Department of Energy
Review Committee Report

on the

Conceptual Design Review

of the

QUASI-POLOIDAL STELLARATOR (QPS) PROJECT

June 2003

EXECUTIVE SUMMARY

A Department of Energy Office of Science project review of the Conceptual Design Report (CDR) of the Quasi-Poloidal Stellarator (QPS) project was conducted at Oak Ridge, Tennessee, on June 23-24, 2003. The review was conducted at the request of Dr. Anne Davies, Associate Director for Fusion Energy Sciences.

The purpose of the review was to evaluate the CDR in all aspects (technical, cost, schedule, and management). The Committee found the CDR on the whole to be adequate and noted 39 recommendations including two actions items that should be completed prior to Critical Decision (CD) 1, Approve Alternative Selection and Cost Range. ES&H, Quality Assurance, and management documents needed for CD-1 were not addressed by the Committee.

The QPS project is a fusion research project proposed for fabrication at the Oak Ridge National Laboratory. The mission of the QPS is to broaden understanding of toroidal magnetic configurations and develop understanding of the key issues for the low-aspect ratio quasi-poloidal approach to a high-_ compact stellarator concept.

Overall, the Committee concluded that the QPS project is being managed as needed, and the technical, cost, and schedule of the CDR is adequate but needs some revision. The progress made by the project to address and resolve the comments from a previous Physics Validation Review were, for the most part, adequately addressed. The Committee felt that the project could meet the QPS technical mission and could manufacture and construct the critical systems. The plans for commissioning and the contingency estimates were adequate at this stage of the project.

The Committee concluded that the management plans and procedures were adequate but needed a number of revisions especially to comply with the new DOE Manual 413.3 requirements. The plans and estimates for the diagnostic capability during operations, planning, and analysis for the QPS research program were also adequate.

The Committee made 39 recommendations, including:

- Explore the consequences of magnetic field errors in coil fabrication and misalignment;
- Identify the steps necessary to manage the risks in developing a modular coil winding facility at the University of Tennessee;
- Plan the means of gas control and gas feed that will permit good control of the density;

- Make maximum use of common approaches with the National Compact Stellarator Experiment (NCSX) project, to streamline design and procurement;
- Evaluate total lift weight of the modular coil assembly to ensure crane capacity is adequate;
- Develop a detailed magnet system testing plan;
- Perform a comparative cost estimate of common elements of QPS verses National Spherical Torus Experiment (NSTX) project;
- Establish level 2 milestones; and
- Re-order the experimental schedule to ensure that novel physics results are produced early.

There were also two action items resulting from this review:

1. Reach agreement on the funding profile with the DOE Fusion Energy Sciences Program Office, prior to CD-1.

2. Develop the preliminary management plan for the coil winding activity at the University of Tennessee, by CD-1. Key issues that must be addressed include staffing, training, supervision (including ORNL oversight), quality assurance, safety, and responsibility for cost, schedule, and technical performance.

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1. INTRODUCTION

The Quasi-Poloidal Stellarator (QPS) is a fusion research project proposed for fabrication at the Oak Ridge National Laboratory (ORNL). The compact stellarator is one of several innovative magnetic fusion plasma configurations supported by the Department of Energy Office of Fusion Energy Sciences (OFES). It has the attractive potential of operating continuously and without plasma disruptions. Also, when extrapolated to a fusion power plant, the compact stellarator is projected to require low operating power compared with that produced by the power plant.

The mission of QPS is to broaden understanding of toroidal magnetic configurations and develop understanding of the key issues for the low-aspect ratio quasi-poloidal approach to a high-_ compact stellarator concept. In addition, QPS will complement the National Compact Stellarator Experiment, which is currently under design at the Princeton Plasma Physics Laboratory, in completing the basis needed for advancing the development of the compact stellarator concept to the next stage of development. Critical Decision 0, Approve Mission Need, was obtained in May 2001. Earlier that year a panel of plasma physicists and engineers conducted a Physics Validation Review of the QPS design. The panel concluded that the physics approach to the QPS design was appropriate for a concept exploration level experiment.

The QPS project involves the design, fabrication, installation, and integrated system tests of a compact stellarator core device consisting of modular coils that provide the primary magnetic field configuration; poloidal, toroidal, and vertical field coils; a vacuum vessel; various auxiliary power; heating, cooling, and control systems; and startup diagnostics. Some of this equipment was previously used in other fusion experiments. This equipment is located at the Y-12 site and will be part of the move of the ORNL Fusion Energy Division from the Y-12 site to the X-10 site. This move is being paid for separately, with the costs being shared between OFES and ORNL. The QPS device would be located in a new building in the 7600 area of the X-10 site.

Because the project primarily involves the fabrication of new equipment, considerable re-use of existing facilities and hardware systems, and minimal civil construction, DOE designated the project as a Major Item of Equipment. In light of the project's proposed FY 2005 start, and considering the proposed funding level, first plasma is expected to be achieved early in 2008.

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2. TECHNICAL SYSTEMS EVALUATIONS

2.1 Physics

2.1.1 Findings and Comments

The QPS team presented the conceptual design of a facility that should address the May 2001, Critical Decision (CD) 0, Approve Mission Need, document, under the section, "Project Purpose and Relation to Program Strategy". The April 2001, Physics Validation Review (PVR) raised a number of physics and other issues, most of which were satisfactorily addressed in this review. With very few exceptions, noted below, the physics studies presented at this review were fully adequate for the present stage of the QPS project.

There have been extensive studies of configurational flexibility and consequences of off-normal machine performance.

There has not been adequate study of the consequences of magnetic field errors arising from coil winding errors, coil misalignments, eddy current fields, etc. Low aspect ratio plasmas require good flux surface quality across the full cross section. The coil design tolerances have not been clearly justified.

Since the PVR, there has been considerable improvement in the database concerning the ability to heat plasma with electron cyclotron resonance (ECR), electron Bernstein wave (EBW), and high harmonic fast wave (HHFW) methods. Nonetheless, the experience on higher density pure radio frequency (RF) heated plasmas remains limited, so that the ability to achieve _ of two percent is not solidly assured.

The magnetic field mapping at one toroidal location may not define the configuration adequately.

The novel physics experiment on QPS tends to be delayed until a later phase of the experimental program. Also, studies of runaways, flows, and fluctuations could easily be done earlier in the experimental program.

2.1.2 Recommendations

1. Explore the consequences of magnetic field errors in coil fabrication and misalignment. Determine the widths of induced islands, if any.

2. Justify the assumed tolerances for errors in magnetic coils fabrication.

3. Add magnetic field mapping at more than one toroidal location.

4. Identify _ limit studies that can be done in the range of one to two percent, especially at the lower end.

5. Develop alternative plasma heating scenarios if the proposed RF heating scenarios fail to achieve higher densities.

6. Re-order the scheduling of the experimental program to permit exciting physics studies earlier in the program.

2.2 Engineering

2.2.1 Findings

The technical progress since the PVR has been excellent. The new coil set and support structure represents a substantial improvement. The project has reduced project costs and risks through:

1. Adopting National Compact Stellerator Experiment (NCSX) design features and R&D results,
2. Re-using legacy equipment from the Advanced Toroidal Facility (ATF) and Princeton Beta Experiment (PBX), and
3. Capitalizing on strategic facility changes in progress at ORNL.

The conceptual design of QPS appears to satisfy the mission requirements. Technical risks are being identified and addressed in design and R&D. Manufacturability and constructability appeared plausible.

Cost and schedule estimates (including contingency) appear reasonable, keying off the NCSX cost and schedule basis.

Management plans and procedures for carrying out the project were not presented in detail, but rather were described as work in progress. Management issues related to developing a modular coil winding facility at the University of Tennessee (UT), training and supervising the supporting staff, and integrating them into the project were not addressed.

2.2.2 Comments

The external vacuum vessel appears to be the appropriate choice for access and assembly for a device of this scale and geometry, even with the attendant issues of vacuum compatibility, electrical isolation, and structural support of in-vessel components. Outgassing from modular coil castings is a particular concern.

The mechanical loads from the vacuum vessel spool piece, where it attaches to the modular shell, could potentially jeopardize the positioning of the modular coil windings.

The risks associated with canning (i.e., forming and welding the coil cans) are significant. Isolating leaks during operation is a specific concern. Continued attention to these risks is encouraged during design, R&D, and production. Measurements to determine whether the modular coil windings relax upon removal of the clamps during installation of the vacuum can and should be performed.

Integration of diagnostics, divertor hardware, and RF launchers with the stellarator core design is essential for the QPS mission. The integration of future upgrades should be a project activity and the budget included in the project cost estimate. A layout of all port-mounted and in-vessel hardware should be done to ensure that all mission critical hardware could be simultaneously accommodated.

The role of UT (partner or supplier) and nature of the contractual arrangement with UT should be clarified. The issues of contract performance (responsibility), safety, and quality assurance should be addressed.

2.2.3 Recommendations

1. Evaluate field errors that are inherent in the design and due to coil imperfections for their impact on plasma performance. Island sizes should be assessed relative to requirements.

2. Give increased attention to the design and fabrication of the centerstack. It is quite complex, perhaps as complex as any element in the stellarator core.

3. Prior to CD-1, complete the development of the technical requirements (GRD) and the management plans that will govern how the QPS project will be run. The plans should:

   - Address the requirements of the new DOE M 413.3-1, Project Management for the Management of Capital Assets.
   - Treat QPS as a $20 million project in terms of project reporting and management systems; and
   - Address design development (design reviews and specifications), change control, earned value reporting, work planning and authorization, and integration of other key participants.

4. Identify the steps necessary to manage the risks in developing a modular coil winding facility at UT, training and supervising the supporting staff, and integrating them into the project. Specifically, address:

   - Training and supervision of temporary technicians and graduate students;
   - Quality assurance;
   - Safety; and
   - Work planning, work authorization, and cost performance reporting.

2.3 Heating

2.3.1 Findings

QPS will be heated primarily by a variety of electron cyclotron heating (ECH) schemes making use of existing ORNL sources and, potentially, a new gyrotron. The secondary heating schemes are ion cyclotron heating (ICH)-based. Ohmic heating is not a large contributor to the power balance. The RF heating is thus essential to QPS's two major goals: 1) confinement studies of low-density, high electron temperature plasmas, and 2) finite-_ studies of stability and low-aspect ratio robustness.

Since the PVR, progress has been made in the specific area of RF modeling. The QPS RF heating group has a wealth of experience in RF technology, and has adequate sources of RF power at appropriate frequencies. Theoretical support of wave propagation and heating at the laboratory is excellent. The QPS RF group collaborates with the National Spherical Torus Experiment that is pursuing the advanced methods of HHFW and electron Bernstein wave (EBW) heating. Thus QPS is well-placed to perform innovative RF heating work and take advantage of ongoing experimental work in advanced methods.

The QPS group plans to start up and heat plasmas at densities $n_e \leq 1.8 \times 10^{19}$ m^{-3} with second harmonic ECRH for neoclassical confinement studies. The method is proven and can be expected to provide good target plasmas for these physics studies.

Because of the density limit imposed by ECH, this method will not allow access to plasma _ values above 0.8-1 percent, and other methods to support and heat higher density plasmas are proposed. These methods are less well-developed and less reliable at this stage. These techniques include EBW heating. In addition, the ICH techniques of HHFW and mode-conversion heating (for electron heating) and direct ion heating at the fundamental frequency are also proposed. The EBW method is still in the early development stage within the world's fusion program and is not yet proven to be a reliable technique to reach high-_ values. The proposed ICH techniques have been tried on other devices, and while they hold promise, their ability to reliably heat high density plasmas is not certain, and usually requires significant attention to antenna development, antenna loading, and antenna-plasma interaction. Indeed, it is difficult to identify experiments that have achieved high-_ values using RF heating alone. Therefore, the implementation of both EBW and HHFW to achieve high density plasmas on QPS are substantial R&D physics investigations that stand on their own merits, but nonetheless entail some technical risk to addressing the physics goal of studying stability and robustness in finite-_ QPS plasmas. Costs of installation of the RF heating systems and antenna construction are not included in the project costs.

2.3.2 Comments

The RF heating plans are complicated by two factors: the complex magnetic geometry, and the large-volume vacuum vessel enclosing the coils. While the former makes analysis and modeling difficult, it is not necessarily a disadvantage. The lack of an internal vacuum vessel introduces two issues. The first is the potential loss of efficiency from low first pass absorption during startup. Secondly, there exists the potential for a large gas load in the volume between the

plasma and the vessel wall. This will require measures to control the density in ECH discharges for confinement studies, and could lead to undesirable antenna arcing in ICH strap antennas. Neutral gas control will be of great importance to the effectiveness of heating in QPS.

2.3.3 Recommendations

1. Plan means of gas control and gas feed that will permit good control of the density.

2. Maintain active participation in experimental groups performing HHFW and EBW heating.

3. Explore avenues to implement low-power conventional ECH at earliest opportunity to smooth operation of first plasma.

2.4 Diagnostics, Central Installation and Commissioning, and Data Acquisition

2.4.1 Findings

The proposed activities and budgets are planned to support system checkout and initial operations ("first plasma"). Both areas are appropriately described, planned, and budgeted for this stage of the project.

2.4.2 Comments

The diagnostics are those needed for basic plasma operation and will also support flux surface studies in the first phase of the experimental program. Extensive use is made of equipment from the ATF experiment, which can easily be adapted for use on QPS. The QPS staff responsible for this work are ideally qualified to carry out this work.

The Installation and Commissioning work is that required to operate the basic machine systems. Data acquisition will use standard hardware and software (MDS-PLUS) widely used in the U.S. and international fusion programs.

Subsequent operations would benefit from the early adoption of fully centralized control of all experimental systems, including legacy equipment, and the use of community standard control hardware and software.

2.4.3 Recommendations

1. Plan for increased automation of large power supplies inherited from the ATF experiment and moved from the Y-12 location. This will speed operations and reduce manpower requirements. Some costs of this might be have to be borne by the QPS project if they cannot be included in Y-12 to X-10 relocation work.

2. Make maximum use of common approaches with the NCSX project, to streamline design and procurement, and also to facilitate collaborative experiments involving staff from the two groups.

2.5 Power Systems, Site, and Utilities

2.5.1 Findings and Comments

Excellent progress has been made. Engineering design is well developed and practical and very likely to meet the QPS technical mission within budget and schedule.

Use of existing Advanced Toroidal Facility (ATF) power supply facilities is very cost effective for QPS. Adequate time and budget needs to be included to allow refurbishment of this equipment. QPS is making effective use of laboratory rearrangement to setup and proof the power supplies. Facility crane capacity rating of 20 tons is close to projected weight of modular coil assembly (estimated to be 17 tons by itself) plus lift fixture weight.

2.5.2 Recommendations

1. Verify functionality and modernize control systems of power supplies to allow efficient interface for operation prior to integrated system testing.

2. Evaluate total lift weight of the modular coil assembly including potential design growth, as well as weight of lifting fixtures to ensure that planned crane capacity is compatible prior to finalizing building design requirements.

2.6 Assembly and Commissioning

2.6.1 Findings

The assembly and commissioning plans for the project are extremely well planned at this point in the project's development. The methods proposed, with additional development, are likely to achieve the desired end result. Risk in accuracy of assembly of coil modules is minimized by shim-to-fit method. Costing for assembly appears to be reasonably developed from process steps and has the highest level of contingency (36 percent, along with the coil modules themselves), appropriate for this complex step. Commissioning plans are under development with project completion defined by ohmic plasma production followed by electron beam mapping.

2.6.2 Comments

The coils and module assembly are on the critical path and present the most risk to project schedule. A schedule revision to begin module assembly after delivery of the first three modules should be examined to add slack time to this program element. Parallel assembly of periods could help with load leveling on resources.

The vacuum vessel is imprecise (by design). Landmarks on coil modules should be transferred to landmarks external to the vessel for diagnostic positioning and TF/PF alignment. Internal references should be accessible through the ports with available Coordinate Measuring Machines. The center solenoid needs to be aligned, not only with respect to the modular coil system, but also with the vacuum vessel for vacuum integrity. A method should be developed to ensure these conditions are met. The complex shape may require additional glow anodes.

2.6.3 Recommendations

1. Develop and implement an R&D plan for the shimming materials and process for assembly of the individual coil modules.

2. Develop a detailed magnet system testing plan and required instrumentation.

3. Examine the coil and coil module assembly schedule to increase slack time and reduce schedule slippage risk, prior to CD-1.

3. COST, SCHEDULE and FUNDING

3.1 Cost

3.1.1 Findings

The proposed QPS project has a Total Estimated Cost (TEC) of $19.95 million, broken down by design, fabrication, and assembly ($15.66 million); and contingency ($4.29 million or 27 percent of TEC).

A detailed Work Breakdown Structure based estimate has been prepared (see Appendix D). Cost estimates that have been prepared for both core systems and ancillary equipment are credible and based on sufficient detail for this phase of the project. For technical equipment, a combination of vendor quotes, catalog costs, with up to 50 percent of equipment costs being vendor quotes. Cost information has been obtained from the NCSX project at the Princeton Plasma Physics Laboratory (PPPL), which is slightly ahead of the QPS project in timing. All costs should be updated prior to CD-1.

Project support costs (management and engineering) are estimated at ten percent of the TEC. The associate components of these costs need further analysis to insure all associated costs have been included.

3.1.2 Comments

Contingency figures are based on a Risk Analysis presented in the CDR that was prepared for the project. In this plan, there are significant risks identified, in particular, those associated with design and fabrication of coils and winding forms. Again, information related to risk has been gained from experience on the NCSX project at PPPL, as similar problems will be encountered on both projects related to coil and winding form configuration. Contingency seems reasonable and comparable with the NCSX contingency estimate. It is not apparent that all project related costs, including Integrated Safety Management, ES&H costs, Quality Management, and cost of DOE imposed reviews, are priced into the current estimates.

3.1.3 Recommendations

1. Perform a comparative cost estimate of common elements of QPS vs NSTX to confirm reasonableness of $19.95 million estimate, prior to CD-1.

2. Ensure that all project related costs, including Integrated Safety Management, ES&H costs, Quality Management and DOE reviews, etc., are priced into the current estimates, prior to CD-1.

3. Develop a cost and schedule estimate "range" prior to CD-1 that reflects uncertainty for the current level of project development, prior to CD-1.

3.2 Schedule and Funding

3.2.1 Findings

The proposed project has a total duration of approximately four years from CD-1 through CD-4. A copy of the schedule is shown in Appendix E. The proposed funding profile (shown in millions of dollars) presented for the project is as follows:

$M	FY03	FY04	FY05	FY06	FY07	FY08	Total
TEC			6.08	7.68	4.85	1.34	19.95
Research Prep			0.6	0.6	2.2	2.0	5.4

Verify that this funding profile is supported by the Office of Fusion Energy Sciences. A three-month schedule contingency has been established within the project baseline.

3.2.2 Comments

While a clear resource-loaded schedule was not provided, it appears that the Budget Authority profile (shown above) supports the project plan for the bulk of the required fabrication and assembly. The schedule presented does not appear to include integration of DOE Milestones and reviews, ES&H, procurement, and other milestones of significance. These items should be added to provide a fully integrated project schedule.

3.2.3 Recommendations

1. Work with the program office to develop supportable funding profile.

2. At a current TEC of $19.95 million, this project is essentially at the management threshold of $20 million established in the DOE Order 413.1. The project should plan to meet all requirements for projects over $20 million as set forth in the DOE Order 413.3.

3. Provide resource loaded schedule to ensure Budget Authority/Budget Obligation compatibility prior to CD-2, Approve Performance Baseline.

4. Provide a fully integrated project schedule, including significant ES&H, procurement, DOE Reviews and Critical Decisions, and other milestones prior to CD-2. Include milestones for other facility projects procured with non-project funds.

5. Establish adequate Level 2 milestones in the Project Execution Plan to provide management control.

6. Ensure that all start-up costs occurring at or after project completion are identified as operating expense vs. capital (TEC).

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4. MANAGEMENT

4.1 Findings and Comments

An experienced management team has been assembled within ORNL for the project, and will use the ORNL Standards Based Management System as a framework for project execution. Further, the project is benefiting from experience gained in the management and execution of the NCSX project at PPPL. An Integrated Project Team has been established and is functioning to guide the project through the early stages of documentation for CD-1 and CD-2. An experienced project team is in place for this effort. The QPS project has developed an excellent working relationship with the NCSX project at PPPL, and both projects are benefiting from this collaboration.

ES&H, Quality Management, and value engineering were not addressed in detail in the CDR documentation and hence were not reviewed at this time.

4.2 Recommendations

1. Initiate PARS reporting for the QPS project. This includes early implementation of Earned Value Management System tracking and reporting at CD-2.

2. The Project Team should consider this to be a project greater than $20 million per DOE Order 413.1, and manage it accordingly.

3. Update all project management documents to reflect current Order 413.1 requirements and the requirements of all additional guidance documents.

4. Management should develop resource plans which account for both NCSX and QPS staffing needs over the life of the project.

5. Develop a risk management plan, prior to CD-2.

6. Develop coordinated procurement plans between NCSX and QPS.

7. Develop a plan to manage coil work being assigned to UT for accomplishment.

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5. RESEARCH PROGRAM PLANS

5.1 Findings

The presented research program plan constitutes a sound approach to addressing the objectives set forth in the QPS mission needs document.

Appropriately, the plan starts with the fabrication of a flexible device equipped with a basic set of support systems and research hardware (diagnostic, heating, plasma control, and power and particle handling subsystems), then progresses through a logical series of phases, building up capabilities as the experimental program dictates.

The baseline set of research hardware tools and their estimated costs are reasonable. The schedule for implementing hardware upgrades will depend on operating budgets that have not been set, but the presented timeline represents a reasonable scenario.

The level of program planning detail up to this time is sufficient to support the selection of research hardware upgrades, so that the machine can be designed to accommodate them. Appropriate selections have been made.

5.2 Comments

An important task for the project will be to design a complete system configuration that integrates the device with all the research subsystems needed to carry out the program. This task has started, but will need to continue through and beyond the advanced conceptual design phase. The requirements for these subsystems, most of which are outside the scope of the MIE project, must be developed and documented as part of the Research Preparation activity.

As a basis for setting requirements, the research program plans should be developed in more detail, establishing clear linkages between the physics objectives, especially the near-term ones, and the hardware capabilities needed to meet them. It will be important for the QPS project to start generating physics results soon after it goes into operation. As noted in Section 2.1, studies of runaways, flows, and fluctuations could yield early results provided the needed diagnostics are available. This should be a consideration in planning the research program, and especially in the scheduling of early hardware upgrades. Developing a compelling research

program and planning the necessary capabilities is a demanding task requiring the focused efforts of an experienced experimental physicist with clear responsibility for leading it and maintaining continuity into the experimental phase.

5.3 Recommendations

1. Continue to develop the research plan, hardware requirements, and integrated system design to ensure that upgrade hardware can be accommodated when needed.

2. Re-order the experimental schedule to ensure that novel physics results are produced as early as possible in the program.

3. Implement the PVR recommendation to promptly bring into the program an experienced experimental physicist to be responsible for the physics program planning and development.