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Mirror Advanced Reactor Study (MARS): Executive Summary and Overview

B. G. Logan

L. J. Perkins

J. D. Gordon*

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*** TRW Energy Development Group,
Redondo Beach, California**

LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California • Livermore, California • 94550

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Contributing Authors

B. G. Logan, C. D. Henning, L. J. Perkins,
G. A. Carlson, R. W. Werner
Lawrence Livermore National Laboratory
Livermore, California

J. D. Gordon
TRW Energy Development Group
Redondo Beach, California

G. I. Kulcinski
University of Wisconsin
Madison, Wisconsin

I. F. Parmer
General Dynamics/Convair Division
San Diego, California

I. I. Ribe
University of Washington
Seattle, Washington

R. J. Herbermann
Grumman Aerospace Corporation
Bethpage, New York

J. R. Bilton
Ebasco Services, Inc.
New York, New York

H. Gurol, J. E. Glancy
Science Applications, Inc.
La Jolla, California

L. C. Brown
GA Technologies
San Diego, California

N. J. Hoffman
Energy Technology Engineering Center (ETEC)
Canoga Park, California

R. W. Conn
University of California
Los Angeles, California

O. K. Kveton
Ontario Hydro
Mississauga, Ontario, Canada

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Mirror Advanced Reactor Study (MARS): Executive Summary and Overview

Abstract

This report provides an executive summary and overview of the Mirror Advanced Reactor Study (MARS), which is a comprehensive conceptual design of a deuterium-tritium-fueled commercial fusion reactor. Its operation is based on the tandem mirror principle exemplified by the Tandem Mirror Experiment-Upgrade (TMX-U) and the Mirror Fusion Test Facility (MFTF-B), two experiments currently being conducted by the Lawrence Livermore National Laboratory (LLNL). Two self-consistent MARS configurations are discussed—a 1200-MWe commercial electricity-generating plant and a synfuels-generating plant that produces hydrogen with an energy equivalent to 26,000 barrels of oil per day. The MARS machine emphasizes the attractive features of the tandem mirror concept, including steady-state operation, a small-diameter high-beta plasma, a linear central cell with simple low-maintenance blankets, low first-wall heat fluxes ($<10 \text{ W/cm}^2$), no driven plasma currents or associated disruptions, natural halo impurity diversion, and direct conversion of end-loss charged-particle power. The MARS electric plant produces 2600 MW of fusion power in a 130-m-long central cell. Advanced tandem-mirror plasma-engineering concepts, a high-efficiency liquid lithium-lead ($\text{Li}_{17}\text{Pb}_{83}$) blanket, and efficient direct electrical conversion of end loss power combine to produce a high net plant efficiency of 36%. With a total capital cost of \$2.9 billion (constant 1983 dollars), the MARS electric plant produces busbar electricity at $\sim 7\text{¢/kW-hour}$. The MARS synfuels plant produces 3500 MW of fusion power in a 150-m-long central cell. A helium-gas-cooled silicon carbide pebble-bed blanket provides high-temperature (1000°C) heat to a thermochemical water-splitting cycle and the resulting hydrogen is catalytically converted to methanol for distribution. With a total capital cost of \$3.6 billion (constant 1983 dollars), the synfuels plant produces methanol fuel at about \$1.7/gal. The major features of the MARS reactor include sloshing-ion thermal barrier plugs for efficient plasma confinement, a high efficiency blanket, high-field (24-T) choke cells, drift pumping for trapped plasma species, quasi-optical electron-cyclotron resonant heating (ECKRH) systems, and a compact gridless direct converter. We have placed special emphasis on fusion's potential for improved safety, lower activation, and simpler radioactive waste disposal as compared with fission. In particular, the $\text{Li}_{17}\text{Pb}_{83}$ blanket concept affords a low blanket tritium inventory ($<8 \text{ g}$), passive cooling during loss of flow or coolant accidents, and activated materials that can be disposed of using criteria established for near-surface burial of radioactive waste.

1. Introduction

The Mirror Advanced Reactor Study (MARS) was a two-year study of a commercial tandem-mirror fusion reactor combining the current plasma confinement concepts used in Lawrence Livermore National Laboratory's (LLNL) Tandem Mirror Experiment-Upgrade¹ (TMX-U) and Mirror Fusion Test Facility² (MFTF-B) with advanced engineering design concepts for efficient production of electricity and synfuels. The MARS program was conducted by LLNL for the U.S. Department of Energy (DOE), with TRW as the prime industrial partner; General Dynamics, EBASCO Services, Inc., and Science Applications, Inc., as subcontractors; and the University of Wisconsin as a university partner. Grumman Aerospace Corp. also contributed a significant portion of the engineering effort, and additional support to the study was provided by the University of California-Los Angeles and Ontario Hydro. Finally, the University of Washington and GA Technologies provided input to the synfuels portion of the program. This report is an executive summary and overview of the MARS Study and is an abstraction from the Final Report,³ which is a comprehensive design document providing detailed reports on all aspects of MARS; the Final Report consists Volume 1-A and 1-B (MARS Commercial Fusion Electric Plant) and Volume 2 (MARS Commercial Fusion Synfuels Plant).

Since its inception in 1976, the tandem mirror concept^{4,5} has evolved rapidly--both experimentally^{6,7} and theoretically^{8,9}--to the point that in 1981 it became possible to envision tandem mirror reactors with both high power density (neutron wall load $\Gamma_n > 2 \text{ MW/m}^2$) and high power gain ($Q = \text{plasma fusion power/plasma heating power} > 25$).^{10,11} With these advances, a commercial fusion power reactor based on the tandem mirror concept exhibits the following attractive features:

- Steady-state operation (no pulsed loads or cycling fatigue);
- Simple, "low-technology" central cell region with linear geometry (locating the higher-technology items in the end cells results in a simple, easy-to-maintain power-producing system in the central cell);
- Low charged-particle heat fluxes to the first wall ($\leq 10 \text{ W/cm}^2$);
- No required driven current and no identifiable plasma disruptions;

- Direct electrical conversion of charged-particle end-loss power;
- Natural impurity diversion via plasma halos;
- High-beta operation as a result of the machine's linear geometry.

In this study we completed and costed a single, self-consistent MARS design, performed some limited cost optimization, and examined alternative parameter ranges. It is important to note that because the MARS study provides only limited parameter surveys, we expect that the tandem mirror reactor can be further refined with respect to performance and cost. The present MARS design represents a major advance in the tandem-mirror reactor concept: the physics and engineering are self-consistent, and they demonstrate that efficient production of electricity and synfuels is feasible at near-competitive costs.

2. Objectives of the Study

The MARS study began in fiscal year (FY) 1981 and was motivated by several developments in tandem mirror physics and technology. As a result of successful electrostatic plugging demonstrated in the earlier TMX experiment,⁶ the MFTF machine (a single, minimum-B mirror experiment) was approved in 1980 for conversion to a large tandem-mirror device² capable of a confinement equivalent to $Q > 0.5$. Therefore, there was a need to fully assess reactors with these design features. There was also a need to design a stable end plug for a reactor configuration that would incorporate advances in tandem mirror microstability and magnetohydrodynamic (MHD) stability with thermal barriers.¹² A complete tandem mirror reactor design was needed with comparable detail in reactor plant equipment and balance of plant, as in the Starfire tokamak study,¹³ to gain a more accurate perspective on the cost of designing and constructing an entire tandem mirror power plant. In addition, in 1980 there was increased interest in the use of high temperature heat from fusion to produce synfuels as well as electricity, plus an increased interest in finding ways to improve fusion reactor safety and reduce the amount and longevity of fusion-generated radioactive waste.

Therefore, the general objectives of the MARS study were:

- To design efficient tandem-mirror reactors, both for electricity and synfuels production, that are consistent with appropriate physics and technology constraints;
- To identify key new physics concepts and feasible technologies that could be developed to improve the reactor's economics;
- To exploit the potential of fusion for improved safety, lower activation, and simpler disposal of radioactive wastes, compared with fission.

Additional guidelines were provided as the result of some programmatic assumptions and groundrules. First, we made technology and cost assumptions for first-generation, but tenth-of-a-kind, commercial reactors circa the year 2020. We included plug physics concepts that incorporated the basic elements of thermal barrier, quadrupole-type plugs to be tested in TMX-U and MFTF-B. Although we allowed for additional physics and technology concepts to improve reactor performance, we specified that they should be developable by the 2020 time frame. We were also required to select structural steels that satisfy the Nuclear Regulatory Commission's (NRC) rules (10CFR61) for near-surface burial of Class C low-level radioactive waste. In addition, the reactor blankets were to have a low tritium inventory (<1 kg) and were not to use flammable liquid metals. Finally, the size of the MARS reactor was to be comparable to Starfire and today's largest nuclear fission plants.

3. Key Features of the MARS Design

The MARS commercial fusion electric plant, described in Ref. 3, Vols. 1-A and 1-B, is shown in Figs. 1 and 2. The reactor has a 130-m-long cylindrical central cell producing 2600 MW of fusion power in steady state. Neutron energy multiplication (1.36) in a liquid lithium-lead ($\text{Li}_{17}\text{Pb}_{83}$, hereafter referred to as Li-Pb) blanket (Fig. 3) increases the reactor's thermal power to 3349 MWth, and efficient direct conversion of the plasma exhaust out the ends (Fig. 4) leads to a high net plant efficiency of 36% and a high net electrical power production of 1200 MWe. Table 1 summarizes key

Fig. 1. General view of the MARS tandem mirror reactor plant.

Fig. 2. View of one end of the MARS reactor.

Fig. 3. A section of the MARS central cell (commercial electric reactor). The method for removing one of the Li-Pb blanket modules is shown.

MARS reactor parameters for electricity production. With a total capital cost of \$2.9 billion (constant 1983 dollars), a 15% fixed charge rate, 6 years of construction, 10% inflation rate, and 73% predicted plant availability, the MARS electric power plant produces busbar electricity at about 7¢ per kW hour, competitive with new electricity costs in many parts of the U.S. today. Table 2 summarizes MARS reactor costs.

Improved safety and reduced environmental hazards will facilitate siting and licensing of MARS fusion reactors compared with today's fission reactors. The HT-9 ferritic steel structure used in the MARS Li-Pb blanket (Fig. 3) will not melt in any loss-of-coolant accident and will last at least 5 years before

Fig. 4. Cross section of the end-plasma technology system located in each end cell. The central, gridless, direct converter comprises an inner and outer collector and is surrounded by the inner halo scraper and the outer halo vented plate.

scheduled replacement. Because nearly all the radioactivity in the steel has less than a 5-year half-life, the spent blanket modules can be simply filled with concrete and safely disposed of using near-surface burial according to NRC regulations for Class C low-level waste. In addition, the liquid Li-Pb coolant will not burn in air or water and contains extremely low concentrations of tritium--less than 8 g in the entire coolant inventory.

The MARS commercial fusion synfuels plant, described in Ref. 3, Vol. 2, uses a slightly longer central cell (150 vs 130 m) and produces more fusion power (3500 vs 2600 MW) compared with the electricity-producing design. A helium-gas-cooled, silicon-carbide, pebble-bed blanket (Fig. 5) provides high temperature heat (1000°C) to a thermochemical water-splitting cycle (Fig. 6), producing hydrogen with an energy equivalent to 26,000 barrels of oil per day.

Table 1. Major parameters for the MARS commercial electric plant.

Central cell length (m)	130
Plasma radius (m)	0.49
First wall radius (m)	0.6
Fusor power (MW)	2600
Plasma power gain Q	26
Average central beta $\langle \beta_c \rangle$	0.23
Peak central density ($\times 10^{20} \text{ m}^{-3}$)	3.3
Ion temperature (keV)	28
Electron temperature (keV)	24
Central cell field (T)	4.7
Peak choke coil field (T)	24 ^a
Yin-yang mirror field (T)	7.5 ^b
First wall loading (MW/m ²)	4.3
Blanket coolant-breeder	Li-Pb
Coolant outlet temperature (°C)	500
Blanket power multiplication	1.36
Tritium breeding ratio	1.15 ^c /1.12 ^d
Anchor ICRH power, absorbed/injected (MW)	5.7/6.7 (each anchor)
Plug neutral beam power, absorbed/injected (MW)	2.84/4.43 (each plug)
ECRH power, absorbed/injector (MW)	42/42 (each plug)
Copper coil power, inserts, and drift pumps (MWe)	50 (each end)
Total recirculating power (MWe)	334
Electric power from the direct converter (MWe)	292 ^e /388 ^f
Net electric power produced (MWe)	1200
Recirculating power fraction	0.22
Total energy stored in magnets (GJ)	49

Efficiencies

Direct converter	0.519/0.68 ^h
475-kV sloshing-ion beams	0.70
ECRH	0.70
Anchor ICRH	0.55
Thermal cycle	0.40
Overall system (plant)	0.36

^a16 T from outer superconducting coil plus 9 T from copper insert coil.

^b10 T on conductor.

^cBlanket local tritium breeding ratio.

^dOverall reactor tritium breeding ratio.

^eNet direct electric conversion.

^fTotal electric power from the end loss plasma conversion.

^gNet direct electric conversion efficiency

^hTotal electric power from the end loss plasma conversion.

Table 2. Summary of capital costs for the MARS electric plant.

Account	Title	Cost (M\$) ^a
20	Land and land rights	5.0
21	Structures and facilities	249.8
22	Reactor system	1,517.3
23	Turbine plant	275.0
24	Electrical plant	160.0
25	Other	33.2
26	Special materials	124.9
91	Construction equipment and services	240.0
92	Engineering and management	189.0
93	Other	<u>118.0</u>
	Total	2,912.2

^aMillions of dollars.

This represents a 43% conversion efficiency of fusion energy to hydrogen energy. The hydrogen is catalytically combined with 1000 tons of coal per day to produce 38,000 barrels per day of liquid methanol fuel for pipeline distribution. The MARS synfuel plant, with \$3.6 billion total capital cost (constant 1983 dollars), 10% interest during construction, 6 years of construction, and 73% maximum capacity factor, would produce methanol fuel for a cost of about \$1.7 per gallon. The need for liquid synfuels-producing MARS reactors is expected to increase when both world oil reserves and low-cost, near-surface coal deposits begin to be depleted some decades after fusion electric plants are introduced.

The MARS electricity and synfuel reactors use similar end cells at each end of their respective central cells (see Figs. 1 and 2). Figure 2 depicts four distinct types of end cell magnets: (1) the transition coil to match the magnetic flux bundle from the choke coil to the subsequent end cell magnets;

Fig. 5. Design of the high-temperature blanket for synfuels production.

Fig. 6. GA Technology's sulfur-iodine cycle for MARS synfuels production.

(2) the anchor minimum-B yin-yang coil set; (3) the plug minimum-B yin-yang coil set; and (4) the recircularizing coil set designed to present a magnetic flux bundle of circular cross section to the direct converter. Within the plug region, continuous injection of neutral beams and microwave heating generate electrostatic potential barriers to confine the steady-state deuterium tritium (DT) plasma in the central cell.

The central cell fusion plasma is fueled with high-velocity (20 km/s) pellets of DT ice near one of the ends. The required injection rate is 6.5 pellets/s. Nearly all 3.5-MeV fusion alpha particles are born mirror-trapped by high-field (24-T) mirrors ("choke coils") at each end, permitting most alpha energy to be transferred to the DT fuel ions and electrons. With positive plug potential barriers ($\phi_{\text{plug}} - \phi_{\text{central cell}} > 150 \text{ kV}$), the central cell ion end loss is reduced enough to allow alpha heating to sustain the residual axial and radial energy losses of the central cell, i.e., the central cell plasma is ignited. Thus, the only auxiliary central cell heating needed is 5 to 10 MW of ion-cyclotron resonant heating (ICRH) for 120-s periods during startup. The power gain factor $Q \equiv \text{plasma fusion power} / \text{plasma heating power}$ then increases roughly linearly with the central cell length. We chose the

length of the MARS central cell (130 m) to produce 1200 MWe of net power, which yields a Q of 26.

The "thermal barriers"⁸ required to moderate end plug heating power are maintained by inducing radial loss of ions trapped in the thermal barrier with low frequency (50-kHz) rf fields, called drift pumping.¹⁴ Because drift pumping of central cell ions that collisionally trap in the plugs represents a loss to the central cell, central cell ignition burn can be controlled by feedback modulation of the drift-pump rf current. Because of the drift-pumping and high plugging potentials, nearly all of the unburned DT fuel, thermalized alpha ash, and other impurities escape by radial diffusion to the plasma edge, or "halo," in the end cell. This diverts the plasma exhaust into annular halo dumps in the end tanks (see Figs. 2 and 4). The unplugged plasma halo, together with drift pumping, acts as an impurity diverter and high-speed vacuum pump, minimizing first wall surface heating and sputtering in the central cell. The plasma electrons are left to escape along the field lines, and are collected by negatively biased end plates inside the halo dumps. The electrons collected at 167-kV negative voltage directly generate enough dc electricity (approximately 300 MWe) to match nearly all plug heating and plant auxiliary power requirements (see Table 1). Radial loss of end-plugged ions eliminates the need for grids,¹⁵ permitting the compact, high-power electron direct converter to fit within an MFTF-size (10-m-diameter) vacuum tank (Fig. 4).

Many of the MARS plasma confinement and magnet design features are derived from related past and present tandem mirror experiments. The MARS end cell magnets (Fig. 2), in the shape of "C" coils or yin-yangs, are similar to those used in 2XIIB,¹⁶ TMX-U,¹ and MFTF-B to obtain high-beta MHD stability. In 1975, the 2XIIB experiment¹⁶ demonstrated near-unity beta in a neutral-beam-sustained plasma with reactor-level plasma pressure (10 keV, 10^{14} cm⁻³ ion temperature and density). The MARS yin-yang magnets are designed and costed in accordance with MFTF-B's successfully tested niobium-titanium superconducting yin-yang magnet. Only modest extrapolations in size are needed to attain the MARS reactor scale; thus, technical risk is minimized. The plasma model¹⁷ used to design the MARS end cell has successfully predicted much of the experimental behavior recently observed in the TMX-U: microstable sloshing ions with loss rates calculable with Fokker-Planck codes, enhanced

potential barrier formation with ECRH, reduction of ion end losses by plugging until residual radial ion losses dominate, net electron current collection on end wall plates, and improved vacuum pumping by the plasma halo. Unique MARS features such as high-field choke coils and drift pumps are planned for testing in TMX-U in the near future.

Several new, but developable, technologies in the MARS design are keys to its performance. The Li-Pb blanket itself (Fig. 3) is very simple and rugged, and blanket modules for remote replacement weigh only 2.7 tons each when drained. Scheduled module replacement every 5 years requires only 11 days of downtime. Critical technologies for this blanket design are double-walled-tube heat exchangers to reduce tritium permeation into the steam cycle to less than 10 Ci/day, and cold traps to control deposition of corrosion products within the main heat transfer loop. Most of the tritium vulnerable to release as T_2 is in the tritium purification and separation system (~ 160 g) and in the pellet injector system (~ 20 g).

The MARS magnet set consists of 42 central cell solenoids spaced 3.16 m apart, followed by an end cell coil set at each end containing a circular high-field choke coil (Fig. 7a and b), a series of 6 C-shaped coils, and a final circular trim coil. All coils use a ductile NbTi superconductor except for the inner layers of the superconducting part of the choke coil, which use Nb_3Sn (doped with Ti) where the local field is 16 T. As maximum wall loading Γ_n and Q both increase strongly with the choke coil field B_{max} , there is a strong incentive for the highest practical B_{max} . To increase B_{max} beyond the limits of practical superconductors (~ 16 T at $r = 1.4$ m), a water-cooled, high-strength copper alloy coil is inserted inside the choke coil shield (see Fig. 7b) to increase B_{max} to 24 T at $r = 0.3$ m. The electricity consumed by the resistive inserts (80 MWe for two inserts) is more than compensated for by reductions in plug heating power, particularly in electron-cyclotron resonant heating (ECRH). The lifetime of the small replaceable insert coils is expected to be about four years with the use of inorganic (ceramic) insulation. The water-cooled copper coils used for the 50-kHz drift pumping (Fig. 8) are expected to last for the operating lifetime of the reactor.

Plasma heating in MARS is summarized in Table 1 in terms of the power each system delivers to the plasma. The large majority of the total heating power is needed to maintain the hot electron thermal barrier (38.5 MW of 60-GHz ECRH power at each end). Such a large ECRH power requirement necessitates

Fig. 7. (a) The MARS magnet system. (b) Cross section of the 24-T choke coil showing the outer superconducting solenoid and the normal conducting insert solenoid (also see Fig. 22).

Fig. 8. Location of the drift pump coils within the yin-yang coil structure.

gyrotrons in unit sizes larger than present-day models, i.e., at least 1 to 2 MW/tube. Figure 9 is a conceptual design of a 2.5-MW tube with a large transverse cavity. Parabolic mirrors reflect the 30-cm-diameter microwave beams from arrays of 20 gyrotron tubes (18 operating + 2 spares) into slots in the yin-yang coil shielding. No microwave windows are required; and, to minimize neutron damage and activation, the demountable gyrotrons are placed outside the line-of-sight to the plug plasma.

Two ICRH systems are used in MARS (Fig. 2). The first--12 MW delivered, 10 MW absorbed--is used only to aid startup in the central cell. The second--6.7 MW delivered, 5.7 MW absorbed at each end--is used to maintain hot ions in

Fig. 9. Schematic cross section of a high-power quasi-optical gyrotron.

each anchor yin-yang for MHD stability. Thus far, experiments in TMX-U have succeeded in producing startup without the aid of ICRH, but we specify 10 MW (absorbed) of ICRH for the added ability to heat the MARS central cell to ignition (see Sec. 4.5). The ICRH frequencies needed (~ 50 to 120 MHz) are typical of those used in tokamaks.

Although the sloshing-ion beam power trapped in the MARS plugs is relatively small (2.34 MW absorbed at each end), the sloshing ions require a large size negative-ion beamline for steady-state injection at 475 kV (Fig. 10). After acceleration to 475 keV, the unneutralized negative ion

Fig. 10. The 475-keV negative-ion neutral beam system for sloshing-ion production in the end cell. The insert at the top of the figure illustrates the neutron shielding for the ion source and accelerator.

beam, in the shape of a wide ribbon, is bent by electrostatic transverse-field-focusing electrodes around neutron shielding to protect the negative ion source and accelerator from streaming neutrons. The advantage of this beamline design is that the high-voltage components are shielded from neutron damage and are easier to access for remote maintenance. A laser photodetachment scheme is used for neutralization.

4. Reactor System

4.1 MARS Reactor Configuration

The MARS reactor configuration (Fig. 11) was selected to incorporate the key features of thermal barrier plugs in the TMX-U (Fig. 12) and MFTF-B (Fig. 13) mirror facilities. Thermal barrier plugs generate the electrostatic potential barriers that axially confine the central cell plasma. Thermal barriers are the primary common element in TMX-U, MFTF-B, and MARS. The special groups of hot ions and electrons that create the thermal barrier in TMX-U have recently been experimentally measured and their respective roles in forming the potential profile shown in Fig. 12 have been experimentally verified.⁷ The positive electrostatic plugging potential at point "a" virtually eliminates axial loss of central cell ions. This plugging potential is generated and controlled by a small amount of ECRH power heating the electrons at point "a" to a temperature well above the central-cell electron temperature. The largest plug plasma heating requirement is ECRH power at point "b," forming mirror-trapped hot electrons and a local dip in potential near the midplane. The potential dip thermally insulates the outer electrons at "a" from the central cell electrons (hence the term "thermal barrier").

The axial pressure of the plugged central cell plasma is confined in steady-state equilibrium mostly by the 24-T choke coil fields at each end of the central cell. The small fraction (<10%) of central cell ions in the loss cone pass into the end cell, reflect off the electrostatic potential peak in the plug, and return to pass through the central cell. The plasma models used to predict the thermal barrier plasma parameters in TMX-U and MFTF-B are essentially the same models¹⁷ used to calculate the MARS plasma parameters.

Whereas axial confinement in the MARS central cell is provided by choke coils and electrostatic potential plugs, radial confinement in the central

Fig. 11. Magnetic field and electrostatic potential profiles as a function of the axial (z) distance from the center of the central cell. The positions of the thermal barrier and electrostatic potential peak are indicated relative to their location in the plug yin-yang.

Fig. 12. Plasma parameters as a function of axial distance for the end cell of TMX-U.

MFTF-B
(1987)

Fig. 13. Plasma parameters as a function of axial distance for the end cell of the MFTF-B facility currently under construction at LLNL.

cell is provided by a 4.7-T solenoidal magnetic field. The high fusion power density in the MARS central cell plasma (27 MW/m^3) requires a significant ratio (beta) of plasma pressure to field pressure ($\beta_c = 0.28$), averaged over the central cell plasma volume. Accordingly, the second key consideration in selecting the MARS configuration was the design of end plug magnets that could provide MHD stability for the MARS plasma at the high beta values required. To allow for both MHD stability and to counter trapped-particle instability¹⁸ (a predicted fast-growing mode that first came to light during the early part of the MARS study), the recommended location of the thermal barriers was within minimum-B magnetic wells,¹⁹ as in TMX-U. Accordingly, during the study, the MARS (and MFTF-B) end plug designs were changed from having thermal barriers in axisymmetric mirror cells (called "TARA" configurations)²⁰ in favor of placing the thermal barriers in additional minimum-B regions, as is shown in Figs. 14 and 15, respectively.

To enhance stability and allow higher central cell beta values compared with MFTF-B, the MARS design adds ICRH to increase the plasma pressure weighting in the positive-curvature region of the transition. Local mirror confinement of the ICRH-heated ions in the positive-curvature transition region (called the "anchor") favors the use of a second yin-yang coil pair for MARS in place of the larger, baseball-shaped transition coil used in MFTF-B. The resulting plasma shape in MARS, however, is nearly identical to the shape in MFTF-B (Figs. 14 and 15), except that an additional C-shaped coil is added to each end of MARS to recircularize the plasma field lines so that they map into a compact, circular, direct converter.

After MHD plasma equilibrium and stability come requirements for controllable plasma transport in the MARS configuration. Geodesic curvature is the component of field-line curvature that projects along the plasma surface, orthogonal to the local normal curvature component. Geodesic and normal curvatures for both MARS and MFTF-B can be seen in Figs. 14 and 15, respectively. Radial diffusion and transport depend mainly on the integral of geodesic field-line curvature seen by central cell ions as they reflect off the potential barriers in the plugs. As Figs. 14 and 15 show, MARS and MFTF-B are each designed with equal and opposite geodesic curvature spikes, so that radial drifts of ions passing through these regions are canceled out. A certain amount of residual plasma transport is desired in MARS to cleanse the plasma of thermalized alpha ash and other impurities, and to simultaneously

Fig. 14. Axial variation of the normal and geodesic curvature components of the MARS plasma bundle.

Fig. 15. Axial variation of the normal and geodesic curvature components of the MFIF-B plasma bundle.

remove DT fuel ions that become trapped in the thermal barrier potential dip as a result of collisions. This desired residual radial transport is achieved by "drift pumping." Here, a small ac magnetic field perturbation, oscillating at the trapped ion bounce frequency, is applied by drift-pump coils above and below the plasma fans in the end cells, thereby producing a slight nonzero cancellation of the geodesic curvature.

Another key element in both the MARS and MFTF-B configurations is a high-field circular choke coil (see Figs. 2 and 7b) whose function is to allow steady-state operation with much higher plasma density in the central cell than in the transition regions and thermal-barriers. With the removal of the majority of trapped ions in the end cell by drift pumping, the allowed ratio of central cell density to end cell density is roughly the ratio of maximum choke-coil field to the end cell fields; that is, the density profile follows the field profile to the right of the coil, as illustrated in Figs. 11, 12, and 13. To maximize central cell fusion power density while minimizing end cell auxiliary heating power density, we desire the maximum central cell-to-plug density ratio, hence the need for the maximum practical choke coil mirror field. Thus, a normal resistive insert coil is used in the MARS choke coil to boost the maximum field beyond that possible with superconductors alone.

The equipment for plasma fueling, heating, and exhaust in MARS is illustrated in Fig. 2, which shows one end of the reactor. At the end of the central cell by the high-field choke coil, a high-velocity (20 km/s) DT pellet injector for fueling the central cell can be seen. The pellets are injected near one of the choke coil mirrors because the plasma radius is smaller in that region (allowing easier penetration) and the number density of fast alphas is small (for reduced pellet ablation). Also, near the choke coils at one end of the central cell, ICRH antennas deliver a total of 12 MW for 120 s to heat the central cell ions to ignition temperature during startup. Once steady-state conditions are attained, the plasma heating required to maintain equilibrium is that required to maintain the thermal-barrier for potential plugging--38.5 MW* ECRH at each end at 60 GHz, 3.3 MW* ECRH at each end at 71 GHz, plus 4.43 MW* sloshing-ion neutral beams at each end at 475 kV--and to maintain the anchor--6.7 MW* ICRH at each end at 55 MHz. Impurity removal and

*Injected powers (i.e., delivered power from heating system).

plasma exhaust are accomplished by two sets of drift-pump coils, which cause nearly all ions to diffuse radially to the plasma edge (halo), where they are diverted along the outer field lines into an annular dump, called a halo scraper. The halo scraper is connected to mechanical vacuum pumps. The plasma electrons escape along the field lines and are received at -167 kV negative potential by a gridless direct converter plate.

The remote maintenance design philosophy in MARS exploits the linear MARS geometry to minimize reactor downtime required for scheduled and unscheduled remote maintenance of critical reactor components. The maximum stable plasma beta is high because the magnetic axis is straight, reducing the average field line curvature. High beta allows high plasma-fusion power density and small radius plasmas, which in turn reduce the size and weight of the blanket sections (2.7 tons each when drained) that need periodic replacement (Fig. 16). The MARS plasma equilibrium requires no driven plasma current, permitting steady-state operation with blankets and magnets subjected to usually only one thermal and mechanical stress cycle per year (during the annual maintenance shutdown period).

The modular MARS central cell configuration (Fig. 17) capitalizes on the small blanket module size by providing for their scheduled replacement through periodically spaced service ports, leaving in place the reflector, shield, and magnets, which are designed to last the life of the plant. To minimize reactor downtime for minor maintenance operations, enough shielding is provided to permit hands-on maintenance to be performed outside the shield within two days after shutdown. In the unlikely event of failure of any reflector, shield, or magnet, the central cell is divided into 6.4-m segments, each with two central cell coils. Each segment can be removed as a whole unit by transhaulers mounted on floor rails and can be replaced by a spare unit.

In a similar fashion, the remote maintenance design philosophy for the MARS end cell is to provide for replacement of all critical end cell components, such as choke coil inserts, drift-pump and ICRH antennas, gyrotrons and neutral beam sources, and the halo scraper portion of the direct converter. These items are designed to be replaceable without moving any of the magnets. However, provision is still made for removing the end cell magnets on a transhauler/rail system, similar to the system used in the central

Fig. 16. Cross section of the MARS central cell showing the Li-Pb blanket.

cell, to minimize reactor downtime in the unlikely event of failure of any end cell magnet or shield. As illustrated in Fig. 18, the linear MARS geometry avoids interlinking any of the magnets by windings or massive structures, so that individual magnets can be replaced if necessary.

Fig. 17. Disassembly sequence of a service station during routine maintenance of the central cell.

Fig. 18. Details of the magnet support and transport structure in the end cell.

4.2 Plasma Engineering Design

4.2.1 Introduction

The primary plasma engineering task for MARS was the calculation of a self-consistent set of plasma and magnetic field parameters that satisfies performance goals, physics constraints, and magnet engineering limits. The study targeted three basic performance goals (not requirements):

- The fusion power should be high enough to produce a net electrical power output comparable to Starfire.¹³ At the beginning of the MARS study, the fusion power target was set at 3500 MW (the same as Starfire). Later calculations of the net electric power indicated that the fusion power could be decreased to 2600 MW to achieve the equivalent net electric power as Starfire (1200 MWe).
- The plasma power gain factor Q (central-cell fusion power)/(plug-plasma heating power) should exceed at least 25 to achieve reasonable recirculating electric power fractions.
- The central-cell neutron wall loading should be in the vicinity of 4 to 5 MW/m² for blanket power densities.

In pursuit of these goals, we maintained a nominal central cell plasma radius of about 0.5 m, and sought a plug design allowing a stable average beta $\langle\beta\rangle = 0.28$ at a constant central cell field $B_c = 4.7$ T, which would produce the desired wall loading. Maintaining constant central cell radius, beta, and field also guaranteed a constant magnetic plasma flux connecting the central cell and plugs, and thus a constant-size aperture requirement inside the choke coil and end cell coil bores. Holding these central cell parameters nearly constant during the study permitted detailed designs of the central cell blankets, shields, and magnets to proceed while the end plug design evolved in several iterations. The main plasma engineering challenge was thus to develop a plug design that could satisfy the physics and engineering constraints and meet the prescribed performance goals for the central cell.

4.2.2 End Cell Design and Power Balance

The final MARS end cell design had to simultaneously satisfy a set of plasma engineering requirements (Table 3), including plasma stability and confinement requirements as well as important end cell magnet requirements affecting the plasma parameters. The most important plasma engineering requirements impacting the end cell magnet design were MHD equilibrium and stability (items 1, 2, and 4 in Table 3), whose simultaneous resolution required a double-ellipse plasma shape between the central cell and plug cell (as shown in Fig. 14), together with ICRH in the anchor yin-yang region to increase the MHD ballooning beta limit to the required value of $\langle \beta_c \rangle = 0.28$ at $B_c = 4.7$ T in the central cell.

The final MARS plug design solution involved repetitive, closely coupled application of three basic plasma engineering design codes: EFFI,²¹ TEBASCO,²² and TMRBAR.¹⁷ Trial values of the coil cross sections and

Table 3. MARS plasma engineering requirements.

-
1. MHD ballooning stability at $\langle \beta_c \rangle = 0.28$.
 2. Trapped-particle mode stability.
 3. Null central-cell radial electric fields.
 4. Null plasma-equilibrium currents in the central cell.
 5. Circular flux tubes in the central-cell, choke coil, and direct converter.
 6. Ignition via central-cell alpha-power balance.
 7. Thermal alpha ash and impurity removal.
 8. Mirror-mode stability in the anchor.
 9. Sloshing-ion confinement, adiabaticity, and microstability.
 10. Ion-ion two-stream stability in the end cells.
 11. Penetration and efficient absorption of ECRH.
 12. Adequate halo fnd1, T_e to ionize gas.
 13. First-wall, end-cell magnet clearance for a one-alpha-orbit-thick halo.
 14. Yin yang access for ECRH, sloshing beams, drift pumping, and shielding.
 15. Maximum yin-yang conductor fields ≤ 10 T.
-

current densities were input to the magnetic field code EFFI and these were iterated to achieve both the desired plasma fields and maximum coil conductor fields (≤ 10 T on the end cell C-shaped coils for NbTi at 1.8 K). The final MARS end cell magnet dimensions and peak conductor field strengths are listed in Table 4. These magnets are illustrated in Figs. 7 and 14. Next, the magnetic fields calculated by EFFI were input to the tandem equilibrium and stability code TEVASCO. TEVASCO then calculated central cell beta limits (Table 5) for both interchange modes and $m = 1$ ballooning modes (ballooning limits stability more than interchange modes). The $m = 1$ ballooning-mode beta limit depends on S_β , the gap between first wall and plasma divided by the plasma radius. For the final MARS design (Table 5), the appropriate value of S_β is 0.22, giving a predicted $\langle \beta_c \rangle$ limit of 0.31, which is slightly larger than the specified central cell requirement of 0.28. Following this, beta limits calculated by TEVASCO were input to the power balance code TMRBAR, which calculates the resulting plasma parameters in the central cell (Table 6) and end cells (Table 7); required end cell ECRH, ICRH, and neutral-beam-injected powers (Table 8); and direct converter parameters (Table 9).

One sequence of EFFI, TEVASCO, and TMRBAR computations was followed by a series of checks on system parameters, including maximum conductor fields, plasma-magnet clearances, microstability, sloshing-ion confinement, heating powers, heating system access, etc. In the event that a consistency check was not satisfied, the sequence was repeated with an appropriate change of an input parameter to TMRBAR or EFFI.

4.2.3 Drift Pumping

Drift pumping produces the most important plasma loss process in MARS, and therefore is the primary factor in determining power balance in the central cell (ignition), as well as in determining steady-state operation by removing trapped ions--including thermalized alpha particles and other impurities--from the transitions and thermal barriers in the end cells. Figure 19 illustrates the basic ion and electron particle flows caused by the drift-pumping process. To the left of the choke-coil mirror peak in Fig. 19 is the central cell, where the majority of ions, including 3.5-MeV alpha particles, bounce back and forth, mirror-trapped between the choke coil mirrors. The fraction of central cell ions with sufficient pitch angle to be

Table 4. MARS magnet dimensions and fields.

Coil	Mean diameter (m)	Central field (T)	Peak field inner radius (T)		Super-conductor
			Major	Minor	
Central cell	5.42	4.7	7.2		NbTi
Choke-background	3.8	24	16.1		Nb ₃ Sn:Ti, Nb ₃ Sn, NbTi
Choke-insert	1.2	24	24		Copper (normal-conducting)
Transition	2.2, 6.5	4.1/7	9.5	2.5	NbTi
Anchor	2.2, 5.0	7.3/3.9/7.3	9.9 9.7	10.5 10.7	NbTi NbTi
Plug	2.2, 6.5	7.2/3.0/7.5	9.2 9.7	9.8 9.8	NbTi NbTi
Recircularizer					
C coil	2.2, 5.0	7.5	9.8	9.5	NbTi
Solenoid	2.2	--	6.5		NbTi

Table 5. MARS MHD stability parameters.

- 150-m-long central cell
- 6% axial field ripple on 3.16-m pitch
- $\langle \beta \rangle = 0.5$ -in. anchor and plug
- β limits for flute interchange; $m = 1$ ballooning:

S_B^a	$\langle \beta_c \rangle$ limit
0	0.335
0.14	0.316
0.65	0.280
1.0	0.265

- MARS S_B in central cell = 0.22
- Predicted $\langle \beta_c \rangle$ limit = 0.31; specified $\langle \beta_c \rangle = 0.28$

^aNote that $S_B = (r_w - r_p)/r_p$, where r_w and r_p are the first wall and plasma radius, respectively.

Table 6. MARS central cell parameters.

Fusion power (MW)	2600
Peak DT density ($\times 10^{14} \text{ cm}^{-3}$)	3.3
Alpha density ($\times 10^{13} \text{ cm}^{-3}$)	2.0
Ion confinement τ_i ($\times 10^{14} \text{ s/cm}^3$)	5.2
Electron confinement τ_e ($\times 10^{14} \text{ s/cm}^3$)	5.3
Central cell magnetic field (T)	4.7
Neutron wall loading (MW/m^2)	4.3
$\langle \beta_c \rangle$	0.28
Plasma radius (cm)	49
Plasma density profile	Quartic
First wall radius (cm)	60
Ion temperature (keV)	28
Electron temperature (keV)	24
Cold fueling current (kA)	2.1

Table 7. MARS end cell parameters.

<u>Choke coil</u>	
Peak field (T)	24
<u>Transition/anchor</u>	
Length (m)	13.3
Passing-ion density at field minimum ($\times 10^{13} \text{ cm}^{-3}$)	1.7
DT particle trapping current at each end (A)	800
Hot-ion density in anchor ($\times 10^{13} \text{ cm}^{-3}$)	4.2
Hot-ion energy in anchor (keV)	690
$\langle \beta_{\text{anchor}} \rangle$	0.5
<u>Plug</u>	
Length (m)	5.3
Passing-ion density at barrier ($\times 10^{12} \text{ cm}^{-3}$)	4.7
Trapped-ion density at barrier ($\times 10^{12}$)	8.2
Sloshing-ion density at barrier ($\times 10^{12} \text{ cm}^{-3}$)	9.4
Warm-electron temperature at potential peak (keV)	124
Hot-electron energy at barrier (keV)	840
$\langle \beta_{\text{plug}} \rangle$	0.5

Table 8. MARS plasma heating requirements.

	Absorbed power, each end (MW) ^a	Delivered power, each end (MW) ^b
Anchor ICRH	5.7	6.7
Sloshing-ion neutral beam	2.84	4.43
ECRH at poing "b" (thermal barrier)	38.5	38.5
ECRH at poing "a" (potential peak)	3.3	3.3
Totals	50.34	52.93

$$\text{Plasma power gain } Q = \frac{\text{plasma fusion power}}{\text{plasma heating absorbed power}} = \frac{2600}{2 \times 50.34} = 26$$

Startup ICRH power (total) for central cell,
absorbed^a/delivered^b is 10/12 MW

^aPower absorbed by plasma.

^bPower delivered to plasma by heating system.

Table 9. MARS direct converter parameters.^a (The energy conversion performance of this system is given later in Table 14.)

Inner halo scraper

2.01-kA ions - 0.12-kA electrons = 1.89 kA

V = 0, P_e = 0, H = 100 MWth

Outer halo vented plate

V = 0, P_e = 0, H = 20 MWth

Outer end collector

0.03-kA ions - 0.32-kA electrons = -0.29-kA net electron current

V = -84 kV, P_e = 25 MWe, H = 22 MWth

Inner end collector

0.15-kA ions - 1.75-kA electrons = -1.60-kA net electron current

V = -167 kV, P_e = 267 MWe, H = 139 MWth

^aV = potential, P_e = directly converted electric power, and H = thermal power.

Fig. 19. Particle transport to the halo by means of drift pumping. The magnet configuration and field/potential profiles are shown on the same axial scale for reference.

mirror-trapped is $(1 - B_c/B_{choke})^{1/2} > 90\%$; thus, the choke coil mirrors hold back the majority of the axial central-cell plasma pressure.

The remaining central cell DT fuel ions pass through the choke coil mirrors, reflect off the potential peaks in the plug mirror cells (shown in Fig. 19), and return back to the central cell. Thus, the plug plasma that generates the potential peak holds back only a small fraction of the central cell pressure. During the average deuterium or tritium ion lifetime of $1.6 \text{ s} \approx 2 \times 10^4$ bounce periods, coulomb collisions cause the average ion's pitch angle to change many times while in the high-density central cell. Collisions in the end cell cause the pitch angle of an average ion to vary only a fraction of 90 deg during the time the ion spends in the lower density regions of the end cell, but this is still enough to trap most DT passing ions between the choke-coil mirror peak and the end plug potential peak. Without drift pumping, trapped ions would slowly accumulate in the end cell as a result of collisions, and would eventually destroy the potential barrier confining the passing ions.

Thus, one basic function of drift pumping is to induce enough radial loss of the trapped ions to match their collisional trapping rate. With drift pumping removing the trapped ions, the resulting axial density profile $n_{\text{transition}}$ in steady state then follows closely the density of the passing ions, so that approximately

$$n_{\text{transition}}(z) \approx n_c B_{\text{transition}}(z)/B_{\text{choke}},$$

where n_c is the central cell density. This transition density is maintained by a continual radial loss of trapped ions induced by the drift pump, as shown schematically in Fig. 19c. When the trapped ion diffuses to a radius just greater than the radial extent of the confining potential barrier, the trapped ions spill out the ends within a thin annulus just at the inside edge of the halo, where they are intercepted by a halo scraper and pumped out of the reactor.

Because the drift-pump rf fields are tuned to the range of ion bounce frequencies, which are much lower than electron bounce frequencies, the induced radial diffusion is selective to the ions, leaving the electrons to escape only along the field lines. The net electron current collected by the direct converter plates at the ends directly generates electric power by forcing electron current at a negative plate potential under load. Thus, by separating ion and electron end losses, the selective ion radial diffusion

inocued by drift pumping allows a simple form of direct energy recovery with negatively biased end wall electron collectors. Another important benefit results from the negative bias of the end walls in that radial electric fields are reduced to nearly zero in the MARS central cell (see Fig. 19b and c), virtually eliminating rotation as an additional contributor to MHD instability and resonant ion-transport as an additional contributor to radial transport in the central cell. Recent evidence indicates that negatively biased end-wall plates reduce nonambipolar ion radial loss in the TMX-U central cell.²³

Another essential function of drift pumping is to remove thermalized alpha ash and other impurities (item 7 in Table 3). After the mirror-trapped 3.5-MeV fusion alpha particles transfer their energy by drag to the central-cell DT ions and electrons, a majority of the alphas ($\geq 70\%$) end up thermalized to the DT ion temperature, at which temperature the axial electrostatic confinement time of the alphas is about 100 times longer than for the DT ions. Without radial loss, the thermalized alpha ash would build up to densities exceeding the DT fuel density, causing drastic reductions in plasma gain Q and wall loading Γ_n . The thermal alphas pass into the end cell and collisionally trap there just as the DT fuel ions do. Drift pump frequencies are therefore broadened sufficiently to pump all species of interest (trapped DT ions, trapped alphas, and plasma impurity ions). Because of the strong potential peak seen by the alphas and impurities in the core of the plasma, nearly all the alphas and impurities divert out along the halo and are removed by the vacuum pumps connected to the halo end structure (Fig. 19). Figure 20 shows the location of the MARS drift pump coils at the peaks of the geodesic curvature in the transitions. There are two hairpin-shaped single-loop coils above and below each plasma fan, at each curvature peak (i.e., two sets of coils at each end of the reactor). The pair of coils on the left peak ("transition" drift pump) remove the majority of the trapped DT ions and thermal alphas, and in addition, the coil pair on the right peak is tuned to pump the sloshing ions (to maintain their double-humped axial profile) and any residual current of deeply trapped cold ions in the thermal barrier. The largest drift-pump amplitude and power requirement by far is for the transition drift-pump coil. Table 10 lists the MARS drift-pump coil parameters.

The trapping and drift pumping of DT ions in the end cells represents a major loss of particles and power from the central cell. Therefore, for fusion alpha heating to balance the central-cell plasma energy losses (ignition), the

Fig. 20. Location of the transition and plug drift pump coils in the end cell plasma ions. The axial variation of the geodesic curvature is shown for reference.

Table 10. MARS drift-pump coil parameters.

Parameter	Transition drift pump coil for spanning DT ions and thermal alphas	Plug drift pump coil for sloshing and deeply trapped ions
Peak rms current, each coil (A)	26,000 18,000	1,400 970
Peak rms voltage, each coil (V)	52,000 37,000	27,000 18,900
Inductance per pair (μH)	3.4	3.4
Ohmic loss per pair (MW)	1.54	0.2
Central frequency (kHz)	47	450
Frequency range ($\frac{\Delta f}{f}$)	0.4	0.66
Perturbing flux $\tilde{B}_1$ (T)	0.0420	0.0023
Number of frequencies N_ω intrinsic bandwidth	10	60
N_ω ($\frac{\Delta f}{f}$) (%)	0.5	9
Dissipated power/coil (MW)	3.4	1.7

axial ion losses must be reduced to levels that are small when compared with the drift-pump-induced losses in MARS. Small axial ion losses determine the large electrostatic plugging potentials ($\phi_{\text{plug}} - \phi_{\text{central cell}} \gtrsim 5 T_{ic}$) in MARS. Since only the smaller of the two ECRH heating powers (ECRH at point "a" in Table 8) controls this potential, there is not much impact on Q to raise the end plug potentials to the point where the direct converter plates collect essentially only the plasma electrons. Since ion radial loss then dominates over axial loss in MARS, drift-pumping then determines the MARS pellet fueling current ($I_{\text{pellet}} \approx I_{\text{trap,DT}} + I_{\text{burnup}} \approx 2 \text{ kA equivalent}$), and the equilibrium thermal alpha concentration ($n_{\alpha}/n_{DT} \approx 1/2 F_b$), where the burnup fraction $F_b \approx 1/2 (n_{\text{radial}} / \langle \sigma v \rangle_{DT} \approx 0.14)$.

4.2.4 Halo Physics and End Plasma Leakage

The drift pumping results in approximately 2 kA of DT ions at temperature $T_{ic} \approx 28 \text{ keV}$ and about 140 A equivalent of thermal alphas at the same temperature, exhausting out the ends of MARS just inside the halo. This end loss current strikes the halo scraper and the resulting neutralized gas becomes ionized and is pumped by the surrounding halo plasma.

Figure 21 shows a schematic of this outer part of the direct converter structure. The outer halo density is sustained primarily by the gas it ionizes near the scraper and down the length of the MARS plasma column. About 3% of the fusion alpha orbits in the central cell intercept and heat the halo electrons, maintaining the halo electron temperature high enough to ionize gas and sputtered impurities ($T_e \approx 50 \text{ eV}$). To maintain enough halo density to strongly attenuate neutrals and impurities incident on it ($n_i \gtrsim 5 \times 10^{12} \text{ cm}^{-3}$), a vented plate is recessed into a reentrant annular cavity so that halo ions recycle off the vented plate an average of 20 times before being pumped through the holes of the vented plate. The number of neutral recycles and, therefore, the resulting halo density are controlled by the pressure in the plenum behind the outer vented plate and the number of holes in the vented plate. The inflowing halo plasma pressure allows a high plenum gas pressure of about $4 \times 10^{-2} \text{ Torr}$, sufficient to allow the MARS vacuum pumping to be achieved with mechanical pumps instead of with cryopanel.

Outside the reentrant halo cavity and the plasma halo, however, the average gas pressure is much lower ($\approx 3 \times 10^{-7} \text{ Torr}$) because of pumping by

Fig. 21. Schematic of the plasma halo dump in the end cell showing the inner scraper and the outer vented plate.

ionization in the halo. The recycling halo in MARS is thus very similar to pumped limiters and diverter chambers being studied for some tokamaks. However, the halo ionization maintains a low neutral pressure at the first wall in the central cell, so sputtering of the first wall can be kept small, less than 0.1 mm per year under pessimistic assumptions. One major feature of the "natural diverter" action of the tandem mirror halo is that first-wall-surface heat loads are very low compared with other plasma confinement concepts. In MARS, the total surface heat flux at the first wall of the central cell is only $\sim 4.7 \text{ W/cm}^2$. The majority of this ($\sim 4.6 \text{ W/cm}^2$) is the result of bremsstrahlung with $\sim 0.1 \text{ W/cm}^2$ attributable to neutral and charged-particle bombardment.

4.3 Magnets

The MARS magnet system is designed to use proven technology from MFTF-B (when possible) and to extend this technology when there is a strong benefit in terms of reactor system performance. The overall magnet system is depicted in Fig. 22. The long central-cell solenoids provide a nearly constant field--5.5% ripple--along the length of the central cell. Magnetic plugging of the central cell plasma is provided by the high field (24-T) choke coils. The transition coil takes the circular flux bundle to an elliptic cross section for entry into the anchor yin-yang pair. The anchor creates a minimum-B well that provides most of the MHD stability for MARS. The plug yin-yang pair assists in providing stability. However, its principal function is to provide the location for the confining potential peak, the thermal barrier, and the sloshing-ion distribution for microstability. The final C coil recircularizes the flux bundle in conjunction with a small outer solenoid coil, thus presenting a plasma of circular cross section to the direct converter. The parameters for all the coils are presented in Table 11.

The greatest extrapolation from present technology is in the high field choke coil. To create a 24-T field on axis, we use a superconducting background coil operating at 15.8 T and a normal conducting insert that provides an additional 8 T on axis and operates at 24.8 T. Each coil provides a significant design challenge that is further complicated by a moderately high ($\sim 2.6\text{-MW/m}^2$) neutron loading. We developed the design of the background coil by using three conductor regions where the material and current density were varied with the field. The high field is, of course, accompanied by high stresses. These were accommodated using a Nitronic 40 steel-reinforced conductor that limits strain to 0.35%. To obtain sufficient current density in the superconductor at the high fields, we chose to use superfluid $^4\text{He II}$ at 1.8 K as the coolant. This also allows an increase in the heat flux, which results in about a factor of two increase in bulk current density. Because of the high cost of this coil, it is highly desirable to make it a lifetime component. Therefore, shielding must be provided to limit damage to the superconductor, insulator, and stabilizer as well as to limit nuclear heating. This shielding is illustrated in Fig. 7, which shows that the resistive insert actually serves as part of the shield. All radiation allowables are met with this design and no annealing of the conductor is required.

Fig. 22. The MARS magnet system and corresponding axial magnetic field profile.

The copper insert coil must be designed to minimize power consumption (both ohmic heating and coolant pumping) while producing the required field, have long life in the high radiation field, and be easily replaced. After a series of trade studies, we selected an internally cooled, uniform-current-density coil. The principal reason for this selection was the need to separate the coolant from the insulation to achieve reliable operation for several years. Our baseline design is a double pancake that is machined from a single plate. The number of double pancakes determines the length of the coil. The material is the cold-worked copper alloy MZC, which has a working

Table 11. Magnet system parameters.

Coil	Peak on-axis field (T)	Peak conductor field (T)	Conductor	Inner winding radius (m)	Width (m)	Build (m)	Current density (A/cm ²)	Major radius (m)	Sweep angle (deg)	Straight section length (m)
Central cell	4.91	7.20	NbTi	2.10	0.77	1.22	{ 956 1206 1460	--	--	--
Choke	24.0		Nb ₃ SnTi				{ 1235			
Superconductor		16.1	Nb ₃ Sn	1.40	3.20	0.992	{ 1445			
Insert		24.8	NbTi	0.30	0.858	0.42	{ 1830	--	--	--
			Cu				{ 2737			
Direct converter	4.0	6.46	NbTi	1.1	0.50	0.50	2000	--	--	--
Transition	7.0	9.5	NbTi	1.1	1.6	0.40	2600	3.25	180	0
Inner anchor	7.3	10.5	NbTi	1.1	1.6	0.40	2600	2.50	180	0.5
Outer anchor	7.3	10.7	NbTi	1.1	1.6	0.40	2600	2.50	180	0.5
Inner plug	7.2	9.8	NbTi	1.1	1.6	0.40	2600	3.25	180	0.4
Outer plug	7.5	9.8	NbTi	1.1	1.6	0.40	2854	3.25	180	0.4
Regularizer	7.5	9.8	NbTi	1.1	1.6	0.40	2946	2.50	140	0

stress of 331 MPa and an acceptably low resistivity. We selected magnesium-aluminum oxide spinel (MgAl_2O_4) as the insulator because of its low rate of neutron-induced swelling and because the swelling is isotropic. The radiation effects that limit the life of the coil are resistivity increases caused by transmutations and swelling of the insulator. The latter dominates. We have selected a design tolerance of 3% volumetric swelling of the spinel as end of life, which results in a coil lifetime of more than four years. In fact, the coil will accommodate more than 3% swelling. However, this lifetime is comparable to the blanket lifetime and the insert coil can be replaced during scheduled blanket maintenance periods. The average power dissipation over the lifetime of each resistive insert coil is 40.4 MW.

The design of the choke coil structure serves several purposes. Foremost, it holds the background coil and resistive insert in place while allowing for easy removal and replacement. Second, it provides the vacuum seal between the central cell and the end cell, including a gate valve to close off the end cell when the central cell is up to air during blanket replacement. Intercoil jacks ensure load continuity between the central cell and end cell. They also provide the capability to adjust the position of the choke coil.

The end cell coils are similar in design to the MFTF-B yin-yangs but are larger and have a higher peak field on the conductor. Because the peak conductor field exceeds 8 T, a design upgrade from MFTF-B was necessary. We chose to retain NbTi because of its ductility for the difficult winding geometry. The coolant selected is superfluid LHe II to allow high current density at 10 T. This also allows a simplified conductor design when compared with MFTF-B. The key issue for the end cell coils is radiation damage and shielding. The peak neutron wall loading in the end cell is 0.13 MW/m^2 . We used a highly efficient composite shield because any increase in shield thickness causes a large increase in coil volume and cost, increases peak field on the conductor (which is near the limit for NbTi technology), and lowers the achievable central cell plasma pressure. Magnet radiation allowables were set by the cost of heat removal at 1.8 and 4.5 K. Radiation-resistant polyimide insulation was used and the stabilizer must be periodically annealed by bringing the coils to room temperature.

We selected a strongback structure for the coil supports. This reduces the bending moments, avoids interference between the structure of adjacent

coils, allows thinner cases to accommodate more shielding, and simplifies access for supplemental heating systems. All end cell coils are removable through the direct converter end dome in the unlikely event of a coil failure.

The end cell also contains drift pump coils that modulate the magnetic field to promote radial transport of ions out of the core plasma and into the unconfined halo region. Our approach, shown in Fig. 8, uses two hairpin coils embedded in the magnet shielding at each end of MARS. The design of the coils is reasonably straightforward, but is somewhat complicated by a high radiation environment and the need for a flux return path. This has been solved by using lead oxide as the magnet's radiation shield.

The central cell coils have technological requirements similar to those in the Large Coil Program technology, i.e., NbTi, pool-boiling LHe I, unreinforced conductor, peak field < 8 T, low radiation levels. The design is relatively simple and the coil could be manufactured with minimal research and development (R&D). The trade studies performed showed that the cost of the cryo plant and the cost of electricity to operate it set an economic limit that precludes making the shield thinner and making the magnets smaller, even though the other radiation levels are well below the allowables. In fact, the magnets never require annealing. In contrast to the end cell where all magnets are in a common vacuum system, each central cell magnet has its own Dewar. Because the 42 central cell magnets comprise 55% of the total magnet weight and 40% of the total magnet cost, there is incentive to examine higher performance, lower confidence designs that would operate at higher current densities to lower the cost of this system.

4.4 Microwave Heating Systems

MARS has two microwave plasma heating systems that use ECRH to preferentially heat electrons. The first of these creates the axial confining potential-peak in the plug. The second system creates the thermal barrier, a potential depression that decouples central cell electrons from the electrons in the region of the potential peak. The thermal barrier is at the location of the plug minimum field. The main parameters for the two ECRH systems are given in Table 12.

Table 12. ECRH system parameters. Values quoted are for one end of the machine.

	Potential peak	Thermal barrier
Total absorbed power (MW)	3.3	38.5
Vacuum magnetic field (T)	3.9	3.
Axial locations (m)	<u>+85</u>	<u>+83.5</u>
Vacuum frequency (GHz)	109	84
Peak beta	0.574	0.75
Electron density ($\times 10^{13} \text{ cm}^{-3}$)	2.54	2.4
Electron temperature (energy ^a) (keV)	123	820
Range of injection angles (deg)	77.5 $\pm$ 3.5	25 to 55
Axial extent of heating zone (cm)	<u>+28</u>	<u>+75</u>
Heating frequency, beta-depressed (GHz)	71	60
Heating mode	Fundamental, extraordinary	Fundamental, extraordinary, wave trapping

^aFor the thermal barrier electron population.

Because of the large amount of required absorbed power (83.8 MW), it was important to design a highly efficient, low cost system. For this reason, we have extrapolated from available technology to produce a cost-effective design. An ECRH system basically consists of the power supply, microwave source, and transmission/launching subsystems.

The source selected for the MARS ECRH system is a multimegawatt quasi-optical gyrotron with a voltage-depressed collector, permitting direct energy recovery of the electron beam. This source is illustrated in Fig. 9. The potential peak system uses 1.65-MW gyrotrons at 71 GHz; the tubes for the thermal barrier are 2.43 MW at 60 GHz. With energy recovery, the tubes have an overall efficiency of ~80%. Both tubes have about 40% frequency variability

for plasma startup purposes. We selected the quasi-optical gyrotron over the free-electron maser (FEM) and the conventional closed-cavity gyrotron.²⁴ The rationale for the selection included the source's potentially high efficiency, its ability to be extrapolated to large tube sizes, frequency variability, and natural selection of the TEM_{00} Gaussian mode for coupling to the quasi-optical transmission system. The power rating of these tubes is significantly above presently achieved levels, particularly since the quasi-optical gyrotron is in the developmental stage. However, the U.S. gyrotron development plan does call for a 2.5-MW device above 100 GHz and a 5-MW device at 60 GHz by 1994. The extrapolation to the MARS design points is reasonable when compared to the rate of development in this area.

The requirements of the transmission/launching system are high efficiency, power handling capability, access constraints, and the ability to deliver the power in the proper polarization. We considered a standard overmoded waveguide system, similar to those used on current experiments, and a quasi-optical transmission system using reflective optics. We selected the quasi-optical transmission system because of its excellent performance, namely, low transmission losses, high power-handling capability, and ability to operate without vacuum windows. Moreover, because of the large tube size, we were able to design a very simple transmission system that satisfied all requirements. The diverging beam from the gyrotron forms an effective conical horn. When a parabolic reflector is placed in the beam path, the beam launcher resembles a conical horn-reflector antenna. The Gaussian output mode from the gyrotron couples to the transmission system without the need for mode converters. A schematic of the thermal barrier ECRH transmission system is shown in Fig. 23. The system layout considerations were dominated by the need to propagate the beams through the 64-cm minor radius gap in the plug coil without compromising the magnet's neutron shielding. This was accomplished with the configuration shown in Fig. 23. In addition, two redundant tubes were added to each end of the reactor to improve ECRH system reliability.

The power supply option selected for MARS is a single large supply for both ECRH systems. It is based on existing technology used in high-voltage high-power dc transmission from electrical generating stations to distribution systems. We chose a one-pole 12-pulse converter because of its inherent high-voltage regulation. Twelve-pulse converters are of a three-quadrupole configuration with four thyristor valves per quadrupole. There is a three-phase

Fig. 23. Thermal barrier ECRH system layout.

transformer for each six-pulse bridge. The large ac-to-dc converter feeds a set of parallel power regulation/isolation networks. Systems of this type are available at about 500 MW. They are presently being developed at 200 MW; the size needed for MARS. This type of system is used on the Pacific Inertie and has demonstrated a reliability of 99.85% at full power.

The MARS ECRH system design achieves high efficiency, >70% wall plug to plasma, at a low cost that is less than 50% of the cost of the ECRH systems on present experiments per watt delivered. Significant development will be required.

4.5 Ion-Cyclotron Resonant Heating Systems

MARS requires two ICRH systems: one for ion heating in the anchor and one for bulk heating of the central cell during startup.

The anchor system is required to heat the trapped-ion current to a high enough energy level to provide a peak beta of 0.75. This requires 11.4 MW of coupled power (total, both anchors). We have decided to heat at the second harmonic of deuterium, or 55 MHz. The system is designed to launch 13.4 MW from eight launchers, two located in the minor radius gap of each anchor magnet (i.e., 6.7 MW delivered to each anchor). The system consists of a coil antenna launcher, a coaxial transmission line with a three-stub tuning system, and a multistage amplifier chain.

We selected a loop antenna for the launcher, primarily because of access limitations in the anchor. The antenna is center-fed to allow an average surface power density of about 2 kW/cm^2 . Although the nuclear radiation levels are about an order of magnitude lower than in the central cell or in a tokamak, radiation damage is still a concern. In addition, good coupling of the energy to the plasma may require imbedding the antenna in the halo, which causes high heat fluxes and erosion. For these reasons, the antenna is designed as an easily replaceable modular unit.

The transmission system is primarily a 9 3/16-in. 50- Ω coaxial line. The third stub provides impedance matching whereas the remaining stubs are used for VSWR control. The coax tapers to 6 1/8 in. for access through the magnet. The system is cooled with pressurized water; the most stringent requirements are for the antenna and interface at 12 gal/min and a $50^\circ\text{C } \Delta T$. The line is evacuated from the third stub to the antenna; the remainder of the line is pressure-controlled with 1 atm of dry air. Overall transmission-efficiency is 89%. The transmission line-antenna interface is illustrated in Fig. 24.

Each antenna is powered by an amplifier chain consisting of an intermediate power amplifier and driver, a low-power 90-deg hybrid splitter, two final power amplifiers (FPA), a high power combiner, a power supplier, and control and protection circuitry and monitoring. The FPA is the Eimac 8974/X-2159 tetrode; the driver is the Eimac 4-cw, 100,000-E tetrode, both in a cathode-driven mode.

Fig. 24. Anchor ICRH transmission line antenna interface.

Overall system efficiency, "wall-plug" to launched power, is 54.3%. We have used "off-the-shelf" hardware. A higher system efficiency could be obtained with specially developed tubes, but we did not make that extrapolation because of the relatively low power of the system.

The startup ICRH system heats the central cell to ignition during the reactor startup phase. It is required to deliver 12 MW for a period of 120 s. We heat at the second harmonic of deuterium, 112.8 MHz, at the end of the central cell where the field is higher and the beta is lower. This allows both higher frequency and a smaller change in resonance frequency during startup. The startup system differs from the one in the anchor in two respects. The higher frequency, improved access, high neutron loading, and high halo density provide a great incentive to use waveguide launchers. We use eight single-ridged waveguides arranged in spoke fashion between the last two

central cell coils, as shown in Fig. 25. The amplifier system is of the same basic design but uses different tubes because of its higher frequency. Total system efficiency is 41.3%. This could be increased by the use of more advanced tubes; however, the efficiency is not as important a consideration for the startup system.

4.6 Neutral Beam System

The beam system is required to deliver 4.43 MW of neutral deuterium into each plug at an energy of 475 keV and an angle of 70 to 80 deg. The high beam energy dictates that a negative ion source be used to achieve reasonable neutralization efficiency. The beam system consists of the ion source,

Fig. 25. Startup ICRH system in the central cell, located between the last two central cell coils.

accelerator, neutralizer, ion and neutral beam dumps, cryo pumping, and magnetic shielding. The beamline and its location in the plug are shown in Fig. 10.

We selected Lawrence Berkeley Laboratory's (LBL) self-extraction negative ion source.²⁵ It uses a cesiated molybdenum surface to convert positive ions formed by an rf plasma generator to negative ions. Geometric shaping of the converter focuses the D^- ions into an extraction slit. Electrons are reflected from the accelerator entrance by the magnetic field produced by a set of $SmCo_5$ magnets. The ion beam has an average current density of 47 mA/cm^2 , which yields a source strength of 7 A/m over a 1.5-cm -wide slot. This is a small increase in the present capability of 5 A/m .

We selected a transverse field focusing (TFF) accelerator (of a type²⁶ under development at LBL) for the beam system. The ions are first pre-accelerated to 80 keV using a standard electrostatic slot accelerator. The TFF is a type of one-dimensional strong-focusing electrostatic system used for both beam acceleration and transport. The focusing produced by the transverse electric field causes the particles to follow circular arcs. A beam particle not on the equilibrium surface will be strongly focused by a combination of centrifugal and electrostatic forces. The TFF accelerator consists of four stages. The focus voltages are progressively increased from about 25 kV at 80-keV ion energy to about 50 kV at 475-keV ion energy. After acceleration, the beam is transported to the neutralizer using two large-radius TFF stages. This transport section allows the ion sources to be out of line-of-sight of the neutron source. The last 50 kV of acceleration between the accelerator and the neutralizer is to inhibit electron flow from the neutralizer back to the accelerator.

The laser photodetachment neutralizer selected for MARS can achieve more than 95% stripping of the ion beam. We use a supersonic chemical oxygen-iodine laser (COIL). The resonator has 40 folds and a power flux of 75 kW/cm^2 . Cooled silicon carbide mirrors with a reflectivity greater than 0.999 are used to accommodate the high flux. A 70-kW COIL is used for each beamline. The complexity, high cost, and power consumption of the laser as compared with a gas neutralizer are completely offset by the increased electrical efficiency of the beam injection system. This allows a smaller source/accelerator system. All other beamline components are also smaller and less costly than they would be if a gas cell were used. Moreover, the internal ion dump can be designed

for very long life because of the low unneutralized currents. Energy recovery of the unneutralized beam is not required.

One of the key issues of the neutral beam system is activation of the source, heating of the cryopanel, and radiation damage to the insulators. We used the MCNP Monte Carlo code to perform an initial analysis of the neutrons streaming through the beamline and found that radiation damage to the insulators is not life-limiting. In addition, the nuclear heating in the cryopanel, laser mirrors, and magnetic shield is low enough so that it does not affect the design. We did not calculate activation of the source; however, the flux at the source is less by eight orders of magnitude than the flux at the duct entrance. Hands-on maintenance of the source may be possible within two days after shutdown. From this analysis, we conclude that the high-energy beam transport section is effective in providing neutron shielding for critical beamline components.

The sloshing-ion neutral beam system achieves an efficiency of 71.5% from wall plug to injected power. This high efficiency is a result of using a laser photodetachment neutralizer. Significant development is needed for both the accelerator and neutralizer. Of these, the TFF accelerator is more straightforward. A gas neutralizer using present technology could be used but with the expense of a decrease in efficiency and an increase in overall system cost.

4.7 End Plasma Technology

The end plasma technology systems provide the functions of particle and energy removal, direct energy conversion, continuous and startup pumping, potential control, and generation of high quality heat. The subsystems included in this system are the inner collector, outer collector, inner halo scraper, outer halo vented plate, continuous-duty mechanical vacuum pumps, cryo pumps for startup, and vacuum tanks. The particle loads on the inner and outer collectors and on the halo scraper are given in Table 13 for both ends of MARS. The collector is segmented to reduce the radial potential gradient. The thermal load on these systems of 280 MW, combined with the 730 MW from the water-cooled reflector, led us to select a coolant temperature operating range of 280 to 320°C. A basic tradeoff in the design is the size of the components vs the heat flux. We selected a compact design with a 5-m radius at a peak

Table 13. End tank subsystem particle loads.

Subsystem	Potential (kV)	Particle type	Current (A)	Average particle energy (keV)
Inner collector	-167	e	1754	23.7
		α (prompt)	20.6	3862
		α (scattered)	50.6	942
		D (sloshing)	9.6	800
		DT (end loss)	73.8	353
Outer collector	-84	e	322	23.7
		α (prompt)	3.8	3691
		α (scattered)	9.4	771
		D (sloshing)	1.8	762
		DT (end loss)	13.6	191
Halo scraper	0	e	116	74
		α (prompt)	1.4	3528
		α (scattered)	3.4	608
		α (drift pump)	208	50
		DT (neoclassical)	78.3	46
		DT (drift pump)	1714	46
		DT (end loss)	4.9	107

heat flux of 2.96 MW/m^2 . This is illustrated in Fig. 4. Because of the high heat flux, temperature, and associated pressure, we selected the molybdenum alloy TZM as the best material to resist the thermal and pressure-induced stresses in the particle collectors and halo dumps.

The inner collector is designed for a peak heat flux of 2.96 MW/m^2 . It is basically a TZM plate with a fully cooled back. It has five vertical 1.2-m-wide sectors in each end with 140 parallel coolant channels per sector. We chose a front plate thickness of 3 mm and a coolant channel width and depth of 6 and 8 mm, respectively, based on an overall stress minimization analysis. We use standard nonboiling, turbulent coolant flow at a velocity of 11.2 m/s. Pumping power is less than 0.5% of the heat removed. Stresses are less than 50% of the conservative ASME Boiler Code allowable. Material loss from sputtering is less than 0.5 mm for the reactor lifetime.

The requirements on the outer collector are less severe. The peak heat flux is 1.90 MW/m^2 . The coolant routing is changed to have five coolant channels in series. Water velocity is reduced to 5.9 m/s and pump power is less than 0.25% of the heat removed.

If the inner halo scraper were normal to the plasma, the peak heat flux would be 8.79 MW/m^2 . In our case it is inclined at more than 70° to reduce the peak heat flux to 2.52 MW/m^2 . This simplifies the heat transfer and deflects particles toward collection ports for pumping; however, it also significantly increases sputtering. Because sputtering would severely limit the lifetime of a bare TZM plate, we have added thick beryllium tiles to the scraper. We have limited the peak beryllium temperature to 70% of its melting point, which sets the tile thickness at 2.1 cm. We obtain a scraper lifetime, set by beryllium sputtering, equal to half the reactor lifetime. Thus, the scraper is designed for periodic replacement. The TZM structure is cooled in much the same manner as the collector plates: three coolant channels are placed in series, the maximum velocity is 14.6 m/s, and the pumping power is about 1% of the heat removed. The outer halo vented plate is subject to much lower heat fluxes and particle loads. The heat flux is 0.47 MW/m^2 . No protective coating is needed; however, the front plate has a maximum thickness of 1.4 cm to allow for 1 cm of TZM erosion over the life of the reactor. The plate has a 5% open area that allows a portion of the plasma flux to enter the pumping plenum. The vacuum system provides pumping to a base pressure of 10^{-7} Torr for startup and continuous removal of the plasma exhaust. A major change in MARS from previous tandem mirror designs is the elimination of a large, continuous, cryopumping system for plasma exhaust. Because of the halo design, the pressure in the plenum is 4×10^{-2} Torr,

which is consistent with mechanical pumps. The vacuum system is integrated with a roughing/backing section and a high vacuum section; both are used for startup. The roughing/backing section includes four compound booster pumps, each rated at 4300 ft³/min at 4×10^{-2} Torr, and each consisting of a mechanical pump and a roots blower. This system provides a base pressure of 10^{-3} Torr for startup and all steady-state pumping. The 10^{-7} -Torr base pressure for startup is provided by two cryopumps, each with a speed of 55,000 liters/s. The pumping surface is double-sided with an area of 1.1 m² per side and is thermally protected by liquid-nitrogen-cooled shields. The cryopumps are isolated from the vacuum vessel during normal operation. This vacuum system design has substantially reduced the size of the end tank and the costs of the components.

The thermal and electrical performance of the end plasma system is given above in Table 9. The overall energy conversion performance is given in Table 14.

We can see that 68% of the power entering the system is converted to electricity. If the heat were not used in the thermal cycle, thus eliminating the high pressure and TZM structure, 51% efficiency would still be achieved.

Table 14. Energy conversion performance of the end plasma system.

Core plasma power leakage, P_1 (MW)	453
Halo plasma power leakage, P_2 (MW)	120
Directly converted power, E_1 (MW)	292
Thermally converted power, E_2 (MW)	96
Direct conversion efficiency (E_1/P_1)	0.64
Net direct conversion efficiency $\left(\frac{E_1}{P_1 + P_2} \right)$	0.51
Overall electrical conversion efficiency $\left(\frac{E_1 + E_2}{P_1 + P_2} \right)$	0.68

The major R&D areas for the end plasma are in TZM brazing and machining of large size panels, sputtering and blistering of surfaces, and halo scraper performance.

4.8 Pellet Injector

The MARS fueling requirements of pellet velocities in the range of 2 to 10 km/s at an injection rate of more than 6.5 Hz for cylindrical pellets 5 mm in diameter and 5 mm long (i.e., 10% of the plasma ion content) are beyond the present state of the art, and significant developments are needed. We have reviewed alternative techniques, primarily the use of centrifugal accelerators, pneumatic gun injectors, and railgun injectors. Of these, railguns offer the best potential for exceeding 2 km/s. We have developed a baseline conceptual railgun system.

A medium-speed centrifugal or pneumatic injector would be used as a preaccelerator for a railgun located at one end of the central cell. For optimum pellet penetration, it is desirable to inject as close to the 24-T point as possible to reduce the velocity requirement because the central cell plasma approaches a minimum radius here. A key issue in the system design is the acceleration strength of the pellet. If we limit the propulsive stress to 3 MPa, based on the tensile strength of frozen DT, we get a launcher length of 21 m for a velocity of 10 km/s. If we assume that a high-strength sabot can take up acceleration stresses and be separated from the pellet before injection, we get a launcher length of only 0.57 m at 300 MPa of propulsive stress. The latter case produces severe rail heating and an optimum would be expected at an intermediate acceleration.

4.9 Blanket, Reflector, and Shield

The MARS blanket and reflector breed tritium and convert nuclear energy to useful heat. Our objectives in designing them were to minimize the cost of electricity, develop a simple maintenance system, minimize long-term radioactive waste, provide a passive safety system, and allow hands-on maintenance at the back of the shield within two days after shutdown. We did achieve these objectives in the MARS design.

We selected Li-Pb as the coolant/breeder. This material has a high tritium breeding potential, permits the design of thin blankets, and affords a high energy multiplication, all of which contribute to a lower cost of electricity. Moreover, the design can be geometrically simple, which helps maintenance and lowers fabrication costs. For the blanket structural material, we chose HT-9 ferritic steel because of its radiation resistance for long life at the high wall loading of MARS, low long-term radioactivity that allows blankets to be disposed of as low-level Class C nuclear waste, and resistance to liquid metal corrosion. The blanket has two radial zones, as is shown in Figs. 3 and 16. The front, or tube, zone has two rows of Li-Pb-filled tubes. This configuration resists internal pressurization better and can accommodate the surface heat flux and high nuclear heating as well as a thin wall. The rear, or beam, zone has a high steel fraction to enhance energy multiplication, and a low void fraction for good space utilization.

The reflector is water-cooled austenitic stainless steel with an outlet temperature of 320°C. It is designed as a lifetime structure, although we have provided for its replacement in the event of failure. A reflector life >24 full power years is possible because the shielding provided by the blanket reduces radiation damage to the reflector structure.

The central cell shield is designed to protect the magnets from permanent damage and minimize the cryogenic heat load. It is composed of three regions: the innermost layer is steel and water, the middle layer is water-cooled boron carbide with a steel structure, and the outermost layer is water-cooled lead with a steel structure. An additional 15-cm-thick biological shield between the magnets allows hands-on maintenance at the back of the shield within two days after shutdown.

An isometric view of the central cell module is shown in Fig. 26; a list of performance and design parameters is presented in Table 15. Key issues in the design are the overall maintenance approach, blanket thermal/hydraulics (including MHD effects), liquid metal corrosion, blanket lifetime, safety under accident conditions, and waste disposal.

The overall layout takes advantage of the linear geometry of the tandem mirror to simplify the fabrication and maintenance approach. Thus, the blanket, reflector, and shield are concentric cylinders. We constrained the design by requiring that the blanket modules be light enough to handle easily by remote control and that no magnets be moved for blanket module replacement.

These considerations resulted in the design shown in Fig. 3, 16, and 26. The central cell has ten service stations: eight of these stations service seven modules; the stations at the ends of the central cell service eight modules each. The modules are translated axially until they are under the service station access hatch and are then removed by a simple vertical lift with an overhead crane (see Fig. 17).

Liquid metal flow and heat transfer in a tandem mirror blanket are dominated by magnetic effects that suppress turbulence, create a flat velocity profile across the tube, and cause the heat transfer to be primarily by conduction. Because the surface heat flux on the MARS first wall is low, 3.8 W/cm^2 , the heat transfer can be accommodated. However, it is the cause of the 50°C difference between the bulk coolant outlet temperature and the maximum structure temperature. In addition, there is an increase in flow resistance when a conducting fluid is moved perpendicular to the magnetic field. We calculated the MHD pressure drop in the blanket to be 1.57 MPa;

Fig. 26. Isometric view of MARS central cell section.

Table 15. Blanket, reflector, and shield parameters.

<u>Blanket</u>	
Extracted power (MW)	2081
Coolant inlet/outlet temperature (°C)	350/500
Minimum/maximum structural temperature (°C)	350/550
Coolant velocity (m/s)	0.17
First wall radius (m)	0.6
Neutron wall loading (MW/m ²)	4.3
Tritium breeding ratio	1.15 ^b /1.12 ^c
Tube zone thickness (cm)	19.2
Beam zone thickness (cm)	19.0
Tube outer diameter (cm)	10.14
Tube wall thickness (cm)	0.23
Maximum dpa rate (FPY ⁻¹) ^a	61
Maximum He production rate (appm/FPY)	482
Module mass, drained (kg)	2.73 x 10 ³
Module mass, filled (kg)	2.95 x 10 ⁴
<u>Reflector</u>	
Extracted power (MW)	730
Coolant inlet/outlet temperature (°C)	280/320
Minimum/maximum structural temperature (°C)	280/340
Coolant velocity (m/s)	1.03
Thickness (m)	0.43
Coolant pressure (MPa)	13.8
<u>Blanket/reflector</u>	
Energy multiplication	1.362
<u>Shield</u>	
Absorbed power (MW)	22
Thickness (m)	0.41
Peak nuclear heating in magnet winding pack (μW/cm ³)	63
Peak damage rate in Cu stabilizer (dpa/FPY)	1.6 x 10 ⁻⁵
Lifetime thermal insulator peak dose (rad)	2.7 x 10 ⁹
Lifetime electrical insulator peak dose (rad)	1.4 x 10 ⁹
Peak neutron fluence in NbTi, n/cm ² > 0.1 MeV	4 x 10 ¹⁷

^aFull power year.^bBlanket local tritium breeding ratio.^cOverall reactor tritium breeding ratio.

this internal pressurization is a principal contributor to blanket stresses. The maximum pressure at the first wall is 0.73 MPa. About 20 MWe are required for primary loop pumping. In the inlet and exit piping, the pipe walls are of a sandwich construction with an electrical insulator between two metallic walls. The inner wall provides a thin conducting liner that limits return

currents, whereas the outer wall takes up the coolant pressure. Insulators are not used inside the blanket where the radiation levels are high.

We have estimated the lifetime of the blanket to be more than 4 full power years based on stresses caused by void swelling and strain induced by irradiation creep. Because the ability to predict lifetime is very tenuous, we have scheduled replacement of modules every five calendar years, which is about 3.6 full power years. The maximum damage to the first wall is about 220 dpa at this lifetime. This high allowable value results from the use of HT-9 with its low swelling and relaxation of stresses by irradiation creep.

A key issue in the viability of the blanket concept is liquid metal corrosion. The data on HT-9 corrosion by $\text{Li}_{17}\text{Pb}_{83}$ are sparse and specific to the experimental conditions. Therefore, we had to extrapolate to MARS conditions. At MARS temperatures, the corrosion rates are low enough so that wall thinning is not a concern. The critical question is whether we can prevent coolant passages from becoming blocked by corrosion product deposition. We have specified a cold trap system to localize deposition and to keep the primary loop below saturation at the coldest point. In addition, our analysis of corrosion product transport and deposition does not identify any regions where blocking or plugging appear to be a serious concern. Although they are not included in our present design, the use of corrosion inhibitors could potentially reduce corrosion products to insignificant levels. In addition, design changes could lower the maximum interface temperature at the expense of a small pressure increase. We believe that the corrosion product deposition problems are tractable at the present design temperature values of the MARS blanket and that methods are available to reduce the magnitude of the effects if necessary. However, this remains an area where additional data are needed.

Inherent reactor safety is a critical area for fusion that must be exploited in designs. The MARS blanket/reflector is the first design with a metallic structure that cannot melt in the event of loss of coolant and/or loss of flow accidents. The worst case is for the simultaneous loss of flow in the blanket and loss of flow or coolant in the reflector. This could occur because of a loss of site power and a failure of the emergency diesel generator. The first-wall temperature excursion is shown in Fig. 27 for this case and for loss of flow in the blanket with flow maintained in the reflector. The melting point of HT-9 (1420°C) cannot be reached. If blanket cooling can be resumed within 3 to 4 hours, which will keep the structure below 800°C,

Fig. 27. Temperature response of the MARS first wall to loss of coolant and loss of flow.

the metal will not be permanently damaged and operation can be resumed. This passive safety feature in fusion reactor designs is unique to MARS.

The MARS blanket, shield, and reflector have satisfied all design objectives and are consistent with a high-efficiency thermal conversion system. The combination of high thermal efficiency and high energy multiplication allows a reduction in fusion power and cost of the fusion island for a given electrical output. The ratio of gross electric output to fusion power is almost 60% in MARS as compared with just over 40% in a standard tokamak reactor. Much of this is a result of blanket performance.

4.10 Heat Transport and Energy Conversion

The heat transport and energy conversion system includes the three primary loops: blanket Li-Pb loop, reflector water loop, and end tank water loop. An optimization of cost-per-unit of electric power generation led to a decision to have two independent cycles. The Li-Pb loop couples to a superheated, single-reheat, extraction steam cycle. The water loops drive a saturated steam cycle similar to that for a pressurized water reactor. This system includes piping, pumps, economizers, steam generators, superheaters, reheaters, cold traps, tritium removal system, and drainage/melting tanks for the Li-Pb loop. The water loop includes piping, pumps, economizers, steam generators, the pressurizer, and water cleanup systems.

The key feature in this system is the use of double-walled heat exchangers for tritium isolation between the Li-Pb and secondary water loops. The tube construction, shown in Fig. 28, has two tubes in close contact. A helium purge flow with 1 Torr of oxygen flows between the tubes to create self-healing oxide barriers to tritium permeation through the tube walls. The tritium that diffuses into the gap is oxidized to T_2O to prevent further permeation. The effectiveness of the system depends on rapid oxidation of T_2 to T_2O in the gap or on keeping the partial pressure of T_2 in the Li-Pb very low. Validation of the double-walled heat exchanger for tritium isolation needs an experimental basis, as does the heat transfer for this design. Methods to validate tritium pressure control in the Li-Pb also need experimental validation.

4.11 Tritium Systems

The tritium systems comprise a wide range of functions that include separating tritium from the Li-Pb breeder and plasma exhaust gases, purifying it for reinjection into the plasma, and ensuring that tritium does not leak into the environment. An overview of the fueling system giving tritium and

Fig. 28. Tube construction for the double-walled heat exchanger.

deuterium flow rates is presented in Fig. 29. The principal parameters of the system are given in Table 16.

The system that removes tritium from the Li-Pb is important because of its potentially high cost and the need to keep the partial pressure of tritium in the Li-Pb very low. Based on an optimization study, we selected vacuum degassing of a droplet spray for the tritium removal system (TRS). Twenty percent of the coolant mass flow is diverted to the TRS; the removal system is 53% efficient. The equilibrium tritium concentration entering the steam generator is 4.56×10^{-4} wppm and the resultant tritium partial pressure is 8×10^{-5} Torr. This is consistent with an effective barrier in the double-walled heat exchangers of about 3×10^4 .

The fuel processing system includes the pellet injector, plasma exhaust pumps, fuel cleanup unit, isotope separation system, tritium waste treatment, fuel blender, and fuel storage, as shown in Fig. 29. These systems contain most of the tritium inventory in the plant and are important because of safety, cost, and performance. The fuel cleanup (FCU) system separates

Fig. 29. MARS tritium flow.

Table 16. Principal tritium parameters for MARS.

Fusion power (MW)	2600
Tritium burn rate (g/day)	400
Tritium injection rate (g/day)	2833
Burn fraction (%)	14
Blanket breeding ratio	1.15
Tritium inventory in blanket (g)	1.0
Total tritium inventory in primary loop (g)	7.5
Tritium partial pressure (Torr)	8×10^{-5}
Extraction method	Vacuum degassing of droplet spray
Sidestream fraction (%)	20
Tritium recovered (%)	53
Heat exchange containment method	Double-walled with He/O ₂ purge
Barrier factor	10^5
Total site inventory (g)	3087
Vulnerable site inventory (g)	<50
Tritium release to environment (Ci/day)	15

hydrogen isotopes from the plasma exhaust. The entire stream is passed to the FCU, which is designed to remove impurity molecules containing carbon, nitrogen, oxygen, heavy metals, and most of the helium. It also decomposes compounds containing tritium, such as CT₄ and NT₃. The FCU design is based on technology being developed at the Tritium System Test Assembly (TSTA) at Los Alamos National Laboratory, Los Alamos, NM, using type 5A molecular sieves. The last stage of the FCU separates helium from hydrogen. This is currently envisioned as being by evaporation from a falling liquid film.

The isotope separation system (ISS) uses cryogenic distillation to prepare three product streams: a pure DT stream for direct supply to the injector, a nearly pure T₂ stream to the fuel blender, and a nearly pure D₂ stream for the neutral beam and fuel blender. The ISS design is also based on TSTA technology.

The fuel blender mixes deuterium and tritium to achieve an atomic ratio of unity. The blending tanks contain agitators for good mixing and an online mass spectrometer to verify the composition.

The tritium waste treatment system removes tritium from FCU and ISS effluents by catalytic oxidation. Its primary function is to limit the tritium loss to the environment.

The fuel storage vault contains tritium as UT_3 on metallic beds. Our baseline for a one-day supply is 2.8 kg in the beds.

It is necessary to remove tritium that permeates into end-tank cooling water to keep the concentration below 1 Ci/kg. It is also necessary to remove tritium from the condensate in the atmospheric detritiation system. Other sources of water that may need tritium removal are the reflector coolant and double-walled heat exchanger purge system. Several techniques were evaluated for the tritiated water removal unit. Based on cost and power consumption, we selected a front-end electrolysis process followed by cryogenic distillation. This system requires only 420 kW of auxiliary power for the electrolysis unit and 100 kW for the cryogenic unit.

Removal of tritium from the building atmosphere is a continuous process that is needed to minimize tritium loss to the environment. The system is sized to keep the steady-state concentration at $50 \mu\text{Ci}/\text{m}^3$. This level requires workers to be protected by bubble suits. The atmospheric detritiation system is also used to clean up the reactor hall atmosphere in the event of a spill. All six units would be used to bring the level to $500 \mu\text{Ci}/\text{m}^3$ within 2.4 days after a release of 2×10^5 Ci (the inventory of the pellet fueler).

MARS has a very low vulnerable tritium inventory because of the selection of a Li-Pb breeder and the use of mechanical pumps for plasma exhaust. The plant inventory is presented in Table 17. The total inventory outside the storage vault is 254 g. Of this, we estimate less than 50 g is vulnerable and the maximum credible release is about 20 g.

4.12 Cryogenic System

The cryogenic system is designed to accommodate all startup and steady-state loads for the reactor. The cryogenic loads are given in Table 18; we have sized the systems to allow 20% over capacity. Cooling and liquid production are performed simultaneously. Neutron-induced heating of the coils is a major contributor to the helium loads, and accounts for 63% of the LHe I load and 90% of the LHe II load. The cryoplant design for the LHe I and LN_2 systems is based on the plant being built for MFTF-B. It has an efficiency of 430 W/W for LHe I and 12 W/W for LN_2 . Little data exist on

large LHe II plants. We have based the MARS plant on a design for the Stanford Linear Accelerator Center. To minimize the distribution losses at 1.8 K, the final heat exchangers are placed in the magnet service stacks. The estimated system efficiency is 1720 W/W.

Table 17. MARS tritium inventory.

	Subsystem inventory (g)	System inventory (g)
<u>Reactor hall and steam generator building</u>		69.5
Fuel pellet injector	20.4	
Reactor exhaust pumps	0.1	
Li-Pb coolant/breeder	7.5	
Water coolant (1 Ci/liter)	21.6	
Neutral beam injector cryopanel	1.0	
End cell structure	18.0	
Central cell structure	0.8	
Reactor plasma	0.1	
<u>Tritium process building</u>		184.4
Fuel cleanup unit	22.4	
Isotope separation system	162.0	
<u>Storage vault (1-day supply)</u>		2833
<u>Total on-site inventory</u>		3087

Table 18. Cryoplant requirements.

System	LHe I		LHe II		LN ₂
	W at 4.5 K	liters/hour	W at 1.8 K	liters/hour	kW at 77 K
Central cell coils	5,250	857	--	--	296
Choke coils	268	--	225	56	19.5
End cell coils	5,208	--	1,898	305	98.1
Beamlines	500	--	45	--	12
Tritium system	730	--	--	--	--
Precooling	--	--	--	--	100
Total	11,956	857	2,168	361	526
Plant capacity	14,500	1,030	2,600	430	630

5. Balance of Plant

An artist's conception of the MARS power plant is shown in Fig. 1. The plant systems are essentially conventional. However, the general arrangement of buildings and functions takes into account the linear nature of the tandem mirror and uses the open access to advantage. One side of the central cell contains all facilities for new, replacement, and spent equipment, whereas the other side contains the energy conversion systems. The site selected for MARS is "Middletown," U.S.A. and, for the purposes of labor statistics, it is assumed to be near Kansas City, Missouri. The site is within Uniform Building Code (UBC) Seismic Zone 2; this provides criteria for seismic design of the structures. The single unique feature of the balance of plant is the use of two independent power cycles, as discussed in Sec. 4.10. The superheated steam cycle is designated Unit 1 while the saturated steam cycle is called Unit 2. The MARS plot plan is shown in Fig. 30.

We have separated the MARS facility buildings into two groups: those that are safety-related and those that are not. The safety-related buildings are designed using a stringent set of codes that encompass NRC regulations and sustain earthquake forces, tornado-generated forces and missiles, accident temperatures and pressures, and operating loads. The buildings are the reactor hall, steam generator hall, hot cell, spent blanket pool, tritium building, control building, and diesel generator building.

The reactor building has 60-cm-thick reinforced concrete walls and roof, stiffened with concrete frames 180 cm deep and 100 cm thick, spaced on 10-m centers. The steam generator and tritium buildings have a 70-cm-thick roof, 60-cm-thick walls, and a structural steel interior framing. The floors and surrounding walls of these buildings are steel lined to a height of 60 cm. The building's interior surfaces are sealed with epoxy paint against tritium leakage and are operated at a subatmospheric pressure of -5 cm of water. We were able to reduce the load conditions on the reactor hall because of a low internal overpressurization under accident conditions.

The secondary loop energy conversion cycles convert the steam generated in the heat transport system to electric power. The Unit 1 system consists of high-pressure, intermediate-pressure, and three low-pressure steam turbine cylinders and a hydrogen-cooled electric generator arranged in tandem. There is a single reheat between the high- and intermediate-pressure turbines. All turbines have nozzles for bleeding extraction steam to feedwater heaters and steam generator feed pumps. The Unit 2 system has high and low pressure

Fig. 30. MARS plot plan.

LEGEND

1. TURBINE GENERATOR BUILDING
2. TRITIUM BUILDING
3. STEAM GENERATOR BUILDING
4. REACTOR BUILDING
5. SWITCHYARD
6. WAREHOUSE
7. NATURAL DRAFT COOLING TOWER
8. CHLORINE CONTAINER BUILDING
9. PUMP STRUCTURE
10. ADMINISTRATION BUILDING
11. PLANT MAINTENANCE BUILDING
12. MAIN TRANSFORMER
13. START UP TRANSFORMER
14. AUXILIARY TRANSFORMER
15. WATER TREATMENT BUILDING
16. CONDENSATE STORAGE TANK
17. AUXILIARY BOILER BUILDING
18. DIESEL GENERATOR BUILDING
19. MECHANICAL DRAFT COOLING TOWER (CIRC WATER SYS)
20. MAGNET FABRICATION BUILDING
21. CONTROL COMPLEX
22. CIRCULATING WATER PIPE
23. HEAT EXCHANGER AREA (AUX CLG WATER)
24. NEW PARTS AND ASSEMBLY AREA
25. SPENT BLANKET STORAGE POOL
26. HOT CELLS AREA
27. POWER SUPPLIES AREA
28. CRYOGENICS LIQUEFYING AREA
29. CRYOGENICS STORAGE TANKS
30. MECHANICAL DRAFT COOLING TOWER (AUX CLG WATER)
31. AUXILIARY CIRCULATING WATER PIPE
32. LOADING DOCK

GENERAL NOTES

1. UNIT NO. 1 IS A 900 MW SUPERHEATED STEAM CYCLE
2. UNIT NO. 2 IS A 350 MW SATURATED STEAM CYCLE
3. NOT ALL EQUIPMENT AND FACILITIES ARE SHOWN

turbines connected in tandem to a hydrogen-cooled electric generator. There is a moisture-separator-reheater between the two turbines. Steam extraction is used for feedwater heating. The performance of the turbine-generator systems is presented in Table 19. Overall efficiency of the combined system is about 40%.

Heat rejection from the cycles is from cooling towers. A hyperbolic natural draft tower is used for Unit 1 and a mechanical draft tower for Unit 2.

The MARS electrical systems are designed to interface the two generators with the electric utility grid, to provide the auxiliary power for startup and normal operation, and to provide standby emergency power. The recirculating power requirements for normal operation are presented in Table 20. The

Table 19. MARS turbine generator performance.

	Superheat cycle Unit 1	Saturated cycle Unit 2
Throttle flow (kg/hour x 10 ⁶)	3.15	1.83
Throttle temperature (°C)	479.4	277
Throttle pressure (MPa)	16.65	6.21
Reheat temperature (°C)	482	263
Gross generation (MWe)	892.8	346.9
Gross efficiency (%)	42.04	33.83
Net turbine heat rate (kJ/kWh)	8563	10642.1

Table 20. MARS recirculating power.

Equipment description	Operating load (MW)
ECRH-B power converter	106.2
ECRH-A power converter	9.1
Neutral beam injection	14.1
Anchor ICRH	28.8
Magnets	81.5
Drift pumps	20.0
Helium I compressor	5.2
Helium II compressor	3.7
Nitrogen reliquifiers	6.7
Li-Pb pumps	21.0
Other plant auxiliaries	38.2
Total	334.7

dominant contributors to the 334 MW of recirculating power are the supplemental heating systems (158 MW) and the resistive magnets, including drift pumps (101 MW).

6. Plant Construction

The design of the MARS plant is amenable to a rapid construction schedule. We have developed an optimistic schedule of 69 months from initial site work to first commercial operation. We have assumed that the site is level to gently rolling, within UBC Seismic Zone 2, with adequate water available for make-up, and located close to existing major access roads, rail lines, and an inland waterway. Construction schedule durations have been based on construction and procurement lead times in the nuclear power industry. We also assume multishift operations and maximum use of preassembled components, either on site or at vendor shops. The schedule does not include site selection or acquisition, nor do environmental studies and licensing constrain the construction schedule.

The critical path for construction is the reactor building, which requires 33 months of initial work before the reactor can be assembled. Reactor installation begins when construction of the reactor building has progressed to a point where the roof is completed. The building requires 24 months to complete. We use parallel assembly of the central cell and end cells. This approach is consistent with the linear nature of MARS and the layout of the reactor building. Subsystem testing will be initiated in the fourth year of construction both at vendor locations and at the reactor site as the equipment arrives. There is a total of 24 months of subsystem and startup testing before commercial operation. The last 12 months are devoted to fully integrated testing of the reactor. A top-level construction schedule is presented in Fig. 31.

7. Plant Operations

Plant operations include maintenance, plant operation, and normal startup and availability modeling.

Fig. 31. Simplified MARS construction schedule.

7.1 Maintenance

The maintenance design for MARS has three basic objectives:

1. Capability for totally remote maintenance, but with sufficient shielding for hands-on operations;
2. Minimized downtime for scheduled maintenance;
3. Capability to replace any reactor component in the event of an unexpected failure without excessive downtime. The central cell and end cell are separated by gate valves and temporary shielding to allow personnel in the end cell area when the central cell is opened.

The two major systems that require periodic replacement are the blanket modules and choke coil resistive inserts. We have developed detailed timelines for servicing these systems.

Each year the blanket modules at two or three service stations will be replaced. Parallel operations are planned for each service station and sufficient equipment is provided for three parallel operations. The timeline for this is presented in Fig. 32, which shows a requirement for 10.3 days from shutdown to the beginning of startup. The first 2.5 days are for reactor shutdown, during which time the magnets are deenergized and the blanket modules are cooled and drained. After this time the headers and vacuum cover are removed; radiation levels are low enough to permit manual assistance.

Fig. 32. Blanket module replacement timeline.

The reflector and shield plug in the service station are removed by a simple vertical lift. In a similar fashion, blanket module 0, which is directly under the access port, is removed. The modules to the side of the service station are translated axially using a worm screw actuator and are then lifted vertically out of the reactor. The reverse process is used for module installation.

We performed a similar analysis and developed a procedure for replacing the choke-coil normal-magnet insert. The entire choke coil assembly is rolled out on rails. The insert is removed and a new insert installed using a floor-mounted remote machine. This operation can be accomplished in less than two

days. However, the insert would be replaced in conjunction with blanket replacement because their lifetimes are similar. An increase in change-out time would not affect overall performance.

In the unlikely event of a failure of a central cell, end cell coil, or other major lifetime component, we have designed the system to accommodate remote change-out of any damaged component. The central cell contains segmentation points where a section containing two magnets and the associated blanket, reflector, and shield modules can be removed. A spare central cell segment is included in the MARS equipment list. The central cell module is removed on permanent rails embedded in the floor; end cell magnets are removed through the direct converter end dome using the same transhaulers used during machine fabrication.

7.2 Reactor Operation

The operation of MARS as a power plant involves several issues in addition to steady-state operation. These include pre-operational testing, initial commissioning, startup procedures, operation and testing at fractions of full power, and shutdown. After pre-operational testing and initial commissioning, the four phases of operation will be repeated over the reactor life. Startup may be either from a cold shutdown mode (Phase IA) when the blankets are drained, the coolant stored, and the magnets deenergized and warmed; or from a hot shutdown mode (Phase IB) when power conversion components and their coolants are maintained near their operating temperatures and pressures. Phase II includes system testing, plasma initiation, and a standby power mode at typically less than 5% of rated power. In Phase III, staged power ascension tests are conducted at several levels. These are typically 0 to 20% of full power, 20%, 50%, 80% and 100%. This phase is expected to take 6 months for initial startup. Phase IV is rated power operation.

Because MARS has a liquid metal blanket, special startup procedures are necessary to avoid thermal shock and stress to the system. For cold startup, we use a helium gas preheat system to condition the primary loop to a uniform temperature of 350°C. This requires about 30 hours. After conditioning, Li-Pb is pumped from the storage tank and the primary loop is filled. We

first fill half of the primary loop, then the blanket from bottom to top, and finally the remaining half of the piping. The temperature in the loop is held constant by pump heat and resistance strap heaters. In startup from hot shutdown, the time period is expected to be much shorter.

In Phase II, much of the activity will be associated with plasma and plasma systems, including supplemental heating, drift pumping, and direct converter testing. This will be done at as low a power level as possible. During staged power operation--Phase III--three tests will be performed at each power level. These are turbine trip, loss of load, and loss of flow. The purpose of the testing is to validate safety analysis models and to collect data on performance under these transient conditions. During the tests, flow conditions are monitored in both the primary and secondary loops and strain gauge measurements for fatigue and vibration analysis are taken. At the 20% power plateau, the initial turbine roll is established and steam cycle performance is validated. At each plateau level, coolant chemistry, primary coolant radioactivity, neutron leakage, and corrosion data are monitored in detail. At the 50% level, offsite power is removed by isolating the startup transformers. The turbine is tripped and blackout conditions are maintained for 30 minutes. All emergency power systems are tested. The ability to respond to a load decrease is validated at the plateaus and a full loss-of-load transient is initiated at 100% power.

The startup of the MARS power plant is similar to other fossil and nuclear systems with the exception of the plasma systems and the liquid metal blanket. The only additional system needed for the blanket is the helium preheater.

7.3 Availability

The availability of the MARS plant has been assessed to determine which subsystems and components have the largest effect on availability, to evaluate how installed component redundancy can improve availability, to determine where minimizing component repair or replacement times will improve reliability, and to support computation of the cost of electricity. All systems in MARS were designed for a lifetime consistent with 80% availability, specifically, 24 full power years. We performed a bottoms-up estimate of availability for

the system. For each major component, the system designer estimated the mean time between failure (MTBF) and mean time to repair (MTTR); and the project team reviewed the estimates for consistency. A standard availability analysis was then performed under the assumption that all failures were uncorrelated and that no credit would be taken for planned outages to improve availability. This analysis also includes failures in the supplemental heating systems that degrade system performance.

The results of the analysis indicate a best-estimate availability of 73% with a 30-day annual scheduled maintenance outage. If the annual shutdown could be reduced to 20 days, the availability would increase to 75%. The analysis also showed that installed redundancy in the neutral beam and ECRH systems is necessary to achieve adequate availability. This provision has been included in the design. The five subsystem groups that have the largest effect on availability are presented in Table 21. Even with redundancy, supplemental heating is still the largest contributor in the reactor systems.

An estimate of MARS availability based on component reliability and repair times indicates the potential for an excellent system, with a computed availability factor of 73 to 75%. With additional work on subsystem designs, we believe the 80% goal could be reached.

Table 21. Factors affecting reactor availability.

Subsystem group	Unavailability effect (%)
Supplemental heating systems	5
Turbine and generator	
Electrical equipment	5
Cryogenics	3.5
Blanket, reflector, and service station	2.5
Normal conducting magnets	1.5

8. Environment and Safety

MARS has been designed to minimize adverse effects on the environment through normal releases of radioactivity, exposure to workers, releases under accident conditions, and waste management. In addition, we have developed a design that has high inherent safety. That is, minimal active measures are required to ensure safe operation of MARS. The materials and operational parameters have been selected to achieve this safety goal.

8.1 Radioactivity

We have addressed several issues under the general title of radioactivity in MARS. These include blanket, reflector, and shield activation to quantify afterheat, coolant activation, biological dose at the back of the central cell shield and the end cell shield, and radioactive waste management.

The afterheat in the central cell is the principal source of energy that must be removed in the event of loss of coolant or loss of flow accidents, discussed in Sec. 4.9. Our analysis showed that the blanket cannot melt from the worst case combination of these causes. Initial afterheat from the structure is about 4% of the steady-state, central-cell thermal power. It is dominated by ^{56}Mn with a 2.58-hour half-life, and drops to about 0.06% of the steady state one day after shutdown.

We evaluated activation of the coolant as a contributor to central cell afterheat, for long-term waste disposal, and as a source of ^{210}Po . Polonium-210 is an energetic alpha emitter ($E_{\alpha} = 5.3 \text{ MeV}$) and has a relatively short half-life ($t_{1/2} = 138.88 \text{ days}$). It is also highly volatile in air and thus could pose a significant hazard if it is released to the environment. Polonium-210 is produced from lead and from bismuth impurities in lead by the following reactions:

The initial production rate from the bismuth impurity (0.0042 wt% for electrolytic lead) is about 6 mCi/s. This rate increases linearly with time,

doubling in about 8 to 9 years, from the double capture reaction. Because of the hazard, we continuously remove ^{210}Po from the coolant in the tritium recovery system. This is possible because the vapor pressure of ^{210}Po at 500°C is 2 Torr. The equilibrium activity of ^{210}Po in the coolant near the beginning of life is estimated to lie between 90 and 20,000 Ci, depending on the chemical activity of polonium in Li-Pb. This value will increase in proportion to the production rate.

The central cell shield is designed for hands-on access at the back of the shield within 1.5 days after shutdown. We evaluated several shielding criteria that are consistent with hands-on maintenance and selected a requirement that a maintenance worker receive no more than 100 mrem in a standard week that commences 1.5 days after shutdown. This is within present NRC 10CFR20 regulations, allows prompt access to the shield, and causes minimal cost penalties for the shield. However, because of this restriction, the final biological shield is of aluminum construction.

We computed the dose at the wall of the end cell vacuum tank for two conditions: (1) behind the magnets and structure and (2) where there are line-of-sight paths to the vessel without intercepting a magnet. In the former case, the dose is low enough to allow access at shutdown. In regions corresponding to the second case, 65 cm of concrete shielding was added to allow access in within 2 days.

We paid particular attention to radioactive waste management with the goal of achieving near-surface disposal of all components according to NRC regulations (10CFR61). We evaluated the blankets, choke coil insert, direct converter, and coolant. The ferritic steel blanket structure has several advantages relative to standard austenitic steels for waste management because of its lower molybdenum fraction, very low nickel fraction, and no intentional use of niobium. We performed a detailed analysis of blanket activation and requirements for disposal. The MARS blanket can be disposed of as Class C low-level waste by encasing it in concrete after a short period of cooling in the reactor spent-blanket pool. As an alternative, we also investigated low-cost isotopic tailoring of the molybdenum to be used in HT-9. We found that, for a 13% increase in blanket cost, we could dispose of a compacted blanket structure as Class C waste without concrete encasement. This allows a 14-fold reduction in the volume of the waste. The MARS design is the only steel blanket to date that achieves this degree of low activation.

The direct converter TZM structures, taken together, would qualify as Class A waste. The inner collector alone would be Class C; however, compacting and mixing all of the TZM yields Class A waste.

The coolant, as extracted from the reactor, would qualify for Class C providing that processing is used to reduce radioactive silver and bismuth contents by a factor of 27. Because the coolant is a large capital investment, it is likely to be used in subsequent plants and not be discarded at the end of plant life.

Because neutron transmutations of copper in the choke coil insert produce ^{63}Ni , the coil is not suitable for near-surface burial. There are three options for disposing of the choke coil: (1) deep geologic burial, which is economically acceptable because of the low volume; (2) dilution by a factor of 6 to 12 between 5 and 100 years after removal from the reactor; or (3) interim storage for about 360 years at which time it qualifies for Class C (700 years for Class A).

We conclude that the radioactive waste requirements for MARS can be made to fall into either Class C or Class A categories. Deep geologic burial may be used for some selected components for economic reasons, but it is not required.

8.2 Normal Radioactivity Releases

There are three sources of normal radioactivity release from MARS. Two of these are associated with tritium. The normal release up the stack is less than 15 Ci/day, as discussed in Sec. 4.11. The loss through the double-walled heat exchangers is less than 10 Ci/day, assuming oxidation of T_2 in the gap between the tubes. The tritium that gets into the secondary loop is not directly lost to the environment. The third source of normal radioactivity release is direct radiation when the plant is operating. MARS has been designed to meet present NRC site boundary dose regulations. The expected levels are innocuous.

8.3 Safety

We performed a safety analysis of MARS under certain chosen accident conditions, in which we found that the radiation releases were far below NRC accident limits because the design includes safety systems and barriers. The accident conditions considered were: (1) release of activated structure;

(2) release of activated corrosion products; (3) release of the activated coolant; and (4) release of tritium. For these analyses we postulated releases into the containment building and evaluated the effect of breach of containment. In many cases, we could not identify any credible mechanisms that would lead to these releases. The resultant doses have been calculated in the event that a credible release mechanism can be postulated.

The results of these analyses are shown in Table 22. The column titled "Containment failure" implies that the particle filters and atmospheric tritium removal systems are inoperative at the time the release occurs. With the containment building intact and safety systems operating, the site boundary doses are very low. Even if the filtering systems fail, we are still well below the present NRC guideline of 25 rem for fission plants. We conclude that MARS is an inherently safe plant.

Table 22. Site boundary doses under worst-case accident conditions.

Occurrence	Site boundary dose (rem)	
	Containment intact	Containment failure
Release of activated structure		
Full blanket	3.2×10^{-5}	0.1
One module	1.2×10^{-6}	4.6×10^{-3}
Release of activated corrosion products	8×10^{-4}	2.6
Release of T_2 in pellet injector	6×10^{-5}	0.016
Release of coolant activation	--	0.024

9. Economic Analysis

The MARS cost and economic analyses provide a detailed breakdown of the capital and operating costs for a tandem-mirror commercial power plant and the resultant cost of electricity. These have been developed consistent with the

1978 DOE guidelines,²⁷ which facilitate comparisons with other fusion reactor studies. We have also used methods of establishing time-related costing that are closer to present utility practices.

The direct capital costs were developed for a first-of-a-kind commercial reactor. This assumes that the equipment research and development costs are not included in the capital costs, but are borne by the demonstration reactor or auxiliary programs. The final costs for MARS are for a tenth-of-a-kind capital cost estimate through the application of learning curves that were applied on the subsystem or component level. These curves quantify a reduction in unit cost of a product as the number of manufactured units increases. The degree of learning, and thus cost reduction, is largest for systems or operations that are labor-intensive in their production, e.g., magnet winding. We have been quite conservative in our use of learning-curves. Thus, the reduction in cost from the first plant to the tenth plant is not as large as has been seen in other reactor design studies. Direct capital costs are presented in 1983 dollars. These are shown in Table 23 for major elements in the code of accounts. The cost estimates for both first- and tenth-of-a-kind plants are given. The direct capital cost for MARS is \$2,365 billion, or \$1,971/kWe. The largest difference between first- and tenth-of-a-kind plant costs occurs in Account 26, special materials, which is primarily the cost of Li-Pb that is 90% enriched in ⁶Li. The reduction stems from a lowering of enrichment costs based on a high product throughput.

The total capital cost is the sum of the direct capital cost and indirect capital costs for construction equipment, facilities, and services (Account 91), engineering and construction management services (Account 92), and other costs including insurance, taxes, and owner's general and administrative expenses (Account 93). These costs are specified in Table 24.

Account 91 is based on a detailed estimate derived from recent light water reactor experience. It is slightly more than the 10% of total direct cost used in many other reactor studies. Account 92 is 8% of direct costs and Account 93 is 5% as specified by the Pacific Northwest Laboratory (PNL).²⁷ The total capital cost is \$2.912 billion, or \$2,427/kWe.

The final contributors to the total capital investment are the time-related costs during the 5.75-year construction period and payout schedule discussed in Sec. 6. During this time the utility will pay interest on the funds already expended or interest during construction (IDC). In

Table 23. MARS direct capital costs.

Account number	Account title	First-of-a-kind cost (M\$) ^a	Tenth-of-a-kind cost (M\$)
20	Land and land rights	5.0	5.0
21	Buildings and structures	264.8	249.8
22	Reactor plant equipment	1,879.4	1,517.3
22.01.01	Blanket and first wall	101.0	71.2
22.01.02	Shield	97.1	75.0
22.01.03	Magnets	576.5	493.0
22.01.04	Supplemental heating	135.2	101.3
22.01.05	Primary structure and support	67.1	54.6
22.01.06	Vacuum systems	8.2	7.0
22.01.07	Power supplies	72.3	63.4
22.01.08	Drift pump coils	5.6	4.7
22.01.09	Direct converter	25.5	22.8
22.02	Main heat transport	292.4	236.6
22.03	Auxiliary cooling system	61.7	50.2
22.04	Radioactive waste treatment	14.3	11.5
22.05	Fuel handling and storage	65.1	45.9
22.06	Other reactor plant equipment	40.5	30.5
22.07	Instrumentation and control	35.2	24.8
22.98	Spares	42.0	32.0
22.99	Contingency	239.7	193.0
23	Turbine generator plant	299.7	275.0
24	Electrical plant	180.0	160.0
25	Miscellaneous plant equipment	36.1	33.2
26	Special materials	177.3	124.9
	Total	2,842.3	2,365.2

^aMillions of dollars.

Table 24. Indirect capital costs.

Account	Account title	Cost (M\$) ^a
	Total direct capital cost	2,365.2
91	Construction facilities, equipment, and services	240.0
92	Engineering and construction management	189.0
93	Other	118.0
	Total capital cost	2,912.2

^aMillions of dollars.

addition, if there is an underlying inflation rate during the construction period then the cost of construction yet to be completed will rise at this rate. This represents an escalation during construction (EDC). We have developed the total capital investment for the four cases given in Table 25. Cases 1 and 2 present costs in "constant 1983 dollars." This assumes that there is no inflation. Case 1 has interest at 5% above the inflation rate (PNL guideline) while Case 2 assumes that the interest rate is 10% above general inflation (non-nuclear utility practice). Cases 3 and 4 present costs in "then current dollars," which account for the underlying inflation rate during construction. Cases 3 and 4 assume 5 and 8% escalation, respectively. The IDC for Case 3 is 10%, or 5% above inflation (PNL guideline). Case 4 shows the effect of a higher escalation rate.

The cost of electricity (COE) is computed from the fixed carrying charge on the total plant investment (C_{AC}) plus the annual operating and maintenance costs ($C_{O\&M}$), annual scheduled component replacement costs (C_{SCR}), annual fuel costs (C_F), the plant availability factor (PAF), plant capacity (PC), escalation rate (E), and construction period (P). The COE is given by

$$COE = \frac{C_{AC} + (C_{O\&M} + C_{SCR} + C_F) (1 + E)^P}{PC (.AF) (8760)},$$

where C_{AC} is given by the product of the fixed charge rate (FCR) and the total capital investment.

We have derived a fixed-charge rate based on financing for an investor-owned utility with 55% debt financing and 45% equity financing. We assumed straight-line depreciation for book purposes, while the sum of the digits is used for income tax purposes on a flow-through basis. The plant life is 30 years with zero net salvage value; this implies that the actual salvage value is equal to the cost of decommissioning. We derive a fixed-charge rate of 0.14913 using these assumptions and use 0.15 in most of the COE computations.

Operations and maintenance costs, scheduled component replacement costs, and fuel costs are \$20.2, 5.3, and 2.8 million per year, respectively, in 1983 dollars.

We compute the cost of electricity for the same four cases given in Table 25. These cases are shown in Table 26. For Case 1, we use a 10% fixed-charge rate in accordance with PNL guidelines. For the other three cases, we use 15%. The plant capacity is 1200 MW and the availability is 75%, as discussed in Sec. 7. We can see that the busbar cost of electricity varies from 46.2 to 98.6 mil/kWh, depending on the economic assumptions used. Cases 1 and 3 are equivalent to the two cases presented in the Starfire study. If costs are normalized to the same year and if we use the availability goals of 80 and 75% for MARS and Starfire, respectively, then the MARS COE is about 4% less than that of Starfire. The difference is well within the uncertainty of the estimates.

The costs presented are within the range of costs for new generation capacity to be installed in the late eighties, and are the upper end of that range. Significant cost reductions can be gained by improved engineering designs without changes in the physics. The areas where the largest reductions can be attained are in the magnets, heat transport system, and electrical system. These, coupled with improved subsystem efficiencies, could result in a 20 to 25% reduction in capital cost per unit of output (\$/kWe). In addition, new physics concepts that allow a reduction in end cell costs can improve the plant cost even further. Both of these can be done without sacrificing the environmental, safety, and maintainability advantages inherent in the MARS design.

Table 25. Time-related costs.

Cost element	Constant 1983 dollars		Then-current 1989 dollars	
	Case 1	Case 2	Case 3	Case 4
	IDC ^a = 5% EDC ^b = 0	IDC = 10% EDC = 0	IDC = 10% EDC = 5%	IDC = 10% EDC = 8%
Total capital cost (M\$) ^c	2912.1	2912.1	2912.2	2912.2
IDC	354.1	708.3	863.2	677.8
EDC	0	0	521.7	938.9
Total capital investment (M\$)	3266.3	3620.5	4297.1	4748.9
Cost per unit generated power (\$/kWe)	2722	3017	3581	3957

^aIDC = Interest during construction.

^bEDC = Escalation during construction.

^cM\$ = Millions of dollars.

Table 26. Cost of electricity (in mil/kWh).

Cost element	Constant 1983 dollars		Then-current 1989 dollars	
	Case 1	Case 2	Case 3	Case 4
	IDC ^a = 5% EDC ^b = 0 FCR ^c = 10%	IDC = 10% EDC = 0 FCR = 15%	IDC = 10% EDC = 5% FCR = 15%	IDC = 10% EDC = 8% FCR = 15%
Annual fixed charge	42.56	70.77	84.00	92.83
Annual O&M, SCK, fuel	3.68	3.68	3.98	5.73
Total	46.2	74.5	88.9	98.6

^aIDC = interest during construction.

^bEDC = escalation during construction.

^cFCR = fixed-charge rate.

10. Power Flow and Cost Scaling

The MARS plant makes very efficient use of the fusion energy it produces because of the following performance factors: (1) high neutron energy multiplication in the blanket; (2) direct conversion of end plasma losses; (3) high-efficiency thermal conversion; (4) high plasma gain; and (5) high-efficiency supplementary heating. These features are illustrated in Fig. 33 with a simplified power flow diagram. The definitions of the quantities in this figure are given in Table 27. We start from the supplemental heating power absorbed by the plasma of 100.6 MW. The plasma gain (Q) of 26 yields a fusion power of 2618 MW. The energy multiplication in the blanket and reflector increases the total thermal power to 3466 MW. Some of the power is lost (PL) before reaching the energy conversion system as a result of synchrotron losses from the plug and neutrons that do not enter the blanket. The useful power is divided among the blanket (PBL), reflector (PREF), and end cell (PEC). The blanket power is converted in a superheat cycle to produce 892.8 MW (PESH) of electricity. A portion of the end cell power is directly converted to electricity (PDC), producing 292 MW. The remainder is obtained as quality heat (PECT) and is combined with the reflector power for conversion in a saturated steam cycle to produce 346.9 MW of electricity (PESAT). Thus, the gross electric generation in MARS (PG) is 1531.7. The reactor requires 334.2 MW of recirculating power (PREC). The choke coil resistive inserts and drift pump coils require 101.5 MW (PMAG). The four supplemental heating systems--thermal barrier ECRH, potential peak ECRH, anchor ICRH, and sloshing-ion neutral beams--require 158.3 MW total (PPHW). The rest of plant, including primary loop pumps, cryo plant, reject cooling pumping, and other auxiliaries, requires 74.4 MW (PAUX). This results in a net generation of 1197.5 MW (PNET).

There are several areas where the power balance could be improved. More efficient ICRH transmitters based on developmental tubes could save about 6 MW. Increasing the field in the superconducting portion of the choke coil to 18 T would reduce the magnet power by more than 20 MW. Improved efficiency of the cryo plant based on newer designs could save about 3 MW. Finally, changing the power split to increase the fraction of energy in the blanket could generate an additional 30 MW of electricity. Thus, without any changes in the

Fig. 33. A simplified model for the MARS power flow system.

physics, plasma configuration, and most subsystems, an additional 60 MW of electricity could be generated.

The unit rating of MARS and the cost of the plant size are closely related. Originally, we sized MARS for 3500 MW of fusion power. Because of the efficient use of fusion power, this resulted in a net generation of about 1700 MW of electricity. We discussed this plant with representatives of the utility industry and decided to reduce the net electric output to 1200 MW to be consistent with recent utility practices. This lower plant size also simplifies comparisons with other fusion reactor studies and standard fission plant designs.

Table 27. Power flow definitions.

Q	Plasma gain, ratio of fusion power to power absorbed by the plasma
PL	Unusable power (synchrotron radiation in the plug and neutrons in the central cell that do not enter the blanket)
PEC	End-cell charged-particle power on the inner and outer collectors, halo scraper, and halo dump
PREF	Reflector power in water coolant
PBL	Blanket power in Li-Pb coolant, including losses to the corrosion product cold trap
η_{ER}	End-region direct-conversion efficiency
PECT	Thermal power from the end cell in water coolant
η_{SAT}	Thermal efficiency of the saturated steam cycle
PESAT	Electric power from the saturated steam cycle
PDC	Directly converted electric power
η_{SH}	Thermal efficiency of the superheated steam cycle
PESH	Electric power from the superheated steam cycle
PPH	Absorbed plasma heating power from ECRH/barrier, ECRH/potential peak, ICRH, and sloshing-ion beam
f_T	Average trapping fraction of plasma heating systems
η_{PH}	Combined efficiency of plasma heating systems
PMAG	Recirculating power for choke coil resistive inserts and drift pump coils
PPHW	Recirculating power for plasma heating systems
PAUX	Recirculating power for primary loop pumping, secondary loop pumping, miscellaneous cooling, cryo plant, cooling tower fans, tritium plant, and electrical systems
PREC	Total recirculating power
PG	Gross electric power
PNET	Net electric power

The tandem mirror reactor has a unique feature that gives it a strong economy of scale: whereas the fusion power increases linearly with the length of the central cell, the end cell cost and the majority of the recirculating power remain approximately constant as the central cell length varies. The total capital cost for a MARS-type tandem mirror reactor as a function of net electric output is presented in Fig. 34. The MARS baseline design point of 1200 MWe and \$2.912 billion is indicated. The cost of a 1700-MWe plant is only 14% above that of the baseline. Of more importance is the cost per unit of net electric power, which is shown in Fig. 35. The unit cost is closely related to the cost of electricity. We can see the very strong economy of scale. The unit cost for a 1700-MWe plant is 19% lower than the unit cost of the baseline; the unit cost of a 2000-MWe plant is 25% less. If cost of the tandem mirror reactor scaled at the 0.8 power, as do many power plants, the reductions at 1700 and 2000 MWe would only be 6.7 and 9%, respectively. We chose to accept these cost penalties to produce a plant design that is within the range of present plant sizes. Today there is a strong desire to build plants smaller than the MARS baseline. Based on the scaling shown in Figs. 34 and 35, the cost of a small reactor obtained by shortening the central cell length in MARS is prohibitive. Therefore, we are currently pursuing alternative design concepts with compact plugs for plants of less than 750 MWe net output.

The baseline MARS design was optimized for a large size plant. The cost of electricity could be reduced significantly if the plant size were increased even further. For small-size tandem mirror reactors, a different design concept for the plugs is indicated and is now being explored.

11. Conclusions of the MARS Study

11.1 Accomplishments

The two-year MARS study produced the most complete and detailed tandem mirror reactor design to date, with self-consistent physics and engineering elements. It gives a fairly clear picture of what a commercial tandem mirror reactor would look like based on the type of thermal barrier plugs in TMX-U at LLNL, and on the plasma/magnet configuration to be tested in MFTF-B (also at LLNL). The MARS study showed that safe, efficient, technically sound

Fig. 34. Capital cost scaling for a tandem mirror reactor as a function of net electric power.

Fig. 35. Unit cost scaling for a tandem mirror reactor as a function of net electric power.

commercial reactors for the production of both electricity and synfuels can be designed based on these plasma confinement concepts. The MARS concept has many characteristics conducive to an attractive central-station fusion plant--high fusion power density, inherent steady-state operation, linear geometry, and direct conversion of plasma energy to electricity. The capital costs of the MARS electricity and synfuel plants are relatively high and thus we would expect the MARS reactor to be limited to large, baseload central power plants. However, improvements in MARS reactor economics can be envisioned by evolution and maturation of fusion technology, and future discoveries in physics can be expected to lead to both simplifications in the design, smaller unit sizes, and, therefore, even lower costs.

The MARS design incorporates the key advances in mirror physics achieved in TMX-U--thermal barrier plugs with enhanced potential plugging using ECRH, and enhanced microstability using sloshing ions. The MARS study has also developed new physics concepts needed for improved reactor performance, such as drift pumping of alpha ash and impurities, vacuum pumping by recycling halo plasmas, and radial-potential reduction by negatively biased end wall plates. Many of these reactor improvement concepts have stimulated similar improvements to be incorporated into TMX-U and into the MFTF-B design. These improved plasma confinement ideas fostered by both experiments and reactor design have enabled MARS to meet its performance goals of high plasma power gain ($Q \approx 25$) and high first-wall loading ($\Gamma = 4.3 \text{ MW/m}^2$).

In addition to improved plasma design concepts, the MARS study also produced higher performance blanket designs, notably a high blanket-energy multiplication ($M = 1.36$) in a Li-Pb blanket for electricity production, and a high-temperature, helium-cooled silicon-carbide pebble bed blanket ($T_{\text{HE max}} = 1000^\circ\text{C}$) for efficient synfuels production. These blankets, coupled with direct conversion of the plasma exhaust, have made it possible for MARS to achieve an impressive overall efficiency of fusion energy conversion to net electricity production equal to 46% of the DT fusion power, and liquid methanol synfuel energy production equivalent to 50% of the DT fusion power in a separate synfuel plant design.

Anticipating that superconducting magnets are a key fusion technology requirement for MARS and that they are one of the larger cost items in the reactor plant, the MARS magnet design adheres as closely as possible to MFTF-B magnet technology and cost data. Except for key portions of the magnet system, such as the high-field choke coils, which require extensive development for MARS, the majority of the MARS magnets require only modest extrapolations in present state-of-the-art superconducting magnet size, fields, and technology. Aggressive magnet design in terms of both increased stored energy per unit mass and radiation tolerance is one future area where we would expect to see big payoffs in terms of system economics.

The MARS study also pioneered several new ideas to exploit inherent fusion possibilities in improved waste disposal and safety. We showed that practical ferritic structural steels could meet NRC rules (10CFR61) for near-surface burial as Class-C low-level waste; and we designed simple, lightweight

blanket modules to meet those requirements with a minimum of processing and transportation. We showed that passive radiation and conduction cooling in the MARS blanket would prevent meltdown in all conceivable loss-of-coolant and loss-of-flow accidents. Reactor vault overpressures in worst-case accidents would not exceed even a small fraction of an atmosphere, reducing containment building complexity and cost.

11.2 MARS R&D Needs

11.2.1 Introduction.

Table 28 identifies some critical technology requirements that are particularly vital in order for us to achieve our performance goals for MARS. The requirements listed in Table 28 need extensive additional R&D, but are not a total list. We also require further data on the effects of corrosion and neutron damage on the constituent materials of most of these technology components (see Table 29). Major areas in which we can define R&D needs are described in the following sections.

11.2.2 Negative-Ion-Based Neutral Beams

Development of negative ion technology is essential to the formation of energetic sloshing ions in the MARS thermal barriers. While the greater neutralization efficiencies and single species characteristics of negative-ion-based neutral beams would be useful everywhere on a mirror reactor, the 475-kV 10-A requirements for the MARS reactor appear to necessitate the negative ion approach. Presently, negative ion sources in the 1-A range are operating in a continuous mode. Also, initial experiments with single-aperture, large-area, multiple-beamlet electrostatic quadrupole accelerators have been performed. However, there is an immediate need for an enhanced negative ion program to complete source development and construct a proof-of-principle accelerator and neutralizer assembly. In addition, photodetachment using lasers merits development to provide the high neutralization efficiencies desired in mirror reactors.

Table 28. MARS critical technology R&D needs.

Technology	Requirement
Negative ion beam	475 kV, 10 A, 0.1 A/cm^2
High-field hybrid magnet	24 T, 60-cm bore, Cu + Nb ₃ Sn + NbTi
Drift pumping	18 kA, 47 kHz, $\Delta f/f = 0.4$
Direct conversion, plasma exhaust	3-MW/m ² gridless direct converters compatible with radial potential control; high recycling halo dumps for 2-kA DT and He pumping
High-speed DT pellet injectors	20 km/s, 6.5 Hz, $r = 2 \text{ mm}$
Quasi-optical ECRH systems	42 MW, 60 GHz, 2.5-MW gyrotron tubes
Li-Pb blankets	$T_{\text{max}} = 500^\circ\text{C}$, $S_w = 5 \text{ W cm}^{-2}$, 0.1-mm/year erosion, $\Gamma > 4 \text{ MW/m}^2$, corrosion product cold traps
Double-walled heat exchangers	10^{-4} attenuation of T_2 from the Li-Pb side to the steam side
High temperature synfuel blankets	$T_{\text{max}} = 1000^\circ\text{C}$, $P = 80 \text{ atm}$, $\Gamma = 4 \text{ MW/m}^2$, $S_w = 5 \text{ W/cm}^2$, 0.1-mm/year erosion
High temperature SO ₃	$P = 80 \text{ atm}$, $T_{\text{max}} = 960^\circ\text{C}$, corrosion-resistant decomposer

Table 29. MARS critical material data needs.

Blanket and coolant

- End-of-life radiation damage effects in HT-9 ferritic steel (i.e., swelling, radiation creep, changes in DBTT, etc.) for first-wall neutron fluences in the range of 5 to 25 MW·yr/m²
- Li-Pb/HT-9 corrosion data:
 - Corrosion rates for interface temperatures of ~500 to 550°C, flow velocities of ~0.1 to 2 m/s and magnetic fields of several teslas
 - Deposition characteristics of corrosion products in turbulent flow regions and cold traps
 - Performance of additives as corrosion inhibitors
- Performance testing of Li-Pb as a self-sealing material for remote joint technology

Superconducting magnets

- Radiation damage properties of organic insulators under stress conditions (shear and compressive) relevant to magnet operation
- Definition of radiation-induced critical-current degradation in NbTi and Nb₃Sn superconductors
- Quantification of radiation-induced resistivity increases in copper stabilizers
- Ongoing development of general radiation-resistant magnet materials for high-field, high-current-density applications

Normal conducting magnets

- Development of high-yield-strength high-conductivity copper alloys for normal-conducting magnet applications
- Radiation damage effects in high strength copper alloys under elevated 14-MeV neutron fluences $>10^{26}$ n m⁻²
- Characterization of ceramic insulator damage under elevated 14-MeV neutron fluences $>10^{26}$ n m⁻²
- Radiolytic dissociation effects in coolant water

Direct converter materials

- High-heat-flux, high-yield-strength, low-sputtering materials for direct converter and halo scraper surfaces
 - Brazing and machining of large-size TZM molybdenum alloy panels
 - Experimental determination of diffusion properties of implanted tritium through proposed direct converter materials
-

11.2.3 Magnet Development

The peak field levels--10 T--and size of the yin-yang magnets in MARS are nearly the same as those recently demonstrated in the MFTF-B magnet system. In addition, 7-T 5-m-bore central solenoid magnets are easily within the reach of existing technology. However, these magnets dominate the cost of the reactor and further development is desired to reduce these costs. The 24-T hybrid-choke-coil magnets require considerably more development. A normal copper hybrid coil producing about 8 T augments a background superconducting coil field of 16 T. The development of 12-T magnets is currently being pursued in the High Field Test Facility at LLNL, and a 13.5-T solenoid is planned for MFTF-B. Future superconducting magnet development plans will include ternary additions, such as titanium, to niobium-tin to reach fields of 15 to 16 T. In addition, development of organic insulators with higher radiation-damage tolerance is certainly required here.

However, a new ingredient in the magnet development plan is normal copper insert coils producing field increments of 9 T in a 60-cm inside bore. The 24-T field produces very high tensile stresses in a high neutron radiation environment. New ceramic insulators must be examined and new coil winding techniques must be developed. Experience with water-cooled Bitter coils indicates that this type of coil is unlikely to be applicable in its present state of development because of short coil lifetimes attributable to shorting and arcing. By contrast, internally cooled MgO-insulated magnets used in the Los Alamos Meson Production Facility (LAMPF) exhibit good lifetimes but low current densities. At a minimum, conductor configuration, insulation, joining, and coil winding techniques need to be demonstrated as a proof-of-principle. Later, small-scale coil tests to full field will be necessary.

11.2.4 Particle Fueling, Exhaust, and Energy Recovery

Steady-state operation in MARS will require 2 kA of DT particles throughput, with repetitive high-velocity pellet injection, radial drift pumping, and exhaust into a halo diverter plasma (see Table 28). The required pellet velocities are estimated to be well beyond the 1-to-2-km/s speeds presently available with centrifugal or pneumatic drives. Linear electromagnetic railguns are the most promising method to achieve the factor of 10 in velocity, and have been achieved with small plastic pellets. Tests of railguns

with hydrogen ice pellets are needed. The key challenge with drift pumps is to obtain rf drivers that can supply the large reactive rf currents at several simultaneous frequencies with low loss (circuit $Q > 200$). The halo dump that receives the drift-pumped DT fuel and alpha ash must trap the resulting neutralized gas in a reentrant cavity with a high recycling coefficient (>10 to 20) and at a useful plenum pressure (5μ or higher). The sputtering lifetime must be usefully long--a minimum lifetime of several years is desirable. Tritium loss into the cooling water must be much less than 1% of the tritium bred in the blanket. The electron exhaust, which is separated from the ion current by the drift-pumping process, must be collected on negatively biased plates within the annular halo dump. The electron collector potentials (-167 kV maximum) must be appropriately graded to keep the central cell plasma near ground potential. Peak collector heat fluxes of 3 MW/m^2 are required for compact direct converters.

11.2.5 Li-Pb Blanket

The use of Li-Pb as the blanket coolant/breeder allows high performance in terms of thermal efficiency, tritium breeding, and energy multiplication, coupled with long life and simplicity of design. One key issue for the blanket is the upper temperature limit set by liquid metal corrosion. Additional data are needed on corrosion rate as a function of temperature and velocity. No data exist on the effect of the magnetic field on corrosion, which could change the results markedly. Most importantly, no work has been performed on methods to reduce the corrosion rate through the use of inhibitors or on the design of the primary loop to accommodate large corrosion rates. The use of traps to avoid plugging of passages indicates great promise. If material thinning is determined to be the only life-limiting corrosion effect, then long blanket life at high ($>500^\circ\text{C}$) temperatures can be attained. One of the principal causes of stress in the blanket is the internal pressurization of the coolant to overcome the MHD-induced pressure drop. More R&D on pumping conducting liquids through a magnetic field is needed. Of particular importance are entrance and exit effects, flow constrictions and expansions, flow striations, and the overall effect on heat transfer. Other fruitful blanket R&D areas would be to investigate relaxation of stresses by radiation-induced creep,

radiation-induced change in the ductile-to-brittle transition temperature, swelling at high displacement-per-atom levels, and design for total deformation as a life-limiting mechanism.

11.2.6 Heat Transfer Components

The primary loop, because of the high density of the Li-Pb coolant, requires component development. Moreover, the size of components is limited due to weight restrictions. Development is needed in heat exchanger design (particularly double-walled heat exchangers), piping supports, and pumps. The design of self-soldering Li-Pb seals used for remote disconnection of the piping needs to be tested.

11.2.7 Tritium Control

Because of the low solubility of tritium in Li-Pb, tritium control in the plant is difficult. We have designed a baseline double-walled steam generator with an active, O_2/He tritium purge to provide a barrier of 10^4 to 10^5 between the primary and secondary loops. The effectiveness of this barrier relies on oxidizing the tritium to T_2O in the gap to preclude further permeation, and on providing a self-healing oxide coating on the tube walls. Tests of this concept are needed to prove its effectiveness as a tritium barrier and for heat transfer. Methods to enhance the oxidation in the gap need development. The method of removing tritium from Li-Pb is important because we desire an equilibrium pressure of T_2 in Li-Pb of less than 10^4 Torr. Further work is desirable to explore the most economic and effective method of implementing this recovery.

11.3 Future Directions

Although MARS represents a significant advance in tandem mirror reactor design, it is important to realize that MARS, like other fusion reactor designs at this early stage of conceptual development, will continue to evolve and improve as new experiments and better ideas are brought to bear. We likely have not yet fully exploited all the intrinsic characteristics of tandem mirrors (see Sec. 1) to achieve an optimum design in terms of reliability and

economics. The tandem mirror reactor concept is still relatively new and has received limited study relative to the tokamak. The simultaneous solution of the large number of physics and engineering requirements that formed the MARS point design commanded almost all of the two years of the MARS study. Now, at the conclusion of the study, we can already see new opportunities for future improvement and optimization of tandem mirror reactors.

We can foresee at least four general areas in which to seek these future improvements:

- We can probably find a better optimization in the tradeoff between central cell field, wall loading, and end cell heating power requirements. In MARS, we prescribed a maximum wall loading ($\Gamma_n > 4 \text{ MW/m}^2$) consistent with the maximum MHD-stable plasma pressure. This maximum wall loading required high plug betas as well as high anchor betas in the MARS end cell, resulting in high synchrotron radiation losses and ECRH power. Some of our recent post-MARS analyses indicate that reducing the wall loading by a factor of two (and central cell field from 4.7 to 3.3 T) could virtually eliminate synchrotron radiation and reduce total plug power by a factor of 4 (which doubles Q to 50). This tradeoff needs further exploration.
- We could obtain a large reduction in magnet weight and cost if we could design superconducting magnets to withstand greater neutron fluence, so that the shields could be thinner until cryoplant cost and power become the fundamental tradeoffs with magnet size and cost. Figure 36 shows the present dominance of magnet costs in the MARS reactor plant equipment (Account 22). Preliminary investigations by Henning et al.²⁸ indicate that neutron fluence effects that could be tolerated by superconducting magnets--dpa-induced resistivity in the copper stabilizer, compressive strength loss in polyimide insulators, and reductions in superconductor-critical current density--could be increased by factors of 100 with proper design allowance in the magnet design parameters. In many cases, particularly in the end cell magnets, shield thicknesses could be reduced by 20 to 40%, and corresponding geometric reductions in magnet volume, stored energy, weight, and cost could be decreased by factors of 2 to 3 compared with MARS.

Fig. 36. Histogrammic representation of the MARS reactor plant equipment costs. The cost of the Li-Pb coolant (classified as "special materials") is shown for comparison.

- We could simplify the MARS main heat transfer system and balance of plant if we could avoid using two coolants in the MARS blankets without losing performance ($M = 1.36$, $\eta_{TH} = 0.40$). This could allow the heat exchangers to be located closer to the reactor vault, economics in piping, and more economical common steam turbines. Coolants other than water should also be investigated for conversion of the thermal fraction of the end loss power. Also, we need to reduce the lithium enrichment to reduce the inventory costs of Li-Pb (Fig. 36).
- Finally, by the end of the MARS study we more fully understood the relationship between the physics requirements for equilibrium, stability, and transport and the resulting size and cost of the MARS end plugs. Figure 36 shows that if the plug costs (unshaded portion of the bars) could be greatly reduced by new design

approaches to solve the physics requirements, then potential reductions in MARS reactor plant equipment of up to 40 to 50% would occur if the central cell became the fundamental lower limit to the costs. Theoretical efforts are presently underway at LLNL, and other laboratories are investigating use of higher-order multipole fields, ELMO-type hot electron rings, and rf ponderomotive forces to stabilize just the outer boundary of "flat" radial-pressure profile plugs, which is the only area that requires stabilization as predicted by theory. The result would be that the plasma core--the central cell--could be plugged with essentially single mirror cells 7 m long on each end, compared with the 30-m length of the MARS end cells.

Although for future improvement most of the above four areas (and others) will be vigorously pursued, there are many physics and engineering concepts used in the MARS design that will likely endure in future tandem mirror reactor designs. These include the central cell with its engineering simplicity and high-performance blankets, the high-field choke coils, drift pumping, sloshing-ion thermal barriers, quasi-optical ECRH systems, and negatively biased direct converters. The real value of MARS, like all reactor studies before it, lies in its problem-solving role and in the new concepts fostered by the study as an invaluable educational process in the design of commercial fusion power plants.

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