MECHANICAL DESIGN OF L.A.S.L. LINAC STRUCTURES - (LAMPF)*

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The LASL Linac consists of two basic types of accelerating structures, the 201 MHz drift tube linac and the 805 MHz side coupled system. The disciplines required for the mechanical engineering of the combination of these two types of structures are numerous. All mechanical design criteria is based on a relatively high duty factor of 12% which places a premium on well engineered vacuum systems, cooling systems and components that do not contain materials susceptible to radiation damage. The drift tube linac will be fabricated from copper clad steel using large rolls, heavy machine tools and hundreds of feet of vacuum tight steel and copper welds. The side coupled structure will be fabricated from OFHC copper forgings which are machined with precision tracer and tape controlled machines and assembled in house by hydrogen furnace brazing. Both structures must be aligned to a common beam center line, evacuated to a pressure less than 10^{-6} torr under full power and cooled with water systems capable of maintaining tank temperatures within close limits.

Time and space does not permit a detailed discussion of even a portion of LAMPF, therefore this discussion will be confined to some of the engineering differences between this and other accelerators.

Figure I is a schematic of the four tank 201 MHz drift tube linac and illustrates the vacuum system array. The beam energy at injection into tank #1 is 0.75 MeV and the exit energy from tank #4 into the 805 MHz side-coupled structure is 100 MeV. The shell material for all tanks is nominally 5/8 inch ASTM A-285 grade C firebox quality steel plate clad with a nominal 1/8 inch thickness of OFHC copper. All tanks are encased by a water cooling jacket of 1/8 inch thick steel. Tanks #2, #3, and #4 are each an assembly of four tank sections. The tanks will be supported by piers located at tank ends and at each intermediate stiffener.

Figure II is a view of a tank cross section and is typical of all tanks except tank #1 which does not contain post couplers. The two coarse tuning bars are actually water cooled copper angles that will be installed by welding after the drift tubes have been hung and a preliminary tank frequency has been determined. Tests have shown that the projected shadow area of the angle has essentially the same tuning effect as a solid bar with the same side dimensions as the angle. The angle is much easier to modify, shape and install than a large solid bar. Full power tests on these coarse tuners have yet to be performed. A post coupler will be installed in each cell of tanks #2, #3, and #4 on alternate sides of the tanks.

Drift tubes for Alvarez type structures invariably seem to be expensive, difficult to fabricate and require a great deal of engineering time. The LAMPF drift tubes are certainly no exception to this rule. Figure III shows most of the components required to assemble one of the drift tubes that will be located at the low energy end of tank #1. The quad winding is first formed from hollow conductor with forming and annealing fixtures and installed on the yoke and porcelainized pole pieces. A fiber glass sleeving is then slipped over the winding and the entire quadrupole potted in ceramic and fired. This quad assembly is then installed in the two OFHC copper body halves along with the bore tube and hydrogen furnace brazed at 1490°F. The stem-to-body joint is then furnace brazed to the drift tube body, after nickel flashing the end and sides of the stem, with a 72 Ag 28 Cu alloy at 1450°F. After brazing the outer stem tube is copper plated. Cooling is accomplished by passing water down the passage between the outer and intermediate stem tubes, through the body cooling channel and out through the space between the inner tube and the intermediate stem tube. The winding of course is cooled by forcing water through the hollow conductor. This particular drift tube shown in Figure III operates at 700 amperes and produces an 8300 gauss/cm field.

Figure IV is a typical view of a drift tube plate without the positioning spider, half drift tube body and vacuum head. As the vacuum head is pulled down, the wave spring along the outer periphery of the plate is compressed which in turn presses the beveled edge of the plate firmly and uniformly against the shell copper at the end of the tank. The drift tube plate, being only 1/8 inch thick and dead soft temper after the brazing operation to install the cooling tubes, deflects easily to match the shape of the shell copper to provide an excellent rf connection. The two plates of tank #1 will be adjustable axially under vacuum to tilt the field. The other six drift tube plates will be rigidly mounted and adjustable only with spacers. In actual practice the drift tube plate, half drift tube body, positioning spider, and vacuum head will be assembled on a bench and installed on the tank end as a unit. The quadrupole magnet associated with the half drift tube will be installed, positioned, and aligned after the vacuum head has been bolted in place.

Past experience with overlaid copper welds has been something less than satisfactory. If the overlay is made directly on the steel, the steel should be preheated to approximately 450°F to drive off moisture and provide better bonding conditions which in turn severely oxidizes the adjacent copper and creates a rather uncomfortable working condition for the craftsman. The other alternative generally employed is first to overlay the steel weld with an intermediate material such as nickel or Monel and then overlay that material with copper requiring at least two passes. In either case the copper overlay is contaminated by the material upon which it is being placed. Slight amounts of contamination in the copper considerably reduce its conductivity and somewhat negate the justification for using OFHC copper in the first place, especially if the direction of current travel is such that it must cross the contaminated overlay. Copper overlays around large openings can and do produce sphinctering stresses capable of causing considerable warpage and deformation of the opening. We have endeavored to design out copper overlays, with the result that the only overlaid weld in LAMPF 201 structures will be the longitudinal tank shell seam welds.

Figure V shows the cross sectional view of a nozzle installation and is typical of all penetrations into the tanks except the drift tube stem openings. The installation of some 200 nozzles of this type not only eliminates 160 feet of overlay welds, but provides a copper liner for the nozzle rf contact and a stainless steel flange for vacuum seals. All nozzle copper to copper welds may be differentially pumped by the soft vacuum system.

Figure VI illustrates the method by which tanks #2, #3, and #4 are assembled. There will be **nine** such joints since each tank is composed of four tank sections. This design developed from the necessity of eliminating elastomer seals from the high radiation areas and the desire to provide a good rf contact between mating tank sections without copper overlays. It also permits the relaxation of tolerances on tank section lengths and flatness of end flanges since it really does not matter if the gap between tank sections is an 1/8 of an inch. Tank sections will be installed on their mounts, aligned to the best average center line and positioned along the beam line such that the ideal spacing between the last drift tube hole in the upstream tank section and the first drift tube hole in the next downstream section is attained. Snug fitting spacers will then be inserted between the flanges and clamped securely by the flange bolts to maintain this position. The intermittent weld joining the adjacent shell plates and the vacuum tight weld around the outer diameter of stiffener rings is then completed. The copper skirt will be cut to the desired width and welded copper-to-copper to provide the rf connection between the two tank sections and a vacuum barrier between the hard and soft vacuum systems.

Figure VII is a schematic of the two types of modules in the side coupled 805 MHz portion of LAMPF. A module by definition is that group of tanks, bridge couplers and related equipment that accepts the power from one rf amplifier. The structures associated with each module is completely independent of all other modules with the exception of a common beam tube on which are located vacuum isolation valves. There will be a total of 104 tanks assembled from 4960 cells. The first eight modules will each contain four tanks and three bridge couplers, whereas the next 36 modules will each contain two tanks and one bridge coupler. All cells in a given tank will have the same shape but unlike the cells in any other tank. Similarly, no two of the sixty bridge couplers are identical. Cell lengths will vary from 3.160 inches to 6.165 inches and inside diameters will range from 10.050 to 10.200 inches.

Fabrication of the side coupled structures will require both the services of outside contractors and considerable effort on the part of LAMPF personnel. Copper forgings of the segments, each of which contains the septum and the two clamshells that make up a coupling cavity will be obtained from commercial forging facilities. These forgings will then be machined in outside shops and shipped to Los Alamos for final tuning and assembly. A ten man shop, part of which is located in a temperature controlled room, will perform the final machining of the drift tube noses of the segments and clamshell tuning bosses to provide the desired resonant frequency. These components are then assembled in house to form tank sections by hydrogen furnace step brazing requiring several heats with different alloys. Twelve rectangular cooling tubes will be attached to the sides of the tank sections by soldering in a specially designed rotissary type oven in an atmosphere of argon or nitrogen to prevent copper oxidation. The vacuum manifolds, fabricated in outside shops, are then joined to the tank section by TIG welding to the tank section pump out nozzles. The tank section assembly will then be moved to the beam channel for installation and laser beam alignment with other tank sections. Bridge couplers will be obtained in much the same manner as the tanks except that there will be several machining operations between brazing heats. Bridge tanks, tank heads, and tuners will be made from OFHC copper forgings and the rf window mounting flanges will be machined from 304L stainless steel investment castings.

Heavy copper sections are difficult to join by any means other than fluxless furnace brazing without creating virtual leaks, contaminating the copper or inducing considerable warpage. Essentially all of our brazing for both the 201 MHz and 805 MHz structures will be performed in house by LAMPF personnel. Considerable time and effort have been expended in our modeling program during the past several years to develop joint designs, alloying techniques, heating and cooling cycles and the evaluation of brazing alloys. Brazing temperatures will range from 1920°F to 1450°F with some components being subjected to a minimum of four separate heats. Two large brazing furnaces, along with five bases and retorts are now on order. The building to house these furnaces and tuning shop is presently being erected on the accelerator site.

Figure VIII is a picture of four segment assemblies in the furnace during the brazing operation to join the coupling cavity and mounting pad to the segment and the pump-out nozzle to the coupling cavity.

Figure IX shows two of the segment assemblies after brazing which represent the shortest cell length is the 805 MHz portion of LAMPF. The same alloy, 50 Au 50 Cu, was used to braze the clamshells together to form a coupling cavity and subsequently to braze the coupling cavity to the segment in two separate heats at 1820°F. This technique of using the same alloy for step brazing operations has been employed with considerable success; however, one must be careful that the original brazed joint is not subjected to undue tensile or shear stresses during subsequent heats.

Figure X is a picture of an actual cross section of an EPA segment assembly ($\beta = 1$) containing the mechanical rf joint knife edge, a mounting pad, a coupling cavity, a pump-out nozzle and a monitor loop nozzle. The copper plated stainless knife edge is 0.040 inches high and functions both as an rf connector and vacuum seal. During assembly this knife edge penetrates the parent copper of the mating half cell of the next tank section approximately 1/8 inch from the rf surface. Every segment assembly in LAMPF will contain a pump-out nozzle and a monitor loop nozzle, but only those segment assemblies located at the ends of a tank section will have a mounting pad.

Figure XI is a picture of segment assemblies stacked in the furnace for the final brazing heat to form a tank section. The alloy being used here is 72 Ag 28 Cu "Flexibraze". This particular section contains eight cells and is approximately 59 inches high. There will be 352 tank sections in LAMPF similar to this section except that most will be longer, up to 78 inches, and all will contain more cells, some as many as seventeen.

Figure XII is a picture of a tank section being installed for one of the models and is very similar to the final design used in LAMPF except that all coupling cavities will be circular in shape and contain a pump-out nozzle. The first tank section is installed and both ends adjusted to the beam center line by placing targets in the drift tube bore of the first and last cells in the tank section and using laser alignment tooling. The other tank sections of a given tank are aligned to the beam line by dowel matching one end of the section to the previously aligned section and the insertion of a laser target in the free end drift tube bore. The thin ring flanges of the vacuum manifolds are then welded together and all joints leak tested. After a complete module has been assembled, final tuning and flattening is accomplished by slightly deforming the main cells in the areas between the coupling cavities as required. If necessary, the gap between the coupling cavity tuning bosses may be altered by inserting a spreader tool through the unused pump-out nozzle in alternate cells or closing the gap by clamping from the outside of the coupling cavity. Once the flattening operation is complete, the monitor loop nozzle in each coupling cavity is sealed by the insertion of a thin walled plug and welding. The unused vertical pump-out nozzles in alternate coupling cavities are sealed by welding a reinforced 0.020 inch thick disc to the thin nozzle flanges.

Figure XIII is a picture of a typical bridge coupler after final brazing. Not shown in this view are the three two inch diameter tuners which penetrate from the far side. The bridge couplers and tanks will be installed simultaneously. The 105 quadrupole doublets may be installed before, during, or after tank installation.

LAMPF will have three different vacuum systems. Ion pumps will be employed throughout for the hard vacuum, trapped staged blower systems for roughing to ion pump starting pressures of 5×10^{-4} or lower and a soft vacuum system to maintain a 50 to 100 micron pressure in the 201 drift tubes and differential pumping of nozzle welds as required. All vacuum pumps in the drift tube linac will be fixed, whereas the roughing for the side coupled structure will be portable. All ion pumps will be started with heavy duty portable starters but operated normally with small power supplies. Considerable design effort has been expended to eliminate elastomer seals from the high vacuum system because of their outgassing characteristics and susceptibility to radiation damage with the result that the only elastomers exposed to high vacuum are the gate seals in the roughing and isolation valves. Practically all of the metal seals will be aluminum "O" rings which have proven to be inexpensive, easy to install, simple and reliable.

Manufacturers rate the pumping speed of ion pumps on air or nitrogen under ideal conditions with small baked out systems. Anyone familiar with ion pump operation is well aware of the pump's characteristic to readily digest those gasses for which it has an appetite and reject those that are distasteful resulting in a true pumping speed on an actual system that is considerably less than its rated speed. An effort has been made to determine the true ion pumping characteristic of copper outgas since practically no information pertaining to this phenomenon has appeared in the literature. Data have been accumulated from six large copper systems using fifteen different pumps of four different sizes supplied by four manufacturers. Several determinations were made for each system and its pumping scheme. Figure XIV is a plot of the average performance of all systems and pumps evaluated to date and represents some 22 separate determinations spread over a five year period. The condition of the ion pumps varied from new pumps to used pumps that had been in service for several years on relatively clean systems.

The minimum rated pumping speed of the ion pumps to meet our evacuation criteria will be determined from the following equation.

$$S_{pr} = \frac{KA}{PE_i}$$

where

S_{pr} = Required manufacturers rated pumping speed (l/sec)

K = Surface outgas rate (torr-l/sec/cm^2)

A = Surface area of tank (cm^2)

P = System operating pressure (torr)

E_i = Pump efficiency factor from Figure 14.

We have chosen a K value of 10^{-9} torr - l/sec/cm^2 to be representative of the outgas characteristics of copper surfaces under full power that have been preconditioned with rf power for two weeks or so. After several months of operation under power we would expect this value of K to diminish by a factor of ten or more. Our maximum allowable design pressure is 10^{-6} torr. The total high vacuum surface area of LAMPF is 21×10^6 cm^2 of which some 80% is under rf power. In nearly all cases the molecular conductance of grills and nozzles between the ion pumps and rf surfaces is ten times or more than the expected outgas speed at our design pressure.

The cooling water systems must dissipate some 4.5 MW of power from the accelerator structures when operating at a 12% duty factor. The highest wet bulb temperature recorded in Los Alamos during a five year period was observed to be 69°F and less than one percent of the time did the wet bulb temperature exceed 60°F. The cooling system design takes full advantage of these relatively low wet bulb temperatures, augmented with some water chilling, to provide tank operating temperatures in the 75°F to 80°F range. Water chilling will not be necessary at any time when operating at duty factors less than 6% and is required only 30% of the time with a duty factor of 12%. Each of the four tanks in the drift tube linac will have three separate closed loop systems, one for quadrupole windings, one for tank shell cooling and one for the clean copper components such as drift tube bodies, pumping grills, post couplers, rf loops, tuning slugs and drift tube plates. Each module of the side coupled structure will be cooled as a unit with a single system. Individual channels of cooling water for a given tank or module is continuous and alternate channels carry cooling water in opposite directions such that every cross section of the tank or module is exposed to the same average cooling water temperature. Cooling water mix tanks, as used in our modeling program, will be employed in lieu of proportional controllers. The mix tanks allow high flow rates through the structures at low pressures, are very tolerant to a broad temperature range of cold water supply and contain immersion heaters to warm the tanks to near operating frequency prior to turning on the rf power.

Acknowledgments

The author would like to express his appreciation to the engineering staff of Group MP-3 who, to a man, have contributed so much to this project; to the LASL Shops Department and Group CMB-6 for their cooperation during the modeling programs; and to E. A. Knapp and D. A. Swenson for their promptness in providing firm physics parameters without which engineering cannot be finalized.

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DISCUSSION

(H. G. Worstell)

LEFEBVRE, SACLAY: In our experience, it is very difficult, if not impossible, to start a large ion pump from a blower even if it is backed up by a liquid air or nitrogen trap.

WORSTELL, LASL: We have not had any trouble. We have been starting six, 1000 litre pumps on one machine simultaneously using blowers. It depends a lot on the ion pump. One manufacturer's pumps are very difficult to start but we don't have any trouble starting any of the ion pumps if we get down to the bottom of the 10-5 torr scale, with the blower pumps.

VOICE: What sort of liquid air trap do you use?

WORSTELL, LASL: It is a very simple trap made by CVC. I don't think the trap helps very much. We use it mainly to keep back streaming oil vapors out of the tank. We do not need the trap to reach the ion pump starting pressure.

POLK, BNL: I think the real point is that you have compound blowers. With one blower you would get down to 10^{-4} torr. The second stage blower lowers the pressure to the range of the ion pumps.

WORSTELL, LASL: For the small pumps such as we use on the 805 modules we use a compound blower. It has four sets of rotors. In the larger systems we will have a blower pump backing a blower pump, which in turn is backed by a two-stage forepump.

HENDRICKS, U. MINN.: Have you done any life tests on the ion pumps under your particular conditions and if so, what are the results?

WORSTELL, LASL: It takes too long. I know of one ion pump that has been in service for 10 years and it is still going strong.

HENDRICKS, U. MINN.: At approximately 10^{-6} torr pressure?

WORSTELL, LASL: No, at much lower pressures, in the 10^{-8} to 10^{-7} range. We ran one pump to destruction on hydrogen just to see what would happen because we would like to use ion pumps in the injector area for pumping the hydrogen.

HENDRICKS, U. MINN.: How long did that take?

WORSTELL, LASL: I don't remember exactly but we were a little surprised at the pumping speed, roughly four times its rating on air, and we ran it at 2 X 10^{-5} torr. Of course, it got hot and failed, due to elements shorting out, but it ran for quite a while.

MUELLER, LASL: That pump ran for about 300 hours, pumping at 1.5 X 10^{-5} torr.

GRAND, BNL: In the 800 structure, how do you plan to control the temperature?

WORSTELL, LASL: We are investigating several schemes. At the present time, the control system on the EPA senses both the VSWR that occurs if the tank is off frequency and the copper temperature of the tank. Both kinds of information are used to change the tank temperature in order to tune the tank to the desired frequency.

GRAND, BNL: How about physical design?

WORSTELL, LASL: We have six rectangular cooling tubes on each side of the tank section, soft-soldered in position in a rotary oven after all brazing operations, leak checking etc. The tubes are clamped in place with solder placed under them. The tank section is then heated in an argon or nitrogen atmosphere to preclude oxidation of the copper.

LEISS, NBS: How do you plan to align the total accelerator?

WORSTELL, LASL: We have made no provision for making total alignment; we don't care if the beam wanders a little provided that it's gradual, "follow me"?

LEISS, NBS: I hear you.

WORSTELL, LASL: The beam may curve slightly, and we are using steering magnets. Asfar as looking right down the bore of the whole thing, no, because that's 2800 ft long. Our tests show that over long distances a laser beam does not work too well in air.

LEISS, NBS: This concerns me, because at SLAC it was originally thought that they would not need this. Their focusing wavelengths are much longer than yours and they certainly found that they needed it.

WORSTELL, LASL: To answer your question, maybe I should simply say that we have made no provision at this time.

LEISS, NBS: What water treatment do you plan?

WORSTELL, LASL: We will do some water treating because these systems are of the closed loop type and the same water continually cycles. The raw water is on the other side of the heat exchanger and we plan to treat this to keep fungus from growing in it. In the 201 we will treat the water for the jacket cooling with a rust inhibitor.

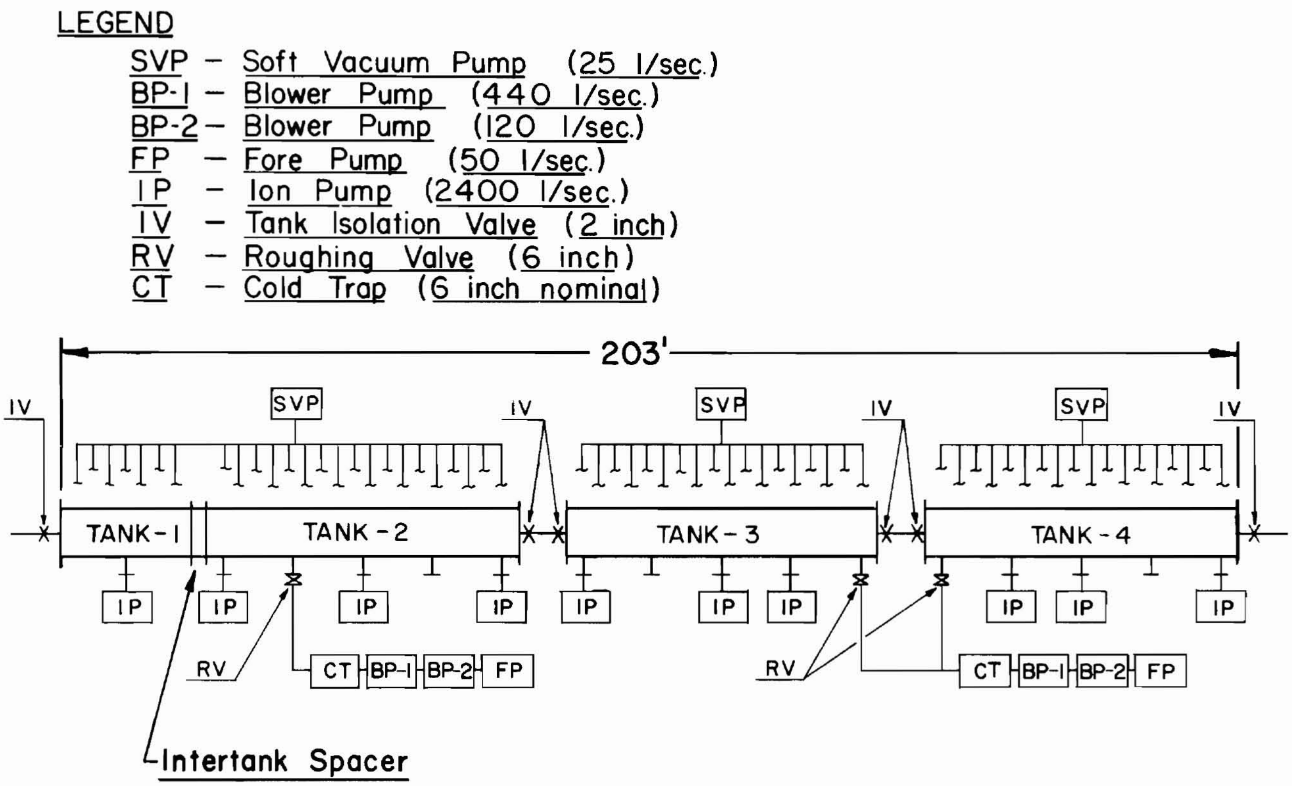

Figure I - Drift Tube Linac Schematic

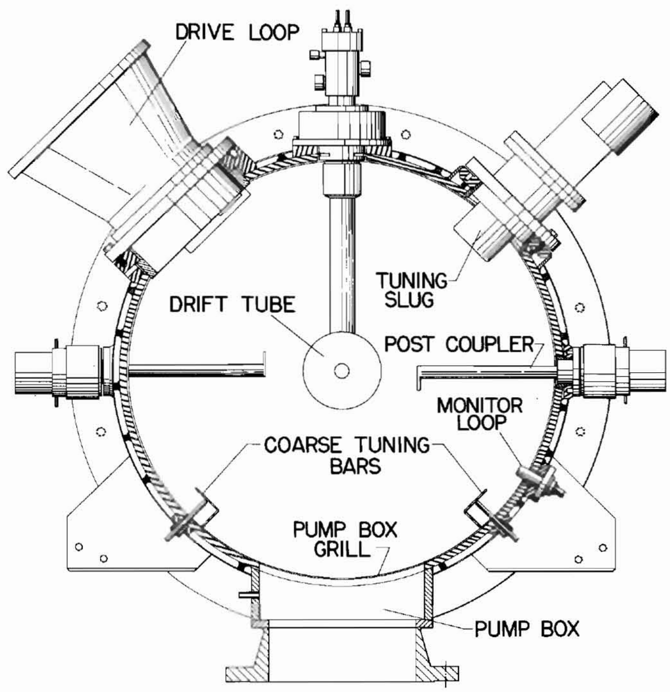

Figure II - Typical Tank Cross Section

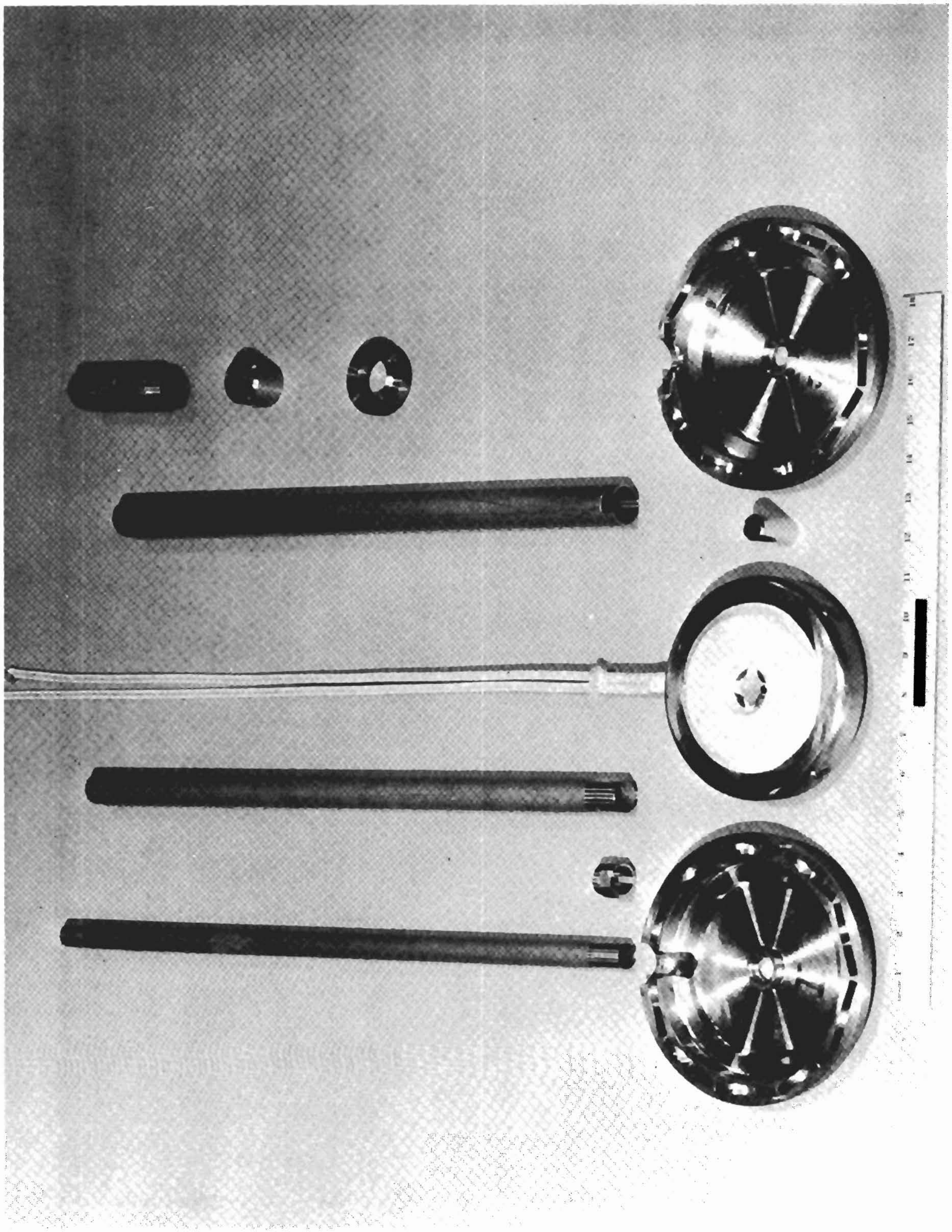

Figure III - Drift Tube Components

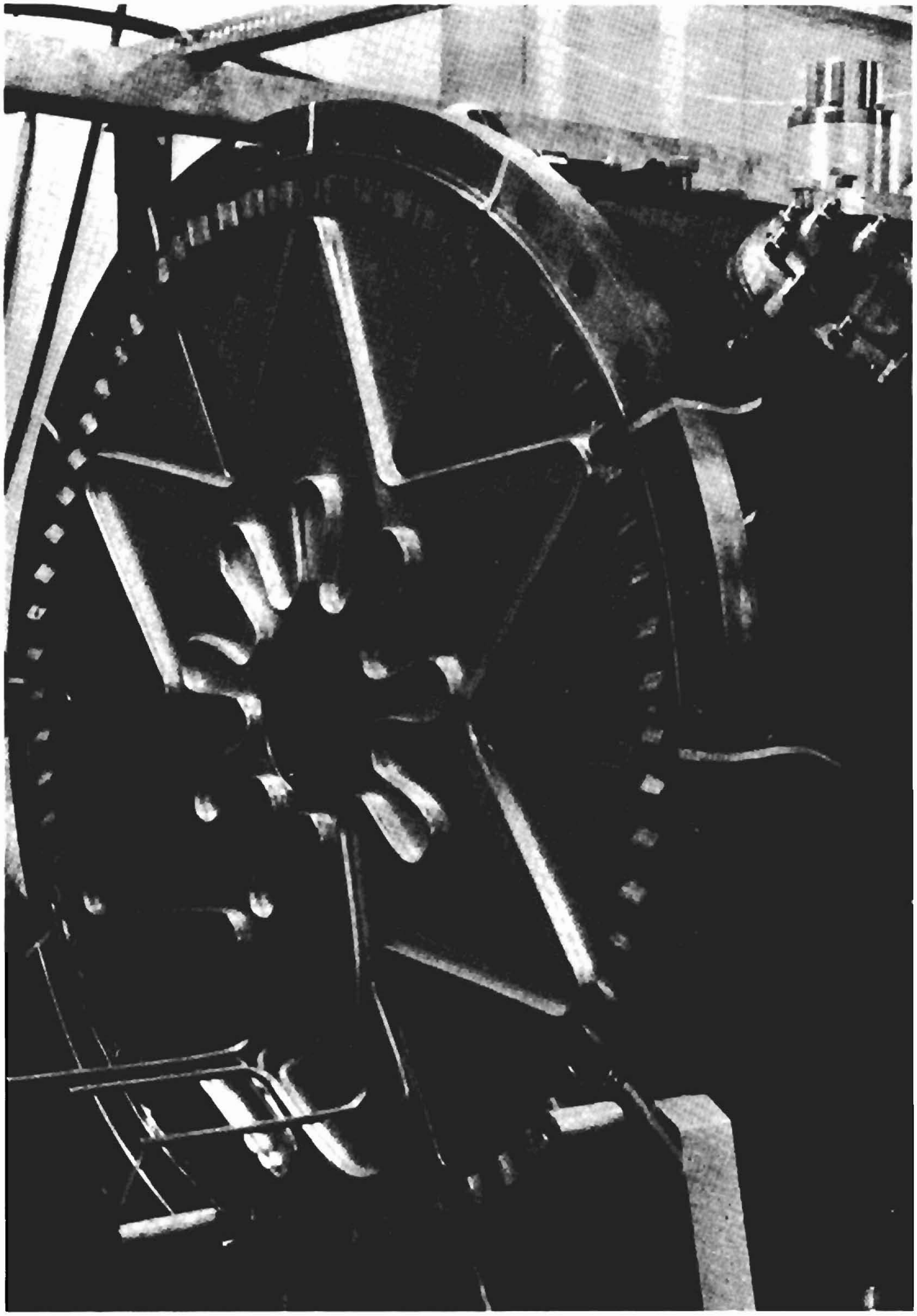

Figure IV - Drift Tube Plate

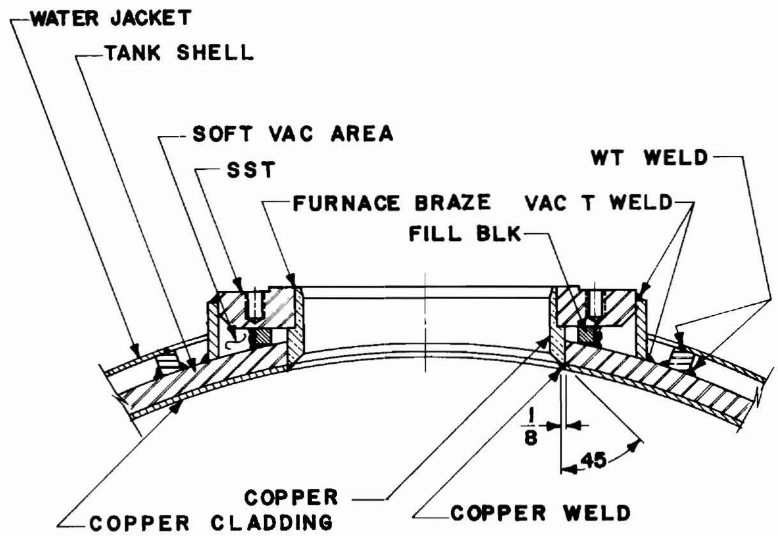

Figure V - Typical Tank Nozzle Cross Section

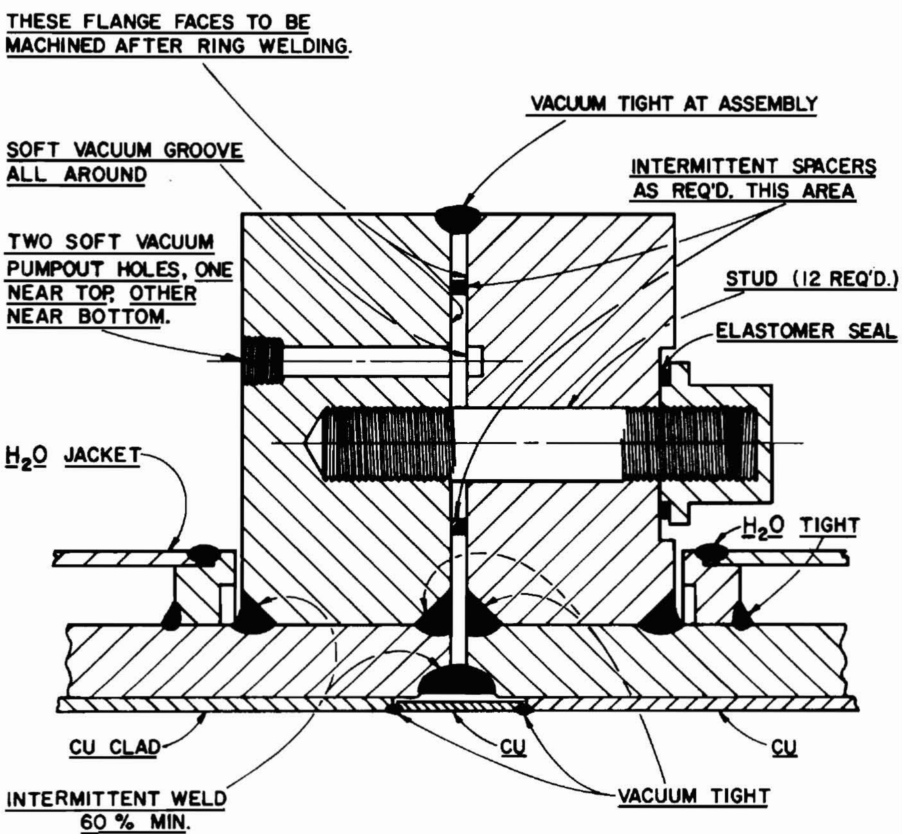

Figure VI - Tank Section to Tank Section Joint

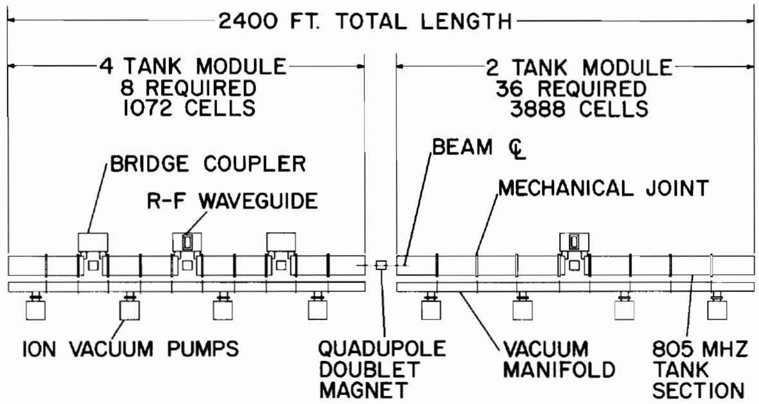

Figure VII - Schematic of 805 MHz Modular Concept

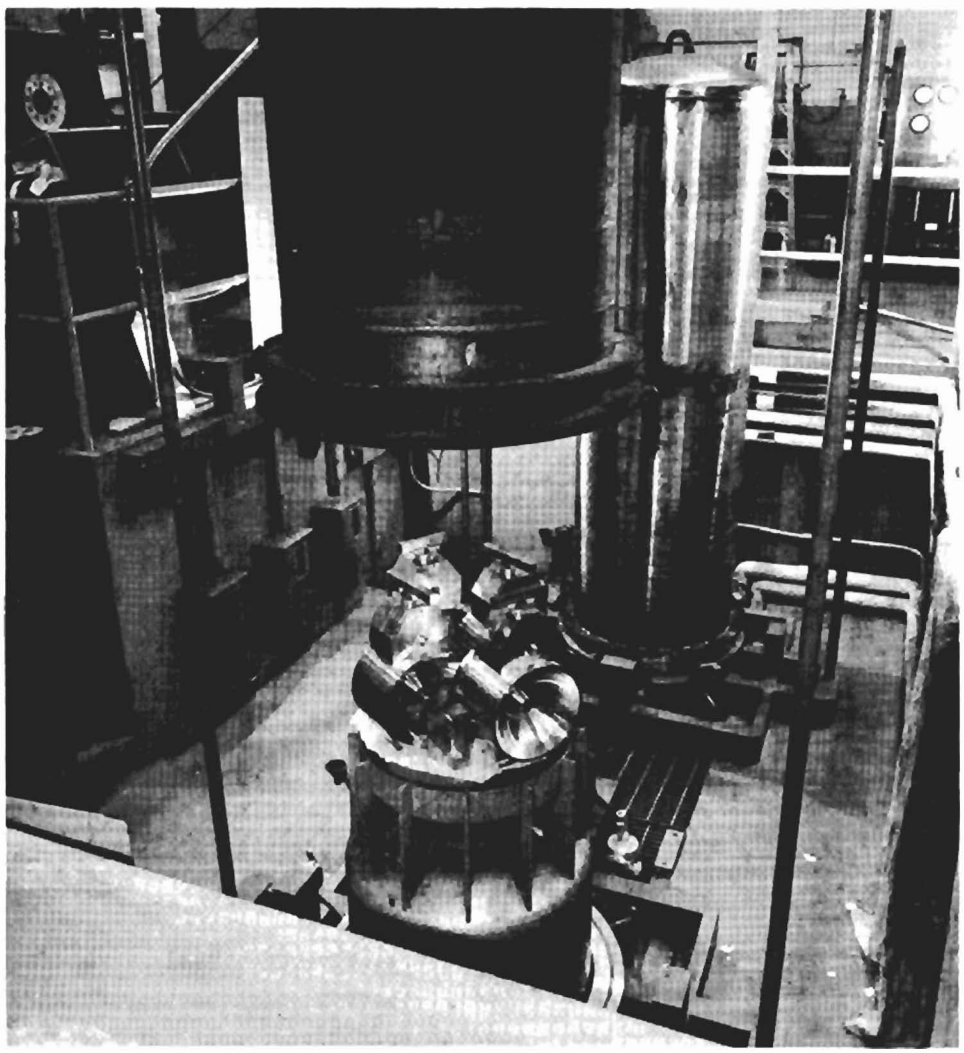

Figure VIII - Segment Assemblies in Furnace

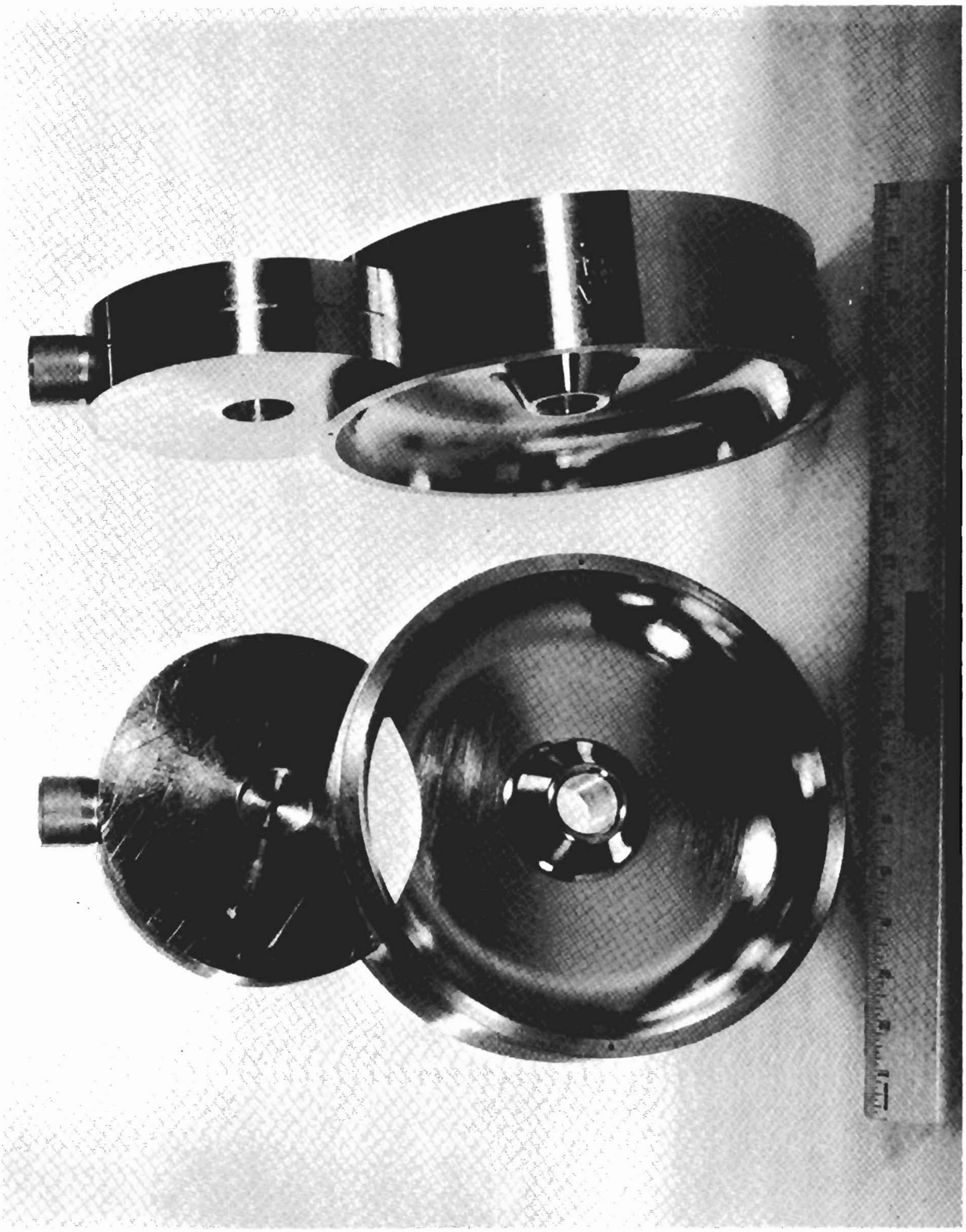

Figure IX - Low β Segment Assemblies

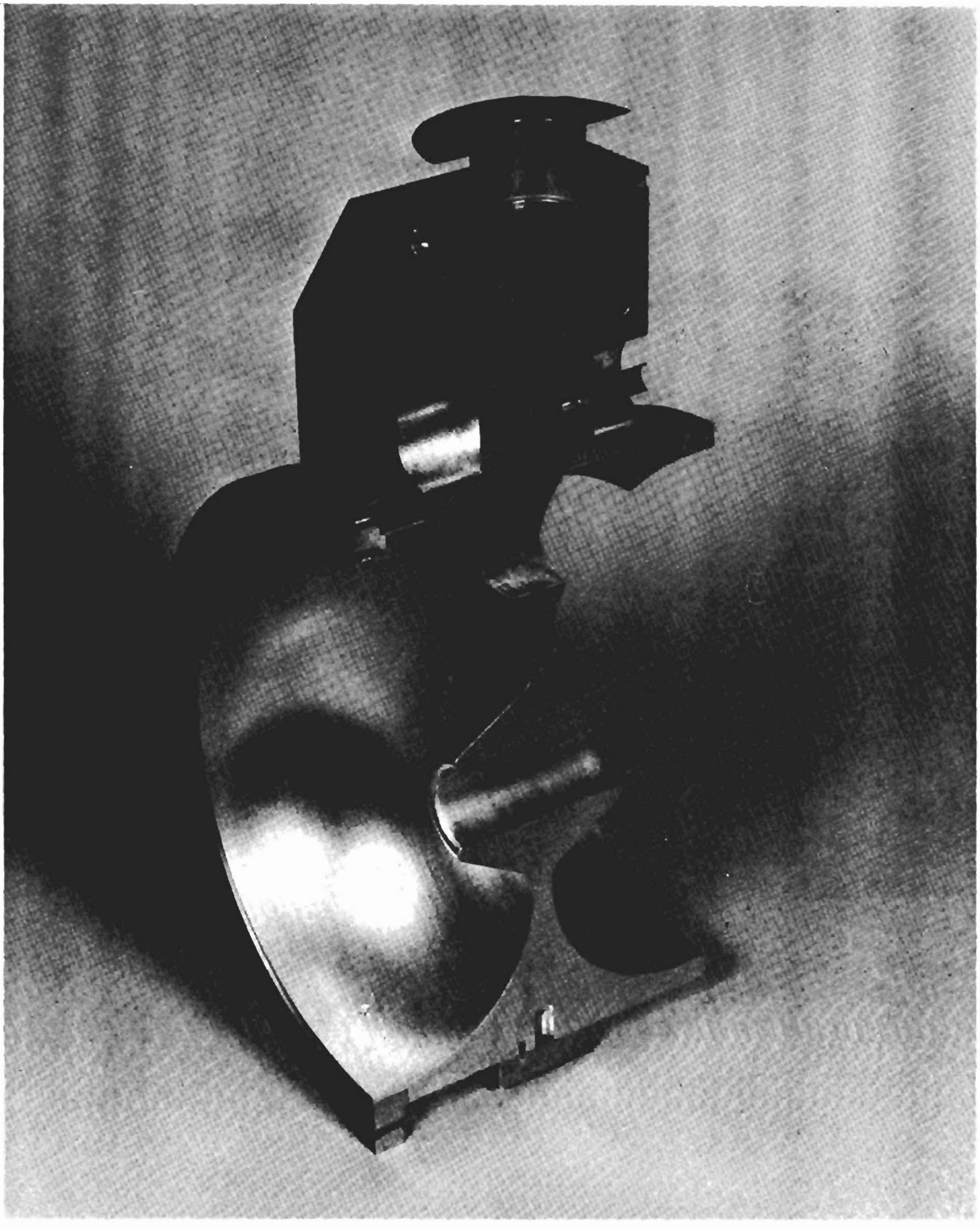

Figure X - Cross Section of Segment Assembly

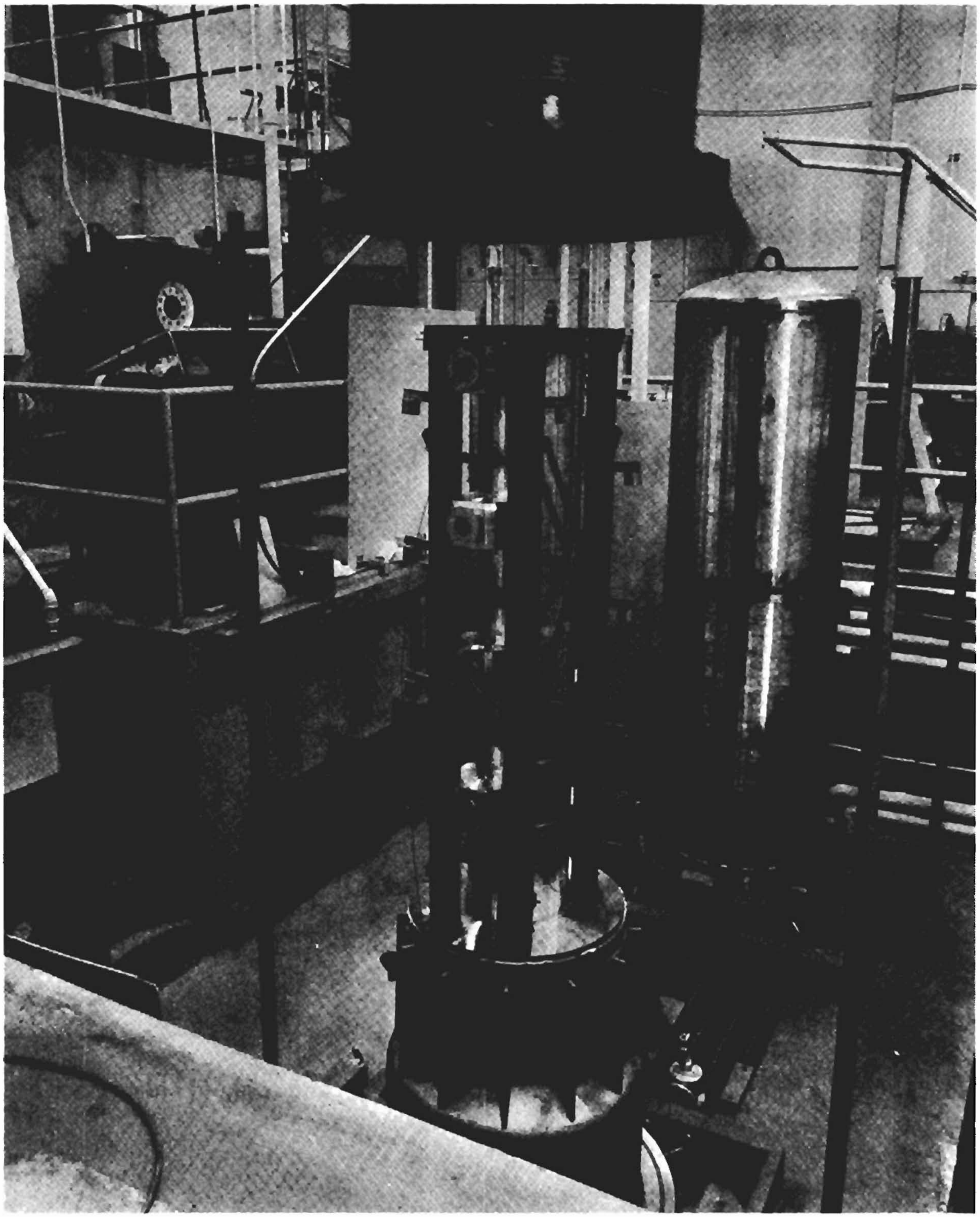

Figure XI - Tank Section in Furnace for Final Heat

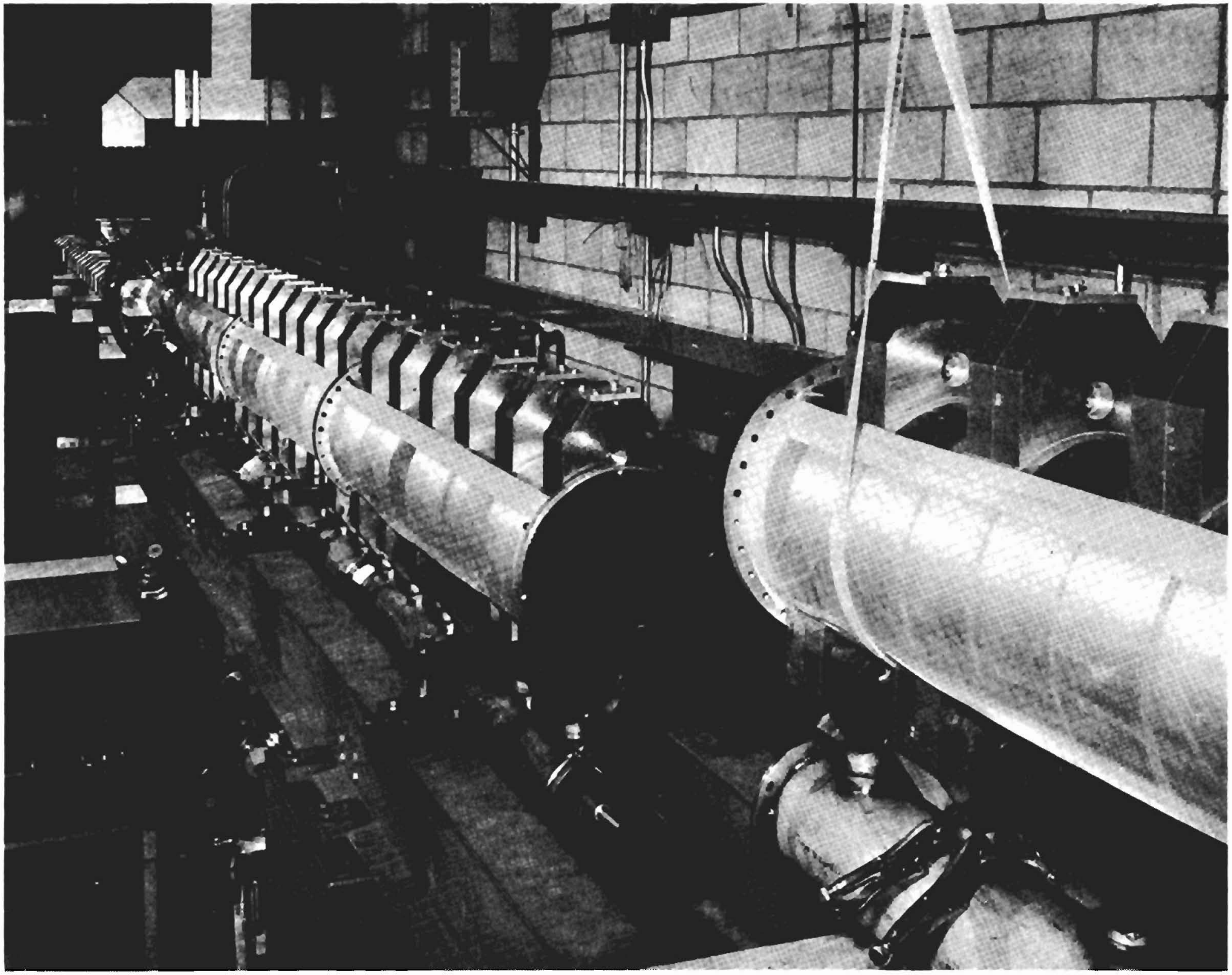

Figure XII - Typical Tank Section Installation

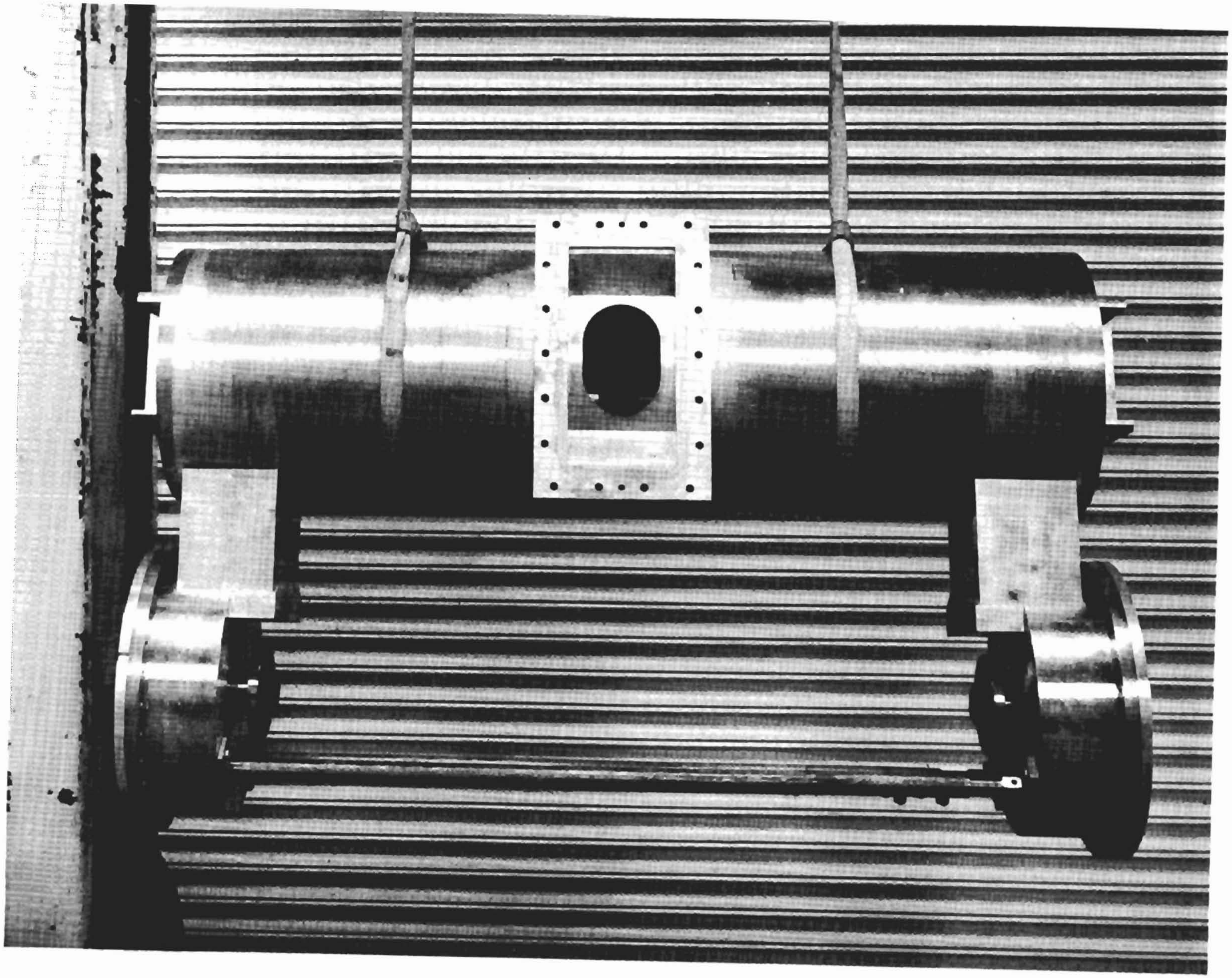

Figure XIII - EPA Bridge Coupler

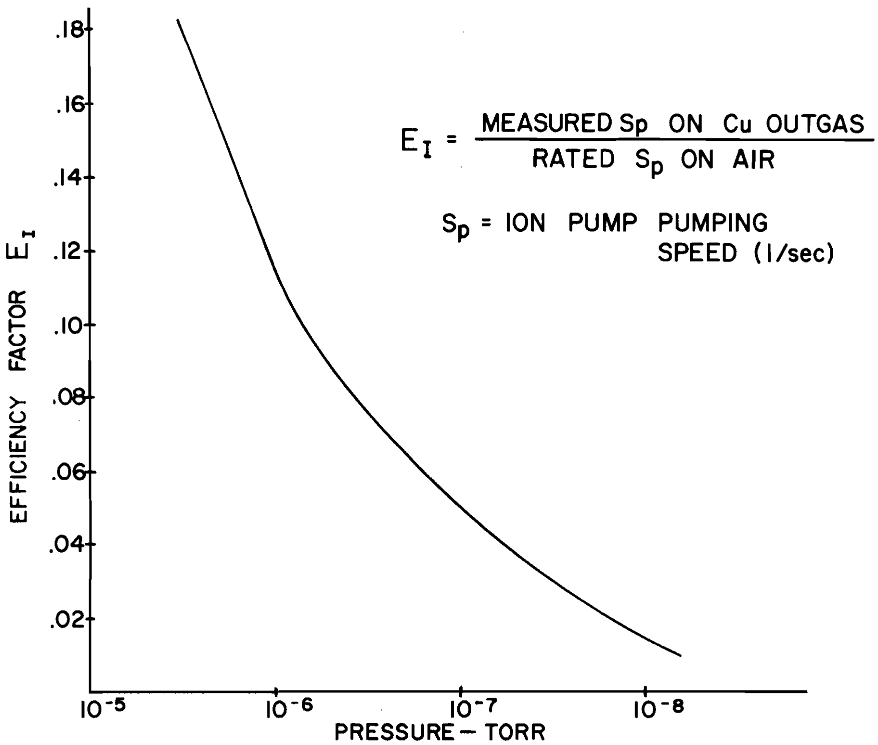

Figure XIV - Ion Pump Efficienty Factor Curve