# NCSX
# Specification

# System Requirements Document (SRD)
# For the
# Modular Coil System (WBS 14)

**NCSX-BSPEC-14-00**

**24 Sep 2004**

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**Record of Revisions**

| Revision | Date | ECP | Description of Change |
|---|---|---|---|
| Rev. 0 | 9/24/2004 | - | Initial issue |

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# 1 SCOPE

The National Compact Stellarator Experiment (NCSX) is an experimental research facility that is to be 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.

A primary component of the facility is the stellarator core, an assembly of four coil systems that surround a highly shaped plasma and vacuum chamber. The four coil systems include the modular coils, the poloidal field (PF) coils, the toroidal field (TF) coils, and the external trim coils. These coils provide the magnetic field required for plasma shaping and position control, inductive current drive, and error field correction.

## 1.1 Document Overview

This document, the System Requirements Document (SRD) for the Modular Coil System (WBS 14), is the complete development specification for this subsystem excluding the Modular Coil Winding Facility and Fixtures (WBS 144), which does not include experimental systems. (Requirements for the Modular Coil Winding Facility and Fixtures (WBS 144) will be separately derived.) Performance requirements allocated to this subsystem in the system specification, the General Requirements Document (NCSX-GRD-01), have been incorporated in this document. **In this document, the term "the system" refers to the overall device and facility and the terms "the subsystem" and "modular coils" refer to the Modular Coil System (WBS 14) excluding the Modular Coil Winding Facility and Fixtures (WBS 144).**

The specification approach being used on NCSX provides for a clear distinction between performance requirements and design constraints. Performance requirements state what functions a system has to perform and how well that function has to be performed. Design constraints, on the other hand, are a set of limiting or boundary requirements that must be adhered to while allocating requirements or designing the system. They are drawn from externally imposed sources (e.g., statutory regulations, DOE Orders, and PPPL ES&H Directives) as well as from internally imposed sources as a result of prior decisions, which limit subsequent design alternatives.

## 1.2 Incomplete and Tentative Requirements

Within this document, the term "TBD" (to be determined) indicates that additional effort (analysis, trade studies, etc) is required to define the particular requirement. The term "TBR" (to be revised) indicates that the value given is subject to change.

## 2 APPLICABLE DOCUMENTS

The following documents form a part of this specification to the extent specified herein. In the event of a conflict, the contents of this specification shall be considered a superceding requirement.

### 2.1 NCSX Documents

Project Execution Plan (NCSX-PLAN-PEP-01)

General Requirements Document (NCSX-ASPEC-GRD-01)

Stellarator Core Systems (WBS 1) WBS Dictionary (NCSX-WBS1-02)

Structural and Cryogenic Design Criteria

Seismic Design Criteria

Grounding Specification for Personnel and Equipment Safety

Reliability, Availability, and Maintainability (RAM) Plan

# 3 SUBSYSTEM REQUIREMENTS

## 3.1 Subsystem Definition

The modular coil set consists of three field periods with 6 coils per period, for a total of 18 coils. Due to symmetry, only three different coil shapes are needed to make up the complete assembly. The coils are connected electrically with three circuits in groups of six coils, according to type. Figure 3-1 shows the general arrangement of the coils and structure.

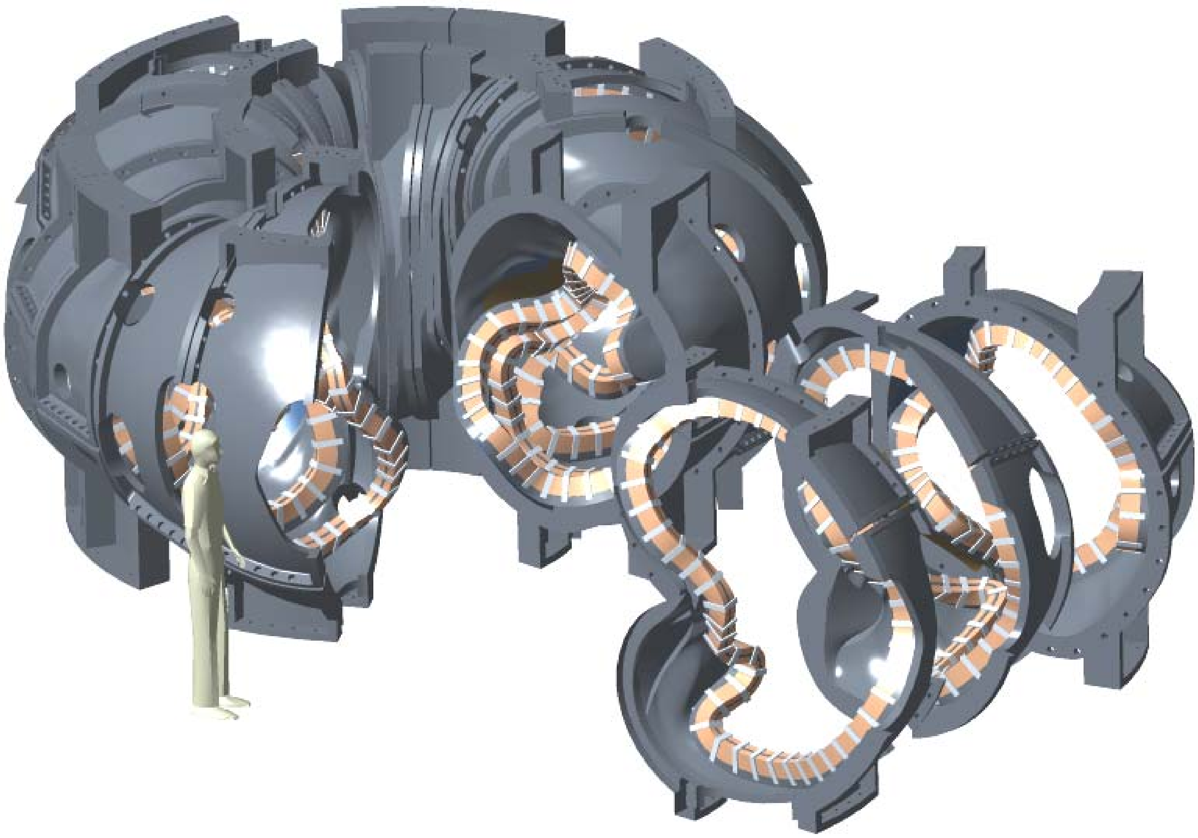

**Figure 3-1 General arrangement of the modular coil system**

Each coil has a structural shell known as the modular coil winding form (MCWF), to which it is attached. Each coil has associated with it local instrumentation and control (I&C), liquid nitrogen ($LN_2$) cooling tubes, and clamps which hold the coils to the MCWF. Poloidal electrical breaks are provided in each MCWF. Within a field period, toroidal electrical breaks are provided between adjacent coils.

### 3.1.1 Subsystem Diagrams

#### 3.1.1.1 Functional Relationships

A block diagram of the Modular Coil System and its environment is depicted in Figure 3-2.

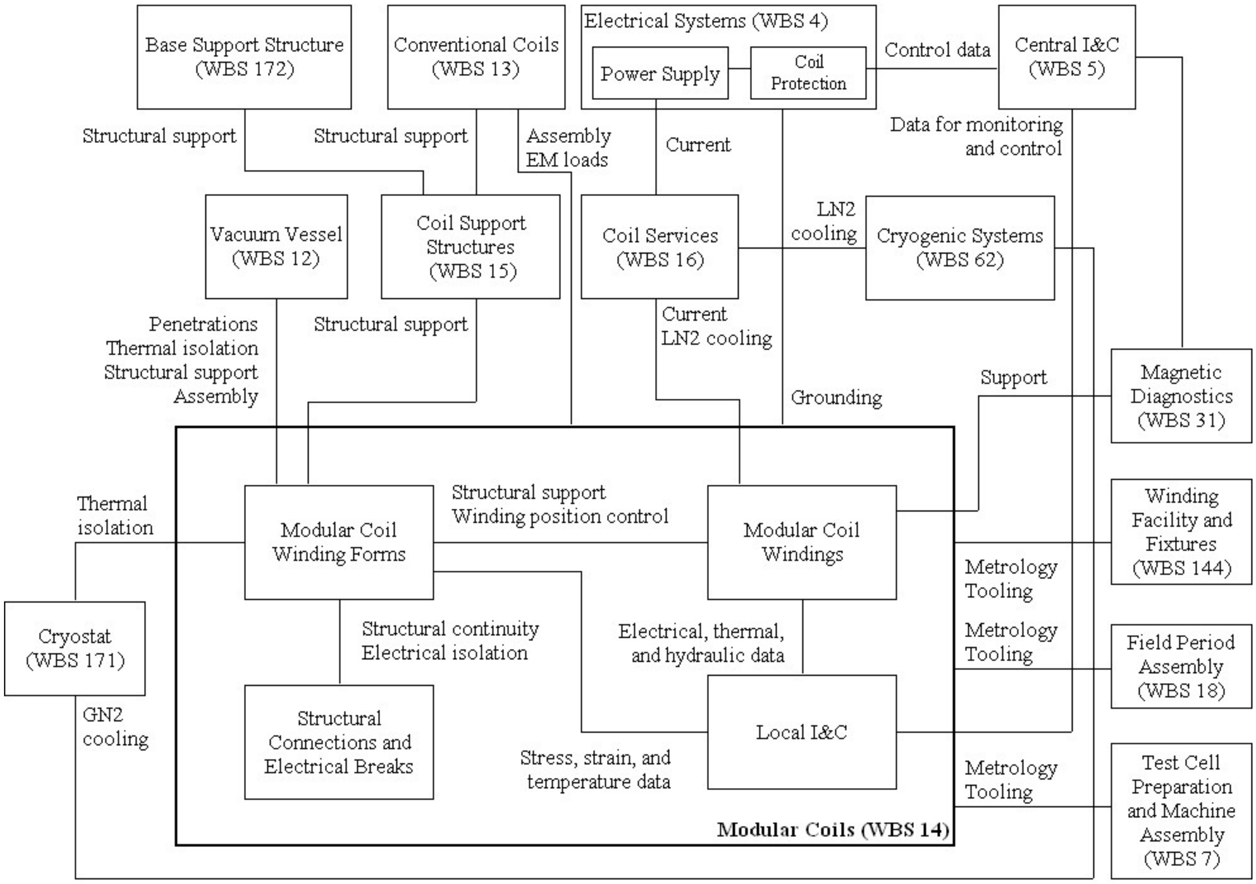


**Figure 3-2 Modular coil system functional relationships**

#### 3.1.1.2 Functional Flow Block Diagram

A functional flow block diagram (FFBD) is provided in Figure 3-3.

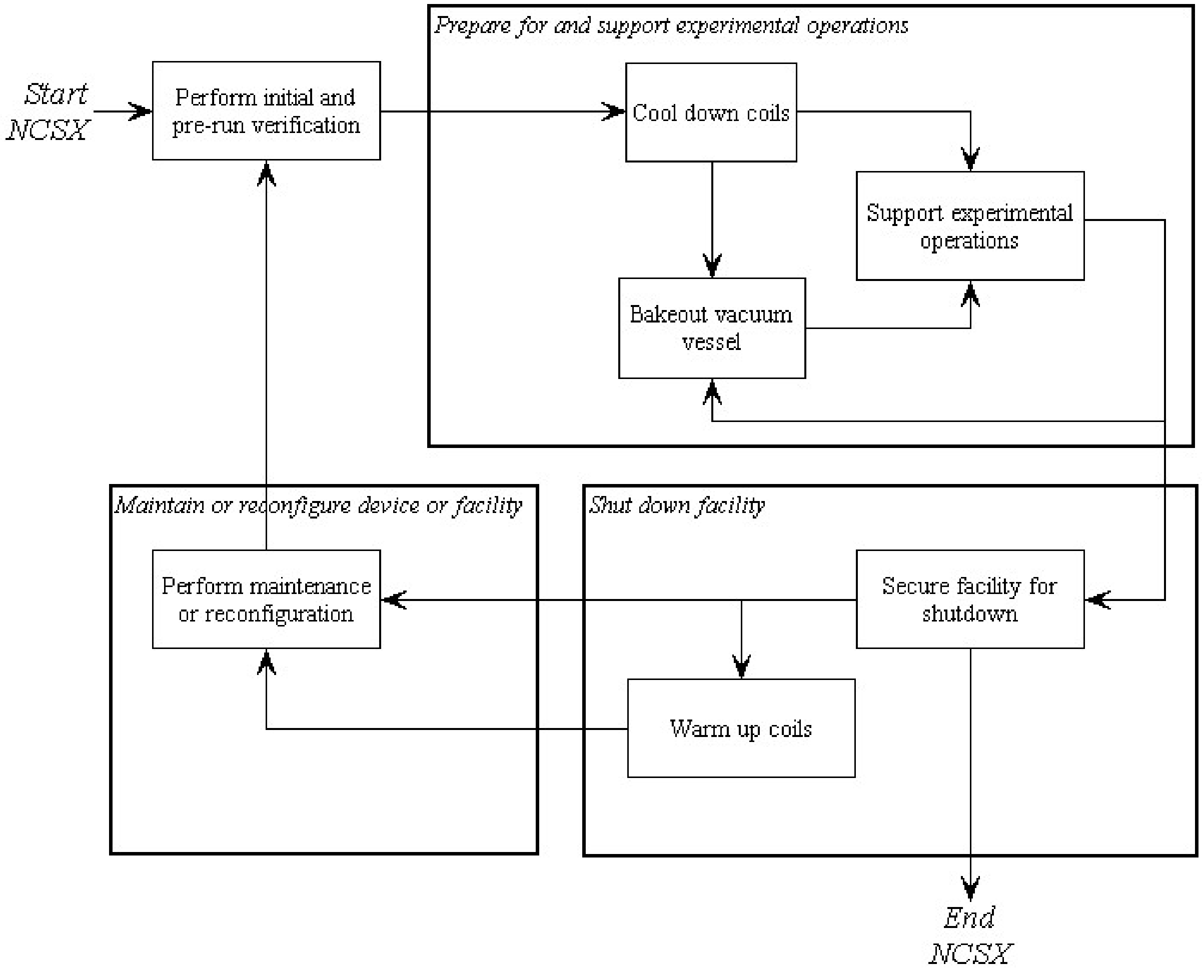


**Figure 3-3 Functional flow block diagram**

### 3.1.2 Interface definition

#### 3.1.2.1 Vacuum Vessel (WBS 12)

a. There are several physical and functional interfaces between these elements. The vacuum vessel is physically supported from the modular coil shell for vertical (gravity and net electromagnetic loads) and lateral loads. The vacuum vessel is thermally insulated to reduce heat leakage from the vacuum vessel to the modular coils. The vacuum vessel port extensions penetrate the modular coil shell.

b. During field period assembly, the modular coils must be able to be assembled over the vacuum vessel.

#### 3.1.2.2 Conventional Coils (WBS 13)

a. Conventional coils include the TF coils, PF coils, and external trim coils. The coils are attached to the Coil Support Structures (WBS 15), which are in turn attached to the Modular Coils (WBS 14) as noted in Section 3.1.2.4.

b. The conventional coils introduce electromagnetic loads on the modular coils and vice versa.

c. During field period assembly, the TF coils must be able to be assembled over the modular coils.

#### 3.1.2.3 Modular Coil Winding Facility and Fixtures (WBS 144)

This WBS element does not include any experimental hardware but rather the winding fixtures, autoclave, and coil test facility that will be used to wind, mold, impregnate, cure, and test the modular coils.

#### 3.1.2.4 Coil Support Structures (WBS 15)

The Coil Support Structures (WBS 15) include a group of elements that form structural plates above and below the modular coils. These elements are attached to the modular coil winding forms. The upper plate supports the gravity and net electromagnetic loads from the upper PF ring coils, upper external trim coils, central solenoid assembly, and cryostat. The upper plate also provides out-of-plane support for the TF coils. These loads are transmitted through the modular coil shell to the lower plate along with gravity loads from the modular coils, vacuum vessel, and in-vessel components. Gravity loads from the stellarator core are transmitted through the lower plate to the Base Support Structure (WBS 172).

#### 3.1.2.5 LN2 Distribution System (WBS 161)

Liquid nitrogen for coil cooling is supplied from the Cryogenic Systems (WBS 62) to the LN2 Distribution System (WBS 161), which in turn supplies the liquid nitrogen to the individual modular coils.

#### 3.1.2.6 Electrical Leads (WBS 162)

The current and voltage required to drive the modular coils is supplied from the Electrical Power Systems (WBS 4) to the Electrical Leads (WBS 162), which in turn supplies the direct current (DC) power to the individual modular coils.

#### 3.1.2.7 Coil Protection System (WBS 163)

The Coil Protection System (WBS 163) includes all the activities required to develop the coil protection logic and specification of coil protection parameters, including modular coils. The Coil Protection System (WBS 163) does not include any hardware or software.

#### 3.1.2.8 Cryostat (WBS 171)

Although there is no physical contact between the Cryostat (WBS 171) and the Modular Coils (WBS 14), the cryostat does provide thermal isolation from the environment outside the cryostat and containment for the cold, dry nitrogen environment inside the cryostat, which is required for cooling and maintaining the temperature of the modular coil shell. The nitrogen environment inside the cryostat is maintained by the Cryogenic Systems (WBS 62).

#### 3.1.2.9 Field Period Assembly (WBS 18)

The modular coils will have interfaces with the tooling and metrology equipment required for field period assembly, including lifting points and monuments to facilitate position measurements.

**3.1.2.10 Magnetic Diagnostics (WBS 31)**

Magnetic loops will be incorporated into the modular coil windings.

**3.1.2.11 Electrical Power Systems (WBS 4)**

a. The current and voltage required to drive the modular coils is supplied from the Electrical Power Systems (WBS 4) to the Electrical Leads (WBS 162), which in turn supplies the direct current (DC) power to the individual modular coils.

b. Electrical Power Systems (WBS 4) provide coil protection via parameters measured in the power supply circuitry based on parameters provided by Coil Protection System (WBS 163) activities. Electrical Power Systems (WBS 4) also provides coil protection via permissives and trip signals provided by Central I&C (WBS 5) in response to the output from sensors included in the local I&C within the Modular Coil System (WBS 14).

c. Electrical Power Systems (WBS 4) are responsible for providing single point grounds for the modular coil winding forms.

**3.1.2.12 Central I&C (WBS 5)**

Central I&C (WBS 5) is responsible for taking the output from the sensors (e.g. strain gauges, resistance temperature detectors, and thermocouples) provided in the local I&C in the Modular Coil System (WBS 14), processing those signals, displaying and storing the data, and providing permissives and trip signals for coil protection to Electrical Power Systems (WBS 4) in accordance with the coil protection logic and parameters specified by the Coil Protection Systems (WBS 163).

**3.1.2.13 Cryogenic Systems (WBS 62)**

a. Cryogenic Systems (WBS 62) are responsible for providing liquid nitrogen cooling for the modular coils via the LN2 Distribution System (WBS 161) as discussed in Section 3.1.2.5.

b. Cryogenic Systems (WBS 62) are responsible for providing the gaseous nitrogen cooling within the cryostat required to cool and maintain the temperature of the modular coil shell.

**3.1.2.14 Test Cell Preparations and Machine Assembly (WBS 7)**

The modular coils will have interfaces with the tooling and metrology equipment required for field period assembly.

**3.1.3 Major Component List**

*There are no major components for which additional development specifications are planned.*

**3.2 Characteristics**

**3.2.1 Performance**

**3.2.1.1 Perform Initial and Pre-run Verification**

**3.2.1.1.1 Initial Facility Startup**

**<u>Background</u>**

Initial facility startup includes all activities required to verify safe operation of NCSX systems after their initial assembly and installation, or after a major facility reconfiguration, and before plasma operations. Initial facility startup activities would be performed prior to First Plasma and will include subsystem pre-operational test procedures (PTPs) and an Integrated System Test Program (ISTP) to verify that the system operates safely and as expected prior to plasma operation. For example, the ISTP will include verification of proper coil polarities and power supply connections. The ISTP will also include verification that, at First Plasma, the system demonstrates a level of system performance sufficient for the start of research operations, as specified in the Project Execution Plan (NCSX-PLAN-PEP-01). A subset of the ISTP will be conducted before the start of a run.

###### 3.2.1.1.1.1 Initial Verification of Operability

The subsystem shall provide the capability to perform subsystem PTPs and support a comprehensive ISTP, to verify, prior to plasma operation that the system is properly configured, functioning correctly, and can be operated safely. [Ref. GRD Section 3.2.1.1]

###### 3.2.1.1.1.2 Field Line Mapping

a. The subsystem shall perform the capability to perform field line mapping with current waveforms as specified in the Field Line Mapping Scenario (Appendix B, Section A.3.2) with the modular coils starting at room temperature prior to completely installing the cryostat.

b. The subsystem shall perform the capability to perform field line mapping with current waveforms as specified in the Field Line Mapping Scenario (Appendix B, Section A.3.2) with the modular coils starting at cryogenic temperature (nominally 80K) after completely installing the cryostat. [Ref. GRD Section 3.1.2a]

###### 3.2.1.1.1.3 Design Verification

The subsystem shall be instrumented such that key modular coil performance parameters (stresses, deflections, temperatures, pressures, etc.) can be measured and compared to calculated values to assure that the subsystem is performing consistent with the design intent prior to First Plasma.

##### 3.2.1.1.2 Pre-Run Facility Startup

**Background**

Pre-run facility startup includes all activities required to verify safe operation of the NCSX subsystems after a major maintenance outage or a minor facility reconfiguration (one affecting a small number of subsystems). Pre-run facility startup activities would typically be performed prior to the start of a run period and would include a subset of the full PTP and ISTP activities referred to in Section 3.2.1.1.1.

**Requirement**

The subsystem shall support the capability to perform a controlled startup of the facility, and verify that the subsystem is properly configured, functioning correctly, and can be operated safely. [Ref. GRD Section 3.2.1.2]

#### 3.2.1.2 Prepare for and Support Experimental Operations

##### 3.2.1.2.1 Subsystem Verification and Monitoring

**Background**

Pre-operational initialization and verification activities would generally cover those activities required prior to the start of an operating day following an overnight or weekend shutdown. Pre-pulse initialization and verification activities cover those activities required prior to the start of each pulse (plasma discharge). The Modular Coil System (WBS 14) should be verified and monitored that the subsystem is functioning correctly and configured properly at the start of an operating day and prior to the start of each pulse.

**Requirement**

The subsystem shall provide the capability to verify that the subsystem is properly configured, functioning correctly, and can be operated safely prior to the start of an operating day and prior to the start of each pulse (plasma discharge). [Ref. GRD 3.2.1.3 and GRD 3.2.1.4]

#### 3.2.1.2.2 Coil Cool-down

**Background**

The Integrated System Test Program (ISTP) will include coil testing and initial field line mapping with the coils around room temperature to facilitate engineering shakedown and testing with portions of the cryostat removed. The coils will be cooled to cryogenic temperatures for First Plasma. (In this context, cryogenic temperatures are around 80K (the saturation temperature of liquid nitrogen at slightly above 1 atmosphere).

Prior to experimental operations, the cryo-resistive coils must be cooled down from room temperature to a pre-pulse operating temperature of about 80K. The coils are located in a dry nitrogen environment that is provided by the cryostat, which surrounds the coils. In order to gain access to the interior of cryostat, the coils must be warmed up from operating temperature to room temperature. The anticipated operational plans are expected to result in up to less than 150 cool-down and warm-up cycles between room temperature and operating temperature over the lifetime of the machine.

##### 3.2.1.2.2.1 Timeline for Coil Cool-down to Cryogenic Temperature

The modular coils shall be capable of being cooled down from room temperature (293K) to their pre-pulse operating temperature within 96 hours with the vacuum vessel at room temperature (20°C). [Ref. GRD Sections 3.2.1.2.1.1 and 3.2.1.2.1.3]

##### 3.2.1.2.2.2 Cool-down and Warm-up Cycles

The design of the modular coils shall allow for at least 150 cool-down and warm-up cycles between room temperature and cryogenic temperature. [Ref. GRD Section 3.2.1.2.1.2]

#### 3.2.1.2.3 Bakeout

**Background**

The temperature of the vacuum vessel shell will be capable of being elevated to a nominal temperature of 150ºC for vacuum vessel bakeout operations and to a nominal temperature of 350ºC to support bakeout of an in-vessel carbon-based liner (to be installed as an upgrade) at that temperature. Initially, there will not be any limiters installed in the vacuum vessel for first plasma or field line mapping. However, later in the program, the liner will be installed inside the vacuum vessel with a surface area that is a substantial part of the vacuum vessel surface area to absorb the high heat loads and to protect the vacuum vessel and internal components.

##### 3.2.1.2.3.1 Coil Temperatures during Bakeout

During bakeout of the vacuum vessel (up to 350ºC in the vacuum vessel shell and 150ºC at the ends of the port extensions), the temperature of the modular coils shall be capable of being kept below 90K and returned to their pre-pulse operating temperatures within the 24 hours following completion of bakeout. [Ref. GRD Section 3.2.1.2.3.3]

##### 3.2.1.2.3.2 Bakeout Cycles

The device shall be designed for at least 1000 bakeout cycles over the life of the machine. [Ref. GRD 2.3.1.2.3.6]

#### 3.2.1.2.4 Pre-Pulse Temperature

The modular coils shall return to a pre-pulse temperature of about 80K, so as to prevent overheating during repeated operation, with a vacuum vessel shell temperature in the range of 40ºC to 250 C. [Ref. GRD Section 3.2.1.4.2]

#### 3.2.1.2.5 Field Error Requirements

**Background**

Field errors are a major concern in the design of the modular coils. The fundamental global requirement is that the toroidal flux in island regions due to fabrication errors, magnetic materials, and eddy currents shall not exceed 10% of the total toroidal flux in the plasma (including compensation). To implement this requirement, external trim coils have been provided for field error correction. Poloidal and toroidal electrical breaks are required in the modular coil structure to reduce the size of the eddy current loops and to reduce the longest eddy current time constant in the modular coils such that the calculated field errors are acceptably low. The electrical breaks also facilitate field penetration from the modular and conventional (PF, TF and external trim) coils. The modular coils will be fabricated and assembled to tight tolerances which are calculated to introduce acceptably low field errors (after correction).

##### 3.2.1.2.5.1 Electrical Breaks

###### 3.2.1.2.5.1.1 Toroidal Electrical Breaks

a. Toroidal electrical breaks shall be provided between adjacent modular coils within a field period. Electrical breaks are not required between adjacent modular coils in adjacent field periods. [Ref. GRD Section 3.2.1.5.2b]

b. Toroidal electrical breaks must be able to withstand an applied voltage of TBD.

###### 3.2.1.2.5.1.2 Poloidal Electrical Breaks

a. A poloidal electrical break shall be provided within each modular coil.

b. Poloidal electrical breaks must be able to withstand an applied voltage of TBD.

##### 3.2.1.2.5.2 Eddy Current Time Constants

The time constant of the longest-lived eddy current eigenmode in the completed modular coil assembly (all eighteen coils excluding the conductor circuits) shall be less than 20 ms. [Ref. GRD Section 3.1.5.2c]

##### 3.2.1.2.5.3 Stellarator Symmetry

Stellarator symmetry shall be preserved in the design of conducting structures in the modular coils and placement of electrical breaks. [Ref. GRD Section 3.1.5.2e]

##### 3.2.1.2.5.4 Winding Tolerance

The local current centroid of each modular coil shall be located within 1.5mm of the nominal location defined in Section A.1.1 Coil Centroids with the modular coils at the pre-pulse operating temperature with zero current.

##### 3.2.1.2.5.5 Deflections under Load

a. Modular coils shall be designed such that deflections due to thermal growth and due to electromagnetic loads preserve stellarator symmetry.

b. Deflections due to electromagnetic loads shall not exceed TBD.

### 3.2.1.2.6 Plasma Magnetic Field Requirements

#### 3.2.1.2.6.1 Magnetic Field Polarity

**Background**

Figure 3-4 illustrates the right-handed coordinate system used for the stellarator and test cell on NCSX. The Z-axis of the coordinate system is vertical. The major axis of the stellarator is coincident with the Z-axis. The following conventions are followed:

- A positive toroidal (plasma) current or a positive toroidal magnetic field point in the $\phi$-direction (counter-clockwise viewed from above).
- A positive vertical magnetic field points in the Z-direction (upward).
- A positive poloidal current (TF or modular coil current in the inner leg) flows in the Z-direction and provides a positive toroidal magnetic field.
- Positive radial magnetic fields and currents are in the R-direction, radially outward from the Z-axis, the major axis of the stellarator.

[Ref. GRD Section 3.2.1.5.3.1]

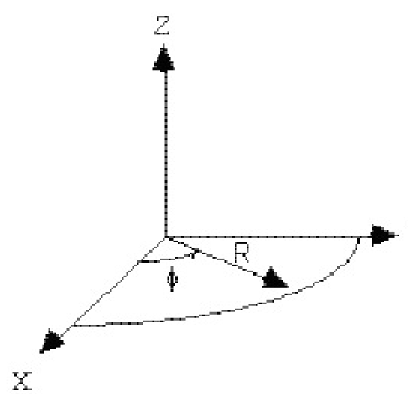


**Figure 3-4 NCSX coordinate system**

**Requirements**

a. The modular coils shall be configured for the standard magnetic field polarity to have its toroidal field in the negative direction.

b. The modular coils shall have the capability to be reconfigured to operate with the magnetic field polarity reversed from its standard direction.

[Ref. GRD Section 3.2.1.5.3.2]

#### 3.2.1.2.6.2 Reference Scenario Requirements

**Background**

NCSX is designed to be a flexible, experimental test bed. To ensure adequate dynamic flexibility, a series of reference scenarios has been established. TF, PF, and modular coil systems and the vacuum vessel will be designed for a plasma with a nominal major radius of 1.4 m and capability to meet the requirements of all the reference scenarios. Electrical power systems shall be designed and initially configured to meet the requirements of the First Plasma and Field Line Mapping Scenarios and shall be capable of being upgraded to meet the requirements of all other reference scenarios.

Reference scenario definitions are provided in Section 3.2.1.5.3.3.1 of the General Requirements Document. Reference waveforms of engineering parameters such as coil currents, voltages, power dissipation, etc. are derived from the scenario specifications and are documented in Appendix B.

**Requirement**

The modular coils will be designed to meet the requirements of all the reference scenarios. [Ref. GRD Section 3.2.1.5.3.3.2]

#### 3.2.1.2.6.3 Flexibility Requirements

**Background**

NCSX is designed to be a flexible, experimental test bed. To ensure that changes in equilibria can be accommodated, several dimensions have been identified over which changes in equilibria must be accommodated.

Flexibility requirements have been established for a toroidal magnetic field of 1.7T. Greater flexibility exists at lower field levels.

The NCSX Project has determined that the required flexibility can be achieved with the modular coil capabilities developed in response to the reference scenarios. Therefore, no additional requirements are placed on the modular coils to satisfy flexibility requirements for the overall device and facility.

**Requirements**

None

#### 3.2.1.2.7 Pulse Repetition Rate

Modular coils shall be designed for pulses to be initiated at intervals not exceeding 15 minutes when constrained by coil cooldown and 5 minutes otherwise. [Ref. GRD Section 3.2.1.5.10]

#### 3.2.1.2.8 Discharge Termination

#### 3.2.1.2.8.1 Normal Termination

**Background**

Normal termination includes all system actions necessary to shutdown the plasma and associated subsystems at the conclusion of a pulse in preparation for the next pulse.

**Requirement**

During a controlled shutdown, the modular coil currents will be driven to zero by the power supplies according to the pre-programmed current waveform. [Ref. GRD Section 3.2.1.5.11.1]

#### 3.2.1.2.8.2 Abnormal Termination

**Background**

Abnormal termination consists of all system responses necessary to remove conditions that occur during experimental operations that could cause significant damage to the NCSX system or cause injury to personnel.

**Requirement**

During an abnormal termination, the modular coil power supplies will be bypassed and the modular coil currents will go to zero on the natural decay times of the coil circuits. [Ref. GRD Section 3.2.1.5.11.2]

#### 3.2.1.3 Shut Down Facility

**Background**

Facility shutdown involves the shutdown of NCSX equipment following the termination of a discharge (per Section 3.2.1.2.8) in preparation for a brief (overnight or weekend) or extended (between run periods) shutdown.

**Requirement**

The NCSX system shall provide the capability to perform a controlled shutdown of the modular coils. [Ref. GRD Section 3.2.1.6]

##### 3.2.1.3.1 Coil Warm-up Timeline

The modular coils shall be capable of being warmed up from operating temperature (80K) to room temperature (293K) within 96 hours. [Ref. GRD Section 3.2.1.6.1]

### 3.2.2 Physical Characteristics

#### 3.2.2.1 Configuration Requirements and Essential Features

##### 3.2.2.1.1 Modular Coil Winding Forms (WBS 141)

**Background**

The winding forms provide an accurate means of positioning the conductor during the winding and vacuum-pressure impregnation (VPI) process. The winding forms are permanent structures that also provide mechanical support for the windings during coil operation. The complete assembly of winding forms is referred to as the structural shell.

**Requirements**

a. Eighteen winding forms of three different types (six of each type) are required to construct the modular coils.

b. Each winding form shall include accurately machined surfaces for positioning the conductor during the winding and VPI process.

##### 3.2.2.1.2 Coil Windings and Assembly (WBS 142)

**Background**

The function of the modular coil windings is to provide the basic quasi-axisymmetric magnetic configuration for the device. The windings can produce alternate magnetic configurations by varying the current for each coil type independently.

**Requirements**

a. Each modular coil shall consist of two winding packs, wound on either side of a structural tee feature on the winding form. The two winding packs comprise a modular coil.

b. The number of turns per coil is as specified in Appendix B, Section A.1.2 Turns per Coil.

c. The modular coils shall be connected electrically in 3 circuits, with coils of each type in series.

d. The maximum weight of a completed Type A modular coil shall not exceed TBD. The maximum weight of a completed Type B modular coil shall not exceed TBD. The maximum weight of a completed Type C modular coil shall not exceed TBD.

#### 3.2.2.1.3 Local Instrumentation and Control (WBS 143)

**Background**

The function of the modular coil windings is to provide the basic quasi-axisymmetric magnetic configuration for the device. The windings can produce alternate magnetic configurations by varying the current for each coil type independently.

**Requirements**

a. Each modular coil assembly shall be equipped with multiple Resistance Temperature Detectors (RTDs) in order to provide pre- and post-pulse monitoring of conductor average temperature.

b. Each modular coil shall be equipped with voltage taps at the leads.

c. Each winding form shall be equipped with strain gages along the length the coil.

### 3.2.3 System Quality Factors

#### 3.2.3.1 Reliability, Availability, and Maintainability

**Background**

The overall objective is to provide a device with high operational availability, meaning that the number of plasma discharges achieved in a run period is a large percentage (greater than 75%) of the number planned after the initial shakedown and commissioning phases of the facility. Bottoms-up reliability predictions are difficult to perform and have large uncertainties for first-of-a-kind experimental devices such as NCSX. Therefore, quantitative RAM requirements on NCSX will be few. Rather, NCSX will rather rely on sound engineering practice to assure high availability in NCSX, which has been the tried-and-true approach on similar scale fusion devices. Sound engineering practices include:

- Applying design principles that promote reliability (e.g., employing an adequate factor of safety on mechanical and electrical stresses, avoiding unnecessary complexity, using proven design approaches and well characterized materials, etc.)
- Optimizing designs for reliability and maintainability through systematic evaluation of design options,
- Performing failure modes, effects and criticality analysis (FMECAs) for RAM design improvement and verification, and
- Employing peer reviews as a mechanism to enhance the design process.

The NCSX RAM Plan defines the processes that will be used by the Project to achieve a device with high availability.

**Requirements**

a. The modular coils shall incorporate reliability and maintainability features in the design that are consistent with achieving a high (greater than 95%) operational availability.

b. Provisions for recovery shall be made for every credible failure mode.

c. The modular coils shall be capable of being disassembled and reassembled to permit replacement of any part or machine reconfiguration that would require disassembly.

d. Provisions for lifting, e.g. lifting eyes, other sling attachment provisions, or equivalent provisions, shall be made in the design of the modular coils.

[Ref. GRD Section 3.2.4.1]

#### 3.2.3.2 Design Life

a. The modular coils shall have a design life of >10 years when operated per the reference scenarios in Section 3.2.1.2.6.2.

b. The modular coils shall be designed for the following maximum number of pulses when operated per the reference scenarios defined in Section 3.2.1.2.6.2 and based on the factors for fatigue life specified in the NCSX Structural and Cryogenic Design Criteria Document:

- 100 per day;
- 13,000 per year; and
- 130,000 lifetime.

[Ref. GRD Section 3.2.4.2]

#### 3.2.3.3 Seismic Criteria

**Background**

NCSX systems shall be designed in accordance with seismic design and evaluation criteria for Performance Category 1 (PC1) facilities, per DOE-STD-1020-2002, “Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities.” The NCSX Seismic Design Criteria provides an NCSX-specific interpretation of those requirements

**Requirement**

The modular coils shall be design in accordance with the NCSX Seismic Design Criteria. [Ref. GRD Section 3.3.1.5]

### 3.2.4 Transportability

All modular coil assemblies and components shall be transportable by commercial carrier via highway, air, sea, or railway. [Ref. GRD Section 3.2.5]

## 3.3 Design and Construction

### 3.3.1 Materials, Processes, and Parts

#### 3.3.1.1 Magnetic Permeability

All materials used in the modular coils must have a relative magnetic permeability less than 1.02 unless otherwise authorized by the Project. [Ref. GRD Section 3.3.1.1]

#### 3.3.1.2 Corrosion Prevention and Control

Materials, processes, and protective surface treatments or finishes shall be provided to ensure that equipment capability during its service life is not degraded due to corrosion. Where possible, contact between dissimilar metals shall be avoided. [Ref. GRD Section 3.3.1.4]

#### 3.3.1.3 Metrology

The modular coils shall provide features (e.g., fiducial markers) to facilitate accurately measuring and locating components relative to the magnetic field for the life of the machine. [Ref. GRD Section 3.3.1.6]

#### 3.3.2 Electrical Grounding

**Background**

The modular coil winding electrical circuits are connected to a single point ground by the Electrical Power Systems (WBS 4). In addition, the modular coil winding forms which are electrically isolated need to be connected to a single point ground.

**Requirement**

The modular coil winding forms shall be connected to a single point grounding system in accordance with the NCSX Grounding Specification for Personnel and Equipment Safety. [Ref. GRD Section 3.3.2]

#### 3.3.3 Nameplates and Product Marking

##### 3.3.3.1 Labels

Equipment and any parts of that equipment to be used by personnel shall be identified with appropriate labels. Labels shall indicate clearly and concisely the function and purpose of the item being labeled. Hierarchical labeling shall be used to facilitate component location on control panels. The terminology used for equipment, procedures, and training materials shall be the same for each case. Label design shall be consistent to promote simplicity and avoid clutter. The use of abbreviations and acronyms shall be minimized. Permanent labels shall be attached to the specific component or equipment in such a manner that environmental conditions or usage by personnel will not remove or destroy the label. Temporary labels shall be used only when necessary and shall not obscure other information or equipment. If a temporary label is to designate a device that is out of service, the label shall be applied so that it prevents the use of that device. Labeling shall be legible and conform to human visual capabilities and limitations in regard to physical characteristics. [Ref. GRD Section 3.3.3.1]

#### 3.3.4 Workmanship

During modular coil fabrication and finishing, particular attention shall be given to freedom from blemishes, defects, burrs, and sharp edges; accuracy of dimensioning radii of weld fillets; making of parts; thoroughness of cleaning; quality of brazing, welding, riveting, painting, and wiring; alignment of parts; and tightness and torquing of fasteners. [Ref. GRD Section 3.3.4]

#### 3.3.5 Interchangeability

Design tolerances shall permit parts and assemblies of the same part number to be used as replacement parts without degrading the specified performance of the parent item. [Ref. GRD Section 3.3.5]

#### 3.3.6 Environmental, Safety, and Health (ES&H) Requirements

##### 3.3.6.1 General Safety

a. When utilized within its intended use and within specified environments, the safe operation, test, handling, maintenance and storage of the subsystem hardware and software shall be provided.

b. The subsystem shall not present any uncontrolled safety or health hazard to user personnel.

c. The subsystem shall detect abnormal operating conditions and safeguard the NCSX system and personnel.

[Ref. GRD Section 3.3.6.1]

#### 3.3.6.2 Personnel Safety

The subsystem shall meet all applicable OSHA requirements in accordance with 29CFR1910. The system shall limit personnel exposure to hazardous materials to below their OSHA permissible exposure limit (PEL). [Ref. GRD Section 3.3.6.3]

#### 3.3.6.3 Flammability

The use of flammable materials shall be minimized. [Ref. GRD Section 3.3.6.4]

## 3.4 Documentation

### 3.4.1 Specifications

Specifications shall be developed for each configuration item as shown in Table 3-1.

**Table 3-1 Modular coil specifications**

| Configuration Item | Specification Identifier | Specification Type |
|---|---|---|
| Modular Coil Winding Form | NCSX-CSPEC-141-03-XX | Product specification – forms the basis of the MCWF procurement |
| Modular Coil Cable Conductor | TBD | Product specification – forms the basis of the conductor procurement |
| Modular Coil Winding Assembly | TBD | Product specification – forms the basis for fabricating and testing the modular coil winding assembly |

## 3.5 Logistics

### 3.5.1 Maintenance

The modular coils shall be maintained using, to the extent possible, standard/common tools and existing multi-purpose test equipment. Use of new/special tools and the number of standard/common tools shall be minimized through maximum commonality of fasteners, clamps, adapters, and connectors.

# 4 QUALITY ASSURANCE PROVISIONS

## 4.1 General

This section identifies the methods to be used for verification of requirements in Section 3.2 of this specification. General definitions of basic verification methods are outlined in Section 4.2. Verification of subsystem requirements will require additional testing in operational or near-operational environments.

## 4.2 Verification Methods

Verification of qualification shall be by analysis, demonstration, inspection, or test. Definition of analysis, demonstration, inspection, and test is as follows:

Analysis: Verification of conformance with required characteristics by calculation or simulation, including computer modeling based on established material or component characteristics.

Demonstration: Verification of conformance with required characteristics by un-instrumented test, performed at ambient, where success is evident by observation; or review of design drawings and specifications; or review of data for similar components and applications

Inspection: Verification of conformance by measuring, examining, testing, and gauging one or more characteristics of a product or service and comparing the results with specified requirements.

Test: Verification by physically exercising a component or system under appropriate loads or simulated operating conditions, including measurement and analysis of performance data.

## 4.3 Quality Conformance

**Background**

This section establishes the specific evaluation criteria for verification of the subsystem characteristics in Section 3.2. In general, all requirements shall be verified under operational or near-operational conditions as possible given test constraints.

**Requirements**

Test methods for each of the performance characteristics in Section 3.2 are identified in Appendix A – Quality Conformance Matrix.

**APPENDIX A – QUALITY CONFORMANCE MATRIX**

| Section | Characteristic | Analysis | Demonstration | Inspection | Test | Comments |
|---|---|---|---|---|---|---|
| 3.2 | Characteristics | | | | | |
| 3.2.1 | Performance | | | | | |
| 3.2.1.1 | Perform Initial and Pre-run Verification | | | | | |
| 3.2.1.1.1 | Initial Facility Startup | | | | | |
| 3.2.1.1.1.1 | Initial Verification of Operability | | X | | | |
| 3.2.1.1.1.2 | Field Line Mapping | | X | | | |
| 3.2.1.1.1.3 | Design Verification | | X | | | |
| 3.2.1.1.2 | Pre-Run Facility Startup | | X | | | |
| 3.2.1.2 | Prepare for and Support Experimental Operations | | | | | |
| 3.2.1.2.1 | Subsystem Verification and Monitoring | | X | | | |
| 3.2.1.2.2 | Coil Cool-down | | | | | |
| 3.2.1.2.2.1 | Timeline for Coil Cool-down to Cryogenic Temperature | | X | | | |
| 3.2.1.2.2.2 | Cool-down and Warm-up Cycles | X | | | | |
| 3.2.1.2.3 | Bakeout | | | | | |
| 3.2.1.2.3.1 | Coil Temperatures during Bakeout | X | X | | | |
| 3.2.1.2.3.2 | Bakeout Cycles | X | | | | |
| 3.2.1.2.4 | Pre-Pulse Temperature | X | X | | | |
| 3.2.1.2.5 | Field Error Requirements | | | | | |
| 3.2.1.2.5.1 | Electrical Breaks | | | | | |
| 3.2.1.2.5.1.1 | Toroidal Electrical Breaks | | X | X | | |
| 3.2.1.2.5.1.2 | Poloidal Electrical Breaks | | X | X | | |
| 3.2.1.2.5.2 | Eddy Current Time Constants | X | | | | |
| 3.2.1.2.5.3 | Stellarator Symmetry | | X | | | |
| 3.2.1.2.5.4 | Winding Tolerance | | | X | | |
| 3.2.1.2.5.5 | Deflections under Load | X | | | X | |
| 3.2.1.2.6 | Plasma Magnetic Field Requirements | | | | | |
| 3.2.1.2.6.1 | Magnetic Field Polarity | | X | | | |
| 3.2.1.2.6.2 | Reference Scenario Requirements | X | | | X | |
| 3.2.1.2.6.3 | Flexibility Requirements | | | | | |
| 3.2.1.2.7 | Pulse Repetition Rate | X | X | | | |
| 3.2.1.2.8 | Discharge Termination | | | | | |
| 3.2.1.2.8.1 | Normal Termination | | X | | | |

| | | | | | |
|---|---|---|---|---|---|
| 3.2.1.2.8.2 | Abnormal Termination | | X | | |
| 3.2.1.3 | Shut Down Facility | | X | | |
| 3.2.1.3.1 | Coil Warm-up Timeline | X | X | | |
| 3.2.2 | Physical Characteristics | | | | |
| 3.2.2.1 | Configuration Requirements and Essential Features | | | | |
| 3.2.2.1.1 | Modular Coil Winding Forms (WBS 141) | | X | X | |
| 3.2.2.1.2 | Coil Windings and Assembly (WBS 142) | | X | X | |
| 3.2.2.1.3 | Local Instrumentation and Control (WBS 143) | | X | | |
| 3.2.3 | System Quality Factors | | | | |
| 3.2.3.1 | Reliability, Availability, and Maintainability | X | X | | |
| 3.2.3.2 | Design Life | X | X | | |
| 3.2.3.3 | Seismic Criteria | X | X | | |
| 3.2.4 | Transportability | | X | | |

**APPENDIX B – TECHNICAL DATA**