UCRL-92023
PREPRINT

CONF-850310--55

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L. J. Perkins, B. G. Logan, R. B. Campbell,
R. S. Devoto, D. T. Blackfield, and B. H. Johnston,

This paper was prepared for submittal to the
6th Topical Meeting on the Technology of Fusion Energy,
San Francisco, California, March 3-7, 1985

April 3, 1985

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UCRL--92023

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PLASMA ENGINEERING FOR MINIMARS: A SMALL COMMERCIAL TANDEM MIRROR REACTOR WITH OCTOPOLE PLUGS*

L. J. Perkins, B. G. Logan, R. B. Campbell,† R. S. Devoto, D. T. Blackfield,†† and B. H. Johnston
Lawrence Livermore National Laboratory, University of California
P.O. Box 5511 (L-644)
Livermore, California 94550
(415) 423-6012

ABSTRACT

With the employment of a novel octopole end plug scheme, we examine the plasma engineering design of MINIMARS, a small compact fusion reactor based on the tandem mirror principle. With a net electric output of 600 MW_e, MINIMARS is expressely designed for short construction times, factory built modules, and a passively safe blanket system. We show that the compact octopole/mantle provides several distinct improvements over the more conventional quadrupole (yin-yang) end plugs and enables ignition to be obtained with much shorter central cell length. In this way we can design economic small reactors which will minimize utility financial risk and provide attractive alternatives to the conventional larger fusion plants encountered to date.

INTRODUCTION

The Mirror Advanced Reactor Study (MARS),[1] the precursor of MINIMARS, was concerned with a relatively large 1200 MW_e commercial tandem mirror reactor with double quadrupole (yin-yang) end plugs. Although we took advantage of both the attractive reactor features of the tandem mirror concept and the potential of fusion for improved safety and environmental impact over fission, we concluded the MARS project with enhanced understanding of how we should fully exploit the intrinsic characteristics of the tandem mirror to achieve an optimum reactor design in terms of economics and utility attractiveness. Accordingly, commencing in FY85, Lawrence Livermore National Laboratory, in partnership with the Fusion Engineering Design Center, the University of Wisconsin, TRW, Grumman Aerospace Corporation, Ontario Hydro, Bechtel Group Inc., General Dynamics/Convair, and Argonne National Laboratory, is conducting a conceptual design of "MINIMARS", a small commercial tandem mirror reactor with novel octopole end plugs.

We have adopted three basic objectives for MINIMARS:

1. Plasma Engineering. A new concept for compact octopole plugs[2] makes it possible to significantly reduce the size, weight, and cost of the end cell magnets relative to MARS and, thereby, attain central cell ignition in much smaller lengths. Accordingly, we are evaluating the plasma engineering issues underlying the octopole concept and performing a comparison with other novel stabilization approaches.

2. Reactor Sizes and Economics. There is increasing utility interest in small, modular power plants and MINIMARS can exploit the potential of the octopole plug concept to achieve small but economic reactors. Accordingly, we are: (a) evaluating a point reactor design at 600 MW_e with short (∿3 year) construction times and factory-built modular construction, and (b) evaluating utility financial risk (total capital investment), growth system cost of electricity (mills/kWhr), and economy of scale of MINIMARS plants ranging from 250 to 2400 MW_e. In this regard, we will continue to make substantial use of the Tandem Mirror Systems Code Optimization Package (see below).

3. Safety, Environment, and Economics. With attention to system power density and judicious choice of materials, we can design for low afterheat, passively-safe shutdown, and blanket systems that sustain no damage from LOC/LOF accidents. Accordingly, we are making safety an inherent part of the MINIMARS design, thereby obviating the need for engineered, or active, safety systems

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

†TRW Inc., LLNL, Livermore, CA 94550.

††TRW Inc., FEDC, Oak Ridge, TN 37830

and facilitating the reduction of the size of the "nuclear grade" envelope. This has the effect of simplifying considerably the plant external to the fusion power core.

PHYSICS BASIS OF MINIMARS

A cross section of the first baseline design of MINIMARS at 600 MW_e is shown in Fig. 1, while a schematic of the plasma/magnet configuration is shown in Fig. 2. Also shown in Fig. 2 is the axial distribution of the magnetic field and plasma potential. As with MARS[1] its predecessor, the axial pressure of the DT fuel ions in the simple solenoidal (∿3 T) central cell is contained mainly by the high field choke coils (∿26 T) at each end. Similarly, nearly all the 3.5 MeV fusion alpha particles are born mirror trapped in the central cell. The small fraction (<10%) of central cell ions which pitch angle scatter into the loss cone and pass into the octopole end cell, reflect off the positive plugging potential and return through the central cell. The magnitude of the potential peak (>150 kV relative to the central cell potential) reduces the central cell ion end loss sufficiently to allow fusion alpha heating to sustain residual central cell energy losses due to end cell trapping (see below); i.e., the central cell is ignited.

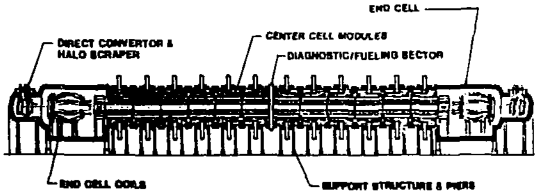

Fig. 1. The first MINIMARS baseline design at 600 MW_e.

In addition to the potential peak, a "thermal barrier"[1] is required in the end cell to moderate electron heat conduction from the peak and, therefore, to reduce end cell heating power. A depression in the end cell ion density is formed by microstable "sloshing ions" fueled by a 475 kV negative-ion neutral beam source. Mirror-trapped hot electrons sustained by ECRH heating at the midplane of the sloshing ion distribution provide the required negative potential (∿-145 kV relative to the central cell) of the thermal barrier (see Fig. 2). MHD stabilization of MINIMARS by means of the octopole coil and a hot electron mantle is discussed in a later section.

Many of the MINIMARS plasma confinement features are derived from past and present tandem mirror experiments at LLNL, especially the Tandem Mirror Experiment-Upgrade (TMX-U)[3] and the Mirror Fusion Test Facility (MFTF-B),[4] In particular, our plasma modeling draws heavily on behavior observed in TMX-U namely: microstable sloshing ions with loss rates predicted by Fokker-Planck codes, enhanced thermal barrier formation with ECRH, reduction of ion end loss by potential plugging so that radial ion losses dominate, net electron current collection on end wall plates, and vacuum pumping by the plasma halo. Plans are now underway for TMX-U to test several MINIMARS-related features such as high-field choke coils, octopole coils, hot electron mantles, and drift pumps.

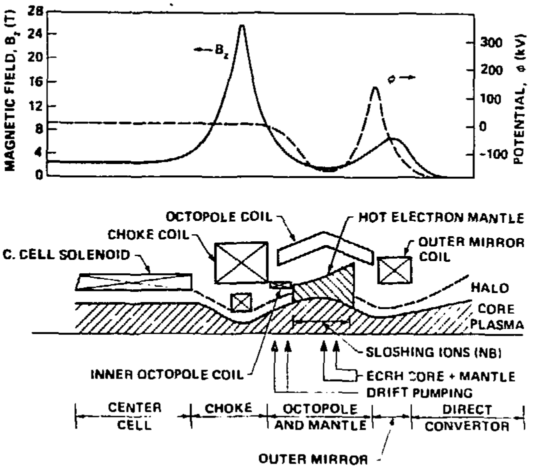

Fig. 2. Schematic of the plasma/magnet configuration of MINIMARS with octopole end cells. An axial distribution of magnetic field and plasma potential is shown on the same scale.

THE RATIONALE FOR OCTOPOLE COILS: THE IGNITION CONDITION

The Mirror Advanced Reactor Study (MARS)[1] employed a quadrupole end cell magnetic configuration in the form of a complex double yin-yang magnet set with recircularizing transition coils. While providing a well-tested method of high beta MHD stabilization, quadrupoles have three disadvantages for tandem mirror reactor applications: (1) the end cell magnet configuration is complex and expensive; (2) the end cell plasma flux bundle is non-axisymmetric with attendant radial drift problems; and (3) the required central cell length for ignition is large making it difficult to achieve small reactors economically.

The last point is particularly important. The condition for ignition of a tandem mirror reactor is that the power deposited by fusion alpha particles in the central cell plasma must be greater or equal to all sources of power loss from this volume. Now passing central cell ions which undergo collisional trapping in the end cell between the potential peak and the choke coil magnetic field peak must be removed (or "pumped") at the rate at which they trap, otherwise the end cell would fill with trapped ions and the thermal barrier would be destroyed. To provide this pumping we configure "drift-pump" coils above and below the plasma in the end cell and effect a resonance between the coil frequency and the bounce frequency of the trapped ions.[1] The resulting enhanced radial diffusion transports these ions to the unplugged halo plasma surrounding the core plasma, and they are swept to the grounded halo dumps at the ends of the machine.[1] The ion trapping rate (and thus drift pump loss rate) of ions in the end cell scales as the end cell plasma volume, the square of the end cell ion density, and the inverse of the central cell ion temperature to the three-halves power.[1] Drift pumping of trapped ions in the end cell represents the major power loss mechanism from the central cell plasma (other losses such as axial ion losses and radiation losses are typically less than 10% of the total), thus we can represent the central cell ignition condition as

$$r_c^2 L_c P f_\alpha \geq c \, r_{ec}^2 L_{ec} n_{ec}^2 T_c^{-3/2} + S \qquad (1)$$

where r_c, L_c, r_{ec}, and L_{ec} are the radius and lengths of the plasma in the central cell and end cell, respectively; P is the central cell fusion power density; f_α is an alpha confinement factor (see below); n_{ec} is the end cell ion density; T_c is the central cell ion temperature; c is a constant; and S represents the small subsidiary central cell losses (e.g., radiation losses). The implication of Eq. (1) is clear. As the length (and thus volume) of the end cell magnetic configuration increases, the dimensions of the central cell plasma must increase so that fusion alpha power can make good the power losses due to increased trapping in the end cell. In this regard, a recent study of tandem mirror ignition machines at LLNL, demonstrated that ignition with a MARS-like quadrupole end cell would require a minimum ignition length approximately three times that of a machine with octopole end cells.[5]

One is justified to ask at this point why the central cell radius r_c cannot be simply increased to meet the ignition criteria with a corresponding reduction in the length L_c, thus providing a short compact machine. However, besides ignition, the second important design criterion that must be met is conservation of magnetic flux mapping through the machine, i.e.,

$$\pi r_c^2 B_c (1 - \langle\beta_c\rangle)^{1/2} = \pi r_{ec}^2 B_{ec} (1 - \langle\beta_{ec}\rangle)^{1/2} \qquad (2)$$

where B represents the vacuum fields and the beta corrections are applied to account for the plasma diamagnetism at high beta. Therefore, assuming that end cell magnetic fields B_{ec} are maintained at their economical maximum, an increase in central cell radius must be matched by a corresponding increase in end cell radius r_{ec} and therefore, by a further increase in end cell trapping volume; this in turn requires a greater central cell length to meet the ignition criteria according to Eq. (1).

Note also that we cannot minimize end cell volumes by simply reducing the end cell plasma radius r_{ec} to arbitrarily small values. By Eq. (2), this would result in small values of the central cell radius r_c with detrimental effects to alpha deposition efficiency. In our high beta, low field, central cell, the gyroradius of the 3.5 MeV fusion alpha particle is typically an appreciable fraction of the plasma radius. Further reductions in plasma radius would result in increased alpha absorption by the halo outside the core plasma, with a resulting decrease in the alpha confinement parameter f_α in Eq. (1).[5]

Here then lies the problem with end cell magnetic configurations such as the MARS quadrupoles which have long characteristic lengths. A long end cell length requires a long central cell for ignition making it impossible to achieve small reactor sizes in an economic fashion. By contrast, the octopole provides a method of obtaining a short end cell configuration with a minimum end cell length (∿7 m) determined only by sloshing ion adiabaticity,[2] thus allowing us to consider economic tandem mirror reactors as small as 250 MW_e. We illustrate this principle in Fig. 3, where the octopole end cell magnet set for MINIMARS (600 MW_e) is compared with the quadrupole set for MARS (1200 MW_e).

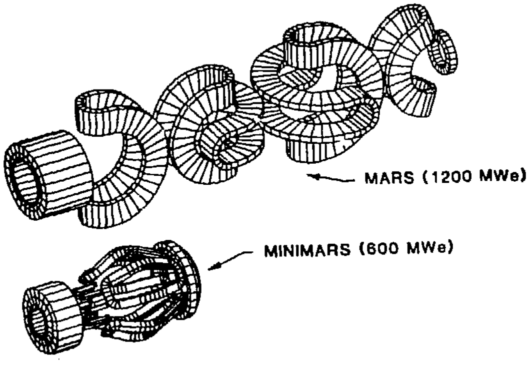

Fig. 3. Comparison of the end cell magnetic configurations for MARS and MINIMARS.

THE OCTOPOLE MAGNETIC CONFIGURATION

Figure 4 is an isometric view of the current MINIMARS end cell magnet set. The outer octopole coil, located between the high field choke coil and the outer mirror coil, is seen to be composed of four discrete coils and represents a distinct improvement over an earlier continuous winding design in terms of access and maintenance. An important feature of multipoles having order N greater than N = 4 for the quadrupole is that the minimum in |B| occurs off the central axis with a period of cos $(N\theta/2)$. Also the near axis multipole field components decrease with increasing N, so the higher the number of bars, the more axisymmetric the near axis field will be. Since there is a limit to the number of bars due to access requirements, we have proposed an octopole (N = 8) configuration for MINIMARS, although we are also assessing hexapole coils (N = 6).

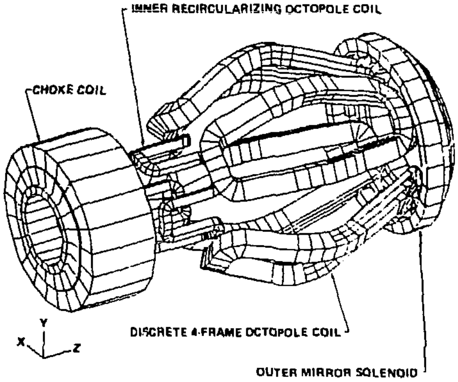

Fig. 4. Details of the MINIMARS end cell magnetic configurations.

The relative magnitudes of the solenoidal mirror fields and the octopole field are adjusted to place the minimum-|B| point outside of the core plasma flux bundle which maps to the central cell. Any residual non-axisymmetry of the flux bundle at the midplane of the octopole can be cancelled by means of the small inner recircularizing octopole coil also shown in Fig. 4. The intervening region between the core plasma and the minimum |B| point is bridged by a "mantle" of mirror-confined hot electrons sustained by an additional ECRH system (see Fig. 2).

Appropriate tailoring of the rising pressure profile of the mantle electrons ensures MHD stability to flute interchange modes driven by the bad curvature regions of the central cell and end cell.[2] Stability against interchange does not, of course, guarantee stability to ballooning modes at high β. However, FLR phenomena are expected to stabilize all ballooning modes except for m = 1, while calculations of this mode in quadrupole-stabilized tandem mirrors have yielded beta limits very close to those predicted by interchange criteria.[2] MHD analysis for MINIMARS continues to be a fruitful research area.

While the end cell core plasma is essentially axisymmetric, the mirror-confined hot electron mantle surrounding the core plasma exhibits the characteristic four-pointed convoluted shape of the octopole field far from the axis. Moreover, the mantle occupies field lines which do not map through the machine. Accordingly, as the study progresses, particular attention will be given to this region regarding ECRH absorption profiles and electron scattering losses.

SYSTEM MODELING AND PARAMETER SELECTION

The initial phases of the MINIMARS project have been characterized by extensive parameter searches to elicit plasma engineering baselines which meet the economic objectives discussed above. To this end, we have made considerable use of our Tandem Mirror Systems Code-Optimization Package, which performs plasma modeling, power balance, and systems optimization functions.[6] With this code, we can optimize a user specified figure of merit [e.g., cost of electricity (mills/kWhr)] subject to a set of constraints [e.g., fixed net electric output power (MW_e)] by variation of up to 26 plasma engineering parameters. Full details are given in a companion paper.[6]

Table 1 lists the major plasma engineering parameters for the current MINIMARS baseline at 600 MW_e. Listed for comparison are the equivalent parameters for a 250 MW_e version of MINIMARS. These parameters are subject to modification as our study matures. Both sets of parameters were determined by the TMSC-Optimization Package configured for optimized (i.e., minimum) cost of electricity at fixed net electric power.[6] Notice the high Q value (i.e., fusion power divided by plasma heating power) which illustrates the beneficial nature of compact end cells. Notice also that optimized design results in relatively long central cell lengths with small plasma radius and, therefore, small end cell volumes with correspondingly low heating powers.

CONCLUSION

Thus far in the MINIMARS study we scoped initial design parameters and cost projections for a small tandem mirror reactor with a net

Table 1. Principal physics parameters for MINIMARS optimized for cost of electricity.

	MINIMARS[a] at 600 MW_e	MINIMARS at 250 MW_e
General		
Fusion power (MW)	1206	553
Q	78	49
Neutron wall loading (MW/m^2)	2.7	1.6
Total capital cost (M$)	1066	687
Cost of electricity (mills/kWh)	56	80
Mass utilization (kW_e/tonne)	65	35
Magnetic fields		
Central cell (T)	2.95	2.76
Choke coil (T)	26.0	24.8
End cell midplane (T)	1.5	1.5
Outer mirror (T)	6.6	6.9
Central cell		
Length (m)	94.9	75.5
Plasma radius (m)	0.42	0.38
Ion temperature (keV)	29.2	32.4
$\langle\beta\rangle$	0.6	0.6
End cell		
$\langle\beta\rangle$	0.33	0.3
Core ECRH power[b] (MW)	4.3	2.7
Mantle ECRH power[b] (MW)	10.9	8.4
NBI power[b] (MW)	0.28	0.19

[a] Baseline case.

[b] Absorbed, both ends.

electric output of 600 MW_e. The novel compact octopole end cell of MINIMARS appears to offer a distinct improvement over the more conventional quadrupole end cell because it permits ignition at much shorter central cell lengths, thus enabling the realization of small but economic tandem mirror reactors. In addition to extensive parameter trade studies with the Tandem Mirror Systems Code, future plasma engineering tasks will include further attention to ECRH ray tracing and absorbtion in the mantle, drift pumping in axisymmetric plasma geometries, physics of the plasma halo, fueling, and enhancement of MHD stability and β limits with conducting walls.

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