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National Spherical Torus Experiment-Upgrade
NSTX-U

SAFETY ASSESSMENT DOCUMENT
(SAD)

NSTX-SAD-052-00

Revision 6

FEBRUARY 2015

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List of Acronyms

ACC	Activity Certification Committee
ACGIH	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
ALARA	As Low as Reasonably Achievable
BL1 & BL2	(Neutral) Beamline 1 & Beamline 2
CAMAC	Computer Automated Measurement And Control
CHERS	Charge-Exchange Recombination Spectroscopy
CHI	Coaxial Helicity Injection
CS	Center Stack
CWS	Cooling Water System
CX	Categorical Exclusion
D-D	Deuterium-Deuterium
D&D	Decontamination and Dismantlement (TFTR)
DATS	Differential Atmospheric Tritium Sampler
DCPS	Digital Coil Protection System
DOE	(U.S.) Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program (for radiation dosimetry)
dTMB	Deuterated Trimethylboron
E-Stop	Emergency Stop
ECH	Electron Cyclotron Heating
ELMs	Edge Localized Modes
EMP	Environmental Monitoring Plan
EPRG	Emergency Planning Response Guide
ERPP	Environmental Radiation Protection Program
ES&H/EB	(PPPL) ES&H Executive Board
ESHD	Environment, Safety & Health Directive
ESU	Emergency Services Unit
ESW	Equivalent Square Wave
FCPC	Field Coil Power Conversion
FIReTIP	Far Infrared Tangential Interferometer
FMEA	Failure modes and effects analyses
FNSF	Fusion Nuclear Science Facility
FWP	Field Work Proposal
GDC	Glow Discharge Cleaning
GDS	Gas Delivery System
GFCI	Ground Fault Circuit Interrupter
GRD	General Requirements Document
H&CD	Heating and Current Drive
HCS	Hardwired Control System
HEPA	High Efficiency Particulate Air
HHFW	High Harmonic Fast Wave
HIS	Hardwired Interlock System

HTS	High Temperature (Bakeout) System
HP	Health Physics (PPPL radiation safety control division)
HVAC	Heating, Ventilation and Air Conditioning
HVE	High Voltage Enclosure
I/O	Input/Output
I&C	Instrumentation and Control
ICRF	Ion Cyclotron Range of Frequencies
IDLH	Immediately Dangerous to Life and Health
IFW	Internal Firewall
ISM	Integrated Safety Management
ISTP	Integrated System Test Procedure
JHA	Job Hazard Analysis
LEC	Liquid Effluent Collection
LIFTER	Liquid Lithium (Li) Filler for LITER
LITER	Lithium Evaporator
LSB	Lyman Spitzer Building
LSOP	Laser Safe Operating Procedure
LTS	Low Temperature (Bakeout) System
MG	Motor Generator
MGI	Massive Gas Injection (valves)
MGF	Motor Generator Flywheel
MPTS	Multi Pulse Thomson Scattering
MSDS	Material Safety Data Sheet
NASA	National Aeronautics and Space Administration
NB	Neutral Beam
NBI	Neutral Beam Injection
NBL	Neutral Beamline
NBPC	Neutral Beam Power Conversion
NEPA	National Environmental Policy Act
NESHAPS	National Emissions Standard for Hazardous Air Pollutants
NIOSH	National Institute of Occupational Safety
NJDEP	New Jersey Department of Environmental Protection
NJPDES	New Jersey Pollutant Discharge Elimination System
NPH	Natural Phenomena Hazard
NSTX-U	National Spherical Torus Experiment Upgrade
NTC	NSTX Test Cell
OH	Ohmic Heating (coil)
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety & Health Administration
PC	Performance Category
PCTS	Power Cable Termination Structure
PEARL	PPPL Environmental, Analytical & Radiological Laboratory

PEL	Permissible Exposure Limit
PEP	Project Execution Plan
PF	Poloidal Field (coil)
PFC	Plasma Facing Component
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
PPLCC	Plasma Physics Laboratory Computer Center
PPPL	Princeton Plasma Physics Laboratory
PSE&G	Public Service Electric & Gas Company
PSO	(DOE) Princeton Site Office
PTP	Preoperational Test Procedure
QAP	Quality Assurance Program
QMS	Quality Management System
RF	Radiofrequency
RGA	Residual Gas Analyzer
RPP	Radiation Protection Program
RWM	Resistive Wall Mode (coil)
SAD	Safety Assessment Document
SBRSA	Stony Brook Regional Sewerage Authority
SDS	Safety Data Sheet
SF6	Sulfur Hexafluoride
SLD	Safety Lockout Device
SSCs	Structures, Systems and Components
ST	Spherical Torus
STOP	Safety Training Observation Program
TCB	Test Cell Basement
TF	Toroidal Field (coil)
TFTR	Tokamak Fusion Test Reactor (operated 1982-97 at PPPL)
TIV	Torus Interface Valve
TLV	Threshold Limit Value
TMB	Trimethylboron
TMP	Turbomolecular Pump
TPX	Tokamak Physics Experiment
TSG	Topical Science Group
TWA	Time Weighted Average
TZM	Titanium Zirconium Molybdenum (PFC alloy)
UPS	Uninterruptible Power Supply
USID	Unreviewed Safety Issue Determination
VESDA	Very Early Smoke Detection Apparatus
VLAN	Virtual Local Area Network
VPS	Vacuum Pumping System
WBS	Work Breakdown Structure
WEEL	Workplace Environmental Exposure Limit
WSHP	Worker Safety & Health Program
X/Q	Atmospheric Dilution Factor
XMP	Experimental Machine Procedure
XP	Experimental Procedure

Executive Summary

This Safety Assessment Document (SAD) documents the safety analysis of the National Spherical Torus Experiment Upgrade (NSTX-U) at the Princeton Plasma Physics Laboratory (PPPL). The National Spherical Torus Experiment Upgrade (NSTX-U) is designed to prove the scientific principle of the spherical torus (ST). The ST plasma is nearly spherical in shape, its minor radius being slightly smaller than its major radius, thus giving an aspect ratio close to one. The NSTX Upgrade Project (2011-15) replaced the previous NSTX center stack (CS) assembly with a new larger radius CS assembly, and added a second neutral beamline (NBL) formerly used for the Tokamak Fusion Test Reactor (TFTR) Project onto the NSTX experiment. NSTX-U is a significant upgrade to the NSTX facility, which operated from 1999-2011, with both additional neutral beam heating and current drive power, and higher toroidal fields and plasma currents. These upgrades are designed to extend the NSTX results to higher current, longer pulse, lower plasma collisionality, and fully non-inductive current drive.

The SAD has been prepared consistent with PPPL requirements, and provides descriptions of the NSTX-U structures, systems and components, identification of hazards, and design features and controls to mitigate these hazards. The items addressed and the level of detail presented in this SAD are consistent with the safety analysis guidelines for Below Hazard Category 3 Facilities in DOE-STD-6003-96, "Safety of Magnetic Fusion Facilities: Guidance", which are applicable to NSTX-U.

Hazards associated with the operation of NSTX-U have been evaluated and potential impacts and their mitigation assessed. In addition, the risks posed by each hazard have been determined based on the risk approach documented in PPPL Procedure ENG-032, "Work Planning Procedure". Risks are characterized as Standard, Serious or Major. Implementation of the hazard mitigations described in the SAD will maintain risks associated with the NSTX–U at the Standard level, i.e., low potential impacts to environment, safety and health that are well within regulatory, DOE and PPPL limits and guidelines.

A Safety Envelope for NSTX-U has been established based on the hazards and mitigations described in this SAD. The NSTX-U Safety Envelope, which is the basis for the conditions and limitations in the Safety Certificate authorizing NSTX-U operations, constitutes the provisions that must be satisfied to permit NSTX-U plasma operations. The Safety Envelope includes limits on fusion neutron generation and hazardous material inventories at risk, as well as methods for controlling these limits. The Safety Certificate is issued by the PPPL ES&H Executive Board (consisting of senior Laboratory managers and chaired by the PPPL Deputy Director for Operations) based on recommendations from the NSTX-U Activity Certification Committee (ACC) following their review of planned NSTX-U operations, including this SAD.

Any proposed changes to NSTX-U facilities, hardware or operations that could impact the SAD, Safety Envelope or Safety Certificate will be reviewed by the ACC. The ACC will report to the PPPL ES&H Executive Board (ES&H/EB) on the findings of its reviews, which will include any recommendations for changes to the Safety Certificate required to authorize NSTX-U operations with the proposed changes, including any relevant conditions or limitations on those operations.

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1.0 INTRODUCTION

This Safety Assessment Document (SAD) documents the safety analysis of the National Spherical Torus Experiment Upgrade (NSTX-U) at the Princeton Plasma Physics Laboratory (PPPL). The SAD has been prepared consistent with PPPL Procedure ESH-025, "Operations Hazard Classification Criteria and Safety Certification System" (Reference 1). It provides descriptions of the NSTX-U structures, systems and components, identification of hazards, and design features and administrative controls to mitigate these hazards. Failure modes and effects analyses (FMEAs) for NSTX-U systems and components are provided in Appendix 1. The items addressed and the level of detail presented in this SAD are consistent with the safety analysis guidelines for Below Hazard Category 3 Facilities in DOE-STD-6003-96, "Safety of Magnetic Fusion Facilities: Guidance" (Reference 15).

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The National Spherical Torus Experiment Upgrade (NSTX-U) is designed to prove the scientific principle of the spherical torus (ST). The ST plasma is nearly spherical in shape, its minor radius being slightly smaller than its major radius, thus giving an aspect ratio close to one. ST plasmas may have several advantageous features, such as a higher pressure for a given magnetic field. Since fusion power density is proportional to the square of the plasma pressure, the ST is a good example of an innovative alternative fusion concept that could lead to smaller and more economical sources of fusion energy.

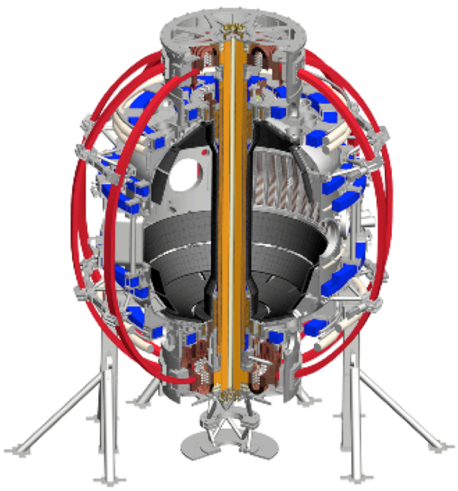

Fig 1: Cutaway drawing of the NSTX-U device. The outer legs of the toroidal field coils are shown in red and the poloidal field coils are illustrated in blue. The dark gray areas inside the vessel are those covered by graphite plasma facing components.

The National Spherical Torus Experiment (NSTX), which operated from 1999-2011, was designed to prove the scientific principle of the spherical torus (ST) plasmas. NSTX-U is a significant upgrade to the NSTX facility, with both additional neutral beam heating and current drive power, and higher toroidal fields and plasma currents. These upgrades are designed to extend the NSTX results to higher current, longer pulse, lower plasma collisionality, and fully non-inductive current drive.

The design and construction of the NSTX was a joint Project of the Princeton Plasma Physics Laboratory (PPPL), the Oak Ridge National Laboratory (ORNL), Columbia University, and the University of Washington. The construction of NSTX-U is a PPPL managed project, with scientific input from many collaborator institutions. The NSTX-U has modular components for ease of repair and upgrade, allowing a flexible program of scientific and technological exploration. PPPL leads the Project and operates the NSTX-U facility.

A National Research Team carries out the Research Program on NSTX-U. The Program covers a broad range of fusion and plasma science topics. A National Process has been established to promote broad research participation by the U.S. fusion energy sciences community.

1.1 Description of NSTX Upgrade Project

The NSTX device has been safely operated at the Princeton Plasma Physics Laboratory (PPPL) since 1999. The NSTX Upgrade Project replaced the current NSTX center stack (CS) assembly with a new larger radius CS assembly, and added a second neutral beamline (NBL) formerly used for the Tokamak Fusion Test Reactor (TFTR) Project onto the NSTX experiment. These upgrades will contribute to understanding Spherical Torus (ST) configuration physics by allowing: (1) study of high beta (ratio of plasma pressure to magnetic field pressure) plasmas at reduced particle collisionality; (2) assessment of full non-inductive current drive operation; and (3) prototyping of heat and particle exhaust solutions for next-step facilities.

1.1.1 Center Stack (CS) Assembly

The new CS Assembly provides higher toroidal magnetic fields (1 Tesla) and plasma currents (2 MegaAmperes) than previously attainable, and allows these parameters to be maintained for longer time periods (5 seconds) than previously possible on NSTX. This allows production of higher temperature plasmas to reduce collisionality of plasma particles (thereby providing hoped for enhanced confinement), as well as more efficient non-inductive current drive sources and better plasma performance.

Work activities to upgrade the NSTX CS Assembly included installations of:

- New Toroidal Field (TF) Hub Assembly
- New TF Flag Assemblies
- New Ceramic Break
- New Inner TF Bundle
- New Ohmic Heating (OH) Coil
- New Inconel Casing and Insulation
- New Plasma Facing Component (PFC) Tiles
- New Poloidal Field (PF) 1a, b & c Coils.

In addition, the following was accomplished:

- Installing reinforcements to existing coil structures (umbrella structure, outer TF coil legs, and the vacuum vessel) to handle the increased magnetic loads
- Installing new PF/TF/OH bus connections
- Repairing leaks and improving the existing cooling water system to cool the outer TF coil legs separately from the inner legs
- Replacing the Center Stack Diagnostics
- Upgrading the TF Coil power supply to support full field capability of 1 Tesla.

1.1.2 Second Neutral Beamline

The second neutral beamline (NBL), which was formerly used in the Tokamak Fusion Test Reactor (TFTR) experiments, provides up to two times higher plasma current drive efficiency and current profile control than previously available with only the existing one NSTX NBL. This enhances heating and current drive for plasma start-up, sustainment, heat flux. and transport studies.

Many of the NSTX-U modification activities involved duplicating the services and equipment already provided for the existing NSTX NBL to facilitate operation of the second NBL.

Work activities associated with the second neutral beamline included:

- Evaluation, decontamination (for tritium) and refurbishment of NBL components, as needed (e.g., cryo-pumping panels, bending magnets, etc.)
- Relocation of one NBL from the former TFTR Test Cell to the NSTX Test Cell
- Provision of a second set of NBL services, i.e., power, water, vacuum and cryogenics, for operation
- Modification of the NSTX Bay K port and fabrication and installation of a duct assembly to connect the second NBL to the NSTX torus
- Refurbishment and installation of existing neutral beam ion sources onto the second NBL
- Installation of tiled water-cooled armor plating inside the NSTX torus to protect in-vessel impinged surfaces
- Routing high voltage power supplies and neutral beam controls to the NSTX Test Cell, and installing/re-commissioning existing High Voltage Enclosures and transmission lines
- Relocating the previous NSTX torus vacuum pumping duct, vacuum control systems, gas injection systems, and diagnostic systems displaced by the addition of the second NBL
- Reworking of NSTX platforms and modification of the fire detection and suppression systems under the platforms.

1.2 Mission

The National NSTX-U Research Program investigates the fusion science principles of the ST plasma, covering:

- noninductive start-up, current sustainment, and profile control;
- confinement and transport;
- pressure limits and self-driven currents;
- scrape-off-layer and divertor physics;
- plasma material interactions and plasma facing component (PFC) studies, including lithium as a PFC, and;
- global stability and disruption resilience.

These principles are investigated in the scientifically interesting regimes that are relevant to near-term applications, such as a Fusion Nuclear Science Facility (FNSF) volume neutron sources and fusion pilot and power plants of the future:

- high average toroidal betas (25 - 45%);
- high pressure-gradient-driven current fractions of 40 - 90%;
- fully relaxed, noninductively sustained current profile;
- collisionless plasmas with high temperatures and densities; and

- aspect ratios (major radius over minor radius) as small as 1.5 and elongations above 3.0;

This mission supports the goals of the fusion energy sciences program in the U.S.

1.3 Design Features

The NSTX-U device (see Figure 1) is designed to operate with the following baseline parameters for plasmas with several forms of divertor and limiter configurations:

The NSTX-U project scope includes the following systems for start-up, heating, and current drive:

- 6 MW of high harmonic fast wave (HHFW) for up to 5 seconds,
- 50 kA of coaxial helicity injection (CHI) injected current for up to 50 ms, and
- 20 kW of electron cyclotron heating (ECH) for up to 5 milliseconds.
- 10 MW of Neutral Beam Injection at 80kV for 5 seconds, with higher power available for shorter heating durations.

The NSTX-U facility design further accounts for the possibility of adding and handling 400 kW of ECH for up to 100 milliseconds for non-inductive startup.

Table 1 National Spherical Torus Experiment Upgrade Baseline Parameters

Parameter	Value
Plasma Major Radius (R_0)	0.9344 meters (m)[1]
Aspect Ratio R_0/a	1.5[1]
Applied Toroidal Field (Bt)	1.0 Tesla (T) at R_0 [1]
Plasma Current (Ip)	up to 2.0 MegaAmperes (MA)[1]
Plasma Elongation (Kappa)	up to ~3.1
Plasma Triangularity (Delta)	0.4-0.9
Edge Safety Factor (q)	5-15
Plasma Pulse Flattop Length	5 seconds at B_T=1.0 Tesla (T)

The center stack of NSTX-U is highly compact to permit a plasma aspect ratio as low as 1.5. The primary components of the center stack are the inner legs of the toroidal field coils, a solenoid to provide full capability for inductive operation at I_P=2 MA, and the center stack casing that provides the primary vacuum boundary and structural support. A set of 6 poloidal field coils (PF-1aU, PF-1aL, PF-1bU, PF-1bL, PF-1cU, PF-1cL) designed to control the boundary triangularity and divertor geometry are attached to the casing, The casing is covered by protective graphite tiles, and is interfaced to the remainder of the device through a set of inconel bellows and ceramic breaks. The center-stack is designed to be replaceable without affecting the rest of the device.

The vacuum vessel is 3.6 meters in height and accommodates a plasma elongation of up to 3.1 and a triangularity of up to 0.9 for aspect ratios of 1.6-1.9. A number of coil systems are supported from the vessel. The PF-2u, and PF-2L coils are generally used with the center stack coils to control the magnetic geometry of the divertor region. The PF-3 coils control the plasma boundary elongation and the plasma vertical position. The PF-4 and PF-5 coils provide the necessary vertical field. The outer legs of the toroidal field coils are mounted off the upper and lower umbrella structures and a series of turn-buckles. The Resistive Wall Mode (RWM) coils are mounted near the midplane, and

[1] Table 1.1 of Reference 2

provide the ability to add n=1, 2, and 3 radial fields to the plasma for magnetic braking, error field correction/application, RWM control, and pedestal physics studies.

Auxiliary heating and current drive for current profile control address another essential part of the NSTX-U mission. The upgraded neutral beam systems are designed to both provide high power-density plasma heating and drive currents. Furthermore, the difference tangency radii of the six neutral beam sources allow the profile of the driven currents to be controlled. The high-harmonic fast-wave heating and current drive system is expected to suit well the high-beta and high-bootstrap-current fraction plasma discharges and fully utilizes radio-frequency power sources available on site. A set of 48 conducting plates, also protected by graphite tiles, is placed near the outboard plasma edge to enable the sustainment of high-β, high bootstrap fraction scenarios. Noninductive start-up is accomplished by coaxial helicity injection, an innovative technique successfully pioneered by the University of Washington, incorporated into the NSTX design, and retained in the NSTX-U design.

The GRD (Reference 2) requires and allows a pulse length of 5 seconds. A future upgrade to a plasma pulse length of up to 10 seconds at reduced toroidal field would allow investigation of fully relaxed current profiles, a condition desirable in future fusion energy sources. Graphite tiles act as plasma facing components (PFCs) on the center column, in most places on the divertors, and on all passive plates to handle the anticipated heat loads for the full plasma pulse. All PFCs are bakeable to 350 degrees Centigrade to speed recovery from a vacuum vent.

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Initially NSTX-U is anticipated to operate on a 40 minute shot cycle for discharges that utilize the full coil capacity; future upgrades may allow this time to be reduced to 20 minutes. The anticipated distribution of discharge parameters is provided in the NSTX-U General Requirements Document (Reference 2), and allows for 20,000 discharges.

1.4 The NSTX-U Plasma

NSTX-U plasmas will be unique in the world in a number of critical ways:

- The good field line curvature of the ST, combined with the nearby passive conductors and active 3D field control, will allow studies of global stability in fully non-inductively sustained plasmas.
- The flexible control of the plasma shape, current drive and torque from the neutral beams, and magnetic braking from the RWM coils will allow the current and rotation profiles to be actively controlled.
- The flexible divertor geometry and high power density will allow the physics and control of tokamak power exhaust to be studied. These studies will include the role of lithium as both a pumping medium and a high heat-flux material and the physics and control of the high flux-expansion divertors, such as the snowflake divertor.
- The high field and current, coupled with the large heating power, will facilitate studies of low collisionality plasmas, allowing the underlying core and pedestal transport physics to be better understood.
- Non-inductive ramp-up studies will utilize the Coaxial Helicity Injection (CHI) capability of NSTX-U to form a target plasma. These targets will then be heated with HHFW. Once hot enough, the neutral beams will be used to further heat the plasma and increase the toroidal current.

2.0 SUMMARY AND CONCLUSIONS

The NSTX experiment was safely operated at PPPL from its first plasma startup in 1999 until the beginning of the Upgrade Project in 2011. The Upgrade Project described in Section 1.1.1 was also safely and successfully conducted. Elements that were applied during these NSTX phases and which are addressed in this SAD, including limits on fusion neutron generation and hazardous material inventories at risk, proper system design and construction, and the presence of features and processes that mitigate the effect of failures, will ensure the safety of personnel, the public and the environment during NSTX-U operations. Relevant safety and environmental requirements of 10CFR851 (Worker Safety and Health Program), 10CFR835 (Occupational Radiation Protection), and DOE Order 458.1 (Radiation Protection of the Public and Environment) have been incorporated into the design and operation of NSTX-U. These requirements are applied at PPPL via implementation of the Laboratory's written safety program document, ESHD 5008 ("The PPPL Safety Manual"); the Laboratory's DOE-approved Worker Safety & Health Program (WSHP), Radiation Protection Program (RPP), and Environmental Radiation Protection Program (ERPP); PPPL policies, procedures and planning documents; and NSTX-U procedures and planning documents.

NSTX-U has been determined to be a Below Hazard Category 3 Facility in accordance with DOE-STD-1027 (Reference 16). During operations, as indicated in this SAD, personnel will generally be excluded from areas such as the NSTX Test Cell (NTC), the NSTX bus tunnel in the Test Cell Basement, and other relevant areas when hazards exist by the use of hardwired interlocks, procedures, signage, indicator lights and training. Entry to hazardous areas will be controlled and limited to trained personnel using carefully prescribed procedures and protective measures.

During maintenance and outage periods, PPPL Safety Division representatives will periodically inspect the work site to determine that sufficient safety practices and equipment are in use. PPPL Health Physics Division representatives will provide support as needed for any radiological activities. When a new task is begun, a pre-job briefing will be held to discuss procedures and the associated Job Hazard Analyses (JHAs). PPPL supervisors (and non-supervisory volunteers) have been trained in the principles and procedures of the DuPont Safety Training Observation Program (STOP) to observe work activities and engage workers in conversations to reinforce safe work practices, and to find the reasons for and correct unsafe behaviors.

Occupational injuries and illnesses will be reported to the Laboratory Occupational Medicine Office, and will be subsequently investigated by the PPPL Safety Division and other relevant personnel for lessons learned (per ESHD 5008 Section 9 Chapter 10, "Accident Investigation", and PPPL procedure GEN-006, "Investigation and Follow-up of Adverse Events and Conditions"). Safety conditions in NSTX-U areas will also be periodically reviewed during Management Safety Walkthroughs per PPPL Policy P-084 ("Management Safety Walkthroughs"), and line management reviews per PPPL Organization Document O-027 ("Line Management Safety Organization").

PPPL uses procedure ESH-025 ("Operations Hazard Classification Criteria and Safety Certification System") as part of its implementation of the Integrated Safety Management (ISM) Guiding Principle for Operations Authorization of experimental projects. The approval process to commence NSTX-U operations and to make future changes to NSTX-U equipment and operational parameters will follow the applicable provisions of ESH-025 and PPPL's Work Planning Procedure (ENG-032). These will include completion of work planning forms, peer and design reviews, reviews and approvals of new procedures, processing of Unreviewed Safety Issue Determinations (USIDs) including any relevant changes to this SAD, and NSTX Activity Certification Committee (ACC) review of new equipment and operational parameters that have implications for the Safety Certificate which authorizes NSTX-U operations. The members of the NSTX ACC include both PPPL and DOE Princeton Site Office (PSO) personnel that have been appointed by the PPPL ES&H Executive Board (ES&H/EB), which consists of senior Laboratory managers and is chaired by the PPPL Deputy Director for Operations. The ACC reports to the PPPL ES&H Executive Board (ES&H/EB) on the findings of its safety reviews, which will include a recommendation on a revision to the existing NSTX Safety Certificate that would authorize NSTX-U operations (and subsequent changes to operations), and any relevant conditions or limitations on those operations.

The conclusion of this NSTX-U Safety Assessment Document (SAD) is that application of the control measures and hazard mitigation features described in this document will provide for a Standard level of risk (i.e., low potential impacts to

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environment, safety and health that are well within regulatory, DOE and PPPL limits and guidelines) for operating NSTX-U per the Laboratory's Work Planning Procedure (see Table 7 of this SAD).

3.0 FACILITY AND SYSTEMS DESCRIPTION

The NSTX-U requirements are outlined in the "General Requirements Document" (GRD), Reference 2. The GRD additionally references a design point spreadsheet which provides parameters for design and analysis (http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html). Section 7.2 of the GRD describes the design verification process that ensures compliance with PPPL procedures and industry standards. The verification process includes multiple levels of design reviews and resolution of resulting "CHITS" in accordance with PPPL procedure ENG-033. Supporting calculations are filed at the project web page, http://nstx-upgrade.pppl.gov/Engineering/Calculations/index_Calcs.htm . Coil structural qualification must satisfy the NSTX structural design criteria, Reference 13. These reviews and calculations form the basis for the acceptable operating space for NSTX-U. To ensure coil operations within qualified boundaries, a Digital Coil Protection System (DCPS) is a part of the Upgrade project. This system is described in Section 3.6 of this SAD. Reliability of the NSTX-U experiment is largely determined by the reliability of the DCPS. Reliability requirements are specified in the GRD.

3.1 NSTX-U Facility

The NSTX-U device is located in the NSTX Test Cell (NTC) at the D-Site Facility of the Princeton Plasma Physics Laboratory (PPPL); see Figures 2 and 3. The PPPL site, located at Princeton University, James Forrestal Research Campus, in central New Jersey within Middlesex County, consists of the C-Site Facility, which houses offices, smaller experiments, the NSTX Control Room, and support facilities; and the D-Site Facility, originally constructed for operation of the Tokamak Fusion Test Reactor (TFTR), which shut down in 1997. The closest urban centers to the site are New Brunswick, 14 miles to the northeast, and Trenton, approximately 12 miles to the southwest. A number of major metropolitan areas including New York, Philadelphia, and Newark are within a 50-mile radius of the site. The municipalities of Princeton, Plainsboro, Kingston, Penns Neck, Princeton Junction, and Cranbury, among others, are in the immediate area of the site. Also, the main campus of Princeton University is located in Princeton, approximately three miles to the west of the site. The site is relatively open with little variation in grade. It is bordered on the north and east by wooded areas, on the south by a detention basin and an outdoor storage area, and on the west by a paved service road that provides access to the site and adjacent PPPL service areas.

The D-Site Facility is completely bounded by a chain-link fence that has four personnel access gates, the operation of which is limited and controlled by card readers. These card readers respond to the magnetic coding on those personnel ID badges that have been previously authorized and programmed into the Security computer. The main personnel gate is located near the northwest corner of D-site. Immediately adjacent is a remotely operated and supervised vehicle gate under the control of the officer at the Laboratory's main security desk, which has 24-hour, 7-day coverage. There is an entrance to an underground tunnel leading into D-site from within the NSTX Control Room and two others from outside it. Passing through the tunnel to enter D-site requires proper ID-card authorization. The final two personnel entrances to D-site are on the west side, next to a cooling-water tower, and near the south-west corner of the facility boundary fence, where there is also a normally locked vehicle gate.

The NTC was formerly known as the Hot Cell during TFTR operations, and was originally designed for testing of TFTR heating neutral beamlines and their components, and to effect maintenance, repairs, or modifications on large, highly radioactivated components and assemblies from the TFTR Test Cell. The NTC is 60 ft x 114 ft and has a ceiling height of 54 ft. The floor is at the same level as that of the adjacent Test Cell for the TFTR. Construction is of reinforced concrete throughout, with a 2 ft thick floor slab. The roof is 5-1/2 ft thick at the high point, the north, south and west walls (the latter separating the area from the TFTR Test Cell) are 4 ft thick, and the east wall is 3 ft thick. A 3-ft wide, 7-ft high, and 1-ft thick tritium seal door (usually open) backed by a three-hour fire door (with crash bar for emergency egress), provides access to the north end of the NTC from the adjacent gallery. A similar pair of doors leads into the south end of the room. A separate 2 ft thick concrete-filled block wall is placed in the adjacent gallery outside the NTC north door for radiation shielding, to replace a similar shield block wall that had been located inside the NTC north door but which had to be removed to accommodate equipment for the second neutral beamline. A concrete-filled large (15 ft wide, 13 ft high, 1 ft thick) tritium seal door is located between the NTC south high bay area and the Neutral Beam Power Conversion (NBPC) building. This door is normally closed except for movement of major pieces of equipment. A 16-ft x 26-ft x 4-ft thick concrete-filled tritium seal door also exists between the TFTR Test Cell and the NTC south high bay area.

Platforms are installed around the NSTX-U device at heights of 9 ft and 18 ft above the NTC floor to allow easy access to machine components and to support device appurtenances. The platforms have aluminum structural members with fire retardant wood decks and masonite tops. Lighting and fire detection/suppression are installed under the platforms. A 2 ft thick concrete shield wall with labyrinth and door (with crash bar for emergency egress), is placed in the NTC south of the NSTX-U device (see Figure 3).

The NTC air is conditioned to maintain 70°F dry bulb temperature and 40% relative humidity. The NTC is maintained at atmospheric pressure using supply and exhaust fans at flow rates up to 16,000 cfm. Room exhaust that is not recirculated is directed to the D-Site facility stack, which is monitored for tritium.

The NTC fire detection system consists of ionization smoke detectors and rate of rise heat detectors located at the ceiling and aspirated smoke detection (Very Early Smoke Detection Apparatus, VESDA) under the platforms. Fire suppression is via a preaction type automatic water sprinkler system similarly located. The detection system, in addition to providing appropriate notification, operates the preaction valve and charges the pipes with water to provide flow to any sprinkler heads that have been caused to open by high temperature. Fire dampers are included in Heating, Ventilation and Air Conditioning (HVAC) ductwork where they penetrate the NTC wall. Each damper has a heat sensitive link that melts and shuts the fire damper at a temperature of 212°F. NTC HVAC duct smoke detectors are designed to shut down HVAC and provide local and remote alarms.

NTC floor drains (located in the trenches for the large tritium seal doors leading to the NBPC Building and the TFTR Test Cell) and HVAC condensate are piped to three 15,000 gallon liquid effluent collection (LEC) tanks located in an outdoor enclosed area on D-Site north of the experimental complex. The contents of these tanks are sampled periodically and, if regulatory criteria are met (tritium concentration $\leq 1.9 \times 10^6$ pCi/liter, cumulative tritium discharge of ≤ 1 Ci per calendar year), the tank liquid is discharged to the sanitary sewer system.

The NTC, along with the rest of the D-Site experimental complex structures, has been determined to have adequate capacity to remain functional under the overall loads due to an earthquake with a horizontal ground acceleration of 0.13g. The NSTX-U platforms have been designed for the seismic requirements of the NSTX-U torus structure (see Section 3.2).

The NTC is structured with a crane haunch and rails to support a 75-ton bridge crane outfitted with an auxiliary 15-ton hoist.

All instrumentation is isolated via optical and/or magnetic (isolation transformer) means prior to exiting the NTC boundary. The isolation is rated to withstand a one minute AC hipot test at 20 kV AC rms.

NSTX-U machine control functions are executed from the NSTX-U Control Room (former TFTR Main Control Room) at C-Site (in the basement of the Lyman Spitzer Building).

For plasma operations (and depending on experimental plans and operational experience), fixed and/or portable gamma and neutron radiation monitors are (or may be) set up at various locations inside the NTC, outside the north, east and west walls of the NTC; south of the 2 ft thick concrete shield wall in the NTC; on the roof of the NTC; and in the Mechanical Equipment Room underneath the NTC.

Electrical power is supplied from the Public Service Electric & Gas Company (PSE&G) 138-kV system. It is transformed for distribution to the switchgear buses of various loads. Since the major experimental system loads are pulsed and exceed the instantaneous power capability of the system, energy storage motor generator flywheel (MGF) units are provided (one of two MG sets is in use by NSTX-U). The system interfaces with the utility power system at an existing substation. The total utility system energy input is divided between two distribution systems, one serving the pulsed MGF loads (e.g., field coil magnets and neutral beamlines) and the other serving auxiliary loads that provide support to the facility. The Field Coil Power Conversion (FCPC) Building, Neutral Beam Power Conversion (NBPC) Building, and Motor Generator (MG) Building on D-Site house equipment that provides the required electrical power to NSTX-U. A 2600 kW diesel generator, located in an outdoor enclosure adjacent to the MG Building, provides standby power to the D-Site electrical system in response to a loss of offsite power. Uninterruptible power is provided for D-Site lighting and other needs by a number of station batteries. Water cooling systems are housed in the NBPC Building, and Radiofrequency (RF) power and control equipment are housed in a separate building at the adjacent C-Site of PPPL and in the D-Site Mockup Building north of the NTC. Additional details on the C- and D-Site facilities can be found in Reference 3.

3.2 Torus Systems

The NSTX-U Torus Systems consist of the Plasma Facing Components (PFCs), Vacuum Vessel and Torus Support Structure, and Magnet Systems (see Figure 1).

3.2.1 Plasma Facing Components (PFCs)

All surfaces which face the plasma are covered with Plasma Facing Components (PFCs), whose materials are either carbon, vacuum-compatible ceramic, or refractory metals designed to absorb the heat and particle 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. The PFCs are required to: (1) accommodate a high temperature (350°C) bakeout mode to liberate trapped impurities; (2) accommodate a helium glow discharge cleaning mode; and (3) be electrically connected to the Vacuum Vessel via their mounting structures. The plasma facing components include the inner wall armor, divertor area strike plates, passive stabilizers, and other associated plasma facing surfaces.

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For baseline operation, there will be no active cooling of the inner wall plasma facing components during a plasma discharge. However, the plasma facing tiles on the outer passive stabilizer and in the divertor regions will be thermally attached to actively cooled plates, such that the tiles will cool to the plate temperature between discharges. The inner wall armor will be thermally isolated from the center stack casing and must rely on radiation cooling to the other plasma facing tiles between discharges.

PFCs are designed to accommodate the heat loads due to 14MW of auxiliary Radiofrequency (RF) + Neutral Beam Injection (NBI) heating power for pulse lengths up to 5 seconds, and repetition period of 300 seconds for Natural Divertor, Single Null, and Double Null plasma configurations. In case the combined RF + NBI heating power exceeds 14 MW the pulse length must be shortened accordingly such that the energy dissipation remains within the power handling limit of the PFCs.

FMEAs are provided in Appendix 1 (WBS Element 1.1).

3.2.1.1 Passive Stabilizers

The passive stabilizers consist of primary (closest to midplane) and secondary (furthest from midplane) pieces, one set above the midplane and one set below the midplane of the NSTX-U device. Each stabilizer is made up of a series of conical shaped copper plates that can be electrically connected in the toroidal and poloidal directions using jumpers. The stabilizer connections to the Vacuum Vessel allow for alignment adjustments and facilitate removal of individual plates for modification to accommodate access for future diagnostic upgrades. The plasma facing surfaces of the stabilizers are protected with graphite tiles. (Union Carbide - ATJ or equivalent). The passive stabilizers have been instrumented with accelerometers to ensure the NSTX-U disruption loads do not exceed the capacity of the plates and their mounting hardware.

3.2.1.2 Inner Wall Armor

The inner wall armor is composed of columns of graphite tiles attached to the center stack casing. The tiles are mounted in such a way that heat transfer from the tiles to the center stack casing is minimized. Slots are provided in the backside of at least half the tiles such that diagnostic wires and magnetic diagnostics can be positioned between the center stack casing and the tiles.

3.2.1.3 *Inboard Divertor Area Strike Plates*

The inboard divertor area strike plates consist of graphite tiles attached to the center stack casing. The poloidal extent of the inboard divertor strike plates is such that it eliminates all line of sight between the upper and lower ceramic ring/bellows assemblies and the plasma. The inboard divertor plates are not traced for active temperature control, but are thermally connected to the upper and lower flanges of the center stack casing. The center stack casing flanges have active temperature control.

3.2.1.4 *Outboard Divertor Area Strike Plates*

The outboard divertor area strike plates usually consist of segmented upper and lower toroidal rings composed of copper plates covered with graphite tiles. The outboard divertor plates are attached to the upper and lower domes of the vacuum vessel, and are traced with stainless steel tubing for active temperature control during bakeout and operation.

An experimental set of High Z PFCs is planned for the lower Row 2 of the outboard divertor. These tiles will utilize the same footprint as the original graphite tiles, but will be made up of 95 Arc-cast TZM tiles and 1 tungsten tile.

3.2.1.5 *Neutral Beam Protective Plates*

Protective Plate Armor mounted on the midplane centered on Bays H is provided to receive beam energy in the absence of plasma, beam shine through during plasmas, and brief tuning beam shots at abbreviated pulse lengths. The Armor is designed to absorb one full power full duration neutral beam shot from both beamlines in the absence of plasma without failure. Interlocks prohibit the pulse or limit the pulse injected into the vacuum vessel protective plates to 50 msec when plasma is not present. Energy deposition for this duration does not appreciably heat the plates. The short pulse is useful for conditioning the beams between injection shots.

3.2.2 Vacuum Vessel and Torus Support Structure

The functions of the vacuum vessel are to:

a. Provide a vacuum boundary around the plasma suitable for high vacuum conditions;

b. Provide structural support for plasma facing components (PFCs);

c. Provide access and structural support for vacuum pumping ducts, plasma heating and current drive, and diagnostics; and

d. Provide a structural support for the coil systems.

The function of the torus support structure is to provide the overall support mechanism for the vacuum vessel and all torus components that are attached to it, as well as support for the center stack assembly.

The vacuum vessel assembly is capable of operation in high vacuum conditions with a base partial pressure of $\leq 1x10^{-8}$ torr, and is capable of handling the heat load resulting from the 350°C bakeout of the plasma facing components.

The NSTX-U vacuum vessel is constructed of 304 stainless steel and has a nominal wall thickness of 0.625-in. It consists of upper and lower domes attached to an outer cylindrical section, and an inner cylindrical section, constructed of Inconel 625, referred to as the center stack casing. The center stack casing is mechanically connected to, but electrically isolated from, the upper and lower domes via a ceramic insulator. This completes the vacuum boundary but allows for an electrical potential difference between the center stack casing and the remainder of the vacuum vessel for Coaxial Helicity Injection Current Drive (CHI; see Section 3.3.2). Ports are provided with dimensions compatible with the requirements of all types of Heating & Current Drive (H&CD) systems, as well as diagnostic systems. Additional openings are provided for personnel access. Unused openings, including windows, are covered to prevent potential personnel injury or damage to windows.

The lower dome of the outer section of the Vacuum Vessel is electrically connected via four toroidally symmetric connections to a single point connection, which is designed to provide a ground connection and a return path for the

CHI current. Connections are sized to carry the current during CHI operations as well as the return of the current during bakeout heating of the center stack casing.

The NSTX-U torus structure was designed to satisfy the Department of Energy (DOE) standard for natural phenomena hazard (NPH) events (Reference 4). Only the effects of earthquakes are considered for the NSTX torus structure. The DOE standard required the use of Performance Categories (PC) to specify the relative risk, environmental impact, importance, and cost of each facility. The assessment for seismic loading and evaluation for seismic response was followed to determine that the design of the structure is acceptable with respect to the performance goals (Reference 5). There are no safety class items associated with the NSTX machine since its failure would not result in the release of significant quantities of hazardous materials. On this basis the seismic performance goal for the NSTX torus structure is to maintain worker safety, placing it in NPH Performance Category 1 (PC-1). Any structures, systems & components (SSCs) whose failure would adversely affect the performance of the NSTX torus structure or create a threat to worker safety are also placed in PC-1. All other systems are placed in PC-0 and thus have no seismic design requirements. For the PPPL Site, a PC-1 earthquake has a maximum horizontal ground acceleration of 0.09g

FMEAs are provided in Appendix 1 (WBS Element 1.2). These include loss of vacuum integrity events that could potentially release tritium from the vacuum vessel to the NSTX Test Cell (see Section 4.1.2).

3.2.3 Magnet Systems

The magnet systems consist of the outer poloidal field (PF) coils, outer legs of the toroidal field (TF) coils and the center stack assembly. The center stack assembly includes the inner legs of the TF coils, two additional PF coils (PF1a and 1b), and the ohmic heating (OH) coil, as well as the center stack casing (see Figure 1). The magnet systems are designed to satisfy the seismic loading for NPH Performance Category 1 (PC-1).

3.2.3.1 Outer Poloidal Field (PF) Coils

The function of the poloidal field (PF) coil system is to: support the plasma against radially expanding current and pressure forces; provide plasma shaping and divertor/scrape-off control; provide vertical/radial position stability control using feedback; help compensate for the error fields of the ohmic heating solenoids; and provide additional flux to the plasma. The outer PF magnets consist of four pairs of water-cooled copper coils designated as PF 2a/2b, 3a/3b, 4b/4c, and 5a/5b. The pairs are symmetric about the same horizontal mid-plane of the NSTX-U device. PF 1a/1b/1c are new coils fabricated for the upgrade and are part of the center stack subsystem. The outer PF coils, PF2, PF3, PF4 and PF5 are existing coils that were being reused from the original NSTX experiment. The outer PF coils are supported off the vacuum vessel structure (the support mechanism is compatible with the vacuum vessel thermal expansion during bakeout).

The maximum current and maximum equivalent square wave for the outer PF magnets (which can be conducted once every 2400 seconds) are:

Table 2 Outer PF Coil Currents

Coil	Max Current (kA)	Max ESW (sec)
PF 2a/2b	15.0	5.5
PF 3a/3b	16.0	5.5
PF 4b/4c	16.0	5.5
PF 5a/5b	34.0	5.5

3.2.3.2 Outer Toroidal Field (TF) Coils

The function of the toroidal field (TF) coil system is to provide the toroidal magnetic field, which is necessary to magnetically confine the NSTX-U plasma. The outer TF coils consist of an outer array of twelve water-cooled copper coil bundles, each containing the return conductors for three turns. The inner legs of the TF coils are part of the center stack subsystem. Demountable joints are provided in the TF outer legs to allow removal/replacement of the center stack assembly. The deadweight of the outer legs is supported through the torus support structure to the floor.

The baseline design of the outer legs of the TF coils is capable of producing the following toroidal fields once every 2400 seconds:

Table 3 TF Outer Leg Performance

Flat Top Duration (sec)	**B_{TF} (R0=0.9344m) (Tesla)**
5	1.0

The outer legs of the TF coils which are installed as part of the baseline are capable of conducting the currents required to produce toroidal fields of 1.0 Tesla for a flat top duration of 5 seconds, and total duration of 6.5 seconds, once every 3600 seconds, in case a NSTX long pulse upgrade is undertaken.

3.2.3.3 Center Stack Assembly

The center stack subsystem includes the inner legs of the TF coils, the Ohmic Heating (OH) solenoid, shaping coils - PF coils 1a/1b/1c, and the center stack casing. The Ohmic Heating solenoid's primary function is to provide sufficient loop voltage for plasma initiation, and sufficient flux swing for inductive plasma current drive. The center stack casing functions as the internal vacuum and thermal barrier and provides support for the center stack coils and inner wall armor. PF and TF coil functions are described in Sections 3.2.3.1 and 3.2.3.2, respectively. The center stack radial build is comprised of the TF inner legs located in the core of the center stack surrounded by the OH solenoid. The PF1a, PF1b and PF1c coils are located over the OH coil symmetrically above and below the mid plane.

3.2.3.3.1 TF Inner Legs

The inner legs of the TF coils consist of tightly-nested fully-bonded copper conductors. The baseline design of the inner legs of the TF coils is capable of producing the same toroidal fields once every 2400 seconds as for the outer TF coils, upgradeable to every 1200 seconds.

3.2.3.3.2 Ohmic Heating (OH) Coil

The OH coil consists of a solenoid surrounding the inner legs of the TF coil. For fully inductive NSTX operations, using a bipolar current, the OH coil is capable of providing a flux swing of 2.1 volt-seconds. The coil has a peak current of 24kA with a maximum equivalent square wave (ESW) of 1.472 sec and a repetition period of 2400 seconds. For partial inductive operations, the fully rated heating and current drive power is assumed deposited within the NSTX machine such that the maximum allowable operating temperature of the center stack casing is, in effect, coincident with the fully rated operation of the OH in the partial inductive, unipolar mode.

3.2.3.3.3 Inner PF Coils

The shaping coils consist of upper and lower coil pair, PF1a, and lower coil PF1b. Current carrying requirements (once every 2400 seconds) for these coils are:

Table 4 PF1a/PF1b Current Requirements

Coil	Peak Current (kA)	ESW (sec)
PF1a	19.0	5.5
PF1b	13.0	2.1
PF1c	16.0	4.3

3.2.3.3.4 Center Stack Casing

The center stack casing is electrically isolated from the outer vacuum vessel and is compatible with operation in high vacuum conditions. Electrical breaks are provided between the vacuum vessel and the center stack casing to support coaxial helicity injection (CHI) during startup. The electrical isolation is rated for 2kV DC CHI operations (upgradable to 4kV), 5kV DC hipot. The center stack casing includes suitable terminals for electrical connections for CHI, and accommodates the passage of a current in the Z direction for the purpose of resistive heating as a source of heat during the bakeout mode. The center stack casing is bakeable to a temperature $\geq$ 350°C.

The center stack includes an air gap and/or insulating material in the annular region surrounding the OH coil for the purpose of thermal and electrical isolation between the coil and the casing. Electrical isolation is designed to withstand 2kV due to the CHI. Thermal isolation is designed to protect the OH coil and surrounding magnetics diagnostics from excess temperatures due to heat influx from bakeout and from normal operations.

FMEAs for the Magnet Systems are provided in Appendix 1 (WBS Element 1.3). These include events that could cause loss of vacuum vessel integrity, which could potentially release tritium from the vacuum vessel to the NSTX Test Cell (see Section 4.1.2).

3.3 Plasma Heating and Current Drive Systems

The Plasma Heating and Current Drive Systems (H&CD systems) consist of the High Harmonic Fast Wave (HHFW) System, the Coaxial Helicity Injection Current Drive (CHI) System, the Electron Cyclotron Heating (ECH) System, and the Neutral Beam Injection (NBI) System. These systems provide energy input into the plasma either directly or as a consequence of providing momentum. This energy input is required to increase and sustain the thermal energy of the plasma. All H&CD systems may be called on to provide current drive in the NSTX plasmas. This current drive may be useful for ramping up the current at the beginning of a discharge, maintaining the flat-top current, or providing radial localized currents for current profile control. These systems may also be used for plasma initiation, breakdown of the prefill gas and preheating.

FMEAs for these systems are provided in Appendix 1 (WBS Elements 2.1, 2.2, 2.3 & 2.4).

3.3.1 High Harmonic Fast Wave (HHFW) System

The High Harmonic Fast Wave Heating and Current Drive system consists of the Radiofrequency (RF) generators, transmission lines (see Figure 4), tuning and matching systems, RF feedthroughs and internal transmission lines, antennas with Faraday shields and protective limiters, and the associated diagnostic and control systems. The functions of the High Harmonic Fast Wave (HHFW) system are to:

a. Provide electron heating power to the NSTX plasma via the fast magnetosonic wave.

b. Provide non inductive current drive.

c. Provide control over the heating/current drive deposition profile, through the antenna phasing.

The HHFW system is designed to deliver at least 4 MW of power to the NSTX plasma for 5 seconds, once every 300 seconds. This system utilizes radiofrequency (RF) power produced by the six existing Tokamak Fusion Test Reactor (TFTR) Ion Cyclotron Range of Frequencies (ICRF) sources (additional information on ICRF can be found in Section 4.8 of Reference 3). The HHFW system uses twelve antennas mounted on the vacuum vessel wall in the gap between the upper and lower passive stabilizing plates. The antennas are arranged toroidally between the NSTX vacuum vessel mid plane ports. Each antenna consists of a current strap, a back plane, a Faraday shield, and a local (bumper) limiter structure. The antennas are compatible with bakeout and glow discharge modes of operation as well as abnormal operating events such as disruptions, plasma control failures, power supply failures, bus opens or shorts, or magnetic faults. The set of six sources (and twelve antennas) are capable of operation at frequencies of 30 MHz. DC shorting stubs are incorporated in the transmission line prior to the point where the line exits the NSTX test cell. A decoupling system provides a DC short circuit across the transmission line to keep the center and outer conductors at the same potential if a Faraday shield fault allows plasma to contact the antenna strap.

RF transmission lines are grounded to the perimeter ground in the NSTX test cell (NTC), and are grounded immediately outside the NTC wall to a plate that is bonded to building steel.

Switches are provided to isolate HHFW power from the NTC. These switches are interlocked with the NTC access control system. Both electrical and mechanical (Kirk Key) interlocks are provided. Whenever personnel must enter the NTC, an emergency stop (E-Stop) is sent to all HHFW sources if any switch is not in the safe (dummy load) position. Local (dummy load) operation of RF sources can be performed during NTC access provided that all of the switches are locked in the safe position. This ensures that the NTC transmission lines are disconnected from the RF sources and that the source outputs are terminated in dummy loads.

An RF survey will be performed upon system commissioning and repeated annually. In addition, HHFW operating personnel are procedurally required to check RF radiation at low power before proceeding to high power whenever any high power transmission line configuration is changed.

To provide reliability and a margin of safety, the RF vacuum feed through can withstand a pressure of 30 psig. The antenna, limiter, and transmission line system is designed to satisfy the seismic loading for NPH Performance Category 1 (PC-1). Because of higher fields and disruption loads associated with NSTX-U, a compliant center conductor has been added.

3.3.2 Coaxial Helicity Injection Current Drive (CHI) System

The Coaxial Helicity Injection (CHI) Current Drive system is provided for non-inductive start-up. The CHI system relies on poloidal breaks that electrically isolate the center stack from the outer vacuum vessel. The electrical isolation is rated for 2kV DC CHI operations, 5kV DC hipot. This break is provided by two toroidal ceramic insulators incorporated into the vacuum vessel design. When the CHI electrodes thus formed are energized, a poloidal component of current flows which, due to the influence of the toroidal field, results in a toroidal component of plasma current. The PFCs which form the electrodes from which the CHI current flows, are designed to dissipate the local power generation due to the CHI current during normal and fault conditions, and are designed to withstand the electromagnetic forces due to the fault current deliverable by the CHI power supply system. The lower dome of the outer section of the Vacuum Vessel is electrically connected via three toroidally distributed connections to a single point connection, which is designed to provide a ground connection and a return path for the CHI current. Connections are sized to carry the current during CHI operations as well as the return of the current during bakeout heating of the center stack casing. The CHI power system is designed to provide a controlled current waveform with a peak current of 50.0 kA and rise time ″ 27ms. Switches are provided to isolate CHI power from the NSTX test cell (NTC), and these switches are interlocked with the NTC access control system.

3.3.3 Electron Cyclotron Heating (ECH) System

The electron cyclotron heating (ECH) system consists of a microwave source and power supply, a transmission system, a vacuum interface and a launching structure along with suitable diagnostics and controls. The function of the ECH system, which is designed to deliver 20 kW for 5 msec, is to provide pre-ionization for plasma breakdown. One ECH launcher is installed at an outboard location in the Vacuum Vessel to direct the microwave radiation toward the desired absorption location. The launcher is compatible with bakeout and glow discharge modes. The launcher has a vacuum window connecting it to the external transmission system. The transmission system (consisting of a waveguide and special components for power measurement) efficiently transports the microwave power from the RF sources to the vacuum window. Switches are provided to isolate 480V AC power from the ECH System in the NSTX test cell (NTC), and these switches are interlocked with the NTC access control system.

To provide reliability and a margin of safety, the vacuum window can withstand a pressure of 30 psig. The launcher and transmission line system is designed to satisfy the seismic loading for NPH Performance Category 1 (PC-1).

3.3.4 Neutral Beam Injection (NBI) System

The NSTX NBI system is designed to inject 80 keV neutral deuterium atoms into the plasma at a power level of 5 MW per beamline, with pulse duration up to 5 seconds. The NBI System is also capable of safe injection of 110 keV neutral deuterium atoms with pulse durations up to 1 second. The system includes two TFTR neutral-beam lines, with each beamline carrying three ion sources (see Sections 4.3, 4.4.2, 4.4.3, 4.5, and 7.3.4 of Reference 3 for additional information), operated at a reduced voltage (TFTR injection was 120keV). The first Neutral Beam Injector (NBI), BL1, injects 3 sources at tangency radii of 50, 60, and 70 cm respectively. The second NBI, BL2, injects 3 sources at tangency radii of 110, 120, 130 cm.

All NBI systems utilize the original TFTR design and recycled or spare components, or newly fabricated components in accordance with the original TFTR design, with the exception of the NBI-to-NSTX torus ducts which both have a physical interface requirement different than that of TFTR and different from each other. In addition to all of the same NB functions, the BL2 duct has been designed to also accommodate the Torus Vacuum Pumping System and its two turbomolecular pumps (TMPs). The NBI beam boxes and the High Voltage Enclosures (HVEs; see item j below) are designed to satisfy the seismic loading for NPH Performance Category 1 (PC-1).

In each ion source, Deuterium ions are generated by passing an electric arc discharge through low pressure deuterium gas to form a plasma within the source. The deuterium ions are extracted and accelerated to a specified energy level by electric fields. The ions are neutralized by charge-exchange on a gas target. Particles that are not neutralized are deflected out of the beam by a deflection magnet and directed onto an ion-beam dump. The beam of energetic neutral particles penetrate the confining magnetic fields of the torus and interact with the plasma. The NBI system for BL1 and BL2 consist of the following main components (see Figures 7 and 8):

a. Each of the three ion sources on a beamline produces a low-voltage, high-current discharge from which deuterium ions are extracted and accelerated by a multiple-slot accelerator. The extraction potential gradient is established between the source grids. The decelerating potential between the suppressor grid and the grounded exit grid prevents electrons in the neutralizer region from being drawn into the accelerator structure.

b. The ion deflection magnet serves to deflect ions from the mixed beam leaving the neutralizer. The magnet is inclined 45 degrees to the beam axis, and consists of six water cooled coils. To minimize stray field at the torus the magnet is shielded by high permeability material.

c. The ion dump absorbs the energy of positive ions deflected out of the beam line by the deflection magnet. The dump consists of three plates positioned based on the expected trajectories of the three deuterium ion energy components (full, 1/2, and 1/3 energy).

d. The calorimeter consists of three copper v-shaped elements and a screw/bellows actuator assembly, which allow the elements to be lowered in to the path of the beam for calibration purposes. Thermocouples are installed to measure the energy distribution. The calorimeter is raised to permit shots into the NSTX torus.

e. The NBI vacuum vessel, or "beam box", is of rectangular shape constructed of 3/4" thick 304 stainless steel with suitable reinforcing elements. A 78" port at the rear is provided for mounting the source and a 48" port is provided at the front for attachment of the duct to the torus. Additional ports are provided on the lid of the box for attachment of the calorimeter and magnet/ion dump assemblies.

f. The Source Mounting, Neutralizer, and Terminal assembly mounts to the rear of the NBI vacuum vessel and contains the water cooled copper duct neutralizers, the sulfur hexafluoride (SF6) pressurized source housing, and terminals for electrical connection of the source with the power supplies at the bottom of the source housing. The source mount is a two-axis gimbal with motor drive, which allows vertical and horizontal aiming adjustment of +/- 0.5 degrees.

g. The NBI support stand consists of 8” x 8” box tube columns that are welded to plates, which are in turn welded to the beam box and bolted to the floor. The support stand is designed to accommodate the unbalanced vacuum load, which tends to push the beam box radially inward toward the NSTX vacuum vessel.

h. The NB-torus connecting duct provides a passage through which the beam can pass with sufficient clearance from the wall. The duct includes a ceramic break to electrically isolate the NBI system from the torus vacuum vessel, a gate valve, duct scrapers and protective plates, attachment bellows, duct joints, and flanges. The gate valve between the torus and NBI vacuum enclosures provides a seal when either the NBI vessel or NSTX vacuum vessel is under vacuum while the other is at atmospheric pressure. The valve has a clear opening of at least 90 cm diameter. Actuation time is less than 30 seconds for translation of the gate from the full-closed and sealed position to the full-open position, or vice versa. Bolted mating flanges are provided at several planes in the NB duct to permit removal of individual components without disturbing the entire NBL. The NB duct scrapers are mounted inside the NB-torus duct and consist of thick copper plates. The NBI attachment bellows are required to allow for assembly and disassembly of the duct onto the NSTX torus. Rectangular bellows matching and mating to the vacuum vessel port geometries provide for expansion of the vacuum vessel during bake-out.

i. The cryopumping system is required to limit the pressure in the duct during a pulse via cryocondensation on to liquid helium cooled panels which are guarded by liquid nitrogen panels and chevron baffles (see Section 4.5 of Reference 3 for additional details on the D-Site Cryogenic Supply System).

j. The NBI power supply system consists of the Accel Power Supply system, the Auxiliary Power Supply system, and the Local Control System. The Accel Power Supply system consists of the primary power selector switch, fast vacuum interrupter, voltage controller, high voltage transformer/rectifier, crowbar, capacitor bank, and modulator/regulator, and serves to provide electric power to the ion sources, along with suitable protection. The Auxiliary Power Supply System consists of the arc, filament, decel, and magnet power supplies. The arc and filament supplies are housed together in an auxiliary tank known as the high voltage enclosure (HVE), which is located on the north end of the NSTX Test Cell, near the NBI. The HVE vessel is pressurized with SF_6 for high voltage insulation. The Local Control System provides interlocking that protects against misoperation of the various components of the NBI power supply system. Each source requires a dedicated NBI power supply system. See Section 7.3.4 of Reference 3 for additional details on the NBI power supply system..

k. The NBI vacuum pumping system consists of turbomolecular, backing, and roughing pumping systems. The roughing system does dual duty in that it can be valved to the NBI vacuum vessel or to the NSTX vacuum vessel, and serves as the NSTX vacuum vessel roughing system. See Section 4.4.2 of Reference 3 for additional details on the NBI vacuum pumping system.

l. The NBI I&C system is a programmable logic controller (PLC) based operating system for monitoring, control, and interlocking of all NBI parameters, which also provides an interface with the NSTX-U Hardwired Interlock System (HIS). Main NBI control is from the D-site 138’ Level.

3.4 Auxiliary Systems

The auxiliary systems consist of the vacuum pumping system, the gas delivery systems, the lithium deposition systems, the glow discharge system, the cooling water system, the bakeout heating/cooling system, the instrument air system and the gaseous nitrogen system. Components whose failure could impact the NSTX-U torus structure are supported in a manner that satisfies the seismic loading for NPH Performance Category 1 (PC-1).
FMEAs are provided in Appendix 1 (WBS Elements 3.1, 3.2, 3.3, 3.4 & 3.5).

3.4.1 Vacuum Pumping System (VPS)

The NSTX-U vacuum pumping system establishes and maintains the vacuum environment within the NSTX-U torus vacuum vessel. It consists of a pumping system, associated piping and valves capable of achieving high vacuum, various pressure-sensing elements and transducers, and an analytical system capable of discriminating gas species. The functions of the VPS are to:

a. Roughdown the NSTX-U device from atmosphere to base pressure.

b. Provide a high vacuum environment compatible with the NSTX experimental program.

c. Remove plasma exhaust and restore base pressure between pulses.

d. Minimize and maintain impurity levels.

e. Provide analytical capability for monitoring and control of machine vacuum conditions.

f. Provide pumping and control of pressure for Glow Discharge Cleaning modes (GDC).

g. Be compatible with, and provide pumping for vacuum vessel bakeout.

h. Provide appropriate safety interlocks for personnel and equipment safety.

The VPS consists of a high vacuum (Hi-Vac) system, a roughing system and a backing system. All components are located in the NSTX Test Cell (NTC). Supports for VPS piping are adequate to satisfy the seismic loading for NPH Performance Category 1 (PC-1).

The Hi-Vac system includes two 2800 liter/sec turbomolecular pumps (TMPs) each connected to the NB #2 (BL2) duct / vacuum vessel via 14" ducts.. The TMPs are mounted within cylindrical magnetic shields to shield the pumps from the machine fields during operations. The Hi-Vac system has a pumping speed of approximately 1600 liters/sec, and is capable of pumping the torus (volume about 30,000 liters) down from a pressure of 10^{-3} Torr to the low 10^{-8} Torr range of free gas in approximately five minutes between discharges.

The roughing system provides torus pumpdown from atmosphere (760 Torr) to less than 100 mTorr in less than one hour, at which point the TMPs pump the torus to high vacuum. This is accomplished through the use of a roughing mechanical pump (~300 CFM) and a roughing booster pump (~2700 CFM)

The backing system provides backing for the TMPs via one mechanical pump (~100 CFM) and one booster pump (~1600 CFM) connected to a 6 inch diameter backing line.

The VPS includes pressure gauges capable of monitoring pressure from atmosphere to high vacuum, and Residual Gas Analyzers (RGAs) capable of discriminating gas species. Service ports, strategically located on the vacuum system and the vacuum vessel are provided to facilitate maintenance and leak checking. A Programmable Logic Controller (PLC) is used for main control and logic functions of the VPS. The PLC communicates with NSTX-U Central Instrumentation & Control and uses engineering displays for process control from the Control Room.

The NBI roughing skid is connected to both the NBs and the NSTX-U vacuum pumping duct (with suitable interlocked isolating valves), and the roughing pump is controlled by the NBI PLC control system.

The VPS directs NSTX-U exhaust gases to the D-Site facility exhaust stack via piping through the NTC floor to the basement Mechanical Equipment Room. During NBI cryopanel regeneration a relatively large quantity of hydrogen gas is boiled off and exhausted by the vacuum pumping system through the stack. By administrative procedures, the maximum allowable amount of condensed hydrogen build-up is limited to 13 Torr, and the NBI PLC control sequence includes nitrogen purge before and after pumping gases liberated from both routine and emergency regenerations. These actions

The VPS is protected against improperly configured operation via an interlocking control program in the PLC. Loss of electric power or a PLC failure will result in components defaulting to safe states. A "watch dog timer" is incorporated in the PLC field distribution network to ensure the removal of electric power until normal conditions for operation are restored. The RGAs and ion gauge controllers have built-in self protection to prohibit operation above design-specified pressures.

3.4.2 Gas Delivery System (GDS)

The Gas Delivery System (GDS) provides the following functions;

a. Provides gas for plasma fueling.

b. Provides gas for glow discharge cleaning (GDC).

c. Provides instrumentation and control for gas injection.

d. Provides capability to select gas to be injected.

e. Provides gas for boronization.

The following features are incorporated into the GDS design:

a. A gas bottle bank with manifolding gas bottles.

b. Multiple gas injection points on the outer vacuum vessel and center stack.

c. Injection valves allowing feedback for real time control.

e. Minimization or elimination of the potential to form explosive mixtures in the system piping and hardware.

f. Remote operation of system.

The GDS, whose components (including gas supply bottles) are located in the NTC, is designed to deliver gasses required for operation of the NSTX device (e.g., deuterium, helium, etc.). Gas is provided by supply gas cylinders for each specified gas. The gasses are routed via austenitic stainless steel tubing to injection assemblies at a number of locations around the vacuum vessel.

Each outer vacuum vessel injection assembly consists of a pneumatically operated isolation valve, injection valve, and a vacuum vessel isolation valve. Gas is selected for delivery and routed to any one or all of the injection assemblies by configuration of valves in the distribution manifolds.

The Center Stack (CS) injector assemblies are electrically isolated from ground potential via a ceramic break. Gas is fed into storage volumes on the CS side of the ceramic break, after which isolating valves are closed and the volume containing the ceramic break is pumped out to ensure suitable pressure and high dielectric strength conditions as required to withstand the CHI voltage. The pressure in the line section containing the ceramic break is monitored and interlocked with the CHI power supply.

Fueling injection to the vacuum vessel, continuously or in discrete pulses, is metered by the piezo-electric valve. Injection can be performed in closed loop mode (setpoint control using the vessel ion or capacitance manometer gauges), in open loop mode (waveform control during plasma), or by manual control of the piezo-electric valves opening. Evacuation of the system is provided by a rotary vane vacuum pump.

Exhaust gasses from the GDS are routed to the D-Site stack via the same line that exhausts the VPS (see Section 3.4.1). The content of the largest gas cylinder (311 cubic ft.) constitutes less than 0.1% of the volume of the NTC (approximately 330,000 cubic ft.). Thus, oxygen concentrations in the NTC would remain at safe levels for personnel even if a gas cylinder's entire contents were released to the room.

A Programmable Logic Controller (PLC) is used for main control and logic functions of the GDS. The PLC communicates with NSTX Central Instrumentation & Control and uses engineering displays for process control from the Control Room. The GDS is protected against improperly configured operation via an interlocking control program in the PLC. Loss of electric power or a PLC failure would result in components defaulting to safe states (gas supply and torus interface valves would close, drive voltage would be removed from the piezo-electric valves, and all injectors would be disabled and disarmed). A "watch dog timer" is incorporated in the PLC field distribution network to ensure the removal of electric power until normal conditions for operation are restored. Loss of communication with the Central I&C System for more than five (5) seconds will cause the PLC to inhibit GDS operations by disabling valve drivers and removing drive voltage from the piezo-electric valves until communications are restored.

In addition to the piezo-electric valves, GDS will also utilize three Massive Gas Injection (MGI) valves, each of which is separately powered by a capacitor. These injection valves are being used to study the effects of injecting massive amounts of gas prior to a plasma disruption on reducing the impacts of disruptions. Each MGI valve has a small solenoid, which is energized when the capacitor fires. The eddy currents induced by the changing solenoid currents generate a force on a small piston, which opens, releasing gas into NSTX-U. Each capacitor (550 µF. 1.5 kV maximum voltage) is housed in a separate enclosure, and is charged by a dedicated power supply in its own separate enclosure. The capacitors and their power supplies are located in racks inside the NSTX-U Test Cell. Access to the caps and power supply enclosures are restricted by lexan/plexiglas doors installed on the racks, and microswitches on the doors will dump power to the enclosure boxes if the doors are opened.

3.4.2.1 Boronization

The injection of deuterated Trimethylboron (dTMB, $B(CD_3)_3$) into a glow discharge in NSTX-U (see Section 3.4.4), in a process called boronization, is intended to provide a hard, insulating coating of boron and carbon (as well as deuterium) to enhance the operational capability of NSTX-U. During the glow discharge boronization process, the dTMB is broken down into highly reactive radicals. These radicals stick to the walls of the vessel and react to form a protective film that is also hydroscopic, enhancing the pumping of deuterium and water vapor in the vessel during a plasma discharge and significantly improving the device's plasma performance.

The injection of dTMB into the NSTX-U vacuum vessel for the purpose of boronization is accomplished using a separate gas delivery and injection system. dTMB is toxic (7ppm Threshold Limit Value (TLV), based upon the TLV of the reaction product B_2O_3) and pyrophoric in air (low limit 0.5%). The quantity of dTMB is limited to a maximum of 50 grams in the NSTX-U test cell at any one time. The 50-gram inventory limits the total amount of this material to a small quantity that presents a slight increase in the flammable material inventory (less than 5% of the typical deuterium inventory in the room). This quantity of gas, if released into the NTC, when well mixed, would not present a level (approximately 2 PPM) in excess of the TLV. This excludes credit for fresh air introduction by the NTC Heating, Ventilation and Air Conditioning (HVAC) System.

The dTMB gas cylinders are contained in a sealed gas cabinet specially designed for toxic gas storage and delivery. A dTMB detector is mounted inside the gas cabinet to continuously monitor for the presence of dTMB within the cabinet. The gas cabinet is also equipped with a fire sprinkler to cool the dTMB gas cylinder in case of fire. Both the detector and sprinkler are interlocked to a local area alarm system (lights and horn) and to the Laboratory's centralized Communications Center (staffed 24/7 by the Emergency Services Unit, ESU). During dTMB operations, these alarms are also interlocked to immediately cease dTMB operations and secure the system. The gas cabinet also has a 6" diameter ventilation duct with a minimum of 300 SCFM of airflow to prevent any dTMB gas buildup inside the gas cabinet. If the system were to have less than the minimum ventilation flow rate, it is interlocked to make notification to the Communications Center and, during operations, to cease dTMB injection and secure the system. All parts of the dTMB system that may contain dTMB at pressures above 1 atmosphere are contained inside the gas cabinet and leak checked prior to filling with dTMB.

The gas delivery line between the gas cabinet and the NSTX-U vacuum vessel consists of a double jacketed line with the inner dTMB line encapsulated in a secondary line that is backfilled with helium. The dTMB in the inner line is at sub-atmospheric pressure with the outer helium jacket maintained at a pressure slightly greater than atmosphere, thus precluding the possibility of a dTMB leak into the NTC. The outer helium jacket is continuously monitored to ensure that it does not develop a leak. Both lines were helium leak checked prior to operations to ensure their vacuum integrity. Loss of helium pressure in the jacket area is interlocked to notify the Communications Center and to shut down injection and secure the system during operations. Handheld gas leak detectors and/or thermal imagers are also used by trained dTMB personnel for detection of leaking dTMB. Provision is made in the operation procedure that all personnel not part of the trained dTMB crew are excluded from the NTC during the boronization process. In the event the glow discharge current stops, the system is interlocked to immediately halt dTMB injection into the vacuum vessel. Additionally, the dTMB system has a nitrogen purge system of the vacuum pump exhaust line to prevent air-dTMB mixture formation in the line and reduce the concentration of residual boron containing gas to a level lower than 7 PPM. This system is also interlocked to shut down the dTMB process in the event of inadequate nitrogen flow to the process exhaust line.

3.4.3 Lithium Deposition Systems

The NSTX-U Experimental Plan calls for density control experiments using deposition of thin lithium films on plasma facing components to reduce fuel gas recycling and impurity influx. This work, depending on the experimental requirements, uses one or more of the following systems: Lithium Evaporator (LITER) and Lithium Granule Centrifugal Injector.

3.4.3.1 Lithium Evaporator (LITER)

Two Lithium Evaporators (LITER) had been provided to deposit lithium films of various thicknesses on plasma facing components in NSTX, and will continue to be used in NSTX-U. This deposited lithium material is expected to absorb atoms and ions exiting the plasma to form deuterides, thereby reducing the number of fuel gas particles recycled back into the plasma. This capability means that the LITER, is a tool for NSTX-U density control, and the lithium films can getter impurities as well.

For LITER, the safety precautions include: keeping the lithium and the LITER loading area (C-Site Lab Bldg, Room C-128, the D-Site TFTR Test Cell or the D-Site NSTX South High Bay) dry; presence of Lith-X fire extinguishers in C-128, TFTR Test Cell or NSTX South High Bay, and during transport of the loaded LITER to the NTC; direct handling of the lithium in an argon atmosphere glove box in C-128; receipt of the lithium in C-128 in sealed containers from the manufacturer; removal of unneeded material in sealed containers by the PPPL Environmental Services Waste Management Group; preventing exposure of the lithium to atmospheres with >50% relative humidity; use of oxygen monitors in C-128 to check oxygen levels prior to full entry into C-128 when argon gas is flowing; and transport of the LITER to the NTC over well-defined low traffic routes.

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Two LITER units are used during NSTX-U operations. Each LITER unit has a capacity of up to 80 g of lithium. Each LITER can be loaded either with lithium pellets of about 0.6 cm in diameter, or a liquid lithium fill system.

The use of pellets involves an effective packing fraction of about 50 grams, thereby limiting the LITER lithium capacity to about 40 grams. The use of liquid lithium allows the full 80 g capacity to be used. The pellets, when used are fabricated in the C-Site Room C-128 Argon Glove box, stored under argon, and transported to NSTX-U under argon. During the lithium pellet loading, the internal LITER ovens receiving the pellets are under argon. The liquid lithium fill system operates at 300°C and is enclosed in a room temperature protective shell. Argon forces the liquid lithium from the enclosed reservoir up into the LITER unit. The loaded units are then promptly installed on the NSTX-U so as to minimize any reaction with air. Each LITER is interlocked to prevent operation when either the LITER or NSTX is not under vacuum.

Each LITER is controlled and monitored from the NSTX-U Control Room. The total amount of lithium deposited via LITER per experimental campaign will not exceed 1600 g (80 g per LITER x 2 LITERS x 10 fills= 1600 g). Prior to entry of personnel into the NSTX-U vacuum vessel following experiments with lithium surface coatings from the LITER, the vessel shall be vented and affected surfaces cleaned to minimize hazards to workers from residual materials. All work shall be performed using approved procedures and appropriate personal protective equipment (PPE).

In addition to using solid lithium pellets, the LITER units can be loaded with liquid lithium using the Liquid Li Filler for LITER (LIFTER) system. When ready for reloading with lithium, the 2 LITER probes are mounted on Parking Stands in the TFTR Test Cell or NSTX South High Bay for the reloading operation. The amount of lithium in a single LIFTER is <80g. Its maximum operating temperature is <300°C. LIFTER is loaded with liquid lithium in the C-128 Argon Glove Box. All procedures approved for lithium handling in C-128 are applicable to loading LIFTER, and its subsequent transport to the TFTR Test Cell or NSTX South High Bay. After the loading of LIFTER with liquid lithium is completed, and LIFTER has cooled to room temperature, and its lithium contents have solidified, it is carried to the D-Site TFTR Test Cell or NSTX South High Bay via a route approved in the C-128 Procedure. The LITER lithium loading work is performed by trained personnel using an approved procedure. LIFTER engineering barriers and equipment placement are designed to provide for personnel safety. A Lith-X Fire Extinguisher will be available in the TFTR Test Cell or NSTX South High Bay during this loading operation. <80g of the LIFTER contents will be loaded per LITER. The total amount of liquid lithium transported to the TFTR Test Cell or NSTX South High Bay per loading will be <160g (<80g per LITER). All lithium remaining in LIFTER after loading is returned to C-128 for subsequent use. The

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possibility of hazardous lithium waste will be minimized by employing the lithium handling procedures used in C-128. Some of the graphite tiles in the NSTX-U divertor will be replaced with molybdenum tiles (TZM alloy, 99.5% Mo, 0.4-0.55% Ti, 0.06-0.12% Zr) and pure tungsten tiles. The LITER evaporators will coat this region during normal usage of the LITERs as described above. The expected lithium usage with this configuration will be the same as with the graphite tiles that were replaced, and is consistent with the total annual lithium usage of less than 2000g described below.

Potential accident scenarios associated with the use of lithium have been evaluated and would result in no serious damage to NSTX-U and no adverse consequences to workers, the public or the environment (see Section 4.2). As an additional precautionary measure, an Argon Purge System has been designed and installed to suppress a potential fire inside the torus vacuum vessel in the very unlikely event that LITER is in operation, lithium is released into the torus uncontrollably, and there is a catastrophic air leak into the torus. Under these conditions, the Argon Purge System would release argon gas into the vacuum vessel to prevent fire development and pressurize the vessel to just below atmospheric pressure. This System consists of 4 argon gas cylinders, injection valves, and controls and interlocks. Vent valves are also provided at the top of the vacuum vessel to purge gas from the torus, if needed. Inadvertent release of argon into the torus vacuum vessel when not needed is prevented by interlocks that require all of the following conditions to be satisfied to release argon: (1) all three vacuum vessel capacitor manometer vacuum gauges are elevated (indicating a large air leak into the vessel); (2) vacuum vessel ion gauges go off (indicating a large air leak into the vessel); (3) torus VPS TIV closes; (4) NB TIV closes; and (5) LITER shutter is open.

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3.4.3.2 Lithium Granule Centrifugal Injector

The Lithium Granule Centrifugal Injector uses an assembly to drop spherical lithium granules of about 1mg mass onto a rotating paddle that hurls the incident particles into the plasma edge at velocities from 0 to 100m/s, at frequencies up to 100Hz. This unit will be used to inject granules for destabilizing Edge Localized Modes (ELMs) at the injection frequency. Since ELMs result in flushing impurities accumulated in the core plasma, being able to apply ELM pacing in a controlled manner would be an important tool for controlling impurity accumulation in ELM-free H-modes. This would be of interest to current experiments and ITER. The lithium loading of this unit is performed in Room C-128. The annual lithium usage of the Lithium Granule Centrifugal Injector will not exceed 200g.

3.4.3.3 Total NTC Lithium Inventory

The total active elemental lithium inventory in the NTC during an experimental campaign will not exceed 2000g (e.g., 1600g for LITER, 200 g for Lithium Granule Centrifugal Injector, and 200g for LITER Fill stand calibrations).

3.4.3.4 Tritium Production from Lithium

A maximum neutron production rate of 4E18 per year is anticipated during NSTX-U operation. If each neutron strikes a lithium nucleus and creates a triton, this results in a maximum tritium generation in the vacuum vessel due to lithium operations of 0.193 curies per year. These amounts, if released to the environment, would be small fractions of the average annual tritium release from the D-Site stack since the end of the TFTR D&D Project (i.e., 12.1 Ci/yr for 2003-12). Measurements of tritium surface contamination by Health Physics Division radiological technicians will be made before entries to the NSTX-U vacuum vessel to determine radiological control requirements for workers.

3.4.4 Glow Discharge Cleaning System (GDC)

The Glow Discharge Cleaning System (GDC) establishes and controls the GDC process in NSTX-U. GDC is a mode of vacuum conditioning in which vacuum vessel internal surfaces are “scrubbed” clean by the bombardment of ions formed during the glow process. The GDC system is highly integrated with the VPS and GDS. The following features are incorporated into the GDC design:

a. Two in-vessel fixed probes, which act as the anodes.

b. Power supply for the anode probes.

c. Two in-vessel filaments to facilitate GDC initiation.

d. Instrumentation and control for operation.

The GDC is remotely configurable and operable, is capable of operating with helium and other gases, and is capable of steady state operation. The system is comprised of two "glow probes", power supply and cabling to the probes, and instrumentation to monitor and control performance. Each probe is driven by a regulated power supply, and acting as an anode, applies a voltage potential across the gas filled vacuum vessel, stripping electrons from the gas.

The ions accelerate toward the vessel wall, which is connected to the negative leg of the power supply. The bombardment of the walls by these energetic ions releases contaminants that are removed by the VPS. Control of the system is accomplished through the NSTX-U Instrumentation and Control (I&C) system via a console in the control room. The GDC can be started at lower pressure and voltage using one or more of the in-vessel filaments provided for this function.

During operation, the torus vacuum vessel is filled with the desired gas (typically helium or deuterium) to a desired pressure. These parameters are controlled by the GDS and VPS. The operator then selects a current to be applied to the circuit. Depending on the "cleanliness" of the vessel, the gas pressure, and the impedance of the circuit, a potential forms across the gas and current flows. The operator then adjusts the current until the desired glow conditions are achieved.

To protect diagnostics from GDC and to prevent coating of windows from impurities generated during GDC, a remotely controlled shutter/torus interface valve (TIV) system is utilized. These diagnostic TIVs and shutters are controlled and monitored using the VPS PLC

The GDC operating parameters are:

Voltage- 400-800 volts.

Current- ~ 3 amperes.

Pressure (He or D_2)- 2 – 4 mTorr

3.4.5 Cooling Water System (CWS)

The cooling water system (CWS) provides active cooling and over-heating protection for the coil systems, bus bars and diagnostics that support NSTX-U (not including the D-site Motor Generator (MG) system which is cooled by the D-Site Cooling Tower Water System and the NBI and NBI power supply system components which are cooled by a separate service water system). All coils and bus bars are inertially cooled during normal operation, with cooling needed for the next shot provided between shots. If cooling is lost during a shot, the coil temperature would be limited by I^2 t integrals in the coil power supply control system, and the Digital Coil Protection System (DCPS). Coils and bus bars require active cooling during bake-out. Specific functions include:

a. Providing chilled deionized water for heat removal in the TF, OH and PF coils.

b. Providing chilled deionized water for bus bar systems, CHI Rings, Upper and Lower CHI Flag Connections, HHFW system and diagnostics. (Note: VPS and the bakeout heating/cooling system are cooled by the HVAC Chilled Water System).

c. Providing flow monitoring to prevent damage due to loss of flow.

d. Providing coil protection for loss of temperature dew point control or pressure.

e. Providing active cooling for the center stack casing during shots to remove plasma heating of the tiles. NSTX did not require active cooling of the casing. The NSTX-U requires active cooling as a consequence of the higher plasma current, heating power, and extension of the pulse length.

The NSTX-U CWS combines a new design with the extensive use of existing equipment (in the D-Site Pump Room and NSTX Test Cell) to provide cooling water to coils, buswork, and various components. Deionized water is provided from the 33,000 gallon storage tank in the Pump Room (which is polished using a deionized water polishing loop and the existing Deionized Water System). Water is circulated through a 100 horsepower (hp) centrifugal pump at up to 600 gallons per minute (gpm) to an existing 400 ton flat plate heat exchanger, which chills the deionized water using the HVAC Chilled Water System as a heat sink. The chilled water is supplied to and returned from the NSTX-U coils and other loads via 4" supply and return piping through the Mechanical Equipment Room to the NTC. Automatic valves on the main supply and return lines provide capability for remotely isolating the CWS from NSTX-U via the NSTX Control Room.

Cooling water is supplied to the TF and PF supply headers at a pressure of about 120 psig. High pressure (420 psig) water is provided to the OH coils by a 5 hp booster pump. A second booster pump with potable water as an alternate supply of cooling provides emergency backup for OH coil cooling. These pumps can be powered from the standby diesel generator. In addition, on loss of all electric power, a manual valve can be opened to introduce potable water into the CWS to help cool the Center Stack (i.e., during bakeout). Both the TF and OH coil cooling systems have features that mitigate thermal shock by initially introducing warmed water in the cool down cycle.

For coil protection, a programmable logic controller (PLC) processes data from pressure, temperature, water resistivity and flow instrumentation on the supply and return paths. NTC dew point is monitored and compared to inlet water temperature. If the water temperature drops below the dew point temperature, the CWS PLC will inhibit the next machine pulse and shut down the CWS.

Component malfunctions (e.g., inadvertent valve alignments) that may result in pressure transients are prevented from causing systems failures by: (1) inclusion of relief valves (to LEC drain); (2) interlocks which prevent adverse conditions from developing (e.g., via shutting down pumps or prevention of supply valve openings); and (3) system design for maximum anticipated pressures.

An emergency stop (E-Stop) button is provided to shut down the CWS (e.g., if water leakage occurs). The CWS will also be shutdown automatically on low water level in the Pump Room storage tank. A flow switch failure during a run day coincident with an actual loss of flow in the affected flow path has the potential to cause coil damage from overheating (adequate cooling is lost and undetected while experiments continue). This dual failure is considered unlikely because the flow switches are effectively tested with each cycle (i.e., the PLC looks for open switches every time water is shutoff).

3.4.6 Bakeout Heating/Cooling System

The NSTX vacuum vessel and plasma facing components (PFCs) must undergo a bakeout scenario that raises the PFC temperature to 350°C and the vacuum vessel temperature to 150°C. Bakeout Heating/Cooling System equipment is designed to operate in the bakeout mode 10 times per year.

The passive stabilizer plates and divertors are heated and cooled by flowing pressurized helium through tubes brazed into slots in the copper backing plates of the PFC tiles. The vacuum vessel is heated or cooled by flowing pressurized water through tubes intermittently welded to the surface of the outer vacuum vessel wall (with heat conductive putty applied to aid heat transfer). Due to space limitations, the center stack (CS) inner wall tiles cannot be heated by this method. These tiles are heated by direct ohmic heating of the center stack casing using a DC Power Supply. To protect the center stack coils, the OH and PF1a, PF1b, and PF1c coils must be water cooled during the entire bakeout cycle (see Section 3.4.5).

The initial operation of the Bakeout Heating/Cooling System used water as the heat transfer fluid. During this mode of operation ("low temperature bakeout") the system has been operated at a maximum temperature of 150°C. High temperature bakeout operations using the helium High Temperature Bakeout Skid increases the bakeout temperature to 350^{o}C, and utilize the LTS (Low Temperature System) to maintain a temperature of 150°C or less using pressurized water.

The low temperature bakeout system has been hydrostatically tested to at least 1.5 times its operating pressure. Precautions are taken to prevent personnel contact with hot surfaces, including restricting access to areas where hot pipe or components are present, posting of warning signs, and personnel training. An FMEA for this system is included in Appendix 1.

During experimental operations mode, two sub modes exist: low power operations and high power operations. During low power operations, the HTS (High Temperature System) circulates helium nominally at 50°C through the

PFCs while the LTS circulates 50°C water through the vacuum vessel circuits. During high power operations, the HTS circulates 50°C helium through the PFCs and vacuum vessel. In both modes, the PFCs and vacuum vessel are maintained at 50°C.

The major components of the LTS are the water storage tank, nitrogen blanketed expansion tank, water circulation pumps, electrical heater, and pressure relief storage tank.

Protective interlocks are provided to prevent excess fluid temperatures (via heater over-temperature switch) and to prevent operation of pumps with misaligned valves. The following conditions will result in alarms that will alert operators to shutdown the bakeout heating/cooling system:

1. Major fluid leak that causes level in expansion tank to drop below alarm point.

2. Blockage in LTS pipeline causing differential expansion due to uneven heating of PFCs and vacuum vessel (vacuum vessel thermocouples will alarm this differential).

3. Loss of nitrogen blanket causing fluid level in the expansion tank to rise to alarm point.

4. Loss of cooling water for water heat exchanger causing vacuum vessel thermocouples to alarm as vessel temperature rises above 50°C.

5. Failure of low temperature pump causing vacuum vessel thermocouples to alarm as vessel temperature rises above 50°C during operations or above 150°C during bakeout.

The skid is equipped with an Emergency Stop pushbutton which, when manually actuated, trips the incoming 480V power, thus shutting down all pumps and heaters and forcing solenoid operated valves to their safe position. Loss of 120V AC signal (i.e., loss of AC power) will initiate an automatic Emergency Stop. Operation of the circulating pumps and heater is predicated on receipt of a permissive signal. Operational and fault status of the LTS is provided by normally open and normally closed contacts on the skid. Manual reset of the contacts is required under fault conditions.

The Helium HTS (High Temperature System) is located in the D Site Pump Room (see Figure 5). Three inch welded piping is run from the Pump Room to the NSTX Test Cell (NTC) to supply the bakeout manifolds on the vacuum vessel with hot pressurized helium. To maintain a temperature of 350°C at the PFCs, a supply temperature of up to 420°C at a pressure of 300 psi will be provided by the HTS. The High Temperature Helium Bakeout Skid has been pneumatically tested to 1.3 times its operating pressure per PPPL Engineering Procedure. All piping is insulated to prevent a burn hazard to personnel. There are access restrictions in the NTC during bakeout operations to limit work in areas near high temperature piping. Over-temperature conditions are protected against using high temperature interlocks tripped by a Programmable Logic Controller (PLC), as well as high temperature element switches built into the heater. The PLC monitors valve positions to ensure correct valve alignment before operation of the blower and heater. Overpressure conditions are protected against through the use of a pressure regulating valve, pressure relief valve, and PLC interlocks. A bypass valve around the blower automatically opens if blower differential pressure parameters are exceeded. While the system operates at a base pressure as high as 300 psi the blower provides only enough pressure differential to move the helium around the loop (nominally 28 psi). This arrangement minimizes the potential to overpressurize the system. Only the addition of gas from the helium bottle or the increase in pressure due to heating of the gas have the potential to drive the pressure up substantially. These are slow events and are protected against with the previously mentioned relief valves and interlocks. The system protects against leakage into the vessel and minimizes potential leaks to the room by sensing low pressure and closing isolation valves. All interlocks and conditions can be monitored actively via the PLC. The system shuts down and isolates if an Emergency Stop (E-Stop) is initiated.

3.4.7 Instrument Air System

This system provides an instrument air utility to operate pneumatic devices in the NTC. It consists of a manifold with valves using the existing D-Site Instrument Air System (see Section 5.11 of Reference 3).

The Instrument Air System provides dry air at approximately 100 psig to operate vacuum, water, and cryogenic valves and other instruments. Air is supplied from compressors in the D-Site Mechanical Equipment Room (located below the NTC). The NSTX-U manifold connects to the D-Site Instrument Air System via a connection on the east wall of the NTC, and consists of 1" diameter piping with about twenty-five (25) ports with ball valves. Process valves and instruments are connected to the nearest port connection on the manifold.

3.4.8 Gaseous Nitrogen System

The Gaseous Nitrogen System provides a source of dry nitrogen to eliminate the introduction of contaminants and water vapor into vacuum spaces. This system is an extension of the existing D-Site gaseous nitrogen system that distributes the gas throughout the facility at a dew point temperature of -70°C and a pressure of 60 psig. Gaseous nitrogen from this system is supplied to a manifold with approximately twenty (20) valves located around the NSTX platform in the NTC. The gas pressure is reduced to 1.3 psig for use by NSTX components via connection to the nearest manifold port.

3.5 Plasma Diagnostics

The purpose of plasma diagnostics is to provide information on discharge parameters to characterize NSTX-U plasmas and guide NSTX-U operations for optimized performance. NSTX-U diagnostics, including those that are essential for machine operations are listed in Table 5.

The near-term NSTX-U program emphasis is on detailed measurements of plasma profiles for understanding the basic confinement and transport properties of 5 second, radio frequency-driven NSTX discharges. Diagnostics, which are available for first plasma operations, are indicated as "Day 0"; diagnostics available after first plasma are indicated as "Day 1".

The long-term objective is to upgrade and expand the diagnostic set further for the study of fluctuations and transport in long pulse, neutral beam-heated NSTX-U plasmas. In addition, plasma diagnostics will provide input for advanced plasma control systems. New concepts and systems developed by the national NSTX team to implement these goals also will be encouraged.

All diagnostics connected to NSTX-U are compatible with a 150^{o} C bakeout temperature at the torus isolation valve. All coils, loops, and other diagnostics mounted inside the vacuum vessel are compatible with a 350^{o} C bakeout temperature for the plasma facing components and a 150^{o} C bakeout temperature at the flanges which provide the interfaces to the diagnostics. All coils, loops, and other diagnostics mounted inside the vacuum vessel are installed in a way that minimizes damage due to interaction with the plasma. This includes protection against high voltages and large heat loads, particularly for components located on the center column. All materials utilized within the primary vacuum boundary are included on the PPPL Vacuum Committee approved list, or have been separately approved by the committee.

All diagnostics are isolated via optical and/or magnetic (isolation transformer) means prior to exiting the NTC boundary; this isolation is rated to withstand a one minute AC hipot test at 20 kV AC rms. All ancillary components which are in mechanical contact with the vacuum vessel are electrically isolated from the vacuum vessel; this isolation is rated to withstand a one minute DC hipot test at 3 kV DC (the outer vacuum vessel is normally operated near ground potential, including CHI operations). Diagnostic elements which are located in the center stack between the OH coil ground plane and the center stack casing (e. g., Rogowski coils and flux loops) are insulated to withstand the full coaxial helicity injection (CHI) voltage, and can be operated either referenced to the center stack casing (at CHI potential) or to ground; this insulation is rated for a one minute DC hipot test at 5 kV. Diagnostic elements that are located on the vacuum side of the center stack are referenced to the inner vacuum vessel wall. Data connections to and from diagnostic equipment in the NTC are with optical fiber, as are connections between the data acquisition systems for each diagnostic. Each diagnostic exterior to the vacuum vessel is independently grounded to a single point ground as determined by the NSTX-U machine grounding specifications. Diagnostic components located outside the NSTX Test Cell are electrically isolated to permit safe access while NSTX-U is operating.

Other safety aspects of NSTX-U diagnostics operations (e.g., laser safety) are required to comply with the relevant requirements of the PPPL ES&H Manual (ES&HD 5008).

The Multi Pulse Thomson Scattering (MPTS) Diagnostic includes two Class IV YAG lasers, laser steering optics, laser input tube, laser beam dump, collection optics and mount, fiber optics and polychromators. The laser and detectors are located in a room on the mezzanine in the NSTX-U gallery to allow personnel access during NSTX-U operation. The beam is directed horizontally into the vacuum vessel by a mirror mounted on the south shield wall. The beam exits through a window at the end of the vacuum pumping duct. This system is operated under an approved Laser Safe Operating Procedure (LSOP). Entry to the NTC during MPTS laser operations will be performed only under carefully controlled Hot Access conditions using approved procedures.

The Far Infrared Tangential Interferometer (FIReTIP) system in the NSTX Test Cell provides toroidal field and line-average density plasma measurements on NSTX-U. This system consists of a Class IIIB far infrared laser (~30 mW) pumped by a Class IV CO2 laser (~100 W). A Class IIIa He-Ne laser is used for alignment purposes. The system is located on an enclosed commercially available optical table for the lasers outside the NSTX Test Cell. Components include an optics table, windows and shutters at Bay G, a retro-reflector at Bay B, power supply (15 kV), chiller, vacuum pumps, gas rack (outside the NTC), PC-based control system (controllable from the NSTX control room or locally for maintenance), and assorted optics (mirrors, etc.). This system is operated under an approved Laser Safe Operating Procedure (LSOP) that specifies protective measures to: prevent laser exposures to personnel; isolate hazards during operation, maintenance and testing; and prevent accidental laser burn through of the enclosure.

Vacuum systems, when required for diagnostics, exhaust to the NSTX-U Vacuum Pumping System (see Section 3.4.1).

FMEAs are provided in Appendix 1 (WBS Element 4X).

Table 5 Baseline NSTX-U Diagnostics Set

Availability	Diagnostic	Function
Day 0	Plasma current Rogowski coils	Total plasma current
	Flux loops	Plasma control and equilibrium reconstruction
	Visible TV camera	External shape for plasma control
	Extreme UV spectroscopy	Impurity identification and concentrations
Day 1	IR camera	Heat loads
	"Slow" diamagnetic loop (using toroidal field coil)	Stored energy
	Halo current Rogowski coils	Halo currents in center stack
	Eddy current Rogowski coils	Eddy currents in passive plate supports
	B_r, B_z coils	Plasma control/magnetic fluctuations
	Mirnov coils	Magnetic fluctuations
	Langmuir probes/thermocouples[1]	Divertor parameters
	Multichannel bolometer	Radiated power profile
	Soft X-ray imaging system	Plasma instabilities and fluctuations
	Ultra-soft X-ray array	Start-up and impurity studies
	H_α detectors	Edge recycling
	CHERS[2]	Ion temperature and toroidal rotation
	PCHERS	Poloidal rotation
	Edge Rotation Diagnostic	Edge rotation
	Visible bremsstrahlung array	$Z_{eff}(r)$ from visible continuum
	Solid State neutral particle analyzers	Core ion temperature and fast ions
	Visible spectrometer	Edge/divertor spectroscopy
	Multi Pulse Thomson Scattering	Electron temperature and density profile
	Far Infrared Tangential Interferometer	Density profile
	Divertor SPRED spectrometer	Impurities in divertor
	Divertor Imaging Radiometer	Impurities in divertor
	Filterscopes	Impurities
	Transmission Grating Spectrometer	Impurities
	Fast IR camera	Divertor heat load
	Wide angle IR camera	Divertor heat load
	MAPP Probe	Plasma surface interactions
	Neutron detectors	Neutron rate
	Gas Puff Imaging	Edge density fluctuations

	Reflectometer	Density fluctuations
	1-D CCD camera	1-D impurity imaging
	Motional Stark Effect	Internal magnetic fields
	Motional Stark Effect-Laser induced Fluorescence	Internal magnetic fields
	SFLIP	Escaping fast ions
	FIDA & T-FIDA	Fast ions
	Quartz Crystal Microbalance (QMB)	Boron/lithium/plasma deposition rate
	Dust Detector	Diagnosis of in-vessel dust

[1]Diagnostics incorporated into plasma facing components
[2]CHERS: Charge-Exchange Recombination Spectroscopy

3.6 Electrical Power Systems

The Power Systems supply and deliver all electrical power to equipment associated with the NSTX-U. These systems utilize the existing connection between PPPL and the local utility (PSE&G), the existing D-Site facilities and equipment that had been used for TFTR (AC Distribution System and Field Coil Power Conversion System), and existing C-Site facilities and equipment for the High Harmonic Fast Wave (HHFW) System (see Section 3.3.1). Power is routed from the existing D-Site equipment to the NSTX Test Cell (NTC) by cabling from the Transition Area (southeast corner of the TFTR Test Cell Basement) through a penetration to the Mechanical Equipment Room, and up through a penetration to the NTC. In the NTC, the power cables are terminated at a Power Cable Termination Structure (PCTS), from which power feeds are extended to the proximity of the machine via buswork and cabling to supply loads. Power cables whose failure could adversely affect the performance of the NSTX-U torus structure or create a threat to worker safety are supported in a manner that satisfies the seismic loading for NPH Performance Category 1 (PC-1).

The existing D-Site electrical power systems being utilized by NSTX, including safety evaluations and failure modes and effects analyses, are described in Chapter 7 of Reference 3. FMEAs for the NSTX-U electrical power systems are provided in Appendix 1 (WBS Element 5X).

3.6.1 AC Power System

The AC Power System is divided into two major sub-elements, namely the Experimental AC Power System (which includes all loads due to toroidal field (TF) coil, poloidal field (PF), and heating & current drive (H&CD) systems); and the Auxiliary Systems AC Power System (which includes all NSTX-U auxiliary or "house" power demands). The function of the AC Power System is to provide the source of all electric power required for the NSTX-U facility. The AC Power System must establish the connection between the PPPL facility and the local utility network in a fashion which permits the pulsed loading required by the NSTX experiment, while maintaining a power source of suitable quality for existing house loads.

The specific functions of the Experimental AC Power System include:

a. Delivery of power to D-Site 13.8kV S1 bus, from primary AC input terminals of transformer XST-1 to S1 bus.

b. D-site MG equipment, including excitation and cycloconverter drive systems, from S1 bus to variable frequency busses SV1 and SV2 (see Figure 6).

c. AC distribution from SV1 and SV2 busses to converter transformer primary AC input terminals, including feeds to neutral beam (NB) equipment.

d. AC distribution from secondary terminals of C-site transformer XQT-1 or XQT-2 to HHFW converter transformer primary AC input terminals.

The specific functions of the Auxiliary Systems AC Power System include:

a. Delivery of power to D-Site 13.8kV S2 bus, from primary AC input terminals of transformer XST-2 to S2 bus.

b. All auxiliary system AC distribution at D-Site, from S2 bus to points of utilization at 13.8kV, 4.16kV, 480V, 208V, and 120VAC levels.

c. 2600 KW standby power diesel generator and all associated equipment.

d. Uninterruptible Power Supply (UPS) systems and all associated equipment.

Experimental power is taken nominally through one of the two D-site Motor-Generator (MG) units. The only exception is the HHFW system, for which the sources are located at C-site.

When the experimental power load is such that the total composite load required by NSTX-U can be supplied directly by the grid, the configuration of the AC systems permits operation directly from the grid without the use of the MG set. Therefore, the AC input to the TF, OH, and PF converters, and the AC input to the CHI equipment, are each separately connectable either to the MG set or to the grid. The most likely mode in which the MG set would not be used is during non-inductive NSTX-U operations when the OH system is not used.

3.6.2 Power Conversion Systems (TF, PF/OH, CHI, HHFW)

The TF Power Conversion System is designed to provide a constant current in the TF magnets during an NSTX-U discharge based on a reference current input signal provided in real time. This system includes all equipment from the AC input power interface through to the DC bus connections to the magnets, converter transformers, thyristor converters, DC cable, DC bus, disconnect switches and bus links, and all associated monitoring, control, and protection equipment.

The PF/OH Power Conversion System provides a variable current in the PF and OH magnet circuits during an NSTX-U discharge based on a reference voltage or current input signal provided in real time. This system includes all equipment from the primary terminals of the converter transformers through to the DC bus connections to the magnets, consisting of phase controlled thyristor converters, disconnect switches and bus links, and all associated monitoring, and protection equipment.

The function of the CHI power system is to energize the CHI electrodes and impart a poloidal component of current flow, which, due to the influence of the toroidal field, results in a toroidal component of plasma current. This consists of capacitor bank system supplies to provide CHI current drive sustainment for the full plasma flat top duration. Also a power circuit consisting of thyristor rectifier power is provided to condition the Vessel electrodes prior to CHI initiation. The HHFW power system utilizes RF power produced by the six existing Tokamak Fusion Test Reactor (TFTR) Ion Cyclotron Range of Frequencies (ICRF) sources.

Features common to the TF, PF/OH and CHI Power Conversion Systems include:

a. No-load disconnect line switches provided to isolate the Power Conversion Systems from the connections to the magnets or the CHI conditioning circuit. In addition, no-load grounding switches are provided to ground the terminals of the connections to the magnets or CHI load circuit. The line switches must be open, the grounding switches must be closed, and the compressed air supply (which actuates the switches) must be vented to permit the Safety Lockout Device (SLD) to be moved to its safe position and allow access to the NTC.

b. The TF and PF/OH Power Conversion Systems include protection to avoid the delivery of current that would overheat the magnets.

The TF Power Conversion System is grounded via high resistance connections at the (+) and (-) coil terminals. A ground fault protection system is used in conjunction with the grounding scheme to detect grounds within the TF circuit. The TF Power Conversion System equipment and bus system external to the NTC are totally enclosed so that access can be maintained around the operating equipment without danger to personnel. Ground detection and protection are also provided for other systems.

The CHI power conversion equipment, capacitor bank, and bus system are totally enclosed so that access can be maintained around the operating equipment without danger to personnel. Protective features are included to prevent the application of excess voltage to the electrodes associated with the center stack. The instantaneous voltage limit is 2.0kV.

A PLC based system is being used for the TF, PF/OH and CHI Power Conversion Systems. Other safety features of the TFTR power conversion systems (e.g., kirk key interlocks, safety lockout device) are also continuing to be used for NSTX-U (see Section 7.3.1.3.2, 7.5 and 9.3 of Reference 3).

3.6.3 Digital Coil Protection System (DCPS)

The Digital Coil Protection System (DCPS) allows the NSTX-U device to be operated over a wide operating space. The high performance level of NSTX-U is made possible by the DCPS since it allows higher coil performance than would be permitted by traditional protection. The DCPS is needed to ensure the integrity of the device mechanical structures during operations and addresses coil Lorentz force interactions and component stresses, not just individual current limits. Design and reliability requirements are outlined in the "Coil Protection System Requirements Document" NSTX-CSU RQMT-CPS-159.

- NSTX-U requires more comprehensive methods of protection due to:
    - Longer pulse length
    - Double the plasma current

- Double the toroidal field
- New TF, OH, and Divertor coils

- DCPS executes a set of protection algorithms utilizing a modern digital computer system to constrain operations within a complex operating envelope

NSTX-U will use a combination of mechanical reinforcement, periodic field inspection, and the DCPS to ensure the mechanical integrity of the NSTX-U device mechanical structures. FMEA's can be found in Appendix 1 under Digitial Coil Protection System (DCPS) FMEA.

3.7 Central Instrumentation and Control

The Central Instrumentation and Control (I&C) System provides remote control, monitoring, data acquisition and data management for the NSTX-U subsystems during machine operation. The system provides researchers with access to the facility in support of the operation, physics planning, analysis and coordination of experimental objectives. The Central I&C system provides all supervisory control and monitoring of the NSTX-U facility, including:

a. Plant Control and Monitoring (asynchronous routine control and monitoring).
b. Synchronization (synchronization of triggered actions from master clock events).
c. Plasma Control Processor and Input/Output (I/O) Interface (digital processor and I/O hardware for interface with plasma control measurements and actuators).
d. Power Supply Real Time Controller (PSRTC)
e. Safety Interlocks (master supervisory control of experiments).
f. Access Control (control and monitoring of access to the NSTX Test Cell).
g. Data Acquisition (periodic sampling, acquisition and display of regularly sampled data, and acquisition and display of data sampled and stored by remote devices).

The Central I&C System consists of the Control System and the Data Acquisition System. It is installed at various PPPL locations, including the C-Site NSTX-U Control Room (Lyman Spitzer Building (LSB) room B006), the C-Site NSTX-U Computer Room (LSB room B003), the D-Site NSTX Test Cell, the D-Site NSTX Diagnostic Facility located in the gallery, the D-Site Junction Area (Field Coil Power Conversion Junction Area), the D-site Motor Generator Control Room, the D-site FCPC (Field Coil Power Conversion) Building TF and PF wings and second floor, the D-Site Mock-Up Building RF Enclosure, the C-Site RF Source Room, C-Site Administration Building Computer Addition room (PPL Computer Center (PPLCC)), and the D-site Neutral Beam Power Conversion (NBPC) Building 138' Level for control of neutral beam injection (NBI).
FMEAs are provided in Appendix 1 (WBS Element 6X).

3.7.1 Process Control System

The NSTX-U Central I&C Process Control System includes instrumentation and controls for the following NSTX-U subsystems: High Harmonic Fast Wave (HHFW), Coaxial Helicity Injection Current Drive (CHI), Electron Cyclotron Heating (ECH), Vacuum Pumping System (VPS), Gas Delivery System (GDS), Glow Discharge Cleaning System (GDC), Cooling Water System (CWS), Bakeout Heating/Cooling System, AC Power Systems, Toroidal Field (TF) Power Conversion System, Poloidal Field/Ohmic Heating (PF/OH) Power Conversion System, and CHI Power Conversion System. It interfaces with existing PPPL Computer Automated Measurement And Control (CAMAC) links and field modules, new I/O points, and stand-alone subsystem controllers to provide supervisory monitoring and control. The Process Control System provides engineering displays in the NSTX-U Control Room (and at other selected locations) to serve as the user interface to the engineering processes, and provides a secure method for transferring engineering subsystem diagnostic data and status information from the Process Control System to the Data Acquisition System.

3.7.2 Safety System

All NSTX-U subsystems' equipment have built-in self-protection. However, the NSTX-U Safety System provides system-wide coordination for personnel and hardware safety. This is accomplished by monitoring subsystem's status, Kirk Keys, E-Stops, and door limit switches via relays to report safety status to operations personnel in the NSTX-U Control Room.

The Safety System consists of the Hardwired Interlock System (HIS) and the Safety Lockout Device (SLD). The HIS provides operational permissives to the field coil power supplies, RF, and NBI systems, and enables them to be configured and operated. The SLD monitors the status of the field coil power system's safety disconnect switches and provides a "safe" signal for NTC access only when all switches are in the safe position and the compressed air supply (which actuates the switches) has been vented. Search and secure loops are provided for the NSTX Test Cell and for the cable spread room to assure no personnel are in those areas when the machine is in a "No Access" mode.

The Safety System provides the following functions:

a. Monitoring and alarming of critical subsystems, and invoking mitigating action to ensure personnel and hardware protection when required.
b. Inhibiting personnel access to the NSTX Test Cell (NTC) and cable spread room when the Safety Lockout Device (SLD) is in an unsafe position.
c. Controlling and monitoring personnel entry to the NTC to ensure personnel safety. The Safety System must ensure personnel safety before machine operation is permitted.
d. Providing a continuously available user interface which presents subsystem equipment permissive status, inter-system interlock status, SLD status, and access mode status.

The following access modes provide a foundation for operational interlocks that regulate personnel access to the NTC:

FREE ACCESS: Free Access imposes no restrictions on personnel entry to the NTC for safety reasons. This form of access may only take place when the SLD is in its safe position (vented) and RF and NB power systems are disarmed and disabled. Access is permitted to the NTC via badge reader.

NO ACCESS: No form of access is permitted to the NTC for safety reasons (e.g., during experimental operations). Prior to entering the NO ACCESS mode from FREE ACCESS, a "Free Access" key is removed from the door status panel at the north door. This step disables the north and south door badge readers simultaneously. A Search and Secure procedure is implemented to establish that no personnel remain in the NTC following Free Access, after which a search and secure key is used to set the NSTX Access Loop. A similar process of search and secure followed by the setting of an access control loop is used for the cable spread room.

HOT ACCESS: Hot Access permits personnel to be present in the NTC while equipment that may present a safety hazard to personnel is operational (e.g., field coils). This scenario is not a standard operating mode and is unlikely to be exercised. The formation of a plasma is prevented by precluding any combination of subsystems that could generate a plasma from being enabled. This mode requires turning a key in the Control Room to prevent simultaneous enabling of TF and PF power supplies, and locking personnel (who retain this key) in the NTC before pressurizing the SLD. The Hot Access key will be used in the NTC to prevent the Multi Pulsed Thompson Scattering (MPTS) laser from being enabled with its shutter open when the NTC Access Loop is set (except for Hot Access sessions for trained MPTS laser personnel). Hot Access is not allowed in the cable spread room.

Opening an NTC door will disable the Power Conversion Systems (Section 3.6.2), the HHFW System (Section 3.3.1), the MPTS laser (Section 3.5), the GDC system (Section 3.4.4), the ECH System (Section 3.3.3), and AC power for the NBI Accel power system and arc and filament power supplies (Section 3.3.4j). Global E-Stops to deenergize all NSTX-U Systems are provided inside the NTC at each exit door (2) and at several other key locations throughout the test cell, and in the Test Cell Basement (2 buttons located near the Waterfall bus work area). A break-glass key box located outside the north door provides emergency access to the NTC; breaking the glass will cause a global E-Stop and release a door key. Local systems E-Stops are discussed in previous sections of this SAD. Access to the Test Cell Basement (TCB), through which NSTX power cables pass mainly inside a fenced area, is controlled using an access card reader. The D-Site shift supervisor will authorize work in the TCB using administrative controls such as the D-Site Work Permit system and other Engineering and NSTX procedures. Authorized work will take precautions commensurate with the proximity to the power cable fenced area. A system of Kirk Keys is used to prevent access to the fenced area when the SLD is pressurized. Height, fencing, and warning signs are used to prevent access to NSTX power cables, which pass for a brief distance through the D-site Basement Mechanical Equipment Room.
The Safety System operates from an Uninterruptible power source to ensure continuous operation.

3.7.3 Control Room, Computer Room, and Cable Tray System

The NSTX Control Room provides a centralized location for researchers to direct and monitor the experimental operation of the NSTX-U device. A cable tray system is installed to economically and easily route power cables, signal cables, and fiber optic cables in the NSTX Test Cell and Gallery for Central I&C System use. The NSTX-U Computer Room provides a centralized location for I&C computers that provide application-specific functions.

3.7.4 Network System

The Network System interconnects the NSTX-U locations identified earlier in Section 3.7. The system can accommodate expansion to other areas when required. NSTX-U uses several PPPL Virtual Local Area Networks (VLAN): 1) Control Systems, 2) Diagnostics, and 3) Systems. Network access between individual VLAN is controlled through an Internal Firewall device (IFW) and the rules for inter-VLAN connectivity is managed by PPPL's Information Technology Department's Cyber-Security Division using approved PPPL policies and procedures.

The Control Systems VLAN is used for networked devices that can affect NSTX-U operations; for example, through control of power supplies, vacuum, water, and neutral beam subsystems. Network access to this VLAN is strictly controlled and minimized. The Diagnostics VLAN is the largest network on NSTX-U. This is suitable for equipment and devices that cannot directly affect NSTX-U operations. The Diagnostics network handles the bulk of NSTX-U data acquisition equipment. The computers on the Systems VLAN are generally used for post-shot data analysis.

Access in the NSTX Control Room to the PPPL networks is provided to support desktop computers, printers, display terminals, data transfer and inter-system communication, and to provide access to the ESnet and the Internet.

3.7.5 Plasma Control System

A multi-core real-time computer system is used to perform feedback control on plasma current, position and shape. Measurements consist of various magnetic diagnostics [plasma current (Ip) rogowski coils, flux loops, and B probes], suitably conditioned (vacuum vessel eddy current estimates are subtracted from the Ip rogowski measurement), along with the coil currents. Output signals are used to control the voltage applied by the power supply sytems to the coils. The development of the algorithms used by the plasma control system is one of the aims of the research program and will evolve with time. The real-time control system also controls gas injection and neutral beams.

3.7.6 Data Acquisition and Storage System

The Data Acquisition System gathers data for the plasma diagnostics set listed in Table 5 (Section 3.5). The Data Acquisition System interfaces with a data management structure to store, catalog, and secure experimental results for subsequent retrieval and analysis. System design facilitates access to archived NSTX-U data, as well as the control of diagnostic data acquisition systems, by parties outside of the NSTX-U control room (e.g., remote collaborators and physicists inside and outside of PPPL).

Multiple electrically isolated, general-purpose signal channels are provided between the NTC and the NSTX Control Room. These signals are displayed in the Control Room in real-time. A subset of these general-purpose signal channels are dedicated to coil system real time displays.

3.7.7 Synchronization System

The Synchronization System generates and distributes synchronous events (preprogrammed) to the NSTX-U subsystems. Synchronous events prescribe a predefined schedule of occurrences to be initiated at preselected times prior to, during, and after the operation of the experiment. The Synchronization System generates and distributes a shot number that is counted sequentially to uniquely identify each shot. In addition, the Synchronization System generates and distributes synchronized clock pulses to subsystems and the Central I&C System devices to initiate and execute time dependent processes by counting periodically generated clock pulses.

3.7.8 Power Supply Real Time Control System

The Power Supply Real Time Control (PSRTC) system acts on the power supply equipment at D-Site, and thereby provides control of the application of voltage to the NSTX coils either in direct response to commands from the NSTX Plasma Real Time Controller (PRTC), or as required to produce a programmable current through the coils via feedback control. In addition to controlling the interaction of the power supply equipment with the coils, the PSRTC provides control of the application of voltage and the delivery of current to the Coaxial Helicity Injection (CHI) system on NSTX-U.

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4.0 HAZARD ANALYSIS

Hazards associated with the operation of the NSTX Upgrade (NSTX-U) have been evaluated and potential impacts and their mitigation assessed. In addition, the risks posed by each hazard, both pre- and post- mitigation, have been determined based on the risk approach documented in Attachment 1 of PPPL Procedure ENG-032, "Work Planning Procedure", which is reproduced in Table 7 below. Risks are characterized as Standard, Serious or Major.

The NSTX-U hazards analysis is provided in the sections below and summarized in Table 6. A summary of maximum credible incidents is provided in Section 4.23. Implementation of the hazard mitigations described in this chapter, (and addressed in the individual facility and systems descriptions in Chapter 3) will maintain risks associated with the NSTX Upgrade Project at the Standard level defined in Table 7 (i.e., low potential impacts to environment, safety and health that are well within regulatory, DOE and PPPL limits and guidelines). Additional information on hazards associated with the D-Site Facility and their mitigation can be found in Sections 9.1 and 9.2 of Reference 3. These hazards have not changed as a result of the Upgrade to NSTX.

The levels of hazards analysis and risk evaluation in this Chapter are consistent with the safety analysis guidelines for Below Hazard Category 3 Facilities in DOE-STD-6003-96, "Safety of Magnetic Fusion Facilities: Guidance" (Reference 15, Section 5.5), which are applicable to NSTX-U.

Table 6 NSTX-U Hazards Analysis Summary

HAZARD	SECTION	SUMMARY
Ionizing Radiation	4.1	Mitigated by limiting annual D-D neutron generation rate, shielding, access controls, radiation monitoring and surveys, & procedures. Occupational exposures will comply with 10CFR835. Routine offsite exposures are expected to be <0.006 mrem/yr. "Worst case" tritium leak would cause maximum potential exposures of ~0.004 mrem to offsite individual and 28 mrem to worker. "Worst case" activated structural material release would cause maximum potential exposure of ~0.005 mrem to offsite individual.
Lithium	4.2	Mitigated by limiting lithium inventory in NTC, avoiding contact with moisture, keeping lithium sealed and under inert (argon) atmosphere whenever possible, availability of special Class D fire extinguishers, passivating lithium inside vacuum vessel before allowing worker entry, and PPE use. Potential accident scenarios would result in no serious damage to NSTX-U and no adverse consequences to workers, the public or the environment.

Deuterated Trimethylboron (dTMB)	4.3	Mitigated by limiting dTMB inventory in NTC, storage of dTMB in specially designed gas cabinet, component leak checking, use of leak detectors, double-jacketed delivery lines, access restrictions for untrained personnel during dTMB use, interlocks, and nitrogen purging of stack vent line to prevent flammable mixture development. Potential accidental dTMB release would not exceed TLV.
Electrical	4.4	Mitigated by equipment design & construction per national codes & standards and PPPL electrical safety program, controlling access to hazardous areas, electrical isolation of instruments in NTC, equipment enclosure in cabinets, use of JHAs, following of lockout/tagout requirements, use of GFCIs, & worker electrical safety training.
Fire	4.5	Mitigated by installed fire protection/suppression systems, fire dampers in HVAC ductwork, onsite trained fire fighters, local fire fighting capability via mutual aid, use of JHAs, wearing of fire retardant clothing when required, following Safety Manual provisions, and issuance of hot work permits.
Seismic	4.6	Mitigated by facility & equipment seismic design. PPPL is not located in a seismically active area.
Vacuum Windows	4.7	Mitigated by protective covers on all windows ≥4" diameter that are not covered by equipment (e.g., diagnostics).
Magnetic Fields	4.8	Mitigated by limiting access to areas where high fields are generated, and procedures.
Radiofrequency (RF) Fields	4.9	Mitigated by systems designed for low RF leakage levels, routine RF leakage checks against standards, interlocks to prevent RF transmission into occupied NTC.
Mechanical	4.10	Mitigated by access controls to NTC, use of hard hats where overhead work is taking place, and proper storage of gas cylinders.
Hot Fluids	4.11	Mitigated by fluid systems pressure tests, access controls to areas of hot components, warning signs, training.
Gases & Cryogenic Liquids	4.12	Mitigated by low inventories (potential releases to NTC would not create oxygen deficient atmosphere), presence of continuous oxygen monitors where needed, routine

		regeneration of neutral beam cryopanels to prevent possibility of explosive hydrogen-oxygen mixture formation, SF6 gas leakage detectors, proper system design and testing, use of PPE.
Laser	4.13	Mitigated by operation and control of Class IIIb & IV lasers under the PPPL Laser Safety Program (per ANSI Z136.1), using trained personnel operating under approved Laser Operating Permits and Laser Safe Operating Procedures.
Confined Spaces	4.14	Mitigated by PPPL confined space program, including mandatory confined space training and entry permits.
Material Handling	4.15	Mitigated by application of the PPPL Hoisting & Rigging Program and Engineering Standard, and the Engineering Standards for use of material handling vehicles (e.g., forklifts, manlifts, etc.).
Waste Handling	4.16	Mitigated by implementing PPPL procedures for hazardous and radioactive waste, and radiation protection.
Environmental	4.17	Mitigated as discussed under Ionizing Radiation (4.1) and Waste Handling (4.16).
Chemical	4.18	Mitigated by application of handling and training requirements of PPPL Safety Manual, prior safety review of proposed chemical purchases, and use of JHAs to identify specific control measures.
Elevated Work	4.19	Mitigated by use of JHAs, fall protection and fall arrest systems, and fall protection training.
Uneven Work Surfaces	4.20	Mitigated by installation of platforms and/or visibility markings as needed, and reviews of hazards and control measures at pre-job briefings.
Noise	4.21	Mitigated by noise measurements and evaluations by PPPL Industrial Hygiene, design of approaches to limit exposures, and use of PPE.
Ergonomic	4.22	Mitigated by approaches that can include use of work breaks, lifting aids & task redesigns as needed.

Table 7 Graded Approach for Risk and Requirements

Risk Type	Level 1. Major	Level 2. Serious	Level 3. Standard
Mission / Program Impact	Potential for failure to cause (1) Significant adverse impact (≥6 months) to completion of a PPPL Project or/collaboration, or to achieving key performance goals/milestones, or (2) Halt of operations for greater than six months (3) Failure to meet DOE or Presidential milestones.	Potential for failure to cause (1) Moderately adverse impact (3-6 months) to a PPPL Project/collaboration (2) Halting, delaying or significantly limiting operations for 1-6 months, or (3) Failure to meet FWP or PEP approved performance goals.	Potential for Minimal impact to a PPPL task, system, component or operations due to a failure.
Environment, Safety, Health and Security	Potential for failure to cause (1) Death, total disability or other severe adverse impact on the health or safety of a worker or the public, (2) Exposure/release to/of radiation or radioactive or hazardous material ≥ 50% of PPPL or regulatory limits, or (3) Environmental damage beyond site boundary or requiring cleanup costs greater than $250k.	Potential for failure to cause (1) Lost time injury or illness, (2) Exposure/release to/of radiation or radioactive or hazardous material <50% of PPPL or regulatory limits but ≥10% of those limits, or (3) On-site environmental damage requiring cleanup costs less than $250k but ≥$25k. (4) Threat to nuclear material (tritium); threat to sensitive equipment, parts and technology	Potential for failure to cause (1) Injury or illness not resulting in lost time, (2) Exposure/release to/of radiation or radioactive or hazardous material <10% of PPPL or regulatory limits, or (3) Negligible impact on the environment that can be mitigated completely at costs <$25k.
Cost (includes all costs – design, mfr, etc.)	Potential for failure to cause financial loss or damage to a facility or equipment of $1,000,000 or more.	Potential for failure to cause financial loss or damage to a facility or equipment of $250,000 -$1,000,000.	Potential for failure to cause financial loss or damage less than $250,000.
Compliance	Potential for inadvertent noncompliance with local, state or federal laws, regulations, contract requirements, or DOE requirements that result in fines or disciplinary actions or require emergency notification of a regulatory agency.	Potential for inadvertent noncompliance with regulations or administrative orders resulting in notification of regulatory agency (e.g., Notices of Violation/Deficiency) or requiring non-routine reporting to an agency.	Potential for minor noncompliance with established management practices, policies or procedures.

4.1 Ionizing Radiation Hazards

The radiological limits and design objectives adopted and approved by DOE for the NSTX-U Project, which are consistent with the requirements of 10CFR835 and DOE O458.1, are shown in Table 8. Radiological doses from NSTX-U operations in both normal and worst-case accident scenarios are shown in this section to be below these regulatory limits and design objectives, as summarized in this section..

Pre-mitigation risks to workers and public/environment are Major for workers and Standard for public/environment.

Table 8 NSTX-U Radiological Limits and Design Objectives

Condition		**P, Probability Of Occurrence In A Year**	**Public Exposure**		**Occupational Exposure**	
			Regulatory Limit (rem per yr)	**Design Objective (rem per yr)**	**Regulatory Limit (rem per yr)**	**Design Objective (rem per yr)**
Routine Operation	Normal Operations	P~1	0.1 total 0.01 airborne 0.004 drinking water	0.01 total	5	1
	Anticipated Events	$1>P\geq10^{-2}$	0.5 total (including normal operation)	0.05 per event		
Accidents	Unlikely Events	$10^{-2}>P\geq10^{-4}$	2.5	0.5	Emergency Exposure Situation: 5 to >25 depending on activity (property protection or lifesaving; see ESHD 5008, Section10.1302)	
	Extremely Unlikely Events	$10^{-4}>P\geq10^{-6}$	25	5		
	Incredible Events	$P<10^{-6}$	NA	NA		

4.1.1 Radiological Sources from NSTX-U Operations

Radiological hazards from NSTX-U operations derive from neutrons produced by the D-D reaction, which can lead to neutron exposure, activation of structural materials, activation of air/water, and tritium production. In addition, the second neutral beam has residual tritium contamination. Each of these sources is discussed below.

Neutron Production: Operation of NSTX-U is expected to increase ionizing radiation via enhanced neutron generation compared with pre-Upgrade operations. NSTX-U is estimated to generate up to 4.0 x 10^{18} D-D neutrons/yr based on the following projections.

NSTX Capability	Increase Neutrons Per Shot	Max Neutrons Per Shot	Max Neutrons Per Day	Estimated Total Neutrons Per Year	Max Neutron Rate [1/s]	Shots Per Day	Current [MA]	NBI Power [MW]	Pulse Length [s]
NSTX	N/A	4E+14	1.28E+16	8E+16	4E+14	32	1.2	6	1
NSTX-U	50	2E+16	4.8E+17	4E+18	4E+15	24	2	10	5

Neutron Activation of Structural Materials: The NSTX-U is constructed from materials that will be activated during operation. Stainless steel and copper components will most likely be the major materials subject to activation. Activation isotopes are listed in Table 1 of the NSTX-U Nuclear Facility Assessment (see Appendix 2). Like the neutron production, the activation level is expected to increase compared with pre-Upgrade operations assuming the maximum neutron production.

Neutron Activation of Air/Water: Neutron activation of air and water molecules can lead to production of Ar^{41} and tritium. In addition, the neutron interaction with lithium used during operation will lead to tritium production. Argon-41 is the product of reaction 40Ar(n,γ)41Ar, induced by secondary neutrons emitted from reaction 18O(p, n)18F. The natural concentration of Argon-40 in the air is 0.93 % (by volume). Argon-41 mainly emits β-particles with maximum energy 1198 keV and gamma rays of 1294 keV with 109.3 minutes half-life. The cross-section of neutron capture by 40Ar is 0.66 barn for thermal neutrons and quickly decreases with increase of neutron energy down to dozens of microbarns typically above 1MeV. The inventory of Ar^{41} from NTC air activation is based on previous calculations for the TFTR Test Cell that were made for the proposed Tokamak Physics Experiment (TPX), scaled as the ratio of the NTC-to-TFTR Test Cell volumes (0.38). During DT operations on TFTR (1993-97), an Argon-41 measurement (real time) program was implemented. After several weeks of DT operations, monitoring was stopped. It was determined that the Ar41 production was below the minimum detectable activity of the flow through intrinsic germanium detector used. Ar-41 production by NSTX-U is expected based on thermal neutron production, therefore grab samples of air during NSTX-U operations and calibrated gamma spectroscopy of the resulting samples will be made to measure actual concentrations of Ar-41.

Tritium is produced via thermal neutron capture by deuterium in airborne water vapor. This reaction has a small absorption cross section. Deuterium accounts for approximately 0.0156% (or on a mass basis: 0.0312%) of all the naturally occurring hydrogen in the oceans, while the most common isotope (hydrogen-1 or protium) accounts for more than 99.98%. Production of tritium from neutron capture in airborne moisture will be negligible.

Tritium Production in NSTX-U Torus: Entrainment inside the NSTX-U torus vacuum vessel of tritium produced by D-D reactions may cause a buildup of releasable tritium in the machine over time. The maximum production is calculated to be 0.193 Ci/yr (4.0 x 10^{18} D-D neutrons/yr x (1 Ci/3.7 x 10^{10} disintegrations per sec) x (ln 2/(12.33 years x 3.15 x 10^{7} sec per yr))). While most of the tritium produced should be vented to the stack by the Vacuum Pumping System (VPS), as much as 45% may be trapped in the torus (note that the routine dose calculation in Section 4.1.2 conservatively assumes that **all** tritium produced is vented to the stack). Assuming that this trapped tritium is not deliberately cleaned out of the torus, the maximum amount of tritium that could be held up in the torus after 10 years of NSTX-U operation assuming no decay could be 10 yr x 0.193 Ci/yr x 0.45 = 0.87 Ci. Tritium produced from lithium application activities may add up to an additional 0.87 Ci (i.e., 10 yr x 0.193 Ci/yr x 0.45) (see Section 3.4.3.4 for basis for tritium generation per year from lithium applications), for a total tritium holdup in the torus of 1.74 Ci over a 10-year operating period.

Residual Tritium Contamination: The NSTX-U Project included transfer of one of the four neutral beam injectors (NBIs) from the TFTR Test Cell to the NTC, and this NBI still has some tritium contamination. Small amounts of tritium from this source may be released at times to the Liquid Effluent Collection (LEC) tanks via condensation on NTC HVAC coils.

4.1.2 Radiological Impacts of Routine NSTX-U Operations

As indicated in Section 4.1.1, operation of NSTX-U is expected to increase ionizing radiation via enhanced neutron generation compared with pre-Upgrade operations. This will result in the generation of up to 4.0 x 10^{18} D-D neutrons/yr. NSTX-U operations will also result in some increased gamma radiation generation from plasma operations, increased activation of NSTX components and some tritium contamination of internal NSTX components, particularly the torus vacuum vessel interior. This increase in activation radionuclides and tritium generated by Upgrade Project operations was assessed by PPPL in 2009 with regard to the status of NSTX-U as a Below Hazard Category 3 Facility (Ref: Letter, A. Cohen to J. Makiel, 7/8/09). It was determined that based on the classification criteria of DOE-STD-1027-92 (Reference 16), NSTX-U would be designated a Below Hazard Category 3 Facility (4 x 10^{18} D-D neutrons/year corresponds to a maximum level of radionuclide isotope production that is approximately 30% of the relevant Category 3 nuclear facility inventory), and the requirements of 10CFR830 Subpart B would not be applicable. See the NSTX-U Nuclear Facility Assessment in Appendix 2 for more information.

Using the sources discussed in Section 4.1.1, estimates have been performed of the maximum expected individual offsite doses (at the PPPL site boundary) from NSTX-U operations. Assumptions used in this calculation are (Reference 6; see Appendix 2):

a. Negative pressure is not maintained in the NSTX Test Cell (NTC), therefore airborne radionuclide releases from this room (i.e., Ar^{41}) are assumed to be ground level releases. Exhaust gases from NSTX-U operations are released to the D-Site facility stack via the Vacuum Pumping System (VPS; see Section 3.4.1).

b. Production of Ar^{41} from NTC air activation by NSTX-U neutrons is based on previous calculations for the TFTR Test Cell that were made for the proposed Tokamak Physics Experiment (TPX), scaled as the ratio of the NTC-to-TFTR Test Cell volumes (0.38). No accounting is made for the effects of the non-borated NTC floor. Boration of the TFTR Test Cell center support plug and the first one-foot of the TFTR Test Cell floor may reduce Ar^{41} production in that room by absorption of thermalized neutrons. Not accounting for the absence of this effect in the NTC should not significantly alter the NSTX-U offsite dose projection because Ar^{41} contributes <10% of the total offsite dose.

c. Maximum offsite dose/Ci for airborne tritium and Ar^{41} are as noted in Reference 7, Table 1 (see Appendix 2, NSTX Dose Calculations, Table 1). Offsite dose/Ci for routine ground level releases (i.e., due to Ar^{41} releases from the NTC) are assumed to scale in the same manner as indicated in Reference 7, Table 1 for accidental releases (i.e., dose/Ci from ground level releases are about three times higher than dose/Ci from stack releases).

d. Tritium condensed on NTC HVAC coils is sent to the liquid effluent collection (LEC) tanks (see Section 3.1) for eventual discharge to the sanitary sewer system. The NSTX-U Project included transfer of one of the four neutral beam injectors (NBIs) from the TFTR Test Cell to the NTC, and this NBI still has some tritium contamination. Thus, the quantity of tritium released annually via this pathway is assumed to be one quarter of the maximum annual quantity of tritium discharged from the LEC tanks during the previous period of NSTX operation (2003-2009) following completion of the TFTR D&D Project and prior to decontamination work on the NSTX-U NBI. This maximum annual LEC tank release was 0.082 Ci, so the NSTX-U annual contribution would be 0.25 x 0.082 Ci, or about 0.021 Ci. Dose calculation for this pathway is as described in Section 8.2.3 of Reference 3 (see Appendix 2).

Worker Dose:

Worker dose from all sources of radiation produced from the operation of NSTX-U will be maintained ALARA and in compliance with PPPL's DOE DOELAP exemption for radiation dosimetry. Conditions of the DOELAP exemption require PPPL to maintain unplanned exposures below 100 mRem/year. Engineering and administrative programs will control worker dose.

1. Engineering controls include shielding, permanent and temporary when permitted. NSTX-U operations are controlled by a site wide access control procedure and safety interlock system. This system prohibits entry into radiation areas inside the NSTX-U Test Cell during operations. Additional shielding has been constructed outside the North doorway to NSTX-U. A shielded high bay and shielded labyrinth protects the south entrance to the NSTX-U test cell. Barriers to the immediate roof over NSTX-U will be in place during operations.
2. Administrative controls will be governed by PPPL Health Physics (HP) Division procedures, including (but not limited to):
    a. HP-OP-07; Radiation Safety Posting & Warning Indicators
    b. HP-OP-08; Access Requirements for Entry into Radiologically Controlled Area
    c. HP-OP-12; Radiological Work Permit Procedure

A defensible ALARA plan will provide additional support to administratively control worker dose. Prohibited access around the North, East and South adjacent walls of the NSTX-U Test Cell will be in place during operations until such time as the HP group can properly assess any potential radiological hazard due to the operation of NSTX-U. Monitoring will continue real time and access restrictions will be enforced or relaxed based on real data. During NSTX-U startup, HP will deploy area monitors capable of detecting environmental levels of neutron and gamma radiation on the east and north walls of the NTC, and the adjacent wall to the south high bay area. The dosimeters are passive and will be placed in a tight grid covering the walls to be used to evaluate potential streaming of neutrons or weaknesses in the shielding wall.

Public Dose:

The dose to the public will be maintained below the design objective of 10 mRem/yr in Table 8. Direct radiation will be monitored using real time neutron and gamma detectors situated at the D-Site boundary, and airborne and liquid tritium releases to the environment will be monitored as indicated in Chapter 8 of this SAD.

A summary of the contributions to the total offsite dose from routine NSTX-U operations is provided in Table 9.

Table 9 Dose Projections from Routine NSTX-U Operations

PATHWAY	ROUTINE ANNUAL RELEASE OR GENERATION	MAXIMUM PUBLIC DOSE
Airborne Tritium (HTO or T_2O) (without lithium use)	0.193 Ci/yr	5.02 x 10^{-4} mrem/yr
Liquid Tritium (HTO)	0.021 Ci/yr	4.20 x 10^{-4} mrem/yr
Activated Air (Ar^{41})	0.035 Ci/yr	4.24 x 10^{-4} mrem/yr
Direct/Scattered Neutron and Gamma Radiation	4.0 x 10^{18} D-D neutrons/yr	4.00 x 10^{-3} mrem/yr
		TOTAL = 5.35 x 10^{-3} mrem/yr

The total estimated maximum site boundary dose from routine NSTX-U operations is 5.35 x 10^{-3} mrem/yr, which is much less than the design objective of 10 mrem/yr (see Table 8). Tritium generated from lithium application activities (see Section 3.4.3.4) may be as much as an additional 0.193 Ci/yr. If all this tritium were released via the D-Site exhaust stack (rather than being partially entrained in the torus as discussed in Section 4.1.1, the estimated maximum incremental site boundary dose would be 5.02 x 10^{-4} mrem/yr and the total maximum annual offsite dose from routine operations would be 5.85 x 10^{-3} mrem/yr.

4.1.3 Radiological Impacts of Worst Case Accidental Releases from NSTX-U

Tritium: As discussed in Section 4.1.1 (under "Residual Tritium Contamination"), entrainment inside the NSTX-U torus vacuum vessel of tritium produced by D-D reactions may cause a buildup of tritium in the machine of up to 1.74 Ci over a 10-year operating period. Based on the results of deliberate air venting of the TFTR torus in 1995, about 15% of this inventory or 0.26 Ci could be released due to an NSTX-U torus leak (e.g., due to a vessel window break or other loss of vacuum event that pressurizes the vessel; see Appendix 1 FMEAs for WBS 1.2 & 1.3). If such a leak was too large to be pumped on to maintain negative pressure in the torus, this quantity of tritium could be released to the NSTX Test Cell (NTC) and subsequently to the environment. The maximum individual site boundary dose from the ground level release of 0.26 Ci of tritiated water vapor would be 0.26 Ci x 0.0157 mrem/Ci = 4.08 x 10^{-3} mrem, much less than the design objective in Table 8 of 50 mrem for this event (which based on information in Reference 3, would have an estimated probability of 3.7 x 10^{-2}/yr). Maximum worker exposure resulting from this release is calculated to be about 28 mrem (based on an 8 hour exposure to 0.26 Ci released to the NTC with no air exhaust), well within the requirements of Table 8.

Activated Structural Material: Direct exposure of the public to hazardous levels of neutron-activated materials is not considered a risk. All activated material will be under constant control by administrative and engineering controls and not available as sources of exposure to the public. It is possible that a quantity of activated material could become mobilized during a magnet arc to the NSTX-U torus vacuum vessel. The presence of coil protection systems (e.g., the DCPS described in Section 3.6.3), which would detect and isolate faults in the magnet systems, and the grounding of coil cases and structures, makes the occurrence of this event very unlikely. Using conservative assumptions on the details of such an arc (two 35-V arcs, one to the vacuum vessel and a return arc from the vessel, having a duration of about 40s) and its deposited energy that were made for the TFTR D-T operations safety analysis (Reference 17, Appendix C; see Appendix 2), an estimated 1.1 kg of activated structural material could be vaporized in such an event. According to the analysis of this event in Reference 17, isotope Mn-56 would be the dominant contributor to potential offsite (site boundary) dose, representing 88.2% of the total exposure. Using the maximum NSTX-U Mn-56 activity produced from 4 x 10^{18} neutrons as indicated in the NSTX-U Nuclear Facility Assessment in Appendix 2 (694 Ci), the total mass on which this activity is based per the Nuclear Facility Assessment (130,000 lb or 58,967 kg), the fraction of Mn-56 contribution to the total dose (0.882) and the ground level dose conversion factor for Mn-56 reported in Reference 17 Table C-1 (0.128 mrem/Ci x 2.8), the worst case site boundary dose from ground level release of activated structural material from NSTX-U would be:

(694 Ci x (1.1kg/58967 kg) x 0.128 mrem/Ci x 2.8) x (1/0.882) = 5.26 x 10^{-3} mrem

This dose is much less than any of the accident exposure design objectives in Table 8. Note that this calculation conservatively assumes that none of the volatilized structural material is captured on filters or plates out on surfaces in the NTC.

4.1.4 Mitigations (design features, engineered controls, administrative controls)

Design Features

Mitigation will include the following: the NSTX Test Cell (NTC) walls, floor and roof are constructed of reinforced concrete with thicknesses ranging from 2 ft (floor) to 5.5 ft (roof high point), along with a separate 2 ft thick concrete-filled block wall outside the NTC north door, which provides shielding (whose effectiveness will be evaluated against the relevant design objectives in 10CFR835.1002 and the public exposure criteria in Table 8).

Administrative Controls

Personnel occupancy of the NTC will be excluded by the NSTX Safety System described in Section 3.7.2, and other areas deemed necessary by the PPPL Health Physics Division will be controlled by engineered and/or administrative means (based on evaluation of exposure levels in areas external to the NTC) during plasma operation and neutral beam conditioning.

The Health Physics Division will regularly monitor and survey NSTX radiation and contamination levels and needed radiological controls and/or supplemental shielding will be provided as needed to protect potentially exposed workers and the public in accordance with PPPL policies and procedures (including the DOE approved PPPL Radiation Protection Program and the PPPL Safety Manual, ESHD 5008 Section 10) and Table 8.

Radiation monitoring of potentially exposed NSTX workers will continue, and monitoring of tritium releases to the environment (air and water) will continue to ensure low impacts and compliance with 10CFR835, DOE O458.1 and PPPL Safety Manual (ESHD 5008) requirements.

Workers entering and performing work in the NTC and other radiologically controlled areas will be radiation safety trained, and required to comply with relevant Radiation Work Permits (RWPs) prepared by the Health Physics Division for access and specific work activities.

Application of these methods of mitigation will ensure that post-mitigation risks to workers and public/environment are Standard.

4.2 Lithium Hazards

Density control experiments conducted during NSTX-U operations will use deposition of thin lithium films on plasma facing components to reduce fuel gas recycling and impurity influx. This work, depending on the experimental requirements, uses one or more of the following systems: Lithium Evaporator (LITER) and Lithium Granule Centrifugal Injector. The total maximum active elemental lithium inventory in the NTC during an experimental campaign will not exceed 2000g. See Section 3.4.3 for details.

Lithium hazards include fire or explosion hazards due to the high reactivity of lithium, and health hazards due to the corrosive and toxic nature of some stable end products of lithium reactions. Pre-mitigation risk to workers is Major. Mitigation will be via procedural safety precautions that include: avoiding lithium contact with sources of moisture, conducting fabrication and transport of pellet material under an argon atmosphere, receipt and disposal of lithium material in sealed containers, presence of special Class D (LITH-X) fire extinguishers during lithium loading activities and transport to the NTC, venting (to allow lithium to be "passivated", i.e., reacted in a controlled fashion with moist air) and cleaning of the vacuum vessel prior to allowing worker entry after lithium experiments, and performing work activities using proper personal protective equipment (PPE). In particular, for Lithium Evaporator (LITER) activities, the safety precautions include: keeping the lithium and the LITER loading area (C-Site Lab Bldg, Room C-128, D-Site TFTR Test Cell or the D-Site NSTX South High Bay) dry; presence of Lith-X fire extinguishers in C-128, TFTR Test Cell or NSTX South High Bay, and during transport of the loaded LITER to the NTC; direct handling of the lithium in an argon atmosphere glove box in C-128; receipt of the lithium in C-128 in sealed containers from the manufacturer; removal of unneeded material in sealed containers by the PPPL Environmental Services Waste Management Group; preventing exposure of the lithium to atmospheres with >50% relative humidity; use of oxygen monitors in C-128 to check oxygen levels prior to full entry into C-128 when argon gas is flowing; and transport of the LITER to the NTC over well-defined low traffic routes. Post-mitigation risk to workers is Standard.

Several potential accident scenarios associated with lithium use are described in the following sections. In all scenarios, there would be no serious damage to NSTX-U and no adverse consequences to workers, the public or the environment. As an additional precautionary measure, an Argon Purge System has been designed and installed to suppress a potential fire inside the torus vacuum vessel in the very unlikely event that LITER is in operation, lithium is released into the torus uncontrollably, and there is a catastrophic air leak into the torus. Under these conditions, the Argon Purge System would release argon gas into the vacuum vessel to prevent fire development (see Section 3.4.3.1).

4.2.1 Potential Energy Release with LITER and Lithium Granule Centrifugal Injector Operation During Accidental Vents

An accidental vent (e.g., due to a vessel window break or other loss of vacuum event that pressurizes the vessel; see Appendix 1 FMEAs for WBS 1.2 & 1.3) during NSTX-U maintenance will involve in-rushing air with a humidity of at least 40%. If a total of 2000 g or 288.2 moles (2000g/6.94 moles/g = 288.2 moles) is injected during the Experimental Campaign, and if this amount has not yet reacted with the residual partial pressures of the vacuum (predominantly H_2O), then it will react with the moisture of the in-rushing air to form Lithium Hydroxide (LiOH), and give off heat. The Li reaction rate for the production of LiOH in air is very fast (~19 g/m2-s)[27] which for 40 m2 of NSTX plasma facing surface would complete the Li + H2O to LiOH + H + Heat (508 kJ/mole) reaction in about 2.6s ([2000g/40m2]/19g/m2-s). This Li reaction would yield 146.4 MJ (508 kJ/mole x 288.2mole). There is about 1.3 x 10^3 kg of graphite in NSTX with a specific heat of about 0.17 cal/g/°K (0.71 J/g/°K). Hence, if the 2000 g of Li were distributed uniformly over the graphite surface, the resulting heat release would raise the graphite temperature by about 158.6°K (146.4x106J/[(0.71J/g/°K)x(1.3x106g)]). Therefore, the resultant graphite temperature undergoes only a relatively benign change, that is far below the burning temperature of graphite in air (>650°C under special conditions). In addition, the hydrogen given off by this reaction is 1 mole of H per mole of Li , which would yield 288.2 moles of H, or 288.2g. If burned, this amount of H would release 36.0MJ (288.2g x 1.25x102 kJ/g). This additional energy is smaller than the Li OH reaction heat yield of 146.4 MJ discussed above. If the sole source of hydrogen was the slower Li reaction, 2Li +H2O -> Li2O + H2, then 1 mole of 2Li would yield 1 mole of H2. Hence, 2000g of Li (288.2mole) gives 144.1 mole of 2Li which yields 144.1moles of H2 or 288.2g

(144.1 mole x 2g/mole). If burned, this amount of H2 would release 36.0 MJ (288.2g x 1.25 x102 kJ/g. Similarly, this energy is smaller than the LiOH reaction heat of 146.4MJ discussed above, and would tend to reduce the amount of lithium available for this reaction branch.

An accidental vent during plasma operations can occur with the LITER and Lithium Granule Centrifugal Injector under two possible conditions. The first exists if all of the lithium in the LITER ovens is liquefied, but still inside the LITER ovens. Under these conditions the lithium in the Lithium Granule Centrifugal Injector would remain at room temperature in stabilized solid form. Assume that the lithium in the oven starts reacting due to the air that is introduced through the oven snout. In this case, the surface area exposed to the lithium is about the cross section of the oven, or 0.002 m2. At a reaction rate of ~19 g/m2-s, this translates into 0.04 g/s, or 3 kJ/s (508 kJ/mole x 0.0058 mole/s). The oven consists of about 320 g of stainless steel with a specific heat of approximately 0.1 cal/g/°K (0.42 J/g/°K). This means that the oven temperature will rise 22 °K in one second (3x103 J/[(0.42J/g/°K)x(320g)]). In the worst case, the starting temperature of the oven is 923 °K (650 °C). The melting point of stainless steel is 1700 °K so, it will take 35 seconds ([1700 °K – 932 °K]/22 °K/s) for the oven to reach this temperature, assuming that a protective skin of the LiOH and Li2O reaction products did not inhibit and gradually stop the reaction.

If the oven fails structurally, assume that 80 g of liquid lithium would fall on about 0.01 m2 of the graphite PFC. In that case, the lithium will turn into lithium hydroxide at a rate of ~0.2 g/s (~19 g/m2-s x 0.01 m2), or liberate about 14 kJ/s (508 kJ/mole x 0.028 mole/s). This is equivalent to 1.4 MW/m2 ([14 kJ/s]/0.01 m2). Since the PFCs are designed to handle much higher power densities (e.g., the outer divertor is designed for 17 MW/m2 power density depositions during neutral beam and RF operations), the worst case scenario of the loss of structural integrity of the oven would not damage NSTX-U.

The preceding analysis is extremely conservative, in that it assumes the entire lithium inventory to be present in the oven and available for reacting with the atmospheric H_2O at the time of the accidental vent. It neglects the restricted flow path for the air to the small space above the lithium in the oven, and this geometry severely limits lithium reaction rate. Furthermore, it ignores any heat dissipation by the air surrounding the LITER or the PFCs should the lithium get there.

The second condition that could exist if an accidental vent occurs during plasma operations is when all of the lithium has been deposited from LITER and the Lithium Granule Centrifugal Injector on to the plasma-facing components (PFC's) in NSTX-U. This will involve a mixing of the deuterium fuel gas with the in-rushing air. The 288.2g of H2 from the Li +H2O reaction would dilute the D2 fuel gas pressure (~$1x10^{-4}$ Torr) by a factor of $14.4x10^4$ (i. e., $8.6x10^{25}$ molecules of H2 diluting a typical discharge particle content of 6 $x10^{20}$). The primary effect is thus the reaction of the lithium with the atmospheric H2O, so this case is not substantially different than that described under an accidental vent during maintenance. It is thus not a concern from the point of potential energy release and heating of the plasma facing components (PFC's).

The above scenario of the entire 2000g of lithium participating in an energy releasing event following a vent is suitable for worse-case estimates, but in practice is very conservative and physically unrealistic, since the lithium is deposited gradually over a 12-18 week experimental campaign, and as this deposition progresses, the fresh lithium reacts with the residual partial pressures of the NSTX vacuum chamber (H2O, CO, CO2), and becomes passivated, and unavailable for the heat-release processes described above.

4.2.2 Lithium Hydride Formation During LITER and Lithium Granule Centrifugal Injector

The case where the least amount of lithium hydride (LiH or lithium deuteride, LiD) is formed is if there is a planned or accidental vent with the initial fill of 160 g of lithium (80g in each LITER oven). In that case, the maximum amount of lithium that could react with the deuterium is 0.08 g on each evaporator interior exposed surface. This translates into a concentration of 0.008 mg/ m3 in the NSTX Test Cell, which is well below the Occupational Safety & Health Administration (OSHA) Permissible Exposure Limit (PEL) of 0.025 mg/m3. Even this is very unlikely, due to the very low vapor pressure of LiD (Reference 8).

The greatest amount of lithium hydride (or lithium deuteride, LiD) exposure would occur if there is a planned or accidental vent when all 2000g of the planned LITER and Lithium Granule Centrifugal Injector lithium inventory coats the PFC's. If a total of 2000 g is injected during the Experimental Campaign, and if this amount is not converted to LiOH by the residual H2O partial pressures of the vacuum (the dominant component), and if this

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amount is all converted to LiD by interaction with the fuel gas, and if all of this LiD is released into the volume of the 9.43 x10^3 m3 Test Cell, as if it were an inert dust and not highly reactive with moist air, the resulting concentration would be 273 mg/m3 (2000g Li/6.94g/mol = 288.18 moles. This combines with 288.18 moles of D, yielding 288.18 x 2 =576.37 g of D. The combined weight of the Li + D forming the LiD is 2000g +576.36 g = 2576.36 g, hence the NTC concentration would be 2576.36 g /9.43x10^3 m3 = 0.273 g/m3). Lithium hydride has an extremely low vapor pressure, so the typical aerosol fraction is conservatively estimated at 3% (Reference 8). This gives a value of 8.2 mg/m3, which is above both the recommended OSHA PEL of 0.025 mg/m3 and the 0.5 mg/m3 National Institute of Occupational Safety (NIOSH) Immediately Dangerous to Life and Health (IDLH) limit. However, this hypothetical treatment of LiD as an inert dust is a very conservative approach which neglects the high reaction rate of LiD with the moist air to form LiOH. This resulting LiOH concentration is discussed below, after the below analysis of the property line release for these hypothetical LiD concentrations.

Lithium hydride has very, very low vapor pressure, so it is expected that only trace quantities of LiH would become aerosol. Lithium hydride has exhibited such behavior in the past. Large quantities of LiH were fabricated for use as a neutron radiation shielding material for spacecraft. The accounts of the National Aeronautics and Space Administration (NASA) work to mix molten lithium at over 700°C with hydrogen gas to produce LiH in furnaces did not reveal any concern over aerosols. The hydride forms a crystalline solid. The NASA furnace production demonstrated that LiH, reaction products stayed in the crust formed in the reaction zone rather than becoming airborne (Reference 9). Using maximum stack and ground release X/Q concentration values measured by the National Oceanic and Atmospheric Administration by tracer gas tests at PPPL (Reference 10), calculations of the site chemical concentrations show little hazard. The assumed worst case is a total lithium reaction with hydrogen yielding a 3% LiH mass release as respirable particles over an hour, no particulate filtration, and both stack venting and ground release venting. The 3% release fraction was taken from the low end of the LiOH production; this is a very conservative assumption when LiH aerosol itself is not expected and a 1% release fraction is often assumed. For those conditions, the stacked plume concentration is less than 0.049 mg/m3, which is well below the Emergency Planning Response Guide (ERPG)-1 value for this extremely unlikely event (Reference 11). The ground release concentration is less than 0.1 mg/m3, which is above the ERPG-1 value [0.025 mg/m3]. However, as noted above, this approach is extremely conservative, since it assumes that all 2000 g of lithium inventory has not been converted to lithium hydroxide (LiOH) by the residual partial vacuum pressure (mostly H2O) and the humidity of the in-rushing air. In addition, given the prompt rate of conversion of lithium hydride to lithium hydroxide discussed below, this greatly reduces the amount available for the ground release concentration. Therefore, even total reaction of 2000 g [2000g for the maximum vessel unreacted inventory] of lithium with the contents of the hydrogen gas cylinder would not produce notable concentrations of hazardous materials at the site boundary due to the small mobilization fraction and atmospheric dispersion. If filtration is operational, the release would be even further reduced.[30]

As noted above, assuming a 3% aerosol fraction (Reference 8), a value of 8.2mg/m3 (0.03 x 2576.3 g / 9.43x10^3 m3) for LiD in particulate form is obtained. This is above both the 0.5 mg/m3 IDLH limit and the recommended OSHA PEL of 0.025 mg/m3. Suppose that only the amount of LiD available and needed to escape from the vacuum vessel to reach the PEL level in the NSTX Test Cell actually escapes; this amount is about 7.8 g ([0.025 mg/m3 x 9.43x103m3]/0.03). The time required for the LiD to reach this level after a planned or accidental vent can be estimated as follows. Assume a reaction rate for the formation of lithium hydroxide from lithium hydride and H_2O that is half of the formation rate of lithium hydride from hydrogen and lithium, or ~0.9 g/m2-s ([~1.9 g/m2-s]/2) (Reference 8). This is because a mole of diatomic hydrogen reacts with two moles of lithium to form lithium hydride, while one mole of H_2O reacts with one mole of lithium hydride to form lithium hydroxide. Given the in-vessel PFC surface area of 40 m2 and a 40% H_2O concentration in air, it takes ~0.5 s (7.8g/[~0.9 g/m2-s]x[40 m2]x[0.4]) for 7.8 g PEL level amount of LiD level to fall below the PEL. However, if prior to an accidental vent, the entire inventory of 2000 g of lithium (288.2 mole) had been converted to LiD (288.2 mole) or 2576.36 g ([288.2mole]x[8.94g/mole]), and if the escape of this LiD from the vessel continued beyond 7.8g until the entire inventory of LiD was released into the Test Cell, it would take 178.9s (2576.36g/[~0.9 g/m2-s]x[40 m2]x[0.4]) for this inventory to be converted to lithium hydroxide and fall below the PEL (and, in addition would be unavailable for transport to the property line or ground release). This is a conservative estimate, furthermore, in that it does not account for the adhesion of the LiD to the PFC's, the known penetration of the lithium ("intercalation") into the graphite tiles, or as noted above, the considerably more efficient production of lithium hydroxide from lithium

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hydride and atmospheric H_2O, and also the restricted flow out of the vessel during a planned or accidental vent. These further limit the lithium hydride that can enter the atmosphere in the NSTX Test Cell, so its formation during the LITER operation should not pose a health risk.

Airborne lithium hydroxide (from Li and LiD reactions with moist air) will slowly react with atmospheric CO2 (0.031% of air by volume) to form Li2CO3. After a 3% aerosol particulate fraction of LiD or 8.65moles (0.03 x 2576.36g/ 8.94g/mole) is converted to 8.65 moles of LiOH or 206.6 g (8.65moles x 23.9g/ mole), and neglecting its subsequent slow reaction with atmospheric CO2, and any removal from the NTC by the 3x per hour air circulation and the associated filtering with 0.3 micron HEPA filters, the NTC concentration would be 21.9 mg/m3 (206.6g /9.43 x103 m3). The American Conference of Governmental Industrial Hygienists (ACGIH), the National Institute of Occupational Safety (NIOSH), and the Occupational and Safety Health Administration (OSHA) have no published limits for lithium hydroxide or carbonate. However, the American Industrial Hygiene Association (AIHA) has a Workplace Environmental Exposure Limit (WEEL) for lithium hydroxide of 1 mg/m3 as LiOH (one minute time weighted average (TWA) ceiling) equivalent to 1.75 mg/m3 as LiOH-HOH. Hence, under the above assumptions the lithium hydroxide level of 21.9 mg/m3 exceeds only the AIHA WEEL of 1 mg/m3. In the case of an accidental vent due to a failed vacuum window during an NTC access period, a much smaller aerosol particulate level would result since the LiOH diffusion out of the vessel to the NTC would be restricted by the relatively small vessel window ports, and which would reduce the above estimated NTC concentration by a factor of 10-100x below the above estimated 21.9 mg/m3. Hence, the real concentration would likely be much below the WEEL concentration of 1 mg/m3. In addition, during plasma operations, the ~15 minutes required to de-energize and secure the NTC for personnel entry would further reduce particulate concentrations due to the NTC 3x per hour air recirculation. This entrance time can be easily lengthened for additional NTC air-change time, if ever required for larger amounts of lithium inventory. During controlled vents with moist air, personnel are present in the NTC but the vessel remains sealed for at least 3 days to allow conversion of any residual lithium to carbonate. Once the vessel is opened, fans draw air from the vessel through High Efficiency Particulate Air (HEPA) filters into the NTC. However, as an added safety capability, during vessel venting, a permanently installed "elephant trunk" hose draws air from the vessel directly to the D-Site exhaust stack, thereby eliminating emission of lithium compounds into the NTC. In addition, a small humidifier is positioned at the vessel air input for several days prior to the initial personnel entrance to increase the humidity of the venting air and accelerate the reaction of lithium compounds with water.

4.3 Deuterated Trimethylboron (dTMB) Hazards

The injection of deuterated Trimethylboron (dTMB) into NSTX-U, in a process called boronization, is intended to provide a hard, insulating coating of boron and carbon (as well as deuterium) to enhance the operational capability of NSTX-U. dTMB is toxic (7ppm Threshold Limit Value (TLV), based upon the TLV of the reaction product B_2O_3) and pyrophoric in air (low limit 0.5%). Pre-mitigation risk to workers is Major.

Mitigation includes low dTMB inventory (no more than 50 grams of dTMB is permitted in the NTC at any time), placement of the dTMB gas cylinders in a sealed gas cabinet specially designed for toxic gas storage and delivery, prior leak checking of components that will be dTMB pressurized above 1 atmosphere, use of portable leak detectors, use of double jacketed dTMB delivery lines with a secondary line backfilled with helium, limiting NTC access during boronization to only dTMB trained personnel, interlocks that halt dTMB injection on various system upsets and loss of glow discharge current, and nitrogen purging of the stack vent line during dTMB injection to prevent air-dTMB mixture formation in the line. The 50-gram inventory limits the total amount of this material to a small quantity that presents a slight increase in the flammable material inventory (less than 5% of the typical deuterium inventory in the room). This quantity of gas, if released into the NTC, when well mixed, would not present a level (approximately 2 PPM) in excess of the TLV. This excludes credit for fresh air introduction by the NTC Heating, Ventilation and Air Conditioning (HVAC) System. Post-mitigation risk to workers is Standard.

4.4 Electrical Hazards

High voltage electrical equipment is present in the NSTX Test Cell (NTC) and other areas associated with NSTX-U (e.g., Field Coil Power Conversion Building, Neutral Beam Power Conversion Building, Motor Generator

Building). Most of this equipment, particularly external to the NTC, is in enclosed cabinets, but shock, burn and/or arc flash hazards are present particularly under faulted conditions. Hazards are enhanced when work is being done on or near electrical equipment. Pre-mitigation risks to workers are Major.

Mitigation for maintenance periods and outages between runs will include use of Job Hazard Analyses (JHAs) per PPPL Procedure ESH-004 to assess specific hazards and control measures, following of lockout/tagout procedures per PPPL Procedure ESH-016, adherence to electrical safety provisions of ESHD 5008 Section 2 (Electrical Safety) and installation procedures (which apply requirements of NFPA 70 and 70E), use of ground fault circuit interrupters (GFCI) extension cords for power tool connections, and electrical safety training of workers per ESHD 5008 Section 2 Chapter 3.

Mitigation for operations will include selection of electrical equipment and the design and construction of electrical distribution systems in compliance with national codes and standards wherever possible, controlling access to hazardous areas via the NSTX-U Safety System (Hardwired Interlock System and Safety Lockout Device) as described in Section 3.7.2, and isolating all instrumentation via optical and/or magnetic (magnetic transformer) means prior to exiting the NTC boundary to prevent electrical hazards from being transmitted outside the NTC boundary.

Post-mitigation risks to workers are Standard.

4.5 Fire Hazards

Fire hazards (particularly during maintenance periods and outages between runs) include hot work activities that involve welding, plasma torch cutting, grinding and brazing. During operations, fire risk also includes electrical faults, use of solvents for cleaning, use of pyrophoric deuterated Trimethylboron (dTMB) for boronization (see Section 4.3), and use of lithium that can react with moisture when unpassivated (see Section 4.2). Pre-mitigation risks to the facility and workers are Major.

Mitigation includes the NTC fire detection system (see Section 3.1), which consists of ionization smoke detectors and rate of rise heat detectors located at the ceiling and aspirated smoke detection (VESDA) under the platforms. NTC fire suppression is a pre-action type automatic water sprinkler system similarly located. Also, fire dampers (with heat sensitive links) are included in HVAC ductwork where it penetrates the NTC wall. In addition, PPPL has trained fire fighters onsite 24/7, and has mutual aid agreements with the local community that provides additional fire fighting capability. Mitigation for hot work will include use of job hazards analyses (JHAs), use of fire retardant clothing, and following provisions of ESHD 5008 Section 9 Chapter 15 on Welding, Cutting and Other Hot Work (including issuance of hot work permits). Mitigation for dTMB use includes use of procedures, low inventory of dTMB (≤50 g in the NTC), gas cabinet storage of dTMB, and use of leak detectors. Mitigation for lithium includes transport in sealed containers under argon atmosphere, venting (for lithium passivation) and cleaning of the vacuum vessel interior prior to worker entry, and presence of Class D (Lith-X) fire extinguishers during lithium handling activities. Post-mitigation risks to workers are Standard.

4.6 Seismic Hazards

PPPL is not located in a seismically active area. In the unlikely event of a serious earthquake, principle hazards include damage to buildings and/or structures, and harm to workers from falling objects. Pre-mitigation risks to the facility and workers are Major.

Mitigation includes the following: the NTC, along with the rest of the D-Site experimental complex structures, has been determined to have adequate capacity to remain functional under the overall loads due to an earthquake with a horizontal ground acceleration of 0.13g. The NSTX-U torus structure was designed to satisfy the Department of Energy (DOE) standard for natural phenomena hazard (NPH) events (Reference 4). Only the effects of earthquakes are considered for the NSTX torus structure. The DOE standard required the use of Performance Categories (PC) to specify the relative risk, environmental impact, importance, and cost of each facility. The assessment for seismic loading and evaluation for seismic response was followed to determine that the design of the structure is acceptable with respect to the performance goals (Reference 5). On this basis the seismic performance goal for the NSTX torus structure is to maintain worker safety, placing it in NPH Performance Category 1 (PC-1). Any structures, systems & components (SSCs) whose failure would adversely affect the performance of the NSTX torus structure or create a threat to worker safety are also placed in PC-1. All other systems are placed in PC-0 and thus have no seismic design requirements. For the PPPL Site, a PC-1 earthquake has a maximum horizontal ground acceleration of 0.09g.

The NSTX-U platforms are designed for 0.09g, the seismic requirements of the NSTX torus structure. Equipment associated with NSTX-U are designed and built consistent with these requirements. Post-mitigation risks to the facility and workers are Standard.

4.7 Vacuum Window Hazards

Vacuum windows in the torus vacuum vessel are a potential hazard to personnel as well as to equipment. If a window fails there may be flying debris. If the opening is large enough, an individual may be drawn to, or into, the opening, potentially causing injury. Pre-mitigation risk to workers during operations from uncovered windows is Major. Mitigation is provided by protective covers on all windows that are 4 inches or more in diameter per ESHD 5008 Section 9 Chapter 14 (Vacuum Windows). Post-mitigation risks to the facility and workers are Standard.

4.8 Magnetic Field Hazards

During NSTX-U operations, magnetic field hazards may exist from the mechanical forces (or interference) exerted by the magnetic field upon ferromagnetic tools and medical implants (e.g., cardiac pacemakers). Adverse effects may also be produced from forces upon implanted devices such as suture staples, aneurysm clips, and prostheses. In addition, touching ungrounded objects that have acquired an induced electrical charge can result in electrical shocks. Pre-mitigation risk to workers is Serious.

Mitigation is provided by preventing personnel from entering the NTC during plasma operations via the NSTX-U Safety System (Hardwired Interlock System and Safety Lockout Device). During the unlikely need for a hot access (access while coils are energized but plasma formation is prevented), the magnetic field strength that personnel are exposed to will be controlled (i.e., via procedures prepared as part of the deliberate process that would be required for any hot access work) so as not to exceed the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value for routine occupational exposure, consistent with the requirements of ESHD 5008, Section 4 (RF/Microwave/Magnetic/Non-Ionizing Radiation). Post-mitigation risks to workers are Standard.

4.9 Radiofrequency (RF) Field Hazards

At sufficiently high intensities, exposure to RF fields can produce a variety of adverse health effects. Such effects include cataracts of the eye, overloading of the thermoregulatory response, thermal injury, altered behavioral patterns, convulsions, and decreased endurance. Pre-mitigation risk to workers is Major.

Mitigation includes designs of RF systems with leakage levels that comply with IEEE Standard C95.1-1991 (outside the NSTX Test Cell), and these systems are routinely checked for leakage (per ESHD 5008, Section 4; see Section 3.3). Switches are provided to isolate HHFW power from the NTC. These switches are interlocked with the NTC access control system. Both electrical and mechanical (Kirk Key) interlocks are provided. Whenever personnel must enter the NTC, an emergency stop (E-Stop) is sent to all HHFW sources if any switch is not in the safe (dummy load) position. Local (dummy load) operation of RF sources can be performed during NTC access provided that all of the switches are locked in the safe position. This ensures that the NTC transmission lines are disconnected from the RF sources and that the source outputs are terminated in dummy loads.

Switches are provided to isolate 480V AC power from the ECH System in the NTC, and these switches are interlocked with the NTC access control system.

Exposures to RF fields will not exceed the limits in ESHD 5008 Section 4. Post-mitigation risks to workers are Standard.

4.10 Mechanical Hazards

Hazards include magnetically propelled projectiles, arc splatter due to magnet or electrical bus failures, objects falling and hitting workers, and gas cylinder projectiles caused by sudden cylinder valve failure (e.g., due to falling of the cylinder and breakage of the valve). Pre-mitigation risks to workers are Major.

Mitigation during operations is provided by preventing personnel from entering the NTC during plasma operations via the NSTX-U Safety System (Hardwired Interlock System and Safety Lockout Device) described in Section 3.7.2. During the unlikely need for a hot access into the NTC, personnel are required to stay in a protective enclosure to protect against magnetically propelled projectiles or possible arc splatter that may attend an electrical bus failure. Workers in areas where overhead work is taking place are required to wear hard hats. Gas cylinders are stored/installed in accordance with PPPL safety procedures (ESHD 5008 Section 9 Chapter 2, Compressed Gas Cylinder Safety) to prevent breaking the cylinder valves, which could propel the cylinders due to a rapid release of gas. Post-mitigation risks to workers are Standard.

4.11 Hot Fluids Hazards

The NSTX-U uses a Low Temperature Bakeout Heating/Cooling System, which is run with water at temperatures up to 150°C, and a High Temperature Bakeout Heating/Cooling System, which uses pressurized helium at temperatures up to 420°C, to bakeout gases from the torus and plasma facing components (High Temperature System requires 420°C supply temperature to maintain the required 350°C at the plasma facing components). Hazards include burns due to contact with high temperature fluids or system components, and potential for injuries from contact with released pressurized helium (due to system leakage). Pre-mitigation risks to workers are Major.

Mitigation for operations includes the following: the Low Temperature Bakeout Heating/Cooling System was hydrostatically tested to at least 1.5 times its operating pressure prior to operations. The High Temperature Bakeout Heating/Cooling System was pneumatically tested to 1.3 times its operating pressure prior to operations. Procedures for operating these systems require precautions to be taken to prevent personnel contact with hot surfaces, including restricting access to areas where hot pipe or components are present, posting of warning signs, and personnel training. Post-mitigation risks to workers are Standard.

4.12 Gases and Cryogenic Liquids Hazards

Gases used during NSTX-U operations include standard gases such as nitrogen, argon and helium, and specialized gases such as deuterium, sulfur hexafluoride (SF6) and deuterated Trimethylboron (dTMB). Cryogens used for cooling of neutral beam cryopanels include liquid nitrogen and liquid helium. All of these were used for years during NSTX operations and will continue to be used for NSTX-U. Hazards include asphyxiation (due to gas and cryogen releases), development of potentially explosive mixtures of hydrogen (or deuterium) and air in a Neutral Beam Injector (NBI) vacuum vessel or the torus vacuum vessel or the D-site facility exhaust stack, worker health effects from exposure to dTMB and dTMB's pyrophoricity in air, and "burn-type" injuries from contact with cold cryogenic liquids. Cryogens will be warmed up and pumped out, SF6 will be removed back to gas cylinders outside the NTC, and dTMB bottles will be stored outside the NTC when not in use for operations (see Section 4.3 for more information on dTMB hazards and their mitigation). Pre-mitigation risk to workers is Major.

Mitigation during operations is as follows:

The content of the largest gas cylinder (311 cubic ft.) constitutes less than 0.1% of the volume of the NTC (approximately 330,000 cubic ft.). Thus, oxygen concentrations in the NTC would remain at safe levels for personnel even if a gas cylinder's entire contents were released to the room. Even for a major leak of helium from the High Temperature Bakeout Heating/Cooling System (HTS), the inventory of helium (equivalent to 3 bottles of compressed helium @ 311 cu ft/cylinder, or less than 0.3% of the NTC volume) is not sufficient to cause dangerous low oxygen conditions in the NTC.

By administrative procedures, the maximum allowable amount of condensed hydrogen (or deuterium) build-up on the cryopanels for each neutral beamline is limited to 13 Torr, and the Neutral Beam Injector (NBI) PLC control sequence includes nitrogen purge before and after pumping gases liberated from both routine and emergency cryopanel regenerations. These actions prevent the formation of potentially explosive mixtures of hydrogen and oxygen in the NBI vacuum vessel and D-site facility exhaust stack. The risk of a deuterium explosion in the torus vacuum vessel is mitigated by engineering controls that include configurations which allow only one bottle of deuterium to be connected to a gas delivery system, multiple valves in series between the gas bottle and vessel, and interlocks that close the gas delivery torus interface valve on vessel pressure excursions.

Since SF6 is heavier than air and can displace oxygen, leakage of the gas could be hazardous to personnel occupying an enclosed area below the leak point. Personnel protection is provided by strategic location of SF6 detection (close to floor level) in the NTC (and elsewhere; see Section 9.1.7.2 of Reference 3) to provide local evacuation alarms. Systems and components handling SF6 (which is used as an electrical insulator in high voltage systems such as the neutral beam injectors) have been carefully examined for leakage potential and fittings tightened to reduce leakage of this greenhouse gas to the environment to the extent possible.

Cryogenic system subsections which may be isolated by valves or other means are provided with pressure relief devices. Appropriate personal protective equipment (PPE) is used by personnel engaged in handling cryogenic fluids. Pressure relief devices have been installed to preclude rupture of sections of the system by excessive internal pressure. All piping has been designed for maximum operating pressure and tested in accordance with applicable ANSI codes. Only materials suitable for cryogenic service are used if in contact with cryogenic fluids or subject to cryogenic temperatures. Consequently, severe rupture of cryogenic system lines are highly unlikely. Assuming a catastrophic failure of a neutral beamline (NBL) released the entire contents of its liquid helium dewar (700 liters), liquid helium panels and piping (50 liters), and liquid nitrogen panels and piping (147 liters), a total of 22,040 cubic ft of gas would be released to the NTC. Assuming no active ventilation (and no other means of exhausting the evolved gas), and that only oxygen is displaced in the 333,017 cubic ft NTC, the concentration of oxygen in the NTC would drop from 20.9% to 19.5%, which is not considered oxygen deficient (per ESHD 5008 Section 8 Chapter 5, Confined Spaces). However, the operation of cryogenic system pressure detection, closure of system valving to isolate affected areas, presence of burst discs to relieve pressure, and the operation of NBL vacuum pumping systems to exhaust gas leaking into the beam box to the stack would be expected to prevent large scale releases to the NTC. Portions of the Cryogenics systems are situated in the Cryogenics Compressor Room located adjacent to the NSTX-U Gallery, and in the Neutral Beam Power Conversion (NBPC) Building Penthouse. These areas have continuously operating oxygen monitors that will warn personnel in the spaces and those about to enter the spaces of low oxygen levels.

Post-mitigation risk to workers is Standard.

4.13 Laser Hazards

Several NSTX-U diagnostics use high energy Class IIIb and Class IV lasers. Lasers emit intense, coherent, electromagnetic radiation that is potentially dangerous to the eye and skin. Other hazards associated with lasers include electrical, fire, and chemical hazards. Pre-mitigation risk to workers for operations is Serious.

All Class IIIb and IV lasers are operated and controlled under the Laboratory's Laser Safety Program, which is documented in ESHD 5008 Section 3 (Laser Safety) and is based on ANSI Z136.1 (American National Standard For the Safe Use of Lasers). High energy laser diagnostics systems are operated by trained personnel under Laser Operating Permits and Laser Safe Operating Procedures (LSOPs) approved by the PPPL Laser Safety Officer. LSOPs specify protective measures to prevent laser exposures to personnel, and to isolate hazards during operation, maintenance and testing. Entry to the NTC during Multi Pulsed Thomson Scattering (MPTS) diagnostic laser operations (which includes a Class IV YAG laser system) are performed only under carefully controlled hot access conditions, as described previously. Post-mitigation risk to workers is Standard.

4.14 Confined Space Hazards

Entry to the torus vacuum vessel and neutral beam enclosures, which are confined spaces, will be required during some maintenance and outage activities. Hazards of entry to confined spaces include but are not limited to exposure to hazardous atmospheres, difficulty leaving the space (particularly in an emergency), and exposure to high voltage. Pre-mitigation risks to workers are Major.

Mitigation is achieved through adherence to the PPPL confined space entry requirements outlined in ESHD 5008 Section 8 Chapter 5. These include mandatory confined space entry training for entrants, obtaining a confined space entry permit from the PPPL Safety Division and following its steps prior to and during entry to a permit-required confined space, and designation of a safety watch outside the space. Post-mitigation risks to workers are Standard.

4.15 Material Handling Hazards (Crane & Rigging Operations)

Material handling via cranes and rigging equipment will occur during operations (i.e., maintenance periods and outages between runs). Hazards during these activities range from minor injuries and/or minor property damage, to fatalities and/or major property losses. Pre-mitigation risks to workers and the facility are Major.

Mitigation is achieved through application of the PPPL Hoisting and Rigging Program documented in PPPL procedure ENG-021, and the PPPL Hoisting and Rigging Standard (ES-MECH-007). ENG-021 describes the responsibilities and authorities for mechanical hoisting operation where rigging is required on the PPPL site. The Standard describes the requirements for mechanical hoisting operation, lift equipment inspection testing and maintenance, training and qualification for operating/using any lift equipment and procurement of rigging equipment or services. Only qualified crane operators may operate cranes at PPPL and only qualified riggers may perform rigging. Additionally, PPPL Engineering Standards for safe operation, inspection, testing, maintenance, procurement and training associated with the use of forklifts, powered industrial trucks, manlifts, and special purpose vehicles & equipment will be applied to material handling activities. Post-mitigation risks to workers and the facility are Standard.

4.16 Waste Handling Hazards

Hazardous and low-level radioactive waste may be generated during NSTX-U operations. Small amounts of tritium contaminated pump oil (< 0.001 Ci per year) are anticipated to be produced during NSTX-U operations. Hazards include potential exposures of workers to radiation, radioactive or hazardous chemical substances during handling activities; loss of control of material; and inadvertent transfer of waste to inappropriate locations or disposal facilities. Pre-mitigation risks due to the potential for regulatory non-compliances are Major; risks to workers, the public and environment are standard.

Mitigation is achieved through implementation of the PPPL hazardous and radioactive waste procedures documented in Laboratory procedure EWM-001 (Hazardous Waste Management), policies and procedures for control of radioactive material documented in ESHD 5008 Section 10 (Radiation Safety) and PPPL Health Physics Division procedures, and waste management and handling procedures of the PPPL Environmental Services Division. All radioactive or hazardous wastes will be disposed at approved offsite facilities. Post-mitigation risks are Standard.

4.17 Environmental Hazards

Environmental hazards for NSTX-U are discussed under Ionizing Radiation Hazards (Section 4.1) and Waste Handling Hazards (Section 4.16) above. A categorical exclusion (CX) under the DOE NEPA rule (10CFR1021) was determined and documented for NSTX-U on 3/31/09. Environmental risks are Standard.

4.18 Chemical Hazards

In addition to chemicals described in previous sections, NSTX-U activities will involve use of cleaning solvents (e.g., alcohol), hydrogen peroxide (3%), ozone, cutting fluids, cable pulling lubricants, Windex, Citro-clean, vinegar and distilled water. Hazards of chemical use are indicated on the Material Safety Data Sheets (MSDSs) and Safety

Data Sheets (SDSs) for each chemical, which are required to be obtained by and available for each user per ESHD 5008 Section 8 Chapter 13 (ES&H Review of Procurements). Pre-mitigation risks vary from Standard to Major depending on the specific chemical.

Mitigation includes the following: the safe handling and storage of chemicals must follow the safety requirements in ESHD 5008 Section 8 Chapters 1 (Chemicals) and 12 (Hazard Communication), and all chemical users must be trained per the requirements of Chapter 12. In addition, all chemicals purchased for use at PPPL must have a safety review by an Industrial Hygienist per ESHD 5008 Section 8 Chapter 13 (ES&H Review of Procurements). Specific control measures for chemical use for NSTX-U are indicated on the Job Hazard Analysis (JHA) for each task, and are reviewed by workers during the pre-job briefings. Post-mitigation risks are Standard.

4.19 Elevated Work (Fall Hazards)

Fall hazards due to elevated work (including work from ladders, aerial lifts and scaffolds) will be present during operations (i.e., maintenance periods and outages between runs). Potential consequences range up to serious injuries and fatalities. Pre-mitigation risks are Major.

Mitigation includes using personal fall arrest systems when working on equipment (e.g., top of the torus vacuum vessel) and on aerial boom lifts, installation of guardrail systems whenever possible, and using workers trained on ladder, scaffold, and aerial lift safety requirements of ESHD 5008 Section 9 Chapters 5 (Portable Ladders, Platforms, and Scaffolds) and 8 (Forklifts, Work Platforms, and Special Purpose Vehicles and Equipment Requirements). All personnel who will be performing elevated work requiring the use of personal fall arrest systems will also receive fall protection training per ESHD 5008 Section 9 Chapter 16 (Fall Protection). Fall hazards and the associated control measures, as with all other pertinent job hazards, are indicated on the Job Hazard Analysis (JHA) for each task and are reviewed by workers during the pre-job briefings. Post-mitigation risks are Standard.

4.20 Hazards of Uneven Work Surfaces

Uneven work surfaces, which may be encountered by workers in the torus vacuum vessel, on or in a neutral beamline, or elsewhere can cause slips, trips and falls whose consequences range from minor injuries to fatalities. Pre-mitigation risks are Major.

Mitigation will include installation of platforms to provide an even surface for workers whenever possible (e.g., inside the torus vacuum vessel), marking of uneven surfaces to increase visibility when practical, and reviews of this hazard when pertinent and its mitigation at pre-job briefings. Post-mitigation risks are Standard.

4.21 Noise Hazards

Noise at high levels can cause hearing loss, interference with communication, and annoyance. Noise hazards may be present from use of loud tools. Pre-mitigation risks are Serious.

Mitigation for any potential exposures to high noise levels will include measurements and evaluations of noise levels by PPPL Industrial Hygiene; coordination among Industrial Hygiene, Occupational Medicine, workers and their supervisors to determine and implement the best approaches to mitigate exposures; and use of personal protective equipment (e.g., ear plugs or muffs) when necessary. The requirements of ESHD 5008 Section 8 Chapter 8 (Noise Control and Hearing Conservation) will be followed. Post-mitigation risks are Standard.

4.22 Ergonomic Hazards

NSTX-U tasks requiring repetitive motions, lifting and awkward positions can cause musculoskeletal injuries that can result in lost time from work. Pre-mitigation risks are Serious.

Mitigation includes work breaks, lifting aids, and redesign of tasks (where possible) to minimize ergonomic hazards. Guidance for safe manual lifting is included in ESHD 5008 Section 9 Chapter 4 (Manual Lifting). The Job Hazard

Analysis form calls out ergonomics as a potential hazard to be considered in job planning, and contacting PPPL Industrial Hygiene for consultation is a control measure to be considered when this hazard applies. Post-mitigation risks are Standard.

4.23 Summary of Maximum Credible Incidents (see Sections 4.1.3, 4.2.1, 4.2.2, 4.3, & 4.12)

Radiological: An NSTX-U torus leak (e.g., due to a vessel window break or other loss of vacuum event that pressurizes the vessel) that is too large to be pumped on to maintain negative pressure in the torus could release up to 0.26 Ci of tritium to the NTC and the environment. The maximum individual site boundary dose would be 4.08 x 10^{-3} mrem, and the maximum worker exposure could be 28 mrem.

A magnet arc to the NSTX-U torus vacuum vessel could vaporize an estimated 1.1 kg of activated structural material. If this material were to be released to the environment, the maximum individual site boundary dose (mostly due to Mn-56) would be 5.26 x 10^{-3} mrem.

These potential exposures are much less than the NSTX-U Radiological Limits and Design Objectives in Table 8.

Lithium: An accidental torus vent (e.g., due to a vessel window break or other loss of vacuum event that pressurizes the vessel) occurs with the maximum amount of 2000 g of unreacted lithium in the vessel. Assuming this quantity of lithium reacts with the moisture of the in-rushing air to form Lithium Hydroxide (LiOH) and heat, the PFC graphite temperature would rise about 158.6°K. The resultant graphite temperature would be far below the burning temperature of graphite in air (>650°C), and there would be no serious damage to NSTX-U. Possible hazardous reaction products (LiH, LiD, and LiOH) generated by 2000 g of lithium reacting with fusion fuel gases and released in an accidental torus vent would not produce notable concentrations of hazardous materials at the site boundary, and would not be expected to pose a health risk to workers.

Deuterated Trimethylboron (dTMB): A release of the maximum allowable inventory of dTMB to the NTC would result in a concentration of about 2 ppm, which is less than the 7 ppm Threshold Limit Value (TLV) based upon the TLV of the reaction product B_2O_3.

Gases: In the event of a major leak of helium from the High Temperature Bakeout Heating/Cooling System (HTS) (equivalent to 3 bottles of compressed helium @ 311 cu ft/cylinder, or less than 0.3% of the NTC volume), oxygen concentrations in the NTC would remain at safe levels.

Cryogens: In the event of a catastrophic failure of a neutral beamline (NBL) that released the entire contents of its liquid helium dewar (700 liters), liquid helium panels and piping (50 liters), and liquid nitrogen panels and piping (147 liters), the concentration of oxygen in the NTC would drop from 20.9% to 19.5%, which is not considered oxygen deficient.

5.0 SAFETY ENVELOPE

PPPL uses procedure ESH-025 (Operations Hazard Classification Criteria and Safety Certification System) as part of its implementation of the Integrated Safety Management (ISM) Guiding Principle for Operations Authorization of experimental projects. The culmination of the NSTX-U Operations Hazard Criteria and Safety Certification process is the issuance by the PPPL ES&H Executive Board of a Safety Certificate based on recommendations from the NSTX-U Activity Certification Committee (ACC). The Safety Certificate constitutes PPPL approval to conduct NSTX-U operation within the constraints indicated therein, and is based on the defined Safety Envelope for NSTX-U operations, as documented in this Chapter. The Safety Envelope is based on the hazards analysis in this SAD (Chapter 4). A copy of the Certificate is posted prominently in a location visible to the operations personnel (in the NSTX-U Control Room).

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Any proposed changes to NSTX-U facilities, hardware or operations that could impact the Safety Envelope or Safety Certificate must be reviewed by the ACC. The ACC will report to the PPPL ES&H Executive Board (ES&H/EB) on the findings of its reviews, which will include a recommendation on a revision to the previous NSTX-U Safety Certificate that would authorize NSTX-U operations with the proposed changes, including any relevant conditions or limitations on those operations.

The NSTX-U Safety Envelope, which is the basis for the conditions and limitations in the Safety Certificate authorizing NSTX-U operations, constitutes the provisions that must be satisfied to permit NSTX-U plasma operations. The Safety Envelope includes the following:

1. All activities must be performed in accordance with approved Laboratory and NSTX-U Project procedures, the PPPL Safety Manual (ESHD 5008), and the NSTX-U safety analysis documented in the approved Safety Assessment Document (SAD).

2. The criteria of procedure OP-NSTX-02 (Integrated Systems Test Procedure) must be satisfied.

3. Maximum neutron generation rate from plasma operations is 4×10^{18} D-D neutrons/year, which corresponds to a maximum level of radionuclide isotope production that is approximately 30% of the relevant Category 3 nuclear facility inventory per DOE-STD-1027-92 (Reference 16). Relevant controls (including those associated with radiation monitoring and control) include:

(a) Detectors for measuring NSTX-U generated neutrons must be verified daily as working and taking data, and the neutron fluence-integration software system must be in use during operations, both in accordance with procedure OP-NSTX-015, NSTX-U HPP Daily Operations.

(b) The neutron detection system must be calibrated at least every three years in accordance with procedure D-NSTX-IP-3190, Ring Neutron Source Calibration of NSTX Fission Detector System.

(c) The NSTX-U Access Control System must be operable and tested annually in accordance with procedures OP-AD-117, Operation of the NSTX Access System, OP-NSTX-05, Testing the NSTX Hardwired Interlock System, OP-NSTX-08, Testing the NSTX Emergency Stop System, OP-NSTX-09, Safety Lockout Device Test Procedure.

(d) Search and secure of the NSTX-U Test Cell (NTC) must be conducted each time the NTC is closed prior to operating NSTX-U in accordance with procedure OP-NSTX-014, NSTX Operations Guide for Startup and Shutdown.

(e) Radiation shielding for neutron and gamma radiation generated by NSTX-U will be under configuration control in accordance with procedure ENG-032, Work Planning Procedure.

(f) Occupational radiation safety controls must be in place in accordance with the approved Radiation Protection Program (RPP).

(g) Neutron and gamma radiation monitors at the D-Site boundary must be operational in accordance with procedure HP-OP-49, Radiation Safety Routine Monitoring in Radiologically Controlled Areas.

4. Operation of the Bakeout Systems may be performed with helium and water to heat the plasma facing components (PFCs) to temperatures up to 350°C and the torus vacuum vessel to temperatures up to 150°C. Relevant controls include:

(a) The Bakeout Systems have been commissioned and must be operated in accordance with procedure OP-G-156, NSTX Integrated Machine Bake-out Operations.

5. Boronization with deuterated Trimethylboron (dTMB) may be performed with no more than 50 grams of dTMB at risk in the NSTX-U Test Cell at any time. Relevant controls include:

(a) The Boronization System has been commissioned in accordance with procedure PTP-dTMB-001, Pre-Operationa Testing of the deuterated Trimethylboron (dTMB) System.

(b) The Boronization System must be operated in accordance with procedures OP-G-155, TMB Cylinder Changeout Only, and OP-G-178, TMB GDC Operation Only.

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6. The total maximum active elemental lithium inventory in the NSTX-U Test Cell during an experimental campaign will not exceed 2000g. Relevant controls include:

(a) The Lithium Deposition Systems have been commissioned in accordance with procedure ISTP-278, NSTX Liter Integrated System Test Procedure.

(b) The Lithium Deposition Systems must be operated in accordance with procedure OP-VAC-762, NSTX Liter Operating Procedure.

6.0 NSTX-U OPERATIONS

NSTX-U generally alternates between maintenance periods and operations periods. There is typically, but not always, a single operations period, or run campaign, during each fiscal year.

During maintenance periods, typically lasting 6-8 months, a number of significant activities occur both within the NSTX-U test cell (NTC) and in the supporting areas. The first activity in the NTC is often a recalibration of the plasma diagnostics utilized during the previous run campaign. This ensures that the data is of high quality, suitable for publication. This calibration phase is followed by maintenance activities on the core NSTX-U device, along with any construction activities. Activities such as modifications to the vacuum chamber or internal structures would be accomplished then. Installation of major new diagnostics or heating and current drive systems would also occur during this phase. Maintenance and upgrades on systems outside of the NTC occur in parallel.

Once major construction activities are complete towards the end of the maintenance outage, the NSTX-U device is prepared for the next run campaign. As a first step, the plasma diagnostics are recalibrated in order to ensure their availability for the run campaign. This is followed by a final cleaning of the vessel interior, followed by a documentation of the in-vessel conditions and an initial pump-down; this sequence of events is generally referred to a “clean, photo, close”. This is followed by an extensive leak-check of the NSTX-U vessel. Finally, a special calibration of the Multi-Pulse Thomson Scattering system (MPTS) is completed, to enable measurements of the plasma density and electron temperature once the research campaign begins. This involves backfilling the vessel with a gas such as argon or nitrogen, and collecting laser light scattered off that background gas.

In parallel with these activities, preoperational test procedures (PTPs) are executed on all of the sub-systems required to operate NSTX-U. A non-exhaustive list of systems receiving PTPs includes the motor-generator (MG) sets, the rectifier systems in the Field Coil Power Conversion (FCPC) building, the emergency stop systems, the neutral beam power systems and controls, the gas injection system, and the digital coil protection system (DCPS). Initial conditioning of the neutral beam sources begins at this time. All of these procedures are coordinated and governed through the use of an operations procedure with system level hold points and sign-offs to approve progressing to the next stage of start up.

When these activities are complete, the final preparation for the run begins. A high-temperature bake-out of the graphite tiles within the NSTX-U vessel is completed. This bakeout, which reaches 350°C, is accomplished by 1) resistive heating of the center column, and 2) hot helium flow in the outer divertors and passive plates. This bakeout phase typically takes approximately 3 weeks to complete. Final conditioning of the neutral beam sources typically occurs during this time.

Once the bake-out is complete, the integrated system test procedure (ISTP) for NSTX-U operations is completed. This procedure demonstrates that the coil protection systems are fully functional. It runs single coil current pulses at various levels, challenging the protection systems, followed by combined field pulses. When the ISTP is complete, the facility is ready for experimental plasma operations.

The research operations phase is managed by the execution of two different procedure types. An experimental machine procedure (XMP) is used to commission a piece of hardware, plasma control algorithm, or diagnostic; the collection of publishable scientific data is not the immediate goal of these procedures. An experimental procedure (XP) is designed for the collection of scientific data for analysis and publication. These procedures are written by the cognizant scientist, reviewed through the topical science group (TSG) organization and NSTX-U Project organization, and given final review by the head of NSTX-U experimental research operations.

The first activity of the run campaign is typically an XMP designed to restore plasma operations. This activity usually requires 1-3 weeks. This is followed by XPs and XMPs, each of which typically requires 0.5-1.5 days to complete. Operations are usually based on a three-week on, one-week off basis, where the off weeks, known as maintenance weeks, are used for facility maintenance and system upgrades during the run. This pattern is repeated in order to accomplish typically 12-18 total weeks of plasma operations.

6.1 Operating Organization

Control of equipment and system status will be exercised using the chain-of-command documented in procedure OP-AD-56, Control of Equipment and System Status. During operations of various systems the D-Site Shift Supervisor will approve and coordinate activities of the Chief Operating Engineers involved in the operation of NSTX-U. During periods of NSTX-U maintenance, repairs and installations, the D-site Shift Supervisor will approve and coordinate activities of the Construction Manager(s) which impact facility equipment.

The PPPL Head, Engineering and Infrastructure, or designee, as the D-Site Manager, directs D-Site facility operations and control of equipment and system status via the D-Site/NSTX-U Operations Manager in accordance with directives of PPPL procedures. The D-Site Manager is responsible for the configuration of the D-Site facility (including NSTX-U), and the maintenance of drawings and other documentation related thereto, and is the Responsible Line Manager (RLM) for D-Site.

The NSTX-U Operations Manager, appointed by the D-Site Manager, is responsible for:

- directing and coordinating NSTX-U operations and control of equipment and system status, with equipment safety and protection of the health and safety of personnel and the public receiving the highest priority;
- acting as the Accountable Technical Individual (ATI) for the overall coordination and conduct of NSTX-U activities;
- ensuring that meetings are held for the purpose of scheduling work to be performed on NSTX-U equipment, systems, and support systems;
- control and documentation of the configuration of equipment within the NSTX-U Test Cell; and
- determination of operating procedures and operating limits related to safe operation of the NSTX device in support of the NSTX experimental program.

The responsibilities of the D-Site Shift Supervisors include:

- coordinating the activities of operations, construction, radiological protection, maintenance/repair, installations, instrumentation and control, and security groups to accomplish the objectives for the shift;
- informing the NSTX-U Operations Manager of any abnormal system conditions or safety concerns;
- ensuring that shift activities are conducted in accordance with procedures;
- ensuring deficiencies are identified and corrective actions are initiated;
- ensuring that emergency operating procedures are correctly implemented when needed; and
- authorizing the removal of equipment and systems from service for maintenance, testing, or operational activities, and authorizing their return to service following maintenance, testing, or operational activities that require non-standard configurations.

The NSTX-U Chief Operating Engineers (COEs) are responsible for:

- directing the activities associated with the operation of NSTX-U such as machine and subsystem operations including power systems, heating systems and instrumentation/control based on direction from the D-Site Shift Supervisor and the NSTX-U Operations Manager;

- keeping the D-Site Shift Supervisor and the NSTX-U Operations Manager informed of the status of systems and equipment under their responsibility; and

- informing the D-Site Shift Supervisor of any out of limit/abnormal system conditions or ES&H concerns, including those associated with the NSTX-U Safety Envelope and Safety Certificate.

Additional details on the NSTX-U operations organization and chain of command can be found in procedure OP-AD-56.

6.2 Assurance Processes

PPPL uses procedure ESH-025 ("Operations Hazard Classification Criteria and Safety Certification System") as part of its implementation of the Integrated Safety Management (ISM) Guiding Principle for Operations Authorization of experimental projects. The approval process to commence NSTX-U operations and to make future changes to NSTX-U equipment and operational parameters will follow the applicable provisions of ESH-025 and PPPL's Work Planning Procedure (ENG-032). These will include completion of work planning forms, peer and design reviews, reviews and approvals of new procedures, processing of Unreviewed Safety Issue Determinations (USIDs) including any relevant changes to this SAD, and NSTX Activity Certification Committee (ACC) review of new equipment and operational parameters that have implications for the NSTX-U Safety Envelope (see Chapter 5 of this SAD) or the Safety Certificate which authorizes NSTX-U operations. The members of the NSTX ACC include both PPPL and DOE Princeton Site Office (PSO) personnel that have been appointed by the PPPL ES&H Executive Board (ES&H/EB), which consists of senior Laboratory managers and is chaired by the PPPL Deputy Director for Operations. The ACC reports to the PPPL ES&H Executive Board (ES&H/EB) on the findings of its safety reviews, which will include a recommendation on a revision to the previous NSTX Safety Certificate that would authorize NSTX-U operations (and subsequent changes to operations), and any relevant conditions or limitations on those operations. The ACC will be maintained as a standing committee for the lifetime of NSTX-U operations. Any future changes to NSTX-U facilities, hardware or operations that could impact the Safety Envelope or Safety Certificate will be reviewed by the ACC, who will recommend to the PPPL ES&H/EB regarding revising the Safety Certificate to authorize NSTX-U operations with the proposed changes.

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During maintenance and outage periods, PPPL Safety Division representatives will periodically inspect the work site to determine that sufficient safety practices and equipment are in use. PPPL Health Physics Division representatives will provide support as needed for any radiological activities. When a new task is begun, a pre-job briefing will be held to discuss procedures and the associated Job Hazard Analyses (JHAs). PPPL supervisors (and non-supervisory volunteers) have been trained in the principles and procedures of the DuPont Safety Training Observation Program (STOP) to observe work activities and engage workers in conversations to reinforce safe work practices, and to find the reasons for and correct unsafe behaviors.

Occupational injuries and illnesses will be reported to the Laboratory Occupational Medicine Office, and will be subsequently investigated by the PPPL Safety Division and other relevant personnel for lessons learned (per ESHD 5008 Section 9 Chapter 10, "Accident Investigation", and PPPL procedure GEN-006, "Investigation and Follow-up of Adverse Events and Conditions"). Safety conditions in NSTX-U areas will also be periodically reviewed during Management Safety Walkthroughs per PPPL Policy P-084 ("Management Safety Walkthroughs"), and line management reviews per PPPL Organization Document O-027 ("Line Management Safety Organization").

7.0 QUALITY ASSURANCE

7.1 Program Description

Princeton University is the prime management and operating contractor for the U.S. Department of Energy (DOE) at Princeton Plasma Physics Laboratory under Contract No. DE-AC02-09CH11466, and is committed to implementing plans, processes, and procedures that institutionalize the DOE Quality Management System (QMS) requirements defined in DOE Order 414.1D, *Quality Assurance.* This order requires that appropriate consensus standards be used, whole or in part, for activities undertaken on behalf of DOE, consistent with regulatory requirements and Secretarial Officer direction. The PPPL Quality Assurance program is modeled after the Part 1 Requirements from ASME NQA-1 – 2008, Quality Assurance Requirements for Nuclear Facility Applications, tailored for the risks present at PPPL. With respect to research, Princeton Plasma Physics Laboratory combines the concepts and requirements of DOE O 414.1D with the guidance provided in ANSI/ASQ Z 1.13-1999, *Quality Systems Guide for Research*.

Princeton Plasma Physics Laboratory is committed to developing, implementing, and maintaining a formal quality management system. This is achieved through the PPPL Institutional Quality Assurance Program (QAP) (EQP-004). This plan describes the integration of quality functions into all aspects of PPPL activities and is mandatory for all PPPL organizations. It follows the Contractor Requirements Document in DOE O414.1D, including suspect/counterfeit item prevention. NSTX-U does not use safety software.

Quality assurance refers to those actions that provide confidence that the items, services, or processes provided meet or exceed requirements and expectations. The PPPL QAP defines the management controls by which its quality assurance (QA) program will meet DOE O 414.1D, *Quality Assurance*, and DOE P 450.4A, *Integrated Safety Management Policy*. This plan sets forth the methods, controls, and processes and defines the responsibilities and lines of communication for assuring that the desired quality is achieved at the NSTX-U.

Specific requirements of the QAP are to be applied to all tasks at the NSTX-U using a graded approach. The stringency with which the requirement of the QAP is applied will be commensurate with the risk of occurrence of undesirable outcomes with respect to health and safety, the environment, property, and resources, as well as the NSTX-U vision and goals. NSTX-U Management ensures that necessary and appropriate resources and capabilities are provided to maintain compliance with the requirements of this document.

Quality achievement is a continuing responsibility of the line organization at all levels of operations. Each individual, including subcontractors, is responsible for achieving quality in his or her own work.

With respect to research, PPPL combines the concepts and requirements of DOE O 414.1D with the guidance provided in ANSI Z1.13-1999, American National Standard Quality Systems Guidelines for Research, including hiring the most qualified personnel and using peer reviews to continually assess PPPL projects or activities.

The effectiveness of this QAP is best determined via the achievement and improvement of quality. This is partially assessed via the Management Assessment Program and the Independent Assessment Program but is primarily assessed via the actual scientific results safely produced by NSTX-U.

7.2 Design Reviews/Design Verification and Validation

A graded approach is used for design verifications based on design complexity and importance to safety. Design validation is accomplished using one or more of the following methods: design reviews, calculation checks including alternate calculations, control of drawings, and qualification testing. These processes are governed by the following PPPL Procedures: ENG-007, “Reliability, Availability, and Maintainability (RAM) Modeling and Apportionment”; ENG-008, “Failure Modes and Effects Analysis”; ENG-010, “Control of Drawings, Software, and Firmware”; ENG-029, “Technical Definitions & Acronyms”; ENG-030, “PPPL Technical Procedures”; ENG-032, “Work Planning Procedure”; and ENG-033 “Design Verification”.

Adequacy of design output is verified prior to release for use. Modifications are fed back to the designer in an iterative process until the design is acceptable. These evaluations are performed by qualified individuals or groups other than those who performed the work and individuals or groups knowledgeable in the application of the design and capable of performing similar design activities.

Design control processes ensure that design input requirements are correctly translated into drawings and specification. Design input/output alignment is an integral part of the design verification process performed during various phases of the design to ensure that the applicable requirements are properly incorporated.

7.3 Environment, Safety and Health Reviews

During the design and development of the engineered technical components and the conventional facilities, due consideration is given to environmental, safety, and health requirements and compliance with applicable codes and standards. Assurance of compliance of standard “off the shelf” items is requested from the vendor. An environmental, safety, and health review of specialty items is required if specific relevant design criteria are not included in the product design specifications.

7.4 Testing Procedures

Inspections and acceptance testing are processes for verifying that the work or product meets requirements. Each person is responsible for the quality of his or her own work, including ongoing and final reviews and inspections, to verify that process requirements are met. However, final acceptance of work is based on inspections or tests conducted by persons other than those performing the work being accepted. The types, numbers, and stringency of acceptance inspections and tests are dependent upon the complexity and importance of the work and are performed by qualified personnel who are knowledgeable of both the acceptance criteria and the technical aspects of the work being assessed.

7.5 Safety Software

As noted in the PPPL Institutional Quality Assurance Program (QAP) (EQP-004), PPPL does not use safety software (as defined in DOE O414.1D) for the design of or review of PPPL facilities, for safety analysis purposes, for supervisory control and data acquisition purposes, or for programmable logic controllers (PLC) software. If future need for such software should arise, PPPL would apply a graded approach to software quality assurance depending upon the risk and safety applications. Such software applications would first be reviewed by persons competent in the field of software quality assurance to ensure that software quality assurance requirements are met.

8.0 ENVIRONMENTAL MONITORING PROGRAM

The Laboratory's environmental monitoring program, which is documented in the PPPL Environmental Monitoring Plan (EMP), is designed to demonstrate compliance with legal and regulatory requirements of applicable federal, state, and local agencies, and to confirm adherence to U. S. Department of Energy (DOE) environmental protection policies. This program also includes parameters not required by statutes, regulations or DOE policies but for which environmental surveillance is performed as a best management practice. Tables 10 and 11 present a summary of the effluent monitoring program, and the environmental surveillance program, respectively. Additional details can be found in the EMP (Reference 12). Environmental monitoring information of particular relevance to NSTX-U operations is included in Sections 8.1 and 8.2.

Table 10 Summary of Environmental Effluent Monitoring Program

Media:	***Radiological***	***Non-Radiological***
AIR	Federal regulation (40 CFR 61) National Emission Standards for Hazardous Air Pollutants (NESHAPs) — DATS (D-site stack)	Boiler and Emergency generators. Clean Air Act Amendments of 1990: (Ozone Non-attainment Area) 40 CFR 63- Subpart JJJJJJ – biennial boiler tune-ups PPPL designated as Minor facility. Emissions calculations, fuel consumption, annual boiler adjustments and observation records maintained for NJ Dept of Environmental Protection (NJDEP) review.
BIOTA	None required	Acute & Chronic Toxicity Tests per New Jersey Pollutant Discharge Elimination System (NJPDES) Permit (surface water).
METEORO-LOGICAL	Precipitation (reported in Annual Site Environmental Report) per DOE requirements.	None required
SOIL	None required	Soil Erosion & Sediment Control per local rules. Soil suspected contamination of hazardous substances/petroleum.
WATER:		
Ground Sump	None required	Lined Surface Impoundment General permit requirements. State regulation (N.J.A.C. 7:14A)
Sanitary	Tritium from Liquid Effluent Collection Tanks (LECTs) (prior to each release), per N.J.A.C. 7:28 and DOE O458.1.	LECT (quarterly volume discharged) per Stony Brook Regional Sewerage Authority (SBRSA) Service Rules
Storm	See Meteorological	None required
Surface	None required	New Jersey Pollutant Discharge Elimination System (NJPDES) Permit: **Monthly**— on-site (1 location) and off-site (2 locations) **Annually** —Waste Characterization Report (1 location) **Once during 5-year permit** – Waste Characterization Report (1 location)

Table 11 Summary of Environmental Surveillance Program

Media	Radiological Program Rationale	Non-Radiological Program Rationale
Air	*To monitor inhalation and absorption exposure pathways for tritium* Weekly measurements: 4 locations on D-site boundary	*To monitor change in operations and/or equipment that may affect air permitting requirements* Periodic review of air inventory and ozone depleting substances
Biota	None	*To monitor ecology of environs* Periodic observations of terrestrial and aquatic life forms
Soil	None	*To determine where soil may be removed off-site* Soil not involved with known spill/release of petroleum/hazardous substance
Ground Water Sump	*To monitor ingestion (drinking water via surface water) exposure pathway for tritium:* Monthly - D-site (2 sumps) *To measure groundwater tritium infiltration:* Quarterly- D-site well sampling (3 wells)	*To measure quantity of ground water discharged to basin/surface water.* Monthly – meter reading (4 locations) *To assess water quality:* Monthly- D-site (2 sumps) for total phosphorous
Sanitary Water	*To ensure water quality of discharges from LECT - gross beta* Prior to release	*To ensure water quality of discharges to LECT* Prior to release – pH and temperature,
Stormwater/ Rain Water	*To measure wash out from D-site stack for tritium* Monthly- on-site (8 locations plus one duplicate)	None
Surface Water	*To monitor ingestion exposure pathway for tritium* Monthly – on-site location (1) and off-site locations (2) Quarterly – on-site location (1) and off-site locations (5)	*To monitor water quality of discharge, and nearby surface waterways* Monthly – on-site location (1) and off-site locations (2) Quarterly – on-site location (1) and off-site locations (5)

Plans, procedures and other documents used by the PPPL to implement the radiological environmental protection requirements of DOE Order 458.1 and other radiation protection programs are included in the DOE approved PPPL Environmental Radiation Protection Program (ERPP).

8.1 Air

Tritium, which may be released to the environment from NSTX-U operations, is the most likely radiological source of exposure to the public, and monitoring its transport is the primary objective of the radiological sample collection

program. Air samples from continuous differential atmospheric tritium samplers (DATS) located at the D-Site exhaust stack (see Section 3.1) and at four locations positioned along the D site fence are analyzed weekly to monitor the airborne tritium releases. DATS is a continuous duty sampler used to determine the tritium concentration in air, as well as differentiating between fractions of tritium present in air moisture (HTO) and the fraction present in the elemental form (HT, and T2). Molecular sieve contained within collection traps, is used as collection medium, and during a normal week, it will absorb greater than 99 percent of the moisture from sample air. A palladium catalyst is used to convert elemental hydrogen into water, which is then collected on an additional molecular sieve trap. A carrier gas (mixture of approximately 3% hydrogen with the balance being nitrogen) is added to sample air. Hydrogen within this carrier gas is used to heat the catalyst (oxidation of hydrogen is exothermic) and carry any converted tritium to the third trap where it is collected.
Annually, a National Emissions Standards for Hazardous Air Pollutants (NESHAPs) report is submitted through DOE to the US Environmental Protection Agency Region II to document the tritium releases from the stack. PPPL uses the COMPLY code to verify compliance with 40 CFR 61.

8.2 Water

Liquid effluent collection tank (LECT; see Section 3.1) water samples are collected prior to discharge to the Stony Brook Regional Sewer Authority (SBRSA) sanitary system. Samples are collected in accordance with D-Site Operations Procedure OP-G-49, “Liquid Effluent Collection Tank (LECT) Monitoring Procedure,” and analyzed for tritium in the PPPL Environmental, Analytical & Radiological Laboratory (PEARL). The LECTs collect water from D-Site facility experimental area room drains (including those in the NSTX Test Cell). The release limits for tritium from the PPPL LECTs to the SBRSA sanitary sewer system is 1.9 X 10^6 pico Curies per liter (pCi/L) (per DOE O458.1), and a total activity limit of 1 Curie (Ci) per year per New Jersey Department of Environmental Protection (NJDEP) rules.

9.0 REFERENCES

1. PPPL Procedure ESH-025, "Operations Hazard Classification Criteria and Safety Certification System".

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2. National Spherical Torus Experiment Upgrade (NSTXU) General Requirements Document, NSTX_CSU-RQMTS-GRD Rev. 5, June 14, 2012.

3. TFTR Final Safety Analysis Report (FSAR), DTSD-FSAR-17, Amendment 9, June 22, 2000.

4. U.S. Department of Energy, "Natural Phenomena Hazards Performance Categorization Criteria for Structures, Systems, and Components', DOE-STD-1021-93, July 1993.

5. U.S. Department of Energy, "Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities", DOE-STD-1020-2002, January 2002.

6. NSTX Project Memo, J. Levine to M. Ono, "Estimated Offsite Doses from NSTX Operations", 71-961217-JDL-01, December 17, 1996.

7. PPPL Memo, J. Levine to J.W. Anderson, "Offsite Doses from TFTR Facility", JL-457, July 2, 1992.

8. L. Cadwallader, INEEL Fusion Safety Program, "Preliminary Failure Modes and Effects Analysis of the Current Drive Experiment – Upgrade Vacuum Vessel for the Addition of a Liquid Lithium Free Surface Limiter," May, 2000.

9. L. Cadwallader (2000), p. 7.

10. G. Start et al, National Oceanic and Atmospheric Administration, "Atmospheric Diffusion for Airflows in the Vicinity of the James Forrestal Campus, Princeton University", May 1989.

11. ERPG-1: Emergency Response Planning Guide Level 1 (lowest exposure level), "The AIHA 2000 Emergency Response Planning Guidelines and Workplace Environmental Exposure Level Guides Handbook," American Industrial Hygiene Association (AIHA), 2000.

12. PPPL Environmental Monitoring Plan, EQP-001, Rev. 5, January 2012.

13. NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc, Feb 2010, I. Zatz.

14. Coil Protection System Requirements Document, NSTX-CSU RQMT-CPS-159.

15. U.S. Department of Energy, "Safety of Magnetic Fusion Facilities: Guidance", DOE-STD-6003-96, May 1996.

16. U.S. Department of Energy, "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports", DOE-STD-1027-92, September 1997.

17. U.S. Department of Energy, Environmental Assessment, The Tokamak Fusion Test Reactor D-T Modifications and Operations, DOE/EA-0566, January 1992.

APPENDIX 1 NSTX Failure Modes And Effects Analysis (FMEA)

Reference: NSTX_FMEA-71-10 20141113

APPENDIX 2 Calculation Documents

1. NSTX-U Nuclear Facility Assessment

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ASSESSMENT OF APPLICABILITY OF 10CFR830, SUBPART B TO NSTX WITH PLANNED UPGRADES

REFERENCES:

1. Letter, J. Makiel (DOE-PSO) to A. Cohen (PPPL), "Hazard Assessment for the National Spherical Torus Experiment (NSTX) Upgrade Project", 5/20/09.

2. Letter, J. Levine (PPPL) to J. Faul (DOE-PSO), "Assessment of PPPL Radionuclide Inventories for Applicability of 10CFR830, Subpart B", 3/9/09.

Reference 1 requested an assessment of the planned major item of equipment (MIE) project for upgrades to NSTX with respect to its current status as a Below Hazard Category 3 facility. These planned upgrades consist of the installation of a new center stack (CS), and installation of a second neutral beam injector (NBI). Reference 1 asked that this assessment be performed considering the two components of the MIE project in aggregate, as well as individually. In addition, any impacts from other planned NSTX modifications outside the MIE project (none are known that would impact this assessment), as well as operational considerations involving experimental run time should be considered.

In March 2009, an assessment of existing PPPL radionuclide inventories, including those associated with NSTX, was performed to determine the status of the Laboratory with respect to 10CFR830 Subpart B applicability (i.e., to identify any Category 3 nuclear facilities). In that assessment, which was documented in Reference 2, the nuclear facility hazard categorization methodology of DOE-STD-1027-92 ("Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports", Change Notice No. 1) was used. In particular, this methodology requires that facilities or facility segments where there are combinations of radioactive materials should be designated as Category 3 if the sum of the ratios of the quantity of each material to the Category 3 thresholds in Table A.1 of the Standard exceeds one (e.g., [inventory of isotope A/threshold of isotope A] + [inventory of isotope B/threshold of isotope B] + [inventory of isotope n/threshold of isotope n] >1). Facilities designated as Category 3 must comply with the applicable requirements of 10CFR830, Subpart B. The Reference 2 assessment determined that PPPL has no facilities that would be designated Category 3 (or higher) nuclear facilities.

The NSTX experiment generates 2.5 MeV neutrons through the fusion of deuterium fuel, which results in activation of materials in nearby components including the torus vacuum vessel, center stack, support structure, and external poloidal field (PF) and toroidal field (TF) coils. Table 1, which is reproduced from Reference 2, provides the sum of the activities of each NSTX activation isotope (assuming approximately a year's worth of current NSTX generation of 1E17 neutrons), comparisons with the Category 3 thresholds, and summation of the radionuclide threshold ratios. As indicated in Table 1, the summation of NSTX radionuclide threshold ratios that determines nuclear facility status is dominated by three short-lived isotopes; Na-24, Mn-56, and Cu-64. These isotopes contribute 98.3% of the summation total, with Mn-56 alone representing 84.4% of the contribution. Thus, this assessment of the impacts of the MIE project on nuclear facility status focuses on these three principal radionuclides.

Table 2 lists the projected neutron production rates for the NSTX upgrades, along with the rates from current NSTX experiments. These rates are used to estimate the expected generation of the principal isotopes mentioned above with the upgrades in place. For this assessment, the following simplifying assumptions were made to conservatively estimate the NSTX radionuclide inventories:

- NSTX runs for two weeks for the year.
- During the first run week (Monday through Friday), NSTX generates its total neutrons for the year (from Table 2) less the amount to be generated during the second week.
- NSTX does not operate over the following weekend.
- NSTX generates the maximum daily amount of neutrons in Table 2 for each of five (5) consecutive days during the second run week (Monday through Friday).
- No decay of the three principal isotopes takes place during the first or second run weeks[1].
- Normal decay of the three principal isotopes takes place during the interval between the end of the first run week and the beginning of the second run week (assumed to be 60 hours[2]).

The results of the assessment are shown in Table 3. The summation of radionuclide threshold ratios is shown for each NSTX upgrade possibility: second NBI only, new CS only, and new CS plus second NBI. Using the 98.3% contribution of the three principal isotopes to the summation total, as indicated above, the overall maximum summations of radionuclide threshold ratios would be:

A. 2nd NBI Only – 0.0196

B. New CS Only – 0.1475

C. New CS + 2nd NBI – 0.2950

All of these summations are <1.

The possibility that the production of daughter products from the decay of NSTX radionuclides could rise to the Category 3 thresholds has also been examined. As noted in Table 5 of Reference 2, most radionuclides generated by neutron activation (including the three principle ones) decay to stable isotopes. For those that don't, Mo-99 and Mo-101, the maximum inventories of the resultant decay products (Tc-99m and Tc-101) would be too small (1.8 Ci and 56 Ci, respectively, for the new CS + 2nd NBI upgrade) relative to their Category 3 thresholds (1.70E+04 Ci and 1.62E+05 Ci, respectively) to change the conclusions regarding the summation of the radionuclide threshold ratios indicated above.

It should be noted that when the residual TFTR tritium and PPPL source inventories reported in Reference 2 are also considered, the maximum summation of radionuclide threshold ratios for PPPL after implementation of the NSTX upgrades would be ≤ 0.645, which is <1.

[1] This is a conservative assumption. 96% of Mn-56 generated during an operating day would, for example, be expected to decay away in the intervening 12 hours before operations resume the next day.

[2] For example, the interval between 7:00 PM Friday and 7:00 AM the following Monday is 60 hours.

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Conclusion

Based on the classification criteria of DOE-STD-1027-92 and the above discussion, NSTX would continue to be designated a Below Hazard Category 3 facility after implementation of all, or any part, of the planned MIE project. The requirements of 10CFR830, Subpart B would not apply to the NSTX Upgrade Project.

Prepared By: Jerry D. Levine, Head, Environment, Safety & Health

Jerry D. Levine

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Addendum (6/24/11): Regarding the new Center Stack, there is a location on the inner TF Coil near the TF flags where the temperature is predicted to exceed 100 C during the maximum power pulse. The CTD-101 epoxy resin system will not provide suitable shear strength at this temperature. The Project plans to use CTD-425, a Cyanate Ester/epoxy resin blend, for this impregnation. The potential activation of this material was examined for impacts on the above conclusion. As indicated in this assessment, the radionuclide levels of importance to nuclear facility status in NSTX are Na-24, Mn-56 and Cu-64. The CTD-425 resin does not contain any components that would lead to higher concentrations of these radionuclides. For instance, Na-24 is produced by neutron bombardment of Na-23 of which there is none in the CTD-425 composition. Similarly, there is no realistic pathway for the production of Mn-56 or Cu-64 in the components of CTD-425. The elemental components of CTD-101 and 425 are very similar, and none of them would add significantly to the radionuclide production due to NSTX operations with the Upgrades installed. Therefore, the conclusion indicated above is not changed.

Table 1 Assessment of Maximum NSTX Activation Products (After 1E17 DD Neutrons)

Isotope	Half-Life	Bq/gm [1]	Ci/lb	**Maximum Total Ci [2]**	**Cat 3 Threshold (Ci)**	**Max Ci/Cat 3 [3]**
H-3	1.23E+01 Yr	1.98E-06	2.42E-14	**3.15E-09**	**1.60E+04**	**1.97E-13**
C-14	5.73E+03 Yr	5.54E-05	6.78E-13	**8.82E-08**	**4.20E+02**	**2.10E-10**
Na-24	1.50E+01 Hr	7.40E+01	9.06E-07	**1.18E-01**	**3.00E+02**	**3.93E-04**
Si-31	2.62E+00 Hr	1.71E+02	2.09E-06	**2.72E-01**	**3.20E+05**	**8.50E-07**
P-32	1.43E+01 Dy	1.28E-01	1.57E-09	**2.04E-04**	**1.20E+01**	**1.70E-05**
P-33	2.53E+01 Dy	3.97E-04	4.86E-12	**6.31E-07**	**9.40E+01**	**6.71E-09**
S-35	8.72E+01 Dy	9.54E-04	1.17E-11	**1.52E-06**	**7.80E+01**	**1.95E-08**
Cl-36	3.01E+05 Yr	2.25E-08	2.76E-16	**3.59E-11**	**3.40E+02**	**1.06E-13**
Ar-39	2.69E+02 Yr	1.04E-05	1.27E-13	**1.65E-08**	**4.00E+04**	**4.13E-13**
K-42	1.24E+01 Hr	1.31E+01	1.61E-07	**2.09E-02**	**4.60E+03**	**4.54E-06**
K-43	2.23E+01 Hr	1.94E-03	2.38E-11	**3.09E-06**	**1.16E+03**	**2.66E-09**
Ca-45	1.63E+02 Dy	3.58E-02	4.39E-10	**5.70E-05**	**1.10E+03**	**5.18E-08**
Ca-47	4.54E+00 Dy	2.24E-03	2.75E-11	**3.57E-06**	**7.00E+02**	**5.10E-09**
Sc-47	3.43E+00 Dy	2.36E-01	2.90E-09	**3.76E-04**	**5.80E+03**	**6.48E-08**
Cr-51	2.77E+01 Dy	3.10E+01	3.80E-07	**4.94E-02**	**2.20E+04**	**2.25E-06**
Mn-54	3.12E+02 Dy	2.52E-01	3.09E-09	**4.01E-04**	**8.80E+02**	**4.56E-07**
Mn-56	2.58E+00 Hr	1.81E+04	2.22E-04	**2.89E+01**	**2.80E+03**	**1.03E-02**
Fe-55	2.68E+00 Yr	5.45E-01	6.68E-09	**8.68E-04**	**5.40E+03**	**1.61E-07**
Fe-59	4.46E+01 Dy	4.86E-01	5.96E-09	**7.74E-04**	**6.00E+02**	**1.29E-06**
Co-58	7.08E+01 Dy	5.78E+00	7.08E-08	**9.21E-03**	**9.00E+02**	**1.02E-05**
Co-58m	9.10E+00 Hr	1.07E+03	1.31E-05	**1.70E+00**	**6.20E+06**	**2.74E-07**
Co-60	5.27E+00 Yr	4.80E-01	5.88E-09	**7.64E-04**	**2.80E+02**	**2.73E-06**
Co-60m	1.05E+01 Mn	9.88E+04	1.21E-03	**1.57E+02**	**5.80E+07**	**2.71E-06**
Co-61	1.65E+00 Hr	7.86E-01	9.63E-09	**1.25E-03**	**8.00E+04**	**1.56E-08**
Ni-59	8.00E+04 Yr	1.55E-04	1.90E-12	**2.47E-07**	**1.18E+04**	**2.09E-11**
Ni-63	1.00E+02 Yr	5.02E-02	6.15E-10	**8.00E-05**	**5.40E+03**	**1.48E-08**
Ni-65	2.52E+00 Hr	2.84E+02	3.48E-06	**4.52E-01**	**9.00E+03**	**5.02E-05**
Cu-64	1.27E+01 Hr	1.27E+05	1.55E-03	**2.02E+02**	**1.54E+05**	**1.31E-03**
As-76	1.10E+00 Dy	2.35E+00	2.88E-08	**3.74E-03**	**2.60E+03**	**1.44E-06**
Zr-93	1.50E+06 Yr	1.10E-09	1.35E-17	**1.75E-12**	**6.20E+01**	**2.82E-14**
Zr-95	6.40E+01 Dy	3.80E-03	4.66E-11	**6.06E-06**	**7.00E+02**	**8.66E-09**
Nb-93m	1.36E+01 Yr	5.95E-02	7.29E-10	**9.47E-05**	**2.00E+03**	**4.74E-08**
Nb-94	2.00E+04 Yr	2.47E-04	3.03E-12	**3.93E-07**	**2.00E+02**	**1.97E-09**
Mo-93	3.50E+03 Yr	6.60E-05	8.08E-13	**1.05E-07**	**2.00E+03**	**5.25E-11**
Mo-99	2.75E+00 Dy	6.00E+01	7.35E-07	**9.55E-02**	**3.40E+03**	**2.81E-05**
Mo-101	1.46E+01 Mn	3.94E+03	4.83E-05	**6.28E+00**	**9.00E+04**	**6.98E-05**
Ag-108m	1.30E+02 Yr	4.23E-04	5.18E-12	**6.73E-07**	**2.00E+02**	**3.37E-09**
Ag-110m	2.50E+02 Dy	5.10E-01	6.24E-09	**8.11E-04**	**2.60E+02**	**3.12E-06**
Pb-205	1.51E+07 Yr	4.27E-14	5.22E-22	**6.79E-17**	**2.40E+03**	**2.83E-20**
Pb-209	3.28E+00 Hr	7.13E-03	8.73E-11	**1.14E-05**	**6.20E+05**	**1.84E-11**
Bi-210	5.01E+00 Dy	4.93E-05	6.04E-13	**7.85E-08**	**3.20E+02**	**2.45E-10**
Bi-210m	3.00E+06 Yr	4.31E-13	5.28E-21	**6.87E-16**	**7.20E+00**	**9.54E-17**

Summation of Radionuclide Threshold Ratios **1.22E-02**

NOTES

1 Specific activity 0 seconds after generation of 1.00 E17 DD neutrons at the rate of 2.00 E14 neutrons per second for 500 seconds.

2 Maximum total Ci for each isotope is obtained by multiplying the T=0 specific activity in Ci/lb by the total combined weight of the NSTX structure, which includes the vacuum vessel, center stack, support structure, and external PF and TF coils. This total combined weight is 130,000 lb (from NSTX Status Report, 2/10/95).

3 Sum of Max Ci/Cat 3 ratios for Na-24, Mn-56 and Cu-64 is 1.20E-02, representing 98.3% of the total NSTX Summation of Radionuclide Threshold Ratios.

Table 2 Projected Neutron Production Rates for NSTX Upgrades

NSTX capability	Increase in neutrons per shot relative to present NSTX	MAX neutrons per shot	MAX neutrons per day	Estimated total neutrons per year	MAX neutron rate [1/s]	Shots per day	Current [MA]	Toroidal field [T]	NBI power [MW]	Pulse length [s]
Present NSTX	1.0	4.0E+14	1.3E+16	8.0E+16	4.0E+14	32	1.2	0.5	6	1
2nd NBI only	2.5	1.0E+15	3.2E+16	2.0E+17	1.0E+15	32	1.2	0.5	8	1
New CS only	25.0	1.0E+16	2.4E+17	2.0E+18	2.0E+15	24	2	1	5	5
New CS + 2nd NBI	50.0	2.0E+16	4.8E+17	4.0E+18	4.0E+15	24	2	1	10	5

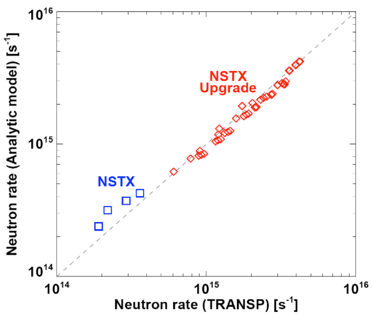


Table 3 Assessment of Maximum NSTX Activation Products for Upgrade Scenarios

C. New CS + 2nd NBI (4E18 Neutrons/yr; 1.6E18 Neutrons 1st week, 2.4E18 Neutrons 2nd week)

Isotope	Half-Life	Cat 3 Threshold (Ci)	Maximum Total Ci after 1st Week [1]	Max Ci/Cat 3 after 1st Week	Residual Ci @ Start of 2nd Week [2]	Maximum Total Ci after 2nd Week + Residual [3]	Max Ci/Cat 3 after 2nd Week
Na-24	1.50E+01 Hr	**3.00E+02**	**1.89E+00**	**6.30E-03**	**1.18E-01**	**2.95E+00**	**9.83E-03**
Mn-56	2.58E+00 Hr	**2.80E+03**	**4.62E+02**	**1.65E-01**	**4.61E-05**	**6.94E+02**	**2.48E-01**
Cu-64	1.27E+01 Hr	**1.54E+05**	**3.23E+03**	**2.10E-02**	**1.22E+02**	**4.97E+03**	**3.23E-02**
Summation of Radionuclide Threshold Ratios				**1.92E-01**			**2.90E-01**

NOTES

1 Calculated by multiplying Maximum Total Ci in Table 1 for each isotope by ratio of 1st week neutrons generated to 1E17.
2 Calculated from product of maximum total Ci after 1st Week and exp (-Lambda*T), where T=60 hours,
and Lambda= ln2/half-life to account for isotope decay over the weekend between the two run weeks.
3 Calculated by multiplying Maximum Total Ci in Table 1 for each isotope by ratio of 2nd week neutrons generated to 1E17,
then adding residual Ci at start of 2nd week.

2. NSTX Dose Calculations

(Reference 6)

NSTX

71-961217-JDL-01
JL-892

TO:	M. Ono	**DATE:**	December 17, 1996
FROM:	J. Levine	**SUBJECT:**	Estimated Offsite Doses from NSTX Operations

REFERENCES:

1. NSTX-RQMT-PDS, Rev-0, NSTX Project Definition Statement, 11/27/96.
2. NSTX-RQMT-GRD, Draft G, NSTX General Requirements Document, 7/16/96.
3. NSTX-RQMT-PRD-025, Draft C, NSTX Project Requirements Document, 7/10/96.
4. DOE/EA-0813, Environmental Assessment, The Tokamak Fusion Test Reactor Decontamination and Decommissioning Project and the Tokamak Physics Experiment at the Princeton Plasma Physics Laboratory, 5/94.
5. PPPL Memorandum, J. Levine to J.W. Anderson, "Offsite Doses from TFTR Facility, JL-457, 7/2/92.
6. DTSD-FSAR-17, Final Safety Analysis Report, Tokamak Fusion Test Reactor, Amendment No. 5, 9/20/96.
7. White Paper, "Tritium Removal and Retention in TFTR; Tenaciously Held Tritium during a Vent," 1/16/96.

Estimates have been performed of the maximum expected individual offsite doses (at the PPPL site boundary) from routine NSTX operations and a postulated leak of tritium from the NSTX machine. This is being done as part of the reexamination of the information in the NSTX Environmental Assessment (DOE/EA-1108, 12/95) relevant to the planned installation of NSTX in the D-Site Hot Cell.

The following assumptions have been used in these estimates:

1. NSTX will be located in the D-Site Hot Cell. Negative pressure will not be maintained in the Hot Cell, therefore airborne radionuclide releases from this room are assumed to be ground level releases (see #7 below). Exhaust gases from the NSTX machine and neutral beam are assumed to be released to the D-Site facility stack.

2. As indicated in Reference 1, Section 1.3, NSTX short pulse (5 sec) capability is 96 pulses/day, 5 days/week, 3 weeks/month, 9 months/year. Repetition rate is 300 sec.

3. As indicated in Reference 2, Section 2.1.3.4, the long pulse upgrade will allow up to 60 sec pulses at a repetition rate of 3600 sec. Scaling from the short pulse scenario, there would be a maximum of 8 60-sec pulses per day (for 5 days/week, 3 weeks/month, 9 months/year).

4. NSTX D-D neutron generation rate is 2×10^{14} neutrons/sec, per Reference 3 (for RF + NBI).

5. Since NSTX D-D reactions will produce some tritium, some D-T reactions are assumed to take place. The D-T neutron generation rate in NSTX is assumed to scale in the same manner as documented in Reference 4 (Appendix A) for TPX. The NSTX D-T neutron generation rate is thus assumed to be 4×10^{12} neutrons/sec.

6. Production of Ar^{41} from Hot Cell air activation by NSTX neutrons is based on TPX calculations for the Test Cell, scaled as the ratio of the Hot Cell-to-Test Cell volumes (0.38). No accounting is made for the effects of the non-borated Hot Cell floor (boration of the Test Cell center support plug and the first one-foot of the Test Cell floor may reduce Ar^{41} production in that room by absorption of thermalized neutrons; not accounting for the absence of this effect in the Hot Cell should not significantly alter the NSTX offsite dose projection because Ar^{41} contributes <10% of the total offsite dose).

7. Maximum offsite dose/Ci for tritium and Ar^{41} is as noted in Reference 5, Table 1. Offsite dose/Ci from routine ground level releases (i.e., due to Ar^{41} releases from the Hot Cell) are assumed to scale in the same manner as indicated in Reference 5, Table 1 for accidental releases (i.e., dose/Ci from ground level releases are three times higher than dose/Ci from stack releases).

A. Offsite Dose from Routine NSTX Operations

(1) Tritium

The annual quantity of tritium produced by NSTX is dependent on the maximum annual NSTX production of D-D neutrons. Using Assumptions nos. 2-4 above, D-D neutron generation would be 2 x 10^{14} n/sec x 5 sec/pulse x 96 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr = 1.3 x 10^{19} n/yr for the short pulse experiments; and 2 x 10^{14} n/sec x 60 sec/pulse x 8 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr = 1.3 x 10^{19} n/yr for the long pulse upgrade. The amount of tritium produced by n neutrons is n x (1 Ci/3.7 x 10^{10} disintegrations per sec) x (ln 2/(12.33 years x 3.15 x 10^{7} sec per yr)). Thus, the amount of tritium produced during short and long pulses with NB would be 0.63 Ci/yr. Assuming that this tritium is all vented via the vacuum system to the stack as tritiated water vapor (HTO or T_2O), the maximum annual offsite individual dose at the site boundary from this pathway would be 0.63 Ci/yr x 0.0026 mrem/Ci = 0.0016 mrem/yr.

(2) Ar^{41}

Using Table A-2 of Reference 4 (attached), the quantities of Ar^{41} generated by NSTX per pulse is projected to be (Bq = Becquerel):

Short pulse- [(8.6 x 10^{-10} Bq/DD neutron x 2.7 x 10^{-11} Ci/Bq x 2 x 10^{14} DD neutron/sec) + (8.8 x 10^{-10} Bq/DT neutron x 2.7 x 10^{-11} Ci/Bq x 4 x 10^{12} DT neutron/sec)] x 5 sec/pulse x 0.38
= 9.00 x 10^{-6} Ci/pulse;

Long pulse- 9.00 x 10^{-6} Ci/pulse x (60 sec per pulse/5 sec per pulse)
= 1.08 x 10^{-4} Ci/pulse.

Assuming that all the Ar^{41} generated is vented to the environment at ground level, the maximum annual releases of this isotope during NSTX operations would be:

Short pulses- 9.00 x 10^{-6} Ci/pulse x 96 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr
= 0.117 Ci/yr;

Long pulses- 1.08 x 10^{-4} Ci/pulse x 8 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr
= 0.117 Ci/yr.

The maximum annual offsite individual dose at the site boundary from this pathway would be 0.117 Ci/yr x 0.004 mrem/Ci x 3 = 0.0014 mrem/yr.

(3) Direct/Scattered Neutron and Gamma Radiation

NSTX's location in the D-Site Hot Cell will put it about 150 m from the nearest PPPL site boundary. Extrapolating from information in Section 4.9.4.1 and Figure 4.9.2-22 of Reference 6, I obtain:

- NSTX neutron + gamma dose per DD neutron is about 1 x 10^{-21} mrem/DD neutron (5 x 10^{-22} mrem/DD neutron from neutron radiation + 5 x 10^{-22} mrem/DT neutron from gamma radiation, using Figure 4.9.2-22);

- NSTX neutron + gamma dose per DT neutron is 8.2 x 10^{-21} mrem/DT neutron (using DT-to-DD dose equivalent ratios in Section 4.9.4.1).

The maximum annual offsite individual dose at the site boundary from this pathway would be:

Short pulse: [(1 x 10^{-21} mrem/DD neutron x 2 x 10^{14} DD neutron/sec x 5 sec/pulse x 96 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr) + (8.2 x 10^{-21} mrem/DT neutron x 4 x 10^{12} DT neutron/sec x 5 sec/pulse x 96 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr)]
= 0.0151 mrem/yr;

Long pulse: [(1 x 10^{-21} mrem/DD neutron x 2 x 10^{14} DD neutron/sec x 60 sec/pulse x 8 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr) + (8.2 x 10^{-21} mrem/DT neutron x 4 x 10^{12} DT neutron/sec x 60 sec/pulse x 8 pulses/day x 5 days/wk x 3 wks/mo x 9 mos/yr)]
= 0.0151 mrem/yr.

DOSE PROJECTIONS FROM ROUTINE NSTX OPERATIONS

PATHWAY	ROUTINE ANNUAL RELEASE OR GENERATION	MAXIMUM SITE BOUNDARY DOSE
Tritium (HTO or T_2O)	0.63 Ci/yr	0.0016 mrem/yr
Activated Air (Ar^{41})	0.117 Ci/yr	0.0014 mrem/yr
Direct/Scattered Neutron and Gamma Radiation	1.3×10^{19} DD neutrons/yr + 2.6×10^{17} DT neutrons/yr	0.0151 mrem/yr
		TOTAL = 0.0181 mrem/yr

The total estimated maximum site boundary dose from routine NSTX operations is 0.0181 mrem/yr, which is much less than the design objective of 10 mrem/yr.

B. Offsite Dose from Postulated Tritium Leak from NSTX Machine

Entrainment inside the NSTX torus vacuum vessel of tritium produced by D-D reactions may cause a buildup of releasable tritium in the machine over time. Most of the tritium produced would be pumped by the NB cryopanels (and subsequently vented to the stack), but as much as 45% may be trapped in the torus (note that the routine dose calculation in Item A1 above conservatively assumed that all tritium produced is vented to the stack). Assuming that this trapped tritium is not deliberately cleaned out of the torus, the maximum amount of tritium that could be held up in the torus after 10 years of NSTX operation could be (10 x 0.63 Ci/yr) x 0.45 = 2.84 Ci. Based on the results of deliberate air venting of the TFTR torus in 1995 as documented in Reference 7, about 15% of this inventory or 0.43 Ci could be released due to an NSTX torus leak. If such a leak was too large to be pumped on to maintain negative pressure in the torus, this quantity of tritium could be released to the room and subsequently to the environment. The maximum individual site boundary dose from the release of 0.43 Ci of tritiated water vapor would be 0.43 Ci x 0.0157 mrem/Ci = 0.007 mrem, much less than the design objective of 50 mrem for this event (which based on information in the TFTR FSAR, would have an estimated probability of 3.7×10^{-2}/yr).

cc: S. Citrolo
J. DeLooper
J. Gilbert
H. Kugel
C. Neumeyer
M. Peng
J. Schmidt

Calculations Checked By:

Jerry D. Gilbert

5

From DOE/EA-0813 (Reference 4)

May 27, 1994

Table A-2. TPX DD Operations: Calculated Production Rates, Releases, and Doses for a Maximum Individual Member of the Public from Air Activation Products

	1 Sec Activity (Bq per neutron)		1 Pulse Activity (Bq)			Release per pulse (Bq)	Release per year (Bq)	Release per year (Ci)	Annual Dose (mrem)
Isotope	DD	DT	DD	DT	Total				
N-13	0	7.8 E-09	0	4.7 E+09	4.7 E+09	3.0 E+08	5.9 E+10	1.6 E+00	5.0 E-03
N-16	0	1.0 E-06	0	6.0 E+11	6.0 E+11	3.6 E+08	7.2 E+10	2.0 E+00	1.4 E-04
Cl-40	0	1.0 E-08	0	6.0 E+09	6.0 E+09	5.3 E+07	1.1 E+10	2.9 E-01	2.3 E-03
S-37	0	2.3 E-09	0	1.4 E+09	1.4 E+09	4.6 E+07	9.1 E+09	2.5 E-01	2.6 E-03
Ar-41	8.6 E-10	8.8 E-10	2.6 E+10	5.3 E+08	2.6 E+10	1.1 E+10	2.2 E+12	6.1 E+01	2.2 E-01
								TOTAL	2.4 E-01

Notes:

1. Neutron production rate: 3.0 E+16 DD neutrons/sec, 6.0 E+14 DT neutrons/sec.
2. DD pulse length used is 1000 seconds.
3. 200 DD pulses per year assumed.
4. 1 Ci = 3.7 E+10 Bq.
5. Dose-to-release ratios are given in Table A-1.

(From Reference 5) TABLE 1 7/2/92

MAXIMUM INDIVIDUAL OFFSITE DOSES FROM TFTR AIRBORNE RADIONUCLIDE RELEASES BASED ON NOAA REPORT*

Prepared: [signature]
Checked: [signature]

	D/Q (mREM/Ci)	D (Q=1KCi) (mREM)	D (Q=10KCi) (mREM)	D (Q=25KCi) (mREM)
MAXIMUM VALUES AT SITE BOUNDARY FOR GROUND LEVEL RELEASE-ACCIDENT	0.0157 (HTO)	16	157	393
	6.28E-07 (T_2)	6.3E-04	6.3E-03	0.0157
	0.0754 (N-13)#	75	754	1885
	0.1130 (Ar-41)#	113	1130	2826
	4.13E-06 (N-16)#	0.004	0.04	0.103
	0.1226 (Cl-40)#	122.6	1226	3065
	0.2125 (S-37)#	212.5	2125	5313
MAXIMUM VALUES AT SITE BOUNDARY FOR STACK RELEASE -ACCIDENT	0.0056 (HTO)	6	56	140
	2.24E-07 (T_2)	2.2E-04	2.2E-03	0.0056
	0.0286 (N-13)@	29	286	715
	0.0400 (Ar-41)@	40	400	1000
	4.93E-04 (N-16)@	0.49	4.9	12.3
	0.0728 (Cl-40)@	73	728	1820
	0.0862 (S-37)@	86	862	2155
MAXIMUM VALUES AT SITE BOUNDARY FOR STACK RELEASE -ROUTINE**	0.0026 (HTO)	2.6	26	65
	1.05E-07 (T_2)	1.1E-04	0.0011	0.0026
	0.0028 (N-13)@	2.8	28	70
	0.0040 (Ar-41)@	4.0	40	100
	6.71E-05 (N-16)@	0.07	0.67	1.7
	0.0082 (Cl-40)@	8.2	82	205
	0.0108 (S-37)@	10.8	108	270

D/Q = DOSE AT SITE BOUNDARY PER CURIE OF INDICATED RADIONUCLIDE RELEASED FROM TFTR; Q REFERS TO THE QUANTITY OF HTO, T_2, N-13, Ar-41, N-16, Cl-40, OR S-37 HYPOTHETICALLY RELEASED.

* G. START, ET AL, "ATMOSPHERIC DIFFUSION FOR AIRFLOWS IN THE VICINITY OF THE JAMES FORRESTAL CAMPUS, PRINCETON UNIVERSITY," U.S. DEPARTMENT OF COMMERCE, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 5/12/89.

** BASED ON USE OF AIRDOS-EPA WITH X/Q= 1.77×10^{-5} SEC/M^3, AS PER M.A. MCKENZIE-CARTER, R.E. LYON & S.K. ROPE, "METHODOLOGY FOR ASSESSING THE RADIOLOGICAL CONSEQUENCES OF RADIOACTIVE RELEASES FROM THE BPX FACILITY AT PPPL," 1991.

ACCOUNTS FOR IN TRANSIT DECAY BETWEEN RELEASE POINT AND SITE BOUNDARY. ASSUMES TRANSIT TIME OF 2 MINUTES BASED ON 1 M/SEC WIND SPEED, AS PER M.A. MCKENZIE-CARTER, R.E. LYON & S.K. ROPE, "METHODOLOGY FOR ASSESSING THE RADIOLOGICAL CONSEQUENCES OF RADIOACTIVE RELEASES FROM THE BPX FACILITY AT PPPL," 1991, PAGE 27.

@ ACCOUNTS FOR IN TRANSIT DECAY BETWEEN RELEASE POINT AND SITE BOUNDARY. ASSUMES TRANSIT TIME OF 1 MINUTE AS PER R. LYON COMMUNICATION AS PART OF TFTR D-T EA PREPARATION (SEE ALSO PG 55 OF "METHODOLOGY" REPORT).

From Reference 6

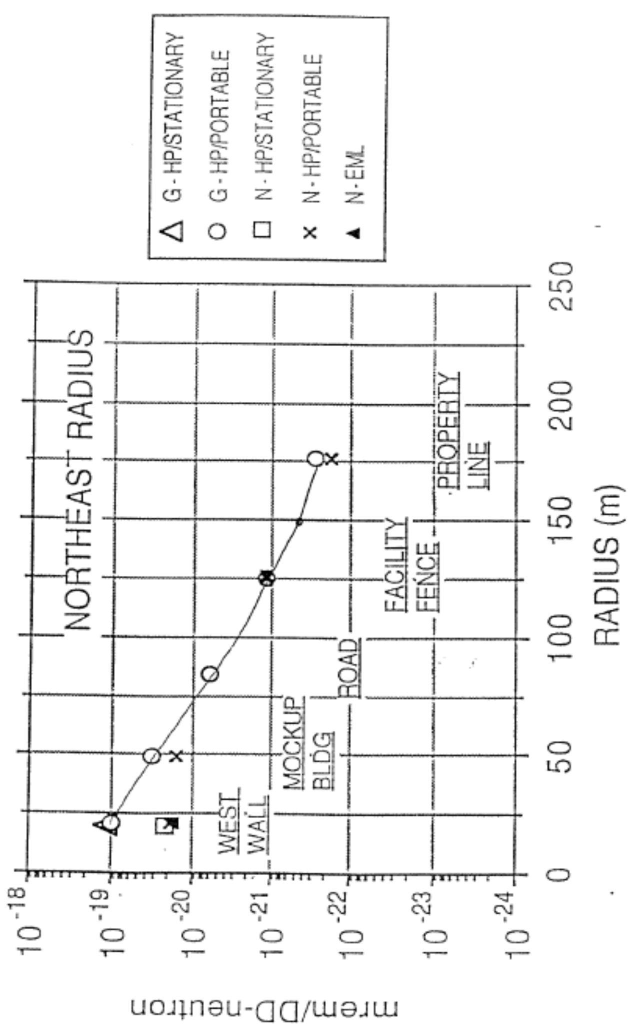


FIGURE 4.9.2-22 NEUTRON AND GAMMA DOSE EQUIVALENT MEASUREMENTS OUTSIDE ALONG THE NORTHEAST RADIUS

3. Liquid Pathway Dose Calculation Basis

(From Reference 3)

8.2.3 Estimated Dose Equivalents

Small amounts of radioactive-contaminated liquids might be released at low concentrations during normal TFTR D-T operations. The most significant of such releases would be the release of tritium-contaminated liquid to the sanitary sewer system. Any liquid releases that do occur would be diluted by the potable water releases from PPPL, which amounted to 82.5 million (21.8 million gal) in 1988 (Reference 8.2-3). In order to assess the consequences of potential liquid radioactive releases from TFTR D-T operations, conservative assumptions were made. The primary assumptions are that the maximum allowed annual release of radioactivity from the liquid effluent collection tanks occurs (1 Ci/yr), and that it is composed entirely of tritium at the maximum allowed concentration (200,000 pCi/). Based on these assumptions, the annual average concentration of tritium in the liquids released from PPPL to the sanitary sewer system would be approximately 12,100 pCi/ : this is approximately one half of the EPA drinking water standard given in 40 CFR 141 (20,000 pCi/). After release from PPPL, this water would be further diluted both prior to and after reaching the Stony Brook Sewer Authority treatment facility. After release from this treatment facility, it would be available for use by the public. The maximum concentration of tritium in the water released from the treatment facility, which has an annual throughput of approximately 10 billion liters (2.6 billion gal), would be approximately 100 pCi/ ; this concentration would result in a dose equivalent of 0.02 mrem/yr to any individual using this water as a source of drinking water (Reference 8.2-4). Therefore, because of the low tritium concentration in the released liquids, combined with the subsequent dilution downstream of PPPL, these potential releases would represent a negligible risk to individuals or the population in the PPPL area.

4. Activated Structural Material Release Dose Calculation Basis

(Reference 17, Appendix C)

APPENDIX C MAGNET ARC TO VACUUM VESSEL

During TFTR D-T operations, large numbers of neutrons will be generated, producing activated solid material in the vacuum vessel, magnets, and other structural material. Quantities of these activated materials could potentially become mobilized during an off-normal event. The only such event of potential significance in this regard would be a magnet arc to the torus vacuum vessel[1]. A study has been performed to determine the amount of activated solids that could be mobilized within the test cell during this event and the resulting effective dose equivalent to the public if all the mobilized material were released up the exhaust stack. This approach places an upper bound on the accident since it does not account for plate-out within the facility and mitigation by high efficiency particulate air (HEPA) filters in the TFTR facility ventilation system.

Specific activity levels were calculated for the stainless steel (SS-304LN) vacuum vessel at 1 hour following exposure of the vessel to 50 consecutive full power pulses (total of 5 x 10^{20} D-T neutrons) spaced one hour apart, using information in Fleming (1990), Ku and Kolibal (1981), and Ku and Kolibal (1982).

The accident scenario is an arc from a toroidal field (TF) coil to the vacuum vessel, resulting in the vaporization of SS-304LN. This arc would consist of two 35 volt arcs, one to the vacuum vessel and a return arc from the vessel, having a duration of about 40 sec. The "worst case assumption," i.e., the situation that would deposit the most energy into the fault, is when the fault is initiated at the start of a pulse (Neumeyer, 1990). Under these conditions, the maximum total energy that could be deposited in the arc is 55.8 MJ. It was assumed that approximately 5 MJ is needed to volatilize 1 kg of vacuum vessel material in an arc (Holland and Lyon, 1989). Therefore the maximum amount of SS-304LN which could be converted to an aerosol is about 11 kg. Recent experiments at the TESPE facility in West Germany indicate that less than 10% of the energy would actually go into vaporizing the metal (Holland and Lyon, 1989). Therefore, 1.1 kg is a reasonable estimate of the amount of material which could be vaporized in this event.

A summary of the inventory of activated materials potentially contributing to individual (at the site boundary) and 50-mile collective effective dose equivalents is shown in Table C-1. The maximum individual

---

[1] The presence of coil protection systems, which would detect and isolate faults in the magnet systems, and the grounding of coil cases and structures in the vicinity of the coils makes the occurrence of this event extremely unlikely.

and collective effective dose equivalents due to a stack release are 0.15 mrem and 8.9 x 10^{-3} person-rem, respectively. For a ground level release (i.e., severe accident calculation), the corresponding effective dose equivalents are 0.42 mrem and 8.9 x 10^{-3} person-rem.

References

Fleming, R. B. 1990. Memo to R. E. Lyon (INEL). "Accidental Release of Activated Solids for TFTR Environmental Assessment." May 25, 1990.

Holland, D. F. and R. E. Lyon. 1989. Potential Off-Normal Events and Associated Radiological Source Terms for the Compact Ignition Tokamak. EGG-FSP-7872, Revision 1, August, 1989. PPPL Controlled Document # AF-890829-I-01.

Ku, L. P. and J. G. Kolibal. 1981. Estimated Neutron Activation Data for TFTR. PPPL-1847, November, 1981.

Ku, L. P. and J. G. Kolibal. 1982. Estimated Neutron Activation Data for TFTR Part II. Biological Dose Rate from Sample Material Activation. PPPL-1898, June, 1982.

Neumeyer, C. 1990. Memo to R. Fleming (PPPL). "TFTR TF-VV Double Arcing Fault." May 24, 1990.

TABLE C-1 SOURCE TERMS AND DOSES FOR MAGNET ARC TO TFTR VACUUM VESSEL[1]

Isotope	Half-life	CF [2] (mrem/Ci)	Release (Ci)	Site Boundary Dose (mrem)[3]	50-Mile Collective Dose (Person-rem)
Cr-49	42.1 min	2.54×10^{-2}	7.32×10^{-4}	1.86×10^{-5}	1.39×10^{-7}
Cr-51	27.7 days	1.18×10^{-1}	8.05×10^{-3}	9.50×10^{-4}	2.02×10^{-4}
Mn-54	312.2 days	2.89	5.23×10^{-4}	1.51×10^{-3}	1.95×10^{-3}
Mn-56	2.579 hrs	1.28×10^{-1}	1.05	1.34×10^{-1}	2.22×10^{-3}
Fe-53	8.51 min	4.81×10^{-3}	1.05×10^{-4}	5.05×10^{-7}	8.42×10^{-10}
Fe-55	2.68 yrs	4.36×10^{-2}	1.57×10^{-3}	6.85×10^{-5}	2.57×10^{-3}
Co-57	271.8 days	6.03×10^{-1}	2.09×10^{-4}	1.26×10^{-4}	8.62×10^{-5}
Co-58	70.91 days	3.32	1.46×10^{-3}	4.85×10^{-3}	1.25×10^{-3}
Co-58m	9.1 hrs	1.71×10^{-2}	1.44×10^{-1}	2.46×10^{-3}	1.31×10^{-4}
Co-61	1.65 hrs	4.56×10^{-3}	2.09×10^{-3}	9.53×10^{-6}	1.05×10^{-7}
Ni-57	36.1 hrs	1.84	4.50×10^{-3}	8.28×10^{-3}	4.77×10^{-4}
Totals			**1.21**	**1.52×10^{-1}**	**8.89×10^{-3}**

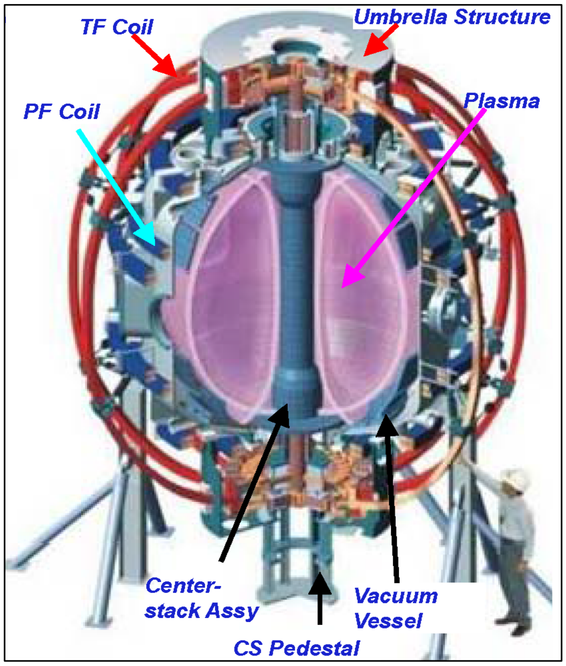
[1] Calculated at 1 hour following exposure of the TFTR vacuum vessel to 50 consecutive full power pulses (total of 5×10^{20} D-T neutrons) spaced one hour apart. Doses are effective dose equivalents.

[2] Accident conversion factors for individuals at the site boundary calculated for stack release using FUSCRAC3 code (see McKenzie-Carter, M. A. and R. E. Lyon. 1989. Methodology for Assessing the Radiological Consequences of Radiological Releases from the CIT Facility at PPPL. EGG-ESE-8600, August, 1989), and based on isotope dose conversion factors from Fetter, S. 1988. Internal Dose Conversion Factors for 19 Target Organs and 9 Irradiation Times and External Dose-Rate Conversion Factors for 21 Target Organs for 259 Radionuclides Produced in Potential Fusion Reactor Materials. EGG-FSP-8036, March 1988.

[3] For ground level release, multiply dose by 2.8.

Figures

Figure 1. NSTX-U Machine



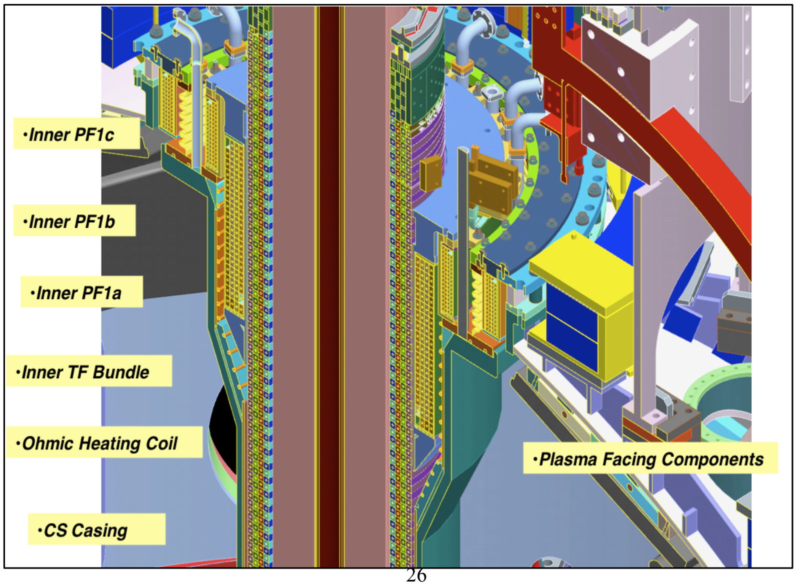


Figure 2. NSTX-U Facility Within D-Site

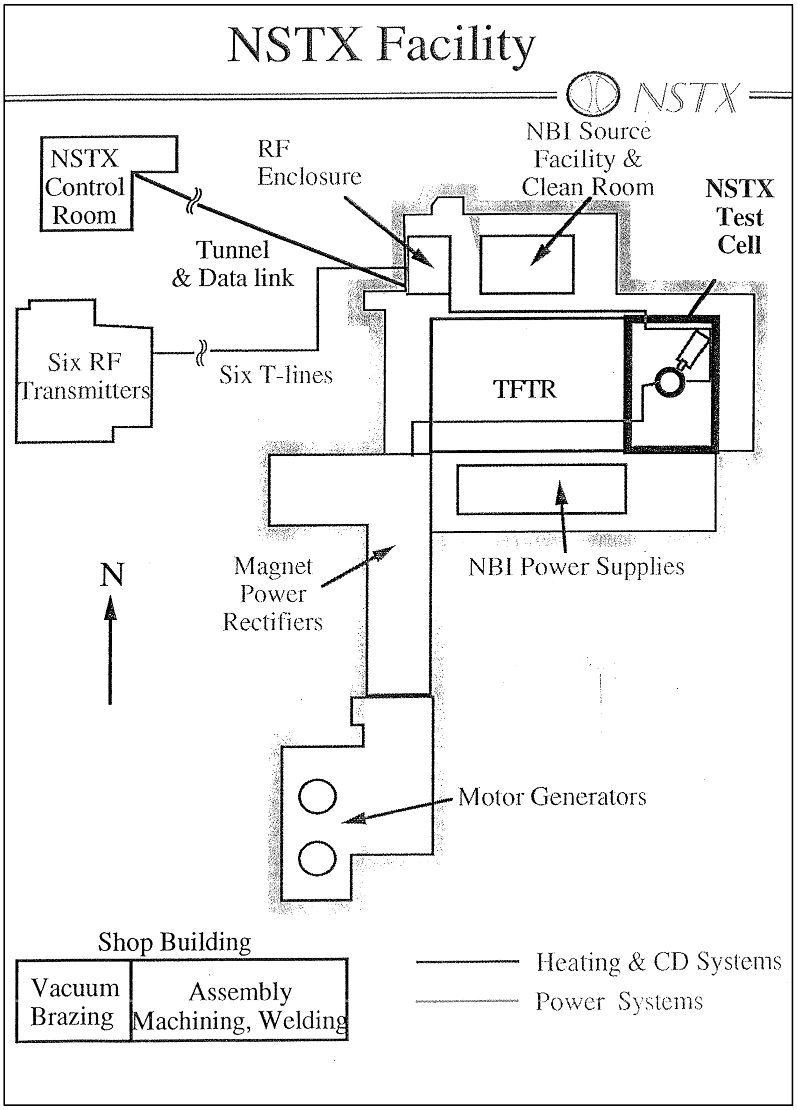


Figure 3. NSTX Test Cell

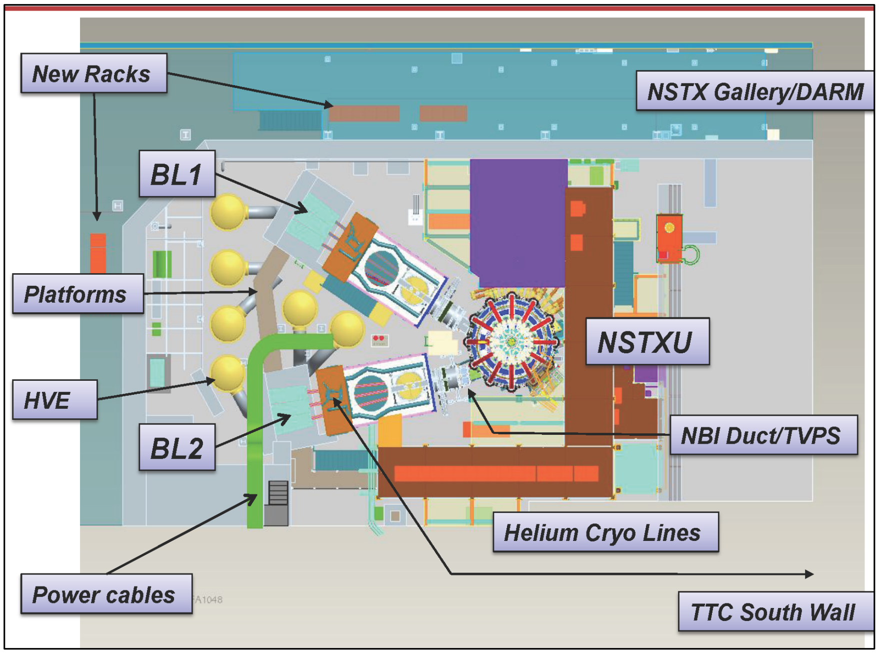
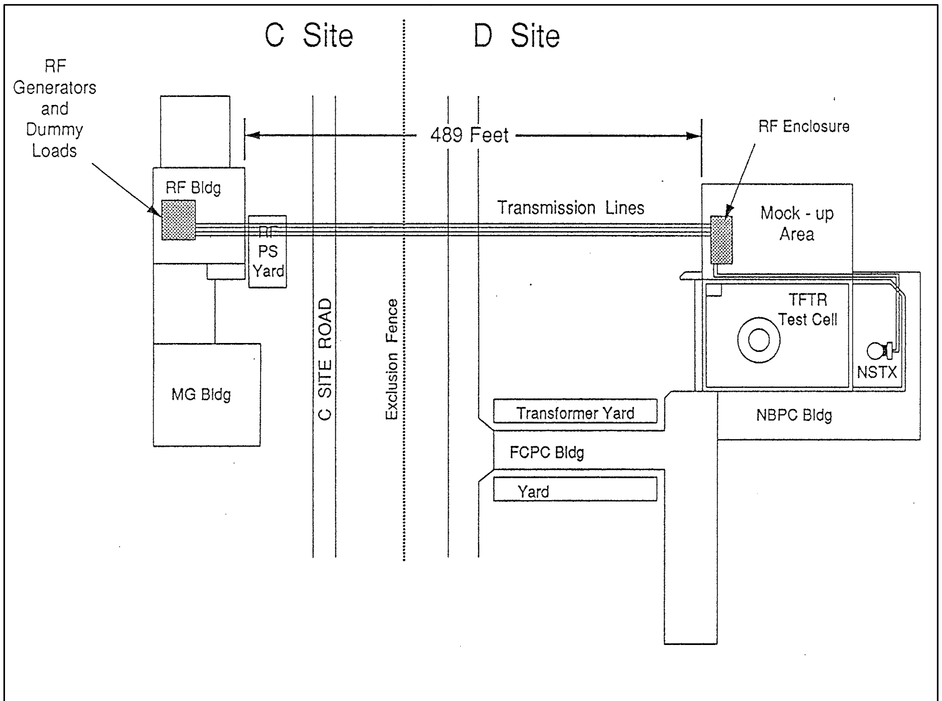


Figure 4. NSTX-U RF Transmission System



RF Transmission System

Figure 5. Helium High Temperature System (Bakeout)

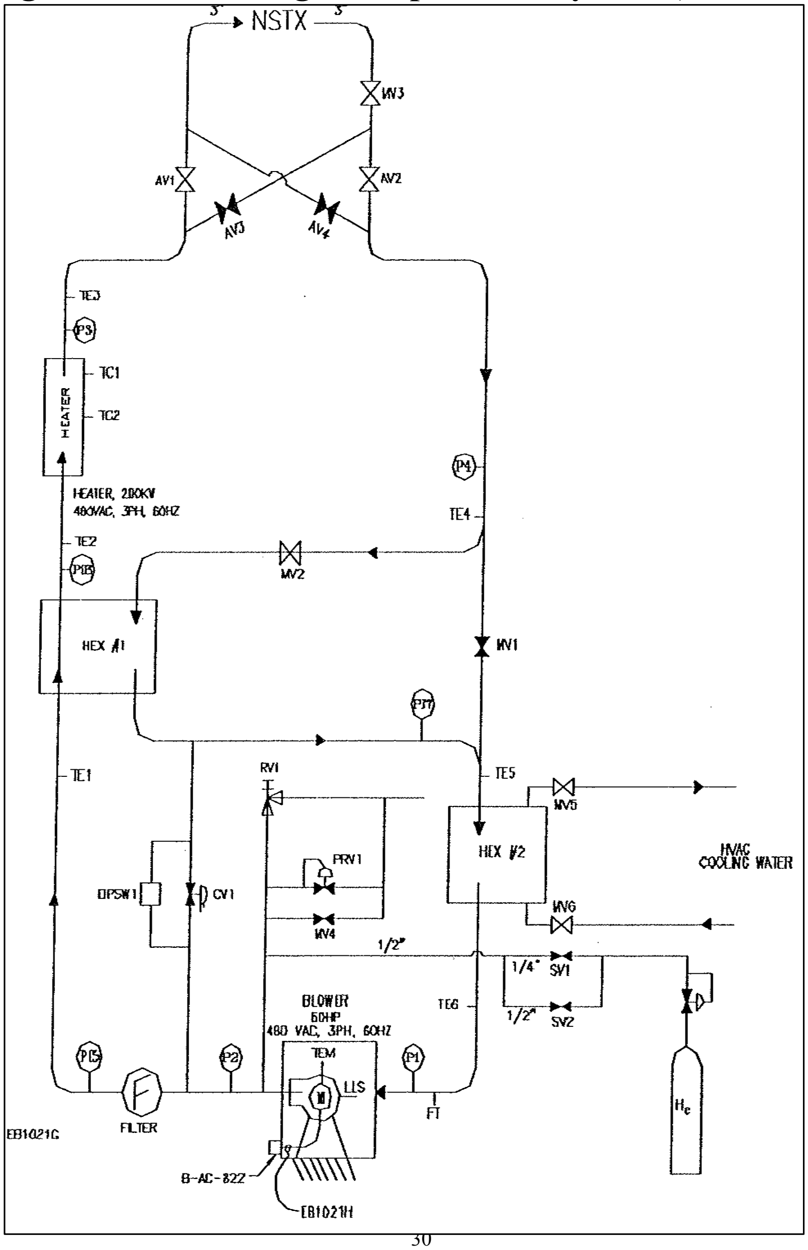


Figure 6. AC Power System

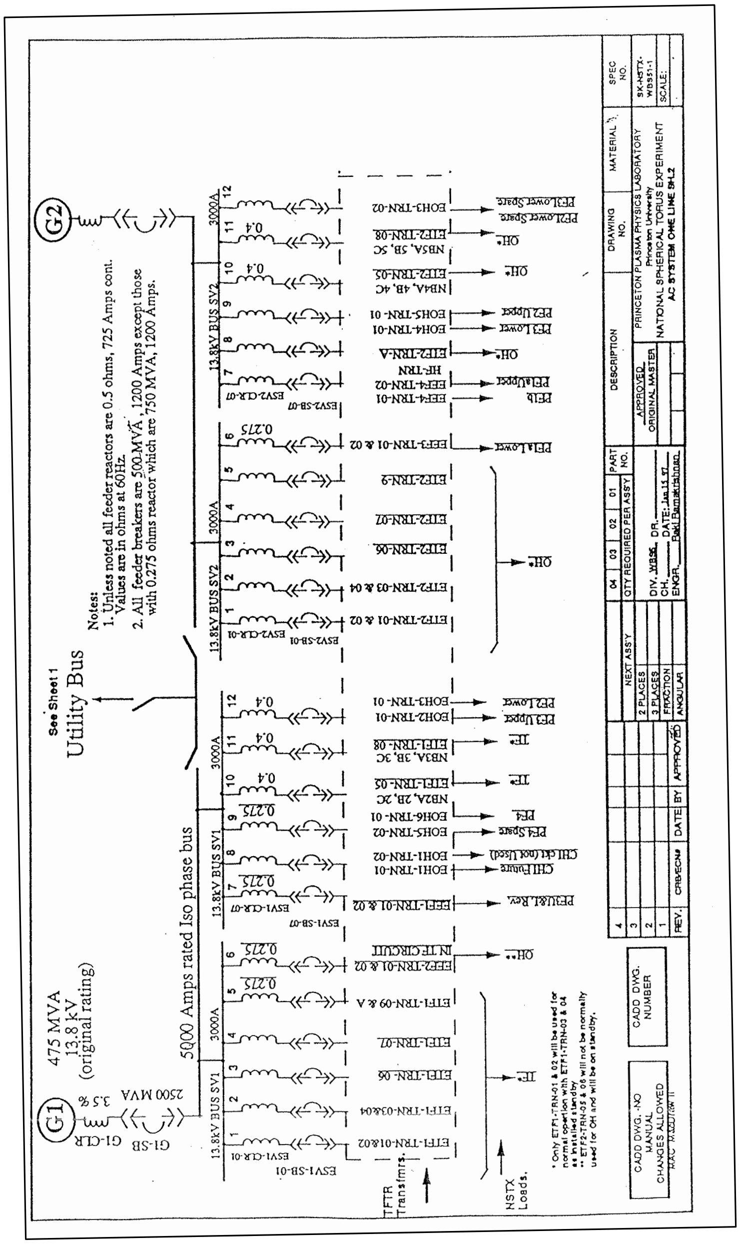


Figure 7. NBI System Principle of Operation

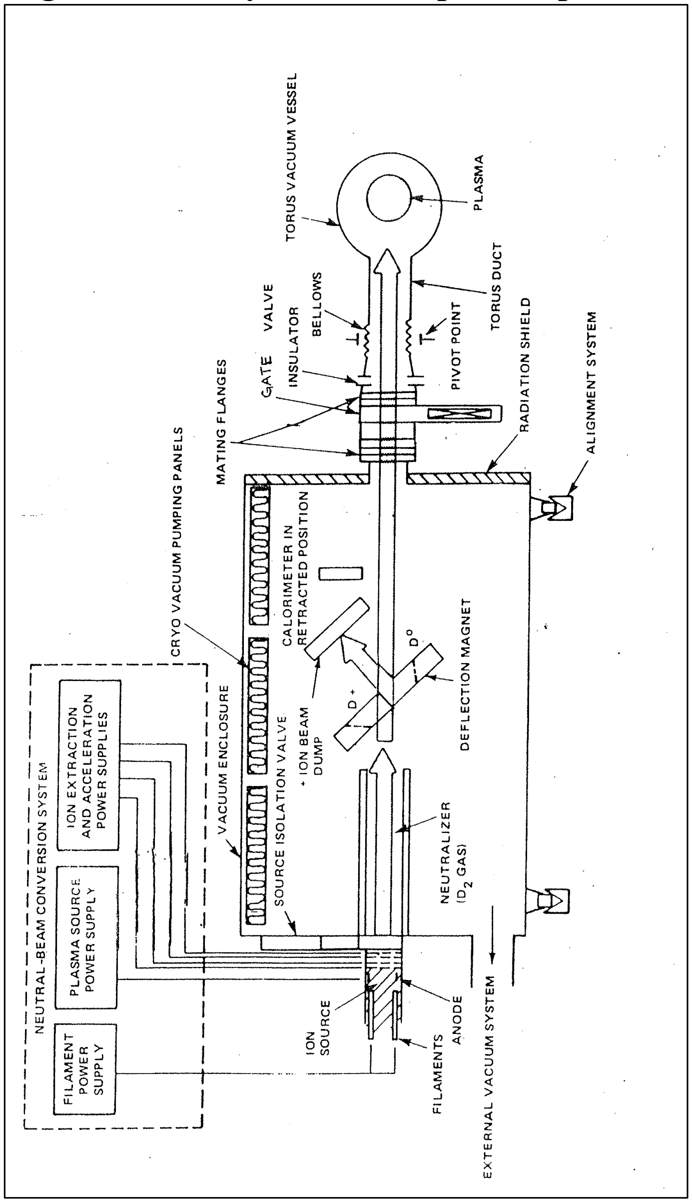


Figure 8. Exploded Neutral Beam Assembly