ROLE OF STELLARATORS IN THE U.S. FUSION PROGRAM

Prepared by

Allen Boozer, Columbia University
(212-854-4785, ahb17@columbia.edu)

James Lyon, Oak Ridge National Laboratory
(423-574-1179, lyonjf@fed.ornl.gov)

Leon Shohet, University of Wisconsin
(608-262-1191, u1451@c.nersc.gov)

with community input

in response to questions from the

Scientific Issues Subcommittee

of the

Fusion Energy Science Advisory Committee

April 18, 1996

The January 1996 report of the Fusion Energy Advisory Committee (FEAC) listed three items under the "New Mission" of the fusion energy sciences program: (1) "Advance Plasma Science," (2) "Develop Fusion Science and Concept Innovation," and (3) "Pursue Fusion Energy as an International Collaboration." The stellarator can make unique and important contributions to all three missions.

1. Advance Plasma Science: The stellarator drives the development of three-dimensional (3-D) plasma physics, which is needed throughout the toroidal fusion program and for the study of naturally occurring plasmas. For example, resistive wall modes and field error effects are 3-D equilibrium problems. 3-D effects provide fundamental limits on the performance of nominally axisymmetric devices like tokamaks and RFP's. Electron orbits in the magnetosphere are studied using the magnetic coordinate and drift Hamiltonian techniques developed for stellarators.

2. Develop Fusion Science and Concept Innovation: The flexibility of the stellarator concept allows unique contributions to concept innovation through: (a) addressing critical issues in plasma science and (b) developing attractive fusion configurations. For example, the stellarator is unique among toroidal systems in being able to have the trapped particles centered on either a magnetic hill, as in a tokamak, or in a magnetic well, which allows critical tests of the theory of trapped electron modes. Also, only stellarators can maintain either sign, or essentially zero, global shear across the entire plasma to study the mechanisms of improved confinement. Devices with quasi-helical symmetry, quasi-toroidal symmetry, or stellarator-tokamak hybrid features allow the study of tokamak-like physics without the complication of the tokamak current. Since the poloidal flux is produced by external coils, no net plasma current is required. This has distinct advantages compared to other toroidal configurations that must deal with current drive, large bootstrap current fraction, major disruptions, and issues of position control.

3. Pursue Fusion Energy as an International Collaboration: Two aspects are (a) collaborations on foreign experiments and (b) a sufficiently strong domestic program to be a valued international partner. The international program in stellarators is second only to that in tokamaks, and the only major magnetic fusion devices under construction are two stellarators, LHD (Japan) and W7-X (Germany).

(a) Collaborations on foreign stellarators would allow the study of issues on machines of a scale that the U.S. fusion program cannot afford. These niche programs should be in areas that connect to domestic programs in stellarator theory, smaller stellarator experiments, and tokamak research. Examples are the use of divertors, pellet fueling, and ICRF heating in plasmas with higher parameters to study confinement improvement.

(b) The U.S. can be a valuable international partner in the larger world stellarator program through innovative theory and well-focused domestic experiments. Unlike the current-maintenance issue of the steady-state tokamak, major stellarator issues do not require the combination of steady-state and high-performance plasmas and can be efficiently studied on well-designed small and medium scale experiments.

The list of questions that the stellarator community was asked follows the Executive Summary. These questions are answered briefly in the Executive Summary (the letters correspond to the questions) and in detail in the numbered sections that follow. The section on alternate concepts and the stellarator in the January 1996 FEAC report is given in the Appendix.

EXECUTIVE SUMMARY

A. World-Wide Status of Research and Achievements on Stellarators

Sufficient confidence in the experimental and theoretical understanding of equilibrium, stability, and transport exists to proceed to integrated tests of stellarators in the one-half to one billion dollar class: the Japanese LHD and the European W7-X.

A1. Experimental achievements: Stellarator plasmas have ion temperatures up to 1.6 keV, electron temperatures up to 3.5 keV, densities to 3×10^{20} m^3, volume-average beta values greater than 2%, and an energy confinement time greater than 40 ms. Plasma heating efficiencies are similar to tokamaks and a divertor concept has been successfully tested.

A2. Theoretical understanding: Reliable codes have been developed for design and interpretation of the equilibrium, stability, and neoclassical transport properties of stellarators over the last 15 years. Analytic expressions for neoclassical transport coefficients have been derived and fundamental understanding of equilibrium and transport properties has been developed using magnetic coordinate representations and a Hamiltonian description of the particle drifts.

A3. Agreement with experiment of theory and empirical scalings: Codes accurately predict the shape of the 3-D pressure surfaces. The neoclassical theory is consistent with the empirical ion transport coefficients at low collisionality and the measured radial electric field. The empirical magnitude and scaling of transport are similar to tokamaks and to a gyroreduced-Bohm Lackner-Gottardi scaling $(\rho_i/qR)(T/eB)$ with ρ_i the ion gyroradius, q the safety factor, and T the temperature.

B. Appropriate Level of Research

B1. Major experimental and theoretical issues: The major issues are understanding and configuration optimization for neoclassical and anomalous transport, divertors, plasma beta, and minimum aspect ratio.

Experiments should: (i) test neoclassical transport and investigate the role and control of radial electric fields at lower collisionality; (ii) study the sensitivity of turbulence and anomalous transport to magnetic configuration and plasma parameters; (iii) further develop the particle and power handling concepts; (iv) investigate the limiting plasma behavior as beta is raised; and (v) test key optimization principles and techniques for confinement improvement.

Theory issues include: (i) the clarification of the constraints on the magnetic configuration imposed by adequate neoclassical confinement; (ii) the modification of the tokamak linear and gyrokinetic codes for application to stellarator configurations; (iii) the development of techniques and codes for studying stellarator divertors; (iv) the augmentation of equilibrium codes to incorporate new effects such as the improvement in the magnetic surface quality in the presence of plasma rotation; and (v) the exploration of new stellarator configurations that maintain desirable properties but are consistent with smaller power plants.

B2. Requirements. Important experimental issues for specific concepts are and will be addressed in an integrated form on the major experimental facilities that exist or are being built in Europe and Japan. However, the range of issues is sufficiently great that critical areas -- like the minimum aspect ratio -- will not be addressed within the present program. Addressing the issues in B1 requires

(a) new experimental facilities and theoretical activities to explore physics issues associated with concept improvement: more compact systems with unique physics features, such as quasi-toroidal symmetry and stellarator-tokamak hybrids; and

(b) expanding the current experimental and theoretical activities to supplement the small residual efforts in theory and international collaboration.

(c) Innovative university programs exist on quasi-helical symmetry and surface reconstruction, and there is a small level of international collaborations. A number of theorists maintain an interest in stellarator problems. These serve as an important base from which stellarator activities could be expanded.

(d) U.S. budgets for theory and international collaborations have declined to very low levels. It is difficult to see how significant issues could be addressed at even lower levels. U.S. support for stellarator research may already be below even the level required to maintain an adequate core of individuals with informed opinions on the world stellarator program. Current U.S. levels of research are approximately 1.3 M$/yr for domestic experiments, 0.4 M$/yr for international collaborations, and 0.2 M$/yr for theory.

B3. Appropriate mix of research activities: Stellarators have the flexibility to design around critical problems and require a broad research program to fully exploit their potential. Small experiments are required to test innovative ideas, theory is required to efficiently choose the most important experiments, and experiments on large facilities are needed to study higher parameter regimes. The appropriate mix of research activities for the United States is discussed in B5.

B4. Research program outside the U.S.: The only major fusion machines under construction in the world program, LHD (1998) and W7-X (2004), will provide integrated tests of particular stellarator configurations using superconducting coils. Divertor, transport and beta limit issues are being studied on CHS in Japan and W7-AS in Germany. TJ-II in Spain (1997) and H-1 in Australia will focus on beta limit issues. Stellarator research is also being pursued in Russia and the Ukraine. The theory programs associated with the major stellarators are focused on support for the experiments. Longer range projects include a better free boundary package for the MHD stability codes, which is under development at Garching. Studies are also starting on the implications of different stellarator configurations for a fusion power plant.

B5. Proper level of U.S. research: The U.S. can make significant contributions to the world program on stellarators through theory, domestic experiments, and selected collaborations on foreign experiments.

(a). A third large superconducting stellarator would be difficult to justify even if it were consistent with U.S. fusion budgets.

(b). The U.S. stellarator program should focus on confinement understanding and concept improvement through innovation in theory, configurations, and experimental design; domestic experiments; and collaborations on larger foreign facilities. The stellarator is a concept in which invention and flexibility can help counterbalance limited resources. Stellarators of international importance, well-differentiated from existing designs, can be built over a broad spectrum from small to large.

There are two rational levels for the U.S. stellarator program:

(i) As a junior partner in the international program. Greater than 6M$/yr would allow the U.S. to contribute to the world experimental program in narrowly focused areas and have a stellarator theory program of international importance. This level of effort is consistent with a core of individuals who are well-informed on the international program.

(ii) Aggressively use the opportunities the stellarator offers to maintain our position as a valued international partner in fusion research. An innovative stellarator could be built utilizing existing resources to study beta limits and confinement at high temperature at a cost of 20–40 M$/yr.

In either program, the minimum levels required for an effective program in theory, smaller experiments, and international collaborations are given below.

(1) About 10% of the total U.S. theory expenditures (about 1.8 M$/yr) would give world leadership in innovative theory for stellarators and 3-D plasmas. It would support the core of theorists required for the interpretation and design of experiments as well as for the invention of new configurations. About 25% of the stellarator theory program should be devoted to the two aspects of optimization of stellarators needed for incisive tests of physics or for power plants: (i) the practical definition of the optimization criteria and (ii) the search for configurations that satisfy these criteria.

(2) Stellarators have many more configurations but are explored in fewer devices than tokamaks. Well-focused experiments of modest cost can perform incisive tests on general issues of toroidal plasmas as well as those specific to stellarators. The HSX experiment (presently 1.2 M$/yr; proposed 1.6–2 M$/yr) will test the basic equilibrium and orbit confinement properties of the quasi-helical stellarator. The CAT experiment (presently 0.1 M$/yr; proposed 0.25 M$/yr) studies basic physics such as the loss of magnetic surfaces. Additional opportunities, such as a low aspect ratio stellarator-tokamak hybrid, exist in this range of funding.

(3) The U.S. can pursue physics issues that are appropriate to large or steady-state stellarators through collaborations on foreign devices. Approximately 2M$/yr would allow the development of a U.S. role on the largest stellarators in the world program in niche areas that connect to domestic programs in stellarator theory, smaller stellarator experiments, and tokamak research. Examples are the use of divertors, pellet fueling, and ICRF heating in plasmas with higher parameters to study confinement improvement.

Larger funding would allow significantly more impact on the world stellarator program. Experiments at the 20–40 M$/yr level could efficiently use existing resources to study beta limits and high temperature transport in an innovative stellarator. An example could be Garabedian's proposal of a quasi-toroidal stellarator with an aspect ratio of 4.5 and particle drift orbits and neoclassical transport similar to that of a tokamak.

C. Potential Impact of U.S. Stellarator Research

Stellarators drive the development of 3-D plasma physics and are needed to define the possibilities and limitations of toroidal confinement.

C1. General plasma physics: Because naturally occurring plasmas are fully 3-D, the theoretical techniques developed for stellarators have application to a broad range of plasma problems, for example, electron orbits in the magnetosphere.

C2. Fusion plasma physics: 3-D equilibrium theory developed for stellarators provides insights and computational techniques for resistive instabilities, wall modes, and field error effects. Transport and particle losses due to symmetry breaking had a natural development in the context of stellarators. Comparisons between stellarator and tokamak experiments have broadened the understanding of bootstrap currents, edge velocity-shear layers, and role of field errors in both systems. Stellarators continue to provide unique plasma configurations and tests of physics: trapped particle instability theory will be tested on W7-X in which most trapped particles are in a region of good curvature. Also, stellarators can maintain a reversed q-profile across the entire plasma and thereby test effects of globally reversed shear (or low shear). A quasi-toroidal stellarator can test tokamak physics without a net plasma current. Quasi-toroidal and quasi-helical stellarators have different signs of the bootstrap current, allowing tests of stabilization and destabilization of magnetic-island-producing perturbations.

C3. Development of fusion energy: By requiring no net current, the stellarator avoids problems associated with current drive requirements, control with a high bootstrap current fraction, major disruptions, and positional control systems and instabilities. Steady-state tokamak designs are highly constrained by the requirement of high poloidal beta for efficient current maintenance and by the avoidance of vertical and major disruptions. The stellarator may lead to an improved, intrinsically steady-state reactor with low recirculating power, a robust magnetic configuration, and lower power density on the in-vessel components. Much of the experience of the world fusion program on steady-state, superconducting devices with divertors will be developed on the LHD and W7-X stellarators. U.S. involvement in these programs will contribute to development of the enabling technologies and operating techniques needed for larger devices.

C4. Developing concept as a power plant: Research is required to determine the extent to which anomalous transport can be controlled by trapping particles in good magnetic curvature or modifying the magnetic shear profile. The recent U.S. Stellarator Power Plant Study has shown that modern stellarator designs can be competitive with tokamaks as fusion power plants. Design optimization studies are needed to obtain more compact configurations with good confinement properties and adequate beta. The higher the aspect ratio the easier stellarators are to design for high beta and good confinement but the larger the minimum-size power plant.

Stellarator research contributes in a unique way to major goals of the science-based U.S. fusion program: confinement understanding and concept innovation. The broader range of magnetic configurations accessible in stellarators and the ability to design a magnetic configuration with desired physics properties allow extension of our understanding, and better optimization, of the toroidal confinement concept. The reasons that are given for maintaining a strong U.S. tokamak program are: (a) as a driver for the development of fusion science, (b) the closeness of the concept to the requirements for fusion power, (c) leverage and the need for information on a much larger world program, (d) a core of scientific leaders in the area, and (e) the efficient utilization of existing experimental facilities. These same reasons also imply that stellarator research is an essential part of an innovative U.S. fusion science program. The flexibility of the concept and the smaller number of world stellarator laboratories gives the United States unique opportunities to remain a valued international partner despite budget limitations.

QUESTIONS FOR ALTERNATE CONCEPTS

Question A: What is the current world-wide status of research and achievements:

A1: What is the present experimental achievements?

A2: What is the present theoretical understanding?

A3: Do theory, modeling, simulations, and empirical scalings fit the experimental observations?

Question B: What is the appropriate level of research for this concept:

B1: What are the major experimental and theoretical issues that should be addressed?

B2:Do the above issues require
(a) launching new experimental facilities and/or theoretical activities?
(b) expanding the current experimental and theoretical activities?
c) they can be addressed at present level of research?
(d) or they can be addresses in a lower level of research?

B3: What is an appropriate mix of research activity for this concept among large facilities and mix of small supporting experiments, theory and modeling, and concept design and evaluation studies?

B4: What is the world-wide research plan (outside U.S.) to address the above issues?

B5: What is the proper level of US research in the context of the international program? In particular:
(a) Is it necessary to have more than ONE NEW international experimental facility?
(b) Given the world-wide plan, which areas US program should focus on?

Question C: What is the potential impact of research on this concept on

C1: increasing our knowledge of general plasma physics?

C2: increasing our knowledge of fusion plasma physics (of this concept as well as physics of other confinement concepts)?

C3: helping develop fusion as an energy source (help develop the data base for fusion development steps such as burning plasmas, volumetric neutron source, etc.)?

C4: developing this concept as a candidate for a fusion power plant?

***Question A**: What is the current world-wide status of research and achievements:* **(3 parts)**

Historical Background. Stellarators became a minor element in the U.S. program after 1969 and did not reappear as a major confinement program element until ATF operated at the end of the 1980's. The Bohm-like confinement in the Model-C stellarator (presumably due to poor magnetic surfaces) had led to the conversion of that facility to the ST tokamak. However basic stellarator research, principally at the University of Wisconsin, continued in the U.S. at a lower level, and Japan and Germany progressed through a number of devices up to Heliotron E and W7-A. The advent of high-power high-frequency electron cyclotron heating and neutral beam heating allowed currentless ("true stellarator") operation and the attainment of significant plasma parameters in Heliotron E and W7-AS by the mid 1980's.

Improvement in Power Plant Prospects. Stellarators were previously thought to be impractical for a fusion power plant because of the combination of toroidal and helical field ripple that led to poor confinement and the large helical coils that were interlocked with toroidal field coils. Interlocking coils were eliminated by the torsatron concept, the basis for the Large Helical Device (LHD) [1] being built in Japan. The construction of LHD demonstrates that large helical superconducting coils can be wound [2]. In addition, many modern stellarators have modular coils in which the required helical structure is produced by non-planar toroidal field coils [3]. The problem of poor orbit confinement can also be solved. For example, the quasi-helical stellarator [4], in which the particle drift trajectories have an approximately conserved helical component of the canonical momentum, has particle drift orbits and neoclassical transport properties that are similar to those of a tokamak. In actuality, losses give rise to an ambipolar electric field which can reduce tranport and make the loss process self healing [5]. The benefits and the control of the radial electric field require further experimental and theoretical investigation before the optimal configuration requirements can be defined. A recent exploration of the reactor potential of stellarators, the U.S. Stellarator Power Plant Study (SPPS) [6] by the same team that has studied tokamak power plants (ARIES, PULSAR), has confirmed that stellarators can be economically competitive with tokamaks [7].

Physics Progress. In parallel, there have been significant advances in plasma parameters and physics understanding that now make stellarators second only to tokamaks in level of development. This is not surprising since both concepts rely on helical (toroidal plus poloidal) magnetic fields with comparable rotational transform for plasma confinement and stability and both use the same heating, fueling, and diagnostic techniques. The higher parameters in present tokamaks are due primarily to their larger plasma sizes, magnetic fields, and heating powers since the L-mode confinement scaling for both is similar. Extensive operating experience at high power in many tokamaks has led to improved confinement regimes in tokamaks. Although confinement is not yet as good as in tokamaks, H-modes and other improved confinement modes have been observed in stellarators [8]. Also, reliable codes now exist for calculating the basic equilibrium, stability, and neoclassical transport properties of stellarators, a development of the last 15 years, which allows design of innovative stellarators with improved confinement properties to address basic toroidal physics issues.

Present Status. Sufficient confidence in the experimental and theoretical understanding of equilibrium, stability, and transport exists to proceed to integrated tests of stellarators in the one-half to one billion dollar class: the Japanese LHD [1] and the European W7-X [9]. These experiments will study stellarator physics at more reactor-relevant parameter regimes: ion temperatures up to 10 keV, betas up to 5%, and energy confinement times above 0.1 s.

Concept Improvement. Two approaches are being followed: studying prospects for improvement of confinement (power thresholds for H-mode, internal transport barriers, control of the electric field and the edge properties) and configurations that have intrinsically better confinement by optimizing the magnetic field structure -- helias, quasi-helical and quasi-toroidal stellarator configurations.

Question A1: What are the present experimental achievements?

Enormous progress has been achieved during the past decade in the world stellarator program, especially with the successful operation of ATF, CHS, and W7-AS. Important contributions have also come from the older stellarators (Heliotron E, L-2, W7A) and university experiments.

Plasma Parameters. Along with this understanding has come significant improvements in plasma parameters: volume-average beta $\langle\beta\rangle$ = 2.1%, nearly half that required for a competitive reactor; electron temperature T_e = 3.5 keV >> T_i, the ion temperature, for studies of electron transport at low collisionality; T_i = 1.6 keV, T_e = 1.8 keV at central electron density $n_e(0) = 5 \times 10^{19}$ m^{-3} for studies of ion transport at low collisionality; $n_e = 3 \times 10^{20}$ m^{-3} for density limit studies; and energy confinement time τ_E > 40 ms for confinement scaling studies. These are the best values for these parameters. Some simultaneous sets of parameters are given in the table below.

	T_i (keV)	T_e (keV)	$n_e(0)$ (10^{20} m^{-3})	B (T)	P (MW)	plasma radius (m)
Low ν_i*	1.6	1.8	0.5	2.5	1.25	0.2
$\langle\beta\rangle$ = 2.1%	- -	- -	>1	0.57	1.8	0.2
τ_E = 43 ms	0.6	0.7	1.1	2.5	0.33	0.2

Medium NBI power, boronization, and optimization of the toroidal variation of the magnetic field led to the 1.6-keV central ion temperature in W7-AS [10]. Higher ion temperatures were prevented by the uncontrolled density increase associated with higher-power NBI and lack of a recycling control system. Transport analysis indicates a key element in this improvement is an ambipolar electric field of ~10–50 V/cm, which reduces the ion neoclassical heat diffusivity by more than an order of magnitude.

Confinement Improvement. Although H-mode and other improved confinement modes have begun to be studied in stellarators, the same degree of confinement improvement that has been observed in the larger tokamaks at high power has not been seen yet. The confinement improvement factor of 2 that is desirable for a reactor has been observed transiently, but factors of ≈1.3 are more typical in steady-state. However, there are several reasons for optimism. The present power levels may not be sufficient for a stable transition to H-mode operation. The Pfirsch-Schlüter and bootstrap currents are reduced in optimized stellarator configurations over those in present stellarators, so there is less free energy to drive instabilities. In addition, the effective helical ripple can be reduced over that in a conventional stellarator using quasi-helically symmetric features, so ripple-induced transport at low collisionality can also be reduced. Comparisons of experimentally determined transport with neoclassical predictions and the empirical confinement scaling is discusses in Question A3.

Finite-Beta Behavior. There are indications that the magnetic fluctuations decreased in amplitude at the highest beta values ($\langle\beta\rangle$ = 2.1%) achieved in CHS [11], consistent with observations on ATF; however more theoretical understanding is needed to interpret the results. Average beta values of 1.8% were obtained in W7-AS at a magnetic field of 1.25 T, above the stability limit for resistive interchange modes [10]. From fluctuation measurements and global plasma parameters, no indication of a stability limit has been observed experimentally.

ICRF Heating. Effective ion cyclotron range of frequency (ICRF) heating in stellarators is important both for steady-state operation of LHD and W7-X and for better understanding of ICRF heating in toroidal geometry. Although successfully used in tokamaks, bulk heating had not been observed in stellarators until recently. Sustained bulk heating with ICRF has now been demonstrated on CHS with a single-strap antenna on the low-field side [12] and on W7-AS with a 1-m toroidally extended antenna on the high-field side [13] in a very different magnetic configuration from that on CHS. The heating efficiency with second harmonic and hydrogen-minority-species plasma heating is similar to that obtained with electron cyclotron heating or neutral beam injection. Sustainment of the plasma density after ECH turnoff with ICRF alone for the duration of the ICRF pulse has been demonstrated on both CHS and W7-AS. The edge electric field reverses during an ICRF pulse, which opens up some very interesting possibilities for transport studies. There is no increase in the total radiated power in contrast to the behavior seen in earlier experiments.

Particle Control. Because of the absence of ohmic current, stellarators do not suffer from major disruptions or vertical displacement events. A comparison of density limits in ASDEX and W7-AS indicate that because of the lack of disruptions, stellarators have the capability of achieving higher densities than tokamaks [14]. Sudo et al. [15] have proposed a maximum line-average density,

$$n_{\mathrm{max}} = 0.25(PB_0/R_0 a_{\mathrm{p}}^2)^{1/2},$$

based on Heliotron E data. However, densities a factor of 1.3 higher than this value have been observed in ATF [16]. This would not have a significant impact on fusion power plant design [7].

Density profile control is an important factor for confinement improvement in both stellarators and tokamaks. Recent pellet injection experiments on W7-AS showed behavior different from that seen in tokamaks or in the absence of pellet injection: a rapid density redistribution without significant loss of plasma accompanied by $m = 0$ damped oscillations in the soft X-ray signals. The density profile reaches the same shape as that before pellet injection but with >50% higher density in less than 1 ms, more than an order of magnitude faster than that expected from the usual particle diffusivity, and evolves slowly afterwards (on a 20-ms timescale) due to wall recycling. The rapid density redistribution, which does not lead to a loss of particles, is accompanied by slow (~1-ms) damped oscillations in the soft x-ray array signals that are in phase across most of the plasma and out of phase at the plasma boundary, indicating an $m = 0$ oscillation that is not seen in tokamaks or in W7-AS in the absence of pellet injection. The sharp rise in the stored energy (increased energy confinement time) following pellet injection is accompanied by a quiescent period in the Mirnov loop signals when the stored energy starts to increase.

Progress has been made on island-based divertors for stellarators. A local island divertor concept which uses an externally produced $m = 1$, $n = 1$ island to avoid the leading edge problem of a pumped limiter by channeling the particle flux into a pump duct has been successfully tested on CHS [17]. In addition to shielding the plasma from incoming gas and impurities and depositing the diverted power on the back of the divertor head away from the leading edge, these experiments also show confinement improvement and the attainment of much higher plasma densities and betas at larger values of the plasma major radius than had been obtainable before in CHS. Understanding of the island structure at the edge of the plasma in W7-AS has progressed to the point where it has been used to design a full divertor system for both W7-AS and W7-X [18]. The W7-X divertor takes the form of a helical stripe that is only on the outside-major-radius side of the plasma where the access is best.

***Question A2**: What is the present theoretical understanding?*

The theory of 3-D plasmas, such as stellarators, has a greater intellectual subtlety than the theory of axisymmetric tokamaks. The beauty and elegance of 3-D theory make it an attractive area of research. Examples include the development of magnetic coordinates that simplify equilibrium and transport theory and the drift Hamiltonian theory [19]. Analytic calculations have determined the fundamental neoclassical transport coefficients and their dependence on radial electric fields [5,20,21]. In 3-D systems, charge neutrality or ambipolarity requires certain values for the radial electric field, called roots. In simple situations, there are two stable roots, an ion and an electron root, which have been shown to have very different transport coefficients [5].

Analytic theory has been an essential element in the development of the codes that are the basis for the design and interpretation of stellarator experiments. The advanced theoretical and computational techniques required to design and interpret fusion-relevant stellarator experiments are a development of the last 15 years. Major codes were written in the United States, Europe, and Japan. Within the stellarator community, there has been a long tradition of sharing codes and techniques, so these codes are used throughout the world stellarator program.

i. Equilibrium Codes

Four equilibrium codes are widely used in the world stellarator program: VMEC, NSTAB, PIES, and HINT. Two of these codes, VMEC and NSTAB, derive efficiency from an assumption that magnetic surfaces exist. VMEC, the most frequently used code, was developed by Steve Hirshman and collaborators at ORNL [22–24]. The NSTAB code is the latest in a series of codes for calculating three dimensional equilibrium and stability that have been developed at NYU by Paul Garabedian and collaborators [25,26]. The PIES code, which was developed by A. Reiman and collaborators at PPPL [27], uses an iterative procedure to find three dimensional equilibria including possible islands and stochastic magnetic fields. In addition to its stellarator applications this code has been used to find tearing mode stability and the field error sensitivity of tokamaks [28]. The HINT code was developed by T. Hayashi of NIFS in Japan [29]. This code uses a finite differencing procedure on the equilibrium equation making no assumption about the existence of surfaces.

ii. Stability Codes

In principle, any three dimensional equilibrium code can also be used as a stability code. Instabilities imply the existence of a second equilibrium with lower energy and symmetry which can be found by adding a small external perturbation to the original equilibrium. If the equilibrium maintains a perturbed form as the magnitude of the external perturbation is reduced, the original equilibrium is unstable. The NSTAB code has been used extensively to study low mode number ideal modes [26], and PIES has been used to study resistive stability in tokamaks [28]. Although any three dimensional equilibrium code can be used as a stability code, specialized stability codes can offer improved accuracy, efficiency, or resolution. As with tokamaks, there are two types of ideal stability codes for stellarators--low mode number codes (analogous to the PEST code) and local ballooning or Mercier codes.

The poloidal magnetic flux in a stellarator is produced almost entirely by the helical structure of the coils rather than a net toroidal current as in a tokamak. Two consequences are that positional instabilities, such as the vertical instability in tokamaks, are of no relevance and low mode number perturbations, which have a strong drive from the gradient of $j_{||}/B$, are of much lesser importance. Consequently, the equilibrium beta limits of stellarators are largely determined by localized modes -- Mercier modes.

Although low mode number instabilities in a stellarator are of less importance than in a tokamak, their stability is and should be analyzed. The two general codes for examining the stability of stellarators to low mode number perturbations are CAS3D developed by C. Schwab at Garching [30] and TERPSICORE developed by W.A. Cooper and collaborators at Lausanne [31]. In addition, the stability of stellarators with circular magnetic axis, such as the LHD stellarator, can be studied using an averaging technique that associates the stellarator with an effective axisymmetric configuration [32].

Localized modes, which often determine stellarator stability limits, are assessed using the JMC code, which was written by Nührenberg's group at Garching [33], or by a routine in the NSTAB equilibrium and stability code [26].

In addition to standard MHD instabilities high energy particles, such as those that result from neutral beam injection, can drive low mode number instabilities. Codes originally developed for the tokamak have been used to interpret mode observations on W7-AS [34].

iii. Particle Orbit and Neoclassical Transport Codes

In three dimensional systems, the design and interpretation of experiments requires a careful calculation of particle orbits and neoclassical transport. In the absence of a conserved component of the canonical momentum, neoclassical transport becomes analytically far more difficult [5,20,21] but experimentally more important than in tokamaks. Quasi-helical stellarators [35–37] have a conserved component of the canonical momentum, but the LHD and W7-X stellarators do not. Neoclassical transport in stellarators is studied using Monte Carlo transport codes descended from one written by Boozer and Kuo-Petravic [38], such as the TRAN code [39] or by DKES, which solves the drift kinetic equation directly [40]. Recent work on the Monte Carlo method [41,42], the so-called delta-f technique, permits the efficient calculation of plasma currents, which formerly could only be computed using DKES [40]. The slowing down trajectories of high energy particles are determined using the Monte Carlo transport codes.

iv. Anomalous Transport Codes

Although some stellarator experiments are consistent with neoclassical theory, anomalous transport plays a major role in the interpretation and the design of stellarators. Relative little work has been done on the microstability of stellarators [43], though the theory should be a direct extension of that developed for tokamaks. The stellarator offers unique tests of the physics. Most of the trapped particles in W7-X bounce in a region of good magnetic curvature [44] unlike the situation in a tokamak. The standard tokamak linear and fully non-linear codes can be generalized to handle 3-D plasmas.

v. Divertor Codes

A tokamak or a stellarator divertor concentrates the plasma exhaust in narrow stripes--easing the removal of particles but complicating the removal of heat. In a tokamak the stripes are continuous circles and in a stellarator helical line segments. In both stellarators and tokamaks it is difficult to handle the power in the divertor stripes unless most of the energy in the exhaust is lost by radiation. The theory of divertors in stellarators has primarily consisted of following magnetic field lines and tracing the motion of particles along those lines [45]. The effects of particle diffusion have been included by the Monte Carlo method. The tokamak divertor codes have been applied to stellarators, but further code development is required

vi. Optimization Codes

The fusion potential of the stellarator is sensitive to the configuration. The optimization of the magnetic configuration has been a relatively minor element in tokamak research, though it is the core of the advanced tokamak program. Stellarator optimization issues include minimal aspect ratio, neoclassical and high energy particle confinement, beta limits, anomalous transport, and divertor configuration. In addition, stellarators can be optimized to provide incisive tests of the physics of toroidal confinement.

The higher the aspect ratio the easier stellarators are to design for high beta and good confinement but the larger the minimum size power plant. A major issue is to how low an aspect ratio can desirable properties be retained. A year ago the answer appeared to be about aspect ratio seven, but Garabedian has discussed a two period quasi-toroidal stellarator which has an aspect ratio of 4.5 and a beta limit of 5%.

The science of optimization has two aspects: (1) the practical definition of optimization criteria and (2) the search for magnetic configurations that satisfy these criteria.

Two codes carry out the search for optimal equilibria using the fact that a curl-free magnetic field is uniquely defined by the shape the outermost magnetic surface and the magnetic flux enclosed by that surface. These codes are the Garching code [46] and the combination of Garabedian's NSTAB and TRAN codes [26,39]. Once a desirable stellarator configuration is found, one can find a set of modular coils, essentially a set of bent toroidal field coils, that accurately produce that field using P. Merkel's code NESCOIL [47].

A different optimization scheme was used to define the LHD device [1]. The winding law for the large helical coils was defined with free parameters which were adjusted to obtain an optimal configuration. Optimization criteria included the volume filled with nested magnetic surfaces, a magnetic well, and the confinement of high energy particles.

The physics of optimization was aided by the insight that the quality of particle orbits [48], equilibrium [49], and stability [33] in toroidal plasmas are largely determined by the form of Fourier series for $1/B^2$ on the magnetic surfaces. For example, the particle orbits and neoclassical transport in a fully three dimensional system can be similar to that of an axisymmetric tokamak if only one helicity appears in the Fourier series for $1/B^2$ [36], the principle of the quasi-helical stellarator [35]. A less restrictive condition is to make all the minima of the field strength on a given magnetic surface have the same value [50]. This condition guarantees the drift orbits of the deeply trapped particles coincide with the magnetic surfaces. Since the orbits of the passing particles lie on the magnetic surfaces, the condition on the minima of the field strength is necessary for good orbit confinement without an electric field. This principle was used in the optimization of W7-X and allowed (1) the parallel plasma current (the Pfirsch-Schlüter plus the bootstrap current) to be made much smaller than in quasi-helical symmetry. (2) the bulk of the trapped particles to be in a region of good magnetic curvature unlike the case in a tokamak or in quasi-helical symmetry. The advantage of small parallel currents is that the shape and location of the magnetic surfaces is essentially independent of plasma pressure assuring that no external fields require adjustment as beta is changed. Having the trapped particles in a region of good curvature should reduce the transport due to trapped particle modes.

***Question A3*: Do theory, modeling, simulations, and empirical scalings fit the experimental observations?**

Ripple-Induced Transport. A disadvantage of stellarators compared to tokamaks is that the asymmetry of the magnetic field, due to a combination of helical and toroidal curvature, can lead to very large neoclassical transport and direct orbit losses. The stellarator community is pursuing two methods experimentally to overcome this limitation. (1) Rely on the ambipolar or externally controlled radial electric field to decrease the neoclassical transport; this aspect is presently being explored in a number of devices. (2) Design the stellarator magnetic field to remove the asymmetry in the magnetic ripple or include such components in the magnetic field spectrum that the neoclassical transport is greatly reduced; these aspects of stellarator research will be explored in the future experiments, HSX and W7X.

Since the early 1980's it has been relatively easy for stellarator experiments to test the confinement of electrons in the low collisionality regime using ECH to heat the plasma. The major conclusion has been that the neoclassical electron thermal diffusivity can indeed be larger than the anomalous transport. Specifically the electron heat diffusivity tends to be neoclassical towards the plasma center and anomalous towards the edge, with the proper mixture of neoclassical and anomalous dependent upon the level of neoclassical transport [51]. Theoretically it has been known that the neoclassical transport can be greatly reduced with a large positive electric field, the so-called 'electron root' of the ambipolarity condition. This root has proven to be elusive to some extent; however, recent experiments on CHS have demonstrated for the first time that the electric field can jump from the 'ion root' to the 'electron root' of the ambipolarity condition by increasing the electron flux with second harmonic ECH [52]. More conclusive evidence that the electric field can significantly reduce the neoclassical transport has been obtained on W7-AS [10].

Wall conditioning has fairly recently progressed to the point in Heliotron E [53] and W7-AS [10] that the ions have entered the low collisionality regime. Indications from W7-AS are that the ion heat flux is close to neoclassical and that the radial electric field decreased the neoclassical heat transport by an order of magnitude. Ion temperatures as high as 1.6 keV have been obtained with less than 1 MW of neutral beam heating.

In both Heliotron E [54] and W7-AS [55] the measured electric field agrees well with the neoclassical ambipolarity calculation, suggesting that anomalous transport is intrinsically ambipolar. In the low aspect ratio CHS, where the direct orbit loss problem is more severe, the measured electric field tends not to agree as well with neoclassical theory [56]. Rotation damping in the toroidal direction has been observed to be neoclassical in CHS and W7-AS, unlike in tokamaks [57]. This is because of the large variation in the magnetic field in this direction. When the variation is reduced, the damping due to perpendicular viscosity is anomalous, as in tokamaks. In the smaller IMS device, where neutral effects are more dominant, good agreement with experimental observations of the plasma flows and rotation damping was observed with a theoretical model that included damping due to both neutrals and parallel viscosity [58].

Finite-Beta Effects. A key experiment was performed in the W7-AS stellarator. This device is a first step toward an optimized stellarator in that the magnetic field was designed to reduce the Pfirsch-Schlüter current by a factor of two with respect to a conventional stellarator. The reduction in the resulting Shafranov shift as a function of beta was experimentally verified [10] and the pressure surfaces measured by soft x-ray emission correspond closely to the the predictions of 3-D equilibrium codes. The experiment provides support for the the more fully optimized stellarator W7-X whose key features will be low neoclassical transport and high stability beta (volume average of 5%).

An additional experiment was performed in ATF in support of the W7-X device. Experimental measurements of the bootstrap current agreed with neoclassical calculations. By varying the spectral components of the magnetic field, the magnitude and direction of the bootstrap current could also be varied [59]. Minimization of the bootstrap current is important in stellarators to maintain the rotational transform profile as a function of plasma beta. W7-X has been designed to have minimal bootstrap current which requires both helical and toroidal components in the magnetic field spectrum.

Confinement Improvement. Anomalous transport in stellarators is not well understood. Experiments on ATF demonstrated that the energy confinement time was dependent on the spatial extent of the magnetic well, suggesting that resistive interchange modes played an important role in determining confinement [60]. With a much smaller minor radius (about 20 cm) than in tokamaks and much lower input power (couple of MW), stellarators lag behind tokamaks in achieving enhanced confinement regimes beyond L-mode scaling. Marginal improvements in the energy confinement time during L-H transitions, on the order of 30%, have been demonstrated in W7-AS [61] and CHS [62] under equilibrium conditions, and up to a factor of 2 transiently in W7-AS. A high ion temperature mode has been reported in Heliotron E due to shear in the radial electric field [63]. Progress in the search for enhanced confinement regimes awaits results from the next generation stellarators LHD and W7-X which have larger plasma radius, greater input power, and active divertor control.

Plasma Heating. Plasma heating efficiencies and understanding of plasma heating mechanisms are similar to those in tokamaks. Neutral beam heating is classical, electron cyclotron heating follows calculated deposition profiles, and recently bulk plasma heating and sustainment of the plasma with ICRF heating alone has been observed in CHS and W7-AS with minority-species and second-harmonic heating [12,13].

Empirical Confinement Scaling. Although there are good theoretical models for transport at low collisionality, performance predictions, as in tokamaks, are better based at present on empirical confinement scaling "laws" because of the importance of anomalous transport in present experiments. The empirical magnitude and scaling of transport are similar to tokamaks and to a gyroreduced-Bohm Lackner-Gottardi scaling $(\rho_i/qR)(T/eB)$ with ρ_i the ion gyroradius, q the safety factor (the rotational transform = $1/q$), and T the temperature. Like tokamaks, different scalings for the global energy confinement time τ_E fit the present data:

(a) the LHD scaling [15], an empirical fit to some stellarator data;

$$\tau_E^{\mathrm{LHD}} = 0.17 R_0^{0.75} a_p^2 n^{0.69} B_0^{0.84} P^{-0.58},$$

(b) gyro-reduced Bohm scaling [64], which is based on drift-wave theory;

$$\tau_E^{\mathrm{grB}} = 0.25 R_0^{0.6} a_p^{2.4} B_0^{0.8} n^{0.6} P^{-0.6},$$

(c) Lackner-Gottardi scaling [65], which fits both tokamak and stellarator data;

$$\tau_E^{\mathrm{LG}} = 0.17 R_0 a_p^2 n^{0.6} B_0^{0.8} P^{-0.6} q^{-0.4},$$

and (d) the 1995 International Stellarator Scaling [66], which was derived from a large number of data sets from the Advanced Toroidal Facility (ATF), CHS, Heliotron E, W7-A, and W7-AS.

$$\tau_E^{\mathrm{ISS95}} = 0.079 R_0^{0.65} a_{\mathrm{p}}^{2.21} n^{0.51} B_0^{0.83} P^{-0.59} q^{-0.4}.$$

Unlike the LHD scaling, the Lackner-Gottardi, gyro-reduced Bohm, and ISS95 scalings are dimensionally correct; that is, they are expressible in terms of dimensionless plasma parameters. Here B_0 is the on-axis field, n is the line-averaged electron density (in 10^{20} m^{-3}), a_{p} is the average radius of the noncircular (and nonaxisymmetric in stellarators) last closed magnetic surface, and P is the absorbed heating power (in MW). All other quantities are in SI units.

Stellarators and tokamaks have similar energy confinement time scaling, indicating that the underlying physics may be dominated by common toroidal plasma physics rather than coil-geometry-specific effects. However, improved confinement modes may depend on more detailed configuration properties such as shear. The external control of the poloidal field in stellarators allows tokamak-like shear, globally reversed shear, or very low shear configurations.

Stellarator values for the energy confinement time τ_E overlie the tokamak L-mode data base [67] when the scaling is expressed in the same units. However, present stellarators are much smaller (a_{p} = 0.2 m) than present tokamaks (a_{p} = 0.85–1.62m) and have not yet demonstrated adequate confinement and beta at parameters that can be extrapolated to the reactor regime. This is a part of the mission of the large next-generation stellarators now under construction.

Question B: What is the appropriate level of research for this concept: **(5 parts)**

Question B1: What are the major experimental and theoretical issues that should be addressed?

EXPERIMENT

The main experimental issues for the stellarator program are:

1. Confinement understanding and improvement. This includes (a) study of neoclassical transport at low collisionality and the role (and control) of ambipolar electric fields; (b) turbulence and the dependence of anomalous transport on magnetic configuration properties (such as sign of shear) and the edge properties (electric field and velocity shear layers); and (c) techniques to improve over the present confinement scaling -- control of the heating (ECH, NBI, ICRF) and particle deposition (pellet injection) profiles, and biasing of limiters and divertor plates.

2. Development of practical particle and power handling schemes. Magnetic-island-based divertors will be further tested in LHD and in W7-AS and W7-X. The main issues are effectiveness of the divertor in pumping particles, handling the power flux from the plasma, shielding the plasma from wall-generated impurities and gas, controlling the edge properties for improved confinement modes, and compatibility with radiative edges or other means to distribute the power flux.

3. Verification of beta limits and techniques to increase them. While there is good agreement between experiment and theory on the finite-beta equilibrium, stellarators have not yet tested stability limits. Increasing the attainable beta needs to be pursued through control of both the pressure profile (control of the power and particle deposition profiles) and the magnetic configuration properties (sign and degree of shear, size and extent of the magnetic well, degree of helical axis excursion, degree of helical or toroidal symmetry, etc.)

4. Tests of key optimization principles. Ingredients such as deepening of the magnetic well with beta, reduction of the Pfirsch-Schlüter current, and quasi-helical symmetry are incorporated in present experiments.

5. Concept improvement. This includes tests of more compact stellarator configurations for development of minimum-size power plants, quasi-toroidal symmetry to study tokamak-like physics without the plasma current, or stellarator-tokamak hybrids to bridge the two configurations.

THEORY

U.S. theorists have a long history of leadership in stellarator theory. Important issues on which rapid progress can be made are:

1. Improved principles for minimizing neoclassical transport and orbit losses. Three concepts should be investigated (a) quasi-helical and quasi-toroidal symmetry, (b) making the minima of the field strength equal on a magnetic surface, and (c) radial electric fields. The first concept is intellectually the simplest and most elegant but is quite constraining on stellarator design.

2. Anomalous transport minimization. The recent results on tokamaks demonstrating the sensitivity of anomalous transport to the magnetic configuration give reason for optimism that anomalous transport in stellarators can be reduced by a clever choice of configuration. The theoretical and computational capabilities that have been developed for the tokamak do not require fundamental changes of logic for application to stellarators. Possibly the most important application will be the design of stellarator experiments that test critical physics issues of anomalous transport minimization.

A conventional stellarator can have neoclassical transport that scales inversely with collision frequency until it reaches quite large values. Microturbulence such as the ITG mode may break the ion longitudinal action invariant, which is responsible for enhanced ion neoclassical transport, and ease a design constraint on stellarators. Action breaking could be studied in existing gyrokinetic codes, and experimental tests could be made on LHD.

3. Divertors. Methods of studying divertors that are appropriate for the more complicated magnetic geometry of stellarators are in an early stage of development. A natural area of advance would be the capability for studying regions of stochastic field lines at the plasma edge. By enhancing the radial transport, stochastic regions may give control over the edge radiation, which is an important condition for a successful divertor in either a stellarator or a tokamak.

4. Equilibrium and stability. Although sophisticated 3-D equilibrium and stability codes exist, important issues remain to be addressed. Even a slow plasma rotation may improve the resilience of the magnetic surfaces to the effects of field errors and Pfirsch-Schlüter currents. Bootstrap currents driven by perturbations can either enhance or degrade the stability of stellarators, but the effects have yet to be included in the codes. Small Fourier terms in the magnetic field strength that cause large transport also drive shielding currents. These currents have not yet been included in the equilibrium codes but may make the particle orbit constraints much easier to satisfy. More efficient numerical algorithms would could greatly extend the practical range of applicability of the equilibrium codes. More assessments should be made of the design constraints that TAE and GAE modes place on stellarators [68].

5. Optimization Studies. The development of the physics principles that define the optimization criteria and the invention of new configurations are both areas of enormous opportunity. Particular issues for optimization studies are the invention of more compact configurations that maintain the other properties required for a power plant and the suggestion of incisive experimental tests of physics principles.

<u>Question B2</u>: What do the above issues (in B1) require?

Important experimental issues for specific concepts are and will be addressed in an integrated form on the major experimental facilities that exist or are being built in Europe and Japan. However, the range of issues is sufficiently great that critical areas -- like the minimum aspect ratio -- will not be addressed within the present program.

(a) Are new experimental facilities and theoretical activities required?

New experimental facilities and theoretical activities are needed to address some of the main issues related to concept improvement. The main direction is toward more compact systems with unique physics features, such as quasi-toroidal symmetry or stellarator-tokamak hybrids.

(b) Is expanding the current experimental and theoretical activities required?

Some of the key issues can be addressed by expanding current experimental and theoretical activities to supplement the small residual efforts in theory and international collaboration. Although the direction needed for theory development is clear, the present level of stellarator theory support is woefully inadequate. Opportunities exist for leveraging on the large world program through experimental collaborations on foreign facilities, but these efforts have also only been funded at a low level.

(c) Can they can be addressed at present level of research?

Although many of the important issues will be addressed with respect to a particular approach in the world program, our ability to take advantage of this progress is severly limited. Innovative university programs exist on quasi-helical symmetry and surface reconstruction, and there is a small level of international experimental collaboration. A number of theorists maintain an interest in stellarator problems. These serve as an important base from which stellarator activities could be expanded.

(d) Can they be addressed in a lower level of research?

U.S. budgets for theory and international collaborations have declined to very low levels. It is difficult to see how significant issues could be addressed at even lower levels. U.S. support for stellarator research may already be below even the level required to maintain an adequate core of individuals with informed opinions on the world stellarator program. Current U.S. levels of research are approximately 1.3 M$/yr for domestic experiments, 0.4 M$/yr for international collaborations, and 0.2 M$/yr for theory.

***Question B3*: What is an appropriate mix of research activity for this concept among large facilities and mix of small supporting experiments, theory and modeling, and concept design and evaluation studies?**

Stellarators have the flexibility to design around critical problems and require a broad research program to fully exploit their potential. Small experiments are required to test innovative ideas, theory is required to efficiently choose the most important experiments, and experiments on large facilities are needed to study higher parameter regimes. The appropriate mix of these research activities for the United States is discussed in Question B5. Given the advanced state of stellarator research and the large level of effort by our international partners in this area of fusion research, such a balance is needed for the United States to take advantage of the exciting opportunities in stellarator research.

***Question B4*: What is the world-wide research plan (outside U.S.) to address the above issues?** *(those in Question B1)*

Stellarator research outside the United States is focused on development of particular stellarator configurations. The main components of these programs are experiments on their domestic experiments and construction of new devices. The theory programs associated with the major stellarators are focused on support for the experiments. Longer range projects include a better free boundary package for the MHD stability codes, which is under development at Garching. Studies are also starting on the implications of different stellarator configurations for a fusion power plant.

In Germany, the focus is the modular-coil "helias" approach in which the spatial Fourier components of the magnetic field were *chosen* to satisfy desired physics optimization criteria that uniquely specify the geometry of the last closed flux surface: (1) high quality of vacuum field magnetic surfaces (small islands, some shear); (2) good finite-beta equilibrium properties (small configuration change with beta, self-healing of magnetic surfaces): (3) good MHD stability properties (global magnetic well, reduced Pfirsch-Schlüter currents parallel to the magnetic field; (4) small neoclassical transport in the $1/\nu$ regime (small effective ripple); (5) small bootstrap current in long-mean-free-path regime (<10% of that in a comparable tokamak); and (6) good collisionless alpha-particle confinement (confinement improvement with beta, <10% orbit losses). The major test of this approach is the superconducting-coil W7-X. The operating W7-AS is testing some of these physics elements (factor of two reduction of Pfirsch-Schlüter currents, neoclassical transport) and develop some of the techniques (effective ICRF heating, island divertor) for W7-X. W7-AS and W7-X have low shear and large aspect ratio (R/a_p = 10–11), but W7-AS has a planar magnetic axis while W7-X features a helical axis.

In Japan, the focus is on helical-coil systems whose optimization is based on increase of the magnetic well with beta and improved orbit confinement at lower aspect ratio (R/a_p = 5–6.5). The major test of this approach is the superconducting-coil LHD. CHS has some of these features and is focusing on transport, MHD, and local island divertor studies as well as diagnostic development for LHD. Both the CHS and the earlier Heliotron E (with a factor of two larger rotational transform and aspect ratio) programs will end in about 1-1/2 years for the start of LHD.

In Spain, the TJ-II "flexible heliac" [69] is the focus of the Spanish fusion program. It features a larger helical axis excursion than W7-X and will have bean-shaped flux surfaces (like those in the PBX-M tokamak, but with low shear) that rotate poloidally about the helical axis. The program emphasis is on transport and beta limits for this configuration. The *Australian fusion program* is also centered around a smaller flexible heliac (H-1) [70].

There are also *stellarator programs in Russia* (L–2) *and the Ukraine* (Uragan 2M and Uragan 3M), but these programs are severely limited by lack of support and older facilities.

The main parameters for these facilities are given in the Table.

Major Device Parameters for Operating and Near-Term Stellarators

Experiment	**Location**	**R_0 (m)**	**a_p (m)**	**V_p (m^3)**	**B_0 (T)**	**P (MW)**	**t_{exp} (s)**
Large-Next Generation Experiments							
LHD (1998)	Japan	3.9	0.5–0.65	30	3 (4)	30	10 – ∞
W 7–X (2004)	Germany	5.5	0.52	30	3	30	10 – ∞
Medium-Size Experiments							
W 7–AS	Germany	2.0	0.2	1.6	2.5	4	3
CHS	Japan	1.0	0.2	0.8	2	2	1
Heliotron E	Japan	2.2	0.2	1.7	2	4	0.2
TJ–II (1997)	Spain	1.5	0.22	1.4	1	1	0.5
H-1	Australia	1	0.21	0.87	1	0.2	0.2
U.S. Experiments							
HSX (1996)	U. Wisc.	1.2	0.15	0.53	1	0.2	0.1
CAT	Auburn	0.53	0.1	0.11	0.2	0.007	120

***Question B5*: What is the proper level of US research in the context of the international program? In particular:**

The U.S. can make significant contributions to the world program on stellarators through theory, domestic experiments, and selected collaborations on foreign experiments.

(a) Is it necessary to have more than ONE NEW international experimental facility?

The necessity of more than one new international experimental facility has already addressed in this decade in successful proposals by Germany (W7-X complementing LHD) and Spain (TJ-II complementing H-1). The complementary nature of the new experiments allows exploring similar physics in different magnetic configurations that are based on different optimization principles. Since there are already two superconducting stellarators in the $0.5–1 billion range under construction, LHD and W7X, that will explore complementary optimization approaches, a third large superconducting-coil stellarator would be difficult to justify even if it were consistent with U.S. fusion budgets.

(b) Given the world-wide plan, which areas should the US program focus on?

The U.S. stellarator program should focus on confinement understanding and concept improvement through innovation in theory, configurations, and experimental design; domestic experiments; and collaborations on larger foreign facilities. The stellarator is a concept in which invention and flexibility can help counterbalance limited resources. Stellarators of international importance, well-differentiated from existing designs, can be built over a broad spectrum from small to large. There are two rational levels for the U.S. stellarator program.

1. As a Junior Partner in the International Program. Greater than 6M$/yr would allow the U.S. to contribute to the world experimental program in narrowly focused areas and have a stellarator theory program of international importance. This level of effort is consistent with a core of individuals who are well-informed on the international program.

(a) ***Theory, modeling, and simulations.*** About 10% of the total U.S. theory expenditures (about 1.8 M$/yr) would give world leadership in innovative theory for stellarators and 3-D plasmas. It would support the core of theorists required for the interpretation and design of experiments as well as for the invention of new configurations, such as quasi-toroidal stellarators [71] or tokamak-stellarator hybrids [72]. About 25% of the stellarator theory program should be devoted to the two aspects of optimization of stellarators needed for incisive tests of physics or for power plants: (i) the practical definition of the optimization criteria and (ii) the search for configurations that satisfy these criteria. Although these efforts can be relatively modest, the payoff could be quite large and is necessary before proceeding to a proposal for a new experiment.

(b) ***Smaller supporting experiments*** are important to the U.S. program because their small size and low cost allows specialized focus, speed of construction/modification, and degree of risk that are not possible on larger devices. In addition, they serve as a training ground for the students who will be the future leaders of the U.S. program. Well-focused experiments of modest cost can perform incisive tests on general issues of toroidal plasmas as well as those specific to stellarators. The HSX [37] experiment (presently 1.2 M$/yr; proposed 1.6–2 M$/yr) will test some of the basic physics (such as drift orbit optimization) underlying the W7-X experiment and the SPPS reactor. It will provide the first test of a stellarator with quasi-helical symmetry in which the particle orbits and neoclassical transport are similar to, but somewhat better than, those in a tokamak. The toroidal curvature component of the magnetic field is reduced to that of a stellarator with an effective plasma aspect ratio ~300 (although HSX itself has a physical aspect ratio of 8: R_0 = 1.2 m, a_p = 0.15 m), resulting in a virtual elimination of all superbanana and direct loss orbits. The smaller Compact Auburn Torsatron (CAT) program (presently 0.1 M$/yr; proposed 0.25 M$/yr) at Auburn University focuses on use of external coils to restore broken flux surfaces and study of particle transport and plasma rotation at low density [73].

Opportunities also exist in this range of funding for study of a low-aspect-ratio stellarator-tokamak hybrid with a simple coil system and a nearly axisymmetric divertor that combines features of compact torsatrons and spherical tokamaks. Its goals would be reduced current requirements, reduced sensitivity to disruptions, and easier startup for study of rf current drive and transport barrier formation [72].

(c) ***Focused experiments on foreign facilities*** allow the United States to (i) develop niche physics areas in which we have special expertise on the largest stellarators in the world program, (ii) connect these results with our domestic tokamak and stellarator programs, (iii) maintain a level of expertise and influence in the larger world program, and (iv) develop a U.S. role on the large stellarators (LHD and W7-X) now under construction. Examples are use of ICRF heating to explore heating regimes and influence confinement (W7-AS [13]), pellet fueling to study particle transport and confinement improvement (W7-AS [74]), and development of divertors to shield the plasma interior from neutrals and impurities and control the edge properties for improved confinement modes (CHS/LHD [17]). Approximately 2M$/yr would allow the U.S. to pursue physics issues that are appropriate to large or steady-state stellarators with more reactor-relevant parameters through collaborations on foreign devices.

(d) ***Fusion power plant studies*** allow us to assess the reactor potential of innovative stellarators and set criteria that a concept should meet to be an attractive reactor candidate. The most recent example is the U.S. Stellarator Power Plant Study [6]. Although there is no funding at present to continue U.S. stellarator reactor studies, other nations (Japan, Germany, Spain, Australia) are continuing to study their stellarator variant for its reactor potential. These nations will be pursuing their separate lines (helical-coil systems and the helias approach), and they have agreed to coordinate these studies under the *IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept* [75]. The United States could participate in selected areas where it has special expertise (systems studies, costing algorithms, blankets and shields, concept innovation, etc.) with relatively modest support. About 0.4M$/yr would allow effective participation in the world effort on power plant studies.

2. Aggressively Use the Opportunities the Stellarator Offers to Maintain Our Position as a Valued International Partner in Fusion Research. A national facility built utilizing existing resources would allow tests of an innovative stellarator concept with energetic ions, moderate (keV) temperatures, relevant betas (few percent range) and lower collisionality instead of the electron-dominated physics accessible in a small experiment. It would serve to focus U.S. stellarator research efforts and maintain the mix of skills needed if we wish to be competitive in this area in the future. An example could be Garabedian's two-field period modular quasi-toroidal stellarator with an aspect ratio of 4.5 and particle drift orbits and neoclassical transport similar to that of a tokamak [71]. The options range from an NSTX-scale experiment at about 20 M$/yr to a high performance but short-pulse stellarator using the TFTR site at a cost of approximately 40M$/yr.

<u>Question C</u>: What is the potential impact of research on this concept? (4 parts)

<u>Question C1</u>: What is the potential impact of research on this concept on increasing our knowledge of general plasma physics?

Stellarator research has driven the development of 3-D plasma physics. The theoretical techniques that have been developed have application over a far broader range of physics than just fusion. Three examples are given below.

(i) The drift Hamiltonian theory developed for stellarators says particle drift orbits depend fundamentally on only the magnetic field strength [19]. The most remarkable implication is quasi-helical symmetry [36] in which the drift Hamiltonian has a continuous symmetry and a conserved component of the canonical momentum even though the exact Hamiltonian has no symmetry directions. Experiments on quasi-helical symmetry, such as HSX [37], test this remarkable property of the drift equation. An important application of the drift Hamiltonian technique has been made to electron orbits in a terrella experiment [76], which is designed study the physics of the earth's radiation belts.

(ii) As part of stellarator research, the magnetic field trajectories were shown to be given by a Hamiltonian of one and a half degrees of freedom [19]. Two results are (a) a simple mathematical structure for studying topology changes in the field lines and (b) new techniques for establishing action-angle variables (magnetic coordinates) for Hamiltonians of one and a half degrees of freedom. Magnetic topology issues play a major role in the interaction of interplanetary and the terrestrial magnetic field as well as the magnetic fields of the solar corona. The same Hamiltonian techniques that were developed for field lines in stellarators apply to vortex lines in fluids and flux tubes in superconductors.

(iii) The drift kinetic equation is not self-adjoint. The DKES code developed for determining stellarator neoclassical coefficients extended the well-known extremizing techniques for solving self-adjoint equations to the drift kinetic equation [40].

<u>Question C2</u>: What is the potential impact of research on this concept on increasing our knowledge of fusion plasma physics (of this concept as well physics of other confinement concepts)?

The broad range of magnetic configurations that can be produced in stellarators allows fundamental tests of the possibilities and limitations of toroidal confinement. Examples include:

(i) The trapped electrons can be centered in the stabilizing region of a magnetic well instead of on a hill. (ii) The magnetic shear can be reversed across the entire plasma cross section. (iii) Tokamak physics can be studied without the complications of a net current in quasi-helical and quasi-toroidal configurations or combined with stellarator features in a stellarator-tokamak hybrid configuration. (iv) Comparisons between stellarator and tokamak experiments showed the plasma current played no essential role in edge turbulence. (iv) The stellarator provided early compelling evidence for the validity of the theory of the bootstrap current.

Theory developed for the stellarator has important implications for all toroidal systems. Resistive instabilities and wall modes develop slowly compared to Alfvén time scales and can be calculated using stellarator equilibrium codes. The singularities that arise near resonant surfaces and are associated with the stabilization of the wall mode are much clearer using a 3-D equilibrium analysis than using an ideal MHD code in which the singularities are smeared by inertial effects. Magnetic field error research had both its experimental and theoretical origins in stellarator work. The importance of field errors has only recently been appreciated in the tokamak community [77].

The Monte Carlo codes that were originally developed to study stellarator transport have had important applications to the loss of alphas on TFTR. This comparison between theory and experiment has provided an impressive test of these techniques [78,79].

3-D equilibrium theory developed for stellarators provides insights and computational techniques for resistive instabilities, wall modes, and field error effects. Transport and particle losses due to symmetry breaking had a natural development in the context of stellarators. Comparisons between stellarator and tokamak experiments have broadened the understanding of bootstrap currents, edge velocity-shear layers, and role of field errors in both systems. Stellarators continue to provide unique plasma configurations and tests of physics: trapped particle instability theory will be tested on W7-X in which most trapped particles are in a region of good curvature. Also, stellarators can maintain a reversed q-profile across the entire plasma and thereby test effects of globally reversed shear (or low shear). A quasi-toroidal stellarator can test tokamak physics without a net plasma current. Quasi-toroidal and quasi-helical stellarators have different signs of the bootstrap current, allowing tests of stabilization and destabilization of magnetic-island-producing perturbations. A stellarator-tokamak hybrid would allow tests of neoclassical theory including viscosity and flows that impact electric field barrier formation.

Stellarators are closely related to tokamaks, so comparisons between tokamaks and stellarators are particularly useful in our understanding of the two dominant magnetic configuration approaches. Tokamak magnetic configurations are characterized by the plasma aspect ratio, elongation, triangularity, and type of separatrix (none, single null, or double null). Stellarators can access a much wider range of magnetic configurations through tailoring of the spatial Fourier components of the magnetic field to emphasize different properties such as sign and degree of shear, size and extent of the magnetic well, degree of helical axis excursion, confinement of trapped particles, shift of the magnetic axis with beta, degree of helical or toroidal symmetry, separatrix geometry, etc.

<u>Question C3</u>: What is the potential impact of research on this concept on helping develop fusion as an energy source (help develop the data base for fusion development steps such as burning plasmas, volumetric neutron source, etc.)?

The poloidal flux in a stellarator is produced by the helical structure of external coils rather than by a plasma current. Implications of having the magnetic surfaces defined by the external coils rather than plasma currents are (1) no need for current drive, (2) no major disruptions, and (3) no issues of positional control or instabilities. By having the magnetic surfaces and the profile of the safety factor externally set, toroidal systems are freed from tights constraints. For example, steady-state tokamaks must operate with a very high bootstrap fraction to have adequate current drive efficiency. This forces tokamak designs to high beta poloidal, near stability limits, and to high elongations with delicate positional control. In addition, a high bootstrap fraction implies the fundamental magnetic configuration of a power plant is dictated by the alpha heating profile which gives a very non-linear coupled system that is difficult to study in modest experiments. The stellarator's use of currents only in external windings leads to the possibility of an improved, intrinsically steady-state reactor with low recirculating power, a robust magnetic configuration, and lower power density on the in-vessel components.

Early in the next decade the world should have two large steady-state superconducting stellarators, LHD and W7-X, and probably only one large steady-state tokamak, Tore Supra. The implication is that much of experience of the world fusion program on steady-state issues, such as particle and power handling, will come through the stellarator program. The U.S. needs to be involved in these programs to benefit as well as to contribute to development of the technology and operating techniques needed for larger devices.

Question C4: What is the potential impact of research on this concept on developing this concept as a candidate for a fusion power plant?

The U.S. has had a stronger interest in compact fusion systems than its international fusion partners, and studies are required to find how compact a stellarator power plant can be. Unlike tokamaks, the higher the aspect ratio the easier stellarators are to design for high beta and good confinement. But, a high aspect ratio increases the minimum size of a power plant. If stellarators are to be developed that fit the U.S. image of a power plant, significant research has to be undertaken to obtain more compact configurations with good confinement properties and adequate beta. Paul Garabedian's two period stellarator with an aspect ratio of 4.5 gives reason for optimism that if the research is undertaken that it will be successful.

Both coil design and physics constraints are important in setting the minimum size of a fusion power plant [7]. Adequate space Δ (>1 m) between the edge of the plasma and the center of the coils needs to be provided in a reactor. For a given stellarator coil configuration, Δ/R_0 is a constant and relatively large; the coils have to be close to the plasma in a stellarator because the higher order multipole components that produce the desired field configuration decay away rapidly from the coils. More compact stellarator reactor designs might be obtained if the physics properties of a more compact stellarator are not compromised too much in the process of reducing Δ/R_0. Such stellarators could have a significant impact on the viability of the stellarator reactor concept.

The level of anomalous (and neoclassical) transport and the beta values that can be expected also determine the minimum size of an ignited stellarator reactor. New experiments should give more confidence in the levels of transport and beta limits to be expected in a reactor. Research is required to determine how the freedom of the stellarator configuration can be used to modify anomalous transport while keeping the neoclassical transport at an acceptable level; for example, the extent to which anomalous transport can be controlled by trapping particles in good magnetic curvature or modifying the magnetic shear profile. Design optimization studies are needed.

REFERENCES

[1] A. Iiyoshi, M. Fujiwara, O. Motojima, N. Ohyabu, and K. Yamazaki, Fusion Technol. 17, 169 (1990).

[2] O. Motojima, 11th Topical Meeting on the Technology of Fusion Energy, New Orleans (1994).

[3] J. Sapper and H. Renner, Fusion Technol. 17, 62 (1990).

[4] J. Nührenberg and R. Zille, Phys. Lett. A129, 113 (1988).

[5] D. E. Hastings, W. A. Houlberg, and K. C. Shaing, Nucl. Fusion 25, 445 (1985).

[6] R. L. Miller (ed.) and the SPPS Team, Univ. of California San Diego report UCSD-ENG-002 (to be published); J. F. Lyon et al., 15th Intl. Conf. on Plasma Physics and Contr. Nucl. Fus. Res., Seville, Spain, IAEA-CN-60/F-1-I-4.

[7] J. F. Lyon et al., Fusion Engineering and Design 25, 85 (1994).

[8] F. Wagner et al., Fusion Technol. 27, 32 (1995).

[9] C. Beidler at al., Fusion Technol. 17 (1990) 149.

[10] R. Jaenicke et al., Plasma Phys. Control. Fusion 37 (1995) A163.

[11] S. Okamura et al., 15th Intl. Conf. on Plasma Physics and Contr. Nucl. Fus. Res., Seville, Spain, IAEA-CN-60/A-2-IV-3.

[12] S. Masuda et al., Nucl. Fusion (to be published).

[13] G. Cattanei, D.A. Hartmann, J.F. Lyon, et al., 23rd EPS Conf. on Controlled Fusion and Plasma Physics, Kiev, Ukraine, 1996.

[14] A. Stabler et al., 14th Intl. Conf. on Plasma Physics and Contr. Nucl. Fus. Res., Wurzburg, Germany, IAEA-CN-56/C-2-6.

[15] S. Sudo, Y. Takeiri, H. Zushi, et al., Nucl. Fusion 30 (1990) 11.

[16] M Murakami, private communication (1990).

[17] A. Komori et al., 12th Intl. Conf. on Plasma Surface Interactions in Controlled Fusion Devices, Saint Raphael, France, 1996.

[18] J. V. Hofmann et al., Proc. 10th Intl. Conf. on Stellarators, IEA Tech. Comm. Meeting, Madrid, Spain (1995) 77; ibid, J. Kisslinger et al., 290.

[19] A. H. Boozer, "Plasma Confinement" in Encyclopedia of Physical Science and Technology (Academic Press, NY 1992) Vol. 13, p.1.

[20] L. M. Kovrizhnykh, Nucl. Fusion 24, 851 (1984).

[21] K. C. Shaing Phys. Fluids 27, 1567 (1984).

[22] S. P. Hirshman and J. C. Witson, Phys. Fluids 26 3553 (1986).

[23] S.P. Hirshman and D.K. Lee, Comp. Phys. Comm. 39 161 (1986).

[24] S. P. Hirshman and O. Betancourt, J. Comp. Phys. 96 99 (1990).

[25] F. Bauer, O. Betancourt, and P. Garabedian, Magnetohydrodynamic Equilibrium and Stability in Stellarators, Springer Verlag, New York (1984).

[26] M. Taylor, J. Comp. Phys. 110, 407 (1994).

[27] A.H. Reiman and H. Greenside, Comput. Phys. Commun. 43, 157 (1986).

[28] A. H. Reiman and D. A. Monticello, Nucl. Fusion 32, 1341 (1992).

[29] T. Hayashi, "Theory of Fusion Plasmas," Chexbres 1988, EUR 12149 EN 11 (1989).

[30] C. Schwab, Phys. Fluids B 5, 3195 (1993).

[31] D.V. Anderson, A. Cooper, U. Schwenn, and R. Gruber in Theory of Fusion Plasmas (eds. J. Vaclavik, F. Tryon, and E. Sidoni, Editrice Compositori, Bologna, 1989) p. 93.

[32] Y. Nakamura, K. Ichiguchi, M. Wakatani, and J. L. Johnson, J. Phys. Japan 9, 3157 (1989).

[33] J. Nührenberg and R. Zille in Theory of Fusion Plasmas (eds. A. Bondson, E. Sidoni, and F. Tryon, Editrice Compositori, Bologna, 1988) p. 3.

[34] A. Weller, D. A. Spong, et al., Phys. Rev. Lett. 72, 1220 (1994).

[35] J. Nührenberg and R. Zille, Phys. Lett. A129, 113 (1988).

[36] A.H. Boozer, Plasma Phys. Control. Fusion 37, A103 (1995).

[37] F.S.B. Anderson, A.F. Alamagi, D.T. Anderson, P.G. Mathews, J.N. Talmadge, and J.L. Shohet, Fusion Technol. 27, 273 (1995).

[38] A. Boozer and G. Kuo-Petravic, Phys. Fluids 24, 851 (1981).

[39] P. Garabedian and M. Taylor, Nucl. Fusion 32, 265 (1992).

[40] W.I. van Rij and S.P. Hirshman, Phys. Fluids B 1, 563 (1989).

[41] M. Sasinowski and A.H. Boozer, Phys. of Plasmas 2, 610 (1995).

[42] Z. Lin, W.M. Tang, and W.W. Lee, Phys. of Plasmas 2, 2975 (1995).

[43] R.E. Waltz and A.H. Boozer, Phys. Fluids B 5, 2201 (1993).

[44] W. Lotz, P. Merkel, J. Nührenberg, and E. Strumberger, Plasma Phys. and Contr. Fusion 34 1037 (1992).

[45] E. Strumberger, Nucl. Fusion 32, 737 (1992).

[46] J. Nührenberg and R. Zille, Phys. Lett. A114, 129 (1986).

[47] P. Merkel, Nucl. Fusion 27, 867 (1987).

[48] A. H. Boozer, Phys. Fluids 27, 2441-2445 (1984).

[49] A. H. Boozer, Phys. Fluids 24, 1999-2003 (1981).

[50] H.E.Mynick, T.K.Chu, A.H.Boozer, Phys. Rev. Lett. 48, 322 (1982).

[51] H. Maassberg et al., Phys. Fluids B 5 (1993) 3627.

[52] H. Ida et al., Phys. Rev. Lett. 71 (1993) 2220.

[53] T. Obiki et al., Proc. 10th Intl. Conf. on Stellarators, IEA Tech. Comm. Meeting, Madrid, Spain (1995) 6.

[54] T. Obiki et al., 15th Intl. Conf. on Plasma Physics and Contr. Nucl. Fus. Res., Seville, Spain, IAEA-CN-60/A-6-I-2.

[55] J. Baldzuhn et al., Proc. 10th Intl. Conf. on Stellarators, IEA Tech. Comm. Meeting, Madrid, Spain (1995) 144.

[56] H. Sanuki, K. Itoh, K. Ida, and S.-I. Itoh, J. Phys. Soc. Jap. 60 (1991) 3698.

[57] K. Ida et al., Proc. Intl. Conf. on Plasma Physics, Brazil (1994) 177.

[58] J. N. Talmadge et al., 15th Intl. Conf. on Plasma Physics and Contr. Nucl. Fus. Res., Seville, Spain, IAEA-CN-60/A6-6.

[59] M. Murakami et al., Phys. Rev. Lett. 66 (1991) 707.

[60] R.C. Isler et al., Phys. Fluids B 4 (1992) 2104.

[61] F. Wagner et al., Plasma Phys. Control. Fusion 36 (1994) A61.

[62] K. Toi et al., Plasma Phys. Control. Fusion 36 (1994) A117.

[63] K. Ida et al., Phys. Rev. Lett. 76 (1996) 1268.

[64] R. J. Goldston, H. Biglari, G. W. Hammett, et al., Bull. Am. Phys. Soc. 34 (1989) 1964.

[65] K. Lackner and N. A. O. Gottardi, Nucl. Fusion 30 (1990) 767.

[66] U. Stroth, M. Murakami, R. A. Dory, H. Yamada, F. Sano and T. Obiki, National Institute for Fusion Science report NIFS-375 (1995).

[67] S. Kaye, et al., private communication, 1992.

[68] D. A. Spong, B. A. Carreras, C. L. Hedrick, J-N. Leboeuf, A. Weller, 15th Intl. Conf. on Plasma Physics and Contr. Nucl. Fus. Res., Seville, Spain, IAEA-CN-60/D-P-II-3.

[69] C. Alejaldre et al., Fusion Technol. 17, 131 (1990).

[70] S. M. Hamberger, B. D. Blackwell, L. E. Sharp and D. B. Shenton, Fusion Technol. 17, 123 (1990).

[71] P. Garabedian, Phys. of Plasmas (to be published).

[72] ORNL Field Task Proposal ERAT 039, April 15, 1996; also P. E. Moroz, submitted to Phys. Rev. Lett. (Jan. 1996).

[73] R. Gandy et al., Nuclear Technology/Fusion 18, 281 (1990).

[74] J. Baldzuhn and the W7-AS group, J. F. Lyon, S. L. Milora, and L. R. Baylor, Bull. Am. Phys. Soc. 40 (1995) 1756.

[75] Minutes of the Executive Committee for the IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept, April 16, 1996.

[76] H. P. Warren and M. E. Mauel, Phys. Rev. Lett. 74, 1351 (1995).

[77] R. J. La Haye, R. Fitzpatrick, T. C. Hender, A. W. Morris, J. T. Scoville, and T. N. Todd, Phys. Fluids B 4, 2098 (1992).

[78] M.H. Redi, M. Zarnstorff, R. White, et al., Nucl. Fusion 35, 1191 (1995).

[79] M. H. Redi, R. Budny, D. Darrow, et al., Nucl. Fusion 35, 1509 (1995).

APPENDIX

Appendix E of the January 1996 report of the Fusion Energy Advisory Committee

Plasma Confinement Research (Alternative Concepts)

The study of plasma science, and the many scientific issues which underlie fusion research, is greatly aided by experiments in which a range of confinement configurations is employed. A key feature of a laboratory experiment is that the experimenter has some control over the plasma conditions, permitting a controlled study of plasma phenomena. However, the range of variation of key parameters in any given plasma configuration is limited. Study of fusion science issues in different confinement configurations greatly expands the range of physical conditions which are accessible; such an approach leads to enhanced understanding and innovation which would not be attainable through the investigation of one confinement concept only. For example, from one concept to another variations occur in magnetic curvature, magnetic shear, fluctuation spectra and amplitudes, electric fields, plasma current, plasma flow, plasma pressure, and many other properties. Moreover, the quest to optimize the properties of a magnetic configuration, with regard to fusion reactor attractiveness, leads scientists to investigate a range of configurations. For example, alternative concepts research aims for smaller size, higher plasma pressure, less plasma current, less plasma disruptions, and lower magnetic field.

Since fusion research worldwide is focused on the tokamak, confinement concepts sufficiently different from the tokamak (or advanced tokamak) have come to be called "alternative concepts." In addition, within the alternative concepts, different magnetic configurations, often differing by only small changes in magnetic field structure, are known by different names. This categorization understates the strong scientific connections among the different concepts, and their cross-fertilization. Inertial confinement fusion is a major, separately funded program (within Defense Programs in DOE), with comparably strong international activity. It is discussed in the next appendix. The decision to concentrate resources on tokamaks, beginning around 1970, was made because confinement times were superior to those achieved in other magnetic configurations at that time. Of course the gap widened in time. In 1990, in response to budget pressure, the alternative concepts program was essentially terminated in favor of schedule-driven development of the tokamak reactor concept. A significant element of the restructured program will be a reinitiation of an alternative concepts research program.

The status of most alternative concepts is such that pressing scientific issues can be addressed in experiments of modest scale. Thus, this is one area in which the United States can participate at the forefront worldwide. The very strong alternative concepts programs in Japan and Europe are focused on the stellarator. In other concept areas the international effort, although much stronger than that in the United States at present, is distributed over medium scale and small experiments. There is a spectrum of alternative concepts which are arguably ready for modest-scale experimentation and theoretical study, exploiting advances in theory/modeling and experimental techniques which has occurred in recent years. FEAC has not attempted to evaluate the scientific value or reactor significance of different alternates. However, for illustration we describe below the status and opportunities of five magnetic confinement concepts.

Conclusions: Alternative concepts offers opportunities to advance fusion science in ways not possible with one concept only, to pursue configurations with possibly attractive reactor features, to excel in selected areas with modest expenditure (even in the context of a constrained overall fusion budget), and to encourage new ideas -- all goals aligned with the restructured fusion program.

Recommendation: The concept improvement program should be expanded to include a spectrum of alternative concepts, including experimental and theoretical research. Several concepts may be ready for experiments to elucidate key physics issues. The precise funding level cannot be prescribed here. It must be driven by peer-reviewed proposals (from national labs, universities, and industry), as for any scientific program. As for the program's major facilities, any experiments which are operated should be supported with healthy funding to operate cost-effectively.

E.5 STELLARATORS

Description and Strengths. The stellarator confining magnetic field is produced entirely by currents flowing in external conductors. It does not require a plasma current. Consequently, stellarators can be intrinsically steady-state reactors and avoid the problems associated with current-driven disruptions, current drive, high bootstrap fraction and positional stability. The lack of current leads to low circulating power. Other reactor advantages include a natural helical divertor and a lower power density on the divertor plates than for a tokamak. To date, no density limits have been observed. Finally, control of the magnetic geometry and rotational transform by means of external coils allows for the possibility of enhanced confinement that is more robust than in a tokamak. Magnetic properties, such as shear, well depth, and localization of particles to the good curvature region can be "hard-wired" into the magnetics.

Status. Stellarator design has advanced such that experiments are now designed from the inside out: the boundary shape is calculated based on a set of prescribed physics properties and a set of helical or modular coils is then determined which produces the desired boundary. This pioneering computational methodology, known as the HELIAS (Helical Advanced Stellarator) approach, was developed in Garching, Germany.

The worldwide stellarator program contains many stellarator configurations. Two large steady-state stellarators with superconducting coils are under construction at a cost in the range of $0.5 - 1.0 B each: LHD, a torsatron with helical coils in Japan; and Wendelstein 7X, an advanced stellarator with modular coils in Germany. An advanced stellarator, W7-AS, operating in Germany, was designed to have a lower Pfirsch-Schluter current than a tokamak or conventional stellarator. A heliac is a class of stellarators with a large magnetic well, with circular coils arranged toroidally about a central conductor so that the center of each coil lies along a helix. A three-field period heliac is operating in Australia (H-1) and a four field period heliac (TJ-II) will begin operation in Spain at the end of 1996. Two low aspect ratio torsatrons are in operation: CHS in Japan and CAT at Auburn University in the United States. HSX, under construction at the University of Wisconsin, is a quasi-helically symmetric stellarator with magnetic properties similar to that of a tokamak (but achieved without plasma current). Conventional stellarators with helical windings are in operation in Japan, Russia, and the Ukraine.

A major liability of the stellarator had been the poor confinement of trapped particles at low collisionality. Experimentally, it has been observed that large neoclassical transport in this regime can exceed anomalous losses. The HELIAS approach to optimizing magnetic configurations was developed in part to overcome these limitations. Neoclassical transport in W7X, for example, is expected to be greatly reduced. The mission of the HSX device is to verify the improved neoclassical transport properties. A difference in the magnetic properties between W7X and HSX is the relative size of the bootstrap current. W7X is designed to minimize the bootstrap current so that finite beta effects will have minimal impact on the magnetics. Confinement scaling in stellarators is similar to that in tokamaks, yet to date significant progress has yet to be made in finding improved confinement regimes. H-modes have been observed, however the energy confinement improvement is small.

Scientific challenges/Opportunities. The optimal trade-off between neoclassical transport, simplicity of coil design and bootstrap current remains to be determined. In addition, study of anomalous transport (including trapped particle effects) is needed to discover the optimal combination of shear and curvature. The role of electric fields, and concomitant flow, is particularly important to confinement in the stellarator.

Another issue is whether there exist magnetic configurations which offer a possible route to higher beta than presently envisioned for a stellarator reactor (about 5%). Theoretical work is needed to understand the ideal MHD stability of stellarators and the breakup of magnetic surfaces from finite pressure effects. Experimental beta values of 2% have been achieved. Exploration of higher beta regimes await TJ-II and LHD.

The U.S. role in the world stellarator program should encompass three research elements (as follows, but not listed in priority order). First, a stellarator theory program, formerly an area of excellence in the United States, could play an important role in the world program. Second, innovative experiments of modest scale can influence the world program. The flexibility of the magnetic configuration of the stellarator offers opportunities to explore variations in coil structure, magnetic field spectrum, aspect ratio, beta stability limits, and improved confinement properties. For example, the geometry of HSX is unique, such that the planned experiments cannot be performed in the large stellarators in Europe and Japan. Third, the United States will benefit significantly from participation in the substantial physics experiments abroad.