December 2015
Project Closeout Report FINAL
National Spherical Torus Experiment (NSTXU) Upgrade

Project # 000509 MIE-NSTX-U
at
Princeton Plasma Physics Laboratory (PPPL), Princeton, NJ

Office of Fusion Energy Science (FES)
Office of Science
U.S. Department of Energy

Date Approved:

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National Spherical Torus Experiment (NSTXU) at the
Princeton Plasma Physics Laboratory (PPPL)

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Anthony Indelicato,
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Project Closeout Report for the
National Spherical Torus Experiment (NSTXU) at the
Princeton Plasma Physics Laboratory (PPPL)

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1. EXECUTIVE SUMMARY

The National Spherical Torus Experiment (NSTX) is an experimental research facility funded by Fusion Energy Sciences (FES) that is operating at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL).

The scope of the NSTX Upgrade Project included design, fabrication, installation, and integrated system testing for the systems affected by the project. The Department of Energy has identified the NSTX Upgrade Project as a Major Item of Equipment (MIE) Project instead of a Line Item construction project. The device is located within existing experimental facilities at PPPL. No major building additions were required to accommodate the device.

The technical goals of the project included;
1) Upgrading the NSTX Center Stack (CS). This was accomplished by designing, fabricating, installing and testing a new CS assembly with a great many parts. These included a new toroidal field (TF) hub assembly; new TF flag assemblies; new ceramic break; new inner TF bundle; new ohmic heating (OH) coil; new inconel casing and insulation; new plasma facing component (PFC) tiles, and new poloidal field (PF) 1a, b & c coils. The supporting ancillary systems (power, water, controls) were also upgraded.

2) Decontaminating, refurbishing, installing and testing a Tokamak Fusion Test Reactor (TFTR) neutral beam-line (NBL) on NSTX. This included the evaluation and refurbishment of internal components such as the cryogenic panels, beam dumps, bending magnets, beam scrapers and calorimeter. Additionally, a second set of beam-line services (e.g., power, water, vacuum, cryogenics, etc.) were provided.

All required processes for commissioning have been completed and the project Key Performance Parameters (KPP's) were achieved on August 11, 2015.

The project was complete on August 11, 2015, one and one-half months ahead of schedule. The Total Project Cost (TPC) of $93.7 M was $0.6M under budget.

2. INTRODUCTION

This is the final project closeout report for the National Spherical Torus Experiment (NSTX) project which was completed in August, 2015 with CD-4 approval in September 2015. The project is located at the Princeton Plasma Physics Laboratory (PPPL) in Plainsboro, New Jersey.

This report documents the scope, the cost and schedule achievements, and the lessons learned.

3. ACQUISITION APPROACH

DOE acquired the project through PPPL, which had the ultimate responsibility to successfully execute the project.
PPPL performed the technical component design, specifications, fabrication, assembly, installation and tests, with support provided by industry for the material and hardware components. Approximately 21 percent of the total project cost was for outside industry procurements.

The following work/acquisitions were performed as follows:

- Project Management: In-house staff;
- Construction Management: In-house staff;
- Engineering and Design: In-house staff;
- Large Components: Combination of fixed price vendor contracts & in-house fabrication;
- Assembly: In-house staff and fixed price vendor contracts;
- Decontamination: In-house staff;
- Ancillary Systems: Combination of vendor contracts and in-house staff, and;
- System Start-up, Tests and Troubleshooting: In-house staff.

Major procurements from industry included;

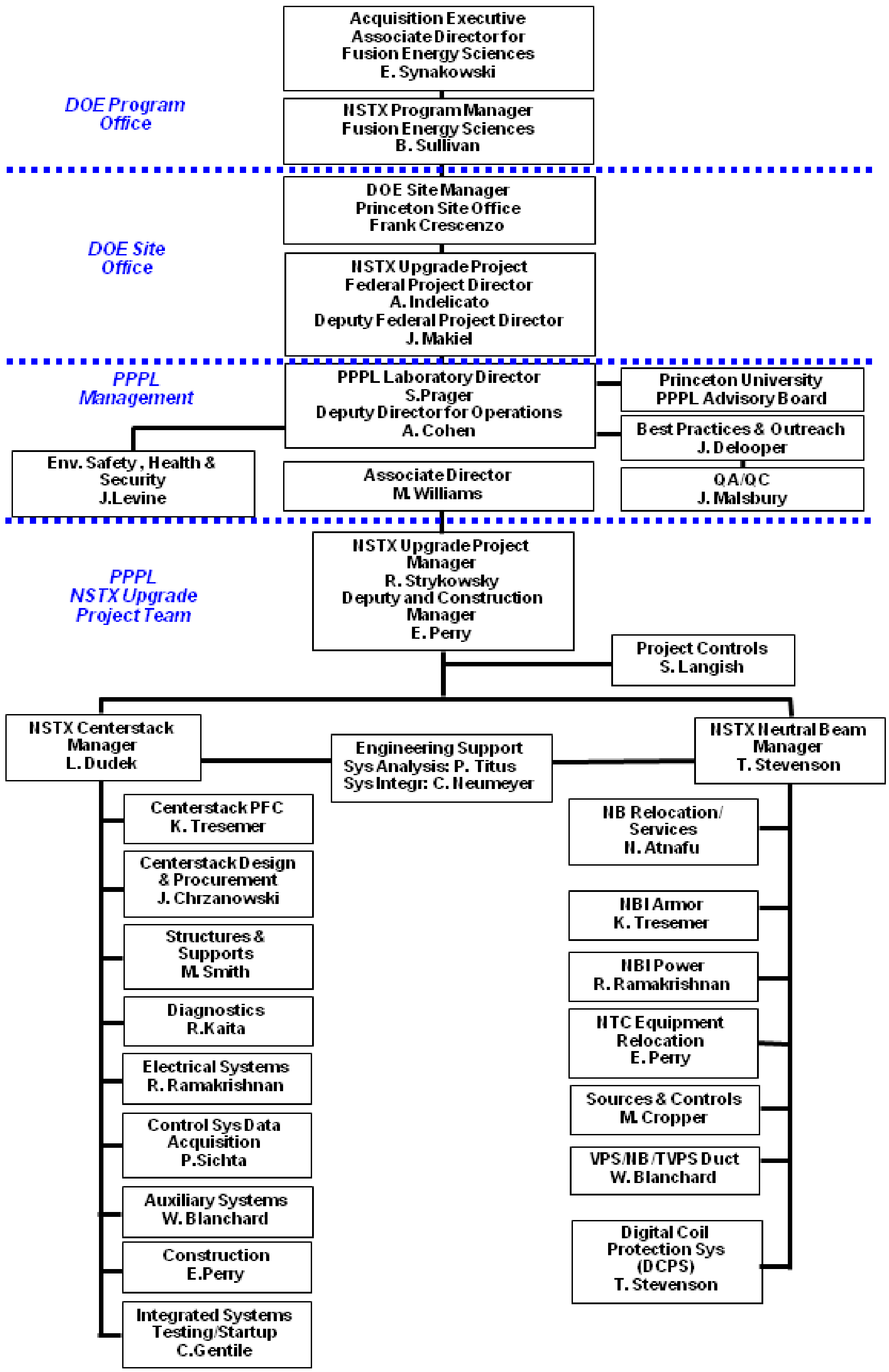
Supplier	**Location**	**Procurement**
Martinez & Turek	Rialto, CA	Centerstack Casing
A&N, Incorporated	Williston, FL	Bay J Port Cover, Bay I Port Cover and various Vacuum Parts
Major Tool and Machine	Indianapolis, IN	Inner TF Conductor Machining
Hollis Line Machine	Hollis, NH	Outer TF Conductor Stiffeners, Organ Pipe Extension Weldment and Ceramic Break Parts
Powers Electric	Columbus, NJ	Wiring and Cabling
Zenex Precision	Paterson NJ	TF Flex Buss
Abcot Amnor	Hawthorne, NJ	Belden/Honeywell Wiring and Cabling
Imperial Machine	Columbia, NJ	G10 Crown Piece and Vacuum Vessel Main Flange Mounting Studs
MWI, Inc.	Rochester, NY	Poco Graphite Tiles
Edison Welding Institute	Columbus, OH	Inner TF Friction Stir Welding
H.C. Starck	Euclid, OH	TZM Molybdenum Inboard Divertor Tiles and Shield Plates
Everson Tesla	Nazareth, PA	PF1 Coils and Outer TF Coil Fabrication
Astro Machine	Ephrata, PA	Copper Lead Spacers, Centerstack Casing Supports, Umbrella Lid and Centerstack Swing Fixture
Carolina Fabricators	West Columbia, SC	Coil Support Structures
Luvata Pori	Kimberly, WI	Inner TF Copper Conductor Extrusions

Seventy-two personnel members from the following institutions provided external technical and management consultation and reviews:

MIT Plasma Science and Fusion Center
U.S. Department of Energy
University of Wisconsin
Argonne National Laboratory
Lawrence Berkeley National Laboratory
Los Alamos National laboratory
Oak Ridge National Laboratory
Fermi
General Atomic
SLAC
National Institute of Standards and Technology
United Kingdom Atomic Energy Authority (UKAEA)

4. PROJECT ORGANIZATION

The project was organized as shown below;



The project team remained relatively intact during course of the project with these exceptions:

1) The Work Breakdown Structure (WBS) manager for the center stack design, Jim Chrzanowski, retired shortly after the center stack was completed and installed. A senior engineer, Steve Raftopoulos was assigned to carry out the remaining installation and fabrication tasks. There was no impact to the project schedule.
2) In March 2014 a senior electrical engineer, Ronald Hatcher, passed away. Ron was instrumental in designing the Digital Coil Protection System (DCPS) and his passing affected the schedule for completing the system.
3) Midway through the project the PPPL Quality Assurance/Quality Control (QA/QC) Organization hired a full-time dedicated inspector, which reduced the workload of the Control Account Managers (CAM's).

5. PROJECT BASELINE

This section documents the project Performance Baseline (PB), which consists of the scope, the cost (Total Project Cost or TPC), the schedule (Critical Decision or CD-4 date), the funding profile, and other information approved at CD-2 and what was achieved at CD-4.

5.1 Scope Baseline

This section describes the project scope and Key Performance Parameters (KPPs) that were approved at CD-2 and the KPPs achieved at CD-4.

The project, located at Princeton Plasma Physics Laboratory (PPPL), designed, constructed, tested, and commissioned the NSTX-U device consistent with the scope defined in the project execution plan.

The major milestone marking the transition from a fabrication project to an operating facility is the first plasma milestone (CD-4). First plasma is defined as:

1) An ohmically heated discharge > 50 kA at a toroidal magnetic field of > 1 kG.
2) The installation of the second neutral beam on NSTX which was considered completed when,
    a. Beamline water, vacuum, cryogenics, and feedstock gas services were attached to the beamline;
    b. Installation of a Torus Isolation Valve and duct interconnecting the NSTX vacuum vessel and the neutral beamline;
    c. Local Control Centers were powered on to monitor power supply status, and;
    d. The project was verified as complete when a 40,000 electron-volt beam was produced and injected into the armor for .050 seconds

The planned and final threshold key performance parameters (KPP) of the project are listed below:

Description of Scope	CD-2 Threshold KPP	KPP Achieved at CD-4	CD-2 Threshold KPP Met or Exceeded?
1. First Plasma *	>50kA plasma at > 1 kG	Completed (8/10/2015)	Exceeded
2a. NBI-Services	Installed/Tested	Installed/Tested	Met
2b. NBI-Connections to Vessel	Installed/Tested	Installed/Tested	Met
2c. NBI-Local controls	Installed/Tested	Installed/Tested	Met
2d. NBI-Beam injection*	≥40kV at 0.05 sec	Completed (5/11/2015)	Exceeded

*Objective evidence for numbers 1 and 2d shown in Appendix J

5.2 Cost Baseline

At CD-2, approved in December, 2010, the actual cost was $14.8M. The total performance measurement baseline was $77.3M and the Total Project Cost (TPC) was $94.3M, leaving a contingency of $17M (27 percent of remaining work)Table 5.2-1 shows the planned cost, the actual cost at CD-4, and the explanations of contingency usage. A more detailed look at draw-downs on contingency is documented by PPPL's Engineering Change Proposal (ECP) and is shown in Appendix F.

	WBS	CD-2 Cost Baseline ($M)	Final Cost ($M)	Delta	Explanation
TEC	1.1 Torus Systems	$13.5	$26.7	$13.2	> Under estimated u tasks & labor cost to Fab/Assy centerstack > Oversight and supervision d > Vendor hardware fabrication cost > Scope enhancements (PF-1c & Passive plates)
	1.2 Plasma Heating	$21.0	$17.6	$3.3	> Over-estimated beamline relocation, NBI power & controls > Under estimated NBI Armor, NBI VPS/Interface duct > Scope enhancements: S-FLIP port installation $165k
	1.3 Auxiliary Systems	$0.4	$0.7	$0.3	Under estimated labor and hardware fabr cost
	1.4 Plasma Diagnostics	$1.6	$2.3	$0.8	> Under estimated MPTS, tFIDA and RWM coil > Scope enhancements
	1.5 Power Systems	$7.9	$10.1	$2.2	> Underestimated DCPS > Underestimated power systems bus bar fabrication > Scope enhancements
	1.6 Central I&C	$0.9	$1.1	$0.2	> Underestimate engineering tasks > Scope enhancements
	1.7 Project Support & Integr	$11.0	$11.3	$0.4	> Project stretch-out increase for project office
	1.8 Assembly	$7.6	$10.3	$2.7	> Under estimated & unforeseen tasks and technician time > Repairs due to Arc fault ($361K)
	TEC Subtotal	**$63.8**	**$80.2**	**$16.4**	
OPC	1.1 Torus Systems	$4.8	$4.8	-	
	1.2 Plasma Heating	$3.6	$3.6	-	
	1.3 Auxiliary Systems	$0.0	$0.0	-	
	1.4 Plasma Diagnostics	$0.2	$0.2	-	
	1.5 Power Systems	$1.4	$1.4	-	
	1.6 Central I&C	$0.0	$0.0	-	
	1.7 Project Support & Integr	$3.4	$3.4	-	
	1.8 Assembly	$0.0	$0.0	-	
	OPC Subtotal	**$13.5**	**$13.5**	-	
	Subtotal (TEC + OPC)	**$77.3**	**$93.6**	**$16.4**	
	Total Contingency	**$17.0**	**$0.6**	**$16.4**	
	Total Project Cost	**$94.3**	**$94.3**	**$0.0**	

Table 5.2-1 Comparison of the project baseline to completed cost including contingency utilization

WBS and CA	CD-2 Cost Baseline ($M)	Final Expected Cost ($M)	Delta
1.1 Torus Systems	$18.3	$31.5	-$13.2
1000 CSU Analytical Support	$0.4	$0.7	-$0.3
1001 CS Plasma Facing Components	$2.2	$1.9	$0.2
1002 Passive Plate Analysis & Upgrade	$0.3	$0.7	-$0.4
1200 Structures & Supports	$3.5	$4.5	-$1.0
1300 Center Stack	$1.1	$3.5	-$2.4
1301 Outer TF Coils	$0.3	$0.5	-$0.1
1302 Center Stack Assembly	$1.0	$1.0	$0.0
1303 TF Joint Test Stand & Test	$0.4	$0.2	$0.1
1304 Inner TF Bundle	$2.6	$4.1	-$1.6
1305 Ohmic Heating Coil	$4.6	$11.1	-$6.6
1306 Inner PF Coils	$0.7	$1.1	-$0.4
1307 CS Casing Assembly (Chrzanowski)	$0.9	$1.7	-$0.8
1310 CSU Magnets Systems	$0.4	$0.4	$0.0
1.2 Plasma Heating	$24.6	$21.3	$3.3
2300 ECH Analysis	$0.1	$0.0	$0.1
2420 2nd NBI Sources	$1.1	$0.1	$1.0
2425 BL Relocation	$1.9	$1.3	$0.6
2430 2nd NBI Decontamination	$2.1	$2.1	$0.0
2440 2nd NBI Beamline	$2.6	$1.6	$1.0
2450 2nd NBI Services (Cropper)	$4.5	$4.4	$0.2
2460 2nd NBI Armor	$0.7	$1.0	-$0.3
2470 2nd NBI Power (Raki)	$3.3	$3.0	$0.3
2475 2nd NBI Controls (Cropper)	$2.1	$1.9	$0.2
2480 2nd NBI/TVPS Duct	$2.3	$2.5	-$0.2
2485 Vacuum Pumping System	$0.4	$0.4	-$0.1
2490 NTC Equipment Relocations (Perry)	$3.6	$3.0	$0.6
1.3 Auxiliary System	$0.4	$0.7	-$0.3
3200 Water Cooling System Mods (Atnafu)	$0.2	$0.5	-$0.3
3300 Bakeout System Mods CSU (Raki)	$0.1	$0.2	-$0.1
3400 Gas Delivery System Mods (Blanchard)	$0.1	$0.1	$0.0
1.4 Plasma Diagnostics	$1.8	$2.5	-$0.8
4100 Center Stack Diagnostics	$0.8	$0.8	$0.0
4500 MPTS VV Modification	$0.9	$1.6	-$0.7
4501 Bay A and L RWM Coil (Labik)	$0.0	$0.1	-$0.1
1.5 Power Systems	$9.4	$11.5	-$2.2
5000 CSU Power Systems (Raki)	$5.7	$4.7	$1.1
5200 DCPS (Stevenson)	$2.5	$4.1	-$1.6
5501 Coil Bus Runs (Atnafu)	$1.1	$2.7	-$1.6
1.6 Central I&C	$0.9	$1.1	-$0.2
6100 Control Sys Data Acquisition (Sichta)	$0.9	$1.1	-$0.2
1.7 Project Support & Integration	$14.4	$14.7	-$0.4
7100 Project Management & Integration (Strykowsky)	$5.8	$7.1	-$1.3
7200 Center Stack Management (Dudek)	$1.5	$1.4	$0.2
7300 NB2 Management (Stevenson)	$1.5	$0.9	$0.5
7400 Health Physics Support (Stevenson)	$2.5	$2.5	$0.0
7710 NSTX-U HP and Other Allocations (Strykowsky)	$3.0	$2.8	$0.2
7900 Integrated System (Gentile)	$0.1	$0.0	$0.0
1.8 Assembly	$7.6	$10.3	-$2.7
8200 CS & Coil Supt Struct Install (Perry)	$6.5	$6.7	-$0.3
8210 Field Supervision & Oversight (Perry)	$0.0	$1.4	-$1.4
8250 Remove/Install Centerstack (Perry)	$1.2	$1.7	-$0.6
8251 OH Arc Fault recovery	$0.0	$0.4	-$0.4
PMB	$77.3	$93.6	-$16.4
Subtotal (TEC + OPC)	$77.3	$93.6	-$16.4
Total Contingency (TEC + OPC)	$17.0	$0.6	$16.4
Total Project Cost	$94.3	$94.3	$0.0

Table 5.2-2 Comparison of project baseline to completed cost at the cost-account level.

PROJECT ID	***MIE-NSTX-U***		
PROJECT NAME	***NSTX Upgrade***		
PROJECT LOCATION	***PPPL***		
TOTAL PROJECT COST ($K)	***$94,300***		
DESCRIPTION OF PROJECT AND UNIQUE FEATURES	***The scope of the NSTX Upgrade Project includes design, fabrication, installation, and integrated system testing of both a new and more robust center coil and the addition of a second neutral beam heating system.***		
DATE OF COST ESTIMATE	**January-2012**		
Cost Categories	**Project $(K)**	**Non-Project $(K)**	**Comments**
Engineering	**$18,659**		
Design (A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc.)	Yes	No	Conceptual, preliminary and final design. Cost estimate based on resource loaded schedule with 10% estimated contingency draw down added.
Value Engineering	Yes	No	
Design Reviews	Yes	No	CDR, PDR, FDR, Peer reviews
Design Support (i.e., soil testing, vibration testing, seismic analysis, etc., needed for design)	Yes	No	
Other (specify)	Yes	No	Includes Title III engineering, necessary R&D development and prototyping
Management	**$12,184**		
Design Management	Yes	No	Cost based on ACWP and ETC for Cost Accounts 7100, 7200,7300,7710
Construction Management	Yes	No	
Project Management (cost estimating, scheduling, project controls, risk assessment, etc.)	Yes	No	Includes cost for non-project initiated reviews
QA,Inspection/testing/acceptance/etc.	No	No	QA, Accounting, Procurement, Safety, ES&H, Environmental are indirect cost included in all cost elements as part of PPPL overhead.
Procurement and Contracting	No	No	
Legal, Accounting, Real Estate	No	No	
Other (specify)	No	No	
ES&H	**$0**		QA, Accounting, Procurement, Safety, ES&H, Environmental are indirect cost included in all cost elements as part of PPPL overhead.
Environmental Permitting	No	No	
Safety documentation	No	No	
Safety Inspection	No	No	
Security	No	No	
Other (specify)	No	No	
Construction/Fabrication	**$62,804**		Includes Decontamination, Fabrication / Assembly, Installation, Procurement, Refurbishment, and Testing. Includes cost accounts 7900 startup
Building & Land	No	No	
Special Equipment (i.e., microscopes, probes, instruments, detectors, etc.)	Yes	No	
Standard Equipment (i.e., furniture, office equipment, benches, kitchen equipment, audio/visual, etc)	Yes	No	
Demolition/Disposal	No	No	
Research and Development (R&D)	No	No	R&D included under engineering
Commissioning and Testing	Yes	No	
Other (specify)	No	No	
Contingency Remaining	**$653**		
Total	**$94,300**	**$0**	
	CD Planned	**Actual Dates**	**Comments**
Critical Decision-1	April 2010 (A)		
Critical Decision-2	January 2011	December 2010 (A)	
Critical Decision-3	January 2012	December 2011 (A)	
Critical Decision-4	September-15	September 2015(A)	

Table 5.2-3 EDIA Cost Compared to Construction. Note: Due to the difficulty in segregating these costs within each control account, the engineering cost was estimated based on the baseline resource-loaded schedule, plus a factor for contingency application.

5.2.1 Contingency

The amount of contingency established at the beginning of the project was based on a risk assessment performed as part of the cost estimating process. Total cost contingency included three elements: 1) a task-by-task subjective contingency assessment for unknowns and uncertainties; 2) a weighted assessment of tabulated risk events, and 3) schedule contingency applied to accommodate potential project stretch-out (a.k.a. "standing army" cost). Schedule contingency (in months) was calculated by applying the task-by-task contingencies to the task durations to calculate the longest path within the project. This was offset partially by the option of using second shift and overtime to maintain the schedule. The initial project contingency level was approved by the Associate Director for Fusion Energy Sciences, acting as the Acquisition Executive for the NSTX Upgrade Project at CD-2, as part of establishing to help establish the overall cost and schedule baseline. The basis for the risk events were based on the project risk registry shown in Appendix E.

End of Fiscal Year	% Project Complete	TPC ($K)	ACWP ($K)	Contingency remaining ($K)	ETC ($K)
FY 2010	18%	$94,300	$13,816	$17,000	$63,484
FY 2011	27%	$94,300	$21,589	$15,330	$57,381
FY 2012	52%	$94,300	$43,081	$11,894	$39,325
FY 2013	72%	$94,300	$63,402	$6,673	$24,225
FY 2014	94%	$94,300	$86,898	$1,842	$5,560
31-July-2015	100.0%	$94,300	$93,546	$753	$101

Figure 5.2-4 Summary of contingency history as function of percent of project complete. Contingency drawdown defined as documented ECP's and cost variances (or simply TPC-EAC).

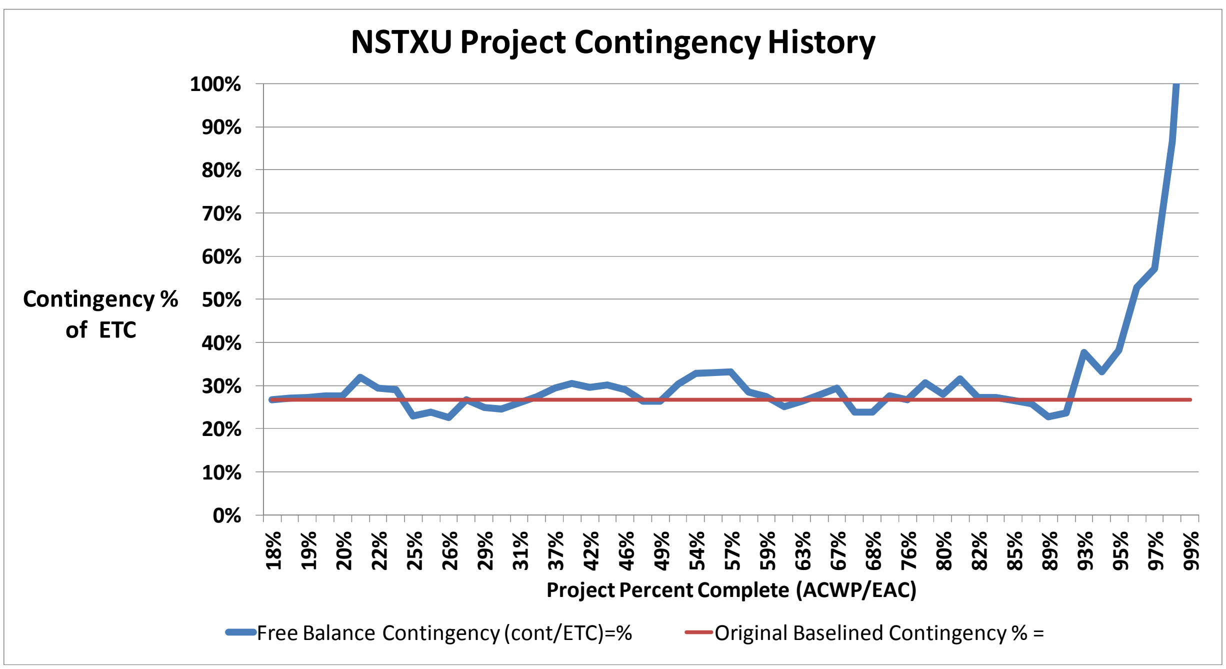


Figure 5.2-5 Contingency usage trend plotted as function of percent of project completed.

5.3 Schedule Baseline

The NSTXU Project was completed in August 2015, approximately one and one-half months ahead of schedule. Table 5.3-1 shows the project milestones per the Project Execution Plan (PEP).

Level	Milestone	Schedule at CD-2 (per PEP)	Actual	Months ahead/ (behind)	
Level I	**Receive CD-0 Approval**	-	**Feb-09**		
Level I	**Receive CD-1 Approval**	-	**Apr-10**		
Level II	Project Preliminary Design Review	-	Jun-10		
Level II	Neutral Beam #2 Decontamination Program Complete	-	Nov-10		
Level I	**Receive CD-2 Approval**	**Jan-11**	**Dec-10**	**1.3**	
Level II	Project Final Design Review	Sep-11	Jun-11	3.3	
Level I	**Receive CD-3 Approval**	**Jan-12**	**Dec-11**	**1.4**	
Level II	Friction Stir weld Coil Leads TF Conductors	Jun-12	(3)		
Level II	NSTX Complete Operations	Jul-12	Sep-11	10.9	
Level II	Begin Upgrade Outage	Aug-12	Sep-11	11.6	(1)
Level II	Begin Inner TF Quadrant Fab (Apply Turn Insul #1 Quad)	Apr-13	Jun-12	10.5	
Level II	Award Neutral Beam (NB) Vessel Cap	Jun-13	Feb-11	28.5	
Level II	Complete Assy and Pot Of 4th Inner TF Quadrant	Oct-13	Jun-13	4.8	
Level II	Complete Fabricate & Test Inner TF/OH Coil Assy	Jul-14	Jul-14	0.3	(2)
Level II	NB Cap Installed	Oct-14	Jan-13	21.9	
Level II	Lift In New Centerstack	Jan-15	Oct-14	3.7	
Level II	Complete ISTP	Aug-15	Aug-15	0.5	
Level II	Resume Operations	Sep-15	Aug-15	1.5	(4)
Level I	**CD-4**	**Sep-15**	**Sep-15**		

Table 5.3-1 Project Milestones

(1) It should be noted that the project began the upgrade outage on September 2011, 11.6 months ahead of schedule AND ahead of CD-3. This acceleration was a result of NSTX operations being curtailed due to an inner TF coil failure. The start of the outage ahead of CD-3 was approved by DOE (ECP-004) and consisted of hardware removal tasks only.

(2) The level II milestone "Complete Fabrication & Test Inner TF/OH Coil Assembly" occurred on July 2014. Its original baseline date was June 2014, but its slippage was anticipated therefore the milestone date was rescheduled by one month as documented in ECP-114.

(3) The level II milestone "Friction Stir Weld Coil Leads TF Conductors" had been planned as a stand-alone subcontract. The scope for this work was added to the overall Inner TF machining subcontract that was awarded to Major Tool & Machine in August 2011.

(4) The initial Integrated System Test Procedure (ISTP) was completed in April 2015. However, an OH coil arc fault occurred during an attempted 100 percent power shot just prior to an attempted first plasma. This led to an extensive internal and external investigation process and to hardware repairs. The PPPL executive ES&H committee approved the resumption of ISTP testing following the hardware repairs and root cause analysis findings. The successful ISTP testing led to a first plasma being achieved on August 10, 2015. Results of the arc fault corrective action plan can be found in appendix O.

Figure 5.3-2 is a high-level summary schedule showing Level I milestones, and tasks. The large bars represent the baseline schedule at CD-2 and the narrow lines show actual completion dates. The critical path is shown as pink/red and the non-critical path is shown as blue. As had been predicted, the critical path was the fabrication and assembly of the center stack magnet assembly. The schedule stretch-out was the result of vendor challenges in machining the inner TF conductors and additional time for PPPL technicians to assemble and test the magnets. Fortunately, the highest risk tasks, TF & OH coil VPI operation, were successfully accomplished.

Prior to the start of the ISTP, a readiness to operate review was conducted by an external committee to ensure that the commissioning and subsequent operation of the National Spherical Torus Experiment Upgrade could be performed in a safe and environmentally responsible manner. (See Appendix M.) Recommendations from the review were implemented, which led the PPPL ES&H executive committee to issue a safety certificate for operation on April 10, 2015 (see Appendix N).

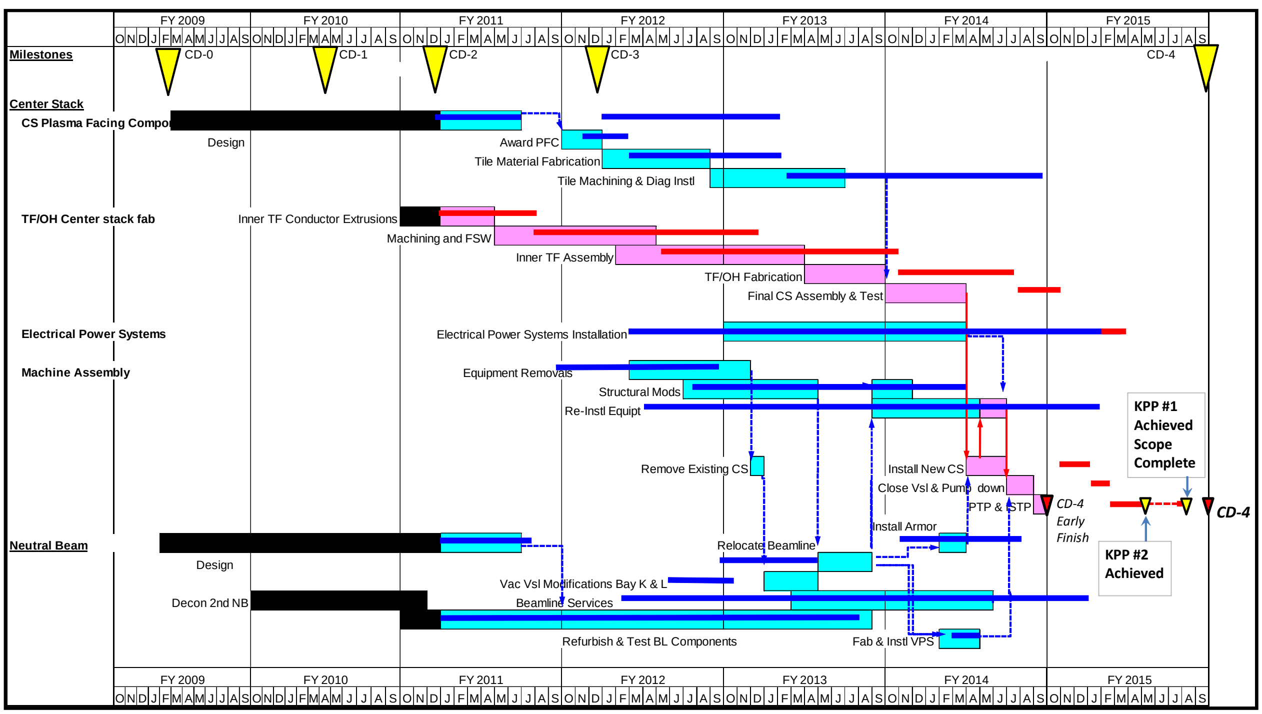


Figure 5.3-2 Summary Schedule

5.4 Work Breakdown Structure

The following is the Level II Work Breakdown Structure for the NSTX-U project, developed for the original construction of the NSTX in 1999. The NSTX-U required changes to a subset of this scope. The detailed NSTX-U WBS dictionary (Level II) is shown in Appendix A with the WBS elements that required changes highlighted in yellow along with their Control Account (CA).

NSTXU Level II WBS

Title	Description
1.1 Torus Systems	The torus systems include all the systems and related elements within the boundary of the NSTX support structure. This WBS element includes the Plasma Facing Components (WBS 1.1), Vacuum Vessel & Support Structure (WBS 1.2), and Magnet Systems (WBS 1.3). The scope of the work contains engineering design, R&D, mockups, procurement activities, and component fabrication. Assembly of the Torus System is included in WBS 1.8.
1.2 Plasma Heating and Current Drive Systems	The heating and current drive systems include all the auxiliary plasma heating and current drive systems. This WBS element includes the High Harmonic Fast Wave (HHFW) Current Drive System, the Coaxial Helicity Injection (CHI) Current Drive System, the Electron Cyclotron Heating (ECH) System, and the Neutral Beam Injection (NBI) System. Only ECH (WBS 1.2.3) and Neutral Beam Injection (WBS 1.2.4) are impacted by the NSTX Upgrade Project. The scope of the work contains engineering design, R&D, mockups, procurement activities, component fabrication, installation, and System Testing. Installation of the WBS 2 systems is included in the individual WBS 2, level 3 elements.
1.3 Auxiliary Systems	This WBS element includes the Coolant Systems, the Bakeout Heating System, Gas Delivery System and the Glow Discharge Cleaning System. The scope of the work contains engineering design, procurement activities, component fabrication, and System Testing. Installation of the WBS 3 systems is included in the individual WBS 3, level 3 elements.
1.4 Plasma Diagnostics	The Plasma Diagnostics provide information on discharge parameters to characterize NSTX plasmas and guide its operation for optimized performance. The near term emphasis will be on detailed measurements of plasma profiles, using equipment presently available at PPPL. The long term objective will be to provide input for advanced plasma control systems, using new concepts and systems developed by the national NSTX team.
1.5 Power Systems	The Power Systems WBS element includes the engineering, design, prototyping, procurement and installation of all the systems and related elements that provide conditioned electrical power and energy to the NSTX systems. It includes the AC Power Systems, the AC/DC Convertors, the DC Systems, the Control and Protection System, and System Design and Integration as well as the coil bus runs..
1.6 Central Instrumentation and Controls (I&C)	This upgrade will be capable of producing plasmas on the order of 6.5 seconds, to-date,they are less than two seconds. For dozens of CAMAC and PC-based data acquisition systems this will require an upgrade and, in some cases, replacement. The real-time plasma control system will require an upgrade to accommodate additional input/output signals, control loops, and a longer control period. The networks and analysis pool computers will need to be upgraded to achieve reasonable performance for time-sensitive functions. Some test cell racks will be relocated; there will be a modest effort required to route the control, timing, and communication cabling, and qualify the systems.
1.7 Project Support & Integration	Project support and integration includes the non-hardware related subsystems such as overall Project Management and Administration, Project Physics as well as Integrated Systems Testing support.
1.8 Site Preparation and Assembly	Site preparation and torus assembly includes modifications to the existing NSTX Test Cell components and subsystems and the assembly and installation of all Torus Systems (WBS 1.1). Modifications to other PPPL facilities, components, and subsystems outside the NSTX Test Cell and the assembly and installation of non-torus components and subsystems are included in the individual components and subsystems.

5.5 Funding Profile

Tables 5.5-1 through 5.5-3 represent the Baseline funding profile, actual funds received and actual cost. DOE had provided accelerated funding starting in FY 2011, primarily to support the acceleration of the machine outage. This accelerated outage was a result of the FY 2012 run period being curtailed due to a failure of the existing inner TF conductor, which was deemed to be irreparable.

Table 5.5-1 Funding Profile Approved at CD-2 ($M)

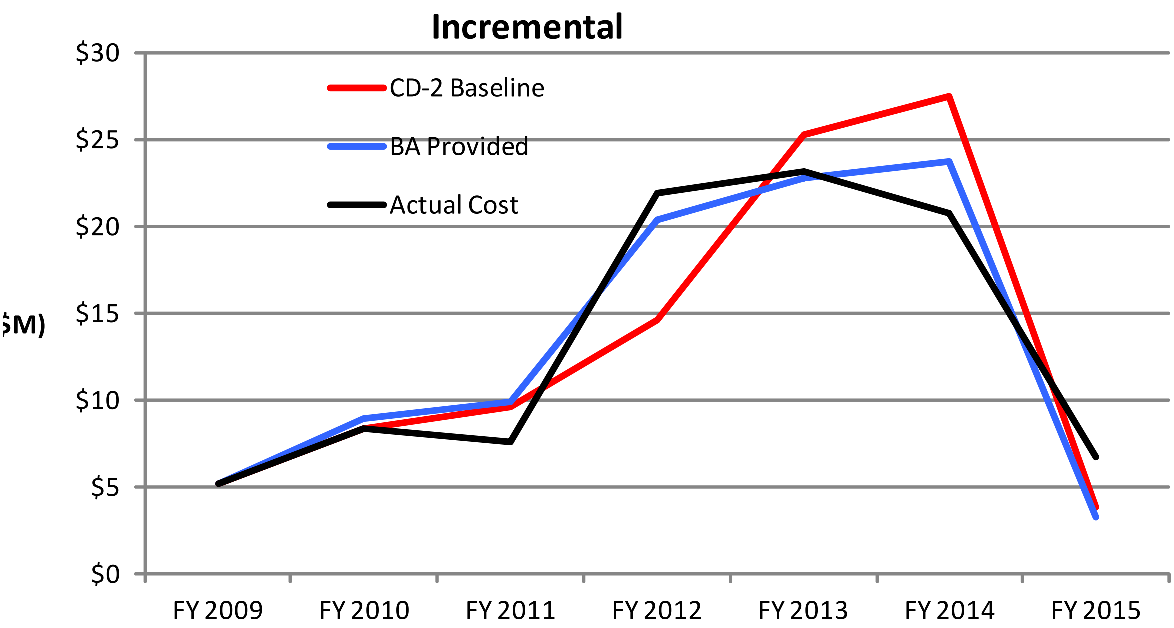
	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	Total ($M)
OPC	$5.1	$5.6						$10.8
TEC		$2.7	$9.6	$14.6	$25.3	$27.5	$3.8	$83.5
TOTAL	**$5.1**	**$8.3**	**$9.6**	**$14.6**	**$25.3**	**$27.5**	**$3.8**	**$94.3**

Table 5.5-2 Actual Funds Received ($M)

	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	Total ($M)
OPC	$5.2	$5.4	$0.1					$10.8
TEC		$3.6	$9.8	$20.4	$22.8	$23.7	$3.3	$83.5
TOTAL	**$5.2**	**$8.95**	**$9.9**	**$20.4**	**$22.8**	**$23.7**	**$3.3**	**$94.3**

Table 5.5-2 Actual Cost ($M)

	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	Total ($M)
OPC	$5.1	$5.6	$0.0					$10.8
TEC		$2.7	$7.6	$21.9	$23.2	$20.7	$6.7	$82.9
TOTAL	**$5.1**	**$8.32**	**$7.6**	**$21.9**	**$23.2**	**$20.7**	**$6.7**	**$93.6**



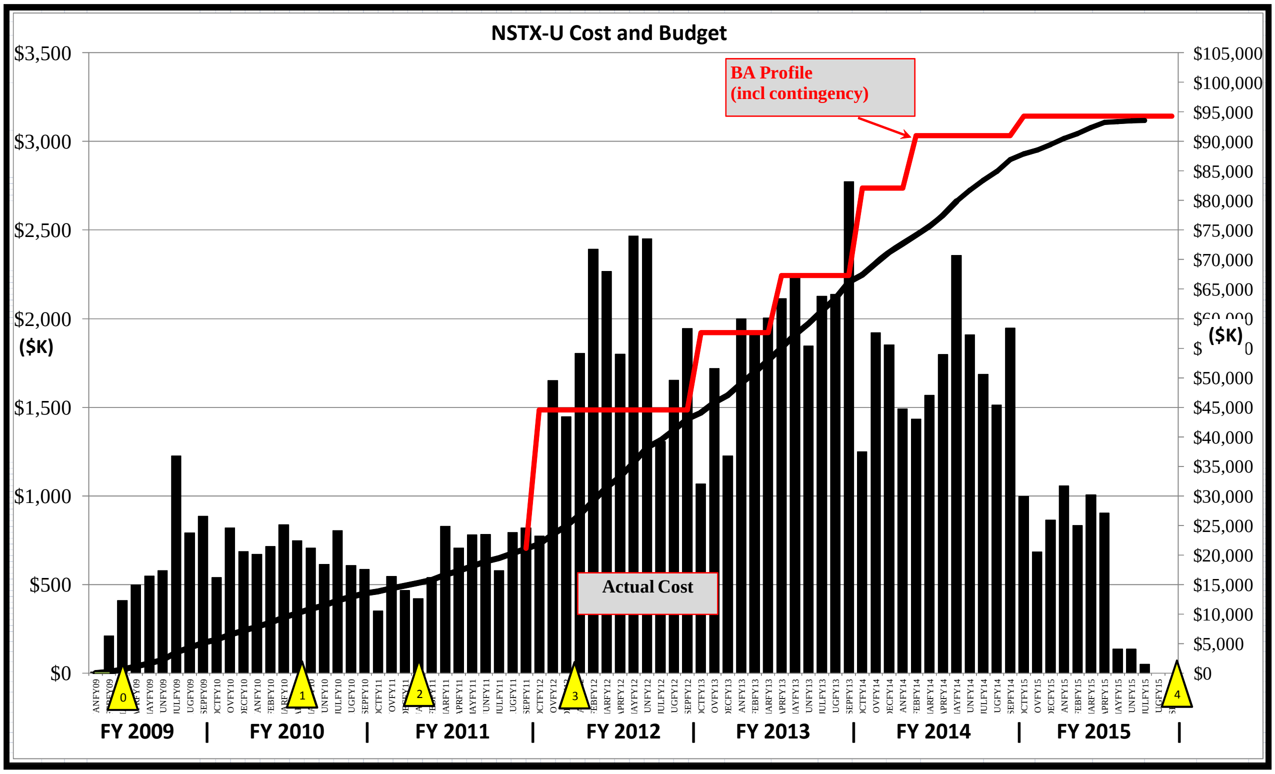


Table 5.5-4 Shows project actual cost detail as compared to the available project BA.

5.6 Staffing Profile

Figure 5.6-1 below shows the actual project staffing profile (in FTE's) profile by fiscal year. Subcontractors and hourly workers consist of engineers, designers, and technicians as required to supplement PPPL staff. Excluded are fixed price subcontracts for Davis–Bacon work. Scientists/Researchers provided consultation during the project and were paid by NTSX-U Operations. Important contributions were provided by PPPL Procurement, QA/QC, Safety, Emergency Services Unit (ESU), and the engineering front office, whose cost was not directly charged to the project but was recovered as part of the PPPL overhead.

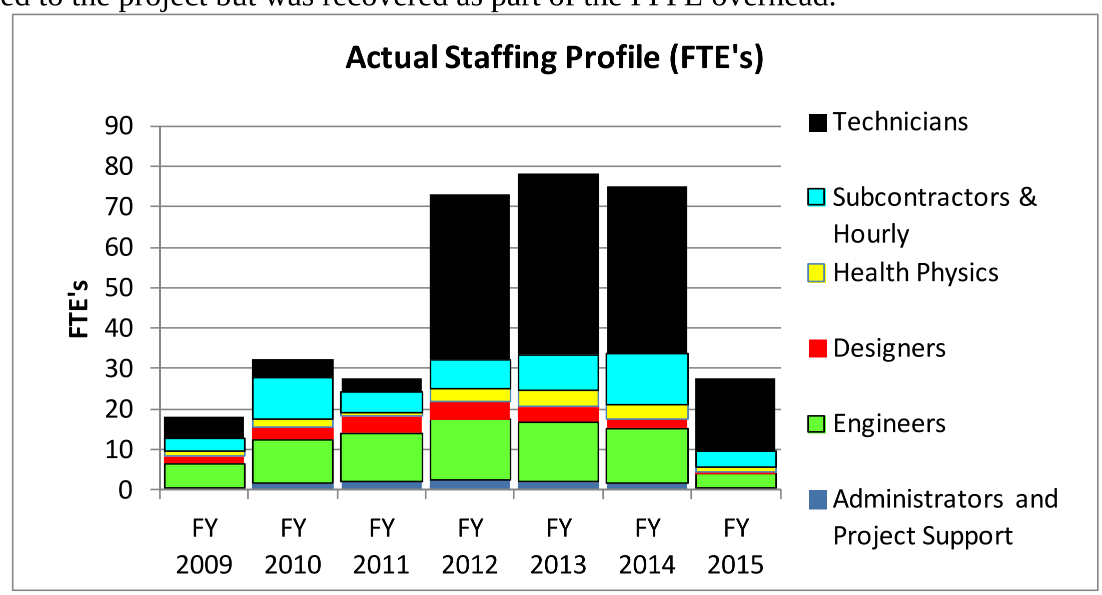


Figure 5.6-Actual project FTE profile by fiscal year.

5.7 Environmental Requirements/Permits

A NEPA determination as a Categorical Exclusion under 10CFR1021, Category B3.13 (magnetic fusion experiments, no tritium fuel use) was made by the DOE-PSO NEPA Compliance Officer in March 2009.
Upgrades to the NSTX experiment had been addressed in the NSTX Environmental Assessment report (DOE/EA-1108; FONSI issued 12/8/95), including plasma currents up to 2 MA and pulse lengths up to 60 sec.

5.8 Safety Record

Table 5.8-1 summarizes the yearly project safety record by organization and type. See Appendix D for the specific injury data.

Table 5.8-1—Summary of Project Safety Record

	Fiscal Year	Hours Worked	Recordable Cases	Recordable Rate	Recordable TARGET DOE (General Industry)	DART cases	DART Rate	DART TARGET DOE (General Industry)
PPPL	FY 2009	31,158	1	6.42		1	6.42	
	FY 2010	56,154	0	0.00		0	0.00	
	FY 2011	47,802	0	0.00		0	0.00	
	FY 2012	126,200	0	0.00		0	0.00	
	FY 2013	134,855	1	1.48		0	0.00	
	FY 2014	129,876	2	3.08		1	1.54	
	FY 2015 (1)	47,560	1	4.21		1	4.21	
	Total Lab	**573,605**	**5**	**1.74**	**3.8** (2)	**3**	**1.05**	**2.2** (3)
Contractors	FY 2009							
	FY 2010							
	FY 2011							
	FY 2012		NONE					
	FY 2013							
	FY 2014							
	FY 2015							

(1)Through 7/31/2015
(2) The "Recordable TARGET DOE (General Industry)" (see http://www.bls.gov/news.release/osh.t01.htm for 2013, Construction).
(3) The "DART TARGET DOE (General Industry)" (see http://www.bls.gov/news.release/osh.t01.htm for 2013, Construction).

6. CLOSEOUT STATUS

As of December, 2015, the following is the status of closeout activities.

Activity and Description	Completed?
CD-4 ESSAB Approved	Yes
Completion of punch list	Yes
Closeout all cost control accounts	Yes
Financial closeout	Yes

7. LESSONS LEARNED

The project compiled and ranked lessons lessons-learned (LL) into three levels. Rank 1 had the most profound effect on the success of the project, or caused the largest cost, schedule and technical impact. Level 1 LL are discussed in this section and the complete listing of LL are shown in Appendix H. These rankings are the subjective opinion of the project manager. Listed below are the top four opportunities and the top three successes.

<u>Top four opportunities:</u>
From the folder of "what would we do differently next time," there are four major events that stand out.

1. <u>Aquapour affair.</u> Aquapour, a water-soluble casting material, was used to maintain a thermal expansion gap between the center stack TF and OH winding. This process proved beneficial in winding the CS OH conductor. However, we were not able to remove the Aquapour as planned, since it became impregnated with epoxy. This setback, which had been postulated in the risk registry, resulted in a delay in the critical path schedule and will impose additional operational considerations. Even though this event was postulated in the risk registry, we may have been able to exercise additional engineering due diligence to better understand the failure mechanisms that could cause the aquapour to become nonremovable. For example, while we did perform two R&D simulations, we did not include the epoxy impregnation step. This may have indicated a failure mode in which the thermal expansion of the conductor and mold could cause the epoxy to migrate into the Aquapour area. Realization that this could happen could perhaps have led to a better sealing scheme or a decision to replace the Aquapour technique with a different boundary material.

   As this incident shows, we need to better think through technical, fabrication and assembly risks and determine mitigation plans. At the very least, we could have had a better understanding of the cost and impact on the schedule.. It must also be pointed out that our project's design underwent multiple external reviews, with many outside labs participating, so this incident should not be looked at as a failure but as an opportunity to take stock and learn. PPPL has very talented and experienced people who have performed similar operations and fabrication tasks successfully in the past. This is the reason that our projects are technically successful. However, experience and familiarity could easily turn into an air of overconfidence, or a “trust us, we’ve done it before” mindset. We need to maintain a healthy dose of skepticism in evaluating our work. For example, while we do have good design reviews, perhaps we need to incorporate an analysis of failure modes and their effect. It’s the underlying human mindset that we must recognize and change. Results of an independent peer review on the operational impacts of the Aquapour can be found in appendix L

2. <u>Better balance in assigning Control Account Managers (CAMs) to scope.</u> The centerstack design and fabrication was assigned to one CAM who was the laboratory's expert in coil manufacturing. The work scope should have been distributed to at least three CAMs. CAM overloads led to some oversights in procurement inspections, lack of timely reconciliation of cooling wave analysis, and absence of more complete field supervision and support of (EVMS) CAM duties. The center stack WBS manager relied heavily on one senior CAM, who quickly became overloaded. This led to a bottleneck in fabrication tooling that required a lot of attention. Some earlier support on engineering the tooling might have helped save rework time.

   Additionally, an overloaded CAM impacted our schedule since we tended to focus on the near critical path issues and big-ticket procurements, or work that was technically challenging. While this helped us to successfully navigate the six largest risks on the project, including the vacuum pressure impregnation of the centerstack, it caused smaller procurements of hardware to receive less attention until it came time for their assembly. Some of these components then had to be reworked by PPPL to meet specifications, which led to internal schedule delays and diversion of critical staff (e.g. welders and machinists).
   - Next time: Ensure that CAMs are not overloaded and adequate staffs are assigned for oversight and supervision. Ensure PPPL QC has adequate resources to support the receipt inspection process.

3. <u>Procurement:</u> We were reminded to “trust but verify” our new vendors, especially before awarding multiple procurements. There were some components that required welding of pieces that were prebeveled (a.k.a. “weld prepped”). We did not require a hold-for-inspection on these components and the vendor proceeded to weld the joints without pre-inspection. Once the hardware was received and inspected by PPPL, we discovered that the welded material had not been properly prepared. PPPL had to grind away and reweld questionable joints. (See "Procurement Lessons Learned Causal Analysis Report" under review documents.)
   - Next time: Ensure that inspection hold points are written into contracts for all critical welds, and especially for work by new vendors. Additionally, provide more thorough vetting of all our vendors.

4. <u>Loss of key personnel:</u> Loss of our DCPS CAM, due to his sudden death, and the temporary loss of the Magnet CAM, due to lengthy illness, impacted the project schedule as others had to fill-in. The secondary impact was an increase in project cost as less-experienced personnel took time to come up to speed and carry on the work.
   - Next time: Cost and schedule risks for loss of key personnel must be more thoroughly analyzed.

Top three Successes:

From the folder of "let's not forget" there are three major successes that stand out.

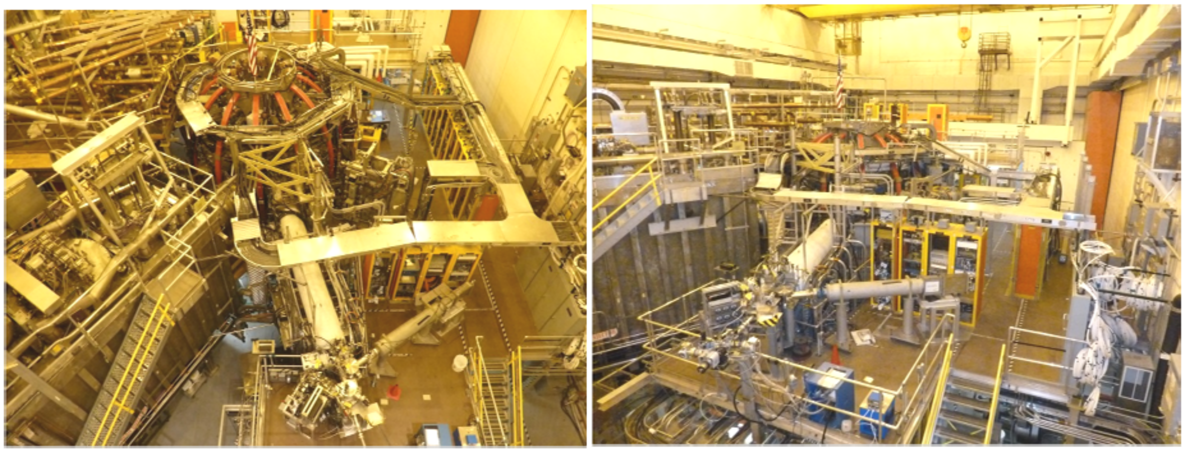
1. Safety: The attention to worker safety resulted in only five reportable minor injuries in over 550,000 hours worked. We have a robust safety organization and up-front management buy-in, and workers did not take risks or shortcuts in the name of schedules or cost. The safety culture at PPPL is one of its strongest assets.

2. Supervision: The work control center provided real value in establishing daily communication and coordination of field activities. Support needs such as QC weld inspections, safety support for walkdowns, and Health Physics analysis, were determined in the center's daily 10 minute meetings. This process was established during the TFTR project, which was successful in finishing safely on schedule and $3.6M under budget.

3. Technology Risk: The project was not risk-averse in employing new processes or technologies to provide engineering solutions. The project utilized seven fabrication and assembly techniques that benefited the construction of the new center stack magnet and vessel upgrade. (See Appendix K for detailed presentation.)
   1. Friction stir welding of copper was used to join high strength to high conductivity copper grades in the TF center bundle conductors.
   2. A new non-ionic soldering process was developed.
   3. Wire Electric Discharge Machining (EDM) was used in the manufacture of the critical TF High Current Connector.
   4. A carefully planned Vacuum Pressure Impregnation (VPI) process with hard metal molds was used to assure the strength and electrical integrity of the center stack.
   5. Cyanate Ester/Epoxy Resin was chosen for its maintenance of strength at elevated temperature.
   6. Electron Beam Welding was used to manufacture the TF Lead Extensions and Passive Plate expansion connectors.
   7. Aquapour, a water-soluble casting material, was used to maintain a thermal expansion gap between the center stack TF and OH winding. This process proved beneficial in winding the CS OH conductor. However, we were not able to remove the Aquapour as planned since it became impregnated with epoxy. This setback resulted in a delay in the critical path schedule and will impose additional operational considerations. This presented PPPL with a sobering lesson-learned opportunity.

8. PHOTOS

Overview of NSTXU Test Cell – Erik Perry

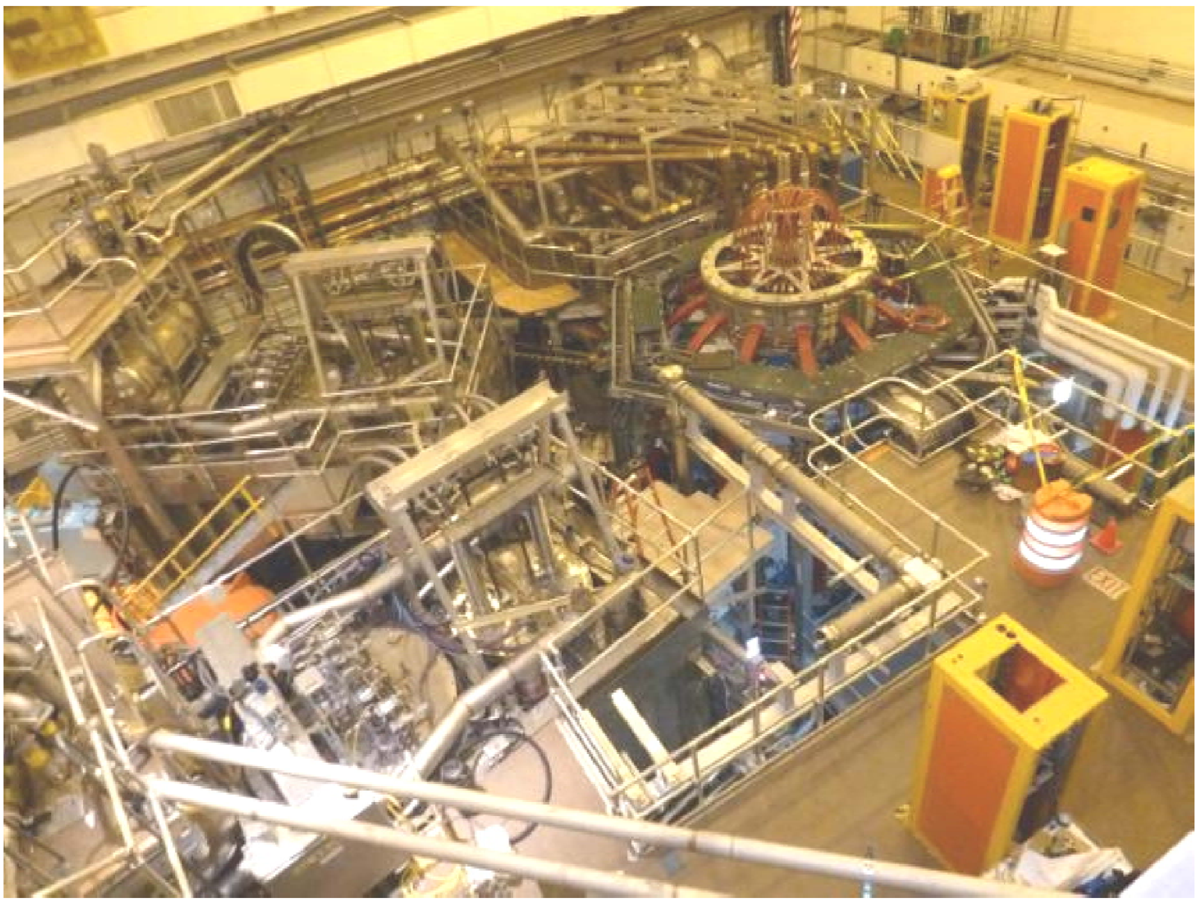


October 2011

October 2012

October 2013

October 2014

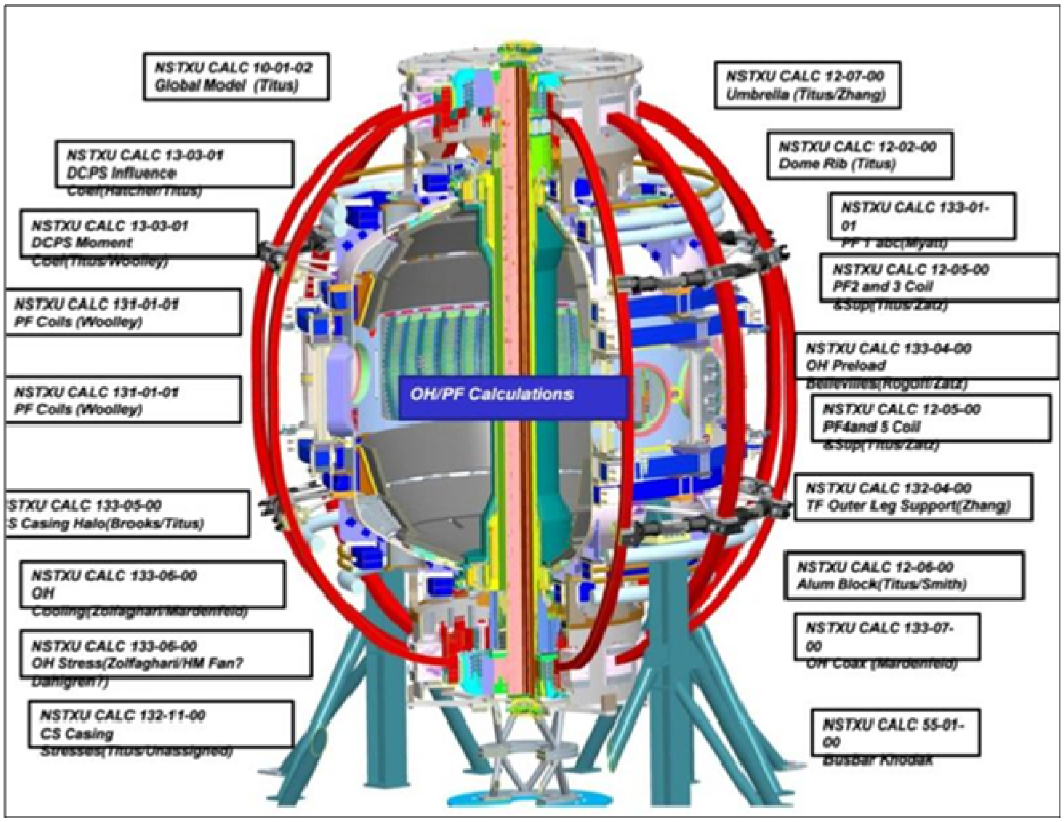


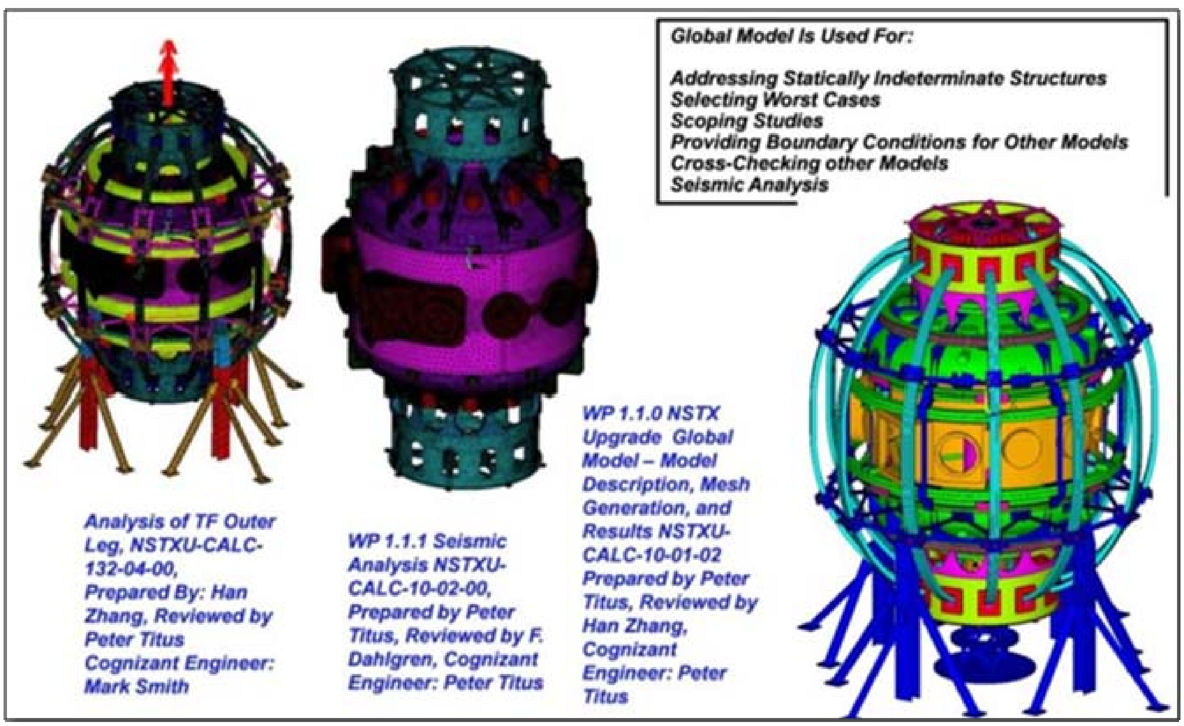
April 2015

<u>1.1 Torus Systems</u>

<u>1000 CSU Analytical Support – Pete Titus</u>

Calculations required to form the basis for designs





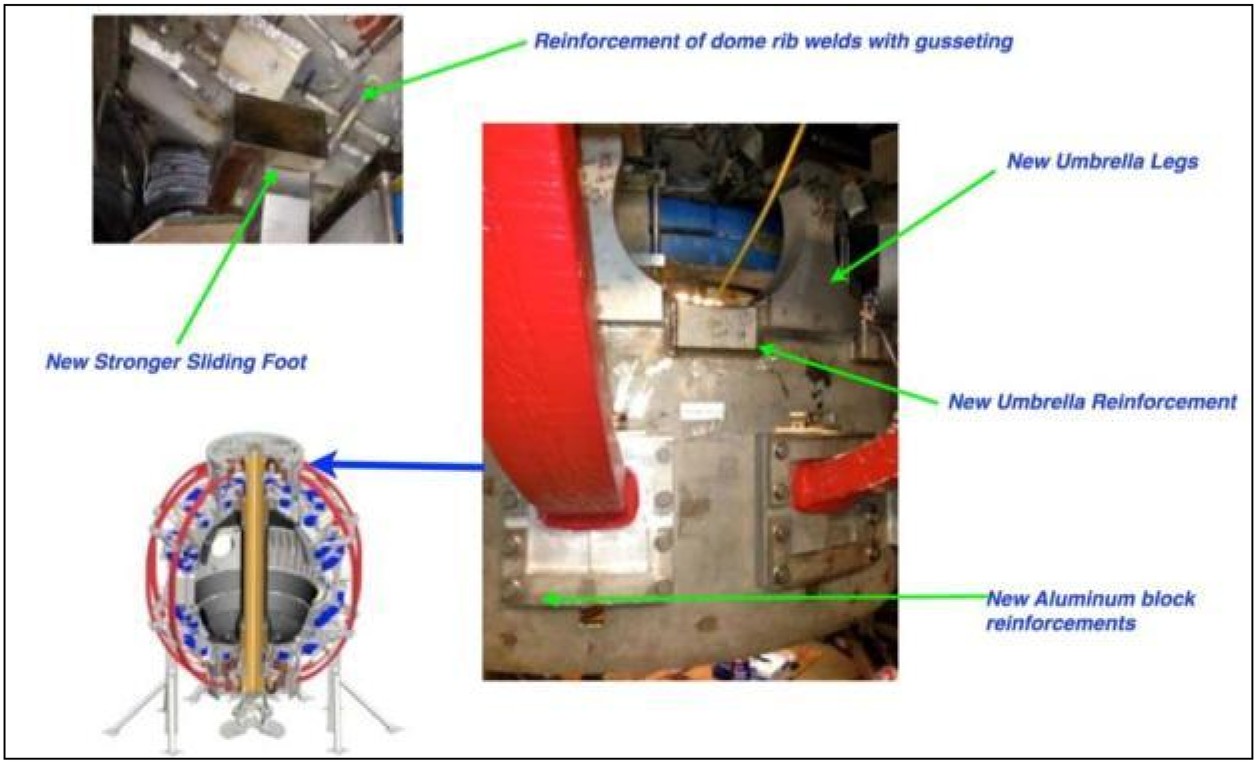
1001 CS Plasma Facing Components – Kelsey Tresemer

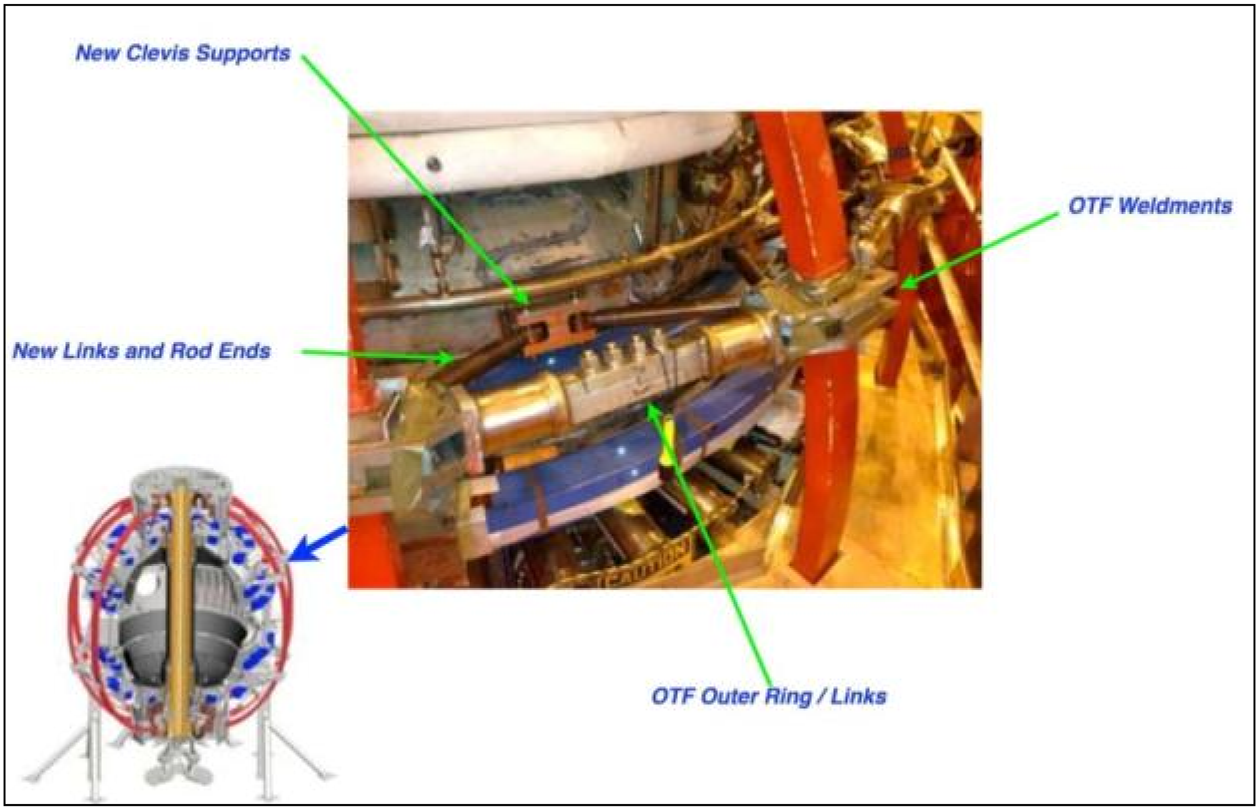
Plasma Facing Component (PFC) tiles installed on the centerstack casing

- Challenge: The existing secondary plates in the Bay A/L were weakene by the thermal cycle during brazing.
- Hardness and tensile test results confirmed that these plates are significantly weaker than the standa plates.
  - Standard (unbrazed) plates = 57 ksi (tensile strength)
  - PCHERS Passive Plate braze joint = 7 k
  - Electron beam weld joint = 40 ksi
  - E-beam Heat affected area = 57 ksi

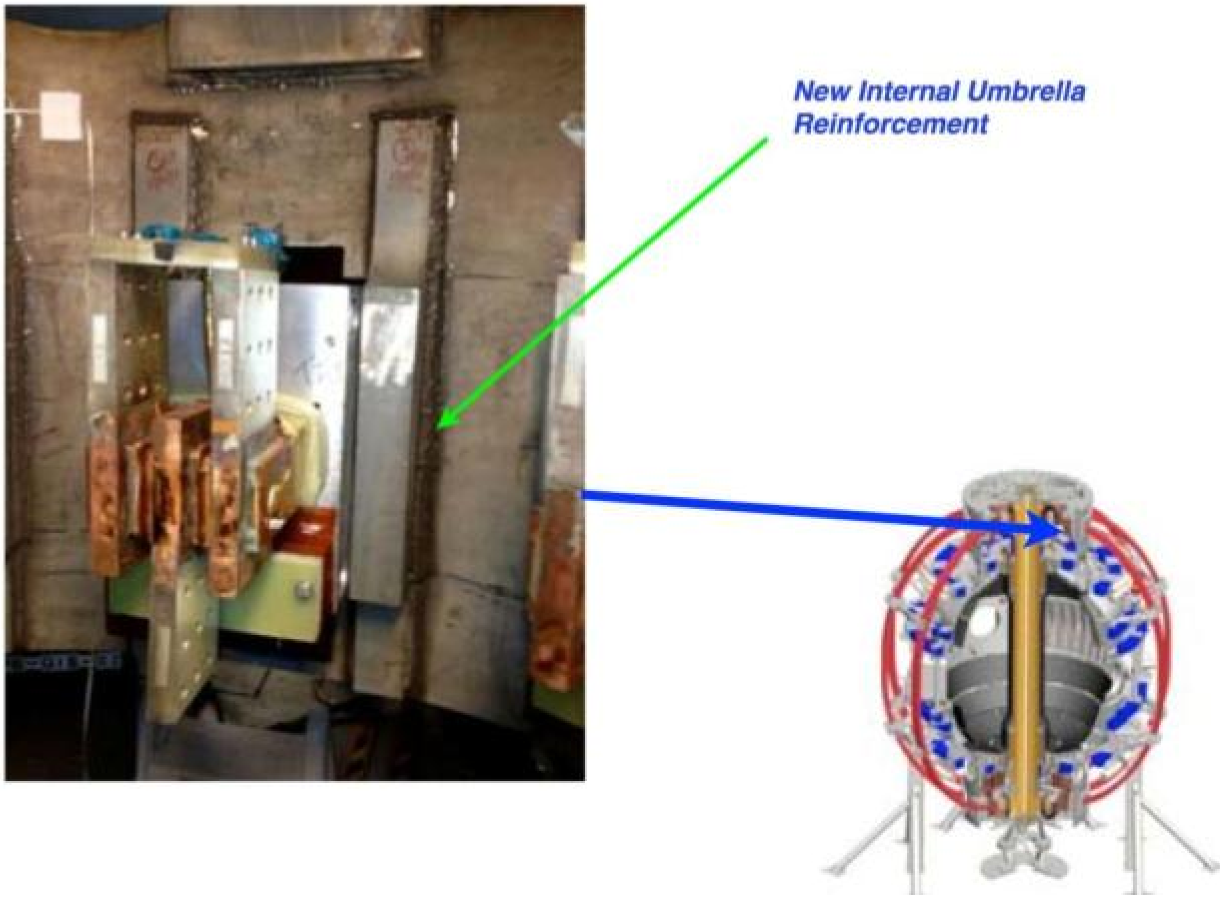
A new Design used E-Beam welding to join the passive plates to the jumpers

1200 Structures & Supp – Mark Smith





1200 Structures & Supp (continued)



More robust umbrella legs designed

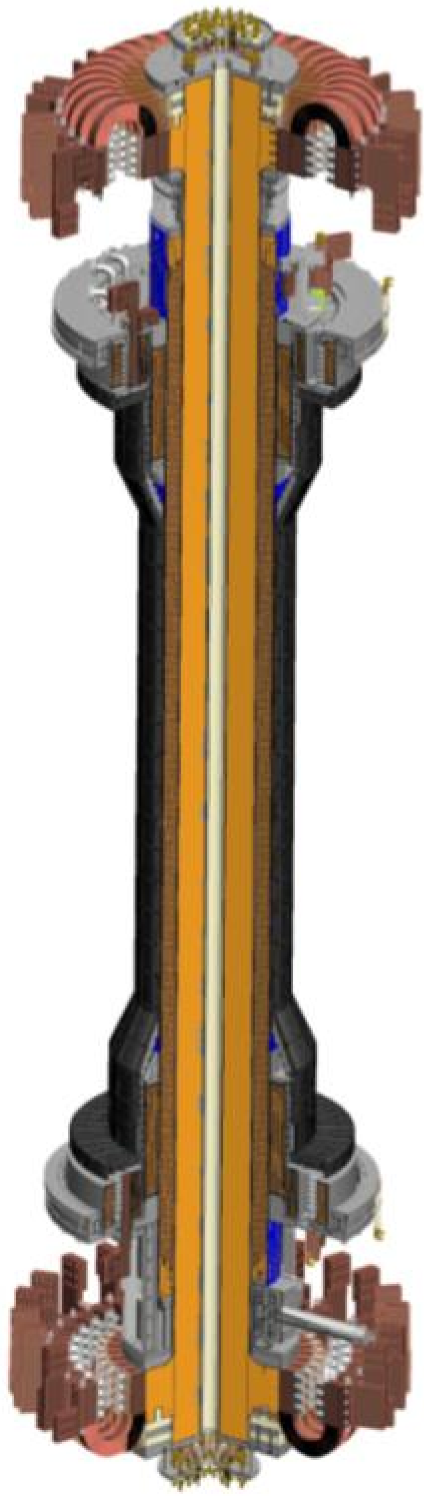
1300 Center Stack
1301 Outer TF Coils



Two new outer TF coils fabricated and installed

1302 Center Stack Assembly

See Section I for detail photos on the Centerstack Fabrication and Assembly



2420 2nd NBI Sources – Tim Stevenson

Beamline 2 Box Lift

Beamline 2 Lid Lift

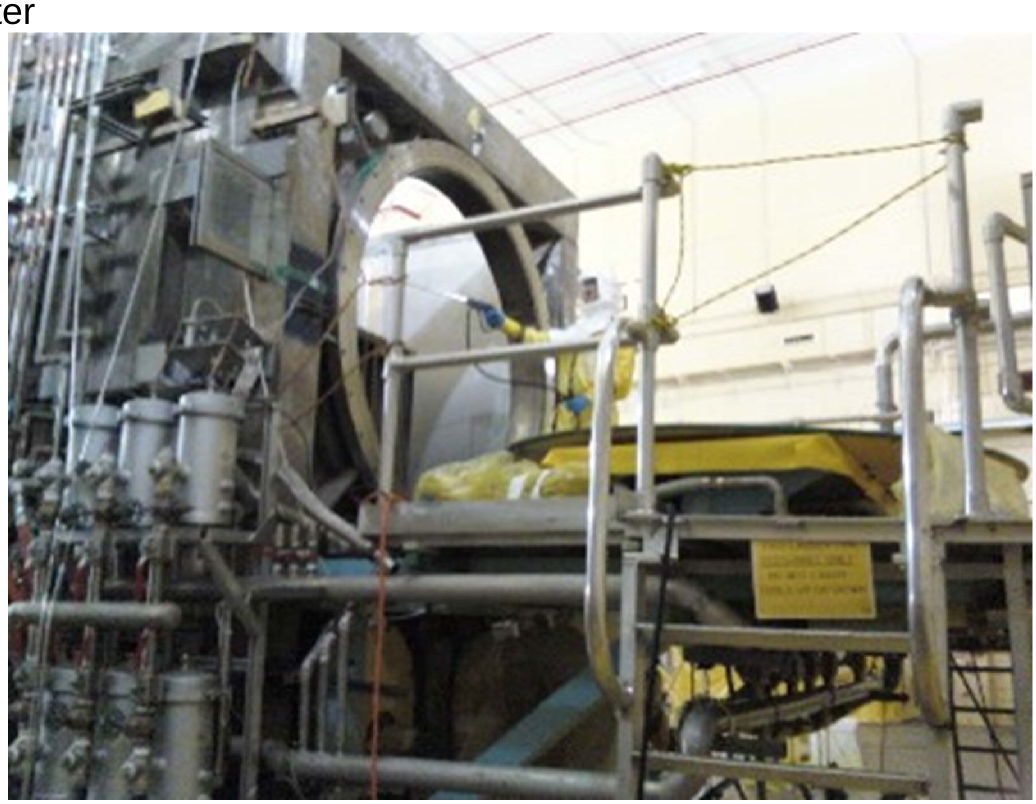
NBI BL Alignment

2425 BL Relocation (continued)

High Voltage Enclosures (HVE's) Relocated

Transmission Lines Installed

Box decon from lift and from source platform using 25 gallon sprayer and DI water



2450 2nd NBI Services – Mark Cropper


Cryogenic LN and LHe Piping installed

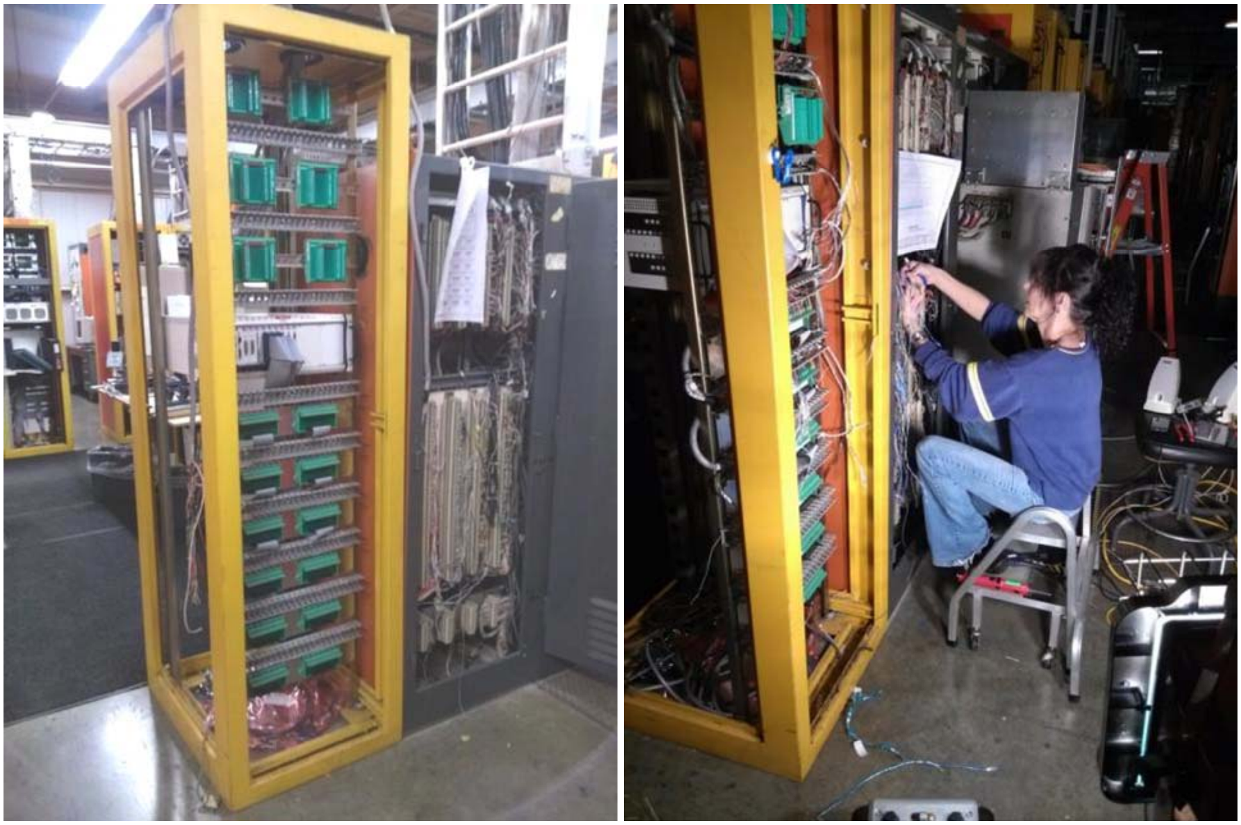

NBI Deionized Water Piping Installed

2460 2nd NBI Armor – Kelsey Tresemer

NBI Armor Installed

Power Cables in TCB,TTC to NTC Installed

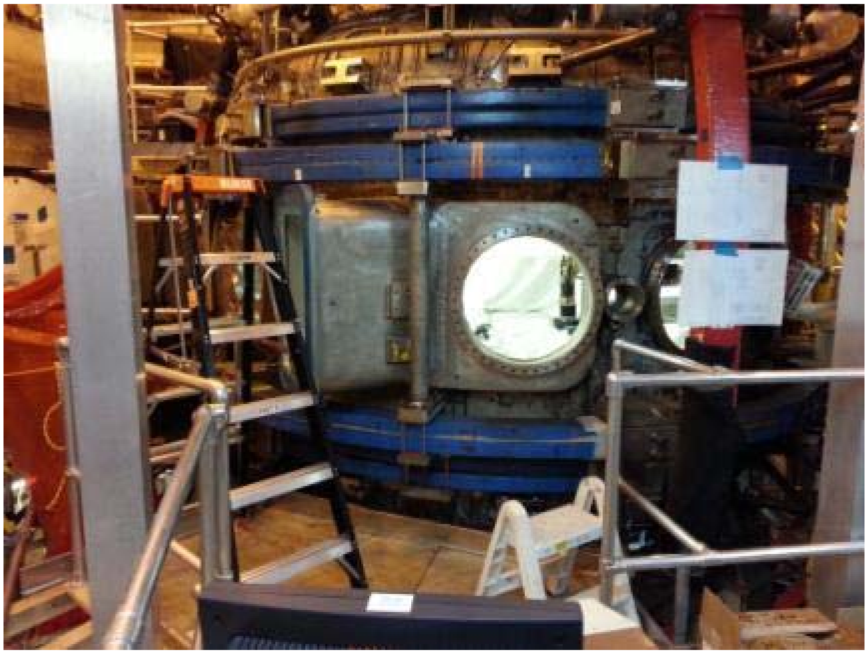
2475 2nd NBI Controls – Mark Cropper



Local Control Center and wiring updated

PLC Gallery Racks, Chassis, software, Cabling Completed

2480 2nd NBI/TVPS Duct – Mark Cropper

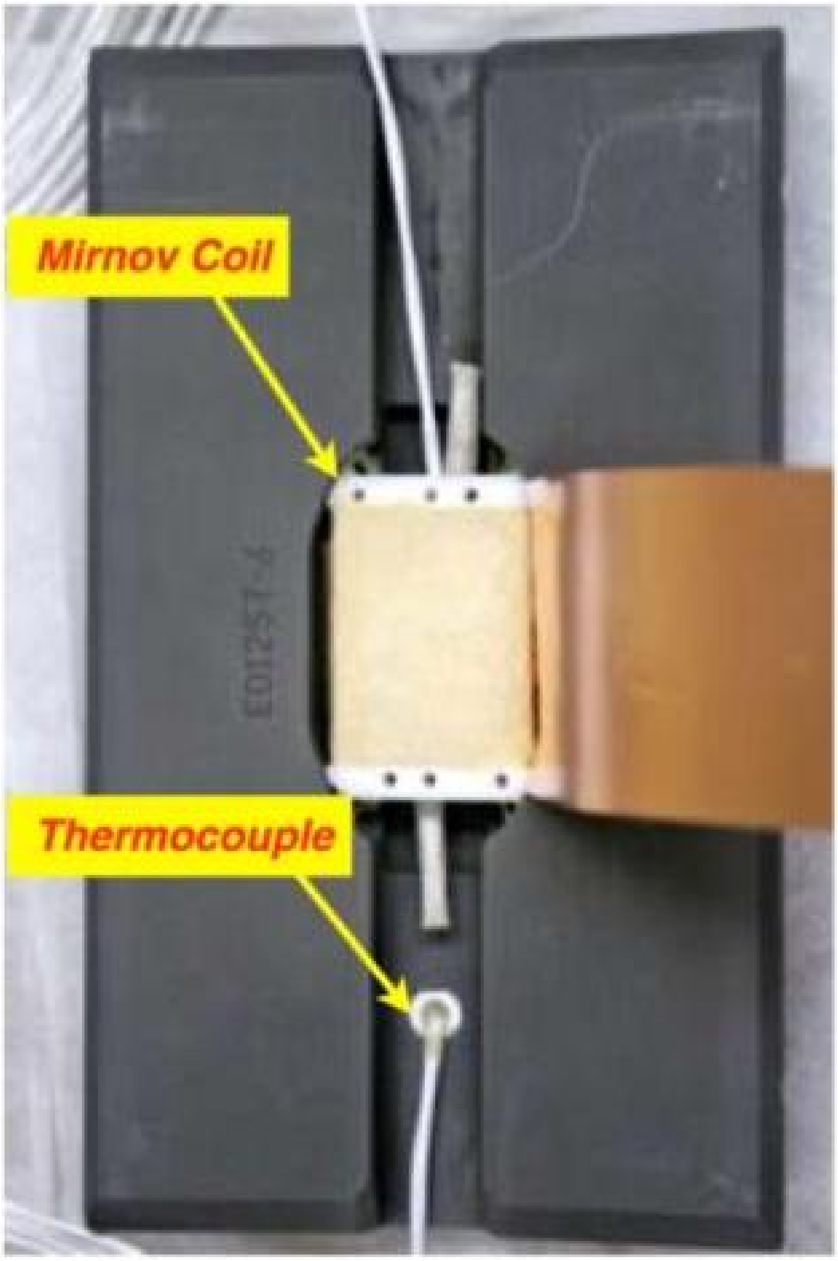


NBI Duct Installed

<u>**2485 Vacuum Pumping System – Bill Blanchard, Mark Cropper**</u>

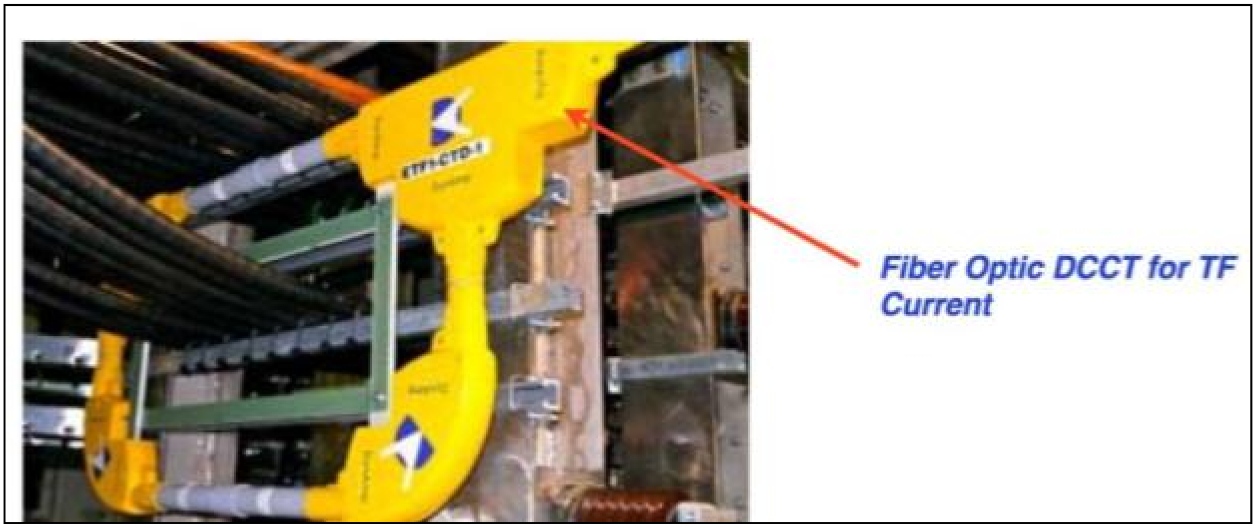
Torus Vacuum Pumping System Installed

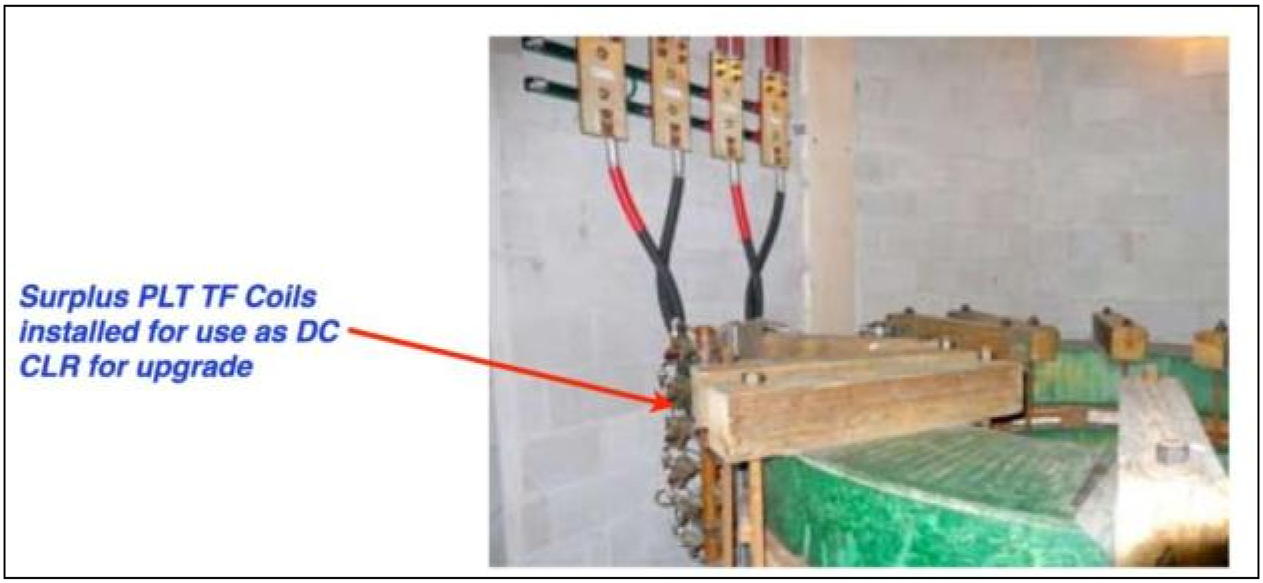
1.4 Plasma Diagnostics – Bob Kaita



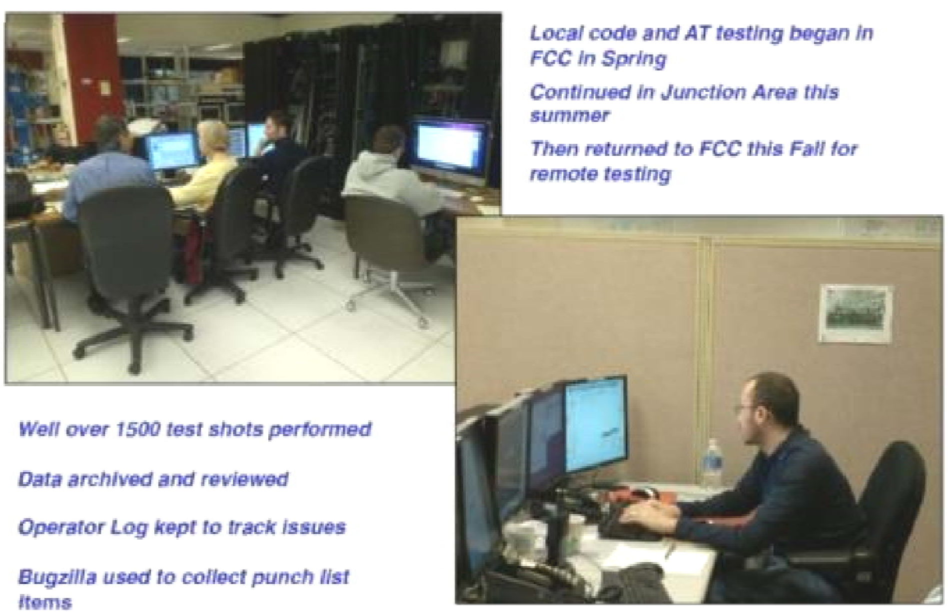
Mirnov coils and Rogowski coils installed into the PFC tiles

1.5 Power Systems
5000 CSU Power Systems (Raki)





DCPS Autotester Interface Panel
Allows local testing of DCPS code



Testing of DCPS with Autotester

5200 DCPS (Stevenson)

Board testing and bench testing of DCPS hardware

Junction area DCPS hardware user interface installed

<u>**5200 DCPS (Stevenson)**</u>

Junction area DCPS complete

DCPS FCC residing on PCS-SRV-1

5501 Coil Bus Runs (Atnafu)

Inner TF bus bar

1.8 Assembly

8200 /8250 Machine installations and assembly – Erik Perry

Lower Passive plates being installed

Outer TF to Umbrella connection **New outer TF coil being installed**

8200 /8250 Machine installations and assembly – Erik Perry (continued)

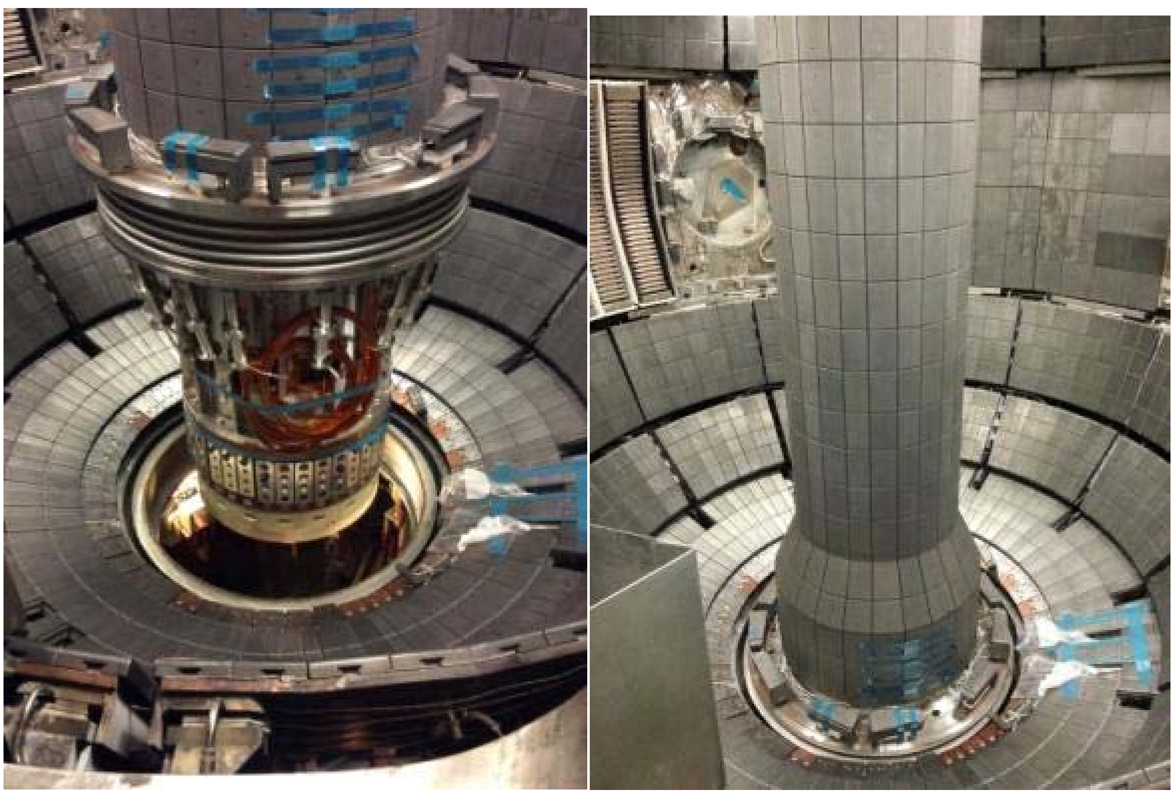
Outer TF Leg turnbuckle supports

Umbrella legs upgraded from 5/8" to 2" thick

8200 /8250 Machine installations and assembly – Erik Perry (continued)

CS Casing being installed over TF/OH bundle

CS assembly being lifted into the machine



New Centerstack installed

9. PROJECT DOCUMENT ARCHIVES AND LOCATIONS

Project documents are archived in the NSTXU database at http:// http://nstx-upgrade.pppl.gov/

Please contact Steve Langish or Ron Strykowsky for assistance

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