New Challenges in Fusion Research for the Materials Scientist

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NEW CHALLENGES IN FUSION RESEARCH FOR THE MATERIALS SCIENTIST

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ABSTRACT

Recent progress in fusion research has led to several unique materials requirements. The use of room temperature magnets to generate magnetic fields of 20 T or more at 1-2 MW/m^2 neutron wall loadings in Tandem Mirror reactors must be demonstrated. Reactor and current experimental device designs have attempted to solve the impurity control problem by placing particle collector plates near the plasma. These plates must handle heat fluxes of several hundred W/cm^2 while at the same time withstand high neutron fluxes and disruptions. The recent trend to use RF power for heating and confinment purposes in tokamaks and mirrors has raised the question of successful operation of antenna or waveguides that face the plasma and its high neutron flux. Finally, recent progress in breeding/cooling materials such as Pb-Li alloys, plus demonstrations of enhanced radiation damage resistance, have opened up the fusion field for ferritic steels. Questions about magnetic field perturbations and magnetic forces on the structure have been addressed and do not appear to be serious in mirror reactors.

INTRODUCTION

For the past 30 years, most materials scientists in the field of Radiation Damage have devoted their efforts to solving two main problems in fission reactors. The effort has been split between the nuclear fuels area and the structural components area with particular emphasis on cladding materials. As these materials scientists turn their attention toward fusion reactors, we find some substantial differences in their approach to the problems. First of all, fusion materials research is only about 10 years old and since there is still no suitable neutron test facility, the studies tend to be analytical in nature or simulations of what we expect to find in fusion devices. The second point is that most of the experimental research that has been done is concentrated on the first wall structural material. In the early 70's refractory metals such as Nb alloys were quite popular but after the first large scale Tokamak reactor designs, such as UWMAK-I (Ref. 1), used austenitic steels, the field quickly moved in that direction. In the mid to late 70's several other materials such as Al and V alloys, C or SiC, were considered but they never were widely used in large scale reactor designs, and the field is now predominantly focussed on the austenitic steels (Ref. 2, 3).

The rather large separation between fusion scientists and materials scientists (both philosophically and often physically) has meant that the materials community has usually reacted to what is proposed by the plasma physicists and not vice versa. As we progress towards a commercial system, it is safe to say that this situation will have to be reversed to allow realistic engineering designs to evolve.

The purpose of this paper is to give the materials scientist a preview of what may be asked of him in the near future as progress in fusion research continues. The four areas which are addressed here are:

1) The need for very high field radiation damage resistant "normal" magnets in Tandem Mirror Concepts and in some Compact Torus applications.
2) The need for impurity control devices such as limiters and divertors in Tokamaks which must face the neutrons from the plasma.
3) The strong shift to RF heating and confinement in both Tokamaks and Mirrors and hence the need to have RF power launchers facing the plasma.
4) The tremendous promise of the Pb-Li alloys in reducing safety hazards and tritium inventory as well as maximizing the breeding ratio and energy multiplication that have led us to consider ferritic steels in magnetic devices.

Obviously, there are other fusion materials requirements that have arisen in the past few years, such as development of solid breeders, the need for inorganic electrical insulators in diagnostics, etc. However, we will have to limit our comments here to <u>neutron</u> effects on <u>metals</u>.

HIGH FIELD NORMAL MAGNETS FOR TANDEM MIRRORS

The physics of the mirror concept has advanced very rapidly over the past 5-10 years with the invention of the Tandem Mirror concept (Ref. 4)

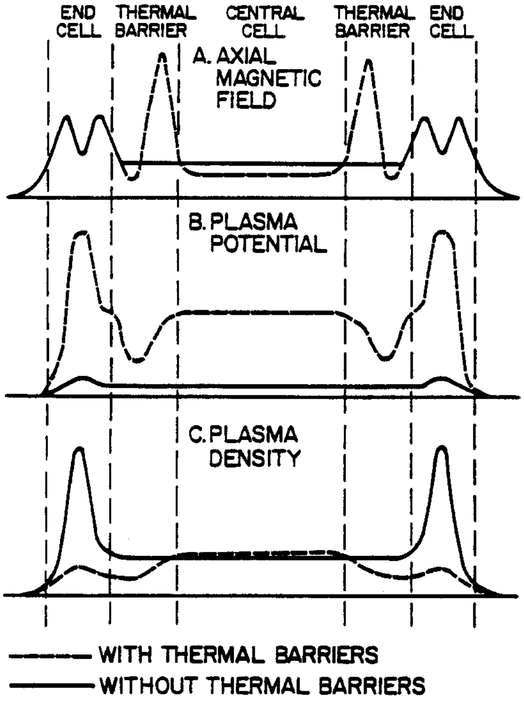

Figure 1. Comparison of critical features of a tandem mirror with and without thermal barriers. Note the high magnetic fields near the central cell region when thermal barriers are generated to isolate the end plug electrons.

and more recently with the thermal barrier (Ref. 5). Figure 1 illustrates some of the main differences between the two concepts.

It can be seen that a simple tandem mirror has relatively modest magnetic fields in the region of the high neutron production (the central cell zone) and this field can be produced by simple solonoidal superconducting coils which are easily shielded from neutrons. However, to reduce the total heating power and general technology requirements, the thermal barrier concept requires a very high magnetic field close to the neutron generating zone. Figure 2 shows such a coil in the recent MARS design (MARS is the Mirror Advanced Reactor Study being conducted in the U.S. by Lawrence Livermore Laboratory, the University of Wisconsin and TRW with participation from General Dynamics, Ebasco, Grumman Aerospace and Science Applications, Inc.) (Ref. 6). This field may have to be as high as 20-25 Tesla and therefore cannot be generated by known superconductors. Such a field can be generated by a hybrid coil consisting of a high field superconductor around a "normal" resistive copper coil running at room temperature. Since the power costs vary with the value of I^2R (where the field dictates the current I and the electrical resistance, R, is a function of the length of the coil), one wishes to make the "normal" coil as small as possible (which means close to the first wall). Hence, it is exposed to very high neutron fluxes.

Examples of such a hybrid (24 T) configuration are shown in Figure 3. The superconducting outer coil provides approximately 15 T while the copper insert coil provides the last 9 T. For the purposes of this paper, we will assume that the superconducting coil can be adequately shielded from neutrons.

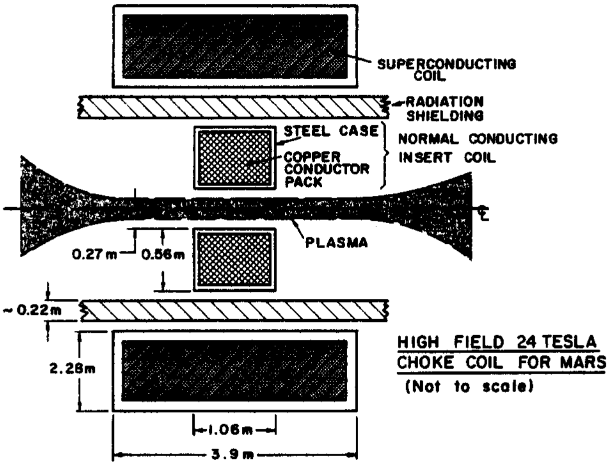

Figure 3. Schematic of high field choke coil for MARS. Much of the shielding is removed for clarity. Note how close the room temperature copper coil is to the plasma.

In order to be more quantitative about what type of material is needed, we can examine the requirements of the MARS "choke" coil. These requirements are summarized in Table 1.

MARS CHOKE COIL REQUIREMENTS

COPPER ALLOY INSULATOR COOLANT	MZC (Mg, Zr, Cr) SPINEL (Mg Al_2O_4) DEIONIZED WATER
MAX. CONDUCTOR TEMP.	140°C
MAX. FIELD IN MAGNET	24 T
CONDUCTOR DESIGN/YIELD STRESS	357/570 MPa (50/80) ksi
MAXIMUM NEUTRON WALL LOAD	2 MW/m^2
ELEC. POWER AT. t=0	41 MW/COIL

Table 1. MARS choke coil requirements.

The choice of the MZC copper alloy was made because of its high yield strength, 570 MPa (80 ksi), and its low electrical resistivity (only ~ 25% above pure copper). The electrical insulator is spinel (which itself is subjected to

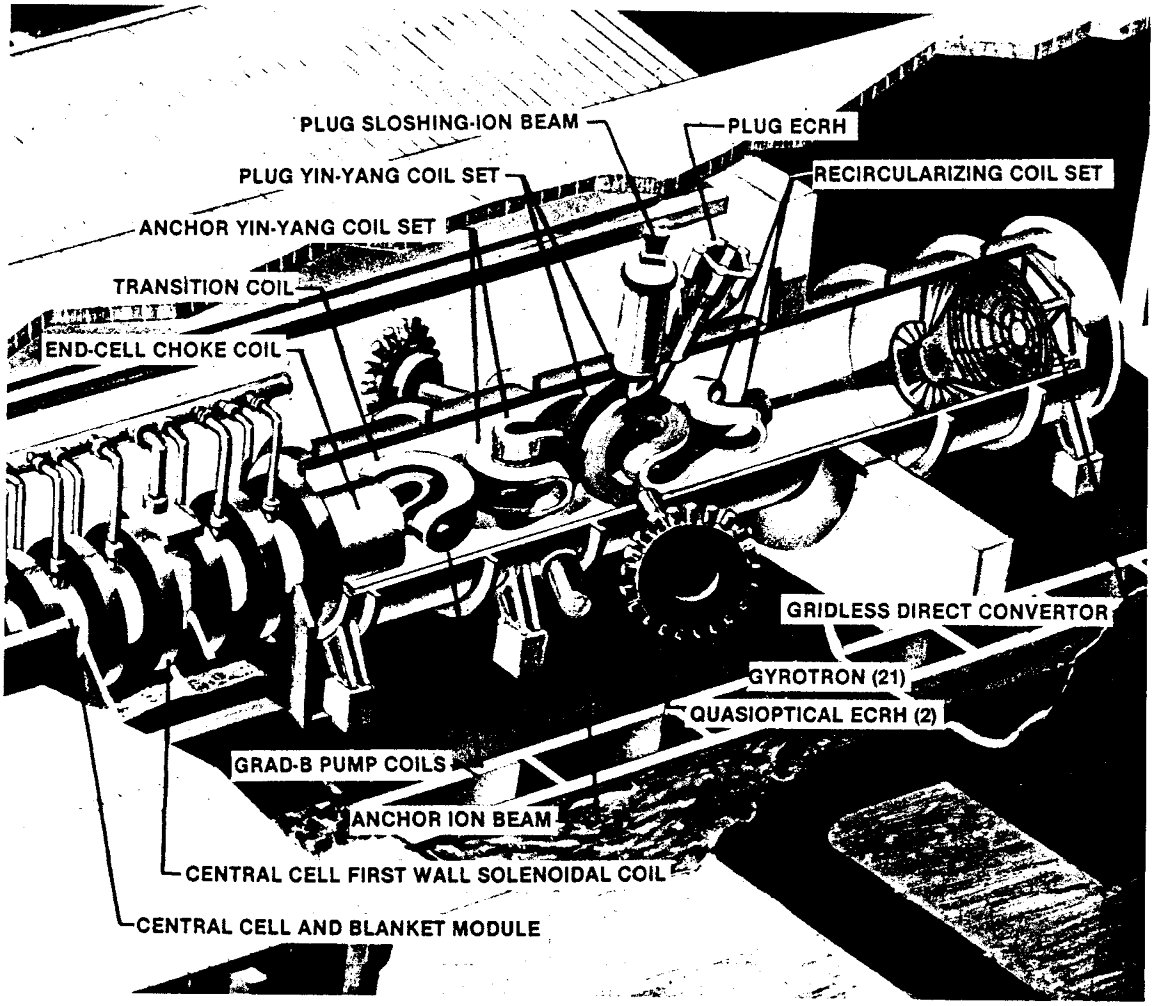

Figure 2. Overview of MARS (Mirror Advanced Reactor Study) conceptual power plant design. The long central cell region is where most of the neutrons are generated and the end plug region is configured to confine the central cell plasma.

high neutron fluences) and the coil is cooled with water. The maximum design stress in the coil is calculated to be 357 MPa (50 ksi) at 140°C. Each coil requires 41 MW of electricity to generate the required fields and the maximum neutron wall loading is ~ 2 MW/m^2.

Calculations of the damage rate in the copper coil reveal that it is ~ 15 dpa per full power year (FPY) and the helium production is ~ 70 appm/FPY (Figure 4). Such damage rates are close to those in the cladding of EBR-II, DFR, and Rapsodie.

Several questions about the coils are currently being asked by the reactor design community:

1) From the dimension stability standpoint:
   - Will voids form in the copper?
   - If so, what magnitude of swelling should be expected?
   - Will the helium generated by the fusion neutrons have any effect on bubble or void formation?

2) From the physical property standpoint: How much will the electrical resistivity change as transmutations are produced and precipitates are dissolved?

3) From the mechanical property standpoint:
   - How much will the yield properties be altered (up or down) by the fusion neutrons?
   - What effect will helium and/or precipitates have on the ductility of the coil during start up or shut down?

4) From the reactor operators' viewpoint:
   - When will the magnet have to be replaced?
   - How long will the insulators last?
   - Can we trade longer life (by shielding the magnet) against higher operating costs (higher R)?

There are no easy answers to these questions but there is one area where the approximate change in the coil performance can be calculated, i.e., the electrical resistivity. Using codes developed for transmutation reactions, Perkins (Ref. 7) calculated the production rate of various elements. Using a reasonable resistivity contribution from these elements, the resistivity increase, the power increase and hence the added

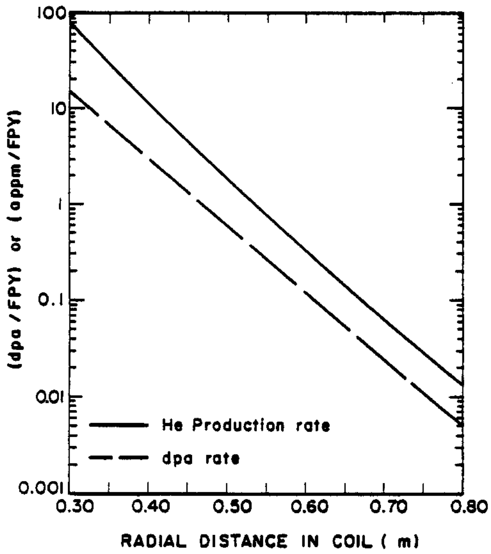

Figure 4. Variation of radiation damage in MARS (Ref. 6) copper choke coil.

cost of the power to run the coil were calculated. These are displayed in Figure 5. It can be seen that considerable increases in the power are required for the choke coil if it is to operate for 5-10 FPY's. In fact the power requirement could increase by 50% in 20 FPY's. For MARS this could amount to added power costs of 100-200 million dollars over the lifetime of the coils.

The mechanical performance of these Cu alloys under such high stresses and neutron fluences are unknown and this area represents one of the new challenges to the materials scientist interested in radiation damage effects.

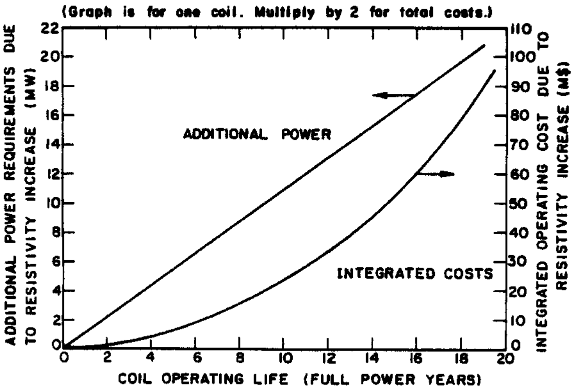

Figure 5. Economic consequences of radiation-induced resistivity increases in the MARS (Ref. 6) normal insert coil.

IMPURITY CONTROL DEVICES

It has now become clear in both Tokamaks and Mirrors that active impurity control devices will be needed. In Tokamaks like INTOR (Ref. 8) and STARFIRE (Ref. 9) this means limiters or divertors will face the plasma (and hence high neutron fluxes) directly. In Mirrors, like MARS (Ref. 6) this means halo scrapers in the end plug region will be needed. For the purpose of this paper we will ignore the effects on the halo scrapers because the flux is relatively low (< 10^{10} n/cm^2-s).

The best example of divertor and limiter designs is for the INTOR (Ref. 8) reactor. The INTOR divertor and limiter designs are shown in Figures 6 and 7 respectively and some general operating characteristics of both systems are shown in Table 2.

INTOR DIVERTOR / LIMITOR OPERATING CONDITIONS

SURFACE COATING	Be, BeO, Ta
HEAT FLUX W/cm^2	200
DISRUPTIONS (MAJOR / MINOR)	
# PER FPY	120/600
MAX. ENERGY FLUX - J/cm^2	460/340
MIN. TIME - ms	5
N DAMAGE	
STRUCTURAL ALLOY	V OR Cu
WALL LOAD - MW/cm^2	1.3
LIFETIME - MW-Y/cm^2	1.3
dpa / FPY	10
appm / FPY	50-100
TEMPERATURE	
STRUCTURE - °C	200-300
COATING - °C	500

Table 2. INTOR divertor/limiter operating conditions.

These surfaces must collect a steady state heat flux of up to 200 W cm^{-2}, they will be subjected to a neutron flux of up to 1.3 MW/m^2 and they are expected to last for 1 full power year. In addition, the Be coating must be able to withstand up to 120 major disruptions in a full power year with peak energy fluxes of 460 J/cm^2 in times as short as 5 ms. The divertor collector surface also needs to withstand up to 600 minor disruptions in a full power year with energy densities of 340 J/cm^2.

The neutron damage to the water cooled structural materials is rather modest. If 1 full power year of operation can be obtained, then the vanadium or Cu alloy structures need only withstand ~ 10 dpa and a helium content of ~ 100 appm. With respect to displacement damage of ~ 10 dpa, V alloys have already performed satisfactorily (Ref. 10), but they contained almost 2

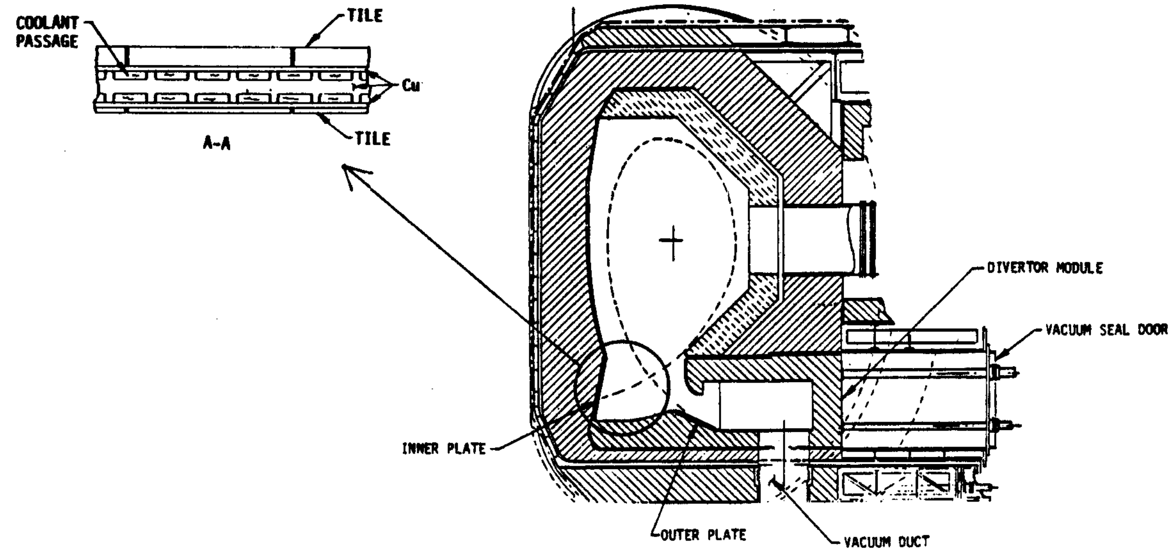

Figure 6. Schematic of INTOR (Ref. 8) impurity control with single null divertor.

orders of magnitude less helium. Copper alloys have not been irradiated to more than 1 dpa and therefore very little is known about their performance at high damage levels.

From the previous discussion, it is clear that high thermal conductivity alloys will be required to reduce thermal stresses in the impurity control devices. However, because of the high heat flux and the desire to maintain a reasonable structure temperature, coolant induced stresses will also have to be considered. The challenge to develop such high thermal conductivity alloys which can also withstand several MW-y/m^2 of neutrons will be almost as great as to develop alloys for the high field magnets.

RADIO FREQUENCY PLASMA HEATING DEVICES

Up to the late 1970's it was commonly thought that the plasmas in magnetic fusion devices would be heated with neutral beams. However, since that time, progress in RF heating and its use for confinement of the plasma has been phenomenal and both Tokamak and Mirror designs are now using more and more RF power at the expense of the more bulky and costly neutral beams. For example, Table 3 lists some of the recent, near term, and long range devices that have utilized RF in their design. In general ICRF (Ion Cyclotron Range of Frequencies) is used to heat the devices and ECRF (Electron Cyclotron Range of Frequencies) is used to heat electrons in Mirrors. Lower hybrid frequencies (~ 1 GHz) are used for current drive in Tokamaks.

It is also important to recognize that antennas are used to launch the lower frequency power (ICRF) while waveguides are used to launch the higher frequency (ECRF) power. An example of the antenna in JET (Ref. 11) is given in Figure 8. The RF antenna conductor is usually a copper alloy but it could be a vanadium alloy as well. The protection limiter on the JET antenna may not be used on commercial reactors where other plasma definition devices could be employed.

USE OF RF POWER IN RECENT EXPERIMENTS OR REACTOR DESIGNS

		ICRF		ECRF	
FACILITY	TYPE	MHz	MW	GHz	MW
PLT	EXP.	42	32	60	0.5
D-III	EXP.	20-60	20	60	2
TFTR	EXP.	55	10-20	—	—
JET	EXP.-CONST.	25-55	15-20	—	—
INTOR	DESIGN-ETR	85	50	136	3.4
STARFIRE	DESIGN-COMM.	—	—	160	16.4
				168	1.53
TMX	EXP.	—	—	28	0.8
MFTF-B	EXP.-CONST.	—	—	56	1.6
TASKA	DESIGN-ETR	30	40	56	15
MARS	DESIGN-COMM.	—	—	60-90	84

Table 3. Use of RF power in recent experiments or reactor designs.

Finally, the STARFIRE waveguide, shown in Figure 9, is a simpler design than the antenna but it still will face neutron wall loadings of 3 to 4 MW/m^2. Dimension stability of the grid spacing over long periods is very important which means that swelling and irradiation creep may play an important part in defining their useful life.

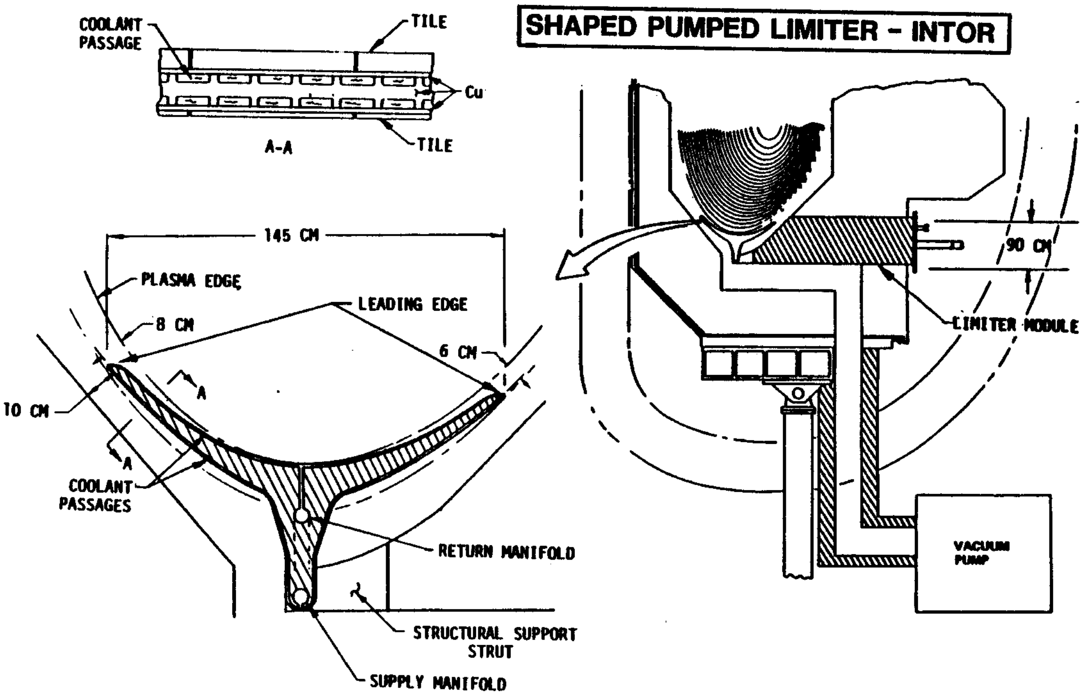

Figure 7. Shaped pumped limiter for INTOR (Ref. 8).

Operating conditions for such power launchers are ill defined as of now, but it is clear that the fusion community intends to make much more use of RF systems in the future.

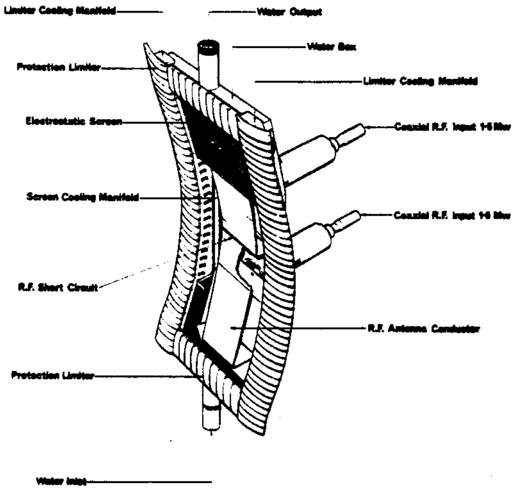

Figure 8. ICRH antenna for JET (Ref. 11).

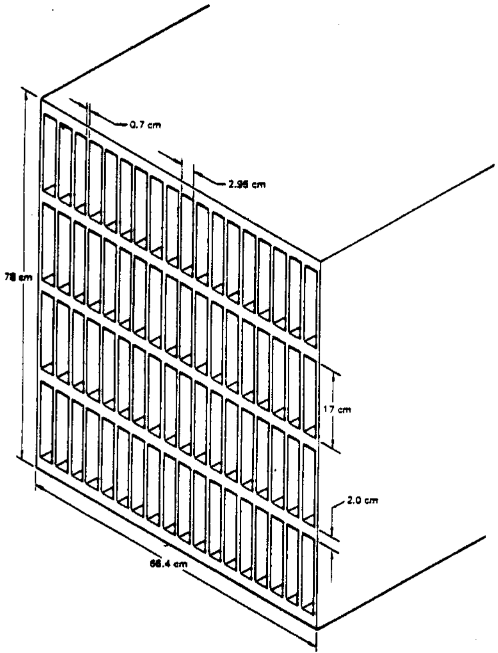

Figure 9. Example of STARFIRE RF waveguide (Ref. 9).

FERRITIC STEELS IN MAGNETIC FUSION DEVICES

Extensive research in the fast fission reactor field has revealed that austenitic steels eventually will suffer from rather high swelling rates. Scientists at HEDL have shown that most austenitic steels follow the same general behavior during high temperature neutron irradiation (Ref. 12) as illustrated in Figure 10. This behavior can be described as an incubation period of little swelling followed by relatively constant swelling rate of ~ 1% per dpa. This swelling rate appears to be independent of alloy composition, thermal mechanical treatment or even temperature. The main difference between various alloys and the irradiation environment is reflected in the length of the incubation dose but regardless of the austenitic system, it will be difficult to obtain useful lifetimes of more than 5 to 10 MW-y/m^2.

Fortunately, even though it was found that ferritic steels also display the incubation dose period, the steady state swelling rate is only ~ 0.1% per dpa. This major difference should extend the useful lifetime of the ferritic steels to 15 to 20 MW-y/m^2 or more.

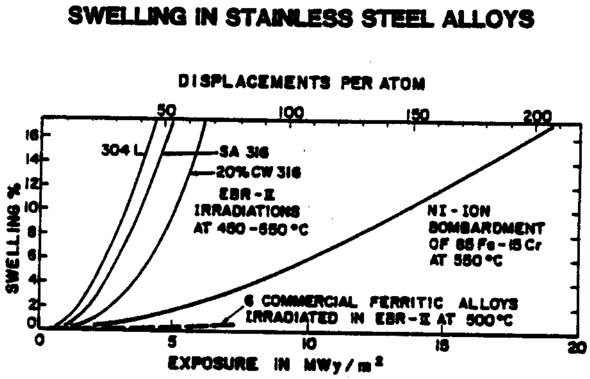

Figure 10. Swelling in stainless steel alloys (see Ref. 12 for most of data).

Another event has occurred in the past few years which has given the ferritic steels a boost, i.e. the use of $Pb_{83}Li_{17}$ alloys for breeding and cooling (Ref. 13). The eutectic alloy does not have the safety problem that is associated with liquid lithium and water, the tritium inventory is as low as 10 parts per billion compared to more than a 1000 parts per billion in Li, and it is a more effective tritium breeder and energy multiplier. Thus far it has been used in several commercial reactor designs: WITAMIR-I (Ref. 14), TASKA (Ref. 15), HIBALL (Ref. 16), and MARS (Ref. 5). An example of a Pb-Li and ferritic steel blanket design is shown in Figure 11.

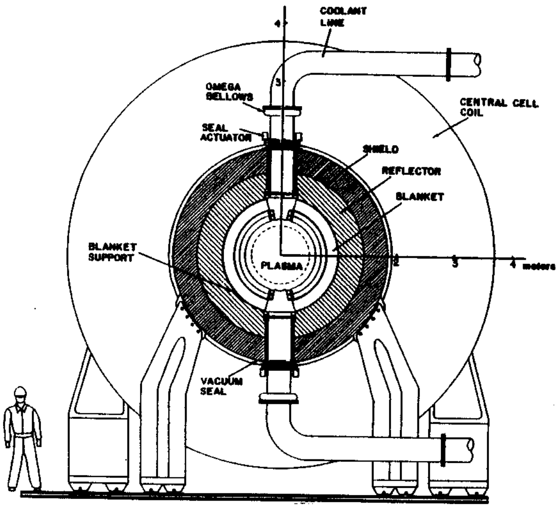

Figure 11. Schematic of central cell design for MARS. The Pb-Li alloy enters at the top of the HT-9 blanket, flows in tubes around either side of the plasma and exits at the bottom of the blanket. Ferritic steel is used because of its high radiation damage resistance and compatability with Pb-Li alloys.

The data that presently exists reveals that ferritic steels are compatible with the Pb-Li alloys up to at least 500°C which allows us to take advantage of its favorable swelling resistance (Ref. 17). However, one important question still is asked:

How do the ferritic steels affect the magnetic field uniformity and how does the magnetic field affect the force on the ferritic steel?

To answer these questions Attaya (Ref. 18) has recently studied the use of HT-9 structural material in MARS. Because the amount of steel surrounding the plasma (see Figure 11) is not uniformly distributed nor at a constant temperature, and because the susceptibility is a function of temperature, it is important to understand how much of a field perturbation might be induced.

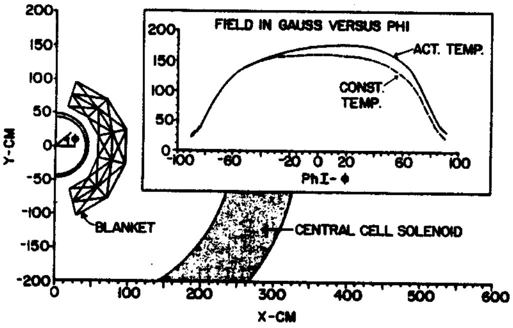

Figure 12. Effect of HT-9 on mod B magnetic field in MARS at r=44.

Figures 12 and 13 show the grad B field contours from the MARS central cell solenoid both in the azimuthal and axial directions. The effect of assuming the blanket was at a constant temperature or using the actual temperature distribution is also included. The calculations were performed with GFUN-3D and reveal that less than 0.2% change in the field contours from the use of ferritic steel. At this time it is felt that such field inhomogeneities are not critical in a Tandem Mirror.

Next, the effect of the magnetic field forces on pipes entering the high field central cell zone from outside were investigated (Ref. 19). Figure 14a shows the magnitude of magnetic forces on a HT-9 pipe running to the MARS central cell module. Figure 14b gives the forces in three directions on the pipe with and without the magnetic fields. This work reveals that the imposition of 4-5 T fields on ferritic structures does not pose any major problems for reactor designers, certainly not much more than the support of the pipe itself filled with Pb-Li alloys. Such a conclusion coupled with the favorable radiation damage resistance of ferritic steels means that this alloy class could replace austenitic steels in future fusion devices.

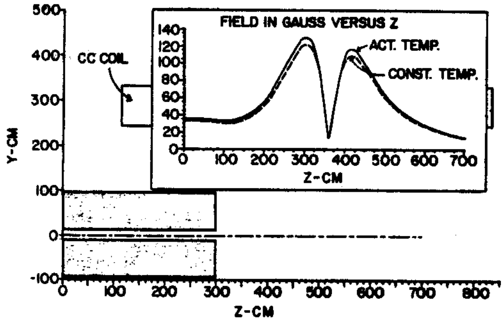

Figure 13. Effect of HT-9 on induced magnetic field, mod B, along axis of reactor.

CONCLUSIONS

This paper has touched on only a few new fields of research that may be important in the next 5-10 years for the materials scientist interest in radiation damage. One common thread that runs through the areas that were considered is the potential use of high strength copper alloys. It appears that the materials community needs to take a long hard look at what it can do to develop such alloys for fusion reactor service. If successful, the promise of fusion may indeed be realized in a reasonable time. If the materials community is not successful, then the plasma physics community will have to "invent" new concepts to confine and heat fusion plasmas. Such a delay may mean that useful fusion power may not be realized for decades.

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REFERENCES

1. B. BADGER et al. "UWMAK-I, A Wisconsin Tokamak Reactor Design," University of Wisconsin Report, UWFDM-68, (1973).

2. G.L. KULCINSKI. "Fusion Reactors: Their Challenge to the Materials Scientist," Contemporary Phys., 20, 417-47 (1979).

3. G.L. KULCINSKI. "Fusion Materials - Adapting to Realism in the Past Decade." To be published. Proc. 3rd IAEA Workshop on Fusion Reactor Design and Technology, Tokyo, Japan, Oct. 5-6, 1981.

4. T.K. FOWLER and B.G. LOGAN. Comments on Plasma Physics and Controlled Fusion 2, 167 (1977). See also G.I. DIMOV et. al., Fizika Plasma, 2, 597 (1976).

5. D.E. BALDWIN and B.G. LOGAN. Phys. Rev. Lett., 43, 1318, (1979).

6. "Mirror Advanced Reactor Study (MARS) - Interim Report," UCRL-53333, Lawrence Livermore National Laboratory (1983).

7. L.J. PERKINS. "Materials Considerations for Highly Irradiated Normal-Conducting Magnets in Fusion Reactor Applications." To be published 1983.

8. W.M. STACEY, JR. et al. "U.S. FED-INTOR Activity," Georgia Tech Report, USA-FED-INTOR/82-1, (1982).

9. "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," Argonne National Lab. Report, ANL/FPP-80-1, (1980).

10. R.E. GOLD, et al. "Technical Assessment of Vanadium Based Alloys for Fusion Reactor Application," Westinghouse Electric Corporation, COO-4540-1 (1978).

11. "JET Joint Undertaking," Euratom Report EUR-7950-EN.

12. See papers by F.A. GARNER, H.R. BRAGER and W.G. WOLFER, this conference.

13. D.K. SZE, R. CLEMMER, and E.T. CHENG. University of Wisconsin Report; UWFDM-378, (1980).

14. B. BADGER, et al. "WITAMIR-I, A University of Wisconsin Tandem Mirror Reactor Design," University of Wisconsin Report UWFDM-400, (1980).

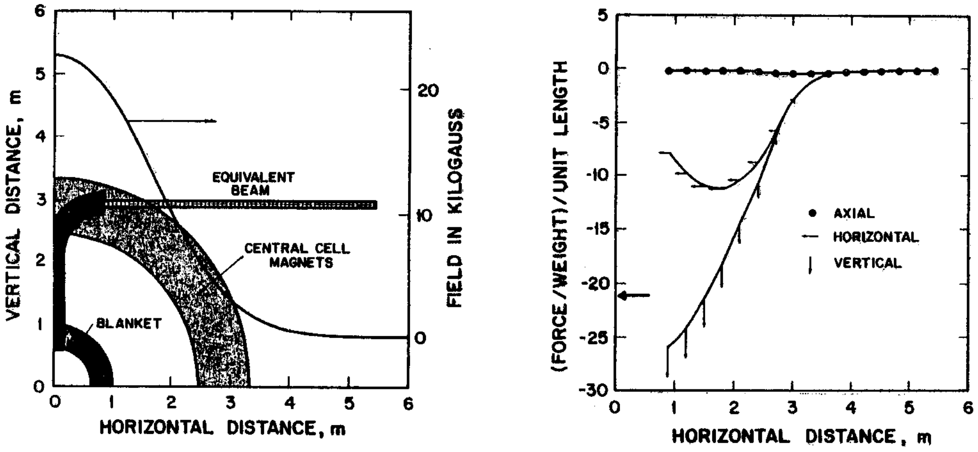
15. B. BADGER, et al. "TASKA, A Tandem Mirror Test Facility," University of Wisconsin Report, UWFDM-500 and Karlsruhe Nuclear Laboratory Report, KfK-3311, both 1982.

16. B. BADGER, et al. "HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study," University of Wisconsin Report UWFDM-450 and Karlsruhe Nuclear Laboratory Report, KfK-3202, both 1981.

17. R.C. ASHER, et.al. Corrosion Science, 17, 545 (1977). See also work at Oak Ridge National Laboratory by P.F. TORTORELLI and J.H. DeVAN.

18. H. ATTAYA and G.L. KULCINSKI. "Effect of Temperature on Magnetic Field Perturbations From the Ferromagnetic Blanket in MARS." To be published.

19. H. ATTAYA, K.Y. YUAN, G.L. KULCINSKI, and W.G. WOLFER. "Implications of Using Ferromagnetic Steels in Tandem Mirror Fusion Reactors." To be published.



a)

b)

Figure 14. Magnetic forces on HT-9 MARS blanket. In a), the model used is shown as well as the magnetic field along the pipe. In b), the force/weight of steel pipe per unit length of the pipe is given for 3 orthogonal directions. The arrow at -21 shows the normal gravitational force for a Pb-filled, 41 cm diameter pipe.