CONF-811046--3

LA-UR-81-2878

TITLE: THE MODULAR STELLARATOR FUSION REACTOR (MSR) CONCEPT

MASTER

AUTHOR(S): R. L. Miller and R. A. Krakowski

SUBMITTED TO: 3rd IAEA Technical Committee and Workshop on Fusion Reactor Design and Technology
October 5-16, 1981
Tokyo, Japan

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

Technical Committee Meeting and Workshop
International Atomic Energy Agency Technical
Committee Meeting and Workshop on Fusion Reactor
Design and Technology
Tokyo, Japan (October 5-16, 1981)

THE MODULAR STELLARATOR FUSION REACTOR (MSR) CONCEPT

R. L. Miller, R. A. Krakowski
University of California
Los Alamos National Laboratory
Los Alamos, New Mexico
United States of America

THE MODULAR STELLARATOR FUSION REACTOR (MSR) CONCEPT

Abstract

A preliminary conceptual study has been made of the Modular Stellarator Reactor (MSR) as a steady-state, ignited, DT-fueled, magnetic fusion reactor. The MSR concept combines the physics of classic stellarator confinement with an innovative, modular-coil design. Parametric tradeoff calculations are described, leading to the selection of an interim design point for a 4.8-GWt plant based on Alcator transport scaling and an average beta value of 0.04 in an $\ell = 2$ system with a plasma aspect ratio of 11. Neither an economic analysis nor a detailed conceptual engineering design is presented here, as the primary intent of this scoping study is the elucidation of key physics tradeoffs, constraints, and uncertainties for the ultimate power-reactor embodiment.

1. INTRODUCTION

The status and history of the stellarator approach to magnetic confinement has been variously reviewed [1-4]. The term "stellarator" is used generically to describe those toroidal devices that produce closed magnetic surfaces by means of external conductors. The stellarator represents one of the earliest magnetic confinement concepts to receive attention [5,6] as a commercial fusion power reactor. Unlike the tokamak, the nonaxisymmetric stellarator achieves equilibrium by externally inducing a rotational transform in the confining magnetic field. Ideally, no axial current need be supported by the plasma column, as is required in a tokamak, although, until recently, stellarator experiments utilized such currents for Ohmic heating. Early calculations [7,8] for toroidal stellarator reactors indicated the related potential problems of low power density, large power output, and high magnet costs. These early survey studies were overshadowed by discouraging physics results for stellarators, anticipated force/stress problems for helical coils, and concurrent progress in tokamak confinement. As a result, reactor interest in the stellarator waned.

More recently consideration of the torsatron [9] reactor using relatively "force-free" helical coils [10] eliminated the toroidal-field (TF) coil set; when coupled with new understanding of stellarator/torsatron physics, more recent interest has been generated in this truly steady-state device as a reactor [10-12]. At the same time, the potential for moderate power output ($\lesssim$ 5 GWt) was emphasized [10]. Recognition that the helical coils can be eliminated in favor of TF coils that have been subjected to a periodic, lateral distortion has given the stellarator the promise of greater and more realistic system modularity [13].

Such a modular-coil configuration allows more optimally oriented coil forces and lower coil stresses for the Modular Stellarator Reactor (MSR). The simplest approach is a sinusoidal deformation [13], although alternative winding laws are possible and may prove advantageous. Figure 1 illustrates the coil layout for a typical $\ell = 2$, $m = 8$ MSR configuration composed of $N = 24$ modular coils; $N/m = 3$ coils per field period results with a lateral coil deformation characterized by $d/r_c = 0.3$. The modular approach has heighted interest in the stellarator reactor, a renaissance that coincides with recent experimental success in heating a low Ohmic-current device [14].

Qualitative advantages that in general have been invoked for the stellarator/torsatron reactor concept include:

- Steady-state magnetic fields and thermonuclear burn.
- Operation at ignition or with a high Q-value for low recirculating power.
- Plasma startup on existing magnetic surfaces with predictable particle and energy confinement at all times.
- Impurity and ash removal by means of a magnetic limiter and helical poloidal divertor that occur as natural consequences of the magnetic confinement topology.
- Evidence of operation without major plasma disruptions that could lead to an intense, local energy deposition on the first wall or in the blanket, shield, or coil regions.
- No auxiliary positioning or field-shaping coils and moderate plasma aspect ratio ($\gtrsim 10$), both of which ease maintenance access.

These advantages remain to be quantified in the context of a comprehensive reactor study that self-consistently incorporates crucial physics issues (e.g., scaling of beta with aspect ratio and the required or optimal rotational transform, magnetic shear, and magnetic-well depth), engineering constraints (e.g., coil design, stresses, accessibility, and maintenance), and economics (e.g., power density, size, and capital and energy costs). Although the more recent torsatron and modular-coil configurations show strong promise in alleviating the historic stellarator coil problem *per se*, a measure of coil performance has been retained as a major element in the present reactor survey and systems analysis [15].

2. PHYSICS BASIS

The MSR concept is characterized by a point plasma model that determines the self-consistent parameters of an ignited, steady-state, DT thermonuclear burn. The alpha-particle energy trapping efficiency, is taken as $f_\alpha = 0.88$ for a plasma aspect ratio, $A = 11$, following separate numerical computations [16]. The radial transport loss is expressed conveniently in terms of the Lawson parameter, $\langle n_e \rangle \tau_E (s/m^3)$, where $\langle n_e \rangle (m^{-3})$ is the average electron density. The $\langle n_e \rangle \tau_E$ parameter for ignited systems as a function of the average plasma temperature, $\langle T \rangle$, exhibits a shallow minimum at ~ $2(10)^{20}$ s/m^3 near $\langle T \rangle = 20$ keV. MSR operation is characterized parametrically by solving the ignition condition and pressure balance equation subject to reactor design goals and conservative engineering constraints.

2.1. Transport Scaling

Radial transport ($\tau_E \propto r_p^2/D$) of energy in a nonaxisymmetric stellarator/torsatron plasma is presently is receiving theoretical attention [17-20]. At this level of study, however, the reactor-survey calculations are performed using simplified, empirical or theoretical models in order that sensitive variables and tradeoffs can be more directly identified.

The Alcator (empirical) transport scaling used here is given by [10]

$$\langle n_e \rangle \tau_{E(Alcator)} = 3.0(10)^{-21} \langle n_e \rangle^2 r_p^2 \quad ,$$

where r_p(m) is the average plasma radius, and is a factor 3/5 more pessimistic than the scaling used typically for tokamaks. Regardless of the details of the particular scaling relationship used, this survey suggests that the transport in a stellarator/torsatron reactor will have to be at least as good as that predicted by this Alcator scaling if the reactor is to be competitive. A more detailed elaboration of transport scaling relationships is presented in Ref. [15], including a quantitative comparison between Alcator, Bohm-like, and neoclassical transport scalings. The issue of transport is central to a selection of a credible MSR design point.

2.2. Plasma Beta Scaling

It is widely recognized that the primary difficulty of the stellarator/torsatron as a reactor may be the relatively low attainable values of beta. Equilibrium and stability considerations impose upper limits on beta and thereby constrain the reactor to limited regimes of plasma aspect ratio, $A = R_T/r_p$. In addition, the beta limits are coupled to the magnetics performance through the rotational transform, ι, produced by the vacuum-magnetic-field topology and follow directly from the coil configuration. For the purposes of this study, a simplified equilibrium/stability relationship between $\langle \beta \rangle$, m, A, ℓ, and ι is enforced in order to maintain a direct coupling between plasma performance (i.e., $\langle \beta \rangle$) and reactor feasibility (i.e., coil-set configuration needed to generate the ι required to achieve a given $\langle \beta \rangle$). These considerations are discussed in greater detail in Ref. [15]. It is recognized, however, that should difficulties be encountered in achieving "acceptable" rotational transforms for a given coil configuration (i.e., d/r_c, ℓ, m, N, etc.), these imposed $\langle \beta \rangle$ versus m, ℓ, and A constraints must be re-examined.

As described in Ref. [15], however, these limits are based conservatively on the assumption that diffusion-driven currents establish both equilibrium (i.e., Pfirsch-Schlüter shift) and stability (i.e., Kruskal-Shafranov modes) constraints. Ongoing theoretical effort is aimed at providing more reliable beta scaling relationships. It is emphasized that maximum beta value for stellarator/torsatrons is intimately associated with coil configuration and magnet design (i.e., A, d/r_c, coil interference, current density, forces, etc.). For this reason, an approximate but analytically self-consistent model was used to relate $\langle\beta\rangle$ to such parameters as ℓ, m, d/r_c, and A, rather than to dictate a value of beta, in order to preserve this close coupling between plasma performance, coil design, and reactor design.

2.3. Selection of Stellarator Physics Parameters

Implementation of equilibrium/stability constraints, that are based on diffusion-driven currents determining upper bounds on $\langle\beta\rangle$, allows a narrowing of attention to $\ell = 2$ systems with $m = 6$ or 8, as seen in Fig. 2. Such systems tend to maximize $\langle\beta\rangle$ under the simultaneous application of the equilibrium limit as well as both the ideal and resistive stability limits at convenient plasma aspect ratios. The attainable value of $\langle\beta\rangle \simeq 0.04$ at $A = 11$ is anticipated to be marginally acceptable from the reactor viewpoint. This beta value is comparable to the value of 0.035 proposed for the T-1 torsatron conceptual reactor design [10], albeit the latter is at a higher aspect ratio (~ 12.5). The next consideration is the positioning of the maximum separatrix radius, r_s, relative to the coil radius, r_c. If r_s is near the first-wall radius, r_w, the overall configuration is compatible with the magnetic-divertor impurity control usually associated with the stellarator/torsatron. However, if $r_s \simeq r_c$, the plasma radius, r_p, must still be constrained by r_w such that not all of the available closed magnetic surfaces are occupied by plasma. This implies a limiter near the first wall to provide plasma-boundary control. Collateral benefits include a lower required rotational transform and higher volume utilization within the first-wall radius. In addition, if $r_s \simeq r_c$, lower valves of coil distortion, d/r_c, are required to achieve a desired value of rotational transform. Lower values of coil distortion are more likely to avoid neighboring coil interference for a given reactor aspect ratio and number of modular coils, N. Numerical magnetics calculations of flux surfaces and rotational transform profiles indicate that $N/m = 3$ coils per field period may be adequate [15,21], leading to $N = 18$ modular coils in an $m = 6$ system.

The quantity $\langle\sigma v\rangle/T^2$ for the DT reaction is constant to within 10% for temperatures in the range of 8-20 keV. Hence, $\langle\beta\rangle^{1/2}B_o$ is a weak function of $\langle T\rangle$ for Alcator transport scaling. If the parameter $\langle\beta\rangle^{1/2}B_o$ is essentially constant, a higher allowed value for B_o can compensate a lower value of $\langle\beta\rangle$ to give equivalent overall reactor performance. An MSR with higher aspect ratio than allowed in an otherwise comparable tokamak reactor, therefore, can tolerate and remain competitive with higher values of B_o and correspondingly lower values of $\langle\beta\rangle$, for a commonly imposed limit on maximum magnetic field strength, $B_c(T)$, on the inboard side of the TF coils. The value of $\langle\beta\rangle \approx 0.04$ allowed for the MSR, therefore, may compare favorably with the value of $\langle\beta\rangle \approx 0.067$ used in the Starfire tokamak conceptual design study [22].

The MSR design point is not selected to minimize the required Lawson parameter, rather, the related parameter grouping, $\langle\beta\rangle B_o^2 r_p$. The interim MSR design point at $\langle T\rangle = 8$ keV is near the minimum of this latter parameter.

2.4. Selection of Thermal Power and First-Wall Neutron Loading

Figure 3 depicts curves of the on-axis magnetic field, B_o, required for ignited MSR operation as a function of $\langle T\rangle$ for the indicated conditions and a range of neutron first-wall loadings, I_w, and total thermal power output, P_{TH}. As I_w increases, the required value of B_o also increases, the plasma radius, r_p, decreases, and B_o must increase to restore the confinement time required for ignition. If B_o is constrained below a maximum value determined by magnet technology, I_w may be limited to a relatively low value. Also, higher values of B_o require larger coil cross sections when the coil current density, j (MA/m^2), is fixed, and more highly distorted coils are more likely to interfere with neighboring coils in a fixed-aspect-ratio device. Larger power systems require larger volumes of reacting plasma (i.e., larger values of r_p) and, because the Lawson parameter for ignition is proportional to B_o^4 for fixed temperature and beta, lower values of B_o are required.

Imposition of a fixed upper limit on B_o, as dictated by magnet technology, and an upper limit on $\langle\beta\rangle$, from equilibrium and stability considerations, therefore, constrains the MSR to operate above nominal minimum thresholds in total thermal output and corresponding physical size. At the same time it is difficult to increase I_w without resulting in excessively large values of B_o in this low-beta device.

2.5. Interim Design-Point Selection

The results of parametric modeling have been used [15] to examine the MSR parameter space quantitatively and to examine tradeoffs among the several key parameters. In this section attention is narrowed to the identification of an interim MSR design point that serves as the basis for review, evaluation, and a more detailed engineering design. The MSR design point suggested on Table I has a physical size that is sufficient to satisfy the coil-interference constraint while not producing an excessively large power output. The MSR thermal power output is $P_{TH} = 4.8$ GWt, which is ~ 20% higher than the Starfire tokamak [22] and EBTR [23] conceptual designs. The MSR design point proposed here on the basis of generally conservative assumptions represents a potentially attractive system of moderate size and favorable performance. The key limiting parameter is the marginally acceptable maximum allowable value of beta.

As stated previously, a major goal of this scoping study was to relate the results of simple plasma and magnetics calculations to the engineering requirements of the modular coils. Results from three-dimensional magnetics computations for this design point, have been made. The dominant mean force (~ 90 MN) component is directed radially outward and can be supported externally. The lateral force component (~60 MN) acts to increase the lateral deformation of the modular coil. There exists a net centering force which can easily be supported by structure in the hole of the torus. The corresponding mean stress is estimated analytically to be ~ 240 MPa (~ 36 kpsi). Consequently, the modular-coil system proposed for this interim design point appears to satisfy basic mechanical and stress design criteria while meeting approximate constraints for modularity, accessibility, maintainability, and manufacturability for a coil set that can be assembled and operated at a conservative overall coil current density (~ 13 MA/m^2).

3. REACTOR LAYOUT AND OPERATION

3.1. Preliminary Indications of Reactor Configuration

The MSR design point assumes steady-state, ignited operation. Except for startup power requirements, therefore, an ignited burn implies operation with low recirculating power beyond that required for auxiliary power uses. Steady-state operation without plasma disruptions can be expected to minimize thermal cyclic fatigue of reactor components. Modularity of the coil set allows exo-reactor testing of components to improve reliability and to assure more rapid change-out in the event of coil failure.

Figure 4 illustrates a schematic layout of the MSR module. The coils are supported against the net centering forces by leaning against a solid central core. Gimballed supports at the top and bottom of the coil are indicated. Modularity for the MSR may imply the ability to remove and to replace efficiently a single coil (mass ≈ 325 tonnes) with minimal disturbance to the neighboring coils. An additional desirable feature in promoting high plant availability would be the ability to replace blanket and shield modules without moving the coils. In the worst case the unit module would consist of a single modular coil with the blanket and shield modules situated within; the total mass of the integrated module would be ~ 1900 tonnes. Removal of modules would entail decoupling of the support structure at the gimbal mounts followed by a radially outward translation. Although not yet investigated in detail, access for vacuum, fueling, electrical leads, and coolant pipes in this moderate-aspect-ratio device appears straightforward and flexible. One option would be to concentrate all access requirements into wedge-shaped submodules (Fig. 4) that would serve as interfaces between right-circular-cylindric coil, blanket, and shield modules. The wedge-shaped region could itself be considered a moveable module or could be fixed to an adjacent coil/blanket and shield module. The wedge-shaped region would contain the pumped-limiter impurity-control mechanism and all heating/fueling/vacuum/coolant penetrations and external connections.

An electric generating plant with a total thermal power output, P_{TH} = 4.8 GWt, will produce a gross electric power output, P_{ET} = 1.68 GWe, for a nominal thermal conversion efficiency, η_{TH} = 0.35. A fraction, f_{AUX}, of the gross electric power must be recirculated within the plant to drive auxiliary systems such as coil refrigeration, vacuum systems, and coolant pumps. An allowance [22] of f_{AUX} = 0.08 for these purposes in an ignited MSR systems leaves a net power output of P_E = 1.53 GWe. No unique requirements for the balance of plant (BOP) are anticipated, although, again, detailed conceptual design of key MSR systems remains to be performed.

3.2. Preliminary Consideration of Reactor Operation

The uniqueness of the stellarator/torsatron approach rests with the generation of the full magnetic-field topology solely by external electrical conductors. Plasma startup would be achieved along an increasing temperature/density trajectory on existing, relatively unperturbed field lines. The nature of the transport scaling during the low-density initiation and subsequent density buildup to an ignited burn will impact the operating mode, in that the delivery systems for the startup power can affect the reactor design while not necessarily impacting the steady-state energy balance *per se*.

When combined with a goal of generating electricity at power levels of approximately 1 GWe with a fusion-neutron first-wall loading of $\gtrsim$ 1-2 MW/m^2, the stability and equilibrium scaling of beta and plasma aspect ratio used for stellarator/torsatron reactors generally leads to plasma densities of ~ $1.5(10^{20})$ m^{-3}, moderate temperatures (8-15 keV), and large minor radii (~ 2 m). For these conditions, edge refueling is not possible and high-velocity (> 10^4 m/s) pellet injectors may be needed. No obstacles to plasma fueling by means of pellet injection and impurity and ash removal by means of either a magnetic divertor or a pumped limiter have been identified in this study. Although the former approach can be a natural consequence of the stellarator/torsatron magnetic-field topology, the engineering convenience and feasibility of extracting open field lines to an adequately engineered divertor plate and vacuum region depends crucially on the coil configuration. Furthermore, location of the separatrix at or near the coil, rather than within the vacuum first wall, may offer some advantage in maximizing the plasma volume utilization within the first wall and minimizing the complexity of the blanket and shield design. Hence, the use of pumped limiters *versus* (natural) magnetic divertors appears strongly dependent upon the specific stellarator/torsatron configuration and remains to be fully quantified.

4. SUMMARY AND CONCLUSIONS

This survey study of the MSR is the first phase of an assessment that quantifies parametrically the reactor potential for this innovative coil concept where appropriate performance goals and constraints have been imposed. On the basis of generally conservative assumptions, but without supporting economic analyses, the interim design point appears to be competitive with other approaches to magnetic fusion. The following major conclusions are drawn from this study.

- Marginally attractive values of average beta, as allowed by approximate and self-consistently applied equilibrium and stability limits, are a key limiting factor in MSR performance. The stability and equilibrium beta limits used in this study are based on a simplified theory of diffusion-driven (toroidal) currents and may represent conservatively low bounds on beta.
- Application of other conservative assumptions and constraints related to alpha-particle effects and coil current density still allows the identification of potentially attractive MSR design points with moderate power output ($P_{TH} \leq 5$ GWt), while self-consistently meeting key stellarator physics constraints in modular engineering configurations with maintenance and reliability advantages.
- Preliminary magnetics and coil-stress computations indicate MSR systems can be constructed with manageable structural requirements and accessibility. This coil design used as an engineering model for this study, however, falls short by a factor of ~ 2 in producing the transform predicted to be necessary on the basis of simplified theories of equilibrium/stability beta limits. Approaches to resolve this issue are discussed in Ref. [15].
- A pumped-limiter impurity-control scheme may improve MSR performance over that with a magnetic divertor that is traditionally associated with the stellarator/torsatron configuration. A detailed tradeoff study of the feasibility and problems of leading open field lines to a divertor plate <u>versus</u> the advantage of higher plasma filling fraction and uncertainties associated with the pumped-limiter approach remains to be performed, however.
- The MSR survey study is based on the applicability of Alcator (empirical) transport scaling, which was shown to give an energy confinement time that is a factor of ~ 60 greater than Bohm like transport, a factor of ~ 2 greater than neoclassical-plateau scaling, and a factor of ~ 10 less than classical transport. The level of energy loss predicted by Alcator scaling is viewed as an upper bound for MSR system viability.

REFERENCES

[1] SPITZER, JR., L., "The Stellarator Concept," Phys. of Fluids 1, 253-264 (July-August 1958).

[2] MIYAMOTO, K., "Recent Stellarator Research," Nucl. Fus. 18, 243-284 (1978).

[3] SHAFRANOV, V. D., "Stellarators," Nucl. Fus. 20, 1075-1083 (1980).

[4] Joint US-EURATOM Steering Committee on Stellarators, "Stellarators-Status and Future Directions," Max Planck Institut für Plasmaphysik report IPP-2/254 (July 1981).

[5] SPITZER, L., GROVE, D., JOHNSON, W., TONKS, L., WESTENDORP, W., "Problems of the Stellarator as a Useful Power Source," USAEC report NYO-6047 (1954).

[6] MILLS, R. G., "Economic Prospects for Thermonuclear Reactors," Princeton Plasma Physics Laboratory report MATT-60 (February 1961).

[7] GIBSON, A., "Permissible Parameters for Economic Stellarator and Tokamak Reactors," Proc. BNES Nucl. Fusion Reactor Conf. at Culham Laboratory, 233-241 (September 1969).

[8] GIBSON, A., HANCOX, R., BICKERTON, R. J., "Economic Feasibility of Stellarator and Tokamak Fusion Reactors," Proc. 4th Inter. Conf. on Plasma Phys. and Controlled Nucl. Fus. Research, IAEA-CN-28/K-4, III, 375-392 (June 17-23, 1971).

[9] GOURDON, C., MARTY, D., MASCHKE, E. K., TOUCHE, J., "The Torsatron without Toroidal Field Coils as a Solution of the Divertor Problem," Nucl. Fus. 11, 161-166 (1971).

[10] POLITZER, P. A., LIDSKY, L. M., MONTGOMERY, D. B., "Torsatrons and the TOREX Proof of Principle Experiment," Massachusetts Institute of Technology report PFC/TR-79-1 (March 1979).

[11] IIYOSHI, A., UO, K., "Heliotron as a Steady Fusion Reactor," Proc. 5th Inter. Conf. on Plasma Phys. and Controlled Nucl. Fus. Research, IAEA-CN-33/G4, III, 619-630 (November 11-15, 1974).

[12] GEORGIEVSKII, A. V., LOKTIONOV, YU. M., SUPRUNENKO, V. A., "Characteristics of a Hypothetical Thermonuclear Stellarator Reactor in the 'Plateau' Regime," Kharkhov Physico-Technical Institute report KhFTI 76-38 (1976) [English Translation in UKAEA Culham Laboratory report CTO/1299 (November 1976)].

[13] WOBIG, W., REHKER, S., "A Stellarator Coil System without Helical Windings," Proc. 7th Symp. on Fus. Technol , Grenoble, France, 333-343 (October 24-27, 1972).

[14] BARTLETT, D. V., CANNICI, G., GATTANEI, G., DORST, D., GRIEGER, C., HACKER, H. H., et al., "Neutral Injection in the Wendelstein VII-A Stellarator with Reduced Ohmic Current," Proc. 8th Inter. Conf. on Plasma Phys. and Controlled Nucl. Fus. Research, IAEA-CN-38/H-2-2 (July 1-10, 1980).

[15] MILLER, R. L., KRAKOWSKI, R. A., "The Modular Stellarator Fusion Reactor Concept," Los Alamos National Laboratory report LA-8978-MS (August 1981).

[16] POTOK, R. E., "Particle Orbits and Diffusion in Torsatrons," Ph.D. thesis, Massachusetts Institute of Technology (May 1980).
[17] SHOHET, J. L., "Transport in Toroidal Stellarators and Torsatrons," Comments Plasma Phys. 5, 55-67 (1979).
[18] POTOK, R. E., POLITZER, P. A., LIDSKY, L. M., "Ion Thermal Conductivity in a Helical Toroid," Phys. Rev. Letters 45, 1328-1331 (October 20, 1980).
[19] MYNICK, H. E., "Verification of the Classical Theory of Helical Transport in Stellarators," Princeton Plasma Physics Laboratory report PPPL-1781 (April 1981).
[20] BOOZER, A. H., KUO-PETRAVIC, G., "Monte Carlo Evaluation of Transport Coefficients," Phys. of Fluids 24, 851-859 (May 1981).
[21] CHU, T. K., FURTH, H. P., JOHNSON, J. L., LUDESCHER, C., WEIMER, D. E., "Modular Coils: A Promising Toroidal Reactor Coil System," Princeton Plasma Physics Laboratory report PPPL-1796 (April 1981).
[22] BAKER, C. C., et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," Argonne National Laboratory report ANL/FPP-80-1 (September 1980).
[23] BATHKE, C. G., et al., "ELMO Bumpy Torus Reactor and Power Plant Conceptual Design Study," Los Alamos National Laboratory report LA-8882-MS (August 1981).

TABLE I
INTERIM MSR DESIGN PARAMETERS

Stellarator Parameters	
Poloidal field periods, ℓ	2
Toroidal field periods, m	6
Rotational transform, ι	0.66
Average plasma radius, r_p(m)	2.11
Major radius, R_T(m)	23.24
Plasma aspect ratio, $A = R_T/r_p$	11.0
Average separatrix radius, r_s(m)	4.48 (~ r_c)
Plasma Parameters	
Radial pressure profile index, ν	3
Average temperature, $\langle T\rangle$(keV)	8.0
Average density, $\langle n_i\rangle(10^{20}/m^3)$	1.50
Average beta, $\langle\beta\rangle$	0.04
Energy confinement time, τ_E(s)	2.5
Lawson parameter, $\langle n_c\rangle\tau_E(10^{20}s/m^3)$	3.7
On-axis magnetic field, B_o(T)	6.0
Plasma power density, $p_F(MWt/m^3)$	2.3
Alpha-particle loss fraction, $1-f_\alpha$	0.12
Alpha-particle partial pressure, P_α/P	0.25
Scrape-off parameter, $x = r_p/r_w$	0.71
Effective charge, $Z_{eff}(n_\alpha/n_i = 0.056)$	1.1
Magnet Parameters	
Number of coils, N(m = 6, ℓ = 2)	18
Coils per field period, N/m	3
Average coil radius, r_c(m)	5.40
Coil aspect ratio, R_T/r_c	4.30
Coil current, I_c(MA)	44.2
Coil current density, $j_c(MA/m^2)$	12.9
Coil lateral distortion, d/r_c	0.4
Coil thickness and width, δ_c(m)	1.85
Peak field at conductor, B_c(T)	~11
On-axis magnetic field, B_o(T)	6.0
Coil volume/mass (m^3/tonne)	130./325.
Stored magnetic energy, E_M(GJ)	~200
Reactor Parameters	
First-wall radius, r_w(m)	2.98
Plasma volume, $V_p(m^3)$	2050.
Neutron first-wall loading, $I_w(MW/m^2)$	1.3
System power density, $p_s(MWt/m^3)$	0.26
Blanket/shield thickness, Δb(m)	1.5
Blanket energy multiplication, M_N	1.1
Total thermal power, P_{TH}(GWt)	4.8
Thermal conversion efficiency, η_{TH}	0.35
Recirculating power fraction, ε	0.08
Net electric power, P_E(GWe)	1.53

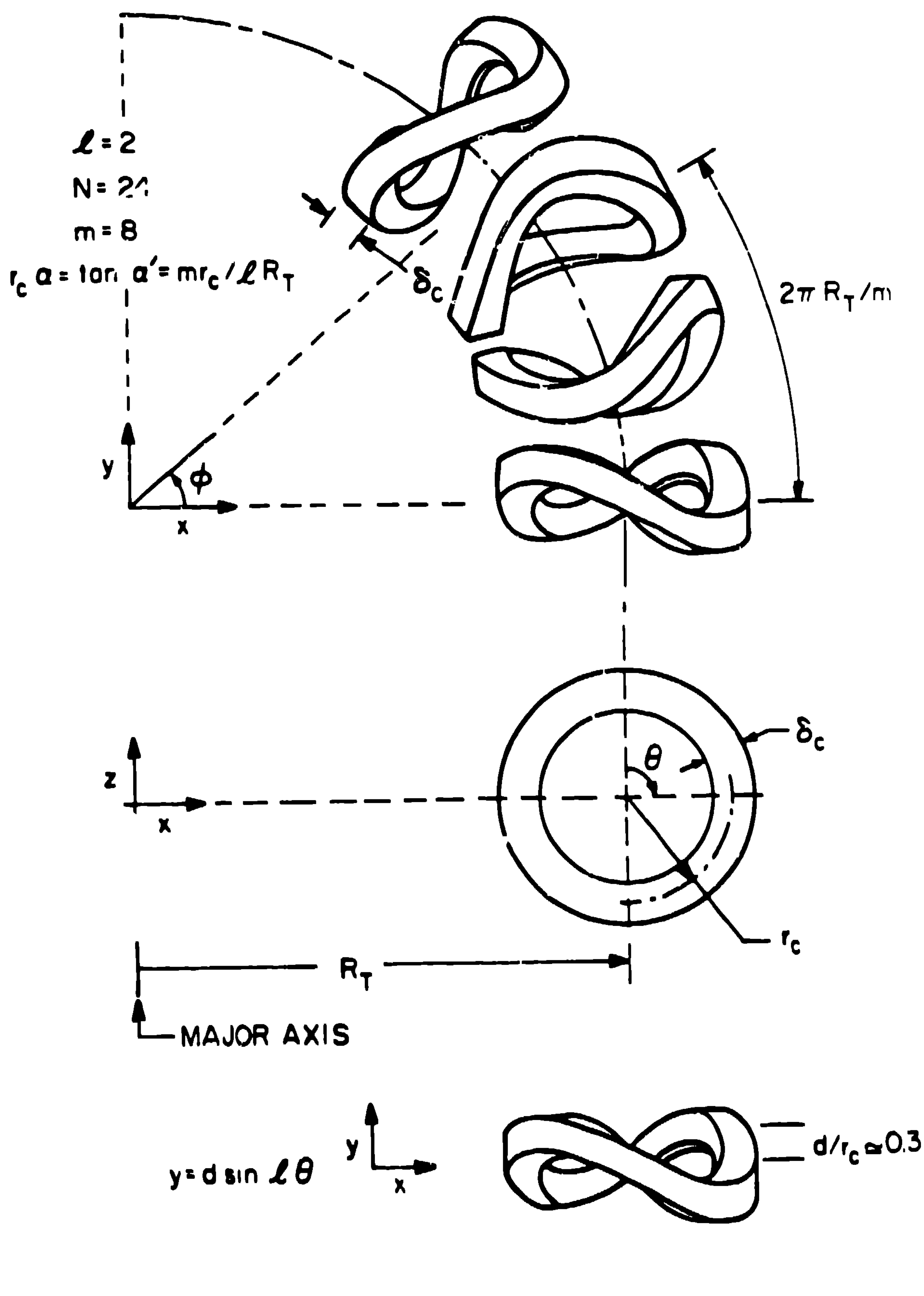
Figure 1. Coil layout for a typical $\ell = 2$ MSR configuration. In this case, $m = 8$, $d/r_c = 0.3$, $N = 24$, and $N/m = 3$ coils per field period. The finite cross-section coils include internal support structure and thermal insulation.

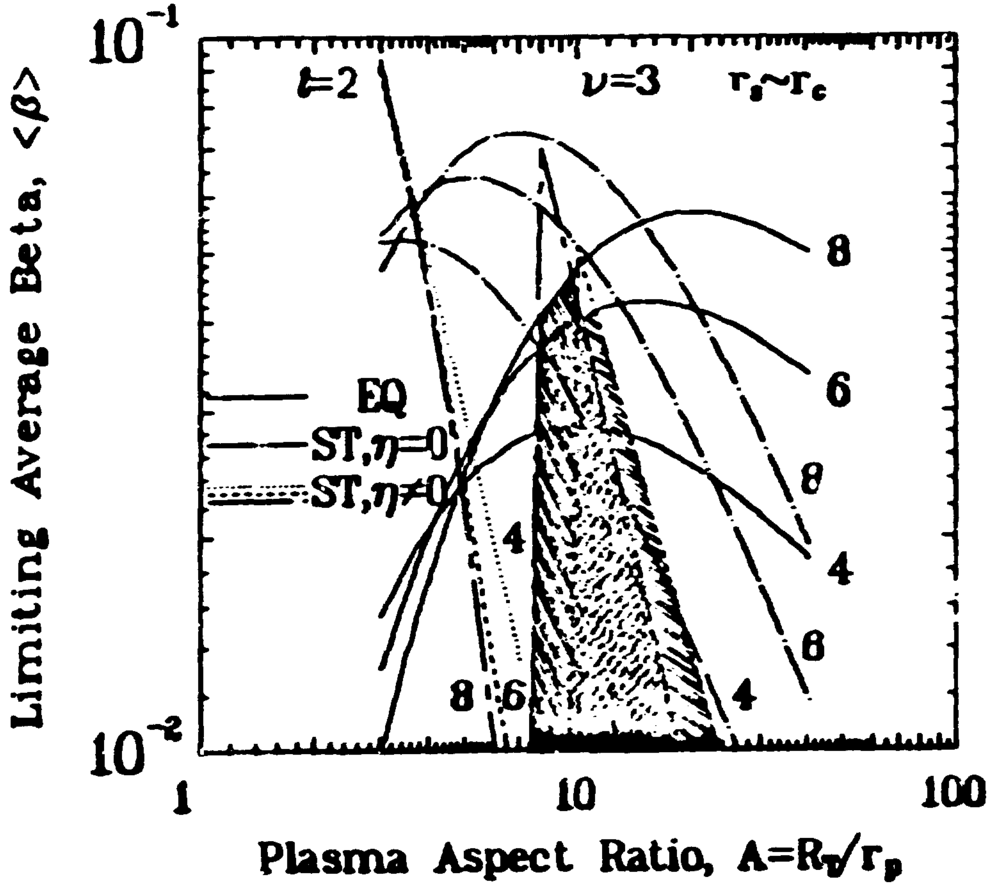
Figure 2. Dependence of combined equilibrium and stability limits on $\langle\beta\rangle$ as a function of plasma aspect ratio, $A = 1/\epsilon = R_T/r_p$, for various values of m for a fixed radial profile index, $\nu = 3$. The $r_s = r_c$ case (implying pumped-limiter impurity control) yields higher $\langle\beta\rangle$ values at a convenient plasma aspect ratio, $A = 11$, than the $r_s = r_w$ case (implying mangetic-divertor impurity control).

Figure 3. Dependence of on-axis magnetic field, B_o on the average plasma temperature, $\langle T\rangle$, required for ignited MSR operation for the indicated values of the ratio $P_{TH}(MW)/I_w(MW/m^2)$ and corresponding plasma radii, $r_p(m)$, for the indicated fixed parameters.

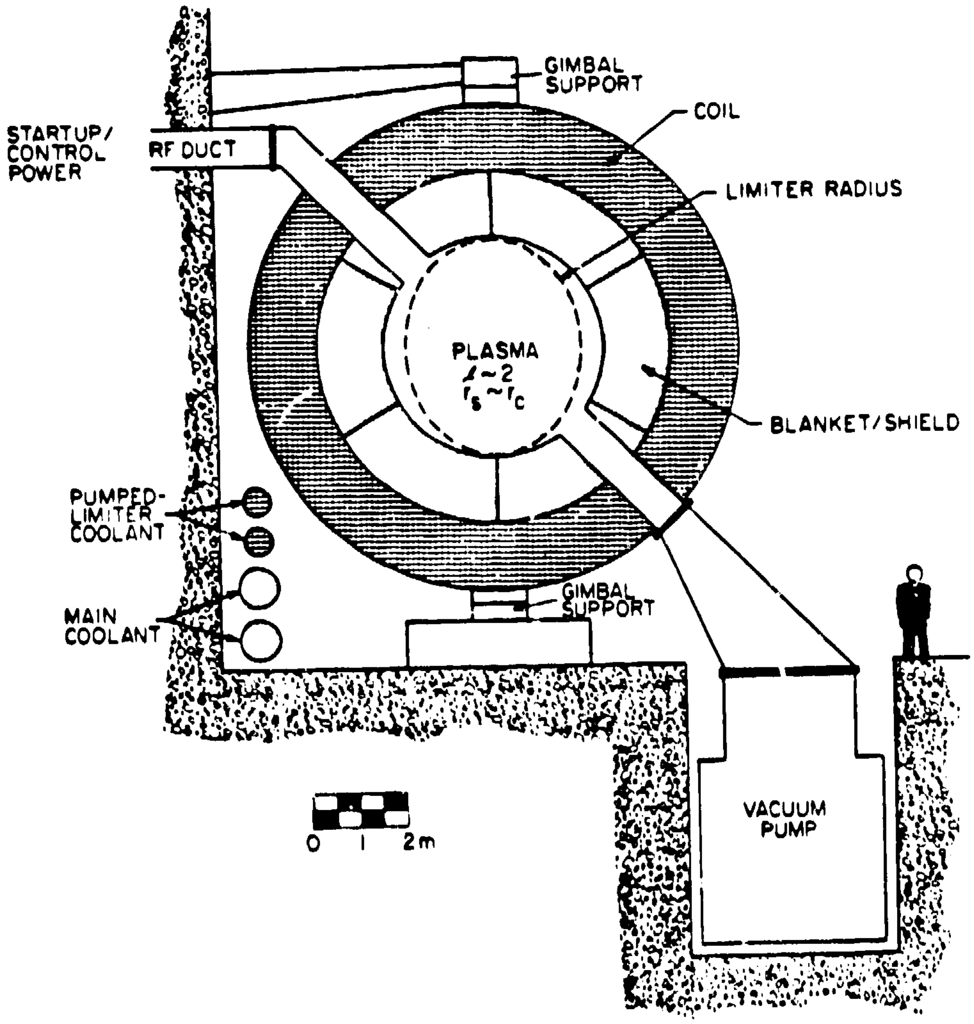
Figure 4. Preliminary reactor layout based on the interim MSR design point for use in examining coil support structure and intercoil forces. Elevation and equitorial-plane views of a sector of the reactor are shown.

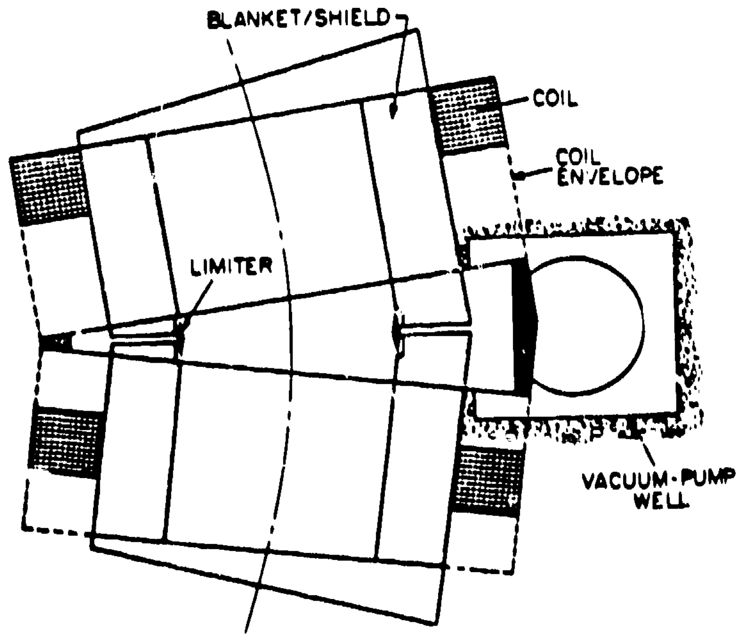
N/m=3 COILS PER FIELD PERIOD





10^{-1}
10^{-2}
1
10
100
Limiting Average Beta, <β>
Plasma Aspect Ratio, A=R_T/r_p
ι=2
ν=3
r_s~r_c
EQ
ST,η=0
ST,η≠0
8
6
4
8
6
4
8
6
4


GIMBAL SUPPORT
COIL
STARTUP/ CONTROL POWER
RF DUCT
LIMITER RADIUS
PLASMA
BLANKET/SHIELD
PUMPED-LIMITER COOLANT
MAIN COOLANT
GIMBAL SUPPORT
VACUUM PUMP
0 1 2m


BLANKET/SHIELD
COIL
COIL ENVELOPE
LIMITER
VACUUM-PUMP WELL