The Stellarator Program

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Abstract

The worldwide development of stellarator research
is reviewed briefly and informally.

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A stellarator is a closed steady-state toroidal device for confining a hot plasma in a magnetic field where the rotational transform is produced externally, from torsion or coils outside the plasma. This concept was one of the first approaches proposed for obtaining a controlled thermonuclear device. It was suggested and developed at Princeton in the 1950's. Worldwide efforts were undertaken in the 1960's. The United States stellarator commitment became very small in the 1970's, but recent progress, especially at Garching and Kyoto, together with some new insights for attacking both theoretical issues and engineering concerns have led to a renewed optimism and interest as we enter the 1980's.

The stellarator concept was born in 1951. Legend has it that Lyman Spitzer, Professor of Astronomy at Princeton, read reports of a successful demonstration of controlled thermonuclear fusion by R. Richter, in Argentina when he was on a ski trip. As he rode up the ski lift he pondered over how this could be achieved. He considered the possibility of mirror containment but dismissed it because of scattering into the loss cone. He preferred steady-state operation and chose not to use internal currents to set up the magnetic fields in closed devices as in pinches or tokamaks. He recognized the problem with toroidal confinement due to $\mathbf{E} \times \mathbf{B}$ drifts, where the electric field is set up by the $\mathbf{B} \times \nabla B$ drifts of the ions and electrons. This led to a need for a rotational transform so that the electrons could flow along the magnetic field lines from regions of accumulation to regions of positive charge, thus eliminating the electric field. Spitzer's big achievement was to recognize that this could be accomplished by bending the torus into a figure-eight shape. Then the electrons would drift upwards in one end of the system and downwards in the other so that the charge could be neutralized by flow along the magnetic field lines. At this time he developed an understanding of

most of the problems associated with thermonuclear containment-auxiliary heating since ohmic heating to ignition is difficult, need for a divertor to protect the plasma from impurities sputtered from the wall, etc. Spitzer's proposal to develop the stellarator concept was supported, and stellarator studies began in the summer of 1951.

A conceptual plan evolved leading to a four stage stellarator program: Model A, a small, low-field, table-top device would demonstrate the feasibility of the idea with confinement of the electrons. Plasma confinement, heating, and divertor action would be demonstrated on one or more Model B devices which would have roughly a two inch tube diameter and a 30 kG field. The Model C Stellarator with an 8 inch diameter vessel and 50 kG field would essentially be a quarter-scale pilot model of a power producing prototype, Model D.

The Model A Stellarator was built in 1952 and showed that breakdown could be achieved more easily in a figure-eight device with a rotational transform than in a pure torus. Although cross-field diffusion seemed higher than expected, it confirmed the theoretical expectations.

The Model B1 Stellarator became operational in 1954 and met significant difficulties with forces on the coils and impurities. After being rebuilt with a stainless steel vessel and incorporating state of the art high-vacuum techniques, this device became quite reliable. Plasma diagnostic techniques, particularly using spectroscopic and microwave methods, were developed on it. Its noteworthy results concerned MHD instabilities. In particular, it was found that if the plasma current associated with ohmic heating exceeded the Kruskal limit, the discharge became violently turbulent and the plasma was rapidly lost to the walls. Instabilities were also observed at lower currents. These are now considered to be tearing modes, but, at the time,

there were questions concerning whether they were associated with a loss of equilibrium due to the rotational transform becoming rational.

As B1 was starting to work, a reactor study, the Model D Report, was initiated to determine whether or not the device would be economically interesting if the physics problems could be solved. It found that β , the ratio of material to magnetic pressure, would have to be very high, ~ 0.7 , largely because of the energy dissipated in the coils, and the total power would be large, $\sim 50W$. On the basis of this design, studies for the Model C device were initiated in 1954.

Very early in the program it was recognized that more than one machine would be needed to investigate all the problems, so B2 was designed and built to investigate magnetic pumping. The field magnitude in a pumping bulge was oscillated at a frequency corresponding to the transit time of a thermal particle. Good energy absorption from the power supply was observed, but so many impurities were introduced that the plasma was actually cooled.

In 1954 Edward Teller raised the question of magnetohydrodynamic instabilities. It was quickly recognized that, with the bulges provided for a magnetic pumping region and for a divertor and with the magnetic field lines twisting with the same pitch, the stellarator was clearly unstable with respect to interchange modes. This quickly led to two actions. First, design efforts for the Model C device were stopped. Second, a major effort on MHD stability was initiated. Again, Spitzer quickly provided the answer: by making the twist or rotation of the magnetic field lines different on neighboring magnetic surfaces, one could make it necessary to bend the field lines to interchange them, thus stabilizing the mode. His technique for providing this shear led to the development of helical windings. Since these provided a rotational transform as well as shear, it was no longer necessary

to utilize the figure-eight geometry.

During this period Thomas Stix proposed a modular way of building the device, which he named B8² since from above it looked like a squared figure eight. At this time the program was classified since success would have produced a copious neutron source, so the AEC security office changed the name to B64 to protect the secret (the number 8). This machine also provided a demonstration of the seriousness of the Kruskal-Shafranov current limit. It incorporated a divertor and demonstrated the efficacy of this idea for improving impurity control. Later, when rebuilt as B65 in a race-track shape, it verified the possibility of obtaining a rotational transform with helical windings.

The need for a well-designed bakable device for impurity control led to the design and construction of B3. One of the many significant results emerging from this machine was the measurement of plasma recycling from the walls, leading to a good determination of particle confinement. This confirmed the earlier indications of much poorer plasma confinement than is predicted classically and led to a major study of pumpout.

A new steady-state machine ETUDE (originally designated as A2) was built in the late 1950's. It's original purpose was to investigate a different modular figure-eight system and to compare the properties of a device using the torsion of the axis to get a rotational transform with one utilizing helical windings, but its major application was to observe and study drift waves, with considerable effort made to determine phase correlations between density and electric field fluctuations.

The improved stability picture with shear stabilization, although with much lower β values than previously hoped for, together with the observation that pumpout was so large in the small devices that the particles could not be

held long enough to be heated to an interesting temperature, led to reinitiating work on Model C. This device, with an eight inch vacuum vessel, helical windings, a divertor, and an ICRF heating port was started in 1957. It was planned strictly as a research device.

This first phase of the stellarator program came to a close at the Second United Nations Conference on the Peaceful Uses of Atomic Energy in Geneva in 1958 when the wraps of secrecy were removed from the controlled nuclear fusion programs in the United States, the Soviet Union, and Europe. These results were presented, with the Model B2 Stellarator providing a working demonstration. Although large problems remained to be solved, it was clear that considerable progress had been made and the concept was viable. The interest generated there stimulated worldwide interest in stellarators.

The second phase of the stellarator program started with the declassification and was marked by increased interest and activity around the world.

The only stellarator experiments reported at the First International Conference on Plasma Physics and Controlled Nuclear Fusion Research, held at Salzburg in 1961, concerned work on the B1 and B3 stellarators and initial operation of Model C. The most important result was the observation of Bohm diffusion, with the containment time scaling as B/T and the magnitude no more than a factor of three better than Bohm's formula.

The stellarator concept was picked up at the Max-Planck Institut in Munchen Germany (later Garching) immediately after declassification in the United States. An essential impact on this program occurred at the Salzburg Conference, where comparison of the Model C results with classical confinement of a thermal cesium plasma in a straight Q-machine indicated that running a thermal, collisional cesium plasma with a "perfect" Maxwellian distribution in

a stellarator configuration should give decisive information on the viability of the stellarator confinement concept. A series of experimental devices were built along this line. The first one, WENDELSTEIN I-A, a small $\ell = 3$ race-track machine ($R = 35$ cm, $a \approx 2$ cm, $B \leq 20$ kG) showed high losses. Introducing some curvature into the magnetic field in a linear Q-machine showed some increase in the loss rates, but this effect could be explained by $\int d\ell/B$ not being constant when the lines were bent. The WENDELSTEIN I-A results were explained by the Pfirsch-Schlüter model according to which the r^2 -dependence of the $\ell = 3$ rotational transform was not sufficient to provide equilibrium. In order to check this, WENDELSTEIN I-B, an $\ell = 2$ stellarator with higher central transform but otherwise the same dimensions as WENDELSTEIN I-A, was built.

Under the influence of the Princeton program, a stellarator program was initiated at the Lebedev Institute in Moscow, U.S.S.R. in the early 1960's. The emphasis was on achieving and measuring high-quality magnetic surfaces. The possibility of obtaining large shear with an $\ell = 2$ system was also recognized.

More work was reported at the Second IAEA conference at Culham in 1965. The big theoretical development in this period was the discovery of resistive instabilities which grow on a much faster time scale than that of transport and thus are particularly dangerous for steady-state devices. Because the magnetic field lines are reconnected by the interchange, magnetic shear provides no stabilization. Thus it is necessary to obtain configurations with minimum average B. Several papers describing techniques for achieving this were reported at this conference, but they all required complicated field configurations.

The Model C Stellarator studies continued to demonstrate Bohm diffusion,

with drift waves associated with the ohmic heating current being ruled out as the major loss mechanism. Favorable results for Ion Cyclotron Radio Frequency heating were reported. Plasma guns were used to inject plasma into L-1, an $l = 2$ stellarator at the Lebedev Institute in Moscow. Good confinement was observed in current-free discharges. The Garching group reported excellent confinement of cesium plasmas, with classical diffusion being the main loss process perpendicular to the field. These losses were so small that even tiny probes, 0.1 mm in diameter, provided a major disturbance. The results in WENDELSTEIN 1-B were extremely sensitive to the proper adjustment of correction fields, which effect was felt to be connected with its race-track type shape and the presence of circularisers at the transitions from the curved to the straight sections. This led to the construction of the somewhat larger, circular WENDELSTEIN II-A device ($l = 2$, $R = 56$ cm, $a = 5$ cm, $B = 12$ kG).

The success of the Lebedev L-1 stellarator with gun-injected plasmas reported at the Culham Conference prompted the setting up of a stellarator program at the Culham Laboratory. Because of the uncertainty over the existence of magnetic surfaces in a high shear, truly toroidal stellarator and their significance in trapping plasma, it was decided to build the well-engineered, high-shear $l = 3$ single-particle experiment CLASP. In this device it was demonstrated that electrons generated by the β -decay of tritium, if passing particles, could be contained for more than 10^7 orbits around the system (i.e., sufficient for a reactor). Simultaneously, the CLEO experiment, a large apparatus with neutral injection, was proposed. It was decided that to build such a device was premature and the PROTO-CLEO ($R = 40$ cm, $a = 5$ cm, $B = 5$ kG) $l = 3$ medium and high shear stellarator was built. This was a rather unconventional experiment, with the helical winding inside the vacuum

vessel. This was necessary to remove the wall-plasma interaction, since the plasma would be produced by gun injection. This experiment was successful in that a tenuous plasma could be contained for a period as long as predicted by neo-classical theory, provided that account was taken of the finite ion gyro-radius (comparable with the density gradient scale length). Simultaneously, a turbulent heating program was carried out using TWIST, a slightly smaller $\lambda = 3$ stellarator. In this experiment, a large ohmic heating current induced electrostatic instabilities and successfully heated the plasma by turbulence, although the magnetic field was too weak to confine the plasma.

A large number of experiments were reported at the Third International Conference at Novosibirsk in 1968. As in the earlier conferences, the major effect reported on the Model C Stellarator was in documenting and understanding the Bohm-like dependence of plasma transport. Studies with washer-gun plasmas and rf generated zero-current plasmas, both with longer mean free paths than before, gave confinement at about five times Bohm. It was noted in passing that significantly better results were being obtained with the R3 and ETUDE Stellarators. In contrast, good confinement was observed on the WENDELSTEIN II device at Garching. This $\lambda = 2$ stellarator with little magnetic shear contained a barium plasma well enough that plasma loss could be accounted for classically, as in its predecessor, WENDELSTEIN 1-B. Since the losses had been so small in that device that even tiny probes provided a major disturbance, the density in WENDELSTEIN II-A was measured by resonance fluorescence so that probes could be avoided. Confinement was found to decrease markedly whenever the rotational transform is a rational fraction where one should expect difficulties with equilibrium. Similar results related to enhanced loss when the rotational transform is rational were observed in L-1. The experiments emphasized the deterioration of the plasma

properties if the magnetic surfaces have island structure.

Several new stellarator groups reported results at this meeting, including the encouraging results from Culham and some interesting work in the U.S.S.R. The Kharkov group used the SIRIUS stellarator (an $l = 3$, $L = 600$ cm, $B = 20$ kG racetrack device) to investigate turbulent heating. As with the TWIST work, they found regimes with high anomalous conductivity but observed that large microwave and x-ray emission was responsible for much of the energy balance. The Novosibirsk group described a small ($R = 50$ cm, $a = 5$ cm, $l = 3$, $B \sim 2-6$ kG) device which they used to study plasma diffusion.

On the theoretical front the developments in this period were relatively pessimistic. Several techniques were developed for constructing systems with minimum average B . On the other hand, new trapped-particle instabilities were discovered that indicated difficulties with three-dimensional systems. The development of neoclassical transport theory showed extremely bad confinement of collisionless plasmas. Difficulties of obtaining equilibria with well defined magnetic surfaces were discussed, with serious questioning of the severity of magnetic island problems and magnetic field line ergodicity.

All these problems emerged just at the time the Soviet researchers were obtaining good results with the T-3 tokamak. Thus it is not at all surprising that, when the Culham group set up a Thompson scattering experiment on the T-3 device at Kurchatov and verified the high temperature claims, the United States abandoned its stellarator program and converted the Model C Stellarator into the ST Tokamak shortly after the 1969 Dubna meeting. Worldwide stellarator enthusiasm dwindled at this time as well, so that the research that continued was made more difficult by the problems associated with obtaining good diagnostic support and reasonable funding for new devices and improvements. The second phase of the stellarator program ended at this time.

with the program in a discouraging position.

Nevertheless, a number of new devices entered the scene as the program began its third phase. It was recognized by the Culham group that the stellarator configuration should be tested under circumstances as comparable with then existing tokamaks as possible (e.g., with T-3 and ST). The CLEO experiment ($R = 90$ cm, $a = 11$ cm, $B = 20$ kG) was thus designed to have an $l = 3$ helical winding similar to that on PROTO-CLEO and to be capable of conversion to a tokamak, so that a comparison between stellarators and tokamaks could be made in the same apparatus.

The heliotron concept was started in 1958 to provide a magnetic separatrix inside the vacuum vessel. The idea was generalized by 1961 to incorporate helical windings. HELIOTRON A (1959), HELIOTRON B (1960), and HELIOTRON C (1965) were built at Kyoto, Japan, with HELIOTRON B demonstrating plasma confinement with a magnetic limiter. HELIOTRON D ($m/l = 25/2$, $R = 109$ cm, $a = 10$ cm, $B = 3$ kG), the first heliotron using helical coils, was built in 1970. Its coil, with m/l the ratio of machine length $2\pi R$ to the pitch length, was inside the vacuum vessel and simultaneously provided large rotational transform and shear; $\chi(0) = 0.6$, $\chi(a) = 2.5$.

At the 1971 Madison meeting, work on collisionless plasmas was reported on the Novosibirsk device, the Lebedev TOR-1 device (with $l = 2$, $R = 60$ cm, $a = 8.5$ cm, $B = 15$ kG and a large transform), and PROTO-CLEO with confinement time one fourth to one twentieth that predicted by neo-classical theory. Probably the most important stellarator experiment reported at the meeting was the demonstration in PROTO-CLEO that bootstrap currents are at least an order of magnitude smaller than was predicted theoretically. Toroidal plasma motion was investigated on L-1. The Lebedev group also reported work on magnetic surfaces and island control in TOR-2 (an $l = 2$, $R = 62.5$ cm, $a = 3.6$ cm,

B = 25 kG device). The SATURN device ($\ell = 3$, $R = 35.6$ cm, $a = 8.6$ cm, $B = 6$ kG) at Kharkov was used for magnetic surface studies in stellarators and torsatrons. This group reported initial operation of URAGAN (a 10 meter race track device with $R = 110$ cm, $a = 10$ cm, $B = 10$ kG, $\ell = 2$) and looked at the nature of anomalous conductivity with large ohmic heating current in SIRIUS, as well as investigated RF heating in OMEGA ($R = 44$ cm, $a = 10$ cm, $B = 10$ kG). Studies of turbulent heating in TWIST were continued. The JIPP-1 stellarator ($\ell = 3$, $R = 20$ cm, $a = 8.4$ cm, $B = 4$ kG) at Nagoya was commissioned and confinement an order of magnitude better than Bohm was reported. The WENDELSTEIN II-A group reported detailed studies of convection in their zero-shear device. This ended the successful work with "model-plasmas" in Garching and WENDELSTEIN II-B was built to investigate higher temperature plasmas. It was identical with WENDELSTEIN II-A but equipped with an ohmic heating transformer because among the available means this was the only one powerful enough to overcome the radiation threshold. The WENDELSTEIN VII-A stellarator ($R = 200$ cm, $a = 10$ cm, $B \leq 40$ kG) was constructed in parallel. It is an $\ell = 2$ machine for avoiding resonances and has some average magnetic well for stability. The device is capable of housing a larger vacuum tube with at least twice the linear plasma dimensions. Some work was reported on high- β stellarators at Garching and Los Alamos at this meeting.

The situation was not drastically different at the 1974 Tokyo meeting. Ohmic heating experiments were carried out in WENDELSTEIN II-B, where the effect of rational magnetic surface resonances, reduced by the shear arising from the ohmic current, was seen. The electron confinement was found to be tokamak-like with some improvement of stability by the external transform; the ion confinement was close to neoclassical; and $T_e = 300$ eV was reached. Ohmic

heating plasmas were also studied in URAGAN 1, JIPP-1B ($l = 2 + 3$, $R = 50$ cm, $a = 7$ cm, $B = 4$ kG), HELIOTRON D, and TORSO (an $l = 3$ ultimate torsatron successor to TWIST with $R = 40$ cm, $a = 6.5$ cm, $B = 20$ kG), resulting in confinement times comparable to pseudoclassical predictions. An ohmic current with $i_{OH} = 0.4$ was observed in HELIOTRON D without instability. The torsatron, with its large helical ripple, was chosen at Culham as an appropriate device for study of the effect of superbananas. The ratio of electron drift velocity to electron thermal velocity was the principal parameter found to characterize the plasma containment. At low collisionality, superbanana diffusion effects were masked by turbulent diffusion due to the high drift velocity. Radio frequency heating studies were reported in URAGAN 1 and HELIOTRON D which achieved $T_e \sim 320$ eV with shear Alfvén waves. CLEO had just begun operation. The ASPERATOR T-3 at Sendai was built to investigate the use of helical windings to heat and stabilize tokamak instabilities. Stringer reported an anomalous particle loss model associated with ion loss cones. Voitsenya and his collaborators made a comparison of confinement work on PROTO-CLEO, SATURN, VINT-20 (a Kharkov torsatron with $l = 1$, $R = 32$ cm, $a \sim 3$ cm, $B = 17$ kG), SPAK-1 (a Nagoya torsatron with $l = 2$, $R = 40$ cm, $a \sim 6$ cm, $B = 2$ kG), and HELIOTRON D. They found that diffusion increases with decreasing collisionality, but not as rapidly as predicted by neoclassical theory. A reactor study based on the heliotron concept was reported. The $m = 1$ axisymmetric instability that had been predicted theoretically for high-beta stellarators was observed on SCYLLAC and ISAR, leading to the abandonment of this approach. The PROTO-CLEO device had just been moved to the University of Wisconsin so that work on stellarators in the United States was resumed.

The next IAEA conference on Plasma Physics and Controlled Nuclear Fusion

was held in Berchtesgaden in 1976. Several new devices became operational at this time. The three that would dominate stellarator research were CLEO at Culham, WENDELSTEIN VII-A at Garching and L-2 ($l = 2$, $R = 100$ cm, $a = 17.5$ cm, $B = 20$ kG) at Lebedev. They all reported studies with ohmic heating. The CLEO team found confinement at least as good as in an equivalent tokamak. Comparison of TORSO and CLEO showed no significant difference between stellarators and torsatrons. Good thermal insulation was demonstrated on L-2. The WENDELSTEIN VII-A experiments started with ohmic heated plasmas and showed that the external transform provides for mode stabilization and completely avoids major current disruptions. For these plasmas, the energy confinement was found to closely follow the drift parameter scaling, that is to improve with decreasing plasma current. Radio frequency heating was investigated in HELIOTRON D, RO-2 (an $l = 2$, $R = 65$ cm, $a = 4$ cm, $B = 15$ kG torsatron at Sukhumi), and in URACAN 2 (an improvement of the device at Kharkov). HELIOTRON DM ($m/l = 21/2$, $R = 45$ cm, $a = 6$ cm, $B = 10$ kG) at Kyoto and JIPP T-2 ($l = 2$, $R = 91$ cm, $a = 17$ cm, $B = 30$ kG) at Nagoya also began operation with HELIOTRON DM having plasma energy increased up to an order above that in HELIOTRON D. The figure-eight approach was resurrected at Kurchatov in M-8, a machine with $L = 270$ cm, $R = 20$ cm, $a = 4$ cm and $B = 15$ kG. Pease pointed out in his closing summary that stellarator results were quite promising.

Experimental results were presented at the Innsbruck 1978 meeting from five groups, CLEO, L-2, WENDELSTEIN VII-A, HELIOTRON D and DM, RO, and PROTO-CLEO. It was becoming well established that helical fields improve the confinement properties of ohmically sustained discharges, with energy confinement increased by a factor of two to ten above that of comparable tokamaks. If the externally imposed transform is sufficiently large,

disruptions can reliably be avoided. Ion heat conductivity appears to be neoclassical. A particularly important and well documented conclusion is that the energy containment improves with decreasing current. Radio frequency heating studies were continued at Sukhumi and Kyoto. An interesting experiment at Kharkov, not reported at the conference, showed that white noise lowered the ion heat transport, presumably by imposing a higher effective collisionality.

Only five experimental groups reported on stellarator experiments at the 1980 Brussels meeting. Probably the most exciting was the work on WENDELSTEIN VII-A, where the availability of about 1 MW of neutral injection energy for plasma heating and careful programming of the helical currents made current-free operation possible. Pure stellarator operation was achieved by starting with an ohmic heating target plasma. Significant plasma parameters, $T_i \approx 700$ eV, $n \approx 10^{14} \text{ cm}^{-3}$, $\tau_E \approx 35$ ms, together with a strong reduction in fluctuation level and vanishing of the MHD activity, were obtained. Currentless plasmas were also obtained in CLEO using ECRH heating. JIPP T-2, HELIOTRON D and DM, and PROTO-CLEO also studied plasmas with auxiliary heating techniques. A new larger device HELIOTRON E [$m/l = 19/2$, $R = 220$ cm, $a \approx 20$ cm, $B = 20$ kG, $\alpha(0) \approx 0.5$, $\alpha(a) = 2.2$] began operation at this time.

There were several conceptual advances reported in this period leading to a very positive outlook for stellarators as this third era drew to a close. Further studies with WENDELSTEIN VII-A current-less discharges gave very favorable confinement times. Initial operation of HELIOTRON E with ohmic heating showed a clear correlation of the electron energy confinement time with the drift velocity over a wide range of current and obtained $n\tau_{Ee} \approx 2.5 \times 10^{12} \text{ sec cm}^{-3}$, comparable with tokamaks. With 10 msec pulses of 100 kW Electron Cyclotron Resonance Heating excitation, current-less plasmas

with $n_e \approx 5 \times 10^{12} \text{ cm}^{-3}$, $T_e \approx 200 \sim 500 \text{ eV}$, $T_i \approx 100 \sim 120 \text{ eV}$, $B = 10 \text{ kG}$, and $\tau_E \approx 40 \pm 8 \text{ msec}$ have been obtained, with near neoclassical thermal conductivity claimed for both the ions and the electrons. On the theoretical side, studies indicate that transport should be significantly lower than that calculated from earlier neoclassical models. This is partially due to the effects of radial electric fields. More importantly, in the earlier work the number of particles in trapped orbits and the time they stayed in them were overestimated. On the engineering side, it has become clear that torsatrons and heliotrons need only one set of helical coils with the forces not pointing radially inward so that structural problems are simplified. Also, new ideas have emerged for obtaining reasonable transforms with discrete, easily supported modular coils. Thus, stellarator construction may be even easier than tokamaks. Preliminary results from reactor studies are encouraging. Thus the stellarator program is entering its fourth period with enthusiasm and optimism.

Most of this discussion was based on papers presented at the series of International Atomic Energy Agency Conferences on Plasma Physics and Controlled Nuclear Fusion Research. A good introduction to the early years can be found in Bishop's book.^[1] A review of the basic MHD considerations of equilibrium and stability was prepared by Greene and Johnson.^[2] A comprehensive analysis of the results obtained on the Model C stellarator was given by Young.^[3] The second and third phases of the program were well summarized in Miyamoto's excellent review paper.^[4] His list of references is especially extensive. A good report on stellarators was given recently by Shohet.^[5] Rabinovich^[6] has also provided a discussion of stellarator history and status. The flavor of the stellarator program was caught well in Shafranov's recent anniversary paper^[7] in Nuclear Fusion.

This work was supported by the U.S. Department of Energy Contract No. DE-
AC02-76-CH03073 with Princeton University.

REFERENCES

- [1] A. S. Bishop, "Project Sherwood; the U.S. Program in Controlled Fusion" (Reading, Mass., Addison-Wesley Pub. Co., 1958.)
- [2] J. M. Greene and J. L. Johnson, "Hydromagnetic Equilibrium and Stability," in *Advances in Theoretical Physics* (K. Brueckner, ed., New York, Academic Press Inc., 1965) Vol. 1, p. 195-244.
- [3] K. M. Young, "The C-Stellarator- a Review of Containment," *Plasma Physics*, Vol. 16, p. 119-152, February, 1974.
- [4] K. Miyamoto, "Recent Stellarator Research," *Nuclear Fusion*, Vol. 18, p. 243-284, February 1978.
- [5] J. L. Shohet, "Stellarators" in *Fusion* (E. Teller, Ed., New York, Academic Press, Inc., to be published) Chapter 4.
- [6] M. S. Rabinovich, "Experimental Research on Stellarators," in *Summary of Scientific and Technical Research* (Plasma Physics Series, Vol. 2) (V. D. Shafranov, Ed., B. B. Kadomtsev, Series Ed., Moscow, All-Union Institute of Scientific and Technical Information, to be published in Russian).
- [7] V. D. Shafranov, "Stellarators," *Nuclear Fusion*, Vol. 20, p. 1075-1083, September 1980.