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# MATERIALS ENGINEERING FOR TANDEM MIRROR REACTORS*

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Recent success in tandem mirror physics experiments has led to several conceptual reactor designs. These studies reveal that there are at least 4 areas in which unique materials problems appear for mirror reactors. The necessity to produce very high magnetic fields (20-24 T) requires the design, construction, and operation of normal copper coils in the intense radiation field of the plasma. A recent proposal to use rapidly changing (50-500 kHz) magnetic fields to reduce the ion density in the transition region has also required Cu coils in the vicinity of the plasma. A third new area is the collection of ion and electron energy and conversion of that energy into useful power. The direct convertor region of tandem mirrors requires the successful operation of very high heat flux components (200-300 W/cm$^2$). Finally, the heating of electrons as well as plasma startup scenarios dictate the extensive use of RF power. The most severe problems seem to be associated with the placement of ICRF antennas at the edge of the plasma and in the vicinity of high neutron wall loadings (1-4 MW/m$^2$). These problems are discussed in light of the recent MARS reactor study.

## 1. INTRODUCTION

In the past 10 years, most of the attention of the fusion materials science community has been focused on the problems associated with the tokamak. Considerably smaller efforts have been expended on other approaches to magnetic fusion reactors such as mirrors, stellarators, compact tori, etc. Recent progress in tandem mirror physics and the enhanced activity in tandem mirror reactor design (e.g., WITAMIR,[1] TASKA,[2] TDF,[3] MARS,[4] TASKA-M,[5] etc.) has shown that there are several unique materials problems associated with mirror systems. The object of this paper is to describe those unique problems and to suggest research programs needed to solve them.

## 2. PREVIOUS TANDEM MIRROR REACTOR DESIGNS

In the past 3 years there have been five major tandem mirror reactor designs (see Table 1). Two of these designs were of the commercial class (WITAMIR[1] and MARS[4]) and three of them were designed for materials and technology testing (TASKA,[2] TDF,[3] and TASKA-M[5]). From Table 1 one can see at least 4 areas where the materials requirements for tandem mirrors will be significantly different than for toroidal systems. These areas are (see Fig. 1): (a) high field, room temperature normal coils near the plasma, (b) grad $\overline{B}$ drift pump coils in the plug region to reduce the ion density in the plug region, (c) halo scraper and direct convertor collection plates at the ends of the machine which are subjected to intense ion bombardment, and (d) RF antennas both in the central cell (CC) to heat ions (ICRF) and in the end plug to heat electrons (ECRH). The rest of this paper will be devoted to these topics even though there are many materials problems in tandem mirrors which are the same as far as toroidal systems. These common problems include: first wall and

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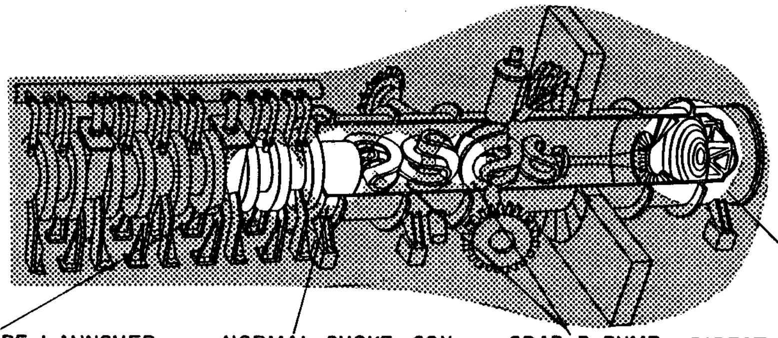
TABLE 1
Summary of Recent Tandem Mirror Reactor Designs

| PARAMETER | WITAMIR-I[1] | MARS[4] | TASKA[2] | TDF[3] | TASKA-M[5] |
|---|---|---|---|---|---|
| Type | Commercial Electric | Commercial Electric | Technology Test Fac. | Technology Test Fac. | Technology Test Fac. |
| Year Published | 1980 | 1983 | 1982 | 1983 | 1983 |
| Physics Basis | Thermal Barrier | Thermal Barrier | Thermal Barrier | Kelley | Kelley |
| Fusion Power, MW | 3000 | 2600 | 86 | 20 | 6.8 |
| Max. Wall Load, $MW/m^2$ | 2.4 | 4.3 | 1.5 | 1.5 | 1.3 |
| Plasma, Q | 28 | 26 | 0.74 | 0.35 | 0.17 |
| Direct Cost, M$ (y) | 2063 (80) | 2352 (83) | 788 (82) | 653 (82) | 400 (83) |
| Heating, MW | | | | | |
| NBI | 74 | 6 | 62 | 56 | 28 |
| ICRF | --- | 11 | 40 | --- | 12 |
| ECRH | 50 | 84 | 15 | 1.2 | --- |
| Fueling Mech. | Pellets | Pellets | Beams | Pellets | Beams |
| Method to Maintain Barrier | NBI | Grad $\overline{B}$ Pump Coil | NBI | None | None |
| Max. Field in Normal Cu Choke/Barrier Coils, T | 15 (S/C) | 24 | 20 | 15 | 18 |
| Max. Heat Flux to Ion/Electron Collectors, $W/cm^2$ | 300 | 250 | 150 | 250 | 500 |
| Configuration | Circular | Circular | Circular | Ellipsoid | Ellipsoid |



| **COMPONENT** | **ICRF LAUNCHER** | **NORMAL CHOKE COIL** | **GRAD B PUMP COIL** | **DIRECT CONVERTER** |
|---|---|---|---|---|
| **POSSIBLE MATERIAL** | STEEL. Cu | •Cu ALLOY<br>•INORGANIC INSUL. | Cu | REFRACTORY |
| **MAJOR PROBLEM** | MECHANICAL & ELECTRICAL PROPERTIES | MECHANICAL & ELECTRICAL PROPERTIES | ELECTRICAL PROPERTIES | EROSION |

FIGURE 1
Unique material problems in tandem mirror reactors.

blanket structural materials, breeding compounds and alloys, superconducting magnets, diagnostics, etc.

## 3. HIGH FIELD BARRIER/CHOKE COILS

It can be seen from Table 1 that all the recent designs have used high field solenoidal coils at the ends of the central cell to either establish a thermal barrier and/or to help confine the central cell ions. In all the designs except WITAMIR, the high fields were provided by a hybrid coil, i.e. a normal copper coil surrounded by high field superconductor. Typically, the superconductor is designed to provide on the order of 14-15 T on-axis and the rest of the magnetic field is provided by the normal inserts (3-10 T). Because the normal coils consume substantial electrical power (~ 20 $MW_e$ or more), and because the stresses on the coil increase rapidly as the diameter of the coil is enlarged, it is highly desirable to reduce the size of the coil. The smallest bore the coil can have is of course that of the first wall. The problem with building the coil that small is that the neutron flux is still very high in that region, on the order of 1-2 $MW/m^2$. Hence one has a situation which is in fact more severe than that of an ordinary first wall because of the very high stresses.

To illustrate the problem more directly, one can consider the MARS choke coil. Table 2 lists the operating conditions of the normal coil and Fig. 2 shows how the coil is placed in relation to the rest of the reactor components. Because of the high fields, the stresses generated in the coil are very high (~ 330 MPa or 48 ksi). This requires a strong conductor and fortunately there is an alloy of copper (MZC which is an alloy of Cu with Mg, Zr, and Cr) which has a yield strength of 550 MPa (80 ksi) at room temperature with electrical conductivity which is ~ 75% of Cu. This alloy must then operate at these stresses and at ~ 150°C while being bombarded with a neutron flux which corresponds to a maximum 2 $MW/m^2$ wall loading. Similarly, the electrical insulation in the coil will be subjected to these neutron fluxes plus high radiation backgrounds of ~ $10^{11}$ Rad/FPY.

TABLE 2
MARS Choke Coil Requirements

| | |
|---|---|
| Copper Alloy | MZC (Mg, Zr, Cr) |
| Insulator | Spinel ($MgAl_2O_4$) |
| Coolant | Deionized Water |
| Max. Conductor Temp. | 154°C |
| Max. Field in Magnet | 24 T |
| Conductor Design/Yield Stress | 330/550 MPa (48/80) ksi |
| Maximum Neutron Wall Load | 2 $MW/m^2$ |
| Elec. Power at t = 0 | 41 MW/coil |

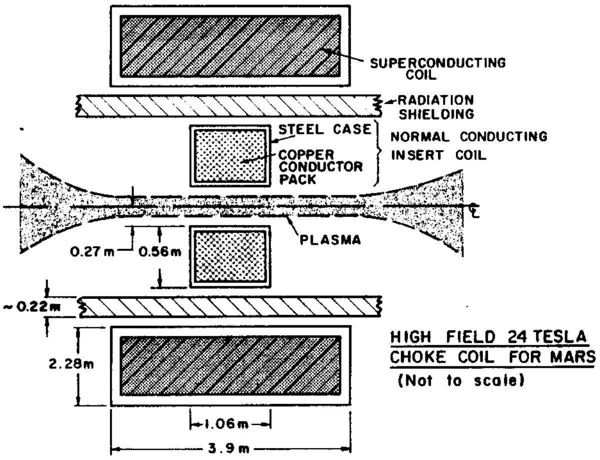


FIGURE 2
Schematic of high field choke coils for MARS. Much of the shielding is removed for clarity. Note how close the room temperature copper coil is to the plasma.

The damage conditions in the Cu MARS choke coil are shown in Fig. 3. The displacement rate ranges from ~ 15 dpa/FPY at the front to < 0.01 dpa/FPY in the back. At this time

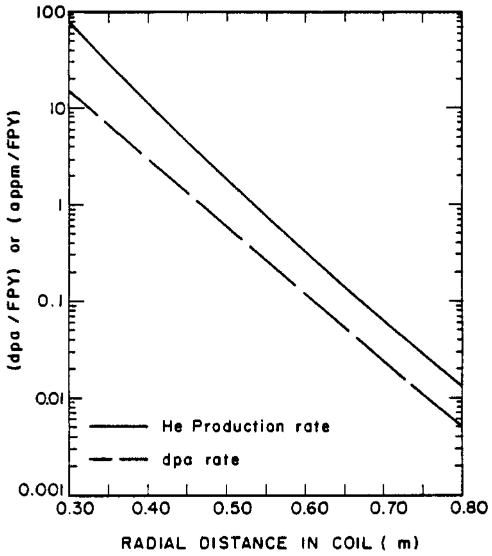


FIGURE 3
Variation of radiation damage in MARS copper choke coil. (Courtesy of L. El-Guebaly.)

there is very little information on how this alloy will stand up to such damage at 150°C and research programs in this area are sorely needed. Basic questions arise about the following areas: (a) yield strength increases, (b) radiation induced creep, (c) ductility, (d) dimensional stability, and (e) microstructural stability.

Another complication with respect to the operation of this coil is its electrical resistivity. At reactor startup each MARS coil requires ~ 40 MW of power. During the neutron bombardment the following elements are introduced by transmutations:

Ni - 1750 ppm per MW-y/$m^2$
Zn - 970 ppm per MW-y/$m^2$
Co - 33 ppm per MW-y/$m^2$

Such transmutations will increase the resistivity of the inner layers of the magnet by ~ 12% per MW-y/$m^2$. When this is averaged through the coils the total electrical requirement is increased by 2.7% per MW-y/$m^2$ exposure (~ 1 $MW_e$ additional per year of operation for each coil). While this does not sound so serious, it will amount to ~ 200 M$ in additional operating costs over a 20 FPY lifetime for both coils.

Finally, one is faced with choosing an inorganic insulator which will withstand high neutron and gamma fluxes. At this time, spinel ($MgAl_2O_4$) seems to be the best choice. Its swelling rate is reasonably low (~ 3% per 4 x $10^{22}$ fission neutrons/$cm^2$) and its fracture toughness actually increases with neutron irradiation. In MARS, a 3% swelling limit was adopted yielding a life of 3.2 FPY[6] for replacing the coil. A much more detailed analysis is required to determine the ultimate lifetime and it is felt that much larger swelling values could be accommodated in the region near the plasma by proper design.

## 4. GRAD $\overline{B}$ DRIFT COILS

One unique feature of tandem mirrors with thermal barriers is the need to continually remove ions which get trapped in the thermal barrier. This originally was done with neutral beams but it has been recently suggested[7] that particles could be pumped from the barrier into the halo plasma by rapidly varying magnetic fields. In the MARS design, these grad $\overline{B}$ drift pump coils are placed between the transition and anchor coils (see Fig. 4) and also between the anchor and plug coils. The magnets are resistive and produce modest alternating magnetic fields. For example the transition/anchor coil operates at a central frequency of 47 kHz and an average magnetic field fluxation of 420 gauss. A series of 10 frequencies placed 1.9 kHz apart induced cross field drift which "pumps" particles from this region into the halo plasma so

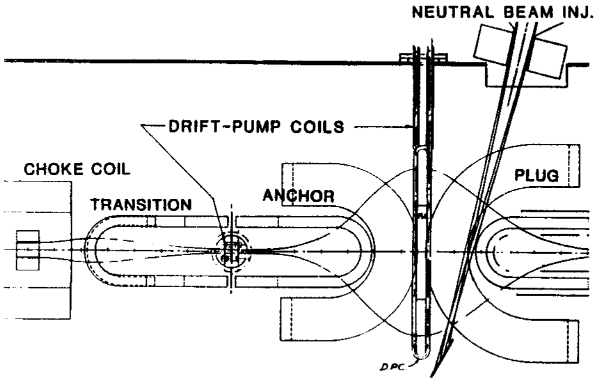


FIGURE 4
Drift-pump coil locations (2 in each end plug) (Ref. 4).

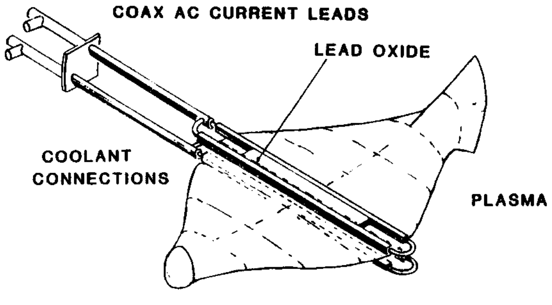


FIGURE 5
Drift-pump-coil pair (Ref. 4).

they can be removed. Similarly the anchor/plug coil set operates at a central frequency of 450 kHz and has a field fluxation of 23 gauss. A series of 60 frequencies are spaced 5 kHz apart to lower the particle density.

There are two features of these coils which could present materials problems: (a) the coils must be close to the plasma (see Fig. 5), and (b) there must be a flux path between the coils made from a suitably conducting material.

In the MARS design requirement (a) was met by placing the coils only 2 cm from the plasma (see Fig. 6) and requirement (b) was met by using PbO between the coils. The neutron wall loading in that region varies from 0.05 to 0.1 MW/m$^2$ which will induce ~ 1 dpa/FPY in the coils and the PbO. Since the coils and the PbO are $H_2O$ cooled, the operating temperature is < 100°C. These damage levels (equivalent to ~ 3 to 4 x $10^{22}$ fission n/cm$^2$ over the life of the device) are probably not sufficient to cause severe mechanical problems but studies do need to be performed on material under alternating stresses to insure long lifetime performance. Similarly, there need to be studies of the irradiation stability of PbO and its ability to retain a high electrical resistivity path over 20-30 FPY's.

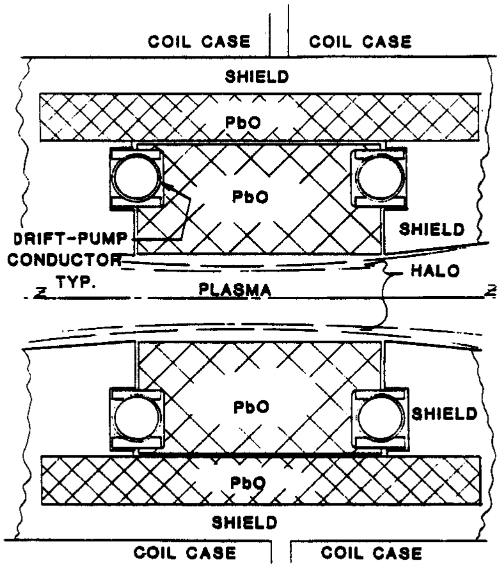


FIGURE 6
Drift-pump/shield-end view (Ref. 4).

## 5. HIGH HEAT FLUX PROBLEMS IN MIRROR END PLUGS

A fundamental characteristic of all tandem mirror machines is that the particles which leak out of both ends of the machine need to be efficiently collected and their energy converted into useful heat or electricity. Older designs used the traditional "grid and plate" design[8] which converted the kinetic energy of the charged particles directly to electricity. Other designs just allowed the particles to be dumped on collector plates which were cooled to remove their energy.[2,5] The MARS design uses a new gridless direct convertor design in which ions go into the "halo" plasma and electrons are collected in the central part of the leaking plasma (see Fig. 7). The inner/outer collector plates can be electrically separated from the inner/outer halo plates to accomplish the direct conversion.

As might be expected, very high heat fluxes can be expected in the end plug region and the design of the collector plates will be a real challenge. A brief review of the MARS design will illustrate that point.

The neutron flux to the collector plates is low (averaging from $10^{16}$ to $10^{17}$ n/cm$^2$ per FPY) so that bulk damage is probably not very important. However, the heat flux normal to the plates can range from 100-900 Wcm$^{-2}$ (see Fig. 8). In order to handle this heat flux and withstand the sputtering that is normally associated with such energetic particles, an inclined water-cooled, Be-coated TZM tubular structure has been proposed. Such a collector would operate at the conditions outlined in Table 3. The thick Be coating (2.1 cm) may reach temperatures up to 800°C initially and the TZM would operate at a maximum temperature of 450°C. It has been calculated that the maximum Be sputtering rates on the inner halo scraper would be 0.185 cm/FPY. High pressure water would be used to cool these collector plates and the stresses induced by the superheated water are not trivial.

In summary, tandem mirrors like tokamaks, will have to handle very high surface heat fluxes. In contrast to tokamaks, these high heat flux regions in tandem mirrors are *not* located in high neutron flux zones and therefore represent somewhat of a smaller problem from bulk damage considerations.

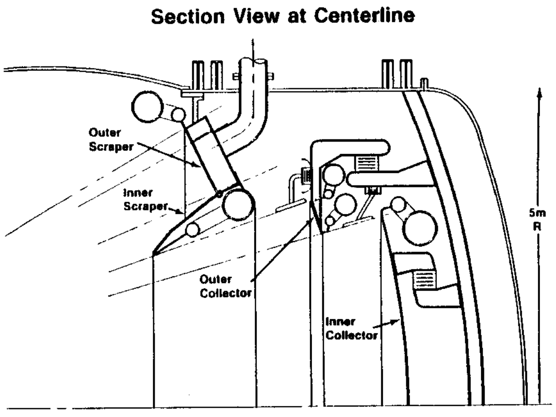


FIGURE 7
MARS end plasma system (Courtesy of Grumman Aerospace Corp.).

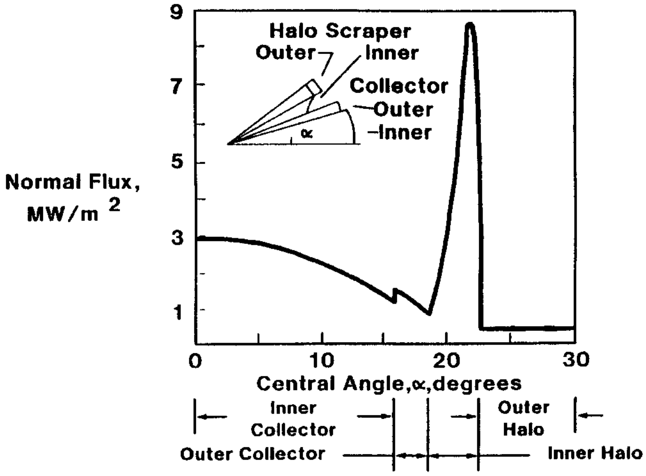


FIGURE 8
Heat flux to convertor elements (Courtesy of Grumman Aerospace Corp.).

## 6. RF LAUNCHERS

It is becoming more and more evident that both tandem mirrors and tokamaks will use substantial amounts of RF power for startup,

TABLE 3
Critical Parameters for MARS Plasma Dumps

| PARAMETER | INNER HALO SCRAPER | INNER ELECTRON COLLECTOR |
|---|---|---|
| Material | Be Coating, TZM Structure | TZM Structure |
| Power (Total), MW | 120 | 139 |
| Maximum Heat Flux, $W/m^2$ | 250 | 240 |
| Coolant | $H_2O$ | $H_2O$ |
| Coolant Temperature, °C | 280/320 | 280/320 |
| Maximum Temperature, °C | Be (795), TZM (445) | TZM (467) |
| Maximum Allowable Stresses TZM, MPa | 193/283 | 144/290 |
| Particle Flux, $cm^{-2}$ $s^{-1}$ | $5 \times 10^6$ (D,T), $3 \times 10^{15}$ (He) | $8 \times 10^{14}$ (D,T) |
| Average Particle Energy, keV | 46 | 353 |
| Maximum Sputtering Rate, cm/FPY | 0.185 | Negligible |

heating, or for special functions like current drive in tokamaks. In tandem mirrors, much of this injection of RF power is done in the end plugs where the neutron flux is low (~ 0.1 $MW/m^2$). However, there are some specific requirements for ICRF heating on both commercial (MARS) and test devices (TASKA and TASKA-M) which must be done in the central cell. The ICRF launching components are then subjected to 1 to 4 $MW/m^2$ neutron wall loadings and therefore will experience 10-40 dpa/FPY. Since most waveguides, antennas and Faraday shields involve copper in one form or another, one again sees the need for an expanded research program in the area of Cu alloys. An illustration of the types of data required can be obtained from Table 4 for the MARS design. The Cu startup waveguide and Faraday shields will operate at < 150°C and the system will be subjected to 4.3 $MW/m^2$. There are three major concerns in such a system; dimensional stability, ductility, and electrical resistance. If voids are formed in Cu at 150°C (0.31 $T_m$), then non-uniform swelling could cause distortion of some of the plates prematurely ending their useful life. The stresses and strains associated with startup and shutdown will also require that the Cu alloy retain a reasonable amount of ductility to avoid cracking. The electrical resistance associated with transmutations will not be as important as in the choke coil because the startup coils are on for only 2 minutes in the beginning of what is hoped to be a several day cycle period.

TABLE 4
Operating Conditions for MARS ICRH Antenna

| PARAMETER | CENTRAL CELL STARTUP | ANCHOR |
|---|---|---|
| Antenna Material | Cu | Cu |
| Faraday Shield Material | Cu | Cu |
| Coolant | $H_2O$ | $H_2O$ |
| Power Delivered to Plasma, MW | 12 (120 sec) | 13.5 |
| Frequency, MHz | 112 | 55 |
| Neutron Flux, $MW/m^2$ | 4.3 | 0.3 |
| Max. Antenna Temp., °C | 200 | 200 |

## 7. CONCLUSIONS

The advent of tandem mirror fusion machines means that the materials scientist will be faced with several new problems. A common thread in these problems is the extensive use of Cu and high strength Cu alloys. These alloys are needed for high field, normal magnets, low field alternating magnets and RF antennas near the plasma. Other unique problems for tandem mirrors include inorganic insulators that can stand high neutron fluences, and refractory alloys that can stand high heat fluxes. The level of research in these areas is relatively low now and prompt action is required to avoid "choking" off the development of this important future source of energy.

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