NCSX Risk Management Plan
October, 2003

The responsibility for risk management rests with the NCSX line management. The System Integration Team (SIT) will facilitate the identification of areas of risk, coordinate the development of risk mitigation plans, and the monitoring of performance against those plans. The design engineers, with the appropriate management oversight, establish the specific approaches to addressing the individual risk elements. This document describes the critical risks and mitigation plans identified at the time of the Preliminary Design Review. The estimated costs and contingencies to mitigate these risks are incorporated in the project's baseline cost and schedule estimates.

The early phases of the NCSX project design process is structured to identify risks. These risks are addressed through design improvements, manufacturing studies, prototypes, schedule contingency, and cost contingency. The cost contingency methodology is outlined in the Project Execution Plan. In many cases the risk mitigation comprises several of the above listed mitigation elements. This risk listing will be tracked and updated by the SIT as a living document so as to avoid overlooking important risks and to assure that the risk mitigation has adequate management oversight.

Risk: Project Cost and Schedule Overruns

Work Breakdown Structure element: All

Identification number: A-1

Risk description: Cost and schedule overruns due to a wide range of causes. For the NCSX project, the most important global cost and schedule risks are judged to be:

- Design delays.
  Schedule delays in Title I design are already a problem, one that could continue in the Title II phase. For NCSX the root cause of delays has typically been the unforeseen time required to overcome technology limitations in the design tools, owing to the difficulty of the design. These schedule delays have been accompanied by cost growth.

- Fabrication costs and durations exceeding estimates.
  The major NCSX components are unique, with very challenging geometries and dimensional accuracy requirements. The computer-aided tools that are needed to build NCSX are at, or in some cases slightly beyond, the technological limits. As we have already seen in the design phase, it is difficult to foresee every problem that will be encountered or all technological developments that will be needed, and thus the accuracy of estimates can be inadequate.

- Requirements creep.
  Escalation of physics requirements has not been a problem in NCSX. However, their implications for lower-tier requirements are sometimes not adequately understood until the design matures, and significant implications may not be recognized until late in the process. The result can be cost growth in the directly affected components, as well as cost and schedule growth if the change requires a rework of the system-level design and impacts multiple components.

Consequence: If the project cost or schedule exceed the DOE baseline objective, the project will experience unwanted attention, the funding profiles will no longer match the budget requirements, and further slips in schedule will result. It could lead to delays or reductions in the scientific output from NCSX, or cause its programmatic need to be reconsidered.

Mitigation Plan:

- System engineering
  The project has implemented a system engineering program to minimize downstream surprises. Functions include: timely identification and analysis of requirements, system analysis to assess design implications, design integration and control of interfaces. Also, a physics analysis activity is maintained in order to assess implications of design tradeoffs on physics performance. The budgets for these activities were increased following the CDR to support adequate resources to control the risks.

- Manufacturing development.
  Manufacturing processes for critical components are developed and demonstrated via the fabrication of prototypes by the prospective manufacturers in order to improve the accuracy of production cost and schedule estimates. Since the prototype fabrication will not be completed when the project is baselined, substantial contingencies are maintained in an attempt to cover the uncertainty.

- Competition.
  The project is qualifying two suppliers each for the modular coil winding forms and vacuum vessel. Each supplier has submitted budgetary cost based on the supplier’s own analysis of the manufacturing process. The project has used these estimates in developing its baseline. The project will select the suppliers for the production program based on their overall performance and fixed price and schedule proposals after the prototype fabrication is complete.

- Adjust Title II design estimates based on Title I experience.
  The Title I design phase took longer and cost more than was estimated in the CDR estimate. Since the root causes of these delays are expected to persist in the Title II phase, a correction factor must be applied to the original estimates for Title II design to realistically reflect expected performance. This has resulted in a significant increase in Title II design durations and costs.

- Maintain ample budget contingency.
  The project’s cost baseline includes 28% budget contingency on the ETC, the same percentage as in the CDR estimate. Within the $73.5M budget envelope, budgets have shifted from lower-risk to higher-risk scope. While much has been learned since the CDR to reduce uncertainties, significant cost risk remains, so

it is premature to reduce the percentage contingency allowance on the remaining work.

- Maintain ample schedule contingency.
  The project's schedule baseline includes 4 months **(tbd)** of schedule contingency, the same as in the CDR estimate. The project has shortened the fabrication and assembly schedule estimates by improving the logic and sequencing, however, the estimated design durations have increased as already noted, so the schedule contingency remains unchanged.

- Establish minimum performance and scope thresholds
  The project has established threshold performance and scope parameters that are more conservative than the baseline objectives. The thresholds define the minimum acceptable level of project accomplishment. In spite of sound estimates, prudent risk mitigation measures, and reasonable contingency reserves when initially baselined, the risk of future baseline deviations cannot be totally eliminated. Should that occur, the project's contingency plan, after all reasonable corrective measures are exhausted, is to reduce performance or scope, remaining above the minimum, or *threshold*, values of these parameters.

Risk: Performance Shortfalls

Work Breakdown Structure element: All

Identification number: A-2

Risk description: Performance falling short of objectives due to a range of causes. For the NCSX project, the most important global performance risks are judged to be:

- Magnetic islands in the plasma
  Field errors can generate magnetic islands in the plasma, reducing its performance. Coil geometry errors and eddy currents in the structure are potential sources of field error. Islands could result from fabrication or assembly errors exceeding tolerances. Violations of stellarator symmetry in the structure could make otherwise tolerable eddy currents intolerable.

- Reduced magnetic field strength due
  The magnetic field strength of NCSX is limited by thermal and magnetic stresses due to heating of the modular coil windings and to magnetic forces during a pulse. If the temperature rise is greater than the design value, or if the allowable temperature rise is reduced, performance margins will shrink. The temperature rise (for a given field strength) could increase if the conductor cross sectional area were reduced. Potential causes are reduced packing fraction due to swelling or deformation (keystoning) of the insulated conductor during manufacture. The allowable temperature rise could decrease if the thermal deformation were found (via analysis) to be worse than expected. The performance would also be reduced if the coil deflections due to magnetic forces were excessive.

Consequence: If the performance falls short of objectives, the repairs needed to recover full performance could lead to major increases in cost and schedule. Reduced machine perfomance, if not corrected, could greatly reduce the scientific output from NCSX. Either of these consequences, if severe enough, could cause the programmatic need for NCSX to be reconsidered.

Mitigation Plan:

- Control of field errors as a high-level system design priority
  Control of field errors is a high priority for the project and receives considerable

attention as a design and fabrication issue. Significant system analysis resources have been budgeted in the project baseline to maintain oversight of this issue. Some of the measures which the project is taking include: 1) identification of field error sources and calculating their effects in terms of island width, 2) adopting a "shim-as-you-go" fabrication and assembly approach to control the position of the winding center to high accuracy, 3) making provision for adjustability of the TF and PF coils after assembly, 4) establishing a metrology working group headed by Steve Raftopoulos to maintain an awareness of available technologies and develop solutions for NCSX metrology problems, 5) requiring stellarator symmetry in the design of structural components, and 6) requiring electrical breaks in nearby structures, and 7) establishing a limit on allowable island width.

- Performance Margins
  The project has adopted a coil design concept that is predicted to meet performance requirements, maintain high accuracy, and minimize fabrication costs. The main uncertainties are the properties of the winding pack composite, the behavior of the conductor during winding, and the deflections during operation. These uncertainties have been reduced via progress to date in materials testing, manufacturing development, and analysis during conceptual and Title I design. During Title II, these activities will continue and the project will build and test both subscale and full-scale prototype coils to demonstrate all aspects of the manufacturing process. The results will be factored into the final design.

- Establish minimum performance thresholds
  The project has established threshold performance parameters that are more conservative than the baseline objectives. The thresholds define the minimum acceptable level of technical performance. Since the risk of future performance shortfalls cannot be totally eliminated, the project's fallback plan, after all reasonable corrective measures are exhausted, is to reduce performance, remaining above the minimum, or *threshold*, values of these parameters.

Risk: The vessel may not have the correct shape

Work Breakdown Structure element: 12

Identification number: 12-1

Risk description: The vacuum vessel is a welded structure which must satisfy a complex 3D shape specification within a tight tolerance band. Shape deviations in the formed panels or weld distortion could cause the subassemblies to acquire the wrong shape.

Consequence: If the vacuum vessel does not meet tolerance requirements it could interfere with the modular coils during assembly, cause misalignment of the field period assembly joint, or leave inadequate space for plasma-facing components between the vessel and plasma. These could result in schedule delays, increased costs, or reduced performance.

Mitigation Plan

- Metrology
  The potential that the vessel will not have the correct shape, is mitigated by the use of modern 3-D measurement equipment such as laser trackers and portable coordinate measurement systems. The vessel can be continuously measured, compared with the 3D CAD model, and corrected during the fabrication process.

- Manufacturing Process.
  Special measures are planned as part of the manufacturing process to ensure accurate dimensions both during manufacture and afterward. Computer modeling and simulation may be used to predict and compensate for weld distortion. Intermediate heat treatment will be provided to reduce residual stresses that could cause distortion during operation. A spacer is included between each field period subassembly that will be used to accommodate any misalignment between field period assembly flanges.

- Manufacturing Process Development
  All the fabrication processes will be demonstrated and optimized during the R&D phase of the vessel procurement, where full scale, partial prototypes will be fabricated and measured. An important element of the prototyping activity will be addressing the issue of vacuum vessel shape. As part of these activities,

special tasks have been developed to allow the prototype vendors to apply their CAD expertise to evaluate shape requirements. The shape and associated tolerances will be an important aspect of the prototype evaluations.

Risk: Vacuum Vessel Welded Joint Assembly

Work Breakdown Structure element: 12

Identification number: 12-2

Risk description: Final assembly of the three vacuum vessel subassemblies involves making up three welded joints. It is a difficult operation because the welding must be done from inside the vessel. Access to the exterior is obstructed at that stage by the enclosing modular coils. Risks are shape deformations resulting from weld contraction during cooling and damage to the insulation or modular coils outside the vessel.

Consequence: Shape distortion could cause parts of the vacuum vessel to shift, closing narrow clearance gaps between neighboring components or introducing large stresses. Damage to the coils or insulation could require significant rework to repair. Schedule delays, cost increases, or performance impacts could result..

Mitigation Plan:

- Design
  Some kind of a shield to protect insulation and coils.

- Process development
  R&D will be carried out to optimize and demonstrate the process for making up the welded joint. The vessel welded joint will be mockup up as a full scale partial prototype, perhaps using the two partial prototype sections currently being constructed as part of the vessel prototype R&D. Predicted weld distortion will be compared to results of tests and pre-positioning offsets for the vessel sectors will be quantified.

Risk: The cost and schedule risks associated with the vacuum vessel

Work Breakdown Structure element: 12

Identification number: 12-3

Risk description: The vacuum vessel fabrication cost and fabrication schedule duration could exceed estimates

Consequence: Schedule delays and increased cost. Since the vacuum vessel is on the critical path the impact could be large.

Mitigation Plan:

Manufacturing studies were carried out during the conceptual design process to obtain advice from manufacturing engineers on ways to make the design easier or less expensive to fabricate. Five different studies of the vessel were carried out, and several fabrication processes were considered, including hot pressing, cold pressing, explosive forming, and casting. Vendor input has been continued after the CDR with an extensive R&D program. This effort will be carried out concurrently with the vessel design process such that the results can be included in the final design. Two different vendors will fabricate partial prototypes of critical regions of the vessel. The forming, welding, machining, polishing, and inspection processes will all be demonstrated and optimized. At the conclusion of the R&D phase, a fixed price contract will be awarded for the production vessel. The selection of two vendors for the R&D phase will result in at least two qualified vendors for the production articles, and provides competitive pressure to keep production costs (and bids) low.

Risk: The modular coils might not have the correct geometry due to fabrication errors.

Work Breakdown Structure element: 14

Identification number: 14-1

Risk description: The modular coils must satisfy complex 3D shape specifications within tight tolerances. Geometry deviations exceeding the tolerances could accumulate in the fabrication of the winding form, fabrication of the coils, or assembly of the field periods.

Consequences:

Performance
If the coils do not have the correct geometry the magnetic configuration would be compromised by islands, impacting performance.

Cost and schedule
If the deviations are large enough it could cause interference with the vacuum vessel during field period assembly. These could result in schedule delays and increased costs. Since the coils and field period assembly are on the critical path, the impacts could be large.

Mitigation Plan:

The potential risk of geometry deviations is mitigated by the 3-D CAD technology, the use of laser scanners and/or multi-link measuring systems to verify geometry, and by using accurate scale models of the vessel and coils during the design and development processes. A 1/12 scale model of the present design verifies that the coils and vacuum vessel can be assembled as planned.

Significant R&D is underway to demonstrate and test all operations connected with the modular coil fabrication. This includes procurement of two cast and machined winding forms, winding up to 12 partial coil packs and at least one full prototype coil, and performing thermal, and fatigue tests on critical features. The scope of the prototyping activity includes the testing of vendor capability to meet tolerance requirements. This will all occur with sufficient time to incorporate any changes to the design suggested by the R&D.

Keystoning of the conductor when wound at a tight radius has been identified as an important issue related to the tolerance of the winding centers. A single and multiconductor keystoning test program has been developed and is underway. The results of this test program have guided the design toward smaller conductor dimensions to minimize the keystoning risk and will be used to establish the final requirements for the winding forms. A shim-as-you-go fabrication process with frequent measurements mitigates the risk of out of tolerance winding forms and uncertainties in predicting keystoning. The metrology working group has been tasked with developing methods to ensure components are accurately positioned.

Risk: The coils might not have the correct geometry due to thermal or mechanical load distortions.

Work Breakdown Structure element: 14

Identification number: 14-2

Risk description: If the coils do not have the correct geometry the magnetic configuration would be compromised.

Consequence: Reduced performance.

Mitigation Plan: The distortions of the modular coils due to thermal and mechanical loads are being analyzed as part of the modular coil modeling activity. The internal and external structural constraints on the coil will be designed to meet distortion limitations.

Risk: Chill plate configuration proves impractical

Work Breakdown Structure element: 14

Identification number: 14-3

Risk description: The chill plates to cool the coils are integrated with the coil clamps. Combining the clamping and coling function into one component may prove too difficult

Consequence: Design change required, delaying the design and impacting cost and schedule. In worst case, cooling performance could be impacted, reducing machine repetition rates.

Mitigation Plan:

A subscale prototype (the so-called "twisted racetrack") will be fabricated based on the chill plate concept. If it proves to be practical, the project will proceed with it. Otherwise, an alternative is to switch to internally-cooled conductor, with the attendant re-design, additional manufacturing development, and testing. The costs would be covered by contingency.

Risk: The coils will fail mechanically or electrically

Work Breakdown Structure element: 14

Identification number: 14-4

Risk description: Faulty design or manufacture could lead to coil failure.

Consequence: Mechanical or electrical failures would compromise operations

Mitigation Plan:
The potential risk, that the modular coils will fail mechanically or electrically, is mitigated by analysis, conservative design criteria, and by an active coil protection system. Critical analysis, such as electromagnetic load calculations, stress and deflection calculations, and thermal stress analysis will be performed by independent groups using different codes and models. The stresses will be compared to the ASME code allowables as specified in the NCSX Structural Design Criteria. The materials chosen for the cast coil form have been demonstrated to have extremely high tensile strength, which adds additional margin. The winding is continuously supported in the cast form, so the winding and coil forms will have approximately the same strain. Since the coil modulus of elasticity is much lower than the steel (~ 1/6), the winding should have relatively low stresses. The only caveat to this point is the thermal strain, since the winding will shrink away from the coil form due to the VPI operation and during cooldown to liquid nitrogen temperatures. The design goal is to push the winding against the form in the highly loaded areas, which also correspond to the regions of the coil where accuracy is most important.. In addition to designing and analyzing expected loading conditions, the coils will be evaluated for and protected from fault conditions by an active coil protection system

The risk of future electrical failure will be addressed via careful control of the coil winding process. It will be done in-house so that the work can be performed and overseen by people experienced in fusion magnet construction and operation. The manufacturing development program will develop the process and qualify staff. Ample quality assurance and control will be provided. Lessons learned from previous fusion magneti-related failures, especially NSTX, will be applied.

Risk: The cable conductor will not behave as planned during winding.

Work Breakdown Structure element: 14

Identification number: 14-5

Risk description: If the cable conductor does not behave as planned accurate winding would be precluded or costly to achieve.

Consequence: Reduced performance or higher cost.

Mitigation Plan: The potential technical risk is that the compacted cable conductor will not behave as planned. This problem is mitigated by design and R&D. The design approach, as explained in detail above, is to fully support the windings against electromagnetic forces, nearly eliminating the cyclic bending strain in the conductor that would normally occur in a free standing coil. Extensive R&D is planned and already underway to build a small racetrack-shaped coil that can be electrically and thermally cycled. The winding, vacuum impregnation, and restraint conditions would be matched as closely as possible to the planned design.

Risk: Cost and schedule risks with modular coils.

Work Breakdown Structure element: 14

Identification number: 14-6

Risk description: The cost and schedule durations could exceed estimates.

Consequence: Increased cost or delayed operations.

Mitigation Plan:

The cost and schedule risks associated with the modular coils could also be significant, but steps have been and are being taken to reduce those risks substantially. Manufacturing studies were carried out during the conceptual design process to obtain advice from manufacturing engineers on ways to make the design easier or less expensive to fabricate. Four different studies of the modular coils were carried out, and various methods for winding, vacuum impregnation, casting and machining were investigated. Vendor input will be continued after the CDR with an extensive R&D program. This effort will be carried out concurrently with the modular coil design process such that the results can be included in the final design. Two different vendors will fabricate full-scale cast and machined coil forms. At the conclusion of the R&D phase, one or more fixed price contracts will be awarded for the production castings. The selection of two vendors for the R&D phase will result in at least two qualified vendors for the production articles, and provides an extra incentive to keep production costs (and bids) low.
This approach also mitigates the schedule risk by starting the R&D process as soon as possible and incorporating any needed design changes as they are uncovered. Two qualified vendors are available at the end of the R&D process, so schedule pressures could be relieved by adding more capacity. It should be noted that the present schedule for procurement of the winding forms is completely consistent with vendor input, and no specific schedule issue is apparent. The coils will be wound in-house at PPPL, which affords more control over the schedule and resource allocation than would be possible with an outside vendor. Slight in-process changes could be made without ponderous approval cycles.
If cost increases cannot be mitigated within the modular coil system then reductions in cost can be sought in other subsystems to offset the increase in the coil system.

Risk: The Neutral Beam System will not meet the cost, schedule or performance requirements.

Work Breakdown Structure element: 25

Identification number: 25-1

Risk description: If the Neutral Beam System runs into equipment difficulties we could exceed our cost or schedule targets or have to reduce performance.

Consequence: Increased cost or delayed operations.

Mitigation Plan: NCSX in its Initial configuration will utilize two of the four existing PBX neutral beams. This equipment will be tested before the NCSX baseline is established.

Risk:

Work Breakdown Structure element: 5

Identification number: 5-1

Risk description:

Consequence:

Mitigation Plan: