Questions of the Stellarator Community

1. *The primary goal as stated is more of a general vision toward fusion energy. Can a more specific goal be formulated in terms of the international stellarator program, and more specifically, how the US efforts and goals could contribute in a significant fashion toward that vision?*

   The primary goal of stellarator research in the ITER era was stated in the white paper to the panel to be:

   > Through experiments and modeling performed on both stellarators and tokamaks (including ITER), international stellarator researchers plan to develop the **level of predictive understanding** in concert with the **attainment of sufficiently promising plasma conditions** that would justify the step to implementing a fully steady-state, disruption-free, externally-controlled, DT-burning stellarator.

   Elaborating on this, we specifically highlight the program's intent to provide a basis for steady-state fusion without disruptions, compatible with ignited or high Q operation, using a stellarator configuration. The goal includes the development of a 3-D divertor concept that would enable the core plasma parameters to be attained in stationary, steady-state discharges with low impurity content, and of magnetic configurations in which energetic particle confinement projects to a level compatible with reactor operation.

   The goal represents a realistic vision based on expected activities in the worldwide stellarator program in the upcoming decades. The US stellarator program can provide significant and unique contributions to this goal by investigating scientifically promising stellarator configurations not currently being studied by the international programs and by investigating specific topics in collaboration with the international program. These studies should build on US strengths. At the same time, it should be clear that US program cannot presume to represent the internal priorities of the large German and Japanese programs.

   Specific US contributions include:

   - Physics of quasi-symmetric configurations
   - Development of compact configurations with aspect ratios substantially lower than the LHD and W7-X experiments
   - Configuration design optimization, including physics and engineering constraints.
   - Reactor-design studies and optimization
   - 3D equilibrium modeling and analysis

2. *A second goal in the document focuses on understanding of 3D effects in toroidal confinement. As stated this goal appears too vague. What are more specific objectives and their measurable outcomes?*

   This is a broad and encompassing goal, which includes several activities:
   - Developing a predictive understanding of plasma confinement in stellarator configurations
   - Applying the understanding and models developed from stellarators to 3D magnetic fields in other magnetic configurations, including equilibrium, stability, and transport properties
   - Using experiments with 3D magnetic fields on all configurations to challenge and validate stellarator models and understanding.
   - The measurable outcomes from this research will be improved understanding, and improved predictive capabilities for stellarator and other configurations.

3. *The cancellation of NCSX necessitates a revision in the US stellarator program. The committee would like to see an initial cut at a "scientific roadmap" to accomplish these revised goals in the "ITER era" timeframe? Please take into account the questions listed below.*

   With the cancellation of NCSX, the community is developing a new plan for US stellarator research that calls for the investigation and experimental testing of key scientific and engineering issues and an overall strengthening of stellarator theory, modeling, and international collaboration. The US program should build upon its recognized strengths, and complement the large international performance-extension scale programs. To accomplish the goal and develop a validated understanding of stellarator confinement, particularly issues related to high beta and ion confinement, requires experiments at the PoP scale and larger. The key issues expected to be addressed in such an experiment are:

   Understanding of beta limits and limiting mechanisms
   Evaluation of 3-D divertor design and peformance
   Understanding of anomalous transport (particularly ions) in QS plasmas
   Impurity transport in hot dense QS plasmas
   Energetic ion stability and confinement in QS plasmas
   Sensitivity of operating limits to heating profiles
   Engineering issues of high performance QS stellarators

   The characteristics and focus of the program elements, including major experiments, will be developed in workshops anticipated to follow the FESAC TAP report. In the interim, the road map shown in Fig. 1 shows the envisioned progress of the US program in relation to ongoing international activities.

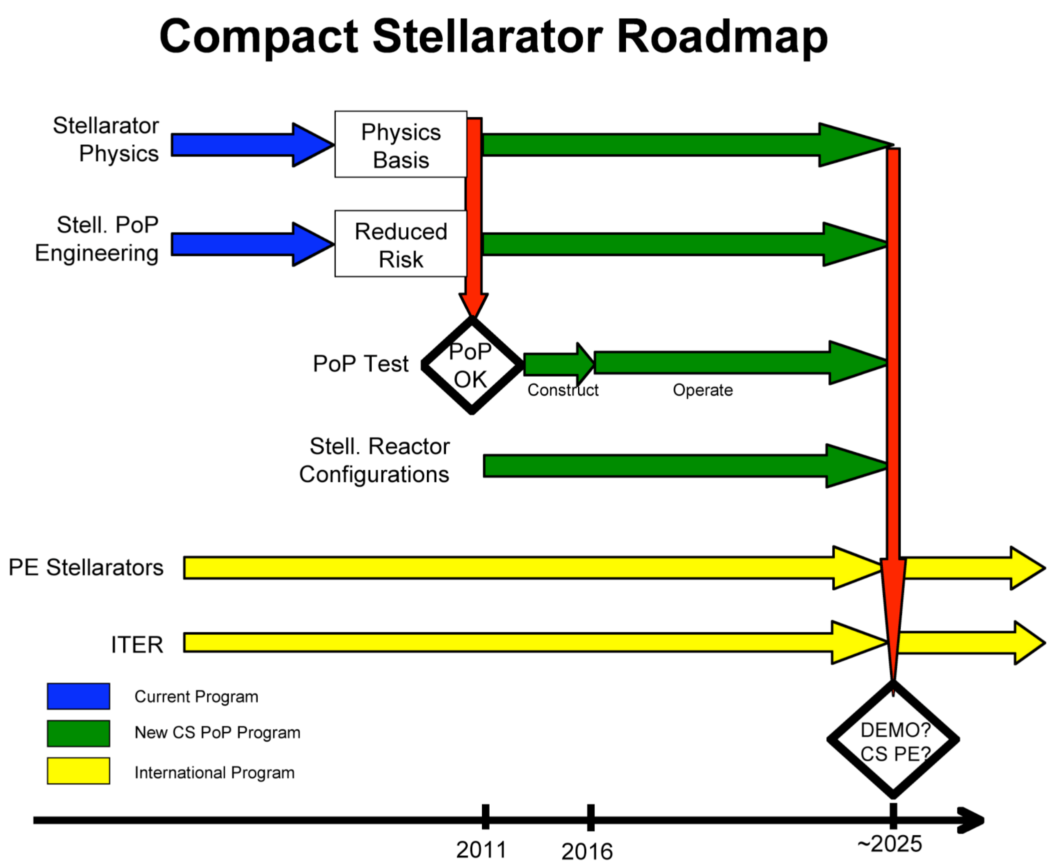

Fig. 1 Schematic road map of US stellarator program in the ITER era

4. *The document expressed a view that the stellarator might go straight to DEMO without a specific stellarator-based DT experiment. This step would be based upon ITER results, confidence in predictive modeling, and results from the PE experiments and other experimental data. Under what conditions would this be a credible option? Where is the decision point?*

- Any step to DEMO will, necessarily, be based on verified predictive models of plasma and system performance, and demonstrated solutions to the outstanding issues. A credible extrapolation of stellarators to DEMO without an intervening DT stellarator experiment can be foreseen if validated predictive understanding in the areas described below is obtained from ITER and large stellarator experiments.
- DT experiments test and explore our understanding of (a) the dependence of plasma confinement on rho*, including isotopic effects, (b) the effect of the alpha particles on plasma stability, (c) the effect of alpha losses on the PFCs, and (d) the effect of alpha-heating on the plasma profiles and operating limits. These issues will be studied extensively on ITER in DT, and the understanding developed on ITER for (a) and (b) can be tested in suitable stellarator experiments without DT. Results from ITER on (c) should be applicable to stellarators. Regarding (d),

stellarator operating limits do not appear to be sensitive to plasma profiles, but this must be explicitly tested and verified.

- Thus, the step to DEMO could be made without a DT stellarator experiment, based on a verifying that our understanding of the effects of DT (developed largely on tokamaks) is correct in stellarator experiments, as discussed above. Particularly for issue (a), this may be easier for quasi-symmetric stellarator configurations.

5. *Divertors are difficult even in an axisymmetric geometry, especially at high power levels. A discussion of divertor problems and options, and their possible resolution within the overall stellarator program would be appreciated.*

   - This is an area of vigorous research in the W7AS, LHD, and W7X programs. W7AS and W7X have designed optimized 'island' divertors, LHD has explored both an island divertor and a continuous helical divertor. In both types of divertors, impurity control has been achieved, and compatibility with enhanced confinement has been demonstrated. The LHD and W7X experiments will examine divertors in near steady-state, but may not attempt reactor-like heat fluxes. W7X has mentioned plans to eventually install tungsten PFCs and divertor tiles.
   - Both W7AS and LHD successfully operated with detached divertors, which minimizes divertor loading. The high density limit and lack of need for off-axis current-drive in stellarators enables plasmas to have lower edge temperature, reducing divertor erosion.
   - A fluid model has been developed (EMC3) which appears to agree reasonably with experiments on regimes of divertor detachment and impurity control [Y. Feng et al., Nucl. Fusion 46 (2006) 807]. This model is also being used to analyze tokamaks with 3D edge magnetic fields.

6. *The panel would appreciate hearing a brief discussion of the following physics topics:*
   a. *Can flux surface be made sufficiently robust to field errors and plasma currents?*

      - In both stellarators and tokamaks, flux surfaces have been made robust against field errors either by use of trim coils (e.g. as done on LHD, DIII-D, and NSTX) or by avoidance of low-order resonances (e.g. as done on HSX, W7-AS, and W7-X). Plasma shielding by finite rotation is also effective (as seen on all tokamaks), but can lead to 'locked modes' when the shielding fails. Generally, field errors with a significant n=1 component are the most troubling, since they have the largest spatial extent.
      - 3D equilibrium codes allow configurations to be explicitly designed to have good surfaces, and allow the assessment of sensitivity to field errors.

New techniques using perturbed equilibrium codes are providing a rapid and routine method for this assessment.
- In configurations with 'reversed shear' (in the tokamak sense), the bootstrap current will act to close equilibrium islands and provide flux-surface robustness.

b. *What amount of plasma current is acceptable for disruption elimination?*

- The answer to this question is not known, especially for pressure-driven bootstrap current. Current-driven disruptions in stellarators are avoided by stabilizing the plasma column against resistive and ideal kinks by control of the rotational transform and by 3-D flux surface shaping.
- LHD and W7X do not generate a large bootstrap current and cannot drive Ohmic current. W7AS typically adjusted its Ohmic current to null its bootstrap and beam-driven currents. A few W7AS experiments produced plasmas with significant bootstrap current (without nulling Ohmic current), and did not observe MHD instabilities or disruptions.
- Ohmic currents have been studied on a number of stellarators (Cleo, L-2, W7A, W7AS, JIPPT-II TJ-II, CTH). In early experiments on Cleo, JIPPT-II and W7A, current-driven disruptions were eliminated provided the coil-generated rotational transform was at least ~0.15 .
- Tearing modes are observed in W7AS, CTH, and other experiments during fast current ramps, when the edge iota is at a low-order rational value. The observed tearing modes on W7AS were generally in good agreement with tearing-mode and double-tearing mode theory, similar to tokamaks. Similar current ramps on W7AS with 'reversed shear' (i.e. down-ramps) did not produce tearing modes. Disruptions could be produced on W7AS with very fast ohmic current ramp-ups and edge q near 2.
- Experiments on LHD observe the theoretically predicted dependence of NTM stability on magnetic shear.
- Based on our theoretical understanding validated by experiments, configurations can be designed to eliminate the instabilities that cause disruptions. NCSX was designed to be passively stable to vertical, kink, ballooning, Mercier, tearing and neoclassical tearing instabilities even in the presence of finite beta and bootstrap current. Without these instabilities, the configuration should be immune to disruptions. NCSX was also designed with sufficient flexibility to vary the threshold for these instabilities to assess their significance.

c. *What is the present understanding of beta limits in stellarators?*

- Both LHD and W7AS have soft beta limits, where the maximum beta achievable is determined by changes in plasma transport, limited by the available heating power, and is a function of the 3D plasma shape. The analysis of the LHD data indicates that the thermal confinement time is decreasing with increased beta, at high beta.

- There are two hypotheses to explain the observed beta limits:
  - Degradation of flux surfaces: reconstructed 3-D equilibria, at the maximum beta achievable for several 3-D shapes, indicate the field lines to be stochastic in approximately the outer 1/3 of the toroidal magnetic flux. This region is measured to have finite pressure gradient on both LHD and W7AS, but the stochastic field may increase transport.
  - LHD observes continuous low-level MHD activity at the iota=1 surface, near the plasmas edge, at high beta. This may increase transport. Similar MHD activity is not observed on W7AS, except when the edge iota is close to a low-order rational (particularly ½ or 3/5). In both LHD and W7AS, the observed edge MHD activity is in reasonable agreement with linear ideal calculations of MHD stability.
- Both of these effects can be designed for, and were addressed in the W7X and NCSX designs. Experiments are needed to test whether such optimized designs produce increased beta limits.

d. *High density operation as proposed for a reactor: Does this scenario exceed the beta limits or provide excessive divertor loads?*

- No, high density operation does not cause an excessive beta value nor does it increase the divertor load.
- The reactor scenarios (e.g. for Aries-CS) are self-consistent, with density and temperature values consistent with beta values, which are within expected limits. At higher density the plasma temperature is lower—crudely nT is constant—so beta limits are not exceeded.
- At high density, the reduction of edge temperature reduces PFC and divertor sputtering and erosion. At high enough edge density the divertor detaches, which means that most power is lost by radiation, reducing divertor loading.

e. *Can sufficient alpha-particle confinement and stability to EPM's be achieved?*

- Alpha particle loss rates of less than 5% are predicted in optimized reactor designs. The losses are predicted to be of partially slowed-down alphas.
- The higher density and lower temperature of stellarator reactor designs substantially reduces the beta of non-thermal particles, such as alpha-particles, relative to projections for ITER and tokamak reactor designs. The expected beta-fast values are predicted to be stable based on approximate analytic expressions developed for tokamaks. However, the fast-particle stability has not been numerically modeled in the actual stellarator geometry has not yet been evaluated numerically, due to limitations in existing codes and models.

f. *How will impurity accumulation issues be addressed without ELM's?*

- Divertors have already been demonstrated to be effective in preventing impurity accumulation in W7AS and LHD in some enhanced confinement regimes, without ELMs. W7AS observed that injected impurities with flushed from the core plasma.
- Quasi-symmetry may enable neoclassical temperature screening to flush impurities.

7. *Stellarators require optimization, at a minimum, to reduce collisionless neoclassical transport. Optimization targets are based on our predictive understanding of critical issues and features desired in the configuration. What are these issues, our level of understanding, and what needs to be done to refine our understanding of these targets?*

- See section IV of the Community white paper and the Aries-CS R&D needs.
- The most critical plasma physics issues for achieving the goal are
  - Understanding the scaling of transport and confinement to the burning-plasma scale. In present stellarators, this is consistent with gyro-Bohm scaling. This will be informed by ITER experiments (for axisymmetric configurations), W7-X, and the development of comprehensive transport modeling for stellarator configurations. A PoP or larger experiment is needed to test the understanding of transport scaling for quasi-symmetric configurations.
  - Understanding operating limits, particularly the beta limit, consistent with steady-state. Determine whether operating limits are strongly sensitive to the profiles of plasma pressure and current. Present experiments show that the beta limit is not due to MHD stability, per se, but may be due to effects of MHD equilibrium or stability on confinement, and do not appear to be strongly sensitive to profiles. This has been studied on LHD and will later be addressed on W7X. A PoP or larger experiment is needed to test the beta limit for compact configurations and for configurations with significant bootstrap current.
  - Understand how much bootstrap current can be allowed without risking the occurrence of disruptions. Past experiments indicated that supplying as little as 15% of the rotational transform from coils was sufficient to prevent disruptions with Ohmic current profiles. Experiments on W7AS with significant bootstrap current did not observe disruptions, but did not attempt to challenge operating limits. This is not currently being studied outside the US. A PoP or larger experiment is needed to test disruptivity with significant bootstrap current and determine how much external transform is required to ensure immunity. This is required for compact or quasi-symmetric configurations.
  - Understand divertor design and plasma wall interaction control in 3D to provide impurity and exhaust control. This is an area of vigorous research in the W7AS, LHD and W7X programs. A fluid model has been developed (EMC3) which appears to agree reasonably with experiments on regimes of

divertor detachment and impurity influx control. This model is also being used to analyze tokamaks with 3D edge magnetic fields. The LHD and W7X experiments will examine divertors in near steady-state, but will not approach reactor-like heat fluxes.
  - Demonstrate the integration of high performance, steady-state consistent plasmas, suitable for extrapolation to DEMO and that this corresponds to the integrated modeling predictions.

- There are a number of materials, fuel, power handling, and safety issues that are largely in common with the tokamak, and are discussed in the Greenwald panel report.

8. *Due to their 3D nature stellarators have additional complexity. Simplified coils and constructability were put forth as an issue needing investigation. What were the main problems in coil fabrication and assembly experience from W7X and NCSX and how will more simplified designs be approached? What is desirable versus required?*

   - The problems encountered in W7X and NCSX are discussed in two documents posted to the TAP web-site
     - "Experience Gained during Fabrication and Construction of Wendelstein 7-X", by R. Haange and the W7-X Team.
     - "Stellarator Constructability and NCSX Experience" by H. Neilson and P. Heitzenroeder.
   - While stellarator modular coils are more complex than planar coils, they can be achieved to required tolerances as demonstrated in W7-AS, IMS, HSX, and NCSX. Superconducting stellarator coils have been constructed in LHD (with helical coils) and W7-X.
   - Design improvements are highly desirable to build upon the lessons learned from the devices constructed, to reduce system costs and risks when scaling to future larger devices.
   - A number of ideas for possible simplification and improvement have been identified, including:
     - Relax physics constraints based on experimental results, e.g. ideal ballooning
     - Greater use of trim coils to compensate for increased construction tolerances, including the plasma response effects, as being done tokamaks.
     - Improved engineering optimization targets, including reactor maintainability, and re-examination of targets for acceptable coil distortion levels and blanket.
     - Improved physics targets, particularly for alpha-particle losses, resonant fields, divertor fluxes, and turbulent transport.
     - Improved strategies for 3D coil construction and system assembly.
     - Continued exploration of the very large configuration space available with 3D shaping, and refinement of a number of promising configurations identified in previous studies (e.g. Aries-CS)

- Research in these areas is needed to determine assess which ideas can have significant impact on our ability to economically produce optimized 3D configurations.

9. *NCSX was designed as a compact device. The ARIES-CS study was based upon a scale up of this design. What are the lessons learned from this study, especially in regard to the level of compactness needed or beneficial for the stellarator? What other problems/issues were identified in this study?*

- As discussed in the Aries-CS final report:
    - Compact stellarator power plants that are similar in size to advanced tokamak-based plants are feasible. It was found that increasing the machine size somewhat relative to Aries-CS would provide more engineering margin and have small cost penalties.
    - The irregular shape of the components requires 3D analyses and a high degree of integration between the analyses and design. Exploring the 3D optimization of all components was beyond the scope of the study.
- The major R&D needs identified were
    - Development and demonstration of configurations with reduced alpha particle losses, particularly alphas > 10 keV
    - Understand beta limits in stellarators
    - Demonstrate achievement of the desired iota profile, including bootstrap current effects
    - Demonstration of adequate divertor geometries in compact stellarators with highly radiative plasmas
    - Demonstration of plasma startup scenarios and the path to ignition
    - Development of high-field 3D superconducting magnets with required shapes
    - Engineering accommodation of lost alpha particles.
    - Demonstration of methods to fabricate, assemble, and maintain large superconductor stellarators free of resonance-inducing field errors

10. *The document supports increased research into use of high temperature superconductors for stellarator applications. Is this a credible step in the near-term? What are the critical fields, bend radii, needed temperatures; what are the specific advantages/disadvantages and opportunities with respect to stellarator applications?*

- High temperature superconductors (HTS) are still under development, but are seeing increasing commercial uses in motors, generators, transmission lines, and other applications with 3D windings. Their application to fusion magnets was identified as a gap in the Greenwald Panel Report.

The advantages and status of HTS stellarator magnets has been explored in the context of the ARIES-CS study by Bromberg, Schultz, and Minervini of MIT.:

- The advantages include
    - Higher temperature and field operation
    - Absence of need for stabilizer/quench protection

- Already compatible with inorganic insulators
- Epitaxial fabrication may allow direct deposition on shaped coil forms.

Disadvantages include

- high cost of commercially-available YBCO HTS at present
- low radiation resistance of YBCO
- strong dependence of its allowable current densities on the normal component of B.

Not all HTS wire materials share these disadvantages. The performance of superconductors and HTSC is highly dependent on the materials and situation. Figure 2, for example, is from a 2006 talk by L. Bromberg (MIT) at the US/Japan Workshop on Power Plant studies,.

- Like most superconductors, YBCO is said to operate most reliably in steady-state. Stellarators may be more suitable for HTS due to reduced need for time-changing magnetic fields.
- Research is needed to develop methods to apply HTSC to fusion in general and stellarators in particular, and determine whether advantages can be achieved.

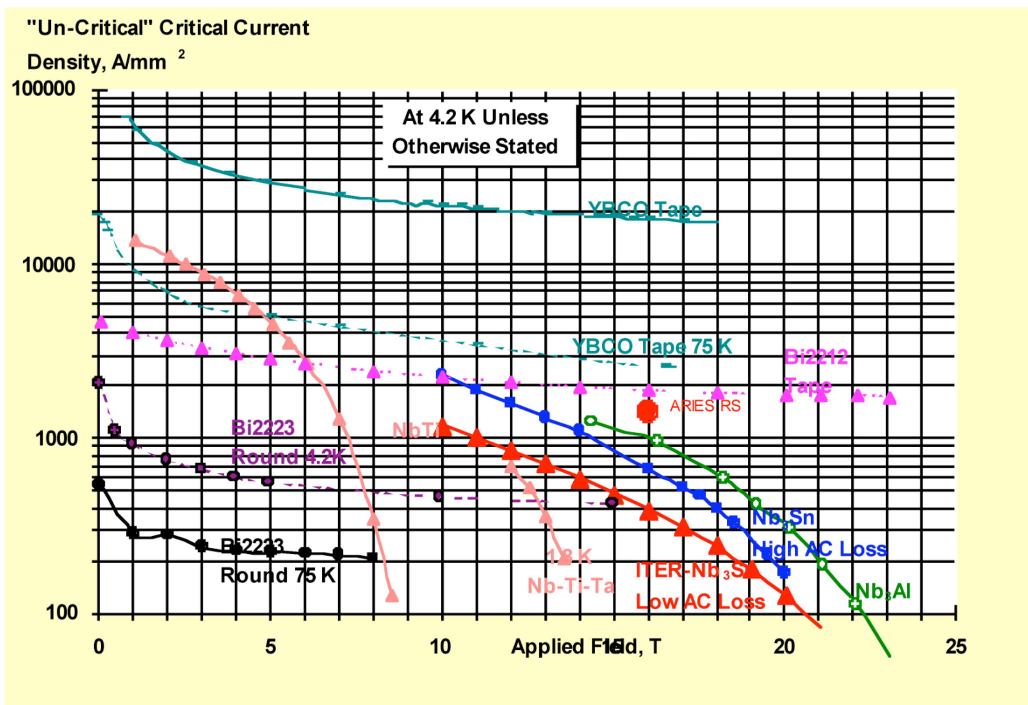

Fig. 2 Critical current densities in various LTS and HTS cable vs. B (attributed to Peter Lee of the National High Field Magnet Laboratory)

11. The panel would appreciate a discussion of the relative priorities assigned to the various scientific and technical issues raised in the white paper or in response to this request.

The basis for selecting priorities to the gaps and opportunities identified in the community white paper is similar to that of the Greenwald Panel Report:

What is the urgency of the specific problem?

What is the state of progress or level of expected effort being devoted to the problem? In what sense is it a gap rather than an ongoing research activity?

As in responses to previous questions, we discuss activities in both the US and international programs. The setting of priorities for the US program depends in part on the progress expected in the larger foreign stellarator program.

Primary priorities (contribution to stellarator goal essential, high promise for attractiveness of concept, comparatively limited work to date relative to benefits):

- **Predictive capability coupled to improved topical theory and modeling; validation of models with experiment**.

  Valid predictive understanding of beta limits, confinement, MHD stability, impurity accumulation are as central to stellarator research as to all concepts. Opportunities should be taken to include 3-D theory and modeling codes in the broad effort to construct integrated simulations of toroidal plasma behavior. Also included in this priority is the strong need for experimental validation of all critical issues and integrated modeling.

  See related submission by Allan Reiman of PPPL on this issue.

  The need for predictive capability in large-scale fusion research is self-evident. What makes it a particularly high priority for stellarators is the fact that the design of an optimized stellarator coil to produce a desired magnetic configuration reflects choices based upon our best theoretical understanding of stellarator behavior. Some choices involve making trade-offs between optimizing predicted stability and confinement as well as pushing against engineering constraints. To reliably guide these choices in configuration optimization, it is crucial to make use of the best validated understanding available.

- **Configuration Optimization**

  Optimization and design of stellarators is one of the most important activities of the US program. US researchers have chosen a strong focus on optimization based on quasi-symmetric principles to reduce neoclassical loss rates, and to gain numerous other benefits. An additional thrust of the US program is the reduction of aspect ratio to achieve relatively large plasmas in smaller, less costly facilities. This general approach complements the development path taken by the successful international program since the mid 1980's largely by including the transformative innovation of quasi-symmetry. Incorporating the diverse range of scientific and technical issues that must be folded into optimal magnetic configurations of a QS design is a major undertaking involving stellarator theory, advanced optimization tools, and deep understanding of stellarator plasmas and physical systems. Furthermore, the use of optimization techniques allow the exploration of quasi-axisymmetric 3-D fields applied to tokamaks to continuously vary the external rotational transform while maintaining near axisymmetry. The appropriate level of quasi-axisymmetric 3-D shaping of a toroidal plasma to provide beneficial stellarator-like characteristics remains to be experimentally determined. For further information on the role of quasi-axisymmetric shaping applied to tokamaks, see submissions by Allen Boozer of Columbia University on the TAP web site.

Understanding of quasi-symmetric optimization is incomplete, and other elements such as accommodation of 3-D divertor structures should be included in the coil optimizing process. Since the start of NCSX construction, progress in this area has slowed greatly, and requires an improved and continuing effort in theory and modeling directed toward this gap.

The high priority assigned to this area reflects the fact that the most difficult aspect of stellarator research is the design and construction of the configuration. A number of potential configurations are possible, and it is not known at this time which type of symmetry, for example, might be best suited for DEMO. One must choose among numerous configurational options afforded by 3-D, and deal with the added complexity of building such a device at a juncture when the least information is available on the actual performance of the device in question. Once built and operating with high density and temperature plasmas, the stellarator is not typically prone to virulent operational limits, nor does it face the strong challenges to steady-state operation - the stellarator's major hurdle comes earlier during design and construction. The need for continued progress in optimizing the configuration from the start necessitates the high priority of this topic.

- **Operational limits**

Hard beta limits set by MHD stability in stellarators are not experimentally observed. The absence of a limit from MHD as well as the impact of high-beta on the equilibrium flux surfaces must be understood so that high performance stellarators can be optimized for the right properties, and not ones that are unimportant.

This continues to be an active area of interest in the international program with studies to be continued on LHD and W7-X. It was also to have been a focus of NCSX research. If the US continues to pursue compact configurations, the effect of aspect ratio on operational limits (beta and density) will be an important research area for the US. In addition, it remains a strong priority of the US program to continue efforts to develop the theoretical tools to understand high-beta stellarator plasmas, particularly the ability to interpret 3-D equilibria, including the effect of pressure-driven magnetic islands.

- **Simpler coil construction**

There is still much to be learned in the construction of stellarators that requires continuing planning on how to assemble them with less risk and cost. This priority refers to rationalizing the design and construction processes of the 3-D coils, vacuum vessel and associated support structure. Regardless of the coil shape, what is needed is the capability to reliably construct and maintain stellarator devices that produce the desired optimized magnetic configuration at a more predictable cost and schedule. The engineering and assembly of coils and the vacuum vessel for high-performance stellarators is typically more complex than for tokamaks, and must be considered to a greater extent in the optimization of machine design and integration of the construction process. For background, we again refer to the documents on the engineering experiences of W7-X and NCSX construction submitted to the TAP web page.

It is obvious that stellarators have been built and operated successfully in the US and abroad. Despite delays, the NCSX coils were successfully constructed. To reduce the risks (level of unpredictability) in stellarator construction, we fundamentally need more experience in designing, building, and testing practical, advanced helical systems. As with every other fusion concept, it is essential to maintain and improve, through practice and experience as well as design, the knowledge of building complex devices.

The emergence of PE-class experiments in the international program is supported by the excellent state of the scientific knowledge base of stellarators and the continuing promise of the stellarator concept to fusion. Budgetary considerations aside, however, there is a gap in the US program that would make it difficult to proceed to the PE stage of stellarator research in the near term. This gap is related to the combined scientific and engineering judgment that facilitates the design of predictably "buildable" configurations. It is a strong priority to close this gap by any means possible. There are some lessons that can be learned from the NCSX construction experience. However, the inability to experimentally test the consequences of the design choices and construction methods, e.g. fabrication tolerances, limits the utility of this experience to future projects.

Secondary priority (areas with considerable work performed nor underway, highly important for continuing progress toward goal):

- **3-D Divertor/ steady-state operation**

  A workable divertor solution is critically important for obtaining high performance steady-state plasmas. Its priority has not been chosen to be in the highest category because of the substantial ongoing activity in 3-D divertors in the international program, backed by the use of comprehensive modeling tools. Experiments on W7-AS and LHD have advanced the understanding of helical and island divertors in stellarators, and distinguished their behavior from their poloidal divertor counterparts on tokamaks. Steady-state island divertors will be extensively investigated on W7-X.

  With the cancellation of NCSX, there is a gap in the US stellarator divertor research effort. The US program should attempt to fill this gap by engaging in international collaborations with the LHD and W7-X divertor activities, and put a high priority on including divertor studies in a future PoP-scale QS experiment.

- **Transport**

  The main niche of US stellarator research within the international program Is based upon improved neoclassical transport and reduced neoclassical viscosity in quasi-symmetric geometry. The low effective magnetic field line ripple achievable with quasi-symmetry is believed to lead to reduced anomalous transport based on results from a number of recent stellarator experiments. Experimental tests of improved collisionless ion confinement in quasi-symmetric configurations remain to be performed.

Understanding of stellarator transport in relation to the underlying magnetic geometry is a strong priority in both theory and experiment. This topic as a gap is not accorded the highest priority because of the ongoing work in this area. The HSX experiment will continue to make seminal progress in understanding QS electron transport despite the gap left by the cancellation of NCSX. The potential for demonstrating adequate collisionless ion confinement in stellarators is limited by the present size of US devices, and would need to be addressed in a larger PoP-scale experiment.

- **Impurity accumulation**

  Stellarators are predicted to suffer from impurity accumulation to a greater extent than tokamaks due to neoclassical transport in the ion root regime. However, as discussed earlier, stationary ELM-free plasma regimes have been identified in stellarators that exhibit acceptably low impurity confinement. Establishing these or similar modes in higher performance plasmas will be continued in LHD and W7-X. Quasi-symmetric stellarators with low radial electric fields in the core may not be as susceptible as non-optimized stellarators to impurity build-up from inward neoclassical convection.

  Because of the importance of achieving high density operation in stationary stellarator discharges, the understanding of core impurity accumulation is a relatively high priority for the international program. It may not be satisfactorily addressed in the experimental US program unless high ion temperatures can be obtained. This issue, and the priority for resolving it, pushes for a PoP level quasi-symmetric experiment as a unique, and needed, contribution to global stellarator research.

- **Advanced coil technology**

  While not absolutely essential to achieve many of the scientific goals of the US stellarator program, the application of HTS magnet technology makes a unique and potentially transformative US contribution to the world fusion program, and to the steady-state vision of the stellarator in particular. It is not likely that fully steady-state experiments could be pursued within the framework of the US stellarator road map without the use of HTS magnets. If the steady-state goal is to be addressed within the US during the 20-year time frame, a moderate level of priority must be allocated to exploring the development of this technology for stellarators.

Tertiary (areas of importance and potential improvement for which sufficient capabilities are at hand, or ones that are not envisioned to limit further progress toward 20-year goal):

- **Disruptions**

With the cancellation of NCSX, the issue of current-driven disruptions becomes less of an immediate priority to present-day stellarator research. Nonetheless, the potential benefits of compact configurations (with bootstrap current) argues for the need to assess current-driven MHD stability in stellarators. The issue of disruption suppression by 3-D effects applied to tokamaks is also of considerable importance.

- **ITB's**

Based on present knowledge, development and exploitation of internal transport barriers, though potentially desirable, is not a requirement to achieve the stellarator goal. Work on several types of internal barriers is taking place on TJ-II and LHD. Because of the ongoing work in this area, and the non-essential need for ITB's, this topic is of lesser priority.

In the US, electron transport barriers will be studied in the existing HSX device. Studies of thermal and energetic ion transport will likely require a larger PoP-scale QS experiment.

- **Plasma start-up/profile control**

The major issue associated with this priority is discharge evolution to the desired finite-beta equilibrium. Because of the relatively weak dependence of stellarator equilibria on pressure-driven currents, this issue remains a relatively low priority of the US and international programs. W7-X will pursue transient beta ramp-up scenarios with ECCD. Within the US program, NCSX, with its large bootstrap current, had developed plans to explore start-up scenarios and would have dealt with this issue in some detail.

- **Maintainability/remote handling**

This issue was called out as one of importance by the ARIES-CS team. Pursuit of this topic will largely take place as part of configuration optimization, but at the present time has lower priority than the optimization of such areas as transport, divertor performance, and high beta operation.