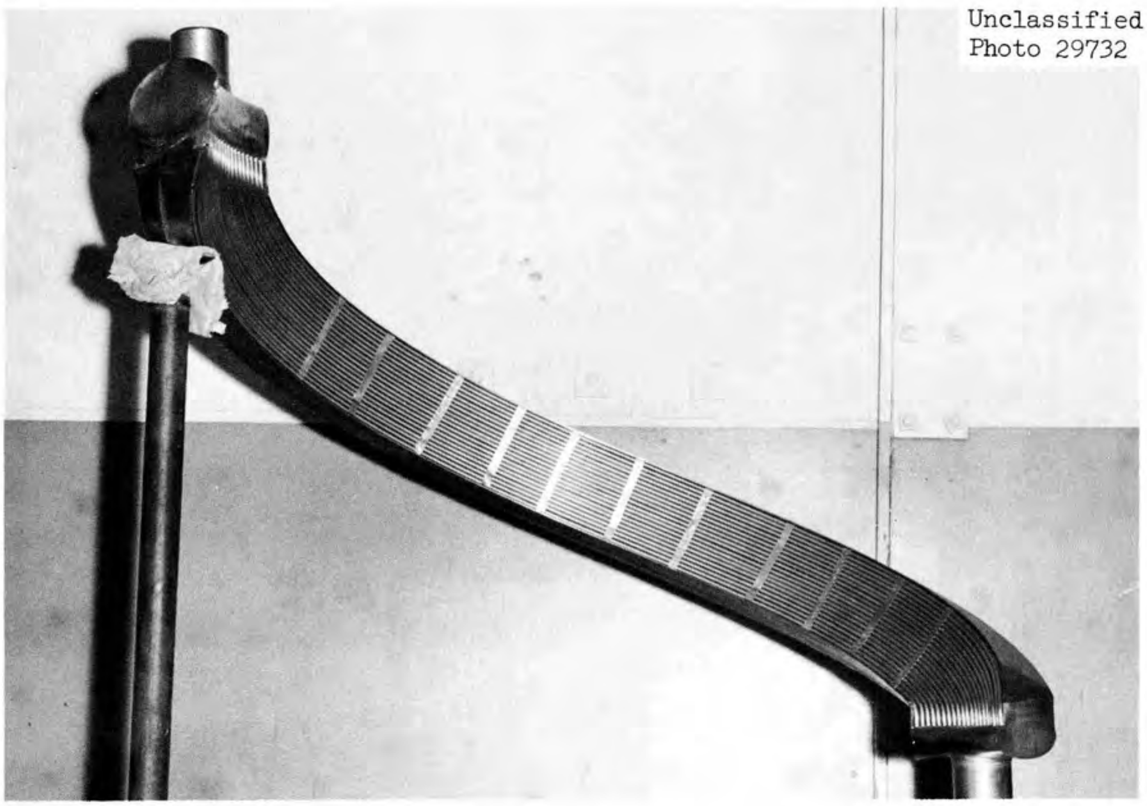

Fig. 9. Large Heat Exchanger Fabricated by Industrial Concern Using the Welded and Back Brazed Procedure.

Tube-to-Fin Joints

The finned tube provides an efficient means for transferring heat to air. Further improvements in heat transfer efficiencies can be obtained by metallurgically bonding the fin to the tube by high-temperature brazing. The complexity of the tube-to-fin brazing problem in the ORNL radiator work can be realized by the fact that there were approx 40,000 such joints in an 0.5 Mw radiator.

The fins used for the radiators in the ORNL study were 0.010 in. thick and were of the high-conductivity type.[8] An 0.006-in. core of copper was roll clad on each side with an 0.002-in. layer of type 310 stainless steel. A composite material of this nature thus possesses good thermal conductivity and exhibits good oxidation resistance. The Inconel tubes passed through holes punched in the fins, and the punched fin lips served as spacers for the individual fins and provided a suitable contact surface for brazing. A sketch showing the tube-to-fin joint configuration and location of the brazing alloy is presented in Fig. 10. It was evident that exposed copper would be present in these fin lips and that this copper must be covered with the brazing alloy during brazing if the ultimate in fin performance was to be realized.

The nickel-silicon-boron alloy[4] was also selected for brazing the radiator fins since it flows at a temperature sufficiently below the melting point of copper (1981°F) to make the brazing of such assemblies feasible.

At the time that the first radiators were fabricated, this brazing alloy was available only as a powder. Procedures for brazing complex units were successfully developed, however, and two completed units are shown in Fig. 11.[9] It was obvious that the preplacement of brazing alloy as rings would permit much more rapid assembly and more accurate and consistent control over the quantity of alloy per joint. Techniques for manufacturing these rings were developed and consisted of melting

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[8] H. Inouye, ORNL-2065 (Jan. 2, 1957) (classified).

[9] P. Patriarca, G. M. Slaughter, W. D. Manly, and R. L. Heestand, Fabrication of Heat Exchangers and Radiators for High-Temperature Reactor Applications, ORNL-1955 (June 14, 1956).

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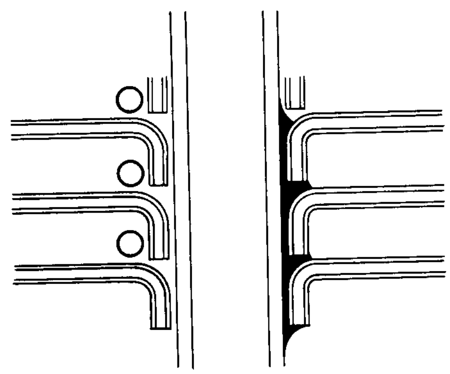

TUBE-TO-FIN
JOINT

Fig. 10. Tube-to-Fin Joint Configuration and Location of the Brazing Alloy.

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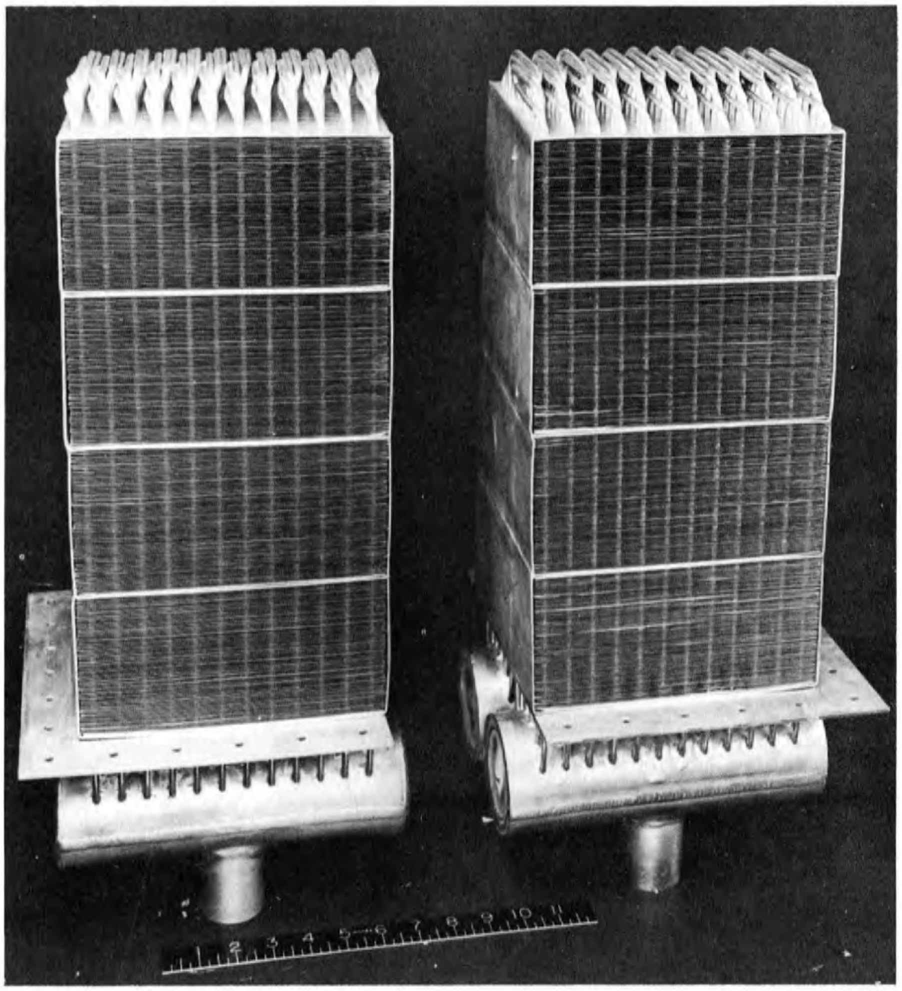

Fig. 11. Two Completed 0.5 Mw Radiators. The brazing alloy was preplaced on all joints as powder.

the powder in small annuli in graphite molds. Future radiators were then fabricated using preplaced cast rings. Assembly rates were increased further by the development and adaptation of a semiautomatic device for placing the rings simultaneously over each of a large cluster of tubes.

As would be expected, however, with initial attempts at brazing large complicated assemblies of such a novel design, some difficulties were encountered. One particularly difficult problem was associated with the incomplete melting of the alloy rings when the rate-of-temperature rise during brazing was too slow. Several apparently unmelted rings are visible in Fig. 12. This condition results from liquation of the lowest melting parts of the brazing alloy as the unit approaches the brazing temperature. The boron and silicon, which are added to the brazing alloy as sharp melting-point depressants, are permitted to diffuse preferentially and prematurely from the ring into the stainless steel fin cladding. Consequently, at the brazing temperature, the major portion of the ring has a melting point considerably higher than that predicted and approaches that of pure nickel.

Experiments were therefore conducted to determine in more detail the influence of rate-of-temperature rise and to determine the minimum permissible rate. Small tube-to-fin specimens were assembled and heated to 1900°F at different rates of rise. At a rate of rise of 100°F/hr, very poor melting of the ring was observed as can be seen in Fig. 13. Some improvement was observed at 200°F/hr, but a rate of rise of 300°F/hr was needed to obtain the complete melting shown in Fig. 14. In practice, a rate of rise of 600–700°F/hr was usually sought in order to ensure that the central portions of the fin bank would exceed the minimum of 300°F/hr.

The necessity of obtaining close temperature control over the complete radiator body during brazing is obvious since a temperature distribution of only 80°F is permissible (the desired brazing temperature is 1900°F and copper melts at approx 1980°F). In initial attempts, a very wide temperature distribution was obtained. This was considered to be unsatisfactory, and, by baffling and furnace-temperature programming,

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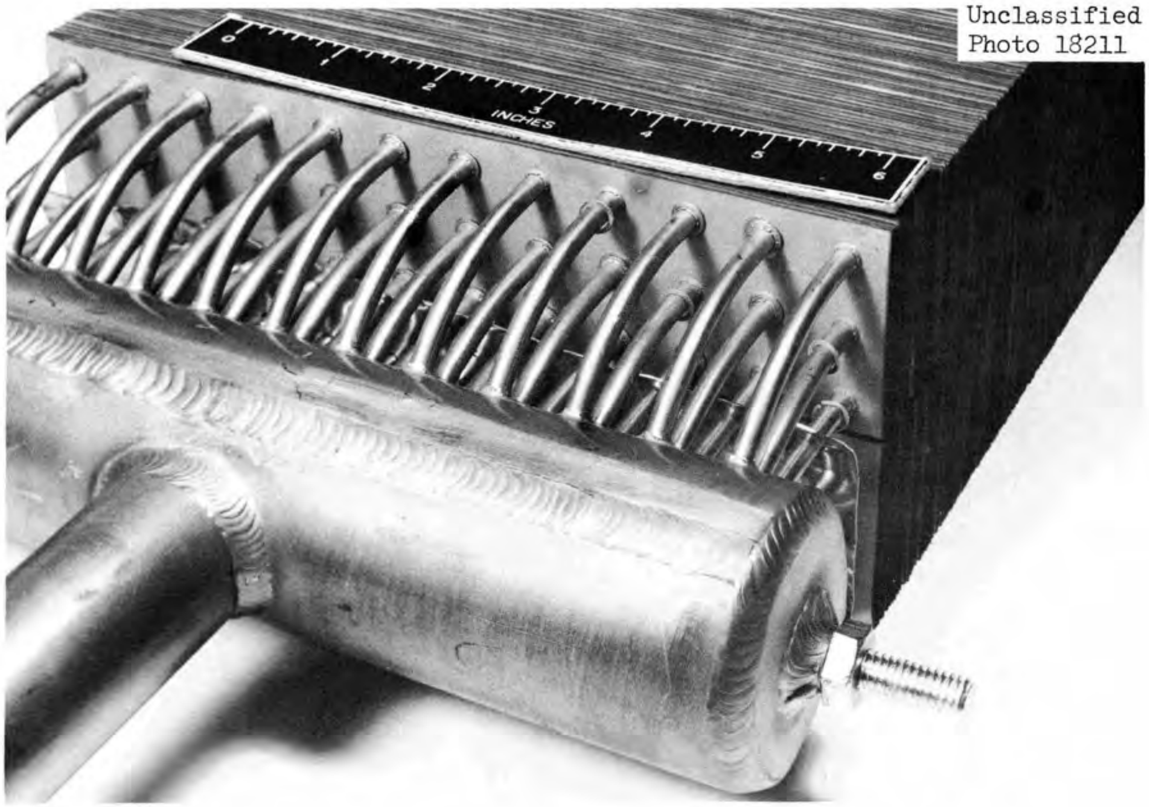

Fig. 12. Section of Radiator Showing Unmelted Rings.

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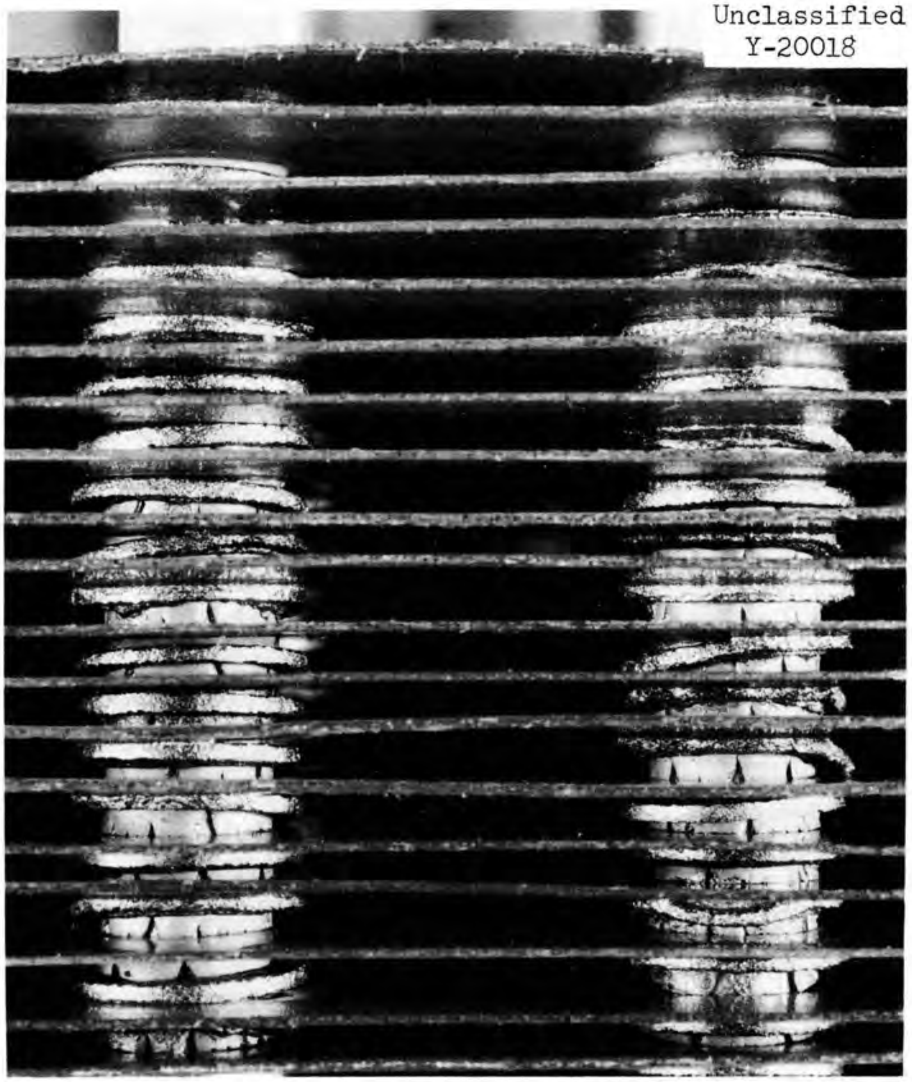

Fig. 13. Test Sample Heated at a Rate of 100°F/hr. Very poor melting of the brazing alloy rings can be seen.

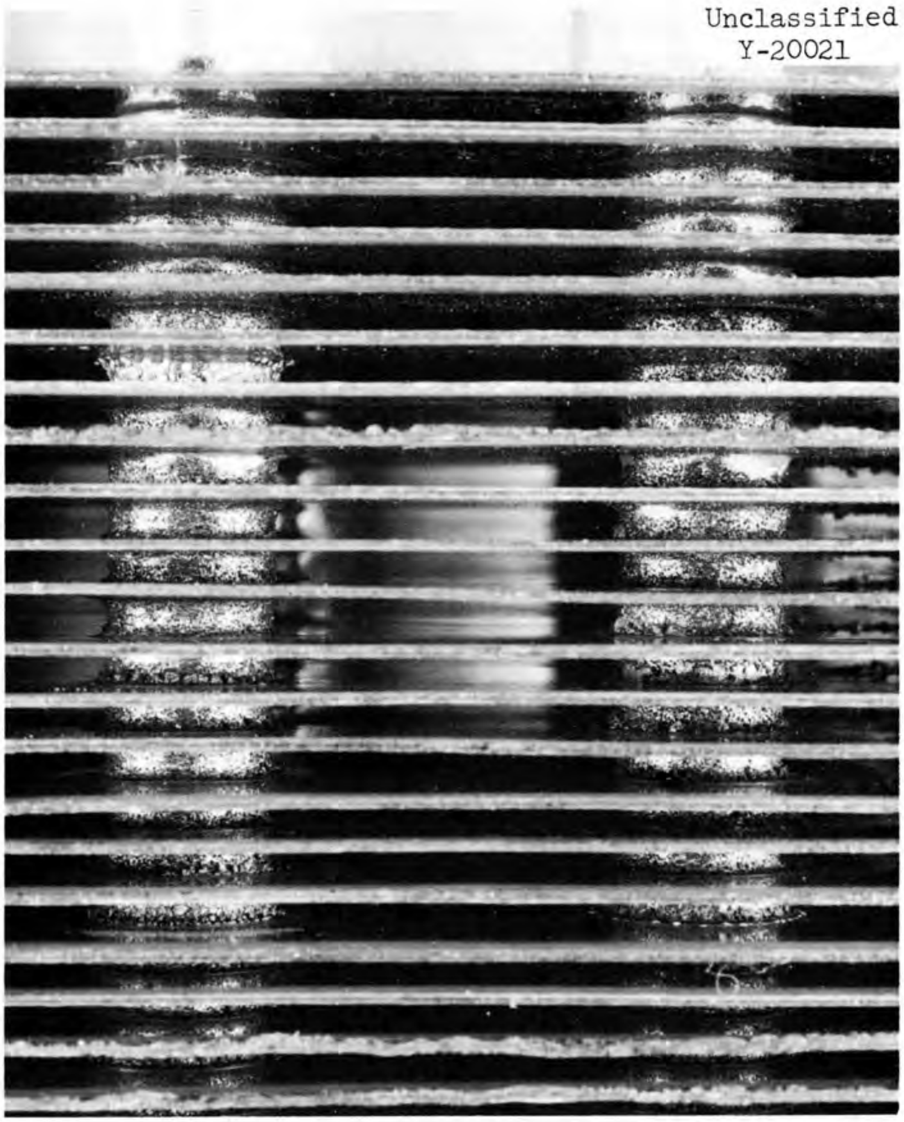

Fig. 14. Test Sample Heated at a Rate of 300°F/hr. Complete melting of the brazing alloy rings is evident.

an excellent temperature profile was observed (Fig. 15). Good brazing alloy filleting was observed consistently when using a furnace cycle of this type. As can be seen in Fig. 16, complete edge protection of the exposed copper was also obtained.

After the welding and brazing procedures for fabricating these complex liquid metal-to-air radiators were successfully developed, they were then utilized in the successful fabrication of similar, but larger, units by an industrial contractor. A photograph of such a unit is shown in Fig. 17.

CONCLUSIONS

The suitability of these fabrication procedures for the very stringent service conditions to which the radiators and heat exchangers were subjected has been demonstrated. No tube-to-tube sheet failures were encountered in any of the thousands of these joints which were welded and back brazed, a truly amazing record when one considers the combined effects of temperature, stress, and corrosion.

The fin-brazing procedures were also adequate for very severe conditions of service. The heat transfer capabilities of these joints were excellent and did not deteriorate appreciably after long-time service at elevated temperatures.

In general, it appears that these methods of welding and brazing should be suitable for fabricating similar types of high-performance components required for space applications.

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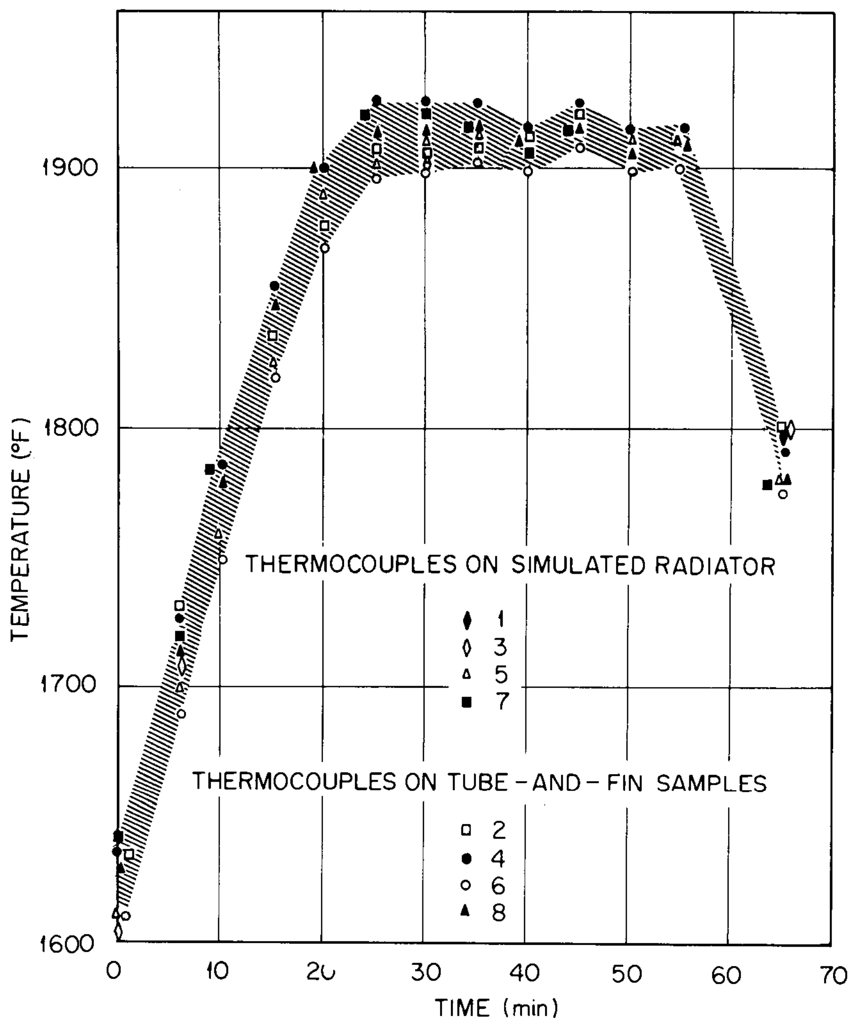

Fig. 15. Narrow Temperature Distribution Obtained After Development of Necessary Furnace Baffling Procedures.

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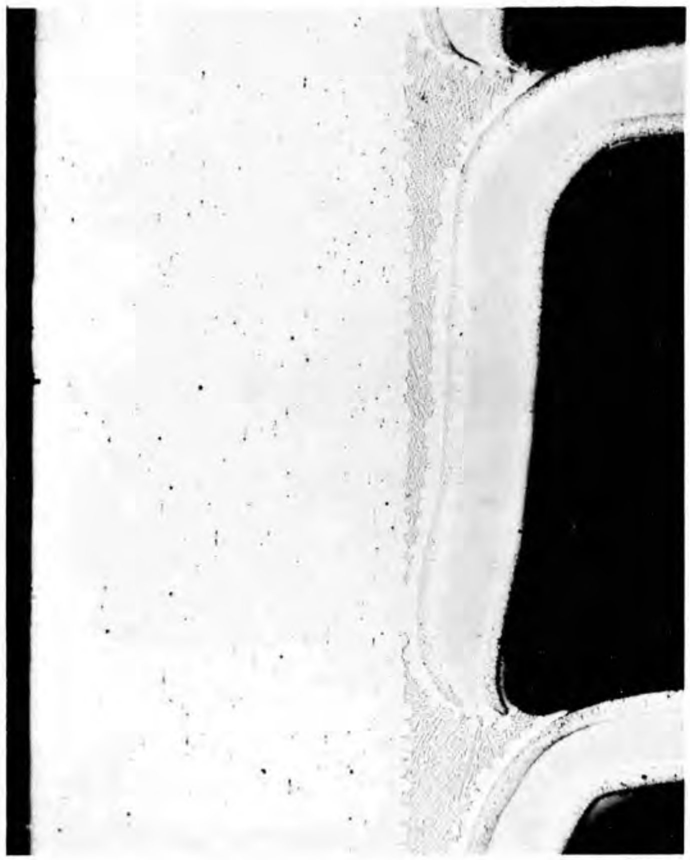

Fig. 16. Photograph of High-Quality Brazed Tube-to-Fin Joint. As-polished. 50X.

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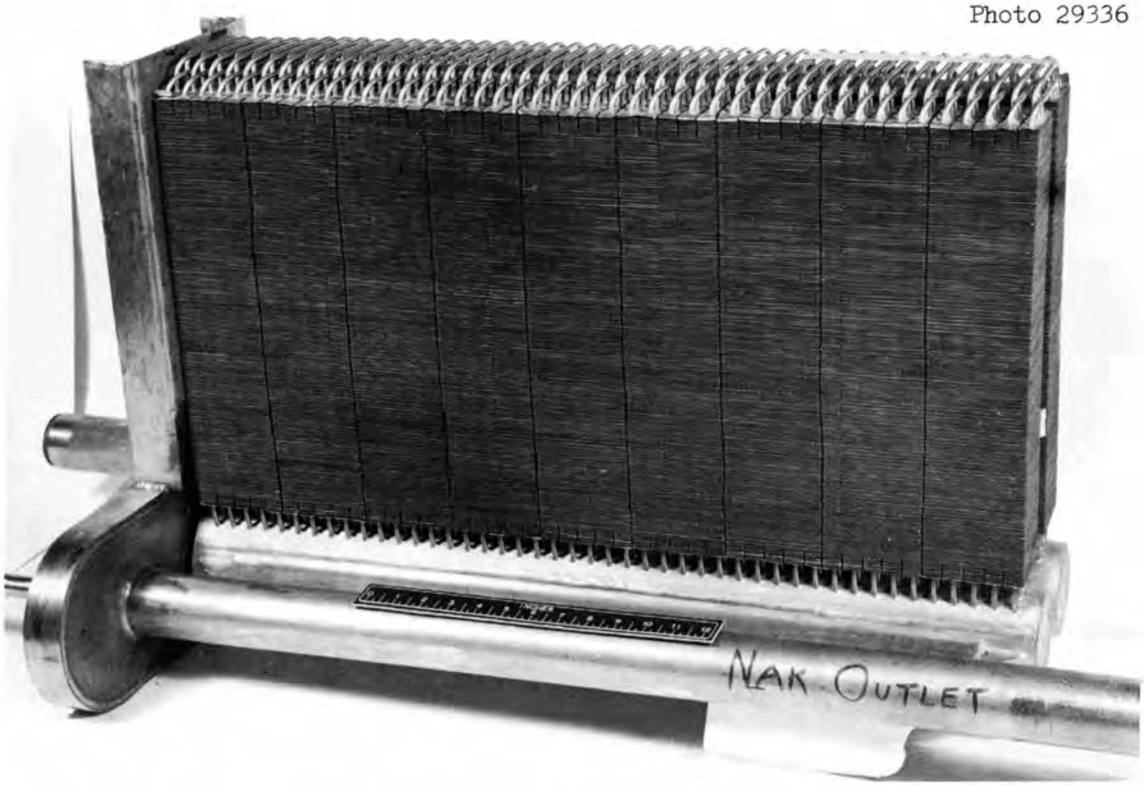

Fig. 17. Large Radiator Fabricated by Industrial Concern.

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