Office of Fusion Energy Sciences (FES)
Office of Science

CD-4 Approve Project Completion
NSTX-U Project
Princeton Plasma Physics Laboratory

A. Purpose

The purpose of this paper is to document the review by the Office of Science Energy Systems Acquisition Advisory Board-equivalent for the Critical Decision "Approve Project Completion (CD-4)" for the NSTX-U Project at Princeton Plasma Physics Laboratory (PPPL). The Total Project Cost (TPC) is $94.3M.

B. Mission Need

The mission of the NSTX program is to explore the properties of compact and high normalized pressure "spherical torus" (ST) magnetic fusion plasmas. The compact and accessible ST configuration is potentially advantageous for the development of fusion energy and also broadens and improves the scientific understanding of plasma confinement in ITER. The plasma confinement capability, and achievable plasma temperature, scale strongly with plasma current in the tokamak and ST. Plasma current in the range of 1 million amperes (1 mega-ampere) is required to access plasma temperatures needed to understand ST physics under fusion-relevant conditions. The only existing DOE facility capable of producing mega-ampere-class ST plasmas is the NSTX facility.

The ST shares many features in common with the conventional tokamak, but several important differences have also been identified – for example the scaling of turbulent energy transport with the frequency of inter-particle collisions. Understanding the causes of these differences is important not only to ST research, but also for developing a predictive capability for magnetic confinement generally. The new center-stack would double the NSTX toroidal magnetic field to 1 Tesla and enable a doubling of the maximum plasma current to 2 MA (million amperes) for the first time in STs. The center-stack upgrade combined with the installation of a second Neutral Beam Injection (NBI) will enable operation at higher magnetic field, current, and plasma temperature, thereby reducing the plasma collisionality to values substantially closer to those projected for next-step ST facilities and for ITER. Access to reduced collisionality will extend the plasma physics understanding of the ST and aid in the development of predictive capability for plasma confinement. Further, controllable fully-non-inductive current-sustainment is predicted to be provided by the second NBI, and would enable tests of the potential for steady-state ST operation and contribute to assessing the ST as a cost-effective path to fusion energy.

The ST is particularly well suited to provide a cost effective test-bed to bridge several gaps from successful ITER operation to a demonstration fusion power plant (Demo) as identified in the Fusion Energy Sciences Advisory Committee (FESAC) report issued October 2007 and entitled:

"Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan for Magnetic Fusion Energy". More recently, in November 2008, the "Report of the FESAC Toroidal Alternates Panel" also found that the ST offers the potential for an attractive test facility for developing fusion components. Upgrading the NSTX facility could significantly narrow or close capability gaps identified above. In support of these upgrades, the NSTX collaborative research team developed its Five Year Program Plan for 2009-2013 which was favorably peer reviewed and strongly endorsed in DOE-FES reviews conducted on July 28–31, 2008. The review panel specifically endorsed NSTX upgrade plans which form the central elements of the NSTX Five Year Program Plan.

Advantages of upgrading NSTX include cost and schedule savings from utilization of the existing NSTX facility and related available infrastructure while minimizing the disruption to ongoing ST research. NSTX was originally designed for upgradable center-stack and the second NBI capability. Most existing diagnostic systems are compatible with these upgraded capabilities. Construction of a new ST facility with similar capability could offer increased flexibility and/or design improvements, however it would require significantly higher cost and time as the NSTX site credit is significant ~ $200 M, and the disruption to ongoing ST research if existing ST facilities were not operated during the design and construction phase of a new ST facility. Based on the above considerations, upgrading the existing NSTX facility is the most promising and practical path to close ST capability gaps in a timely and cost-effective manner.

In February 2009, Patricia Dehmer (Acting Director, Office of Science) signed a Mission Need Statement (MNS) supporting improved ST capabilities in the FES program.

C. Scope Baseline

The NSTX center-stack upgrade entails the replacement of the slender central column, which holds a subset of the NSTX magnets, with a wider column (by ~ 13 cm in radius), capable of ~2x higher confining magnetic fields to bring NSTX to within approximately a factor of two of next-step STs and longer pulses to validate physics at current relaxed conditions ("physics" steady-state). The NSTX center-stack is replaceable as an integrated assembly such that the work to remove the existing center-stack and install the new one can be carried out in a few months. The original NSTX General Requirements Document anticipated a new center-stack with longer pulse and higher field, and the design of NSTX includes suitable provision in related components (toroidal field (TF) outer legs, poloidal field (PF) coils, power supplies, etc.) The key technical approach for the NSTX center-stack upgrade project is the fabrication and assembly of a new center-stack assembly, consisting of the inner legs of the toroidal field (TF) coil, the ohmic heating (OH) solenoid, the center-stack casing, the center-stack plasma facing components, the inboard plasma facing components, and the inboard PF-1 coils. The project scope also includes associated sensors (TF joint sensors, magnetic sensors and thermocouples), reconfiguration of the TF power supplies for higher current operations, and enhancements of support structures for higher field and higher current operation.

The NSTX second NBI installation entails moving a TFTR Neutral Beam heating and current drive system to NSTX, thereby doubling the NSTX neutral beam power and injecting more tangentially, similar to the injection geometry proposed for next-step STs. The NSTX second NBI project task is similar to the first NBI system installed in FY2000. The project will largely utilize one of the existing four TFTR NBI systems. The second NBI will be installed at Bay K where the vacuum vessel Bay K port area will be modified. The new duct will require a new circular and rectangular bellows and an appropriate set of protective shields. The new duct will also incorporate a vacuum pump duct. Prior to the second NBI installation, the NSTX Test Cell Bay K area must be cleared which includes the Bay L pump duct, Bay K diagnostics, existing platforms, diagnostic and vacuum system racks, and gas injection system racks. Following the second neutral beam installation, the vacuum pumping and gas injection control racks will be relocated and brought back to an operational state. For this second NBI upgrade, decontamination of the TFTR beam line (a large high vacuum stainless steel box enclosure containing various NBI components including cryogenic-panels, beam dump, bending magnets, calorimeter, etc.) will take place prior to refurbishment. Replacement components will be fabricated for items which cannot be satisfactorily decontaminated.

The key technical objectives of the NSTX Upgrade Project are as follows:

<u>Technical Performance Baseline Parameters</u>

To meet the mission need objective, the existing NSTX device at PPPL will be upgraded to increase the current NSTX operational performance criteria as follows:

- Increase toroidal field from 0.5 tesla to 1.0 tesla;
- Increase pulse length from ~1.0 second to 5.0 seconds;
- Increase plasma current from 1MA to 2MA;
- Increase neutral beam heating from 5-7MW to 10-14MW.

<u>Project Completion Criteria</u>

<u>Scope</u>

The scope includes Title I through Title III engineering, fabrication, assembly and installation, integrated systems testing, and project management associated with producing the in-scope equipment to meet the baseline parameters outlined above. The scope consists of two primary elements:

<u>Center Stack Upgrade.</u> Design, Build and Install New CS Assembly including a new toroidal field (TF) hub assembly, new TF flag assemblies, new ceramic break, new inner TF bundle, new ohmic heating coil, new iconel casing and insulation, new plasma facing component (PFC) tiles, and new poloidal field (PF) 1a, b & c coils.

<u>2nd Neutral Beam-line (NBL)</u>. Decontaminate and prepare a TFTR beam-line (NBL) for installation on NSTX. Evaluate and refurbish internal components as necessary (cryogenic

panels, beam dumps, bending magnets, beam scrapers, calorimeter, etc). Relocate the NBL and provide a second set of beam-line services (power, water, vacuum, cryogenics).

Demonstrated Performance

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 an ohmically heated discharge > 50 kA at a toroidal magnetic field of > 1 kG. The Operations phase will resume upon completion of the first plasma milestone.

The installation of the second neutral beam on NSTX shall be considered complete at the stage where each item below has been demonstrated:

a. Beamline water, vacuum, cryogenics, and feedstock gas services have been attached to the beamline;

b. A Torus Isolation Valve and duct interconnects the NSTX vacuum vessel and the neutral beamline;

c. Local Control Centers have been powered on to monitor power supply status, and;

d. Project will be verified as complete when a 40,000 electron-volt beam has been produced.

As can be seen in table 1, both demonstrated performance criteria (first plasma, neutral beam ops) were exceeded by the project.

Table 1. Key Performance Parameters

KPP at CD-2	*Description*	*Attained*	*Current Status*
1. First Plasma	>50kA plasma at > 1 kG	Completed (8/10/2015) >100kA @ 5 kG	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) 45kV @>0.05sec	Exceeded

D. Total Project Cost

The TPC for this project is $94.3M. The current Estimate at Completion (EAC) is $93.7M, $0.6M under the original TPC.

A summary of costs by Work Breakdown Structure (WBS) is provided in Table 2. Unspent funds will be used for other NSTX-U program priorities with FES approval.

Table 2. Cost Summary by WBS ($M)

	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 > Over sight 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**	

E. Schedule Baseline

Project management and control milestones are shown in Table 3. The NSTX-U Project CD-4 (Approval of Project Completion) date is September 30, 2015. CD-4 is anticipated in September 2015, which is on schedule.

Table 3. Milestones

Level	Milestone	Schedule	Actual
1	CD-0 Approve Mission Need	02/23/09	02/23/09
1	CD-1 Approve Alternative Selection	04/15/10	04/15/10
2	Complete Preliminary Design Review	06/2010	06/2010
2	Neutral Beam #2 Decontamination Complete	11/2010	11/2010
1	CD-2 Approve Project Baseline	2nd QTR 2011	12/20/10
2	Complete Final Design Review	09/2011	06/2011
1	CD-3 Approve Start of Construction	2nd QTR 2012	12/19/11
2	Friction Stir Weld Coil Leads to TF Conductor	06/2012	08/2011
2	NSTX Complete Operations	06/2012	09/2011
2	Begin Upgrade Outage	08/2012	09/2011
2	Begin Inner TF Quadrant Fabrication	04/2013	06/2012
2	Award Neutral Beam Vessel Cap Contract	06/2013	02/2011
2	Complete Assembly and Pot of 4th Inner TF Quadrant	10/2013	06/2013
2	Complete Fabrication and Test Inner TF/OH Assembly	07/2014	07/2014
2	Neutral Beam Cap Installed	10/2014	01/2013
2	Lift in New Centerstack	01/2015	10/2014
2	Complete Integrated System Test Procedure	08/2015	08/2015
2	Resume Operations	09/2015	08/2015
1	CD-4 Approve Project Completion	9/30/15 (F)	

F. Funding Profile

The project schedule and milestone dates were based on receiving project funds in the Fiscal Years shown in Table 4. The project was funded within NSTX-U's expected budget authorizations.

Table 4. Funding Profile ($M)

Fiscal Year	TPC ($M)		
	OPC	**TEC**	**Total**
2009	5.2	0	5.2
2010	5.4	3.4	8.8
2011	0	9.9	9.9
2012	0	20.5	20.5
2013	0	22.8	22.8
2014	0	23.8	23.8
2015	0	3.3	3.3
Total	**10.6**	**83.7**	**94.3**

G. Baseline Change Control

There were 136 Engineering Change Proposals (ECP) processed on the project during its execution. Of the $17M in contingency at CD-2, $17.1M was needed for cost overruns, $0.5M for the mitigation of the OH arc event, $3.5M was returned to contingency as a result of over estimates, and $2.3 million was used for scope enhancements. There is $0.6M in contingency remaining that is available for use by the FES program. Nearly all of the 12 months of schedule contingency was used, as well as the additional schedule that was gained in the beginning of the project because of a NSTX machine failure.

H. Transition to Operations/Project Completion

The project team developed an extensive plan to restore NSTX-U to operations following over four years of construction efforts. The following explains the reviews and committees that were utilized in making this transition.

- PPPL Activity Certification Committee (ACC). This committee consisted of internal PPPL engineers and scientists as well as Federal Site Office employees. The committee was charged to validate that NSTX-U construction activities were complete and that the machine was ready for a safe restart. (June 2013 – December 2014)
- Readiness for Operations Review. This review was conducted by Princeton University as the prime contractor. The review committee was made up of several fusion energy experts as well as members from other Office of Science facilities that operate large scientific devices. The review team issued a formal report, with 13 recommended actions, six of which were required to be closed prior to machine restart. (Dec 2014)
- The ACC reported to the PPPL ES&H Executive Board that NSTX-U construction efforts were complete and that the machine was ready for restart. They recommended approval of the NSTX-U Safety Certificate (April 2015)
- The Safety Certificate was approved by PPPL Chief Operations Officer with concurrence by DOE Princeton Site Office Manager (April 2015)

- NSTX-U entered the Integrated System Testing Procedure (ISTP-001) following Safety Certificate approval. This procedure steps the machine through individual coil energization at low power levels to integrated coil energization. The following key events occurred during this testing:
  - Machine bakeout and coil energization tests
  - First plasma attempt failure (April 24). An arc occurred between cooling fittings for the Ohmic heating (OH) coil and a grounding strap during ISTP.
  - First Neutral Beam shot into armor completed (May 11)
- As corrective action from the OH Arc fault event, investigations were conducted by two teams of fusion energy science experts; one internal committee and one external committee. (May – July) A formal Root Cause Analysis (RCA) was also conducted to ensure that all appropriate lessons were learned and that the machine could be restarted safely. Several action items were required to restore the machine to operations.
  - Hardware redesigns and installations (May – June)
  - Machine re-assembly (July – August)
- All required actions for restart were validated by the ACC and a formal recommendation was made to the PPPL ES&H Executive Board for Safety Certificate to re-start (August). The team executed ISTP-001, and first plasma exceeding KPP requirements was generated on August 11, 2015.

Other documents prepared and issued by the project team include the final Hazard Analysis Report (updated Safety Assessment Document), and a draft Project Closeout Report. The FPD also requested a validation that all work scope was completed and closed-out in support of CD-4. The Control Account Managers (CAM) each validated that their project work scope was complete and closed-out with a signature document; a process that was adopted from Brookhaven National Laboratory close out of the NSLS-II project.

An SC Independent Project Review (IPR) was held on September 2, 2015 to determine if the NSTX-U project was ready for CD-4 approval. The IPR committee recommended that the following item be completed: A Transition to Operations Plan be developed that captures all of the project planning activities that were completed as part of machine restart prior to ESAAB; this report was issued by the Project Manager on 9/17/15. After completion of this item it was recommended that the project proceed to CD-4 ESAAB.

Submitted by:

_______________________________ 9/25/15
Anthony Indelicato, NSTX-U Federal Project Director — Date
Princeton Site Office, Office of Science

_______________________________ for: B. Sullivan 9/25/15
Barry Sullivan, NSTX-U Program Manager — Date
Office of Fusion Energy Sciences, Office of Science

Recommendations:

The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of CD-4, Approve Project Completion, for NSTX-U, as noted below.

______________________ 9/25/15 Yes ✓ No ____
ESAAB Secretariat, Office of Project Assessment Date

______________________ Yes ____ No ____
Representative, Office of Budget Date

______________________ 9/22/2015 Yes X No ____
Representative, Safety and Security Policy (ES&H) Date

______________________ 9/25/2015 Yes ✓ No ____
Representative, Safety and Security Policy (Security) Date

______________________ Yes X No ____
Representative, Non-Proponent SC Program Office Date

______________________ 9/25/15 Yes ✓ No ____

______________________ 9/25/2015 Yes X No ____
Representative, Non-Proponent Federal Project Director Date

Approval:

Based on the information presented above and at this review, Critical Decision-4, Approve Project Completion for the NSTX-U Project, is approved.

______________________ 9/25/15
Edmund Synakowski, Project Management Executive Date
Associate Director of Science for the
Office of Fusion Energy Sciences