National Spherical Torus eXperiment Upgrade

Recovery Project
Systems Engineering Overview

NSTX-U Recovery Project FDR – March 17, 2020

Peter Dugan

NSTX-U Recovery Project Systems Engineering

Last edit: 3/10/20

PPPL PRINCETON PLASMA PHYSICS LABORATORY

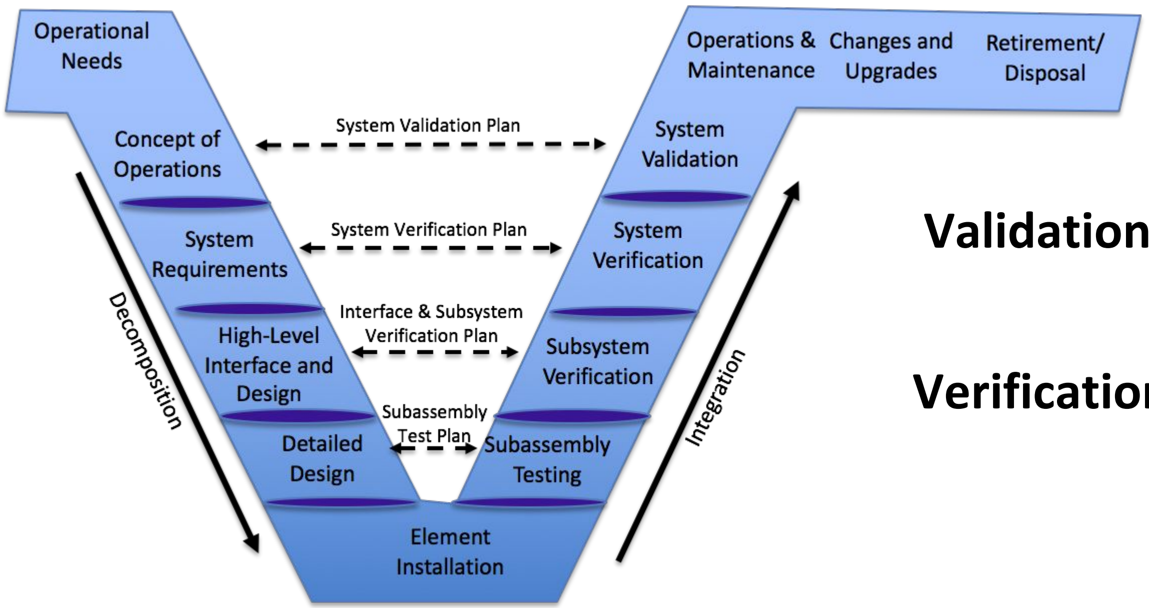
PRINCETON UNIVERSITY

Systems Engineering Overview

System Decomposition

Requirements

Interface Control



Validation

Verification

Risk

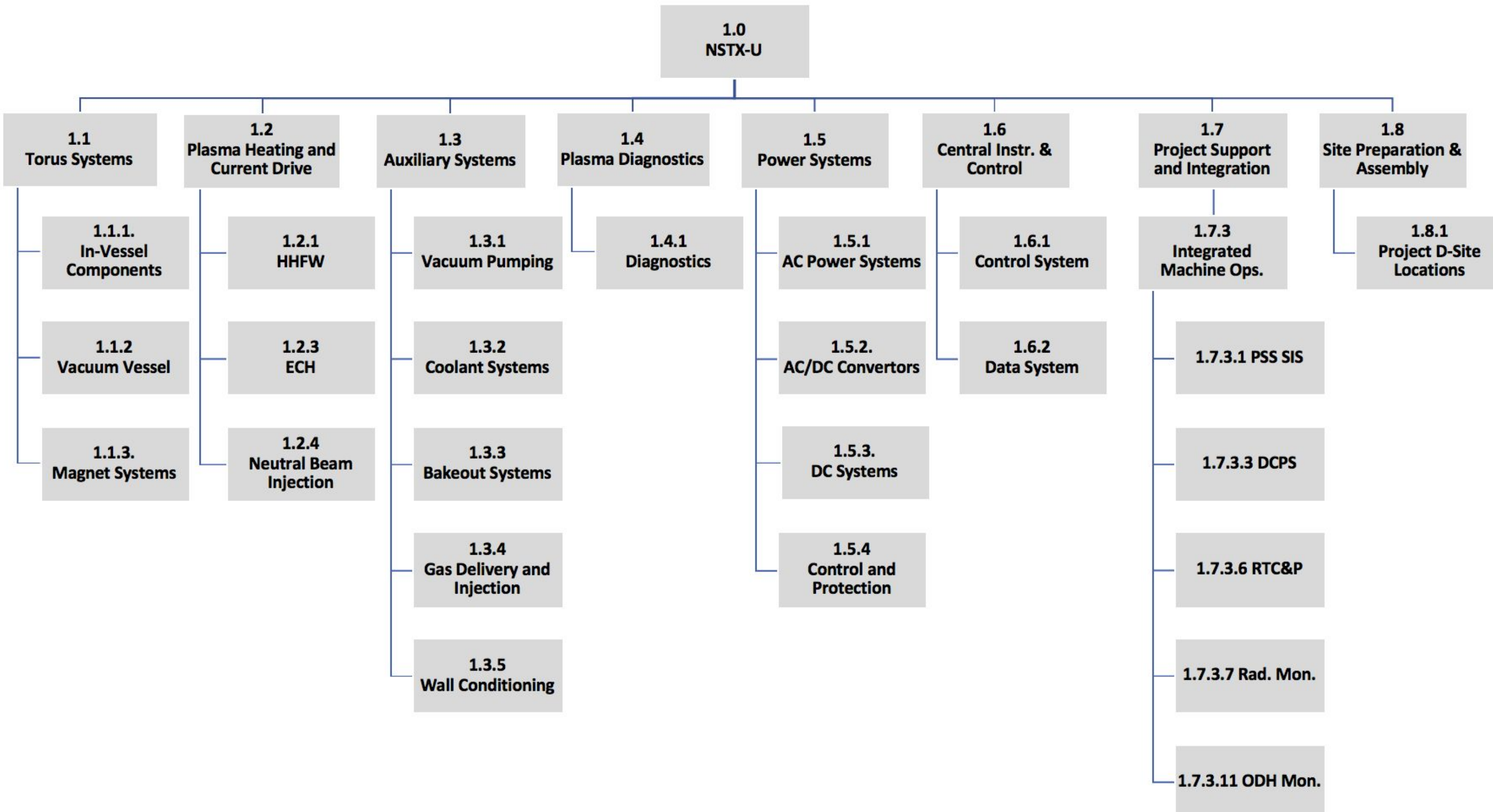
System Decomposition managed via a system breakdown structure

- NSTX-U provides a functional decomposition of component elements

PPPL	PRINCETON PLASMA PHYSICS LABORATORY	PROCEDURE	No. ENG-063 Rev 0 page 1 of 4
Subject: System Breakdown Structure and Categorization		Effective Date: 8/1/18	Initiated by: Head, Engineering Department
		Supersedes: NEW	Approved: Director

- System breakdown structure (SBS) breaks down all components
- Work breakdown structure (WBS) used for project scope
- SBS is used by Quality Assurance, Interface Control, and FMECA, Procurement, Calculations, Design Reviews, Travellers, V&V
- Document Management System (DMS) uses the SBS to assign document numbers

Top tiers of the NSTX-U system breakdown structure



Responsible Engineers manage SBS elements

- Responsible Engineers are ultimately responsible for all aspects of the SBS across the lifecycle
- Cognizant individuals will contribute the the Execution of SBS elements

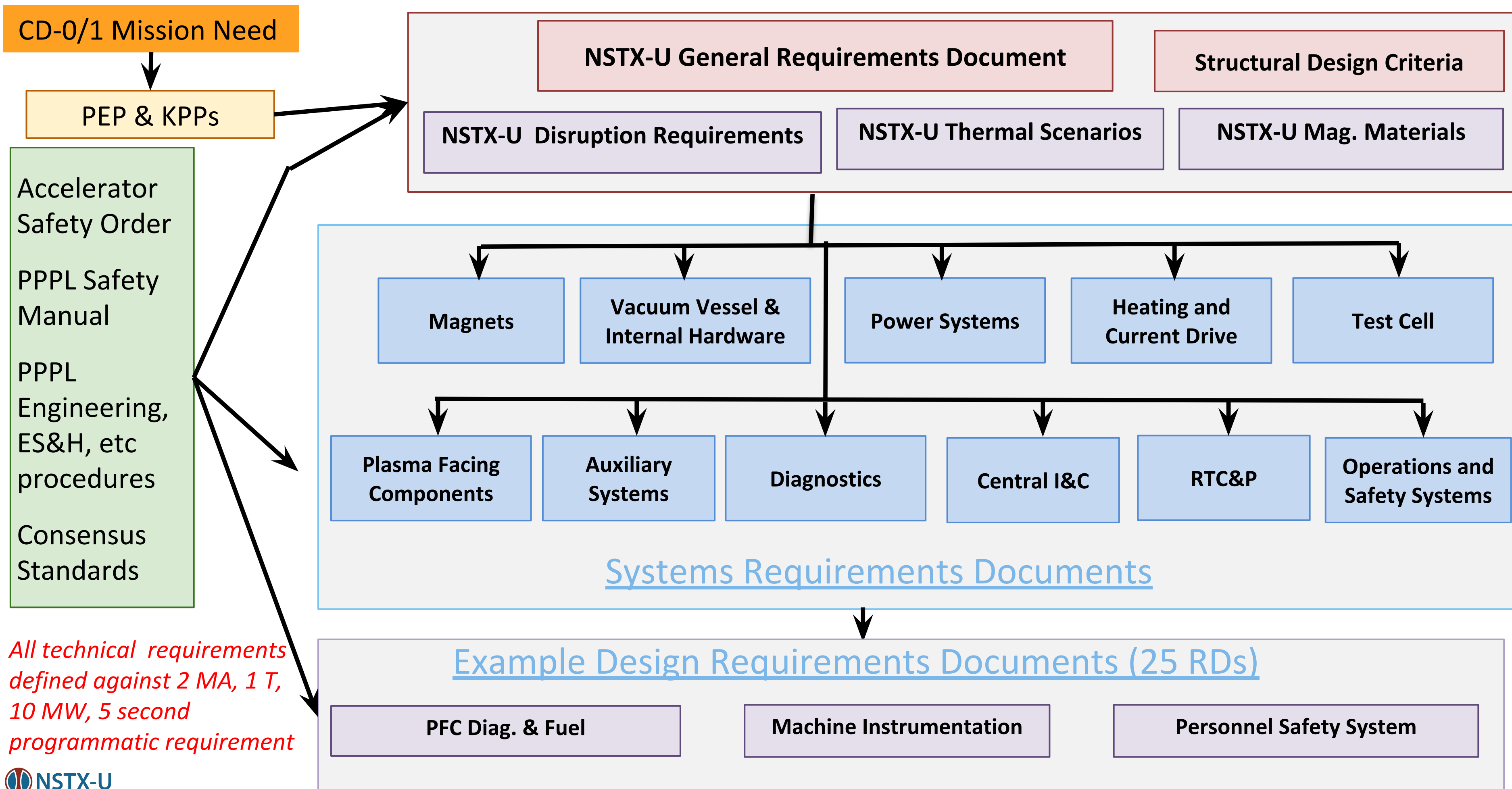
L2	L3	System Breakdown Structure (SBS)	L4		L5		VV & Internal Hardware	Magnets	V, C, & F	Bakeout System	Cooling Systems	Diagnostics	Power Systems	Heating Systems	Real-Time Control & Protection	Central I&C	Test Cell	Operational & Safety Systems
1.1		**TORUS SYSTEMS**																
	1.1.1	In-Vessel Components					X											
			1.1.1.1	Plasma Facing Components			X											
					1.1.1.1.1	Center Stack First Wall PFCs	X											
					1.1.1.1.2	CSAS PFCs	X											
					1.1.1.1.3	Vertical Target PFCs	X											
					1.1.1.1.4	Horizontal Target PFCs	X											
					1.1.1.1.5	Outboard Divertor PFCs	X											
					1.1.1.1.6	Passive Plate PFCs	X											
					1.1.1.1.7	Neutral Bean Armor PFCs	X											
					1.1.1.1.8	PFC Thermocouples						X						

Requirements are managed via Engineering Procedure ENG-050

PPPL	PRINCETON PLASMA PHYSICS LABORATORY	PROCEDURE	No. ENG-050 Rev 3 page 1 of 5
Subject: Job Requirements Documentation & Control		Effective Date: January 31, 2018	Initiated by: Head, Engineering Department
		Supersedes: Rev 2, Dated December 19, 2014	Approved: Director

- General Requirements Document
  - High-Level Project Wide Requirements
  - Defines the projects goals and objectives
- System Requirements Documents
  - Detailed engineering requirements to meet general requirements
  - Consists of functional, materials and design, configuration, performance, upgrade requirements, and interfaces
- Requirements Documents
  - Derived requirements created as needed to meet specific project goals and objectives

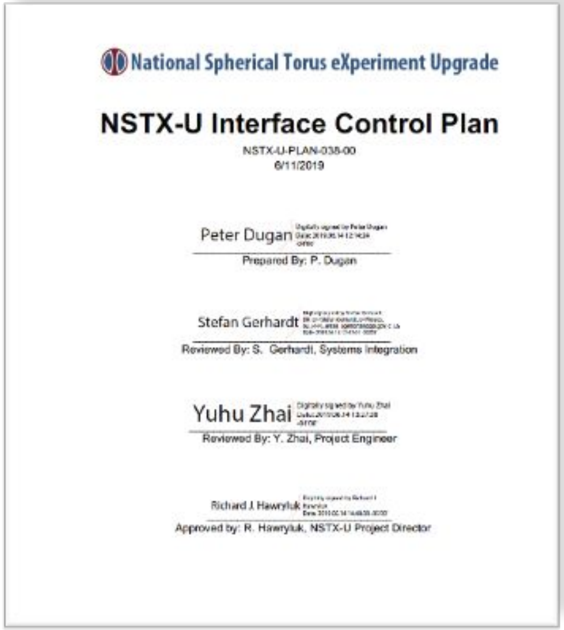
Requirements Flow from Stakeholder and Laboratory Level Down to Sub-Systems



All technical requirements defined against 2 MA, 1 T, 10 MW, 5 second programmatic requirement

Interface Control Process managed using engineering procedure ENG-064 and NSTX-U interface control plan

- SRDs establish initial set of interface requirements
- Interface control captures agreements among the Responsible Engineers (REs)
- Design modifications affecting interfaces need to be agreed to by REs
- Interface control is a living process to identify and manage interfaces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NSTX-U Interface Control Plan

NSTX-U-PLAN-038-00
6/11/2019

Peter Dugan
Prepared By: P. Dugan

Stefan Gerhardt
Reviewed By: S. Gerhardt, Systems Integration

Yuhu Zhai
Reviewed By: Y. Zhai, Project Engineer

Richard J. Hawryluk
Approved by: R. Hawryluk, NSTX-U Project Director

[Link to Plan]

Interface Control Documents provide the mechanism for documenting interfaces

- There are approximately 1,150 interfaces maintained in an interface spreadsheet
- Interface Control Documents tailored template to capture system interfaces
- Drawings, Calculations and walkdowns are principle mechanisms for identifying interfaces

Abbreviation	Interface Category	Interface Type
Me	Mechanical	Structural (S)
		Spatial (Sp)
		Location (L)
		Wall/Floor Penetration (Wp)
Ep	Electrical Power	Electrical Power
Si	Signal	Electrical Signal
		Ethernet
		Fiber Optic
Di	Diagnostic	Diagnostic
Gf	Gas/Fluid	Gas (G)
		Fluid (F)
Va	Vacuum	Vacuum
Sw	Software	Software
Th	Thermal	Thermal
Pe	Plasma/Eddy/Halo Current	Plasma (P)
		Eddy/Halo Current (E)

Identifier	Interface	Artifacts
1.1.1.1.4-1.1.3.3.9-S	**Horizontal Target PFCs** tiles and their backing structures react to disruptions loads to the **Horizontal Target Cooling System** at the surface of the casing flange or cooling plate.	See Paragraph 4.2.1.1 Ref 16, Ref 19, Drawings ED1433, DC11124, DC11125, ED1391

[ICD Repository Link]

Physical and functional interfaces are managed using an N^2 diagram

Plasma Facing Components	Me,Th, Pe		Me,Th, Va,Pe						Me	Me	Me, Pe		Me			
	In-Vessel Structures	Me,Di,Pe			Th			Me,Th, Pe	Me		Me, Pe			Di		
		Vacuum Vessel Structures			Me,Va	Me, Va	Me	Me, Th, Pe	Me	Me,Va	Me,Di, Va		Si	Di,Me		
		Va	**Centerstack Structures**			Va, Th	Me, Gf	Me	Me							
		Me	Me, Th, Ep	**Magnets**				Me			Di		Si	Di	Me	
Si		Me, Va			**Heating Systems**		Gf	Me		Me		Si	Si	Si	Si	
					Si, Va, Me, Sw, Gf	**Vacuum Pumping Systems**		Me	Si	Si	Si		Si,Va	Si	Si	
				Gf,Si			**Coolant Systems**	Me				Gf,Sw	Si, Sw	Si	Si	
	Th, Gf	Ep,Di, Th, Va	Ep, Gf, Th, Pe		Si		Si	**Bakeout Systems**							Si, Me	
			Gf,Va			Me, Gf,Si			**Gas Delivery Systems**	Gf	Si,Sw		Si,Sw	Si	Me, Si	
		Gf				Si,Gf,Va			Me	**Wall Conditioning Systems**	Si,Sw		Si,Sw		Me	
		Me,Va	Me,Va	Me	Me	Gf,Si	Gf			Va, Ep	**Diagnostics**		Si,Sw	Si	Me, Si	Si
				Ep	Ep	Ep	Ep	Ep	Ep	Ep	Ep	**Power Systems**	Ep,Si	Ep, Si	Me, Ep, Si, Di, Gf	Ep
					Si					Me, Si	Si		**Centralized Instrumentation and Control**	Si, Me		
												Si	Si,Sw	**Integrated Machine Operations**		
								Ep							**Operations & Safety Systems**	
Me		Me	Me	Me	Me	Me		Me	Me	Me	Me	Me	Me	Me	Me, Ep	**D-Site Locations (Test Cell**

Recovery Interface

Interface Pair

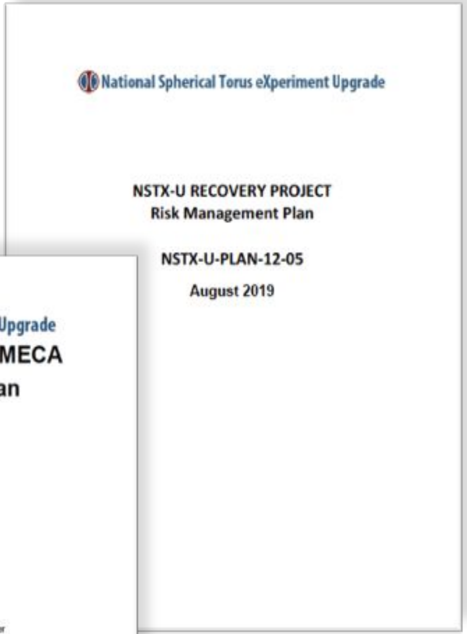
Non-Recovery

Risk Management is addressed by using the Project Risk Management Plan and FMECA plan

- Project Risk Management Plan addresses project risks addressing cost and schedule using Monte Carlo Analyses
- Failure Modes and Effects Criticality Analysis (FMECA) Plan addresses technical operations risks and focuses risk mitigation and detection
- Both plans are constantly managed

FMECA Plan Link

FMECA Link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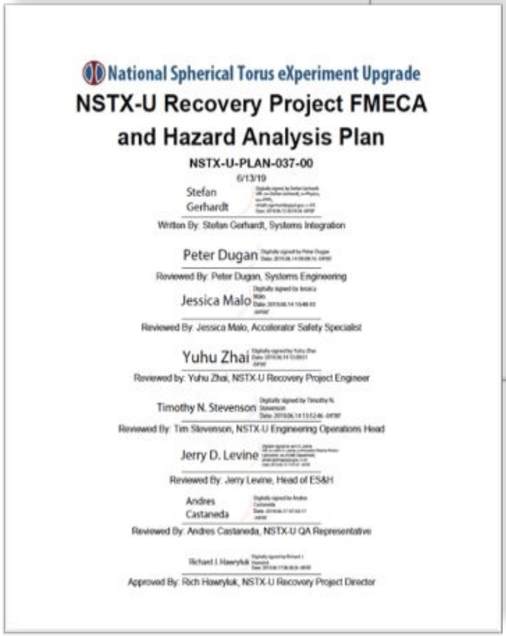
NSTX-U RECOVERY PROJECT
Risk Management Plan

NSTX-U-PLAN-12-05

August 2019


National Spherical Torus eXperiment Upgrade

NSTX-U Recovery Project FMECA and Hazard Analysis Plan

NSTX-U-PLAN-037-00

6/13/19

Stefan Gerhardt
Written By: Stefan Gerhardt, Systems Integration

Peter Dugan
Reviewed By: Peter Dugan, Systems Engineering

Jessica Malo
Reviewed By: Jessica Malo, Accelerator Safety Specialist

Yuhu Zhai
Reviewed by: Yuhu Zhai, NSTX-U Recovery Project Engineer

Timothy N. Stevenson
Reviewed By: Tim Stevenson, NSTX-U Engineering Operations Head

Jerry D. Levine
Reviewed By: Jerry Levine, Head of ES&H

Andres Castaneda
Reviewed By: Andres Castaneda, NSTX-U QA Representative

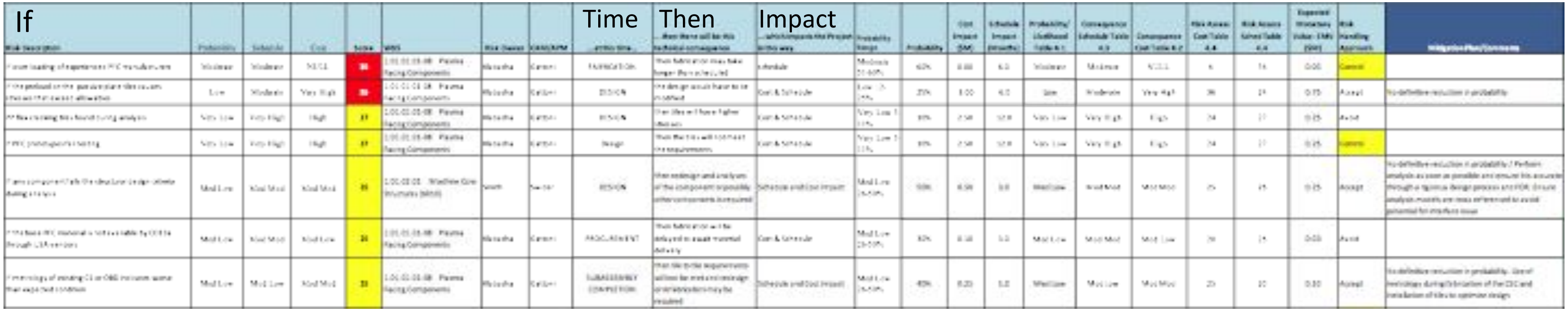
Richard J. Hawryluk
Approved By: Rich Hawryluk, NSTX-U Recovery Project Director

Risk Management Plan Link

Risk Register Link

Project risk management addresses the cost schedule impacts of both technical and programmatic risks

- Control Account Managers (CAMs) are responsible for individual risk management
- Common risks that occur across multiple control accounts are rolled up into a project-level risk
  - Example: Nine separate risks rolled up in “If there are general assembly issues, equipment problems, etc.” Impact: Cost and Schedule



Operations risk management uses engineering procedure ENG-008 and NSTX-U FMECA plan

- NSTX-U uses a project-wide FMECA to manage risk to operations, ordered using SBS numbers
- FMECA considers Probability, Severity, and systems for detection/mitigation, all managed in a template
- Severity categories consider personnel safety, radiological, environmental, cost, & schedule impacts
- Where unacceptable unmitigated risk is identified, a specific mitigation/detection system must be identified
  - This identification of mitigation/detection systems is used to find systems that must be operational during operations.

Selection Criteria

	P	0	1	2	3	4
S		Incredible Events	Extremely Unlikely Events	Unlikely Events	Anticipated Events	Normal Events
0	No Impact	0	0	0	0	0
1	Negligible Severity	0	1	2	3	4
2	Low Severity	0	2	4	6	8
3	Medium Severity	0	3	6	9	12
4	High Severity	0	4	8	12	16

Unmitigated risks >8 requires a defined mitigation to bring the residual risk <8. Only small number of failures have residual risk >8, and receive additional scrutiny

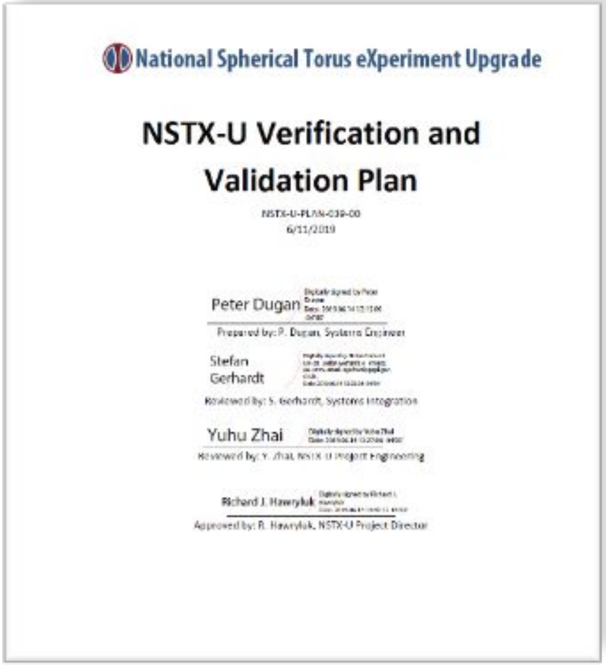
FMECA considers risk, risk priority number, residual risk, and controls

				Failure Modes and Effects Analysis					Criticality			Detection and Mitigation Systems					Residual
SBS#	System	Recovery WBS	Responsible Engineer	Failure Mode	Failure Cause	Failure Effect	Operations Phase	Probability Without Detection (P)	Probability With Detection (P_D)	R	RPN	SBS of Primary Detection/ Mitigation (1)	Primary Detection / Mitigation System (1)	SBS of Secondary Detection / Mitigation (2)	Secondary Detection / Mitigation System (2)	Detection/ Mitigation Elaboration	R_R
1.1.1.1.1	Center Stack First Wall PFCs	1.1.1.1	VV & Internal Hardware	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	Coil Testing & Plasma Ops.	Anticipated Events	Unlikely Events	9	45	1.7.3.6.6	DCPS Software		None	Cameras or poor plasma performance may reveal the problem after the failure; DCPS limits fields and currents	6
1.1.1.1.1	Center Stack First Wall PFCs	1.1.1.1	VV & Internal Hardware	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	Coil Testing & Plasma Ops.	Anticipated Events	Anticipated Events	6	30	1.7.3.6.3	Real Time Control Software (PCS, FPDP)		None	chips may be detectable after they occur, but not likely before; PCS can limit beam power	0
1.1.1.1.2	CSAS PFCs	1.1.1.7	VV & Internal Hardware	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	Coil Testing & Plasma Ops.	Unlikely Events	Unlikely Events	6	30		None		None	Cameras or poor plasma performance may reveal the problem after the failure	6
1.1.1.1.2	CSAS PFCs	1.1.1.7	VV & Internal Hardware	Failure of T-bar or bolts attaching tiles to angled portion of casing	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	Coil Testing & Plasma Ops.	Unlikely Events	Extremely Unlikely Events	6	18		None		None		0
1.1.1.1.2	CSAS PFCs	1.1.1.7	VV & Internal Hardware	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	Coil Testing & Plasma Ops.	Anticipated Events	Anticipated Events	6	30		None		None	chips may be detectable after they occur, but not likely before	0
1.1.1.1.3	Vertical Target PFCs	1.1.1.3	VV & Internal Hardware	Castellation failing at root	Excessive thermal stress due to localized overheating	Inability to place strikepoint on that surface due to large non-axisymmetry in tile surface	Coil Testing & Plasma Ops.	Unlikely Events	Unlikely Events	6	30	1.4.1.14	Physics Imaging Systems	1.4.1.4	Plasma TV	castellation failure may be detectable after they occur, but not likely before	6
1.1.1.1.3	Vertical Target PFCs	1.1.1.3	VV & Internal Hardware	Tile structural failure results in tile breaking loose from mounting structure	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	Coil Testing & Plasma Ops.	Unlikely Events	Unlikely Events	6	30		None		None	Cameras or poor plasma performance may reveal the problem after the failure	6
1.1.1.1.3	Vertical Target PFCs	1.1.1.3	VV & Internal Hardware	Failure of rods and other hardware in individual tile hold-down mechanism	Excessive Halo Currents	Plasma cannot be run due to large exposed leading edge, potential graphite "chunks" on the divertor floor	Coil Testing & Plasma Ops.	Extremely Unlikely Events	Extremely Unlikely Events	3	15		None		None		0
1.1.1.1.3	Vertical Target PFCs	1.1.1.3	VV & Internal Hardware	Tile edge chipping	Excessive thermal stress	Reduced heat flux handling capability at tile that is chipped	Coil Testing & Plasma Ops.	Anticipated Events	Anticipated Events	6	30		None		None	chips may be detectable after they occur, but not likely before	0

There are currently more than 750 failure modes generated and managed

Requirements verification and validation managed using NSTX-U Verification and Validation Plan

- Requirements Traceability Verification Matrix (RTVM) map to a verification method: Analysis, Demonstration, Inspection or Test
- Pre-operational Test Procedures (PTP) verify that components meet requirements
- Validation conducted through Integrated System Test Procedure (ISTP)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NSTX-U Verification and Validation Plan

NSTX-U-PLAN-039-00
6/11/2019

Peter Dugan
Prepared by: P. Dugan, Systems Engineer

Stefan Gerhardt
Reviewed by: S. Gerhardt, Systems Integration

Yuhu Zhai
Reviewed by: Y. Zhai, NSTX-U Project Engineering

Richard J. Hawryluk
Approved by: R. Hawryluk, NSTX-U Project Director

V&V Plan Link
RTVM Link

Example of three Plasma Facing Component (PFC) GRD requirements in the RTVM

Filter	SEQ. #	Req't ID	Subsystem Name	Sub-Count	SBS	Requirement	Figure Ref.	Anal	Demo	Insp	Test	Analysis Artifacts	Demonstration Artifacts
PFCs	Plasma Facing Components												
PFCs	177	GRD-6.1.1.1.1.a	Plasma Facing Components	1	1.1.1.1	The Plasma Facing Component (PFC) tiles shall consist of carbon-based materials designed to absorb the heat, particle, and photon flux from the plasma and heating systems, to minimize the influx of impurities to the plasma, and to withstand the electromagnetic forces associated with plasma disruption.		X			X	CSFW: NSTX-U-CALC-11-10-00, CSAS: NSTX-U-CALC-11-11-00, NSTX-U-11-21-00, IBDV: NSTX-U-CALC-11-19-00, IBDH: NSTX-U-CALC-11-18-00, OBD12: NSTX-U-CALC-11-22-00, OBD3: NSTX-U-CALC-11-14-00, OBD4: NSTX-U-CALC-11-16-00, OBD5: NSTX-U-CALC-11-12-00	
PFCs	178	GRD-6.1.1.1.1.b	Plasma Facing Components	2	1.1.1.1	PFC tiles shall be installed on the Center Stack casing, divertors, passive plates, and neutral beam armor.		X	X			CSFW: NSTX-U-CALC-11-10-00, CSAS: NSTX-U-CALC-11-11-00, NSTX-U-11-21-00, IBDV: NSTX-U-CALC-11-19-00, IBDH: NSTX-U-CALC-11-18-00, OBD12: NSTX-U-CALC-11-22-00, OBD3: NSTX-U-CALC-11-14-00, OBD4: NSTX-U-CALC-11-16-00, OBD5: NSTX-U-CALC-11-12-00	Passive Plates PFCS and Neutral Beam Armor will use existing tiles. Not in scope for recovery project
PFCs	179	GRD-6.1.1.1.2.a	Plasma Facing Components	3	1.1.1.1	Plasma facing components shall be formed from fine-grain isotropic graphite or carbon-carbon composites.		X				CSFW: NSTX-U-CALC-11-10-00, CSAS: NSTX-U-CALC-11-11-00, NSTX-U-11-21-00, IBDV: NSTX-U-CALC-11-19-00, IBDH: NSTX-U-CALC-11-18-00, OBD12: NSTX-U-CALC-11-22-00, OBD3: NSTX-U-CALC-11-14-00, OBD4: NSTX-U-CALC-11-16-00, OBD5: NSTX-U-CALC-11-12-00	

RTVM is a living document and is constantly managed

Conclusion

- An integrated systems engineering process is implemented across NSTX-U
- Systems elements managed by SBS
- Requirements are managed, addressed during design phase, and traced for verification/validation
- Interface control reduced risk at the element boundaries
- Project and technical operations risk management is continually managed