National Spherical Torus eXperiment Upgrade

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GENERAL REQUIREMENTS DOCUMENT

NSTX-U-RQMT-GRD-001-00

Revision 0

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Change Record

Revision	Date	Description of Change
0		Initial Release

References

[1] J. Menard, et al, Nucl. Fusion **52** 083015 (2012)
[2] NSTX-RQMT-GRD-018-011-02 , NSTX General Requirements Document (GRD)
[3] NSTX_CSU-RQMT-GRD, NSTX-U CS Upgrade GRD
[4] NSTX-RQMS-GRD-108, NSTX-U Second Neutral Beam GRD
[5] NSTX-U-RQMT-SRD-002, NSTX-U SRD - Magnets
[6] NSTX-U-RQMT-SRD-003, NSTX-U SRD - Plasma Facing Components
[7] NSTX-U-RQMT-SRD-004, NSTX-U SRD - Vacuum Vessel and Internal Hardware
[8] NSTX-U-RQMT-SRD-005, NSTX-U SRD - Auxiliary Systems
[9] NSTX-U-RQMT-SRD-006, NSTX-U SRD - Power Systems
[10] NSTX-U-RQMT-SRD-007, NSTX-U SRD - Plasma Heating and Current Drive
[11] NSTX-U-RQMT-SRD-008, NSTX-U SRD - Realtime Protection and Control
[12] NSTX-U-RQMT-SRD-009, NSTX-U SRD - Central I&C
[13] NSTX-U-RQMT-SRD-0100, NSTX-U SRD - Test Cell
[14] NSTX-U-RQMT-SRD-011, NSTX-U SRD - Diagnostics
[15] NSTX-U Design Point Spreadsheet, Design Point Spreadsheet Page
[16] NSTXU-CALC-10-03-00, Design Point Calculations for NSTX Center Stack Upgrade
[17] VES-170602-SPG-01, Use of Water Cooling Inside the NSTX-U Vessel
[18] NSTX-U-RQMT-RD-003-00, NSTX-U Disruption Requirements
[19] NSTX-CRIT-0001-02, NSTX Structural Design Criteria
[20] NSTX-U-RQMT-RD-010-00, NSTX-U Magnetic Permeability Requirements
[21] NSTX-U-QAP-001, NSTX-U Quality Assurance Plan

1. Project Overview

The NSTX-U experiment is a world class spherical torus (ST) research facility operated at Princeton Plasma Physics Laboratory (PPPL). Since starting operation in 1999, NSTX has demonstrated both i) the attractiveness of the ST concept characterized by strong intrinsic plasma shaping and enhanced stabilizing magnetic field line curvature, and ii) the scientific benefits to fusion science accrued by operating in a unique parameter regime.

The NSTX-Upgrade Project expanded the operating space of the device by implementing two major improvements . The first change increased the field and current capability of the device by replacing the centerstack (CS) assembly with a new, high performance version; here the centerstack assembly includes the CS casing (CSC) and tiles mounted thereon, the OH coil, the inner legs of the TF coil, and the three pairs of inner-PF coils. With the new CS assembly, the aspect ratio A (= ratio of major radius R_0 to minor radius a) of the upgrade is increased to 1.5 from the original value of 1.26, which increases the cross sectional area of the center stack by a factor of 3 and makes possible higher levels of performance and longer pulse duration. The new center stack provides a toroidal magnetic field at the major radius R_0 of 1 Tesla (T) compared to 0.6T in the original NSTX device, and will enable operation at plasma current I_p up to 2 Mega-Amp (MA) compared to the 1MA rating of the original device.

Table 1-1 - Summary of Machine Parameters

	NSTX	NSTX-Upgrade
R_0 [m] [1]	0.8540	0.9344
A [2]	1.266	1.500
I_p [MA]	1.0	2.0
B_t [T]	0.6	1.0
T_{pulse} [s]	0.5	5.0
$T_{repetition}$ [s]	600	2400 initially, 1200 as an upgrade
$R_{center\ stack}$ [m]	0.1849	0.3148
$R_{antenna}$ [m]	1.5740	1.5740

[1] R_0 is the plasma major radius defined here as the midpoint, on the midplane, between the inboard side of the last closed flux surface of an x-point plasma located 5cm outboard of the center stack and the outboard side of the last closed flux surface of the x-point plasma located 7cm inboard of the HHFW antenna guard.
[2] A is the aspect ratio defined here based on the plasma chamber major radius located at the midpoint, on the midplane, between the outboard surface of the center stack PFCs and the inboard surface of the HHFW antenna guard, divided by one-half of the distance, on the midplane, between the outboard surface of the center stack PFCs and the inboard surface of the HHFW antenna guard.

The second improvement associated with the NSTX-U project was the addition of a second neutral beam line, containing three ion sources in addition to the three ion sources on the original beamline. This addition doubles the power from 5 MW to 10 MW (5 second pulse duration). The second neutral beam has larger tangency radii then the first (R_{tan}= 110, 120, 130 cm compared to R_{tan}=50, 60, 70 cm for the original beamline), increasing the current drive efficiency of those sources.

Additional information on the physics motivation for the Upgrade Project can be found in Ref. 1.

Due to various technical issues associate with the NSTX-U Project, and Extent of Condition review was performed, leading to the development of a Corrective Action Plan (CAP) and an NSTX-U Recovery Project. This version of the GRD is consistent with the evolution of the NSTX-U device consistent with the CAP and the NSTX-U Recovery Project.

2. GRD Scope

This document provides general requirements for the NSTX-U device following the completion of the Upgrade project. It is based on, and supersedes, legacy requirements such as:

- The NSTX General Requirements Document (GRD) [2]
- The NSTX-U Center Stack Upgrade GRD [3]
- The NSTX-U Second Neutral Beam GRD [4]

Both project-wide and system-specific requirements are provided. The system requirements are further enumerated in specific System Requirements Documents (SRDs) [5-14] and Requirements Documents. Specific numeric values for various parameters are provided in the Design Point Spreadsheet (DPSS) [15,16]. These parameters include, but are not limited to:

- Coil dimensions and turn counts
- Coil insulation properties
- Electromagnetic loads on coils and coil assemblies
- Coil currents corresponding to the 96 target equilibrium scenarios.

3. OBS & WBS Structure

This document provides requirements for each Work Breakdown Structure (WBS) element as indicated in Table 3-1. This table covers the scope of the NSTX-U device and infrastructure (both upgrade and legacy) down to WBS Level 3. In some of the more complex systems the WBS definitions extend down to Level 5. Note that this WBS dictionary differs from that used to describe the work scope of the NSTX-U Recovery Project that defines the scope specific to that project.

The systems and tasks in the WBS breakdown are assigned to the Organizational Breakdown Structure (OBS) shown in Table 3-2.

Table 3-1: *WBS structure through level 3.*

L1	L2	L3	Work Breakdown Structure (WBS)
1			NSTX-U
	1.1		TORUS SYSTEMS
		1.1.0	Project Integrated Model
		1.1.1	In-Vessel Components
		1.1.2	Vacuum Vessel and Support Structure
		1.1.3	Magnet Systems
	1.2		PLASMA HEATING & CURRENT DRIVE SYSTEMS
		1.2.1	High Harmonic Fast Wave (HHFW)
		1.2.2	Coaxial Helicity Injection (CHI) Current Drive
		1.2.3	Electron Cyclotron Pre-Ionization (ECH)
		1.2.4	Neutral Beam Injection (NBI)
	1.3		AUXILIARY SYSTEMS
		1.3.1	Vacuum Pumping System
		1.3.2	Coolant Systems
		1.3.3	Bakeout Heating and Cooling Systems
		1.3.4	Gas Delivery & Injection Systems
		1.3.5	Wall Conditioning
	1.4		PLASMA DIAGNOSTICS
		1.4.1	Diagnostics
	1.5		POWER SYSTEMS
		1.5.1	AC Power Systems
		1.5.2	AC/DC Converters
		1.5.3	DC Systems
		1.5.4	Control and Protection Systems
		1.5.5	General Power Systems and Integration
	1.6		CENTRAL I&C
		1.6.1	Control System
		1.6.2	Data System
	1.7		PROJECT SUPPORT AND INTEGRATION
		1.7.1	Project Management and Integration
		1.7.2	Project Physics
		1.7.3	Integrated Machine Operations
	1.8		SITE PREPARATION AND ASSEMBLY
		1.8.1	Test Cell
		1.8.2	Torus Assembly and Construction

***Table 3-2**: OBS Structure of the Recovery Project*

1	VV & Internal Hardware
2	Plasma Facing Components
3	Magnets
4	Vacuum & Fueling Systems
5	Cooling Systems
6	Diagnostics
7	Power Systems
8	Heating Systems
9	Real-Time Control & Protection
10	Central I&C
11	Bakeout System
12	Test Cell
13	Operations
14	Systems Engineering & Integration
15	Construction Management
16	Project & Operations Management

4. General Requirements

Information which applies to the NSTX-U device broadly, rather than to specific WBS elements, is contained in this section.

4.1. Performance Criteria

4.1.1. Field Directions and Coordinates

a. The NSTX-U device shall be oriented so that the axis of the TF inner bundle points towards the ceiling of the NSTX-U Test Cell (NTC).

b. A right hand coordinate system (R, ϕ ,Z) shall be established so that[3]:

- Positive Z has an origin at the machine midplane and points toward the NTC ceiling
- Positive R has an origin at the center of the TF bundle and points outward
- Positive ϕ has an origin along a line pointing towards the north wall[4], directly between the centerlines of Bays A and L, increasing in a counterclockwise direction when viewing from above.

c. The plasma current shall be positive in this coordinate system (i.e. counter clockwise when viewed from above)

d. The toroidal field shall be negative in this coordinate system (i.e. clockwise when viewed from above)

e. The coils shall have as their baseline directions the values in Table 4.1.1-1.

Table 4.1.1-1: *Typical current directions for standard plasmas. All direction statements are referenced as viewing from above.*

Coil	**Current Direction**
TF	clockwise field, or current in the inner legs flowing downward
PF-4, 5	Clockwise current (negative)
PF-3U,L	Counter clockwise during field null phase (positive), clockwise current during plasma equilibrium phase (negative)
PF-2U/L, -1aU/L, -1bU/L, -1cU/L	Either direction, pending divertor scenario
OH	Counter clockwise pre-charge (positive), swings to clockwise direction (negative) to apply loop voltage
Plasma	Counter clockwise (positive).

f. The 12 bays are given nominal angle definitions as in Table 4.1.1-2. Actual bay positions may differ slightly due to fabrication tolerances, and bay letters should be used only in a reference sense.

[3] Note that some legacy documents use a left handed coordinate system, with R and Z defined as above but the toroidal angle ϕ increasing in the clockwise direction when viewed from above. It is recommended to always specify the handedness of the angles when discussing them.

[4] The north wall of the NSTX-U Test Cell is not true north, but rather NNW.

***Table 4.1.1-2**: Toroidal angles of NSTX-U Bays.*

Bay	**Legacy Left Handed System**	**Reference Right Handed System**
A	15	345
B	45	315
C	75	285
D	105	255
E	135	225
F	165	195
G	195	165
H	225	135
I	255	105
J	285	75
K	315	45
L	345	15

4.1.2. Baseline Operations Scenarios

a. Nominal plasma current (I_p) waveform for engineering design purposes shall consist of linear ramp-up from zero to 2MA at a rate of 2MA/sec, flat top (constant 2MA) with duration up to 5.0 sec, and linear ramp-down from 2MA to zero at a rate of 1MA/sec [15]. Total duration 2/2 + 5 + 2/1 = 8.0 sec, with an ESW time of 6 seconds (Figure 4.1.2-1). This waveform is referred to as the “Long Pulse Partial Inductive” (LPPI) waveform. The “Short Pulse Full Inductive” (SPFI) waveform is similar, but with a flat-top duration of only 2.5 seconds

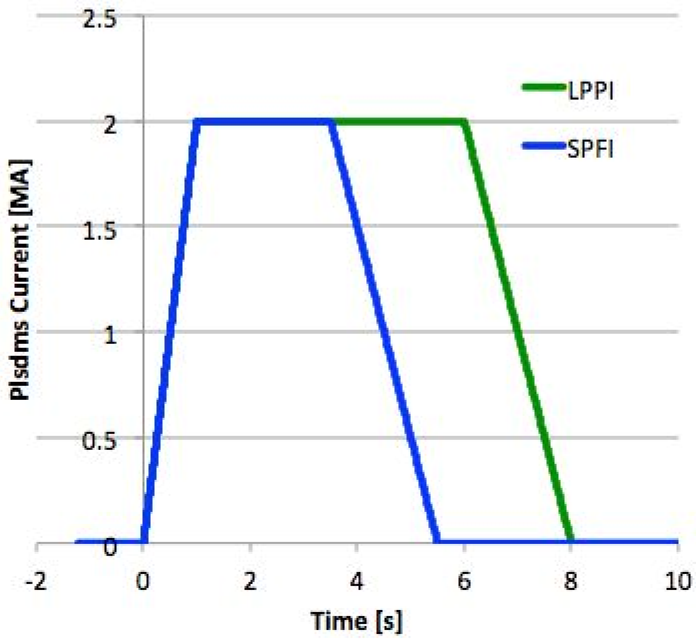

Figure 4.1.2-1 - Reference 2 MA plasma current waveforms.

b. For engineering purposes the nominal plasma cross section is approximated by a wall-limited plasma whose r, z coordinates are described by the following equations:

$$r(\theta) = R_0 + a * \cos(\theta + \delta * \sin(\theta))$$

$$z(\theta) = \kappa * a * \sin(\theta)$$

where:

R_0 = major radius (m)
a = minor radius (m)
A = aspect ratio = R_0 /a
κ = elongation
δ = triangularity
θ = poloidal angle

Two cross sections are described. The cross section defining the 100% flux surface is descriptive of the full size of the plasma chamber, approximately equal to the shape of the plasma if limited by the walls. The 95% flux surface is most relevant to physics operations and corresponds approximately to the last closed flux surface for X-point plasmas. Data for the two cross sections is given in Table 4.1.2-1.

Table 4.1.2-1 - Plasma Dimensions

	95%	100%
R_0 [m]	0.9344	0.9450
A	1.6405	1.5000
A	0.5696	0.6300
R_0-a [m]	0.3648	0.3150
R_0+a [m]	1.5040	1.5750
Inboard midplane gap [m]	0.0500	0.0000
Inboard midplane hardware [m]	0.3148	0.3150
Outboard midplane gap [m]	0.0700	0.0000
Outboard midplane hardware [m]	1.5740	1.5750
Elongation κ	2.5000	2.5000
Triangularity δ	0.6000	0.6000

The nominal major radius R_0 is based on the 95% flux surface. The nominal aspect ratio A is based upon the 100% flux surface. Plasma cross sections along with outline of plasma facing surfaces is given in the Figure 4.1.2-2.

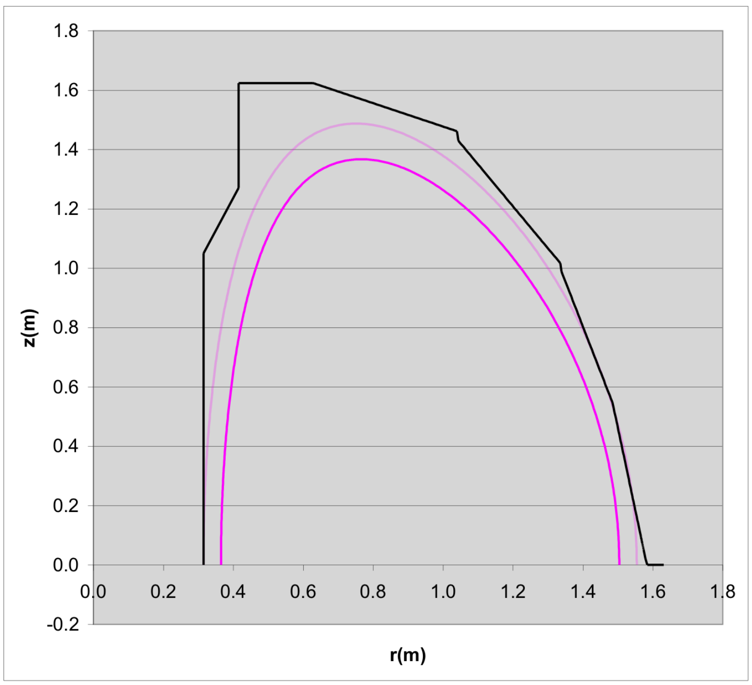

Figure 4.1.2-2 - 95% and 100% cross sections and plasma facing surfaces. The limiter boundary is the reference surface, and may differ slightly from the final design surface [6].

c. Plasma scenarios and the OH coil evolution shall be designed so that the frictional interaction between the OH coil and the TF inner leg bundle is acceptable. This is accomplished by keeping the bulk average temperature of the OH coil (T_{OH}) always greater than that of the TF inner leg bundle ($T_{TF,inner}$).

d. The coil protection systems shall have mechanisms to enforce $T_{OH}>T_{TF,inner}$.

4.1.3. Auxiliary Heating Input Power

a. HHFW - For engineering purposes, the HHFW system shall be assumed to deliver a maximum of 4 MW to the plasma for 5 s.

b. NBI - For engineering purposes each NBI beam line shall be assumed to deliver a maximum power to the plasma as indicated in Table 4.1.3-1.

Table 4.1.3-1: NBI Power To Plasma per Beam Line

Pulse length (sec)	Power to Plasma (MW)
5	5.0
4	5.4
3	6.0
2	6.8
1.5	7.5
1.25	8.2
1	9.0

c. The initial total combined heating power will be that deliverable from the HHFW plus one NBI beamline (9 MW), or two beamlines (10 MW), for 5 seconds[5].

4.1.4. Pulse Duty Factor

The plasma pulse length requirement is given in Section 4.1.2.

a. At the full rated pulse length, the repetition period shall be 2400 sec, but upgradeable to 1200 sec. via modification and upgrades to components outside the tokamak core Therefore, all components in the tokamak core shall be designed for the 1200 sec. repetition rate.

b. Plasma pulses with shorter duration may be performed at a more rapid rate, consistent with the cooling of the coils and in-vessel components.

[5] Note that combined NB and HHFW heating has not been reliably achieved, due to physics considerations associated with HHFW propagation in the scrape-off-layer and deleterious interactions of the fast waves with the fast particles injected by the neutral beams. Studying this physics, with the aim of increasing the heating efficiency of HHFW heating when neutral beams are used, is a key research topic

4.1.5. Heat Removal Capabilities

a. The average power load to the PFCs and VV is summarized in Table 4.1.5-1.

Table 4.1.5-1 – Pulsed Input Power and Average Power Loss

Case	**P_{Ohmic} (MW)**	**P_{aux} (MW)**	**T_{pulse} (sec)**	**T_{rep} (sec)**	**P_{avg}[6] (kW)**
NSTX-U, 1 NB + HHFW, upgraded rep rate	0.5	4 RF+5 NBI = 9	5	1200	40
NSTX-U, 2 NB, upgraded rep rate	0.5	2*5 NBI = 10	5	1200	44
NSTX-U, 1 NB + HHFW, baseline rep rate	0.5	4 RF+5 NBI = 9	5	2400	20
NSTX-U, 2 NB, baseline rep rate	0.5	2*5 NBI = 10	5	2400	22

b. The minimum heat removal capabilities from the divertors of the device shall be based on a 30% radiation fraction, with a 50/50 up-down power split and an 80/20 in/out power split. Therefore, the heat removal capability shall be as per Table 4.1.5-2.

c. The heat removal capability of the first wall shall be determined by the high radiation fraction scenario of Table 4.1.5-3.

d. The radiated power number from tables 4.1.5-2 and 4.1.5-3 shall be taken as uniformly radiated from within the 95% plasma boundary in Section 4.1.2.

Table 4.1.5-2: Moderate Radiation Fraction Scenario

Plasma Reference	**Location**	**Instantaneous Power**	**Average Power, Base Duration**	**Average Power, Upgraded Duration**
---		**MW**	**kW**	**kW**
Inner Strikepoint Conduction	Each of Two Inner Vertical Targets	0.7	1.5	3.1
Outer Strikepoint Conduction	Either Both Inner Horizontal Targets or Both Outboard Divertor Targets	2.9	6.1	12.3
Radiated Power	Uniformly Radiated	3.2	6.6	13.1

[6] P_{avg} is computed by dividing the total energy input to the plasma by the repetition rate.

Table 4.1.5-3: 100% Radiation Fraction Scenario

Plasma Reference	Location	Instantaneous Power	Average Power, Base Duration	Average Power, Upgraded Duration
---		**MW**	**kW**	**kW**
Inner Strikepoint Conduction	Each of Two Inner Vertical Targets	0.0	0.0	0.0
Outer Strikepoint Conduction	Either Both Inner Horizontal Targets or Both Outboard Divertor Targets	0.0	0.0	0.0
Radiated Power	Uniformly Radiated	10.5	21.9	43.8

d. Any in-vessel cooling loops shall follow the following guidelines [17]

- If made from single-walled tubing, then water cannot be used following the introduction of any lithium into the machine. Any tubes used in this fashion should be isolated from water supply and pumped out to $1x10^{-3}$ torr before lithium introduction.
- If cooling loops can be formed with double wall tubing or other secondary barrier to the vacuum, then water cooling may be used during lithium operations. These cases require a system or program to positively verify on a daily basis that both barriers are intact. If either barrier is found to be compromised, then the system shall be taken out of service. Design should carefully guard against common mode failures that may simultaneously compromise both barriers.

4.1.6. Shot Spectrum

a. For engineering purposes, the number of NSTX-U pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of 20,000 pulses based on the pulse spectrum given in Table 4.1.6-1.

Table 4.1.6-1: NSTX CSU Pulse Spectrum

Performance	60%	75%	90%	100%	
B_t	0.6	0.75	0.9	1	T
I_p	1.2	1.5	1.8	2	MA
$T_{pulse}=T_{flat—Ip}$ (sec)					Total pulses
3	200	1800	1200	1000	4200
3.5	200	1800	1200	1000	4200
4	200	1800	1200	1000	4200
4.5	200	1800	1200	500	3700
5	200	1800	1200	500	3700

Total	20000

4.1.7. Field Errors and Component Alignment

a. Manufacturing and assembly tolerances shall be provided in the appropriate SRD or RD.

4.1.8. Static EM Loads

a. The DPSS [15,16] establishes minimum static electromagnetic loads. Derived loads using other codes is permitted if the loads are verified to be greater than or equal to those established by the DPSS.

B. All static electromagnetic loads shall be computed from prescribed coil currents in the DPSS.

4.1.9. Disruption Requirements

a. NSTX-U plasma facing components, internal hardware (PFC tiles, passive plates, outboard divertor, neutral beam armor, cooling systems, shutters, etc), CSC, VV, and RF antennae shall be designed to withstand the forces and loads due to plasma disruption.

b. The loads shall be calculated as described in Ref. [18].

4.2. Engineering Criteria

4.2.1. Design Criteria

4.2.1.1. General Design Guidelines

a. Table 3.1-1 of the original NSTX Project GRD [2] is repeated as Table 4.2.1.1-1 and shall apply to the center stack upgrade.

Table 4.2.1.1-1: General Design Guidelines

Operating Condition	**Description**	**P, Probability Of Occurrence In A Year**	**General Design Guidelines**
Normal Events	Events that are planned to occur regularly in the course of facility operation	P=1	Provide safe and reliable operation
Anticipated Events	Events of moderate frequency which may occur once or more in the lifetime of a facility	$1>P\geq10^{-2}$	The facility should be capable of returning to operation without extensive corrective action or repair
Unlikely Events	Events which are not anticipated but which may occur during the lifetime of a facility	$10^{-2}>P\geq10^{-4}$	The facility should be capable of returning to operation following potentially extensive corrective actions or repairs, as necessary
Extremely Unlikely Events	Events which are limiting faults and are not expected to occur during the	$10^{-4}>P\geq10^{-6}$	Facility damage may preclude returning to operation

	lifetime of a facility but are postulated because of their safety consequences		
Incredible Events	Events of extremely low probability of occurrence or of non-mechanistic origin	$P<10^{-6}$	Not considered in the design

4.2.1.2. Failure Mode Effects Analysis

a. The FMEA which was prepared for the original NSTX Project and revised during the Upgrade project shall be updated, including an analysis of all changes implemented by the Recovery Project and redesign.

b. Failure probabilities shall be quantified based on engineering judgment per the General Design Guidelines Table 4.2.1.1-1. Failure consequences shall be quantified based on engineering judgment per Table 4.2.1.2-2.

Table 4.2.1.2-1: Failure Consequence Categories

Consequence	**Criteria**
Minimal	Time to correct/repair < 1 week and Cost < $10K
Minor corrective action (not extensive)	Time or Cost greater than entry above, and Time to correct/repair < 1 month and Cost < $100K
Extensive corrective action	Time or Cost greater than entry above, and Time to correct/repair < 12 month and Cost < $5000K
Irreparable facility damage	Time or Cost greater than entry above or other factor preventing future use of facility

4.2.1.3. Structural Design

a. All NSTX-U mechanical design shall follow the NSTX-U structural design criteria [19].

b. All designs shall maintain the midplane symmetry of the device to the greatest extent possible.

c. Toroidally continuous passive structures shall be minimized to the extent that other design constraints permit, and shall be made of high resistivity materials (316 SS, Inconel) where compatible with component function.

4.2.2. Materials Selection

4.2.2.1. Magnetic Permeability

a. Magnetic permeability of components shall be as defined in Ref. [20].

4.2.2.2. Materials Inside the Vacuum Vessel

a. All materials utilized within the primary vacuum boundary shall be on the PPPL Vacuum Committee approved list, or shall be approved by the committee.

b. All materials utilized within the primary vacuum boundary shall be designed to withstand the anticipated temperatures during plasma and bakeout operation. See Section 6.3.3.

c. All viton O-ring seals shall be maintained at a temperature lower than 180 degC during any operational or bakeout scenario.

e. All materials with line of sight exposure to the lithium evaporators or otherwise determined to be at risk to exposure to lithium films shall be approved for use under that condition.

4.2.3. Electrical Isolation and Grounding

a. The NSTX-U vacuum vessel shall be single-point grounded during operations. There shall be a mechanism to open the ground connection for testing purposes. When opened, the vessel vacuum vessel isolation shall be rated to withstand a one minute AC hipot test at 2 kV AC rms.

b. Where sensors are installed inside the vacuum vessel, any associated instrumentation rack shall be electrically referenced to the vacuum vessel. Those racks shall be electrically isolated from structures, and on their AC power feed, with isolation rated to withstand a one minute AC hipot test at 2 kV AC rms.

c. All instrumentation originating from the test cell should be isolated prior to exiting the test cell boundary. The isolation shall be rated to withstand a one minute DC hipot test at 5kV. Examples of this isolation include optical and/or magnetic (isolation transformer) means. If this isolation cannot be achieved, then the equipment outside the test cell boundary shall be placed under access control as part of the primary test cell access control system

d. With the exception of dedicated grounding bus, components which are in mechanical contact with the vacuum vessel shall be electrically isolated from the vacuum vessel. The isolation shall be rated to withstand a one minute AC hipot test at 2 kV AC rms.

e. Conducting loops of area greater than 0.2 m^2 formed by metallic structures within a radius of 3 meters from the centerline of the torus shall be broken by insulating breaks, unless specific exception is granted. The insulation shall be rated to withstand a one minute AC hipot test at 2 kV AC rms.

4.2.4. Component Leak Rates

a. Individual vacuum system components have a bench leak rate no greater than 1×10^{-9} standard cubic centimeters per second (sccs) air equivalent as measured by a Helium Mass Spectrometer Leak

Detector (HMSLD). The total aggregate leak rate for the NSTX-U Vacuum vessel/vacuum system shall not exceed 1x10^{-5} sccs air equivalent.

4.3. Future Upgrades

a. Systems within the ST core should be designed to accommodate a 1200 second repetition rate under the full heating power of Section 4.1.3. Systems external to the core shall meet the requirements for a 2400 second repetition rate, with the prospect of future upgrades to achieve a 1200 second rate.

b. The design should accommodate the upgrade of the PF-5 power loop to permit operation of that circuit beyond the 24 kA rating of a single power supply branch, likely to 34 kA capability.

c. The design should accommodate future facility enhancements to the extent that the needs for those upgrades are understood and accommodation is cost effective. These potential enhancements include:

- Multi-MW 28 GHz ECH/EBW system.
- Non-Axisymmetric Control Coils (NCCs).
- A lower divertor cryo-pump
- High-Z PFC Upgrade
- Liquid lithium divertor upgrade
- Coaxial Helicity Injection (CHI) with discreet in-vessel biasing plates.
- Bi-polar operations of the PF1A, PF1B, PF2, & PF4 coils.
- He cooling of in-vessel components such as the passive plates and outboard divertors
- Water cooling of the outer vacuum vessel wall.

5. System Requirements Documents (SRDs) and Requirements Documents (RDs)

a. SRD and RD naming and signature conventions are defined in the NSTX-U QA Plan [21].

b. The WBS-specific requirements are described in the system requirements documents (SRDs) as in Table 5-1.

Table 5-1: The contents of NSTX-U SRDs.

SRD	System	WBS
Magnets Systems [5]	Outer PF Coils	1.1.3.1
	TF Outer Legs	1.1.3.2

	TF Inner Legs	1.1.3.3.1
	OH Solenoid	1.1.1.3.2
	Inner PF Coils	1.1.3.3.3
	Bus Bar Systems	1.1.3.4
	Resistive Wall Mode Coils	1.1.3.5
Vacuum Vessel and Internal Hardware [7]	Vacuum Vessel, Ports, and Vessel Legs	1.1.2.1
	Passive Plates	1.1.1.2.1
	Outboard Divertor Structures	1.1.1.2.2
	Neutral Beam Armor	1.1.1.2.3
	In-Vessel Heating Cooling Tubes	1.3.3.1.3
	Vessel, Passive Plate, Outboard Divertor, and In-Vessel Tubing TCs	1.1.2.2
	Coil Support Structures	1.1.2.3
	CS Casing, Pedestal, and Ceramic Breaks	1.1.3.3.4
Plasma Facing Components [6]	Plasma Facing Components	1.1.1.1
Auxiliary Systems [8]	Vacuum Pumping System	1.3.1
	Cooling Water System	1.3.2
	Bakeout System	1.3.3
	Gas Delivery and Injection System	1.3.4
	Wall Conditioning Systems	1.3.5
Heating and Current Drive Systems [10]	High-Harmonic Fast Wave Heating	1.2.1
	Electron Cyclotron Pre-Ionization	1.2.3
	Neutral Beam Injection	1.2.4
Power Systems [9]	AC Power Systems	1.5.1
	AC/DC Converters	1.5.2
	DC Systems	1.5.3
	Control and Protection Systems	1.5.4
Central Instrumentation and Control [12]	Central I&C	1.6
Realtime Control and Protection [11]	Miscellaneous Interlocks	1.7.3.5

	Real time control protection hardware and software	1.7.3.6
Diagnostics [14]	Plasma Diagnostics	1.4.1
	Machine Instrumentation	1.7.3.4

c. As per the NSTX-U QA Plan [21], SRDs shall be reviewed by the relevant Responsible Engineers (REs) and the NSTX-U Engineering Director, and approved by the Project Director

d. For each WBS element in the SRD, the following sections shall be used to articulate the requirement:

- Functions
- Materials and Design Requirements
- Configuration Requirements & Essential Features
- Baseline Performance and Operational Requirements
- Upgrade Performance and Operational Requirements
- Interfaces

e. At a minimum, the interfaces should be documented with a table having the following headings:

Interfacing System	Interfacing WBS	Type of Interface	Interface Boundary	Interface Description	Required Interface Documentation
(describe the system to which the interface is made)	(the WBS # of the interfacing system)	(see table below)	(Precise description of the physical interface between systems)	(numerical values if possible or reference to the source of values)	(Types of documents that must be produced)

Specific elaboration may be provided in the text as appropriate

f. The “Type of Interface” column shall have one of the following entries:

Interface Type	Description
Structural	An interface with a requirement for the transfer of structural load
Thermal	An interface with a requirement for the transfer of heat.
Space Allocation	An interface with a requirement to avoiding interferences or provide a spatial allocation

Electrical Power	An interface with a requirement for the transmission of electrical power or for the provision of a ground reference.
Electrical Signal	An interface with a requirement for the electrical transfer of information
Fiber Optic	An interface with a requirement for the fiber-optic transfer of information
Software	An interface requirement between software elements that pass data via a defined framework
Fluid	An interface with a requirement for the conveyance of fluids
Gas	An interface with a requirement for the conveyance of gas
Vacuum	An interface with a requirement for the interaction between two vacuum volumes, or that provides a primary vacuum seal.
Plasma	An interface directly to the plasma heat flux, electromagnetic loading, etc.
Diagnostic	A sensor placed on a system, designed to measure some characteristic w/o disturbing or impacting the basic function of the system
Other	An interface not described by any other category above

g. The “Interface Description” column describes the nature of the interface, including configuration and performance requirements as known, or references to those quantities.

h The “Required Interface Documentation” column describes documentation that must be provided in order to document the interface. Examples may be engineering calculations, P&IDs, mechanical drawings, CAD global model, and control wiring documents; other types of documents may also be acceptable.

i. SRDs must have a revision log, tracking all changes to the document.

6. WBS Specific Requirements

6.1. Torus Systems (WBS 1.1)

6.1.1. In-Vessel Components (WBS 1.1.1)

6.1.1.1. Plasma Facing Components (WBS 1.1.1.1)

6.1.1.1.1. Performance

a. The Plasma Facing Component (PFC) tiles shall consist of carbon-based materials designed to absorb the heat, particle, and photon flux from the plasma and heating systems, to minimize the influx of impurities to the plasma, and to withstand the electromagnetic forces associated with plasma disruption.

b. PFC tiles shall be installed on the centerstack casing, divertors, passive plates, and neutral beam armor.

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6.1.1.1.2. Engineering Requirements

a. Plasma facing components shall be formed from fine-grain isotropic graphite or carbon-carbon composites.

b. Tile surfaces may be designed to be non-axisymmetric (e.g. shaped in the toroidal direction) to avoid leading edges to meet heat flux requirements. Shaping shall be in accordance with the field polarities listed in Section 4.1.1.

c. PFC tiles shall be classified as "critical components" for design evaluation per the definition given in the Structural Design Criteria [19].

d. Tile design shall be based on accommodation of 10 MW input power for 5 seconds duration with a 2400 second repetition rate and the baseline cooling methods (radiation, conduction, and baseline levels of heat extraction with ex-vessel water or He).

e. Heat extraction capability shall be installed in the tokamak core to allow an upgrade to a 1200 second repetition rate without perturbation to the implemented core design. See Table 4.1.5-2.

f. PFCs shall be designed to accommodate independent or concurrent i) bakeout and ii) glow discharge cleaning or boronization.

h. Sufficient number of tiles shall be instrumented with thermocouples to confidently assess their temperature during plasma and bakeout modes of operations.

6.1.1.2. In-Vessel Structures

6.1.1.2.1. Passive Plates

6.1.1.2.1.1. Performance

a. The passive plates shall consist of four rows of copper stabilizing plates, two above the midplane and two below the midplane.

b. There shall be 12 copperplates per row.

c. The plate thickness shall be sized to accomplish stabilization of n=0 and n=1 plasma instabilities (here, n is the toroidal mode number).

6.1.1.2.1.2. Engineering Requirements

a. The passive plates and their mounting structures shall be designed to withstand all loads during operation due to dead-weight, thermal gradient, and electromagnetic effects.

b. The passive plate brackets shall have provision to bake their carbon plasma facing components.

6.1.1.2.2. Outboard Divertor Structures

6.1.1.2.2.1. Performance

a. The outboard divertors shall provide a mechanical structure on which to mount plasma facing components that protect the lower and upper sections of the vacuum vessel from direct plasma impingement.

6.1.1.2.2.2. Engineering Requirements

a. The outboard divertors shall be designed to withstand all loads during operation due to dead-weight, thermal, and electromagnetic effects.

b. The outboard divertors shall have provision to bake any carbon plasma facing components.

6.1.1.2.3. Neutral Beam Armor

6.1.1.2.3.1. Performance

a. The neutral beam armor shall provide a mechanical structure on which to mount graphite plasma facing components that protect the vessel wall from direct impingement by the neutral beam

6.1.1.2.3.2. Engineering Requirements

a. The neutral beam armor shall be designed to accept at least a single case with full energy and duration beam impingement from both beam lines, for any power & duration case listed in Table 4.1.3-1.

b. The neutral beam armor shall be designed to withstand all loads during operation due to dead weight, thermal, and electromagnetic effects.

c. The neutral beam armor shall have provision to bake the plasma facing components.

6.1.2. Vacuum Vessel and Support Structure (1.1.2)

6.1.2.1. Performance

a. The outer vacuum vessel shall, along with the centerstack casing, provide the primary vacuum boundary.

b. The outer vacuum vessel shall provide the primary structural support of the outer TF legs and outer PF coils.

c. The vacuum vessel shall support in-vessel components such as the neutral beam armor, the passive plates, the RF antenna, and the outboard divertors.

6.1.2.2. Engineering Requirements

a. The outer vacuum vessel and support structure shall be designed to withstand all loads during normal operation due to seismic loads, dead weight, vacuum, thermal, normal electromagnetic, and disruption electromagnetic.

b. The outer vacuum vessel and support structure shall be designed to withstand all loads during bakeout due to seismic loads, dead weight, vacuum, and thermal conditions.

c. The outer PF and TF outer leg support structures shall have allowance for all thermal scenarios, including coil thermal expansion during operations and vessel thermal expansion during bakeout

c. The centerstack casing (CSC) shall be mechanically connected, but electrically isolated, at the upper interface between the CSC and the outer vacuum vessel. Insulation shall be designed to withstand a one minute AC hipot test at 2E+1=1kV AC rms.

d. The CSC and outer vacuum vessel shall not include any ceramic insulator feature at their lower interface (as was the case for the original versions of NSTX and NSTX-U)..

e. The vacuum vessel shall accommodate two TFTR neutral beam lines at the desired tangency radii described in Section 6.2.4.2.

6.1.3. Magnets (WBS 1.1.3)

6.1.3.1. Outer and Inner PF Coils (WBS 1.1.3.1, WBS 1.1.3.3.3)

6.1.3.1.1. Performance

The PF coils shall provide field nulling for plasma initiation and shall provide equilibrium and shape control during ramp-up, ramp-down, and flat-top..

a. Unless otherwise specified, all PF coils, when separately and singularly energized, shall be capable of supplying 100% of their rated ampere-turns, including any engineering headroom, in the form of a linear ramp-up, flat top, and linear ramp-down waveform synchronized with the I_p waveform given in section 4.1.2.

b. For engineering purposes, the nominal design requirement for all components and systems shall be based on the load combination of PF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with Ip=0 or $\neq$ 0, shall be allowable.

In the event that this design requirement cannot be satisfied without significant cost impact and/or technical risk, exception may be taken. In this case:

- the design requirement may be reduced from the assumption of maximum possible currents to the PF/OH current distributions derived from the range of plasma equilibria specified by the physics requirements, including any applied headroom. The derivation shall be based on the nominal equilibria currents but adjusted for the post-disruption current distribution.

- the relationship between the design-driving quantity and the PF/OH/TF currents and the plasma current shall be determined and described by an algorithm to be used in the real-time coil protection system (see section 6.7.3.5) as appropriate.

6.1.3.1.2. Engineering Requirements

a. The PF magnets shall consist of the Outer PF coils (PF2a, 2b, 3a,3b,4b,4c, and PF5) and the Inner PF coils (PF1a, PF1b, PF1c), as listed in Table 6.1.3.1.2.-1.

Table 6.1.3.1.2-1: PF Coils

Designation	**Source**
PF1a	Fabricated for NSTX-U Recovery Project
PF1b	Fabricated for NSTX-U Recovery Project
PF1c	Fabricated for NSTX-U Recovery Project
PF2a	S-1, EF-1a
PF2b	S-1, EF-1b
PF3a	S-1, EF-2a
PF3b	S-1, EF-2b
PF4b	S-1, EF-3b
PF4c	S-1, EF-3c
PF5a	Fabricated for NSTX
PF5b	Fabricated for NSTX

b. The PF coils listed in Table 6.1.3.1.2-1 shall be connected in series groups with independent current control as indicated in Table 6.1.3.1.2-2.

Table 6.1.3.1.2-2: Independent PF Circuits

PF Circuit	**Coil Grouping**
PF-1aU	PF1aU
PF-1aL	PF1aL
PF-1bU	PF1bU
PF-1bL	PF1bL
PF-1cU	PF1cU
PF-1cL	PF1cL
PF-2U	PF2a, PF2b, upper
PF-2L	PF2a, PF2b, lower
PF-3U	PF3a, PF3b, upper
PF-3L	PF3a, PF3b, lower
PF-4	PF4b,PF4c, upper & lower
PF-5	PF5a, PF5b, upper & lower

c. Structural design of PF coils and their supports shall accommodate any combination of PF, OH, and TF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with I_P=0 or $\neq$ 0 except where this is judged impractical and special exception is taken. See 6.1.3.1.1e.

d. The PF coil system winding packs boundaries shall be nominally symmetric about the midplane.

e. Turn counts, turn layouts, maximum currents, maximum voltages, required action integrals, and other numerical parameters for the PF coils shall be provided in the DPSS [15].

f. Cooling for the PF coils shall be provided consistent with a 1200 sec repetition period, or a 2400 sec repetition period upgradeable to a 1200 sec repetition period w/o modification of the coils.

g. Electrical insulation design for the PF coil, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a one minute DC hipot test voltage of 2E+1kV. For coils configured with two wire connections, E shall correspond to the maximum power supply line-to-line DC voltage. For coils configured in three-wire configurations, E shall correspond to the sum of the line-to-line DC voltages.

h. All series coil connections indicated in Table 6.1.3.1.2-2 shall result in current flow which is equal in magnitude, and in the same ϕ direction, in the series connected coils.

i. The outer PF coils shall be supported from the vacuum vessel.

j. Structural support of the PF coils shall allow for axial & radial thermal expansion while ensuring that the coils remains centered and restrained against vertical motion when subject to electromagnetic loads.

k. All aspects of the PF coils design shall be compatible with NSTX-U operation with plasma current and toroidal field in either ϕ direction.

6.1.3.2. TF outer and inner legs (WBS 1.1.3.2, WBS 1.1.3.3.1)

6.1.3.2.1. Performance

a. Toroidal field (B_t) shall be 1.0T at R_0=0.9344m, maintained constant for the full 5.0 s duration of the LPPI plasma current flat-top based on the nominal I_p waveform, as given in Fig. 6.1.3.2.1-1 and Table 6.1.3.2.1-1 [15]. The TF waveform for the SPFI scenario is given in Fig. 6.1.3.2.1-1 and Table 6.1.3.2.1-2

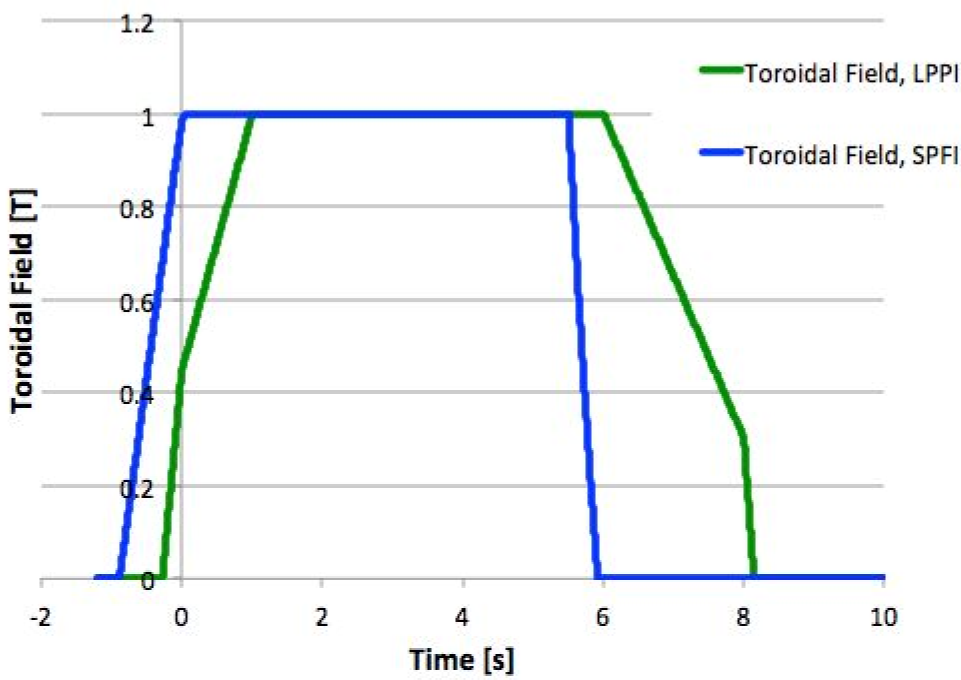

Figure 6.1.3.2.1-1: Waveform of the toroidal field.

Table 6.1.3.2.1-1: Waveform of the TF coil current, LPPI configuration

Time [s]	B_T [T]
-0.28	0
0.00	0.45

1.00	1.00
6.00	1.00
8.00	0.30
8.18	0

Table 6.1.3.2.1-2: Waveform of the TF coil current, SPFI configuration

Time [s]	B_T [T]
-0.89	0
0.00	1.00
5.50	1.00
5.96	0

6.1.3.2.2. Engineering Requirements

a. Structural design of TF coils and their supports shall accommodate any combination of PF, OH, and TF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with I_P=0 or ≠ 0 except where this is judged impractical and special exception is taken. See 6.1.3.1.1e.

b. Final values for turn counts, turn layouts, maximum currents, maximum voltages, required action integrals, and other numerical parameters for the TF coil shall be provided in the DPSS.

c. Cooling for the TF coil shall be provided consistent with a 1200 sec repetition period.

d. Electrical insulation design for the TF coil, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a one minute DC hipot test voltage of 2E+1kV. For the TF coils, E shall correspond to the maximum power supply line-to-line DC voltage.

e. The outer TF legs shall be supported from the vacuum vessel.

f. The inner-TF legs shall be supported as part of the CS assembly.

g. Demountable joints shall be provided between the TF outer legs and TF inner legs to allow removal/replacement of the Center Stack assembly.

h. Structural support of the TF inner leg shall allow for axial thermal expansion and restraint against electromagnetic loads.

i. Structural support of the TF outer leg shall allow for thermal expansion and restraint against electromagnetic loads.

j. All aspects of the TF coil design shall be compatible with NSTX-U operation with plasma current and toroidal field in either ϕ direction.

6.1.3.3. Ohmic Heating Solenoid (WBS 1.1.3.3.2)

6.1.3.3.1. Performance

a. The OH coil shall provide loop voltage for plasma initiation, ramp-up, sustainment, and ramp-down, consistent with the plasma current waveform in Fig. 4.1.2-1.

b. The breakdown loop voltage shall be >=4.2 volts for >= 0.02 seconds [3].

c. For engineering purposes, the required ramp-up flux swing can be taken as 0.7 Wb, and the required sustainment flux swing can be taken as 0.81 Wb for the LPPI case and 1.29 Wb for the SPFI case.

6.1.3.3.2. Engineering Requirements

a. Structural design of OH coil and its supports shall accommodate any combination of PF, OH, and TF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with I_p=0 or $\neq$ 0 except where this is judged impractical and special exception is taken. See 6.1.3.1.1e.

b. Final values for turn counts, turn layouts, maximum currents, maximum voltages, required action integrals, and other numerical parameters for the OH coil shall be recorded in the DPSS.

c. Cooling for the OH coil shall be provided consistent with a 1200 sec repetition period.

d. Electrical insulation design for the OH coil, including turn insulation, ground insulation, as well as strike and creep distances of leads and fittings shall be conservatively designed based on a hipot test voltage of 2E+1. For the OH coil, E shall correspond to the maximum power supply line-to-line DC voltage.

e. Structural support of the OH coil shall allow for axial thermal expansion while ensuring that the coil is constrained to allowable levels when subject to electromagnetic loads.

f. The OH coil shall be supported as part of the CS assembly.

g. All aspects of the OH coil design shall be compatible with NSTX-U operation with plasma current and toroidal field in either ϕ direction.

6.1.3.4. Center Stack Assembly and Ceramic Break (WBS 1.1.3.3.4)

6.1.3.4.1. Performance

a. The Center Stack Assembly shall consist of the TF inner legs, inner PF coils, Center Stack Casing, ceramic break assembly, pedestal, and inboard PFC tiles.

6.1.3.4.2. Engineering Requirements

a. The Center Stack Assembly shall be designed in such a way that it can be extracted whole or in parts from the NSTX-U outer vessel.

b. The pedestal shall support the CS assembly against gravity, and share in the transfer of seismic and electromagnetic loads.

c. The assembly shall include provision for bakeout of the inboard PFC tiles and for cooling during plasma operations, including electrical isolation at the upper mechanical interface to the vacuum vessel.

d. Appropriate thermal isolation shall be provided between coils in the centerstack assembly and any components that achieve the bakeout temperature.

e. All vacuum seals associated with the mechanical interface between the CS casing and the vacuum vessel shall use either i) double O-rings with pumped interspaces or ii) welded lip seals.

6.1.3.5. Bus bar systems (WBS 1.1.3.4)

6.1.3.5.1. Performance

a. The bus bar system is used to bring electrical power to coils, and to provide for the DC bakeout current path to the vessel and centerstack casing.

6.1.3.5.2. Engineering Requirements

a. Thermal capacity of coil bus runs shall be consistent with the action integrals of the coils to which they are attached.

b. All bus runs should accommodate a 1200 s repetition period, and may be water cooled as necessary.

c. Structural support of bus runs should accommodate the full range of allowed PF, OH, and TF currents, except where this is judged impractical and special exception is taken. See 6.1.3.1.1e.

d. All aspects of the bus bar design shall be compatible with NSTX-U operation with plasma current and toroidal field in either ϕ direction.

6.1.3.6. Resistive Wall Mode Coils (1.1.3.5)

6.1.3.6.1. Performance

a. The RWM coils are used to apply non-axisymmetric (radial) fields at the vessel midplane, for the purpose of Resistive Wall Mode (RWM) control and error field correction.

6.1.3.6.2. Engineering Requirements

a. The RWM coils shall consist of six coils mounted at the vessel midplane, each producing radial field. The coils shall fit in the opening between the PF-5 supports, and shall as a group toroidally span the full vessel.

b. The coils shall be independently fed, allowing the application of even-n or odd-n fields depending on power supply connections.

c. They shall be sized to support a 6 kA-turn pulsed rating with the 1200 s duty cycle.

d. All aspects of the RWM coil design shall be compatible with NSTX-U operation with plasma current and toroidal field in either ϕ direction.

6.2. Plasma Heating and Current Drive Systems (WBS 1.2)

6.2.1. High Harmonic Fast Wave System (WBS 1.2.1)

6.2.1.1. Performance

a. The HHFW system shall deliver 4 MW of power to the plasma for 5 seconds, every 1200 seconds.

6.2.1.2. Requirements

a. The HHFW system shall utilize RF power produced by the six existing Tokamak Fusion Test Reactor (TFTR) Ion Cyclotron Range of Frequencies (ICRF) sources.

b. The HHFW system shall utilize a twelve strap antenna mounted on the vacuum vessel wall in the gap between the upper and lower passive stabilizing plates. The antenna shall be arranged toroidally between the NSTX-U vacuum vessel mid-plane ports.

c. Each current strap shall include a back-plane, a Faraday shield, and a local (bumper) limiter structure.

d. The antenna shall be compatible with bakeout and glow discharge modes of operation.

e. The twelve antennas shall be capable of operating at frequencies in the range of 30MHz to 40MHz. All RF generators operating at any single frequency shall be phase locked to provide control over the wavenumber spectrum excited in the plasma at that frequency.

f. Switches shall be provided to isolate HHFW power from the NSTX test cell. These switches shall be interlocked with the test cell access control system.

g. Antenna structures shall be qualified for the full disruption loads specified in Ref. [18].

6.2.2. Coaxial Helicity Injection (WBS 1.2.2)

a. The requirement to support coaxial helicity injection by biasing the outer vessel relative to the inner vessel was removed from NSTX-U in 2017.

6.2.3. ECH Pre-Ionization (WBS 1.2.3)

6.2.3.1. Performance

a. The EC system shall provide microwave RF power in the electron cyclotron range of frequencies for preionization.

6.2.3.2. Requirements

a. One EC launcher shall be installed at an outboard location in the Vacuum Vessel to direct the microwave radiation toward the desired absorption location.

b. The launcher must be compatible with bakeout and glow discharge modes. The launcher shall have a vacuum window connecting it to the external transmission system. This window must have low electrical loss at microwave frequencies and satisfy the thermal and mechanical requirements for vacuum interfaces.

c. The system shall provide >20 kW of power, for a duration >20 msec, every 1200 seconds.

d. The EC power shall be interlocked to the test cell access control system.

6.2.4. Neutral Beam Injection

6.2.4.1. Performance

a. Two beamlines, with three ion sources each, shall be installed on NSTX-U at Bays A and K.

6.2.4.2. Requirements

a. The neutral beam system shall use the TFTR-era beamlines, ion-sources, cryo-systems, and control. Modernizations for these systems shall be undertaken as appropriate.

b. The beamlines shall be isolated from NSTX-U primary vacuum by torus isolation valves.

c. One beamline shall inject through Bay A, and shall have beam tangency radii of R_{tan} of 50, 60, and 70 cm.

d. One beamline shall inject through Bay K, and shall have beam tangency radii of R_{tan} of 110, 120, and 130 cm.

e. Beam delivered power per beamline shall be as per Table 4.1.3-1.

6.3. Auxiliary Systems (WBS 1.3)

6.3.1. Vacuum Pumping System (WBS 1.3.1)

6.3.1.1. Performance

a. The Vacuum Pumping System shall provide the required high vacuum environment for plasma operations. It shall pump the vessel from atmosphere to base vacuum, exhaust the spent plasma constituents after each pulse, and shall exhaust the impurities associated with the bakeout and glow discharge cleaning of the PFCs.

b. The Vacuum Pumping System shall be equipped a Residual Gas Analyzers (RGA) that can be operated during both glow discharge cleaning and normal high vacuum conditions.

c. The vacuum pumping system shall have a capability to evacuate the inter-spaces on double O-ring seals

6.3.1.2. Requirements

a. The roughing pump(s) shall be capable of evacuating the vacuum vessel from atmosphere to $1x10^{-3}$ Torr in less than 4 hours.

b. The TVPS shall be capable of achieving a base pressure of $2x10^{-8}$ Torr following bakeout, excluding fueling gas.

6.3.2. Cooling Water Systems (CWS) (WBS 1.3.2)

6.3.2.1. Performance

a. The CWS shall provide deionized cooling water to the TF coil, PF coil, OH coil and bus work, as well as selected additional components, with parameters to support a 1200 second repetition rate.

6.3.2.2. Requirements

a. All coil, vessel, and bus-work cooling paths shall be individually monitored and interlocked for flow and temperature on the outlet side. Other paths may also be monitored and interlocked in this fashion.

b. Cooling loops for the TF coils should be designed to minimize thermal shock to the TF inner legs.

c. The CWS configuration for the OH coil shall minimize layer-to-layer temperature differences during cooldown.

d. The CWS configuration for the OH coil should be configured to mitigate thermal stresses due to cooling waves.

f. Where multiple flow path are mechanically bonded (for instance, the TF inner legs, the OH coil), loss of flow in one path shall result in termination of flow in all other paths.

g. Loss of cooling flow in any or all TF inner leg circuits should result in termination of flow in all OH circuits.

h The capability shall exist to display alarms and remove the power supply permissive under low-flow or high temperature conditions.

6.3.3. Bakeout Heating and Cooling Systems (WBS 1.3.3)

6.3.3.1. Performance

a. The bakeout system shall include means for heating the full volumes of the carbon PFCs to the required temperatures for an indefinite period while maintaining the vacuum vessel and components connected thereto to temperatures within their temperature ratings.

b. Here, carbon PFCs refers to the graphite or carbon-carbon composite tiles covering the CS first wall, CS angled section, inner divertor vertical target, inner divertor horizontal target, outboard divertor, primary and secondary passive plates, and neutral beam armor.

6.3.3.2. Requirements

a. The volume of all carbon PFCs shall be heated to >300 degC during bakeout.

b. The average measured temperature of PFCs over a given region (CSFW, OBD, PPPs, SPPs, IBDH, IBDV, etc.) shall not exceed 350 degC.

c. The temperature of the vacuum vessel surfaces shall be heated to > 115 degC during bakeout.

d. The average measured temperature of the vacuum vessel surface shall not exceed 160 degC.

e. Bakeout heating systems shall be designed to heat the vacuum vessel and PFCs to the required temperature in 48 hours.

f. After completion of bakeout, the machine shall be cooled down to an operation temperature (nominally room temperature) in less than 24 hours.

6.3.4. Gas Delivery and Injection Systems (WBS 1.3.4)

6.3.4.1. Performance

The gas delivery and injection system shall provide the following operational fueling capabilities:

a. Prefill - maintain a low fill pressure on order of 10^{-5} Torr before the discharge
b. Low field side injection - inject gas with pulse width modulated piezo valves on the outer vessel once the discharge has been initiated, for core plasma fueling
c. High field side injection - Inject gas from the high field side for increased fueling efficiency.
d. Divertor injection - Inject gas into the divertor region.

b. Specific research-related systems will have separate requirements documentation.

6.3.4.2. Requirements

a. The gas delivery system (GDS) shall provide a means to connect gas cylinders to gas injection valves on the machine.

b. For baseline operations, the gas injection system (GIS) shall provide at least three piezoelectric valves on the Vacuum Vessel for low field side injection, with independent control of the fueling gas in each injector.

c. For baseline operations, the GIS shall provide three injectors on the CS. Two shall have orifices located near the midplane, and one shall have an orifice located near the CSAS tiles.

d. The GIS shall provide four divertor injectors, two on the center stack and two on the lower outboard divertors.

6.3.5. Wall Conditioning Systems (WBS 1.3.5)

6.3.5.1. Performance

a. There shall be a glow discharge conditioning (GDC) system installed, capable of cleaning the PFC and vessel wall surfaces in zero-field conditions via bombardment of ions formed during the glow process. This system shall consist of ionizing filaments, electrodes, power supplies, gas delivery and control system components. Some of these components may be shared with other systems.

b. These shall be a system to “boronize” the vacuum vessel inner surface with deuterated Trimethylboron. This system may share components with other systems.

c. Additional research-oriented wall conditioning systems, potentially involving conditioning of the PFC surfaces with lithium, may be specified in other documents.

6.3.5.2. Requirements

a. The NSTX shall be equipped to provide glow discharge cleaning (GDC) mode with DC glow for indefinitely long periods, as well as between discharges.

b. The system shall have at least two electrodes, biased relative to the vacuum vessel, and physically separated to provide a more uniform glow discharge.

c. The system shall provide pre-ionization filaments near each electrode, and each filament location shall have redundant filaments.

d. The system shall function with either standard GDC with Ne, Ar, He or D_2, or with the boronization system.

6.4. Plasma Diagnostics (WBS 1.4)

6.4.1. Performance

a. A base set of operations diagnostics should be provided to support basic routine operations at modest parameters, as per Table 6.4.1--1

Table 6.4.1-1: Diagnostics to support basic routine operations

Diagnostic	**Measured Quantity**
Plasma Current Rogowskis	Plasma current
Mirnov Sensors	Poloidal field at specific locations
Poloidal Flux Loops	Poloidal flux at specific locations
Visible TV Cameras	Plasma shape, wall interactions, fuelling
Filterscopes	Deuterium and impurity visible light emitted by plasma
Fission Chamber Neutron Detectors	Total neutrons emitted by plasma
Thomson Scattering	Electron density and temperature radial profiles
Tile thermocouples	Temperature of the tiles between discharges
Tile Langmuir probes	Electron density and temperature at the face of tiles
EUV Spectrometers	Impurities in the plasma

b. Additional research diagnostics will be provided, often via collaborating institutions. These diagnostics may be required to do specific experiments, or to explore new regions of operating space.

6.4.2. Requirements

a. All diagnostics shall be compatible with the full range of bakeout and operations temperatures, with any required additional cooling implemented in a way that is consistent with other GRD requirements.

6.5. Power Systems (WBS 1.5)

6.5.1. AC Power Systems (WBS 1.5.1)

a. The AC Power Systems shall provide all electrical power required for the NSTX facility.

6.5.2. AC/DC Convertors (WBS 1.5.2)

6.5.2.1. TF Power Conversion System (1.5.2.1)

6.5.2.1.1. Performance

a. TF power supplies shall supply current to the TF coils to produce a toroidal field (B_t) ≤ 1.0T at R_0=0.9344m, maintained constant for the full 5.0s duration of plasma current flat-top based on the nominal I_p waveform given in section 4.1.2. Corresponding flat top coil current is 129.8kA.

6.5.2.1.2. Requirements

a. Baseline repetition period shall be 2400s.

b. Waveforms for current rise and fall, including L/R decay in case of a fault, shall be coordinated with design of the TF coil in terms of heating.

e. Redundant measurements of the TF coil currents shall be provided with accuracy of 0.2% (magnitude of DC measurement error at full rated current).

f. Current during flat top shall be regulated to within 0.5%.

g. Bus links or other means shall be provided in order that the current in the TF magnets can be driven in either direction. The polarity reversal procedure shall require 4 hours or less.

h. Additional parameters regarding the TF power conversion system are specified in the DPSS[15].

6.5.2.2. OH Power Conversion System (1.5.2.2)

6.5.2.2.1. Performance

a. The OH circuit shall provide four quadrant operation over a current range of +/- 24 kA, and a voltage range of +/- 6 kV.

6.5.2.2.2. Requirements

a. The OH circuit shall be bipolar (current supplied in both directions during a pulse).

b. Baseline repetition period shall be 1200 s.

c. Redundant measurements of the OH coil currents shall be provided with accuracy of 0.2% (magnitude of DC measurement error at full rated current).

d. Bus links or other means shall be provided in order that the connection between the power supplies and coils can be established in either direction. The polarity reversal procedure shall require 4 hours or less.

e. Additional parameters regarding the OH power conversion system can be found in the Design Point Spreadsheet [15].

6.5.2.3. PF Power Conversion System (1.5.2.3)

6.5.2.3.1. Performance

a. The PF power systems shall provide current and voltage to the PF-1a through PF-5 coils at levels defined by the DPSS [15] and the magnets SRD [5].

6.5.2.3.2. Requirements

a. In the base configuration, the PF1C, PF1B, and PF3 circuits shall be bipolar (current supplied in both directions during a pulse). Other PF circuits shall be unipolar, with no design choices being made to preclude an upgrade to bipolar operations.

b. Baseline repetition period shall be 1200 s.

c. Bus links or other means shall be provided in order that the connection between the power supplies and coils can be established in either direction. The polarity reversal procedure shall require 4 hours or less.

d. Redundant measurements of the PF coil currents shall be provided with accuracy of 0.2% (magnitude of DC measurement error at full rated current).

e. Additional parameters regarding the PF power conversion system can be found in the Design Point Spreadsheet [15].

6.5.2.4. Switching Power Amplifiers (1.5.2.4)

a. The RWM coils shall be powered by bipolar switching power amplifiers (SPAs), capable of frequency response 0 - 100Hz.

b.The SPAs shall be capable of providing at least 3.3 kA for at least six seconds into either a single or series connected pair of RWM coils.

6.5.3. DC Systems (WBS 1.5.3)

6.5.3.1. Performance

a. The DC systems shall connect the AC/DC convertors in FCPC to the Power Cable Termination Structure (PCTS) in the NTC.

b. These systems shall consist of disconnnect and grounding switches, power cables, DC current transducers, and ground fault detection

6.5.3.2. Requirements

a. The TF, OH, and each PF circuits shall be equipped with disconnect switches to isolate the power supply systems from the connections to the magnets.

b. In addition, no-load grounding switches shall be provided to ground the terminals of the connections to the magnets.

c. These ground and disconnect switches shall be interlocked with test cell access control.

d. The baseline repetition period of the DC systems shall be 2400s, upgradeable to 1200s.

e. Additional numeric parameters of the DC systems are specified in the DPSS [15].

6.6. Central I&C (WBS 1.6)

6.6.1. Performance

a. The Central I&C system shall provide supervisory control and monitoring of the NSTX-U facility, including:

- Plant Control and Monitoring (asynchronous routine control and monitoring)
- Timing and synchronization (synchronization of triggered actions from master clock events)
- Data acquisition
- Data archiving
- Visual and audio monitoring and archiving of specific areas of the test cell
- Configuration of the NSTX-U control room and Fusion Control Center

6.6.2. Requirements

a. The NSTX-U Control Room shall be installed in the location previously occupied by the TFTR Control Room.

b. The Central I&C systems shall include a data archival mechanism archiving all data from each discharge within 900 seconds of the end of pulse. It shall be possible to adjust the order in which data is collected.

c. This archival system shall allow on-line access to all NSTX and NSTX-U shot data, for users both at PPPL and off-site.

d. The Central I&C systems shall provide a system for distributed process control of the NSTX-U plant over the full 1200 second shot cycle, as well as during periods when no operations are occurring. This system shall have a graphical user interface accessible throughout the facility, with provision for continual expansion of the input and output capabilities.

e. The Central I&C systems shall provide a programmable clock system to synchronize events within the NSTX-U clock cycle.

f. The central I&C systems shall provide systems to monitor sounds and movement within the test cell. Images and sounds shall be archived for interrogation following the discharge.

g. The Central I&C system shall provide sixteen (16) electrically isolated, general purpose signal channels between the test cell and the control room. These signals shall be displayed in the control room in real-time.

6.7. Project Support and Integration (WBS 1.7)

6.7.1. Accelerator Safety Order (WBS 1.7.1.3)

a. NSTX-U systems and procedures shall comply with the Accelerator Safety Order (DoE Order 420.2c)

6.7.2. Project Physics (WBS 1.7.2)

a. NSTX-U project physics shall provide engineering support when called upon. Examples of such support may include, but not be limited to:

- Discharge scenario development
- System requirements definition
- Review participation

6.7.3. Integrated Machine Operations (WBS 1.7.3)

6.7.3.1. Hardwired Interlock System

a. A system shall be provided to prevent access to the NSTX-U test cell and related areas when they are in an unsafe condition, and provide emergency stop capability.

b. This system shall include E-stops in the control room, test cell, and other locations with the capability to de-energize all heating and coil systems.

6.7.3.2. NTC Ground Fault Monitor

a. A system shall be provided to annunciate if a ground fault is made on either the vacuum vessel or diagnostic ground.

6.7.3.3. Machine Instrumentation

a. Machine instrumentation shall be provided to both validate mechanical models of the structure and to trend the long term behaviour of the mechanical system.

b. Components to instrument may include the passive plates, outer TF legs, and various coil supporting structures.

6.7.3.4. Pulse Duration and Period Timer

a. A system shall be provided to enforce a maximum on-duration of the FCPC rectifiers, as well as the minimum duration between pulses.

b. The two durations on this system shall be reconfigurable.

6.7.3.5. Realtime Control and Software (WBS 1.7.3.6)

6.7.3.5.1. Performance

<u>Coil Protection Systems</u>

a. The Digital Coil Protection System (DCPS) system shall be used when the allowances of section 6.1.3.1.1b are invoked.

b. The DCPS system shall be able to compare coil current values to limits.

c. The DCPS system shall be able to compare coil action calculation to limits.

d. The DCPS system shall be able to enforce the limit of $T_{OH}>T_{TF}$.

e. The DCPS system shall be able to computes forces, moments, and stresses on individual coils and coil mounting structures, and compare to limits.

f. The DCPS system shall have the ability to compute combinations of forces and compare to limits.

g. The coil protection system shall have the capability to detect turn-to-turn and coil-lead arc faults, here referred to as the Shorted Turn Protection System

h. Both systems shall have the capability to declare an FCPC Level-1 fault if limit values are exceeded or a turn-to-turn or coil-lead arc is detected.

Plasma Control System

a. A real-time plasma control system shall be installed, capable of closed loop control of the plasma current, shape, gas fuelling, heating systems, RWM coil currents, and other properties.

6.7.3.5.2. Requirements

Coil Protection System

a. There shall be at least two separate, redundant, instances of the Digital Coil Protection System operating during any discharge.

b. There shall be at least one instance of the Shorted Turn Protection System operating during any discharge

Plasma Control System

a. The system shall have a distributed input data stream for data relevant to plasma operation. Data shall be converted and packaged as necessary for transporting it.

b. The input data stream shall be continuously expandable

c. The sampling rate of the input stream shall be >= 5 kHz.

d. The system shall have an output stream with control information of rectifier firing angles (for transrex rectifiers) or a current reference (for the SPAs), as well as for gas valve modulation, and neutral beam on/off.

e. Additional outputs should be anticipated in the future, and provision for expansion should be made.

f. The system shall have a realtime computer interfacing to the data streams, capable of executing the required algorithms, and with the ability to add additional algorithms.

6.7.3.6. Radiation Monitors (WBS 1.7.3.7)

a. Annunciated radiation area monitors shall be deployed in order to ensure compliance with applicable regulations.

6.8. Site Preparation and Assembly (WBS 1.8)

6.8.1. Test Cell

6.8.1.1. Performance

a. NSTX-U shall reside in the former D-Site hot cell, also known as the NSTX-U Text Cell (NTC).

b. The NSTX-U Test Cell (NTC) provides:

- structure support for equipment located there
- fire barriers to adjacent fire zones
- radiation shielding for adjacent areas
- access control during operations

6.8.1.2. Requirements

a. The test cell shall be provided with an oxygen deficiency hazard (ODH) monitoring system.

b. Platforms shall be provided for access to the midplane and upper levels of the machine.

c. A fire protection system shall be provided.

d. Penetrations in the text cell walls and floor shall have appropriate neutronics shielding or labyrinths.

e. Oil-free, dry compressed air shall be provided for equipment in the test cell.

7. ES&H Requirements

The design, manufacture, fabrication, construction, installation, test, operation, maintenance, modification, and eventual decontamination and decommissioning of the NSTX-U including all features associated with the Center Stack Upgrade shall be accomplished in a manner that will protect personnel, visitors, the public, property and the environment from injury. Pursuant to this policy, the NSTX-U project shall:

- Comply with all applicable Federal, State, Local, and PPPL ES&H regulations;
- Assess and minimize the risks inherent in the NSTX program;
- Actively encourage ES&H awareness on the part of NSTX personnel and visitors.

In particular, NSTX shall be designed and operated in accordance with DOE Orders and PPPL Environment, Safety and Health Directives.

8. Common Acronyms

Acronyms commonly found in this GRD, SRDs and RDs, or other NSTX-U technical documents include the following list.

ACC: Activity Certification Committee
ACDS: AC distribution system
ARR: Accelerator Readiness Review
ASE: Accelerator Safety Envelope
ASO: Accelerator Safety Order
BES: Beam Emission Spectroscopy
BL: Beamline (for neutral beams)
CAD: Computer Aided Design
CHI: Coaxial Helicity Injection
CI&C: Central Instrumentation and Control
CLR: Current Limiting Reactor
CDR: Conceptual Design Review
COE: Chief Operating Engineer
CPLD: Complex Programmable Logic Device
CHERS: Charge Exchange Recombination Spectroscopy
CS: Center Stack
CSC: Center stack casing
CSAS: Center Stack Angled Section
CSFW: Center stack first wall
CWDM: Coarse Wave Division Multiplexer
DCPS: Digital Coil Protection System
DNB: Diagnostic Neutral Beam
DoE: Department of Energy
DIMS: Divertor Imaging/Multicordal Spectrometer
DITS: Digital Input and Time Stamp module
DPSS: Design Point Spreadsheet
DSS: D-Site Shift Supervisor
dTMB: deuterated trimethylboron
DTI: Divertor Tangential Imaging
DVVR: Design Verification and Validation Review
ESW: Equivalent Square Wave
EoC: Extent of Condition

EoD: End of Discharge
EoFT: End of Flat Top
EoP: End of Pulse
ECH-PI: Electron Cyclotron Heating Pre-Ionization
EIES: Edge Impurity and neutral Emission Spectroscopy
EFC: Error field correction
EFIT: Equilibrium Fit
EPICS: Experimental Physics and Industrial Control System
FCC: Fusion Controls Center
FCPC: Field Coil Power Conversion
FD: Fault Detector
FDR: Final Design Review
FES: Fusion Energy Sciences
FG: Firing Generator
FIR: Far Infrared
FIMM: FPDP Input Multiplexing Module
FPDP: Front Panel Data Port
FIDA: Fast Ion D-alpha
FIMM: FPDP Input Multiplexing Module
FIReTIP: Far Infrared Tangential Interferometer and Polarimeter
FMEA: Failure Modes Effects Analysis
FOMA: FPDP Output Module - Analog
FOMD: FPDP Output Module - Digital
FOMS: FPDP Output Module - Serial
FPGA: Field Programmable Gate Array
FVI: Fast Vacuum Interrupter
GIS: Gas Injection System
GDC: Glow Discharge Cleaning
GDS: Gas Delivery System
GPI: Gas Puff Imaging
GRD: General Requirements Document
GRP: Glass Reinforced Plastic
HIS: Hardwired Interlock System
HCS: Hardwired Control System
HFS: High Field Side
HHFW: High Harmonic Fast Wave
HTHS: High Temperature Helium Skid
HMI: Human Machine Interaction
I&C: Instrumentation and Control
IBDH: Inboard Divertor, Horizontal
IBDV: Inboard Divertor, Vertical
IGBT: Insulated Gate Bipolar Transistor
IVPS: Interspace Vacuum Pumping System

JA: Junction Area
LADA: Lyman-Alpha Detector Array
LCC: Life Cycle Cost
LCC: Local Control Center
LITER: Lithium Evaporator
LFS: Low Field Side
LGI: Lithium Granule Injector
LHe: Liquid Helium
LN: Liquid Nitrogen
LoC: Loss of Cooling
LoWEUS: Long-Wavelength Extreme Ultraviolet Spectrometer
LPPI: Long Pulse Partial Inductive
MAPP: Materials Analysis Particle Probe
MDS+:
MG: Motor Generator
MGI: Massive Gas Injection
MHD: Magnetohydrodynamics
MonaLISA: Metal Monitor and Lithium Spectrometer Assembly
MPTS: Multi-Pulse Thomson Scattering
MSE: Motional Stark Effect
MSE-CIF: Motional Stark Effect, Collisionally Induced Fluorescence
MSE-LIF: Motional Stark Effect, Laser Induced Fluorescence
NBI: Neutral Beam Injection
NIR: Near Infrared
NTC: NSTX-U Test Cell
NSTX-U: The National Spherical Torus Experiment – Upgrade
OBD: Outboard divertor
OBS: Organizational Breakdown Structure
OH coil: Ohmic heating coil
PDR: Preliminary Design Review
PDP: Pulse Duration and Period Timer
PCS: Plasma Control System
PCTS: Power Cable Termination Structure
PF coil: Poloidal field coil
PF-1: Any of the six coils (PF-1aU, PF-1aU, PF-1bU, PF-1bL, PF-1cU, PF-1cL) installed on the NSTX-U center column
PFC: Plasma Facing Component
PFR: Private Flux Region
PLC: Programmable Logic Controller
PPP: Primary Passive Plate
PPPL: Princeton Plasma Physics Laboratory
QA: Quality Assurance
QC: Quality Control

QMB: Quartz Micro-Balance
RE: Responsible Engineer
RD: Requirements Document
RF: Radio Frequency
RGA: Residual Gas Analyzer
RWM: Resistive Wall Mode
SAD: Stand Along Digitizer
SAD: Safety Assessment Document
SAMI: Synthetic Aperture Microwave Imaging
SCR: Silicon Controlled Rectifier
SDD: System Description Document
SDS: Safety Disconnect Switch
SIV: Source Isolation Valve
SF6: Sulfur Hexafluoride
SFP: Small Form-factor Pluggable transceiver
SGI: Supersonic Gas Injector
SLD: Safety Lockout Device
SoD: Start of Discharge
SoFT: Start of Flat Top
SoP: Start of Pulse
SPA: Switching Power Amplifier
SPFI: Short Pulse Full Inductive
SPP: Secondary Passive Plate
SRD: System Requirements Document
SXR: Soft X-Rays
TAE: Toroidal Alfven Eigenmode
TIV: Torus Interface Valve
TC: Thermocouple
TF coil: Toroidal field coil
TFOL: Toroidal Field coil Outer Leg
TFTR: Tokamak Fusion Test Reactor
TTC: TFTR Test Cell
TVPS: Torus Vacuum Pumping System
USI: Unreviewed Safety Issue
USI: Unreviewed Safety Issue Determination
UPS: Uninterruptable Power Supply
VIPS: Visible Impurity Photometric Spectrometer
VME: Versa Module Europa
VPI: Vacuum Pressure Impregnation
VUV: Vacuum Ultraviolet
VV: Vacuum Vessel
XEUS: Extreme Ultraviolet Spectrometer
WAF: Work Approval Form

WBS: Work Breakdown Structure
WP: Work Package