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APS STORAGE RING VACUUM CHAMBER FABRICATION

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ABSTRACT

The 1104-m circumference Advanced Photon Source Storage Ring Vacuum System is composed of 240 individual sections, which are fabricated from a combination of aluminum extrusions and machined components. The vacuum chambers will have 3800 weld joints, each subject to strict vacuum requirements, as well as a variety of related design criteria. The vacuum criteria and chamber design are reviewed, including a discussion of the weld joint geometries. The critical fabrication process parameters for meeting the design requirements are discussed. The experiences of the prototype chamber fabrication program are presented. Finally, the required facilities preparation for construction activity is briefly described.

INTRODUCTION

The basic Storage Ring lattice is divided into 40 sectors, each of which is composed of six individual sections, totaling 27.6 meters in length. Except for the insertion device, injection and abort chambers, and rf cavity, the vacuum chamber cross section is identical. Each of the sections is unique; however, being different in length and in the accommodation of ancillary components such as magnets, vacuum pumps, crotch and distributed absorbers, and beam diagnostics. Some of these components require direct access to the interior of the vacuum chamber, resulting in the use of several sizes of vacuum flange. With the varied locations of the flanges on the vacuum chamber, there are several intersection weld joint geometries that must be machined and welded to exacting requirements. In total, there are almost 3800 welded joints, each meeting the design requirements imposed by the operating characteristics of the Storage Ring.

The fabrication of the Storage Ring vacuum chambers requires integration of several manufacturing processes, closely related and well controlled in order to meet the quality requirements of the end product. The critical process steps are extruding, machining, cleaning, welding, inspection and leak checking.

EXTRUDING

The vacuum chamber is fabricated from a 6063T5 aluminum extrusion (see Figure 1). Aluminum was chosen for the vacuum chamber because it can be

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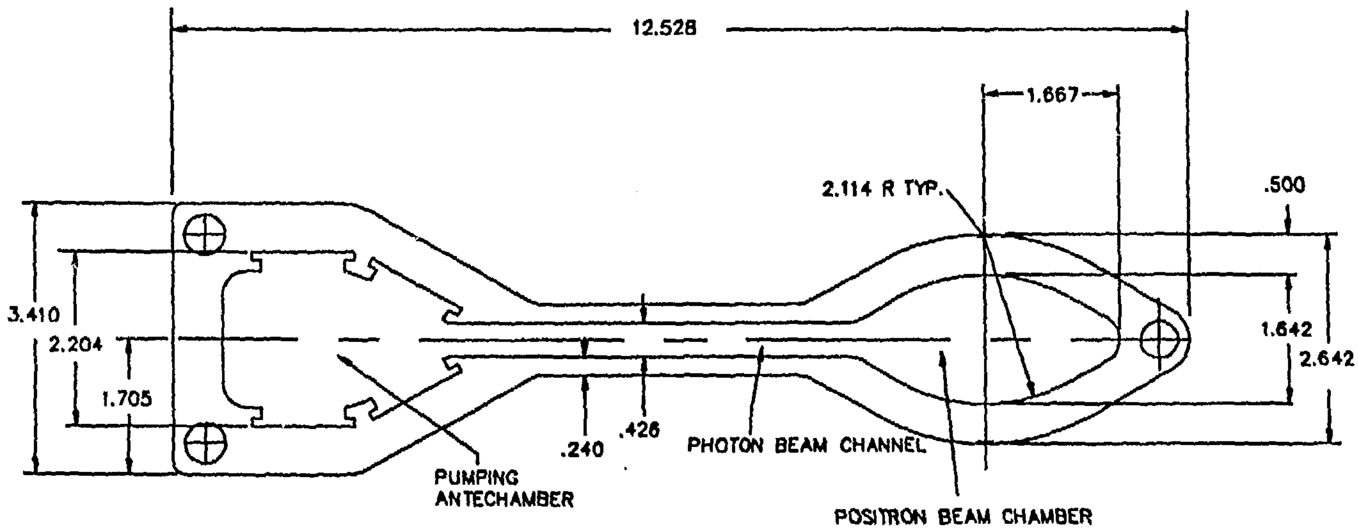
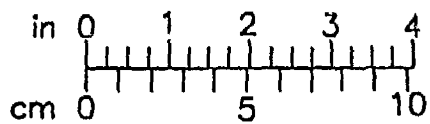


FIGURE 1

STORAGE RING VACUUM CHAMBER EXTRUSION



economically extruded and machined, has good thermal conductivity, low thermal emissivity, low outgassing rate, low residual radioactivity, and is non-magnetic. The 6063 aluminum-silicon-magnesium alloy provides high strength combined with good machining and weldability characteristics.[1] This alloy experiences negligible distortions when subjected to an oven heat treatment to achieve the T5 strength characteristics.

Extruding and heat treatment of 60' lengths is followed by a controlled stretching operation to obtain the straightness required. The stretching also provides for dimensional control of the critical chamber cross section geometry.

The extrusion process provides the interior surface finish needed for the ultrahigh vacuum environment. At 64 micro inches, the only chamber interior surface preparation needed is chemical cleaning and removal of the magnesium oxide and aluminum oxide layers.

FORMING

There are six sections in the Storage Ring lattice, two of which are bent to a 1533.9" radius. The bending must occur after extruding and before machining. This process operation requires precise control, although it can be done using standard shop equipment. The photon beam channel closes up during bending, requiring a subsequent pressurizing of the interior of the extrusion to expand this area to the required dimension. This is accomplished using a high pressure water system.

MACHINING

The machining requirements of the APS Storage Ring can be accommodated using conventional machine tool technology. The vacuum chamber sections have a substantial amount of machining applied in preparation of the weld joints. Ninety-five percent of the machining is milling operations, 62% of which is applied to the extrusions. The remaining is turning work on the vacuum Conflat flanges.[2]

The milling activity consists primarily of CNC (Computer Numerical Control) machining. This is a multi-axis cutting operation needed for the contoured intersections of the Conflat flanges to the vacuum chambers, and for the end flange transitions between the vacuum chamber and the vacuum flanges. The sequence of fabrication for the vacuum chamber sections is unusual in that no machining is done after welding; final dimensions and position accuracies must be maintained during the welding operation.

Given this sequence, and the requirements of the subsequent automatic welding operation, requires that a high degree of precision be obtained during machining. The mating component machining tolerances are in the order to 0.002" to 0.006". Due to the large quantity of components, the pieces must be interchangeable with the same degree of accuracy, i.e., no hand-fitting for proper match-up.

An initial constraint was to perform all machining without the use of cutting tool lubricants or coolants. This was thought to be necessary in order to preserve the vacuum qualities of the extrusion interior surfaces. The disadvantages of this approach were reduced cutting speeds and feed rates, rapid tool wear, and lack of proper cutting chip removal necessitating extra care during cleaning. Subsequent studies conducted at Argonne National Laboratory (ANL) and at the University of Texas have concluded that there is little variation in the surface and near surface composition after cleaning between control samples which were dry machined vs those which were machined with water soluble coolants.[3] Future machining operations will therefore allow the use of tool coolant, eliminating the disadvantages previously encountered.

CLEANING

A cleaning step is performed after machining, and just prior to welding. The purpose is to remove all residue of the machining and handling operations, to remove and control the oxide layers resident on the vacuum chamber surfaces, and to prepare the machined surfaces for welding.[1]

Two cleaning stations are required. One is for the 6063 extrusions, the other for the 2219 aluminum flanges and ancillary components.

The degreasers and etchants used are contained within stainless steel tanks. These welded assemblies have circulating pumps and heaters to maintain a constant 65°C temperature, as required. An overhead gantry crane is used to rapidly transfer the extrusion from tank to tank. After final rinse and blow drying, the extrusion is lowered onto a manual material handling cradle for transfer into the welding cell.

The use of ultrasonics is being considered for the extrusion cleaning process. The ultrasonic transducers are placed directly into the cleaning tank, and are activated during the degreasing cycle. Studies have shown that this addition speeds up the cleaning process, and provides a surface that is cosmetically improved over the standard procedure.

WELDING

The performance requirements of the Storage Ring place severe demands on the welds that are necessary to fabricate a chamber assembly. The quantity of ultra-high vacuum welds, and the contoured geometry, requires a process that is repeatable and highly reliable. Aluminum joining is commonly done with TIG (Tungsten Inert Gas) welding; in this application, TIG is combined with the machine tool precision of a standard rectilinear motion robotic welding system. The choice of a well known process applied by a standard machine limits the risk, and reduces the development effort to establishing the weld joint designs, materials selection, tooling, and weld schedule programming. A DC welding power supply was chosen in order to obtain narrow, deep weld cross sections.

The individual welds to be applied to each vacuum chamber section were classified and grouped into six (6) types, Type "A" through Type "F".[4]

This broad classification grouped similar weld joints by the type of joint geometry needed to effect acceptable results. Table I lists the application by type.

Table I Classification of Weld Joints

Type A	End Flange to Vacuum Chamber Extrusion
Type B	6" and 8" Conflat to End Flange
	2 3/4", 4 1/2", and 6" Conflat to Vacuum Chamber Extrusion
Type C	Elliptical Beam Tube to End Flange
Type D	8" Conflat to Vacuum Chamber Extrusion
	12" Conflat to Vacuum Chamber Extrusion
Type E	Photon Beam Port to Vacuum Chamber Extrusion
Type F	Blank Conflat to Elliptical Beam Tube Mini-Conflat to Blank Flange

All of these welds are to be applied using automatic welding equipment. One additional joint to be hand welded was the water tube extensions from the extrusion water passages. Designs to improve this joint and weld automatically are underway.

Given the requirements of UHV vacuum integrity, low rf impedance, and the 150°C chamber bakeout procedure, a set of criteria for weld joint design was established:

- Cracks, incomplete fusion, and cold laps are unacceptable.
- Porosity, inclusions, undercut, craters, and any imperfections that have sharp terminations, are unacceptable.
- Small scattered porosity within the scope allowed by MIL-STD-2219 for Class A welds would be considered acceptable.

The Type A, C, D, and E welds utilized an automatic system having axis motions in x, y, z, and rotary. These motions were programmed as required to accommodate the geometry being welded. The robotic end effector, or weld package, was changed as required. Type B and F welds also used an automatic system, which was an orbital weld head limited to rotary motion with a self contained wire feed mechanism.

Programming of the machine axis motions is a small part of the effort needed to arrive at a suitable welding schedule. The important parameters are arc voltage, current, wire feed speed, and axis velocity. Beginning with set values from experience, the final parameters are arrived at by laboratory weld trials. These are then integrated into the motion program.

The early laboratory trials are directed at simulated weld joints, using the selected materials. For the APS Storage Ring, a thorough weld development program was undertaken, including the development necessary to machine full size extrusions to the exacting tolerances needed for acceptable weld results.

TYPE A WELD JOINT

The end flange to vacuum chamber extrusion weld requires that a portion of the weld joint wrap around the positron beam. Excessive weld underbead in the beam chamber area would increase RF impedance, causing losses. The requirement for this weld was full penetration with an underbead reinforcement not exceeding 0.020" around the beam chamber and into a portion of the photon beam channel.

Critical to this development effort was the selection of material for the end flange. The 6000 series aluminum welds are crack sensitive. 4043 aluminum was attempted, but failed to produce an acceptable surface finish for the UHV environment when machined. The flange material was changed to 2219-T851, requiring the need for filler wire of 4043 aluminum to prevent solidification cracking.

The cross section wall thickness of the extrusion varies, (see Figure 2). This is extremely difficult for the welding process, given the performance requirements of the Storage Ring. Local machining of the extrusion ends to create a butt joint and a weld path geometry suitable for continuous welding from the outer surface was necessary. The geometry was also designed to facilitate the x, y, and r contouring axis of the automatic welding system. The pivot point for the rotary, or r axis, is within the elliptical positron beam port. This locus was chosen to maximize the dynamic accuracy of the velocity along the path, the z-axis position of the tungsten electrode, and the torch attitude with respect to the joint surface in the region where underbead control was essential. The three-axis contouring program arrived at provides constant relative vector velocity between the tip of the torch tungsten electrode and the outer surface of the joint path. It also maintains the axis of the tungsten perpendicular to the joint surface and its distance from that surface constant.

Figure 3 shows the 2219 machined joint relative to the 6063 extrusion machined joint. This design provides a 1/4" ligament of constant thickness on each side of the joint interface which serves to reduce the effect on the weld of the dramatic changes in adjacent extrusion mass. The tongue and groove, when

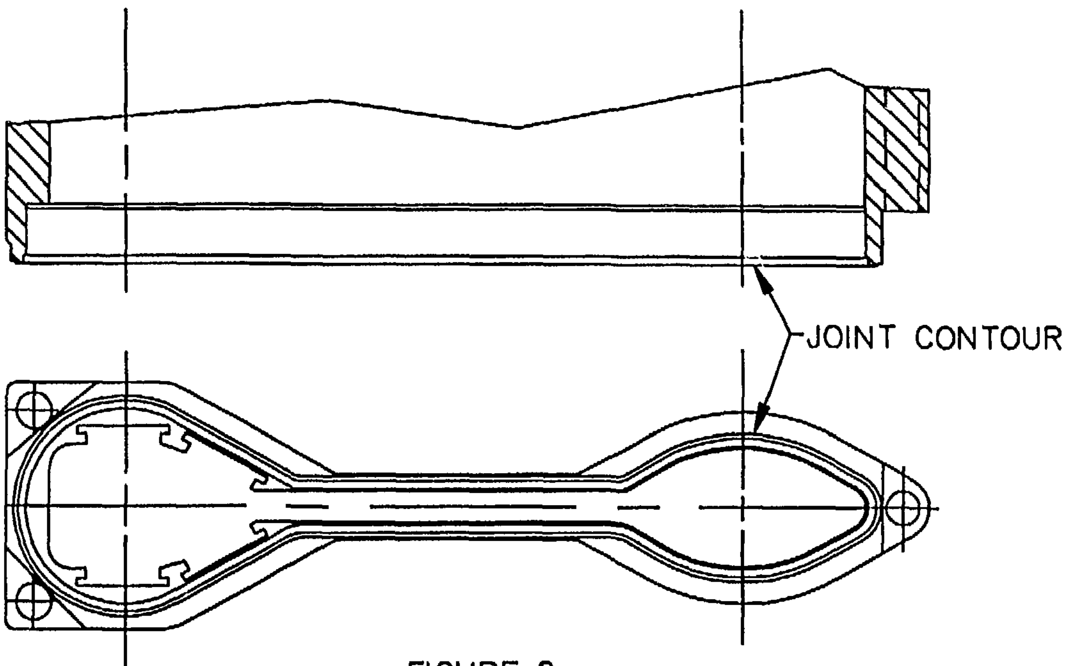
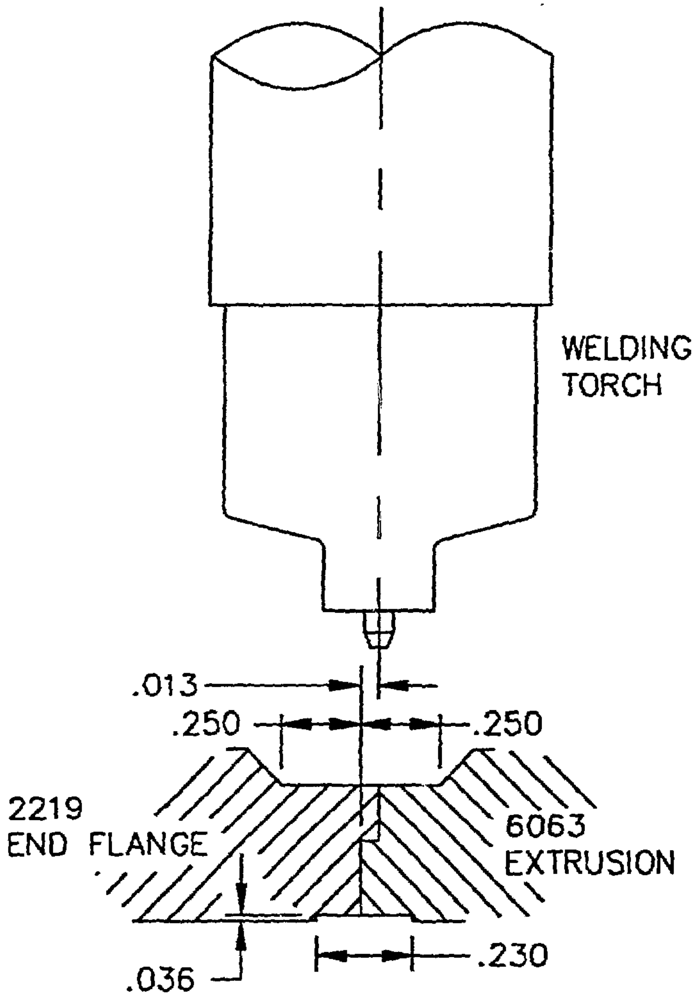


FIGURE 2

CONTOUR OF JOINT MACHINED INTO EACH END OF A STORAGE RING VACUUM CHAMBER SECTION



NO SCALE

FIGURE 3

CORRECT LOCATION OF TUNGSTEN ELECTRODE FOR WELDING TYPE "A" JOINT engaged, insures that the half of the contoured joint machined into the end flange is accurately aligned with the mirror image joint machined into the extrusion. The 0.036" deep by 0.230" wide groove on the vacuum side of the butt joint allows an underbead as much as 0.036" to be acceptable from a functional standpoint. The walls of the groove as positioned on both sides of the underbead are very effective heat sinks that inhibit growth of underbead height.

Due to the difference in thermal conductivity between the 6063 and 2219 alloys, the tungsten must be incremented 0.013" toward the 6063 extrusion for the underbead to be centered in the groove. The acceptable position tolerance about this offset is +/- 0.0025".

TYPE B WELD JOINT

The Type B joint accommodated all vacuum Conflat welds not requiring a contoured weld path. They are circular welds, in the same plane. A generalized joint design utilizing fillet welds was initially selected. This approach promised minimum costs for weld joint machining preparation, while also requiring the minimum space.

After an intensive effort, and examination of dozens of cross sections of Conflat fillet welds, it was found to be difficult to obtain defect-free welds. The results of this joint design are weld root defects and porosity which could not be eliminated without edge melting of the Conflat flange. This constitutes an unacceptable condition for vacuum integrity when considering the possibility of fatigue cracking as a result of strains imposed on the vacuum chamber by the 150°C baking cycles.

The fillet weld design provided no convenient means of inspection. Given the quantity of Conflats to be welded on the entire Storage Ring, this presented a dilemma for construction. Vacuum integrity could not be verified immediately after the welding operation. The fillet weld approach was concluded to be unacceptable.

The Type B joint has been redesigned as a butt weld. It remains as a circular weld in a single plane, and will allow visual inspection of the underbead as quality verification measure. This approach will also alleviate the concerns of fatigue cracking after repeated bake cycles.

TYPE C WELD JOINT

An elliptical beam tube is welded to the upstream flange of Section 1 and to the downstream flange of Section 5. The beam tube in cross section is an ellipse, retaining the geometry of the positron beam chamber through the opening in the end flange except that it is a closed section. It terminates in a blank Conflat, continuing the elliptical cross section through the thickness of the Conflat.

Two welds are required; one is the Type C, joining the tube to a mating stub machined on the end flange; the other is the Type F. These welds are only 5" apart, so that any distortion of the elliptical tube caused when making one weld will affect the joint fit up for the second weld. A procedure was devised that requires tooling both weld joints before either weld is made.

The requirements for UHV and underbead control are the same as for the Type A joint. Therefore, a geometry similar to that for Type A was chosen for Type C. 2219-T851 was selected as the material for the beam tube. The axis of the tungsten electrode is positioned directly on the joint interface, with no offset. The weld torch was programmed to follow the elliptical path at a constant vector velocity relative to the outer surface of the joint, and with a constant distance above that surface. This is a three-axis (x, z, r) contoured weld.

By using the Type A joint design, the process development task was limited to establishing a program for varying the welding current as a function of distance along the joint path.

TYPE D WELD JOINT

The 8" Conflats are welded to Sections 3 and 5; the 12" Conflats are welded to Sections 2 and 4. They are welded back-to-back, that is, opposite each other on the same vertical axis (see Figure 4).

The function of these openings is to allow mounting of a distributed absorber (8") or a crotch absorber (12") for intercepting non-experimental synchrotron photon radiation, and ion and NeG pumps to provide local control of desorbed gases. The intersection of the Conflat tube with the extrusion is not in a plane due to the geometry of the extrusion. Hence the need for CNC machining preparation of the weld joint interfaces, and subsequent contour welding.

After experiencing difficulty with the fillet welds on the small conflat joints, it was decided to design a square butt joint for the 8" and 12" Conflats. This design allows the added advantages of providing a full penetration weld, and after-weld visibility of both sides of the joint as a QC measure. The only weld defect to be guarded against is porosity, which can be controlled by careful welding procedures. The full penetration weld provides strength to the interface, as these Conflats are more heavily loaded than the others due to the large vacuum pumps mounted to them.

A physical constraint imposed upon these welds is maintaining parallelism of the Conflat mounting surfaces. This is a problem that must be addressed in machining and welding. The opposing Conflat interfaces to the extrusion are a mirror image, while the vertical projection of the interface forms a plane. These two planes must be machined parallel to the centerline of the extrusion as well as to each other. The maximum gap that can be tolerated by the automatic welding process is 0.005" for this weld, placing demands on the CNC programming and machining for both the extrusion and the Conflats.

In machining to these exacting requirements, control of the photon beam channel dimension of 0.426" required a certain sensitivity. After boring the large

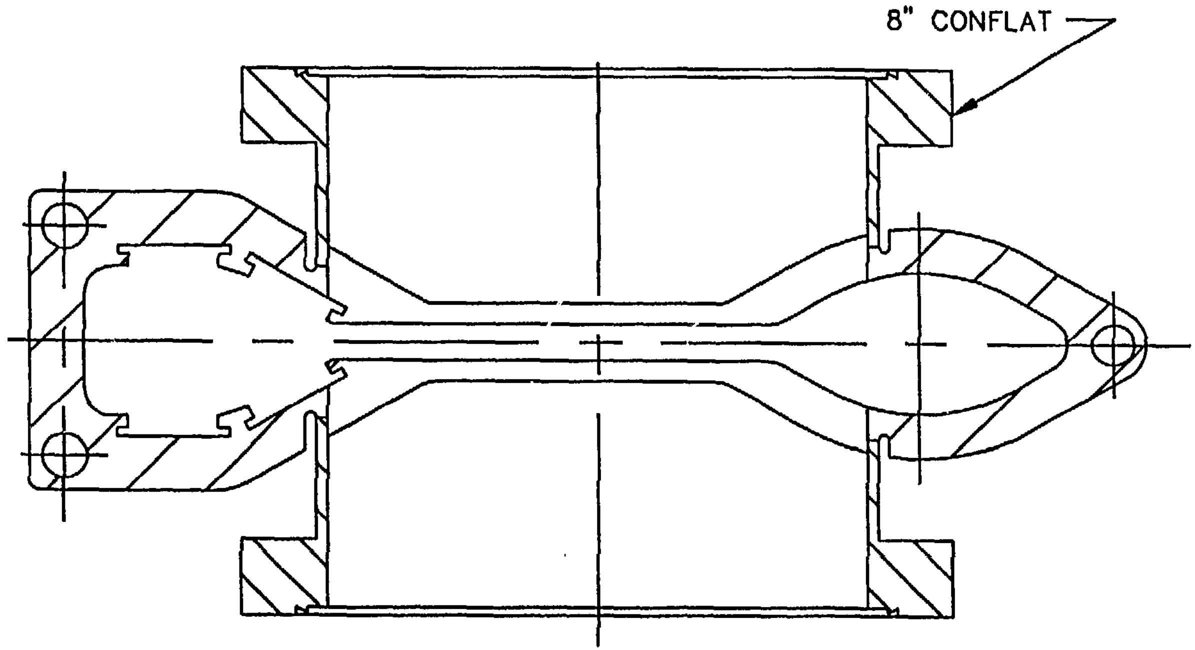
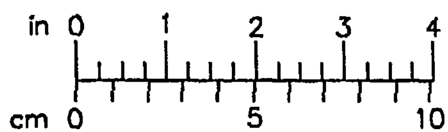


FIGURE 4

STORAGE RING 8" CONFLAT TO EXTRUSION



hole in the extrusion equal to the Conflat inside diameter, the vertical dimension of the photon beam channel decreased.

After initial weld trials, the dimension was found to decrease by 0.017" on the average. The tooling designed for welding restrains the Conflats from translation or rotation, and utilizes four die springs arranged to apply an adjustable clamping force. The compressive load applied by the springs through the opposing Conflats was locally deflecting inward the walls of the extrusion. This, in combination with the high welding temperatures and the thermo-physical properties of the dissimilar alloys being joined, caused the plastic deformation in the photon beam channel region of the extrusion.

The solution to this problem was found in the use of an adjustable interior support tool. Made of stainless steel, the tool sizes the photon channel, expanding the gap slightly prior to welding while maintaining Conflat flange surface parallelism. The low thermal conductivity of the stainless steel, with the programming ability for arc current control, ultimately provided a full penetration weld with a uniform underbead for the complete 360 degree 8" Conflat weld. The development efforts, and final implemented solutions, were similar for the 8" and 12" Conflats.

TYPE E WELD JOINT

A photon beam exit port is provided on each of the Sections 3 and 5, allowing the extracted photon beam to enter the experimental facilities. The interior surface of the beam port to extrusion interface is not accessible to the welding torch or tooling. The inner surface contains the underbead, which is in contact with the vacuum environment. There are no requirements for precise underbead height control in this area, but discontinuities that would result in a virtual leak are unacceptable.

Borrowing again from the favorable experience of the Type A joint, a square butt joint geometry providing for alignment of the interior surfaces without the use of back-up tooling, and a balancing of the material mass to compensate for the difference in thermal conductivity between the 6063 extrusion and the 2219 beam port, was successfully arrived at.

The resultant design requires that the torch be tilted at a slight angle from perpendicular to the joint (see Figure 5). Indexing the torch axis toward the base metal of highest thermal conductivity (the 6063 material) also requires the use of a special shielding gas nozzle developed specifically for the Type E joint.

TYPE F WELD JOINT

This joint application is for the elliptical beam tube to blank Conflat at the upstream end of Section 1 and at the downstream end of Section 5, and for the mini-Conflat to blank Conflat for NeG strip electrical feedthrus. Both welds were

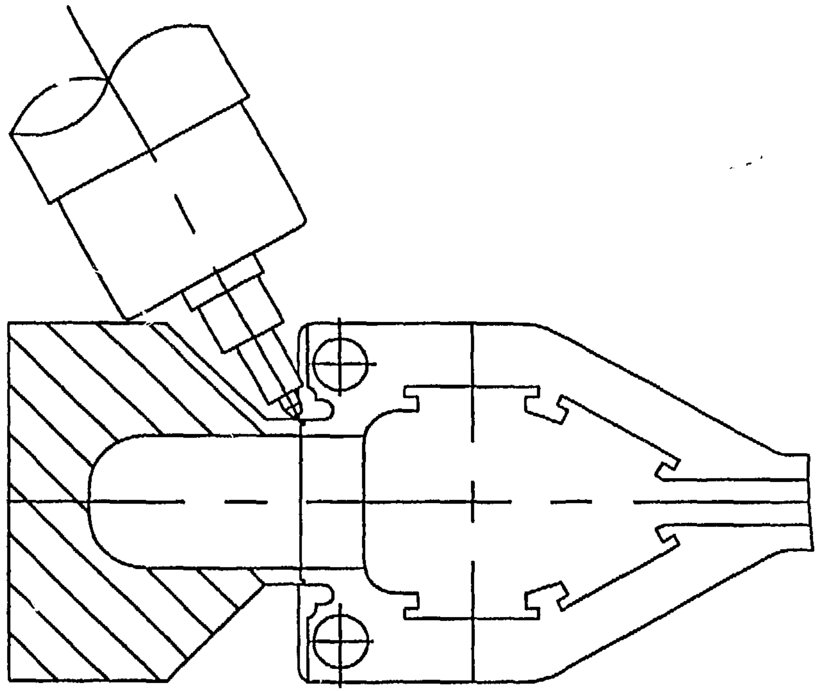
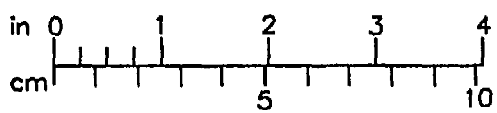


FIGURE 5

PHOTON BEAM EXIT PORT TO STORAGE RING EXTRUSION



designed to be autogenous partial penetration edge butt welds. Suitable procedures were developed to give satisfactory results with a minimum of effort. It was necessary however, to provide a means of venting trapped air from the beam tube to Conflat weld to prevent porosity problems encountered with the initial weld trails.

INSPECTION AND TESTING

Each Storage Ring vacuum chamber section will be inspected for conformance to the drawing dimensions. Conventional inspection equipment and techniques will be used to provide a quality control checkpoint on the set-up and use of the welding fixtures. Vacuum integrity of the welding operation will be verified by leak testing

The vacuum chambers will be assembled individually with all pumping components and valves normally associated with that chamber. An ion gauge and RGA head will also be fitted. A turbopump is used to check for weld leaks at $10E^{-6}$ Torr, after which the bakeout water will bring the chamber to 150°C until the pressure has stabilized (~ 24-36 hours). The NeG strip is activated after the ion pump is flashed and all filaments are outgassed. The chamber is then allowed to cool. The RGA scan is monitored, and the ultimate pressure recorded. This UHV check will also test commercial vacuum components. The chambers are finally vented with dry nitrogen, removed from the test stand, and prepared for a brief storage period.

PROTOTYPE CHAMBER FABRICATION

The developmental work in extruding, machining, cleaning, and welding has been applied to the fabrication of five vacuum chamber sections, using the processes and procedures derived from trials in each of these primary fabrication areas. Substantial data has evolved in support of the final process procedures, and improvements have been identified to provide further efficiency to the construction tasks.

Significant effort has gone into the design and build of special tooling and heat sinks for the welding operations. The automatic welding system consists of a head and tailstock assembly used with the orthagonal axis motions. Closed loop servo-control is provided for the headstock; the tailstock is mounted on an adjustable slide to accommodate the various lengths of vacuum chambers. Precision tooling is provided as necessary to register weld joint components. An invaluable aid during welding development was a closed circuit TV camera system directed at the end of the wire feed guide tube and the adjacent tungsten electrode. This allowed set-up and adjustment parameters to be established for the wire feed system until the filler wire was reliably fed into the leading edge of the weld pool over the complete path of the Type A joint, for example. Of the five sections that have been fabricated, Sections 1 and 2 have been evaluated for dimensional stability, and Sections 1, 2, 4, and 5 have been evaluated for vacuum performance.

CHAMBER STABILITY DURING BAKEOUT CYCLING

Sections 1 and 2 were mounted to a concrete floor using supports designed for the final installation. They were joined by a connecting bellows. Chamber motion was measured by a combination of optical survey targets and dial indicators. Various locations were targeted for inspection. Several bakeout test cycles were performed between room temperature and 150°C, and back to room temperature. The purpose of the test procedure was to determine if the chamber sections returned to their original position after experiencing bakeout cycling. The section assembly was subjected to 25 bake-cool cycles. The initial tests resulted in a modification to the chamber supports to prevent a loose condition found in the mounting hardware. Most measured variations in the "X" or radial direction were within + or - 0.003", measurements along "Z", in the direction of the positron beam, and "Y" vertical, were within 0.002".

CHAMBER DEFLECTION DURING VACUUM CYCLING

Targets were placed on the outside of the positron beam chamber, and on the photon beam channel area of the extrusion. The beam chamber height deflection averaged approximately 0.010", depending on location. The beam chamber returned to its original location to within + or - .0015". The photon beam channel returned to within 0.001" at three measured locations, after the first two cycles. Deflection of the beam channel under vacuum at the dipole and sextupole areas was 0.027", and 0.021" at the end quadrupole magnet location.[5]

CHAMBER VACUUM EVALUATIONS

Four of the five prototype vacuum chamber sections have been evaluated. Three sections, identified as S1, S2, and S4, were leak tight; Sections S3 and S5 leaked in the 6" Conflat fillet weld area of the end flange assembly. Both leaks have been repaired, and evaluations on S3 and S5 are continuing.

Individual vacuum tests have been completed on S1 and S4. Each chamber was configured with the pumps and instrumentation as designed for use in the Storage Ring. S1 was assembled with two 30 l/s ion pumps, ST 707 NeG strips, and a nude ion gauge. S4 was assembled with a 220 l/s ion pump, NeG strips, and an ion gauge. Additionally, a quadrupole mass spectrometer (QMS) was added for diagnostic purposes.

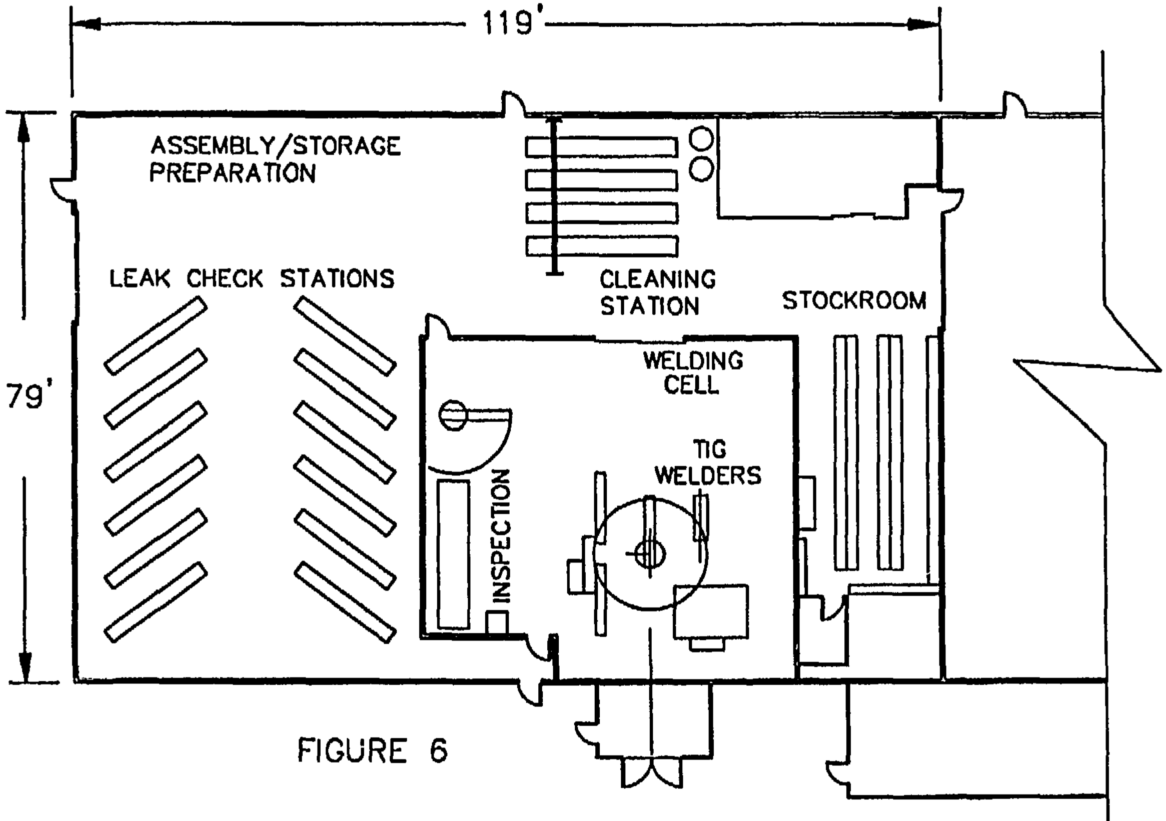


FIGURE 6

STORAGE RING VACUUM CHAMBER FABRICATION FACILITY

The chambers were roughed out with a 360 l/s turbo pump, while baking at 150°C with heat tapes. The pressure stabilized after 25 to 36 hours, at which point the instrumentation was outgassed before cooldown commenced.

The ultimate pressure for S1 was $4E^{-11}$ Torr; S4 ultimate pressure was $3E^{-11}$ Torr. The pressure of S4 was confirmed by use of an extractor gauge. After bakeout, the QMS indicated a water peak almost as large as the carbon monoxide peak. This could be the result of a relaxation of the flange to gasket seal, which was observed during cooldown, just prior to reaching room temperature. The Storage Ring vacuum Conflat bolt holes are threaded; this design has presented additional sealing problems, which are currently under consideration.[6]

FABRICATION FACILITY

An area of approximately 9600 square feet is being prepared to clean, weld, assemble, and test the approximately 240 vacuum chamber sections which will be installed in the Storage Ring (see Figure 6). The inter-dependance of these primary process steps, with the attendant quality control requirements, is best managed under one roof. The area is assigned according to functional process operations.

Of utmost importance is facility cleanliness and humidity control. The interior has been thoroughly cleaned and painted, including sealing of the concrete floor. Electrical and water service is being installed for each station, as required. The welding cell will be enclosed and air conditioned, and provides for local weld fume removal from each of two automatic welding systems.

The vacuum chamber assembly and leak check stations will also be provided with local air conditioned environments. Movement into and out of the fabrication area of materials and personnel will be routed through an adjoining wall to another area, thus providing a form of air lock to the outside. Material handling will be accomplished with a combination of gantry cranes, floor mounted jib cranes, and specialized material handling carts.

Two small component stores areas are located within the building, one, a controlled access area for tools, gauges, and instruments. A mobile office is adjacent to the building, providing a location for a Production Management Center, building construction personnel, technical documents, and a master drawing set.

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