NCSX
Specification

System Requirements Document (SRD)
For the
Vacuum Vessel System (WBS 12)

NCSX-BSPEC-12-00

Draft D

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Prepared by: ______________________________
P. L. Goranson, Vacuum Vessel System (WBS 12) Manager

Concur: ______________________________
M. Viola, Technical Representative for Vacuum Vessel System (WBS 12) Procurements

Concur: ______________________________
B. Nelson, Project Engineer for Stellarator Core Systems (WBS 1)

Concur: ______________________________
M. Zarnstorff, Head, Project Physics

Concur: ______________________________
R. Simmons, Systems Engineering Support Manager

Concur: ______________________________
W. Reiersen, Engineering Manager

Concur: ______________________________
J. Levine, ES&H

Concur: ______________________________
J. Malsbury, Quality Assurance

Approved by: ______________________________
G. H. Neilson, NCSX Project Manager

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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 Vacuum Vessel System (WBS 12), is the complete development specification for this subsystem. 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 "vacuum vessel" refer to the Vacuum Vessel System (WBS 12).**

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

Vacuum Materials List

3 SUBSYSTEM REQUIREMENTS

3.1 Subsystem Definition

The vacuum vessel is a contoured, three-period torus with a geometry that repeats every 120º toroidally. The geometry is also mirrored every 60º so that the top and bottom sections of the first (0º to 60º) segment, if flipped over, are identical to the corresponding sections of the adjacent (60º to 120º) segment. The vessel will be fabricated in three subassembly (VVSA) units (each including a spool piece to join the segments together) and joined together at the assembly site. With the exception of the large vertical ports and the neutral beam port located mid-segment, all port assembly extensions are required to be installed onto the three vessel sub-assemblies after installation of the modular coils and TF coils as part of the NCSX field period assembly operation. The VVSA will be supported from the modular coil shell structure via adjustable hangers. The VVSA will be traced with tubes and resistance strip heaters, which will be used for temperature control.

All work required to execute the Project has been identified in the Stellarator Core Systems (WBS 1) Work Breakdown Structure Dictionary. A listing of Level 4 (3-digit) WBS elements included in the Vacuum Vessel System (WBS 12) is provided below:

- Vacuum Vessel Assembly (WBS 121)
- Vacuum Vessel Thermal Insulation (WBS 122)
- Vacuum Vessel Heating and Cooling Distribution Systems (WBS 123)
- Vacuum Vessel Supports (WBS 124)
- Vacuum Vessel Local I&C (WBS 125).

3.1.1 Subsystem Diagrams

3.1.1.1 Functional Relationships

A block diagram of the Vacuum Vessel System and its environment is depicted in Figure 3-1.

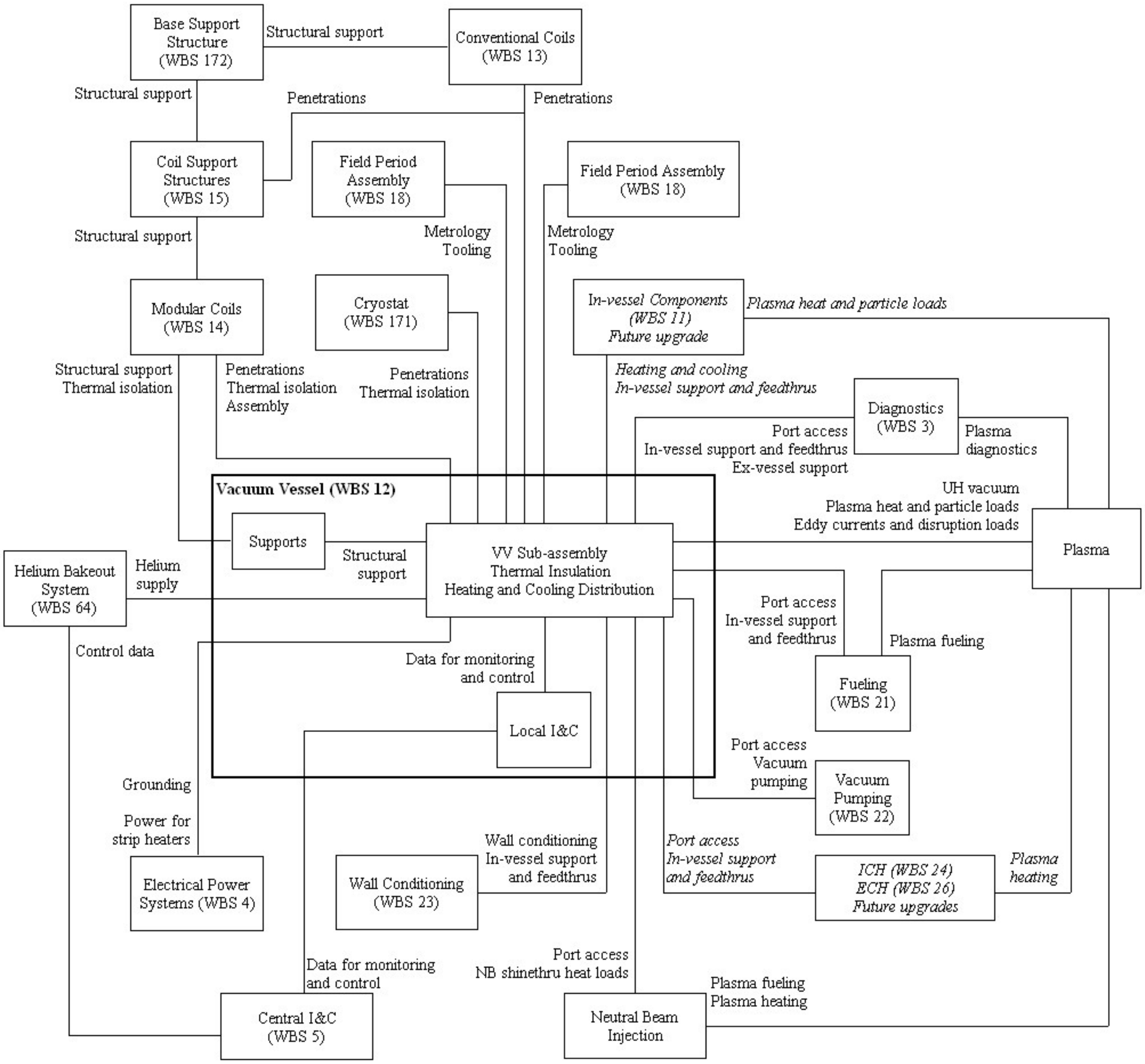

Figure 3-1 Vacuum vessel system functional relationships

3.1.1.2 Functional Flow Block Diagram

A functional flow block diagram (FFBD) is provided in Figure 3-2.

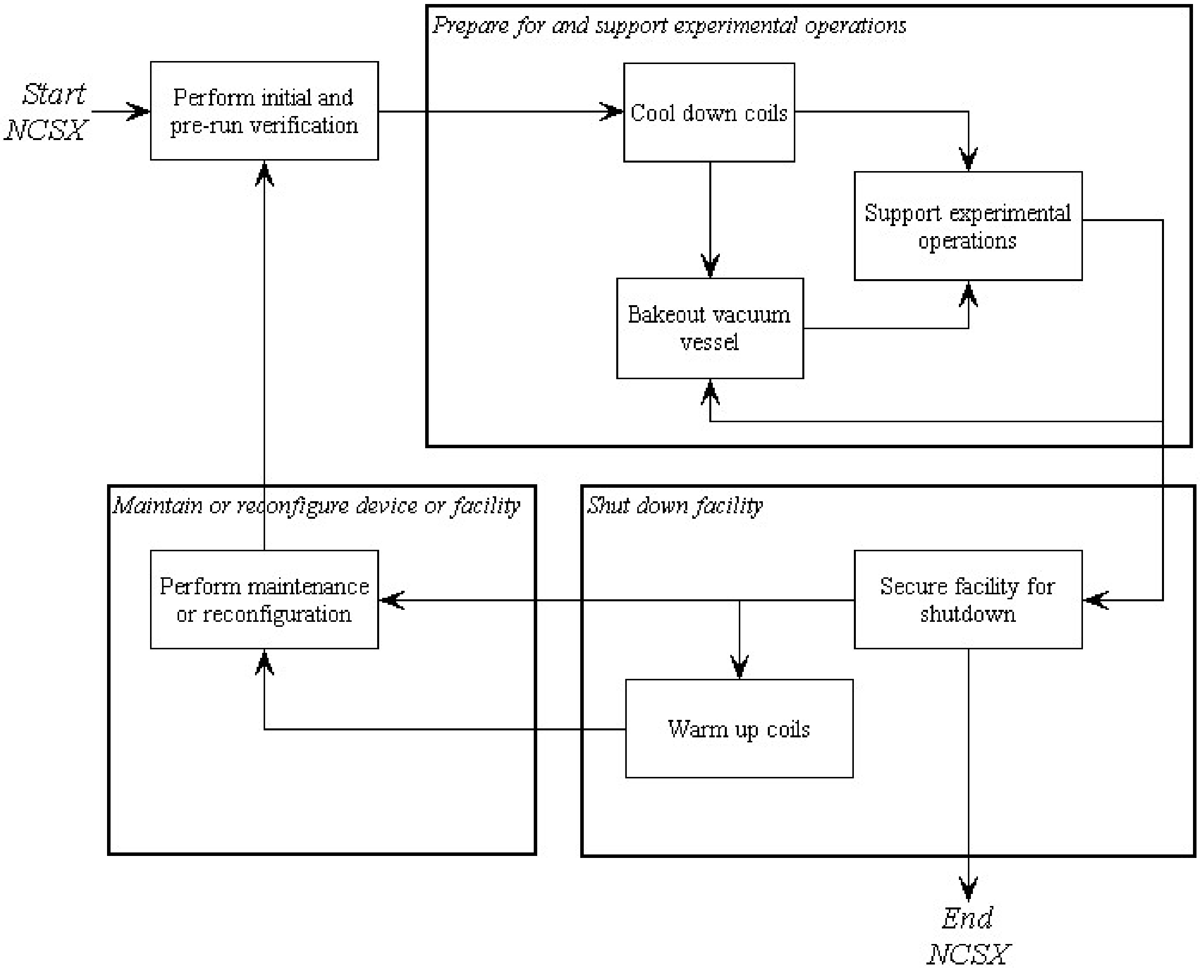

Figure 3-2 Functional flow block diagram

3.1.2 Interface Definition

3.1.2.1 In-vessel Components (WBS 11)

In-vessel Components (WBS 11) include limiters, an internal liner, internal trim coils, and local instrumentation and control (I&C). These elements are not included as part of the MIE project. However, it is necessary to assure that the full complement of in-vessel components can be accommodated as a future upgrade. These components will be supported from the vacuum vessel. Vacuum feedthroughs may be needed for electrical and cooling lines. In-vessel components with be baked to 350ºC by elevating the vacuum vessel to that temperature. In-vessel components may also be cooled via the vacuum vessel for modest heat loads.

3.1.2.2 Conventional Coils (WBS 13)

Conventional Coils (WBS 13) include the toroidal field (TF), poloidal field (PF), and external trim coils. Although there is no physical contact between these coils and the vacuum vessel, they are all inside the cryostat. Port extensions from the vacuum vessel pass through these coils to the exterior of the cryostat. It is essential that clear access (without interference) be maintained under all operating conditions.

3.1.2.3 Modular Coils (WBS 14)

Modular coils have key interfaces with the vacuum vessel. The vacuum vessel is structurally supported off the modular coils for vertical and lateral loads. The vacuum vessel operates at or substantially above room temperature whereas the modular coils operate at cryogenic temperature. This requires that the modular coils be thermally isolated from the vacuum vessel in the structural supports and with thermal insulation around the vacuum vessel shell and port extensions. Since the vacuum vessel shell is surrounded by the modular coil windings and structure, all of the vacuum vessel port extensions must penetrate through the modular coils without interference. The close proximity of the vacuum vessel and modular coils requires careful attention to clearances during field period and final assembly.

3.1.2.4 Coil Support Structures (WBS 15)

Coil support structures include shelves above and below the modular coils. Since these structures are inside the cryostat, port extensions from the vacuum vessel must pass through these structures to the exterior of the cryostat. It is essential that clear access (without interference) be maintained under all operating conditions.

3.1.2.5 Cryostat (WBS 171)

The vacuum vessel is located inside the cryostat. Each of its port extensions represents a penetration of the cryostat. The function of the cryostat is to maintain a cold, dry nitrogen environment for the cryo-resistive coils inside the cryostat. The vacuum vessel operates at or substantially above room temperature, so it must be thermally isolated from the cryostat environment.

3.1.2.6 Field Period Assembly (WBS 18)

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

3.1.2.7 Fueling Systems (WBS 21)

Gas fueling will be accomplished via gas injectors located inside the vacuum vessel. Pellet fueling will be accomplished via pellet injectors located outside the vacuum vessel, which will fire fuel pellets on a line-of-sight into the plasma or into guide tubes to facilitate launch from the high field side. Interfaces include port access, in-vessel support, and feedthroughs.

3.1.2.8 Torus Vacuum Pumping System (WBS 22)

Functionally, the Torus Vacuum Pumping System (TVPS) provides the vacuum pumping required to achieve ultra-high vacuum conditions inside the vacuum vessel. This is requires that ample port access be provided for attaching the TVPS to the vacuum vessel.

3.1.2.9 Wall Conditioning Systems (WBS 23)

This WBS element includes systems which facilitate achieving the vacuum conditions required for good plasma performance such as glow discharge cleaning, boronization, and lithiumization. These systems will typically require in-vessel support and port feedthroughs.

3.1.2.10 ICH (WBS 24)

The vacuum vessel must be designed to accommodate (as a future upgrade) three inboard ICH launchers. This requires in-vessel support for the launchers plus port access for the RF feeds.

3.1.2.11 Neutral Beam Injection System (WBS 25)

The Neutral Beam Injection (NBI) System consists of a single co-injected beam installed initially with future upgrades for co- and counter-injected beams. Unobstructed tangential access is a critical interface requirement. The beam energy which is not absorbed by the plasma or shinethrough armor will impinge directly on the vacuum vessel.

3.1.2.12 ECH (WBS 26)

The vacuum vessel must be designed to accommodate (as a future upgrade) ECH launchers. This requires port access for the ECH launchers.

3.1.2.13 Diagnostics (WBS 3)

Diagnostic interfaces with the vacuum vessel are pervasive. Magnetic diagnostics will be mounted on the interior and exterior of the vacuum vessel. In-vessel diagnostics will require structural support and feedthroughs. Sightlines and view angles are critical for port-mounted diagnostics. The vacuum vessel must be designed to accommodate (as a future upgrade) the full complement of required diagnostics.

3.1.2.14 Electrical Power Systems (WBS 4)

Electrical power systems provide the electrical grounding for the vacuum vessel. They also provide the electrical power for the resistive strip heaters which control the temperature of the vacuum vessel port extensions.

3.1.2.15 Central I&C (WBS 5)

Central I&C (WBS 5) is responsible for taking the output from the sensors provided in the local I&C in the Vacuum Vessel System (WBS 12), processing those signals and displaying and storing the data.

3.1.2.16 Helium Bakeout System (WBS 64)

The Helium Bakeout System provides high pressure helium to the vacuum vessel for heating and cooling the vacuum vessel.

3.1.2.17 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

Background

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 Design Verification

The subsystem shall be instrumented such that key vacuum vessel performance parameters (deflections, temperatures, 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 Vacuum Vessel System (WBS 12) 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

Prior to experimental operations, the cryo-resistive coils must be cooled down from room temperature to a pre-pulse operating temperature of approximately 80K. The coils are located in a dry nitrogen environment that is provided by the cryostat, which surrounds the magnets. 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.

Requirement

The vacuum vessel shall be capable of maintaining a temperature at least 20ºC (293K) during and after the time the cryo-resistive coils are being cooled down from 293K to 80K and the machine is not being pulsed. [Ref. GRD Section 3.2.1.2.1]

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. The capability to bake the vessel with the cryo-resistive coils at cryogenic temperature is required.

3.2.1.2.3.1 Vacuum Vessel Bakeout Temperatures

During vacuum vessel bakeout, the temperature of the vacuum vessel shell and ports shall be maintained at 150ºC +5/-25ºC. [Ref. GRD Section 3.2.1.2.3.1]

3.2.1.2.3.2 Carbon-based Plasma Facing Components (PFCs) Bakeout Temperatures

During carbon-based PFC bakeout, the temperature of the vacuum vessel shell and carbon-based PFCs (to be installed as a future upgrade) shall be maintained at 350ºC±25ºC, and the temperature of the vacuum vessel ports shall be maintained at 150ºC +5/-25ºC. (The 350ºC bakeout capability may require an upgrade in the Helium Bakeout System (WBS 64), but not the vacuum vessel.) [Ref. GRD Section 3.2.1.2.3.2]

3.2.1.2.3.3 Coil Temperatures during Bakeout

The capability to bakeout the vacuum vessel with the cryo-resistive coils below 90K shall be provided. [Ref. GRD Section 3.2.1.2.3.3]

3.2.1.2.3.4 Bakeout Timelines

a. The vacuum vessel and all components internal to the vacuum vessel shall be capable of being raised to their bakeout temperatures within 36 hours and maintained at that temperature for a period up to 21 days.

b. Following bakeout, the vacuum vessel and all components internal to the vacuum vessel shall be capable of being returned to 40ºC within 36 hours.

[Ref. GRD Section 3.2.1.2.3.4]

3.2.1.2.3.5 Glow Discharge Cleaning (GDC) During Bakeout

The vacuum vessel shall accommodate glow discharge cleaning (GDC) capability during bakeout operations with the vacuum vessel and all components internal to the vacuum vessel at their nominal bakeout temperature. [Ref. GRD Section 3.2.1.2.3.5]

3.2.1.2.3.6 Bakeout Cycles

The device shall be designed for at least 1000 bakeout cycles over the life of the machine. [Ref. GRD Section 3.2.1.2.3.6]

3.2.1.2.4 Vacuum Requirements

3.2.1.2.4.1 Base Pressure

a. The device shall be designed and facility shall be upgradeable to produce, through design and the use of baking and wall conditioning, high vacuum conditions with a global leak rate of less than or equal to $2x10^{-5}$ torr-l/s at 293K and a base pressure of less than or equal to $2x10^{-8}$ torr, when equipped with its full pumping compliment.

b. The base pressure shall be measured with a standard, magnetically shielded, nude ion gauge. The device shall accommodate additional nude ion gauges and at least one fast neutral pressure gauge as future upgrades. The partial pressure components of the base pressure shall be measured with a Residual Gas Analyzer (RGA) mounted at a location on one of the pump ducts near the turbo-molecular pumps.

[Ref. GRD Section 3.2.1.2.2.1]

3.2.1.2.5 Glow Discharge Cleaning (GDC) Between Pulses

a. The vacuum vessel shall accommodate the capability to perform GDC between pulses with the vacuum vessel and all components internal to the vacuum vessel at their nominal pre-pulse operating temperatures.

b. The vacuum vessel shall accommodate use of any of the following gases for GDC: hydrogen, deuterium, helium, and other non-corrosive gases.

[Ref. GRD Section 3.2.1.4.1]

3.2.1.2.6 Pre-Pulse Temperature

a. Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall return to a prescribed pre-pulse temperature in the range of 40-100ºC while maintaining port end flanges in the range of 20-40ºC.

b. Interior vacuum vessel surfaces and all in-vessel components except for the Plasma Facing Components shall be capable of being maintained at a pre-pulse temperature of 210ºC (as a future upgrade) to facilitate the use of liquid lithium while maintaining port end flanges at or below 150ºC.

[Ref. GRD Section 3.2.1.4.2]

3.2.1.2.7 Field Error Requirements

Background

Field errors are a major concern in the design of the vacuum vessel. 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. The vacuum vessel shell is constructed out of Inconel because of its high strength at elevated temperature, high stiffness, and high electrical resistivity. These factors allow a thin shell that will have a short time constant, which minimizes the impact of eddy currents on field errors and relieves the need to incorporate electrical breaks. Inconel also has a very low magnetic permeability, which minimizes the impact of magnetic materials on field errors. The vacuum vessel has been designed to preserve stellarator symmetry, thus further mitigating the impact on the plasma form field errors related to eddy currents.

3.2.1.2.7.1 Eddy Current Time Constants

The time constant of the longest-lived eddy current eigenmode in the vacuum vessel and in-vessel structures shall be less than 10 ms. [Ref. GRD Section 3.1.5.2a]

3.2.1.2.7.2 Stellarator Symmetry

Stellarator symmetry shall be preserved in the design of the vacuum vessel. [Ref. GRD Section 3.1.5.2e]

3.2.1.2.8 Disruption Handling

The vacuum vessel shall be designed to withstand electromagnetic forces due to major disruptions characterized by instantaneous disappearance of the plasma at with a maximum plasma current of 320 kA. [Ref. GRD Section 3.1.5.5]

Note: Instantaneous decay is assumed for simplicity and is conservative for EM load calculations. Induced voltage effects due to disruptions are ignored because of the relatively low plasma current and continuous vacuum vessel in NCSX.

3.2.1.2.9 Pulse Repetition Rate

The vacuum vessel shall be designed for pulses to be initiated at intervals not exceeding 15 minutes when constrained by cool-down and 5 minutes otherwise. [Ref. GRD Section 3.2.1.5.10]

3.2.1.2.10 Discharge Termination

3.2.1.2.10.1 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

The vacuum vessel shall accommodate a controlled shutdown of the plasma and associated subsystems at the conclusion of a pulse.

3.2.1.2.10.2 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

The vacuum vessel shall accommodate the capability to shut down the plasma and associated subsystems (including the vacuum vessel) if a condition occurs during experimental operation that could cause significant equipment damage or cause injury to personnel.

3.2.1.3 Facility Shutdown

Background

Facility shutdown involves the shutdown of NCSX equipment following the termination of a discharge (per Section 3.2.1.2.10) 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 facility.

3.2.1.3.1 Coil Warm-up Timeline

The vacuum vessel shall be capable of maintaining a temperature at least 20ºC (293K) while the cryo-resistive coils (TF, PF, and modular coils) are being warmed up from operating temperature (80K) to room temperature (293K) within a period of 96 hours.

3.2.1.3.2 Vacuum Vessel Venting

Provisions shall be made to vent the vacuum vessel in preparation for a vacuum opening.

3.2.2 Physical Characteristics

3.2.2.1 Configuration Requirements and Essential Features

3.2.2.1.1 Vacuum Vessel Sub-assemblies (WBS 121)

Background

The vacuum vessel provides a vacuum boundary around the plasma chamber suitable for high vacuum conditions; structural support for all internal hardware and access for other subsystems, notably Diagnostics (WBS 3). The vacuum vessel consists of three vacuum vessel sub-assemblies (VVSAs). Each makes up a 120º section of the vacuum vessel. The vacuum vessel sub-assemblies (VVSAs) each consist of a vessel shell referred to as a vacuum vessel period assembly, a spacer assembly, and the port extension assemblies with their associated blank flanges, seals, and fasteners. Three VVSA units, including all hardware, are to be procured, fabricated, and delivered by an industrial supplier. The three VVSA units will be welded together to form the vacuum vessel during final assembly at the operation site. The final assembly will be the responsibility of the Laboratory. The maximum height and weight of a VVSA must be controlled to permit entry into the test cell and lifting of a completed field period by the test cell crane.

Requirements

a. The vacuum vessel shell shall be made as large as practical subject to the constraint that a three-coil assembly of modular coils can physically slide over the vacuum vessel without interference.

b. Port extensions shall be designed such that they can be installed after assembly of the modular and conventional coils during field period assembly.

c. Port extensions shall feature bolted flanges outside the modular coil shell to facilitate reconfiguring the outer part of the port extension for improved diagnostic access during operation where practical.

d. The height of the VVSA shall not exceed TBD.

e. The weight of a VVSA shall not exceed TBD.

3.2.2.1.2 Vacuum Vessel Thermal Insulation (WBS 122)

Background

Thermal insulation is required between the warm vacuum vessel (293K and above) and the cold coils and structures (80K). The thermal insulation must be able to conform to the highly contoured shape of the vacuum vessel.

Requirements

a. All exterior surfaces of the VV, including shell, supports, and the port extensions out through the cryostat, shall be covered with semi-pliable insulation.

b. The thermal insulation shall be of a thickness and insulation value (thermal conductivity) sufficient to meet the operation and bake out temperatures and timelines set forth in Section 3.2.1.2.3. Wherever practical, the insulation thickness shall be maximized to reduce the thermal loads between the vacuum vessel and the cryogenic components, e.g. the modular coils and cryostat interior.

c. The insulation must maintain the required performance requirements while contacting surfaces of 350 C and 80K on its inner and outer surfaces.

3.2.2.1.3 Vacuum Vessel Heating and Cooling Distribution System (WBS 123)

Background

The vacuum vessel shell is maintained at its desired temperature by circulating helium gas coolant through coolant tubes attached to the exterior of the shell. These coolant tubes are part of the Vacuum Vessel Heating and Cooling Distribution System. The helium is supplied by the Helium Bakeout System (WBS 64). Port extensions are maintained at desired temperature by electrical strip heaters attached to the exterior of the port extensions. Electrical power for the strip heaters is supplied by the Electrical Power System (WBS 4).

Requirements

a. The temperature of the vacuum vessel shell shall be maintained by circulating gas coolant through coolant tubes attached to the exterior of the vacuum vessel shell.

b. The heating and cooling distribution system and its attachments to the vacuum vessel shell shall be designed to remove 14.4MJ (assumed to be uniformly spread over the vacuum vessel shell) between pulses.

c. The coolant tube design must accommodate the installation of an extensive array of magnetic loops on the exterior of the vacuum vessel shell.

d. The temperature of the port extensions shall be maintained by electrical strip heaters attached to the exterior of the port extensions.

3.2.2.1.4 Vacuum Vessel Supports (WBS 124)

Background

Vertical supports are required to hang the vacuum vessel from the modular coils. These supports must accommodate gravity loads, net disruption (electromagnetic) loads, and seismic loads. In addition, lateral supports are required for unbalanced pressure loads and seismic loads.

Requirements

a. The vacuum vessel shall be suspended from vertical supports attached from the vacuum vessel shell to the modular coil shell. Upper vertical supports shall be designed to accommodate gravity loads, net downward disruption loads, and seismic loads. Lower vertical supports shall be designed to accommodate upward disruption loads and seismic loads.

b. Lateral supports shall be provided between the vacuum vessel and modular coil shell to react unbalanced radial (pressure) loads and seismic loads.

c. Vacuum vessel supports shall be designed to minimize the flow of heat from the vacuum vessel to the cold mass.

d. The vacuum vessel supports shall electrically isolate the vacuum vessel and modular coils.

e. The vacuum vessel supports shall be designed such that the midplanes and major axes of the modular coils and vacuum vessel are aligned with the vacuum vessel shell at 40ºC and the modular coils at 80K.

f. The vacuum vessel supports shall be adjustable and permit free thermal expansion and contraction of the vacuum vessel relative to the modular coils over the full range of temperature conditions.

3.2.2.1.5 Vacuum Vessel Local I&C (WBS 125)

Background

This WBS element provides the local I&C required by other WBS elements included under Vacuum Vessel Systems (WBS 12).

Requirements

a. Sensors shall be provided to monitor the temperature of the vacuum vessel shell and port extensions.

b. Sensors shall be provided to monitor the flow parameters in the coolant tubes.

c. Sensors shall be provided to monitor the stresses at critical locations in the vacuum vessel.

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 vacuum vessel 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 vacuum vessel 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 vacuum vessel.

e. Accommodations shall be made to facilitate installation and maintenance activities inside the vacuum vessel.

[Ref. GRD Section 3.2.4.1]

3.2.3.2 Design Life

a. The vacuum vessel shall have a design life of >10 years.

b. The vacuum vessel shall be designed for the following maximum number of pulses 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 vacuum vessel shall be designed in accordance with the NCSX Seismic Design Criteria. [Ref. GRD Section 3.3.1.5]

3.2.4 Transportability

All vacuum vessel 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 (including weld materials) used in the vacuum vessel 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 Vacuum Vessel Shell Material

The vacuum vessel shell shall be made of Inconel 625.

3.3.1.3 Vacuum Compatibility

a. The vacuum vessel interior and all in-vessel metallic components shall be electropolished prior to installation, except when authorized by the project.

b. The vacuum vessel interior shall be degreased and cleaned prior to installation. All in-vessel components shall be made of vacuum compatible materials and degreased and cleaned. They shall be vacuum baked prior to installation, except when authorized by the project.

c. All in-vessel materials shall be approved by the Project for vacuum compatibility. Pre-approved materials are catalogued in the NCSX Vacuum Materials List.

d. The vacuum vessel shall be designed for high vacuum compatibility: The vacuum vessel shall be designed to preclude trapped volumes and virtual leaks. The vacuum vessel shall be designed to allow for leak checking and repair of leaks.

[Ref. GRD Section 3.3.1.2]

3.3.1.4 Structural and Cryogenic Criteria

The vacuum vessel shall be designed in accordance with the NCSX Structural and Cryogenic Design Criteria. [Ref. GRD Section 3.3.1.3]

3.3.1.5 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]

3.3.1.6 Metrology

The vacuum vessel 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

a. The vacuum vessel shall be connected to a single-point electrical grounding system, provided in accordance with the NCSX Grounding Specification for Personnel and Equipment Safety.

b. Voltage isolation shall be provided between the vacuum vessel and systems attached to the vacuum vessel, in accordance with the NCSX Grounding Specification for Personnel and Equipment Safety.

c. RF Shielding shall be provided 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

- 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.
- The subsystem shall not present any uncontrolled safety or health hazard to user personnel.
- 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 Vacuum Implosion

Vacuum windows of 4 inches diameter or greater shall incorporate protection from accidental vacuum implosion. [Ref. GRD Section 3.3.5.2.5]

3.3.6.4 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 Vacuum vessel specifications

Configuration Item	Specification Identifier	Specification Type
Vacuum Vessel Sub-assembly	NCSX-CSPEC-121-02-XX	Product specification – forms the basis of the VVSA procurement
Heating and Cooling Distribution System	TBD	Product specification – forms the basis for the procurement for the formed tubing which will be applied to the exterior of the vacuum vessel shell

3.5 Logistics

3.5.1 Maintenance

The vacuum vessel 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 the Quality Conformance Matrix in Appendix A.

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	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 Cooldown		X			
3.2.1.2.3	Bakeout					
3.2.1.2.3.1	Vacuum Vessel Bakeout Temperatures		X			
3.2.1.2.3.2	Carbon-based Plasma Facing Components (PFCs) Bakeout Temperatures		X			Field periods baked to 350C during field period assembly. Completed vacuum vessel not baked to 350C until after first plasma.
3.2.1.2.3.3	Coil Temperatures during Bakeout		X			
3.2.1.2.3.4	Bakeout Timelines		X			
3.2.1.2.3.5	Glow Discharge Cleaning (GDC) During Bakeout		X			
3.2.1.2.3.6	Bakeout Cycles	X				
3.2.1.2.4	Vacuum Requirements					
3.2.1.2.4.1	Base Pressure			b	a	
3.2.1.2.5	Glow Discharge Cleaning (GDC) Between Pulses	X				
3.2.1.2.6	Pre-Pulse Temperature	b	a			
3.2.1.2.7	Field Error Requirements					
3.2.1.2.7.1	Eddy Current Time Constants	X				
3.2.1.2.7.2	Stellarator Symmetry		X			
3.2.1.2.8	Disruption Handling	X				
3.2.1.2.9	Pulse Repetition Rate		X			
3.2.1.2.10	Discharge Termination					
3.2.1.2.10.1	Normal Termination		X			
3.2.1.2.10.2	Abnormal Termination					
3.2.1.3	Facility Shutdown		X			
3.2.1.3.1	Coil Warm-up Timeline		X			
3.2.1.3.2	Vacuum Vessel Venting		X			
3.2.2	Physical Characteristics					

Section	Characteristic	Analysis	Demonstration	Inspection	Test	Comments
3.2.2.1	Configuration Requirements and Essential Features					
3.2.2.1.1	Vacuum Vessel Sub-assemblies (WBS 121)		X			
3.2.2.1.2	Vacuum Vessel Thermal Insulation (WBS 122)		X			
3.2.2.1.3	Vacuum Vessel Heating and Cooling Distribution System (WBS 123)		X			
3.2.2.1.4	Vacuum Vessel Supports (WBS 124)		X		d	
3.2.2.1.5	Vacuum Vessel Local I&C (WBS 125)		X			
3.2.3	System Quality Factors					
3.2.3.1	Reliability, Availability, and Maintainability		X			
3.2.3.2	Design Life		X			
3.2.3.3	Seismic Criteria		X			
3.2.4	Transportability		X			