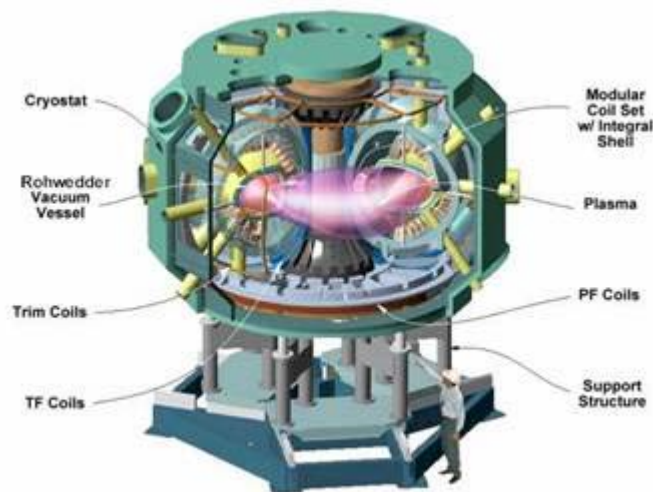


Princeton University Plasma Physics Laboratory

National Compact Stellarator Experiment (NCSX)

**Vacuum Vessel Manufacturing Development and Prototype
Fabrication**



3.1.1 Manufacturing Methods for Fabricating the VVSA

In Reference to Section 3.1.1 of NCSX-SOW-121-01-01

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1.0 CAD/CAM

Rohwedder/NVSI will take a full CAD/CAM approach in the engineering, fabrication and inspection of the VVSA, using Pro/E software throughout the manufacturing process. The first step will be to decide on the proper segmentation of the vessel and to create the segments inside the Pro/E models created by PPPL. It is initially anticipated that the segmentation already developed by PPPL will be used unless further investigation by Rohwedder/NVSI determines a more efficient segmentation philosophy. Since Rohwedder/NVSI plans to create the contours of the vessel segments through a forming process, computer models of the necessary die assemblies will then be created matching the profile of the chosen vessel segments. Pro/E Prismatic Milling Software (a CAM package) will be utilized in setting tooling paths, speeds and feeds, and finally to create machine code to control the CNC milling stations that will be used in final machining of the die plates and the vessel segments. The computer modeling and machining of the segment end flanges, port flanges and support hangers as well as the fitting of the port extensions to the contour of the vessel, will be handled in a similar fashion. Throughout the manufacturing process, several inspection points will be inserted for measurement and verification of dimensional tolerances. Data taken from a Coordinate Measurement Machine (CMM) and/or other devices will be compared either to the original Pro/E models or IGES conversions of these models for verification of compliance to PPPL specified tolerances. Using the original file format of the VVSA models (Pro/E) in conjunction with full Computer Aided Manufacturing of the components and assemblies is the most efficient way to complete the manufacture of such complex geometry, while assuring the most dimensionally accurate end product.

2.0 FORMING METHODS

2.1 Forming of Segments

Rohwedder/NVSI will use a series of step dies in forming the various segments of the VVSA. It is anticipated that six (6) step dies sets (male/female) will be needed to form the segments that constitute the repeated 60° geometry. The selected segmentation of the vessel will be based on balancing a desire to minimize the number of dies to reduce costs and fabrication time with creating die geometries that minimize distortion and avoid material entrapment. It is

also beneficial to reduce the number welds both to decrease the number of set-up and alignment operations necessary and to reduce heat distortion induced by the welding process. As mentioned above, it is initially anticipated that the segmentation already developed by PPPL will be used unless further investigation by Rohwedder/NVSI determines a more efficient segmentation philosophy.

Prior to manufacturing the production die sets, Rohwedder/NVSI will manufacture a prototype die set for a single segment. The test die will be used to qualify our proposed manufacturing and inspection procedures and techniques, material properties and material “spring back” rates, and general tolerance requirements for material pre-cutting and developed length analysis. The step dies will consist of individual carbon steel rib plates aligned in a die enclosure with a ¼” stainless steel or Inconel “scab” plate covering the press surface to eliminate any contamination potential. The plate will be formed to the contour of the rib edges in the die itself and secured using plug welds at points coincident with the edge surface of the underlying rib plates. The individual ribs will be made of ¾” to 1” thick plates set 2” apart along the length of the rib enclosure. The rib and enclosure plates will first be rough cut on a water jet cutting machine, then using Pro-E Prismatic software, a machine code program will be created for 3-axis milling machines to final machine the overall size of the rib and the complex, contoured edge of the rib that will be used to form the Inconel material. The enclosure will be designed using tight tolerances and “key lock” control on the ribs. After the ribs are welded in place in the die enclosure, the enclosure will be filled with concrete approximately two-thirds the height to the lowest point of the die for increased strength. After the concrete is set and the final contour of the die plates has been determined, the scab plate will be added. Currently, alterations to the die set design philosophy are being considered to reduce the difficulty in making additions/modifications to the dies and to allow heat treating the segments while still in the dies. This is discussed in more detail in *3.1.2 Subcontractor Recommendations, Section 3.0 Reusable Die Sets*. When the enclosure is complete, the locking key slot will be machined to match the forming vendor’s press machinery. After the segment plates are cut oversized on a water jet machine, they will be placed in the dies and formed using a hydrostatic press.

2.2 Forming of Port Extensions

For some of the vessel ports, it will be necessary to perform simple forming operations. Circular cross sectioned port extensions will be made of purchased seamless tubing. For port extensions with non-circular cross sections, the tubes will be made up of segments that can be created on standard bending equipment, which will then be welded together before machining the extensions to length. During the fabrication of the port extensions, reference points will be added that will aid in the cutting of the extensions to the contour of the vessel and will aid in aligning the ports correctly for fixturing and welding.

2.3 Forming Inspection & QA

Inspection and Quality Assurance for forming of the NCSX will focus on maintaining dimensional tolerances, surface cleanliness and low magnetic permeability. The overall inspection/test plan and quality assurance plan will be within the ISO9001/2000 certified quality manual, the ASME certified quality manual, and the PPPL quality requirements as outlined in NCSX-SOW-121-01-00 and NCSX-CSPEC-121-02-00.

2.3.1 Dimensional Inspection & QA

To maintain dimensional tolerances throughout the manufacturing of the VVSA, physical reference points located on the vessel segments and support hardware to perform verification of tolerance compliance to the original Pro/E models of the segments and die plates. First, reference points will be placed on the precision dies which will be machined and dimensionally verified with a portable CMM against the original Pro/E models of the dies. These points will be in the form of tooling balls, small indentations or precision machined surfaces. These points will then, in turn, be referenced in placing reference points on each segment during or immediately after they are formed. The physical reference points will aid in the machine set-up and dimensional verification for final machining of vessel segments and later for weld fit-up of the segments, port extensions, end flanges and support hangers. Since the reference points will exist in both the model and on the part, it will be possible to align the model of the part with the actual part in the CMM software so that actual location can be compared to nominal when checking tolerances along the dimensional test grid specified in Section 4.2.4 of NCSX-CSPEC-121-02-00.

In order to reduce distortion of the segments due to the high stresses induced into the material when forming the complex shapes with high-tonnage presses, each segment will be stress relieved after it is formed (See *Section 5 Heat Treatment*).

2.3.2 Surface Cleanliness/Magnetic Permeability Inspection & QA

In order to maintain surface cleanliness as well as low magnetic permeability, the press breaks used in the forming process will be thoroughly cleaned per 3.3.2.4 of NCSX-CSPEC-121-02-00 and segregated in an area allowing for separate material receipt and proper material handling/storage for the materials used in the project. The cleaning and forming will only be done when there is a qualified inspector present. If it is determined that the forming must be done during “off hours” to further limit contamination from stray carbon particles, the process will proceed accordingly. Covering the die sets with stainless steel or Inconel “scab plates” will help eliminate any contamination potential from the die ribs themselves.

3.0 MACHINING AND FINISHING

3.1 Machining of Segments

After the vessel segments are formed in the step-dies and stress relieved to reduce distortion, it will be necessary to machine them to final shape for fixturing and welding since the segment plates will be initially cut oversized. The reference points (tooling balls, indentations or precision machined surfaces) that were mentioned in *Section 2 Forming Methods* will be located on each segment using CMM referencing points on the precision machined dies. The reference points will be used to fit the part computer models to the oversized segments. Once aligned, the CMM can find the correct edge locations on the surface of the segments, which will be marked for cutting. The segment edges will then be machined on a milling center and ground, as necessary, during weld fit up to ensure an edge contact between segments to ensure a quality weld seam.

3.2 Fixtures

Stainless steel “cage” type fixtures will be developed and designed to completely capture the VVSA sections after fabrication to allow accurate positioning of the vessel for aligning,

welding and machining of the port extensions and when boring out each individual port diameter/shape in the VVSA sections after the ports are cut off. The cage fixtures will be fabricated using stainless steel angle and I-beam stock. The fixtures will be machined after fabrication to provide for precise positioning locations when inserting the fabricated VVSA sections and for precise positioning locations on the machining centers. The position locations will allow for controlled, consistent movement of the VVSA section so that it can be positioned at angles, horizontally, vertically, and flipped in any orientation without losing the control needed to handle the chamber and provide for repeatable results throughout the length and diameter of the chamber. The cage fixtures will be designed to allow unblocked CMM access to all reference points. To aid PPPL in the alignment and re-weld of the port extensions at Princeton, it would be beneficial to have the ability to use the Rohwedder/NVSI cage fixtures. Due to the potential interference of the modular coil units and coil support structure, close cooperation would be required between Rohwedder/NVSI and PPPL to assess the feasibility of designing cage fixtures with this dual functionality. This is addressed in more detail in *3.1.2 Subcontractor Recommendations, Section 4.0 Machining and Weld Fixtures*.

3.3 Machining of Ports

In the machining of the port extensions to the contour of the vessel, a CMM will precisely locate and then indicate the center point for all of the flanges referencing the reference points on the appropriate segments. During initial fabrication, the ports will be oversized so that after they are individually positioned in the cage, welded and axial position is verified to be within tolerance, they can be trimmed to precise length and the flanges welded in place. At this point, the final length of the ports will be intentionally left 1/8" long to account for the material that will be removed when the ports are cut-off for shipping and installation.

To cope the ports to follow the vessel surface geometry, the ports will first be rough cut using a plasma cutter. Then, using Pro-E Prismatic software; a machine code program will be created for 3-axis milling machines to final machine the contoured weld edge of the extension. A CMM, in coordination with the reference points added to the extensions during initial fabrication, will be used to align the port in the milling center for fixturing and to verify the compliance with dimensional tolerances after machining is complete. The port extensions will

then be placed in the cage weld fixture, position checked with the CMM, welded and position verified again.

3.4 Machining of Eng Flanges and Support Hangers

To create the VVSA section end flanges and vessel support hangers, their computer models will be imported into Pro/E Prismatic Milling Software (a CAM package) in order to set tooling paths, speeds and feeds, and finally to create machine code to control the CNC milling stations that will be used in final machining of the flanges and hangers. A CMM will be used for verification of part tolerances.

3.5 Machining of Section Spacers

The initial plan for manufacturing the segment spacers is to reverse engineer the final geometry based on the variations in actual manufactured geometry of the VVSA segments. First, the three VVSA sub-sections will be fixtured to match their final assembled positions relative to each other and using a CMM, several data points will be taken from the two section end flanges for each joint to indicate surface and hole locations. The inferred surfaces and hole locations will be used in the creation of computer models of the three custom segment spacers. They will then be manufactured with a CAD/CAM approach similar to that used on the end flanges.

3.6 Containment Control

Rohwedder/NVSI has extensive experience in manufacturing vacuum chambers, and therefore, has a solid knowledge base of vacuum specific cleaning and surface finishing requirements and techniques. Only biodegradable, water based UHV compatible cutting fluids, oils, greases, and hand tapping fluids will be used. A high pressure, high temperature steam cleaner with biodegradable UHV compatible detergent will be used to rinse every component prior to welding/fabrication, and then rinse again after fabrication is complete. Final cleaning will include isopropyl wipe-down using lint-free wipes and drying with oil-free instrument air as per 3.3.2.4 of NCSX-CSPEC-121-02-00.

3.7 Material Finish

It is planned to purchase Inconel material pre-polished with a #4 polish on both sides. This will provide a maximum of a 63 RMS finish on the plates. Rohwedder/NVSI will work with the material vendor and specify the type of grinding/finishing products they can use and the process steps they should take so that we eliminate any contamination potential. After forming, additional polishing and electro-polishing will be performed to meet the 32 RMS on interior surfaces specified by PPPL. After welding, a “weld stripe” concept will be incorporated in the finishing of the internally ground welds on the VVSA. The “weld stripe” concept requires that the fabricator mask a small strip/stripe along the weld seam (typically .5” beyond the farthest grind line on the joint), then the fabricator will blend in a smooth, consistent finish that is at an RMS rating equal to or better than the overall surface finish on the inside body of the chamber. This method, which is used extensively by NVSI on ASME certified stainless steel pharmaceutical steam sterilizers, allows for localized finishing on the joint areas and prevents over finishing and unnecessary blending finishing to large areas inside the chambers.

3.8 Machining and Finishing Inspection & QA

Inspection and Quality Assurance for machining and finishing of the NCSX will focus on maintaining dimensional tolerances, surface finish, surface cleanliness and low magnetic permeability.

3.8.1 Dimensional Control & Verification

As mentioned in *Section 2 Forming Methods*, physical reference points, such as tooling balls will be used throughout manufacture of the VVSA to maintain dimensional tolerances. They will be located on the vessel segments, port extensions, dies and other fixturing to be used in verification of tolerance compliance to the original Pro/E models. The points will be indispensable in assuring proper locating and fixturing of the die-plates for final machining and trimming of the segments after forming. Also, because the reference points will exist in both the model and on the part, it will be possible to align the model of the part with the actual part in the CMM software, so that actual location can be compared to theoretical, when verifying tolerances with the portable CMM after final machining is complete.

3.8.2 Surface Finish Control & Verification

To assure that the surface finish of the vessel complies with those set forth in 3.2.1.2 of NCSX-CSPEC-121-02-00 and ASME B46.1, the finish of incoming raw materials and finished weld joints and sealing surfaces are to be monitored by visual inspections and qualified/verified by a calibrated digital profilometer throughout the manufacturing/fabricating process.

3.8.3 Magnetic Permeability Control & Verification

Magnetic permeability will be controlled through material selection, machining and polishing techniques, use and careful control of proper tooling and consumables. Inconel 625 will be used for the segments and port extensions and ASME/AWS SFA/A 5.14 ERNiCr-3 or ERNiCrMo-3 welding wire, as required by PPPL due to their innate low magnetic permeability. It is expected that Rohwedder/NVSI will also refuse any work from other customers that require the use of carbon steels for the duration of the project. All the finishing tools and consumables used in the finishing processes will be purchased new, and will be segregated, labeled, and secured for use only on this project until the project is complete. Facility maintenance and equipment control will be handled within the procedures detailed in the NVSI ISO9001/2000 certified quality program and manual. Rohwedder/NVSI intends to purchase a Severn Permeability Indicator in order to verify magnetic permeability compliance with the PPPL requirements in the SOW and Product Specification. Calibration and control of the detector will be within the elements of the ISO9001/2000 certified quality program/manual.

4.0 WELDING AND WELD REPAIR

The design of the weld joints will facilitate a metal to metal contact of the segments and end flanges when they are fitted together for the welding process, reducing the amount of heat and weld wire needed to fabricate the VVSA sections. This will aid in reducing distortion and tolerance shifting and eliminate the problem of holding the individual segments “in the air” to prep and weld the joints. Adjustable internal spreaders/spiders will also be used that are designed to and verified against the PPPL assembly models as well as the incremental step die shapes, and the tolerance requirements of the overall VVSA project. Additionally, it is planned to use small Inconel 625 bridge tacks on the outside skins of the segments to help support the VVSA sections as they are wrapped around the internal spreaders and the joints are fit together.

After each VVSA section is completely welded including end flanges, support hangers and port extensions, the VVSA section(s) will be stress relieved to eliminate stresses induced during the welding/fabrication process.

During the welding of the support hangers, end flanges and port extensions to the vessel and when welding the flanges to the ends of the port extensions, the reference points will be used to verify tolerance compliance to the original Pro/E models. As mentioned in *Section 2 Forming Methods*, it will be possible to import part models into the CMM software to align the reference points of the part model with the actual part, allowing verification of tolerances during weld fixturing and after welding is complete. Following the welding operation, port extensions will be cut with a plasma cutter and labeled for correlation to vessel location for re-weld at Princeton. The most logical cutting approach will be determined for each port in order to ensure no port stub will extend past 1" from the vessel surface to allow for fit-up of the modular coil units. Either straight angle cuts or one following the surface contour will be used, depending on the size of the port and the local vessel contour. As mentioned in *Section 3 Machining and Finishing*, the extra 1/8" left in the port length initially, will be removed during the cutting process, allowing the length of the ports at final assembly at Princeton to be within the Port Assembly Length tolerance specified in NCSX-12-122002-PH.

4.1 Weld Inspection & QA

Inspection and Quality Assurance for welding of the NCSX will focus on maintaining dimensional tolerances, surface finish, surface cleanliness and low magnetic permeability.

Welding and NDE of the NCSX VVSA will follow the guidelines dictated by the ASME "U" and "R" certification held by NVSI, Section 4.2.6 of NCSX-CSPEC-121-02-00 and all documents specified within. A Weld Procedure Specification (WPS) will be generated, which will detail general joint details, procedures for welding wire, backing gas, backing materials, welding machine settings, torch controls, welder position requirements, etc. All welders working on this project will be qualified in a 6G position to the project WPS. This means each welder will be tested by an ASME certified independent testing facility to determine if they qualify or "pass" welding in any position (6G certification) while following the procedures and welding the materials necessary per the WPS for this project.

Following ASME guidelines, a weld map will be generated for fabrication of the VVSA sections. In a weld map, each joint is detailed on a print and is assigned a specific number which is used for identification to the welders, internal inspectors, customer representatives, and to any independent inspection facilities. The individual joint is defined by the required procedure in the WPS and a sign-off is required by the weld map supervisor and by the person who fabricated/welded the joint. The individual weld number sequence supports in-process review of individual performance that can be performed at any time. A series of formal and informal inspection hold points will be incorporated into the VVSA fabrication process that will include visual and/or radiographic inspections of the weld seams. These inspection hold points must be signed off before any further work can commence. The inspections will only be done by approved quality inspectors within our quality system or, when required, by certified independent testing facilities/inspectors.

All required formal NDE will be done by independent testing facilities. Independent review helps to confirm our performance and provide assurance to the customer/end user that the work is being done in full accordance/compliance with the SOW and Product Specification.

Developing the most efficient and effective weld joint configuration possible will also reduce the final magnetic permeability of the VVSA. Minimum weld length (joint length) will result in less welding induced magnetism within the VVSA sections.

5.0 HEAT TREATMENT

The initial Rohwedder/NVSI heat treating (stress relief) plan is for a two-step process. First, the individual rough formed segments will be heat treated to remove any stresses induced by forming. Second, the entire fabricated 120° assembly will be heat treated prior to final machining after installation into the stainless steel cage fixture and positioned for final machining and port location. It is not certain how feasible the plan of "double" stress relief will be, so an initial test run will be performed on sample pieces prior to initiating the production process.

The planned method of stress relieving is to place each component or assembly in an inert gas (Argon) furnace and heat to 1600 Fahrenheit, hold the temperature for one hour and

oven cool until it reaches ambient temperature. It must be noted that through the stress relieving, the tensile strength of the Inconel will drop from 155,000psi to 144,000psi.

6.0 VACUUM TESTING

Vacuum testing of the vessel and the port extensions shall be conducted in accordance to Section 3.2.1.1 of NCSXCSPEC-121-02-00 and the ASTM E498 specification referenced within. All surfaces will be thoroughly cleaned per Section 3.3.2.4 prior to initiating leak check procedures. To leak check the main vessel shell sub-assemblies, custom blank-offs will be manufactured and mounted to VVSA. The vessel will be pumped down using a turbomolecular pump to a $< 1 \times 10^{-7}$ torr and leak checked at a detection sensitivity of 10^{-10} scc/sec He, with a mass spectrometer leak detector connected to the turbo pump foreline. The ports will be similarly blanked-off and leak checked prior to cutting away the ports and boring the port extension holes in the vessel shell. All leaks will be documented in nonconformance reports and repaired.