Conceptual Design Review (CDR) Committee Report

for the

National Spherical Torus Experiment (NSTX)

Upgrade Project

Princeton Plasma Physics Laboratory
Princeton, NJ

October 28-29, 2009

Table of Contents

1. Introduction **2**

2. Summary of Response to the Charge **3**

3. Technical Systems Evaluations **4**

3.1. Center Stack Upgrade *4*

Findings 4

Comments 5

Recommendations 6

3.2. Second Neutral Beam *7*

Findings 7

Comments 8

Recommendations 9

4. Cost and Schedule **9**

4.1. Findings *9*

4.2. Comments *10*

4.3. Recommendations *10*

4.4. Findings for CD-1 Requirements *11*

5. Appendices **12**

5.1. Charge Letter *13*

5.2. CDR Charge *14*

5.3. Review Participants *15*

5.4. Review Agenda *16*

1. Introduction

A Conceptual Design Review was held at the Princeton Plasma Physics Laboratory (PPPL) for the NSTX Upgrade Project on October 28-29, 2009 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 ESH status in preparation for the CD-1 milestone review to be held in December 2009. The committee was asked to review the NSTX center stack upgrade and the addition of a second neutral beam for plasma heating to assess whether; the general requirements have been addressed; the risks have been appropriately identified and adequately addressed by the project plans; there are any "show stoppers"; the ES&H issues have been properly addressed; the cost range is adequate and the proposed schedule realistic for this stage of the project; the project organization and staffing appropriate; and if the project is ready for CD-1.

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 l.0 T, and l.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 upgrade task including, TF, OH, PF coils, and structure modifications; the task for the addition of the second neutral beam; ES&H issues; project cost and schedule, and; readiness for CD-1. All presentations were very comprehensive in content, well organized, and professional in presentation, which allowed the committee to understand the complexity of the upgrade project and the supporting programmatic and administrative requirements. The presentations were supported by extensive project documentation provided to the committee including Work Approval Forms (WAFS), costs, and project schedule broken down by WBS, etc.

The committee was very impressed with the level of effort and comprehensiveness of the design effort to date, and commends the project management and team for their dedication to making this project a success. The committee appreciates 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 committee report are given in the following sections.

1. *Have the requirements for the NSTX Upgrade Project, delineated in the General Requirements Documents, been addressed?*

   Yes, GRDs have been generated for both the Center Stack and the Second Neutral Beam. The design and analysis to date address the requirements at an appropriate level for this stage of conceptual design.

2. *Does the Conceptual 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"?*

   Yes, successful technical reviews have been completed to this stage;
   bottoms-up cost and schedule details have been generated for all jobs

3. *Have risks been appropriately identified? Are project plans adequate to address/retire the identified risks? Are there any "show stoppers?" Are ES&H issues properly addressed?*

   Yes, the risks identified at CD-0 and forward are being appropriately addressed. The Risk Registry is established and is in constant update as new risks are identified with mitigation plans being developed (to be completed before CD-1 Review). There are no apparent "show stoppers" at this stage; ES&H is being appropriately addressed in designs and the Preliminary Hazard Analysis is based on current plans using the hazard analysis summary in the NSTX Safety Assessment Document.

4. *Is the proposed cost range adequate (for CD-1)? Is the proposed schedule realistic (for CD-1)?*

   Yes, a well detailed ~1500 WBS element project schedule has been developed and resource loaded. WAFs have been generated and provide the basis for all cost and schedule estimates. The resource loaded project schedule is realistic for this project stage at CD-1.

5. *Is the project organization/staffing appropriate?*

   Yes, laboratory management have established an appropriate project organization and applied sufficient design/analysis staffing for the conceptual design phase. Future staffing requirements needed for the next phase of the project have been generated as part of the project plan. Staff have been identified and project management have determined that these resources are available as required.

6. *Is the project ready for CD-1 per DOE Order 413.3A?*

Yes, the project is ready for CD-1 as described next, assuming the recommendations in Section 4.3 and the CD-1 requirements in Section 4.4 are completed before the December 2009 Lehman Review.

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 Cost and Schedule.

3.1. Center Stack Upgrade

Findings

A comprehensive amount of detailed design and technical analysis was presented for a CDR level review. The project has chosen a very conservative design philosophy based on designing the coils and structure to handle maximum output from power supplies. If the conservative design cost becomes to expensive, the fallback position will be to design to the required operational levels and loads, which will be agreed upon doing preliminary design.

The Center Stack upgrade scope includes the following items:

- Inner TF bundle (centerstack)
- TF Flex bus
- OH coil
- Inner PF coils
- Enhance outer TF supports
- Enhance PF supports
- Reinforce umbrella structure
- New umbrella lids

The project team plans to fabricate the new TF inner leg bundle in-house and then wind the OH coil directly on top of the TF legs. Estimates are based on the actual costs of designing, fabricating and installing the current center stack. These are considered to be conservative allowing opportunities for further cost reduction.

The new TF coil flexible joint appears to be greatly improved from the previous version, although it was unclear what load cases and fault conditions the machine was being designed for. Potential problem areas/ risks have been identified for the design, manufacture, and assembly and are being addressed. Issues for the design life remain to be addressed for the legacy components, i.e. TF outer legs and PF coils.

Since CD-0, 10 risks have been addressed and retired and about 50 new ones have been added to the Risk Register.

The critical path runs through the copper for the inner TF legs and OH conductor, including long lead procurement time, machining, and stir welding of the joint. The project will request an early procurement of the copper

Comments

There appear to be no show-stoppers in the chits. In-line braze joints in 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 joint is needed.

Stress in the epoxy insulation of ~22MPa appears too high for this material at 100°C for routine operation. Few, if any, fusion magnets have ever been proposed using VPI epoxy resin operating at 100°C.

Friction stir welding seems a good solution for joining the flags to the wedges and it is good to see new manufacturing techniques being developed and applied.

Much effort appears to have been directed at the TF joint design but it is important not to lose sight of the other critical areas of the machine. The tradeoff appears to be the captured OH coil on the TF center-stack. This can create problems if severe thermal stresses on the OH coil if TF-only shots are performed with TF inner leg temperatures reaching 100C while the OH coil is cold. Running TF only shots needs to be assessed on the OH. Perhaps a trade off study between radial build and optimal performance is warranted.

The fault load cases that have been analyzed for stresses are overly conservative when compared to the design basis. Some structures are designed to the Monte Carlo/excel solver routines (which result in much higher electromagnetic loading) while others are designed according to the 96 specified plasma scenario load cases. A clear design basis is required for design operations and fault conditions. The interface between machine protection system and design needs to be clearly defined.

Another issues is the how to handle the existing cycle count on legacy hardware i.e., how much fatigue life has been used in the outer TF legs and PF coils? Also, a fault occurred at one point in the life due to the TF leads that needs to be accounted for in the current cycle count.

Performance (in general) appears to have been favored over technical functionality.
The support structures for the PF coils and TF outer legs need continued evolution in the design process. In particular, the lower TF supports and the interfaces between the TF and PF need attention. The present structural support system seems to have grown spatially and while being constrained by the legacy components, e.g. TF outer legs and supports, PF coils and supports, vacuum vessel, etc. This makes adding new support structure for the significantly higher loads (~3.5 times greater) non-ideal, unsymmetrical, and likely requires complex 3-D FEA.

Heat loads in the divertor area develop temperatures that may require an engineered cooling solution. Upgrade of the divertor to accept higher heat loads is not included in this upgrade project. If it is found necessary, it will have to done in the physics operational phase.

The machine cannot meet the design criteria under static-only loading cases. Dynamic impulse analysis is being used to meet the design criteria for the structure. Thus, it is very important that this dynamic analysis be performed correctly by properly specifying the input load durations and time dependencies.

Error fields from the eddy current loop created by vacuum vessel patch for the new NB port have not been performed yet, although the project team believes these will not significantly affect the plasma.

High pressure in small cooling channels seems excessive. The inlet pressure of 550 psi in the cooling channels may present as a personnel hazard.

Recommendations

Slip plane
Consider improving the design of the slip plane to give sufficient strain isolation between the solenoid and centre rod to allow TF only operation. Consider using removable axial strips, as demonstrated on Alcator C-mod and MAST, to give a small radial gap. This may mean adding a few mm to this slip plane at the expense of reduced I^2t in the solenoid.

Solenoid conductor braze joints
It may be possible to eliminate the need for these in-line braze joints by forming the conductor using a continuous extrusion process called CONFORM. This process has been developed by Luvata in Finland for copper and allows very long lengths of high conductivity copper to be produced. However, the silver content in the copper may be limited to very small amounts which may lead to larger volumes of annealed copper at the interlayer braze joints.

If the in-line joints cannot be eliminated then careful NDT of each joint is needed i.e. X-ray of the braze joint in two directions. If in-line ferrules are used in these joints they may give rise to stress concentrations that can limit the fatigue life so fatigue tests of the joints should be considered.

Manufacture of centre rod wedge conductors
Consider asking Kabelmetal at Osnabruck, Germany, to quote for the extrusion of the wedges. They have previously made the wedges for MAST centre rod, which included the cooling channel inside the wedge, which reduces machining and soldering. Consider not machining the main side faces of the wedges to avoid the possible deformation due to residual stresses.

Centre stack and solenoid insulation
Operation of the insulation at 100°C and at a shear stress of 22MPa appears to be too high for routine operation. Various alternatives/changes should be considered including:

- Use of B-stage insulation for the centre stack, which should offer higher temperature operation.
- Alternative primers for the copper conductors that offer higher operating temperatures than the conventional DZ80 primer.
- If VPI epoxy is used, consider increasing the curing temperature or add a post cure cycle to increase the glass transition temperature. However, this may also reduce the fracture toughness of the material.
- Consider reducing the maximum operating temperatures of the copper conductors.

Need to bring together what little test data exists for epoxy at 100°C and then determine what further static and fatigue tests, especially for shear strength, need to be carried out to qualify this material at the required temperature, stress levels and number of cycles. Tests on alternative primers and cure cycles may also be needed.

Reconsider radial build of the center stack to allow a more effective slip plane between the components even if there is some loss of i^2t capability on the solenoid.

Structural Design

Develop criteria for allowable load conditions that require protection by the MPS, as soon as possible, to be used for preliminary design. Write a design specification to collect and identify all design critical components that exceeded allowables that would guide the MPS design.

Establish, document, and carryout a supporting R&D program for all components and processes as required.

3.2. Second Neutral Beam

Findings

The second neutral beam scope includes:
- Disassemble and evaluate a TFTR beamline
- Decontaminate
- Refurbish for reuse
- Relocate pump duct, 22 racks and numerous diagnostics to make room in the NSTX Test Cell
- Install new port on vacuum vessel to accommodate NB2
- Move NB2 to the NSTX Test Cell
- Run services (power, water, cryo and controls)

Estimates are based on the actual costs of designing, refurbishing, and installing NSTX Neutral Beam #1. The beamline decontamination estimates are based on actual experience with TFTR neutral beams. The project believes these estimates to be conservative. They include costs for making new parts that might be able to be decontaminated for reuse. Whenever decontamination succeeds this results in opportunities for reducing costs.

Some of the risks identified at CD-0 have been retired.

The plan for re-using an old contaminated beamline seems to be appropriate, although the decontamination is a necessary, time-consuming part of the task. The human effort is significant and the safety aspects are crucial.

The beamline armor appears to take quite a lot of power. The visual evidence of the beam footprint was very illuminating. Perhaps some real-time monitoring of the power is advisable.

The proposed NB port modification of the vacuum vessel creates a new worst case for wall stabilization, error fields, weld stresses, etc.

Comments

The operation and maintenance of the new beamline must be handled differently than the first, due to the lingering tritium contamination. Care must be taken to strictly enforce different procedures, especially with respect to personnel working on or near the beamlines.

The general requirements mentioned that the radiological impact on NSTX operation was not significantly impacted by the upgrade. However, the plasma current, toroidal field, injected power, and pulse length are all much bigger. There definitely IS a radiological impact.

How is the decommissioning of the contaminated beamline determined to be complete? How is success measured there? How will long-term beamline surface contamination or cooling down be measured?

The committee feels a more modest modification should be considered instead of the proposed large cutout of the vacuum vessel for the new beamline. The committee is concerned that the vacuum vessel (and beamline) support systems may not be able to react the load sufficiently for the new beamline on the same side of the vessel caused by the asymmetry of the pressure.

It was not made clear whether the beamline internal copper components (collimators) will be replaced or if they will be decontaminated, refurbished, and re-used. The project should consider the difference in the effort and cost for each option.

Bellows (especially large ones) are risks. Are all the bellows associated with the transition duct necessary for the second beamline? The present design includes two large ones and two smaller ones for the vacuum lines. Also, the support system for the transition duct was not shown in the presentation. The bellows and ceramic breaks cannot take the weight, so extra supports are required. It was reported that the extra supports are included, but they were not presented at the review.

Recommendations

Perform eddy current/error field analysis on the new very large vessel cutout port box assembly.

Consider replacing data acquisition and I&C CAMAC systems with a more modern and reliable solution.

Incorporate better interlocks (Ip and density) and monitoring (real-time pyrometers) of the beam armor tiles.

Install and maintain strict procedures for radiological control for contaminated beamline maintenance.

Installation procedure recommendations for the large beam port:

- Increase port width as needed
- Remove diagnostic port
- Reinforce vessel wall with insert welded into the diagnostic port hole
- Replace curved plate leak check fixture into vessel for use in checking port welds
- Position and weld NB port box
- Leak check port box welds
- Consider option to install smaller or relocated diagnostic port
- Cut the leak check plate if required for removal

4. Cost and Schedule

4.1. Findings

Cost Estimates

A project plan with ~1500 WBS elements has been developed and resource loaded. Excellent process has been put in place for estimating costs and a bottoms-up cost estimate has been performed for all scope. Lead engineers have developed Work Authorization Forms (WAFs) for their task areas. A top-down review of each WAF was performed by the AD and the Department Heads. The Levels of WAF completion and consistency, however, are uneven (*e.g.,* quantifying bases of estimates, risk likelihood and impacts), and will be further developed.

The cost estimate is in the range $71M-$95M with project completion in 2014 for the baseline case.

Schedule
Bottoms-up staffing estimates have been loaded to the Project schedule.
A detailed near-term staffing plan has been developed through CD-1.

Risk Management
Excellent process, guidelines, and risk registry are established.
Some documentation of plan is given in the WAF and in the PPEP.
Few “opportunities” to reduce cost are listed in risk registry.
Risk registry largely is incomplete.
The contingency estimate is based on risk and uncertainty roll up.

DOE relationship and communication appears to be very good
The local Site Office is satisfied with the Project performance at this stage.

4.2. Comments

It is essential that all Job Managers “own” their Project assignments, as evidenced by preparation of a complete WAF, and intimate knowledge of resource-loaded schedules and milestones. Incomplete risk and opportunity assessments limit contingency justification and distribution estimates. NCSX Lessons Learned appear to have been appropriately applied. This needs to be continued, *e.g.,* developing a detailed near-term staffing plan that will meet the CD-2 milestone on time in June 2010. Deployed staffing levels are appropriate, and need to be continued

4.3. Recommendations

The following recommendations should be completed before the December 2009 Lehman Review.

1) Complete all elements of all WAFs, maintaining a common, crisp format.
2) Complete all fields in the risk registry.
3) Document the risk management plan (a CD-1 requirement) in the PPEP
4) Establish and implement a staffing plan to CD-2 that accounts for monthly assignments of specific tasks, self-consistent with the resource-loaded schedule.
5) Continue to implement PU Advisory Board recommendations to refine and improve the rigor of the risk/contingency development in advance of CD-2. Also, consider using risk matrix deadline dates to inform contingency distribution plan before Lehman CD-1 review and, continue to develop more “opportunities.”

4.4. Findings for CD-1 Requirements

- Conceptual Design Report not drafted yet; plan to start and complete by Nov 17.
- Acquisition Strategy: Major procurements identified and scheduled; DOE approval (CD-2a and 3a?) expected at CD-1.
- Preliminary Project Execution Plan draft prepared; risk management plan is at very high level, and does not describe methodology used.
- Integrated Project Team (IPT) formed and Federal Project Director named. IPT meeting regularly.
- NEPA: Categorical Exclusion requested and granted by DOE.
- Preliminary Hazard Analysis Report generated and submitted to DOE for approval.
- Preliminary Security Vulnerability Assessment Report: Not examined at this review.
- Initial Cyber Security Plan: Not examined at this review.
- QA Program: Not examined at this review.

5. Appendices

5.1. Charge Letter

PRINCETON UNIVERSITY

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

July 31, 2009

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 (PPPL) is planning a Conceptual Design Review for the NSTX Upgrade Project on October 28-29, 2009. We would be honored and grateful if you could agree to serve as the Chairman of the Review Committee. To help you with the administrative aspects of this responsibility, I intend to appoint Mr. Al von Halle of PPPL as Vice-Chair.

The NSTX Upgrade Project intends to replace the NSTX "center stack" in order to effectively double the magnetic field and plasma current (from 0.5T to 1.0T 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. Additional pertinent information will be provided prior to the review.

If you have any questions, please contact me (at 609-243-2866 or williams@pppl.gov) or Erik Perry (at 609-243-3016 or eperry@pppl.gov). Please let me know of your intentions by August 14, 2009.

Sincerely,

Michael D. Williams
Associate Laboratory Director
Engineering and Infrastructure

cc: A. Cohen
E. Perry
S. Prager
S. Smith (PU)

5.2. CDR Charge

1. Have the requirements for the NSTX Upgrade Project, delineated in the General Requirements Documents (attached), been addressed?
2. Does the Conceptual 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)?
3. Have risks been appropriately identified? Are project plans adequate to address/retire the identified risks? Are there any "show stoppers?" Are ES&H issues properly addressed?
4. Is the proposed cost range adequate (for CD-1)? Is the proposed schedule realistic (for CD-1)?
5. Is the project organization/staffing appropriate?
6. Is the project ready for CD-1 per DOE Order 413.3A? Is the required documentation for this phase in order?

5.3. Review Participants

CDR Committee:

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5.4. Review Agenda

NSTX Upgrade Project
Conceptual Design Review
October 28-29, 2009
Agenda

<u>Wednesday October 28th</u>

0800	Executive Session	
0830	Welcoming remarks and introductions	
0845	Project Overview	Perry
0900	Motivation for upgrade and selection of design point	Menard
0920	Overview of centerstack upgrade	Dudek
0940	Analysis summary	Titus
1025	Break	
1045	TF, OH and inner PF coils	Chrzanowski
1130	TF Flex joint and TF bundle stub	Willard
1150	Outer TF/PF structure	Dudek
1210	Power and controls	Ramakrishnan
1230	Lunch	
1330	Neutral Beam overview and status of decontamination Stevenson	
1410	Beamline relocation and services	Denault
1430	Beamline duct and vacuum vessel modifications	Priniski
1500	In-vessel armor	Tresemer
1515	Beamline power and controls	Stevenson
1600	Executive session	

<u>Thursday October 29th</u>

0800	Executive session	
0830	Cost and Schedule	Strykowsky
0900	CD-1 Readiness	Perry
0930	Tour of NSTX	
1030	Additional presentations as requested by reviewers	
1130	Preparation of closeout presentation by reviewers	
1500	Closeout meeting	