

Final Design Review (FDR) Committee Report
for the

**National Spherical Torus Experiment
(NSTX)
Upgrade Project**

**Princeton Plasma Physics Laboratory
Princeton, NJ**

June 22-24, 2011

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1. Introduction

A Final Design Review (FDR) was held at the Princeton Plasma Physics Laboratory (PPPL) for the NSTX Upgrade Project on June 22-24, 2011 at the request of Dr. Michael D. Williams, Associate Laboratory Director, Engineering and Infrastructure. The purpose of the review was to assess the project's technical, cost, schedule, and ES&H status in preparation for the CD-3 milestone review to be held in October 2011. The committee was asked to review the NSTX center stack upgrade and the addition of a second neutral beam for plasma heating:

The NSTX is the world's highest performance Spherical Torus (ST) research facility and is the centerpiece of the U.S. ST research program. Since starting operation in 1999, NSTX has established the attractiveness of the low-aspect-ratio tokamak ST concept characterized by strong intrinsic plasma shaping and enhanced stabilizing magnetic field line curvature. The purpose of the NSTX Center Stack Upgrade project is to expand the NSTX operational space and thereby the physics basis for next-step ST facilities.

The plasma aspect ratio (ratio of plasma major to minor radius) of the upgrade is increased to 1.5 from the original value of 1.26, which increases the cross sectional area of the center stack by a factor of ~ 3 and makes possible higher levels of performance and pulse duration. The project intends to replace the NSTX "center stack" in order to effectively double the magnetic field and plasma current (from 0.5T to 1.0 T, and 1.0 MA to 2.0 MA, respectively), increase the plasma pulse length (from nominally 1 second to 5 seconds), and add an additional neutral beam injector to effectively double the neutral beam heating power.

The NSTX Upgrade Project team presented to the review committee technical details of the center stack and magnet systems upgrade task including, TF, OH, PF coils, and structure modifications. They also presented detailed progress for the task of adding the second neutral beam, as well as ES&H and management issues. The project cost and schedule was presented. All presentations were very comprehensive in content, well organized, and professional in presentation, and they were supported by extensive project documentation provided to the committee.

The committee recognizes the significant amount of work that has been applied to advancing the NSTX Upgrade Project to Final Design status. The information presented to the review committee was extensive and comprehensive, as appropriate for an FDR. The organization and efficiency of the management and design team is exemplary. We were very impressed that the project team properly addressed every recommendation that this committee made during the CDR review.

We appreciate the support given to the committee and the responsiveness of the project team during this review.

2. Summary of Response to the Charge

A summary of the review committee response to the charge is given below. Further details of the committee report are given in the following sections.

1. *Are ES&H issues being properly addressed for the fabrication, assembly and testing?*

- The NSTX Upgrade Project has incorporated ES&H into its activities, including fabrication, assembly and testing, and will draw on the well-established ISM culture and infrastructure at PPPL.
- A Construction Health and Safety Plan has been drafted.

2. *Does the final design meet the requirements for the NSTX Upgrade Project as delineated in the General Requirements Documents?*

- The project designs are consistent with the PEP and GRD deliverables.

3. *Does the Final Design Review satisfy the objectives of PPPL Procedure ENG-033, "Design Verification", Attachments 4 and 6, "Design Review Objectives and Input Documentation" and "Human Performance Improvement/Factors Considerations in Design Reviews"?*

- The final design satisfies the requirements and is ready for implementation. The designs and analyses have been iterated with project physics and meets the design requirements as defined in the GRD and deliverables in the Project Execution Plan.
- Detailed analyses, calculations, and tests to validate the design are 90%^(per DOE) complete and documented. Most R&D, mockup and developmental trials have been completed.
- The final product, both the new center stack and second beamline, can be manufactured, inspected, assembled and installed reliably, safely and cost effectively. This is based on previous experience with the first beamline installation and decades of experimental magnet fabrication as well as experience removing, rebuilding and replacing the existing center stack on NSTX.
- Human performance and human factor considerations are appropriately addressed in the design. A center stack manufacturing plan has been developed, a construction safety and health plan has been drafted, and job hazards analysis will be prepared for all fabrication and assembly work.
- Procurement issues have been identified and resolved. Vendor contacts have been made for manufacturability and cost estimating where appropriate. Lists of procurements have been tabulated in the work authorization forms (WAF's). Long lead and critical procurements have been identified and approved for procurement by DOE.
- Appropriate documentation is available for producing the final product. Detailed part drawings will be produced from the completed models. Installation procedures have been identified and will be prepared prior to assembly.
- Appropriate test plans for the final product have been identified and they will be

- prepared prior to the component testing and ISTP tests.
- Previous review chits and recommendations have been incorporated or reconciled. Results are being independently verified.
- Manufacturability of the critical hardware and assemblies has been verified.

4. *Have previous recommendations from previous reviews been adequately addressed?*

- Previous review chits and recommendation have been incorporated or reconciled. Results are being independently verified by QA.

5. *Have risks been appropriately identified? Are project plans adequate to address/retire the identified risks? Are there any "show stoppers" to starting fabrication and assembly?*

- Risks are being retired consistent with a more mature design.
- Opportunities are continuing to be explored that could reduce cost and accelerate schedule.
- The project continues to identify and track risks and their impact on fabrication and assembly.
- There are no show stoppers. Project should proceed with procurement, fabrication and assembly as planned.

6. *Have the cost and schedule estimates been updated? Do they reasonably reflect the cost, schedule, and resource efforts required to complete the project?*

- The project has performed a bottoms-up estimate-at-completion that reflects the more mature design. The updated cost profile is consistent with available funding. Opportunities for future savings are being pursued.
- The overall project schedule is on track. The critical path through the center stack fabrication is being supported with advanced procurements.
- Staffing needs have been identified by name and are achievable to support the project based on the current foreseen workloads at PPPL.

7. *Given the current stage of the project, is the project's management structure and team appropriate, and are the plans to support the next phase of the project sufficient?*

- The project has implemented sound management processes and has effective communication with all stakeholders.
- DOE has demonstrated their support and confidence in the project by authorizing advanced procurements and field tasks (pre-CD-3 scope).

8. *Is the project proceeding along a plan to be CD-3 ready by this summer? Has the required documentation been identified and currently being prepared as required by DOE 413.3B?*

- CD-3 checkpoint documentation per DOE 413.3B is currently being updated and

will be completed this summer.

9. *Outage planning and coordination - Has a construction plan been developed that adequately ensures the proper sequencing of field tasks? Have key positions and responsibilities been defined? Has worker coordination been addressed (i.e. daily job briefings, hazards analysis, procedures etc.)?*

- A Machine Installation and Outage Coordination Plan has been drafted and currently being iterated. The plan will be instrumental to ensure that field work is conducted efficiently and safely. The project will establish a work control center as done for TFTR D&D where work assignments, schedules, pre/post job briefs will be performed on a daily basis. All key positions and responsibilities have been identified and filled with qualified personnel.

3. Technical Systems Evaluations

The following sections provide the findings, comments, and recommendations broken down for the major program elements of Center Stack Upgrade, Second Neutral Beam, and Management, Cost, and Schedule.

3.1 Center Stack Upgrade

Findings

- A summary of the large amount of detailed design and technical analysis was presented by the project team. It was clear that nearly all significant outstanding issues, chits, and many risks have been resolved or retired.
- The project team detailed the plans to fabricate the new TF inner leg bundle in-house and then wind the OH coil onto the TF legs. A dissolvable filler product called Aqua Pour[®] will be used to fill the gap between the TF inner stack and the OH windings to maintain concentricity during winding. This material has been shown to be "fit for the purpose" and detailed process steps are being developed to be used during the fabrication phase.
- All the TF inner leg copper extrusions have been purchased and delivered by Luvata. They are slightly oversized to be machined to final dimensions and installation of an axial cooling tube.
- Friction stir weld tests have been performed with successful results. This process will be used to connect the flexible copper flags to the TF legs .
- Vendors have been identified for many of the major components and bids/contracts are being evaluated for some.
- The outer TF cage and PF supports design has been finalized.

- There is a location on the inner TF near the TF flags where the temperature exceeds 100 C during the maximum power pulse. The CTD 101 epoxy resin system will not provide suitable shear strength at this temperature. As a result, the project plans to use CTD 425, a Cyanate Ester/epoxy resin blend for this impregnation. Three-point-bending shear bond tests have been performed, including development of an S/N curve at 80 and 100 C.
- The inner vessel protective tiles are now made from radiatively cooled ATJ Graphite, some with Grafoil™. The mechanical fastening method is similar to that used in other machines. Carbon Fiber Composites (CFC) will only be used on the beam armor/plates. ATJ is used everywhere else where radiative cooling is sufficient. The CFC tiles are already on hand and thus cost and schedule savings are realized.
- The DCPS (two independent systems) has been further developed with an algorithm-based scheme and all the components needed to assemble the system have been specified. Software development is underway and will be tested during the upcoming NSTX run. This system will be ready for FDR in July 2012.
- The project critical path now runs through center stack fabrication. Tiles are no longer on critical path thanks to switching from CFC to ATJ in most locations.
- 40 minute rep rate is limited by power system TF cabling and not by thermal (cooling) performance on the OH coils (estimated at 15 minutes).

Comments

- There are no show-stoppers in the chits. The amount of work performed by designers and analysts meets FDR requirements. The team is to be commended for their extensive work.
- In-line braze joints in the central solenoid conductor may be eliminated using the CONFORM™ continuous extrusion process presently being used by Luvata in Finland. If joints are kept, then careful NDT of the joints is needed, which has been demonstrated many times before at PPPL.
- CTD 425 has been selected with the Cyanate Ester primer as the insulation system. The CTD fatigue data on insulation shear strength was carried out at 10 Hz, but normal operations are at a much slower rate (2-5 seconds). Hence, the fast fatigue data may be optimistic and not correctly account for combined creep and fatigue.
- Friction stir welding (FSW) is a good solution for joining the flags to the wedges. Test results are now available for FSW and indicate acceptable use for copper connections on NSTX and future fusion applications.

- Heat loads in the divertor area develop high temperatures and a radiatively cooled scheme is proposed. The GRD can be met by tuning (if necessary) the standard 96 operational scenarios.
- Further work is needed to resolve stress analysis discrepancies (i.e. slow discharge disruption calculations which showed 10 x difference).

Recommendations

- Aluminum blocks support the TF legs at the umbrella structure. Consider thermal expansion mismatch and eddy currents. Does this still work effectively with larger thermal and EM forces in upgrade configuration?
- Recommend building a mock-up fixture to simulate OH and TF inner leg interface to practice working with a long length of Aqua Pour[®] removal in relevant geometric configuration.
- Recommend developing a controlled access procedure for the DCPS hardware and software changes.
- PF Bus leads appear to diverge. This separation increases the torques on the leads. Can this be reduced?
- Please put wrench flats on struts at the ends, not the middle. The flat at the middle degrades buckling.
- Almost all TF and PF coil loads are carried by the NSTX-U vacuum vessel. The vacuum vessel should be subjected to a buckling analysis using combined disruption and coil loadings.
- Actual vessel measurements showing dominant deviations from design dimensions should be included in computer models used for mechanical analysis.
- Consider reducing the GRD specified number of full power load cycles for the center column structures, i.e. TF inner legs/OH coil and possibly the center vacuum tube.
- If funding becomes available, please consider purchasing TF power cabling.
- Perform copper/insulation fatigue strength tests on SBS test samples at a cyclic rate that is more consistent with the operational loading rate so that effects of creep are included.

3.2 Second Neutral Beam

Findings

The second neutral beam scope includes:

- Disassemble and evaluate a TFTR beamline
 - Decontaminate the beamline and internal components
 - Refurbish for reuse
 - Relocate numerous diagnostic systems, work platforms, etc., to make room for beamline in the NSTX Test Cell
 - Replace bay K, J ports with new design to accommodate beamline
 - Move NB2 to the NSTX Test Cell
 - Align beamline and ion sources
 - Run services (power, water, cryo and controls)
 - Connect and activate instrumentation and control systems
-
- Decontamination efforts on the TFTR beamline have been successful enough to allow the beamline to be moved and installed into the NSTX Test Cell.

 - Appropriate radiological control procedures are going to be used near the beamline throughout the relocation and after, as necessary. When the beamline is installed and closed, the area may be released from the RWP if it is determined to be safe.

 - Plans for relocating the beamline and supplying it with necessary services are comprehensive and incorporate a large number of other coordinated system relocations.

 - The beamline armor protection system has been improved and analyzed extensively, with several “worst case” scenarios studied. Results indicate the system will perform adequately in all cases. Several methods are used to prevent an excessively long beam pulse into the armor, even if the plasma current interlock fails.

 - The port modifications to incorporate the second beamline and the MPTS system require a significant amount of cutting and welding on the vacuum vessel. The new port cap has been strengthened to restore vessel integrity after these modifications.

Comments

- The NSTX Upgrade team is to be commended for the accomplishments of refurbishing and decontaminating TFTR beamline safely.

- A planned reduction and future phase-out of CAMAC equipment is applauded.

- Care should be taken to perform large vacuum vessel welds appropriately to avoid

creation of virtual leaks within the welds.

- Aiming the new beams to larger radii allows exploration of promising new off-axis current drive scenarios.

Recommendations

Expecting all the old CAMAC equipment to function properly after years of hibernation is not wise. Plans should incorporate some significant debugging and repair time to bring up the old equipment.

3.3 Management, Cost, and Schedule

Findings

- The NSTXU project team is in place, fully staffed and functioning effectively.
- Lab management strongly supports the NSTX Upgrade Project
- CD-2 was approved by DOE in December 2010 with a TPC of \$94.3M and CD-4 date of September 2015
- The current BAC is \$77.3M with an early finish date of September 2014.
- The DOE funding plan is supportive of the project schedule.
- Long lead fabrication work has been approved by DOE.
- Through May 2011 the project is 22 % complete.
- An initial bottoms up ETC was just completed. Based on this, the available contingency is 21% of remaining work.
- An EVMS certification review will be conducted by SC in October 2011.
- A Lehman Review to assess readiness for CD-3 will be conducted in October 2011, which is expected to support a CD-3 approval by December 2011.
- An Integrated Project Team is in place and functioning.
- A Risk Management Plan is in place. The current Risk Register has 77 identified risks. 27 have been retired.
- PPPL intends to establish an external advisory committee for the NSTX Upgrade project. The Lehman Review Committee endorsed this idea last year, but it has

not yet occurred.

Comments

- The cost estimates are considered to be at the midpoint of the estimating range, which PPPL project management believes that a moderate number of setbacks in execution can be accommodated without drawing on contingency. This seems reasonable but needs to be monitored closely.
- PPPL is highly motivated to keep NSTX-U on or ahead of schedule in order to minimize the downtime from physics operations. The intent is to advance work if there is favorable cost experience during execution. This seems reasonable.
- Staffing required to support the schedule consists of people already on board which adds to the schedule credibility. Also, essentially all of the necessary work is similar to work previously performed at this facility.
- The proposed use of the work control center by E. Perry for the outage work is cited as good management practice. It supports safety and regulatory compliance.

Recommendations

1. Revise the Project Execution Plan by September 2011.
2. Establish an independent, external Project Advisory Committee by September 2011.

4 Appendices

4.1 Charge Letter



Plasma Physics Laboratory
James Forrestal Campus
P.O. Box 451
Princeton, New Jersey 08543

January 13, 2011

Dr. Joseph Minervini
Massachusetts Institute of Technology
Plasma Fusion Center
Room NW22-129
77 Massachusetts Avenue, NW16
Cambridge, MA 02139

Dear Dr. Minervini,

The Princeton Plasma Physics Laboratory is planning a Final Design Review for the NSTX Upgrade Project on June 15-17, 2011. We would be honored and grateful if you could agree to serve, again, as the Chairman of the Review Committee. Mr. Al von Halle of PPPL will be available to help you with the administrative aspects of this responsibility.

Due in large part to the successful reviews you previously chaired, the Laboratory recently received CD-2 approval from DOE for this project signifying their support of the project and acceptance of our cost and schedule baseline. This approval allows us to perform the final design activity as well as starting long-lead procurements essential for the critical path. The next major milestone, CD-3, will enable us to begin full construction activities. The Final Design Review will prepare us for this stage. Additional pertinent information will be provided prior to the review.

If you have any questions, please contact me (at 609-243-2866 williams@pppl.gov) or Ron Strykowski (at 609-243-2674 or rstrykowski@pppl.gov). Please let me know of your intentions by February 18, 2011.

Sincerely,

A handwritten signature in black ink, appearing to read "M. Williams".

Michael D. Williams
Associate Laboratory Director
Engineering and Infrastructure

cc: A. Cohen
S. Prager
S. Smith (PU)
R. Strykowski

4.2 FDR Charge

1. Are ES&H issues being properly addressed for the fabrication, assembly and testing?
2. Does the final design meet the requirements for the NSTX Upgrade Project as delineated in the General Requirements Documents (attached)?
3. Does the Final Design Review satisfy the objectives of PPPL Procedure ENG?033, "Design Verification", Attachments 4 and 6, "Design Review Objectives and Input Documentation" and "Human Performance Improvement/Factors Considerations in Design Reviews" (attached)?
4. Have previous recommendations from previous reviews been adequately addressed?
5. Have risks been appropriately identified? Are project plans adequate to address/retire the identified risks? Are there any "show stoppers" to starting fabrication and assembly?
6. Have the cost and schedule estimates been updated? Do they reasonably reflect the cost, schedule, and resource efforts required to complete the project?
7. Given the current stage of the project, is the project's management structure and team appropriate, and are the plans to support the next phase of the project sufficient?
8. Is the project proceeding along a plan to be CD-3 ready by this summer? Has the required documentation been identified and currently being prepared as required by DOE 413.3B?
9. Outage planning and coordination - Has a construction plan been developed that adequately ensures the proper sequencing of field tasks? Have key positions and responsibilities been defined? Has worker coordination been addressed (i.e. daily job briefings, hazards analysis, procedures etc.)?

4.3 Review Participants

FDR Committee:

Joe Minervini (MIT), Chair
Tim Scoville (GA)
Gary Voss (UKAEA)
Kevin Freudenberg (ORNL)
Les Price (Consultant)
Bob Parsells (Consultant)

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4.4 Review Agenda

NSTX Upgrade Project			
Final Design and CD-3 Readiness Review			
June 22 - 24 th 2011			
AGENDA			
Wednesday June 22, 2011			
Room B318			
Morning			
	Time	Title	Speaker
	8:00 AM	EXECUTIVE SESSION	
	8:30 AM	Welcoming Remarks / Introductions	Mike Williams
	8:35 AM	Project Overview	Ron Strykowski
	8:50 AM	Center Stack Upgrade Overview (Chits, design deliverable status,risk retired)	Larry Dudek
	9:20 AM	Neutral Beam Overview (Chits, design deliverable status,risk retired)	Tim Stevenson
	9:50 AM	BREAK	
	10:05 AM	Center Stack Analysis Summary	Peter Titus
	11:05 AM	TF, OH , Inner PF Coils and flex joint design	Jim Chrzanowski
	11:50 AM	LUNCH	
	12:50 PM	CS manufacturing plan	Jim Chrzanowski
	1:35 PM	Vacuum Vessel, Support Structures, and coil bus runs	Mark Smith
	2:00 PM	CS Plasma Facing Components	Kelsey Tresemer
	2:20 PM	Center Stack Upgrade Power and Controls	Raki Ramakrishnan
	2:55 PM	Coil Protection System	Ron Hatcher
	3:20 PM	BREAK	
	3:35 PM	MPTS Vacuum Vessel Interface	George Labik
	3:55 PM	Central I&C	Paul Sichta
	4:15 PM	Diagnostics	Bob Kaita
	4:30 PM	Ancillary Systems (Water, Gas, Bakeout)	Larry Dudek
	4:50 PM	EXECUTIVE SESSION	Review Team
	5:50 PM	Project Debrief / questions, request for data / additional materials	
	6:20 PM	Dinner	
Thursday June 23, 2011			
Room 318			
Morning			
	8:30 AM	Beamline TVPS	Bill Blanchard
	8:45 AM	Beamline Relocation ,services, Duct , and Vacuum Vessel Modifications	Martin Denault
	9:30 AM	Beamline Armor	Kelsey Tresemer
	9:50 AM	Machine Installations & Outage Coordination	Erik Perry
	10:35 AM	BREAK	
	10:50 AM	Integrated Systems Testing	Charlie Gentile
	11:00 AM	Health & Safety	Jerry Levine
	11:10 AM	Cost and Schedule & CD-3 Readiness (EAC, schedule, risks, CD-3 doc,EVMS)	Ron Strykowski
	11:30 AM	LUNCH	
Afternoon			
	Director's Conference Room		
	1:00 - 4:00	Management, Construction, and ES&H breakout session	Les Price, Bob Parsells
	Room 318		
	1:00 - 4:00	Neutral Beam & Center stack technical break-out session	Tim Sooville, Garry Voss, Kevin Freudenberg , Joe Minervini
	4:00	EXECUTIVE SESSION	Review Team
	5:00	Project Debrief / questions, request for data / additional materials	
Friday June 24, 2011			
Room 318			
	8:30 - 11:00	Executive session and report preparation (incl working lunch)	Review Team
	11:00 AM	CLOSEOUT MEETING	
	12:00 PM	Adjourn	