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CONCEPTUAL DESIGN STUDIES OF THE MODULAR STELLARATOR REACTOR (MSR)*

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Summary

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.

Introduction

The status and history of the stellarator approach to magnetic confinement has been reviewed elsewhere.[1-3] The term "stellarator" is used generically to describe those confinement devices that produce closed magnetic surfaces by means of external conductors. 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. New understanding of stellarator/torsatron physics and recent experimental successes have resulted in renewed interest in this truly steady-state device as a reactor.[3] Recognition that the helical coils can be eliminated in favor of toroidal-field (TF) coils that have been subjected to a periodic, lateral distortion has given the stellarator the promise of greater and more realistic system modularity.[4] Such modular-coil configurations allow more optimally oriented coil forces and lower coil stresses for the Modular Stellarator Reactor (MSR).[5] 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 $d/r_c = 0.3$.

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.
- 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 study that self-consistently incorporates crucial physics issues (e.g., scaling of beta with aspect ratio and the required 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).

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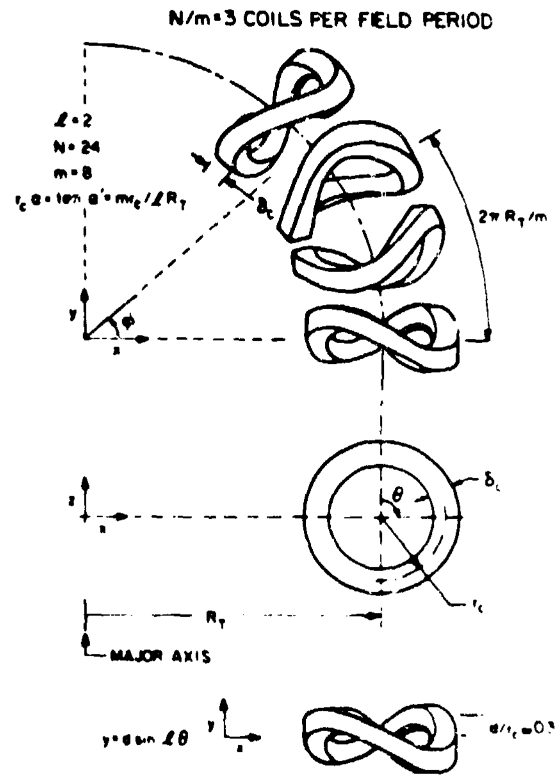

Fig. 1. Coil layout for a typical $\ell = 2$ MSR configuration. In this case, $m = 8$, $d/r_c = 0.3$, $N = 24$, and $N/m = 3$ coils per field period. The finite cross-section coils include internal support structure and thermal insulation.

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 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 broad minimum at $\sim 2(10)^{20}$ 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.

Transport Scaling

Radial transport ($\tau_E \propto r_p^2/D$) of energy in a nonaxisymmetric stellarator/torsatron plasma is modeled presently using simplified, empirical, or theoretical models in order that sensitive variables and tradeoffs can be more directly identified. The Alcator (empirical) transport scaling used[5] 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. 5. The issue of transport is central to a selection of a credible MSR design point.

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, both through the rotational transform, ι, and the shear, $d\iota/dr$, produced by the vacuum-magnetic-field topology; both 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 $\langle\beta\rangle$). It is recognized,[5] 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. 5, 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[3] 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.

Selection of Stellarator Physics Parameters

Implementation of equilibrium/stability constraints allows a narrowing of attention to $\ell = 2$ systems with m = 6 or 8. These parameters tend to maximize $\langle\beta\rangle$ on the basis of the simplified stability/equilibrium theory described above.[5] The attainable value of $\langle\beta\rangle = 0.04$ at A = 11 is anticipated to be marginally acceptable from the reactor viewpoint.

The next consideration in selecting an MSR design point 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 rotational transform required for a given beta and higher volume utilization within the first-wall radius. In addition, if $r_s \simeq r_c$, lower values 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,[5] leading to N = 18 modular coils in an m = 6 system.

The quantity, $\langle\beta\rangle^{1/2}B_o$, required for ignition is a weak function of $\langle T\rangle$ for Alcator transport scaling. Therefore, a higher allowed value for the on-axis magnetic field, 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 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.

Reactor Design Point

Figure 2 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

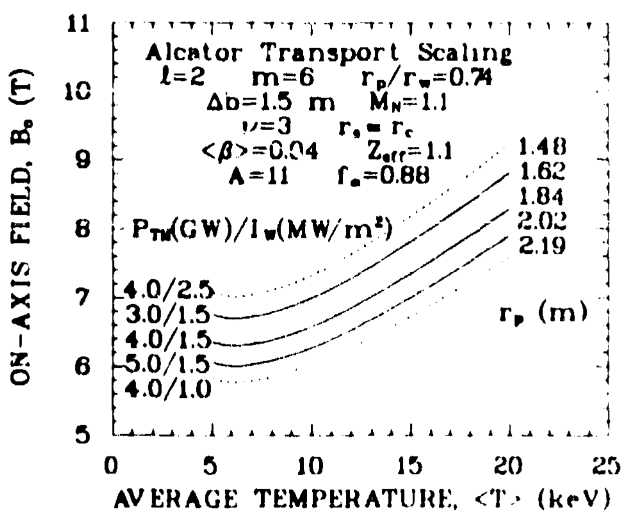

Fig. 2. Dependence of on-axis magnetic field, B_o, on the average plasma temperature, $\langle T\rangle$, required for ignited MSR operation for the indicated values of the ratio P_{TH}(MW)/I_w(MW/m^2) and corresponding plasma radii, r_p(m), for the indicated fixed parameters.

ignition is proportional to $B_o^4 r_p^2$ 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.

The results of parametric modeling have been used[5] 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.

TABLE I
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 ($\sim r_c$)
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, $\langle n_e\rangle\tau_E(10^{20}s/m^3)$	3.7
On-axis magnetic field, B_o(T)	6.0
Plasma power density, $p_F(MWt/m^3)$	2.34
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

The MSR design point proposed here on the basis of generally conservative assumptions represents a potentially attractive system of moderate size and favorable performance.

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. The dominant mean force component (~ 90 MN) 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. 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 on 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).

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 3 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. 3) 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 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,

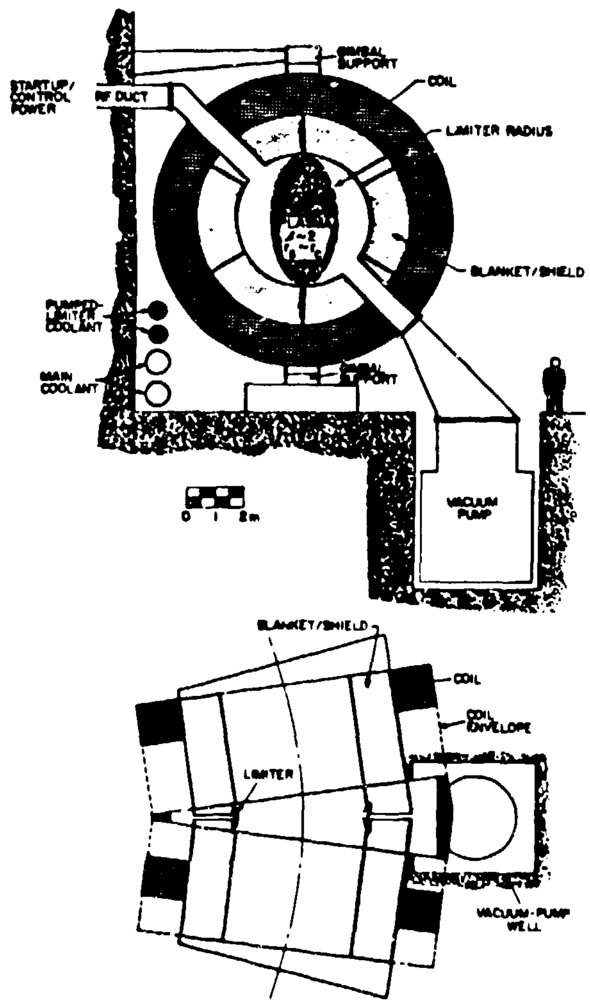

Fig. 3. Preliminary reactor layout based on the interim MSR design point for use in examining coil support structure and intercoil forces. Elevation and equitorial-plane views of a sector of the reactor are shown.

detailed conceptual design of key MSR systems remains to be performed.

Preliminary economic analysis of the MSR design point indicates a direct investment cost of 1790 $/kWe in 1980 dollars. Assuming a nominal construction time of 10 years, the total investment cost becomes 2190 $/kWe in constant dollars and 3550 $/kWe in then-current dollars. The corresponding energy costs are 55 mills/kWeh and 89 mills/kWeh, respectively, assuming a plant availability of 76%.

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, 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. 5.
- 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.
- 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 neo-classical-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.

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