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EFFECT OF TEMPERATURE ON MAGNETIC FIELD PERTURBATIONS FROM THE FERROMAGNETIC BLANKET IN MARS

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ABSTRACT

The effect of temperature variation in the ferromagnetic blanket of MARS on the induced magnetic field from that blanket is studied. A simple analytical model is used to show that the effect will be mainly at the ends of the blanket. Numerical calculations using the computer program GFUN3D are presented and show that the effect is reasonably small.

INTRODUCTION

Because of its high resistance to irradiation damage, the martensitic stainless steel alloy HT-9 (12Cr-1Mo-0.3V) is proposed for use as the structural material in the MARS[1] (Mirror Advanced Reactor Study) blanket. Many questions, however, have been raised about the interaction of this ferromagnetic material with the magnetic field of the device. One of these questions arises from the fact that the magnetization is a function of the temperature, and because the temperature (hence the magnetization of HT-9) in the blanket varies with the position. The question addressed here is "will that variation of the magnetization produce any magnetic effect in the plasma region?"

TEMPERATURE DEPENDENCE OF THE SATURATION MAGNETIZATION

The dependence of the saturation magnetization M_s on the temperature as predicted by theory and as measured experimentally for Fe, Ni, and Co is shown in Fig. 1.[2] There are only two experimental values of M_s that are known for HT-9[3]; at the temperatures 25°C and 500°C. The Curie temperature, T_c, of HT-9 has not been measured. According to the measurements of Praeg[4] on a similar martensitic stainless steel alloy (9Cr-2Mo), the Curie temperature of that alloy is 705°C. In this work we assume that the Curie temperature of HT-9 is 700°C, and M_s would have the same dependence on the temperature as that shown in Fig. 1.

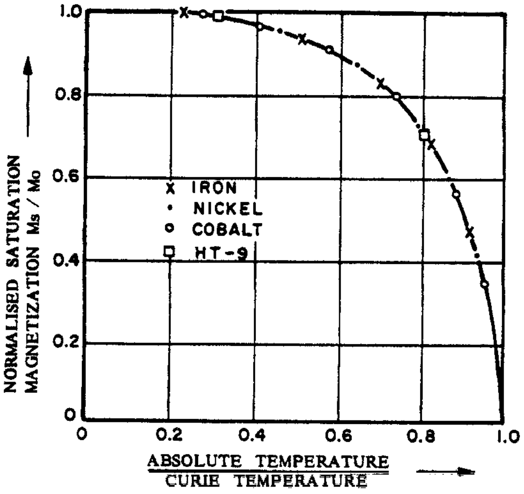

Fig. 1. Temperature dependence of M_s; M_o is the magnetization at the absolute zero temperature. □ : known experimental values of M_s for HT-9 assuming Curie temperature of 700°C.

TEMPERATURE AND MAGNETIZATION DISTRIBUTION IN MARS BLANKET

In the MARS blanket, the LiPb coolant enters from the top of the blanket at 330°C and leaves the bottom of the blanket at 500°C. The temperature at any angle θ is[1]

$$T = 330 + \frac{(500 - 330)\theta}{\pi} \qquad (1)$$

where θ is the angle measured as shown in Fig. 2. Since the magnetic field on the plasma axis in the central cell is about 4.7 tesla and is in the z direction, the magnetization of HT-9 reaches its saturation value M_s and is in the

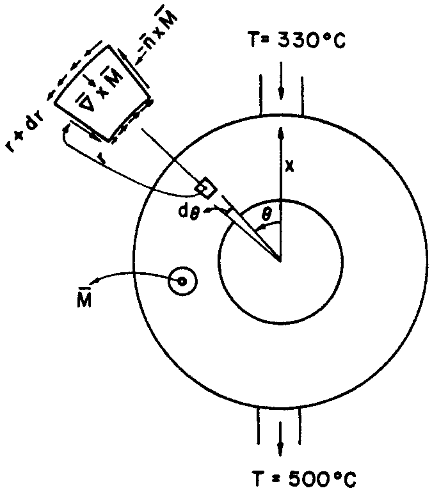

Fig. 2. Schematic cross section. The arrows in the infinitesimal area show the directions of the surface current densities ($-\overline{n} \times \overline{M}$) at each side, and the direction of the volume current density ($\overline{\nabla} \times \overline{M}$).

direction of the field, i.e.

$$\overline{M} = M_s(T(\theta))\hat{z} \ , \qquad (2)$$

where $\hat{z}$ is a unit vector in the z direction.[5] The measured value of M_s at 500°C is 8.8 x 10^5 A/m, and the extrapolated value of M_s at 330°C from Fig. 1 is 1.02 x 10^6 A/m.

INDUCED MAGNETIC FIELD DUE TO A MAGNETIZED STRUCTURE

If one knows the distribution of the magnetization in a magnetized structure, one can estimate the field due such structure (outside it) by using either the corresponding distributions of magnetic pole densities given by[5]

$$\text{surface pole density} = \sigma_p = \overline{n} \cdot \overline{M} \qquad (3)$$

$$\text{volume pole density} = \rho_p = -\overline{\nabla} \cdot \overline{M} \qquad (4)$$

or by the corresponding distribution of Amperian current densities given by:

$$\text{surface current density} = \overline{k} = -\overline{n} \times \overline{M} \qquad (5)$$

$$\text{volume current density} = \overline{J} = \overline{\nabla} \times \overline{M} \ . \qquad (6)$$

In the above equations $\overline{n}$ is a unit vector normal to the surface.

Consider first the case where no temperature variation exists, i.e. the magnetization is uniform and constant throughout the blanket ($\overline{M} = M_s z$). In this case both $\overline{\nabla} \times \overline{M}$ and $\overline{\nabla} \cdot \overline{M}$ vanish. Thus we could evaluate the induced field from the magnetized blanket by either using the surface pole density $\overline{n} \cdot \overline{M}$ which will have values only at the end faces of the blanket, or by surface current densities which will have equal but opposite values on the outer and inner surfaces of the blanket. The induced field from the blanket is then equal to the field of two concentric solenoids having the same length and carrying equal but opposite current. The use of either of these two models shows that the field due to the magnetized blanket will be mainly at the ends of the blanket.[6]

Now consider the case in which the magnetization obeys Eq. 2. The volume current density exists and has a value in the radial direction only, i.e.:

$$\overline{\nabla} \times \overline{M} = \overline{\nabla} \times (M_s(T(\theta)))\hat{z} = \frac{1}{r}\frac{\partial M_s}{\partial \theta}\hat{r} = \frac{M_s'}{r}\hat{r} \qquad (7)$$

where $\hat{r}$ is a unit vector in the radial direction. Multiplying Eq. 7 by an infinitesimal volume = dv = r dθdrdz, one gets the current in dv = (M_s' drdθdz)r, which is equal and opposite to the sum of the surface current at θ, which is (M_s(θ)drdz)r, and the surface current at θ + dθ, which is -(M_s(θ + dθ)drdz)r. In the limit as dv goes to zero M_s(θ + dθ) could be expanded as (M_s(θ) + M_s' dθ), so that the sum of the surface currents at θ and at θ + dθ is -M_s' drdθdz r. Thus the volume current cancels the net radial current and the induced field will be mainly due to the surface currents on the inner and on the outer surfaces of the blanket which are opposite in direction and equal in magnitude within each differential azimuthal section dθ. The induced field, as in the case of constant M_s, will be maximum at the far ends of the blanket, but will have different azimuthal dependence. This conclusion could be reached directly using the pole model where $-\overline{\nabla} \cdot \overline{M}$ is still zero, and the surface pole density $\overline{n} \cdot \overline{M}$ exists only at the end faces of the blanket and decreases as the angle θ (or the temperature T) increases.

NUMERICAL RESULTS

The computer code GFUN3D[7] was used to investigate the effect of the temperature variation in the blanket on the induced field from the ferromagnetic regions (that are made of HT-9) of the blanket. The induced field of interest here is that which could be felt by the plasma. Two cases are considered: in the first case the temperature effect on the magnetization is taken into account, and in the second case the temperature is assumed constant throughout the blanket. A brief description of the modeling of both cases is given in the following.

The ferromagnetic regions in the MARS blanket could be classified as: the upper (inlet) manifold; the lower (outlet) manifold; the tube section which starts at radius 0.6 m and has a radial thickness of 0.192 m; the beam section which starts at radius 0.8 m and has a thickness of 0.19 m. The volumetric fraction of HT-9 in the tube section is 7.1% and is 15% in the beam section. The manifolds of the blanket are neglected in modeling the blanket since the volume concentration of HT-9 in them is very small, and the field they produced will be a dipole type field which dies very quickly with distance. The HT-9 is considered homogeneously distributed within the tube and the beam section. The homogenization procedure was described and tested previously.[6]

In the first case, each of the tube and the beam regions is modeled by five azimuthal sections to account for the temperature variation. The temperature is assumed constant within each section. Each section has its own characteristic B-H curve which takes into account the effect of the temperature on M_s and the HT-9 concentration within that section. Thus total of ten B-H curves are used in the first case to calculate the magnetization in the blanket. In the second case only two B-H curves are used, one for the tube section, and the other for the beam section to account for the difference of the concentration of HT-9 in both sections.

Four modules of the blanket are simulated in both cases. The axial length (in the z direction) of the blanket module is 1.8007 m with a 0.005 m gap between each module. The actual number of blanket modules in the central cell is 84. Since the induced field from the blanket is primarily an end effect, the four modules used in these calculations are sufficient to illustrate the effect. Using the symmetry options in GFUN3D, 300 tetrahedral elements are used in the first case to simulate the four modules. In the second case, because the temperature is assumed constant throughout the blanket, more symmetries are invoked, and only 180 tetrahedral elements are used. Figure 3 shows a cross section of the blanket as simulated in the first case, with the average temperatures assumed in each azimuthal section. The constant temperature assumed in the second case is 415°C.

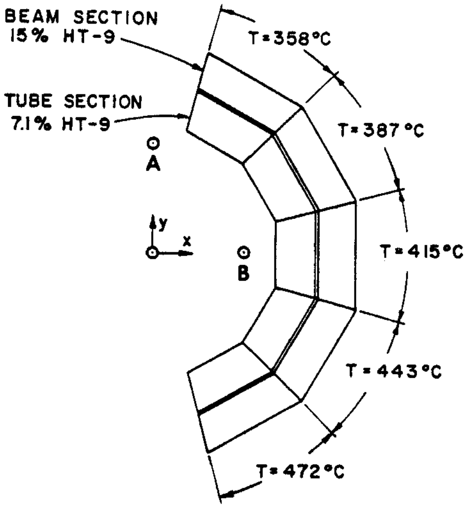

Fig. 3. A cross section of the blanket (first case). Θ indicates the positions of the lines along which the fields are calculated.

The induced magnetic fields along three different lines parallel to and including the z axis have been calculated in both cases and are shown in Figs. 4-6. The locations of the three lines are shown in Fig. 3. Figure 4 shows the induced magnetic field along the z axis. The induced field has a maximum value of about 0.011 T just before the end of the blanket at about 3 m from the center. The field is in the negative z direction, i.e. opposing the magnetic field of the central cell solenoids. The induced field decreases in magnitude and vanishes at about the end of the blanket (at 3.61 m), whereafter it reverses its direction and increases to a maximum of 0.01 T at $z \approx 4.2$ m from the center. The average induced field within the blanket region is of the order of 0.003 T (30 gauss). The same behavior exists in both cases. The second case (the constant temperature case) shows very little difference in the magnitude of the field.

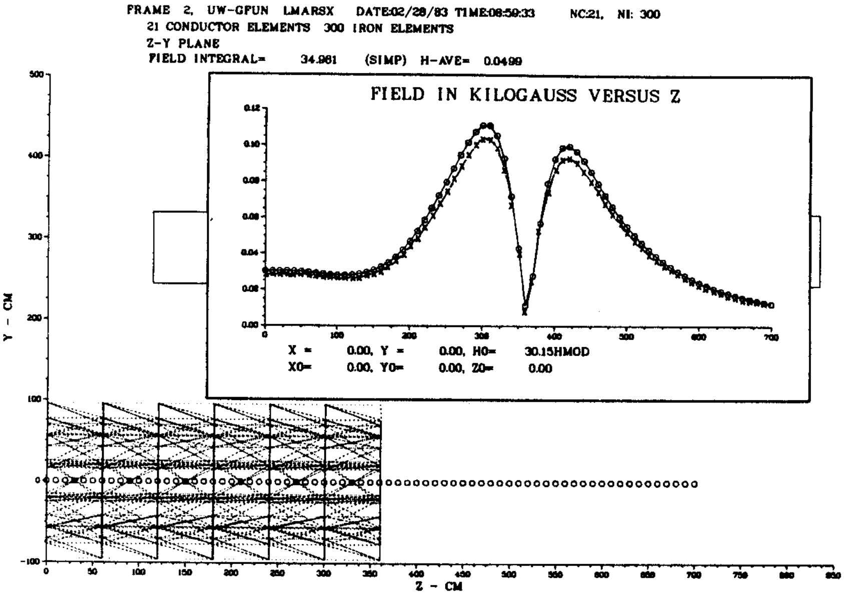

Fig. 4. The induced magnetic field mod(B) from the blanket along the axis of the reactor; the field of the varying temperature case is marked by o, and that of the constant temperature case is marked by x.

Figure 5 shows the induced fields in the two cases along the line x = 0 and y = 0.44 m, i.e. just under the upper manifold and on the upper edge of the plasma. The field is very slightly higher than that along the z axis, and does not vanish at the end of the blanket because the y component of the field is maximum at that point. Figure 6 shows the induced fields from both cases along the line x = 44 and y = 0, i.e. on the right edge of the plasma. The induced field along this line shows no minimum. Although the z component of the field reverses its direction at the end of the blanket, the x-component has a maximum negative value at that point. Again the difference between the constant temperature case and the variable temperature case can hardly be noticed.

Finally Fig. 7 shows the induced field obtained in both cases as a function of the azimuthal angle ϕ at radius 0.44 m and in the plane z = 3.60 m, i.e. at the end of the blanket. The fields drop to a minimum near the manifolds ($\phi = -90$, $\phi = 90$), and reaches a maximum value of 0.018 T for the variable temperature case at $\phi = 25°$. In the constant temperature case, the maximum value of the field is 0.016 T and is at $\phi = 0$. Although the difference between the two cases is still small, it does exist, as shown in Fig. 7. The induced field decreases as the temperature increases. Near the outlet manifold, the induced field from the constant temperature blanket (T = 415°C) is slightly higher than that induced from the variable temperature blanket because the temperature is higher in the latter model.

CONCLUSIONS

The induced magnetic fields from the ferromagnetic blanket of MARS have been investigated. The induced fields, which should be considered as perturbations to the magnetic field of the device, are shown to be maximum at the axial ends of the blanket. When the temperature effect on the magnetization is included, the perturbations change slightly and are shown to have weak azimuthal dependence. The maximum magnitude of these perturbations with or without the effect of the temperature is less than 0.4%

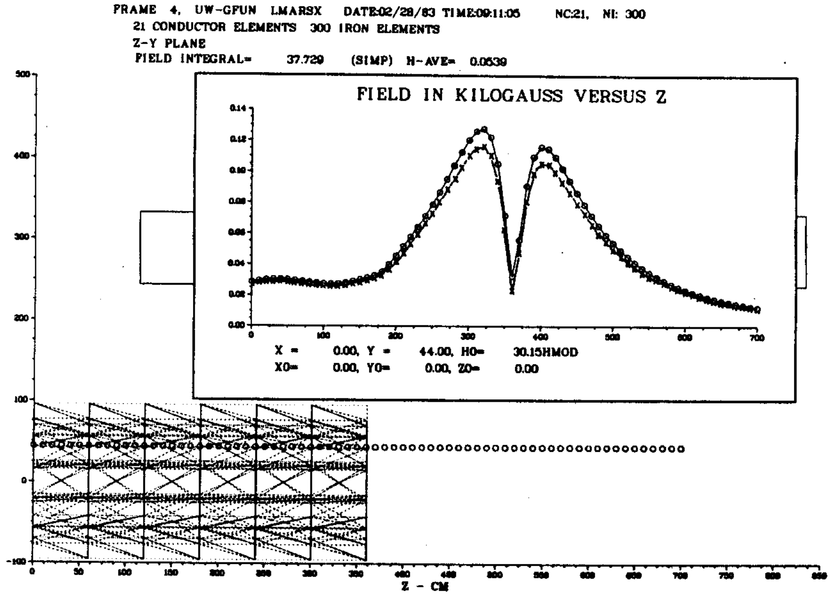

Fig. 5 The induced magnetic fields, mod (B), along the line x = 0, y = .44 m (see point A on Fig. 3) produced by the variable temperature blanket (o), and the constant temperature blanket (x).

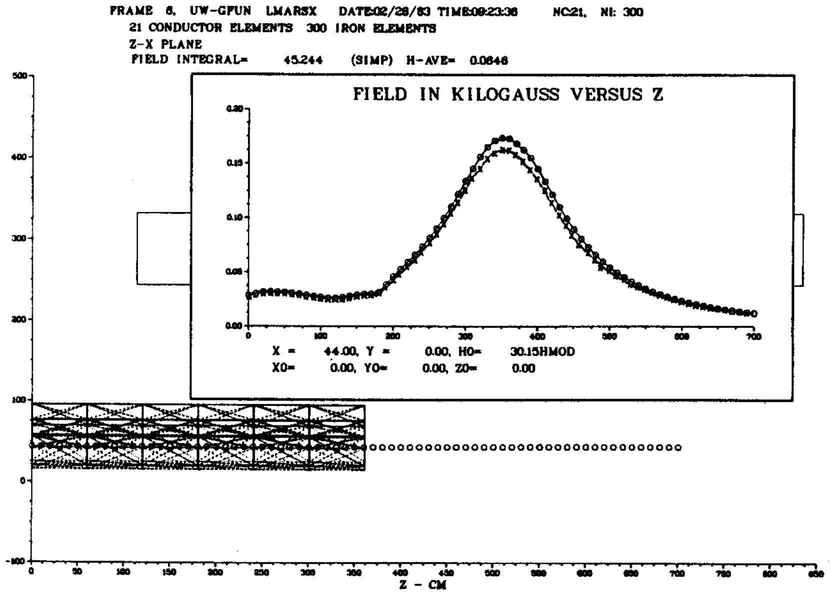

Fig. 6. The induced magnetic fields, mod (B), along the line x = .44 m, y = 0 (see point B on Fig. 3), from the variable temperature blanket (o), and from the constant temperature blanket (x).

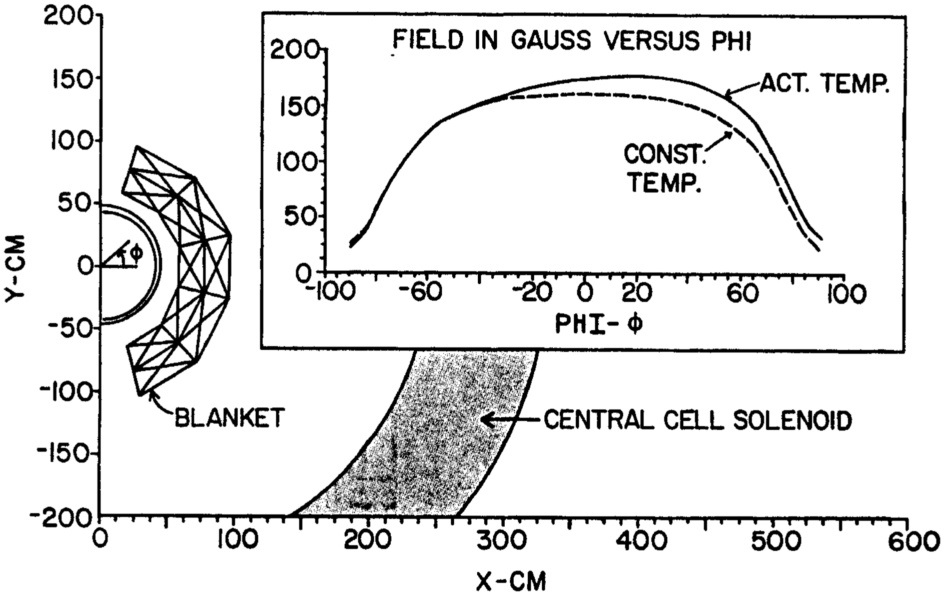

Fig. 7. The azimuthal variation of the induced magnetic field, mod (B), at radius=.44 m and in the plane z = 3.60 m.

of the magnetic field of the device. These perturbations are believed not to affect the confinement of the plasma.[8]

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