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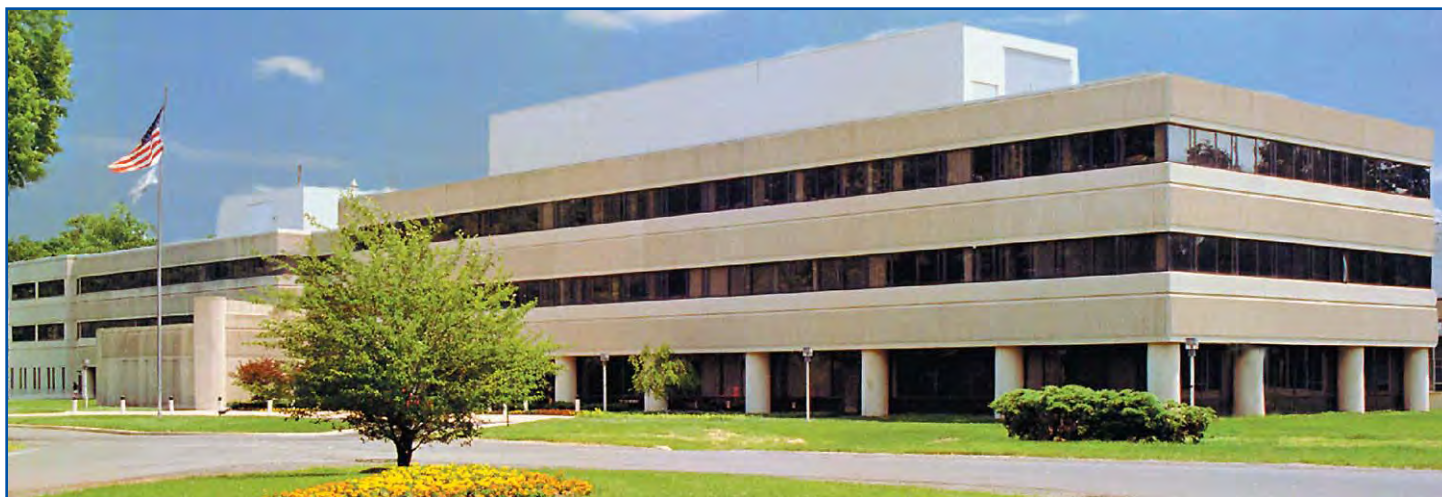
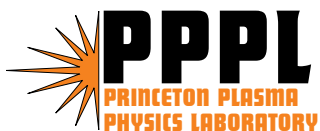
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NCSX VACUUM VESSEL FABRICATION

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I. INTRODUCTION

The National Compact Stellarator Experiment (NCSX) is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in conjunction with the Oak Ridge National Laboratory (ORNL). The goal of this experiment is to develop a device which has the steady state properties of a traditional stellarator along with the high performance characteristics of a tokamak. A key element of this device is its highly shaped Inconel 625 vacuum vessel shown in Fig. 1. This paper describes the manufacturing of the vessel. The vessel is being fabricated by Major Tool and Machine, Inc. (MTM) in three identical 120° vessel segments, corresponding to the three NCSX field periods, in order to accommodate assembly of the device. The port extensions are welded on, leak checked, cut off within 1" of the vessel surface at MTM and then reattached at PPPL, to accommodate assembly of the close-fitting modular coils that surround the vessel. The 120° vessel segments are formed by welding two 60° segments together. Each 60° segment is fabricated by welding ten press-formed panels together over a collapsible welding fixture which is needed to precisely position the panels. The vessel is joined at assembly by welding via custom machined 8" (20.3 cm) wide spacer "spool pieces" shown as bands in Fig. 1. The vessel must have a total leak rate less than 5×10^{-6} t-l/s, magnetic permeability less than 1.02 μ , and its contours must be within 0.188" (4.76 mm). It is scheduled for completion in January 2006.

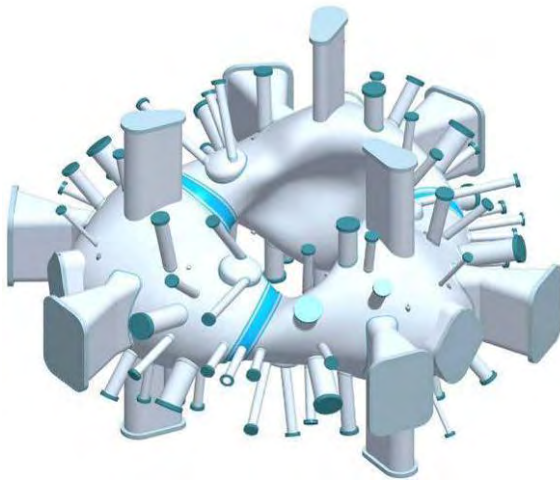


Figure 1. NCSX Vacuum Vessel

II. PROTOTYPE VACUUM VESSEL (PVVS)

The NCSX team decided to solicit fabrication of a prototype vacuum vessel. This would both solicit interest and develop techniques for the fabrication of the final vacuum vessel. A Statement of Work (SOW) was written which defined the manufacturing development activities for the 120° Vacuum Vessel Sub-Assembly (VVSA) and the production of a full-scale 20° prototype vacuum vessel segment (PVVS). These activities were also meant to give the fabricator the experience needed to develop and submit a firm fixed price and schedule proposal for producing the three VVSA units. The SOW focused on the critical aspects of manufacturing the vessel:

- Forming methods to be used in the fabrication of the shell,
- Methods for locating, machining, and welding the ports. (The spatial and angular orientation of ports is critical on NCSX.),
- Methods of controlling distortion of the vessel shell and maintaining the required tolerances,
- Welding and Non Destructive Examination (NDE),
- Vacuum testing (both to locate leaks in welds and verifying leak rate and base pressure),
- Cleaning and surface finishing operations,
- Measurements of the complex formed surfaces and comparison with the reference Pro/Engineer model,
- Magnetic permeability control and verification,
- Quality assurance plans that address all of the requirements of the SOW and the applicable specification,
- Methods for locating the port cut line and actual method of cutting of the ports within the surface profile, as indicated on the drawings,
- Method of cutting the hole in the vessel shell inside the port after it is cut in the above step,
- Method of reattaching the port by welding it from the inside.



Figure 2. NCSX Prototype Vacuum Vessel by Major Tool and Machine

Two companies were chosen that submitted competitive solutions with the most promising technique. Both companies produced prototype vacuum vessels and Major Tool and Machine was chosen for the production of the VVSA based on performance (see Fig. 2).

III. FABRICATION OF THE VACUUM VESSEL SUBASSEMBLY

Major Tool chose to segment the Vacuum Vessel Subassembly (VVSA) into ten pieces for optimization of complexity of forming vs. weld distortion (see Fig. 3). The VVSA is fabricated by first forming the ten individual panels using kirksite dies (see Fig. 4). Each panel is formed and then trimmed to size. Once trimmed the panel is annealed and then pressed a second time in the die set. Pieces of wood and/or rubber are used to make any further adjustments. A set of ten gauges (see Fig. 5) have been fabricated to enable the die operator to quickly determine where the panel is within the shape tolerance or where rework is necessary. Once the panel is formed, it is set aside for mounting onto the 60° fixture.

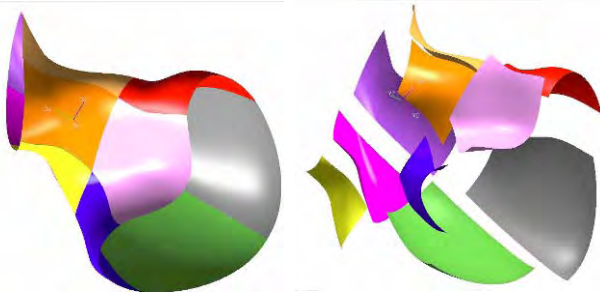


Figure 3. 10 panel segmentation scheme



Figure 4. Kirksite forming



Figure 5. Panel gauge

Once all ten panels have been formed, they are placed on the 60° fixture (see Fig. 6), aligned in groups, and final trimming is performed. Measurements are made using a laser tracker coordinate measuring machine (see Fig. 7). The 60° fixture (see Fig. 8) is ingeniously designed with many features. It allows for the mounting of the ten panels in two 5-panel sections upper and lower. It is also keyed and segmented to allow for easy disassembly after the 60° segment is welded. Additionally it provides the stiffness necessary to hold shape and control distortion of the segments during welding. It can be bolted together as one assembly or as two individual upper and lower assemblies. It has cutouts to allow a person to stand and weld within the fixture as well as allow for seams to be made which cross the fixture plates.

The panels are tacked together in a three panel and a two panel configuration on the upper or lower fixture. Once these two partial assemblies are made then they can be joined into one complete upper or lower five panel segment. Final measurements are taken; the upper and lower segments are mounted back onto the complete 60° fixture and welded into their final configuration. This completes the formation of a 60° segment.



Figure 6. two panels tacked on the 60° fixture lower section



Figure 7. Final measurements being taken with a Laser Tracker

Once two 60° segments have been completed (see Fig. 9), they are mounted onto the 120° fixture (see Fig. 10). This fixture allows two 60° segments to be aligned and a best fit analysis is performed using Verisurf© software. The two 60° segments are then welded together to form the final 120° shell (see Fig. 11). The 120° fixture also has some unique features serving multiple needs. This fixture is used to position and join two 60° degree vessel segments together, provide support and rigidity for machining the port holes, and is also the basis for support during the installation of the port extensions and vacuum testing operations. It is designed to uniformly support the highly shaped vessel surfaces (minimizing gravity induced distortion). It includes features such as strategically placed adjusting rods (used for “fine tuning” the position of the two 60° vessel segments prior to welding), personnel access (necessary for completing the circumferential weld), a separate center support structure (which locates inside the vessel to eliminate gravity induced distortion and provide a solid backing at the center weld seam), datum reference monuments (used for accurate re-positioning of the laser tracker during profile inspection, and ensure geometrical accuracy during machine tool setup).



Figure 9. 60° segments

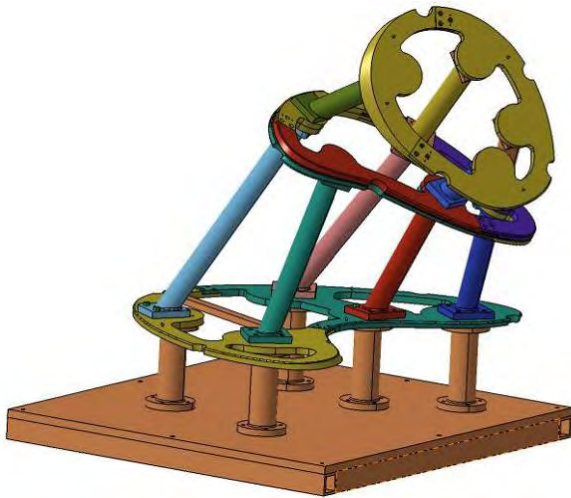


Figure 8. 60° fixture

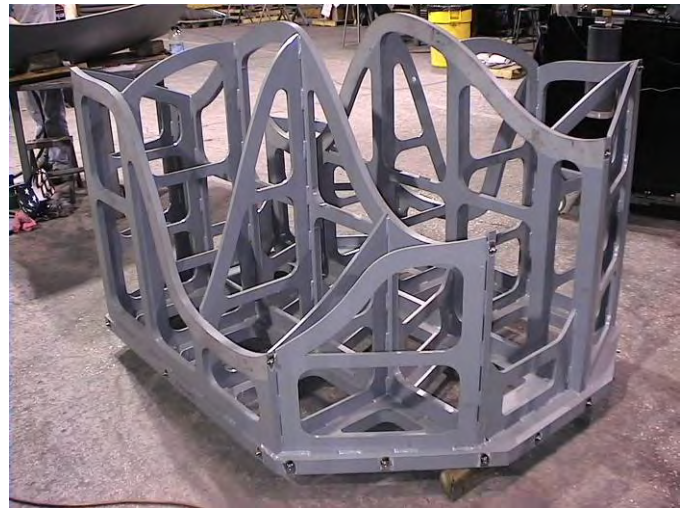


Figure 10. 120° fixture sketch or photo



Figure 11. 120° segment

The 120° segment is then placed on a five axis mill in order to bore the various holes required for the ports (see Fig. 12). Once bored, the shell is placed back onto the 120° fixture and the ports are then welded into place. The ends will then be capped to allow for a vacuum leak check and also thermal cycling three times to 375° C. During this thermo-cycle the ports may not exceed 150° C because of the material property differences between the 316 S. S. flanges and the Inconel 625 port tube extensions. After successful completion of these tests, the ports are then cut off within 1" of the shell surface. This allows for the future installation of the modular coil sets over the vacuum vessel as part of the final assembly process at Princeton Plasma Physics Laboratory. A sketch of one completed VVSA is shown in Fig. 13.

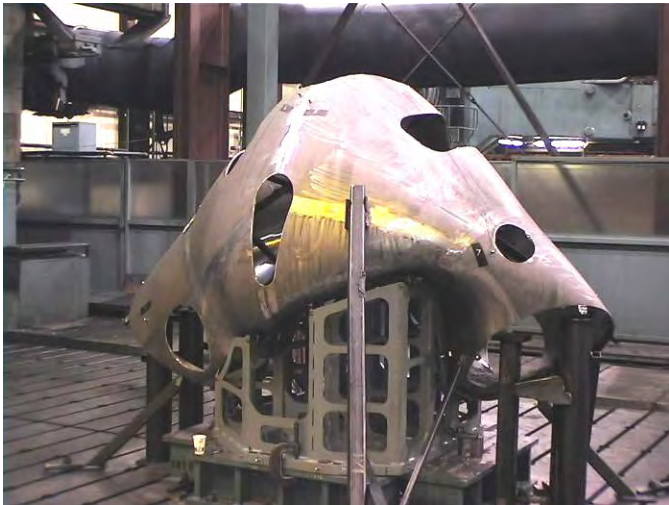


Figure 12. VVSA port holes being bored on the 5 Axis mill

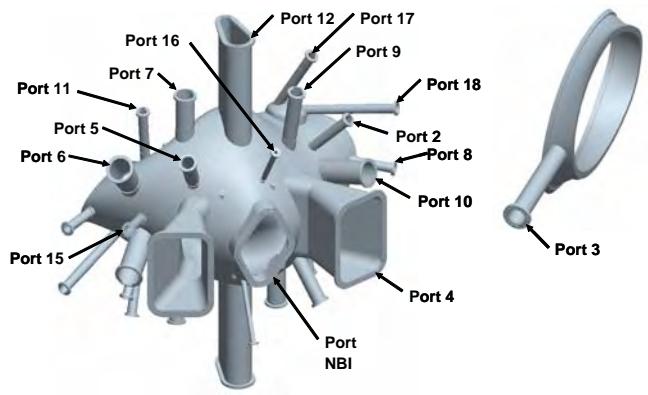


Figure 13. Complete VVSA Sketch

ACKNOWLEDGMENTS

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