DRAFT of 3/25/08 (p.m.)

National Compact Stellarator Experiment

Baseline Change Proposal

March 26, 2008

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1. Introduction

The National Compact Stellarator Experiment (NCSX, see Fig. 1) is an experimental research facility under construction at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL). The compact stellarator is one of several plasma confinement concepts being investigated by the Office of Fusion Energy Sciences (OFES). The mission of NCSX is to acquire the physics knowledge needed to evaluate the compact stellarator as a fusion concept, and to advance the understanding of 3D plasma physics for fusion and basic science. The project is led by PPPL, in partnership with the Oak Ridge National Laboratory (ORNL).

The NCSX mission need (CD-0) was approved in May, 2001. The performance baseline range (CD-1) was approved in November, 2002, and the project started on April 1, 2003. The initial performance baseline (CD-2) was approved in February, 2004 with a TEC of $86.3M and a completion date of May, 2008. Start of fabrication (CD-3) was approved in September, 2004, and contracts for the modular coil winding forms and vacuum vessel were then placed. The

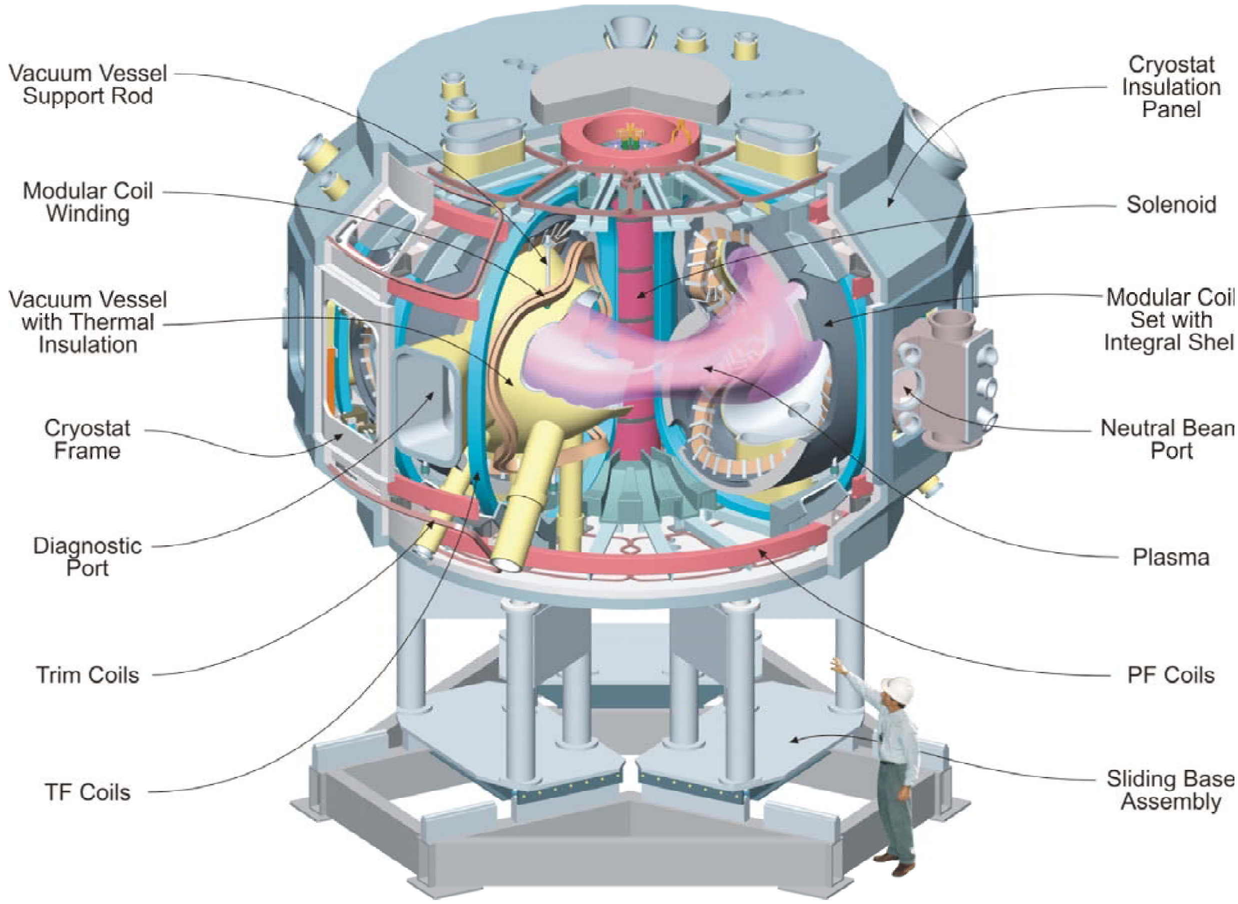


Figure 1. NCSX stellarator device

Figure 2. Vacuum Vessel

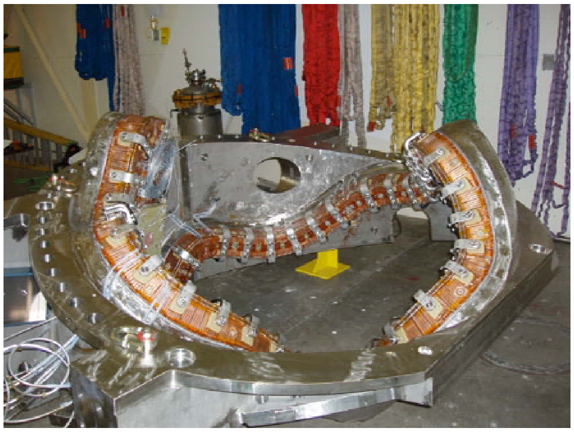


Figure 3. Modular Coil

current performance baseline, with a TEC of $92.4M and a completion date of July, 2009, was approved in July, 2005 following a directed change to accommodate a stretchout of the funding profile. However, by 2007 it became clear that the baseline cost and schedule objectives could not be met. In early 2008, following reviews of the project's scientific mission, engineering feasibility, and cost and schedule, the Department directed the project to submit this baseline change proposal.

The NCSX is technically challenging because of its complex geometry and the extreme accuracy required in the realization of its magnetic configuration. In order to control field errors, demanding requirements for accurate construction (e.g., ±1.5 mm tolerance on the coil current center position), low magnetic permeability materials, and field error compensation coils must be satisfied. The vacuum vessel (Fig. 2) and sixteen (to date) of the eighteen modular coils (Fig. 2) have been fabricated using state-of-the-art computer-aided design and manufacturing technologies, and have met project requirements. The toroidal field coils are under construction in industry, and nine of eighteen have been delivered. Procurement of the poloidal field coils has been initiated. Field period assembly has begun.

The design of the "inner core" of the stellarator was recently completed. This is the most technically challenging part of the system and includes the vacuum vessel, vacuum vessel services, modular coils, modular coil interface hardware, assembly tooling, and assembly sequence plan. Completion of this part of the design eliminates a major source of uncertainty from the remaining work. Outside the modular coil shell the design is in varying stages of maturity, with some systems already in procurement (e.g. the TF and PF coils) while others (e.g., the cryostat and several ancillary systems) are at a conceptual level. Although the incompleteness of the design is a source of estimate uncertainty and risk, these systems are more conventional than the inner core, so their risks are more accurately evaluated. A summary assessment of the design maturity and attendant risks is provided in Appendix D, Design Status Summary.

With the benefit of five years' experience in addressing the technical challenges of NCSX, the project has now performed a thorough, bottom-up re-estimate of the cost and schedule to complete the project. Cost and schedule contingency requirements have been quantified based on a project-wide risk assessment and a probabilistic analysis of the uncertainties and risks. New baseline cost and schedule objectives are proposed here based on these analyses. The CD-4 performance objectives and overall machine capabilities are consistent with the 2005 baseline. Value improvements have resulted in changes which affect design details without impacting the physics capabilities of the machine.

The root cause of the deviation from the DOE approved baseline is that the earlier estimates did not reflect adequate understanding of the complexity and tight tolerances necessary to meet the requirements of NCSX. In retrospect, the design maturity and manufacturing development status at the time the project was baselined did not provide an adequate basis for estimating the cost and schedule or for quantifying the risks in this technically challenging project. Now, the project team has gained experience with the fabrication of the modular coils and the process development for field period assembly. Completion of the two largest and riskiest procurements, the modular coil winding forms and the vacuum vessel, and of the design of the stellarator "inner core," has retired some significant risks. The gains in understanding provide a much better basis of estimate and risk assessment. Improvements in estimating methodology, risk evaluation, and risk-based contingency analysis also contribute to putting the new estimates on a sound basis. In addition, management corrective actions have been implemented based on a detailed lessons-learned analysis of problems on NCSX to date; these are discussed in Section 6 of this BCP.

2. Summary of Cost, Schedule and Funding Changes

The new baseline parameters and management plans are documented in the Project Execution Plan, included as Appendix A of this BCP. The changes from the current baseline (approved in 2005) are summarized hered.

Item	Current Baseline	Proposed Baseline	Comment
Cost ($M)			
Cost through Jan. 31, 2008	76.4	76.4	
ETC from Feb. 1, 2008 (w/o contingency)	16.0	61.8	
EAC (w/o contingency)	92.4	138.2	
Contingency free balance at Feb. 1, 2008	–	22.4	36% of ETC
Total Estimated Cost (TEC)	**92.4**	**160.6**	**$68.2M increase**
Pre-CD1 planning & conceptual design	9.6	9.6	
Total Project Cost (TPC)	**102.0**	**170.2**	
Schedule			
ETC from Feb. 1, 2008 (w/o contingency)	18	48	
Early Finish	Jul. 2009	Jan. 2012	
Contingency (months)	–	19	40% of ETC
Project Completion (CD-4)	**Jul. 2009**	**Aug. 2013**	**49 months delay**
Funding Profile ($M)			
2003	7.9	7.9	
2004	15.9	15.9	
2005	17.5	17.5	
2006	17.0	17.0	
2007	15.9	15.9	
2008	15.9	15.9	
2009	2.3	19.6	Cong. budget
2010		20.1	OFES guidance
2011		22.1	
2012		8.7	
2013		–	
Total	**92.4**	**160.6**	

3. New Estimate to Complete

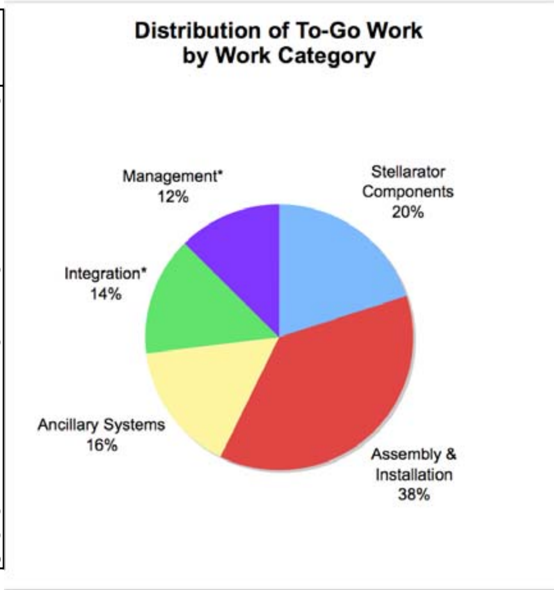
This proposal is based on a new estimate to complete (ETC) all of the remaining project work from February 1, 2008. It also includes a new estimate of the contingencies needed to manage the risks and uncertainties in that work. The results are summarized by WBS in the table below.

Cost in $k	Actual 4/1/03 thru 1/31/08	Estimate to Complete from 2/1/08	EAC	per cent to-go
1 Stellarator Core	**60,647**	**29,023**	**89,670**	32%
12. Vacuum vessel	9,743	1,429	11,172	13%
13. Conventional Coils	3,832	4,256	8,088	53%
14. Modular Coils	38,168	2,563	40,731	6%
15. Coil Structures	545	1,528	2,073	74%
16. Coil Services	3	1,085	1,087	100%
17. Cryostat & Base Structure	489	1,497	1,986	75%
18. Field Period Assembly	5,550	14,412	19,962	72%
19. Stellarator Core Mgt. & Int.	2,317	2,255	4,572	49%
2 Auxiliary Systems	**348**	**1,018**	**1,365**	75%
3 Diagnostics	**1,130**	**811**	**1,941**	42%
4 Electrical Power Systems	**615**	**2,719**	**3,333**	82%
5 Central I&C/Data Aq.	**33**	**2,099**	**2,132**	98%
6 Facility Systems	**24**	**2,423**	**2,447**	99%
7 Test Cell Prep & Machine Assy.	**708**	**8,577**	**9,285**	92%
8 Project Mgt. & Integration	**12,784**	**15,145**	**27,930**	54%
81. Project management	4,029	4,814	8,843	54%
82. Engineering Mgt. & Integration	6,497	7,608	14,105	54%
84. Project Physics	470	-	470	0%
85. Integrated System Testing	-	795	795	100%
89. Allocations	1,788	1,928	3,716	52%
Total Work	**76,289**	**61,815**	**138,104**	**45%**
DCMA	75	-	*75*	0%
	-	-		
Contingency	**-**	**22,410**	**22,410**	
Total	**76,364**	**84,225**	**160,589**	
Schedule in Months				
Total Work	**58**	**48**	**106**	**45%**
(Early Finish)			**Jan-2012**	
Contingency		**19**	**19**	
Total	**58**	**67**	**125**	
CD-4			**Aug-2013**	

In the following table and chart show, the remaining work is divided into five categories: Stellarator Components, Assembly and Installation, Ancillary Systems, Integration, and Management.

Cost in $k	Estimate to Complete from 2/1/08	per cent of to-go work
Stellarator Components	**12,357**	**20%**
12 Vacuum Vessel	1,429	2%
13 Conventional Coils	4,256	7%
14 Modular Coils	2,563	4%
15 Coil Structures	1,528	2%
16 Coil Services	1,085	2%
17 Cryostat & Base Structure	1,497	2%
Assembly & Installation	**22,988**	**37%**
18 Field Period Assembly	14,412	23%
7 Test Cell Prep & Machine Assy.	8,577	14%
Ancillary Systems	**9,864**	**16%**
2 Fueling & Pumping	1,018	2%
3 Diagnostics	811	1%
4 Electrical Power Systems	2,719	4%
5 Central I&C/Data Aq.	2,099	3%
6 Facility Systems	2,423	4%
85 Integrated System Testing	795	1%
Integration*	**8,892**	**14%**
Management*	**7,713**	**12%**
Total Work	**61,815**	**100%**

***in WBS 19, 81, 82, 89**



As can be seen, more than one-third of the remaining work (37%) is in completing the assembly of the device and installing systems. Completion of stellarator components and ancillary systems together comprises approximately another third or more of the work (36%). Integration (14%) embraces a range of functions that are necessarily addressed at the system level (as opposed to the subsystem or component level): system engineering, design integration, system analysis, dimensional control and metrology coordination, and risk management. These functions are critical for successful NCSX execution because of the technical challenges of the system itself: complex, tightly-integrated sub-systems; tight assembly tolerances; cutting-edge technology. As discussed in Section 5, the Integration functions have been strengthened, with attendant increases in cost, as part of this proposal. Management (12%) includes the project manger, deputy project manager, engineering managers, project control staff, and PPPL allocations. These functions have also been strengthened.

a. Work Estimating Process

All remaining work was analyzed at the job level (Level 4), i.e. from the bottom-up. Job managers (equivalent to cost account managers) further sub-divided their work into activities (at least 10 and as many as several hundred) and estimated required labor resource hours, materials and services (M&S) dollars, and durations for each activity. Labor resource needs were identified by skill in order to ensure that the proper rates were applied and, as far as possible, by the assigned individuals' names. Estimates included realistic allowance for technical problems that would normally be encountered in the work, in the expectation that actual costs can turn out to be either greater or less than the estimate. Each activity estimate and its basis were documented in a job-level Work Authorization Form (WAF), which provides a standardized format for estimate data entry into the resource loaded schedule, facilitates review, and documents work authorization once approved. All estimates underwent internal reviews led by the PPPL Engineering Department, with project office staff and affected job managers participating in each review to ensure complete identification of all work and interfaces. In many cases, multiple iterations were performed to ensure that review findings were properly incorporated into the estimates. The work breakdown structure is provided as Appendix E of this proposal and the WAFs are provided as Appendix F.

The job estimates were then integrated into a resource-loaded schedule using Primavera software. In the integration step, the Laboratory-specified labor and overhead rates, as well as escalation rates, are applied. The work is scheduled based on the job manager's estimated task durations and logical linkages, subject to applicable funding constraints. Risk minimization is an important consideration in the scheduling process. For example, free float is provided to ensure that components are available when needed to support the critical path, and cost contingency is budgeted year-by-year to ensure that contingency will be available when needed to keep the project on schedule when cost risks are realized. The resource-loaded schedule is provided as Appendix G of this proposal and a summary of the critical path schedule is provided as Appendix H.

b. Contingency Estimating Process

Contingencies were quantified based on a bottom-up assessment of uncertainties and risks at the job level. A probabilistic analysis was used to estimate the cost and schedule contingencies required to successfully manage the uncertainties and risks in the remaining project work. The uncertainty assessments, risks, and contingency analysis were reviewed by project management and by external reviewers as part of the preparations for this proposal. The contingency estimating process is briefly summarized here, while further details are documented in the project's Contingency Analysis Report (Appendix K), Risk Management Plan (Appendix L), and Risk Registry (Appendix M).

Estimate uncertainties are a function of the complexity and maturity of a job. Job managers ranked their jobs on a high-medium-low scale for both parameters. The rankings are documented in the WAFs. An uncertainty range was assigned based on the rankings: from -5% / +10% to -30% / +60%.

Risks were identified at the job level and higher levels, and documented in a project-wide risk registry. The risk registry provides a management tool that the project uses to track risks and mitigation activities so as to actively minimize their consequences. For purposes of estimating contingency, the likelihood of each risk occurring and its cost and schedule impacts were estimated.

The probabilistic analysis uses Monte Carlo simulations of cost and schedule outcomes based on the job uncertainty ranges and risk likelihoods and impacts. The results are used to set cost and schedule contingencies that provide a high level of confidence (e.g. 90% confidence) in successfully completing the project..

4. New Level 1 and 2 Milestone Table

A new set of Level 2 milestones and one Level 1 milestone (CD-4) are proposed as the new schedule baseline. These are also included in the Project Execution Plan (Appendix) and constitute the DOE schedule baseline.

Milestone	Level	Date	√= complete
Complete Physics Validation Review	2	Mar. 01	√
Complete CD-0 Milestone	1	May 01	√
Select Conceptual Design Configuration	2	Dec. 01	√
Submit NEPA Preliminary Hazards Analyses	2	Apr. 02	√
Complete Conceptual Design Review	2	May 02	√
Receive FONSI	2	Oct. 02	√
Complete CD-1 Milestone	1	Nov. 02	√
Award Prototype Contracts for Modular Coil Winding Forms	2	Mar. 03	√
Award Prototype Contracts for Vacuum Vessel	2	Apr. 03	√
Start Preliminary Design (Title I)	2	Apr. 03	√
Complete Project Preliminary Design Review for Vacuum Vessel and Modular Coils	2	Oct. 03	√
Complete External Independent Review and DOE Performance Baseline Review	2	Nov. 03	√
Authorize Prototype Fabrication of MCC and Vacuum Vessel	2	Dec. 03	√
Complete CD-2 Milestones	1	Feb. 04	√
Initiate Modular Coils Winding Process on a 3D Surface	2	Mar. 04	√
Produce First Prototype Modular Coil Winding Form Casting for Machining	2	June 04	√

Milestone	Level	Date	√= complete
Complete Final Design Review for Modular Coils Winding Forms	2	Jul. 04	√
Complete Final Design Review for the Vacuum Vessel	2	Jul. 04	√
Complete Prerequisites for the CD-3 Milestone for Procurement and Fabrication of Components	2	Sep. 04	√
Award Conductor Contract	2	Dec. 04	√
Complete CD-3 Milestone	1	Sep. 04	√
Award Production Contract for Modular Coils Winding Forms	2	Oct. 04	√
Award Production Contract for Vacuum Vessel	2	Oct. 04	√
First Modular Coil Winding Form Delivered	2	Jul. 05	√
Begin fabrication activities for TF Coils	2	Jul. 05	√
Complete First Modular Coil Fabrication	2	Mar. 06	√
Vacuum Vessel Sectors Delivered	2	Sep. 06	√
Last Modular Coil Winding Form Delivered	2	Sep. 07	√
Begin Assembly of First Field Period	2	Jul. 07	√
MC Interface Overall FDR (excl C-C)	2	Nov. 07	√
TF Coils (4) for FPA #1 assy delivered	2	Aug. 08	√
Shims required for 1st MCHP Assy. (Sta. 2) available	2	Feb. 08	√
Complete PF Coil PDR	2	Dec. 07	√
Complete Trim Coil PDR	2		Mar. 08
Complete Trim Coil (including structure) FDR	2		Jun. 08
Complete Base Support Structure FDR	2		Jul. 08
Award PF Coil fabrication contract	2		Aug. 08
Award Trim Coil fabrication contract	2		Sep. 08
Complete VPI of 18th (last) modular coil	2		Nov. 08
Complete Electrical Power systems PDR	2		Dec. 08
Last TF coil delivered	2		Jan. 09
Award Coil Support Structure fabrication contract	2		Feb. 09
Complete Station 6 specification & assy drawing	2		Mar. 09
Complete first modular coil half-period assembly (Sta 2)	2		May 09
Trim Coils for FPA #1 assembly delivered	2		Jun. 09
Complete Cryostat CDR	2		Jul. 09

Milestone	**Level**	**Date**	**√= complete**
Complete third modular coil half-period assembly (Sta 2)	2		Oct. 09
Coil Structure components delivered	2		Oct. 09
PF 5&6 Lower delivered	2		Dec. 09
Complete first modular coil-to-vacuum vessel assembly (Sta 3)	2		Jan. 10
Complete first Field Period assembly (Sta. 5)	2		May 10
Complete power systems FDR	2		Aug. 10
Complete 2nd modular coil-to-vacuum vessel assembly (Sta 3)	2		Sep. 10
Complete cryostat FDR	2		Oct. 10
Complete 3rd modular coil-to-vacuum vessel assembly (Sta 3)	2		Dec. 10
Complete base support structure assembly	2		Feb. 11
Complete second Field Period assembly (Sta. 5)	2		Mar. 11
FPA #3 installed on assembly sleds	2		Jun. 11
C-site DC Systems installed	2		Jun. 11
E-beam mapping apparatus ready for installation	2		Oct. 11
Move FPA's & spacers together for fitup check	2		Nov. 11
complete central safety & interlock systems pre-ops tests	2		Feb. 12
Vacuum vessel joint welding complete (3 FP's)	2		Jul. 12
Begin vacuum vessel pumpdown	2		Oct. 12
All PF Coils installed	2		Dec. 12
Begin cryostat installation	2		Feb. 13
PSO Operational Readiness Assessment	2		Apr. 13
Begin start-up testing	2		May 13
Complete cooldown of machine	2		May 13
NCSX Startup Complete / CD-4	1		Aug. 13

5. Reconciliation of New Cost Estimate with the 2005 Baseline

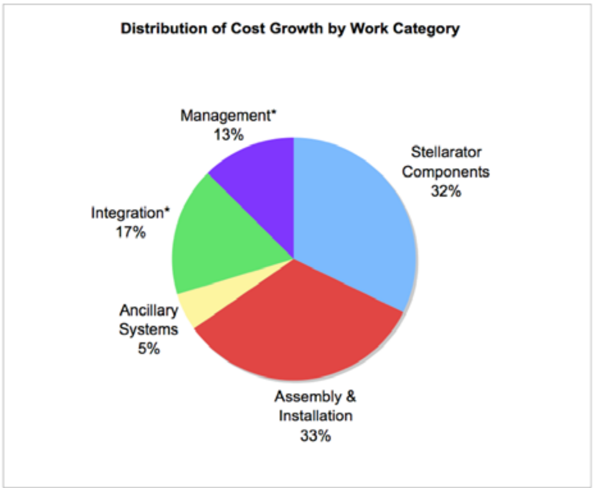
The new proposed baseline for the NCSX would supersede the current performance baseline (ECP-031), which was approved by the Deputy Secretary in July, 2005. The new EAC is compared, by WBS, with that of ECP-031 in the following table (costs in $k).

Cost in $k	EAC ECP-031 8/11/05	EAC New Baseline 3/26/08	EAC Change from ECP-031
1 Stellarator Core	**54,507**	**89,670**	**35,163**
12. Vacuum vessel	9,531	11,172	1,641
13. Conventional Coils	4,790	8,088	3,298
14. Modular Coils	28,092	40,731	12,639
15. Coil Structures	1,412	2,073	661
16. Coil Services	1,140	1,087	(53)
17. Cryostat & Base Structure	1,360	1,986	626
18. Field Period Assembly	5,430	19,962	14,532
19. Stellarator Core Mgt. & Int.	2,752	4,572	1,820
2 Auxiliary Systems	**784**	**1,365**	**581**
3 Diagnostics	**1,143**	**1,941**	**798**
4 Electrical Power Systems	**3,301**	**3,333**	**32**
5 Central I&C/Data Aq.	**2,050**	**2,132**	**82**
6 Facility Systems	**691**	**2,447**	**1,756**
7 Test Cell Prep & Machine Assy.	**4,412**	**9,285**	**4,873**
8 Project Mgt. & Integration	**12,704**	**27,930**	**15,226**
81. Project management	4,584	8,843	4,259
82. Engineering Mgt. & Integration	4,884	14,105	9,221
84. Project Physics	470	470	0
85. Integrated System Testing	1,189	795	(394)
89. Allocations	1,577	3,716	2,139
Total Work	**79,592**	**138,104**	**58,512**
DCMA	-	*75*	75
Contingency	**12,809**	**22,410**	**9,601**
Total	**92,401**	**160,589**	**68,188**

The changes are explained, by WBS, later in this section. As an introduction, the table and pie chart below provide a global perspective on the cost growth contributors by work category. Stellarator components account for about one-third of the growth. Most of the work in this category is complete and the largest risks are retired, so the cost growth is to a large extent already realized. Assembly and installation accounts for another third of the cost growth, but as most of this work is still to go, the growth largely reflects a re-estimate of future work based on better understanding gained through experience on the project since 2005. Ancillary systems accounts for a small fraction of the growth. As discussed in Section 3, integration and management are critical because of the technical challenges of NCSX, and have been strengthened as part of this proposal.

Cost in $k	EAC Change from ECP-031	per cent of to-go work
Stellarator Components	**18,811**	**32%**
12 Vacuum Vessel	1,641	3%
13 Conventional Coils	3,298	6%
14 Modular Coils	12,639	22%
15 Coil Structures	661	1%
16 Coil Services	(53)	0%
17 Cryostat & Base Structure	626	1%
Assembly & Installation	**19,405**	**33%**
18 Field Period Assembly	14,532	25%
7 Test Cell Prep & Machine Assy.	4,873	8%
Ancillary Systems	**2,855**	**5%**
2 Fueling & Pumping	581	1%
3 Diagnostics	798	1%
4 Electrical Power Systems	32	0%
5 Central I&C/Data Aq.	82	0%
6 Facility Systems	1,756	3%
85 Integrated System Testing	(394)	-1%
Integration*	**10,062**	**17%**
Management*	**7,378**	**13%**
Total Work	**58,512**	**100%**

***in WBS 19, 81, 82, 89**



To explain the causes for the growth in cost, several factors are considered:

- Design Maturity (DM): advances in design maturity and understanding leading to revised estimates for the to-go work.
- Process Maturity (PM): advances in fabrication and assembly process development and understanding, after the design has matured, leading to revised estimates for the to-go work.
- Procurement / Fabrication (PF): change in procurement or in-house fabrication costs after the basic process or approach has matured.
- Risk Mitigation (RM): additional work budgeted for the purpose of reducing risks.
- Stretchout (SO): Cost of an extended period of performance for management and engineering integration driven by schedule growth in critical path work packages.

The causes of cost growth since ECP-031 have been analyzed by WBS and attributed to one or more of the above factors.

12. Vacuum Vessel +$1,641K

- Heating and cooling system: re-designed from hard tubing to flexible tubing after the procurement solicitation resulted in no bids. (+$432k, PF)
- Port heater control system: added to avoid thermal stresses which could damage flange welds when the machine is cold. (+$642k, RM)
- Neutral beam transition ducts: added to provide permanent instead of temporary interface for vacuum pump duct. (+$567k, RM)

13. Conventional Coils +$3,298K

- TF coils: Firm fixed price contract was placed but price exceeded project estimates. Drivers were the wedge support casting and tolerance requirements on the dee-shaped coil (+$1,596k, PF)
- PF coils: Procurement estimate increased based on vendor quotes for coils and structures. A value improvement change to using existing NSTX coils instead of building new coils for the central solenoid, partially offset the increase. (+$478k, PF)
- Trim coils: The baseline trim coil set was expanded from 2 to 48 coils to provide increased field error compensation capability. The previous plan was to install additional trim coil as a future upgrade. The extended array is being included in the baseline to mitigate schedule risks associated with meeting tight assembly tolerances and performance risks associated with uncompensated magnetic islands. This decision was supported by both Science and Engineering reviews in 2007. (+$1,224k, RM)

14. Modular Coils +$12,639k

At the time of ECP-031, a contract was in place for the modular coil winding forms but the supplier's manufacturing process was then still being developed and deliveries had not yet started. The twisted racetrack R&D coil was being fabricated. Now, all design and R&D work has been completed, the MCWF contract is finished, coil production is nearly completed, and interface parts needed for the first half-period assembly have been procured.

- Design and R&D: Design and R&D costs for the modular coil winding pack assemblies and the modular coil interface hardware grew due to greater than expected complexity and difficult requirements. (+$3,212k, DM)
- Modular coil winding forms (MCWF): The fabrication contract took 8 months longer than planned. A contract price increase was negotiated to incentivize schedule performance and a more favorable delivery sequence. Supplier process development and the longer performance period resulted in increased Laboratory engineering costs for Title III design and vendor management. (+$1,562k, PM, PF)
- Modular Coil Fabrication: Fabrication costs grew based on experience from the twisted racetrack R&D coil and the first production coil. MC interface hardware estimates grew when the design matured and the requirements were found to be more complex than expected. (+$6,881k, DM, PM, PF)
- Cold Testing: Problems encountered in constructing and operating the test facility and testing two coils (the twisted racetrack and one production coil) were greater than expected. (+$984k, DM, PM)

15. Coil Structures +$661k

- The conceptual design was changed from castings to weldments to reduce cost and schedule risks based on problems experienced in the other work packages. The design was also impacted by design developments in interfacing systems which necessitated changes. (+$661k, DM)

16. Coil Services –$53k

- Estimates were adjusted based on updated analysis of remaining work. (–$53k, DM)

17. Cryostat and Base Support Structure +$626k

- <u>Cryostat</u>: estimated design and R&D costs have increased to address interfaces with other systems (+$745k, DM)
- <u>Base support structure</u>: concept was simplified by no longer having to support the moving together of the field periods during final assembly; that function is now provided by separate tooling in another work package. (-$119k, DM)

18. Field Period Assembly +$14,532k

- At the time of ECP-031, tooling design and area preparation were in early stages. Understanding of assembly requirements and costs has matured as the component designs and assembly processes (especially metrology) have matured, leading to substantial net cost growth. (+$14,532k, DM, PM)

19. Stellarator Core Management & Integration +$1,820k

- <u>Integration</u>: Estimates for stellarator core integration have increased to provide adequate engineering support of assembly operations by the ORNL stellarator design group, including risk mitigation activities. Tasks including CAD modeling, engineering analysis, and mockup studies, will be performed to resolve actual and potential assembly problems to keep them from impacting the schedule. (+$1,038k, RM, SO)
- <u>Management</u>: Estimates have increased to provide adequate ORNL engineering management for a longer period of performance due to project stretchout is also a factor in the cost growth (+$782k, SO)

2. Auxiliary Systems +$581k

- The fueling (+$250k) and vacuum pumping system (+$331k) estimates were adjusted based on updated analysis of remaining work. (+$581k, DM)

3. Diagnostics +$798k

- Fabrication of magnetic diagnostic loops has proven to be more difficult than expected due to requirements for insulation and component protection. First plasma imaging and electron-beam mapping costs have been reduced as a result of equipment loan and collaboration arrangements, providing a modest offset. (+$798k, PF)

4. Electrical Power Systems, +$32k

- Estimates were adjusted based on updated analysis of remaining work. (+$32k, DM)

5. Central I&C and Data Acquisition, +$82k

- Estimates were adjusted based on updated analysis of remaining work. (+$82k, DM)

6. Facility Systems, +$1,756k

- Cryogenic Systems: estimates have increased based on actual experience with the coil test facility. (+$1,105k, DM)
- Vacuum Vessel Bakeout System: A vacuum vessel bakeout system has been added to reduce the risks in meeting CD-4 requirements for 150 C bakeout and achieving adequate vacuum conditions for first plasma. (+$634k, RM)
- Other: (+$18k, DM)

7. Test Cell Prep & Machine Assembly, +$4,873k

- Understanding of final assembly requirements and costs has matured as the component designs and assembly processes (especially metrology) have matured. (+$4,873k, DM, PM)

81. Project Management, +$4,259k

- Integration: A project integration manager has been added to the Project Office staff to strengthen risk management, physics-engineering integration, and transition to operations. These areas are critical to improving project performance going forward. (+$1,603k, RM, SO)
- Management: A senior project manager from LANL has relocated to PPPL to lead the NCSX project. Also, estimates have increased to strengthen cost and schedule management (e.g., maintaining up-to-date ETCs, tracking lower-level schedules) by augmenting project control staff. The ORNL project office has been strengthened as well. The longer period of performance due to project stretchout is also a factor in the cost growth. (+$2,656k, RM, SO)

82. Engineering Management and Integration, +$9,221k

- Integration: (System Engineering, Design Integration, System Analysis, Metrology coordination, Plant Design) System engineering has been strengthened to ensure good control of technical baseline data (e.g., requirements, specifications) and timely processing of document (e.g., NCRs) to resolve fabrication issues. Estimates increased to ensure adequate design integration support of design and construciton, “back office” support of assembly operations, interface control, and dimensional control planning. Experience in modular coils and initial field period assembly operations has shown that adequate engineering support staffing is critical for avoiding delays in both design and construction operations. (+$7,420k; RM, SO)

- Management: estimates have increased to ensure adequate overall engineering leadership of design and construction. The longer period of performance due to project stretchout is also a factor in the cost growth. (+$1,801k, RM, SO)

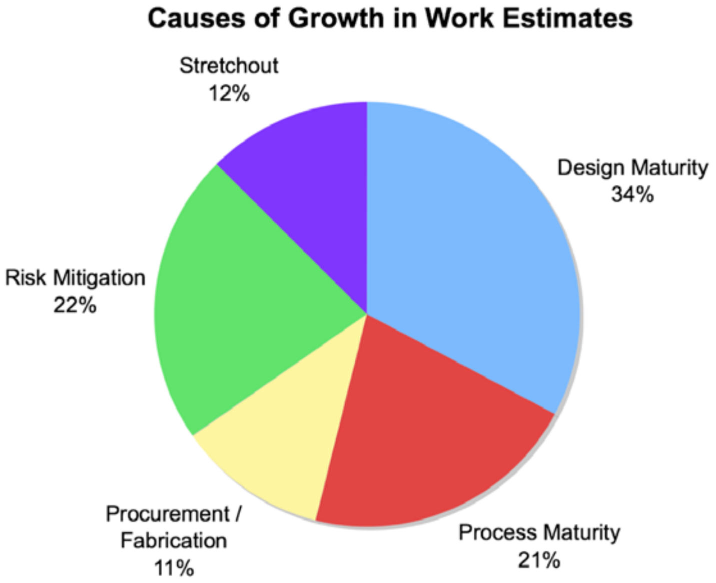
85. Integrated System Testing, -$394k

- Since ECP-031, integrated system testing plans have been streamlined, consistent with minimum CD-4 objectives and the experience on NSTX. (-$394k, DM)

89. PPPL Allocations, +$2,139k

- Management: The estimate for PPPL indirect cost allocations to the NCSX project has increased due to the forecast extended duration of the project. (+$2,139k, SO)

The distribution of cost growth by cause is summarized in the following chart:



This assessment highlights the main factors in the cost growth since the 2005 baseline. Over half the growth is a result of advances in design and process maturity which has led to a better understanding of the work requirements since 2005. Better understanding has led to cost growth, but also provides a sounder basis for the estimates of remaining work. Likewise, the risks are now better understood and this has led the project to budget activities specifically designed to mitigate risk, as well as larger contingencies. The growth in cost, especially of assembly activities, has been accompanied by schedule growth and a longer period of performance for management and support activities, driving stretchout costs.

In summary the growth of understanding due to advances in design and process maturity is the primary cause of the large growth in cost over the 2005 baseline. It has also produced a sounder basis for the estimating both the costs and risks in the remaining work.

6. Project Management Corrective Actions in the New Baseline

The magnitude of the proposed baseline cost and schedule increases clearly calls for changes in how the NCSX project is managed if the new baseline is approved. A lessons learned study was conducted by Princeton University and the PPPL to better understand issues that led to cost and schedule variances and to establish corrective actions to prevent reoccurrence of similar problems in future projects. The following issues were identified:

1. Premature definition of the project cost and schedule when the project baseline was established at CD-2.
2. Underestimate of the implications of meeting the tolerance requirements of a complex three-dimensional structure
3. Lack of independent internal review of cost and schedule
4. Inadequate Princeton University and PPPL Oversight of the NCSX Project
5. Inadequate communication with DOE
6. Lack of appreciation of the high risks associated with the application of cutting edge technologies.
7. Insufficient management and project execution.

Lessons learned & corrective actions include:

1. Prior to establishing a baseline, R&D and design needs to be completed sufficiently to establish a sound technical basis for the estimates. To the extent that such tasks are still outstanding at the time a baseline is established, it poses a risk which must be recognized, quantified, and managed with mitigation plans and contingency. In retrospect, the NCSX design was not at a PDR level and assembly process for many critical components, and more importantly critical prototyping tasks were still outstanding, when the project was baselined in 2003. Even now, since not all of the design and prototyping has been completed, there remain risks to the proposed Project baseline. These risks have been identified and the management of these risks has been addressed in this BCP.
2. The use of formal risk assessment techniques based on a risk register and analysis of the tasks at the job level is required to establish the need for cost and schedule contingency. In support of the NCSX rebaselining effort, Princeton University hired a consultant to augment PPPL capabilities and apply more modern approaches such as Monte Carlo analysis to transform the risks identified in the risk registry into contingency requirements, and to help distinguish cost estimation uncertainty from risk. The risk

registry including risk mitigation plans has become a key management tool for the project and will be updated monthly.

3. When reporting estimates, it is important to realistically assess the uncertainties, their sources, and the prospects for reducing them. Subjective characterizations of “confidence” should be avoided. Comparison with previous similar experience can be misleading if it does not adequately take into account the special circumstances of a complex project like NCSX.

4. The project was remiss in characterizing its December, 2006 estimate as a “high-confidence” estimate, given its basis. The Project and PPPL Director’s Office should have stated that a bottom-up analysis of all remaining work, risks, and uncertainties was required to provide a high-confidence estimate. Subsequently, all NCSX job estimates were extensively revised to incorporate new analyses and lessons learned particularly in the areas of metrology and Title III engineering associated with fabrication of the modular coils and vacuum vessel. There is now a uniform format for developing NCSX cost estimates, designed to decrease the likelihood of missing sub-tasks in a cost estimate, and of elements being missed at the interface between jobs. Bottom-up estimates-to-complete will be performed every six months for all remaining jobs. Projected estimates-to-complete will be estimated each month as part of the Project management documentation.

5. The formality of the development of the job estimates has been increased. The job manager, the NCSX Responsible Line Manager, NCSX Project Manager and the Associate Director for Engineering and Infrastructure will sign off on all cost and schedule changes, thus documenting their commitment to meeting the proposed estimate. They will also identify risks and opportunities associated with the job estimate as input to the Risk Registry. Lower level milestones at approximately monthly intervals will be identified for each job and tracked and statused by the Engineering Managers such that off-critical path tasks are given greater visibility.

6. Projects need to use care when planning to use high technology tools at or near their upper limits. Examples from NCSX include three-dimensional CAD modeling, metrology, and low-distortion welding. The needed capabilities must be confirmed prior to establishing the cost and schedule baseline. Training on high technology tools needs to be scheduled and done before their use is required. To improve implementation times and usage estimates, other more experienced users of the technology should be consulted. The NCSX project has recently consulted CERN and W7X for their expertise in metrology and low-distortion welding.

7. The Project Team needs to develop stronger ties not only with other fusion laboratories but also with particle physics laboratories to take advantage of new technology. The Team will develop a long range plan for ensuring that staff are abreast of new technologies and partnerships with other organizations to leverage their experience. It is an expectation that engineers attend conferences (e.g., SOFE, SOFT) that provide

opportunities to network with other fusion projects facing similar problems. The project will use external reviewers, especially from other DOE-SC Labs in major project reviews.

8. A monthly review is being held with the PPPL Director, the Deputy Director, Associate Laboratory Director for Engineering and Technical Operations, the Head of Best Practices and External Affairs and the NCSX Project to review in detail: the project cost and schedule performance; update of the Risk Registry including impacts of recent actions on future costs; action plans for jobs which have encountered cost and schedule problems; update of risk mitigation plans; identification of resource requirements from PPPL and ORNL; and proposed drawdowns for contingency. The Deputy Director summarizes the results of that review and provides them to the Dean for Research. PPPL Director, Deputy Director and Project Manager will meet with the Princeton University. Oversight Board periodically to report results of monthly reviews. The Dean for Research briefs the University President and Provost of developments on NCSX on a monthly basis.

9. The University is strengthening project management at PPPL. The current training budget for engineering will be augmented. For NCSX, Princeton University engaged Jim Anderson with extensive PM experience, to make immediate changes and improvements on NCSX. Don Rej from LANL has assumed the leadership role as Project Manager in February 2008. Rej has agreed with and has accepted all of these corrective actions; moreover, he is expected to strengthen other project management areas, with particular emphasis on instilling a culture of personal accountability and increased focus on driving schedule, without ever compromising safety and quality. New Lab-wide project management policies, procedures and plans will be adopted, and modifications will be made to existing ones, based on this lessons-learned review. The formal cost estimating process used to develop this baseline proposal is being incorporated into PPPL policies and procedures.

10. The Project needs to have greater direct access to key members in the Office of Science and improve communication both about the Project successes and issues. We propose monthly meetings of the Princeton Dean for Research, PPPL Director, PPPL Deputy Director and NCSX Project Manager with DOE-SC Associate Director for Fusion Energy Sciences and DOE Director of Office of Project Assessment to report progress, issues, plans.

11. Princeton University has set up an external review committee, composed of project management experts as well as experts in constructing stellarators and similar complex experimental facilities to review the project progress and plans. This is to ensure that the University is kept fully informed of the Project status. This Committee will meet every six months, in general prior to DOE Science Project Assessment reviews. They will report to the Princeton Dean for Research and the Princeton Provost, who will brief the President on the outcome of these reviews.

7. CD-4 Project Objectives

In this section we address the Project Objectives that are documented in the NCSX Project Execution Plan. The CD-4 performance objectives and overall machine capabilities are consistent with the 2005 baseline. Value improvements have been made, affecting design details without impacting the physics capabilities of the machine. In each of the following sub-sections we first describe the CD-4 objective, as specified in the Project Execution Plan, and describe the project's plan for addressing that objective.

a. First Plasma

<u>PEP Table 2-1</u>:
An Ohmically heated stellarator discharge will be produced with:

- major radius 1.4 m.
- magnetic field of ≥ 0.5 T
- plasma current of ≥25kA
- at least 50% of the rotational transform provided by stellarator fields.

The three-dimensional stellarator geometry will be confirmed by taking video images of the plasma.

<u>Plan</u>:
Produce the specified plasma. The geometry will be documented with a visible TV camera. The plasma current will be measured with a Rogowski coil.

b. Coils and Power Supply Performance

<u>PEP Table 2-1</u>:
The coils will be operated at cryogenic temperature and energized with the baseline power supplies (except as noted) to the following currents:

- Modular coils: 12 kA
- TF Coils: 2 kA
- Central Solenoid Coils: 12 kA [formerly PF1 & PF2 coils]
- PF4 Coils: 3 kA [formerly PF3-4 coils]
- PF5-6 Coils: 2 kA
- External Trim Coils: 1 kA. (w/ temp. power supplies).

Plan:

The changes noted are due to a change in the central solenoid design since 2005. The original design, which featured three pairs of coils, PF1, PF 2, and PF3, was replaced by a two-coil design using existing coils previously used on NSTX. The new design reduced cost and risk and will meet the project's needs through at least the first plasma heating campaign. Recent analysis shows that segmenting the solenoid (as in the original PF1,2,3 design) has minimal impact on plasma shaping, so the solenoid function can be more simply performed by simple, less expensive coils as a value improvement. Depending on research results, if higher levels of bootstrap current are produced by the plasma, a future upgrade to increase the capacity of the central solenoid may be needed. It is now considered unlikely that the original PF1,2,3 design would be the cost-effective choice for such an upgrade.

The coils will be operated at cryogenic temperature for first plasma. The baseline power supplies will be a subset of the existing C-Site rectifiers. The First Plasma scenario has been optimized to minimize power supply cost and risk, resulting in lower coil currents and fewer units and circuits than originally thought necessary. Coil performance requirements will be satisfied as follows:

- Modular coils: Energize to 9 kA as part of the First Plasma scenario. Energize to 12 kA independently using a temporary re-connection of one of the baseline power supplies.
- TF coils: Not used in the First Plasma scenario. Energize to 2 kA independently using a temporary re-connection of one of the baseline power supplies.
- PF 1 Coils: Energize the two central solenoid coils (formerly the NSTX PF1a coils) to 17 kA as part of the First Plasma scenario.
- PF 4 Coils: Energize to 2.8 kA as part of the First Plasma scenario.
- PF 5 Coils: Not used in the First Plasma scenario. Energize to 2 kA independently using a temporary re-connection of one of the baseline power supplies.
- PF 6 Coils: Only requires 0.2 kA as part of the First Plasma scenario. Energize to 2 kA independently using its assigned power supply.
- External trim coils: Not used in the First Plasma scenario. Energize to 1 kA independently using a temporary connection of one of the power supplies.

c. Magnet System Rating

PEP Table 2-1:

It will be demonstrated on the basis of component design verification data that the stellarator magnet system of modular coils, TF coils, and PF Ring coils is rated for operation at cryogenic temperatures to support plasma conditions with:

- high beta (4%)
- magnetic field up to 1.6 T (0.2 s) or 1.2 T (1 s)

- Ohmic current drive up to 250 kA
- flexibility per the General Requirements Document

Plan:

The coils will be operated at cryogenic temperature for First Plasma. The coils are designed to satisfy reference operating scenario requirements that are specified in the GRD and that meet or exceed the PEP objectives. Conformance of the coil design to the GRD requirements will be verified by analyses appropriately documented. The coils were fabricated according to product specifications and manufacturing procedures that were developed based on the design. Conformance of the components to the design was verified by in-process tests and inspections, including cooldown of a modular coil to cryogenic temperature and full-current pulsing of that coil at cryogenic temperature. Testing of the C1 coil is documented in NCSX-TEST-14-01.

d. Magnet System Accuracy

PEP Table 2-1:

It will be demonstrated on the basis of design verification data, including electron-beam flux-surface mapping with the coils at room temperature, that the stellarator magnet system of modular coils, TF coils, and PF coils produces vacuum magnetic surfaces.

Plan:

The physics requirement for good magnetic surfaces was translated into a design requirement, documented in the GRD, that limits the allowable island size due to fabrication errors, magnetic materials, and eddy currents. That requirement translated into design choices, particularly tolerances, material choices, and lead arrangements that are documented in lower-tier component specifications and procedures. It also drove the requirements and configuration design for the trim coils. Analyses verified that the designs conformed to the GRD requirement. Conformance of the fabricated components and sub-assemblies was verified by in-process tests and inspections, including dimensional measurements with metrology equipment and magnetic permeability measurements. Inspection and test results are documented in the run-copy manufacturing procedures and travelers for each coil. An electron-beam mapping test will be performed to confirm that the final assembly produces vacuum magnetic surfaces. While a room temperature e-beam test is allowed, it will most likely be done with the coils at cryogenic temperature, a more stringent and more relevant condition.

e. Vacuum Vessel System Rating

PEP Table 2-1:
It will be demonstrated on the basis of component design verification data that the vacuum vessel system is rated for high-vacuum performance with:

- base pressure less than or equal to 8×10 8 torr @293K
- global leak rate less than or equal to 5×10 5 torr l/s @293K
- bakeable at 150 C.

Plan:
Vacuum test data from in-process manufacture and assembly will be used to document the vacuum vessel base pressure and leak rate. The device will be capable of being baked to 150 C.

f. Vacuum Pressure and Pumping

PEP Table 2-1:
A base pressure of 4x10-7 torr will be achieved.
A pumping speed of 1,300 l/s at the torus will be achieved.

Plan:
The specified base pressure will be achieved with the NCSX turbomolecular pumping system, permanently attached via a duct to the vacuum vessel interior.

g. Controls

PEP Table 2-1:
Integrated subsystem tests, to the level required for First Plasma, will be completed for the following systems:

- Safety interlocks.
- Timing and synchronization.
- Power supply real time control.
- Data acquisition.

Plan:
These systems will be operational during the integrated system test program (ISTP) and First Plasma. Specifically:

- Safety interlocks. NCSX will incorporate a Central Safety Interlock System which will provide centralized control and monitoring of high energy subsystems and hazardous areas.
- Timing and synchronization. The Facility Timing and Synchronization System, based on a single master clock encoder and a fiber optic broadcast transmission system, will provide a sufficient number of events triggers for first plasma.
- Power supply real time control. The power supply real time control system will provide the control signals to drive the power supply rectifier triggers. The hardware and software will be patterned after NSTX.
- Data acquisition. The data acquisition system, using hardware and software patterned after NSTX, will be implemented to a degree sufficient for First Plasma.

h. Neutral Beams

PEP Table 2-1:
For one neutral beam injector:

- Beamline operating vacuum shall have been achieved.
- Beamline cryopanels shall be leak-checked.
- A source shall be leak-checked

Plan:
These tests were completed in 2004.

i. Readiness for Research

PEP Section 2.2:
“The NCSX will provide the initial set of equipment necessary to achieve the CD-4 First Plasma milestone defined herein and to begin the research program.”
“The First Plasma milestone will demonstrate a level of system performance sufficient for the start of research operations.”

Plan:
The MIE project will provide the equipment needed for first plasma and e-beam mapping. We will have 5 power supply circuits connected to the machine at the time of first plasma. They are connected to MA, MB+MC, PF1A, PF4, and PF6. The TF and PF5 are not powered in the first plasma scenario, but will be used in the first research campaign following CD-4, magnetic configuration studies. Since PF1A is not required for magnetic configuration studies, it frees up

one power supply circuit. Another circuit can be freed up, if necessary by connecting all the modular coils series. The magnetic configuration studies research campaign, including studies with the TF and PF5, can thus proceed with the equipment provided by the MIE project.

j. Scope

PEP Section 2.2.3:
"The NCSX fabrication project scope includes all the equipment required at the start of operations (First Plasma and initial field mapping) with coil operation at cryogenic temperatures, and refurbishment and testing of equipment for 1.5 MW of neutral beam heating power."
"See Annex I for detailed scope by WBS."

Plan:
We will meet the requirement stated in the first sentence. Annex I has been updated to eliminate redundancies and to reflect approved changes that are consistent with CD-4 objectives and the level of machine performance provided in the 2005 baseline. The differences are minor, specifically,

- We will have 5 magnet coil circuits, not 6, for First Plasma, but all circuits will be tested by reconnecting the baseline power supplies in various ways.
- Reference to "External" trim coils are deleted. All planned trim coils, both baseline and potential upgrades, are external to the vacuum vessel.

Appendixes

A. Project Execution Plan
B. General Requirements Document (Technical Basis)
C. Assembly Sequence Plan (Technical Basis)
D. Design Status Summary
E. Work Breakdown Structure
F. Work Authorization Forms (Job estimate packages)
G. Resource Loaded Schedule
H. Critical Path Schedule
I. Milestone Table
J. Financial Summary (BA/BO analysis, etc.)
K. Contingency Analysis Report
L. Risk Management Plan
M. Risk Registry
N. Responses to Past Review Recommendations