NCSX Engineering Design Document

Engineering Design Overview

NCSX CDR

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1 INTRODUCTION

The National Compact Stellarator Experiment (NCSX) is an experimental research facility that is to be designed and constructed at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL). Its mission is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the understanding of 3D plasma physics for fusion and basic science.

2 DESIGN REQUIREMENTS

The design requirements for NCSX flow from its mission. These requirements have been documented in the **General Requirements Document** (GRD), which is the system (top-level) specification for the NCSX Project and provided as part of the Conceptual Design Report. It provides the basis for developing all lower level (subsystem and equipment) specifications.

NCSX is designed to be a flexible, experimental test bed. To ensure adequate dynamic flexibility, a series of reference scenarios has been established. Reference scenario parameters are provided in Table 2-1.

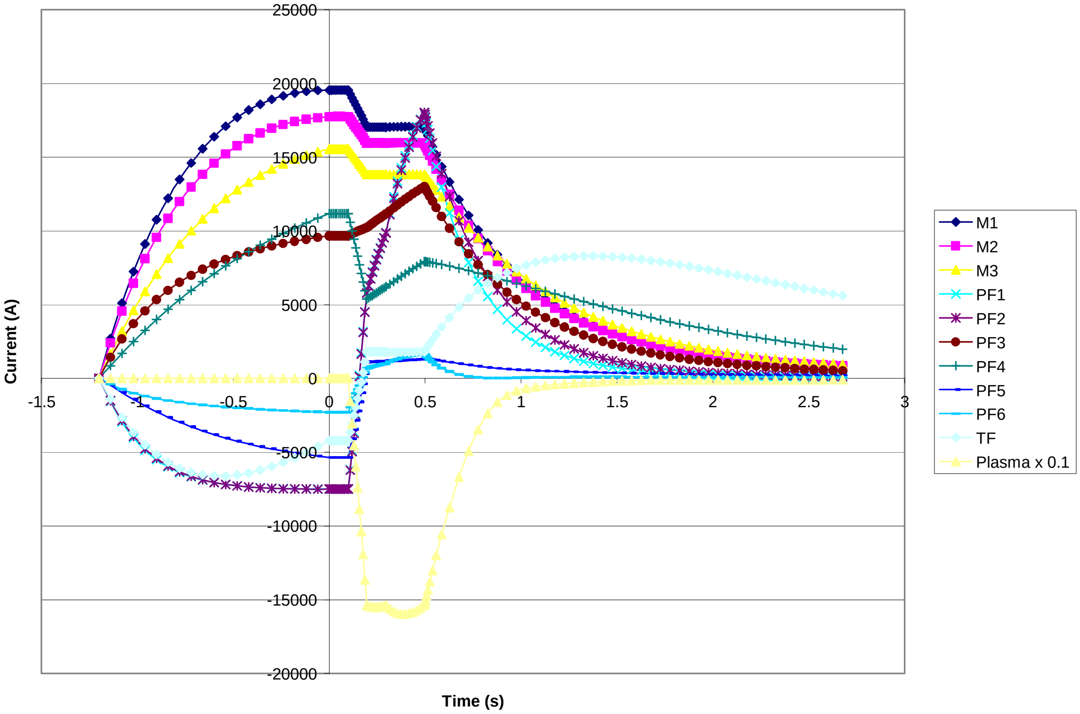
Table 2-1 Reference Scenario Parameters

Reference Scenario	Toroidal Field (R=1.4m)	Plasma Current	Plasma Current Ramp Rate	Plasma Current Flattop	Design Significance
Initial Ohmic	1.5 T	154 kA	1.6MA/s	0.3 s	Determines initial power supply complement
1.7T Ohmic	1. 7 T	175 kA	3.0 MA/s	0.3 s	Max (-) currents PF5 and PF6
1.7T High Beta	1.7 T	175 kA	3.0 MA/s	0.3 s	Max (+) current in PF4 Max (-) TF current
2T High Beta	2.0 T	205 kA	3.0 MA/s	0.1 s	Max (+) current in modular coils, PF3, and PF5
350kA Ohmic	1.8 T	350 kA	3.0 MA/s	0.3 s	Max (+/-) current in PF1 and PF2 Max (+) current in TF and PF6 Max (-) current in PF3 and PF4 Max (-) plasma current

TF, PF, and modular coil systems and the vacuum vessel will be designed to meet the requirements of all the reference scenarios. Electrical power systems will be designed and initially configured to meet the requirements of the Initial Ohmic Scenario and shall be capable of being upgraded cost-effectively to meet the requirements of all other reference scenarios.

For each of the reference scenarios, current waveforms and related technical data have been developed. Figure 2-1 illustrates the current waveforms for the Initial Ohmic Scenario. Initially, the modular coils are driven to the currents required for the vacuum state and held there for 100ms to allow eddy currents to subside and closed magnetic surfaces to form. The plasma is initiated inductively with the current being ramped from zero to 154 kA at a rate of 1.6 MA/s. The plasma is then allowed to relax at constant current for 300 ms. TF coil currents change on the same timescale as the modular coil currents, maintaining constant toroidal field from the vacuum state through the end of the current flattop. PF coils provide inductive current drive and plasma position and shape control. At the end of the current flattop, the power supplies are assumed to be bypassed (in response to a detected fault condition) to assure that coil temperatures do not exceed allowable limits. None of the circuit currents exceed 24 kA, the nominal rating of the power supplies. **Technical Data** for each scenario has been provided as part of the Conceptual Design Report.

Figure 2-1 Initial Ohmic Scenario Waveforms



The reference scenarios themselves ensure substantial flexibility in plasma current, beta, and pulse length. For instance, the plasma current flattop can be extended from 0.3s in the 1.7T High Beta Scenario to 1.7s at 1.2T. Each scenario has unique design significance as summarized in Table 2-1. In addition to the reference scenarios, the GRD also includes flexibility requirements, which further ensure that NCSX will be a flexible, experimental testbed. These additional flexibility requirements are listed in Table 2-2. The coils will be designed and the power systems will be cost-effectively upgradeable to meet the flexibility requirements listed.

Table 2-2 Flexibility Requirements

Parameter	Flexibility Requirement
Quasi-symmetry	Vary quasi-symmetry by varying the effective ripple from the reference value to 10 times the reference value
External Iota	Vary the rotational transform from -0.2 to +0.1, relative to the reference profile, while holding the global shear ($\iota(a)-\iota(0) \sim 0.2$), plasma current (175kA), and toroidal field (1.7T at R=1.4m) constant
Global Shear	Vary the global shear ($\iota(a)-\iota(0)$) by -0.2 to +0.2, relative to the reference value, while holding the central iota (0.4), plasma current (175kA), toroidal field (1.7T at R=1.4m) constant
Beta Limit	Reduce the kink stability beta limit to 1% from its reference value of ~4%

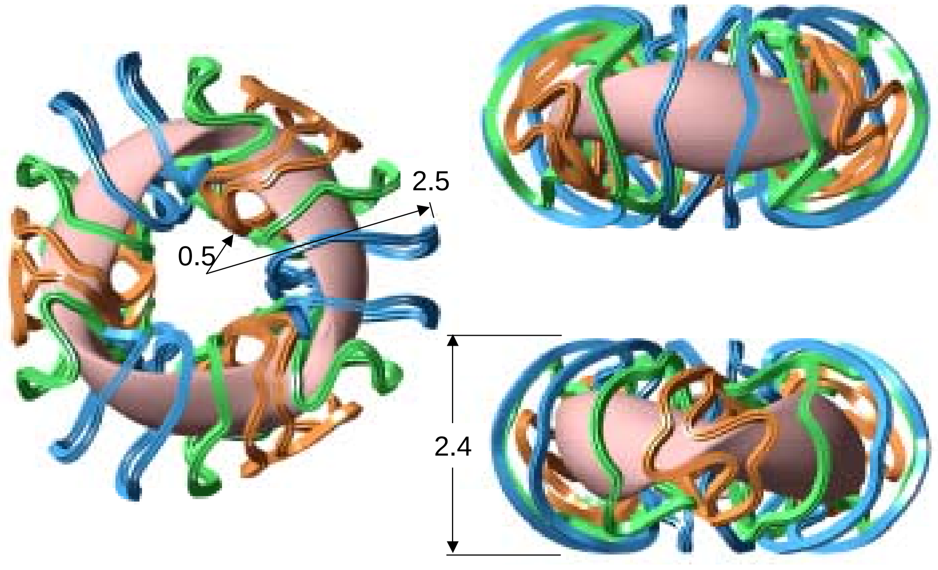
Work will continue on developing the GRD through the end of Conceptual Design (September, 2002), filling in those items that are marked TBD (to be determined), whereupon the document will be formally approved and placed under configuration control.

3 DESIGN DESCRIPTION

3.1 Stellarator Core

The heart of the NCSX design is the stellarator core. The plasma has three field periods and is surrounded by eighteen (18) modular coils (6 per field period). Figure 3-1 shows the NCSX plasma surrounded by the modular coil windings. Due to stellarator symmetry, there are only three distinct modular coil types, which are color-coded in Figure 3-1.

Figure 3-1 Modular Coil Windings

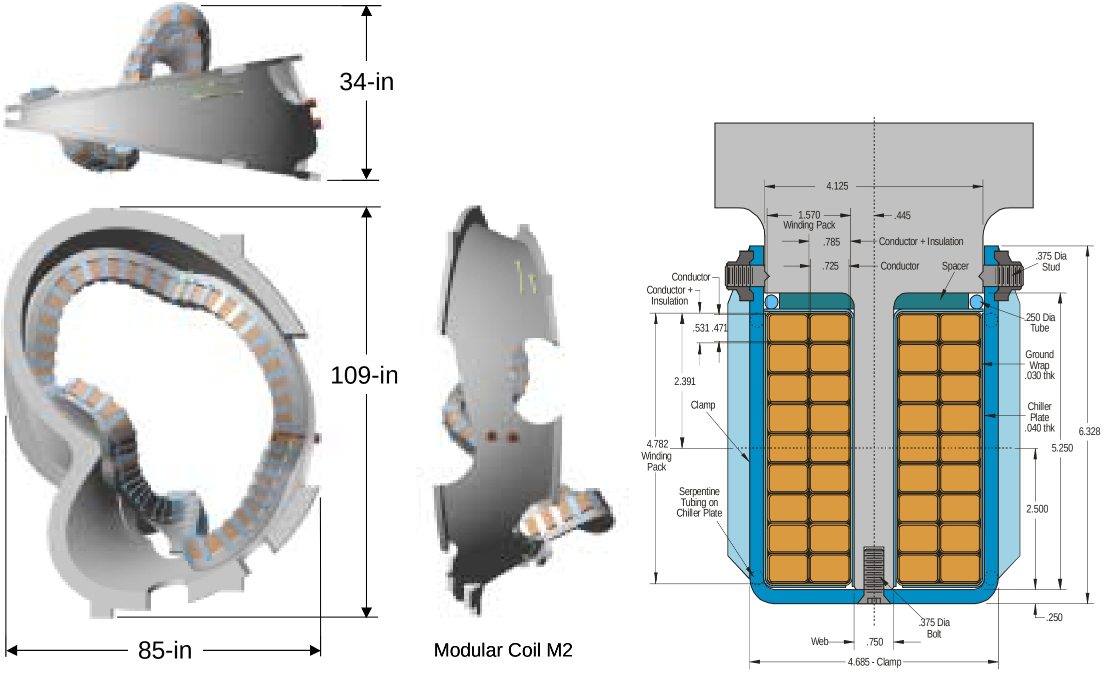


Modular coils were chosen because of their attractive features:

- Modular coils can provide good physics properties;
- Modular coils can be located far from the plasma, creating a large experimental volume that accommodates an expanded vacuum vessel with space for in-vessel components and plasma shape flexibility;
- Modular coils provide low stray fields outside the bore of the modular coils, which is important for the operation of neutral beams and turbomolecular vacuum pumps; and
- Modular coils permit modular assembly of the device.

The modular coils are wound onto a winding form that also serves as the coil structure. The coils are wound against a high precision surface resembling a tee-shaped section projecting inward from a shell. There is a winding pack on each side of the tee, as shown in Figure 3-2. Access from both the sides and bottom of the tee-shaped section greatly facilitates winding the coil. The preliminary specification for locating the current center of the winding packs is ±1.5mm (0. 1%), which is consistent with historical precedent and manufacturing capabilities. Studies are underway to investigate field errors arising from potential construction errors to better understand tolerance requirements.

Figure 3-2 Modular Coil Concept



This main attraction of this concept is its simplicity. Electromagnetic loads on the winding pack are predominantly directed towards each other (clamping the winding packs to the tee in the toroidal direction) and towards the shell (pushing the winding packs against the shell in the radial direction). Thus, the winding packs tend to attach themselves to the structure under load. No fasteners are required to attach the tees to the shell because they are features of a single structure. This eliminates a potential weak link, i.e. fasteners, from the structure and reduces the tolerance buildup in coil fabrication and assembly. The concept is structurally robust because the thickness of the tee and shell can be tailored to structural requirements. In the localized regions of high curvature, EM loads might tend to pull the winding packs off the tee-shaped structure. Here, local clamps are added for structural support. Adjacent modular coils are bolted together along radial planes to form a strong, toroidally continuous structure.

The coil is wound with flexible, cable conductor, compacted to have a rectangular cross-section and a high volume fraction (78%) of copper. The flexible conductor facilitates winding. The conductor is wrapped with fiberglass and Kapton tape prior to winding. After winding, each coil is vacuum pressure impregnated with epoxy to form a monolithic copper-glass-epoxy composite.

The modular coils operate at high copper current density, up to 16 kA/cm^2, with an equivalent square wave time of approximately 1 s. If the starting temperature of the coils were room temperature (293 K), the coils would experience an adiabatic temperature rise of 157 K during a pulse. By pre-cooling the coils to liquid nitrogen temperature (80 K), the adiabatic temperature rise is reduced to 37 K. Thermal stresses are reduced. Electrical power and energy requirements are also reduced.

The conductor is cooled indirectly through copper straps which are bonded to the outside of the ground wrap and connected to coolant tubes at the end of each winding pack. Although the temperature of the copper in the modular coils may go as high as 125K, the temperature rise at the coolant tube is very small (a few degrees), due to the thermal resistance between the coolant tube and the copper in the winding. This allows a simple, low-pressure liquid nitrogen cooling system to be used without any worry about 2-phase flow. Cooling the modular coils with liquid nitrogen avoids failure modes commonly experienced on fusion devices with water leaks compromising the electrical insulation.

The vacuum vessel fills the internal volume of the modular coils to provide the maximum space for plasma shape flexibility and in-vessel components. The vacuum vessel assembly is constructed of Inconel 625. Inconel was chosen because of its high stiffness and strength, high electrical resistivity, and low magnetic permeability. Ports were added wherever there was space to put one of useful size and orientation, creating substantial viewing access for diagnostics. The vacuum vessel assembly, complete with ports is shown in Figure 3-3. The auxiliary systems duct (also shown in Figure 3-3) provides a cost-effective solution for several needs – neutral beam access, diagnostic access, personnel access to the vacuum vessel interior, and a high conductance path for vacuum pumping. The number of ports and the size of each port are shown in Table 3-1. (Ports that are in the Auxiliary Systems Duct are not included in the tabulation.)

Figure 3-3 Vacuum Vessel Assembly

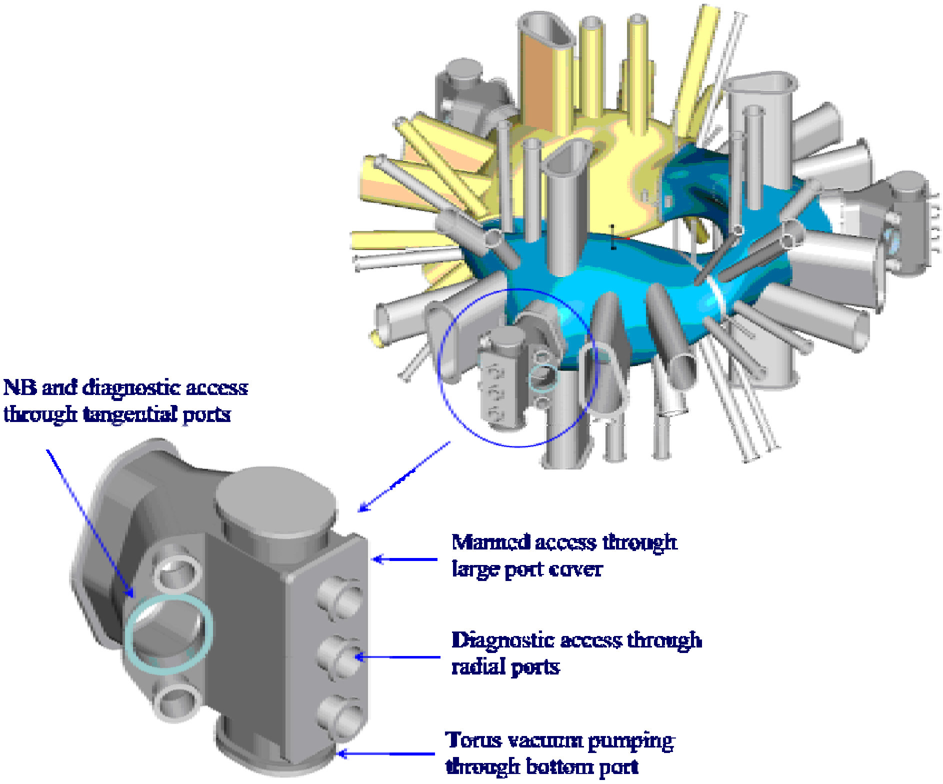


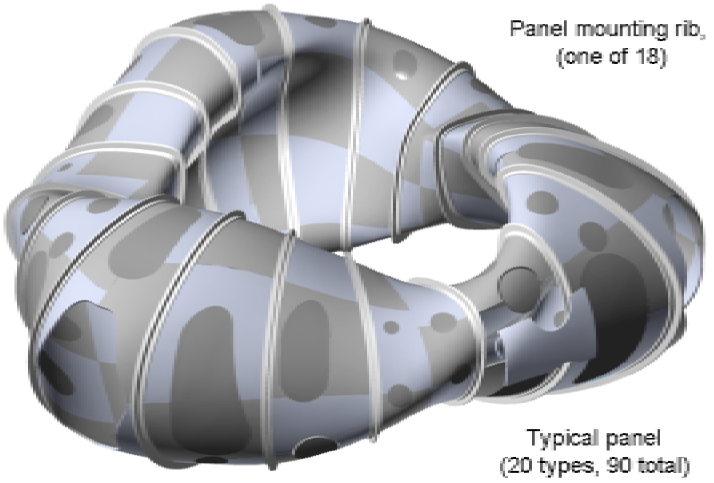
Table 3-1 Number and Size of Vacuum Vessel Ports

Port ID	No. per period	O.D. (inches)	total	Port ID	No. per period	O.D. (inches)	total
2	2	4 .	6	10	2	6 x 6 x 8	6
4	2	12 x 18 x 23.25	6	11	2	6	6
5	2	8	6	12	2	9 x 15 x 17.25	6
6	2	12	6	Neutral Beam	1	33 x 23	3
7	2	8	6	S1	2	2	6
8	2	6	6	S2	1	2	3
9	2	6	6	Total number of ports			72

Initially, discrete limiters will be provided inside the vacuum vessel for the modest heat loads (less than 350 kW) associated with ohmic operation. When auxiliary heating is added, an internal liner that conforms to the vacuum vessel and is constructed of poloidal ribs and carbon fiber composite (CFC) panels, will be added. This concept is illustrated in Figure 3-4. The liner will serve the following functions:

- Provide power handling, neutral recycling control, and impurity control
- Provide for limiter or divertor operation
- Protect the vacuum vessel and in-vessel components from heat loads due to plasma losses and neutral beam shinethrough.

Figure 3-4 Internal Liner Concept for Plasma Facing Components (PFCs)



The vacuum vessel and liner with both be baked to achieve optimal high vacuum conditions. The vacuum vessel assembly, which has temperature sensitive components mounted to it (such as diagnostic windows, trim coils, and Viton seals), will be baked to 150ºC. It will be heated to its bakeout temperature by helium gas circulating through tubes attached to the outside of the vessel shell and port extensions, as successfully demonstrated on NSTX. The liner, which features large CFC panels, needs to be baked to 350ºC. It is supported off the vacuum vessel such that it is free to expand in the radial and vertical directions. It will be separately heated to 350ºC by helium gas circulating through tubes attached to the poloidal ribs, as also demonstrated on NSTX.

The modular coils are supplemented by toroidal field (TF) and poloidal field (PF) coils. An array of 18 identical, equally spaced TF coils provide a 1/R toroidal field of ±0.5T with low ripple. Six pairs of up-down symmetric PF coils provide shape flexibility, plasma position control, and inductive current drive. The TF and PF coils are constructed from conventional, hollow, copper conductor. The current densities in the TF and PF coils result in a small adiabatic temperature rise, less than 10 K. The coils are easily cooled with low pressure liquid nitrogen. A set of field error correction (trim) coils similar to those used for locked-mode suppression in tokamaks (Figure 3-5), was also incorporated to suppress low-order (m=2,3) islands.

Figure 3-5 Ex-Vessel Trim Coils

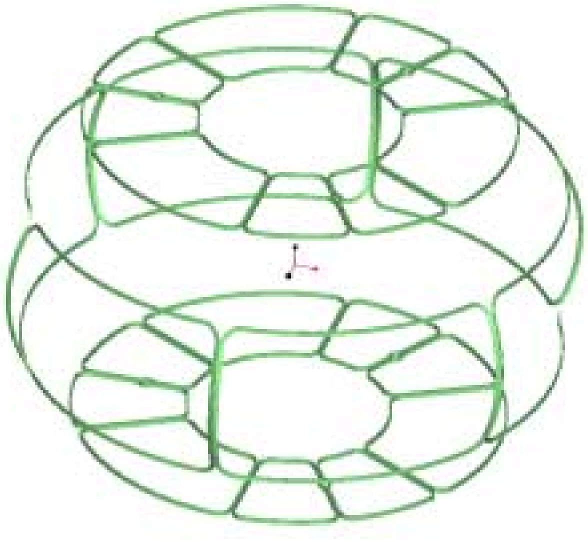
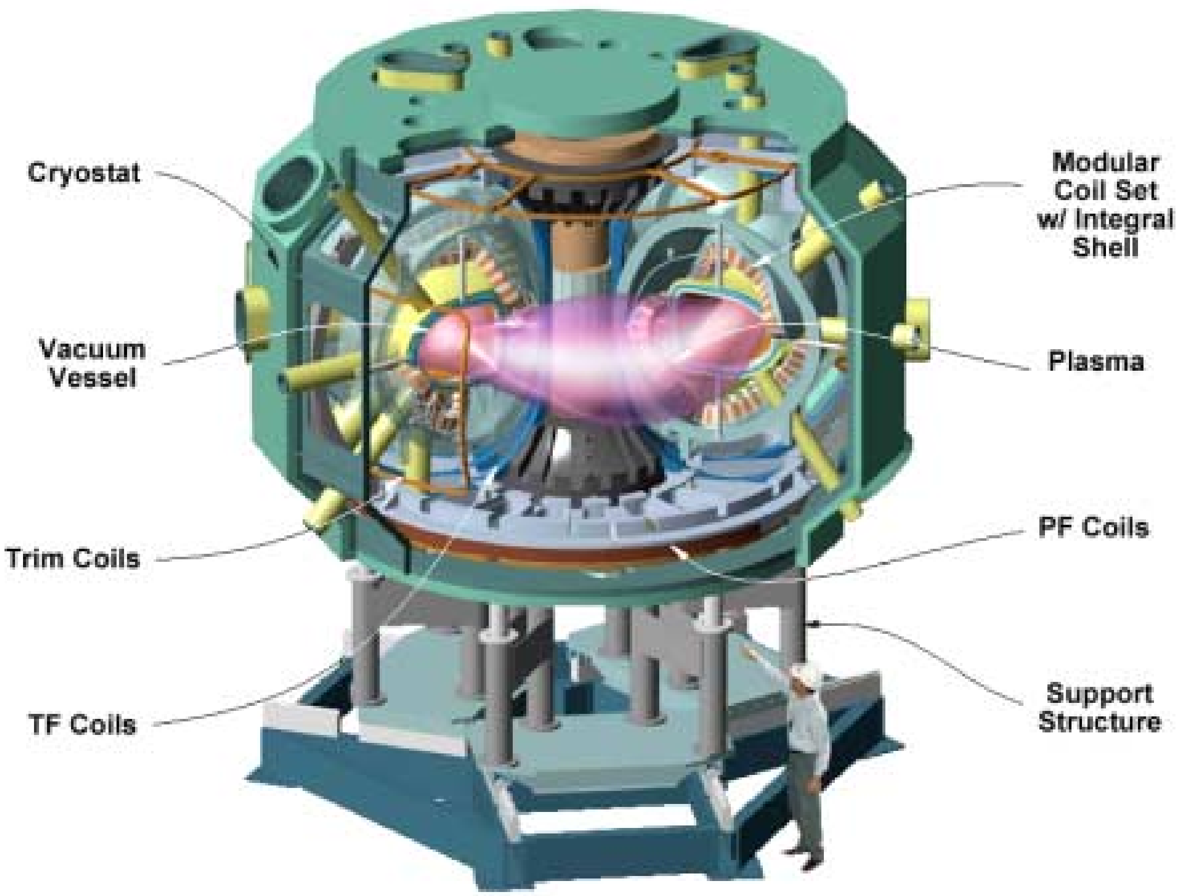


Figure 3-6 Cut-Away View of Stellarator Core



All of the coils – modular, TF, PF, and ex-vessel trim coils – are attached to the coil support structure, as shown in Figure 3-6. Out-of-plane forces on the TF coils are reacted by the upper and lower shelves and the coil support structure around the TF outer legs. The upper and lower shelves are connected through the modular coil assembly. Centering forces on the TF coils are reacted by a bucking cylinder that is part of the central solenoid (CS) assembly. The CS assembly contains the PF1 and PF2 coils. The inner ring coils, PF3 and PF4, are attached to the crown structures that bridge the CS assembly and the upper and lower shelves. The PF5 coils are attached to the upper and lower shelves. The PF6 coils are attached to the coil support structures around the TF outer legs.

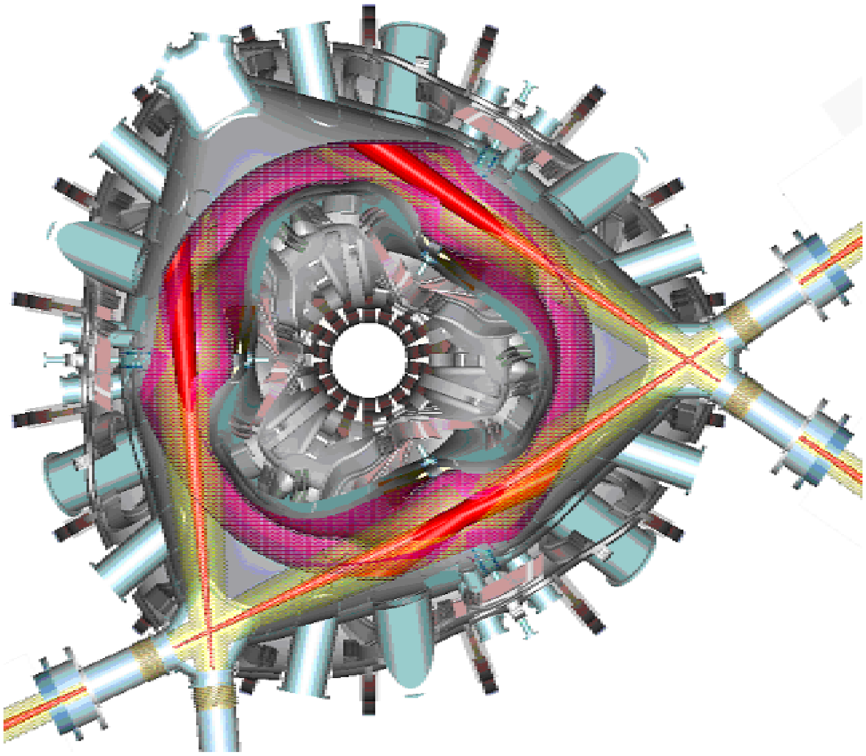
The lower shelf is attached to the machine base structure. This structure allows radial motion, which is needed for assembly of the field periods. Once assembled, the base plate will be secured and seismic supports added. The entire stellarator core is then enclosed in a cryostat built up from fiberglass panels and sprayed urethane foam insulation. The interior of the cryostat is filled with dry nitrogen gas at slightly above atmospheric pressure to avoid the ingress of moisture. The completed stellarator core is shown in Figure 3-6.

3.2 Plasma Fueling, Heating, and Vacuum Pumping

NCSX will capitalize on the equipment available from PBX-M for plasma fueling, heating, and vacuum pumping. The plasma will initially be fueled using gas injection. Provisions will be made for accommodating pellet injection (including an inside launch capability) as a future upgrade.

Auxiliary heating is a basic facility capability that is required for the NCSX mission. Two of the PBX-M beamlines, which are each capable of providing 1.5 MW for 0.3 s, will be installed prior to first plasma. One beam will be oriented for co-injection, the other for counter-injection. The beamlines will be tangent to the plasma near the magnetic axis and, as shown in Figure 3-7, will not directly impinge in the inboard first wall. Neutral beam armor will be added for shinethrough heat loads. The device and facility will accommodate the installation of the remaining two PBX-M beamlines as a future upgrade. The four beamlines can be configured in a 2 co-, 2 counter-injected beam configuration or a 3 co-, 1 counter-injected beam configuration.

Figure 3-7 Neutral Beam Injection Into Plasma



On PBX-M, each of the 4 beamlines was demonstrated to operate with deuterium at 40 keV and 1 MW, to pulse lengths of 0.5 s. In addition, the MAST experiment, which is presently using similar ORNL-style beamlines, is planning to upgrade to 1.5-3 pulse length capability. If successful, NCSX may adopt this technology for long pulse NBI.

NCSX can accommodate up to 6 MW of ICH (as a future upgrade) with a pulse length of 1.2s and frequency of 20-30 MHz. Three launchers will be provided on the inboard side, one at each of the three v=0.5 cross-sections. Space has been allocated for these launchers. Existing RF sources at C-site can be modified to power these launchers.

The device and facility shall be equipped with the four PBX-M 1500 l/s turbo-molecular pumps. The required base pressure is 2×10^{-8} torr. This base pressure was achieved at room temperature during PBX-M operations using the proposed pumping system with a total net pumping speed of 2600 l/s. The pumping port, located at the bottom of the Auxiliary Systems Duct (Figure 3-3), will increase the gas conductance to the 4 turbo-molecular pumps by about a factor of 1.8 above the PBX-M value.

3.3 Diagnostic Systems

The diagnostic systems provide the detailed measurements of the plasma parameters that are critical to the research goals of NCSX. For example, the spatial profiles of electron temperature and density are fundamental inputs needed for nearly all of the envisioned research topics. These systems typically include state-of-the-art instrumentation detecting light or particles from the plasma or plasma facing components, and the supporting interface hardware that provides the required views. The requirements for measurements are derived from the NCSX research program. Table 3-2 lists the research topics in each of the phases of the program, along with the required plasma measurements which need to be added as the program advances in maturity. Also listed are the proposed diagnostic techniques planned to be used to make these measurements.

The diagnostics which are part of the NCSX Fabrication Project, are those needed to verify that the core device has met its engineering goals. These are the diagnostic systems listed in Phases 1 and 2 – the Initial Operation Phase and the Field Mapping Phase. However, it is essential to consider the full complement of diagnostics needed for the research mission, in order to insure that the design of the core machine is consistent with diagnostic requirements.

Viewing concepts for a few diagnostics have been completed already. However, the large number of ports and the total port area appear to be commensurate with diagnostic needs.

Table 3-2 Diagnostic Requirements

research topic	essential new measurements	new diagnostics
1. Initial Operation		
initiate plasma: exercise coil set	plasma current	plasma current Roqowskis
Ip >25 kA	conductivity	flux loops
checkout vacuum diagnostics	plasma position	saddle loops
checkout magnetic diagnostics	total stored energy	B-dot probes
initial wall conditioning		diamagnetic loop
	plasma/wall imaging	fast visible cameras
	line integrated density	1 mm interferometer
2. Field Line Mapping		
map flux surfaces	vacuum flux surfaces	e-beam probe
verify iota and QA	variable energy trace particles	fluorescent rod probe
		high dynamic range CCD
3. Initial Ohmic		
initial plasma control, plasma evolution control	electron density profiles	multichord FIR interf./ polarim.
global confinement & scaling, effect of 3D shaping	electron temperature profiles	Thomson scattering
density limit & mechanisms	radiated power profiles	core foil bolometer array
study of Te and ne profiles.	magetic axis position	compact SXR arrays
vertical stability	low (m,n) MHD (<100kHz)	
current-driven kink stability	flux surface topology	
effect of low-order rat. surf. on flux-surface topology	impurity species	visible spectrometer
initial study of effect of trim coils, both signs	impurity concentration	abs. UV spectroscopy
effect of contact location on plasma edge & recycling	Zeff	filtered 1D CCD camera
initial attempts to control plasma contact location	hydrogen recycling	visible filterscopes
4. Initial Aux. Heating		
plasma control with NB heating and CD		diagnostic neutral beam
test of kink & balooning stability at moderate beta	ion temperature profile	toroidal CHERS
effect of shaping on MHD stability	toroidal rotation profile	
initial study of Alfvenic modes w/ NB ions	poloidal rotation profile	poloidal CHERS
confinement scaling w/ iota, B, …	radial electric field	MSE polarimeter
local transport measurements, perturb. meas.	iota profile	
test of quasi-symmetry on confinement and transport	fast ion loss	fast ion loss probe
density limits and control with heating	ion energy distribution	neutral particle analyser
use of trim coils to minimize rotation damping	neutron flux	epithermal neutron detector
blip measurements of fast ion conf. and slowing down	first wall surface temperature	compact IR cameras
initial attempts to obtain enhance confinement regimes	high frequency MHD(<5Mhz)	high frequency Mirnov coils
pressure effects on surface quality		fast tang. x-ray pinhole camera
controlled study of neoclassical tearing using trim coils		enhanced x-ray tomography
wall coatings with aux. heating	SOL tmperature and density	moveable Langmuir probe
edge and exhaust charact. with aux. heating	neutral pressure	neutral pressure gauges
attempts to control wall neutral influx		
wall biasing effects on confinement		
5. Confinement & beta push		
stability tests at beta >~ 4%	edge/div. radiated power profile	divertor foil bolometer arrays
detailed study of beta limit scaling	divertor recycling	divertor filtered CCD cameras
detailed studies of beta limiting mechanisms	edge temp. and dens. prof.	fast scanning edge probe
disruption-free operating region at high beta	divertor target surface temp.	fast IR camera
active mapping of Alfvenic mode stability (with antenna)		divertor thermocouples
enh. conf.: H-mode, hot ion modes, RI mode, pellets	core helium density	He CHERS system (with DNB)
enhanced confinement, rotation effects	target Te, ne	plate mounted Langmuir probes
scaling of local transport and confinement	divertor impurity concentration	divertor UV spectroscopy
turbulence studies	core density fluct. amp. & spec	fluctuation diagnostics TBD
scaling of power or other thresholds for enh. conf.		
ICRF wave propagation and damping (possible)		
perturbative RF measurements of transport (possible)		
divertor operation optimized for power handling		
trace helium exhaust and confinement		
scaling of power to divertor		
control of high beta plasmas and their evolution		
6. Long Pulse		
long pulse plasma evolution control	more detailed divertor profiles	divertor Thomson scattering
equilibration of current profile		divertor diagnostics (TBD)
beta limits with ~ equilibrated profiles		
edge studies (3nd generation wall)		
long-pulse power and particle exhaust w/ div. pumping		
compatibility of high conf., high beta, and div. ops		

3.4 Electrical Power Systems

The main loads for the Electrical Power Systems come from:

- Stellarator Core Systems. The stellarator core has 3 modular coil circuits, 1 toroidal field (TF) coil circuit, and 5 poloidal field (PF) coil circuits in the initial configuration.
- Neutral Beam Injection (NBI) System. Two beamlines will be installed at the time of first plasma.

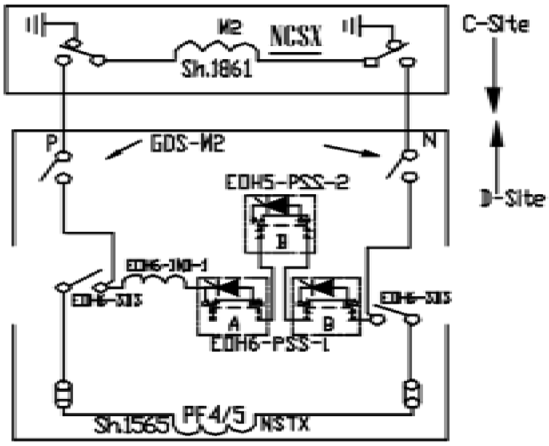
The Electrical Power Systems requirements for the coil systems are derived from the reference scenarios. The Electrical Power Systems are designed to meet the requirements of the Initial Ohmic Scenario and be upgradeable to accommodate the requirements of the remaining reference scenarios.

The existing D-Site DC power conversion equipment will be utilized for NCSX in order to meet the operational requirements of NCSX in a robust and cost-effective manner. D-Site power conversion equipment will be shared with NSTX. The shared circuit arrangement for Modular Coil 2 circuit is shown in Figure 3-8 as an example. DC power will be brought over to C-Site via overhead cables that will be constructed.

Power supply requirements have been calculated for each phase of operation. In each circuit, the maximum current is less than 24 kA. The minimum number of power supply sections (1 kV, 24 kA units) required for the Fabrication Project (Phases 1, 2, and 3) is 30. The number grows to a maximum of 58 for full operational capability.

Maximum active and apparent power requirements and stored energy requirements are well within the capability of the D-site AC power system using the available line power and only a single MG set. The remaining electrical loads, including neutral beams, should be comparable to electrical loads already handled by the C-site AC Power System during PBX-M operation.

Figure 3-8 Modular Coil 2 Circuit Schematic



3.5 Central Instrumentation and Controls

The Central Instrumentation and Control System will provide the remote control and monitoring, diagnostic data acquisition and data management for the various subsystems on NCSX. The system has the following elements:

- The TCP/IP Network Infrastructure will provide a common backbone for all data acquisition, and I&C communications.
- A Central Process Control System will provide supervisory control and monitoring (with a common user interface), to all engineering subsystems and high-energy systems.

- The Diagnostic Data Acquisition System will provide a data management software structure to catalog and manage experimental results for subsequent retrieval and analysis.
- The Facility Timing and Synchronization System will provide preprogrammed event triggers to define the NCSX shot cycle.
- Real time software will provide two functions - Power Supply Real Time Control and Plasma Control.
- The Central Safety Interlock System will provide system wide coordination of personnel and hardware interlocks.
- The Control Room Facility will provide a centralized location for researchers (PPPL physicists, engineers and collaborators) to direct and monitor the experimental operation of NCSX.

The PLT and PBX-M control room areas will be combined for NCSX. The combined area is approximately 2400 sq. ft. Approximately 1400 sq. ft. of the contiguous PLT DAS computer area will be integrated with the main control room for a total of 3800 feet, providing ample space for research and operations staff. Approximately 600 sq. ft. of this space, adjacent to the test cell wall, will be reserved for diagnostic instrumentation racks.

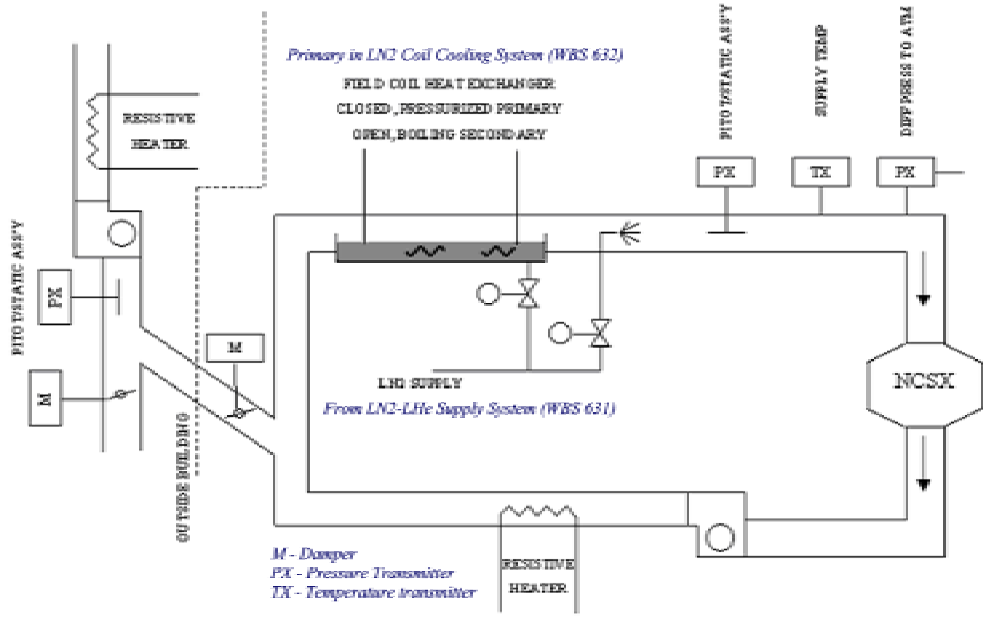
3.6 Facility Systems

Facility systems include water systems, cryogenic systems, utility systems (compressed air, vacuum pump venting and gaseous nitrogen manifolds), and the helium bakeout system.

Cooling water is required for neutral beams, vacuum pumping, the helium bakeout system, and diagnostics. The Fabrication Project includes all the work required to add cooling loops to the existing C-site (CS) and HVAC Water Systems as required for NCSX subsystems.

Coils inside the cryostat are cooled with liquid nitrogen. Heat is removed from the coolant loop through a heat exchanger. Liquid nitrogen is boiled off on the secondary side of the heat exchanger to remove the heat. Structures within the cryostat are cooled by circulating cold nitrogen gas through the cryostat. The boil-off from the secondary side of the heat exchanger serves as a source of cold nitrogen gas for cooling structures within the cryostat. A schematic of the system is shown in Figure 3-9.

Figure 3-9 GN2 Cryostat Cooling System Schematic



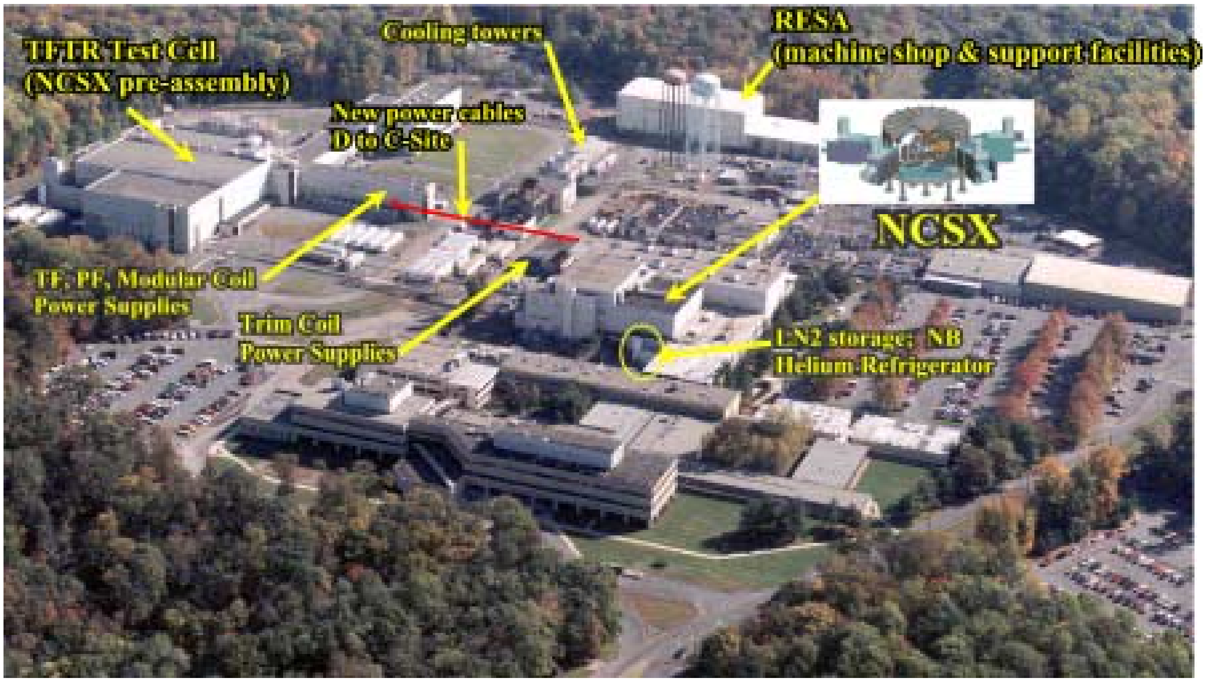
Liquid nitrogen is supplied for cooling the coils and structures inside the cryostat from the liquid nitrogen dewar in the courtyard outside the NCSX Test Cell. The liquid nitrogen dewar has a capacity of about 34 m^3 with an expected peak NCSX demand of about 20 m^3 per day (about 0.8 truck deliveries per operating day).

The NCSX Helium Bakeout System is patterned directly after the system used on NSTX. Initially, the capability to maintain the temperature of the vacuum vessel and PFCs between 25ºC (the normal operating temperature) and 150ºC (for bakeout of the vacuum vessel and other metallic structures inside the vacuum vessel) will be provided. Pressurized helium gas will be circulated to effect temperature control through tubing attached to the outer surface of the vacuum vessel and port extensions. Maximum temperatures in the helium loop will be kept below 175ºC due to the use of elastomer seals. Heat losses through the thermal insulation between the vacuum vessel and the coils and structures (at 80K) are calculated to be 12 kW with the vacuum vessel at 150ºC. The system will be upgraded to Initial Auxiliary Heating to heat the internal liner to 350ºC.

4 SITE PREPARATION, ASSEMBLY, AND TESTING

NCSX will be sited at C-site at PPPL. The NCSX Test Cell will be the same Test Cell first used for the C-Stellarator and subsequently used for the PLT and PBX-M tokamaks. The three field periods will be pre-assembled in the TFTR Test Cell prior to final assembly in the NCSX Test Cell. The modular coils will also be wound in the TFTR Test Cell. Figure 4-1 shows the location of the Test Cell and other facilities at PPPL that will support the fabrication and operation of NCSX.

Figure 4-1 NCSX Facility Locations



All work activities associated with the NCSX Project will be performed in accordance with Princeton Plasma Physics Laboratory (PPPL) Engineering and ES&H Procedures and Directives. A summary of these is provided below:

- Integrated Safety Management (ISM). All work activities will be completed using the guiding principles of ISM. This is an adopted DOE approach to doing work safely. All personnel involved will be trained to using this approach.
- Job Hazard Analysis (JHA). Line managers and workers will generate JHAs to identify existing or potential workplace hazards and to evaluate the risk of worker injury or illness associated with job tasks. A JHA will be generated for all work activities associated with the preparation, fabrication and assembly of the NCSX device. (Reference document ESH-014 “Job Hazard Analysis”)
- Engineering Work Package (EWP). Engineering Work Packages (EWP) will be utilized for used for consolidation of documentation and accountability for tasks being performed in the field. An EWP is a package, which contains all pertinent documentation necessary to complete an activity. The package will contain approved RUN copies of the procedures, pertinent Job Hazard Analysis, permits, drawings etc.
- Installation Procedures. Procedures will be generated for the installation and removal of all major components and systems. These procedures will be generated, reviewed and approved in accordance with Engineering procedure ENG-030 “PPPL Technical Procedures for Experimental Facilities”.

- Safety Procedures. All work will performed in accordance with PPPL ES&H Directives and Procedures.
- Pre-Job Briefings. A pre-job briefing will be held prior to the start of any new work activity. The purpose of the briefing will be to discuss specific work activities, responsibilities of the participants, a review of the JHA/safety issues, and to respond to all questions and concerns. The participants at these briefings should include all individuals who will be involved with the activity including lead technician, field crews, and supervisors. Representatives from construction safety, Industrial Hygiene, Health Physics and Quality Control will be included as required.
- Post-Job Briefings. A post-job briefing will be held at the conclusion of a work activity. The purpose of the briefing will be to discuss the completed work activities. It should include lessons learned including technique problems, improvements and safety related issues. The participants at these briefings should include all individuals involved with the completed activity or procedure. It should include the lead technician, field crews, and supervisors. Representatives from construction safety, Industrial Hygiene, Health Physics and Quality Control will be included as required.
- Training. Training of personnel is the key to completing the NSCX fabrication safely. Courses will offered for all personnel, instructing them in the proper use of tools and equipment; personal protective equipment (PPEs); and general laboratory policy and safety requirements.

To ensure that all field activities are conducted safely, a full time Construction Safety Representative will be utilized throughout the construction phase. Representatives from Industrial Hygiene, Health Physics, and Quality Control will provide support as required.

4.1 Facility Modifications and Test Cell Preparations

The Test Cell, Test Cell basement and control rooms are in the process of being cleared. These areas and the adjoining rooms to be utilized by the NCSX Project will be received equipped with the required:

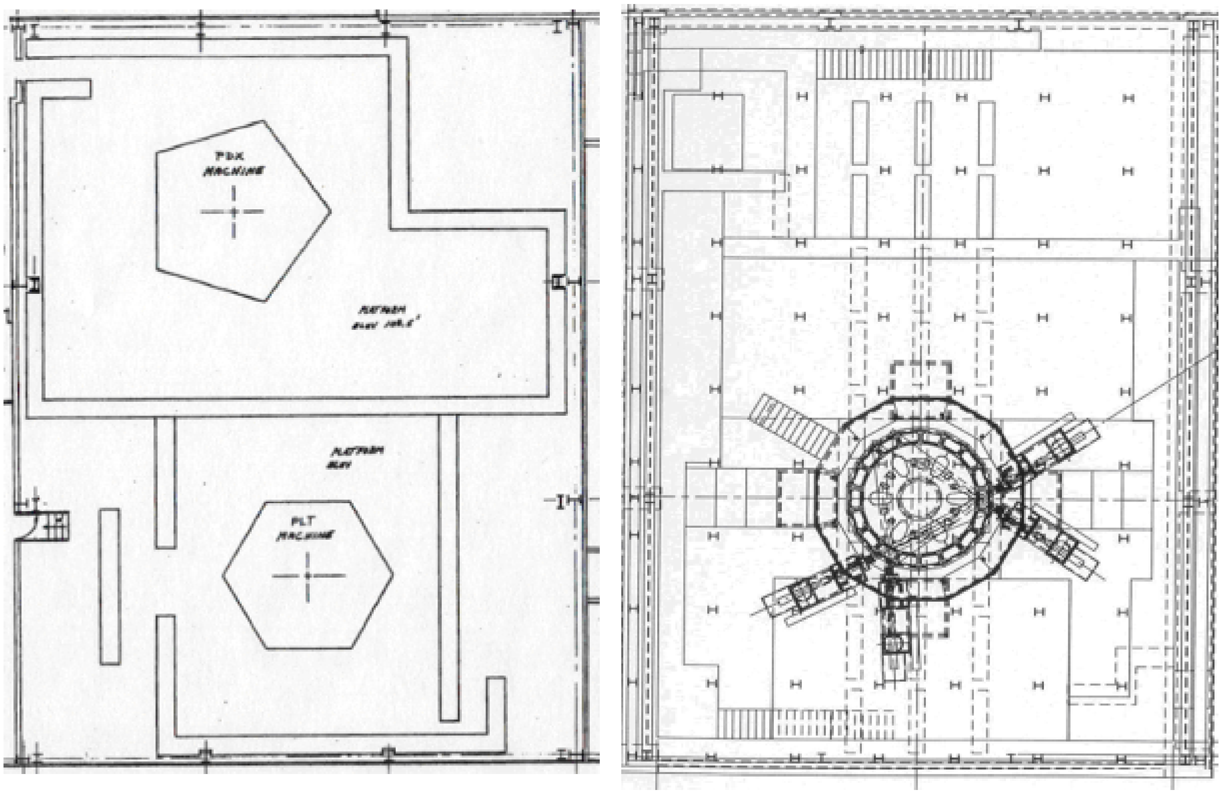
- Shelter from the environment (roofing and walls)
- Lighting
- Environmental (temperature, humidity, and air exchange) control
- Fire suppression

Three changes will be made, as part of the NCSX Project, to the shield walls in the Test Cell:

- The shield walls will be relocated, combining the two experimental areas for PLT and PBX-M into a single, spacious area for NCSX;
- The height of the shield walls will be raised to reduce radiation exposure during operations; and
- The shield walls will be seismically reinforced to meet current code requirements.

The new layout, shown side-by-side with the previous layout in Figure 4-2, will provide an effective experimental area, with space for unloading equipment upon entering the Test Cell area, an open hatch for crane access to the basement, and three ways of emergency egress from the Test Cell.

Figure 4-2 Reconfigured Shield Walls in Test Cell



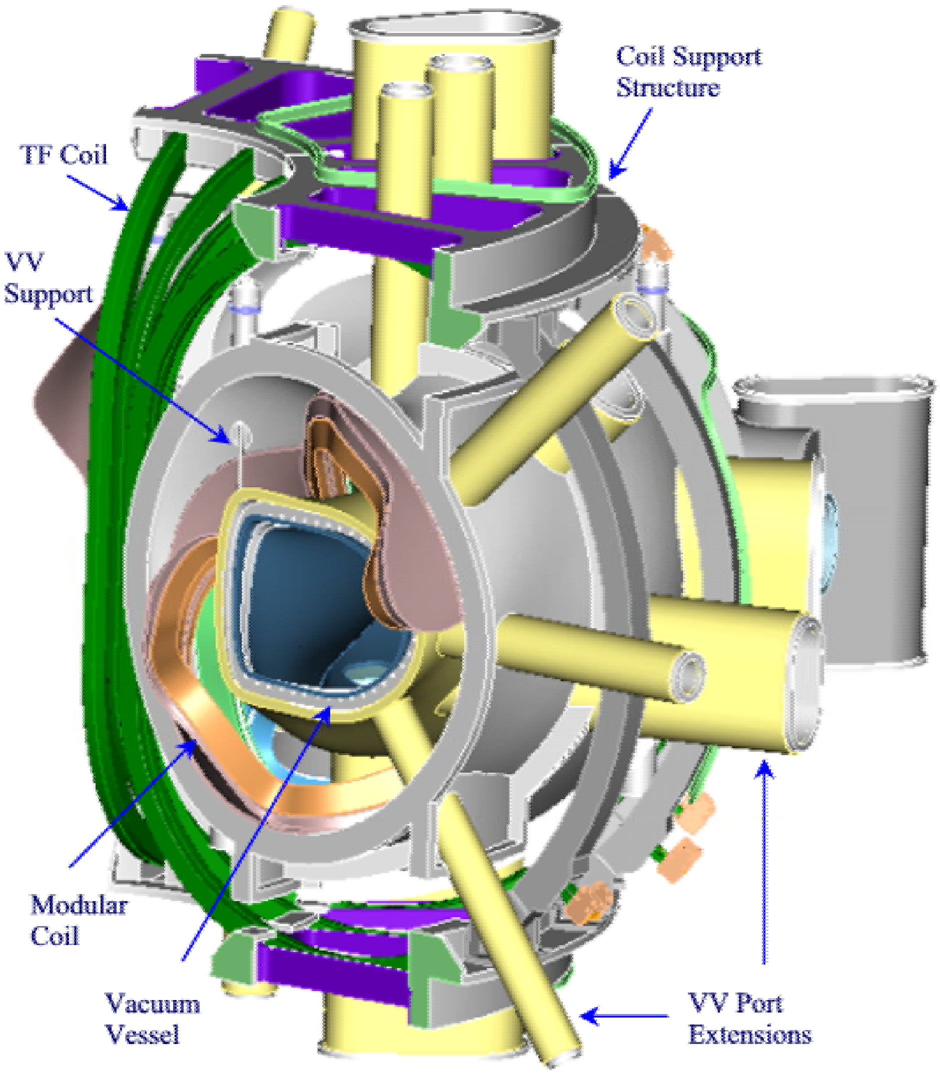
4.2 Machine Assembly and Testing

The three field periods will be pre-assembled as individual units, and then transported to the NCSX Test Cell for final machine assembly. The present plan is to utilize the TFTR Test Cell at D-site for assembling the three field periods. The TFTR Test Cell was selected because of its large open floor space, crane capacity, abundant electrical power, good lighting, and ventilation control. Ample floor space is provided for assembly of several field periods in parallel, without interfering with preparation and final assembly activities in the NCSX Test Cell.

The first step will be to place the vacuum vessel segment into an assembly fixture that will position and support the vacuum vessel to allow three of the modular coils to be slid over the VV and assembled from one end. The remaining three modular coils will be then assembled from the opposite end of the vacuum vessel. It will be necessary to temporarily support the vacuum vessel inside of the modular coils until the vacuum vessel supports have been installed.

The TF coils and coil support structure will be pre-assembled in two 60º segments, with three TF coils per segment. Once the modular coils have been joined with the VV, the TF coil and coil support structure segments will be added to the field period assembly. Port extensions will be welded onto each VV segment. The ports and ends of the vacuum vessel will be sealed and a vacuum leak check performed. Then, the field period will be readied for transport to the NCSX Test Cell. The assembled field period is shown in Figure 4-3.

Figure 4-3 Assembled Field Period



Prior to installation of the first field period in the NCSX Test Cell, all of the shield walls will be installed except for the area in front of the receiving area. Leaving this area open will allow larger components, such as the field periods, to be lifted with greater ease. Following installation of the shield walls, the machine base structure will be positioned, leveled, and mounted on the Test Cell floor.

Once the machine support structure has been installed, the installation of the platform around the machine will begin. Three-quarters of the platform will be installed. The northeast section of platform will not be installed to facilitate setting the field periods on the machine base structure. The field periods enter the Test Cell from the northeast corner overhead door via a lowboy trailer and will be raised into position using the 30-ton overhead crane.

Each of the three field periods will be delivered and positioned on the machine support structure. The support structure was designed to allow the field periods to be moved radially together. The three field periods will be carefully slid together and the vacuum vessel segments fastened together using appropriate hardware from inside of the vacuum vessel. Once the vacuum vessel segments are joined, the modular coils and machine support structures will be joined.

Once the last field period has been delivered to the Test Cell, the remaining sections of the machine platform will be installed. The completed platform is 9 feet off the floor of the Test Cell, allowing easy access underneath. The platform will provide a good working area at the level of the machine, especially for diagnostics. The platform will be modular in design, similar to the NSTX platform, allowing for fabrication of standard parts and minimizing costs. The platform will have exit stairways in the southeast and northwest corners of the Test Cell. A 5-foot wide walkway will extend completely around the machine at the platform level and connect via a catwalk to the entrance of the Control Room. The last sections of the shield wall in front of the receiving area can also be completed at this time.

The vacuum pumping duct will be connected to the vacuum vessel so that the vacuum integrity of the vacuum seals can be verified. Once these tests have been completed, the vacuum vessel will be vented and the remaining components assembled. The beamlines can be connected to the vacuum vessel. The lower PF coils will be raised into position. This will be followed by the installation of the PF solenoid assembly, which includes the upper and lower PF1 and PF2 coils. Once these have been secured to the coil support structure, the upper PF coils will be installed.

Next, the top and side walls of the cryostat are installed. The remaining installation of coil bus and cable runs, helium gas bakeout lines, water cooling lines, liquid nitrogen lines, and diagnostics can be completed. Upon completion of all subsystem testing, the machine is now ready for Integrated Systems Testing, which includes the first energization of the coil systems and first plasma.

5 DESIGN BASIS

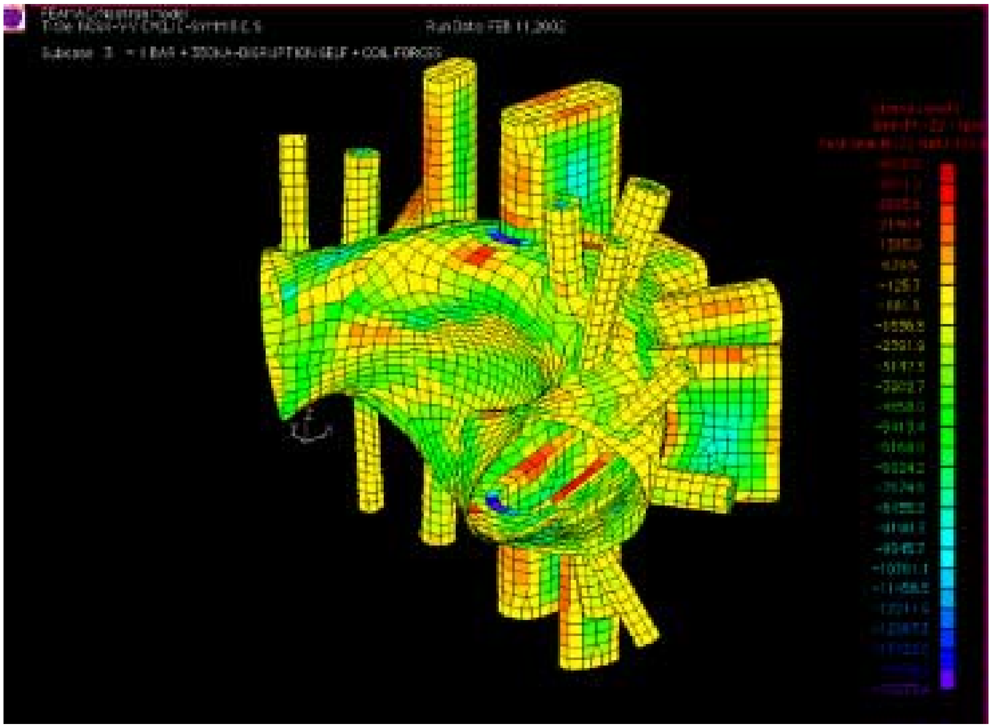
Extensive engineering analysis has been performed to underpin the design of the stellarator core. The extensive re-use of existing equipment and facilities minimizes the engineering analysis effort required outside the stellarator core. Analyses of the stellarator core include:

- Buckling and stress analysis of the vacuum vessel under atmospheric and disruption loads
- Stress analysis of a conformal CFC liner under disruption loads
- Field, force, and stress analysis of the modular coils under electromagnetic loads
- Thermal analysis of the modular coil windings
- 2-D thermal modeling of the modular coil winding pack and surrounding structure
- Thermal-hydraulic modeling of liquid nitrogen coolant paths
- Transient electromagnetic analyses to determine vacuum vessel time constant
- Analysis of field errors from coil windings and construction errors

The results of these analyses are very encouraging – no significant problems have been encountered in achieving the required machine capabilities. A more complete discussion of the analysis results may be found in the **Stellarator Core Systems Description**, included as part of the Conceptual Design Report.

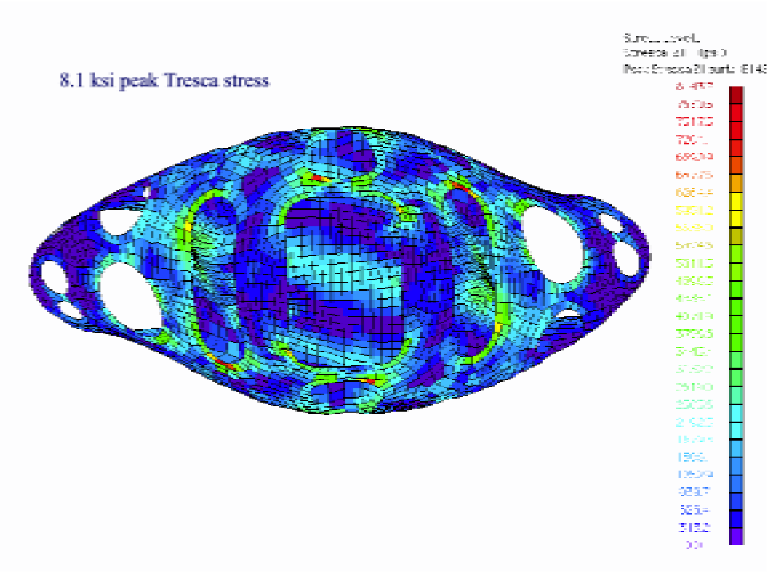
In the vacuum vessel, relatively moderate stresses were found for the various loading conditions investigated, including the disruption of a 350 kA plasma. The peak stress intensity is 17.5 ksi, occurring at the vessel shell/support bracket intersection. Safety factors on stress allowables for the Inconel 625 material are generally 1.6 or greater and margins on buckling exceed those required in the ASME Boiler & Pressure Vessel Code. The nominal 0.375” thickness for the Inconel 625 shell appears to be ample.

Figure 5-1 Minor Principle Stresses in VV Under 1 Atm Pressure and 350 kA Disruption Loading



A disruption analysis was also conducted for the conformal CFC liner. The liner was represented as a simple 1" shell with cutouts. Material properties were based on material properties for CFC material. The peak stress of 8.1 ksi was highly localized near one of the large cutouts, as shown in Figure 5-2. This could be reduced if necessary, through stiffening of the edges. While this model is simplistic and does not feature details such as poloidal ribs or discrete tiles, it does provide confidence that a design solution for a conformal shell can be developed in the future.

Figure 5-2 Tresca Stress Distribution on CFC Liner



Modeling of the modular coils was done, accurately representing the complex geometry of the winding and shell support structure. A picture of the FEA model is shown in Figure 5-3.

Forces were calculated for the coil currents at each of the breakpoints in the reference scenarios. The largest forces on the modular coils appeared to occur at the t=0 point in the 2T High Beta Scenario. Subsequent analysis was based on these coil currents. It is recognized that the full range of loading conditions needs to be analyzed; however, this appeared to be the most prudent starting point. Analysis of the force distribution on the winding indeed showed that lateral forces were always in the direction of the tee, except in very localized regions of sharp curvature.

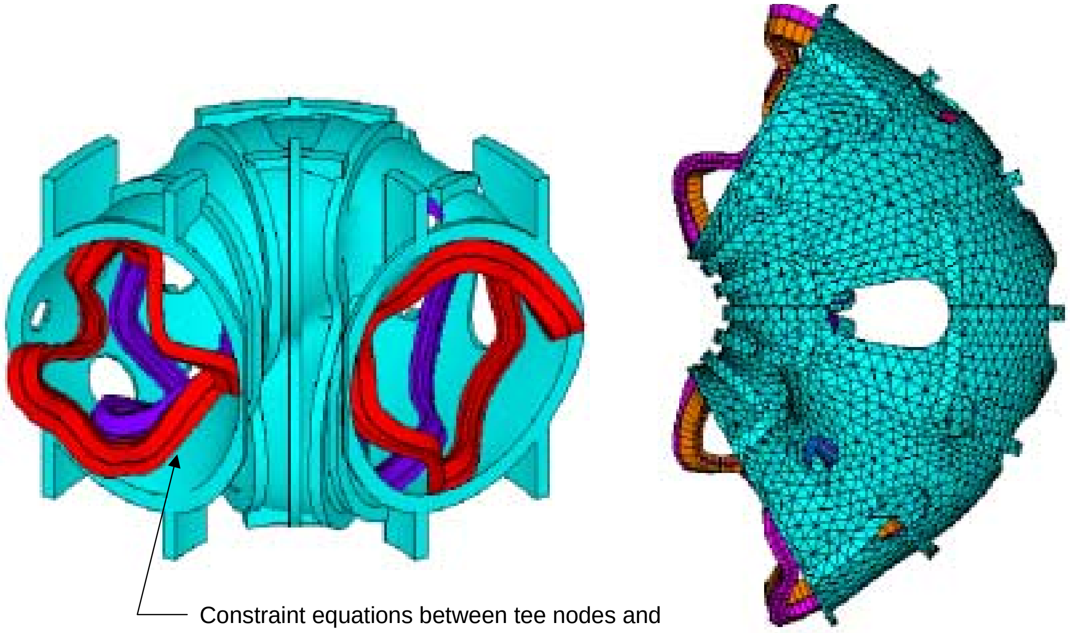
For the stress analysis, assumptions had to be made regarding the elastic modulus of the copper-glass-epoxy composite winding pack. The analysis considered two cases: [1] the modulus was assumed to be 5% of the modulus of copper, and [2] the modulus was assumed to be 50% of the modulus of copper. Preliminary R&D indicates that the actual modulus is in between these limits, around 10% of the modulus of copper. This approach provides bounding results for the winding pack (stresses are highest when the assumed modulus is high) and shell and tee structures (stresses are highest when the assumed modulus is low).

Maximum displacements were calculated to be around 0.5mm, occurring at the top of the shell structure. Maximum stress intensities are summarized in Table 5-1. Contour plots of stress intensities are provided in Figure 5-4 and Figure 5-5.

Table 5-1 Modular Coil Stress Intensities

Winding Pack Modulus (MPa)	Shell (ksi)	Coil (ksi)	Tee (ksi)	Spacer (ksi)
65500	12.7	7.2	20.2	1.8
6550	13.0	2.6	32.1	2.2

Figure 5-3 FEA Model of Modular Coil Winding and Shell



NCSX will benefit from the improved strength of stainless steel at cryogenic temperatures. Allowables for the shell are derived from the properties of the cast material, which is assumed similar to SS317. W-7X features modular coil casings made from a cast stainless steel material (G-X2CrNiMoN 18 14) that appears well suited for NCSX. The material has a minimum yield at 77K of ~79 ksi and a minimum tensile strength of ~137 ksi, based on the test data provided by Osterby Gjuteri AB and shown in Figure 5-6. The design stress value (S_m), the lesser of 2/3 of the minimum yield and ½ of the tensile strength for this material would be 52 ksi. This would be the allowable stress intensity for general primary membrane stresses in the base material (not near welds). The maximum stress intensity seen in the stress analyses is well below this value – 13 ksi in the shell and 32 ksi in the tee.

Work remains to be done in selecting and characterizing a material for the shell and in performing a more detailed stress analysis in the regions of highest stress. However, the initial calculations, which show peak stresses in the structure that are well below expected allowables, are very promising.

Under EM loads, the calculated maximum stress intensity in the winding pack is in the range of 2.6-7.2 ksi. Design allowables for the winding needs to be determined by testing because of the composite nature of the material. However, the modest maximum stress intensity calculated for EM loading is expected to be within allowables.

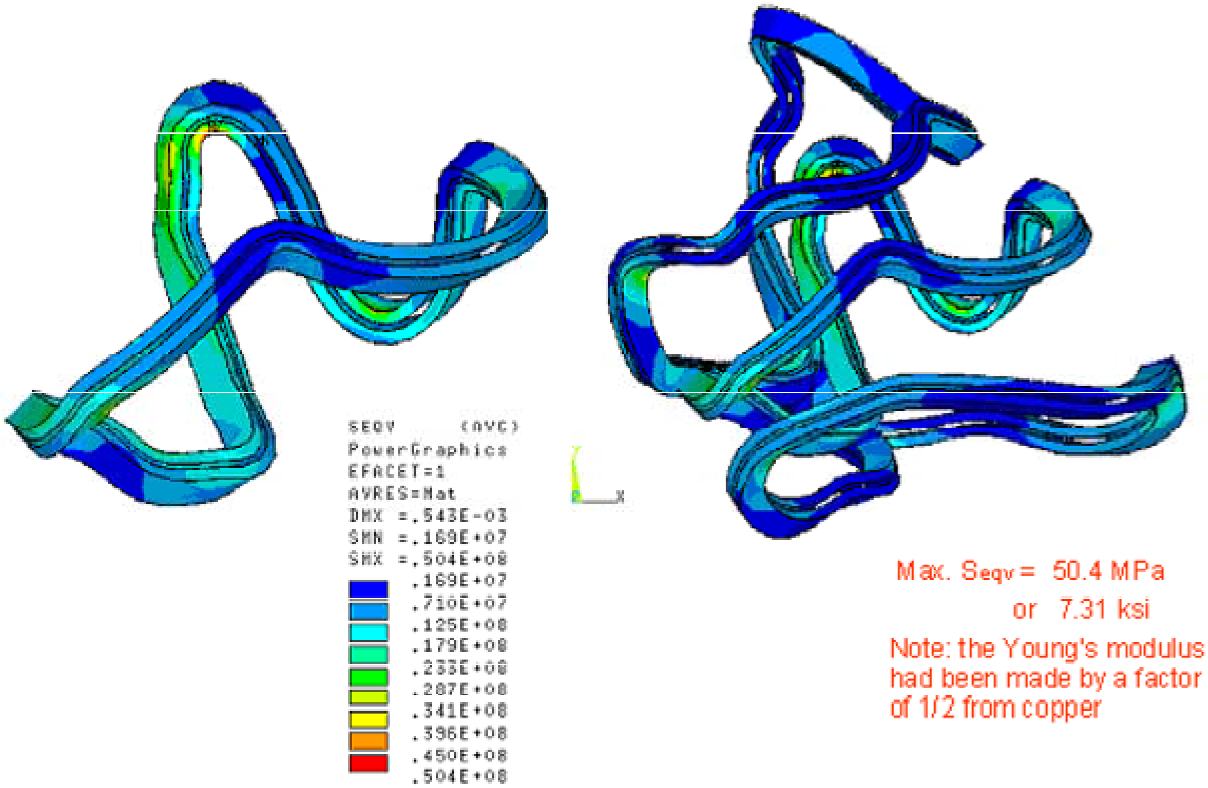
Thermal stresses will arise in the winding pack due to the sudden increase in temperature relative to the structure during a pulse. Sudden temperature rises of up to 40K are planned. Preliminary stress analyses indicate that the maximum thermal stress will be less than 2 ksi, assuming a modulus of 13100 MPa (10% that of copper). The areas where the winding pulls away from the tee appear to be very localized, with a total deflection less than 0.03”. The behavior of the winding pack under thermal loads is an issue that the Project is planning to address in the R&D program in FY03.

A 2-D thermal analysis of the coil cool-down has been performed. It appears that the modular coils can easily be cooled down from a peak temperature of 125K to 85K in 15 minutes assuming a LN_2 coolant temperature of 80K. The temperature distributions immediately after a pulse and 15 minutes later are shown in Figure 5-7.

A thermo-hydraulic analysis was performed for all three coil systems (PF, TF, and modular coils). The coils can easily be cooled with LN2 in a closed loop system with an inlet temperature of 80K and pressure of 200 psi and a total flow rate of 46 gpm. The pressure drops in the coolant loops are less than 10 psi in the modular coils and 2 psi in the TF and PF coils. The temperature rise in the coolant loops is small, typically only a few degrees Kelvin. It appears that with additional optimization, the flow rate and pressure drop in the modular coils could be significantly reduced.

Structural analysis of the TF and PF coils is presently underway. However, they are low field systems of conventional design and construction with a great deal of available space should design modifications be required. There is high confidence of being able to develop a robust design solution for these conventional systems, even if the initial results were not within allowables.

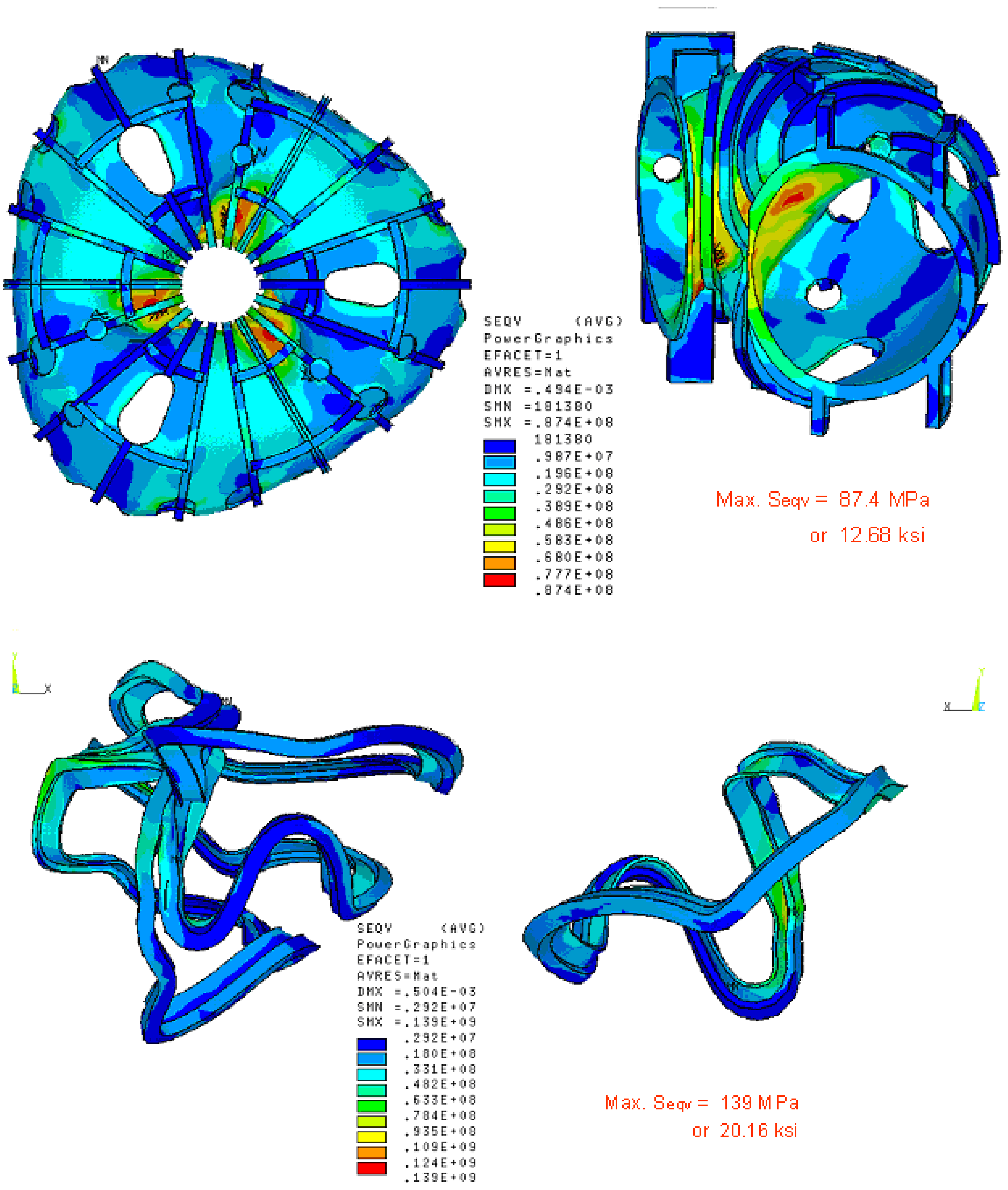
Figure 5-4 Modular Coil Winding Stress Intensity



Max. S_{eqv} = 50.4 MPa or 7.31 ksi

Note: the Young's modulus had been made by a factor of 1/2 from copper

Figure 5-5 Modular Coil Stress Intensities in Shell and Tee



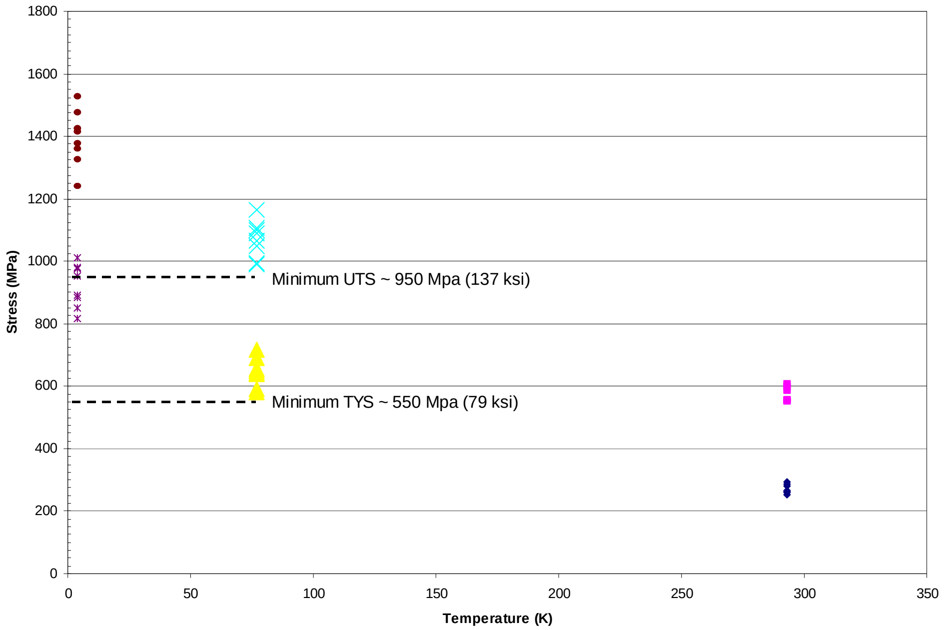


Figure 5-6 Test Data From W-7X Coil Casings

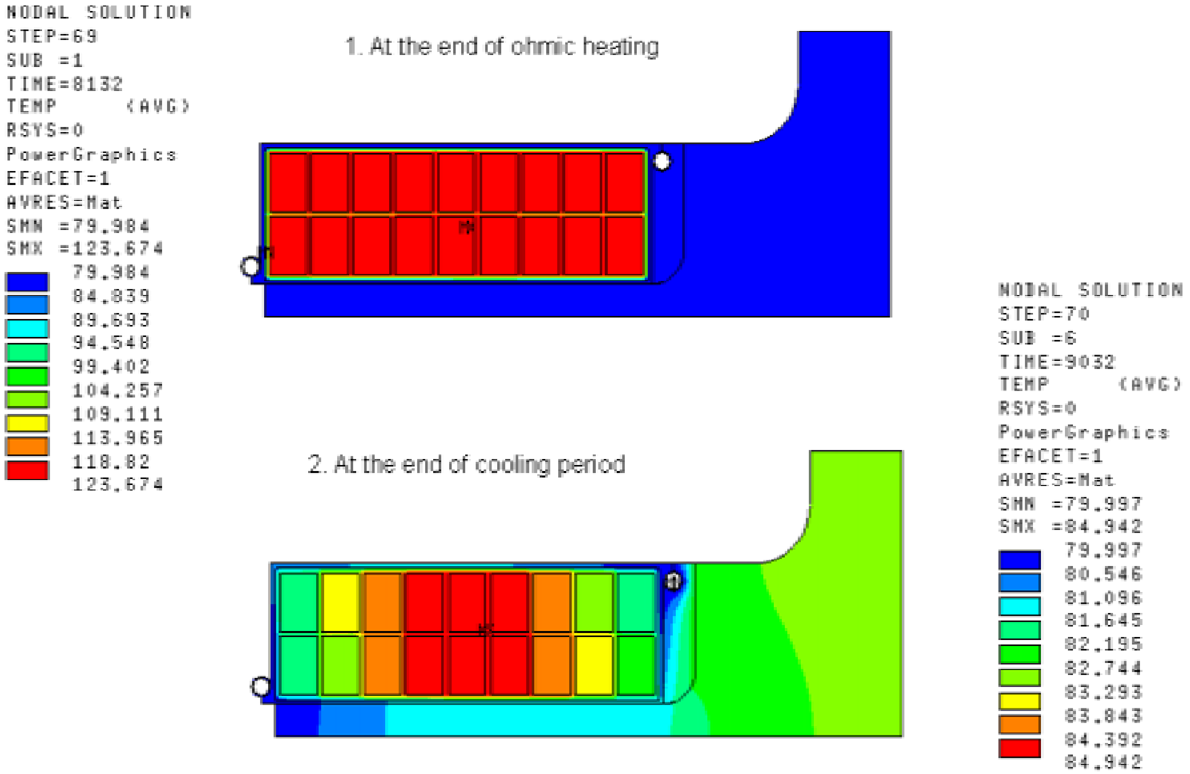


Figure 5-7 Cool-Down of Modular Coils Between Pulses

A transient, electromagnetic analysis of the vacuum vessel was performed to determine the time constant of the vacuum vessel. The calculated longest time constants for decay of toroidal and poloidal currents were both 5 ms, well below the upper limit of 10ms. The 10 ms limit was set to avoid having kink instabilities being masked by stabilizing eddy currents in the vacuum vessel. The short time constant should be very beneficial for quickly ramping the plasma current to generate broad or hollow current profiles.

Control of field errors is a critical requirement in the design of the stellarator core. Islands can form as a result of field errors due to the presence of low m symmetry-preserving and symmetry-breaking resonances, and the requirement for a flexible operating space which increases the number of resonances that can be encountered. Thus, control of field errors has been a high priority in the design process. Islands are virtually nonexistent, as achieved by appropriate shaping of the modular coils. However, there are many potential sources of field errors that must still be considered. On NCSX, we have gone to extreme lengths to mitigate potential sources of field errors:

- Preserving stellarator symmetry. Stellarator symmetry is being rigidly preserved in the design of the stellarator core. This avoids designing in n/m=1/2 and n/m=2/3 field errors.

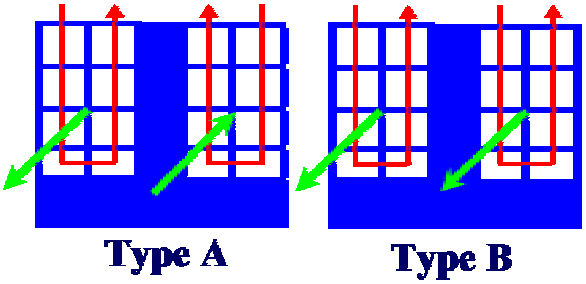
- Avoiding magnetic materials. Magnetic materials in the stellarator core are being studiously avoided. The vacuum vessel is being constructed of Inconel 625, which is non-magnetic, even in the weld regions. The shell in the modular coil assembly is a low permeability, stainless steel casting. On W-7X, a magnetic permeability on the modular coil casings of less than 1.01 was achieved.

- Minimizing weld distortions. No welding is required in the assembly of NCSX other than the Inconel port extensions, thereby minimizing the potential for weld-induced distortions.

- Minimizing time constants in surrounding structures. The time constants in the structures surrounding the plasma will be minimized to reduce the magnitude and duration of eddy current flowing in those structures and the resulting field errors. High resistivity material (Inconel 625) is used in the vacuum vessel. The structures outside the vacuum vessel will feature electrical breaks in at least six toroidal locations.

- Using coaxial leads (or equivalents). The leads for all of the coils inside the vacuum vessel and cryostat will be fed by current leads with very low field errors, either coaxial leads or multi-conductor leads with equivalently low field error contributions at the plasma. The connection between the leads and the conductor is also critical for field errors.

- Optimizing the winding design. Each modular coil consists of two winding packs, one on each side of the tee. Each winding pack consists of two layers. Layer-to-layer transition regions will be localized. The winding packs will be wound such that the field errors introduced by the current loops formed by the layer-to-layer transitions, cancel each other (Type A) rather than reinforcing each other (Type B). This "opposing double-layer construction" will be applied to the TF and PF windings also. It requires that the number of layers in each coil be a multiple of four. All coils except PF4 and PF6 presently satisfy this constraint.



- Minimizing conductor size and current. Minimizing the conductor size and current are both favorable for reducing field error contributions. Smaller conductor size means that transitions and lead connections can be more compact. Smaller conductor current means that the field error from a given transition or lead connection is smaller. Conductor sizes and currents for the modular coils are already at their minimum. The number of turns in the TF and PF coils will be adjusted to minimize field error and also to optimize matching with the power supplies once the structural and thermal analysis of those components has been completed.

- Minimizing tolerance buildup. Each time two things are connected, there is a tolerance on their relative position, and it becomes harder to control the overall tolerance. In the design of the modular coils, the surfaces against which the coils are wound and the flat, radial planes on which adjacent modules are joined, are machined into the same part.
- Minimizing displacements under load. The modular coils are connected together to form a thick, continuous, toroidal shell. The windings are continuously supported by the tee and shell. Maximum displacements in the shell under EM loads are small, under 0.5mm.
- Utilizing state-of-the-art measurement techniques. Components cannot be positioned more accurately than their position can be measured. NCSX will be assembled at PPPL using state-of-the-art mechanical and laser measurement systems that can accurately measure position to sub-millimeter accuracy.

Even after these measures have been taken, construction errors still represent a potential source of field errors. A preliminary study of the sensitivity of plasma surface quality to coil construction and assembly errors, including the effectiveness of correction coils to compensate for such errors, was performed. New tools were developed, incorporating approximate methods that make it possible to evaluate island widths efficiently, including the effects of symmetry-breaking perturbations and correction coils. The tools were benchmarked against the PIES code for symmetry-preserving cases and found to be in good agreement. Over five hundred perturbations, representing possible coil construction and assembly errors, were analyzed. It was found that such perturbations could excite low-order (m=2,3) islands, as expected, but that they are readily corrected with a system of field error correction coils similar to those used for locked-mode suppression in tokamaks. Other findings include:

- Errors in modular coils have a much larger impact on field errors than do errors in TF or PF coils
- Systematic perturbation of all modular coils of a given type is not much worse than a single coil
- The effectiveness of in-vessel trim coils (m=5, m=6) in conjunction with ex-vessel trim coils (m=1, m=2) should be further investigated
- Softening the tolerances on TF and PF coils should also be investigated

The array of trim coils used to suppress the m=2 island should be very useful (Figure 3-5). Current requirements are modest and the leads for all coils will be accessible for maximum flexibility in their electrical configuration. These trim coils complement the m=5 and m=6 trim coils, which are planned to be installed inside the vacuum vessel as a future upgrade, if required.

6 DESIGN IMPLEMENTATION

Implementation of the ancillary systems should be straightforward. Many of these will take advantage of the existing equipment and facilities at PPPL. The work in these areas typically involves refurbishing and reinstalling hardware with which the engineers and technicians are already familiar. New equipment is commercial, off-the-shelf (COTS) equipment, so industrial methods for assembly, installation, and test apply. Systems such as the Central I&C and Helium Bakeout Systems, will be patterned after similar systems recently installed on NSTX, thereby facilitating the design implementation.

Clearly, the difficulties and risks in design implementation revolve around the stellarator core. There are two components whose manufacturability and constructability are special concerns – the vacuum vessel and the modular coils. The vacuum vessel is a highly shaped structure that must withstand pressure and disruption loads and provide an ultra-high vacuum in its interior. Existing modular torsatrons such as W-7AS and HSX faced significant challenges in getting similar vessels designed and built. The NCSX vacuum vessel will also be challenging to build. The modular coils are also highly shaped, with large forces and strict dimensional tolerances. The Project needs to verify that the modular coils too, can be affordably built.

The other components in the stellarator core – the TF, PF, and ex-vessel trim coils; and the coil support structure – do not pose the level of concern. All of the coils are planar and constructed with conventional, hollow copper conductor. The coil support structure would likely be fabricated as castings with minimal machining required. The Project plans to issue two Requests for Proposals (RFPs) – one for the coils and one for the structure – for the fabrication of those components. Both will be fixed price procurements with no R&D.

The NCSX Project developed an acquisition strategy for the vacuum vessel and modular coils that was aimed at getting industry involved at the earliest opportunity in the design of these critical components. The strategy featured 3-stages of industrial involvement:

- Manufacturing studies,
- Manufacturing R&D, and
- Production of final articles.

The manufacturing studies were performed during Conceptual Design and involved the following tasks:

- Recommending a manufacturing process
- Identifying design changes to make the product more readily manufactured
- Recommending appropriate R&D and prototyping activities
- Providing a budgetary cost and schedule estimate for the production vessel
- Reviewing the product specification and recommending appropriate changes

Contracts for these studies were awarded in the fall of 2002. There were four contracts awarded for the vacuum vessel: Hitachi, Mitsubishi Heavy Industries, Major Tool, and INTERM (a Ukrainian consortium). Four contracts awarded also for the modular coils: Hitachi, Mitsubishi Electric, Ansaldo, and Osterby Gjuteri. In addition, a contract was awarded to Atlas Foundry & Machine to investigate casting of both the modular coil winding form and the vacuum vessel. The participants did an outstanding job in responding to their charge. It was encouraging to know that such well-qualified companies are interested in participating in the manufacturing of NCSX components. All of the foreign companies had previous stellarator experience. The domestic companies did not have stellarator experience, but they demonstrated a quick grasp of the technical issues and impressive manufacturing capabilities.

Numerous manufacturing processes were studied for the vacuum vessel, including (hot and cold) press forming, explosive forming, investment casting, and other methods. Press forming was the method of choice for most of the participants. All of the vendors agreed that fabricating the Inconel vacuum vessel in the shape and thickness specified was technically feasible with the equipment in their facilities.

Numerous suggestions to improve the manufacturability of the design were offered. Manufacturing R&D requirements were identified. It does not appear that fabrication of an entire 120º segment of the vacuum vessel is necessary, but development and demonstration of the critical processes are necessary. These include:

- Forming the highly shaped panels to the required dimensions
- Welding the panels together with acceptably low distortion
- Joining the port stubs to the vessel shell

Budgetary cost and schedule estimates were provided. The Project developed composite cost and schedule estimates based on the supplier input, which have been incorporated in our overall cost and schedule estimate.

A competitive procurement is planned for the next phase, manufacturing R&D. Two contracts will be awarded early in FY03. Awarding two contracts for manufacturing R&D has the following advantages:

- Fosters competition among suppliers for the production contract
- Provides an opportunity for the Project to better understand the capabilities of the potential suppliers and evaluate the proposals for the production contract
- Provides an opportunity to get input from two suppliers instead of one on design specifications and design improvements.

The penalty for going this route is the cost of the second contract for manufacturing R&D. Following completion of the manufacturing R&D, a single production contract will be awarded.

The manufacturing studies for the modular coils were also profitable. Osterby Gjuteri and Atlas Foundry and Machine focused on casting and machining of the winding form. Ansaldo focused on coil winding and impregnation. Two of the vendors, Mitsubishi Electric and Hitachi, provided manufacturing studies as integrated manufacturers, addressing winding form fabrication and subsequent coil winding and impregnation.

All of the vendors agreed that casting the winding form, machining it to the specified tolerances, winding the conductor, and vacuum impregnating the winding appear feasible. Numerous suggestions were made on how to improve the manufacturability of the design. Creative ideas were proposed for vacuum pressure impregnation.

The vendors were in accord that a complete coil, preferably the most challenging of the three coil types, should be produced as part of the manufacturing R&D. Budgetary cost and schedule estimates were provided for the modular coils.

Our plans for the modular coil procurement were strongly influenced by the manufacturing studies. It became clear that an attractive option would be to wind the coils in-house at PPPL. PPPL has a wealth of experience winding coils. Winding the coils with the flexible conductor appears well within PPPL's capability. Industry did not appear to offer any special advantage in capability or experience for coil winding, and carried extra costs. If the coils were wound at PPPL, it avoids the risk of passing finished coil winding forms from one industrial supplier to another for coil winding because of potential contractual problems if delivery dates were missed.

For these reasons it was decided that the project will procure the winding forms from industry and wind the coils at PPPL. This gives the Project direct control of two important risk elements: quality and schedule. The possibility of hidden problems in the winding pack is reduced by the project taking direct responsibility for the manufacture. If the winding forms were delivered late, we could wind the coils on two shifts per day if necessary to recover schedule delays that might impact first plasma. Composite cost and schedule estimates were developed, based on the information provided in the manufacturing studies and this revised approach, and incorporated in the overall Project cost and schedule estimates.

A competitive procurement for the modular coil winding forms is planned for the next phase, manufacturing R&D. Two contracts will be awarded early in FY03 for the same reasons cited for the vacuum vessel. Following completion of the manufacturing R&D, a single production contract will be awarded.

Manufacturing R&D for the coil winding and impregnation to be conducted at PPPL will also be initiated in FY03. The finished winding forms will be delivered to PPPL. The modular coils will be wound onto them in the TFTR Test Cell, where pre-assembly of the field periods will take place.

7 COST AND SCHEDULE

7.1 Methodology

Inputs for the cost and schedule estimates were received from industry in the manufacturing studies of the modular coils and vacuum vessel. Separate vendor inputs were received for other components, such as the TF and PF coils and coil support structure. Recent procurements and work on NSTX for similar systems (particularly the Central Instrumentation and Control System, Electrical Power Systems, Helium Bakeout System, and Diagnostic Systems) provided valuable, detailed cost and schedule information. Past work on PBX-M provided a basis for estimating labor hours for refurbishing and reinstalling PBX-M equipment, such as the Neutral Beam System and Torus Vacuum Pumping System.

The cost and schedule estimates were developed using the Primavera database and scheduling software. Labor was input in hours and the non-labor (e.g., M&S, travel, etc.) was input in direct dollars. Since the majority of procurements will be handled by PPPL Procurement, a PPPL-specific MHX G&A rate was applied. However, both ORNL and PPPL provided labor rates by labor type and the projected escalation factors to be used. This information was input into the Primavera database so appropriate rates and escalation could be applied by year of expenditure.

Linkages between tasks were input and the critical path as identified. Resources were shifted where possible to achieve a spending profile that approximated the overall DOE guidance.

A standardized approach for developing contingency was utilized. The contingency estimate was developed by assessing risks and assigning weighting factors in three areas: technical, cost, and schedule. This approach has been utilized on major DOE construction projects and, most recently, on NSTX.

Details supporting the summary cost estimates were provided by the WBS Managers and are available in the Cost and Schedule Document.

7.2 Project Cost

The Total Estimated Cost (TEC) is $72M in year-of-expenditure dollars. A summary of the cost by WBS and by phase is provided in Table 7-1. A **Project Cost Summary** is provided as part of the Conceptual Design report.

The dominant cost element, representing more the half (51%) of the TEC (before contingency), is the Stellarator Core (WBS 1), which costs $28.6M. Within the Stellarator Core, the Modular Coils (WBS 17) is the single largest cost element at $16.9M, or 59% of the cost of the Stellarator Core.

One reason the Stellarator Core is such a large fraction of the TEC is due to the many assets at PPPL that are being re-used in the ancillary systems and facilities, including:

- The NCSX experimental complex (test cell, basement, control rooms, and adjoining rooms for mechanical and electrical equipment)
- The TFTR Test Cell for coil winding and pre-assembly of field periods
- 3 MW 50 keV Neutral Beam System
- 30 D-Site power supplies
- Four 1500 l/s turbomolecular pumps from PBX-M
- Water systems and cryogenic storage and supply systems
- Sophisticated measuring systems for machine assembly including a Leica laser scanner and a Faro mechanical measuring arm

The contingency of $15.7M represents 28% of the TEC (before contingency).

Table 7-1 Project Cost Summary

WBS		R&D	Design	Fabrication & Assembly	Installation & Test	Total
11	**PFCs**	$14,937	$110,096	$134,572		$259,605
12	**Vacuum Vessel**	$670,552	$508,256	$3,661,042		$4,839,850
13	**TF**		$196,911	$1,299,554		$1,496,464
14	**PF**		$500,225	$1,346,455		$1,846,680
15	**Cryostat**		$189,642	$320,614		$510,256
16	**Support Structure**		$492,938	$1,752,500		$2,245,438
17	**Modular Coils**	$3,929,992	$1,264,754	$11,733,659		$16,928,406
18	**Trim Coils**		$56,905	$221,580		$278,485
19	**LN2 Distribution**		$107,841	$105,645		$213,486
1	**Stellarator Core**	$4,615,481	$3,427,569	$20,575,621		$28,618,671
21	**Fueling**		$35,907	$4,800	$101,459	$142,166
22	**Vacuum Pumping**		$77,007	$129,603	$88,861	$295,471
23	**Wall Conditioing**		$69,118	$1,600	$28,059	$98,777
25	**Neutral Beams**		$558,346	$810,350	$299,722	$1,668,417
2	**Auxiliary Systems**		$740,378	$946,352	$518,100	$2,204,831
3	**Diagnostics**		$1,066,469	$1,358,545		$2,425,014
4	**Electrical Power**		$1,238,456	$1,246,401	$2,942,048	$5,426,905
5	**Central I&C**		$777,039	$3,220,013		$3,997,052
61	**Facility Modifications**		$140,925	$158,658	$443,439	$743,023
62	**Water Cooling**		$123,721		$156,227	$279,948
63	**Cryogenic Systems**		$103,803	$262,257	$332,258	$698,318
64	**Utility Systems**		$29,334		$62,112	$91,446
65	**Helium Bakeout**		$135,351	$170,441	$237,479	$543,271
66	**Facility Sys Integration**		$153,052			$153,052
6	**Facility Systems**		$686,186	$591,356	$1,231,516	$2,509,058
7	**Machine Assembly**		$525,969	$1,250,356	$2,384,743	$4,161,068
81	**Project Mgmt & Control**		$3,070,174			$3,070,174
82	**Project Engineering**		$2,099,690			$2,099,690
84	**Project Physics**		$504,933			$504,933
8	**Project Oversight & Support**		$5,674,797			$5,674,797
9	**Integrated Systems Testing**				$461,603	$461,603
	Allocations					$852,849
	Contingency					$15,668,100
	Grand Total	$4,615,481	$14,136,863	$29,188,644	$7,538,011	$71,999,949

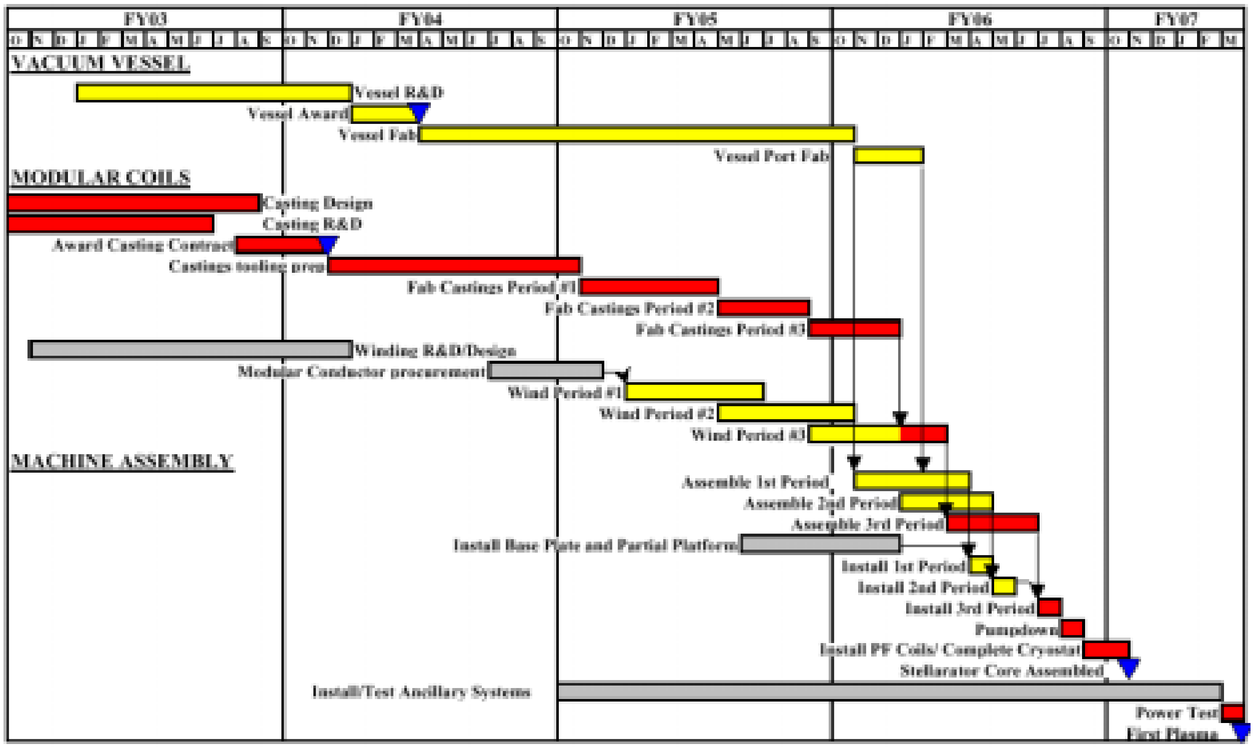
7.3 Project Schedule

The Fabrication Project will begin on October 2002 at the start of FY03. First Plasma is scheduled for March 2007. The critical path is shown in Figure 2-1. The critical path runs through the:

- Design and fabrication of the modular coil winding forms,
- Winding of the modular coils in the 3rd field period,
- Pre-assembly of the 3rd field period in the TFTR test cell,
- Installation of the 3rd field period in the NCSX Test Cell, and
- Completion of the stellarator core assembly.

In order to keep this schedule, it is essential that manufacturing R&D and Title I and Title II design for the modular coil winding form be completed in FY03. There is four months of schedule contingency (slack) between the scheduled completion of final assembly and the start of integrated systems (power) testing. Winding of the modular coils in the 2nd field period and delivery of the 3rd vacuum vessel segment are close to being on the critical path. In order to keep on schedule, it is essential that manufacturing R&D and Title I and Title II design for the modular coil winding form be completed in FY03.

Figure 7-1 Critical Path Schedule



The **Project Master Schedule** is provided as part of the Conceptual Design Report.

8 RISK MANAGEMENT

There are three types of risk that the Project has to manage: technical, cost, and schedule risk. On NCSX, these risk elements are greatest in the modular coils.

Controlling field errors is the most significant technical concern. NCSX is taking "belt and suspenders" approach to this issue. In an effort to keep field errors from arising, we are:

- Seeking to understand what construction errors are most important to control, in order to develop cost-effective tolerance specifications
- Optimize the design and fabrication, assembly, and measurement procedures to minimize the buildup of tolerances.

For those field errors that do get built into the device, NCSX will optimize the design of trim coils that will be effective in suppressing any serious islands that might arise.

Stresses in the winding pack are a technical concern because there is still significant uncertainty in the stress levels and allowable stresses. The models generated so far have been fairly coarse and simple. Improved models will continue to be developed. Initial R&D tests to determine the stiffness of the conductor indicated that the stiffness was much less that would be calculated assuming a simple mixture rule, which was very encouraging. R&D will be conducted in FY03 to accurately determine the mechanical properties of the winding pack. The maximum temperature rise has been limited to 40K in an effort to keep thermal stresses low. Tests will be conducted in FY03 on a winding constrained by a tee-shaped structure to determine thermal stress limits.

A third technical concern is whether the manufacturers can actually build the winding forms to specified tolerances at an affordable cost. To mitigate this risk, the Project will sponsor a manufacturing R&D program with two vendors to build the most difficult coils.

The most significant cost risk also lies with the modular coils; in particular, in the fabrication of the cast and machined winding forms. The manufacturing R&D program will assist the Project in generating a design that can be readily manufactured. Having a competitive procurement for the production contract should provide a cost benefit. The Project has an overall contingency of 28% to help manage cost risk.

The critical path runs through the modular coils. Again, the manufacturing R&D program should provide much useful information on how long the coil winding forms will take to fabricate. Having the coils wound at PPPL builds in schedule contingency, because the coil winding operation can go to two or more parallel paths and multiple shifts to recoup time lost due to late deliveries. The Project also has 4 months of schedule contingency (slack time) between the completion of the stellarator core and the start of integrated systems testing and First Plasma.

In summary, the significant risks are seen with the modular coils. The Project is taking prudent measures to mitigate those risks.