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MIRROR ADVANCED REACTOR STUDY
(MARS)

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THE MIRROR ADVANCED REACTOR STUDY (MARS)*

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ABSTRACT

Progress in a two year study of a 1200 MWe commercial tandem mirror reactor (MARS - Mirror Advanced Reactor Study) has reached the point where major reactor system technologies are identified. New design features of the magnets, blankets, plug heating systems and direct converter are described. With the innovation of radial drift pumping to maintain low plug density, reactor recirculating power fraction is reduced to 20%. Dominance of radial ion and impurity losses into the halo permits gridless, circular direct converters to be dramatically reduced in size. Comparisons of MARS with the Starfire tokamak design are made.

INTRODUCTION

The Mirror Advanced Reactor Study¹ (MARS) is a major two-year study, now about two-thirds complete, of a commercial tandem mirror reactor. The study is conducted by the Lawrence Livermore National Laboratory for the US Department of Energy, with TRW as the prime industrial partner, General Dynamics, EBASCO, and SAI (La Jolla) as subcontractors, and the University of Wisconsin as a university partner. Grumman Aerospace Corp. is also contributing a significant portion of the engineering effort. The main objectives of MARS are: (1) to design an attractive tandem mirror fusion reactor producing electricity and synfuels (in alternate versions), (2) to identify key development and technology needs for the commercial tandem mirror reactor and its forerunner, the Fusion Power Demonstration reactor (FPD) (the mirror ETR described by Henning, et al., elsewhere in these proceedings), and (3) to exploit the potential of fusion for safety, low activation, and simple disposal of radioactive waste. While some design areas are still evolving, we can summarize here the major reactor system design elements for a reference case MARS producing 1200 MW(e) of electricity. Another version of MARS employing a higher temperature

blanket for production of synfuels and/or electricity is described elsewhere in these proceedings by Gordon, et al. For brevity, we limit descriptions of the reactor systems to highlights of the magnets, blanket, plug heating systems and direct converter. Some comparisons between the Starfire tokamak design² and MARS will be discussed in the conclusions.

SYSTEM OVERVIEW

MARS (Figs. 1,2) is a linear tandem mirror fusion reactor using electrostatic plugs^{3,4} to confine a steady-state fusion plasma in a long solenoid (cross-section shown in Fig. 3), in which typically 20 to 23 MW fusion power is generated per meter length. Table 1 summarizes key MARS reactor parameters. The main fusion plasma in the solenoid (central cell) is pellet-fueled, and with sufficient plug confining potentials ($\phi_{\text{plug(max)}} - \phi_{\text{central cell}} \geq 150$ kV), fusion alpha heating sustains the central cell axial and radial energy losses, i.e., the central cell is ignited. While fusion power then increases roughly linearly with central cell length, both plugs require continuous injection of about 100 MW of heating power (see Table 1), nearly independent of central cell length. About 50% of the injected plug power and alpha-generated power is directly converted from the plasma exhausting out the ends. Thus, assuming constant Table 1 efficiencies, net electric power scales faster, and total reactor cost slower, than proportional to central cell length, due to fixed plug power and cost. Therefore, we expect MARS capital cost per unit of net power will exhibit a strong economy of scale favoring larger reactors.

Because of rapidly evolving plug designs, we did not select a reference case MARS based on cost optimizations, so we initially considered a

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Table 1. Characteristic MARS Parameters

Central Cell Length	130 m
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Peak Choke Coil Field	24T(16T SC+8T Cu insert)
Yin-Yang Mirror Field	7.5T (10T on conductor)
First Wall Loading	4.3 MW/m^2 ($r_{\text{wall}}=0.6 \text{ m}$)
Blanket coolant-breeder, temp., & power multiplication	$\text{Li}_7\text{Pb}83$, 500°C, $M=1.39$
Plug Neutral Beam Absorbed	3.0 MW each plug
Plug ECRH Absorbed	42 MW each plug
Anchor ICRH Absorbed	4 MW each anchor
Normal Insert Coil Power	43 MWe each plug
Total Recirculating Power	300 MWe
Direct Converter Power (Total)	400 MWe
Net Electric Power Produced	1200 MWe
Recirculating Power Fraction	0.20
Magnet Stored Energy (total)	45 GJ
<u>Efficiencies</u>	
Direct Converter	0.58
475 kV Slashing Ion Beams	0.60
ECRH	0.65
Anchor ICRH	0.50
Thermal Cycle	0.39
Overall System (Plant)	0.36

point design with a solenoid length^a of 160 m producing 3500 MW fusion power, the same fusion power as Starfire. Recent adoption of drift pumping in lieu of inefficient neutral beam charge-exchange pumping to maintain the plugs (described by Carlson et al. elsewhere in these proceedings) has halved plug injection power, and because we have designed a blanket with high energy multiplication ($M = 1.39$), and because of efficient direct conversion of plasma energy losses, this size MARS is now calculated to produce 1700 MWe net power, 40% more electricity for the same fusion power as in Starfire. To facilitate comparisons with other reactor designs, we have reduced the reference case MARS central cell length to

135 m, and the first wall loading Γ from 5 MW/m^2 down to 4.3 MW/m^2 , to reduce fusion power to 2574 MW and net power to 1200 MWe. The optimum size MARS for commercial power production, however, will depend strongly on uncertain future utility needs. If trends continue toward centralized multi-owner facilities selling electricity to several utilities, then MARS reactors even larger than 1700 MWe may be desired.

MAGNET SYSTEM

The magnet set for MARS shown in Figs. (1) and (2) consists of a central cell of 42 solenoids spaced 3.16 meters apart, followed by a plug coil set at each end consisting of a high field hybrid choke coil (Fig. 4) and a series of 6 Cee-shaped coils and one circular tria coil. All coils use ductile NbTi superconductor except for the inner layers of the choke coil which are Nb_3Sn (Ti doped) superconductor and high strength copper alloy for the normal coil insert (see Fig. 4). The mean radius of the central cell solenoids and the mean major arc radius of the plug Cee coils are all about 3 meters, largely determined by space required for blankets and neutron shielding, since the plasma radius is only about 0.5 m. The total stored magnetic energy of the MARS magnet set is about 45 GJ, about three-fourths that of Starfire. Roughly, two-thirds of the total stored energy and magnet weight is in the central cell solenoids. The average central cell field at the plasma is 4.7 tesla, with a 6% ripple due to the 3.16 meter coil spacing required to allow regular blanket module replacement without moving any coils. The field ripple degrades the MHD beta limit by only 6%, and because of axisymmetry, does not enhance trapped ion radial transport. Grading the solenoid coil current density in three layers ($j = 1330 \text{ A/cm}^2$ outer layer, 1210 middle layer, 1070 inner layer) keeps the average stress level in the self-supporting conductor layers to less than 200 MPa, and limits the peak conductor field to 7T. Therefore, the central cell solenoids in MARS do not appear to require any large extrapolations in superconducting magnet technology.

The MARS end plug magnets are similar to those used in the TMX-U, TARA, and MFTF-B experiments in that high beta MHD stability derives from mirror-trapped plasma pressure in

^aQuoted length is between mirrors. An equivalent volume uniform plasma is slightly shorter due to tapering at the ends.

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minimum-8 quadrupole magnets. The allowed central cell beta in MARS is more than doubled by the use of two yin-yang mirror cells (designated anchor and plug in Fig. 2). The MARS yin-yangs are slightly (30%) larger in linear dimensions than the MFTF-B yin-yang successfully tested at LLNL. However, because the peak conductor fields in the MARS yin-yangs are 10T instead of the 6T in MFTF-B, the yin-yang NbTi conductor must be cooled with superfluid helium at 1.80 K. The yin-yang's and transition Tee coils in MARS have been designed to cancel parallel components of plasma current and to minimize neoclassical radial transport.

Because collisionally-trapped warm ions are radially transported out of the plug plasmas by drift-pumping, the central cell density and plasma pressure is higher than in the plugs by about the ratio of choke coil mirror field to plug yin-yang midplane field. The relatively high central cell pressure is consistent with MHD stability since the bad field curvature at the central cell ends is relatively much weaker than the good-field curvature in the yin-yangs. Then, for given plug pressure and central cell fusion power/m, the plasma radius scales as $r_{\text{central}} \propto B_{\text{choke}}$ or, for given central density and radius, the plug injection power scales as $q_{\text{plug}} \propto B_{\text{choke}}$. This scaling gives strong incentive to design maximum practical choke coil mirror fields. We find total electrical recirculating power is reduced by adding field inside the 16T superconducting choke coil with normal resistive coil inserts (see Fig. 4), up to the point where the electrical power consumed by the normal inserts begins to exceed the plug injection power. This point is approached in MARS with $B_{\text{insert}} = 8T$, where $P_{\text{insert}} = 80 \text{ MWe}$ (both inserts) $\leq P_{\text{injection}}$ (both plugs). The current density in this hybrid choke coil is graded in layers so that hoop stresses in each layer ($\sigma = j r B$) are less than 290 MPa in the superconductor layers, and less than 350 MPa in the normal insert layers. Many design issues other than stress, such as neutron damage, cooling, and remote maintenance, have been taken into account. Insert life is estimated to be 1-2 full power years (FPY), with neutron-induced increase in resistivity one of the major factors determining useful insert life.

FIRST WALL-BLANKET-SHIELD DESIGN

The MARS blanket (Figs. 3,5) is an optimized version of the Witamir design⁵ initially developed by Kulcinski's group at the University of Wisconsin. This simple, rugged design for MARS uses the low melting tempera-

ture lithium/lead eutectic Li₁₇Pb₈₃ as both coolant and breeder, flowing vertically through HT-9 tubes and channels. Due to low surface heat flux ($< 4 \text{ W/cm}^2$), no separate first wall is needed besides the HT-9 tubes. The tubes and channels are grouped into 73 replaceable modules weighing only 2.7 tons each when drained. Scheduled module replacement every 2-3 FPY requires 11 days down time. The reflector, shield and coils are not moved for module replacement, although provision is also made for their replacement in the event of failure (see paper by Young, et al., and also by Li, et al., elsewhere in these proceedings). The MARS blanket is optimized to maximize blanket energy multiplication ($M = 1.39$) while maintaining 1.13 tritium breeding ratio, and to minimize blanket, reflector, and shield thickness ($= 1.22$ meters total) while preserving coil life ($\leq 10^{-5}$ stabilizer dpa/FPY) and "hands on" maintenance in back of the shield within 2 days. The resulting inner coil radius of 2.1 m minimizes central cell cost [see Perkins, these proceedings].

As in Witamir, the entire blanket tritium inventory in MARS is very low, less than 5 grams at 10^{-4} torr partial pressure due to the low solubility of T₂ in Li₁₇Pb₈₃ at 500°C. The low tritium solubility also facilitates tritium extraction by simple vacuum pumping with a modest 5×10^5 liter/sec pumping speed. Double-walled heat-exchangers currently under development for the LMFBR program should eliminate the need for intermediate loops for tritium containment, as we calculate a loss rate of less than 10 Ci/day of T₂ through the duplex tubes to the steam side. Thermal, hydraulic and materials parameters for the MARS Li₁₇Pb₈₃ blanket are summarized in Table 2.

Table 2. Thermal, hydraulic and materials parameters for the MARS Li₁₇Pb₈₃ blanket

Blanket thermal power, MW	2070
Reflector thermal power, MW	790
Dia./Thickness of blanket tubes, cm	10/0.23
Max. Li ₁₇ Pb ₈₃ coolant velocity, m/s	0.17
Max. MHD pressure drop, MPa	1.57
Li ₁₇ Pb ₈₃ pumping power, MWe	40
Min./Max. structure temp., °C	350/550
Max. dpa rate, FPY ⁻¹	71
Max. appm He production/FPY	560
Max. corrosion rate, cm/FPY	0.0002
Steam temperature, °C	480
Steam pressure, MPa	16
Net efficiency (inc. pumping)	37%
Net central cell power, MWe	1110

Since one-half to one-third of the MARS blanket modules would be replaced during annual maintenance periods, approximately 70 to 100 tons of radioactive waste are generated annually from MARS, comparable to that generated by today's light water reactors. We have considered how well HT-9 and some other steel alloys would meet 10CFR61 HRC rules for near-surface burial of class C low level wastes (Table 3). The motivation for class C wastes would be that they might be buried on site, minimizing hot cell processing and transportation for fusion wastes. With some specified processing, alloys such as HT-9 with waste disposal rating (WDR) of 20 or less can be converted to class C waste. If no processing is desired (our preferred option), isotopic tailoring of the 1% nickel and moly constituents of HT-9 can be used to lower its WDR to less than one. Because of the small size and weight of the MARS blanket modules, and the low Li₇PbBg pressure (1.6 MPa), future use of advanced materials such as vanadium alloys and silicon carbide may prove feasible.

END PLUG HEATING SYSTEMS

Table 1 lists injection powers trapped in the plasma, required to maintain each end plug of MARS in steady state. Startup power has not yet been fully quantified, but in addition to the above plug injection powers, there will likely be about 50 MW of auxiliary ion cyclotron resonance heating (ICRH) in the central cell to initially heat a lower density central cell plasma to ignition temperature, in a pulse length of about 10 seconds (at full steady-state parameters, the MARS central cell plasma stores about 300 MJ energy). Note in Table 1 that the largest single steady state heating requirement in the plugs is electron cyclotron resonance heating (ECRH) = 82 MW for both plugs. Of this, 78 MW at 60 (84) GHz forms hot mirror trapped electrons at the plug midplanes (called the thermal barrier³) and 4 MW at 100 (112) GHz heats warm electrons at the outermost plug regions, which generates and controls the potential plugging central cell ions. Startup will require the higher frequency value in parenthesis for vacuum field resonance; the steady state values are lower due to beta and relativistic down-shifts of the electron cyclotron resonance. With proper microwave beam injection angle, ray tracing calculations indicate that wave-trapping captures essentially all the incident microwave power.

TABLE 3. Waste Disposal Ratings (WDR) for MARS First Wall

Isotope	50 Years After Shutdown		
	HT-9	SS316	PCA
all with $t_{1/2} < 5$ yrs	3E-440	3E-440	3E-440
Co60	3E-540	1E-340	1E-340
C14	6E-5	1E-1	3E-1
N159	5E-2	2	2
N163	7E-1	3	3
Hb94	2E1	5E1	2E2
Tc99	3	1E1	1E1
Sr90			
Surrogate	1E-1	3E-1	3E-1
Cs137			
Surrogate	7E-6	2E-5	7E-5
Total	2E1	7E1	2E2

$$WDR = \sum_i A(i)/L(i)$$

$A(i)$ = activity of i th isotope in Ci/m³
 $L(i)$ = maximum permissible activity of i th isotope (Ci/m³) from 10CFR61.
 If $WDR < 1$, material can be disposed of by near-surface burial without processing.

Table 4. Direct Converter Parameters

Central cell plasma potential	4 kV
Halo potential	0.1V
Collector potential	-169 kV
Halo ion current (both ends)	1.94 kA
Collector ion current	0.19 kA
Collector electron current	2.13 kA
Collector electrical power	328 MW
Halo heat	79 MW
Collector heat	160 MW
η_{dc}	0.578

In order for the sloshing plug ions to withstand the large electrostatic forces tending to expel them, they must be injected at very high energy (475 kV), requiring negative ion beams. With injection at the inboard-fan turning point, we estimate 57% of the incident neutral beam current is usefully trapped, so a 10 amp, 475 kV beam must be delivered to each plug to supply the power in Table 1.

The only other significant plug heating system listed in Table 1 is for 4 MW of ICRH (absorbed) required to maintain a high beta ($\beta \approx 0.5$) in the anchor yin-yang cells for MHD stability. A few amperes of hydrogen gas or low energy beams is used for fueling, with the ICRH tuned to the hydrogen minority fundamental cyclotron frequency (55 MHz) for efficient fast wave heating and mirror-trapped tail formation. Second harmonic heating at 110 MHz is also being considered which could use waveguide launchers. 85% absorption is assumed.

At this time integration of the MARS heating systems with plug magnets, neutron shielding, and vacuum tanks is in progress. Figs. 6 and 7 show components for a 2.5 MW, tunable 84 GHz quasioptical gyrotron and for a 5 MW, 475 kV transverse field focused (TFF) negative ion beam line, respectively, which will be included in the integrated plug design. Details of these critical plug elements, which are in the beginning stages of development at Berkeley and NRL, are discussed by Freije and Perkins elsewhere in these proceedings. The essential design approach will be to put the neutron-damage-sensitive sources outside the plug magnets and shields, and out of direct line-of-sight to the plasma. Thus, arrays of gyrotron microwave beams are reflected 90° off paraboloidal mirrors before entering channels through the neutron shielding. There will be no ECRH windows in this scheme. Similarly, the transverse-field-focusing of the negative ion beam (Fig. 7) keeps the negative ion source and high voltage accelerator out of direct line of sight to the plasma. Assuming the anchor ICRH and drift-pump coils can be split into 1/2 turn segments supported on recessed insulator-feedthroughs, all MARS heating system components will be accessible for remote maintenance without the need to move plug magnets (although provision to replace end plug magnets is retained).

DIRECT CONVERTER

Fig. 8 shows the MARS power direct converter designed to handle a peak end loss

plasma heat flux of 1.24 MW/m². Recent designs using TZM molybdenum collector plates and halo dumps allow a higher heat flux of 2.5 MW/m², so that a similar but smaller direct converter can fit inside a straight extension of the yin-yang plug tank (10-12 m diameter as in Fig. 2). This vacuum tank is about the same diameter as the MFTF-B tank at LLNL. The direct converters in MARS have the functions of plasma exhaust, impurity removal and vacuum pumping as well as direct conversion of the plasma energy. The smaller size of this design compared to previous direct converter designs is the result of two innovations: (1) radial drift-pumping, which causes 95% of the central cell ions, thermal alphas and impurities to exhaust into an outer plasma annulus called a halo, leaving essentially only electrons to be collected at negative collector plate potentials inside the halo, and (2) reentrant halo pumping plenums, which uses the halo plasma as a pump to force high neutral pressures at the back plate of the plenum. The first of these innovations uses the induced radial transport of drift-pumping (needed to maintain the thermal barrier anyway) to enhance an effect already seen in TMX - that radial transport is selective to ions,⁶ including impurities,⁷ so that net electron current is collected at the end walls inside the halo layer. The selective ion transport eliminates the need for grids to separate the ion and electron currents, and grids were previously limiting the designable heat flux. The second innovation is akin to the pumped-limiter concept in tokamaks, in which the flow of cold plasma in the diverted layer (here, the halo layer) generates gas pressures at the neutralizing surface high enough to pump with Roots blowers instead of cryopanels. As in TMX, the directed plasma layer or halo in MARS pumps most of the background gas within the main vacuum chamber. Some of the MARS direct converter parameters are listed in Table 4. More details are given by Barr, et al., elsewhere in these proceedings.

CONCLUSIONS

Although the MARS study will not be completed until Sept. 1983, enough of the reactor systems have been designed that the general characteristics of MARS can be identified. These characteristics can be illustrated by comparison with the Starfire tokamak study.¹ Based on present plug designs, MARS is clearly a large reactor - roughly comparable in volume, weight, and magnetic stored energy as in Starfire for the same 1200 MWe net electric power. With the drift-pumping innovation (as important to MARS

as current-drive was to Starfire), the steady state plasma heating power is about 100 MW in both reactors. The MARS plant efficiency $\eta_{\text{plant}} = P_{\text{net}} / [(0.8 M + 0.2) \times P_{\text{fusion}}]$ is higher than Starfire (36% versus 30%) due to efficient direct conversion, but this advantage may only offset the complexity and cost of the MARS plugs. Thus, although MARS cost estimates are not yet completed, we can expect roughly comparable capital costs for MARS and Starfire, if we made common unit cost assumptions. One must remember that while both concepts will undoubtedly continue to improve, much experimental physics and technology development is still to be proven in both concepts, with more physics to be proven for the tandem mirror than for the tokamak. Similar conclusions were reached by the first MFAC advisory panel.⁸

Finally, however, there are potential advantages to the tandem reactor concept compared to the steady state tokamak concept, deriving fundamentally from the tandem's linear geometry, which motivate parallel development of the tandem mirror:

1. **Higher Beta.** Linear geometry permits higher beta essentially because the field lines are nearly straight, with relatively weak curvature. The payoff is that maximum desired fusion power densities in the first wall and blanket can be achieved with small bore magnets (4 m in MARS versus 8 x 12 m bore in Starfire). For given superconductor designs, stress increases with magnet bore.
2. **No Disruptions.** Linear tandem mirror MHD equilibria require no driven plasma current. Experimentally and theoretically, tandem mirror MHD modes are predictable and controllable - a basic prerequisite for reliable reactor designs.
3. **Direct Conversion.** Access to plasma exhaust arises naturally in linear geometry. The payoffs are: (a) Higher plant efficiency, achieved cost-effectively. This conclusion has been confirmed by every quantitative study of direct conversion. (b) A natural divertor for impurities. (c) A low surface heat flux on the walls where the fusion power is generated. (d) Simultaneous power production with plasma formation aids startup.
4. **Expedited Nuclear Development.** Linear geometry with no interlocking magnets allows progressive iterations of blanket technology, and successive increases in fusion power level, in a single DT-burning tandem mirror. Thus, the first tandem mirror large enough to demonstrate DT ignition (FPD), starting with shielding only and minimum

availability, can be upgraded to power production and higher availability in phases using the same magnet set.

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FIG. 1 MARS TANDEM MIRROR REACTOR

MARS END-PLUG

FIG. 2

FIGURE KEY

- A. CENTRAL CELL BLANKET MODULE
- B. CENTRAL CELL SOLENOIDAL COIL
- C. END CELL CHOKE COIL
- D. TRANSITION COIL
- E. ANCHOR YIN-YANG COIL SET
- F. 475 KEV PLUG SLOSHING ION BEAM
- G. PLUG YIN-YANG COIL SET

- H. 112 GHZ PLUG ECRH
- I. REGULARIZING COIL SET
- J. 4.75 KEV ANCHOR ION BEAM
- K. 84 GHZ BARRIER QUASIOPTICAL ECRH (2)
- L. GYROTRON
- M. HALO SCRAPER
- N. GRIDLESS DIRECT CONVERTER

FIG.3 MARS CENTRAL C.F.L. CROSS-SECTION

FIG.4 MARS - CHOKE COIL

MARS Li-Pb ELECTRIC-POWER BLANKET

FIG. 5

FIG. 6 QUASIOPTICAL GYROTRON

Assumed Device Parameters

	1MW	2MW	2.5MW
Cathode Voltage	-80V	-50V	-90V
Cathode Current	31.25A	55.6A	70.6A
Beam Energy	.5Me	5Me	6.4Me
First Anode Voltage	-451V	-451V	-451V
Gross Efficiency	40%		
Net Efficiency	80%		
rf Cavity Length	50cm		
Mirror Diameter	12cm		

FIG. 7 MARS SLOSHING ION BEAM LINE

FIG. 8 MARS POWER DIRECT CONVERTOR (LARGE VERSION)

$$Q(\text{PEAK}) = 1.24 \text{ MW/M}^2$$