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H₂ -Atmosphere Furnace-Brazing
and Soldering-Oven Production Operation
at LAMPF

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scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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H₂-ATMOSPHERE FURNACE-BRAZING AND SOLDERING-OVEN PRODUCTION OPERATION AT LAMPF

by

Steven P. Koczan, Richard L. Rhorer, Gilbert Suazo, and Hairston G. Worstell

ABSTRACT

Industrial furnaces and a soldering oven were used at the linear accelerator site to assemble the side-coupled 805-MHz components on a production basis. The brazing and soldering operations required to assemble the 352 tank sections and 60 bridge tank couplers used in the 2,400 ft length of the side-coupled portion of LAMPF are discussed, step by step, including part preparation and processing.

I. INTRODUCTION

This report describes the assembly steps and equipment used to produce the major components of the 805-MHz part of the Clinton P. Anderson Meson Physics Facility (LAMPF) linear accelerator (linac). This part of the accelerator, in the beam channel, appears in Fig. 1 which shows the major components mechanically joined together on a supporting structure. The 352 tank sections and their 60 bridge tank couplers are labeled. This is a downstream view of the approximately 2,400 ft of

side-coupled linac made up of these tank sections and bridge tank couplers. H₂-atmosphere brazing was used to provide the clean surfaces and joints necessary for the electrical-conductivity and high-vacuum requirements of the LAMPF accelerator.

The typical products of the H₂-atmosphere furnace-brazing and soldering-oven production facility are shown in Figs. 2 and 3, ready for delivery to the beam channel for final bolting together on the accelerator support structure. To produce these parts, using the step-brazing techniques developed at LASL, slightly over 1,200 production

Fig. 1.

805-MHz part of accelerator in beam channel.

Fig. 2.

Tank section on roll cart ready for delivery to beam channel; 352 of these sections were required.

Fig. 3.

Bridge tank coupler, in protective rack, ready for delivery to beam channel; 60 were required.

brazing heats, each taking an average of 16 h, were run for the entire 805-MHz part of LAMPF.

II. ASSEMBLY STEPS

A. Tank Sections

The brazing assembly steps needed to prepare a tank section for attachment of cooling tubes to its exterior are shown schematically in Fig. 4 which shows the relationships of the parts and their assembly sequence through as many as five brazing steps. Brazing temperatures started at a high of 1925°F and decreased to a final braze at 1450°F. The flow lines in Fig. 4 are in the direction of decreasing temperatures.

Cooling tubes and pads, which were soldered to the exterior of the tank sections, are shown schematically in Fig. 5. All joints that would be exposed to rf fields and vacuum were furnace brazed in a dry H₂ gas atmosphere. Solder was used only on the outside of the tank section to attach the cooling tubes and cooling pads.

B. Bridge Tank Couplers

Figure 6 shows the part relationship leading to a completely brazed bridge tank coupler as it progressed through four brazing steps. These steps included attaching cooling tubes to the exterior of the tanks. In this assembly sequence, the cooling tubes could easily be attached in combination with the other brazing steps, so no solder was used.

C. Brazing and Soldering Temperatures

Since the temperature sequence also played an important part in the assembly steps, the joining temperature at each step is shown on the three schematics. The decreasing temperatures with the proper braze alloy for each allow step-by-step assembly. Alloys used to join the parts, and the placement of these alloys at the braze joints are discussed in detail later.

D. Quantities of Parts Processed

The quantities of parts at each assembly step are also shown on the schematics. Parts were processed through each step at a rate that allowed serial production of the tank sections and bridge tank couplers, thus permitting steady delivery to the beam channel. This was done so that tank sections and bridge tank couplers could be installed at a rate matching that of the production facility, with only a few weeks lead time between production and installation.

E. Braze-Joint Integrity

Each brazing step was followed by a check of the braze-joint quality using a helium-sensitive mass spectrometer. Parts in which a leak was detected were not allowed to progress to the next brazing step. Later, after a few parts were accumulated, they were separated into a repair or replacement category and processed accordingly. Parts with repairable leaks were realloyed and placed in heats with other parts having joints of the same alloy. Irreparable parts were replaced from an inventory of spares. Replacement was rare and occurred only in the very early steps of brazing. No major assemblies had to be replaced.

III. BRAZE ALLOYS¹⁻⁵

A. Step Brazing

Alloys for brazing Type 304 stainless steel and OFHC copper used in the LAMPF accelerator were selected from commercial grades made up of gold, copper, nickel, and silver. The selected alloys were of vacuum-tube purity. From these available alloys, six were chosen using experience gained while building several prototype accelerators before LAMPF fabrication. Step brazing with these alloys allowed the assemblies to be built, as shown in Figs. 4 and 6, without risk of remelting previously made joints during subsequent braze assemblies.

Fig. 4.
Assembly steps - tank sections.

Fig. 5.

Cooling tubes soldered to tank section exterior (typical tank section).

Fig. 6.
Assembly steps - bridge tank couplers (typical).

The regular production alloys were in the form of 0.020-in.-diam wire and 0.002- to 0.003-in.-thick foil.

Braze alloys used are listed in decreasing order of brazing temperature as follows.

1. *Alloy 62 wt% Cu-35 wt% Au-3 wt% Ni, Braze Temperature 1925°F.* This alloy was used to make stainless steel-to-copper joints on parts that were to be brazed again. Since 1925°F is near the melting point of copper, and some part distortion occurred at this temperature, critical machining was scheduled to be done after this first braze. The part design allowed enough material for further machining.

2. *Alloy 50 wt% Cu-50 wt% Au.* In production, this alloy was used at two temperatures, 1850 and 1825°F. It was used to join all clamshells into coupling cavities at 1850°F, and to make the 4856 segment assemblies at 1825°F, as shown in Fig. 4. The versatility of this braze alloy allowed us to join copper to copper and stainless steel to copper in one braze heat. This permitted us to attach stainless steel probe tubes to the coupling cavities during the coupling-cavity braze. It also allowed the stainless steel nozzle (and, when required, the mounting pad) to be attached to the segment assembly during its braze heat. Other miscellaneous stainless steel to copper brazes also used this alloy.

3. *Alloy 60 wt% Au-20 wt% Cu-20 wt% Ag, Braze Temperature 1585°F.* This alloy was used only on the bridge tank couplers of Fig. 6, to braze the joint between the cylindrical tank and a nickel-plated stainless steel waveguide flange. It was more expensive than the two previously discussed alloys because of its higher gold content, but its lower brazing temperature made it desirable in making this waveguide joint, to prevent distortion of the thin wall of the copper cylinder that would have resulted at higher temperatures.

4. *Alloy 71.15 wt% Ag-28.1 wt% Cu-0.75 wt% Ni.* This alloy was used at two brazing temperatures. At 1480°F, the two segment assemblies that were to receive a monitor-loop pad were joined. At 1470°F, the monitor-loop pad was joined to the two segment assemblies over the previously made braze joints, as in Fig. 4.

5. *Alloy 72 wt% Ag-28 wt% Cu, Braze Temperature 1450°F.* This alloy was used for the final braze when segment assemblies were stacked to form a tank section, Fig. 4. It was the lowest temperature production braze alloy used in fabricating the 805-MHz part of the LAMPF accelerator.

6. *Alloy 63 wt% Au-27 wt% Cu-10 wt% In, Braze Temperature 1380°F.* Although not a regular production alloy, this alloy was used if a leak was detected in a completely brazed assembly. It was placed over the identified leak, and a braze heat was run with the part temperature carefully controlled to avoid remelting the previous braze joint.

B. Braze-Alloy Application

Details of braze-alloy placement on the part joints are given later. However, it is important to note that use of step brazing permitted parts to be assembled with very few positioning or support fixtures. Basically, the previously attached parts provided enough joint strength⁶ as the braze temperatures were decreased, to be self-supporting in each of the subsequent braze steps. Small locating pins at the joints provided the only needed control of the relative part positions during a particular braze heat. This feature was provided in the engineering definition of the parts and assemblies, and the locating-pin holes were drilled as part of the regular production machining operations on all parts where orientation control was desired. These locating pins remained in the joints.

C. Solder for Attaching Cooling Tubes

A commercial grade of solder, in 0.005-in.-thick by 1.5-in.-wide foil strips, was used to attach cooling tubes and pads to the exterior of all 352 tank sections. This 63 wt% Sn-37 wt% Pb solder was used with a noncorrosive paste flux, and the joints were made at 450°F by heating a tank section, with the cooling tubes and pads clamped in place, in an electrically heated oven. Details of the soldering and the oven are given later.

IV. ASSEMBLY OF PARTS

This section traces the assembly steps shown in Figs. 4-6. It concentrates on the part preparation and placement of the welding alloys on the parts to be joined. The photographs in this section were made during the 2-1/2-yr fabrication period which ended in February 1972, and show actual production parts as they moved through the brazing and soldering facility.

Not every assembly step for each part is shown, since many of these steps are alike for similar parts, such as the clamshells for tank sections in Fig. 4, and those for bridge tank couplers in Fig. 6. However, there is at least one

photograph of a production part involving use of each of the five production alloys.

A. Tank Section Assembly (Fig. 4)

1. Ring Segment. Starting with the highest temperature braze alloy (62 wt% Cu-35 wt% Au-3 wt% Ni, 1925°F), the ring segment was assembled before its final machining, so that part distortion at this high temperature could be corrected. (Lower temperature brazes did not present a part-distortion problem.) Figure 7 shows a fine-grit abrasive being used to clean the part of the joint that will be in contact with the braze alloy. The fit was checked at this step to ensure proper mating of the parts. This check was important since the design required that a particular ring size be matched to an identifying number stamped on the outer surface of the segment. Also, this check verified that there was enough space for the braze alloy. After abrasive cleaning, the parts were washed in clean solvents, first trichloroethylene, then trichlorotrifluoroethane. Clean parts were handled only with clean cotton gloves to keep finger prints and grease or dirt off the braze alloy or joint area.

After the parts had been cleaned, the braze alloy was placed at the joint. Figure 8 shows a serrated, 0.002-in.-thick by 11/32-in.-wide, foil being placed on the horizontal shouldered surface of the copper segment. The serrations allow the foil to follow a horizontal curve. This form was used for all braze alloys applied in this manner, where flexibility in a horizontal plane was required. Next the stainless steel ring was placed in position, Fig. 9, and finally a 0.003-in.-thick by 1-in.-wide foil was inserted between the ring and copper segment as shown in Fig. 10.

Nine ring segments, arranged on the furnace base as shown in Fig. 11, were furnace brazed per production

Fig. 8.
Placing serrated alloy on segment shoulder.

Fig. 9.
Placing stainless steel ring over the serrated brazing alloy on shoulder of copper segment. Proper matching of ring to segment is verified at this step.

Fig. 7.
Abrasive cleaning joint area of ring-to-segment assembly.

Fig. 10.
Inserting vertical strip of 0.003-in. foil.

Fig. 11.

Furnace base containing nine brazed ring segments. Thermocouple leads are in place.

Fig. 12.

Clamshells and alloy ready for assembly.

heat. Brazing these parts required approximately 70 furnace heats for the 624 ring segments.

2. Tank Head. The same alloy was used as for the ring segments (the parts were assembled as shown in Fig. 4), with a 0.002-in.-thick by 1/2-in.-wide foil wrapped around the joint area of a stainless steel nozzle, and a 0.002-in.-thick alloy washer between the nozzle end and the counterbored hole in the copper tank head. (Figure 48 shows a similar nozzle and its alloy washer.) A total of 88 tank heads were brazed, 9 at a time, requiring 10 furnace heats.

3. Coupling Cavity. These parts were brazed with the second highest temperature braze alloy (50 wt% Cu-50 wt% Au, 1850°F). Two forms of this alloy were used for the coupling cavities. It was also used to join the coupling cavities for bridge tank coupler assembly (Fig. 6).

Figure 12 shows two copper clamshells, a stainless steel probe tube with two turns of 0.020-in.-diam wire alloy attached, two stainless steel locating pins, a length of serrated, 0.0025-in.-thick by 3/8-in.-wide foil, and an equal length of the wire alloy. These parts make up one coupling cavity, shown ready for assembly. The parts were cleaned with abrasives and solvents before assembly, which progressed as follows.

Two locating pins were placed in the holes of one clamshell; then, the flexible foil was placed on the joint surface. To clear the locating pins, small V notches (Fig. 12) were cut in the foil before this step. The foil was held by pressure-sensitive tape until the other clamshell was positioned over it with its two locating-pin holes providing the necessary orientation. This step is shown in Fig. 13. The tape was removed after this step. Next the 0.020-in.-diam wire was fitted into a groove along the

Fig. 13.

Positioning clamshell over alloyed mating part to form a pre-brazed coupling cavity.

outside corner of the joint face of one of the two clamshells, directly under the foil. After the alloyed coupling cavity was turned over to expose a previously bored recess, a probe tube was positioned as shown in Fig. 14.

The accelerator required 4856 of these coupling cavities. With 40 cavities per furnace heat, this represented 122 heats. A typical production heat is shown on a furnace base with the work-load thermocouples in place in Fig. 15. After these parts were furnace brazed, they were vacuum leak-checked at a pumpout station as shown in Fig. 16. The leak-tight parts were then delivered for their final machining which consisted of boring the coupling cavity for insertion of a pumpout nozzle and match-machining a radius and two dowel-pin holes on the concave surface of the cavity. This radius thus provided a precise match to a segment for the next brazing step.

Fig. 14.

Placing stainless steel probe tube in recess in alloyed coupling cavity.

Fig. 15.

Typical production load of coupling cavities on braze furnace base.

Figure 17 shows two coupling cavities on the left as they appeared after brazing and leak checking; the two at the right have been machined.

4. Segment Assembly. This assembly was brazed using the same alloy as the coupling cavity, with the braze temperature lowered to 1825°F. This alloy was 0.003-in.-thick by 1/2-in.-wide foil for the joint between the coupling cavity and the segment, and 0.002-in.-thick by 1/2-in.-wide foil for the joint between the stainless steel pumpout nozzle and the coupling cavity. A wrap of 0.020-in.-diam alloy wire held the 0.002-in.-thick foil in

Fig. 16.

Leak checking coupling cavities using helium-sensitive mass spectrometer.

Fig. 17.

Furnace-brazed coupling cavities before and after machining.

place against the nozzle and provided additional braze alloy needed for this joint.

The coupling cavity and segment were stamped with matching cell numbers during electronic tuning before this alloying step. These parts were then processed in matched sets through the entire alloying sequence, to maintain their tuning relationship.

Cleaning the braze surfaces with a fine grit abrasive as shown in Fig. 18 was always the first step. At this point, the technician verified that he had a matched set of parts in his work rack. The same technician then followed this set of parts through the entire alloying operation. The segment assembly parts were solvent rinsed to remove abrasive particles and other dirt or grease (Fig. 19), as described previously.

Figure 20 shows one set of segment parts ready for the alloy assembly operation. The segment rests in a work cradle. The precut alloy foils, the matching coupling

Fig. 18.

Abrasive cleaning braze-joint surfaces of segment assembly.

Fig. 20.

Parts and alloys arranged for a segment assembly.

Fig. 19.

Solvent rinsing segment assembly parts.

Fig. 21.

Positioning coupling cavity on segment.

cavity, a stainless steel nozzle, two locating pins, and work tools are at its right. Proper fit between the coupling cavity and the segment was then checked by placing these two parts in their relative positions and verifying that a 0.002-in.-thick feeler gauge would not pass between the two. The two 0.003-in.-thick alloy foils were then placed on the segment along the circumferential part of the joint. These foils are held in place by locating pins that passed through punched holes in the foil and into the locating-pin holes previously drilled into the segment. The two

locating pins also oriented the coupling cavity. The coupling-cavity pin holes can be seen in Fig. 17.

Figure 21 shows the coupling cavity being positioned to engage the two locating pins in the segment. Next, a length of 0.003-in.-thick foil was inserted underneath each edge of the coupling cavity longitudinally to the segment. Only the cavity weight kept these two lengths of foil in their proper position on the segment. The four pieces of 0.003-in.-thick alloy foil completely covered the contact surfaces of this joint and were positioned so that there was a 1/32-in. overhang along the inside edges to provide a slight excess of alloy to form a fillet along the

inside joint edge that would be exposed to both the rf fields and the accelerator vacuum.

The stainless steel pumpout nozzle, previously alloyed with one wrap of 0.002-in.-thick foil and one turn of 0.020-in.-diam alloy wire, fitted into the counterbored hole of the coupling cavity. Figure 22 shows a technician working the alloy wire down into this hole after the nozzle was placed in contact with the shoulder of the counterbore.

After the segment assemblies were alloyed, they were placed on a furnace base where a final check was made for proper alloy placement and to ensure correct matching of assembly numbers. Then the segment assemblies that required a mount pad (Fig. 4) were placed on that pad with a braze-alloy (50 wt% Cu-50 wt% Au) foil at the interface. The pad then became a brazed part of the segment assembly, as well as providing support for the segment on the furnace base. The other segment assemblies were supported by steel cradles that held them upright on the furnace base, as shown in the next three figures.

In Fig. 23, one technician is recording the segment assembly numbers and the segment's position on the furnace base. He also records the position of temperature-monitoring thermocouples. The other technician is adjusting the braze-alloy foil for the proper amount of overhang.

Figure 24 shows a completely brazed load of segment assemblies. This photograph was taken just after the atmosphere retort was lifted off the furnace base. A thermocouple can be seen in the segment at the right. Five others also had thermocouples in the same relative position. On top of the stainless steel pumpout nozzles are steel weights used to keep the nozzles completely

seated in the counterbored shoulder of the coupling cavity. This figure also shows the mineral-fiber sheets used to isolate the supporting cradles from the segments and the weights from the nozzles. The fiber sheets provided enough separation to prevent unwanted brazing.

A total of 4867 segment assemblies were furnace brazed for this accelerator, requiring 270 furnace heats of an average of 18 segment assemblies each.

Fig. 23.

Placing segment assemblies on furnace work base.

Fig. 22.

Positioning stainless steel nozzle and alloy in coupling cavity counterbore.

Fig. 24.

Segment assemblies on furnace base after brazing.

The brazed segment assemblies, upon removal from the furnace base, were placed in racks and moved to a leak-checking station like that used to leak check the coupling cavities. Additional braze alloy was placed over the suspected area of any leaking part, and the part was cycled through a furnace heat with a regular production run of segment assemblies. Leak-tight segment assemblies were sent in two directions: those that were to receive a monitor-loop pad were returned to the furnace room for additional brazing steps; the others were accumulated until a complete set needed for a tank section was ready. (This flow relationship is shown in Fig. 4.)

The leak-checking area is shown in Fig. 25. The technician has a segment assembly on the pump-out port of a mass spectrometer. In front of him are brazed segment assemblies awaiting leak checking. Behind him are two brazed tank sections, in a vertical position and in the process of being leak checked.

5. Monitor-Loop Pad Stack. Some of the tank sections (144 out of 352) required a small pad for later mounting of an electrical monitor loop. The pad location straddled a segment-to-segment joint, and the segments had to be spotfaced as an assembly after brazing for proper positioning and joint fit of this pad. The alloy used to join these two segment assemblies was a 0.002-in.-thick by 3/8-in.-wide serrated foil (71.15 wt% Ag-28.1 wt% Cu-0.75 wt% Ni, 1480°F) placed at the joint interface. The relationship of this pad and the segments is shown in Fig. 4.

Figure 26 shows the braze assembly step completed on four pairs of segment assemblies. These assemblies are still on a furnace base, and the work-load thermocouples used to monitor the brazing temperatures can be seen in position. After this braze step, the machining (spotface) for the monitor-loop pad was done and the assembly was then returned to the furnace room for braze attachment of the pad. This braze step is shown in Fig. 27, where the

technician on the left has positioned a pad on a 0.002-in.-thick foil alloy disk placed over the spotfaced area of the joined segments. A ceramic positioning plug passes through the pad hole and into the monitor-loop hole previously machined into the segment. This plug controlled concentricity between the pad and segment hole during this braze step. The alloy for this step was the same as that used to join the segments, but it was brazed at a slightly lower temperature, 1470°F. At the right, in Fig. 27, the technician is placing a work-load-temperature monitoring thermocouple near the previously prepared pad-to-segment braze joint. This braze was made at 1470°F to avoid remelting the previous braze joint made using the same alloy at a 10°F higher temperature. (Remelt. temperatures⁶ are slightly higher than original braze temperatures.)

Fig. 26.
Monitor-loop pad stack segment-to-segment braze.

Fig. 25.
Leak checking brazed segment assemblies.

Fig. 27.
Monitor-loop pad to stack braze.

The alloy at this step of the sequence, being high in silver content, shows a blush condition common to high-silver braze alloys. Blush is movement of the alloy out of the joint area, having no apparent thickness, but giving a wetted appearance. Blush can be seen in Fig. 26, as an irregular band around the segment-to-segment joint. On the segment assembly pair at the right, blush occurs above, as well as below, the joint. The joint design forces the expected blush to occur on the outside surfaces of the parts that do not see the accelerator rf or vacuum. The main feature preventing internal blush of the high-silver alloys is that the foil is allowed to overhang slightly on the outside surface of the braze joint but none is allowed to extend into the inside surfaces of the assembly. The technician who placed the braze alloy on the joint area controlled its position.

A total of 144 of these monitor-loop pad assemblies were brazed as described above. They were brazed four per furnace heat and in two braze steps, 1480 and 1470°F. This required 72 furnace braze heats. Following leak checking, these assemblies were matched to the other segment assemblies for a particular tank section. The final braze step followed.

6. Tank Section. This final production braze step, shown in Fig. 4, was carried out by stacking the segment assemblies in proper order with a 0.002-in.-thick by 3/8-in.-wide, serrated, 72 wt% Ag-28 wt% Cu, 1450°F foil between each segment-to-segment joint. Numbers stamped into the outside surface of each segment during electronic tuning indicated the proper order. These segment assemblies, as were all parts to be brazed, were cleaned as previously described. The cleaned parts awaiting stacking were stored in clear plastic bags as seen in the background of Fig. 28. As the segment assemblies were selected for stacking, the flexible braze-alloy foil was placed on the segment joint surface and held in place by a strip of pressure-sensitive tape that was removed after stacking was completed. The weight of the segments kept the foil in the joint area. Here again, as in the monitor-loop pad stack and the coupling-cavity braze steps, small locating pins placed in previously bored holes in the braze-joint surface oriented the stacked parts.

The stacks of matched sets of segment assemblies were made either directly on the furnace base, as shown in Fig. 28, or on stainless steel staging fixtures, as shown in Fig. 29. Both of these figures show a stack being built, with a technician guiding an alloyed segment assembly into position. In Fig. 29 the technician on the right is operating an overhead crane to slowly lower the segment assemblies into position. Also in this figure are other stacked tank sections waiting to be loaded on a furnace base for brazing. Two of the tank sections have lifting

Fig. 28.
Stacking segment assemblies into a tank section for brazing on a furnace base.

Fig. 29.
Stacking segment assemblies into a tank section on fixture in staging area of furnace room.

fixtures attached. Those lifting fixtures also can be seen in Fig. 30, as the technicians prepare to move one tank section from the furnace-room staging area to a furnace base for brazing. The lifting fixture, except for the stainless steel base plate, was removed from the assembly after the tank section had been placed on a furnace base. The segment assembly on the bottom is separated from the base plate by a mineral-fiber sheet.

After the tank section had been placed on the furnace base and the lifting fixture was removed, work-load thermocouples were inserted into the pumpout nozzles of the segment assemblies. For the tank-section braze heat, a total of six thermocouple leads were used—two near the bottom, two at the middle, and two at the top. The braze was made by controlling the temperature at each of these three levels to within 5° of the 1450°F braze temperature. The thermocouple leads are shown being placed in Fig. 31. Their location was recorded on a log sheet used for each braze heat. After the atmosphere retort was placed over the furnace base and the H_2 gas cycle was started, the furnace was lowered over the work base and the braze heat was run. Figure 32 shows the furnace being

removed using an overhead crane. This was done at the moment the thermocouples reached the desired braze temperature. In the foreground of this figure is a completely brazed tank section just after the atmosphere retort had been removed. The work-load thermocouples were still in place.

To remove a brazed tank section from the furnace base, a lifting fixture was attached to the top of the tank

Fig. 30.
Moving stacked tank section to a furnace base for brazing.

Fig. 31.
Inserting thermocouples in tank section on furnace base before brazing heat.

Fig. 32.
Removing furnace from base upon reaching required braze temperature.

Fig. 33.
Removing brazed tank section from base.

Fig. 34.
Blanking off brazed tank section.

section, which was lifted and moved to a roll cart, using an overhead crane. This is being done in Fig. 33, and in Fig. 34 the tank section can be seen resting on its roll cart. During this unloading operation, blank-off flanges were attached to the two ends of the tank section and rubber stoppers were inserted into all its other openings. The technician in Fig. 34 is doing this. Then he also purged the sealed tank section with a dry inert gas, thus retarding formation of oxides on its inside surfaces. This was important because no further furnace brazing of the assembly was scheduled and the interior, cleaned by the H_2 atmosphere of the brazing operation, had to be kept clean until placed under vacuum in the accelerator beam channel; the remaining processing involved only exterior surfaces.

After these steps, the tank section was moved to a specially modified machine that supported it horizontally and machined 12 longitudinal flats on its outside surface. A completely machined set of flats for the cooling tubes can be seen on the tank section in Fig. 35 as it is about to be removed from the flat-cutting machine.

A leak check using the helium-gas-sensitive mass spectrometers started the flow sequence of Fig. 5. If a

Fig. 35.
Tank section after flat cutting for longitudinal cooling tubes.

leak was detected, the tank section was returned to the furnace room for braze repair; the leak-tight tank sections were directed to the cooling-tube soldering operation. Thus the flat-cutting machine separates the flow sequence of Fig. 4 from that of Fig. 5. One tank section was brazed per furnace heat.

B. Cooling-Tube Soldering Sequence (Fig. 5)

The twelve longitudinal cooling tubes were placed over the flats and attached with soft solder (63 wt% Sn-37 wt% Pb, 450°F). These tubes⁷ were made from rectangular 1-1/2- by 3/4-in., 3/32-in.-thick copper tubing by torch brazing (alloy 15 wt% Ag-80 wt% Cu-5 wt% P) a standard 1-1/4- by 1-in. reducer fitting into a machined hole at each end. The fitting had been notched on one side so that it sealed the end of the rectangular tube and provided an opening for passage of the cooling water.

As stated in Fig. 5, 4224 of these tubes, 50 to 80 in. long, depending on the particular tank-section length, were used for the 352 tank sections in this accelerator. These flat tubes constitute the primary cooling system.

The secondary cooling system⁸ consists of U-shaped, rectangular, 1/2- by 1/4-in., 0.048-in.-thick copper tubes and pads curved to match the segment diameter and width. These tubes and pads were attached to the tank section with the same solder alloy used to attach the primary cooling tubes. A total of 5312 U-shaped tubes, of the two types shown in Fig. 5, and 4400 of the curved pads were soldered to the 352 tank sections.

Figure 36 shows the three fabrication steps required to produce 4856 of these tubes. The copper tube was first straightened, next its ends were swaged to allow later attachment of standard round tubing interconnections, and then it was formed into the U shape for attachment to the coupling cavities. The 456 curved tubes followed a similar series of fabrication steps, except that they were curved to contact the outside surface of the segments. These tubes were used on the tank-section segments containing one of the stainless steel mounting pads (Fig. 4).

The curved pad (basically a water jacket) was made from copper sheet stock, and its fabrication steps are shown in Fig. 37. At the left is a 1/4-in.-thick sheet that has had a 1/8-in.-deep water channel machined into it. At each end of the channel, a hole has been drilled for later attachment of water fittings. The 0.086-in.-thick jacket cover sheet is next, and to the far right is a completed pad. The jacket cover was torch brazed, (alloy 45 wt% Ag-15 wt% Cu-16 wt% Zn-24 wt% Cd, 1175°F) onto the 1/4-in.-thick machined sheet, then the pad was formed and a radius was machined to accurately fit the outside diameter of the segment. The pad widths increased in six

Fig. 36.
Typical fabrication steps for 5312 U tubes.

Fig. 37.
Typical fabrication steps for 4400 curved cooling pads.

increments, from 3 in. to 5-1/2 in., as the segment lengths increased. The required total of 4400 pads, including 144 special pads required on the segments having the monitor-loop pads, was made in this manner. Each cooling pad had a hole in the center, used to hold it during soldering by inserting a bolt through this hole and into the tapped handling hole in each segment.

The primary and secondary cooling system was attached to the outsides of the tank sections primarily with solder, as mentioned earlier. This solder, in the form of foil strips, was placed on surfaces of the cooling tubes

that had been cleaned with a power-driven wire brush followed by a solvent rinse like that used to clean furnace-brazed parts. A noncorrosive paste flux was brushed onto this cleaned surface, and the solder foil was pressed onto the flux. The flux was adhesive enough to hold the foil in place during subsequent handling. In Fig. 38, a technician is placing the solder foil on a long rectangular tube after having cleaned and applied flux to the solder surface. In the background are curved pads on which the solder foil has already been placed.

Figure 39 shows the cleaning of the machined flats of a tank section. In addition to cleaning the soldering surface, this step removed machining burrs that remained after the flat-cutting operation. After abrasive cleaning, a solvent wipe was used to remove abrasive particles and copper chips from the flats and the other solder surfaces, then a layer of paste flux was brushed on all of these surfaces.

The tank section was supported during the entire soldering operation by special grooved end-support plates bolted directly to it. The grooves in the end plate rode on small rollers, allowing the tank section to be rotated easily at a convenient work height. This fixturing feature is directly in front of the technician in Fig. 40. The end plate had radial location holes tapped in it, to which was attached a small bracket that held the longitudinal tubes in proper orientation. The technician in Fig. 40 is positioning the longitudinal tubes using the location fixtures described above. After the 12 longitudinal tubes were placed, the curved pads previously alloyed with solder foil were bolted into place through the hole provided. The bolts were removed after the solder-oven operation. All

U-shaped tubes were also placed around the coupling cavities and held in position by twists of wire (see Fig. 44). Circumferential fixture rings with pressure pads were then placed over the tank sections and used to apply radial pressure to the 12 longitudinal tubes to minimize formation of gaps along their relatively long solder joints. A tank section, completely fixtured, with both the primary and secondary cooling tubes in place is shown in Fig. 41. Temperature-monitoring thermocouples along the tank section can also be seen.

Fig. 39.
Surface preparation of machined flats.

Fig. 38.
Placing solder foil on cooling-tube solder surfaces.

Fig. 40.
Positioning cooling tubes on flats.

Fig. 41.

Cooling tubes in position on tank section and retained by soldering fixtures.

Fig. 43.

Tank section from soldering oven being inspected for voids.

Fig. 42.

Tank section ready to enter soldering oven.

At this point, a trickle flow of dry inert gas was started through the tank section. This flow prevented oxidation of the internal rf and vacuum surfaces during the soldering-oven heating cycle, as well as during cooling after soldering.

The tank section in Fig. 41 was ready to be moved into the soldering oven for its heating cycle. A rail leading into the oven provided a track for the tank-section support fixture. Both the support fixture and tank section were rolled into the soldering oven. Figure 42 shows the operation ready to take place. The temperature-monitoring thermocouples verified the 450°F soldering temperature during the heating, and the hot tank section was then rolled back out of the oven.

Fig. 44.

Filling voids between cooling tubes and tank section.

In Fig. 43, while the tank section is still hot, the solder joints are examined for voids. Using the stored heat in the tank section, additional wire-form solder was puddled into these voids. Figure 44 is a closer view of this operation. Several different alloys of tin-lead soft solder were used. For example, we used a 40 wt% Sn-60 wt% Pb, alloy that, because of its higher liquidus temperature (455°F), would not run out of the voids as easily as the eutectic-alloy foil. Figure 44 also shows one of the 456 curved U-shaped tubes with its soldering-operation holding fixture in place around the stainless steel mounting pad of the tank section.

The cooled tank section was wiped with solvents to remove the excess soldering flux after all of the fixtures had been dismantled. Before leaving the soldering area, the tank section was again purged with an inert gas and all openings were blanked off. It was then moved to an air-powered grit blaster as shown in Fig. 45, and the exterior was cleaned to remove the oxides that formed during the soldering-oven heating. After grit blasting, and with their interconnecting water-passage tubes soldered in place, the tank sections were carefully wiped clean of residual grit, as shown in Fig. 46.

Figure 47 is a close-up of the plumbing tying together the secondary cooling system (pads to U tubes). Below it is one of the horizontal cooling tubes of the primary cooling system that had been soldered to the longitudinal flats of the tank section.

After the cleanup, the outside of the tank section was sprayed with a light coat of clear acrylic to retard formation of oxides. It was then placed on a roll cart ready for delivery to the beam channel for installation.

Fig. 45.

Tank section ready to be placed in grit blaster.

Fig. 46.

Tank section cleanup.

C. Bridge Tank Couplers - Assembly Steps (Fig. 6)

1. *Bridge Tank Head.* Brazed assembly of the bridge tank head used the highest temperature braze alloy (62 wt% Cu-35 wt% Au-3 wt% Ni, 1925°F). Before the alloy was placed on the braze joints, the parts were cleaned as described earlier. This first braze step joins a copper head, a stainless steel ring, a stainless steel head nozzle, and a copper block. The head, ring, and nozzle were alloyed like the tank section ring segment and its tank head. In addition, a copper block with a 0.003-in.-thick braze foil cut to its size was added. Final machining of this part followed the brazing, thus correcting for any part distortion caused by this high brazing temperature. The same procedure was followed on similar parts brazed with this high-temperature alloy.

The technician in Fig. 48 is assembling a bridge tank head. The stainless steel ring is in place, and he is placing the copper block over the braze foil. Two locating pins fitted into previously bored holes in the head position the block, which also has two locating-pin alignment holes in it. These pins, as in other braze assemblies, remained in the joint. On the copper head, to the left, is a stainless steel nozzle to be inserted in the counterbored hole in the center of the head. Resting against the nozzle is a precut braze foil that will be placed in the counterbored hole to provide the braze joint between the nozzle end and counterbore shoulder of the head.

A typical bracing-furnace load of bridge tank heads is shown in Fig. 49. The parts are supported on the furnace base by steel blocks placed between the base plate and the stainless steel ring of the assembly. Steel blocks also serve as weights on the nozzle and copper block of this assembly. Sheets of mineral fiber separate the weights from the actual assembly. The work-load-temperature monitor thermocouples are also shown. Nine assemblies were run

Fig. 47.

Cooling-pad to coupling-cavity cooling-tube-water connections.

Fig. 48.
Assembling a bridge tank head.

per furnace heat, and the 120 assemblies (2 each for 60 bridge tank coupler assemblies) required 14 furnace braze heats.

2. Bridge Tank Head Cooling Tube. After final machining, the heads were returned to the furnace room where a 3/8-in.-diam copper cooling-water tube was brazed into a groove in the copper end surface. This braze step did not require vacuum quality, the only requirement being to attach the cooling-water tube with a braze alloy that would not remelt during a subsequent braze. We decided to use a powdered alloy mix of one-half 77 wt% Ag-21 wt% Cu-2 wt% Ni and one-half powdered copper. The curved copper tube was inserted into the machined groove of the head, and the alloy powder mix was spread over the tube, covering it. The braze heat was run at 1585°F (1560°F is normal for this braze alloy), to ensure flow of the liquidus alloy into the groove and around the 3/8-in. tube.

It should be pointed out that the cooling-tube ends extended out beyond the head for future plumbing tie-in performed in the beam channel. This projection would have interfered with final machining of the head, thus leading to the flow sequence of this part described above and shown in Fig. 6.

This braze step required 14 furnace braze heats run at an average of 9 per heat for the total of 120 heats.

3. Tank End. The copper ends of the tank cylinders required a stainless steel flange at the center. This flange,

Fig. 49.
Typical production braze heat of bridge tank heads.

located with two locating pins and appropriately matched locating-pin holes, was brazed using a 0.002-in.-thick, 50 wt% Cu-50 wt% Au, 1830°F foil, cut to the size of the flange. A total of 120 of these ends were needed for the 60 bridge tank couplers. At an average of 6 per furnace heat, they required 20 production braze heats. The highest temperature braze alloy, 1930°F, could not be used for this assembly step because the copper head had relatively thin walls that would have unacceptably distorted at the higher temperature. Therefore, we selected the 50 wt% Cu-50 wt% Au braze alloy for this step.

4. Coupling Cavities for Bridge Tank Couplers. These parts, being similar to the coupling cavities used on segment assemblies, were brazed using the same 50 wt% Cu-50 wt% Au alloy and the same alloying steps. Two of these parts were required for each bridge tank coupler and they were brazed in production heats of other parts having the same braze alloy. They were processed four at a time as needed to support production of the main assemblies. Final machining of the concave radius of these parts and boring of orientation dowel-pin holes followed the brazing, as shown in Fig. 6.

5. Bridge Tank Coupler Cylinder. This cylinder, as shown in Fig. 6, is brazed with a serrated 50 wt% Cu-50 wt% Au braze foil, 0.002 in. thick by 3/8 in. wide. After cleaning, the three parts of each cylinder tank were assembled vertically, directly on the furnace base. Pressure-sensitive tape kept the serrated foil on the braze surface until the parts were in position, and locating pins provided orientation. (This technique was identical to that for building segment assemblies into tank sections.) After the alloyed

assembly was made on the furnace base, the tape was removed and a circumferential wrap of 0.020-in.-diam braze-alloy wire was added to the joint. This wire provided additional braze alloy required to properly fill the joint area. A small shoulder machined into the outside diameter of one of the parts at each of the two joints held the alloy wire at the joint.

After this braze, the cylinder was further machined to turn the outside diameter, mill four flats for rectangular cooling tubes, and mill flats and bore three holes for three mounting pads. (The outside diameter was turned to match the concave radius of a stainless steel waveguide flange; an rf iris hole was also bored for this flange.) Small locating-pin holes were bored to orient three tuning-slug mount flanges and a waveguide flange to be attached during the next braze.

This assembly step was at a rate of 4 tanks per braze heat, and 15 heats were required for the 60 tanks.

6. Tank Assembly. This was the only braze assembly in the entire production operation that used a 60 wt% Au-20 wt% Cu-20 wt% Ag, 1585°F brazing alloy. This 0.003-in.-thick foil alloy was trimmed to fit the braze-joint area. Since the four rectangular water-cooling tubes attached during this braze did not require a vacuum-tight braze, we used a less expensive 0.010-in.-thick foil of 77 wt% Ag-21 wt% Cu-2 wt% Ni to attach them to the tank flats. This was the only braze step that used different braze alloys in the same furnace heat. Vacuum-tight joining of three tuning-slug flanges to all assemblies and the rf waveguide flange to 44 of the 60 assemblies was the purpose of this step.

Figure 50 shows the tank at this step of assembly. This tank, on a furnace base, rests on the waveguide-flange braze surface, its ends supported by counterbalanced cradles, which together supported two-thirds of its weight. The end support was to limit the pressure resting on the waveguide-flange braze joint, to one-third of the total weight. This prevented distortion of the thin tank wall that would have occurred during the braze heat, had the entire weight rested on the flange.

On top of this tank, and under the positioning weights, are three tuning-slug mounting flanges with work-load-temperature monitoring thermocouples passing through them. The four rectangular cooling tubes were held in place during the braze heat by seven wraps of nichrome wire that can also be seen. The 60 assemblies needed for the accelerator were brazed 2 at a time and required 30 furnace heats.

7. Bridge Tank Coupler Assembly. The final braze of this assembly was made with 71.15 wt% Ag-28.1 wt% Cu-0.75 wt% Ni alloy at 1470°F. This 1/2-in.-wide by

Fig. 50.

Tank assembly on furnace base with fixtures and weights in place.

0.002-in.-thick alloy foil was used at the joint between one concave end of each coupling cavity and the tank and between the opposite end and the head. The cleaning was done before placement of the alloy foil, and the actual assembly for brazing was made on a furnace base. The alloy placement using locating pins for part and alloy orientation was exactly the same as that for segment-assembly alloying.

Counterbalanced cradles, with the counterbalance force adjusted for the assembly weight distribution just described, were used to support the assembly on the furnace base and can be seen in Fig. 51. The weight of the waveguide flange was also counterbalanced. Temperature-monitoring thermocouples can also be seen in this figure at the tank ends. These 60 assemblies were brazed 2 at a time and required 30 furnace heats. Upon removal from the furnace base, the assemblies were leak checked and filled with inert gas and the openings were blanked off. A spray coat of clear acrylic was applied to the outside surface of those assemblies that were leak tight, and they were then placed in racks for transport to the beam channel.

D. Final Assembly Operation

The 805-MHz furnace-brazing and soldering was successfully concluded in mid-February, 1972, and the last production assembly was transported to the beam channel. This tank section (104-D), the last of 352, appears in Fig. 52.

Fig. 51.
Final braze assembly of bridge tank coupler.

V. PRODUCTION EQUIPMENT

A. H_2 -Atmosphere Furnace-Brazing Facility⁹

Figure 53 is an overall view of the furnace room. This room contains seven fixed bases positioned over service trenches (K). Bases A, B, F, H, and I are used to braze the parts. Bases B, F, and H are covered with atmosphere retorts made of Inconel 600; bases A and I have the electric furnaces over the retorts. Two bases, not shown, are used only as parking positions for the two electric furnaces when they are not being used in production. Bases F, H, and I are used with the short furnace (I). These three bases can accommodate a braze work load 50 in. in diam by 38 in. high. Bases A and B are used with the tall furnace (A), and can accommodate a work load 30 in. in diam by 84 in. high.

The service trench (K) contains all the necessary service supply lines: hydrogen gas, argon gas, cooling water, plant air, vacuum manifold, valves, electric power, instrumentation leads, and process atmosphere vent lines.

To move the retorts and electric furnaces, either a monorail crane or a bridge crane is used. The tall furnace (A) is a fire-brick-lined, bell-type, electric furnace with three 70-kW heating zones, each separately controlled from panel L. The short furnace (I) is a 180-kW, fire-brick-lined, bell furnace having a single heating zone with

Fig. 52.
Last tank section of the 352 assembled for the 805-MHz part of LAMPF.

*Fig. 53.
Brazeing furnaces and controls in furnace room.*

heating elements under the base cap of each work position. This single-heating-zone furnace is controlled from panel E.

Adjacent to the furnace-control panels (E and L) are five gas-control panels (G), four of which are shown. Mounted in each of these panels is a six-point strip-chart recorder used to monitor the work-load temperature of its respective base. Both gas cycle and gas flow are controlled at the panels.

The hydrogen process gas enters the building at approximately 15 psig and passes through two gas-drying and -purifying units, one of which, D, is shown. After purification, the H_2 gas is reduced to 1/2-psig pressure and fed into each gas panel. Gas flow through the atmosphere retorts is maintained at a minimum of 150 ft³/h during the entire heating and cooling cycle. Process gas is vented through a bubbler-type vent, (C). There is a vent for each of the five work bases. The bubbler provides a back pressure of 1/2 psig.

A typical braze-operation cycle, in brief, is as follows.¹⁰⁻¹¹

1. Place parts to be brazed on work base.
2. Place retort over base.
3. Evacuate air from retort.
4. Back fill with hydrogen gas and establish steady flow.
5. Move furnace into position over retort, start heat.
6. Monitor work-load thermocouples. Complete heat.
7. Remove furnace. Work-load cooling to take place (Fig. 55).
8. Evacuate hydrogen from retort.
9. Back fill with inert back-up gas.
10. Remove retort.
11. Unload brazed parts from base.

The gas-cycle control system contains certain safety features in the form of interlocks that do not allow any

deviation from a normal start-up. Pressure switches are part of the interlock system and will not allow a start-up without the required pressure of argon (used as both emergency backup and purge gas), hydrogen process gas, plant air, and base-seal cooling water.

An alarm condition during start-up causes automatic purging of the gas system with argon, and sounds an audible alarm. During operation with hydrogen gas, interruption of any service except the base-seal cooling water causes automatic argon purging and an audible alarm; any cooling-water interruption causes an audible alarm only.

On the wall of the furnace room are both warning lights and status lights (J). The status lights indicate which bases are on process hydrogen-gas flow. The warning lights give a visual indication of any loss of supply pressure or any service interruptions (plant air, water, gas) to the furnace room. These warning lights operate from a set of pressure switches independent of those in the gas-control panel. Air and gas supply lines entering the furnace room have check valves to prevent back-flow in case of a supply failure. The plant air-supply line is backed up, through a pressure regulator, by a bottle of nitrogen gas in the furnace room. This would permit operation of the pneumatically operated valves to continue without plant air if necessary. A bank of argon bottles, through a pressure regulator, automatically backs up the main argon supply should it fail when back-filling or purging of the gas system is necessary.

A diesel-engine generator set is tied into the electric supply system. When it is turned on, its power is transferred to the cranes and the strip-chart recorders. This would permit removing the furnace from over the retort at a critical point in the heating cycle without using the main power supply and would allow monitoring of the work-load thermocouples without normal building power.

Figure 54 is a closeup of the control panels, showing the operators starting the tall-furnace heating cycle. The operator at the left is filling out the operation log sheet mentioned earlier. The one at the right is adjusting the control for the middle heating zone of the three-zone furnace.

The most critical part of a braze heat occurs as the furnace controllers are manually adjusted to bring the work load to and hold it at (or within 5°F of) the liquidus temperature for the particular braze alloy. This control adjustment is necessary to achieve a minimum temperature gradient for uniform brazing of the production parts throughout the work zone of the relatively large atmosphere retort. Once the work-load temperature is stabilized near the alloy liquidus temperature, usually about 6 h after the start of the heating cycle, the maximum power of the furnace is used to increase the work-load temperature to the actual brazing temperature for that particular

Fig. 54.
Furnace-control and gas-flow panels.

alloy. Approximately 30 min is required to increase the work-load temperature to the desired point above the liquidus temperature for proper brazing. Upon reaching the brazing temperature, the furnace is promptly lifted off the atmosphere retort to allow rapid cooling. This fast cooling allows the braze alloy to return quickly to below its solidus temperature, thus minimizing the blush formation mentioned earlier and reducing the flow time of the alloy in its liquidus condition. Figure 55 shows the furnace being lifted off an atmosphere retort. The complete brazing cycle, including cooling time, requires approximately 16 h.

B. Soldering-Oven Facility

The electric soldering oven used to soft-solder the cooling tubes to the tank sections was specially designed, and built by lining a steel shell with insulating fire bricks and attaching electric heating elements. The elements provided about 30 kW of heat, and the oven was capable of temperatures of about 1000°F . A tank section could be heated to about 450°F in approximately 2 h. The oven had windows in one side for observing the melting of the solder. It also had penetrations in the end for gas connections to the tank section, a crank mechanism to turn the tank section, and a vent hole to exhaust fumes. The tank section was set on a fixture that allowed it to turn and roll in and out of the oven. The oven with a tank section ready to roll in is shown in Fig. 56.

A typical operating procedure for soldering the tubes on a tank section follows.

Fig. 55.
Lifting furnace off atmosphere retort.

Fig. 56.
Oven for production soldering cooling tubes to tank sections.

1. Install special ends and place the tank section in the fixture extended from the oven.
2. Connect inert-gas-flow connections and start purging tank.
3. Clean tank, place flux and solder, and clamp tubes in place.
4. Roll tank section into the oven.
5. Close doors, connect thermocouples, and verify inert gas flow.
6. Turn on heat.
7. Watch solder and read thermocouples until solder has melted and good wetting has occurred (about 450° F).
8. Open vent damper and turn on exhaust fan.
9. Disconnect gas hoses and thermocouples, open doors, and roll tank section out.
10. Reconnect gas hoses and start filling voids with wire solder by hand.
11. Check tube straightness and continue filling voids if necessary until tank section cools below the solder melting temperature (about 10 min).
12. Continue inert gas flow until tank is cooled to room temperature.
13. Remove clamp fixtures and remove excess flux with solvent.
14. Remove tank section from fixture.

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