Summary of NCSX Response to Recommendations from the Physics Validation Review Pertaining to Design and Fabrication

from Charge #1: Comment on the progress made by the project to address and resolve the comments from the PVR pertaining to NCSX design and fabrication.

Introduction

A Physics Validation Review (PVR) of NCSX was held in March, 2001. The very positive PVR panel report contained 29 recommendations addressing issues of design, research planning, and program management. Following the PVR, the project and the Department of Energy prepared a disposition plan for the PVR recommendations. The plan calls for those issues pertaining to the design and fabrication of NCSX to be resolved by the time of this Conceptual Design Review. Some of the PVR issues pertain to NCSX operation or stellarator development more broadly, or are of a programmatic or management nature. While these are not directly relevant to the design and fabrication of NCSX, the project responses are included here for completeness.

Recommendation II-1. Promote 3D Plasma Physics

PVR panel report: An important scientific frontier area is understanding the behavior of magnetized plasmas in 3 dimensional configurations. We find that the NCSX experiment will act as a focus and driver for the intellectual development of this important area of plasma physics in the U. S. plasma community. We recommend this scientific leadership role should be more clearly built into the description and execution of the NCSX program mission.

Project response: The NCSX project has taken specific steps to promote 3D plasma physics research and incorporate advancement of 3D plasma physics into the NCSX mission description. This is a programmatic issue which will receive our continued attention, but there are no issues as far as NCSX design and fabrication are concerned.

Recommendation II-2. Size and Design Point

PVR panel report: There is concern that the present pre-conceptual design point may be "too small." This view is due to the marginal parameters in NCSX across a broad spectrum of experimental design factors such as: high energetic NBI ion losses, low base heating power, confinement assumptions needed to reach design beta, very small plasma/pfc distances for some equilibria, and neutral penetration concerns. We recommend that as the Project prepares for a Conceptual Design, the size of the design be carefully considered and well justified at the time of the CDR to allay concerns that critical parameters are being fit within a predefined budget envelope.

Project Response: A number of design changes have been made since the PVR to improve physics capabilities. However, the project decided not to increase the machine size or baseline neutral beam heating power for several reasons. The PVR design point is sufficient to satisfy the physics requirements and accomplish the mission. The availability of ready upgrades in either neutral-beam or radiofrequency wave heating power mitigates the risk that the plasma heating may be inadequate. Some margins were increased through design improvements without increasing the size. While there would be physics benefits to increasing the size or power, doing so would increase the cost and probably delay the program. The PVR design point thus provides the appropriate balance between cost and risk considerations. Further details are provided in an appendix to this report and in the CDR Physics Document.

Recommendation II-3. Develop compact stellarator reactor vision.

PVR panel report: An attractive vision of a CS based fusion power system has not yet clearly articulated by the Project and a comprehensive fusion reactor design study has not yet been carried out. This situation makes it more difficult to build community enthusiasm for the CS concept and to justify the design requirements in key physics parameters for the PoP program. We recommend the Project devote some effort to developing this reactor vision and also to strongly support the initiation of a comprehensive fusion reactor design study of the CS concept.

Project Response: Comprehensive reactor design studies are an element of the proposed compact stellarator proof-of-principle program. Up to now, limited compact stellarator reactor extrapolation studies have carried out by the project; those were documented in the PVR documentation. Future reactor studies will be led by the ARIES team and should be based on a CS magnetic configuration that is optimized as a reactor, which needs to be developed as part of a comprehensive study. NCSX project leaders and PPPL management are working with the ARIES team to develop a plan for preparatory work, starting after the CDR, and a CS reactor study. This is a programmatic issue, which will receive our continued attention, but there are no issues as far as NCSX design and fabrication are concerned.

Recommendation II-4. Flow drive and damping in QAS.

PVR panel report: Plasma flow in a QAS stellarator has been identified by the NCSX Project as a key physics issue which also connects CS and tokamak confinement physics. The Project should more seriously investigate expected flow drive and damping mechanisms in 3-D plasmas in planning the experimental program on NCSX.

Project response: The critical quantity for the stellarator design is the toroidal flow damping rate, since it could set the upper bound on acceptable ripple. Neutral beams and mode-conversion RF (as an upgrade) will provide a source of flow. The project will use analytic calculations to estimate flow rates expected in NCSX, however because of the low effective ripple (0.01%) in the core, 3D effects are not expected to dominate in that region. The project will work with the Theory community to encourage research on flow drive and damping mechanisms.

Status: Flow damping torques due to residual ripple have been estimated for the design reference configuration. The damping torque is negligible in the plasma core in comparison with the available neutral beam torque. The ripple damping torque is calculated to be large enough at the plasma edge to prevent the edge from accessing co-rotation. This issue is discussed further in Chapter 7 (Transport) of the Physics Design Description.

Recommendation II-5. Physics program – Diagnostics Linkage

PVR panel report: The link between primary experimental physics objectives and the critical diagnostics needed to achieve these objectives is not yet well defined. Careful definition of this important part of the science mission and experimental program of NCSX is essential and should be completed as part of the conceptual design.

Project response and status: The project has developed an experimental plan at a level of detail appropriate for current design purposes. It is documented in "Mission, Experimental Plan, and Preparations," where the measurement needs and diagnostics required for each phase of the program are identified. The Diagnostics section (WBS 3) of the Engineering Design Description documents the requirements in detail.

Recommendation II-6. Role of NCSX and QAS in Relationship to Other Stellarators

PVR panel report: The review lacked a full discussion of the status of QAS vis-à-vis the large range of stellarator possibilities. While the advantages of QAS were made clear, there was essentially no discussion of its limitations. The presentation of these comparisons would likely increase the desirability of diverse stellarator experiments and enhance understanding of the role of the CS in the portfolio of toroidal magnetic configurations by the broad fusion science community.

Project response:
NCSX selected quasi-axisymmetry for optimizing plasma confinement in order to build upon the considerable tokamak database, including the use of undamped flows, and due to its natural compatibility with low aspect ratio. As an added benefit, the bootstrap current increases the rotational transform (thus improving confinement and stability) without the need for further distortion of the coils. However, it is important to realize that quasi-axisymmetric designs inherit some of the limitation of tokamaks, relative to the other stellarator transport-optimization strategies. The drift-orbit width (banana width) for energetic ions can be quite large, generating significant alpha losses in reactors with 'reversed shear' profiles. In contrast, both quasi-helically symmetric and quasi-omnigenous configurations can be designed to have drift-orbit widths comparable to the gyro-radius. Also, the bootstrap and Pfirsch-Schlüter currents strongly modify the equilibrium, potentially introducing additional resonant perturbations and driving MHD instabilities. While we have taken these modeled these effects in the design of NCSX, quasi-helical and quasi-omnigenous (especially W7-X like) configurations have much less bootstrap current and thus a more rigid equilibrium.

The NCSX mission, including its role the U.S. and world fusion program, is summarized in the Physics Design Document, Chapter 1, "Motivation and Goals". There are no issues as far as NCSX design and fabrication are concerned.

Recommendation III-1. Effect of Finite-Build Coils on the Physics

PVR panel report: Examine island formation, destruction of flux surfaces, and maintenance of QA symmetry, using *finite model* coil configurations close to the final design.

Project response: The quality of magnetic surfaces, quasi-symmetry of plasma fields, and property of MHD stability have all been examined for the full beta, full current (S3) state using a multi-filament model to represent the finite dimension of modular coils. Preliminary results show that all the properties remain essentially unchanged from those based on the single filament model. Studies are underway to examine other points of interest in the potential operating space.

Discussion:

Representation of finite coils: Modular coils are modeled as rectangles in cross section, 0.12 m in height and 0.10 m in width, with a 0.02 m web at the center which separates each coil into two halves. There are 8x2 turns for each coil half; each turn is modeled as a filament. This coil model resembles the proposed winding discussed in the Engineering Design Document. The version of the coils we used is that with the reduced resonance perturbation (healed), M45_60241. Effects due to defects/deviation in manufacturing, construction, and installation are addressed in a separate section.

QA symmetry: Using effective ripple as a measure of quasi-symmetry, the results of NEO calculation based on VMEC equilibria show that the difference is less than 1.5% between single- and multi-filament models throughout the entire plasma volume. The effective ripple is 0.21% at r/a=0.5 for the single filament model, whereas it is 0.213% for the multi-filament model. Similarly, at r/a=0.9 it is 1.026% for the single-filament versus 1.029% for the multi-filament model.

Flux Surface Quality: PIES calculations indicate that flux surfaces at a comparable number of iterations are somewhat better for the multi-filament model than for the single-filament model at the reference S3 state. The finite build of the coils does not appear to introduce extra resonance perturbations that destroy the properties of the healed coils, which are designed using the single filament model at the present state of PIES convergence. A comparison of Poincaré plots is given in the Physics Design Document, Chapter 3.

Recommendation III-2. Effects of Coil Errors and Other Field Perturbations.

PVR panel report: Study the effects of coil construction errors, and other field perturbations, on flux surfaces in particular, and equilibrium and stability in general.

Recommendation III-3. Symmetry Breaking Field Perturbartions.

PVR panel report: Carry out, where appropriate, calculations of island formation and destruction of surfaces in the full torus, dealing with perturbations that break the 3-fold symmetry.

Project response: The effects of field errors, including symmetry-breaking ones, due to coil construction and assembly errors have been analyzed, using various approaches, to set tolerances and correction coil requirements. A range of in-tolerance coil perturbations, representing potential manufacturing and assembly errors, was analyzed. Low-mode-number (e.g., $m = 2$, $n = 1$) island widths up to 19% in toroidal flux were found to be possible. To mitigate the risk of unacceptable performance impacts, a system of low-mode-number trim coils was added to the stellarator core design. The power supply requirements will be determined after e-beam mapping results become available. An initial system, based on existing supplies available at PPPL, will be implemented thereafter as an upgrade. Further details are provided as an appendix to the Engineering Design Document.

Recommendation III-4. Improved Startup Simulations

PVR panel report: Develop additional self-consistent startup evolutions, using the final coil set, with realistic, time-dependent collisionalities, especially in the evaluation of the bootstrap current.

Project response: A transport model has been incorporated into TRANSP for use in modeling the magnetic flux evolution. A second modification prevents the lower hybrid current, which is used to model the external transform, from impacting the energy balance (via its effect on the Ohmic power).With these tools it is possible to maintain an accurate energy balance while evolving the discharge. New discharge simulations have been developed using these tools. Results are qualitatively similar to work reported at the physics validation review in March, 2001. A stable path to the high beta state with virtually all the current contributed by the bootstrap effect has been obtained with new coil sets. This work is documented in Chapter 9 of the Physics Design Description.

Recommendation III-5. Flux Surface Quality for Multiple Equilibrium States.

PVR panel report: Use these self-consistent start-up scenarios in PIES and other codes to examine flux surface quality and stability properties at a number of points along the evolution path.

Project response: A self-consistent startup scenario has been analyzed with PIES and with the COBRA and TERPSICHORE MHD stability codes to examine flux surface quality and stability properties, as described in more detail in Chapter 9 of the Physics Design Document. Calculations with the COBRA ballooning stability code and with the TERPSICHORE global MHD stability code verify that the plasma is stable throughout the evolution. The flux surface quality has been assessed at five points along the evolution path, ranging from 50 to 303 msec, with beta values ranging from 1.2% to 4.6%. The assessment of flux surface loss uses an estimate of neoclassical effects to correct the island widths calculated by PIES, and takes into account the effect of the finite ratio of cross-field diffusion to diffusion along the field lines in assessing the effects of the islands on confinement. The flux surface quality is acceptable during the evolution. Without trim coils, the flux surface quality is marginally acceptable for some times during the current ramp. The flux surface quality at these times can likely be further improved using trim coils.

Recommendation III-6. Real-Time Reconstruction of Last Plasma Surface

PVR panel report: Develop real-time reconstruction of the last plasma surface from external magnetic measurement, for purposes of real-time control.

Project response: We agree that real-time plasma control is needed and expect this capability to be developed in stages, starting with simpler approaches than real-time reconstruction. The envisioned stages are:

- Linear flux projection (constant coefficients).
- Nonlinear flux projection (plasma parameter-dependent coefficients)
- Real-time reconstruction.

Development of a 3D reconstruction code (recommendation III-7a) is necessary for the development of both flux-projection methods. A ORNL-GA proposal for development of a 3D equilibrium reconstruction code, that encompasses Recommendations III-6, III-7a, and III-7b, has been funded by DOE, and the work is under way.

Recommendation III-7 (a). Develop a 3D equilibrium reconstruction code (V3FIT)

PVR panel report: Develop a 3D counterpart to the EFIT code for reconstructing equilibrium profiles from internal and external experimental measurements.

Project response: We agree that this capability is needed and should be developed. It is also needed for tokamaks and other stellarators. A ORNL-GA proposal for development of a 3D equilibrium reconstruction code, that encompasses Recommendations III-6, III-7a, and III-7b, has been funded by DOE. Work has begun on formulating the problem for stellarator equilibria.

Recommendation III-7 (b). Critical Measurements for Reconstruction

PVR panel report: Identify the critical measurements necessary to accurately reconstruct the equilibrium so that they can be integrated into the NCSX machine design.

Project response: It is anticipated that a variety of magnetic sensors, including Rogowski coils, flux loops, saddle loops, and B-dot probes will be used for reconstruction and eventually for plasma control. Selection of the optimum number, type and location of these sensors will be done in the preliminary design phase, on the basis of numerical modeling (see III-7(a)). As a precursor to the reconstruction code called for in recommendation III-7(a), we will develop V3POST, a post-processor for VMEC equilibrium. This will be used in the generation of simulated signals from trial magnetic diagnostic sets. A database over a reasonable range of plasma conditions will allow us to determine whether the trial diagnostic set can provide the required plasma control. The mathematical formulation of the plasma part is being explored both in VMEC and Cartesian coordinates. This work will not require the very high computational speed and/or computer power needed for the equilibrium reconstruction problem.

Recommendation III-8. Promote 3D tearing mode theory and computation.

PVR panel report: The NCSX Project should promote the development of 3D tearing mode theory and computation.

Project response: The development of the M3D code to address this issue was a topic discussed at the 3D Physics Theory Workshop held January, 2002, in Oak Ridge. In addition, M3D effort has received funding for stellarator work via SCIDAC. This is an issue for long-term research, but there are no issues as far as NCSX design and fabrication are concerned.

Recommendation IV-1. Plan on 6 MW of NBI.

PVR panel report: The Panel recommends that the NCSX team plan on using 6 MW of NBI power as the primary heating source.

Project response: Two beams (3 MW) are included in the baseline project and will be installed and tested for use in the initial heating phase of the experimental program. The facility is designed so that the remaining two beams (for a total of 6 MW) can be accommodated as an upgrade.

Status: The project decided not to increase the baseline neutral beam heating power. The initial 3 MW is sufficient to test beta-limit physics issues, using the machine's flexibility to move stability boundaries to lower beta values. The availability of ready upgrades in either neutral-beam or radiofrequency wave heating power mitigates the risk that the plasma heating may be inadequate. The PVR design point thus provides the appropriate balance between cost and risk considerations. Further details are provided in the appendix to this report.

Recommendation IV-2. Absorbed heating power and flow shear control.

PVR panel report: The present machine design results in significant beam orbit losses. This lowers the absorbed heating power somewhat, and also reduces the room for maneuver in setting up configurations with balanced momentum input or sheared rotation. The Panel recommends that these marginal conditions in the current design, which may limit control of flow shear and optimization of absorbed power, be carefully considered and clear solutions (*e.g.* flexibility in re-orienting the beam lines) be identified prior to the CDR.

Project response: In selecting its reference coil design for the CDR, a high-priority goal was reducing the calculated neutral-beam orbit losses. A design with calculated loss of 1.5 times that the reference plasma was not accepted. The coil design effort was extended by three months to bring the losses down to the level of the reference plasma. The physics goals can be accomplished with this design. Aiming flexibility, which is tightly limited by the beam and machine dimensions, is not available to any significant degree as a solution to this issue. Reduced beam losses wil available for transport and flow shear control experiments by operating at the highest magnetic fields, 1.7 – 2 T.

Recommendation IV-3. Increase the NBI pulse length to 500 ms or more ASAP.

PVR panel report: The Panel thus recommends that the NCSX team plan to increase the NBI pulse length to 500 ms or more as soon as possible.

Project response: The NB power handling surfaces were engineered by ORNL to operate at a maximum of 500 msec pulses at the full power peak power density of 3 kW/cm^2. Both ORNL and PPPL have previously demonstrated the ability to operate with H^0 and D^0 species at this pulse length and power. In addition, experiments at MAST are exploring even longer pulse lengths.

The initial NB injection is for 300 ms. The operations team will handle upgrading from 300 to 500msec during the initial plasma heating phase. Only modest instrumentation and control improvements are need. There may be some small amount of procurement required which cannot be determined until we start bringing up the systems. The schedule for this will be approximately the beginning of the 2nd operating period following first injection. This will allow using the first major maintenance period following the first injection to repair systems and prepare for longer pulse operation. No further work planned at this time.

Recommendation IV-4. Accommodate antennas on the high-field side.

PVR panel report: The Panel recommends that provision to accommodate suitable antennas on the high-field side of the torus be made in the base machine design, with actual deployment of the antenna system coming after the experiments with NBI are well in hand.

Project response: In developing the NCSX conceptual design, the capability to accommodate high-field-side antennas is now considered to be a requirement, and is satisfied by the current design.

Recommendation IV-5. Defer work on HHFW.

PVR panel report: The Panel therefore recommends that work on HHFW for NCSX be deferred to a later stage in the NCSX program.

Project response: Agree. The machine is designed to also accommodate HHFW antennas on the outboard side. The antenna system would be added as an upgrade if needed. More data on this scenario will likely be available from NSTX well before decisions on implementation have to be made. No further work planned at this time.

Recommendation IV-6. Circuit and image currents in discharge scenario calculations.

PVR panel report: The Panel recommends that calculations of the circuit and image current responses be coupled into the development of experimental discharge control scenarios.

Project response: At this time, we do not think this is necessary as part of the conceptual design, as the wall time-constant is much less than the time-scale for anticipated magnetic field changes (by design). This will be developed and investigated during preparation for operations. No further work planned at this time.

Recommendation IV-7. Edge modeling and neutral penetration.

PVR panel report: The Panel recommends that, now that the general magnetic configuration has stabilized, an intensive investigation of the neutral penetration issue be carried out. This would involve detailed study of the 3-D field structure and application of existing edge physics models in appropriate frames of reference, and comparison with relevant experimental results, especially those from Wendelstein 7AS, which has a similar edge topology. The Panel notes that this project would be an excellent target for expanded collaboration with the US edge physics and stellarator community as well as with overseas stellarator programs.

Project response: The transport of neutrals from recycling surfaces into the SOL and core plasma of NCSX is studied with a Monte Carlo neutrals code. Although fully three-dimensional simulations are in preparation, the work carried out so far is limited to two-dimensional calculations. Effects of the 3-D geometry are determined with calculations in toroidally axisymmetric geometry for various poloidal cuts combined with a toroidal midplane cut. Particular attention is focused on neutral penetration of the radially thin region near the "bean" cross section (ϕ=0). In addition, we have implemented a fluid neutrals model in the 3-D BORIS code developed at IPP Greifswald. In the next step the 3-D fluid results will be benchmarked with 2-D Monte Carlo results and the latter will be expanded to 3-D. Results of all calculations are described in some detail in Chapter 10, "Power and Particle Handling", of the Physics Design Description.

While the neutrals calculations look very promising, even more convincing are the experimental results of W7-AS which has a much smaller full-width at the radially thin cross section. The minimum waist full-width of NCSX is at least 24 cm for all M45 configurations. The W7-AS plasma has a waist that is about 14-17 cm minimum full-width, depending on the configuration, and yet, with the new divertor, W7-AS obtains excellent plasma parameters with no indication of detrimental neutrals interactions. One also has to keep in mind that the neutral penetration in a stellarator, where the narrow waist regions are toroidally localized, is much less than it would be in an axisymmetric device with the same minimum waist width. Close contacts, especially with the W7-AS group, have been established. The project has encouraged and supported international collaboration on this topic.

Further details on NCSX edge physics modeling are documented in the Physics Design Document, Chapter 10.

Recommendation IV-8. Relate program physics issues to diagnostics.

PVR panel report: The Panel recommends that prior to the CDR the NCSX team develop a matrix relating the key program physics issues to the diagnostic requirements to investigate them, as well as the geometric access required to perform the measurements. This will facilitate setting priorities, staging, and even port allocation, and will also catalyze the expansion of collaborative relationships with the US and international fusion communities by providing accessible entry points.

Project response: The project has developed an experimental plan at a level of detail appropriate for current design purposes. It is documented in “Mission, Experimental Plan, and Preparations,” where the measurement needs and diagnostics required for each phase of the program are identified. The Diagnostics section (WBS 3) of the Engineering Design Description documents the requirements in detail as well as a start of the geometrical access requirements for diagnostics in the plan.

In addition, we have begun to integrate diagnostic access requirements with the VV and coil design for particular diagnostic systems included in the diagnostic implementation plan with initial assessments of sightlines and fields of view obtainable, and identified critical issues. The magnet design was modified to improve diagnostic access to symmetry planes; all six symmetry planes are now accessible for viewing. Particular attention has been given to diagnosing the 3D nature of the plasma.

Recommendation IV-9. Rapidly deployable electron beam flux surface mapping.

PVR panel report: Because of the special concerns about flux surface robustness at low aspect ratio, the unique magnetic geometry of NCSX, and the anticipated use of trim coils to fine tune the magnetic configuration in the presence of both predictable and discovered perturbation fields, the Panel recommends the deployment of a system for convenient, rapid electron-beam flux surface measurements as part of the permanent operational equipment of the machine. Such a system should use retractable components so that it can be operated without causing major interruptions to plasma operation.

Project response: Several concepts are being considered for tlux surface mapping, and design requirements are being defined. One of the design requirements is the capability of deployment without venting the machine. The concept that was the basis for cost estimates is documented in the Diagnostics section (WBS 3) of the Engineering Design Description.

Recommendation IV-10. Integrate magnetic diagnostics and analysis with the design.

PVR panel report: Experience on other toroidal confinement experiments indicates that measurements of the changes in the magnetic field induced by the plasma provide the basis for the reconstruction of equilibria, physics analysis, and ultimately optimal control of plasma performance. The Panel recommends that the development of magnetic diagnostics and analysis be integrated with the configuration and engineering design process.

Project response: Early in the preliminary design, detailed modeling is planned to ascertain the optimum number, type, and placement of the sensors needed for equilibrium reconstruction and control. It is important to do this work, because it may be very difficult to add sensors in some locations, particularly outside the vacuum vessel, after the machine is fully assembled. The computational tools development needed to perform this analysis will be funded by the NCSX Program. [See Recommendations III-7(a) and (b).] Space has been reserved for in-vessel sensors, between the PFCs and the inner surface of the vacuum vessel. Similarly, consideration has been given to reserving port space for electrical feedthroughs.

Recommendation IV-11. Turbulence and flow measurements.

PVR panel report: The QAS configuration was chosen in large part because of its predicted capacity to support sheared flows like those developed in enhanced confinement tokamak plasmas in which turbulent energy transport is greatly reduced. The Panel thus recommends that measurements of turbulence and flow with sufficient spatial resolution to address key physics questions should play a more prominent role in the diagnostics program than appears to be the case at present.

Project response: As shown in the Diagnostics section (WBS 3) of the Engineering Design Description (Tables 2.3.1.2 and 2.3.6.1), the current diagnostic implementation plan calls for toroidal and poloidal flow measurements in Phase 4, the Initial Auxiliary Heating Phase, along with several other key profile diagnostics. The current concept calls for high-resolution poloidal and toroidal CHERS measurements using a diagnostic neutral beam. Profile diagnostics are needed for many areas of research, including interpretation of turbulence measurements. Turbulence diagnostics are planned for Phase 5, along with research topics concentrating on Confinement and Beta Push. Development of new turbulence measurement techniques with high spatial and spectral resolution is currently a very active area of research, and it is thus appropriate to consider the diagnostic technique as “TBD” at this stage, ~8 years before implementation.

Recommendation IV-12. Diagnostics for a 3D configuration.

PVR panel report: The three-dimensional nature of the stellarator configuration places additional demands on diagnostic development, favoring the use of multi-view and large area imaging systems. The Panel recommends that greater consideration be given to the specifications of such systems in preparation of the detailed experimental program.

Project response: We agree that the stellarator has special features that affect the optimization of the diagnostic configuration. We have taken these into account and identified solutions in the course of developing the diagnostic configuration for the CDR. In addition, we have integrated diagnostic access requirements with the VV and coil design for particular diagnostic systems included in the diagnostic implementation plan and have identified critical issues. The magnet design was modified to improve diagnostic access to symmetry planes; all six symmetry planes are now accessible for viewing.

Recommendation V-1. Adopt a More Inclusive Management Approach

PVR panel report: The PPPL/ORNL partnership has been successful in developing the NCSX pre-conceptual design. However, looking forward to the CDR and beyond, we recommend that a more inclusive management approach be adopted to successfully implement the CS PoP program with NCSX playing the primary organizing role. The NCSX management should try to involve all elements of the US and international stellarator activities to form a truly National CS Program with international collaborations. This should include both experimental and theoretical activities. For example, (i) more direct contact and collaboration with existing stellarator experiments is needed to solidify the physics and operational base for the Conceptual Design; (ii) opportunities exist to benchmark the PIES code against similar codes (*e.g.* HINT at NIFS in Japan) and against experimental stellarator results; (iii) serving as a focus for or supporting organizing efforts in the theory community to more effectively address 3D magnetized plasma physics; and (iv) making plans to begin establishing a national experimental research team to carry out experiments on NCSX.

Project response: While NCSX project management focuses on its responsibility to construct the NCSX facility and, ultimately, to carry out the experimental research on NCSX, the project also works to encourage strong programs in 3D theory, 3D diagnostic development, and international collaboration on stellarators. Specific measures:
1) The Project has been working with the International Collaboration leadership at PPPL and ORNL in the planning of collaborations with LHD and W7-AS. As a result, existing theory collaborations, including PIES-HINT benchmarking, have already been strengthened. An experimental collaboration is planned to participate in the final campaign of W7-AS. This will take place immediately after the CDR.
2) The Project worked with the Theory Program leadership (Don Batchelor and others) and support their efforts in organizing a successful 3D Physics Theory Workshop in January, 2002, in Oak Ridge.
3) The NCSX Program Advisory Committee's charter has been revised, broadening it to encompass other PPPL stellarator activities and to provide the opportunity for stellarator groups outside of PPPL to make presentations if they wish. The PAC-5 meeting in November included presentations and discussion on theory and collaboration.
4) The stellarator community is working with the ICC community to prepare for the Snowmass meeting on burning plasmas in July.

In summary, specific steps have been taken to adopt a more inclusive management focus. This will receive continued attention, but there are no issues as far as NCSX design and fabrication are concerned.

Recommendation V-2. Comprehensive compact stellarator reactor study.

PVR panel report: The FESAC Program & Balance Report set out a 10-year goal to "Determine attractiveness of a Compact Stellarator by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3-D divertor operation." We find that the CS PoP program plan presented to us by the Project is aimed at meeting this goal, and that NCSX is the central element in that plan. However, we note that other supporting elements are called out including theory and modeling support, and CE level experimental programs (some of which are already funded projects by DOE). In addition to these elements listed by the NCSX Project, we recommend that a comprehensive CS fusion reactor design study be included in the PoP plan as an important element in achieving this FESAC 10-year goal to determine the attractiveness of the CS concept.

Project Response: Comprehensive reactor design studies are an element of the proposed compact stellarator proof-of-principle program. Up to now, limited compact stellarator reactor extrapolation studies have carried out by the project; those were documented in the PVR documentation. Future reactor studies will be led by the ARIES team and should be based on a CS magnetic configuration that is optimized as a reactor, which needs to be developed as a first step, before a comprehensive study is undertaken. NCSX project leaders and PPPL management are working with the ARIES team to develop a plan for preparatory work, starting after the CDR, and a CS reactor study. This is a programmatic issue which will receive our continued attention, but there are no issues as far as NCSX design and fabrication are concerned. (Also see response to Recommendation II.3.)

Recommendation V-3. OFES and FESAC decision processes.

PVR panel report: We note that the PoP Panel endorsed classification of the CS as a PoP program. We recognize that construction of NCSX would be a relatively costly investment over many years by the Fusion Energy Sciences Program. Therefore, we recommend the OFES and FESAC address the larger programmatic issues to determine whether or not to proceed with construction of NCSX and, if so, on what time scale. These include the issue of program balance within available fusion program budgets, needs of present elements in the program, and opportunities for other new starts and collaborations.

Project response: The stellarator community presentations to FESAC in May and August, 2001, explained the program goals, the purpose of each element of the program and their interrelationships, the costs, and the program's expected benefits to fusion science and energy. The FESAC endorse the PoP panel recommendation to designate NCSX as a PoP experiment, and the Office of Fusion Energy Sciences approved Critical Decision 0, Mission Need, authorizing the start of conceptual design. The project will continue to support decision processes, but there are no issues as far as NCSX design and fabrication are concerned.

Appendix
NCSX SIZE AND HEATING REQUIREMENTS
May, 2002

1. Introduction

The Physics Validation Review committee was concerned about the size and heating power planned for NCSX and recommended that the project give continued attention to these issuse:

> *PVR panel Recommendation II-2:* There is concern that the present pre-conceptual design point may be "too small." This view is due to the marginal parameters in NCSX across a broad spectrum of experimental design factors such as: high energetic NBI ion losses, low base heating power, confinement assumptions needed to reach design beta, very small plasma/pfc distances for some equilibria, and neutral penetration concerns. We recommend that as the Project prepares for a Conceptual Design, the size of the design be carefully considered and well justified at the time of the CDR to allay concerns that critical parameters are being fit within a predefined budget envelope.
>
> *PVR panel Recommendation IV-1:* The Panel recommends that the NCSX team plan on using 6 MW of NBI power as the primary heating source.

Following the PVR, machine configuration design was changed in various ways to provide better physics capabilities. The number and arrangement of coils and ports was changed to improve diagnostic access and more space was provided in the vacuum vessel for divertors and radio-frequency wave launchers. However, the project decided not to increase the machine size or baseline neutral beam heating power for the following reasons:

- The PVR design point is sufficient to satisfy physics requirements.
- Margins could increased through design improvements without increasing the size.
- While there are physics benefits to increasing the size or power, doing so would increase cost and probably delay the program.
- The PVR design point provides the appropriate balance between cost and risk considerations.

2. Adequacy of Heating

The NCSX baseline includes 3 MW of balanced neutral beam heating power and the ability to accommodate a total of up to 6 MW through future upgrades. The design is based on use of the 4 existing PBX-M neutral beams. Up to 6 MW of radiofrequency wave heating power can also be accommodated as an upgrade, using existing sources. Beam-orbit loss considerations set the minimum useful magnetic field for a given machine size. For the NCSX design point with major radius R = 1.4 m, the minimum magnetic field B_0 = 1.2 T. In that case the calculated neutral beam orbit loss fraction is 24% (18% of the counter-injected power and 30% of the co-injected power), based on Monte Carlo beam deposition and slowing-down calculations for the reference fixed boundary plasma. The NCSX modular coils presented at the conceptual design review have been designed to produce a free-boundary plasma equilibrium with the same physics properties as the reference, including the same beam orbit losses as calculated for standard conditions.

These losses were taken into account in analyses that involve confinement predictions (Physics Document, Chapter 7). With 3 MW injected and a confinement time of 2.9 times ISS95 stellarator empirical scaling, or equivalently 0.9 times ITER97P tokamak L-mode scaling, plasma conditions with beta $\langle\beta\rangle = 2.6\%$ and collisionality $\nu_I^* = 0.25$ are predicted. If the density is allowed to rise to the stellarator density limit (Sudo scaling), $\langle\beta\rangle = 2.6\%$ is predicted to be achievable with an ISS95 enhancement factor of 1.9 and a relatively high collisionality. While the NCSX design is optimized around a $\langle\beta\rangle = 4\%$ configuration, there is sufficient flexibility to test beta limit physics at lower values, i.e. to less than 2%, by modifying the plasma shape (Physics Document, Chapter 8). If the plasma heating should prove inadequate to fully explore the physics, it can be increased by installing more heating power, either neutral beams or radio-frequency, as an upgrade. With 6 MW of injected neutral beam power and an ISS95 enhancement factor of 2.9, or equivalently an ITER97P enhancement factor of 0.9, plasma conditions with beta $\langle\beta\rangle = 4\%$ and collisionality $\nu_I^* = 0.25$ are predicted.

These analyses indicate that the baseline design point with R = 1.4 m and 3 MW of initially installed neutral beam heating power will enable the critical physics issues to be addressed. The program will need to develop operating experience at the 3 MW level before it could productively use higher power levels. The ability of the design to accommodate readily available heating power upgrades mitigates the risk of the power being inadequate. Thus, the project's plan is well matched to the needs of the program.

It is the case that there would be physics benefits in increasing the major radius. A larger machine would provide a wider operating range in magnetic field, which would mean greater flexibility and access to higher plasma parameters and lower collisionalities. However, it would come at a considerable increase in machine cost and likely program delay. Since the PVR design point is sufficient for the needs of the program, incurring the additional cost and delay is not warranted.

3. Neutral Penetration

Neutral penetration was among the concerns expressed by the PVR panel in connection with size. The PVR panel recommended more extensive edge and neutrals modeling:

> *PVR panel Recommendation IV-7:* The Panel recommends that, now that the general magnetic configuration has stabilized, an intensive investigation of the neutral penetration issue be carried out. This would involve detailed study of the 3-D field structure and application of existing edge physics models in appropriate frames of reference, and comparison with relevant experimental results, especially those from Wendelstein 7AS, which has a similar edge topology. The Panel notes that this project would be an excellent target for expanded collaboration with the US edge physics and stellarator community as well as with overseas stellarator programs.

The project's studies in response to this recommendation are fully documented in the Physics Document, Chapter 10. An important requirement for the NCSX design is that the neutrals generated at the plasma boundary do not penetrate too far into the plasma discharge for a reasonable range of operating parameters. Modeling calculations at the time of the PVR showed the importance of controlling the location of recycling sources. A design objective is to ensure that recycling occurs at the banana tips or the mid-plane of the bullet cross section and not the mid-plane of the banana cross section where the plasma is narrowest. New neutral transport calculations of the spatial distribution of neutrals for various source and sink locations are documented in detail in Chapter 10.

Neutrals control in NCSX looks promising when compared with the recent experimental results on W7-AS [P. Grigull, EPS 2001]. The W7-AS has only about ~18 cm diameter in the midplane of the bean-shape cross-section (*vs* ≥24 cm in NCSX). Even before it had a divertor, the W7-AS experiment had obtained temperatures up to ~2keV (and peak T_e as high as 5keV) with a minimum waist diameter of about 14-17 cm, depending on the configuration. With the recent island divertor operation, density control and plasma collapse which used to be a problem in W7-AS before the installation of the divertor, has been solved due to a combination of recycling control and particle confinement. It appears that the divertor plates and baffles provide the needed neutrals control at the source so that the neutral penetration at the midplane should not be a machine size determinant but careful design of the PFC configuration and location are important for neutral control.

4. Adequacy of Access

The overall machine size affects the access for personnel, heating (particularly beam heating) and diagnostics. The status of the access for the NCSX configuration and size are summarized below for each of these areas.

A. For Personnel

Personnel entry access into the vacuum vessel is not limited by the present size of the machine. Ports have been provided specifically for this purpose. The present design provides adequate space and maneuvering room inside the vessel for installation and maintenance of in-vessel hardware.

B. For Neutral Beams

The neutral beam optics has been modeled for the PBX neutral beams in the NCSX geometry. The modeling uses the measured PBX beam characteristics as input. The beam "footprint" size is not small compared to the plasma cross section, as shown in the following figure, but does enclose ~96% of the injected power from the most poorly focussed beam. The geometrical modeling supports the conclusion that the R = 1.4 machine size is adequate, although marginal and likely to be limited in aiming flexibility.

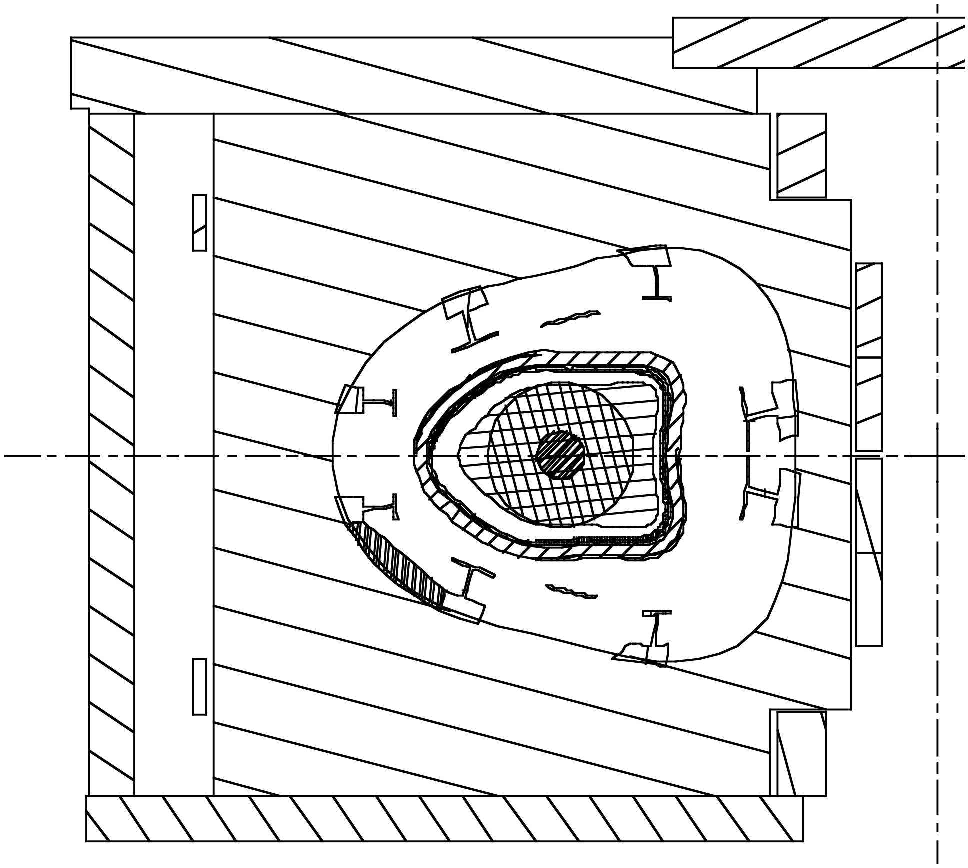

Figure 6. NBI footprint (circles) for the most poorly focussed beam superimposed on the oblate plasma cross section. The larger circle encloses ~96% of the injected power, the smaller circle encloses 47%.

C. For Diagnostics

Diagnostic access in NCSX is challenging due to the complexity of the stellarator geometry, and not so much because of the size. The challenge has been addressed in the conceptual design, which provides ports for a complete set of diagnostics. The situation has improved since the PVR because the18-coil design is significantly better for diagnostic access than the 21-coil design presented at the PVR. Fewer coils obviously means more space between coils, but more importantly the new design has its TF coils at the same toroidal angles as the modular coils instead of midway in between and it has no coils on symmetry planes. Diagnostic access to symmetry planes, which are the most valuable locations for stellarator diagnostics, is substantially improved as a result of these changes. These improvements have come about through design optimization, not increasing the machine size.

5. Summary

The project's analyses indicate that the physics requirements can be satisfied, and the physics mission accomplished, at the PVR design point. While a larger machine would indeed provide some physics benefits, such as access to lower collisionalities and improved access for neutral beams and personnel, it would come at a significantly higher cost. Performance margins have been increased more cost-effectively by design improvements since the PVR. The capability to accommodate ready heating upgrades, either NBI or rf, mitigates the risk of any potential inadequacies in the baseline heating complement. The PVR design point and baseline heating configuration thus provides the appropriate balance between cost and risk considerations and has been retained.