QPS Risk Management Plan

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QPS Risk Management Plan

The responsibility for risk management rests with the Quasi-Poloidal Stellarator (QPS) line management. The QPS Work Breakdown Structure (WBS) leaders and project management identify risk areas, develops risk mitigation plans, and monitors performance against those plans. The design engineers, with the appropriate management oversight, establish the specific approaches to addressing the individual risk elements. An important asset in identifying and mitigating risks is the QPS Team's close connection with the National Compact Stellarator Experiment (NCSX) project, which has most of its features in common with QPS. ORNL is a partner with the Princeton Plasma Physics Laboratory (PPPL) in the NCSX project and responsible for the design of the stellarator core. The principal members of the QPS Team are on the NCSX System Integration Team and are involved in identifying risks in the NCSX project and the plans to mitigate them. NCSX precedes QPS in the approval and fabrication phases by 1-2 years, which allows time for the experience gained in the NCSX project to be factored into the QPS project.

This document describes the critical risks and mitigation plans identified at the time of the QPS Conceptual Design Review. The estimated costs and contingencies to mitigate these risks are incorporated in the project's preliminary cost and schedule estimates.

The early phases of the QPS project design process are 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 Preliminary Project Execution Plan and is the same as that used for the NCSX project. In many cases, the risk mitigation comprises several of the mitigation elements listed above. This risk listing will be tracked and updated by the QPS WBS leaders and project management as a living document so as to avoid overlooking important risks and to assure that the risk mitigation has adequate management oversight. In addition, the QPS WBS leaders and project management will keep a close watch on any changes in risk identification and risk mitigation plans for the NCSX project, and will revise the QPS risk identification and risk mitigation plans appropriately.

The risk descriptions are grouped by category:

- general risks, which apply to a number of all WBS elements;
- the vacuum vessel, particularly the center stack, which contains the center legs of the toroidal field (TF) coils and the Ohmic current windings (WBS12);
- the external coils (WBS13);
- the nonplanar modular coils, which are the most complex component and are in the vacuum tank (WBS14);
- coil assembly (WBS18);
- power supplies and auxiliary equipment (WBS42);
- plasma performance (not a WBS element).

The following sections provide for each risk element:

- an identification number (for tracking);
- the corresponding WBS number;
- a short descriptive title;

- a description of the risk involved;
- the possible consequences if there is a problem; and
- the plan to avoid or mitigate that risk. The risks are listed in the table and are described in detail in the following pages.

QPS Risk Elements

Area	Label	Title
General all WBS	A-1	Performance shortfalls
	A-2	Project cost and schedule overruns
Vacuum Vessel WBS12	12-1	The vacuum vessel will not permit a high quality vacuum
	12-2	The vacuum vessel could introduce static or transient field errors
	12-3	The vacuum vessel could fail mechanically
	12-4	The center stack has structural or vacuum problems
	12-5	The vacuum vessel will not permit sufficient access for inspection, maintenance or reconfiguration of internal components
	12-6	Cost and schedule risks associated with the vacuum vessel
VF Coils WBS13	13-1	The ATF and PBX-M vertical field coils might not be useable
Modular Coils WBS14	14-1	The coils do not have the correct geometry and tolerance
	14-2	The cable conductor will not behave as planned during winding
	14-3	The coil structure could introduce transient field errors
	14-4	The modular coil cooling could be inadequate
	14-5	The modular coils could fail mechanically or electrically
	14-6	The modular coil cans could develop a leak into the plasma vacuum region
	14-7	The cooling lines on the coil cans could develop a water leak into the vacuum tank
	14-8	Energetic electrons could damage the modular coil cases
	14-9	Difficult to satisfactorily wind, can, and pot the modular coils at the University of Tennessee
	14-10	Cost and schedule risks with modular coils
Coil Assembly WBS18	18-1	The time needed to adequately align the modular coils for field period assembly and for assembly of the two field periods is longer than planned
Power Supplies	42-1	The coil and rf power supplies might need refurbishing or a better control system
Program	P-1	QPS is not able to access high plasma density

GENERAL RISKS (all WBS elements)

Cost growth.

The main drivers for cost growth are changes to the design concept during preliminary design. These can occur as a result of changes to the requirements, infeasible fabrication, or lack of functional performance. These have been addressed for all these components by adopting a simple concept that can be readily modified without affecting other components of the machine. For example, if the cooling is found to be inadequate after a more thorough analysis, it can be revised with little cost impact. If the structure is too weak, the structural sizing of any of the components can be modified with very little impact. All the assemblies are bolted together, so they can be disassembled and re-assembled without impairing its accuracy (as opposed to welded structures). Finally, there is no new technology to develop for this concept, so no development should be required.

A-1. Performance Shortfalls.

Risk description: Performance falling short of objectives due to a range of causes. For the QPS 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 and pulse duration.* The magnetic field strength and pulse duration for QPS are 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.
- *Poor vacuum.* Vacuum leaks, inadequate pumping speeds, and poorly prepared materials near the plasma can result in plasmas with high impurity densities and lower plasma densities.

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 performance, if not corrected, could greatly reduce the scientific output from QPS. Either of these consequences, if severe enough, could cause the programmatic need for QPS to be reconsidered.

Mitigation Plan:

- *Control of field errors as a high-level 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 will be budgeted in the project baseline to maintain oversight of this issue. Some of the measures which the project is taking include: (1) identifying 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 adjusting the TF and PF coils after assembly; (4) interacting with the NCSX metrology working group to maintain an awareness of available technologies and to develop solutions for QPS metrology problems; (5) requiring stellarator symmetry in the design of structural components; (6) requiring electrical breaks in the modular coil support structure and bellows in the vacuum tank to reduce eddy currents; (7) establishing a limit on allowable island width; and (8) using plasma current to avoid low-order rational values of the rotational transform in the plasma.

- *Performance Margins.* The QPS 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 by taking advantage of progress to date in the NCSX project on materials testing, manufacturing development, and analysis during conceptual and Title I design. During NCSX Title II, these activities will continue and the NCSX project will build and test both subscale and full-scale prototype coils to demonstrate all aspects of the manufacturing process. The QPS project will take advantage of the lessons learned in this process, but will also fabricate the most demanding of the modular coils in the R&D phase of the QPS project so the results can be factored into the final design of the coils.

- *Establish minimum performance thresholds.* The QPS project will establish 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 the performance while remaining above the minimum, or *threshold*, values of these parameters.

- *Adopt more rigorous fabrication procedures and inspection plans for critical components.* In addition to the magnetic-related issues described above, vacuum material compatibility, surface finish techniques, and pre-assemble testing will be a priority.

A-2. Project Cost and Schedule Overruns.

<u>Risk description</u>: Cost and schedule overruns can occur due to a wide range of causes. For the QPS project, the most important global cost and schedule risks are judged to be:

- *Design delays*. Schedule delays in Title I design could be a problem, one that has occurred for NCSX and 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. The QPS project has benefited from the development of these design tools. Their further development in Title I design for NCSX should mitigate, but not eliminate, risks in this area.

- *Fabrication costs and durations exceeding estimates*. The major QPS components are similar to NCSX components, but have some unique features. They share the very challenging geometries and dimensional accuracy requirements of NCSX. The computeraided tools that are needed to build QPS are at, or in some cases slightly beyond, the technological limits. As has already been seen in the design phase for NCSX, it is difficult to foresee every problem that could be encountered or all technological developments that will be needed, and thus the accuracy of estimates can be inadequate. Because of the schedule difference between NCSX and QPS, the unavoidable portion of the NCSX growth has already incorporated in the QPS cost and schedule estimates, and closer attention will be given to remaining common issues.

- *Requirements creep*. Escalation of physics requirements has not been a problem in QPS. However, their implications for lower-tier requirements may not adequately be 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 components that are directly affected, as well as cost and schedule growth if the change requires a rework of the system-level design and impacts multiple components.

<u>Consequence:</u> If the project cost or schedule exceed the DOE baseline objectives, 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 QPS, or cause its programmatic need to be reconsidered.

<u>Mitigation Plan:</u>

- *System engineering*. The QPS project will implement a system engineering program similar to that in the NCSX project to minimize downstream surprises. Functions will include: timely identification and analysis of requirements; system analysis to assess design implications; design integration; and control of interfaces. Also, a physics analysis activity will be maintained in order to assess implications of design tradeoffs on physics performance. Information developed in the corresponding NCSX effort will be used to minimize risks on QPS.
- *Manufacturing development*. Manufacturing processes for critical components are developed and demonstrated by 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 will be maintained in an attempt to cover the uncertainty.
- *Competition*. The NCSX project is qualifying two suppliers for the modular coil winding forms. Each supplier has submitted budgetary cost based on the supplier's own analysis of the manufacturing process. The QPS project has also obtained independent estimates in developing its cost estimate. The QPS project will select the suppliers for the production program based on their overall performance and on fixed price and schedule proposals after the NCSX and QPS prototype fabrication activities are complete.
- *Maintain ample budget contingency*. The project's cost baseline will include 27% overall budget contingency on the TEC, the same percentage as in the CDR estimate. While much has been learned in the NCSX project on reducing uncertainties, significant cost risk remains, so it is not prudent to reduce the percentage contingency allowed for QPS.
- *Maintain ample schedule contingency*. The project's schedule baseline will include five months of schedule contingency, two months more than in the CDR estimate. The

fabrication and assembly schedule could be shortened, but it is prudent to keep the proposed schedule contingency for unforeseen developments.

- *Establish minimum performance and scope thresholds*. The project will establish 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.

VACUUM VESSEL (WBS element 12)

12-1. The vacuum vessel will not permit a high quality vacuum.

Risk description: Leaks in the vacuum vessel seals or outgassing from the vacuum vessel or in-vessel components could increase the impurity gas level in the vacuum vessel to an unacceptable level.

Consequence: Air leaks or outgassing could increase the impurity level in the plasma to an unacceptable level, increasing impurity radiation high enough to limit electron temperatures below that needed for some experiments, or in an extreme case to radiative collapse of the plasma at low density.

Mitigation Plan: High vacuum quality is addressed in the design, the procurement specification, and the manufacturing, inspection, and test plan for the vacuum vessel. The vacuum vessel will have the minimum number of welds consistent with the fabrication technique. The welds will be full penetration welds with a GTAW root pass and GTAW or GMAW filler passes, and no SMAW welding permitted. The vessel will be leak-checked at the fabricator. The interior surfaces will be polished and cleaned according to accepted vacuum equipment standards. All vacuum vessel ports will have copper conflat seals, except the large-diameter toroidal seal surfaces above and below the midplane and the large oblong top and bottom ports, which will have double Viton O-rings or a metal seal and a Viton seal with differential pumping. Heaters and thermal insulation blankets on the vacuum tank will be used to provide bakeout capability with a temperature goal of 150 ºC based on the temperature limit of the solenoid winding in the center stack. The internal modular coils and support structure will be baked by convection heating using high-pressure argon or nitrogen gas in the vacuum tank. Additional impurity control is obtained through helium glow discharge cleaning, boronization, and control of the plasma-surface interactions on the divertor baffles.

12-2. The vacuum vessel could introduce static or transient field errors.

Risk description: High magnetic permeability or eddy currents in the vacuum vessel could create field errors.

Consequence: Magnetic field perturbations due to localized regions of high magnetic permeability or eddy currents in the vacuum vessel could create magnetic islands and spoil confinement.

Mitigation Plan: This is mitigated by the choice of material and the strict adherence to stellarator symmetry. The magnetic permeability of the material, 316L stainless steel, is easier to control during welding than 304L stainless steel, so field errors due to induced magnetism should be negligible. To limit poloidal eddy currents induced by ramping up the toroidal field, a bellows is included that limits the poloidal time constant to <2 ms. Finally, the port locations and geometry are stellarator symmetric, so that any currents that are induced in the vessel should also be stellarator symmetric.

12-3. The vacuum vessel could fail mechanically.

Risk description: The vacuum vessel could buckle.

Consequence: Cost to redo the vacuum vessel.

Mitigation Plan: This is mitigated by analysis and conservative design criteria. Critical analyses, such as stress and deflection calculations and buckling analysis, will be performed by independent groups using different codes and models. The stresses will be compared to the ASME code allowables, which provide a safety factor of 1.5 on yield for primary membrane stresses at the operating temperature.

12-4. The center stack has structural or vacuum problems.

Risk description: The center stack containing the center legs of the TF coils and the Ohmic winding is a vacuum boundary that is subjected to large magnetic forces.

Consequence: Structural or vacuum problems with the centerstack could compromise performance and require removal for repairs.

Mitigation Plan: The structural and vacuum integrity of the center stack is strengthened by analysis and conservative design criteria. Critical analysis, such as stress and deflection calculations and buckling analysis will be performed by independent groups using different codes and models. The stresses will be compared to the ASME code allowables, which provide a safety factor of 1.5 on yield for primary membrane stresses. Numerous pins restrain the magnetic load from the Ohmic solenoid and a thick casing is used for structural and vacuum integrity. The center stack can be removed without disassembling other components by undoing the top and bottom joints in the TF legs.

12-5. The vacuum vessel will not permit sufficient access for inspection, maintenance or reconfiguration of internal components.

Risk description: The ports on the vacuum vessel do not allow sufficient access to the interior for inspection, repairs, or additions to the in-vessel components.

Consequence: Inability to have sufficient access to the interior for inspection, repairs, or additions to the in-vessel components would limit installation the of new diagnostics and ion cyclotron range of frequency (ICRF) antennas

Mitigation Plan: This is mitigated by providing as many ports as possible that are large enough for manned access. The 24 large vertical ports and the 12 large midplane ports are large enough for manned access. In addition, both vessel domes can be removed independently from the cylindrical spool piece and the modular coils for very good access.

12-6. Cost and schedule risks associated with the vacuum vessel.

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

Consequence: The main impact is increased cost, but the vacuum vessel is not a major cost component. The vacuum vessel is not on the critical path, so a delay in fabrication does not have a significant impact.

Mitigation Plan: The QPS vacuum vessel was designed as a simple cylindrical spool piece and two domes that are commercial items. The only complications arise in the fabrication of the side, top, and bottom ports and the racetrack-shaped centerstack (discussed in 12-5). The cost and schedule risks associated with the vacuum vessel are relatively small, but two potential vendors were consulted during the conceptual design process to obtain advice on ways to make the design easier, or less expensive, to fabricate. This interaction will continue during the advanced conceptual design and preliminary design phases.

EXTERNAL COILS

13-1. The ATF and PBX-M vertical field coils might not be useable.

Risk description: Two of the four sets of circular vertical field coils used for positioning and shaping the plasma are from earlier experiments and have not been used for several years.
Consequence: Lack of these coil sets would severely limit the flexibility of the QPS experiment to study various magnetic configurations. Replacing these coils would add to the cost of the QPS experiment, but would not impact the schedule because they are external to the vacuum vessel.

Mitigation Plan: The coil sets will be tested electrically and measured for geometrical accuracy. In addition, the cooling paths will be tested. A second set of vertical field coils, which were trapped inside the PBX-M vacuum vessel when it was scrapped, is being obtained. Repairs will be made to the coils if feasible, and new coils will be fabricated if necessary.

NONPLANAR MODULAR COILS (WBS element 14)

14-1. The coils do not have the correct geometry and tolerance.

Risk description: The modular coils must satisfy complex 3-D 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.

Consequence: Errors in the shape or alignment of the modular coils could produce magnetic islands if the resulting magnetic field perturbation has a component that is resonant with a low-order rational value of the rotational transform. Sufficiently large magnetic islands would increase plasma transport and complicate the analysis of the confinement behavior.

Mitigation Plan: The potential risk that the coils will not have the specified geometry and accuracy is addressed in the design, in R&D, in the fabrication process, in the assembly process, and in operation.

Design: The coil design approach is based on a very accurately cast and machined winding form with the winding surfaces and mounting features integrated into a single unit. The coils are wound directly onto this form and vacuum pressure impregnated with epoxy. The casting is massive (just like the frame of a high precision machine tool) and deflections due to the winding and assembly process should be negligible. Since the windings are not removed from the winding form, the distortions that would normally occur during this operation are avoided. In addition to the basic design concept, the coil leads and bus interfaces are designed for minimum field errors. Distortions of the modular coils due to thermal and mechanical loads are 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.

R&D: Significant R&D is planned (primarily as part of the NCSX project) 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 NCSX prototyping activity includes the testing of vendor capability to meet tolerance requirements. The QPS project will also fabricate a prototype coil. This will all occur with sufficient time to incorporate any changes suggested by the R&D into the modular coil design and/or fabrication.

Fabrication: The coil forms are dimensionally stabilized prior to machining to an accuracy of +/- 0.25 mm anywhere on the winding surface. The forms can be readily and independently inspected by QPS personnel with conventional laser tracker or multi-link coordinate measuring systems to confirm compliance with specifications. Once acceptable coil forms are delivered, the coils will be wound at the University of Tennessee with QPS personnel having total control over all processes. The use of the modern 3-D measurement equipment mentioned above will allow the conductor placement to be continuously measured and, if indicated, corrections to be made throughout the winding process. Once the coils are completed, additional measurements of the as-built geometry can be entered into codes, and the relative placement of each coil can be optimized, if necessary, for best control of error fields.

Assembly: Continuous measurements will be made during the assembly process to ensure that the coils are aligned correctly. Each coil will be located to a global reference frame that is continuously updated for the best fit to the coil array.

Operation: Photographs of the plasma will be taken with a CCD camera during First Plasma operation, and compared with the calculated flux surfaces. This should reveal the presence of any large edge islands that limit the plasma radius. Magnetic flux surfaces will then be mapped under vacuum with an electron beam and fluorescent screen. This will give a detailed picture of magnetic islands over the plasma cross section. Any islands detected will be compared with calculations to determine the source of the field perturbation that produced them. A vacuum field line following code embedded in an optimizer will then be used to determine values for the nine independent coil currents that minimize the islands, and the flux surface mapping will be redone with those currents to confirm the compensation for the field errors. The impact of any residual islands will be minimized by using an Ohmic current to tailor the rotational transform profile to avoid low-order rational values.

14-2. The cable conductor will not behave as planned during winding.

<u>Risk description</u>: If the compacted cable conductor does not behave as planned, accurate winding would be precluded or costly to achieve.

<u>Consequence</u>: Reduced performance or higher cost.

Mitigation Plan: This problem is mitigated with careful design and adequate R&D. The design approach 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 in the NCSX project to test one or more small racetrack-shaped coils 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. 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 multi-conductor keystoning test program has been developed and is underway for NCSX. The results of this test program have guided that design toward smaller conductor dimensions to minimize the keystoning risk, and will be used to establish the final requirements for the QPS winding forms. A shim-as-you-go fabrication process with frequent measurements mitigates the risk of winding forms that are out of tolerance and uncertainties in predicting keystoning.

14-3. The coil structure could introduce transient field errors.

Risk description: Eddy currents in the structural shell could create field errors.

Consequence: Magnetic field perturbations due to eddy currents in the structural shell could create magnetic islands that spoil confinement.

Mitigation Plan: Eddy currents in the structural shell are mitigated by including insulating breaks at the flanges in the shell structure and by strict adherence to stellarator symmetry. The time constant for decay of these eddy currents is estimated to be ~27 ms. The flat-top time of the magnetic field is 1.5 s at 1 T, long enough to allow ~0.1 s before initiation of the plasma for these eddy currents to decay.

14-4. The modular coil cooling could be inadequate.

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

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

Mitigation Plan: The risk that the coils will not cool down in the specified time between shots will be mitigated by providing two chill plates for each winding and cooling from both ends of the chill plates. Multiple cooling circuits may also provide redundancy. A subscale prototype (a “twisted racetrack”) will be fabricated based on the chill plate concept for the NCSX project. If it proves to be practical, the QPS project will proceed with it. Otherwise, an alternative is to switch to an internally cooled conductor, with the attendant re-design, additional manufacturing development, and testing. The additional costs would be covered by contingency.

14-5. The modular coils could fail mechanically or electrically.

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

Consequence: Mechanical or electrical failures would compromise operations.

Mitigation Plan: The risk is mitigated by analysis, conservative design criteria, and by an active coil protection system. Independent groups using different codes and models will perform critical analysis, such as electromagnetic load calculations, stress and deflection calculations, and thermal stress analysis. The stresses will be compared to the ASME code allowables, which provide a safety factor of 1.5 on yield for primary membrane stresses at the operating temperature. The materials chosen for the cast coil form have been demonstrated to have reliably 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 lower than the steel, the winding should have relatively low stresses. The only caveat to this point is the thermal stress, where the coil form restraint adds stress to the winding. Again, a lower stiffness mitigates this problem significantly. Nevertheless, R&D testing will be performed to determine thermal stress limits during the preliminary design phase. If necessary, a compliant layer will be added to the design to mitigate the thermal stresses.

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. A coil fault detection system would prevent operation of the coils outside their design envelope. The system would be programmed to monitor the signals from voltage, strain, temperature, and possibly magnetic field sensors on or around the various coil windings and structures as the coils were being energized. If any of the sensor signals were out-of-bounds for the specific current scenario being run, the fault system would crowbar all the power supplies. The system would guard against control errors and physical faults, such as shorted buswork. Electrical failures are mitigated by a redundant insulation system and non-conducting coolant. The insulation will consist of three overlapping layers of Kapton tape, in addition to the four layers of interlaced glass tape. The fiberglass/epoxy matrix is adequate by itself, but just in case there are small dry areas between turns, the Kapton will provide more than adequate insulation strength.

14-6. The modular coil cans could develop a leak into the plasma vacuum region.

<u>Risk description</u>: The modular coils are inside the vacuum vessel. The interior of the coil cans is filled with epoxy at atmospheric pressure.

<u>Consequence</u>: Epoxy or trapped air pockets in a small region could be exposed to the plasma or vacuum region and outgas, introducing impurities into the plasma and increasing the impurity radiation.

<u>Mitigation Plan</u>: The coil can will be carefully welded, checked and vacuum tested before the coils are vacuum pressure impregnated with epoxy. The QPS vacuum will be routinely monitored for leaks. If a leak is detected and is large enough, the coils will be tested with helium leak detection to locate which coil has the leak. The coil can either be evacuated with an external vacuum pump, or the leak can be repaired after opening the vacuum vessel for access.

14-7. The cooling lines on the coil cans could develop a water leak into the vacuum tank.

<u>Risk description</u>: The cooling lines that cool the modular coils between shots are welded to the outside of the modular coil cans, which are inside the vacuum tank. A water leak from the cooling lines into the vacuum tank could develop for a number of reasons.

<u>Consequence</u>: A leak in one of the coil cooling lines would introduce water into the vacuum tank, increasing the oxygen impurity level and associated radiative losses. If large enough, it would raise the vacuum vessel pressure to a high value and could affect coil cooling.

Mitigation Plan: The QPS vacuum will be routinely monitored for leaks. If a leak is detected, the coil cooling lines will be tested with helium leak detection to locate the leak. If large enough, the leak can be spotted visually from the water leak itself. The leak would be repaired after opening the vacuum vessel for access.

14-8. Energetic electrons could damage the modular coil cases.

Risk description: Energetic electrons produced during run up or run down of the magnetic field or with electron cyclotron heating (ECH) at low density could impact the coil cases or cooling lines and cause damage.

Consequence: Impact of a sufficient current of energetic electrons on the coil cases or cooling lines could damage them and lead to outgassing of epoxy or a water leak into the vacuum vessel.

Mitigation Plan: Studies of energetic electron orbits will be done to calculate possible impact points on the coil cases and cooling lines. If necessary, the coil cases could be thickened or armor added in those areas. A paddle and helium gas puff will be used during run up or run down of the magnetic field to suppress energetic runaway electrons, as was done in the ATF stellarator. Limiter and divertor plates will be used to intercept the normal plasma heat flux at the top and bottom around the bean-shaped cross sections.

14-9. Difficult to satisfactorily wind, can and pot the modular coils at the University of Tennessee.

Risk description: The arrangements at the University of Tennessee (UT) are not satisfactory for winding, vacuum canning and potting the modular coils.

Consequence: Another location would be needed for winding, vacuum canning and potting the modular coils, which would increase their cost and increase the time needed for their fabrication.

Mitigation Plan: A management plan has been developed by the QPS Team and iterated with UT. The plan covers: general organization, contractual arrangement, and responsibilities for cost, schedule, and technical performance; winding team personnel and supervision / oversight; facilities, tooling, fixtures, and special equipment; R&D and training of team members; QA, QC, and risk mitigation; safety considerations; work planning, work authorization, and performance reporting; and cost and schedule accounting. Careful control of the coil winding process at UT is possible because the work can be performed and overseen by ORNL people experienced in fusion magnet construction and operation. The manufacturing development program will develop the process and qualify the staff. Ample quality assurance and control will be provided. Lessons learned from previous fusion magnetic-coil-related failures and fabrication of the NCSX coils will be applied. If insurmountable problems are encountered, a fallback plan is to wind the coils at PPPL or ORNL.

14-10. Cost and schedule risks with modular coils.

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 be significant, but steps have been and are being taken to reduce those risks substantially in the NCSX project, and those will be implemented in the QPS project as appropriate. Manufacturing studies were carried out during the NCSX preliminary 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 in the NCSX project, and various methods for winding, vacuum impregnation, casting and machining were investigated. Vendor input has continued with an extensive R&D program. One of the two vendors qualified in the NCSX project will be selected to fabricate a full-scale cast and machined coil form for the most difficult of the QPS coils. At the conclusion of the R&D phase, one or more fixed-price contracts will be awarded for the production castings. The selection of one of the two NCSX vendors for the R&D phase would result in a qualified vendor for the production articles and takes advantage of the NCSX competition to keep production costs (and bids) low. In addition, a foreign qualified vendor exists that is fabricating the coil winding forms for the W-7X stellarator, which has similar modular coils.

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 in either the NCSX or QPS projects. Two qualified vendors are available at the end of the NCSX R&D process, so schedule pressures could be relieved by adding more capacity. The present schedule for procurement of the winding forms is consistent with vendor input, and no specific schedule issue is apparent. The coils will be wound at the University of Tennessee, which affords more control over the schedule and resource allocation than would be possible with an outside vendor. Slight in-process changes can be made without ponderous approval cycles.

If cost increases cannot be mitigated within the modular coil system, then reductions in cost would be sought in other subsystems to offset the increase in the coil system as much as practical.

COIL ASSEMBLY (WBS element 18)

18-1. The time needed to adequately align the modular coils for field period assembly and for assembly of the two field periods is longer than planned.

Risk description: The time needed to adequately align the modular coils for field period assembly and for assembly of the two field periods is longer than planned.

Consequence: Delay of the assembly schedule and completion of the project, which leads to increased personnel cost.

Mitigation Plan: The primary element of risk for the stellarator core assembly is the time needed to adequately align the modular coils for field period assembly and for assembly of the two field periods. This could result in delays and some cost growth. To mitigate this risk, the design is equipped with shimmed joints between all of the coil winding forms, such that alignment of one component is essentially independent of the alignment and tolerances of the mating components. Each modular coil winding form can be positioned independently into its “best fit” position.

POWER SUPPLIES AND AUXILIARY EQUIPMENT (WBS element 42)

42-1. The coil and rf power supplies might need refurbishing or a better control system.

Risk description: The ATF power supplies for the coils are old and might need refurbishing.

Consequence: The ATF power supplies are needed for the QPS coil systems. Refurbishing them or improving the control systems would increase the cost of the QPS project, but it would not impact the schedule since they are independent of the rest of the project.

Mitigation Plan: The ATF power supplies will be tested into a dummy load as part of moving the infrastructure from building 9201-2 to the new multi-purpose building (7625) in which QPS will be sited. Any deficiencies in the operation of the power supplies will be analyzed at that time and a plan to correct them will be implemented. The cost for this refurbishing will come from contingency in the QPS project. The control system should be adequate for first plasma operation. Improvements and modernization of the control system, if needed, will come from QPS program funding. The rf power supplies that will also be moved from building 9201-2 to building 7625 are needed for ECH and ICRF heating. They will be tested and used for other applications before they are needed for QPS, so they will be in working order.

PLASMA PERFORMANCE (no WBS elements)

P-1. QPS is not able to access high plasma density.

Risk description: QPS is not able to operate at high density because efficient plasma heating cannot be obtained with ICRF heating or with electron Bernstein wave (EBW) heating. While ECH is well established at lower density, theoretically a density gap exists between the ECH regime and the EBW heating regime that is effective at higher density.

Consequence: Failure to operate at high density would severely limit the maximum beta obtainable in QPS and jeopardize a secondary goal of the QPS experiment—the study of beta limits and the character of MHD instabilities in the QPS configuration.

Mitigation Plan: A number of different rf heating (ECH+EBW, ICRF, lower hybrid) scenarios should be available to reach high density, and the QPS Team has plans to test them on other experiments. These tasks are planned as part of the Research Prep activities. Recent experiments on stellarators in Japan (CHS) and in Germany (WEGA) have demonstrated transition from ECH to EBW heating without a density gap. In addition, transport analysis will be carried out to determine what can be achieved with ECH alone. CAD drawings of the QPS vacuum vessel and modular coil structure show that there is adequate access for neutral beam injection (NBI) heating if all of the rf scenarios fail. NBI would require a major upgrade to the QPS facility.