NSTX
FAILURE MODES AND EFFECTS ANALYSIS (FMEA)
Revision 7
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I. PREFACE

SCOPE

This revision of the NSTX FMEA is intended to reflect the configuration of the NSTX device and following the upgrade to the Center Stack and addition of a second NBI system. . Compared to the prior revision of the FMEA this version includes two new columns, one for failure probability and one for failure consequence. [See memo 71-091211-CLN-01, "Procedure to Update the NSTX Failure Modes and Effects Analysis (FEMA) Document."

NSTX utilizes the auxiliary systems of D-site. The TFTR FSAR includes FMEAs for these systems, including effects of failures on the auxiliary systems themselves. For NSTX this document only addresses failures which impact the NSTX device. Effects of failures on the auxiliary systems themselves are covered by the TFTR FSAR.

In general, single failure modes are addressed. In some cases, for failures which would have severe consequences in terms of damage to hardware or risk to personnel safety, multiple failures are addressed.

SAFETY IMPLICATIONS

Certain failures can increase the risk of injury to personnel. For any particular failure, the level of risk of injury to personnel depends on several factors including:

1) the nature of the failure
2) the presence or absence of features which mitigate the effect of the failure (e.g. redundancy, energy isolating barriers, etc.)
3) the presence or absence of personnel in the area where the failure has occurred
4) the level of training of the personnel

This FMEA addresses 1) and 2) above. Items 3) and 4) relate mainly to administrative procedures which aim to prevent access to hazardous areas or to limit access to personnel trained to conduct themselves safely in potentially hazardous areas. This FMEA *does not* address administrative procedures.

This FMEA addresses new systems which will exist in the NSTX Test Cell, as well as other D-site systems whose failure could damage the NSTX device, or which have been significantly modified for use on NSTX, or which relate to safe access to the NSTX Test Cell.

This FMEA *does not* address safety issues related to the conduct of operations throughout the balance of the D-site facility. Considering that the safety of operations of TFTR was documented and approved via the TFTR FSAR, and demonstrated to be effective for more than a decade, it would not add to the safety of NSTX operations to repeat that analysis herein.

Considering its role in establishing safe access to the NSTX Test Cell, the Safety Lockout Device (SLD), along with the interface between the SLD and the power supply system Safety Disconnect Switches (SDS), and the supervision of operation of the power supply system by the Hardwired Interlock System (HIS), *these safety related systems have been addressed herein, even though they have not been changed for NSTX in any substantial way. The SLD and SDS interface remain absolutely unchanged. The HIS has been modified to reflect the simpler requirements for NSTX but the TFTR concepts (redundancy, etc.) and actual components have been fully retained.*

Hot Access is a special mode which allows for the presence of a limited number of personnel in the NSTX Test Cell during coil energization in order that they can observe first hand any unexpected behavior. These persons will each have in their possession a key which locks the HIS in the Hot Access Mode, preventing simultaneous TF and PF energization (and the possibility of plasma formation) *using exactly the TFTR HIS interlocking mechanism*. Compared to an observer outside of the NSTX Test Cell, these persons will unavoidably be exposed to a higher level of risk of injury. However, via design of protective shields as well as administrative procedures to ensure their use, all reasonable measures will be taken to minimize this risk. *The design of these shields and the administrative procedures is outside of the scope of this FMEA. However, it is expected that the design of these shields will be similar to the design used for TFTR, and it is noted that the ability of NSTX to emit projectile is considerably less than TFTR, owing to its much lower magnetic fields.*

II LIST OF ACRONYMS

ACP	Analog Coil Protection system	NSTX	National Spherical Torus Experiment
B	magnetic field	NTC	NSTX Test Cell
CHI	Coaxial Helicity Injection	OH	Ohmic Heating
COE	Chief Operating Engineer	PAUX	Permissive relay for Auxiliary Systems
DCCT	DC Current Transducer	PC Link	Power Conversion (power supply command data) Link
DCPT	DC Potential (voltage) Transducer	PF	Poloidal Field
E-stop	Emergency Stop	PFC	Plasma Facing Component
ECH	Electron Cyclotron Heating	PLC	Programmable Logic Controller
EIC	(FCPC) Engineer In Charge	PPPL	Princeton Plasma Physics Lab
EPICS	Experimental Physics Instrumentation & Control System	PSRTC	Power Supply Real Time Controller
FCPC	Field Coil Power Conversion	RF	Radio Frequency
FMEA	Failure Modes & Effects Analysis	RGA	Residual Gas Analyzer
HCS	Hardwired Control System (in FCPC)	RIS	Rochester Instrument System (fault detector)
HHFW	High Harmonic Fast Wave	rms	root mean square
HIS	Hardwired Interlock System	SDS	Safety Disconnect Switch
HSC	Halmar Signal Conditioner	SLD	Safety Lockout Device
HVAC	Heating/Ventilating/Air Conditioning	SOL	Scrape Off Layer
I	current	TF	Toroidal Field
I&C	Instrumentation & Control	TFTR	Tokamak Fusion Test Reactor
I/O	Input/Output	TMB	Trimethylboron
IR	Infra Red	TMP	Turbo Molecular Pump
LEC	Liquid Effluent Collection tank	UPS	Uninterruptable Power System
MGD	Master Gate Driver	VPS	Vacuum Pumping System
NBI	Neutral Beam Injection	WBS	Work Breakdown Structure

III. WBS ELEMENTS

1 Torus Systems

WBS Element 1.1 Plasma Facing Components: Component: Graphite & Carbon Fiber Composite Tiles

Function: **The PFC (Inner Wall, Inboard Divertor, Outboard Divertor, and Passive Plate) tiles comprise the surface which interacts with the plasma and forms the plasma boundary**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Tile overheating due to misalignment, or plasma misoperation (control system failure, CHI misoperation, etc.)	Impurity influx into plasma, reduced performance	Visible camera, Infra Red (IR) camera, Residual Gas Analyzer (RGA)	Control plasma shape and Scrape Off Layer (SOL) to avoid localized heating, repair tile when vacuum vessel accessible.	UNLIKELY	MINOR
Partial (cracked tile) or complete tile detachment from mounting surface/backplate due to thermal shock and/or eddy currents and electromagnetic forces.	Loose tile piece will fall down in vacuum vessel, could bridge isolating gap (e.g. ceramic insulator, passive plate toroidal gap, etc.), leading to localized diversion of plasma.	Visible camera, IR camera (depending on effect).	Repair tile, remove broken piece(s) when vacuum vessel accessible.	UNLIKELY	MINOR
Tile support rail or T-bar or other mounting hardware detachment from mounting surface/backplate due to thermal shock and/or eddy currents and electromagnetic forces.	Loose metallic piece will fall down in vacuum vessel, could bridge isolating gap (e.g. ceramic insulator, passive plate toroidal gap, etc.), leading to localized diversion of plasma.	Visible camera, IR camera (depending on effect).	Shutdown, vent vacuum vessel, repair	UNLIKELY	MAJOR

WBS Element 1.1 Plasma Facing Components Component: Passive Plates

Function: The Passive Plates provide transient stabilization of the plasma vertical position, and determine the plasma outboard boundary.

Failure Mode	Effect	Detection	Recovery	Probability	Consequenc
Loose connections leading to excessive contact electrical resistance on toroidal or poloidal segment-to-segment jumpers, or saddle jumpers	Electrical arcs, local copper melting, excessive resistance and reduction in current flow, impurity influx into plasma, reduced performance	Visible camera, Infra Red (IR) camera, Residual Gas Analyzer (RGA), magnetic diagnostics	Repair when vacuum vessel accessible	UNLIKELY	MINOR
Loose connections leading to excessive contact thermal resistance on toroidal segment-to-segment jumpers.	Increased thermal resistance, higher plate temperatures during operations, lower plate temperatures during bakeout., higher thermal gradients, higher stresses, reduced performance	Thermocouples, IR camera.	Repair when vacuum vessel accessible	UNLIKELY	MINOR
Mechanical deformation/failure of supports due to eddy currents and electromagnetic forces.	Misalignment and/or dislocation of plate structures into plasma envelope, loss of machine operability	Visible camera	Shutdown, vent vacuum vessel, repair	UNLIKELY	MAJOR
Cooling circuit leak	Release of heat exchanger fluid into vacuum vessel	Residual Gas Analyzer (RGA)	Shutdown, vent vacuum vessel, repair, bakeout	UNLIKELY	MAJOR

WBS Element 1.1 Plasma Facing Components Component: Inboard & Outboard Divertors

Function: The Inboard & Outboard Divertors provide Scrape Off Layer (SOL) heat flux and impurity targets for diverted (X-point) plasmas. The Lower Inboard & Outboard Divertors provide the sink and source for the CHI current drive.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Outboard Divertor, Loose connections leading to excessive contact electrical resistance on plate-to-ring connections.	Electrical arcs, local copper melting, impurity influx into plasma, reduced performance	Visible camera, Infra Red (IR) camera, Residual Gas Analyzer (RGA), magnetic diagnostics	Repair when vacuum vessel accessible	UNLIKELY	MINOR

WBS Element 1.1 Plasma Facing Components Component: Inboard & Outboard Divertors (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Outboard Divertor, Mechanical deformation/failure of supports due to eddy currents and electromagnetic forces.	Misalignment and/or dislocation of plate structures into plasma envelope, loss of machine operability	Visible camera	Shutdown, vent vacuum vessel, repair	UNLIKELY	MAJOR
Outboard Divertor, Cooling circuit leak	Release of heat exchanger fluid into vacuum vessel	Residual Gas Analyzer (RGA)	Shutdown, vent vacuum vessel, repair, bakeout	UNLIKELY	MAJOR

See PFC Tile FMEA

WBS Element 1.1 Plasma Facing Components Component: NBI Protective Plates

Function: The Protective Plates consist of an array of graphite tiles mounted on a structure inside the NSTX vacuum vessel centered about the midplane at bays H & I. The system is designed to absorb neutral beam energy that is not absorbed by the plasma.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Tile overheating due to misalignment or non-conventional beam strike	Impurity influx into plasma, reduced performance	Visible camera, Infra Red (IR) camera, Residual Gas Analyzer (RGA) & Thermal couples	Terminate beam operation.	UNLIKELY	MINOR
Partial (cracked tile) or complete tile detachment from mounting surface/backplate due to thermal shock and/or eddy currents and electromagnetic forces.	Loose tile piece will fall down in vacuum vessel, could bridge isolating gap (e.g. ceramic insulator, passive plate toroidal gap, etc.), leading to localized diversion of plasma.	Visible camera, IR camera (depending on effect).	Vent machine & Repair tile, remove broken piece(s) when vacuum vessel accessible. Consider limitation of beam operation.	UNLIKELY	MINOR

WBS Element 1.1 Plasma Facing Components Component: NBI Protective Plates (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Tile support rail or T-bar or other mounting hardware detachment from mounting surface/backplate due to thermal shock and/or eddy currents and electromagnetic forces.	Loose metallic piece will fall down in vacuum vessel, could bridge isolating gap (e.g. ceramic insulator, passive plate toroidal gap, etc.), leading to localized diversion of plasma.	Visible camera, IR camera (depending on effect).	Shutdown, vent vacuum vessel, repair	UNLIKELY	MAJOR
Loose support connections leading to excessive contact electrical resistance	Electrical arcs, local copper melting, excessive resistance and reduction in current flow, impurity influx into plasma, reduced performance	Visible camera, Infra Red (IR) camera, Residual Gas Analyzer (RGA),	Repair when vacuum vessel accessible	UNLIKELY	MINOR
Loose tile connections leading to poor thermal contact.	Increased thermal resistance, higher plate temperatures during operations, lower plate temperatures during bakeout., higher thermal gradients, higher stresses, reduced performance	Thermocouples, IR camera & thermal couples	Repair when vacuum vessel accessible	UNLIKELY	MINOR
Mechanical deformation/failure of supports due to eddy currents and electromagnetic forces.	Misalignment and/or dislocation of plate structures into plasma envelope, loss of machine operability	Visible camera	Shutdown, vent vacuum vessel, repair	UNLIKELY	MAJOR
Cooling circuit leak	Release of heat exchanger fluid into vacuum vessel	Residual Gas Analyzer (RGA)	Shutdown, vent vacuum vessel, repair, bakeout	UNLIKELY	MAJOR

WBS Element 1.2 Vacuum Vessel & Support Structures **Component: Vacuum Vessel (VV)**

Function: **The primary function is to provide a high vacuum boundary suitable for plasma operations. The secondary function is providing structural support for vacuum ports/ducts, plasma heating, current drive and diagnostic systems.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
External leak during pump down. Cause: Failed port flange vacuum seal.	Vacuum level not achieved.	Residual Gas Analyzer Vacuum System Gauges	Repair seal.	NORMAL	MINIMAL
External leak during bakeout & normal operations. Cause: Failed port flange vacuum seal.	Loss of vacuum level.	Residual Gas Analyzer Vacuum System Gauges	Attempt temporary in situ repair, otherwise shutdown, vent VV, repair.	ANTICIPATED	MINOR
Out of dimensional tolerance. Cause: Excessive VV deformation.	Misalignment of attached components.	Visible & IR Cameras Diagnostics	Shutdown, vent VV, repair.	UNLIKELY	MAJOR
External leak. Cause: Failed structural materials or welds.	Loss of vacuum level.	Residual Gas Analyzer Vacuum System Gauges	Provisions: Inspect welds annually. Recovery: Shutdown, vent VV, repair.	UNLIKELY	MAJOR

WBS Element 1.2 Vacuum Vessel & Support Structures Component: Support Structures (SS)

Function: The SS includes all components required to mechanical support the: Vacuum Vessel, Center Stack, PF Coils and TF Coil Outer Legs. In addition, the SS provides dielectric breaks where required.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failed structural materials or welds. Cause: electromagnetic, vacuum and/or thermal loads.	Misalignment of components: VV, CS, coils, diagnostics, etc. Perturbation of magnetic field, Possible: mechanical damage electrical damage Ground or turn to turn faults. Loss of vacuum integrity Water leaks / damage	Monitor VV displacement. Maintenance Inspection, Visible & IR Cameras Diagnostics Residual Gas Analyzer System Pressure & Vacuum Gauges	Provisions: Maintenance Inspection. Recovery: Shutdown, vent VV, repair	UNLIKELY	MAJOR
Failure: Outer PF sliding joint. Cause: excessive resistance to sliding.	Misalignment of outer PF coils, Perturbation of magnetic field, Possible mechanical and/or electrical damage to PF coil	Maintenance Inspection, Diagnostics, Ground fault detector.	Provisions: Maintenance Inspection. Recovery: Shutdown, vent VV, repair	UNLIKELY	MAJOR
Failure: Outer PF sliding joint. Cause: excessive resistance to sliding.	Excessive stress and/or deformation, and possible mechanical damage in VV & SS. Misalignment of components.	Maintenance Inspection, Visible & IR Cameras Diagnostics	Provisions: Maintenance Inspection. Recovery: Shutdown, vent VV, repair	UNLIKELY	MAJOR
Failure: During bakeout umbrella structure sliding joint. Cause: excessive resistance to sliding.	Excessive stress and/or deformation, and possible mechanical damage in umbrella, VV & SS. Misalignment of components.	Inspection, Visible & IR Cameras Diagnostics	Provisions: Maintenance Inspection. Recovery: Shutdown, vent VV, repair	UNLIKELY	MAJOR

WBS Element 1.2 Vacuum Vessel & Support Structures Component: Support Structures (cont'd)

Failure Mode	***Effect***	***Detection***	***Recovery***	***Probability***	***Consequence***
Failure: During bakeout, VV leg support sliding joint. Cause: excessive resistance to sliding.	Excessive stress and/or deformation, and possible mechanical damage in support legs, VV & SS. Misalignment of components. Dislocation of VV, Loss of vacuum integrity	Monitor VV displacement. Maintenance Inspection, Visible & IR Cameras Diagnostics Residual Gas Analyzer Vacuum System Gauges	Provisions: Maintenance Inspection. Recovery: Shutdown, vent VV, repair	UNLIKELY	MAJOR
Failure: During non-CHI Ops of VV leg or Outer PF support dielectric joints.	Conducting electrical loops. Perturbation of magnetic field.	Inspection & Testing. Magnetic diagnostics, System ground and over current fault detection.	Provisions: Maintenance Inspection. Recovery: Shutdown and repair	UNLIKELY	MINOR
Failure: During CHI Ops of VV leg or Outer PF support dielectric joints.	Fault on CHI power supply, Electrical Damage.	Inspection & Testing. Magnetic diagnostics, System ground and over current fault detection.	Provisions: Maintenance Inspection. Recovery: Shutdown and repair	UNLIKELY	MINOR

WBS Element 1.3 Magnets Component: Outer PF Coils (WBS 1.3.1)

Function: The Outer PF Coils contribute the magnetic field topology required for plasma position and shape control.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage of cooling water circuit	Reduction in cooling water flow, reduction in rate of cooling between pulses[1].	Flow switches which are interlocked to prevent power supply operation	Shutdown & flush/ clear coolant passage.	UNLIKELY	MINOR
Leak in cooling water circuit	Depending on extent of leak, reduction in cooling water flow, possible ground fault	Flow switches[2], power supply system ground fault detection, visual inspection	Shutdown and repair.	UNLIKELY	MINOR
Delamination/debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None	None	UNLIKELY	MAJOR
Electrical failure of groundwall insulation at single location3	If non-CHI operations, or CHI operations and outer vacuum vessel grounded, small leakage current to ground (limited by high resistance grounding), and redistribution of voltage to ground. If CHI operations and outer vacuum vessel energized by CHI power supply, small leakage current between CHI and affected PF circuit.	Power supply system ground fault detector.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[1] During pulse, cooling is not significant and is not required

[2] Flow switches are located on return manifold such that flow must pass through coil in order to reach flow switch

[3] Multiple ground faults not considered herein

WBS Element: 1.3 Magnets Component: Outer PF Coils (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposite to direction of normal current flow to oppose flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil.	Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR
Loss of contact pressure leading to excess electrical contact resistance and /or open circuit condition under load at coil terminals or coil leads	Excess joint resistance and heating, arcing, melting, if lead(s) become physically disconnected, could be displaced from normal point of connection, possible diversion of current into other metallic path(s), possible destruction of coil[4].	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement); Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[4] Maximum stored magnetic energy in any NSTX coil is 3.75 MJoule (NSTX-SRD-5X-019)

WBS Element 1.3 Magnets Component: Outer TF Coils (WBS 1.3.2)

Function: The Outer TF Coils provide the return path for the Inner Leg TF Bundle

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage of coolant circuit	Reduction in coolant flow, reduction in rate of cooling between pulses[5].	Flow switches which are interlocked to prevent power supply operation	Shutdown and flush/clear coolant passage.	UNLIKELY	MINOR
Leak in coolant circuit	Depending on extent of leak, reduction in coolant flow, possible ground fault	Flow switches[6], power supply system ground fault detection, visual inspection	Shutdown and repair.	UNLIKELY	MINOR
Delamination/debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None	None	UNLIKELY	MAJOR
Electrical failure of groundwall insulation[7]	If non-CHI operations, or CHI operations and outer vacuum vessel grounded, small leakage current to ground (limited by high resistance grounding) and redistribution of voltage to ground. If CHI operations and outer vacuum vessel energized by CHI power supply, small leakage current between CHI and TF	Power supply system ground fault detector.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[5] During pulse, cooling is not significant and is not required

[6] Flow switches are located on return manifold such that flow must pass through coil in order to reach flow switch

[7] Multiple ground faults not considered herein

WBS Element 1.3 Magnets Component: Outer TF Coils (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposite to direction of normal current flow to oppose flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil.	Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR
Loss of contact pressure leading to excess electrical contact resistance and /or open circuit condition under load at coil terminals or coil leads	Excess joint resistance and heating, arcing, melting, if lead(s) become physically disconnected, could be displaced from normal point of connection, possible diversion of current into other metallic path(s), possible destruction of coil[8].	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement); Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[8] Maximum stored magnetic energy in any NSTX coil is 3.75 MJoule (NSTX-SRD-5X-019)

WBS Element 1.3 Magnets Component: TF Inner Leg Bundle (WBS 1.3.3.1)

Function: The TF Inner Leg Bundle current forms the toroidal field for plasma confinement.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage of coolant circuit	Reduction in coolant flow in blocked paths, differential temperature between turns in bundle, reduction in rate of cooling between pulses[9].	Flow switches which are interlocked to prevent power supply operation	Shutdown and flush/clear coolant passage	UNLIKELY	MINOR
Leak in coolant circuit	Depending on extent of leak, reduction in coolant flow, possible ground fault	Flow switches[10], power supply system ground fault detection, visual inspection	Shutdown and repair	UNLIKELY	MINOR
Delamination/debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None	None	UNLIKELY	MAJOR
Electrical failure of groundwall insulation[11]	Small leakage current to ground (limited by high resistance grounding), and redistribution of voltage to ground.	Power supply system ground fault detector	Shutdown, repair if possible, or replace	UNLIKELY	MAJOR
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposing current flow and flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil	Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace	UNLIKELY	MAJOR

[9] During pulse, cooling is not significant and is not required

[10] Flow switches are located on return manifold such that flow must pass through coil in order to reach flow switch

[11] Multiple ground faults not considered herein

WBS Element: 1.3 Magnets Component: TF Inner Leg Bundle (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
~~Loss of structural integrity of hub assembly and/or contact pressure on radial flags connecting inner legs to flexible connectors~~	~~Excess joint resistance and heating, possible contact surface melting, arcing, could lead to open circuit condition~~	~~Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement)~~	~~Shutdown and repair~~	DELETE	DELETE
TF Flexes- Inner to Outer TF coil- laminates begin to develop cracks	If crack propagates through entire laminate- Outer laminate in particular- the laminate could short to the umbrella lid or adjacent TF flexes	During visual maintenance inspections	Replace damaged TF flex bus	UNLIKELY	MAJOR
Loss of contact pressure on flexible joints connecting ~~radial flags~~ inner TF Bundle to outer legs	Excess joint resistance and heating, possible contact surface melting, arcing, could lead to open circuit condition	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement)	Shutdown and repair	UNLIKELY	MAJOR

WBS Element 1.3 Magnets Component: OH Solenoid (WBS 1.3.3.2)

Functio: The OH Solenoid provides loop voltage for plasma initiation and flux swing for inductive generation of plasma current

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage of cooling water circuit during normal operations[12,13]	Reduction in coolant flow and heat removal rate between pulses[14], reduced performance (reduced pulse repetition rate)	Flow switches which are interlocked to remove power supply permissive via PAUX relay	Monitor cooling water flows and temperatures, and OH coil groundwall temperatures, continue operations at reduced repetition rate or discontinue. Flush/clear coolant passage after shutdown.	UNLIKELY	MINOR
Blockage of cooling water circuit during bakeout	Reduction in coolant flow and heat removal rate, interruption of bakeout or reduction in allowable bakeout temperature	Flow switches and thermocouples measuring temperature of water returning to outlet manifold, thermocouples measuring temperature of OH groundwall insulation.	Discontinue heat input and/or switch to cooling, monitor cooling water flows and temperatures, and OH coil groundwall temperatures, continue bakeout at reduced temperature or discontinue. Flush/clear coolant passage after bakeout shutdown.	UNLIKELY	MINOR

[12] There are 8 parallel cooling water circuits; blockage of multiple circuits is not considered herein

[13] Sources of heat are I2R losses in coil plus heat flow inward from center stack casing

[14] During pulse, cooling is not significant and is not required

WBS Element: 1.3 Magnets Component: OH Solenoid (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Leak in cooling water circuit	Depending on extent of leak, reduction in cooling water flow, possible ground fault	Flow switches[15], power supply system ground fault detection, visual inspection	Shutdown and repair.	UNLIKELY	MAJOR
Delamination/ debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None	None	UNLIKELY	MAJOR
Electrical failure of groundwall insulation[16]	Small leakage current to ground (limited by high resistance grounding), and redistribution of voltage to ground.	Power supply system ground fault detector.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposite to direction of normal current flow to oppose flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil.	Magnetic diagnostics.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR
Delamination/ debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None	None	UNLIKELY	MAJOR
Electrical failure of groundwall insulation[17]	Small leakage current to ground (limited by high resistance grounding), and redistribution of voltage to ground.	Power supply system ground fault detector.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[15] Flow switches are located on return manifold such that flow must pass through coil in order to reach flow switch

[16] Multiple ground faults not considered herein

[17] Multiple ground faults not considered herein

WBS Element 1.3 Magnets Component: OH Solenoid (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposite to direction of normal current flow to oppose flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil.	Magnetic diagnostics.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR
Mechanical failure of in-line conductor[18] or conductor joint	High resistance, overheating, arcs, burning, melting	Excessive coil impedance	Shutdown, remove center stack and OH coil, repair if possible, or replace	UNLIKELY	MAJOR
Loss of contact pressure leading to excess electrical contact resistance and /or open circuit condition under load at coil terminals or coil leads	Excess joint resistance and heating, arcing, melting, if lead(s) become physically disconnected, could be displaced from normal point of connection, possible diversion of current into other metallic path(s), possible destruction of coil[19].	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement); Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[18] OH coil conductor lifetime is fatigue limited (function of number of pulses at various load levels)

[19] Maximum stored magnetic energy in any NSTX coil is 3.75 MJoule (NSTX-SRD-5X-019)

WBS Element 1.3 Magnets Component: Shaping Coils (PF1a, PF1b and PF1c) (WBS 1.3.3.3)

Function: The PF coils shall provide field nulling for plasma initiation and shall provide equilibrium and shape control during sustainment.

~~PF1a provides plasma shaping. PF1b provides control of the shape of the X-point for CHI and provides a means for plasma current Rogowski Loop calibration.~~

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage of cooling water circuit	Reduction in cooling water flow, reduction in rate of cooling between pulses[20].	Flow switches which are interlocked to prevent power supply operation	Shutdown and flush/clear coolant passage.	UNLIKELY	MINOR
Leak in cooling water circuit	Depending on extent of leak, reduction in cooling water flow, possible ground fault	Flow switches[21], power supply system ground fault detection, visual inspection	Shutdown and repair.	UNLIKELY	MINOR
Delamination/debonding of turn-to-turn insulation	Possible motion of conductors under load, abrasion, eventual electrical failure	None	None	UNLIKELY	MAJOR
Electrical failure of groundwall insulation[22]	Small leakage current to ground (limited by high resistance grounding), and redistribution of voltage to ground.	Power supply system ground fault detector.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR
Electrical failure of turn-to-turn insulation	Fault current flow in shorted turns, opposite to direction of normal current flow to oppose flux produced by non-shorted turns, large internal repulsive forces between shorted and non-shorted turns, arcing, burning, and melting in region of failure, possible destruction of coil.	Magnetic diagnostics.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

[20] During pulse, cooling is not significant and is not required

[21] Flow switches are located on return manifold such that flow must pass through coil in order to reach flow switch

[22] Multiple ground faults not considered herein

WBS Element: 1.3 Magnets Component: Shaping Coils (PF1a, PF1b and PF1c) (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of contact pressure leading to excess electrical contact resistance and /or open circuit condition under load at coil terminals or coil leads	Excess joint resistance and heating, arcing, melting, if lead(s) become physically disconnected, could be displaced from normal point of connection, possible diversion of current into other metallic path(s), possible destruction of coil[23].	Maintenance (bolt torque), inspection (temperature stickers), test (joint resistance measurement); Magnetic diagnostics, unusual electrical impedance and response to power supply excitation.	Shutdown, repair if possible, or replace.	UNLIKELY	MAJOR

WBS Element 1.3 Magnets Component: Center Stack Casing (WBS 1.3.3.4)

Function: The Center Stack Casing provides the inner vacuum boundary, and is physically connected to the vacuum vessel but electrically isolated via ceramic insulator assemblies. The Inner Wall PFC's are attached to and supported by the Center Stack Casing. Thermal Insulation within the Center Stack Casing bore serves to thermally isolate the OH coil from the casing. Pedestal mounted to test cell floor provides support and dielectric breaks.

Failure Mode	**Effect**	**Detection**	**Recovery**	**Probability**	Consequence
Excessive deformation of structural materials	Misalignment of PFC components.	Visible Camera, Infrared (IR) camera, magnetic diagnostics	Shutdown, vent vacuum vessel, repair	UNLIKELY	MINOR
Failure of structural materials or welds	Vacuum Leak	Residual Gas Analyzer (RGA), and Vacuum Pumping System pressure gauges	Shutdown, vent vacuum vessel, repair	UNLIKELY	MINOR

[23] Maximum stored magnetic energy in any NSTX coil is 3.75 MJoule (NSTX-SRD-5X-019)

WBS Element 1.3 Magnets Component: Center Stack Casing (WBS 1.3.3.4)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure of vacuum seal connections	Vacuum Leak	Residual Gas Analyzer (RGA), and Vacuum Pumping System pressure gauges	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINOR
Electrical breakdown of ceramic insulator	During non-CHI operations, conducting electrical loops, perturbation of magnetic field. During CHI operations, fault on CHI power supply, arcing, burning, melting, possible loss of vacuum conditions	Power supply overcurrent and ground fault detection, Visible Camera, Infrared (IR) camera, magnetic diagnostics, Residual Gas Analyzer (RGA), and Vacuum Pumping System pressure gauges.	Shutdown, vent vacuum vessel, repair if possible or replace	UNLIKELY	MAJOR
Electrical breakdown of thermal insulation	If during CHI operations with center stack casing energized, fault current flow through OH coil ground plane and instrumentation mounted thereon, arcing, burning, melting, possible OH ground fault and possible destruction of OH coil.	OH and CHI power systems ground fault detection systems.	Shutdown, remove center stack assembly and OH coil, repair if possible or replace.	UNLIKELY	MAJOR

WBS Element 1.3 Magnets Component: Center Stack Casing (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Degradation of thermal insulation due abrasion, heat, or coolant leak from coil system etc.	Low thermal resistance between center stack casing and OH/PF1a, excess temperature rise on OH/PF1a coil ground plane, reduced performance (reduced repetition rate and bakeout temperature).	Thermocouples on OH and PF1a coil ground planes.	Shutdown, remove center stack assembly and repair or replace thermal insulation	UNLIKELY	MAJOR

WBS Element 1.3 Magnets Component: Water Cooled Flexible Cable Leads

Function: The Water Cooled Flexible Cable Leads provide the electrical connection between the terminals of the WBS 5 air cooled bus and the magnet coil terminals

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Water leak	Water on floor, depending on extent of leak, possibly draining to Liquid Effluent Collection (LEC) tank, possible ground fault, small leakage current to ground limited by high impedance grounding resistors	Depending on extent of leak, flow switch drop out, ground fault indication on power supply system ground fault detector	Repair or replace	UNLIKELY	MINOR

WBS Element 1.3 Magnets Component: Water Cooled Flexible Cable Leads (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electrical breakdown of dielectric	Likely to occur on one conductor first, accompanied by a water leak, possible ground fault, small leakage current to ground limited by high impedance grounding resistors, prior to developing unnoticed into a line-line fault	Water leak and/or electrical leakage to ground, depending on extent of water leak, possible flow switch drop out, possible ground fault indication on power supply system ground fault detector	Repair or replace	UNLIKELY	MINOR

2 Plasma Heating and Current Drive Systems

WBS Element 2.1 High Harmonic Fast Wave (HHFW) Radio Frequency (RF) System

Function: High Harmonic Fast Wave (HHFW) Radio Frequency (RF) System provides plasma heating and current drive.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Plasma strike on HHFW antenna loops	Could impress high voltage on antenna loops	Plasma TV	Plasma striking the antenna loops is prevented by Faraday shields	ANTICIPATED	MINIMAL
Faraday shield HHFW antenna loop ablated by severe plasma strike	Could impress high voltage on antenna loops	Plasma TV	In the unlikely event of a Faraday shield failure, current flowing on the transmission line inner conductor is prevented from getting out of the Test Cell area by the antenna's DC breaks	UNLIKELY	MINOR

WBS Element 2.1 High Harmonic Fast Wave (HHFW) Radio Frequency (RF) System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Plasma strike on HHFW antenna loops	Could impress high voltage on antenna loops	Plasma TV	Plasma striking the antenna loops is prevented by Faraday shields	ANTICIPATED	MINIMAL
HHFW antenna's inner conductor DC breaks short out	Could impress high voltage on transmission line(s) center conductor(s)	Ground fault detector, routine vacuum vessel Hi-pot	Shunted via chokes between the inner and outer conductors in the antenna's Tuning and Matching components	UNLIKELY	MINOR
HHFW antenna's outer conductor DC breaks short out	Could impress high voltage on transmission line(s) outer conductor(s)	Ground fault detector, routine vacuum vessel Hi-pot	Shunted via grounding cables connecting transmission lines outer conductors to building steel and grounding mats along lines' entire path	UNLIKELY	MINOR
HHFW RF power transfer switch atop the RF Enclosure in the MockUp Building in ENABLED (unsafe) position while personnel are in the Test Cell	Could direct RF power into the Test Cell	NSTX Hardwired Interlock System (HIS)	HIS monitors the positions of all D-Site RF transfer switches and imposes RF global E-STOP should any switch be in the ENABLED position during access to the NSTX Test Cell.	EXTREMELY UNLIKELY	MINOR

WBS Element2.1 High Harmonic Fast Wave (HHFW) Radio Frequency (RF) System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Mechanical damage punctures outer conductor of HHFW transmission line	Possible RF radiation exposure of personnel in vicinity of puncture	Pressure switches in transmission lines	The HHFW hardwired control system monitors gas pressure in the transmission line. It automatically prohibits rf pulsing should the pressure in any line drop below its set point	EXTREMELY UNLIKELY	MINOR
HHFW transmission line flange not tightened after servicing	Possible RF radiation exposure of personnel in vicinity of loose flange	Standard test procedure	RF radiation survey is performed whenever the transmission lines are serviced. The survey is also performed annually. Any leaks are immediately repaired	ANTICIPATED	MINOR
Anode DC-blocking capacitor in HHFW high power amplifier shorts out	Could impress high voltage on transmission line center conductor	High Voltage Power Supply (HVPS) over-current interlocks	Shunted via chokes between the inner and outer conductors in the amplifiers' output transmission lines	UNLIKELY	MINOR

WBS Element: 2.1 High Harmonic Fast Wave (HHFW) Radio Frequency (RF) System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Lightning strike or other phenomena that may cause difference in potential between D-Site and C-Site building steel	Could impress high voltage on Control wiring from D-Site to C-Site	None	In the event that an appreciable difference in potential occurs between the building steel at each Site, gas-filled spark gaps limit "touch" potential to < 15 volts at either end of the control wiring.	UNLIKELY	MINOR
Unplanned loss of AC power at D-Site	Possible loss of coordination between D-Site RF transfer switches and NSTX Test Cell access state	NSTX Hardwired Interlock system (HIS) and HHFW local control system	A loss of AC power at D-Site causes a loss in the "NOT E-STOP" Hardwired Interlock System signal to the HHFW System. This automatically precipitates an Emergency Stop to the HHFW System, opening all of its high voltage power supply circuit breakers	ANTICIPATED	MINOR
Unplanned loss of water to NTC HHFW Antenna	Possible thermal stress or failure to HHFW antenna	RF PLC	Loss of water in NTC causes RF controls to inhibit high power RF pulsing	ANTICIPATED	MINOR

WBS Element 2.2 Coaxial Helicity Injection (CHI) System

Function: **The Coaxial Helicity Injection (CHI) Current Drive System provides non-inductive plasma current drive by providing a potential difference between the center stack casing and the outer vacuum and injecting a current. Components involved are the CHI buswork, the lower inboard and outboard PFCs (which act as electrodes, see WBS 1.1), the CHI power supply (see WBS 5) and the lower dome gas injection systems (see WBS 3.4). Only the buswork is covered in this section. The buswork is also used to carry current during ohmic heating of the center stack casing during bakeout operations.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage or leakage of cooling water circuit during normal operations	Reduction in cooling water flow in water circuit involving CHI and other water cooled cable conductors in same water circuit, reduction in rate of cooling, possible ground fault	Flow switches which are interlocked to prevent power supply operation, ground fault detection	Shutdown normal operations and restore integrity of coolant passage.	UNLIKELY	MINIMAL
Blockage or leakage of cooling water circuit during bakeout	Reduction in cooling water flow in water circuit involving CHI and other water cooled cable conductors in same water circuit, reduction in rate of cooling, possible overheating of bus due to latent heat from center stack casing	Flow switches which are interlocked to prevent power supply operation, visual inspection	Shutdown bakeout operations and restore integrity of coolant passage.	UNLIKELY	MINIMAL
Electrical failure of insulation	If line to line, CHI power supply short circuit, overcurrent, large forces, heating, arcing, burning; if line to ground, CHI ground fault, small fault current, limited heating and burning of insulation.	Power supply system overcurrent and ground fault detection.	Shutdown, repair if possible, or replace.	UNLIKELY	MINIMAL

WBS Element 2.2 Coaxial Helicity Injection (CHI) System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure of structural support due to electromagnetic loads during normal operation	Possible open circuit, joint resistance heating, arcing, melting, possible ground fault, possible diversion of current into other metallic path(s).	Improper circuit electrical function and/or ground fault, visual inspection of impending condition during maintenance	Shutdown, repair if possible, or replace.	UNLIKELY	MINIMAL
Fail to deliver CHI power on receipt of trigger signal from central control system	Loss of pre-ionization function, reduced plasma performance	Transient digitizer analysis	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element 2.3 Electron Cyclotron Heating (ECH) System

Function: **The ECH System provides pre-ionization of the plasma fuel gas to facilitate avalanche breakdown and inductive current drive by the OH loop voltage. The ECH power supply and all waveguide/launcher components are located in the NSTX Test Cell. The input 480V AC circuit breaker is interlocked with the Hardwired Interlock System and Test Cell access control.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Fail to deliver RF power on receipt of trigger signal from central control system	Loss of preionization function, reduced plasma performance	Transient digitizer analysis	Troubleshoot and repair	ANTICIPATED	MINIMAL
Delivery of RF power outside time window of trigger signal	If during pulse, minor deviation from expected auxiliary heating profiles, if outside pulse window (in vacuum) possible overheating of internal vacuum vessel wiring or damage to sensitive diagnostics	Transient digitizer analysis, RGA analysis	Troubleshoot and repair	ANTICIPATED	MINIMAL

WBS Element 2.3 Electron Cyclotron Heating (ECH) System (Cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Fail to deliver RF power on receipt of trigger signal from central control system	Loss of preionization function, reduced plasma performance	Transient digitizer analysis	Troubleshoot and repair	ANTICIPATED	MINIMAL
Delivery of RF power outside time window of trigger signal	If during pulse, minor deviation from expected auxiliary heating profiles, if outside pulse window (in vacuum) possible overheating of internal vacuum vessel wiring or damage to sensitive diagnostics	Transient digitizer analysis, RGA analysis	Troubleshoot and repair	ANTICIPATED	MINIMAL
Electrical breakdown of DC break	If CHI operations with outer vacuum vessel energized, ground fault for CHI power supply, small fault current flow through waveguide, arcing, burning, melting. Otherwise, ground loop eddy currents and very minor magnetic field perturbation.	If CHI operations , power supply ground fault detection. Otherwise, detected at time of next vacuum vessel hipot.	Repair if possible or replace	UNLIKELY	MINIMAL
Launcher/window vacuum leakage	Depending on leak, possible interruption of operations	Pressure instrumentation, rate of rise measurements	Depending on leak rate, shutdown, vent vacuum vessel, repair or replace	UNLIKELY	MINOR
RF leakage from power supply enclosure or waveguide	RF energy outside waveguide in test cell[24], possible malfunction of nearby electrical equipment	Periodic RF surveys	Repair waveguide/shielding	UNLIKELY	MINOR

[24] Note: No personnel will be present in NSTX Test Cell during ECH operations

WBS Element 2.3 Electron Cyclotron Heating (ECH) System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Unplanned loss of water to ECH source equipment	Possible thermal stress or failure of ECH klystrons	RF PLC	Loss of water in NTC causes RF controls to remove high voltage from ECH klystrons	ANTICIPATED	MINOR
Attempted energization of ECH during personnel access in the Test Cell	Possible RF radiation exposure of personnel in Test Cell	NSTX Hardwired Interlock System (HIS)	HIS monitors status of the ECH PI 480VAC and imposes an RF global E-STOP should it be ENABLED during general personnel access in the NSTX Test Cell.	UNLIKELY	MINOR
480V AC main input circuit breaker failure to close	Unable to operate ECH	EPICs Process Control	De-energize AC input power at higher level, access NTC, troubleshoot and repair	ANTICIPATED	MINOR
480V AC main input circuit breaker failure to open	Indication to Hardwired Interlock System (HIS) preventing normal means of access to NSTX Test Cell (NTC)	HIS "unsafe" indication	De-energize AC input power at higher level, access NTC, troubleshoot and repair	UNLIKELY	MINOR
480V AC main input circuit breaker failure to open	Indication to Hardwired Interlock System (HIS) preventing normal means of access to NSTX Test Cell (NTC)	HIS "unsafe" indication	De-energize AC input power at higher level, access NTC, troubleshoot and repair	UNLIKELY	MINOR

WBS Element 2.3 Electron Cyclotron Heating (ECH) System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Leakage of Dielectric Fluid[25] from HV Tank	Fluid contained in collection tray with hose-connection to drum below, possible electrical breakdown if significant quantity lost	Maintenance inspection, or functional failure if significant quantity lost	Repair leak and/or electrical components	UNLIKELY	MINOR

WBS Element 2.4 Neutral Beam Injection (NBI) System Component: General

Function: **The NBI System provides plasma heating via one TFTR beam line, consisting of three ion sources injecting 80keV neutral particles at 5MW for pulses of 5 second duration, or up to 110 keV particles for pulses up to 1 second duration, into the NSTX plasma. In addition, brief (50mS) conditioning pulses are performed between NSTX machine discharges, without plasma, with the NBI power being deposited on the protective plates.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Misoperation of Accel Power System, or Auxiliary Power System, Ion Sources, Beam Line Accelerating Systems, or Control System, *NBI power waveform does not conform to pre-programmed request.*	One or more ion sources fails to deliver intended power vs. time to plasma.	Physics waveforms	Troubleshoot and repair. Depending on cause of fault, could require access to NTC.	ANTICIPATED	MINIMAL
Misoperation of Control System, *NBI power is injected outside of normal intended time interval.*	Unintended NBI power is deposited on protective plates, possible overheating.	Physics waveforms	Troubleshoot and repair.	ANTICIPATED	MINIMAL
Failure of plasma permissive interlock, *NBI occurs in absence of plasma.*	Unintended NBI power is deposited on protective plates.[26]	Physics waveforms	Troubleshoot and repair.	UNLIKELY	MINIMAL

WBS Element: 2.4 Neutral Beam Injection (NBI) System Component: NBI Duct

Function: **The NBI Duct provides a means for connection to the NSTX vacuum vessel. Equipment consists of the flange connections to vacuum vessel, bellows assemblies and flanges, Torus Isolation Gate Valve (TIV), ceramic**

[25] "R-Temp" high flame temperature oil

[26] Protective plate armor is designed to absorb 5MW-5sec without damage.

insulator assembly and flanges (on NSTX side of TIV), and protective scraper plates to protect the duct wall and TIV from beam divergence. The TIV provides a vacuum seal for the NBI at atmosphere with NSTX at vacuum, or vice-versa. Actuation time from open to closed position, or vice-versa, is 30 seconds.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Excessive deformation of structural materials	Depending on extent, could involve buckling of duct, and/or vacuum leak, possible interruption of operations; in case of major vacuum leak, will result in automatic closure of TIV.	Pressure instrumentation, rate of rise measurements	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	EXTREMELY UNLIKELY	MINOR
Failure of structural materials or welds	"	"	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	EXTREMELY UNLIKELY	MINOR
Failure of vacuum seal connections	Vacuum leak, possible interruption of operations	"	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINOR

WBS Element: 2.4 Neutral Beam Injection (NBI) System Component: NBI Duct (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electrical breakdown of ceramic insulator	If CHI operations, ground fault for CHI power supply, small fault current, arcing, burning. Otherwise, ground loop eddy currents and very minor magnetic field perturbation.	If CHI operations , power supply ground fault detection. Otherwise, detected at time of vacuum vessel hipot.	Depending on leakage resistance, and need to operate CHI, shutdown, vent NSTX, repair.	UNLIKELY	MINOR
TIV Failure to Fully Open	Beam pathway to torus is partially or totally blocked preventing NBI operations.	No "beam ready to arm" indication	Troubleshoot and repair, depending on failure, could require venting NSTX.	UNLIKELY	MINOR
TIV Failure to Fully Close	Inability to seal NB duct and beam line from NSTX vacuum vessel.	Ion gauges read pressures from vessel activity	Troubleshoot and repair, depending on failure, could require venting NSTX.	UNLIKELY	MINOR
TIV Excess leakage across valve	"	Ion gauges read pressures from vessel activity	Troubleshoot and repair, depending on failure, could continue operations via vacuum pumping and cryopumping on NBI side of valve, could require venting NSTX.	ANTICIPATED	MINOR
TIV Excessive leakage across valve during TMB operation	Very small amounts of TMB may be pumped on cryopanels if plasma discharge or GDC current extinguishes during boronization	Ion gauges reading increase during He pre-glow period in TMB procedure.	Halt TMB procedure. Cycle/repair valve or suspend TMB operation.	ANTICIPATED	MINOR

WBS Element 2.4 Neutral Beam Injection (NBI) System **Component: NBI Vacuum Vessel**

Function: **The NBI Vacuum Vessel provides the main vacuum envelope for the NBI Beam Line Accelerating Systems, and the NBI Cryopumping systems**.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Excessive deformation of structural materials	Depending on extent, could involve buckling of duct, and/or vacuum leak, possible interruption of operations; in case of major vacuum leak, will result in automatic closure of TIV, possible fast regeneration of cryopumping system (see FMEA entry for NBI Cryopumping System).	Pressure instrumentation, rate of rise measurements	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	INCREDIBLE	MINOR
Failure of structural materials or welds	"	"	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	INCREDIBLE	MINOR
Failure of vacuum seal connections	Vacuum leak, possible interruption of operations, possible fast regeneration of cryopumping system (see FMEA entry for NBI Cryopumping System).	"	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINOR

WBS Element: 2.4 Neutral Beam Injection (NBI) System Component: Beam Line Acceleration System

Function: The Beam Line Accel System consists of the Ion Sources, Neutralizers, Deflection Magnets, Ion Dumps, Beam Scrapers, and the Calorimeter, and the associated water cooling system.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Incorrect aiming of beamline and/or abnormal divergence.	Impingement of beamline onto duct scrapers and/or protective plates in duct, local melting/sputtering of metallic surfaces.	Thermocouple monitoring	Steering alignment	ANTICIPATED	MINIMAL
Ion Source filament, arc, or accel grid misoperation.	Reduced generation of beam current; affected power supply shutdown, but continued operation of other ion sources.	Source waveforms	Troubleshoot and repair; if source hardware failure involved, repair or replace affected source during maintenance period.	ANTICPATED	MINIMAL
Neutralizer misoperation	Reduced neutralization, excess ion current, mismatch with deflection magnet current, ions are not efficiently deflected onto the ion dump but are sprayed on to the beam scrapers in the beam box and duct, local melting/sputtering of metallic surfaces.	Ion gauge waveform abnormal, loss of beam ready to arm due to magnet power supply controller	Reset bending magnet, repair beamline if required	ANTICIPATED	MINIMAL

WBS Element: 2.4 Neutral Beam Injection (NBI) System Component: Beam Line Acceleration System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Ion deflection magnet misoperation	Ions are not efficiently deflected onto the ion dump but are sprayed on to the beam scrapers in the beam box and duct, local melting/sputtering of metallic surfaces.	Ion gauge waveform abnormal, loss of beam ready to arm due to magnet power supply controller	Reset bending magnet, repair beamline if required	ANTICIPATED	MINIMAL
Loss of water cooling system to one or more beam line components	Low flow and/or high water exit temperature to affected component, NBI shutdown via interlocks, possible freezing of water lines, possible leak (see next FMEA entry)[27].	Flow and temperature interlocks.	Troubleshoot and repair; if beam line hardware failure involved, repair or replace affected components during maintenance period.	ANTICIPATED	MINIMAL
Water leak from ion source, ion dump, calorimeter, beam scraper, neutralizer, or deflection magnet.	Depending on size of leak, vacuum vessel pressure rise; shutdown of water system;, water condensation on cryopanels; cryopumping system shutdown; possible fast regeneration of cryopumping system (see FMEA entry for NBI Cryopumping System);possible closure of TIV, possible opening of pressure relief valve; discharge of water into local containers.	Pressure instrumentation, rate of rise measurements	Repair or replace component(s) during maintenance period.	ANTICIPATED	MINOR

[27] Water circulation systems use standby diesel generator power, plus an additional back-up electrical generator in case of failure of main standby diesel generator

WBS Element: 2.4 Neutral Beam Injection (NBI) System Component: Beam Line Acceleration System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
SF_6 leak in NTC or NBI Power Conversion Building[28]	SF6 detectors sound alarm and close valves on SF6 supply skid, small quantity of SF6 released.	SF6 detectors	Shutdown NBI operations and repair leak.	ANTICIPATED	MINOR
SF_6 leak into ion source.	Ion source misoperation and shutdown; possible closing of source isolation valve. If valve remains open, SF_6 is trapped on cryopanels and subsequently pumped from machine when panels are regenerated. If valve closes, gas is pumped out via source roughing system.	Poor base pressure, rate of rise in source during regens, poor source performance	Repair or replace affected ion source during maintenance period	ANTICIPATED	MINOR
Calorimeter failure to raise	Beam pathway to torus is partially or totally blocked preventing NBI operations.	No ready to arm, no beam	Troubleshoot and repair; if necessary repair or replace affected assembly during maintenance period via venting of NBI vacuum vessel.	ANTICIPATED	MINOR
Calorimeter failure to lower	Inability to perform beam power calibration shots.	No ready to arm, no beam	Troubleshoot and repair; if necessary repair or replace affected assembly during maintenance period via venting of NBI vacuum vessel.	ANTICIPATED	MINOR

WBS Element 2.4 Neutral Beam Injection (NBI) System Component: Cryopumping System

Function: The cryopumping system assists the active pumping systems to maintain high vacuum in the NBI vacuum vessel and duct, and the NSTX vacuum vessel, via cryocondensation on to liquid helium (LHe) cooled panels guarded by

[28] Leakage along route from NBPC through pump room and mechanical equipment room to NTC is considered extremely unlikely due to use of all-welded piping.

liquid nitrogen (LN_2) cooled panels. System consists of the LHe and LN refrigeration systems, piping systems, and cryopanels in the NBI vacuum vessel.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Cryopumping system, cryogen supply low flow or high inlet temperature.	Depending on nature/extent of reduction in supply, reduction in cryopumping effectiveness; possible NBI shutdown; possible regeneration (boil off) of absorbed gases (exhausted by vacuum pumping systems); possible fast regeneration of cryopumping system (see FMEA below).	Operator annunciated fault condition by PLC, security, and procedural phone calls to cog engineer	Operator adjustments, repair refrigerator.	ANTICIPATED	MINIMAL
Fast regeneration of Cryopumping System.	Rupture of pressure relief (burst) disks external to NBI vacuum vessel box, inside NTC; cryogen supply valves will close; cryogenic vapors will be released into NTC; boil-off of condensed gases from cryopanels, will be released to vacuum vessel and exhausted by vacuum pumping system; NBI TIV will close.	Operator annunciated fault condition by PLC, security, and procedural phone calls to cog engineer	Operator adjustments, repair refrigerator.	ANTICIPATED	MINIMAL
High H concentration in pumping exhaust during regeneration	Potential explosion hazard[29]	Vacuum gauge reading during regenerations	Pump out lines	ANTICIPATED	MINIMAL

WBS Element: 2.4 Neutral Beam Injection (NBI) System Component: Cryopumping System (con't)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Cryogenic line inward leakage to	Potential explosion hazard.	Loss of thermal	Pump out lines	ANTICIPATED	MINOR

[29] Administrative procedures limit maximum allowable condensed H_2. PLC control sequence includes N_2 purge before and after pumping gases liberated from both routine and emergency regenerations. These measures are taken to preclude potential development of explosive mixtures.

vacuum jacketed supply lines and condensation of oxygen[30]		resistance of jacket, excess temperature rise of cryogens.			
Cryogenic line rupture external to NBI vacuum vessel.	Release of cryogenic fluid and vapor into NTC, cryogen supply valves will close, NBI TIV will close, fast regeneration will occur (see prior FMEA entry).	Plumes	Repair lines	ANTICIPATED	MINOR
Cryogenic line rupture internal to NBI vacuum vessel.	Release of cryogenic fluid and vapor into NBI vacuum vessel, cryogen supply valves will close, NBI TIV will close, fast regeneration will occur (see prior FMEA entry).	Ion gauge	Vent beamline, repair leak, or replace beamline cryo panels	ANTICIPATED	MINOR

WBS Element 2.4 Neutral Beam Injection (NBI) System **Component: Local PLC Controller**

Function: Provides PLC based operator interface and interlocks for NBI equipment protection.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of PLC functionality	Shutdown of NBI, all power supply systems, valves and pumps revert to safe state, interruption of machine operations	Status signals to EPICS Process Control System and PLC monitor	Troubleshoot and repair	ANTICIPATED	MINIMAL

[30] Very unlikely due to all-welded pipe construction.

WBS Element 2.4 Neutral Beam Injection (NBI) System Component: Local PLC Controller

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
PLC I/O failure	Loss of action/reaction confirmation, PLC alarm condition	PLC logic	Troubleshoot and repair	ANTICIPATED	MINIMAL

3. Auxiliary Systems

WBS Element: 3.1 Vacuum Pumping System Component: Main Pumping Duct

Function: The main pumping duct, consisting of flange connection to vacuum vessel, bellows assembly and flanges, ceramic insulator assembly and flanges, as well as tee ducts and flanges for connections to TMP and Roughing isolation valve assemblies, provides the physical means for connection of the pumping system to the vacuum vessel, as well as provision for interface of diagnostics and vacuum pumping I&C [including the Residual Gas Analyzer (RGA)].

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Excessive deformation of structural materials	Depending on extent, could involve buckling of duct, and/or vacuum leak, possible interruption of operations	Pressure instrumentation, rate of rise measurements	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	EXTREMELY UNLIKELY	MINOR
Failure of structural materials or welds	"	"	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL
Failure of vacuum seal connections	Vacuum leak, possible interruption of operations	"	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL

WBS Element: 3.1 Vacuum Pumping System Component: Main Pumping Duct (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electrical breakdown of ceramic insulator	If CHI operations with outer vacuum vessel, ground fault for CHI power supply, small fault current, arcing, burning. Otherwise, ground loop eddy currents and very minor magnetic field perturbation.	If CHI operations , power supply ground fault detection. Otherwise, detected at time of next vacuum vessel hipot.	Shutdown, vent vacuum vessel, repair if possible or replace	UNLIKELY	MINIMAL

WBS Element 3.1 Vacuum Pumping System Component: Turbomolecular Pumps (TMP)

Function: The Turbomolecular Pumps (TMP) and associated duct, bellows, isolation valve, backing valve, and flange which connects to the main pumping duct provide the high vacuum pumping of the vacuum vessel.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Vacuum leak on duct side of isolation valve	Vacuum leak, possible interruption of operations	Pressure instrumentation, rate of rise measurements	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL
Vacuum leak on pump side of isolation valve	Vacuum leak, possible interruption of operations, or reduced pumping speed	"	Close valve, repair leak	UNLIKELY	MINIMAL
Isolation valve closed, vacuum leak across isolation valve seat	Depending on leak rate and state of TMP, possible interruption of operations	Pressure instrumentation	Depending on leak rate, back fill TMP volume with He, or shutdown, vent vacuum vessel, repair	ANTICIPATED	MINIMAL

WBS Element 3.1 Vacuum Pumping System Component: Turbomolecular Pumps (TMP)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Isolation valve fail to close	No immediate effect	PLC logic	Troubleshoot and repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL
Isolation valve fail to open	Reduction in pumping capability, reduced performance	PLC logic	Troubleshoot and repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL
TMP failure (fail to start, or trip)	Reduction in pumping capability, reduced performance	TMP instrumentation and/or PLC logic	Close isolation valve, backfill TMP volume with N_2, repair	UNLIKELY	MINOR
TMP foreline valve fail to open	-Loss of TMP and reduced pumping speed and possible interruption of machine operations	PLC logic	Close all TMP isolation and backing valves, repair	UNLIKELY	MINOR

WBS Element: 3.1 Vacuum Pumping System Component: Roughing Pump Skid

Function: Roughing Pump Skid and associated duct, bellows, isolation valve, nitrogen vent valve, and flange connect to the main pumping duct to provide rough pumping of the vacuum vessel. Note: The roughing pump skid is shared with the NBI system, and is controlled by the NBI PLC.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Vacuum leak on duct side of isolation valve	Vacuum leak, possible interruption of operations	Pressure instrumentation, rate of rise measurements	Provide temporary repair in situ if possible, otherwise shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL
Vacuum leak on pump side of isolation valve	"	"	Close valve, repair leak	UNLIKELY	MINIMAL

WBS Element: 3.1 Vacuum Pumping System Component: Roughing Pump Skid

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Isolation valve closed, vacuum leak across isolation valve seat	Depending on leak , possible interruption of operations	Pressure instrumentation	Depending on leak rate, back fill TMP volume with He, or shutdown, vent vacuum vessel, repair	UNLIKELY	MINIMAL
Isolation valve fail to open	Rough pumping not available, pump down and machine operations precluded	PLC logic	Troubleshoot and repair	UNLIKELY	MINIMAL
Isolation valve fail to close	Transition from rough pumping to high vacuum pumping not possible, machine operations precluded	PLC logic	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element 3.1 Vacuum Pumping System Component: Backing Pump Skid

Function: Backing Pumps and associated duct, nitrogen vent valve, and flange connect to the TMPs backing isolation valve to provide low pressure conditions on back side of TMPs.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Vacuum leak in foreline	Possible interruption of operations	Pressure instrumentation, rate of rise measurements	Close TMP backing isolation valve and TMP foreline valves, backfill TMPs with N_2, repair leak	UNLIKELY	MINIMAL
Pump failure (fail to start, or trip)	High vacuum pumping precluded, interruption of operations	Pressure instrumentation and/or PLC logic	Close isolation valve, backfill TMP volume with N_2, repair	UNLIKELY	MINIMAL

WBS Element 3.1 Vacuum Pumping System Component: Backing Pump Skid (cont'd)

Backing skid valve fails to open	TMP operations precluded, interruption of NSTX operations	Pressure instrumentation and/or PLC logic	Backfill TMP with N_2 and repair	UNLIKELY	MINIMAL

WBS Element 3.1 Vacuum Pumping System Component: N2 Vent Valves
Function: Provide connections to N_2 source for backfilling TMP, Backing, and Roughing volumes

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
N_2 Vent Valve of TMP system leaks or fails to stay closed	Automatic isolation of effected system, possible interruption of operations	Pressure instrumentation and PLC monitor	Troubleshoot and repair	UNLIKELY	MINIMAL
N_2 Vent Valve of Backing system leaks or fails to stay closed	Automatic isolation of effected system, possible interruption of operations	Pressure instrumentation and PLC monitor	Troubleshoot and repair	UNLIKELY	MINIMAL
N_2 Vent Valve of Roughing system leaks or fails to stay closed	Automatic isolation of effected system, possible interruption of operations	Pressure instrumentation and PLC monitor	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element 3.1 Vacuum Pumping System Component: Vacuum Pumping System Local I&C

Function: Provides PLC based operator interface and interlocks for VPS equipment protection

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of PLC functionality	Shutdown of VPS, all valves and pumps revert to safe state, interruption of machine operations	Status signals to EPICS Process Control System and PLC monitor	Troubleshoot and repair	Anticipated	Minimal
PLC I/O failure	Loss of action/reaction confirmation, PLC alarm condition	PLC logic	Troubleshoot and repair	Anticipated	Minimal

WBS Element 3.1 Vacuum Pumping System **Component: Residual Gas Analyzer (RGA)**

Function: Analysis of content of residual gasses.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Measurement head failure	Temporary loss of RGA functionality	Loss of signal and status from RGA monitor	Revert to installed spare measuring head	Anticipated	Minimal
RGA monitor failure	Loss of RGA functionality, loss of information to machine operators	Loss of signal and status from RGA monitor	Troubleshoot and repair	Anticipated	Minimal

WBS Element 3.2 Cooling Water System

Function: Provides cooling to magnets during plasma operations and bakeout.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of cooling function during plasma operations	Interlock with power supply system via PAUX relay prevents plasma operations.	PLC interlock status on EPICS display pages in control room.	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element 3.2 Cooling Water System (cont'd)

Loss of cooling function during bakeout	Temperature of Center stack and outer PF coils will increase. Interlock with DC bakeout power supply system via water system PLC shuts down ohmic heating of center stack.	Operator monitoring of equipment status and temperatures.	Shutdown bakeout High Temperature Skid (HTS). Continue operation of bakeout Low Temperature Skid (LTS) with reduced temperature setpoint to promote cooling and limit VV temperature. Troubleshoot and repair water cooling problem. If conditions warrant, switch to back-up water supply to maintain OH coil cooling.	UNLIKELY	MINIMAL

WBS Element 3.2 Cooling Water System **Component: Coolant Distribution in Test Cell**

Function: Distributes coolant from main manifolds to NSTX coils, coil leads, and detects loss of flow

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Coil coolant circuit leak, supply side hose	Reduction/loss of flow to coil; large leak would result in flow into floor drain system, eventually to TFTR Liquid Effluent Collection (LEC) tank	Depending on extent of leak, flow switch dropout[31], or low tank level, and PLC logic response (loss of flow removes PAUX permissive from power supply system, low tank level causes operator alarm)	Shutdown and repair	UNLIKELY	MINIMAL
Coil coolant circuit leak, return side hose[32]	Large leak would result in flow into floor drain system, eventually to TFTR Liquid Effluent Collection (LEC) tank	Depending on extent of leak, flow switch dropout[33], or low tank level, and PLC logic response (loss of flow removes PAUX permissive from power supply system, low tank level causes operator alarm)	Shutdown and repair	UNLIKELY	MINIMAL

WBS Element: 3.2 Cooling Water System Component: Coolant Distribution in Test Cell (cont'd)

[31] Every NSTX coil cooling water path is equipped with a flow switch

[32] Most likely on coil side of flow switch since venturi and subsequent connection to return manifold consists of hard piping with predominantly welded joints

[33] Every NSTX coil cooling water path is equipped with a flow switch

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Coil connection hose electrical breakdown	Small leakage current to ground (limited by high resistance grounding)	Depending on failure, maintenance inspection & test (Megger/hipot), ground fault detected by power supply system ground fault detector	Troubleshoot and repair	UNLIKELY	MINIMAL
Piping water leak	Water dripping on floor, possible reduction/loss of flow; large leak would result in significant flow into floor drain system and rapid reduction in tank level	Maintenance inspection, or low flow switch flow, or low tank level, and PLC logic response (loss of flow removes PAUX permissive from power supply system, low tank level causes operator alarm)	Shutdown and repair	UNLIKELY	MINIMAL
Venturi sensor tubing leak, low pressure side	Venturi pressure independent of flow, false indication of flow	PLC logic checks that all flow switches are dropped out prior to energizing pumps (not detected until pumps are de-energized)	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element: 3.2 Cooling Water System Component: Coolant Distribution in Test Cell (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Venturi sensor tubing leak, high pressure side	Venturi pressure independent of flow, false indication of low flow	PLC logic response as if low flow (remove PAUX permissive from power supply system)	Troubleshoot and repair	UNLIKELY	MINIMAL
Flow switch stuck open	False indication of low flow	PLC logic response (removes PAUX permissive from power supply system)	Troubleshoot and repair	UNLIKELY	MINIMAL
Flow switch stuck closed	False indication of adequate flow	PLC logic checks that all flow switches are dropped out prior to energizing pumps (not detected until pumps are de-energized)	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element: 3.2 Cooling Water System Component: Pumps & Automatic Valves
Function: The Low Pressure Pump provides cooling water flow, the High Pressure Pump (and redundant back-up unit) boosts the pressure for the OH coil. The Automatic Supply and Return Valves control the overall supply of cooling water to the NTC.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Low Pressure Pump failure	Loss of coolant flow to NTC	Flow switch measurements, de-energize PAUX relay to power supply system permissives	Shutdown and repair or replace	UNLIKELY	MINIMAL
High Pressure Pump failure	Loss of OH pressure, reduction of OH coolant flow	Flow switch measurements, de-energize PAUX relay to power supply system permissives	Switch to back-up unit	UNLIKELY	MINIMAL
Automatic Supply Valve failure to open	Delivery of coolant to NTC precluded, PLC logic prevents starting of pumps	PLC logic	Troubleshoot and repair or shutdown and replace	UNLIKELY	MINIMAL
Automatic Supply Valve failure to close	Loss of ability to isolate NTC water circuits from pump room, PLC logic prevents closing of Automatic Return Valve	PLC logic	Close manually, troubleshoot and repair or shutdown and replace	UNLIKELY	MINIMAL
Automatic Return Valve failure to open	Delivery of coolant to NTC precluded, PLC logic prevents opening of Automatic Supply Valve	PLC logic	Troubleshoot and repair or shutdown and replace	UNLIKELY	MINIMAL
Automatic Return Valve failure to close	Loss of ability to isolate NTC water circuits from pump room	PLC logic	Close manually, troubleshoot and repair or shutdown and replace	UNLIKELY	MINIMAL

WBS Element: 3.2 Cooling Water System Component: Auxiliary Components

Function: The D-site HVAC cooling system provides chilled water for removing heat from the coil cooling water and the Vacuum Pumping skids. The Deionizing System maintains high coil cooling water resistivity. Filters remove particulate from the coil cooling water system. Dew Point Detection System prevents operation of coils below dew point temperature.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
D-site HVAC cooling system failure	Loss of chilled water, loss of cooling of Vacuum Pumping System, interruption of operations	Vacuum Pumping System PLC loss of cooling water flow alarms, Cooling water PLC high temperature alarm, interlocked with PAUX relay to power supply system permissives	Shutdown and repair	UNLIKELY	MINIMAL
De-ionizing System failure	Gradual decrease in cooling water resistivity, possibly leading to ground fault, small leakage current to ground	Daily hipot of coils prior to energization, power supply system ground fault detection	Troubleshoot and repair	UNLIKELY	MINIMAL
Blockage in filters	Reduced coolant flow, possibly leading to drop out of flow switches, interruption of operations	Pressure drop across filters is monitored by water system operators	Perform maintenance	UNLIKELY	MINIMAL

WBS Element: 3.2 Cooling Water System Component: Auxiliary Components (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Dew Point Detection System failure	Inaccurate dew point indication, possible condensation on coils, possible ground fault, small leakage current (limited by high resistance grounding), redistribution of voltage to ground, Level 1 power supply fault (suppress/bypass)	PLC logic indicating input out of normal range, power supply system ground fault detection	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element: 3.2 Cooling Water System Component: Cooling Water Local I&C
Function: PLC system monitors flow switches, valve positions, temperatures, etc., provides interlocks to ensure proper sequence of operations and configuration, and provides interlock to Power Supply System PAUX relay which is required to issue power supply permissive to energize the coils.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of PLC functionality	Interruption of machine operations, PAUX relay drops out due to loss of "keep alive"[34]. State of water system components depends on failure scenario, all components could stay in last commanded state	Status signals to EPICS Process Control System and drop out of PAUX relay to power supply permissive interlock	Manually position all valves and pumps set to safe state, troubleshoot and repair	UNLIKELY	MINIMAL
PLC I/O failure	Loss of action/reaction confirmation, PLC alarm condition	PLC logic	Troubleshoot and repair	UNLIKELY	MINIMAL

[34] "keep alive" signal is the regularly transmitted PLC scanning signal (approx. once per second) which, if not received by output module, will trip "scan loss detector" and cause PAUX relay dropout

~~**WBS Element: 3.2 Cooling Water System Component: Fluorinert**~~ **[REMOVED]**

WBS Element: 3.3 Bakeout System Component: High Temperature Skid (HTS), Low Temperature Skid (LTS), Associated Piping, and DC Power Supply

Function: The Bakeout system heats the plasma facing components (PFCs) and vacuum vessel (VV) to elevated temperatures (350^{o}C and 150^{o}C respectively) for cleaning, and provides heating and cooling during operations. The system consists of a high temperature skid (HTS) using helium to heat the PFCs to 350^{o}C and to provide cooling during plasma operations, a low temperature skid (LTS) using water to heat and cool the outer vacuum vessel to 150^{o}C, along with associated piping both internal and external to the vacuum vessel. In addition a DC power supply is used to heat the center stack casing.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure of HTS heating during bakeout operations	Loss of control of heat input to PFCs	Operator monitoring of equipment status and temperatures	Troubleshoot and repair	UNLIKELY	MINIMAL
Failure of HTS cooling during plasma operations	Loss of heat removal from PFCs	Operator monitoring of equipment status and temperatures	Troubleshoot and repair, limit NSTX pulse length, repetition rate and auxiliary heating power to avoid ratcheting of temperature of internal hardware.	UNLIKELY	MINIMAL
Failure of LTS cooling during bakeout operations	Loss of cooling of VV, excess temperature on VV	Operator monitoring of equipment status and temperatures	Shut down all heat inputs (HTS and DC power supply)	UNLIKELY	MINIMAL
Failure of LTS heating during plasma operations	Loss of ability to maintain specific VV temperature, possible degradation of plasma performance	Operator monitoring of equipment status and temperatures	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element: .3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure of DC power supply	Loss of ability to maintain	Operator	Troubleshoot and	UNLIKELY	MINIMAL

during bakeout operations	or add heat directly to CS casing, reduction in bakeout effectiveness.	monitoring of equipment status and temperatures	repair		
Excess temperature gradients during start-up or shutdown due to operator error	Excess thermally induced stress, possible mechanical failure of internal hardware, helium loop piping, or VV.	Operator monitoring of temperatures and control of HTS and LTS.	Vent machine and repair failure.	UNLIKELY	MINOR
Operation of HTS without LTS due to operator error	Excess temperature on VV, possible failure of appendages and seals on ports.	Operator monitoring of equipment status and temperatures	Troubleshoot and repair/restore proper conditions.	UNLIKELY	MINORL
Operation of LTS without HTS due to operator error	No consequence other than lack of ability to reach high bakeout temperature.	Operator monitoring of equipment status and temperatures	Troubleshoot and repair/restore proper conditions.	UNLIKELY	MINIMAL
Operation of LTS without magnet cooling water flow due to operator error	Outer PF coil temperature rises but to safe temperature (less than $100^{o}C$)	Operator monitoring of equipment status and temperatures	Troubleshoot and repair/restore proper conditions.	UNLIKELY	MINIMAL
Operation of HTS without magnet cooling water due to operator error and PLC Failuer or Flow Switch Error	Excess temperature on center stack coils after several hours, possible damage to coil insulation.	Operator monitoring of equipment status and temperatures	Troubleshoot and repair/restore proper conditions. Repair/replace coil(s) if damaged.	UNLIKELY	MINOR

WBS Element: 3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Leak in HTS helium Piping inside Vacuum Vessel	If small leak, no consequence since helium is an inert gas. If large leak, vacuum pressure will rise, helium loop pressure will fall, causing skid isolating valves to close, VV pressure remaining sub-atmospheric.[35] If large leak, loss of high temperature bakeout and/or cooling capability.	RGA and/or skid pressure sensing.	Vent machine and repair leak.	UNLIKELY	MINIMAL
Operation of LTS without magnet cooling water flow due to operator error	Outer PF coil temperature rises but to safe temperature (less than 100^{o}C)	Operator monitoring of equipment status and temperatures	Troubleshoot and repair/restore proper conditions.	UNLIKELY	MINIMAL

[35] If isolating valves fail to close, then pressure of VV and helium loop would equilibrate at 11 psig; some of the VV windows may break under this condition, and machine may vent.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
~~Leak in HTS helium Piping inside Vacuum Vessel~~	~~If small leak, no consequence since helium is an inert gas. If large leak, vacuum pressure will rise, helium loop pressure will fall, causing skid isolating valves to close, VV pressure remaining sub-atmospheric.[36] If large leak, loss of high temperature bakeout and/or cooling capability.~~	~~RGA and/or skid pressure sensing.~~	~~Vent machine and repair leak.~~		
Leak in HTS helium Piping outside Vacuum Vessel	If small leak, helium leak checking is impacted. If large leak, potential safety hazard due to hot gas stream and/or oxygen depletion.[37] If large leak, loss of high temperature bakeout and/or cooling capability.	HTS skid detects low pressure, shuts isolation valves and shuts down heater and blower. Solenoid valve on gas bottle shuts to limit inventory of gas.	Troubleshoot and repair leak	UNLIKELY	MINIMAL
Leak in LTS water Piping outside Vacuum Vessel	Hot water released into NSTX Test Cell, possible injury to personnel if in contact with hot liquid[38]	Expansion tank level detection	Troubleshoot and repair leak	UNLIKELY	MINIMAL

[36] If isolating valves fail to close, then pressure of VV and helium loop would equilibrate at 11 psig; some of the VV windows may break under this condition, and machine may vent.

[37] Personnel access in NSTX Test Cell and skid areas will be limited during bakeout, Thermal insulation on helium piping will diffuse gas stream exiting from most leaks. Inventory of helium (equivalent to 3 bottles of compressed helium @ 311 cu ft/cylinder)) is not sufficient to cause dangerous low oxygen conditions in NSTX Test Cell.

[38] Personnel access in NSTX Test Cell and skid areas will be limited during bakeout.

WBS Element: 3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Blockage in Pipeline	Uneven heating and/or cooling	Thermcouples on NSTX machine and IR Camera	If inside, vent VV and remove blockage; if outside, remove blockage	UNLIKELY	MINIMAL
Contamination of Dielectric Breaks in manifolding	Loss of electrical isolation of outer VV	Hipot leakage measurements	Clean	UNLIKELY	MINIMAL
Electrical breakdown of Dielectric Breaks in manifolding	If CHI operations with outer vacuum vessel energized, ground fault for CHI power supply, small fault current flow through manifolding to ground. Otherwise, small ground loop eddy currents and resultant magnetic field perturbation.	If CHI operation, power supply ground fault detection.	Repair if possible or replace	UNLIKELY	MINIMAL
Loss of Heater Power in LTS	Loss of heat input to VV	Thermocouples on NSTX machine	Troubleshoot and repair	UNLIKELY	MINIMAL
Failure of Pump in High Temperature Loop in LTS	Loss of heat input to VV	Over-temperature switch trips off heater	Troubleshoot and repair	UNLIKELY	MINIMAL
Failure of Pump in Low Temperature Loop in LTS	Loss of heat removal from VV	Thermocouples on NSTX machine	Shutdown all heat inputs, including HTS. Troubleshoot and repair	UNLIKELY	MINIMAL
Loss of Nitrogen blanket in Expansion Tank in LTS	Expansion Tank level rises	Expansion tank level detection	Repair leak and restore blanket	UNLIKELY	MINIMAL
Reduction of HVAC cooling water flow and/or excess cooling water temperature in LTS	Reduction in cooling capability	Skid control panel logic, Thermocouples on NSTX machine	Shutdown all heat inputs and restore HVAC cooling water supply	UNLIKELY	MINIMAL

WBS Element: 3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure of Temperature Controller in LTS	Temperature not per setpoint, if overtemperature, possible boiling of heat exchanger fluid, possible opening of pressure relief valve	Over-temperature switch trips off heater	Troubleshoot and repair	UNLIKELY	MINIMAL
Blower Seal Failure in HTS	Lubricating oil enters helium stream but trapped by filter	Float switch in oil reservoir reported to PLC.	Troubleshoot and repair	UNLIKELY	MINIMAL
Blower failure (seizure or other mechanical failure)	Loss of gas flow through system, heater control limits power to rods, low flow and high temperature interlocks shut off heater.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
Heat Exchanger failure (gas to gas heat exchanger HE#1) due to blockage or contamination in HTS	Reduction in heat transfer capability, reduced performance	Reduced performance	Troubleshoot and repair	UNLIKELY	MINIMAL
Heat Exchanger failure (gas to water heat exchanger HE#2) due to valving error, blockage or contamination in HTS	Reduction in heat removal from gas stream output from VV into blower, thermocouples detect high blower inlet temperature and shut down blower and heater.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
Heater failure in HTS	Loss of control of heat input to system, resulting in excess heat input and/or high heater temperature, or lack of demanded heat input. If high heater or NSTX return temperature, system shuts down heater and blower.	If high heater temperature or NSTX return temperature, PLC interlocks; if lack of heat input, reduced performance.	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element: 3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Supply or Return valve misoperation (AV1-AV4) in HTS	Excess pressure across blower, bypass valve opens and provides alternate flow path, high pressure interlock and/or motor overtemperature switch causes shutdown of heater and blower.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
Blower bypass valve failure (CV1) in HTS	VFD limits blower rpm to limit pressure, high pressure interlock and/or motor overtemperature switch shuts down heater and blower.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
Pressure regulating valve failure in HTS	If sticks open, equivalent to helium system leak. If sticks closed, helium pressure will rise, high pressure interlock will shut off heater and blower, relief valve will open to relieve pressure, and isolation valves will close to isolate skid from NSTX Test Cell.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL

WBS Element: 3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Solenoid valve failure (SV1, SV2) in HTS	If sticks open, system remains equalized with helium bottle regulator pressure. If sticks closed, loss of ability to replenish helium, low pressure interlock shuts down blower and heater.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
Helium bottle regulator failure in HTS	If sticks open, high pressure interlock results in closure of solenoid valves. If sticks closed, low pressure interlock shuts down blower and heater.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
HE1 bypass valve misalignment MV1, MV2) in HTS	If valves aligned for cooling during bakeout operations, excess temperature at blower inlet, high temperature interlock shuts down blower and heater. If valves aligned for bakeout during cooling operations, reduced cooling effectiveness. If both valves open or both valves closed, PLC interlock prevents system startup until MV1 and MV2 are in the proper configuration.	PLC interlocks	Reconfigure valves to proper position.	UNLIKELY	MINIMAL

WBS Element: 3.3 Bakeout System Component: HTS, LTS, Piping, & DC Power Supply (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure to drive current in CS casing in DC Power Supply	Loss of heat input to CS casing, reduced bakeout effectiveness	Operator monitoring of equipment status and temperatures.	Troubleshoot and repair	UNLIKELY	MINIMAL
Failure to shut down in case of loss of cooling water indicated by water systems PLC in DC power supply	Excess temperature on OH, PF1a, and TF center stack coils, possible coil damage.	Interlock shuts down power supply automatically. Operator monitoring of equipment status and temperatures.	Troubleshoot and repair	UNLIKELY	MAJOR

WBS Element: 3.4 Gas Delivery System (GDS)

Function: **The Gas Delivery System provides storage of gases and delivers prescribed quantities of same at prescribed rates in pulses which are synchronized with the NSTX facility clock system. In addition the system provides vacuum pumping to remove and exhaust residual gases from gas delivery lines. Control is via the Vacuum Pumping System PLC**.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
TIV fails to close	Inability to isolate pulse valve from vacuum vessel	Valve status indication on PLC	Possible need to pump out and backfill volume. Troubleshoot and repair.	UNLIKELY	MINIMAL
TIV fails to open	Inability to utilize injector	Valve status indication on PLC	Troubleshoot and repair.	UNLIKELY	MINIMAL
Piezoelectric injection valve failure to open	Gas delivery from failed valve precluded, reduced performance	Injection volume and vacuum vessel pressure instrumentation monitored via PLC	Troubleshoot and repair if possible, or replace during vacuum opening	UNLIKELY	MINIMAL

WBS Element: 3.4 Gas Delivery System (GDS) (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Piezoelectric injection valve failure to close, or leakage across valve	Leakage of gas from injection volume into vacuum vessel, gas delivery from failed valve precluded, reduced performance	Injection volume and vacuum vessel pressure instrumentation monitored via PLC	Troubleshoot and repair if possible, or isolate and evacuate injection volume and replace during vacuum opening	UNLIKELY	MINIMAL
Vacuum pump failure	Inability to remove residual gases from portions of the GDS or gas injection assembly	Vacuum pump status indication, line pressure instrumentation monitored by PLC	Troubleshoot and repair	UNLIKELY	MINIMAL
Failure of GDS pumpout valve	Inability to remove residual gases from portions of the GDS or gas injection assembly	Vacuum pump status indication, line pressure instrumentation monitored by PLC	Troubleshoot and repair.	UNLIKELY	MINIMAL
Leakage in GDS due to faulty welds or leaky fittings	Inability to achieve required vacuum in gas delivery system	Pressure instrumentation monitored via PLC	Troubleshoot and repair	UNLIKELY	MINIMAL
TMB leakage due to faulty welds or leaky fittings	TMB leaking into NTC where TMB pressure > atm. pressure (typ. to Piezoelectric valves)	With handheld gas leak detector or thermal imager, or inability to hold pressure in system.	Close all remotely actuated valves. Attempt to isolate leak. If safe, wearing SCBA close TMB cylinder valve.	UNLIKELY	MINIMAL

WBS Element: 3.4 Gas Delivery System (GDS) (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Gas cylinder or supply piping leak, due to faulty valve or fittings	Release of gas into NTC[39]	Loss of gas pressure monitored via PLC	Repair or replace	UNLIKELY	MINIMAL
TMB Gas cylinder or supply piping leaking due to faulty valve or fittings	TMB leaking into NTC where TMB pressure > atm. pressure	With handheld gas leak detector or thermal imager or inability to hold pressure in system.	Close all remotely actuated valves. Attempt to isolate leak. If safe, wearing SCBA close TMB cylinder valve.	UNLIKELY	MINIMAL
Lower Dome Gas Injection System, excess gas pressure in forelines involving ceramic insulator break between center stack casing and ground	Electrical breakdown across ceramic, arcing, burning, melting	Pressure instrumentation monitored via PLC and interlocked with CHI power supply permissive	Repair/replace/adjust malfunctioning components	UNLIKELY	MINIMAL
Lower Dome Gas Injection System, excess gas pressure in forelines involving ceramic insulator break between center stack casing and ground	Electrical breakdown across ceramic, arcing, burning, melting	Pressure instrumentation monitored via PLC and interlocked with CHI power supply permissive	Repair/replace/adjust malfunctioning components	UNLIKELY	MINIMAL
Lower Dome Gas Injection System, excess gas prefill pressure in injection reservoir	If not detected, excess gas would be admitted to vacuum vessel leading to reduced dielectric strength across various ceramic insulator gaps	Pressure instrumentation monitored via PLC and interlocked with CHI power supply permissive	Repair/replace/adjust malfunctioning components	UNLIKELY	MINIMAL

[39] Hydrogen gas inventory less than 311 cubic feet (per cylinder), insufficient volume to develop an explosive concentration in the NTC

WBS Element: 3.4 Gas Delivery System (GDS) (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure of Portable Gas Leak Detector for TMB	Unable to detect TMB in the NTC atmosphere	Unable to calibrate, either manually or via self-calibration.	Suspend TMB injection. Close all remotely actuated GDS valves. Trouble shoot and repair. If repair infeasible, terminate TMB injection.	UNLIKELY	MINIMAL
Vent stack nitrogen purge fails	Lack of nitrogen flow in vent stack will lead to presence of air in vent stack. Possibility of fire or explosion during TMB injection if plasma discharge or GDC discharge current is lost..	Lack of flow in vent stack	Halt NBI or TMB operation as appropriate. Trouble shoot system. Once on line- resume normal operation.	UNLIKELY	MINIMAL
Plasma discharge current stops during TMB injection.	TMB does not break down and deposit on surfaces. TMB pumps through NSTX vacuum system. Vent stack purged with nitrogen, so no possibility of combustion in vent stack.	Either the plasmas current interlock senses low plasma current and automatically shuts down TMB injection, or the Gas Injection System PLC Timeout Interlock automatically shuts down TMB injection after 1 sec.	Restart plasma discharge and return to operation. If repeated failure of system to maintain plasma current, trouble shoot system up to and including aborting TMB operation.	ANTICIPATED	MINIMAL

WBS Element: 3.4 Gas Delivery System **Component: Lithium Evaporator (LITER)**

Function: This is an analysis of the failure modes, effects, detection, and recovery for using the Lithium Evaporator (LITER) to evaporate lithium coatings on the plasma-facing surfaces in NSTX. This analysis has the following parts:

- **Failure modes during LITER loading, transport to test cell, and installation on NSTX;**
- **Failure modes during LITER operation on NSTX; and**
- **Failure modes after the vessel is vented for maintenance**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
During LITER loading, the Argon Glove Box becomes aerated due to emptying of the Argon cylinder.	Possible oxidation and moisture interaction with lithium.	Argon flow stops, gas cylinder gauge indicates empty.	Replace empty Argon cylinder with full cylinder. Dispose of all exposed lithium. Restart LITER loading procedure from beginning.	UNLIKELY	MINOR
During transport of LITER to NSTX Test Cell in argon atmosphere, argon is lost.	Possible oxidation and moisture interaction with the lithium.	The plug for LITER is found to be loose or missing.	Return all exposed lithium to waste container in Room L-111, Argon Glove Box. Restart LITER loading procedure from beginning.	UNLIKELY	MINOR
During loading or transport of LITER to NSTX Test Cell, lithium-filled LITER is dropped.	Possible oxidation and moisture interaction with the lithium if argon atmosphere is lost due to loosening of plug or damage to LITER.	The plug for LITER is found to be loose or missing or damage to LITER is noticed at point of impact with floor.	Return all exposed lithium to waste container in Room L-111, Argon Glove Box. Repair LITER if damaged. Restart LITER loading procedure from beginning.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
LITER probe head is not properly aligned with divertor gap	LITER inward motion stopped by passive plate or divertor gap edges.	Window with mirror allows direct visual observation of alignment.	Realign Bellows Motion Drive until LITER is observed to be properly aligned.	UNLIKELY	MINOR
Minor vessel leak occurs.	Possible oxidation and moisture interaction with lithium in LITER and films deposited on in-vessel surfaces.	Vessel vacuum instrumentation.	Fix leak. Restore good vacuum conditions as soon as possible.	UNLIKELY	MINOR
NBI TIV O-ring gets coated with lithium	Cannot close TIV sufficiently to allow associated appurtenance to be vented	Argon challenge procedure detects throughput leak.	Vent vessel and repair TIV.	UNLIKELY	MINOR
Li coating builds up on MPTS laser baffles	Excessive light reflection.	MPTS data analysis.	Vent vessel and clean baffles.	UNLIKELY	MINOR
Li coats MPTS windows	Window transmission decreases.	MPTS data analysis.	Vent vessel and clean windows.	UNLIKELY	MINOR
Lithium reacts with TMB	Inert compounds unsuitable for particle pumping formed.	Poor density control. Analysis of sample coupons after run.	Deposit fresh lithium.	UNLIKELY	MINOR
Lithium deposits prevent TIV's from sealing properly	Cannot close TIV sufficiently to allow associated appurtenance to be vented.	Argon challenge procedure detects throughput leak	Vent vessel and repair TIV.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Lithium coats CHI absorber insulator	Upper and Lower CHI Insulators are not in direct line-of-sight of LITER output. Secondary or tertiary Li bounces may result in thin film coating on nearest insulator extremities.	Lower DC resistance across CHI gap.	Apply CHI bias in presence of deuterium fill gas until sufficient current is drawn to evaporate film and/or convert it to non-conducting compound.	UNLIKELY	MINOR
Lithium coats windows, insulators, and feedthroughs	Windows will have reduced transmission. Insulators and feedthroughs will have increased conductance to "Category 4" (CAT4) ground.	Data analysis will indicate reduced window transmission. Insulators and feedthroughs will exhibit increased conductance to CAT4 ground.	Stop LITER operation. If additional non-lithium operation does not erode lithium film from the windows, and convert conducting films on insulators and feedthroughs to non-conducting films, vent vessel and clean surfaces.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
LITER in vertical position expels liquid lithium	Liquid lithium drips from output aperture of LITER.	Available windows allow inspection of the LITER output aperture.	Cool LITER to below Li melting temperature and remove from NSTX to determine cause of expulsion. Expelled lithium to be passivated and removed from vacuum vessel according to vent procedure at next scheduled opening.	UNLIKELY	MINOR
LITER seals fail	LITER Guard Vacuum pressure leaks to vessel and raises vessel pressure.	Vessel vacuum gauges and RGA.	Withdraw LITER probe from vessel and fix broken seal. Reload and reinsert LITER.	UNLIKELY	MINOR
Liquid clogs snout when LITER is mounted in vertical position	Evaporation of lithium into NSTX ceases	Clogging detected by real-time lithium deposition monitoring and/or unusual temperature and power supply profiles.	Turn off reservoir heater and unclog by evaporating lithium using snout heaters only.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System (con't) Component: LITER (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Probe drive fails at high LITER operating temperature	Bellows Motion Drive will not withdraw probe	Bellows Motion Drive shaft encoder and TV observation indicate no motion.	Turn off all heater voltages. Wait until temperature indicators (multiple redundant thermocouples) indicate that LITER has cooled. Withdrawn LITER probe manually (probe designed to be operated safely by hand crank as well as drive motor.)	UNLIKELY	MINOR
Failure of guard vacuum pump	Raises base pressure in NSTX vacuum vessel if guard vacuum chamber develops leak.	LITER control system indicates pump failure and NSTX base pressure rises if guard vacuum develops leak.	Withdraw LITER and replace guard vacuum pump. Repair leak in guard vacuum chamber if detected.	UNLIKELY	MINOR
Software safety interlocks fail to prevent LITER overheating	Overheating or continuous operation occurs.	Performance noted by operators and associated indicators.	Redundant Hardwire Interlock System turns-off LITER. Diagnose, fix, and restart.	UNLIKELY	MINOR
Loss of air cooling capability	Loss of LITER temperature control leads to loss of lithium evaporation rate control.	LITER control system indicates loss of air cooling capability and thermocouples indicate loss of temperature control.	Turn off all heater voltages. Repair air cooling capability.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of electrical power	LITER unable to maintain temperature for lithium evaporation. LITER cannot be withdrawn manually.	Control system indicates loss of electrical power at LITER and thermocouples indicate dropping temperature.	Wait until electrical power is restored. Wait until LITER is cool (based on known cooling rate) prior to withdrawing manually if electrical power is completely lost. Note that probe is designed to be operated safely by hand crank as well as drive motor.	UNLIKELY	MINOR
After venting and several days of ventilation, hazardous dust or granules are found in lower region of vessel.	Eye, nose, and inhalation hazard.	Visual inspection reveals surface coatings of dust or granules.	Sweep, vacuum, or use damp fireproof cloth to remove as indicated in Vessel Maintenance Procedure using appropriate personnel protective equipment (PPE), e. g., gloves, face masks, face shields, and goggles.	UNLIKELY	MINOR
After venting and several days of ventilation, oxidized or nitrated lithium compounds are found on surfaces needing mechanical or welding work.	Possible eye, nose, and inhalation hazard.	Visual inspection reveals surface coatings.	Use damp fireproof cloth to clean the work area using appropriate PPE, e. g., gloves, face masks, face shields, and goggles.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System **Component: Lithium Dropper (Raindrops)**

Function: **This is an analysis of the failure modes, effects, detection, and recovery for using the Lithium Dropper (Raindrops) to deposit lithium coatings on the plasma-facing surfaces in NSTX. This analysis has the following parts:**

- **Failure modes during Raindrops loading, transport to test cell, and installation on NSTX;**
- **Failure modes during Raindrops operation on NSTX; and**
- **Failure modes after the vessel is vented for maintenance**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
During Raindrops loading, the Argon Glove Box becomes aerated due to emptying of the Argon cylinder.	Possible oxidation and moisture interaction with lithium.	Argon flow stops, gas cylinder gauge indicates empty.	Replace empty Argon cylinder with full cylinder. Dispose of all exposed lithium. Restart Raindrops loading procedure from beginning.	UNLIKELY	MINOR
During transport of Raindrops to NSTX Test Cell in argon atmosphere, argon is lost.	Possible oxidation and moisture interaction with the lithium.	The endcap for Raindrops is found to be loose or missing.	Return all exposed lithium to waste container in Room L-111, Argon Glove Box. Restart Raindrops loading procedure from beginning.	UNLIKELY	MINOR
During loading or transport of Raindrops to NSTX Test Cell, lithium-filled shaker vessel is dropped.	Possible oxidation and moisture interaction with the lithium if argon atmosphere is lost due to loosening of endcap or damage to shaker vessel.	The plug for shaker vessel is found to be loose or missing or damage to shaker vessel is noticed at point of impact with floor.	Return all exposed lithium to waste container in Room L-111, Argon Glove Box. Repair shaker vessel if damaged. Restart Raindrops loading procedure from beginning.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: Raindrops (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Minor vessel leak occurs during operation.	Possible oxidation and moisture interaction with lithium in Raindrops and films deposited on in-vessel surfaces.	Vessel vacuum instrumentation.	Fix leak. Restore good vacuum conditions as soon as possible.	UNLIKELY	MINOR
Vessel viewport shatters and air rushes into vessel while graphite power handling surfaces are hot.	Possible oxidation and moisture interaction with lithium in Raindrops, and with lithium thin films deposited on vessel surfaces. Surface temperature rise is small ($7.3x10^6$J/[(0.71J/g/°K)x ($1.3x10^6$g)] = 7.9 °K) due to large surface area of vessel surfaces compared to amount of lithium deposited (see NSTX SAD for more details.)	Vessel vacuum instrumentation and TV cameras.	Fix or replace failed component. Restore good vacuum conditions as soon as possible. Remove Raindrops assembly and return to Room L-111 Argon Glove Box. Refill Raindrops with lithium and return to NSTX.	UNLIKELY	MINOR
Li coating builds up on MPTS laser baffles	Excessive light reflection.	MPTS data analysis.	Vent vessel and clean baffles.	UNLIKELY	MINOR
Li coats MPTS windows	Window transmission decreases.	MPTS data analysis.	Vent vessel and clean windows.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: Raindrops (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Lithium reacts with TMB	Inert compounds unsuitable for particle pumping formed.	Poor density control. Analysis of sample coupons after run.	Deposit fresh lithium.	UNLIKELY	MINOR
Lithium deposits prevent TIV's from sealing properly	Cannot close TIV sufficiently to allow associated appurtenance to be vented.	Argon challenge procedure detects throughput leak	Vent vessel and repair TIV.	UNLIKELY	MINOR
Lithium coats CHI absorber insulator	Upper and Lower CHI Insulators are not in direct line-of-sight of LITER output. Secondary or tertiary Li bounces may result in thin film coating on nearest insulator extremities.	Lower DC resistance across CHI gap.	Apply CHI bias in presence of deuterium fill gas until sufficient current is drawn to evaporate film and/or convert it to non-conducting compound.	UNLIKELY	MINOR
Lithium coats windows, insulators, and feedthroughs	Windows will have reduced transmission. Insulators and feedthroughs will have increased conductance to "Category 4" (CAT4) ground.	Data analysis will indicate reduced window transmission. Insulators and feedthroughs will exhibit increased conductance to CAT4 ground.	Stop Raindrops operation. If additional non-lithium operation does not erode lithium film from the windows, and convert conducting films on insulators and feedthroughs to non-conducting films, vent vessel and clean surfaces.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: Raindrops (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Raindrops in standard installed position expels lithium powder when not appropriate to do so.	lithium powder falls from output aperture of Raindrops.	Available windows allow inspection of the Raindrops output aperture during discharges.	Close the associated Bay I TIV and remove from NSTX to determine cause of expulsion. Expelled lithium to be passivated and removed from vacuum vessel according to vent procedure at next scheduled opening.	UNLIKELY	MINOR
Raindrops vacuum seals fail	Air leaks into NSTX and raises vessel pressure.	Vessel vacuum gauges and RGA.	Close Bay I TIV and remove Raindrops from vessel to fix broken seal. Reload and reinstall Raindrops.	UNLIKELY	MINOR
Lithium powder starts to react with ambient gases (viz: deuterium, water vapor or air) when Raindrops is mounted on NSTX vessel	The temperature of the lithium powder rises.	Powder temperature monitored by real-time monitoring of Raindrops internal thermocouple	Shut the Bay I TIV and flood the Raindrops vessel with Argon	UNLIKELY	MINOR
Probe drive fails at high LITER operating temperature	Bellows Motion Drive will not withdraw probe	Bellows Motion Drive shaft encoder and TV observation indicate no motion.	Turn off all heater voltages. Wait until temperature indicators (multiple redundant thermocouples) indicate that LITER has cooled. Withdrawn LITER probe manually (probe designed to be operated safely by hand crank as well as drive motor.)	UNLIKELY	MINOR

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Software safety interlocks fail to prevent LITER overheating	Overheating or continuous operation occurs.	Performance noted by operators and associated indicators.	Redundant Hardwire Interlock System turns-off LITER. Diagnose, fix, and restart.	UNLIKELY	MINOR
Loss of electrical power	LITER unable to maintain temperature for lithium evaporation. LITER cannot be withdrawn manually.	Control system indicates loss of electrical power at LITER and thermocouples indicate dropping temperature.	Wait until electrical power is restored. Wait until LITER is cool (based on known cooling rate) prior to withdrawing manually if electrical power is completely lost. Note that probe is designed to be operated safely by hand crank as well as drive motor.	UNLIKELY	MINOR
After venting and several days of ventilation, hazardous dust or granules are found in lower region of vessel.	Eye, nose, and inhalation hazard.	Visual inspection reveals surface coatings of dust or granules.	Sweep, vacuum, or use damp fireproof cloth to remove as indicated in Vessel Maintenance Procedure using appropriate personnel protective equipment (PPE), e. g., gloves, face masks, face shields, and goggles.	UNLIKELY	MINOR
After venting and several days of ventilation, oxidized or nitrated lithium compounds are found on surfaces needing mechanical or welding work.	Possible eye, nose, and inhalation hazard.	Visual inspection reveals surface coatings.	Use damp fireproof cloth to clean the work area using appropriate PPE, e. g., gloves, face masks, face shields, and goggles.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System **Component: LITER to Evaporate Lithium**

Function: **This is an analysis of the failure modes, effects, detection, and recovery during LLD operations using LITER to**

deposit lithium coatings on the plasma-facing surfaces in NSTX. This analysis has the following parts:

- **Failure modes LITER loading, transport to test cell, and installation on NSTX;**
- **Failure modes during LITER operation on NSTX;**
- **Failure modes during LLD operation on NSTX using LITER; and**
- **Failure modes after the vessel is vented for maintenance**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
During LITER loading, the Argon Glove Box becomes aerated due to emptying of the Argon cylinder.	Possible oxidation and moisture interaction with lithium.	Argon flow stops, gas cylinder gauge indicates empty.	Replace empty Argon cylinder with full cylinder. Dispose of all exposed lithium. Restart LITER loading procedure from beginning.	UNLIKELY	MINOR
During transport of LITER to NSTX Test Cell in argon atmosphere, argon is lost.	Possible oxidation and moisture interaction with the lithium.	The plug for LITER is found to be loose or missing.	Return all exposed lithium to waste container in Room L-111, Argon Glove Box. Restart LITER loading procedure from beginning.	UNLIKELY	MINOR
During loading or transport of LITER to NSTX Test Cell, lithium-filled LITER is dropped.	Possible oxidation and moisture interaction with the lithium if argon atmosphere is lost due to loosening of plug or damage to LITER.	The plug for LITER is found to be loose or missing or damage to LITER is noticed at point of impact with floor.	Return all exposed lithium to waste container in Room L-111, Argon Glove Box. Repair LITER if damaged. Restart LITER loading procedure from beginning.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
LITER probe head is not properly aligned with divertor gap	LITER inward motion stopped by passive plate or divertor gap edges.	Window with mirror allows direct visual observation of alignment.	Realign Bellows Motion Drive until LITER is properly aligned.	UNLIKELY	MINOR
Minor vessel leak occurs.	Possible oxidation and moisture interaction with lithium in LITER and films deposited on in-vessel surfaces.	Vessel vacuum instrumentation.	Fix leak. Restore good vacuum conditions as soon as possible.	UNLIKELY	MINOR
Vessel viewport shatters and air rushes into vessel while graphite power handling surfaces are hot.	Possible oxidation and moisture interaction with lithium in LITER, and with lithium thin films deposited on vessel surfaces. If the total amount of lithium in LITER and on the in-vessel surface is 360g (51.4 moles), the surface temperature rise is small ($26.4x10^6$J/[(0.71J/g/°K)x($1.3x10^6$g)] = 28.6 °K) due to large surface area of vessel surfaces compared to amount of lithium deposited (see NSTX SAD for more details.)	Vessel vacuum instrumentation and TV cameras.	Fix or replace failed component. Restore good vacuum conditions as soon as possible. Remove LITER assembly and return to Room L-111 Argon Glove Box. Refill LITER with lithium and return to NSTX.	UNLIKELY	MINOR
NBI TIV O-ring gets coated with lithium	Cannot close TIV sufficiently to allow associated appurtenance to be vented	Argon challenge procedure detects throughput leak.	Vent vessel and repair TIV.	UNLIKELY	MINOR
Li coating builds up on MPTS laser baffles	Excessive light reflection.	MPTS data analysis.	Vent vessel and clean baffles.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Li coats MPTS windows	Window transmission decreases.	MPTS data analysis.	Vent vessel and clean windows.	UNLIKEY	MINOR
Lithium reacts with TMB	Inert compounds unsuitable for particle pumping formed.	Poor density control. Analysis of sample coupons after run.	Deposit fresh lithium.	UNLIKELY	MINOR
Lithium deposits prevent TIV's from sealing properly	Cannot close TIV sufficiently to allow associated appurtenance to be vented.	Argon challenge procedure detects throughput leak	Vent vessel and repair TIV.	UNLIKELY	MINOR
Lithium coats CHI absorber insulator	Upper and Lower CHI Insulators are not in direct line-of-sight of LITER output. Secondary or tertiary Li bounces may result in thin film coating on nearest insulator extremities.	Lower DC resistance across CHI gap.	Apply CHI bias in presence of deuterium fill gas until sufficient current is drawn to evaporate film and/or convert it to non-conducting compound.	UNLIKELY	MINOR
Lithium coats windows, insulators, and feedthroughs	Windows will have reduced transmission. Insulators and feedthroughs will have increased conductance to "Category 4" (CAT4) ground.	Data analysis will indicate reduced window transmission. Insulators and feedthroughs will exhibit increased conductance to CAT4 ground.	Stop LITER operation. If additional non-lithium operation does not erode lithium film from the windows, and convert conducting films on insulators and feedthroughs to non-conducting films, vent vessel and clean surfaces.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
LITER in vertical position expels liquid lithium	Liquid lithium drips from output aperture of LITER.	Available windows allow inspection of the LITER output aperture.	Cool LITER to below Li melting temperature and remove from NSTX to determine cause of expulsion. Expelled lithium to be passivated and removed from vacuum vessel according to vent procedure at next scheduled opening.	UNLIKELY	MINOR
LITER seals fail	LITER Guard Vacuum pressure leaks to vessel and raises vessel pressure.	Vessel vacuum gauges and RGA.	Withdraw LITER probe from vessel and fix broken seal. Reload and reinsert LITER.	UNLIKELY	MINOR
Liquid clogs snout when LITER is mounted in vertical position	Evaporation of lithium into NSTX ceases	Clogging detected by real-time lithium deposition monitoring and/or unusual temperature and power supply profiles.	Turn off reservoir heater and unclog by evaporating lithium using snout heaters only.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Probe drive fails at high LITER operating temperature	Bellows Motion Drive will not withdraw probe	Bellows Motion Drive shaft encoder and TV observation indicate no motion.	Turn off all heater voltages. Wait until temperature indicators (multiple redundant thermocouples) indicate that LITER has cooled. Withdrawn LITER probe manually (probe designed to be operated safely by hand crank as well as drive motor.)	UNLIKELY	MINOR
Software safety interlocks fail to prevent LITER overheating	Overheating or continuous operation occurs.	Performance noted by operators and associated indicators.	Redundant Hardwire Interlock System turns-off LITER. Diagnose, fix, and restart.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of electrical power	LITER unable to maintain temperature for lithium evaporation. LITER cannot be withdrawn manually.	Control system indicates loss of electrical power at LITER and thermocouples indicate dropping temperature.	Wait until electrical power is restored. Wait until LITER is cool (based on known cooling rate) prior to withdrawing manually if electrical power is completely lost. Note that probe is designed to be operated safely by hand crank as well as drive motor.	UNLIKELY	MINOR
NSTX Vacuum If NSTX vacuum rises to >900 mT.	Liquid Li on LLD starts to react with atmosphere and forms Li compounds.	NSTX vacuum gauges and PLC response.	Disable LLD heaters and enable LLD cooling for all four quadrants. Fix vacuum failure. Restore good vacuum conditions as soon as possible.	UNLIKELY	MINOR
Hardware Interlocks NSTX CONFIGURE If NSTX Not Configured for LLD Operation.	Possible undesirable heating of LLD during other operations.	Interlock signal. Disable LLD Heaters and Enable LLD Cooling for all four quadrants.	Investigate loss of Configuration and fix.	UNLIKELY	MINOR

WBS Element:3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Hardware Interlocks WATCH DOG TIMER If the LLD Controller fails to update the Timer Disable LLD Heaters	Uncontrolled operation. Possible undesirable heating of LLD during other operations.	Interlock signal. Disable LLD Heaters and Enable LLD Cooling for all four quadrants	Investigate failure to update Watch Dog Timer and fix.	UNLIKELY	MINOR
Hardware Interlocks TC OVER TEMPERATURE If any LLD quadrant TC > 395 degrees C Disable LLD Heaters	Uncontrolled operation. Possible undesirable heating of LLD during other operations.	Interlock signal. Disable LLD Heaters and Enable LLD Cooling for that quadrant	Investigate failure and fix.	UNLIKELY	MINOR
Software Interlocks TC OVER TEMPERATURE If any LLD quadrant TC or Heater Control TC > 375 degrees C	Uncontrolled operation. Possible undesirable heating of LLD during other operations.	Interlock signal. Disable LLD Heaters and Enable LLD Cooling for that quadrant	Investigate failure and fix.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Software Interlocks COOLING GAS PRESSURE Each of the four LLD plates has a cooling line for 95psi air cooling gas. On each cooling line, at its entrance into the vessel, there is a cooling gas pressure transducer whose trip level is set at 85psi. The signal from each transducer will be sent to a hardwired interlock. The hardwired interlock will turn-off the heaters for a particular heater quadrant if the cooling gas pressure is < 85psi AND the plate TC temperature >395°C.	Uncontrolled operation. Possible undesirable heating of LLD during other operations.	Disable LLD Heaters and Enable LLD Cooling for affected quadrants	Investigate failure and fix	UNLIKELY	MINOR
Software Interlocks NETWORK COMMUNICATION If loss of LLD – EPICS Communication Software Interlocks SHOT TIME If Shot Time > T+ 90 Seconds or < T+ 20 Seconds	Uncontrolled operation. Possible undesirable heating of LLD during other operations. JxB forces on heater cables.	Disable LLD Heaters and Enable LLD Cooling for all four quadrants Disable LLD Heaters and Enable LLD Cooling for all four quadrants.	Investigate failure and fix. Investigate failure and fix.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
DATA to EPICS via LLD CONTROL SYSTEM SOFTWARE NETWORK COMMUNICATION FAILURE *LLD QUADRANT ON* Definition: Any LLD TC or Heater TC > 50 deg. C or any Heater > 5 Watts *LLD QUADRANT EVAPORATING* Definition: Any LLD TC or Heater TC > 375 deg C *LLD QUADRANT COOLING* Definition: Cooling On/Off Status for each quadrant *LLD TC TEMPERATURES* Definition: Temperature in degrees C of all Hardwire Interlocked TC's *QUADRANT HARDWIRE INTERLOCK STATUS* Definition: Hardwire Interlock Good/Not Good Status for each quadrant	LLD heating system shutdown.	Disable LLD Heaters.	Investigate failure and fix.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
DATA From EPICS to LLD CONTROL SYSTEM SOFTWARE NETWORK COMMUNICATION FAILURE *SHOT NUMBER* Definition: NSTX Shot Number *SHOT TIME* Definition: NSTX Shot Clock Time *NETWORK COMMUNICATION HANDSHAKE* Definition: EPICS SystemResponse/Query *EPICS – PLC COMMUNICATION STATUS* Definition: EPICS – PLC Communication Good/Not Good Status	LLD heating system shutdown.	Disable LLD Heaters.	Investigate failure and fix	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: LITER to Evaporate Lithium (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
After venting and several days of ventilation, hazardous dust or granules are found in lower region of vessel.	Eye, nose, and inhalation hazard.	Visual inspection reveals surface coatings of dust or granules.	Sweep, vacuum, or use damp fireproof cloth to remove as indicated in Vessel Maintenance Procedure using appropriate personnel protective equipment (PPE), e. g., gloves, face masks, face shields, and goggles.	UNLIKELY	MINOR
After venting and several days of ventilation, oxidized or nitrated lithium compounds are found on surfaces needing mechanical or welding work.	Possible eye, nose, and inhalation hazard.	Visual inspection reveals surface coatings.	Use damp fireproof cloth to clean the work area using appropriate PPE, e. g., gloves, face masks, face shields, and goggles.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: During Lithium Pellet Injection (LPI) Operation

Function: A Lithium Pellet Injector (LPI) is provided to inject lithium pellets into NSTX plasmas. In addition, the LPI is used as a versatile low-Z impurity injector for recycling, transport, and wall conditioning studies.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
During LPI pellet fabrication, the Argon Glove Box becomes aerated due to emptying of the Argon cylinder.	Possible oxidation and moisture interaction with the pellets and exposed lithium.	Argon flow stops, gas cylinder gauge indicates empty.	Replace empty Argon cylinder with full cylinder. Dispose of all exposed pellets and lithium. Restart pellet fabrication procedure from the beginning.	UNLIKELY	MINOR
During transport of the LPI pellets to the NSTX Test Cell in the Argon atmosphere, the Argon is lost.	Possible oxidation and moisture interaction with the pellets.	The container lid is found to be opened.	Return all exposed pellets to waste container in Room L-111, Argon Glove Box. Restart pellet fabrication procedure from the beginning.	UNLIKELY	MINOR
During loading of the pellets into the LPI, pellet-loaded cartridges are dropped.	Possible oxidation and moisture interaction with the pellets.	The numbered cartridge required for a particular numbered barrel is missing.	Find missing cartridge. Return all exposed pellets to waste container in Room L-111, Argon Glove Box. Restart pellet fabrication procedure from the beginning.	UNLIKELY	MINOR
During transport of the LPI pellets to the NSTX Test Cell in the Argon atmosphere, the Argon is lost.	Possible oxidation and moisture interaction with the pellets.	The container lid is found to be opened.	Return all exposed pellets to waste container in Room L-111, Argon Glove Box. Restart pellet fabrication procedure from the beginning.	UNLIKELY	MINOR

WBS Element: 3.4 Gas Delivery System Component: During Lithium Pellet Injection (LPI) Operation (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
The loading of the pellets-loaded cartridges into the LPI takes longer than specified in the procedure.	Possible oxidation and moisture interaction with the pellets.	Note and record start and completion time.	Return all exposed pellets to waste container in Room L-111, Argon Glove Box. Restart pellet fabrication procedure from the beginning.	UNLIKELY	MINOR
Insufficient LPI propellant pressure.	Poor acceleration of cartridge.	Indicated by LPI velocity diagnostics.	Replace gas cylinder or malfunctioning gas handling component.	UNLIKELY	MINOR
LPI Control malfunction.	Fill pressure, propellant triggering, or magazine rotation inoperative.	Indicated by LPI control system sensors.	Replace malfunctioning component.	UNLIKELY	MINOR
A minor vessel leak occurs during or after LPI operations.	Possible oxidation and moisture interaction with the pellets in the LPI and thin films deposited on vessel surfaces.	Vessel vacuum instrumentation.	Fix leak. Restore good vacuum conditions as soon as possible.	UNLIKELY	MINOR

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
A vessel viewport shatters during or after LPI operations, and air rushes into the vessel while graphite power handling surfaces are hot.	Possible oxidation and moisture interaction with the pellets in the LPI and thin films deposited on vessel surfaces. Possible rapid oxidation of small lithium granules. Essentially no (<1°K) rise in graphite temperature.[40] Any lithium deuteride (LiD) generated & released to the NTC should result in room concentrations < OSHA permissible exposure limit (PEL).[41]	Vessel vacuum instrumentation and TV cameras.	Fix or replace failed component. Restore good vacuum conditions as soon as possible. Return all exposed pellets to waste container in Room L-111, Argon Glove Box and replace with fresh pellets.	UNLIKELY	MINOR
The plasma current fizzles or fails to exceed 100 KA during LPI operations.	No LPI trigger.	Indicated by LPI control system sensors.	Await improved discharge conditions.	UNLIKELY	MINOR
After venting and several days of ventilation following LPI operations, hazardous dust or granules are found in the lower region of the vessel.	Eye, nose, and inhalation hazard.	Visual inspection.	Sweep, vacuum, or use damp fireproof cloth to remove as indicated in the Vessel Maintenance Procedure.	UNLIKELY	MINOR

[40] Reaction of lithium with water vapor in the inrushing air would produce LiOH and hydrogen. The energy released from this reaction and the burning of hydrogen would be about 90 kJ, which would raise the graphite temperature by about 0.1°K. The resulting temperature would be far below the ignition temperature of graphite (650°C). See Reference 24 for details.
[41] 0.025 mg/m^3. See Reference 24 for details.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
After venting and several days of ventilation following LPI operations, oxidized or nitrated lithium compounds are found on surfaces needing mechanical or welding work.	Possible eye, nose, and inhalation hazard.	Visual inspection.	Use damp fireproof cloth to clean the work area.	UNLIKELY	MINOR

WBS Element: 3.5 Glow Discharge Cleaning (GDC) System
Function: GDC provides conditioning of the vacuum vessel and PFCs via bombardment by particles from a diffuse plasma in helium. Vacuum vessel and center stack casing will be grounded. The GDC system for 1st plasma will consist of a retractable probe attached to a portable power supply.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Short circuit between probe and vacuum vessel	GDC power supply will trip on overcurrent. No measurable potential rise of grounded vacuum vessel will occur due to limited current delivery of GDC power supply.	Loss of GDC current as indicated by GDC power supply instrumentation	Troubleshoot and repair	UNLIKELY	MINOR
Failure of GDC power supply current limiting resistor	GDC power supply will trip on overcurrent. No measurable potential rise of grounded vacuum vessel will occur due to limited current delivery of GDC power supply.	Loss of GDC current as indicated by GDC power supply instrumentation	Troubleshoot and repair	UNLIKELY	MINIMAL
Incorrect helium pressure	GDC current could become concentrated and sputter metallic impurities onto PFCs leading to loss of conditioning	Visible arcing	Increase pressure to reduce arcing and achieve uniform GDC	UNLIKELY	MINIMAL

WBS Element: 3.5 Glow Discharge Cleaning (GDC) System

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Glow stops during TMB injection.	TMB does not break down and deposit on surfaces. TMB pumps through NSTX vacuum system. Vent stack purged with nitrogen, so no possibility of combustion in vent stack.	PLC observes low GDC current and automatically shuts down TMB injection.	Restart GDC with He and return to operation. If repeated failure of system to maintain GDC, trouble shoot system up to and including aborting TMB operation.	UNLIKELY	MINIMAL
Vacuum window breaks or vacuum seal leaks during boronization under vessel bakeout conditions	The rise in vessel pressure due to in-rushing air would trigger the pressure interlock to shut down gas injection and close valves to isolate the TMB gas delivery system. Little or no in-vessel damage due to possible auto-ignition of TMB would be expected.	PLC interlocks	Troubleshoot and repair	UNLIKELY	MINIMAL
~~GDC probe stuck~~	~~If stuck in retracted position, unable to perform GDC, if in extended position, unable to resume normal NSTX operations~~	~~Local probe position indication~~	~~Remove actuator, bellows enclosure, withdraw probe, and repair.~~		

WBS Element: 3.5 Glow Discharge Cleaning (GDC) System Component: (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
~~GDC probe vacuum leak~~	~~Depending on leak, possible interruption of operations~~	~~Pressure instrumentation, rate of rise measurements~~	~~Withdraw probe, close torus interface gate valve, remove probe and repair~~		

4 Plasma Diagnostics

WBS Element: 4X Diagnostics Component: Plasma Current Rogowski Coils See Footnote[42]

Function: Two (2) Plasma Current Rogowski Coils provide redundant measurements of plasma current

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Shorted turns	Reduced voltage per unit of plasma current derivative	Difference between redundant measurements	Adjust scaling, replace coil if and when NSTX center stack removed and disassembled	LOW	MINIMAL - use redundant sensor and continue plasma operations
Open circuit	Loss of signal	Difference between redundant measurements	Revert to single measurement, replace coil if and when NSTX center stack removed and disassembled	LOW	MINIMAL - use redundant sensor and continue plasma operations
Groundwall insulation failure to OH ground plane	Common mode voltage electrically coupled into integrator circuitry	Noisy signal	Revert to single measurement, replace coil if and when NSTX center stack removed and disassembled	LOW	MINIMAL - use redundant sensor and continue plasma operations

[42] A large variety of diagnostics are planned for NSTX. The diagnostic components evaluated herein are those which are essential for machine operations

WBS Element: 4X Diagnostics Component: Plasma Current Rogowski Coils (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Groundwall insulation failure to center stack casing[43]	If non-CHI operations or CHI operations with center stack casing grounded, common mode voltage electrically coupled into integrator circuitry. If CHI operations with center stack casing energized, fault path for CHI power system, possible destruction of coil, arcing, burning, melting of leads to integrator rack and/or integrator circuit board	If non-CHI operations or CHI operations with center stack casing grounded, noisy signal. If CHI operations with center stack casing energized, CHI power supply system ground fault and/or overcurrent detection	Revert to single measurement, replace coil if and when NSTX center stack removed and disassembled	LOW	MINIMAL - use redundant sensor and continue plasma operations
Integrator failure	Signal error	Difference between redundant measurements	Troubleshoot and repair/replace	LOW	MINIMAL - use redundant sensor and continue plasma operations

WBS Element: 4X Diagnostics Component: Flux Loops

Function: Single turn flux loops (redundant pairs, each loop wired to instrument rack, one instrumented) installed at approx. 50 locations inside/outside vacuum vessel. Used for plasma control (shape reconstruction) and calculation of eddy currents in conducting passive structures.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Open circuit	Loss of signal	Abnormal magnetic reconstruction	Revert to spare loop, replace failed loop when accessible	LOW	MINIMAL - use redundant sensor and continue plasma operations

[43] See FMEA for Center Stack Casing (WBS 1.3.3) for electrical failure of center stack thermal insulation

WBS Element: 4X Diagnostics Component: Flux Loops

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Groundwall insulation failure to structure at same circuit common as instrumentation	Small common mode voltage electrically coupled into integrator circuitry	Noisy signal	Revert to spare loop, replace failed loop when accessible	LOW	MINIMAL - use redundant sensor and continue plasma operations
Center stack flux loop (around OH coil ground plane) groundwall insulation failure to center stack casing[44]	If non-CHI operations or CHI operations with center stack casing grounded, small common mode voltage electrically coupled into integrator circuitry. If CHI operations with center stack casing energized, fault path for CHI power system, possible destruction of loop, arcing, burning, melting of leads to integrator rack and/or integrator circuit board	If non-CHI operations or CHI operations with center stack casing grounded, noisy signal. If CHI operations with center stack casing energized, CHI power supply system ground fault and/or overcurrent detection	Diagnose extent of failure and damage, repair and replace as required.	LOW	MINIMAL - use redundant sensor and continue plasma operations
Integrator failure	Signal error	Abnormal magnetic reconstruction	Troubleshoot and repair/replace	LOW	MINIMAL - use redundant sensor and continue plasma operations

[44] SeeFMEA for Center Stack Casing (WBS 1.3.3) for electrical failure of center stack thermal insulation

WBS Element: 4X Diagnostics **Component: Thermocouples**

Function: **Thermocouples (approx. 50 in vessel, 20 ex-vessel) installed on PFC backplates, vacuum vessel, center stack casing, and OH groundwall insulation. In general, toroidal redundancy is provided (for each poloidal location, several toroidal locations are instrumented).**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Open circuit or short circuit	Loss of signal	Signal outside normal range, alarm via EPICS Process Control	Use nearby thermocouples or others in same poloidal location	LOW	MINIMAL - use redundant sensor and continue plasma operations
Groundwall insulation failure to structure at same circuit common as instrumentation	Small common mode voltage electrically coupled into monitoring circuitry, signal noisy during pulse	Noisy signal during pulse	Ignore noisy signal during pulse	LOW	MINIMAL - use redundant sensor and continue plasma operations
Center stack thermocouple (around OH coil ground plane) groundwall insulation failure to center stack casing[45]	If non-CHI operations or CHI operations with center stack casing grounded, small common mode voltage electrically coupled into monitoring circuitry. If CHI operations with center stack casing energized, fault path for CHI power system, possible destruction of thermocouple, arcing, burning, melting of leads to instrument rack and/or monitoring circuitry board	If non-CHI operations or CHI operations with center stack casing grounded, noisy signal. If CHI operations with center stack casing energized, CHI power supply system ground fault and/or overcurrent detection	Ignore noisy signal during pulse. If failure, diagnose extent of failure and damage, repair and replace as required.	LOW	MINIMAL - use redundant sensor and continue plasma operations
Monitoring electronics failure	Signal error	Signal outside normal range, alarm via EPICS Process Control	Troubleshoot and repair/replace	LOW	MINIMAL - use redundant sensor and continue plasma operations

[45] See FMEA for Center Stack Casing (WBS 1.3.3) for electrical failure of center stack thermal insulation

5 Power Systems

WBS Element: 5X Power Systems Component: AC Power Systems (WBS 5.1)

Function: **AC Power Systems receives power from the 138kV utility grid and supplies all electrical power to the NTSX experiment - this includes Auxiliary (House) AC Power and Experimental AC Power.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of 138kV AC power to PPPL	Interruption of NSTX operations, Vital loads supplied immediately by UPS power: - NTC Fire Protection Panel - NTC Emergency Lighting - HIS Critical loads supplied by Standby Diesel Generator after start up delay of approximately 10 seconds: - NTC Cooling Water Skids & PLC - NTC Vacuum Pumping Skids & PLC - NTC Lighting - NSTX Control Room - NBI Helium Refrigeration and Water Systems	Various	Await restoration of power	NORMAL	MINIMAL
Loss of AC power to any/all components of Cooling Water System	If pumps, cooling water flow ceases; if automatic valves, valves remain in last position, all valves remain manually operable	PLC and EPICS Process Control	Await restoration of power	NORMAL	MINIMAL
Loss of AC power to any/all components of Vacuum Pumping System and Gas Delivery System	All components revert to safe state	PLC and EPICs Process Control	Await restoration of power	NORMAL	MINIMAL

WBS Element: 5X Power Systems Component: AC Power Systems (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Standby Diesel Generator failure during 138kV utility outage	All components revert to safe state. If bakeout underway[46], revert to alternate 26kV line to PPPL or, if 26kV not available, configure cooling water system valves to circulate municipal water supply through OH coil. Loss of power to Helium Refrigeration System; regeneration of cryopanels, possible rupture of burst disks, possible freezing of water cooling lines (see NBI FMEA).	Loss of power	Await restoration of power	NORMAL	MINIMAL

[46] Latent heat due to bakeout could overheat the OH coil after approx. 5 hours if water cooling is entirely absent

WBS Element: 5X Power Systems **Component: AC/DC Power Supply Converters**

Function: The AC/DC Power Supply Converters (a.k.a. Transrex power supplies) convert AC power to controlled DC power in the TF, PF, OH, and CHI circuits.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Thyristors failure to block voltage when system has been disarmed (requires that ≥ 2 Master Gate Drivers suffer spurious missfire, or ≥ 4 thyristors suffer spurious missfire without MGD pulse). Note: since the permissive relay contacts directly disable the MGD optodriver boards, control failures (firing generator, Central I&C, etc.) cannot cause this fault.	Voltage applied to output terminals, unintended flow of current in the coils if SDS line switches closed and SDS ground switches open. Will result in Level 1 fault, followed by Level 2 fault and AC breaker trip	Power supply fault detector will detect loss of permissive during pulse, (internal power supply Level 1 faults), and failure to suppress firing (Level 2 fault and AC circuit breaker trip).	Troubleshoot and repair	ANTICIPATED	MINIMAL

WBS Element: 5X Power Systems Component: AC/DC Power Supply Converters (con't)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of normal thyristor gate pulse control due to: - miscellaneous power supply internal fault conditions detected by power supply fault detector - firing generator malfunction - master gate driver malfunction - loss of incoming 13.8kV - loss of 120V control power	Output voltage waveform not in accordance with PSRTC software command, load (coil) current not controllable, possible overcurrent or excessive duration of current. After detection of fault, shutdown by suppress, bypass action with delivery of additional volt-seconds to load depending on AC sine wave phase angle at time of fault initiation, possible AC feeder breaker trip. Current waveform after fault depends on time delay to suppress/bypass, phase angle at time of suppress/bypass initiation, and load inductance, as well as shutdown sequence of mutually coupled circuits[47]	PSRTC software branch and/or load overcurrent detection, Power supply fault detector including section overcurrent, module overcurrent, and overtime detection (internal power supply Level 1 faults), Analog Coil Protection overcurrent/overtime detection, Rochester Instrument System (RIS)[48] overcurrent and $\int i^2(t)dt$ detection (external Hardwired Control System (HCS) Level 1 faults) , AC feeder breaker overcurrent and overtime detection	Troubleshoot and repair or swap power supplies if spare available	ANTICIPATED	MINIMAL

[47] PSRTC shuts down circuits individually, whereas HCS faults result in common shutdown amongst mutually coupled circuits

[48] RIS protection is applied to TF, OH, PF2L, PF3U&L only

WBS Element: 5X Power Systems Component: AC/DC Power Supply Converters (con't)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Failure to suppress/bypass after internal Level 1 fault	Continued flow of current in converter transformer and application of voltage to load following initial fault detection, transition to power supply internal Level 2 fault state, command to trip AC feeder breaker, AC feeder breaker trip	Power supply fault detector Level 2 fault detection and AC feeder breaker overcurrent and overtime detection	Troubleshoot and repair or swap power supplies if spare available	ANTICIPATED	MINIMAL
Ground fault	Shift in voltage to ground around circuit, small leakage current to ground (limited by high resistance grounding), suppress/bypass per HCS Level 1 fault	Power supply system ground fault detection	Troubleshoot and repair or swap power supplies if spare available	ANTICIPATED	MINIMAL
CHI power supply delivers current without B_{tf} > threshold due to control failure	None; Master Gate Drivers (MGDs) of CHI power supplies are blocked unless RIS indicates I_{tf} > threshold	Absence of TF current above threshold and of correct polarity	Diagnose and troubleshoot	ANTICIPATED	MINIMAL

WBS Element: 5X Power Systems **Component: Safety Disconnect Switches**

Function: **The Safety Disconnect Switches (SDS) provide two pole no load line disconnect switches and two pole grounding switches which connect the power supply system to the load. They serve to isolate the NTC from electrical hazards due to the power supply system during access to the NTC via interlocks in the Safety Lockout Device (SLD). They include spark gaps and non-linear resistors (surge arrestors) connected to ground.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Line switch fail to open	Unable to effect normal isolation of power supply system from load, unable to place SLD in "safe" state, unable to access NTC	Limit switch detectors monitored by EPICS Process Control, HCS, SLD, and HIS	Provide alternate means of isolating energy source (e.g. rack out AC feeder breakers), troubleshoot and repair	ANTICIPATED	MINIMAL
Line switch fail to close	Unable to connect power supply system to load	Limit switch detectors monitored by EPICS Process Control, HCS, SLD, and HIS	Troubleshoot and repair	ANTICIPATED	MINIMAL
Ground switch fail to close	Unable to effect normal grounding of power supply system, unable to place SLD in "safe" state, unable to access NTC	Limit switch detectors monitored by EPICS Process Control, HCS, SLD, and HIS	Provide alternate means of isolating energy source (e.g. rack out AC feeder breakers), troubleshoot and repair	ANTICIPATED	MINIMAL
Ground switch fail to open	Unable to place power supply system in operating configuration (unable to "arm")	Limit switch detectors monitored by EPICS Process Control, HCS, SLD, and HIS	Troubleshoot and repair	ANTICIPATED	MINIMAL

WBS Element: 5X Power Systems Component: Safety Disconnect Switches (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Line switch limit switch failure, or short or open in wiring	Disparity between status of the two limit switches mounted on the two line switch poles actuated by common pneumatic mechanism; if line switches are open and failed limit switch indicates closed, unable to place SLD in safe state, and data highlighted as erroneous on EPICs display. If line switches are closed and failed limit switch indicates open, data highlighted as erroneous on EPICs display.	Limit switch detectors are monitored by EPICS Process Control and SLD	Troubleshoot and repair	ANTICIPATED	MINIMAL

WBS Element: 5X Power Systems Component: Safety Disconnect Switches (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Ground switch limit switch failure	Error in status reported by the single limit switch mounted on the common pneumatic mechanism which actuates the two ground switch poles; if ground switches are open and failed limit switch indicates closed, SLD electrical interlock would not block transition to the safe state with switches open[49]. If ground switches are closed and failed limit switch indicates open, could close line switches and arm power supplies with ground and short circuit on system, possible ground and overcurrent condition	If fail to indicate open, would close (audible event in FCPC building) upon venting SLD. If fail to indicate closed, ground fault and overcurrent detection, HCS Level 1 fault	Troubleshoot and repair	ANTICIPATED	MINIMAL

[49] Probability of overall event sequence leading to SLD transition to safe state with switches open is remote because, in addition to the electrical interlock, the air supply is cut off and vented and the ground switches, which require air pressure to remain open, will be forced closed by mechanical springs and will remain closed even if commanded to open.

WBS Element: 5X Power Systems Component: Safety Disconnect Switches (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Pressure switch failure, or short or open in wiring	Error in status reported by pressure switch on the pneumatic reservoir; if reservoir is vented and failed switch indicates pressure, unable to place SLD in safe state. If reservoir is not vented and failed switch indicates vented, SLD could transition to safe state with pressure remaining in reservoir. If ground or line switches changed state as a result of this pressure being available, electrical interlocks in SLD would issue an E-Stop condition, all ground switches would close, all line switches would open, and all AC feeder circuit breakers would open.	If pressure switch status stuck indicating vented condition, would report erroneous data when pressurized (would be noticed on EPICs mimic display if failure affected EPICs signal). If pressure switch status stuck indicating pressurized condition, unable to place SLD into safe state.	Troubleshoot and repair	ANTICIPATED	MINIMAL
Ground switch fail to open	Unable to place power supply system in operating configuration (unable to "arm")	Limit switch detectors monitored by EPICS Process Control, HCS, SLD, and HIS	Troubleshoot and repair	ANTICIPATED	MINIMAL

WBS Element: 5X Power Systems Component: Safety Disconnect Switches (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Loss of contact pressure on line switch blades	High contact electrical resistance, possible arcing, melting, burning	Maintenance (mechanical adjustment and joint resistance measurement) and inspection (temperature stickers)	Troubleshoot and repair	ANTICIPATED	MINIMAL
Spark gap electrical breakdown[50]	Ground fault, small leakage current (limited by high resistance grounding), redistribution of voltage to ground, Level 1 (power supply suppress/bypass) shutdown	Power supply system ground fault detection	Troubleshoot and re-adjust	ANTICIPATED	MINIMAL
Surge arrestor electrical breakdown (due to energy overload)	Arcing and burning within SDS metal enclosed cabinet (or, in case of CHI, within metal enclosure containing additional protection unit located in NSTX Test Cell)	Depending on cause, Power supply system ground fault detection and/or power supply overcurrent condition	Replace	ANTICIPATED	MINIMAL
DC Potential Transducer (DCPT) failure	Error in measurement of voltage to ground (information only signal: not used for control or interlocking)	Abnormal signal	Troubleshoot and repair	ANTICIPATED	MINIMAL

[50] Spark gaps are not required for NSTX but cannot be removed (built into the ground switches); they will be adjusted out of normal range of voltage

WBS Element: 5X Power Systems Component: DC Current Transducers

Function: The DC Current Transducers (DCCTs) measure the branch currents in the power supply system, which sum to the load currents in the NSTX coils and CHI circuit. They consist of, in most cases "Halmar" zero flux non-contact transducers, and in some cases "shunts" (current viewing resistors) whose voltage drop is transmitted to ground potential using a fiber optic v/f-f/v link. The signals are received by a "Halmar Signal Conditioner" which provides buffering and fan out to the various destinations. Redundant measurements of load current provided in all cases.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Excessive drift or failure of electronics	Measurement error, possible current control error (control in PSRTC shifts to signal with largest magnitude), interruption of pulse via PSRTC or HCS Level 1 suppress/bypass shutdown	Comparison with redundant measurement in PSRTC software (alarm) and in RIS[51] (HCS Level 1 fault)	Troubleshoot and repair	ANTICIPATED	MINIMAL
Loss of AC power	Loss of AC Power to DCCT; HCS will invoke a Level 1 Fault"	"	"	NORMAL	MINIMAL

[51] RIS coverage for TF, OH, PF2L, PF3U&L only

WBS Element: 5X Power Systems Component: Rochester Instrument System (RIS) Fault Detector

Function: The RIS receives the output of redundant DCCTs from the TF, OH, PF2L, and PF3U&L circuits. It compares redundant signals and performs single time constant exponential ∫i2(t)dt simulation (heating and cooling) to detect current/time overloads, and detects overcurrents. In addition it produces a signal when |Itf| exceeds a setpoint, for interlocking CHI operation.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Fail to detect DCCT discrepancy	None, detected in PSRTC	Operational diagnosis of system fault response or maintenance/test	Troubleshoot and repair	NORMAL	MINIMAL
Fail to detect overcurrent	None, overcurrent detected in PSRTC, ACP, power supply fault detectors, AC feeder protective relaying	Operational diagnosis of system fault response or maintenance/test	Troubleshoot and repair	UNLIKELY	MAJOR
Fail to detect ∫i2(t)dt overload during pulse	None, detected in PSRTC, and backed up by overtime detection in ACP, power supply fault detectors, AC feeder protective relaying	Operational diagnosis of system fault response or maintenance/test	Troubleshoot and repair	UNLIKELY	MAJOR
Fail to detect ∫i2(t)dt overload caused by repetition rate error by operators	Abnormally high temperatures before and after pulse	EPICS alarms on cooling water outlet temperatures returning to collection manifolds	Troubleshoot and repair	UNLIKELY	MAJOR

WBS Element: 5X Power Systems Component: Analog Coil Protection (ACP)

Function: The ACP receives outputs from the DCCTs, via the Halmar Signal Conditioner (HSC), and detects overcurrent and current overtime conditions.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Fail to detect overcurrent	None, overcurrent detected in PSRTC, RIS , power supply fault detectors, AC feeder protective relaying	Operational diagnosis of system fault response or maintenance/test	Troubleshoot and repair	UNLIKELY	MAJOR
Fail to detect overtime	None, detected in PSRTC, $\int i2(t)dt$ detection in RIS , power supply fault detectors, AC feeder protective relaying	Operational diagnosis of system fault response or maintenance/test	Troubleshoot and repair	UNLIKELY	MAJOR

WBS Element: 5X Power Systems Component: Ground Fault Detection

Function: The Ground Fault Detection system monitors the current through the high resistance grounding resistors located in the SDS cabinets. The current is sensed via an electromagnetic relay as well as an electronic level detector.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Electromagnetic relay malfunction	Overall I vs. T limits based on electronic level detector only	Maintenance testing	Troubleshoot and repair	UNLIKELY	MAJOR
Electronic sensor malfunction	Overall I vs. T limits based on electromagnetic relay level only	Maintenance testing	Troubleshoot and repair	UNLIKELY	MAJOR

WBS Element: 5X Power Systems **Component:** **Power Supply Real Time Controller (PSRTC)**

Function: **The Power Supply Real Time Controller (PSRTC) provides control of the voltage and current delivered by the power supply system to the NSTX coils and CHI circuit. It includes the computer processors and I/O equipment located in and associated with the "Skybolt/DAS" computer system as well as the "Power Conversion Link" (PC Link) which delivers the PSRTC commands to the individual AC/DC converters.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Delivery of excess current magnitude due to, software, computer, or I/O failure	Overcurrent (level depends on failure mechanism, circuit in question, protection settings), HCS Level 1 fault (suppress bypass), possible AC feeder breaker trip	RIS[52], ACP, power supply fault detector, AC feeder protective relaying	Diagnose, troubleshoot and repair if required	NORMAL	MINIMAL
Delivery of excess $\int i2(t)dt$ due to, software, computer, or I/O failure	Excessive temperature rise in load (level depends on failure mechanism, circuit in question, protection settings), HCS Level 1 fault (suppress bypass), possible AC feeder breaker trip	RIS (exponential heating/cooling simulation), ACP (overtime), power supply fault detector (overtime) , AC feeder protective relaying (overtime)	Diagnose, troubleshoot and repair if required	NORMAL	MINIMAL
Delivery of excess rms current due to operator error (repetition rate too high)	Excessive ratcheting of load temperature (level depends on failure mechanism, circuit in question, protection settings), HCS Level 1 fault (suppress bypass), possible AC feeder breaker trip	RIS (exponential heating/cooling simulation), (overtime) , AC feeder protective relaying (thermal replica)	Diagnose, troubleshoot and repair if required	NORMAL	MINIMAL

[52] RIS coverage for TF, OH, PF2L, PF3U&L only

WBS Element: 5X Power Systems Component: PSRTC (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Delivery of command to CHI power supply without Btf > threshold due to operator, software, computer, or I/O failure	None; Special interlock is provided such that Master Gate Drivers (MGDs) of CHI power supplies are blocked unless RIS indicates Itf > threshold in appropriate direction	Absence of CHI current	Diagnose and troubleshoot	ANTICIPATED	MINOR
Delivery of OH and PF1b current combination producing excess axial force in (+) z direction (launching load) due to software or I/O failure	None; Special interlock is provided such that Master Gate Drivers (MGDs) of PF1b power supplies are blocked unless RIS indicates Ioh > threshold in appropriate direction	Absence of PF1b current	Diagnose and troubleshoot	ANTICIPATED	MINOR

WBS Element: 5X Power Systems Component: Hardwired Control System

Function: The Hardwired Control System (HCS) provides interlocks which prevent misoperation/misconfiguration of the power supply systems and which interface with the overall Hardwired Interlock System (HIS). Two fault levels (1 and 3) are communicated throughout each system using both series and parallel loops, referred to as L1S, L1P, L3S, L3P.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Power Supply Arm Permissive interlock chain, one or more input contact states invalid (do not reflect true equipment state)	Possible power supply operation in invalid configuration or with equipment status not ready, possible overcurrent or ground fault on power supply system, Level 1 HCS Fault (suppress/bypass)	RIS[53], ACP, power supply fault detector, ground fault detector, AC feeder protective relaying	Diagnose, troubleshoot and repair if required	ANTICIPATED	MINOR

[53] RIS coverage for TF, OH, PF2L, PF3U&L only

WBS Element: 5X Power Systems Component: Hardwired Control System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Configure Permissive interlock chain, one or more input contact states invalid (do not reflect true equipment state)	Possible SDS operation in invalid configuration, possible overcurrent or ground fault on power supply system, Level 1 HCS Fault (suppress/bypass)	RIS, ACP, power supply fault detector, ground fault detector, AC feeder protective relaying	Diagnose, troubleshoot and repair if required	ANTICIPATED	MINOR
Level 1 or Level 3 fault line, series loop short circuit results in bypass of status from power supplies to HCS	None, redundant parallel lines	Disagreement between L1S and L1P (or L3S and L3P) states.	Diagnose, troubleshoot and repair if required	ANTICIPATED	MINOR
Level 1 or Level 3 fault line, parallel loop open circuit results in disconnect of status to/from power supplies & HCS	Redundant series lines, but slower fault response of PS to HCS (approx 50 mS), disconnected power supplies g to fault state upon open circuit and report to HCS via series loop	Disagreement between L1S and L1P (or L3S and L3P) states.	Diagnose, troubleshoot and repair if required	ANTICIPATED	MINOR

6 Central Instrumentation and Control (I&C)

WBS Element: 6X Central I&C **Component: EPICS Process Control System**

Function: The Experimental Physics Instrumentation and Control System (EPICS) Process Control System provides the operator interface for non-real time control and monitoring of the NSTX device

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Any failure mode	No deleterious effect on equipment or personnel safety; all NSTX systems required to be immune to failure of Central I&C in this regard. Operations will be interrupted. Information regarding status of facility, beside that reported via the HIS, may not be available to the operators.	Various	Diagnose, troubleshoot and repair if required	UNLIKELY	MINOR

WBS Element: 6X Central I&C **Component: MDS+ Data Acquisition System**

Function: The Modular Data Systems Plus (MDS+) Data Acquisition System provides the operator interface for diagnostics control and monitoring of the NSTX device, and provides facility for archiving experimental data

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Any failure mode	No deleterious effect on equipment or personnel safety; all NSTX systems required to be immune to failure of Central I&C in this regard. Operations will be interrupted. Information regarding status of facility, beside that reported via the HIS, may not be available to the operators.	Various	Diagnose, troubleshoot and repair if required	UNLIKELY	MINOR

WBS Element: **6X Central I&C** **Component:** **Safety System**

Function: **The Safety System consists of the Hardwired Interlock System (HIS) and the Safety Lockout Device (SLD). The HIS provides permissives to the power supply, RF, and NBI systems which enable them to be configured and operated. The SLD monitors the status of the power supply system safety disconnect switches and provides a "Safe" signal only when all switches are in the safe position and the compressed air supply (which actuates the switches) has been vented. Two search and secure loops are provided, one for the NSTX Test Cell and one for the cable spread room. These loops must be armed in order for permissives to be issued.**

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
HIS UPS failure	E-stop condition, permissives to power supply, RF, and NBI systems removed, search and secure loops drop out, status indications in control room not functional.	Loss of indications on HIS control panel in NSTX control room	Troubleshoot and repair	LIKELY	MINOR
SLD electrical interlock failure indicating SDS ground switches in safe condition when in unsafe state	Overall SLD "Safe" status not achieved, since SDS ground switches cannot be open without air supply, and SLD"Safe" status not issued if air supply still available	EPICs Process Control in combination with SLD status indicator lamps	Troubleshoot and repair	VERY UNLIKELY	MAJOR
SLD electrical interlock failure indicating SDS ground switches in an unsafe condition when in safe state	Unable to achieve "Safe" status required for area access	EPICs Process Control in combination with SLD status indicator lamps	Troubleshoot and repair	VERY UNLIKELY	MINOR

WBS Element: 6X Central I&C Component: Safety System (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
SLD electrical interlock failure indicating SDS line switches in safe condition when in unsafe state	Loss of one level of isolation. However, permissive to power supply AC/DC converters not issued in "Safe" state. Even if AC/DC converters failed to block, closed ground switches would prevent high voltage from appearing on bus bars in NSTX Test Cell	EPICs Process Control in combination with SLD status indicator lamps	Troubleshoot and repair	VERY UNLIKELY	MINOR
SLD electrical interlock failure indicating SDS line switches in unsafe condition when in safe state	Unable to achieve "Safe" status required for area access	EPICs Process Control in combination with SLD status indicator lamps	Troubleshoot and repair	VERY UNLIKELY	MINOR
SLD electrical interlock failure indicating compressed air vented when pressure still present	Loss of one level of prevention of SDS line or ground switch changing state to unsafe position. However, electrical interlocks still in effect. In case a switch changed state, an E-stop would result.	EPICs Process Control in combination with SLD status indicator lamps	Troubleshoot and repair	VERY UNLIKELY	MINOR
SLD electrical interlock failure indicating compressed air not vented after venting has occurred	Unable to achieve "Safe" status required for area access	EPICs Process Control in combination with SLD status indicator lamps	Troubleshoot and repair	VERY UNLIKELY	MINOR

WBS Element: 6X Central I&C Component: Safety System (cont'd

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
HIS interface wiring (e.g. permissive, status, search and secure, etc.) open circuit or short circuit	None, receiving end will revert to safe condition since all signals are 120VAC sourced and energized in safe state	Loss of expected 120V AC signal	Troubleshoot and repair	VERY UNLIKELY	MINOR
Search and secure loop relay stuck in armed position	Search and secure procedure, which first drops the loop, will reveal the deficiency	Loop does not drop when door to area is opened.	Troubleshoot and repair	VERY UNLIKELY	MAJOR

9 Operations

WBS Element: Operations

Function: Operations personnel (Chief Operations Engineer (COE), Power Supply Engineering In Charge (EIC), and Field Coil Power Conversion (FCPC) operators) set the configuration of the power supply system and program the PSRTC.

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Programming of input data leading to excess current magnitude, $\int i2(t)dt$, or duration	Fault detected by PSRTC, suppress/bypass shutdown	PSRTC	Correct programming error	UNLIKELY	MINOR
Programming of CHI operation with incorrect Btf magnitude and polarity	None; Master Gate Drivers (MGDs) of CHI power supplies are blocked unless RIS indicates Itf > threshold	Absence of CHI current	Correct programming error	UNLIKELY	MINOR
Programming of OH and PF1b current combination producing excess axial force in (+) z direction (launching load) due to operator error	Fault detected by PSRTC, suppress/bypass shutdown	PSRTC	Correct programming error	UNLIKELY	MINOR

WBS Element: Operations (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Excess applied voltage due to operator error, too many power supply sections connected in series (administrative procedures not correctly followed)[54]	Safety Disconnect Switch (SDS) surge arrestor voltage limiting, possible surge arrestor energy overload and short circuit, short circuit on power supplies, overcurrent, suppress/bypass per HCS Level 1 fault	Power supply module and section overcurrent detection	Replace arresters	UNLIKELY	MEDIUM
Voltage unbalance in parallel or antiparallel configurations due to operator error (administrative procedures not correctly followed), unequal number of power supply sections in parallel or antiparallel strings	Short circuit current circulating between antiparallel strings, possible electrical breakdown of thyristors/snubber components, suppress/bypass per HCS Level 1 fault	Power supply fault detector section and module overcurrent	Reconfigure, replace modules if damaged	UNLIKELY	MEDIUM
CHI power supply connected (line switches closed) but PSRTC not in normal (plasma) mode	Pulse inhibited	PSRTC	Open switches or switch PSRTC modes	UNLIKELY	MINOR

[54] Kirk Keys which permit the insertion of power supplies not planned for NSTX use will be removed and stored elsewhere via administrative procedures (e.g. in the D-site Shift Supervision lock box); therefore the probability of this failure is considered to be remote

WBS Element: Operations (cont'd)

Failure Mode	Effect	Detection	Recovery	Probability	Consequence
Upper/lower PF coil currents opposite polarity due to operator error (administrative procedures not correctly followed)[55], incorrect SDS bus link configuration (PF1aU/L, PF2aU/L, PF3aU/L)	Repulsive instead of attractive axial forces between coils, possible mechanical damage to coil supports, coil displacement, possible coil damage	Abnormal magnetic topology and coil impedance	Reconfigure links, repair damage (if any)	UNLIKELY	MEDIUM
Attempt to operate power supply system with SDS ground switches closed	None, prevented by HCS interlock	No response to command to HIS arm permissive	Open ground switches	UNLIKELY	MINOR
Attempt to open SDS line switches under load	None, prevented by HCS interlock (power supply and configure permissives are mutually exclusive)	No response to EPICS process control command	Disarm power supplies, place HIS system into "configure"	UNLIKELY	MINOR

**** END OF FMEA ****

[55] Reconfiguration of bus links is a lengthy procedure typically performed by one or more technicians under the supervision of the FCPC EIC via administrative procedures; therefore this failure mode would require incorrect action on the part of several individuals over a period of several hours. On this basis the probability of this failure is considered to be small.