National Compact Stellarator Experiment (NCSX)

In May, 2008 the Department of Energy announced its decision to terminate the NCSX project due to programmatic uncertainties. In June, the NCSX project developed a close-out plan which was accepted in July. This close-out plan was structured to capture many benefits of the project, *e.g.*, completion of the modular and toroidal field coils, safekeeping of materiel, and thorough documentation of designs, R&D achievements, retired and residual risks, and lesson learned, to allow revisiting this particular design if future developments in the fusion program warrant it. By the end of FY 08, all of these objectives were achieved and NCSX is now in safekeeping mode. Some of the key objectives are described below:

- **All (18) modular coils were successfully completed at PPPL**. A completed coil is shown in Figure 1. All technical requirements were achieved. The chief dimensional accuracy of the coils was very good. Figure 2 shows the measurement data for the types C modular coils. Approximately 90% of the measured points were within the +/- 0.020" (0.5 mm) tolerance allocation for this fabrication step. The accuracy of Type A and B are roughly similar. Note that coil to coil similarity of tolerances was imposed on the winding fabrications to provide stellarator symmetric geometry which reduces the effect of winding errors. Further improvement in the magnetic field is achieved by realignment based on the measured data during assembly.

  Data on the resources required for fabrication of the modular coil components and windings were carefully gathered and analyzed throughout the project to provide performance metrics. Figure 3 shows the so-called "learning curves" for the pouring of the modular cil castings, delivery of the modular coil winding forms, and for modular coil fabrication. In addition to providing feedback to the NCSX project during its execution, this data will help improve our estimating and scheduling methodology for future first-of-a kind, high technology projects.

Figure 1 - A Type C Modular Coil after Vacuum Impregnation and Installation of Coil Clamps

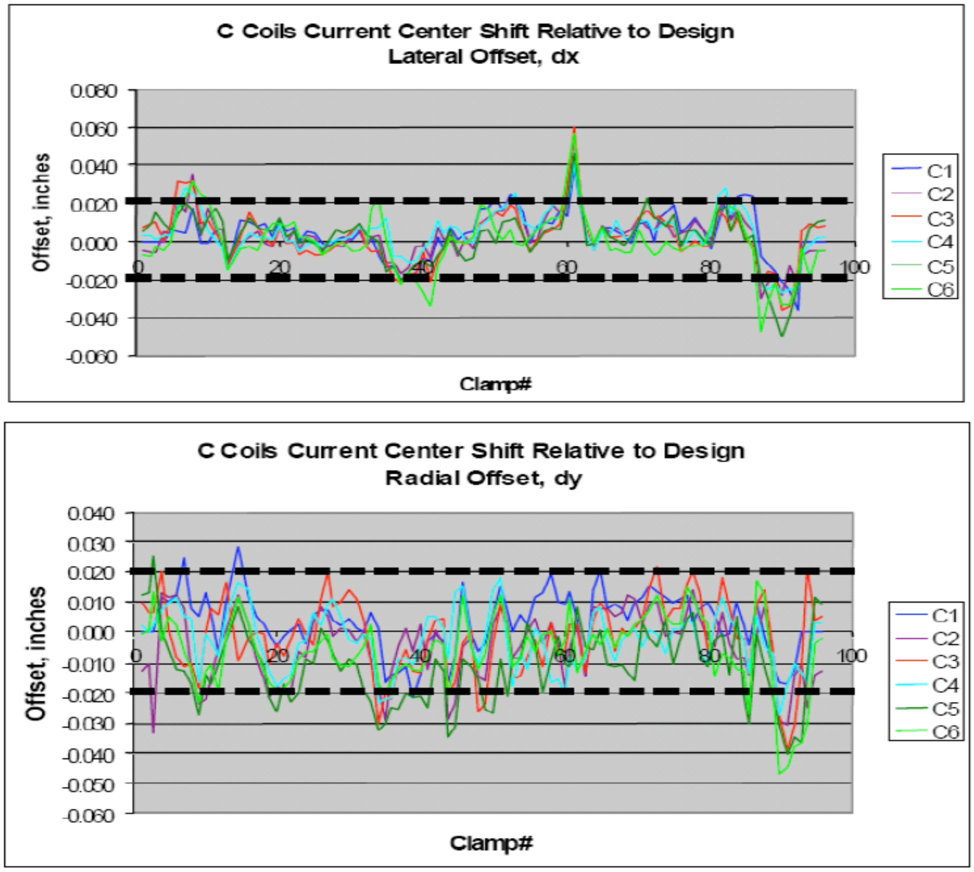
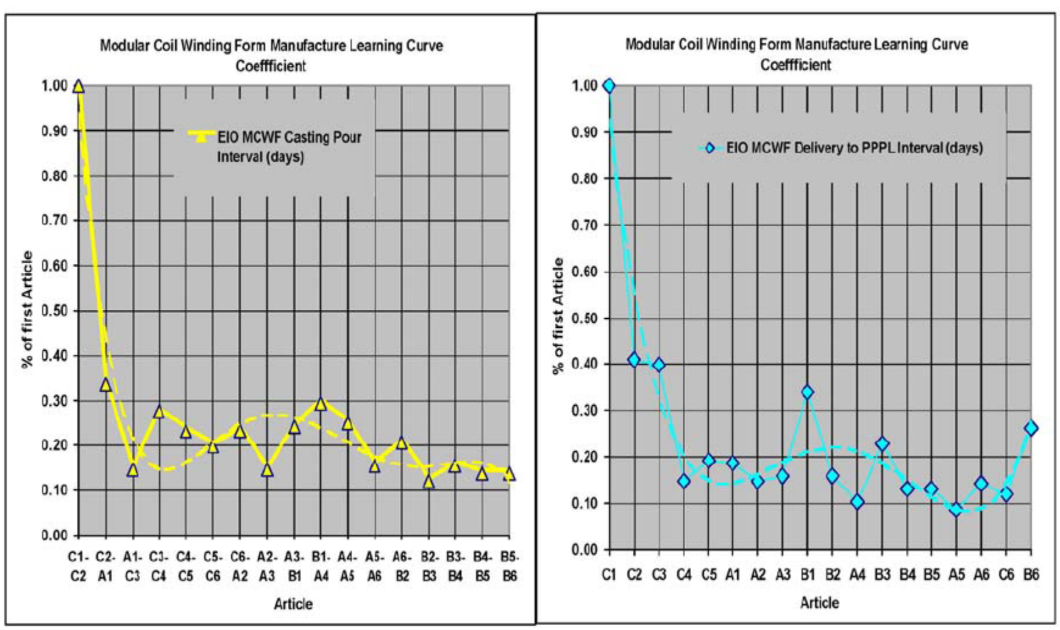


Figure 2 - Radial And Vertical Current Center Offset Data For All (6) Type C Coils. Note That All Coils were Manufactured to be Similar in These Respects To Lessen the Effects of Such Errors



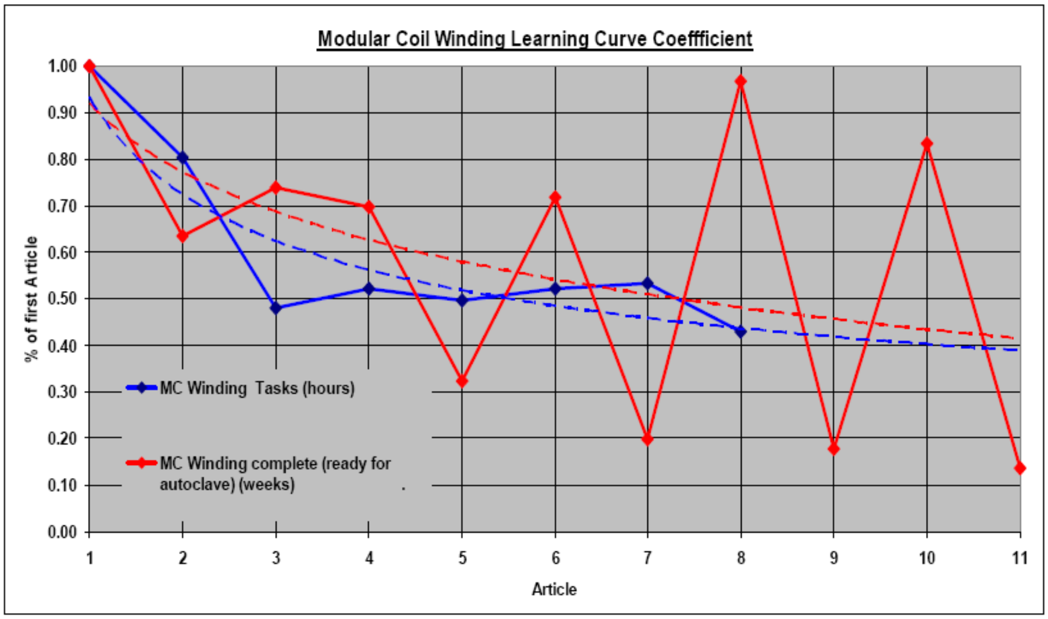


Figure 3 - Learning curve data showing the improvement in productivity for the modular coil casting pours, modular coil winding form deliveries to PPPL, and winding of the modular coils at PPPL

- **All (18) toroidal field coils were successfully completed and delivered to PPPL by Everson-Tesla, its supplier**. All technical requirements including their dimensional accuracy were achieved. Fig. 4 shows probably control tests being performed during manufacture.

Figure 4 - Quality control tests being performed on a NCSX TF coil at the Manufacturer

- **The construction of all (3) vacuum vessel sectors was completed**. A vessel sector is shown in Figure 5 with the heating and cooling lines installed. These assemblies are complete except for some rework of components that had quality issues that was in progress at the time of termination.

Figure 5 - A Vacuum Vessel Sub-Assembly

- **A (48) coil trim coil system was developed**. This coil system, shown in Figure 6, provides the ability to compensate for "as built" conditions such as alignment deviations or out of spec magnetic material properties which might affect the quality of the magnetic fields. Having such a system permits flexibility in the disposition of as-built conditions. Rather than having to always correct non-conforming hardware conditions, one can now evaluate the cost vs. benefit and chose between correction or compensation. The methodology and computer code developed for designing the trim coils can rapidly analyze a number of coil parameters to optimize the design, and has potential applicability to other systems of coils used to generate corrective magnetic fields.

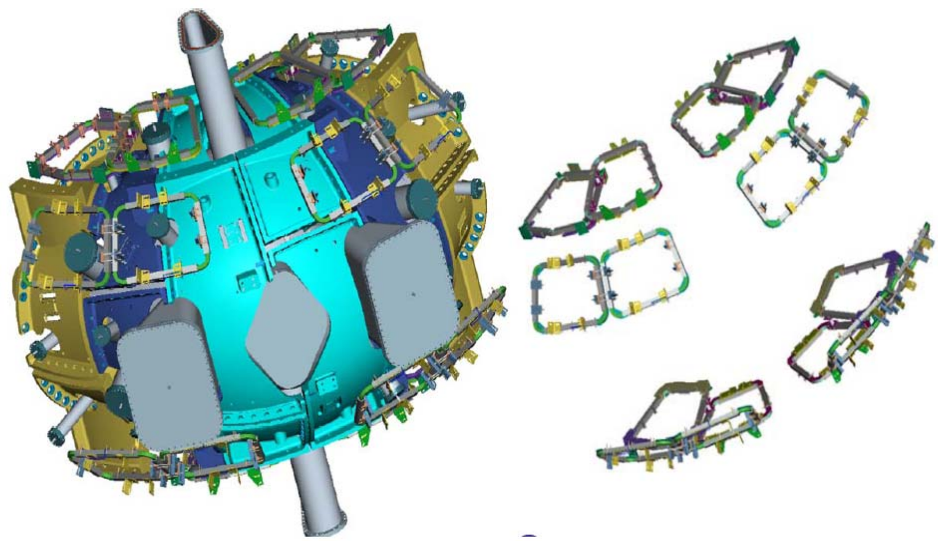


Figure 6 - The NCSX trim coil system. A set of 48 resistive (copper) coils located around the modular coil set can be powered in various modes to correct for field errors due to modular coil misalignments, magnetic materials, etc

- **The poloidal field (PF) coil system design, shown in Figure 7, was completed** and ready for fabrication. This system uses liquid nitrogen cooled copper coils which utilize well established, conventional fabrication techniques.

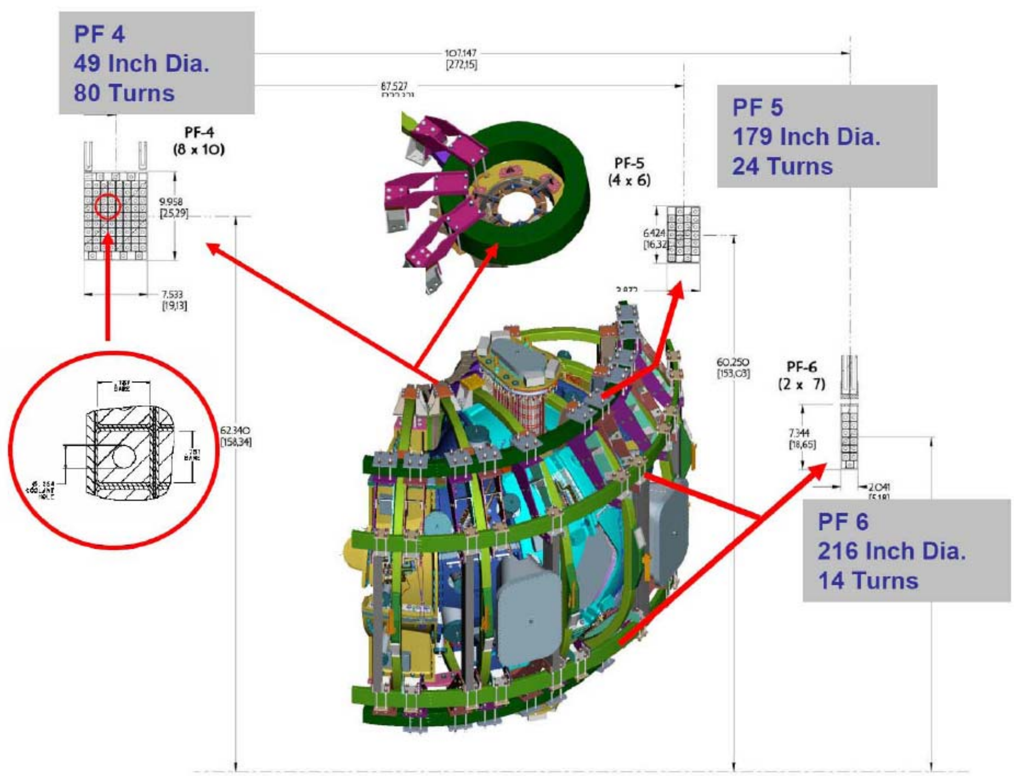
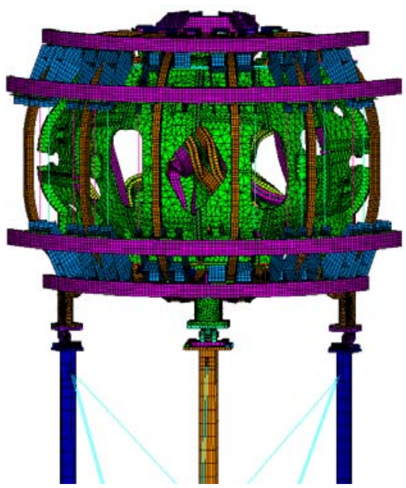


Figure 7 - The NCSX Poloidal Field (PF) Coil System

- **The designs of the support systems were completed.** These systems are designed to support the coils for all of the NCSX operating scenarios.

  The designs must account for cool-down from room temperature (293 K) to its pre-shot temperature of 77K. They are designed for fatigue lifetimes of 130,000 full power shots; loads considered in the design include gravity loads, horizontal seismic loads, thermally induced stress loads, and normal and fault electromagnetic loads. Figure 8 shows the finite element model for the TF and PF structural design and the calculated maximum displacements. The base structure, shown in Figure 9, supports the entire weight of NCSX. In addition to being designed for the conditions defined above, they must minimize heat transfer to control heat flow into the cryostat and its design must compatible with the cryostat. The analysis of the temperature distributions across the inboard and outboard supports is shown in Figure 10.



Model Details:

#Nodes	450,843
#Elements	275,627
#Coupled nodes	9,717
#Forces	135,180
#Constrained nodes	1,197
Tref	298 K
Tload	77 K
Solver	Sparse

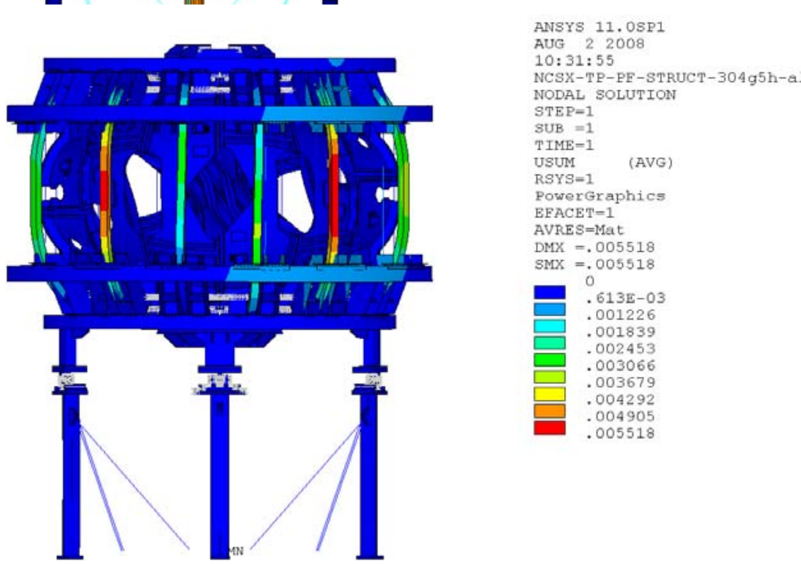


Figure 8 - (top) the Finite Element Analysis (FEA) model for the TF and PF coil support systems and (bottom) displacements due to EM loads. The color contours indicate the displacements in m

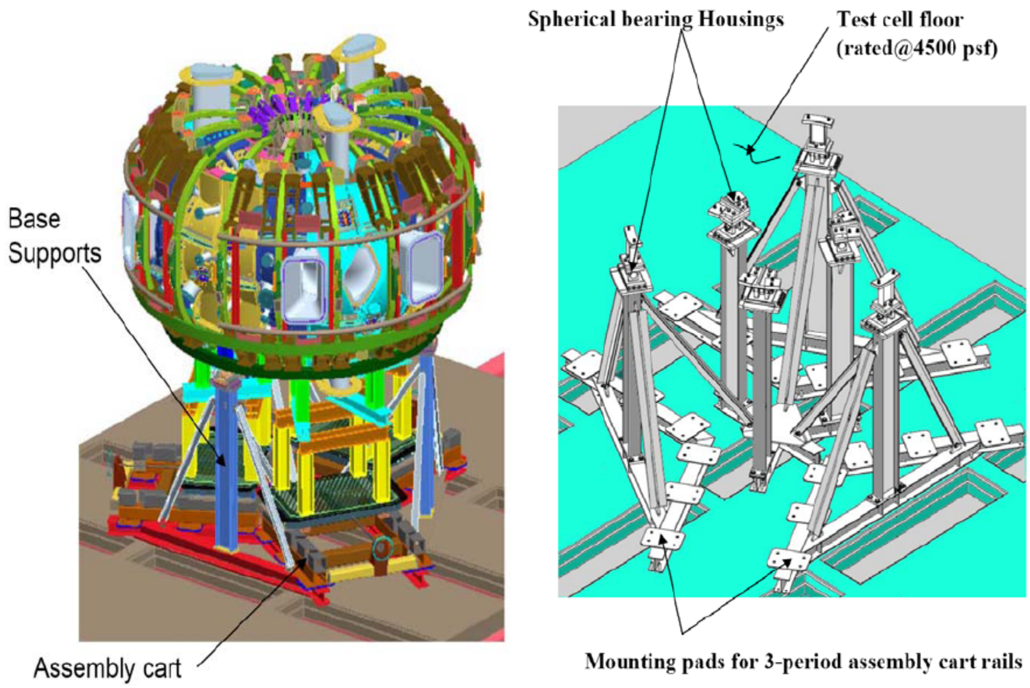


Figure 9 - The NCSX base support structure

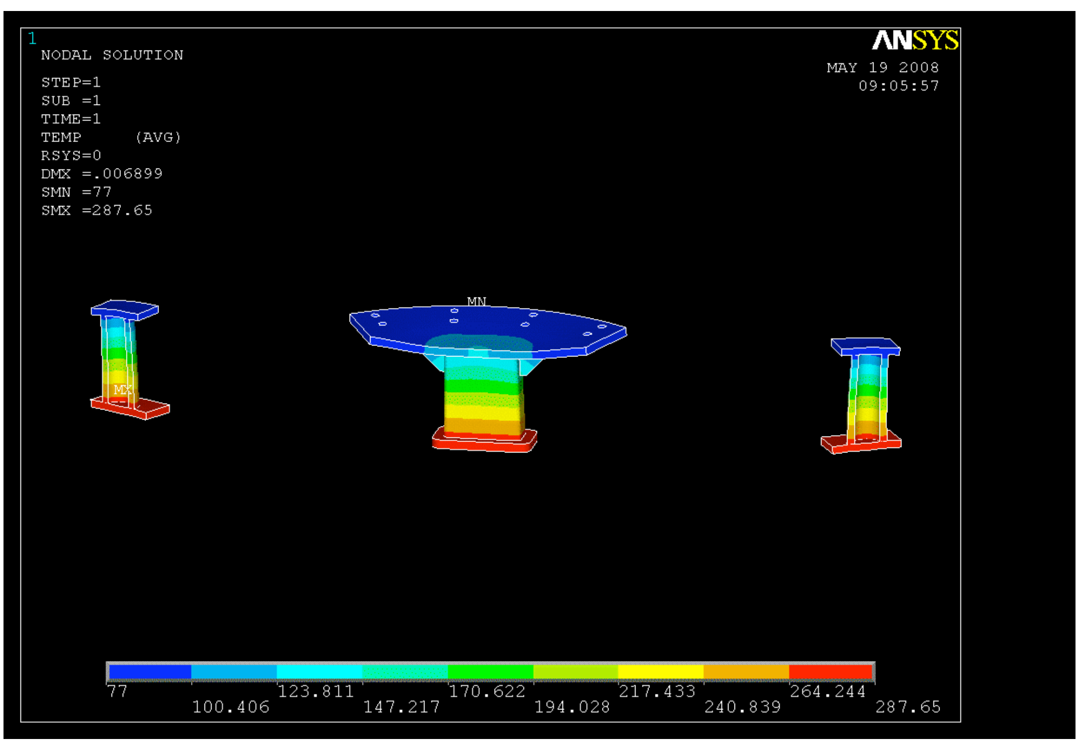


Figure 10 - FEA analysis of the temperature across support elements. These calculations indicate a heat flow of 316 W from the 3 inboard supports and 251 W. from the outboard supports

- **Two half period assemblies were successfully completed**. Figure 11 shows a half period assembly, and Figure 12 shows the dimensional achievements for the two half periods. The results were excellent, with the dimensional deviations falling into roughly half of the +/- 1 mm (0.03937") tolerance band. These assemblies validated the assembly techniques and the interface design that was developed last year. Figure 13 shows the low-distortion weld configuration that is used between the inboard sections of coils within a field period; Figure 14 is a macrophotograph of a weld. Gas Metal Arc Welding GMAW with flux core wire is used to develop high quality welds with good penetration with reduced heat to minimize distortion.

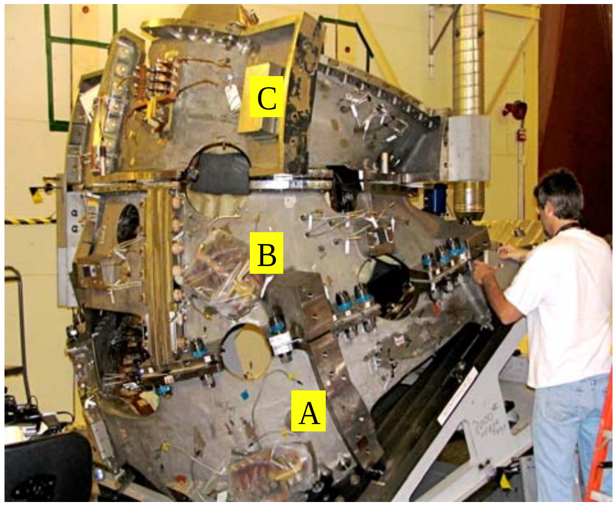


Figure 11 - Half Period Assembly

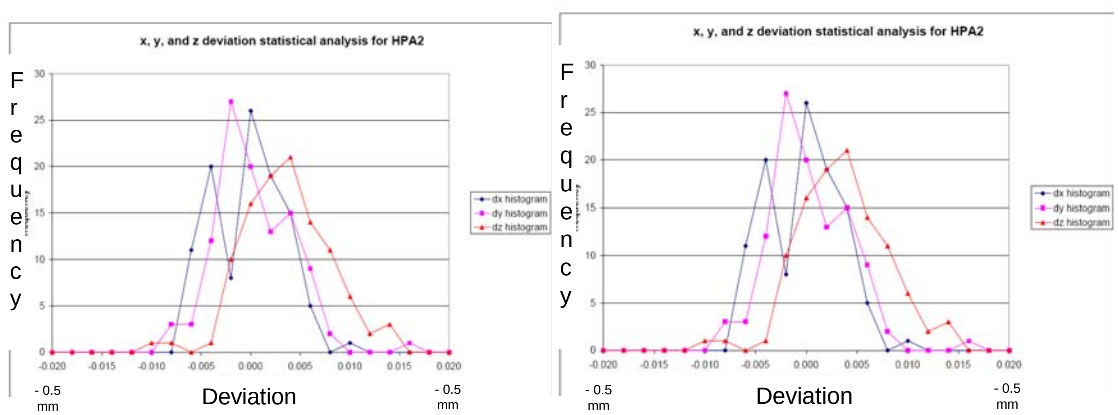


Figure 12 - Statistical analysis of the dimensional deviations in the x,y, and z directions for the first two half period assemblies

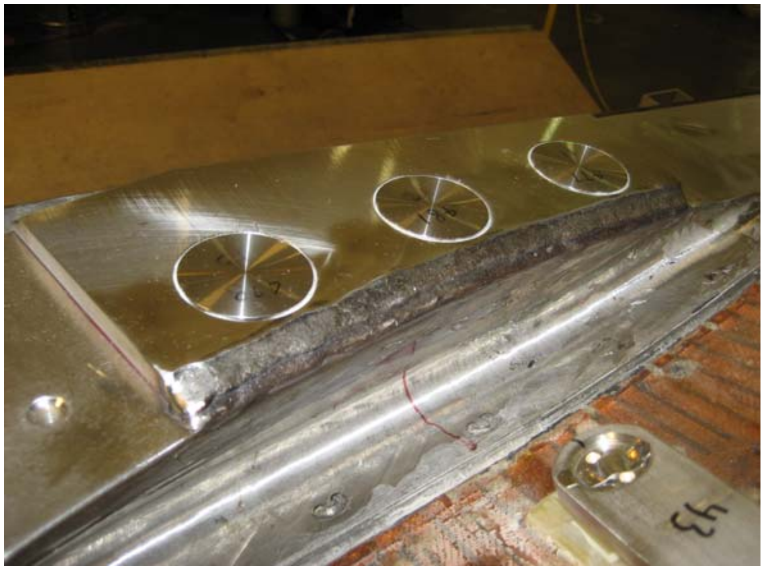


Figure 13 - Low-distortion weld interface developed for joining the inboard portions of the NCSX modular coils during assembly

Figure 14 – Macrograph of a Weld

- **Field period assembly methods were finalized and demonstrated.** The critical aspect of the field period assembly is being able to manipulate a ~9-ton assembly over the complex geometry of the vacuum vessel with clearances as small as 0.5 mm (check) between the bore of the modular coils and the vacuum vessel surface. A unique handling system and procedure was developed that provides carefully controlled motion with 6 degrees of freedom. This system, shown in Fig. 15, consists of (3) gear reduced actuators with encoders which are attached to the 110 ton D-Site test cell crane. The actuator control system provides fine adjustment of the stroke of each of the actuators; the test cell crane is equipped with controls that permit fine adjustment of up/down motion and hook rotation. Lasers attached to the modular coil assembly are used to guide the motions. The motions are adjusted so the laser points follow along motion paths defined on CAD-generated plots which are mounted on screens adjacent to the winding form and on the floor. This system worked extremely well; the time required to complete the assembly significantly exceeded the estimates. The vessel segment with a half period installed is shown in Fig. 16.

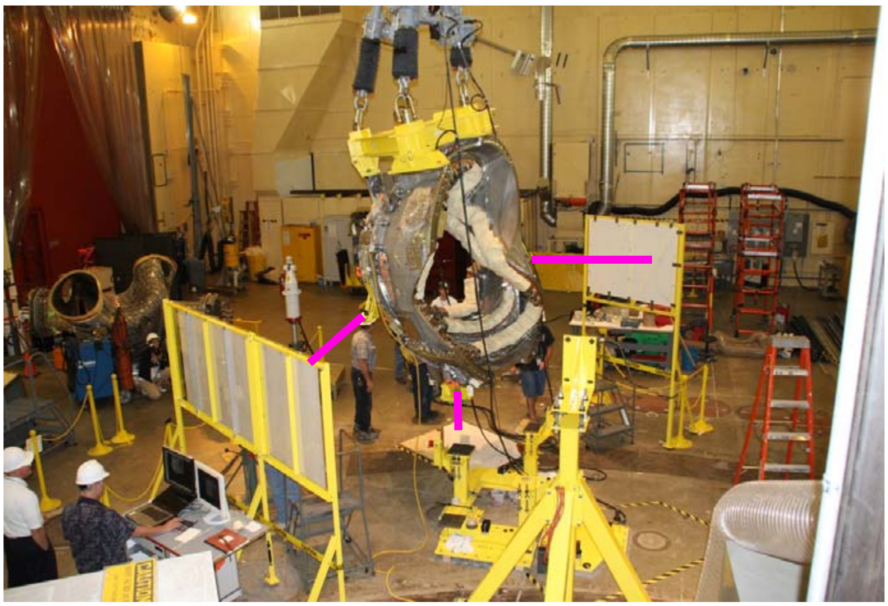


Fig. 16. A half period assembly during motion trials.

Figure 15 – Field Period Assembly Demonstration

- **Considerable progress was achieved on the highest area of remaining risk: the design of the cryostat and cryogenic systems.** Figure 16 shows NCSX as it would look with the cryostat, neutral beams and vacuum pumps installed. By the fiscal year's end, progress was such that completion of the final design was estimated to be less than a year away.

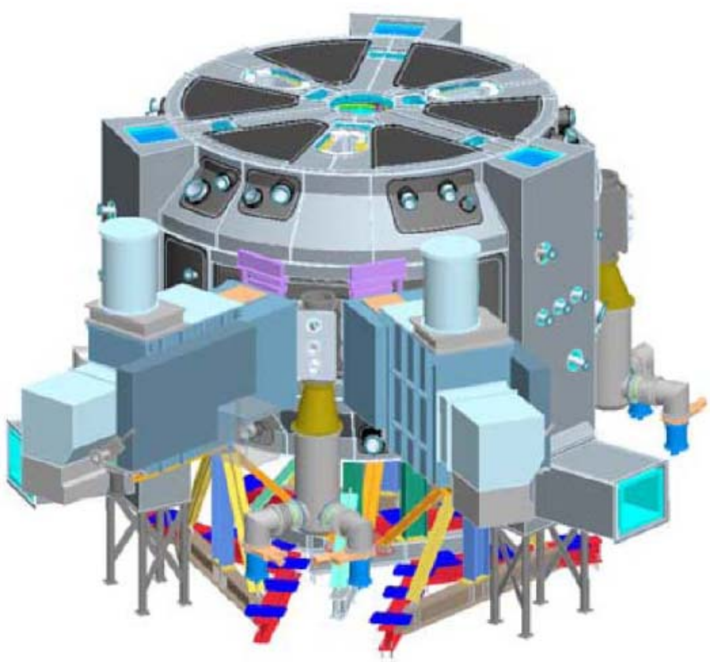


Figure 16 – NCSX with Cryostat, Neutral Beams, and Vacuum Pumps Installed

- **Safekeeping of the hardware was completed and archiving of Project documentation is nearing completion.** Figure 17 shows a series of photos showing the NCSX hardware as it is stored for safekeeping in what was to be the NCSX test cell. Project documentation including design and analyses information, design review files, and engineering notes are archived on the NCSX engineering website. The files for this website are located on a secure server which is regularly backed up. A final audit is scheduled for early next year to ensure that all of the appropriate data has been captured, secured, and is retrievable if needed in the future.

Figure 17 – Storage of NCSX Hardware in the Proposed NCSX Test Cell

Although NCSX was only partially completed, substantial progress was made in the design and analysis of state-of-the-art fusion devices, component fabrication, metrology, and assembly. One of NCSX's most significant accomplishments was a rigorous translation of a physics optimized magnetic configuration design into actual equipment, consistent with its mission requirements for performance, flexibility, geometry, and accuracy. These improved capabilities are now being applied to a variety of projects throughout the fusion community.

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