ORNL/TM-10482

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Progress in Stellarator/Heliotron Research: 1981–1986

Executive Summary

B. A. Carreras
G. Grieger
J. H. Harris
J. L. Johnson
J. F. Lyon
O. Motojima
F. Rau
H. Renner
J. A. Rome
K. Uo
M. Wakatani
H. Wobig

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

ORNL/TM-10482
Dist. Category UC-20 a,d,f,g

Fusion Energy Division

PROGRESS IN STELLARATOR/HELIOTRON RESEARCH: 1981–1986

Executive Summary

B. A. Carreras
G. Grieger
J. H. Harris
J. L. Johnson
J. F. Lyon
O. Motojima
F. Rau
H. Renner
J. A. Rome
K. Uo
M. Wakatani
H. Wobig

Date Published - September 1987

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

CONTENTS

PREFACE

This report is the first of two volumes—an executive summary and a full report—that document progress in stellarator/heliotron research in the five years (1981–1986) since a previous U.S.-EURATOM assessment of stellarator research. The present study was carried out under the terms of the IEA Implementing Agreement for Cooperation in Development of the Stellarator Concept by researchers from the Kyoto University Plasma Physics Laboratory in Japan (O. Motojima, M. Wakatani, and K. Uo), the Max-Planck-Institut für Plasmaphysik in the Federal Republic of Germany (G. Grieger, F. Rau, H. Renner, and H. Wobig), and the Oak Ridge National Laboratory (B. A. Carreras, J. H. Harris, J. F. Lyon, and J. A. Rome) and the Princeton Plasma Physics Laboratory (J. L. Johnson) in the United States of America.

This executive summary is being published as ORNL/TM-10482 by the Oak Ridge National Laboratory, as IPP-2/286 by the Max-Planck-Institut für Plasmaphysik, and as PPLK-7 by the Kyoto University Plasma Physics Laboratory. The full report will be published as ORNL/TM-10483, IPP-2/287, and PPLK-8.

The eight numbered sections of the executive summary correspond to the first eight chapters of the full report. An introduction to the topic (Sect. 1) is followed by an assessment of the existing data base (Sects. 2–5), a discussion of the information expected from the present generation of experiments (Sect. 6.1), and brief reviews of facilities needed in the future (Sect. 6.2), engineering issues (Sect. 7), and reactor considerations (Sect. 8). The executive summary concludes with a statement of the essential ideas presented in this document and in the full report.

PROGRESS IN STELLARATOR/HELIOTRON RESEARCH: 1981–1986

Executive Summary

INTRODUCTION

Stellarators and heliotrons have some similarities to tokamaks, but at the same time they have some distinct and favorable differences. Startup from existing magnetic surfaces and the possibility of a steady-state burn in the absence of dangerous disruptions are major advantages of this type of fusion reactor. The prospect for continuous operation of the reactor allows different approaches for the coil engineering and avoids problems associated with cyclic loads, which must be addressed in pulsed systems (mainly in the first wall, in the blanket, and in the coils and their support structure). Furthermore, less circulating power is required in steady-state systems. A moderate aspect ratio alleviates problems regarding the first wall power loading.

Substantial progress in plasma parameters, physics understanding, and stellarator/heliotron concept improvement has been made in the five years since a previous assessment of the field [1]. This includes (1) substantial achievements in higher plasma parameters and currentless plasma operation; (2) new theoretical results with respect to higher beta limits, second stability region, effect of a helical axis, effect of electric fields on transport, and reduction of secondary currents; and (3) improvements to the reactor concept. The key issues have been further refined, and the short-term direction of the program is clear; a number of new facilities that were designed to resolve these issues are about to come into operation or are in the

[1] *Stellarators: Status and Future Directions, Joint U.S.-EURATOM Report,* IPP-2/254, Max-Planck-Institut für Plasmaphysik, July 1981 (DE81026572, National Technical Information Service, Springfield, Virginia).

final design stages. Details of the design of the next-generation experiments will follow from the results of the near-term experiments.

1. Definitions and New Experimental Facilities

1.1. Definitions

Stellarators/heliotrons belong to the toroidal family of magnetic confinement devices, along with tokamaks and reversed-field pinches. This family is characterized by toroidally closed, nested magnetic surfaces produced by helical magnetic field lines (with toroidal and poloidal components). In the stellarator/heliotron concept, both poloidal and toroidal field components are produced entirely by currents in external windings. In principle, this field can be created by a single coil system. This allows full external control of the magnetic confinement geometry and provides a rich spectrum of possible configurations. In this report, the term stellarator/heliotron is used to describe the general class of external helical confinement devices, which includes classical stellarators, Advanced Stellarators, heliotrons or torsatrons, heliacs, etc. Now that stellarators/heliotrons operate without large net tokamak-like plasma currents, they are less subject to current-driven effects.

1.2. New Experimental Facilities

The Heliotron E device at Kyoto University in Japan has come into full operation. Japan is building a small, low-aspect-ratio Compact Helical System (CHS) and designing the next large helical system of the MoE (the Ministry of Education, Science, and Culture) which should demonstrate the reactor potential of the Heliotron-like approach. The European Community has nearly completed the modular-coil Advanced Stellarator Wendelstein VII-AS at the Max-Planck-Institut für Plasmaphysik, Garching, to replace the Wendelstein VII-A stellarator, which has been operating since 1975. At the same laboratory, Wendelstein VII-X, a large device with the aim of demonstrating the key elements of the reactor potential of Advanced Stellarators, is in the state of definition and concept development. In Spain, CIEMAT (Centro de Investigaciones Energèticas, Medioambientales, y Tecnològicas) in Madrid is planning a medium-size flexible heliac (TJ-II). The United States has built the Advanced Toroidal Facility (ATF) torsatron at Oak Ridge National Laboratory, the first large stellarator experiment in this country since the Model-C Stellarator at Princeton was shut down in 1969. A next-step facility, ATF II, is under study at Oak Ridge. The United States has also built a number of smaller research facilities: the IMS modular stellarator at the University of Wisconsin–Madison, the HBQM high-beta linear heliac at the University of Washington–Seattle, and the Auburn torsatron at Auburn University. At the Kharkov Physico-Technical Institute in the U.S.S.R., the Uragan-3 torsatron has come into operation, and a large torsatron, Uragan-2M, is under construction. At the Australian National University, Canberra, the small heliac SHEILA has started operation, and a larger heliac (H-1) is under construction.

The substantial advances in stellarator/heliotron research, the increasing size and diversity of new facilities, and the countries that have begun contributing in a major way to stellarator research (the United States, Australia, and Spain) are a measure of the vibrancy of this field.

EXISTING DATA BASE

2. Magnetic Configurations and Coil Systems in General

Stellarator/heliotron configurations can be created by using a variety of coil sets. Indeed, a given magnetic configuration can almost always be produced in more than one way. This follows from the basic properties of magnetic fields in toroidal geometry. For a given stellarator field configuration and an arbitrarily chosen toroidal surface that encloses the confinement volume, it is possible to calculate the surface current distribution required to produce the desired field configuration. Furthermore, the internal field configuration remains unchanged if this surface current distribution is modified by the addition of any surface current distribution that produces no magnetic field inside the enclosed volume. The families of surface current distributions determined in this way can be used to lay out coil systems of many different types. It is now possible to discuss and compare the properties of such configurations without constant reference to the particular coil set used to realize the configuration in an experimental device.

There are many different kinds of stellarator/heliotron configurations, but they all can be characterized in terms of the magnetic properties that determine a configuration's confinement physics. Key characteristics are the profiles of the rotational transform, $\iota(r)$, shear, and magnetic well or magnetic hill, together with their relation to regions of rational transform; field ripple, $\epsilon(r)$; the toroidal aspect ratio, $A = R/a$; the poloidal variation of $\int dl/B$ within a magnetic surface ($\delta \int dl/B$); and the helical axis excursion. These characteristics are not independent, so configuration design requires trade-offs to obtain desirable overall performance. Although the number of possible combinations is large, four different design strategies have emerged as leading candidates and are being pursued worldwide. They differ from each other by emphasizing particular subsets of the key characteristics and putting less emphasis on the others.

1. **High-transform, high-shear stabilized configurations** have fairly high plasma aspect ratios ($A \gtrsim 10$), edge transforms $\iota_a \gtrsim 2$, and strong shear ($\Delta\iota/\iota_0 \sim 5$). The high transform reduces the finite-beta shift and provides equilibrium even at high $\langle\beta\rangle \simeq 10\%$. The transform passes through low-order rational values at $\iota = 1$, $3/2$, 2, etc., and stabilization is by strong shear. The high helical symmetry leads to improved confinement of helically trapped particles. This configuration is typified by Heliotron E.

2. **Moderate-transform, shear/magnetic-well stabilized configurations** can have lower aspect ratios ($A = 4$ to 9), $\iota_a \leq 1$, $\Delta\iota/\iota_0 \simeq 3$, and a central magnetic well. The transform profile passes through the $\iota = 1/2$ resonance but avoids $\iota = 1$. The lower transform and aspect ratio lead to a larger finite-beta shift, but operation with $\langle\beta\rangle \gtrsim 8\%$ is predicted if additional poloidal field shaping is used to control $\iota(r)$ and reduce the variation in $\int dl/B$ on the flux surfaces. The outward shift of the magnetic axis deepens the magnetic well, and theory predicts access to a second stability regime. An example of this class is ATF.
3. **Moderate-transform, low-shear, magnetic-well stabilized, $\delta \int dl/B$-reduced and drift-optimized configurations** have higher aspect ratios ($A \gtrsim 10$), $\iota < 1$, and a global magnetic well. The low shear makes it possible to avoid low-order resonant values of transform entirely by carefully controlling the transform profile. In multiple-helicity configurations with reduced poloidal variation of $\int dl/B$, theory predicts reduced shift of the magnetic axis and improved confinement ($\langle\beta\rangle \simeq 5\%$). These configurations also have the potential to reduce the radial drift of trapped particles. Wendelstein VII-AS is a step in this direction.
4. **High-transform, low-shear, magnetic-well stabilized configurations** have moderate to large plasma aspect ratios ($A \gtrsim 7$), $\iota > 1$, and global magnetic wells. The very high transform is obtained from the torsion of a helical magnetic axis and the helically symmetric $\ell = 2$ content of the flux surfaces. The magnetic well is produced mainly by the strong helical curvature in combination with the indentation of the magnetic surfaces. In the limit of infinite aspect ratio, these systems would be capable of stably confining plasmas with $\langle\beta\rangle > 10$–30%. For finite aspect ratio, the expected beta values are much smaller. Examples are H-1 and TJ-II.

Experiments will be performed in ATF and Wendelstein VII-AS in the near future to test the principles of approaches 2 and 3. These approaches are continually being refined to form the basis for the next-generation experiments. ATF-II is an extension of approach 2 to lower aspect ratio ($A \simeq 4$) that retains the potential for high-beta operation. Wendelstein VII-X is based on the Helias concept, which combines elements of approaches 3 and 4. For this concept, stability against resistive interchange modes up to $\langle\beta\rangle \simeq 9\%$ is predicted.

3. Equilibrium and Stability

The identification of the essential variables influencing the physics parameters of MHD equilibria would make it possible to control the evolution of equilibria, to enhance the plasma stability, to broaden the operational range of devices, and to add experimental flexibility. Destruction of magnetic surfaces and island formation in regions of rational rotational transform constitute a major problem that limits confinement in three-dimensional configurations. Techniques for reduction of island growth are being developed and applied. One approach to reaching this goal is the application of shear; the other is complete avoidance of low-number rational values of ι at regions of steep pressure gradients. The influence of higher order rational values will in any case be reduced by moderate shear.

Pfirsch-Schlüter or secondary currents provide a plasma shift that stabilizes the ideal ballooning mode and provides access to the second stability regime, but they can drive nonlocal kink instabilities. On the other hand, minimization of the poloidal variation of $\int dl/B$ allows reduction of the secondary currents and thus of transport without destruction of the magnetic well.

Computational tools for addressing equilibrium and stability problems have improved dramatically. Good agreement has been achieved in the prediction of axis shifts and growth rates of unstable modes with codes that are based on different theoretical models and that use different computational algorithms.

MHD theory has played a crucial role in the determination of the main parameters and coil configurations for near-term stellarators:

- Optimization studies to minimize the Pfirsch-Schlüter currents and provide a magnetic well led to the Wendelstein VII-AS design.
- ATF was based on optimization of the magnetic configuration to access the second stability region and provide flexibility.
- MHD studies for TJ-II resulted in a wide range of variation of ι, providing flexibility to avoid or control the low-order resonant surfaces.

Similarly, MHD theory has been essential to the interpretation of experimental observations in Wendelstein VII-A and Heliotron E:

- At low values of beta, the observed plasma shift with increasing beta is equal to the Shafranov shift, $\Delta \sim \beta/\iota^2$.
- The sensitivity of plasma containment in Wendelstein VII-A to the value of ι at the plasma edge can be explained as a magnetic-island-induced equilibrium and transport problem, with control achieved by the introduction of a small amount of shear.
- The high-beta limitation observed in Heliotron E for peaked pressure profiles is determined by an $m/n = 1$, pressure-driven internal mode that can be removed by appropriately broadening the pressure distribution.

4. Transport

Much progress has been made in recent years on the theory of transport in stellarators/heliotrons. Neoclassical theory, based on binary collision processes, has been expanded both in the analytic field and in the field of numerical simulation. The availability of powerful computers has allowed the use of Monte Carlo techniques for calculating transport coefficients and loss rates and comparing them with analytic theory. Less developed is the theory of anomalous transport in these configurations. In particular, the effect of partially destroyed magnetic surfaces, and the conditions under which they appear, must be investigated. The problem of convective cells and turbulent losses arising from instabilities is a problem common to the stellarator/heliotron and the tokamak.

Better understanding of particle orbits is the key to advances in neoclassical theory. The introduction of flux coordinates (or magnetic coordinates) was a major milestone in the analysis of particle orbits. The kinetic theory of neoclassical transport makes extensive use of the magnetic coordinate system. The formulation in magnetic coordinates also allows the radial electric field to be included. Reduction of neoclassical losses due to this field has been verified experimentally. In nearly the entire regime of collisionality, good agreement with analytic theory has been found.

Monte Carlo codes are developed for two major purposes: (1) calculation of slowing-down processes for determining the heating rate from neutral beam injection and (2) investigation of diffusion processes and loss rates in a thermal plasma. Other codes have been developed to solve the drift kinetic Fokker-Planck equation for guiding-center motion and for bounce-averaged orbits of helically trapped particles. The results agree well with the Monte Carlo calculations. The Fokker-Planck DKES code is applicable to any given magnetic field and yields the total Onsager matrix of transport coefficients.

The moment equations approach for axisymmetric configurations was extended to nonaxisymmetric devices. Written in Hamada coordinates, these equations are the basis for the flux-friction relations which relate the thermodynamic fluxes through each magnetic surface to the tangential friction forces in that surface. The neoclassical effects enter through the viscosity term, which must be derived from drift kinetic equations. The moment equations allow a self-consistent calculation of the radial electric field and the bootstrap current if the losses are neoclassical.

The algebraic equations for the radial electric field as derived from the moment equations lead to the problem of multiple roots. Stability arguments determine the root adopted by the plasma. The remaining problem of radial discontinuities of the electric field can be removed by including finite-orbit effects, resulting in a differential equation for the electric field which describes a smooth transition in the radial direction.

In a large-aspect-ratio device, the radial electric field generated by perpendicular neutral beam injection (NBI) shifts the resonance layer of those particles responsible for the plateau diffusion from $v_{\parallel} \simeq 0$ to the tail of the Maxwellian distribution, thus reducing the plateau transport coefficients.

For the future, codes must be developed to treat equilibrium and transport in a combined fashion. Improvement is needed in the theory to treat multispecies plasmas, including impurity ions and alpha particles, and to investigate large-orbit effects. Furthermore, better experimental tests of the theoretical predictions are necessary.

5. Experimental Results

Since 1981, the parameter range of experimental investigations has been extended considerably. Values of the line-averaged density $\bar{n}_e \gtrsim 10^{20}$ m^{-3} and central temperatures T_e, $T_i \gtrsim 1$ keV have become accessible for currentless operation of stellarators/heliotrons. Major contributions have come from Heliotron E ($a \simeq 20$ cm) and Wendelstein VII-A ($a \simeq 10$ cm), both of which have achieved significant plasma energy densities and beta values within the limits of their available heating power.

Highest plasma parameters attained in currentless plasmas

Highest value	Plasma parameters						Device[c]
	$\bar{n}_e$ (10^{20} m^{-3})	$T_i(0)$ (keV)	$T_e(0)$ (keV)	$\langle\beta\rangle$(%) at B_0(T)	$\bar{n}_e\tau_E$[a] $\times10^{18}$ (m^{-3}·s)	$P_{\rm abs}$ (MW), type[b]	
T_e	0.1	0.11	<u>2.4</u>	0.1, 2.5	0.04	0.11, ECH	W VII-A
T_i	0.26	<u>1.6</u>	0.66	0.3, 1.9	0.26	<u>3.5</u>, NBI	H-E
Pressure	1.2	1.0	0.7	<u>0.45, 3.2</u>	2.5	0.46, NBI	W VII-A
$\langle\beta\rangle$	0.9	0.41	0.41	<u>2</u>, 0.94	0.63	1.8, NBI	H-E
$\bar{n}_e\tau_E$[a]	1.4	0.3	0.3	0.47, 1.9	<u>5.0</u>	2, NBI	H-E

[a]Here τ_E is the net energy replacement time corrected for radiation losses.
[b]ECH = electron cyclotron heating, ICH = ion cyclotron heating,
NBI = neutral beam injection.
[c]W VII-A = Wendelstein VII-A, H-E = Heliotron E.

Plasmas were heated effectively by NBI and by application of electron cyclotron heating (ECH) and ion cyclotron heating (ICH). NBI was done in a nearly perpendicular mode (Wendelstein VII-A) and with a combination of perpendicular and 28° off-perpendicular injection (Heliotron E). Classical collisional slowing down was found in all cases. The radial electric fields, arising from loss regions accessed by high-energy ions, reduced the ion orbit losses and ion heat conduction in agreement with theory. The corresponding poloidal rotation was measured spectroscopically (in Wendelstein VII-A). Application of ECH allows heating at plasma densities up to the cut-off density. For $\omega_{\rm ce}$ and $2\omega_{\rm ce}$, the heating efficiency was found to be in agreement with ray-tracing calculations. Various power deposition profiles have been realized by irradiation with polarized modes and off-axis resonance conditions.

In Wendelstein VII-A, the influence of details of the magnetic configuration on plasma confinement was studied in depth. Both the transform and shear are affected by currents driven by NBI, RF, and pressure gradients. A careful choice of $\iota\!\!\!-$, excluding major resonances from the entire plasma region, together with low but positive shear, allows arranging for optimal confinement conditions. In Heliotron E, MHD instabilities related to the $\iota = 1$ surface could be avoided by properly broadening the pressure profile.

Stellarator neoclassical transport theory adequately describes the electron heat conduction of the bulk plasma, where the anomalous contribution to the electron heat conduction is expected to be small in comparison to the neoclassical terms. Anomalous, enhanced electron heat losses are necessary to fit the measured electron temperature profiles in the plasma boundary. The ion heat conduction follows the neoclassical model if its reduction by radial electric fields arising from the ambipolarity condition for $v_{\vec{E}\times\vec{B}} > v_{\rm th}\iota/A$ is properly taken into account.

Neoclassical models for particle and impurity transport have also been tested, starting from the experimentally determined n, T, and radiation profiles. Simulation experiments by ablation of tiny amounts of aluminum and silicon at the plasma boundary yielded agreement between experiment and theory if the measured profiles of the underlying bulk plasma were used.

6. Near-Term and Next-Generation Experiments

The present generation of stellarators/heliotrons has made significant progress in extending plasma parameters and understanding the behavior of currentless plasmas. New facilities are required to advance the development of the stellarator/heliotron reactor concept from the present level, to investigate the improved concepts, and to demonstrate the reactor potential of this approach. These devices are now under construction and should start yielding results in the period from 1987 to 1989. The larger, more ambitious next-generation devices should explore reactor-relevant regimes of stellarator/heliotron operation.

INFORMATION EXPECTED FROM THE PRESENT GENERATION OF EXPERIMENTS

6.1. Near-Term Experiments and Their Aims

In addition to the operating Heliotron E, six facilities are under design or construction. The two major ones are Wendelstein VII-AS, an Advanced Stellarator in Garching, and ATF, an $\ell = 2$ torsatron in Oak Ridge. Two other $\ell = 2$ experiments are under construction: the Uragan-2M torsatron in Kharkov and the small, low-aspect-ratio CHS in Nagoya. The other two systems are heliacs, which possess a magnetic axis of considerable helicity. These are H-1 at Canberra and TJ-II at Madrid. All these devices will explore different regimes of configuration space. The following information is expected from the major devices.

- Heliotron E ($R = 2.2$ m; $a = 0.2$ m; $B_0 = 2$ T; 4-MW NBI; 3-MW ICH; 1-MW, 53-GHz ECH) will continue to study beta limits and confinement in a more helically symmetric, high-transform, high-shear configuration.

- Wendelstein VII-AS ($R = 2$ m; $a = 0.2$ m; $B_0 = 3$ T; modular coils; 3-MW ICH; 1.5-MW NBI; 1-MW, 70-GHz ECH) will test the principles of Pfirsch-Schlüter current reduction, optimization of circulating particle orbits, and magnetic well stabilization.
- ATF ($R = 2.1$ m; $a = 0.3$ m; $B_0 = 2$ T; $\ell = 2$ torsatron; 4.5-MW NBI; 2-MW ICH; 0.4-MW, 53-GHz ECH) will study high-beta confinement, access to the second stability regime, and low-collisionality confinement using a variety of stellarator configurations.

FACILITIES NEEDED IN THE FUTURE

6.2. Next-Generation Experiments

The follow-on set of stellarator/heliotron experiments aims at demonstrating the scientific feasibility or potential of this concept for an attractive steady-state reactor with relevant plasma parameters. Whether this involves deuterium-tritium (D-T) operation depends on whether information from tokamaks or other types of D-T plasmas can be conclusively applied to stellarators. The definition process for these experiments has been started already with studies of Wendelstein VII-X at Garching, ATF-II at Oak Ridge, and the next large helical system of the MoE in Japan.

7. Engineering

Full exploitation of the advantages offered by the stellarator/heliotron fusion reactor concept will depend on the availability of accurate and economical methods for constructing coil systems and vacuum vessels of the required non-conventional shape. Such methods have been developed, tested, and successfully applied in the construction of new devices. Most of these technologies can readily be extrapolated to reactor conditions. In some cases, supporting technologies have been developed and have passed their first tests.

For heliotrons and torsatrons, helically shaped continuous coils have been successfully built with vessel support (for Heliotron E) and with a mechanically decoupled vacuum vessel (for ATF). These coils consist of accurately shaped copper conductors of large cross section with carefully aligned current connections to ensure negligible deviations from the desired winding law. For modular stellarators, non-planar coils have been successfully built (for Wendelstein VII-AS) by winding stranded cables into an accurate mold and curing the coil with epoxy resin to achieve full mechanical stability. In all these cases, accuracies below 1 mm were achieved without excessive effort. This accuracy is sufficient. Tools to measure coil positions and to determine the actual magnetic configuration (e.g., electron beams) are available.

Larger, steady-state machines will require superconducting coils. The Wendelstein VII-AS modular coil fabrication method lends itself directly to large superconducting coils. The ability to construct coil segments with joints is an important element for devices with continuous coils. Prototype superconducting joints have been developed and tested in preparing for the construction of superconducting Heliotron devices. Thus, it can be concluded that the technologies needed for the construction of large superconducting coils are available.

Various methods of vacuum vessel production have been developed and successfully applied. These range from the pressing and welding of large, thick steel plates (Heliotron E) to computerized cutting, bending, and welding of sheet metal (Wendelstein VII-AS). Again, the accuracy achieved is within millimeters. In particular, it has been demonstrated that, by efficient use of computerized tooling machines, vacuum vessels of nearly arbitrary shape can be made with high precision and at costs not significantly higher than those of more conventional shapes.

8. Reactor Considerations

Stellarator/heliotron systems constitute viable options for development of steady-state fusion reactors. In recent years, reactor studies have focused on the clarification of critical issues.

Stellarator/heliotron reactors with continuous helical windings are being studied at small, moderate, and large values of the plasma aspect ratio, ranging from 4 in an Oak Ridge study to 18 in one of the Kharkov systems.

The ATR reactors (Oak Ridge) are minimum-size, $\ell = 2$, continuous coil, low-aspect-ratio ($A = 3.9$–7.8) torsatron reactors. The distance between the plasma edge and the coil is minimized by using a tungsten shield and no blanket under the inboard coils. Cases studied have a thermal fusion power of $P_{\rm th} = 4$ GW, using $\langle\beta\rangle = 6$–9% at an average neutron wall load of 2.4–3.4 MW/m^2. The major radii are in the range of 8–11 m.

The Heliotron H reactor (Kyoto) is designed with a moderate aspect ratio, modular blanket and shield structures, and local divertors. Jointed coils permit parallel construction, which reduces construction time and cost and increases reliability. At a major radius of 21 m and average values of $\langle\beta\rangle = 6\%$ and $P_{\rm th} = 3.4$ GW, the averaged neutron wall load is 1.3 MW/m^2. The local enhancement factor is less than two. A tritium breeding ratio of 1.17 was obtained with lead as a neutron multiplier.

Modular non-planar coils are optimal for producing the appropriate combination of poloidal field components in Advanced Stellarators. Advanced Stellarator Reactor (ASR) and Burner (ASB) systems are being developed at Garching in collaboration with Karlsruhe. Moderate plasma aspect ratios around 10 are used, at major radii of 20 to 25 m in ASR and 15 m in ASB. Although shear stresses are considerable, the modular coils look feasible. Heating and burn scenarios yield values for the fusion power of $P_{\rm th} \simeq 0.4$ GW in ASB at $\langle\beta\rangle = 2.5\%$ and about 3.9 GW in

ASR, accounting for a radiative edge layer of 0.3 GW in the latter case. An average beta of 5% is calculated for ASR, which is comparable to the computed equilibrium beta limit. The average neutron wall load is about 2 MW/m^2. A modern thin blanket of the type proposed for the ATR reactors yields a breeding ratio of 1.05. Using lithium-lead and beryllium as neutron multipliers/moderators in the blanket and an effective reflector shield outside it helps to reduce the system size; pumped limiters and a radiative layer are considered for edge control.

IN ESSENCE

Stellarators and heliotrons confine plasmas by means of externally produced magnetic fields. For this reason, they cannot be axisymmetric, but they are inherently capable of steady-state operation. The confinement potential of such systems depends on the combination of a number of properties of the selected magnetic configuration, including rotational transform, shear, magnetic well or hill, field ripple, poloidal variation of $\int dl/B$, etc. These properties are not independent of each other and thus cannot be selected freely; rather, choices and compromises must be made according to the characteristics desired for particular objectives. Four basic lines have emerged on which different groups concentrate:

- High-transform, high-shear stabilized configurations are being investigated by the Heliotron group, Kyoto.
- Moderate-transform, shear/magnetic-well stabilized configurations with access to a second stability regime are being studied by the ATF group, Oak Ridge.
- Moderate-transform, low-shear, magnetic-well stabilized, $\delta \int dl/B$-reduced, drift-optimized configurations are the focus of the Wendelstein group, Garching.
- High-transform, low-shear, magnetic-well stabilized configurations with large helical excursions of the magnetic axis are being investigated by groups in Spain and Australia.

These programs will establish the relative importance of the different field properties and jointly produce a data base from which it will be possible to draw conclusions on optimal configurations.

Significant progress has been made in developing detailed theoretical pictures of equilibrium, stability, and transport properties. Together with the availability of more powerful codes and computers, this has increased the reliability of theoretical predictions. Experiments have been successful not only in achieving higher plasma parameters but also in extracting important information about the effects of shear, trapped particles, electric fields, resonances, and islands.

Economically viable methods for building the required coils (continuous and modular) and vacuum vessel, with the required precision, have been demonstrated by the construction of ATF and Wendelstein VII-AS. Most of these methods can be extrapolated to reactor conditions.

Three next-generation devices (Wendelstein VII-X in Garching, ATF-II in Oak Ridge, and the next large helical system of the MoE in Japan) that combine elements of the four lines of investigation are already being developed. These approaches extrapolate to reactor devices capable of ignited, steady-state, disruption-free operation at $\langle\beta\rangle \geq 5\%$.

ORNL/TM-10482
Dist. Category UC-20 a,d,f,g

INTERNAL DISTRIBUTION

1. L. A. Berry
2–11. B. A. Carreras
12. R. A. Dory
13. J. L. Dunlap
14. R. H. Fowler
15–24. J. H. Harris
25. H. H. Haselton
26. P. N. Haubenreich
27. S. P. Hirshman
28. R. C. Isler
29. T. C. Jernigan
30. M. S. Lubell
31–40. J. F. Lyon
41. P. K. Mioduszewski
42. O. B. Morgan
43. M. Murakami
44. G. H. Neilson
45. Y-K. M. Peng
46–55. J. A. Rome
56. M. W. Rosenthal
57. M. J. Saltmarsh
58. T. E. Shannon
59. J. Sheffield
60. D. W. Swain
61. P. B. Thompson
62–63. Laboratory Records Department
64. Laboratory Records, ORNL-RC
65. Document Reference Section
66. Central Research Library
67. Fusion Energy Division Library
68–69. Fusion Energy Division Publications Office
70. ORNL Patent Office

EXTERNAL DISTRIBUTION

71. Office of the Assistant Manager for Energy Research and Development, U.S. Department of Energy, Oak Ridge Operations Office, P. O. Box E, Oak Ridge, TN 37831
72. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706-1687
73. J. F. Clarke, Director, Office of Fusion Energy, Office of Energy Research, ER-50 Germantown, U.S. Department of Energy, Washington, DC 20545
74. R. W. Conn, Department of Chemical, Nuclear, and Thermal Engineering, University of California, Los Angeles, CA 90024
75. S. O. Dean, Fusion Power Associates, 2 Professional Drive, Suite 248, Gaithersburg, MD 20879
76. H. K. Forsen, Bechtel Group, Inc., Research Engineering, P. O. Box 3965, San Francisco, CA 94105
77. J. R. Gilleland, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550

78. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125
79. R. A. Gross, Plasma Research Laboratory, Columbia University, New York, NY 10027
80. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
81. M. Roberts, International Programs, Office of Fusion Energy, Office of Energy Research, ER-52 Germantown, U.S. Department of Energy, Washington, DC 20545
82. W. M. Stacey, School of Nuclear Engineering and Health Physics, Georgia Institute of Technology, Atlanta, GA 30332
82. D. Steiner, Nuclear Engineering Department, NES Building, Tibbetts Avenue, Rensselaer Polytechnic Institute, Troy, NY 12181
84. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India
85. Bibliothek, Max-Planck-Institut für Plasmaphysik, D-8046 Garching, Federal Republic of Germany
86. Bibliothek, Institut für Plasmaphysik, KFA, Postfach 1913, D-5170 Julich, Federal Republic of Germany
87. Bibliotheque, Centre de Recherches en Physique de Plasmas, 21 Avenue des Bains, 1007 Lausanne, Switzerland
88. F. Prevot, CEN/Cadarache, Departement de Recherches sur la Fusion Controlee, F-13108 Saint-Paul-lez-Durance Cedex, France
89. Bibliotheque, CEN/Cadarache, Departement de Recherches sur la Fusion Controlee, F-13108 Saint-Paul-lez-Durance Cedex, France
90. Library, Culham Laboratory, UKAEA, Abingdon, Oxfordshire, OX14 3DB, England
91. Library, FOM-Instituut voor Plasmafysica, Rijnhuizen, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands
92. Library, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan
93. Library, International Centre for Theoretical Physics, P.O. Box 586, I-34100 Trieste, Italy
94. Library, Laboratorio Gas Ionizatti, CP 56, I-00044 Frascati, Rome, Italy
95. Library, Plasma Physics Laboratory, Kyoto University, 611 Gokasho, Uji, Kyoto, Japan
96. Plasma Research Laboratory, Australian National University, P.O. Box 4, Canberra, A.C.T. 2000, Australia
97. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai Establishment, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
98. G. A. Eliseev, I. V. Kurchatov Institute of Atomic Energy, P. O. Box 3402, 123182 Moscow, U.S.S.R.
99. V. A. Glukhikh, Scientific-Research Institute of Electro-Physical Apparatus, 188631 Leningrad, U.S.S.R.

100. I. Shpigel, Institute of General Physics, U.S.S.R. Academy of Sciences, Ulitsa Vavilova 38, Moscow, U.S.S.R.
101. D. D. Ryutov, Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the U.S.S.R., Sovetskaya St. 5, 630090 Novosibirsk, U.S.S.R.
102. V. T. Tolok, Kharkov Physical-Technical Institute, Academical St. 1, 310108 Kharkov, U.S.S.R.
103. Library, Academia Sinica, P.O. Box 3908, Beijing, China (PRC)
104. R. A. Blanken, Experimental Plasma Research Branch, Division of Applied Plasma Physics, Office of Fusion Energy, Office of Energy Research, ER-542, Germantown, U.S. Department of Energy, Washington, DC 20545
105. K. Bol, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
106. R. A. E. Bolton, IREQ Hydro-Quebec Research Institute, 1800 Montee Ste.-Julie, Varennes, P.Q. JOL 2P0, Canada
107. D. H. Crandall, Experimental Plasma Research Branch, Division of Applied Plasma Physics, Office of Fusion Energy, Office of Energy Research, ER-542 Germantown, U.S. Department of Energy, Washington, DC 20545
108. R. L. Freeman, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
109. K. W. Gentle, RLM 11.222, Institute for Fusion Studies, University of Texas, Austin, TX 78712
110. R. J. Goldston, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
111. J. C. Hosea, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
112. S. W. Luke, Division of Confinement Systems, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20545
113. E. Oktay, Division of Confinement Systems, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20545
114. D. Overskei, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
115. R. R. Parker, Plasma Fusion Center, NW 16-288, Massachusetts Institute of Technology, Cambridge, MA 02139
116. W. L. Sadowski, Fusion Theory and Computer Services Branch, Division of Applied Plasma Physics, Office of Fusion Energy, Office of Energy Research, ER-541 Germantown, U.S. Department of Energy, Washington, DC 20545
117. J. W. Willis, Division of Confinement Systems, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20545
118. A. P. Navarro, Division de Fusion, Asociacion EURATOM/CIEMAT, Avenida Complutense 22, E-28040 Madrid, Spain

119. Laboratory for Plasma and Fusion Studies, Department of Nuclear Engineering, Seoul National University, Shinrim-dong, Gwanak-ku, Seoul 151, Korea
120. J. L. Johnson, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08544
121. L. M. Kovrizhnykh, Institute of General Physics, U.S.S.R. Academy of Sciences, Ulitsa Vavilova 38, 117924 Moscow, U.S.S.R.
122. O. Motojima, Plasma Physics Laboratory, Kyoto University, 611 Gokasho, Uji, Kyoto, Japan
123. V. D. Shafranov, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, U.S.S.R.
124. J. L. Shohet, Torsatron/Stellarator Laboratory, University of Wisconsin, Madison, WI 53706
125. H. Wobig, Max-Planck Institut fur Plasmaphysik, D-8046 Garching, Federal Republic of Germany
126. N. A. Davies, Office of Fusion Energy, Office of Energy Research, ER-51 Germantown, U.S. Department of Energy, Washington, DC 20545
127. W. F. Dove, Office of Fusion Energy, Office of Energy Research, ER-543 Germantown, U.S. Department of Energy, Washington, DC 20545
128. R. J. Dowling, Office of Fusion Energy, Office of Energy Research, ER-53 Germantown, U.S. Department of Energy, Washington, DC 20545
129. D. Markevitch, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20545
130. D. B. Nelson, Office of Fusion Energy, Office of Energy Research, ER-54 Germantown, U.S. Department of Energy, Washington, DC 20545
131. T. K. Chu, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08544
132. H. Furth, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08544
133. P. Rutherford, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08544
134. W. Stodiek, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08544
135. G. Grieger, Max-Planck-Institut für Plasmaphysik, D-8046 Garching bei München, Federal Republic of Germany
136. F. Rau, Max-Planck-Institut für Plasmaphysik, D-8046 Garching bei München, Federal Republic of Germany
137. H. Renner, Max-Planck-Institut für Plasmaphysik, D-8046 Garching bei München, Federal Republic of Germany
138. A. Iiyoshi, Plasma Physics Laboratory, Kyoto University, 611 Gokasho, Uji, Kyoto, Japan
139. K. Uo, Plasma Physics Laboratory, Kyoto University, 611 Gokasho, Uji, Kyoto, Japan

140. M. Wakatani, Plasma Physics Laboratory, Kyoto University, 611 Gokasho, Uji, Kyoto, Japan
141. M. Fujiwara, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan
142. H. Ikegami, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan
143. T. Uchida, Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan
144. O. Pavlichenko, Kharkov Physico-Technical Institute, 310108 Kharkov, U.S.S.R.
145. R. Davidson, Plasma Fusion Center, Massachusetts Institute of Technology, NW16-202, 167 Albany St., Cambridge, MA 02139
146. I. N. Sviatoslavsky, Fusion Technology Institute, 529 Engineering Research Building, 1500 Johnson Drive, Madison, WI 53706-1687
147. D. T. Anderson, Torsatron/Stellarator Laboratory, 1420 Engineering Building, 1415 Johnson Drive, Madison, WI 53706
148. H. Weitzner, Courant University of Mathematical Sciences, New York University, 251 Mercer Street, New York, NY 10012
149. P. R. Garabedian, Courant University of Mathematical Sciences, New York University, 251 Mercer Street, New York, NY 10012
150. K. B. Kartashev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, U.S.S.R.
151. G. H. Miley, 216 Nuclear Engineering Laboratory, University of Illinois, 103 S. Goodwin Avenue, Urbana, IL 61801
152. D. G. Swanson, Department of Physics, Auburn University, College Street, Auburn, AL 36849
153. F. L. Ribe, 319 Benson Hall, BF 10, University of Washington, 1400 Northwest Campus Parkway, Seattle, WA 98195
154. R. K. Linford, Controlled Thermonuclear Research Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
155. T. K. Fowler, L-640, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
156. D. E. Baldwin, L-640, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
157. A. J. Wootton, Fusion Research Center, RLM 11.222, The University of Texas at Austin, Austin, TX 78712
158. H. L. Berk, Institute for Fusion Studies, RLM 11.222, The University of Texas at Austin, Austin, TX 78712
159. T. Ohkawa, Fusion and Advanced Technologies, GA Technologies, Inc., P.O. Box 85608, San Diego, CA 92138
160. S. M. Hamberger, Plasma Research Laboratory, Research School of Physical Sciences, Australian National University, P.O. Box 4, Canberra, A.C.T. 2600, Australia

161. A. H. Boozer, Physics Department, College of William and Mary, Williamsburg, VA 23185
162. Library, JET Joint Undertaking, Abingdon, Oxon OX14 3EA, England
163. Library, Japan Atomic Energy Research Institute, Naka, Japan
164. Bibliothek, Kernforschungszentrum Karlsruhe GmbH, Postfach 3640, D-7500 Karlsruhe 1, Federal Republic of Germany
165. T. C. Hender, Culham Laboratory, UKAEA, Abingdon, Oxfordshire, OX14 3DB, England
166. A. Gran Malonda, Division de Fusion, Asociacion EURATOM/CIEMAT, Avenida Complutense 22, E-28040 Madrid, Spain

167–301. Given distribution as shown in TIC 4500, Magnetic Fusion Energy (Distribution Category UC20 a,d,f,g: Plasma Systems, Fusion Systems, Experimental Plasma Physics, Theoretical Plasma Physics)