Report of the NCSX Review Committee

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Executive Summary

The NCSX Review Committee was appointed by the Fusion Energy Sciences Advisory Committee to respond to a charge from Dr. Raymond Orbach, Under Secretary of Science, US Department of Energy, that was issued on August 9. Details of the charge, and the procedures used by the Committee in its deliberations, may be found in the text of this report. The present summary provides a condensed version of the Committee's answers to each question (shown in boldface) in the charge.

1. Critical issues for the US compact stellarator program

a. What unique toroidal fusion science and technology issues can a compact stellarator program address independent of its potential for a reactor concept?

Stellarator research programs have the generic mission of studying a confinement system that addresses two key issues in fusion energy research: disruption avoidance and steady-state operation. This mission is approached by means of plasma shaping in three dimensions, sacrificing the axial symmetry of the tokamak, and thus allowing scientific exploration of the opportunities and penalties associated with three-dimensional geometry. The scientific issues to be addressed in the program include transport, energetic particle confinement, equilibrium, stability and density limits (including disruption avoidance), and particle and power handling. Technology issues to be explored include simpler magnet coils and support structures, metrology, correction coils and divertors.

The *compact* quasi-axisymmetric stellarator is distinctive in having relatively small aspect ratio – typically less than five. In this respect its geometry approaches that of a tokamak, and indeed the scientific and technical similarity with the tokamak, along with improved cost-effectiveness, provides the main scientific impetus for compactness: there is no strong motivation for low aspect ratio from the perspective of stellarator physics. One expects experiments on a compact stellarator to provide particular insights into tokamak physics; and similarly one expects existing knowledge of tokamak behavior to benefit particularly a compact stellarator research program. The Committee finds these potential mutual rewards to be plausible and significant.

b. What are the advantages and disadvantages of the quasi-symmetric stellarator as a potential fusion system concept? What unique features does the compact stellarator offer in this regard?

Stellarators offer the important advantages of steady-state operation with relatively soft and forgiving stability limits – advantages that might become especially important as the international fusion program begins to study the DEMO device that is expected to follow ITER. Quasi-symmetry reduces the effective radial widths of particle drift-orbits, thereby ameliorating the large neoclassical transport rates associated with more conventional stellarator designs. Because it allows for decreased zonal-flow damping, quasi-symmetry may also reduce turbulent transport rates, although this apparent advantage requires more study.

The key disadvantage of the stellarator is the complexity and cost of its field coils, whose precise construction and alignment are essential for acceptable confinement. Compactness exacerbates this problem, in that the increased toroidicity for a given rotational transform makes the flux surfaces more fragile. The Committee points out that present coil designs significantly complicate external access to the plasma and to the plasma blanket, for maintenance or other purposes, in a stellarator reactor.

A study by the ARIES team indicates somewhat smaller construction and operation costs for a compact stellarator, compared to a stellarator with large aspect ratio. At the same time it is recognized that, at this early stage of investigation, there remain many unanswered questions about compact stellarator reactor performance. In particular the smaller surface to volume ratio associated with compactness is disadvantageous with regard to heat removal and tritium self-sufficiency.

c. What scientific and technical issues need to be resolved to evaluate the compact stellarator as a viable concept for a fusion energy system?

Many issues, detailed in the body of this report, will need to be addressed in the design of a stellarator for fusion energy production. Three issues of particular note for compact stellarators as a fusion concept are: determination of the size scaling of confinement; the required tolerances for coil construction; and the magnitude of plasma current below which disruptions due to plasma instabilities are avoided.

2. Role of NCSX in the international context:

a. What critical, unique contributions does NCSX offer for addressing the issues identified in (1)?

NCSX is designed to address most of the critical physics and technology issues discussed in this report, using a compact, quasi-axisymmetric configuration that is unique in the world stellarator program. The Committee finds that, assuming successful construction and testing phases, the NCSX device is likely to perform at a level sufficient to address its scientific and technical missions. Therefore the Committee expects the NCSX experimental program to have a profound impact on stellarator research worldwide.

There are several methods to ameliorate the large orbital excursions that can degrade confinement in non-axisymmetric systems. Quasi-symmetry, the approach now favored in the US, itself includes several varieties: quasi-poloidal symmetry (QPS), quasi-helical symmetry (QHS) and quasi-axial symmetry or quasi-axisymmetry (QAS). NCSX is the only experimental device in the world program that would employ the QAS concept.

By virtue of both QAS and compactness, NCSX offers a similarity to tokamak science that is unmatched by any other stellarator device. In this regard, the hybrid nature of NCSX confinement – that is, dual origin of its rotational transform, which is produced partly from external coils and partly from plasma currents – should allow a particularly instructive research program. Similarly its resemblance to the tokamak should allow NCSX to illuminate a number of issues concerning symmetry and effects of symmetry-breaking on confinement.

NCSX is a Proof-of-Principle (PoP) class experiment, minimally sized to provide credible integrated confinement and stability results. Thus it is larger than such stellarators as HSX at the University of Wisconsin-Madison, but smaller than, for example, the DIII-D National Tokamak Facility, and the stellarators W7-X (Germany) and LHD (Japan). Comparative studies of the three major lines in the international stellarator program – LHD , W7-X , and NCSX – will inform a decision on which system has the highest reactor potential, and thus influence discussions on the continuation of the fusion program toward the DEMO reactor.

b. Given PPPL's [Princeton Plasma Physics Laboratory's] proposed plans for operation of the National Spherical Torus Experiment [NSTX] and NCSX, what would be the timetable for resolving relevant issues identified in (1) above?

NCSX plans to achieve its first plasma in 2012, two years before W7-X and four years before ITER. For the following several years, the NCSX team plans to alternate its operation with that of NSTX; thus the key initial experimental results for NCSX would be obtained in FY2013 and FY2015. The Committee is concerned about the practical realism of this plan; we find in particular that the resolution of key experimental issues is likely to require five years of actual operation.

One technical requirement that the Committee considers likely to affect the timeliness of physics results is the quality of the magnetic flux surfaces in three-dimensional geometry. The NCSX team has developed appropriate strategies, involving both assembly procedures and the use of an array of trim coils, for constructing and maintaining flux surfaces with relatively few magnetic islands and relatively small chaotic regions. While finding these strategies to be well thought out, the Committee recommends that attention to construction details that may affect flux-surface quality, and the study of their effects and methods to counteract them, remain top priorities for the project.

c. What are the technical differences of the current NCSX design compared to other stellarators operating or being built abroad? What is the significance of these differences? Does NCSX fill a critical void in the development of the stellarator concept as a viable fusion energy system?

As pointed out earlier in this summary, NCSX will be unique in the world stellarator research program, because of both its quasi-axisymmetry and its compactness. The W7-X device uses a distinct configuration optimization, has a large aspect ratio, and moreover is designed to minimize plasma currents (recall that NCSX will depend upon self-induced plasma current for a fraction of its rotational transform). The LHD device achieves reduced orbital excursions by means other than quasi-symmetry; it has a intermediate aspect ratio. Both W7-X and LHD employ super-conducting magnets. The Committee finds that the comparison of these three devices will be extremely useful in understanding the physics optimization of advanced stellarator configurations.

3. Options for the US stellarator program

a. If the NCSX program were not continued, what options would exist or would be possible to address the key issues of the quasi-symmetric stellarator in general and the compact stellarator in particular?

The present US stellarator research program includes other devices, planned or in operation, that could address at various levels a subset of the key issues listed in the response to question 1. However no US experimental program, present or planned, could provide the breadth of scientific and technical information that is expected to come from NCSX. The only PoP scale device in the US repertoire that addresses quasi-symmetry is NCSX, and NCSX is the only such device capable of examining the key issues in an integrated context. Therefore, if NCSX were abandoned, the US would have to reduce significantly its ambitions in stellarator research, or begin constructing a new PoP stellarator experiment.

The Committee finds it important that the US have a significant stellarator presence as part of its magnetic fusion energy research program. The Committee notes that at present about 75% of the US stellarator effort is focused on the construction of NCSX, so the loss of NCSX would change the basic character of the US program. The program would lose its integrated PoP facility and the most relevant connections to tokamak research.

b. Assuming NCSX is not available, what program elements would be required to maintain the US as a significant participant in the international stellarator program?

i. Identify potential opportunities for US leadership.

ii. Include more international collaboration as appropriate.

The US has the only operating quasi-symmetric stellarator device in the world, the HSX at the University of Wisconsin-Madison; it allows fundamental tests of quasi-symmetry and can span a range of symmetry-breaking geometries. The CTH device is a low aspect-ratio stellarator at Auburn University that is used to study passive disruption avoidance. Both of these relatively small experiments provide valuable scientific information, and both could be upgraded, but neither could provide the sort of integrated research program of a PoP device like NCSX.

The proposed QPS device at Oak Ridge National Laboratory is a low aspect ratio stellarator with quasi-poloidal symmetry. It has some similarity with the (much higher aspect ratio) W7-X device; furthermore it should allow strong poloidal flows, unlike those seen on existing toroidal confinement experiments. Thus QPS could extend the stellarator data base in a useful way. But it would not replace the scope of the NCSX program, in particular having much weaker links to tokamak behavior.

The Committee recommends that the construction decision on QPS be expedited if NCSX is cancelled. However, we find it illogical to cancel a stellarator project that is nearing its final construction phases only to begin a new stellarator with poloidal rather than toroidal quasi-symmetry.

In the absence of NCSX, a restructured US stellarator program could maintain scientific leadership in selected research topics, but would have difficulty playing a significant role in the direction of worldwide stellarator research. International collaboration is already a key element of US stellarator research and would remain so in the absence of NCSX. However, the benefits gained from such collaboration would be diminished without a domestic stellarator experiment on the PoP scale.

Quasi-symmetry is one of many ways to optimize 3-D configurations; other optimization schemes could be pursued. If NCSX were discontinued, the US stellarator program should consider a variety of approaches to stellarator optimization in proposing a new PoP stellarator project.

The US has been a leader in theory and computation on three-dimensional confinement, in large part because of the impetus provided by the NCSX and QPS design programs. There are many opportunities for useful theoretical and computational advance, and encouragement by the Office of Fusion Energy Sciences of such research would help the US maintain its presence in the international effort. However, the loss of a world-class experiment in the US would hurt the recruitment of young scientists into stellarator theory.

Introduction

The NCSX Review Committee was formed in response to a charge to the Fusion Energy Sciences Advisory Committee (FESAC) from Dr Raymond Orbach, Under Secretary for Science at the Department of Energy (DOE), issued on August 9, 2007. The full charge is appended to this report (Appendix A); it requests FESAC to "conduct a scientific and programmatic review focused on evaluating the NCSX program and its potential effect on the US fusion energy sciences program." The charge lists four detailed questions concerning technical and scientific aspects of (i) compact stellarator research, and (ii) the NCSX program specifically.

It was decided from the start, in discussion with Dr. Fonck, Associate Director of the Office of Fusion Energy Sciences, that the Review Committee would focus its attention of the first three of the four questions; these questions are repeated as headings of the three numbered Sections in the Committee's report that follows.

The ten members of the Review Committee are listed in Appendix B. The membership includes prominent scientists and engineers from laboratories, universities and private industry. Leading stellarator researchers from the US, Europe and Japan are Committee members, as well as scientists working outside the stellarator program.

The Review Committee began its work by reviewing a large body of technical literature: technical articles on stellarators and NCSX from the published literature; unpublished reports and presentations on the NCSX program, including the May 2001 FESAC Report of the NCSX Physics Validation Review; and a special summary report, prepared as a service to the Committee by the ARIES team. In addition, members of the NCSX team provided documents addressing each question raised in the Review Committee's charge. The Committee takes this opportunity to thank the ARIES and NCSX scientists for their time and effort in compiling this extremely helpful material.

Most of the Review Committee's discussions were conducted by teleconference and email. (Email correspondence was simplified by a Review Committee email reflector, set up with help from the US Burning Plasma Organization, whom we thank.) The Committee met once at the NCSX experimental site at the Princeton Plasma Physics Laboratory (PPPL). The site visit included extensive presentations by members of the NCSX team addressed specifically to the Committee's charge, as well as a brief tour the NCSX construction.

All members of the Review Committee participated in the discussion of each charge question, and all members agreed to the conclusions presented in this report.

Before addressing the specific questions in the Charge, we survey the scientific and programmatic context of the NCSX project.

The US stellarator program has chosen a research path that emphasizes simultaneously two design principles: quasi-symmetry and compactness. A quasi-symmetric configuration is one in which the magnitude of the magnetic field in a particular direction along the torus is roughly constant even though the components of B are not. Such a device combines the inherent steady-state nature of the stellarator as a magnetic confinement scheme for fusion with the good single-particle confinement of a tokamak. The main element of the program is the PoP experiment under construction, NCSX at Princeton Plasma Physics Laboratory (PPPL), which is quasi-symmetric in the toroidal direction (quasi-axisymmetric, or QAS).   The other experimental elements of the program are the quasi-helical HSX at the University of Wisconsin-Madison, which is operating and the quasi-poloidal QPS at the Oak Ridge National Laboratory (ORNL) which is under prototype development but not yet approved for construction. In addition, CTH at Auburn University is a nonsymmetric stellarator with ohmic heating that is exploring equilibrium and stability issues that are relevant to the operation of a compact stellarator with substantial plasma current. The designation of “compact” within the framework of the US stellarator program typically means that the aspect ratio is less than five. Only HSX has an aspect ratio greater than this. The other key elements of the US compact stellarator program are theory and computation.

1. Critical Scientific Issues For The US Compact Stellarator Program:

a. *What unique toroidal fusion science and technology issues can a compact stellarator program address, independent of its potential for a reactor concept?*

Tokamaks rely on plasma shaping in the poloidal and radial directions to improve plasma stability and confinement. The compact stellarator program utilizes additional shaping of the magnetic surfaces in the toroidal direction to explore the potential science, technology and reactor benefits as well as possible challenges. The scientific issues to be addressed in the program include disruptions, transport, energetic particle confinement, equilibrium, stability and density limits, and particle and power handling. Technology issues to be explored include simpler magnet coils and support structures, metrology, correction coils and divertors. While operating stellarators at an aspect ratio comparable to tokamaks may help elucidate differences in scaling laws, transport and stability, there is no strong motivation for low aspect ratio from the perspective of stellarator physics. Rather, the incentives for compactness are a stronger tie to the tokamak database and the prospect that lower aspect ratio will decrease capital costs and lead to a more economical fusion reactor.

Disruptions: Quasi-axisymmetric stellarators like NCSX would have large bootstrap currents. Disruptions in currentless stellarators are generally not observed, even when operated at betas above the ideal stability limits. The key issue for these devices is to determine at what level of free energy in the magnetic field due to plasma current do disruption-like effects begin to appear. Stellarators with plasma current can also contribute to understanding and controlling tokamak instabilities such as Neoclassical Tearing Modes (NTM) (which limit many tokamak operating regimes) and Edge Localized Modes (ELMs) (which may limit the lifetime of plasma-facing components in large-scale tokamaks).

Transport: While tokamaks have good particle confinement due to symmetry in the toroidal direction, conventional stellarators have poor neoclassical transport properties at low collisionality because of the breaking of that symmetry. The innovative concept of quasi-symmetry bridges the gap between stellarators and tokamaks by restoring a direction of symmetry in the magnetic field magnitude. Results from the HSX experiment with quasi-helical symmetry at moderate aspect ratio have demonstrated reductions in plasma flow damping, particle transport and electron thermal conductivity.

As neoclassical transport is reduced, it is anticipated that turbulent-driven transport (so-called "anomalous" transport) as seen in tokamaks will become increasingly important for the compact stellarator program. Tokamak transport is believed to be strongly influenced by the presence of large-scale plasma flows. With quasi-symmetric stellarators, anomalous transport could be strongly affected in the same manner as in tokamaks because there is now a direction of symmetry along which plasma can flow. Zonal flow damping in such configurations may also be reduced. A stellarator with the capability to heat with or without applied torque in a magnetic configuration with varying degrees of quasi-symmetry should be a powerful physics tool for understanding flows and their role in plasma confinement. Once the character of the turbulence in stellarators is understood, the design tools created to optimize quasi-symmetry might also be applied to optimize the magnetic geometry for neoclassical and anomalous transport simultaneously.

Energetic Particle Confinement: Another issue related to transport is that of energetic particle confinement. Ripple and stochastic transport are issues for high energy particles in tokamaks and needs to be explored in the compact stellarator program as well. How susceptible energetic particles are to Alfvenic instabilities needs to be addressed. Whether fast particle losses can be mitigated by operation at higher densities in stellarators or by other means also needs to be explored.

Equilibrium: There is some indication that equilibrium limits in stellarators may be set by the degradation of magnetic surface quality. The response of the plasma to magnetic perturbations is a cross-cutting issue with ties to the tokamak program. A key element of the compact stellarator effort is to accurately reconstruct the 3D magnetic equilibrium from magnetic coils and other diagnostics. Such capability would be beneficial to tokamaks which also exhibit signs of 3D behavior. At present, the CTH stellarator is the primary test bed for this work. An important addition to the 3D reconstruction effort would be the inclusion of magnetic islands in the equilibrium.

Stability and Density Limits: Experimental evidence indicates that operational limits of pressure and density in a stellarator are relatively benign and lead to degraded performance, in contrast to tokamaks where encounters with the operational boundaries can lead to termination of the plasma. A volume-averaged beta of 5% was recently achieved in LHD, which is above the calculated limit for ballooning modes. Plasma pressure in conventional stellarators is not limited to the linear ideal MHD stability threshold. A compact stellarator experiment with significant bootstrap current needs sufficient auxiliary heating to reach the theoretical beta limit and a long enough pulse length so that the total rotational transform remains steady. Data from such an experiment would also allow correlation with the extensive database of tokamak stability. Similar arguments also apply to density limits. The density limit in tokamaks and stellarators may eventually be shown to arise from radiative cooling of the plasma edge; however, the limit often leads to disruption in tokamaks, while in stellarators, the plasma simply collapses from recombination. Experiments are needed to test the density limit in compact stellarators with plasma current.

Particle and Power Handling: A key challenge for stellarator design is to deal with the heat and particle fluxes in the complex 3-D magnetic configuration. It is important to assess these issues in a plasma that is sufficiently opaque to neutrals and has sufficiently high heat fluxes so that both the confined plasma and the edge plasma are in regimes interesting for fusion. In a compact stellarator design, it should be possible to reach and study these conditions more easily (smaller device with lower power) than with a conventional design. The sensitivity of the magnetic configuration at low aspect ratio to applied fields that break the stellarator symmetry may actually be advantageous to this area of research. Tokamaks, for example, are investigating symmetry-breaking at the plasma edge to control ELMs.

Coils and Structures: As for technology issues, a main concern that could be addressed is that of designing and building simpler magnetic coils and support structures. These are issues that are presently causing difficulties in the W7-X and NCSX construction projects. Much depends on understanding the scientific issues within an overall optimization scheme such as how low an effective ripple is needed or what constraints are necessary to satisfy stability criteria. Relaxation of such constraints might lead to coils that are easier to build. Also the issue of tolerance requirements needs to be addressed for magnet coil manufacture as well as coil and field period assembly. Field error control, mode locking and subsequent disruptions are concerns related to tolerance requirements for tokamaks.

Metrology: A necessary adjunct to this effort is the need to accurately determine the as-built structure of the magnetic coils and sensors. The development of metrology capabilities significantly beyond that existing in the US fusion program is being driven by the stellarator community. This is applied to the quality assurance in component fabrication and assembly. Such capabilities might be transferred to other scientific and industrial applications.

Correction Coils: Once the coils are built and mounted within the support structure and the metrology capabilities determine the tolerance that has been achieved, the next technology issue to be addressed is that of correction coils. Inevitably there are deviations of the as-built device from the design coils and correction coils may be helpful in relaxing tolerance requirements as well. This is an area of concern for tokamaks as well as stellarators, so understanding the physics of error correction (and shielding by rotation and plasma currents) and developing a technology for minimizing the impact of imperfect design implementation should benefit all magnetic fusion research.

Divertors: Another important technology issue to be addressed in the compact stellarator program is that of particle and power handling. The 3D shaping capabilities of stellarators allow for flexibility in edge geometry including local island divertors and ergodic regions. Control of neutral recycling and impurities needs to be demonstrated. A key issue to be addressed is whether the divertor in a lower aspect ratio device can handle the higher heat flux. Also to be determined is what design constraints can be relaxed by operating at higher densities and with radiative cooling.

b. What are the advantages and disadvantages of the quasi-symmetric stellarator as a potential fusion system concept? What unique features does the compact stellarator offer in this regard?

The compact quasi-symmetric stellarator could address questions arising in the transition from ITER to a DEMO fusion reactor. Specifically, first-wall lifetime and reactor availability require disruption and ELM suppression. Stellarators have already demonstrated the ability to operate disruption-free also at stability boundaries. They rely on external currents instead of current drive to provide rotational transform and are inherently steady-state. High density operation is possible in stellarators without regard for the rotational transform. This facilitates solutions for divertor operation and allows the density to be chosen to minimize potential problems due to the fast-particle population and synchrotron radiation losses.

The quasi-symmetric approach to plasma shaping overcomes the poor neoclassical confinement of conventional stellarators at low collisionality. Without the resulting increased gain, a stellarator reactor would have difficulty reaching ignition conditions.

From the science perspective, a disadvantage of the quasi-symmetric approach is that the reduction in the effective ripple, while beneficial for transport, makes access to the electron root of the ambipolarity constraint more difficult. This could imply that shear stabilization of turbulence by the neoclassical electric field, through the proximity of electron and ion roots, may no longer be possible. A quasi-symmetric stellarator would then have the same problems faced by tokamaks: E × B shear stabilization may not scale to a reactor because of small ρ^* (ratio of gyroradius to minor radius); additional momentum input may be required. Another disadvantage of the quasi-symmetric approach is the complex technology of the modular coils that are needed for the plasma shaping.

Compared to a higher aspect ratio stellarator, a compact stellarator offers the possibility of lower initial capital cost, lower cost of electricity (COE), lower fusion power output (for more flexible application) and lower volumes of radioactive waste. These are the major arguments why the US stellarator community advocates a stellarator reactor with a tighter aspect ratio. The ARIES-CS (CS for compact stellarator) fusion reactor design study was completed in 2006 based on an NCSX-class quasi-axisymmetric configuration. The device has a major radius of 7.75 m and an aspect ratio of 4.5. The size and mass were similar to an advanced tokamak power plant.

In a summary report to this Committee, the ARIES-CS team described some of problems associated with compact stellarator reactor design. For a major radius less than 7.5 m, there was not enough space for blankets to provide tritium self-sufficiency. There were concerns with high heat flux to the first wall and divertors. More work was needed to reduce the energetic alpha loss further. A complex support structure was designed which would be difficult to build with conventional manufacturing. A new fabrication technology called “additive manufacturing” was assumed. Access to the blanket was challenging because of the modular coils. The ARIES team emphasized that in their estimates of the COE they did not include a penalty for the complexity of the components or a possible lower reliability because of that complexity. Hence they stated that cross-comparison with a tokamak is not meaningful, although comparisons with other stellarators was valid.

The ARIES team did make a comparison to a larger aspect-ratio stellarator reactor design conducted in 1996. This was the SPPS study which was based on a configuration similar to HSX. The SPPS reactor has a major radius of 14 m and an aspect ratio of 8.5. At roughly half the aspect ratio of SPPS, the ARIES-CS COE was only 20% lower at 78 mills/kWh. Furthermore, they stated “System analysis, however, shows very little cost benefits in going to smaller size devices.”

The ARIES team took special note of two points, which we quote:

a- “The ARIES-CS study was the first major study of compact stellarators. As such, it was conducted in the `problem finder’ mode. For example, the design point was pushed to the limit for a “compact” configuration with low aspect ratio to better understand the constraints imposed by the “compactness” and the possible trade-offs. In most areas, we find that increasing the machine size compared to ARIES-

CS reference design will provide more margins on space and engineering constraints such as material stress, temperature limits, etc.

b- Most of the engineering research was performed on NCSX-class quasi-[axi]symmetric configuration. Caution should be used in extrapolating to other compact stellarator configurations."

c. What scientific and technical issues need to be resolved to evaluate the compact stellarator as a viable concept for a fusion energy system?

A number of scientific issues need to be resolved to evaluate the compact stellarator as a fusion reactor. Some of these issues directly impact the problems tokamaks face in making the transition from ITER to DEMO. For a quasi-axisymmetric (QAS) stellarator in particular, because of the relatively large bootstrap current, it is important to understand how much external rotational transform is needed to eliminate disruptions. Does the 3D shaping stabilize neoclassical tearing modes? What magnetic structure at the plasma edge is effective in eliminating large ELMs? Does the combination of internal rotational transform (from the bootstrap current) and externally generated transform indeed lead to stable steady-state operation?

Some of the scientific issues are generic to the quasi-symmetric concept. At this time, it is still not clear how low the effective ripple should be. What is the relative role of neoclassical versus anomalous transport? To what extent does zonal flow damping affect turbulent transport? Does drift optimization reduce turbulent transport as well as neoclassical transport? Is it possible to increase the E × B shearing rate in a quasi-symmetric stellarator to the extent that it scales to a reactor? How does quasi-symmetry affect energetic particle confinement and stability? Finally, which form of quasi-symmetry makes the best reactor? Do we have to test them all or are there distinguishing features that favor one form over another?

Other scientific issues are more generic to stellarators in general. This part of the assessment is carried out within the world-wide stellarator community, of which the major devices are LHD (a superconducting heliotron device in Japan that achieves some improvement in transport by shifting the plasma inward), W7-X (a superconducting, large aspect ratio device in Germany that relies on transport optimization that is not quasi-symmetric and also minimizes plasma currents) and NCSX. Being a compact stellarator with a tokamak-like aspect ratio and quasi-symmetry, NCSX could play a unique role in this assessment. What limits the plasma beta and density in a stellarator? How can impurity transport be controlled? How does the plasma respond to magnetic perturbations? How do equilibrium islands and flux surface robustness scale with increasing pressure? Is it possible to do 3D equilibrium reconstruction that detects the presence of island structures in a stellarator?

The scaling of energy confinement with size is also important to the viability of stellarators as a fusion energy concept. The size scaling determines how large a reactor must be to produce fusion power with sufficient gain. While most of the issues discussed previously can be studied effectively in a single stellarator, determination of the size scaling needs data from an array of stellarators. The two methods now employed to determine the size scaling of tokamaks, database analysis and dimensionless parameter scaling, have also been applied to stellarators. From database analysis, the confinement in stellarators appears to scale with volume, which is favorable compared with tokamaks. It will be important to determine whether the scaling of optimized stellarators also follows such scaling. It will be challenging to compare the many varieties of stellarators in the absence of a validated first-principles model for stellarator confinement.

In addition to the issues of fusion science, a number of technical issues need to be resolved for the compact stellarator to be properly evaluated. One issue that is very much dependent on a resolution of the scientific issues is whether certain constraints such as stability or confinement can be relaxed so that magnet coils can be designed that are easier to build. An issue that the ARIES-CS team faced is whether a complex support structure for a compact stellarator reactor could be built without inventing a new fabrication technology. If such a technology is needed, how easy is it to develop? Does failure of a magnet coil compromise the power plant or can the coils be replaced remotely? Is there a remote handling scheme that can deal with the complex geometry of a compact stellarator? How reliable are the complex components needed for a compact stellarator? How does that affect availability and the cost of electricity (COE)? What is the best way to control particle and heat fluxes at the plasma edge? Which stellarator geometries best accommodate divertors?

One central question that needs to be addressed is raised by the report produced by the ARIES-CS team. They found that for configurations of the NCSX-type there was little benefit in terms of COE in going to even lower aspect ratio. Are there any compact stellarator configurations at aspect ratio much lower than five that show a significant decrease in the cost of electricity?

2. The Role of NCSX in an International Context

(a) *What critical, unique contributions does NCSX potentially offer for addressing the issues identified in (1)?*

NCSX is designed to address most of the critical physics and technology issues discussed in this report using a compact, quasi-axisymmetric configuration that is unique in the world stellarator program. The Committee finds that, assuming successful construction and testing phases, the NCSX device is likely to perform at a level sufficient to address its scientific and technical missions. Thus the Committee expects the NCSX experimental program to have a profound impact on stellarator research worldwide.

As described in Section 1, the fusion program's strong interest in the stellarator approach is that it potentially offers solutions to the important problems of disruption avoidance and steady-state operation facing tokamaks in going from ITER to a DEMO fusion reactor. Specifically, first wall lifetime and reactor availability require nearly complete disruption elimination and ELM suppression. Stellarators have already demonstrated the ability to avoid disruptions and where ELMs have been observed, they are not severe. Furthermore, by relying primarily on external currents instead of current-drive or bootstrap currents to provide rotational transform in the confining magnetic field, stellarators can more easily operate in steady state.

To explore the potential advantages of disruption avoidance and steady state operation in a more compact (low aspect ratio) advanced stellarator employing the quasi-axisymmetric magnetic configuration, the NCSX experiment was approved by FESAC in 2001 as a PoP class device in the US fusion energy science program. This places it between smaller Concept Exploration experiments, such as HSX at the University of Wisconsin-Madison, and larger Performance Extension class experiments, such as the DIII-D National Tokamak Facility in the US, the LHD stellarator in Japan, the W7-X stellarator under construction in Europe and the even larger burning-plasma class experiment, ITER.

There are two other PoP class experiments in the US fusion program: the NSTX experiment at PPPL, exploring the compact torus magnetic configuration, and the MST experiment at the University of Wisconsin-Madison, exploring the reversed field pinch magnetic configuration. The characteristic of a PoP class experiment is that it has the size, magnetic field, and plasma heating systems to allow study of key physics behaviour of the magnetic configuration concept with collisionless ions and electrons for many energy confinement times. With these parameters, the PoP class experiment is minimally sized to provide credible integrated confinement and stability results that scale to the 10 keV fusion power plant regime of temperature and collisionality, and hence prove the basic physics principles of the confinement configuration under study. This normally requires temperatures of both ions and electrons at the keV level, 1 to 2 Tesla magnetic fields and several MW of external heating input to the plasma for several tenths of a second. In terms of key dimensionless parameters, this requires collisional mean free paths to be dominated by Coulomb collisions and to be an order of magnitude larger than toroidal or poloidal connection length scales; a device size many times the characteristic size of the ion gyroradius; and a plasma pressure normalized to the magnetic energy density β of at least several percent.

The NCSX experiment was designed to meet these conditions for the exploration of the quasi-axisymmetric stellarator (QAS) magnetic configuration. Using expectations of stellarator confinement based on an extensive data base, the NCSX design projects central ion temperatures of 1 to 2 keV, magnetic field values of 1 to 2 Tesla, dimensionless collisionality, $\nu^* \sim 0.1$, $\beta \sim 5\%$, and at least 10 poloidal ion gyroradii across the 0.33 m average minor radius using 6 MW of neutral beam heating. Thus, NCSX is well positioned to carry out PoP experimental tests of the QAS magnetic configuration.

Three principal concepts are possible for quasi-symmetry: quasi-helical, quasi-poloidal and quasi-axisymmetry (QAS). Each of the three principal quasi-symmetric stellarator concepts is being pursued in the world fusion program. Quasi-helical symmetry is being studied in HSX, which has been operating for several years; quasi-poloidal symmetry is the guiding principle of the configuration design of the QPS device proposal. There are also techniques for optimizing particle orbits outside of quasi-symmetry. W7-X (under construction in Germany) and Heliotron-J (operating in Japan) pursue such alternative approaches to advanced stellarator design. There is some experimental confirmation that orbit optimization, using quasi-symmetry or other means, significantly improves neoclassical confinement. For example HSX has demonstrated reduced neoclassical losses.

As the only representative of quasi-axisymmetry in the world program, NCSX is intended to demonstrate the performance of a quasi-axisymmetric system, and explore the performance consequences of its mix of internal and external rotational transform. It will demonstrate whether good confinement, sufficient equilibrium and stability beta limits can be achieved, specifically with regard to current-driven modes, and whether the potential for steady-state operation can be achieved simultaneously by the proper mix of internal and external transform. Because of the complicated nonlinear interaction between plasma profiles, bootstrap current and confinement, these are issues considerable scientific and fusion interest.

Among the advanced stellarators, QAS has two attractive and unique features. First, the QAS design fits naturally into a low-aspect-ratio configuration because it requires relatively strong toroidicity compared to other components of the magnetic field curvature. Thus, the QAS is a good candidate for a ‘compact’ (low aspect ratio) stellarator configuration. Second, confinement studies with QAS would have many common physics elements to tokamak research. From this aspect, QAS should produce complementary physics results to tokamak research aimed at fusion energy development. An important question is whether the tendency for impurity accumulation is controlled in NCSX by inducing current-driven core instabilities to prevent it. Finally, when all systems have been studied in detail, the three major lines – LHD (Heliotron), W7-X (optimization outside of quasi-symmetry), and NCSX will allow us to decide which system has the highest reactor potential. This information will influence the debate on the continuation of the fusion program toward a DEMO reactor.

Because sufficient confinement requires a large volume, toroidal systems deliver fusion power at a level that motivates steady-state operation from an engineering and grid-integration point of view. Current-driven tokamaks resort to high bootstrap-current fractions, with the complications of non-linear interactions between confinement, equilibrium and stability, NCSX aims to explore these regimes with the help of external contributions to rotational transform. Thus it should allow study of the criticality of bootstrap-current based equilibria in a unique way. For this assessment the low-aspect ratio of NCSX, which is comparable to that of tokamaks, makes the comparison especially relevant.

> (b) *Given PPPL’s proposed plans for operation of the National Spherical Torus Experiment and NCSX, what would be the timetable for resolving relevant issues identified in (1) above?*

The time scale of fusion development is determined to a large degree by that of ITER. Major decisions on the direction of DEMO are unlikely to be made before clear answers are obtained on the critical burning plasma issues that can only be addressed by ITER, such as stability with α-particles, burn control and ash removal. When these burning plasma studies are completed, the stellarator research findings will be needed to enter into the general debate on how to structure the next steps beyond ITER. The time scale set by NCSX projects the achievement of first plasma in 2012 and initial results in 2013. W7-X is scheduled for first plasma in 2014 and ITER is presently scheduled for operation in 2016. LHD and HSX are operating now and will continue to contribute.

The NCSX team proposed a timetable for the scientific exploration during the first years including operation in alternate years with NSTX. Since this schedule extends to a time beyond even the proposed next 5 year plan for NSTX, it cannot be considered certain. The planned phases of NCSX device commissioning, preparation of the necessary diagnostics in line with the major topics to be addressed and the development of the divertor and the heating periphery are well thought out. The planning reflects the considerable experience at PPPL on commissioning such experiments.

The question whether NCSX can indeed meet its proposed resolution of critical issues with only FY13 and FY15 was discussed in detail by the committee. Based on the PPPL experience with the comparably sized NSTX experiment which has a comparable operation budget level as NCSX, a more likely time frame for resolving the initial set of critical issues is about 5 years of actual operation, with detailed scientific understanding and an extrapolable basis for optimization of follow-on devices requiring about 10 years of experimental operation.

Technical requirements that may extend the time scale for resolving the initial set of critical issues include achieving (and maintaining) sufficient quality of the confining flux surfaces. The quality of flux surfaces depends on symmetry breaking field errors introduced by tolerance deviations of single components or by errors introduced by assembly. The project has shown that it follows the development of the components in detail by calculating the resulting island widths from resulting mechanical deviations. The project has also developed strategies how to cope with errors of the components (by compensating it by slight changes to the geometry of the device during assembly) and by installation of specific trim coils. Trim coils are also the selected compensation method on ITER and other stellarators (LHD, W7-X). It is important that these studies are continued during NCSX assembly. In addition the Committee recommends that attention to construction details that may affect flux-surface quality, and the study of their effects and methods to counteract them, remain top priorities for the project.

Other technical or managerial risks affecting the timetable are not part of the charge and were not addressed.

> (c) *What are the differences of the current NCSX design compared to other stellarators operating or being built abroad? What is the significance of these differences? Does NCSX fill a critical void in the development of the stellarator concept as a viable fusion energy system?*

NCSX is designed as quasi-axisymmetric stellarator with low aspect ratio. In both properties, NCSX is unique. If NCSX were not completed, both stellarator and tokamak research will suffer. W7-X is optimized using a different scheme than quasi-symmetry (with superconducting coils) and all currents in W7-X, apart from the diamagnetic current, are strongly reduced. In NCSX, with its compact, quasi-axisymmetric configuration, the bootstrap current is maximal. The comparison between these two devices will be extremely useful in understanding the physics optimization of these advanced stellarator configurations. Beyond obvious criteria (confinement), the stability against current driven modes, the known differences between tokamaks and stellarators (*e.g.* the isotopic effect in anomalous confinement), the different flow pattern and the level of damping will be of extraordinary importance.

With respect to compactness or small aspect ratio, W7-X has a large aspect ratio, LHD a middle aspect ratio, and NCSX the smallest aspect ratio. In developing lower aspect ratio approaches in the stellarator configuration, NCSX clearly plays a significant role. In demonstration of the potential for steady-state operation, LHD and W7-X are significant because they employ superconducting magnets. In terms of the tokamak program benefitting from 3D magnetic configuration physics, NCSX is also significant because of its quasi-axisymmetry and large bootstrap driven currents, as discussed above.

3. Options for the US stellarator program

a. *If the NCSX program were not continued, what options would exist or would be possible to address the key issues of the quasi-symmetric stellarator in general and the compact stellarator in particular?*

In the absence of NCSX, the Committee recommends that the DOE enhance the remaining US stellarator program to enable the US to continue as a participant in the worldwide stellarator research program. The present US stellarator research program includes other devices, planned or in operation, that could address at various levels a subset of the key issues listed in Section 1. However, such studies would have to be done at lower plasma parameters, and at some somewhat less relevant values of the dimensionless parameters. Examples of such studies are :

- Effects of strongly reduced effective ripple on energy confinement.
- Determination of pressure limits in 3D configurations.
- Disruption stabilization and avoidance.
- Reduction of turbulent transport by flows and 3D shaping optimization.
- Stabilization of equilibrium islands and tearing modes.

The Committee emphasizes that no US experimental program, present or planned, could provide the breadth of scientific and technical information that is expected to come from NCSX. The only PoP scale device in the US repertoire that addresses quasi-symmetry is NCSX, and NCSX is the only such device capable of examining the key issues in an integrated context. Thus, without NCSX there would be no experiment to address the issues of quasi-axisymmetry and the potential of lower-aspect ratio stellarators. Furthermore, there would be no way to study hot-ion and high beta physics in a low-aspect ratio quasi-symmetric 3D system. NCSX occupies a unique niche in the complex stellarator design space.

Therefore, if NCSX were abandoned, the US would have to significantly reduce its ambitions in the quasi-symmetric stellarator research area, or begin constructing a new PoP stellarator experiment.

The Committee finds it important that the US have a significant stellarator presence as part of its magnetic fusion energy research program. The loss of NCSX would have serious negative consequences for the US and worldwide stellarator research programs. In particular, the US would lose its world leading position in developing the compact, quasi-axisymmetric approach to stellarator confinement research. The Committee notes that at present about 75% of the US stellarator effort is focused on the construction of NCSX so the loss of NCSX would change the basic character of the US program. The program would lose its integrated PoP facility and the most relevant connections to tokamak research through quasi-axisymmetry.

b. Assuming NCSX is not available, what program elements would be required to maintain the US as a significant participant in the international stellarator program?
  i. Identify potential opportunities for US leadership
  ii. Include more international collaboration as appropriate.

The US stellarator program has several existing components that make important contributions to the worldwide stellarator effort. These activities are addressing selected key issues. In the event that NCSX is not available, these activities should be strengthened and new stellarator research opportunities should be explored.

In the absence of NCSX, a restructured US stellarator program could maintain scientific leadership in selected research topics, but would have difficulty in playing a significant role in the direction of worldwide stellarator research. Furthermore, the lack of a domestic PoP program would diminish the benefits the US could gain from international collaboration.

Nonetheless international collaboration is a key element to the US stellarator research effort, as it is to every element of the US fusion energy science program. With the loss of NCSX, it can be expected that international collaboration will occupy a larger proportion of the US effort. In particular the US has the opportunity to participate in experiments on the LHD device in Japan (currently operating) and the W7-X device currently under construction in Germany. Although these devices at not low-aspect ratio, they will provide critical information on stellarator plasmas at higher density and plasma temperatures, higher beta and steady-state operation. The US would seek to expand its opportunities to study 3D physics on LHD and W7-X.

Theory and computation research in the US has developed significantly in recent years and developed and employed a number of world-class numerical tools. To a large degree, this resurgence in US stellarator theory is due to the NCSX and QPS design programs. There have been a number of recent advances in the theory of magnetic surface fragility, 3D MHD equilibrium and stability, transport, concept improvement and reactor optimization. Opportunities exist to strengthen this work in areas such as high-beta and high-density operation of stellarators, micro instabilities in 3D configurations, zonal flows and flow damping and simplification of future devices and reactor concepts. However, the loss of a world-class stellarator experiment in the US would make it more difficult to attract young theorists to specialize in the area of 3D magnetic confinement research.

The US has the only operating quasi-symmetric stellarator in the world, the HSX at the University of Wisconsin-Madison. Because of its quasi-helical symmetry and very low ripple, HSX has a very high effective transform that is responsible for very narrow banana widths, reduced Pfirsch-Schlüter and bootstrap currents and low neoclassical transport. With additional diagnostics and heating capabilities, HSX can address issues of turbulent transport and zonal flows, confinement scaling, plasma stability, low collisionality ion transport, energetic particle confinement and impurity transport.

The CTH device at the University of Auburn investigates the stability of current-driven discharges, from tokamak-like ranges of vacuum transform near zero to values of transform characteristic of NCSX. Furthermore, CTH evaluates the effects on equilibrium and stability of magnetic islands and error fields in helical configurations in which the rotational transform is not tightly prescribed, as in NCSX. Improved support for reliable electron temperature profile and current profile diagnostics would directly add to the effectiveness of this research program.

The proposed QPS device at the Oak Ridge National Laboratory is a low-aspect ratio quasi-poloidal symmetric configuration that approximates linear linked mirrors with end losses in a toroidal geometry. It may allow large poloidal flows and can potentially study the effects of flow and flow shear on plasma turbulence. The physics program of QPS would connect to higher-aspect ratio stellarator devices like W7-X. QPS would extend the stellarator database to very low-aspect ratio, similar to what the ST does for the tokamak database. However, while QPS would have an important role in the world stellarator program, it would not be able to replace the scope of the NCSX research program. In particular QPS could not address the assessment of quasi-axisymmetry or the close link to tokamak behavior.

The Committee did not evaluate in detail the merits of the QPS device, which is currently in an R&D and prototype-fabrication stage. Thus the Committee cannot judge whether the DOE should proceed with the construction of QPS. The Committee notes that it would seem illogical to cancel a stellarator project nearing the final stages of construction only to begin a new compact stellarator with poloidal rather than toroidal quasi-symmetry. However, in the situation where NCSX is not available, the Committee believes that the DOE should expedite the decision on the construction of QPS.

The Committee also recognizes that it might be possible to consider adding concept-exploration level stellarator experiments to the US program. Potentially, such devices could pursue the quasi-axisymmetric optimization path. However the Committee did not receive any specific suggestions for such an undertaking nor did the Committee have time to carefully explore such possibilities.

In the absence of NCSX, the US stellarator program could pursue stellarator concepts outside of the compact quasi-symmetric path. Quasi-symmetry is one of many ways to optimize 3-D configurations; other optimization schemes could be pursued. Without the presence of NCSX, the US stellarator program should consider a variety of approaches to stellarator optimization in proposing a new PoP stellarator project.

Appendix A: Charge to FESAC

August 9, 2007

Professor Stewart C. Prager, Chair
Fusion Energy Sciences Advisory Committee
Department of Physics
University of Wisconsin
1150 University Avenue
Madison, Wisconsin 53706

Dear Professor Prager:

The National Compact Stellarator Experiment (NCSX) project, which is being built at the Princeton Plasma Physics Laboratory (PPPL), is projecting substantial cost (~$40 million) and schedule (~2 year delay) overruns. These overruns are large enough to add new burdens on the limited resources of the U.S. fusion energy sciences program, as well as undermine confidence of the Administration and Congress in the ability of the Office of Fusion Energy Sciences and the Office of Science to manage large and technically challenging construction projects. Given the magnitude of the increases projected for NCSX, all options, including termination of the project, must be considered. In that context, we would like the Fusion Energy Sciences Advisory Committee (FESAC) to conduct a scientific and programmatic review focused on evaluating the NCSX program and its potential effect on the U.S. fusion energy sciences program. Below is a list of questions that we believe must be answered in order to allow us to make a decision on the best course of action for the U.S fusion energy sciences program. This review will comprise part of the set of reviews that will be conducted to inform a decision.

Questions for Scientific and Programmatic Review of NCSX:

1. Critical scientific issues for the U.S. compact stellarator program:
    a. What unique toroidal fusion science and technology issues can a compact stellarator program address, independent of its potential for a reactor concept?
    b. What are the advantages and disadvantages of the quasi-symmetric stellarator as a potential fusion system concept? What unique features does the compact stellarator offer in this regard?
    c. What scientific and technical issues need to be resolved to evaluate the compact stellarator as a viable concept for a fusion energy system?

2. Role of NCSX in the international context:
    a. What critical, unique contributions does NCSX potentially offer for addressing the issues identified in (1)?
    b. Given PPPL's proposed plans for operation of the National Spherical Torus Experiment and NCSX, what would be the timetable for resolving relevant

issues identified in (1) above?

    c. What are the differences of the current NCSX design compared to other stellarators operating or being built abroad? What is the significance of these differences? Does NCSX fill a critical void in the development of the stellarator concept as a viable fusion energy system?

3. Options for the U.S. stellarator program:
    a. If the NCSX program were not continued, what options would exist or would be possible to address the key issues of the quasi-symmetric stellarator in general and the compact stellarator in particular?
    b. Assuming NCSX is not available, what program elements would be required to maintain the U.S. as a significant participant in the international stellarator program?
        i. Identify potential opportunities for U.S. leadership
        ii. Include more international collaboration as appropriate.

4. Role of the stellarator and NCSX in the long-term U.S. fusion energy sciences program:
    a. For a compact stellarator to be a viable reactor concept, what other experimental facilities would be required to develop the required knowledge base?
    b. For the cases with and without NCSX in the program, how can results from the U.S. stellarator program impact the direction and/or risk level of the development of the knowledge-base needed for a fusion energy system:
        i. On the timescale for a first-generation DEMO after ITER?
        ii. Longer-term, beyond a first-generation DEMO?

In summary, FESAC should answer all of these questions and provide their responses so we can evaluate the situation and choose the most appropriate course of action. Given the urgency of the situation, we would appreciate it if your answers could be provided by the scheduled FESAC meeting in October 2007. I very much appreciate your assistance in addressing these questions on such an expedited basis.

Sincerely,

/s/

Raymond L. Orbach
Under Secretary for Science

Appendix B: Members of the NCSX Review Committee

Dr. Charles Baker, Sandia National Laboratories (consultant)

Prof. Richard Hazeltine, University of Texas at Austin (Chair)

Prof. Chris Hegna, University of Wisconsin

Dr. Timothy Luce, General Atomics

Prof. Gerald Navratil, Columbia University

Prof. Shoichi Okamura, National Institute for Fusion Science (Japan)

Prof. Ron Parker, Massachusetts Institute for Technology

Dr. Max Tabak, Lawrence Livermore National Laboratory

Dr. Joseph Talmadge, University of Wisconsin

Prof. Dr. Friedrich Wagner, Max-Planck-Institut für Plasmaphysik (Germany)