DESIGN, DEVELOPMENT, AND FABRICATION OF MULTICAVITY
805 MHz ACCELERATOR TANKS**

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The development of full scale 805 MHz tank models for the proposed LAMPF accelerator has been both challenging and unique from the engineering standpoint. In the design and fabrication of these models one must take into consideration such things as materials, machining, joining techniques, allowable stresses (especially at elevated temperatures), good quality control at all times, heat transfer and the provision of an evacuation system capable of maintaining a good clean high vacuum under full power operation. Most of these engineering problems are further aggravated by the extensive use of OFHC copper with its inherently very poor mechanical properties.

OFHC copper is initially procurred in the form of standard cast billets ranging in sizes from three to ten inches in diameter and weighing between 100 and 1300 pounds per billet. The preferred method of forming the tank segments is by hot forging slugs cut from these billets to the desired premachined part. We allow for 1/8 inch minimum stock removal from the forging for final machining clean up in addition to all tolerance accumulation in both the forging and machined segment. This amount of copper removal has proven to be sufficient in eliminating surface penetrated oxygen during the forging process. Copper formed thusly is soft, dense, has fine grain structure and is free of residual stresses. Very little local deformation has been encountered from stress relieving during subsequent brazing operations with no noticable grain growth after as many as six heats required for step brazing.

Simple copper castings have been used in some of the model components to expedite model fabrication. The possibility of using precision castings produced by either the investment or plaster mold methods has been evaluated. Castings in any form can be porous and will have large crystal structure. Intricate parts such as thin webs are difficult to cast soundly because of the high shrinkage rate of copper during solidification and its tendency to form pipes and cold shuts. During all melting, pouring and cooling the copper must be subjected to vacuum or inert atmosphere if the OFHC quality is to be maintained.

Rolled OFHC copper plate has been used extensively for several tank components with good results. Hard copper plate deforms or changes shape considerably more than the softer material from stress relief during brazing. These deformations are unpredictable and nonuniform even with identical parts in the same heat. If finish machining is not performed after brazing, it is recommended that hard copper stock be annealed prior to machining and final brazing.

Dimensional tolerances of the segments and coupling cavities are held within the capability of standard good machine shop practice. Cavity segment forgings and coupling cavities for three of the long models have been machined in three different production orientated shops, using tracer type machine tools, quite successfully. Compensation for deviations from the nominal, or ideal, dimension is attained by removing material from the drift tube noses as required to provide the desired resonant frequency after production machining and prior to furnace brazing. Flatness and parallelism of the brazing surfaces are held to less than 0.002 inches total indicated run out with relative ease.

Heavy sections of copper are very difficult to join by any process other than furnace brazing. On the other hand few metals lend themselves to this type of assembly as does OFHC copper. Copper brazed in a hydrogen atmosphere is very clean, bright, and provides an excellent surface for rf currents. In our modeling program we have used as many as seven different fluxless brazing alloys with brazing temperatures ranging from 1375° F to 1820° F and on one occasion have employed the same alloy for three different joining heats.

The design criteria, from the point of conception to point of operation, is profoundly effected by the incorporation of tank component assembly by furnace brazing. One must pay close attention to joint design, sequence of brazing, alloy selection, heating cycles, thermocouple location, and in some cases the design of special furnaces and furnace fixtures. Each brazing alloy has its own particular metallurgical characteristics such as wetability, sluggishness, blushing, tendency to liquate, flow and filleting nature, errosive effect on copper and the deleterious result of subsequent heats during step brazing. The utilization of proper heating cycle can minimize some of the undesirable characteristics of an alloy. Generally an alloy is simply selected because of its melting point with little regard to joint configuration, but quite frequently joint configuration is designed specifically to take advantage of an alloy's desirable characteristic or to mitigate an undesirable feature.

The brazing of OFHC copper to stainless steel presents additional complications in the form of a stress problem because of their differences in thermal expansion. Either the stainless steel, the braze alloy or the copper must give or yield to prevent failure during the cooling cycle or the reheat for the next step braze. The filler alloy must be compatible with both the steel and copper. The lowest temperature at which stainless steel oxides can be reduced with hydrogen is near the upper limit to which copper may be heated safely. This limits the number of available alloys that can be used for brazing these two metals unless steps are taken to preclude, or eliminate, the formation of stainless steel oxides. Stainless steel and copper has been successfully brazed with a relatively low temperature alloy by first flashing the brazing area with approximately 0.0003 inches of nickel.

Time and space does not permit detailed

analysis of the methods employed in the development of these full scale tanks. To briefly illustrate these techniques of assembly, the fabrication of the 40 cavity Cloverleaf Tank (Model B) and the 39 cavity Side Coupled Tank (Model F) will be discussed.

Figure 1 is a picture of the OFHC copper cloverleaf forging weighing approximately 160 pounds. The pattern on the far side of the septum is identical to the near side except that it is rotated 45° about the beam axis. Figure 2 is a picture of one of the segments machined from the forging. Each segment consists of a septum, a drift tube, eight coupling slots, and a half cell on each side of the septum containing four nose cones and cooling water pockets. Each machined segment is 5.2 inches long (β = 0.71).

Figure 3 is a view of one of the two pumping box prebraze assemblies. The stainless steel nozzle was first welded to the pump box bottom plate which in turn was brazed to the copper box body using a 50 Au-50 Cu alloy. Two segments were then brazed together with a 60 Au-20 Ag-20 Cu "Flexibraze" alloy. The pumpout grill was milled into the side removing approximately 50% of the material bounded by adjacent nose cones and adjacent septums. The o.d. of this two segment assembly was turned to match the existing diameter of the pump box opening. Brazing of the pumping box to the pair of prebrazed segments was accomplished by positioning the two segement assembly on top of the pumping box and supporting the bottom of the pumping box in an area outside of the nozzle. The brazing alloy was the same as used to join the two segments previously (60 Au-20 Ag-20 Cu). The rf window flange was brazed to its mating segments in the same manner as the two pumping boxes were joined to their segments.

There was no change from the original gap between the drift tubes after being subjected to several heats. However, the nose cones of the open ends of all stacked sections did deform or sink approximately 0.010 inches below the plane of the outer rim. This yielding or creepage is believed to be a shear flow type of failure in the half nose cone only due to a combination of the absence of a holding alloy and nonuniform cooling of the complete stack. Heavy copper heat sinks placed over the open ends during subsequent heats reduced this deformation considerably but did not completely eleminate the creepage. The final solution was to employ a pulling fixture to straighten the nose cones and the use of dial indicator sweeping mechanism to check flatness of all open ends prior to their brazing.

Figure 4 shows one of the two identical end section major subassemblies consisting of a head with nozzle, 15 segments and one pumping box assembly. This unit is 80 inches high, weighs over 1500 pounds and was assembled directly on a furnace base using a "Flexibraze" alloy of 72 Ag-28 Cu. The third major subassembly, or center tank section, composed of 10 segments and containing the rf window flange was assembled in the same manner as the other two major subassemblies.

Figure 5 is a picture of the special clamshell furnace being installed to braze the joint between one of the end sections and the middle tank section. This furnace was designed to con-

centrate the heat on this single joint without over heating the lower segments to an unsafe temperature.

After the first heat with this furnace, two of the four interior nose cone joints were not vacuum tight and the outside of the tank was badly oxidized some two feet below the heat zone. It is now believed that the heating cycle was too rapid and that the outer shell of the water pocket between the interior nose cone and heating elements functioned as a heat baffle. The oxidation was attributed to the formation of water vapor by the combination of furnace hydrogen with oxygen from the fire brick. As this water vapor traveled down the outside of the tank it came in contact with copper at a temperature high enough to oxidize readily but not high enough to be reduced by the excess furnace hydrogen. These two tank sections were separated by reheating the defective joint and pulling on the upper section of ten segments with special fixtures and a dynomometer. The brazing ends of these two sections were then remachined for flatness and alloy removal and reassembled in the clamshell furnace. All of the tank openings were sealed with copper plugs and foil, thermocouples relocated and the joint temperature brought up to brazing heat more slowly. Hydrogen was forced through the tank in a downward direction and argon forced through the void between outer shell of tank and furnace interior in an upward direction. This combination of changes proved to be a success.

The final joint between the middle tank section and the second end section was brazed using the same alloy (63 Ag-27 Cu-10 In) and technique as developed previously except that a restraining mechanism was employed to prevent overstressing the rf window section during conductive heating from the brazing area. Figure 6 shows the complete tank assembly immediately after the final heat. This assembly is almost 18 feet high, weighs 4000 pounds and contains over 300 feet of vacuum tight braze joints.

Figure 7 is a picture of the final installation. There are four different water cooling channels, two flowing in each direction. Each channel runs the complete length of the tank and spirals around the tank 10 times. In this manner each cavity is exposed to the same average cooling water temperature. The combined rating of the two ion pumps is 1200 ℓ/sec and maintains a vacuum in the lower 10^{-8} torr range.

Model F is a 38 cavity, straight wall, side-coupled structure with a cell length of 4.76 inches (β = 0.65). This model is comprised of three brazed tank sections which in turn are bolted together. The two mechanical joints function very well in providing both a good rf connection and a metal-to-metal high vacuum seal. No difference in Q could be detected between the cavities with brazed joints. This joint consists essentially of a knife edge machined into one of the stainless steel flanges which buries itself 0.030 inches into the copper segment of the mating tank section when the flanges are pulled together. The knife edge has a straight edge toward the rf surface to prevent deforming or detuning the cavity and is copper plated.

Figure 8 is an exploded schematic view of the

components comprising a segment assembly. The coupling cavity clamshells were machined from OFHC copper plate and the segment machined from a copper forging shown in Fig. 9.

The sequence of assembly is as follows:

1. Seventy-six clamshells were brazed together to form 38 coupling cavities with an alloy of 82 Au-18 Ni. Final machining was then performed to install probe loop parts, pump-out opening and turning the segment matching radius.

2. Two head nozzles and four mechanical rf joining rings were brazed to their respective heads and segments with an alloy of 82 Au-18 Ni followed by machining to final dimensions and copper plating of the knife edges.

3. The individual segments and their coupling cavities were tuned by removing material as required from the drift tubes of the segments and tuning bosses of the coupling cavities.

4. Segments number 19 and number 20 contain the rf window flange. The coupling cavities were brazed to these two segments with an alloy of 81.5 Au-16.5 Cu-2 Ni to form two segment assemblies which were in turn brazed together with an alloy of 60 Au-20 Ag-20 Cu. The rf window flange was brazed to this pair of segment assemblies using the same 60 Au-20 Ag-20 Cu alloy. Special support fixtures for the coupling cavities were required during these last two heats. After brazing of this subassembly was complete, the rf opening, or iris, was machined into the flange and cavity wall.

5. The balance of the segments were brazed to their respective coupling cavities using the 60 Au-20 Ag-20 Cu alloy.

6. Figure 10 is a picture of one of three tank sections containing 13 segment assemblies with the coupling cavity support fixture in place. This fixture utilizes counterweights which support the coupling cavities at their cg to prevent loosening the previous braze and drooping during the final assembly heat. Figure 11 shows the same tank section after fixture removal. A "Flexibraze" alloy of 72 Ag-28 Cu was used to braze the segment assemblies for each of the three tank sections.

Figure 12 is a picture of the Model F tank assembly prior to flattening and cooling tube installation. Figure 13 is a view of the final installation ready for electron beam and high power rf experiments.

Most of the alloys used in the fabrication of these models were in the form of 0.002 inch thick foil.

One eighth inch stainless steel dowell pins have been used extensively to position, or locate, components with respect to each other during the brazing cycle.

Each brazed joint was helium leak tested following every heat.

Table I lists some of the characteristics of the full power 805 MHz models developed for the LAMPF modeling program.

Table I

Model Designation	No. of Cells	Cell Configuration	β	Copper Form
AF	2	Cloverleaf	0.71	Forging
B	40	Cloverleaf	0.71	Forging
D	2	Side coupled-straight wall	0.65	Forging
E	2	Side coupled-radius wall	0.71	Casting
F	39	Side coupled-straight wall	0.65	Forging
H	4	Side coupled-optimum shape	0.43	Casting
J	2	Side coupled-radius wall	0.65	Casting
K*	61	Side coupled-optimum shape	0.65	Forging
L	5	Side coupled-optimum shape	1.0	Casting

*Nearing completion.

**Work performed under the auspices of the U. S. Atomic Energy Commission.

DISCUSSION

H. G. WORSTELL, LASL

NITSCHKE, LRL: What is the final vacuum on this tank?

WORSTELL: The cloverleaf tank is running in the lower 10^{-8} torr range and the side-coupled tank is operating in the upper 10^{-8} torr range--6 or 7 x 10^{-8} torr, I guess. It really isn't much of a problem to obtain a good vacuum on either of these tanks since both are slightly over pumped. However, we haven't had much rf power in the tanks yet.

VOELKER, LRL: If you had it to do over would you use more knife edges and less brazes?

WORSTELL: No, as a matter of fact, I would like to have less knife edges, but not many less. The fewer knife edges employed for a given tank length, the longer each tank section will be. I don't believe we would have any trouble making the tank section height 7-1/2 or even 8 ft. high. The cloverleaf structure would be almost impossible to put knife edges on.

POLK, BNL: Was this technique of brazing the same technique as you have used before, where each one of these pieces was put into a welded steel can?

WORSTELL: No. Only one of these tanks employed that technique. The cloverleaf tank was built in one facility and the other tank was built in another facility.

POLK, BNL: Where was it done and what technique was used?

WORSTELL: The cloverleaf tank was done at the Pyromet Co. in San Carlos and the side-coupled tank was brazed at Vac-Hyd in Torrance, California. The latter was an interesting operation and caused us some shuddering. Vac-Hyd modified a vacuum furnace by building a special hydrogen retort. The way the furnace was built, we had to load, or stack, all the parts on the graphite block, or a furnace bottom plate, then pick up the entire works and load it into the retort. The retort was then picked up and placed in the furnace. The reverse of this procedure was necessary when unloading the retort after the heat. We almost lost it once but aside from that the operation was fine. I would go a little further on that. I would say that with the side-coupled structures, where we use the fixturing along with the loose tank parts, we would recommend a bell-type furnace or a furnace that does not require moving the heat after alloy placement.

TUNNICLIFFE, AECL: How much solder is there in the joint after brazing? In other words, does the space between the nose cones have an allowance for the thickness of the solder?

WORSTELL: I think you are asking how big was the gap between the copper after the joint was brazed.

TUNNICLIFFE: Yes. How big was the gap? Do you allow for this thickness in final machining?

WORSTELL: No. We keep these parts flat within 0.002 in., actually less than 0.0015 in. with little effort. The alloy foil is 2 mils thick, and the joint is kept slightly deficient of alloy to prevent the stuff from running out. The copper parts will come together copper-to-copper and the alloy will fill the voids in the areas where there is no copper-to-copper contact.

LEBOUTET, CSF: How much frequency drift do you get before brazing and after brazing?

WORSTELL: That's hard to say; it depends upon which tank you are talking about and to whom you are talking, I think. Where is Ed Knapp? This morning you said something like 200 kc, didn't you?

KNAPP, LASL: I said that we had like ± 500 kc frequency scatter from cell to cell after brazing and like ± 50 kc before brazing, although the measurement after brazing is not accurate. There is a big uncertainty in that 500 kc measurement. The over-all frequency did not change appreciably.

WORSTELL: The only way I could answer your question is that, in the case of the three cloverleaf minor subassembly brazes we could not measure any change of the spacing between the drift tube noses after they were brazed. We could get into these three parts through the pump-out slots or waveguide window opening with "jo" block mikes. There could be some change during brazing, yes, but I don't think it's anything to be worried about. During the tuning before brazing, the parts are setting copper-to-copper, and there could be a little error here because of incomplete contact. The newer structures that we have now should have much less frequency change from brazing because the septum is more rigid and much more rugged than those we showed earlier. The side-coupled structure discussed here had a straight wall and flat septum except for the drift tube.
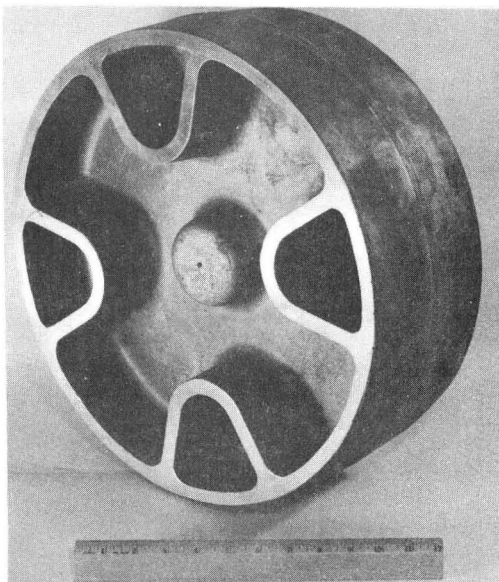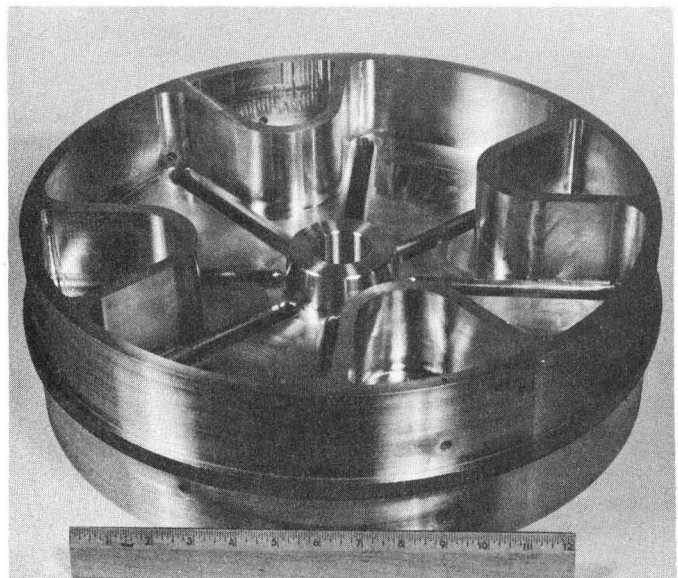

Fig. 1. Cloverleaf forging.
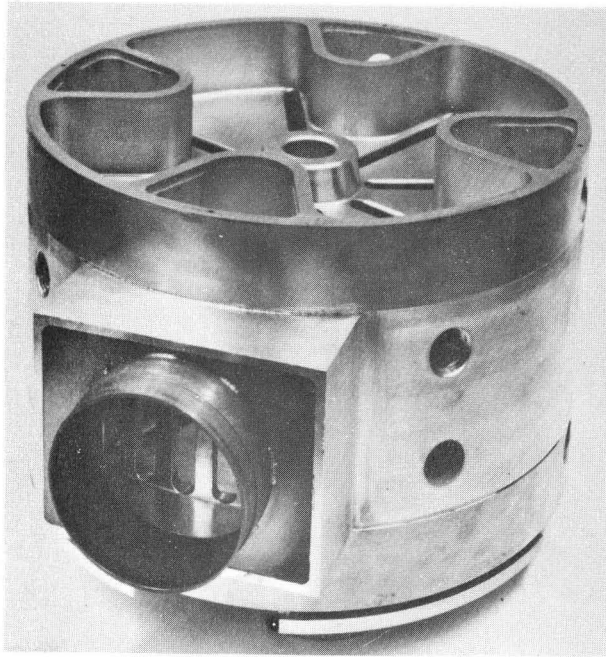

Fig. 2. Cloverleaf machined segment.

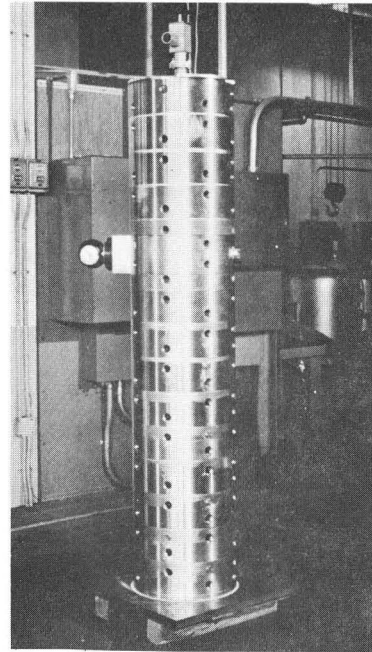Fig. 3. Pumping box subassembly.

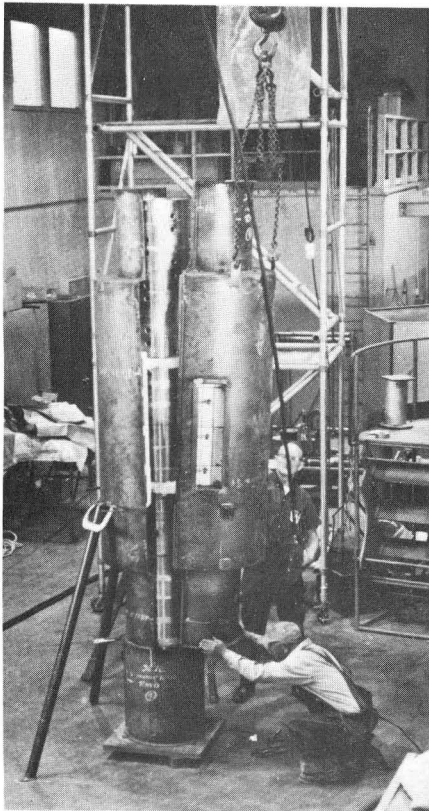Fig. 4. Brazed subassembly-segments 1-15.
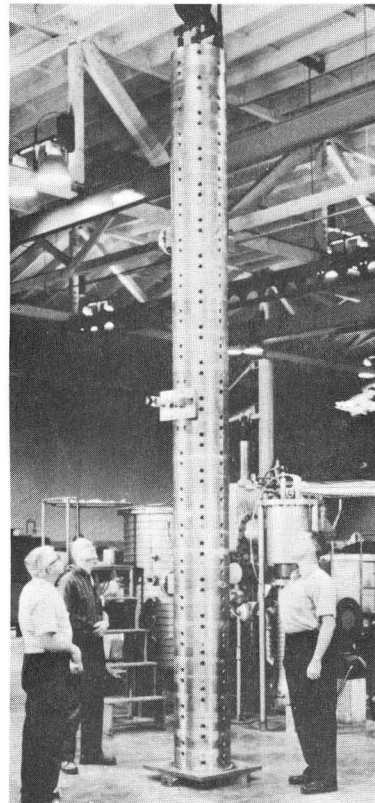

Fig. 5. Clamshell furnace.

Fig. 6. Completed cloverleaf tank
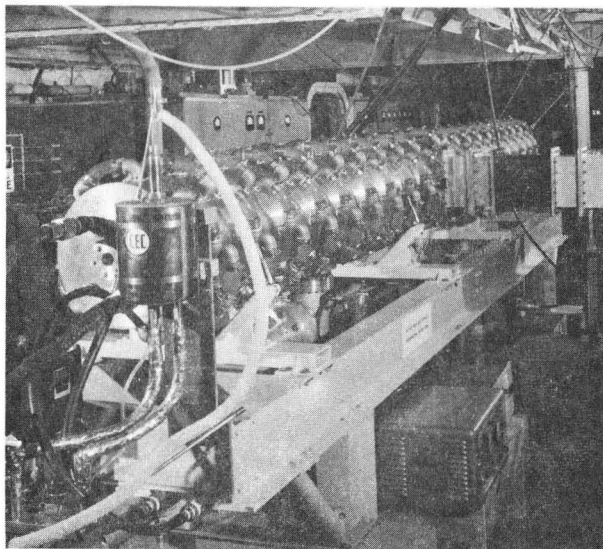(40 cavities).
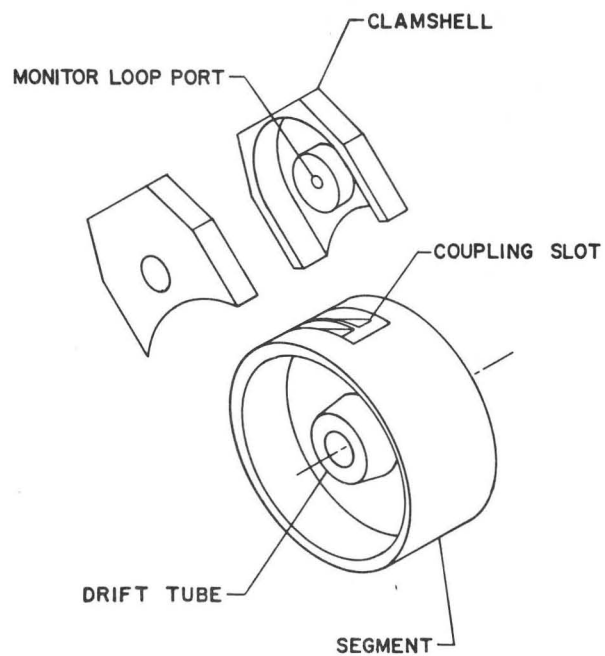
Fig. 7. Cloverleaf tank installation.

Fig. 8. Model F segment assembly schematic.

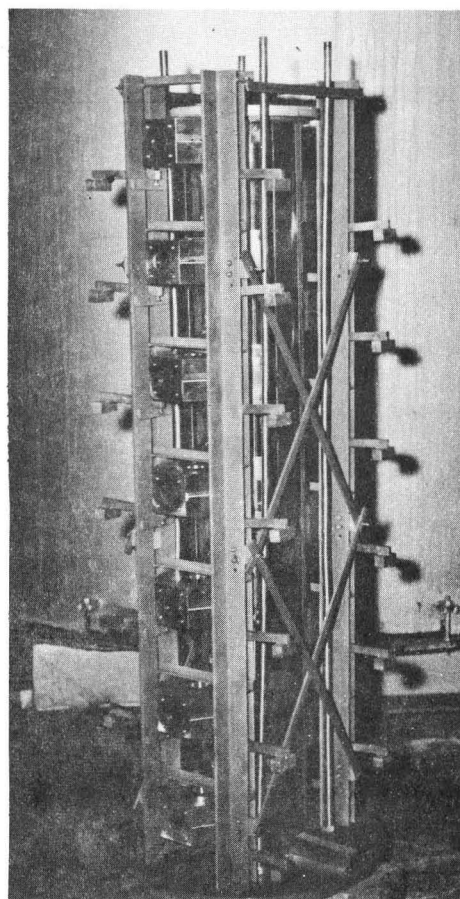
Fig. 9. Model F segment forging.
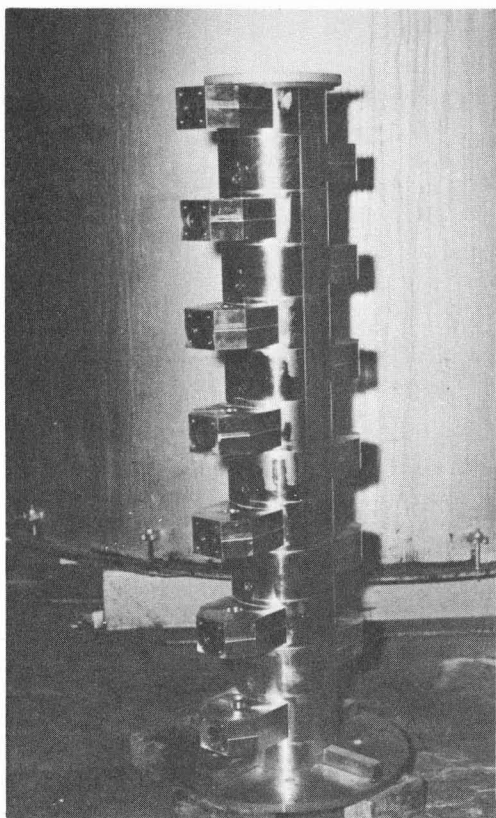

Fig. 10. Model F furnace support fixture.
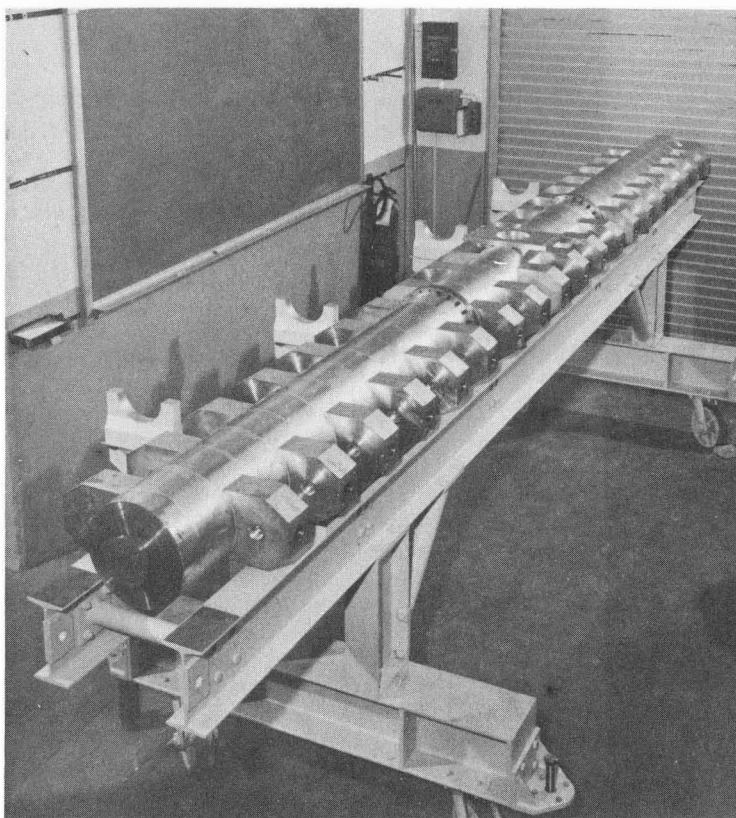
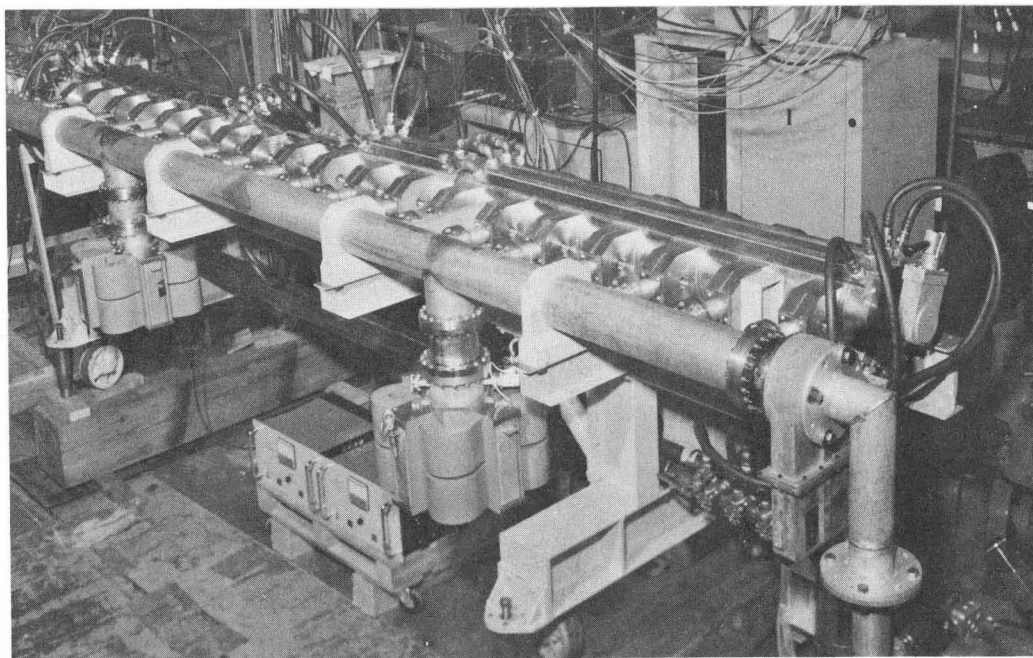Fig. 11. Model F tank section - segments 1-13.

Fig. 12. Model F final assembly.

Fig. 13. Model F final installation.