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Performance Limits of High Field Tokamak Reactors*

by

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ABSTRACT

An analysis has been performed to investigate the limits of high field commercial tokamak reactors. Variations of maximum mechanical stress, major radius and performance parameter B^2a (where B is the magnetic field on axis and a is the minor radius) were investigated to evaluate the potential impact of higher strength structural materials and higher field superconductors. For fixed values of major radius and stress, tokamak parameters were chosen to optimize machine performance. Increasing values of allowable stress correspond to decreasing capital cost, and may be an effective approach to economical commercial fusion. The prospects of using very high strength structural materials to provide sufficiently high field for ohmic dominated heating to ignition in power reactors with major radius ~ 6 meters are discussed.

I. Introduction

Significant physics and engineering advantages may be obtained by operating tokamak reactors at very high magnetic fields.[1] High field operation could provide capability for high $n\tau$ in relatively modest size plasmas, as well as strong ohmic heating. It could allow relatively low current operation, provide high wall loading in DT plasmas with low β and compact size, and make possible advanced fuel operation with moderate values of β. Super High Field Tokamak reactor design concepts have been proposed to exploit these advantages.[2,3,4]

Although high field operation makes the toroidal field magnet design more difficult, it could simplify the engineering of many other systems. Strong ohmic heating could greatly reduce or possibly eliminate startup auxiliary heating power requirements. Current drive requirements could be significantly reduced in two ways: (a) lower current requirements for sufficient $n\tau$ due to high aspect ratio operation and, (b) more efficient current drive, such as improved lower hybrid current drive efficiency due to better accessibility.[1,5] Low β operation might also reduce the need to finely tune and shape the plasma, thus simplifying the plasma magnetics and reducing problems due to disruptions. Furthermore, if high field operation provides adequate confinement for tritium–lean or advanced fuel operation[6], it could substantially simplify the blanket design by reducing the required tritium breeding ratio.

II. Limit Analysis

It is natural to ask about the limits of this approach. To assess the point of diminishing returns of high field operation, a limit analysis has been performed. This analysis considers the impact on tokamak reactors of extrapolations of the maximum stress in structural materials and the maximum field at which a superconductor can carry adequate current density. The maximum allowable stress has been extrapolated to 1.5 GPa, and the maximum field with current to 39 T. The limits of extrapolation are based on the properties of existing laboratory materials – with extrapolation to improved performance and new fabrication techniques; and production on a larger scale and in more complicated geometries than is currently possible. Timescales for development are ten to twenty years assuming solid but not 'crash program' support levels.

With respect to the superconductor, Nb_3Sn is capable of carrying sufficiently high current density ($J \geq 1x10^4$ A/cm^2) at $B \simeq 0.75B_{c2}$, where B_{c2} is the upper critical field.[7] A similar A–15 superconducting compound, Nb_3(Al,Ge), has an upper critical field $B_{c2} \sim 52$ T. A non–optimized Nb_3(Al,Ge) tape has already carried 1x10^4 A/cm^2 at 31 T,[8] and further increases in current density at higher fields can be expected. Furthermore, a B1 class superconductor, $PbMo_6S_8$, has an upper critical field $B_{c2} \sim 60$ T.[9] This conductor is difficult to fabricate and progress in its development has been relatively slow. If these low temperature materials can be developed to the level of present day Nb_3Sn, it may not be unreasonable to extrapolate superconductor operation to 45 T. Furthermore, many of the recently discovered perovskite high temperature superconductors have an upper critical field in excess of 100 T,[10] and thus might be ultimately capable of creating effectively unlimited magnetic fields. To be used in practical magnets, however, these superconductors will have to overcome many obstacles, including problems associated with anisotropy and grain boundaries. For this analysis the field limit resulting from $J_c(H)$ is taken to be 39 T, based on Nb_3(Al,Ge).

Structural steels currently have ultimate tensile stresses in the neighborhood of 1.8 - 2.0 GPa (e.g. Inconel 9XA, JBK–75, Fe-Mn alloys).[11] Nickel-Cobalt and Nickel-Titanium maraging steels, however, have cryogenic strengths in the neighborhood of 2.5 - 3.3 GPa and Carbon, Silicon Carbide, Boron and polymer fibres have strengths in the range of 3.5 to 4 GPa.[12,13,14] In addition to high strength, the utilization of these materials will require high fracture toughness and fabricability. Composite materials combining fibres with aluminum have already been successfully produced and are available commercially with ultimate tensile strength greater than 1.7 GPa.[15] Thus, one can imagine a composite comprised of a high strength steel matrix and very high strength fibres to produce a material capable of operating with an allowable equivalent tensile stress greater than 2 GPa. However, as there is no experimental database to demonstrate that these materials are compatible as composites, a less aggressive extrapolation philosophy has been employed. Our approach is to assume the development of laboratory materials to usable, commercial products. On this basis, the materials described above provide an allowable stress in the neighborhood of 1.5 GPa.

III. Performance Parameter B^2a

The comparison of reactors requires a goodness parameter that quantifies reactor performance. Using Neo-Alcator scaling for ohmically heated plasmas ($\tau_E \sim naR^2$)[16], the ratio of ohmic power (P_Ω) to power losses (P_{Loss}) is found to be

$$\frac{P_\Omega}{P_{Loss}} \sim \frac{B^2a}{T^{\frac{5}{2}}} \tag{1}$$

where B is the toroidal magnetic field, a is the plasma minor radius and T is the plasma temperature. For pure ohmic heating,

$$\frac{P_\Omega}{P_{Loss}} = 1 \Longrightarrow T_\Omega \sim (B^2a)^{\frac{2}{5}} \tag{2}$$

where T_Ω is the maximum temperature achievable with pure ohmic heating. Thus, T_Ω scales with B^2a.

Under certain circumstances, the confinement parameter $n\tau$ also scales with B^2a. The plasma density is constrained by the Greenwald limit[17] and β limit. The scaling for density is

$$n \sim \kappa J \sim B/Rq_* \rightarrow n\tau \sim (B/Rq_*)\tau \tag{3}$$

$$n \sim \beta B^2 \rightarrow n\tau \sim (\beta B^2)\tau \tag{4}$$

where β is the plasma beta. With Neo-Alcator confinement scaling, the Greenwald limited case becomes

$$n\tau \sim B^2 a/q_*. \tag{5}$$

Since the maximum temperature from ohmic heating scales with B^2a, high B^2a tokamaks may require minimum auxiliary heating power. If the auxiliary power is much smaller than the ohmic heating power, neo–Alcator scaling may be the most appropriate confinement scaling law. Alternatively, if Kaye-Goldston confinement scaling for auxiliary power heated plasmas is the used with alpha power substituted for input power,[2] one obtains $n\tau \sim (B^2a)^{0.6}$. Thus B^2a could be an effective measure of reactor performance for either confinement scaling.

Moreover, if the density is Greenwald limited, it can be shown that the wall loading scales as

$$P_w \propto B^2 a/R^2. \tag{6}$$

Although P_w is also limited by first wall material properties, B^2a again plays an important role.

IV. Parametric Studies

Parametric analysis was performed to determine the effects of increased reactor size and allowed stress level on the performance parameter B^2a. The assumed input parameters which are constant for all parametrics can be seen in Table 1. A plasma – TF coil distance of 1.4 m will allow tritium breeding and sufficient reduction of the neutron flux into the magnet for at least 30 years of magnet operation. Owing to very large forces in the TF coil, the current density in the TF coil, J_{TF}, is less than that in the ohmic heating coil, J_{OH}. The maximum field in the ohmic heating coil, B_{OH}, could be increased to the limit value of $\sim$ 39 T, however substantial reductions in the required area would not be obtained. The inductive capability indicates the number of seconds the OH coil is capable of driving the plasma without other forms of current drive. For a combination of allowed stress level and major radius, the field strength, minor radius and aspect ratio are chosen such that the reactor performance B^2a is maximized.

Figure 1 plots B^2a vs. major radius at the limit stress $\sigma = 1.5$ GPa. This stress represents the average equivalent stress in the TF coil structural material. This shows the smallest major radius that may ever achieve a given level of reactor performance. For example, if it is found that $B^2a = 250$ T^2m provides ohmic ignition, then a major radius of ≈ 6 m is required to achieve this goal.[1,18]

Figure 2 shows the toroidal magnetic field strength at the coil (B_c) and at the plasma (B_o) as a function of major radius for $\sigma = 1.5$ GPa. The superconductor must be able to carry adequate current density at B_c for the corresponding reactor in Figure 1 to be built. If it were ever desirable to build the largest machine indicated, $R_o = 10$ m, $P_{thermal,blanket} = 10$ GW_{th} (at maximum density, see Figure 3), the required field at the coil is 31 T. This is achievable today in the laboratory with $Nb_3(Al,Ge)$,[8] and could thus preclude the need for the less developed $PbMo_6S_8$ and the high temperature perovskites (although there may be other advantages to operating superconducting magnets at higher temperature). Furthermore, for a reactor of more reasonable size (R_o=6.0 m, $P_{thermal,blanket}$ =2.3 GW_{th}), the required field at the coil for optimum B^2a is 27 T; the strength of structural materials and not the properties of the superconductor limit the field.

Figure 3 shows wall loading and fusion power for combined β and Greenwald limits. The transition from β limited operation to Greenwald limited operation occurs at $R_o \sim 6$ m. The Greenwald limit was taken to be

$$n(10^{20}m^{-3}) \simeq 0.75\kappa B_o/R_o \qquad (7)$$

where κ is the plasma elongation, while the β limit was

$$\beta(\%) \simeq 3I/aB_o \tag{8}$$

where I is the plasma current in MA. The wall loading limit due to first wall material properties may be the dominating limit for R_o greater than about 3 m.

Figure 4 shows reactor performance (B^2a) and Figure 5 shows the maximum blanket thermal power and the maximum neutron wall loading as a function of allowable stress level for a tokamak with $R_o = 6$ m. The maximum power is calculated based on operating the density at the lesser of the Greenwald and β limits. If the maximum wall loading is greater than the maximum allowed by the first wall material, then both the wall loading and the blanket thermal power must be scaled down. The flattening of the power and wall loading curves at about $\sigma = 1.8$ GPa in Figure 5 corresponds to the transition from β limited density operation to Greenwald limited operation. If the Greenwald density limit increases, the transition will occur at a higher stress level and higher fusion power densities might become obtainable. The power limits associated with economic first wall operation must also be obeyed.

As material properties improve with experience and time, the 'Equivalent Tensile Stress' axis in Figures 4 and 5 could be equivalently considered as a time dependence. Since these figures are for fixed size ($\sim$ fixed capital investment), the increasing fusion power corresponds to decreasing COE. Figure 6 shows the field strength at the TF coil required for these reactors ($R_o = 6$ m). It is interesting to note that full utilization of currently producible $Nb_3(Al,Ge)$ requires an equivalent tensile stress in the neighborhood of 3 GPa. From the perspective of this analysis, the development of high field superconductors leads the development of high strength structural materials.

Figure 7 offers an alternative perspective. This figure plots the required stress level as a function of major radius to obtain a fixed level of performance. A performance level of $B^2a = 250\ \mathrm{T^2m}$ was selected as a point for which ohmic ignition,[1,18] or at least ohmic dominated ignition,[1] might be obtainable. The upper curve assumes that the stabilizer material (usually copper) supports a stress of 300 MPa (as assumed in Figures 1–6). The lower curve shows the impact of a high strength stabilizing material, such as CuNb or Al-SiC. This curve assumes a stabilizer stress level of 800 MPa. Thus the combination of high strength, low resistivity materials for magnet stabilization and protection and very high strength structural materials may allow a reduction in the size of the tokamak.

This is further seen in Figure 8. As the allowed stress level increases from about 640 MPa to 1500 MPa, the required plasma volume is reduced by a factor of 3. If the allowed stress level in the structure can be increased from 1.5 to 2 GPa, and the stress in the stabilizer increased from 300 to 800 MPa, then the major radius of the tokamak can be decreased from 6 m to 5.5 m, thus providing a substantial cost savings. As the major radius decreases further, the rate of increase of the required stress level eventually becomes infinite. Figure 7 can be equivalently thought of as a plot of time vs. cost. If the allowed stress intensity increases with time, then the required capital cost of the reactor could decrease.

V. Conclusions

Obtaining very high magnetic field strength ($B_{coil} > 18$ T) in a superconducting tokamak will require development of both superconductor and structural materials. Presently, sufficient current density at high field in Nb_3Al and $Nb_3(Al,Ge)$ is only obtainable when the superconductor is in a tape form. Tape superconductors are inherently unstable in the presence of a magnetic field normal to the face of the tape. Thus, dynamic stabilization is required and the allowed width of the superconductor may be limited. Furthermore, unconditional cryostability would appear not to be possible for these compact, high field magnets. Further investigation into the stability of Nb_3Al and $Nb_3(Al,Ge)$ tapes is required. If Nb_3Al or $Nb_3(Al,Ge)$ could be developed to carry high current density at high magnetic field in a multifilamentary form, some of these restrictions would be removed. Furthermore, optimization of Nb_3Al and $Nb_3(Al,Ge)$ processing, including improved flux pinning to increase J_c at higher magnetic fields in Nb_3Al and consistent production of very long lengths with quality assurance may lead to the commercial availability of a superconductor capable of performing at over 30 T.

The development of stronger structural materials, capable of supporting allowable stresses near the ultimate stress of currently available materials will greatly enhance the prospects for very high field tokamaks and thus possibly fusion power development as a whole. Obtaining materials capable of supporting stresses beyond the capabilities of currently available advanced steels is likely to require the development of fibrous composites and/or maraging steels. Presently developmental laboratory materials should be capable of eventual utilization in toroidal field magnets with stresses around 1.5 GPa. Candidate fibre materials are carbon, silicon carbide, boron and poly-(p-phenylene benzobisthiazole). Furthermore, the development of CuNb microcomposite or Al-SiC to a bulk form (i.e. strips) may also improve overall reactor performance.

In general, increased attention to high strength materials and advanced superconductors may provide a significantly accelerated path for the development of fusion power systems.

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Table 1

Input Parameters for Parametrics

κ	1.8
Plasma-TF coil distance (m)	1.4
q_*	4
B_{OH} (T)	32
J_{OH} (MA/m^2)	30
J_{TF} (MA/m^2)	20
$\sigma_{stabilizer}$ (MPa)	300
Inductive Capability (s)	300
Blanket Power Multiplication	1.2

$$I_p = 5a^2\kappa B_{plasma}/R_o q_*$$

$$\beta_{max} = 0.03 I_p / a B_{plasma}$$

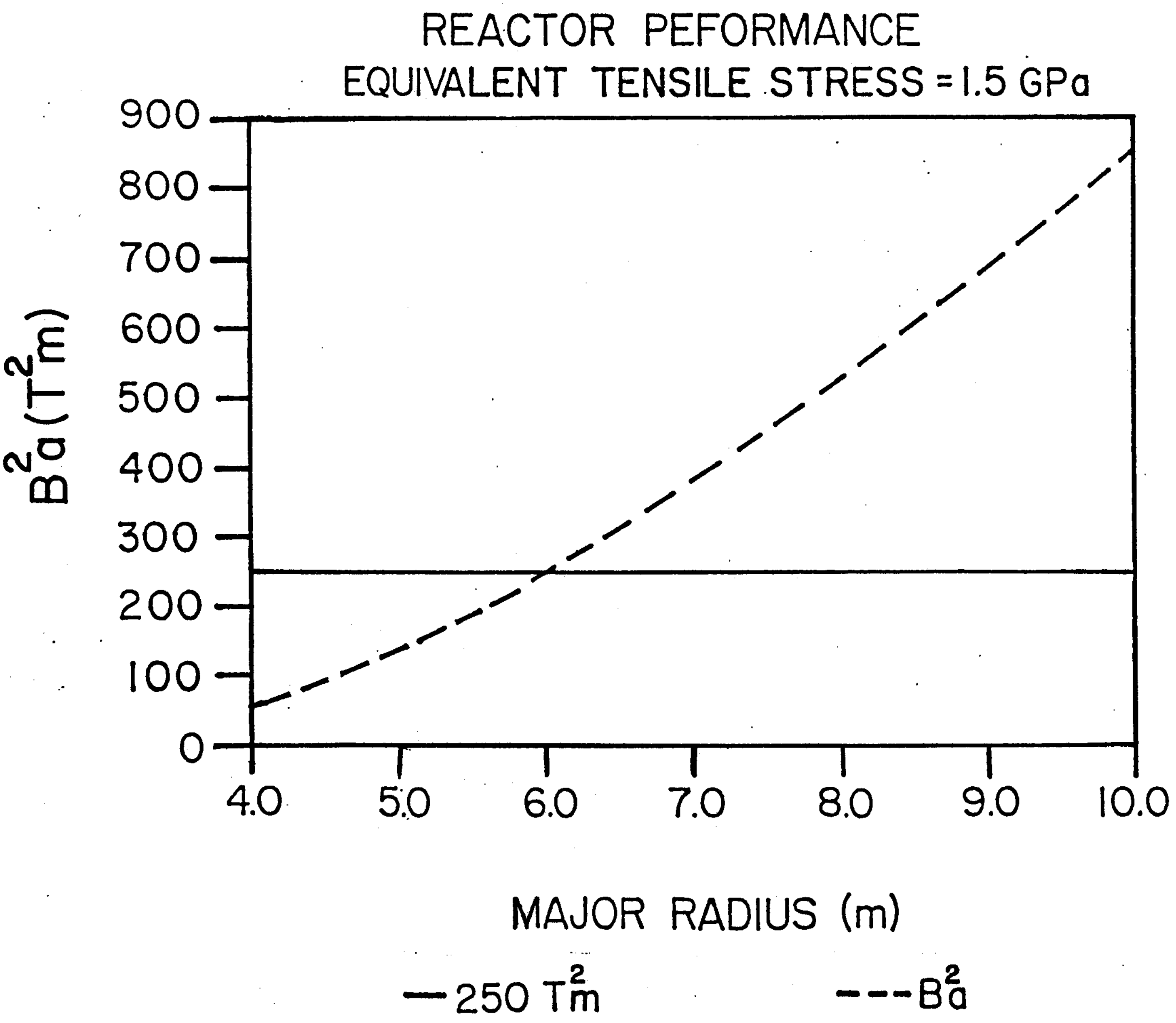

REACTOR PEFORMANCE
EQUIVALENT TENSILE STRESS = 1.5 GPa
$B^2a (T^2m)$
900
800
700
600
500
400
300
200
100
0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
MAJOR RADIUS (m)
— $250\ T^2m$
--- B^2a

FIGURE 1

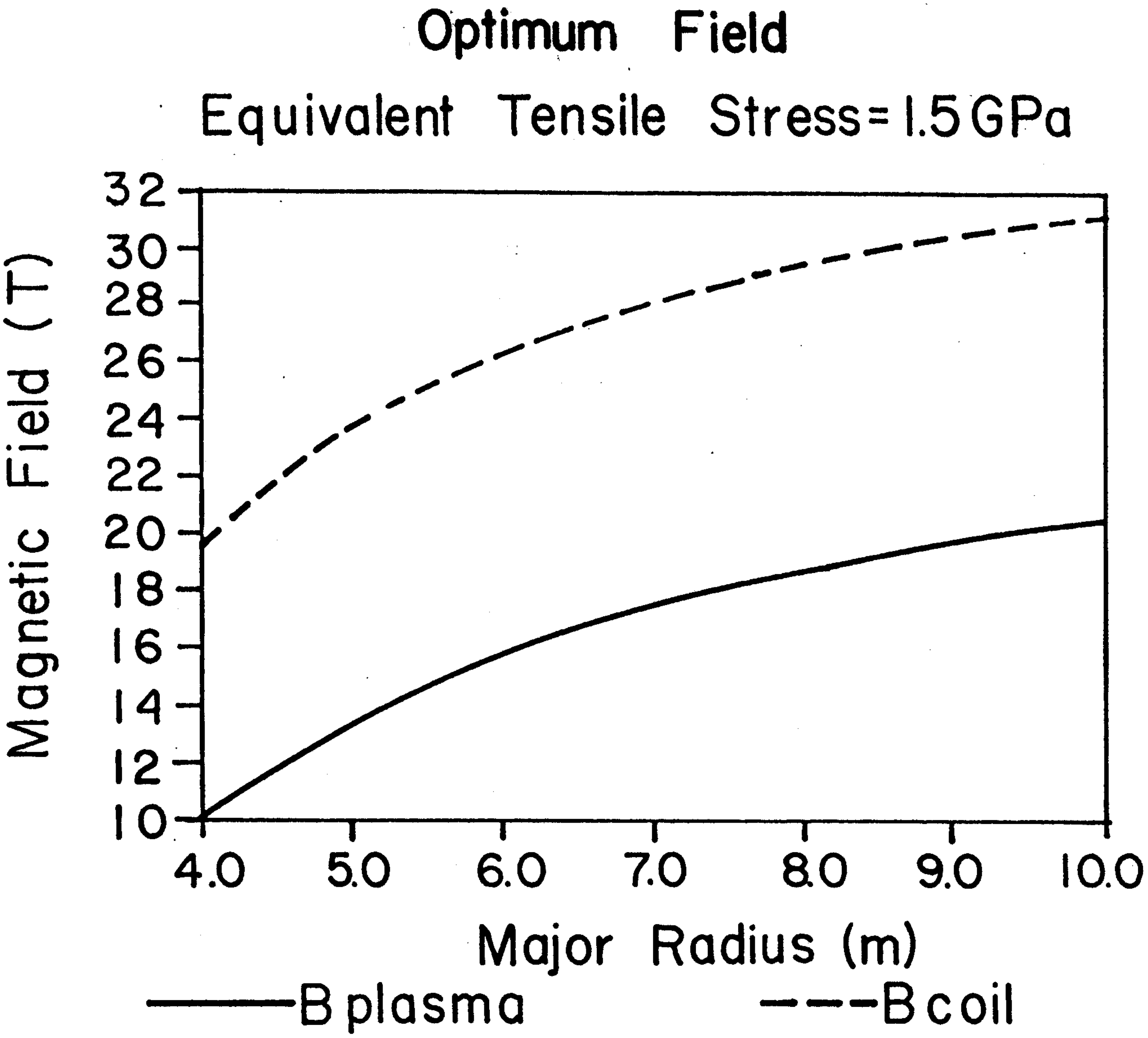
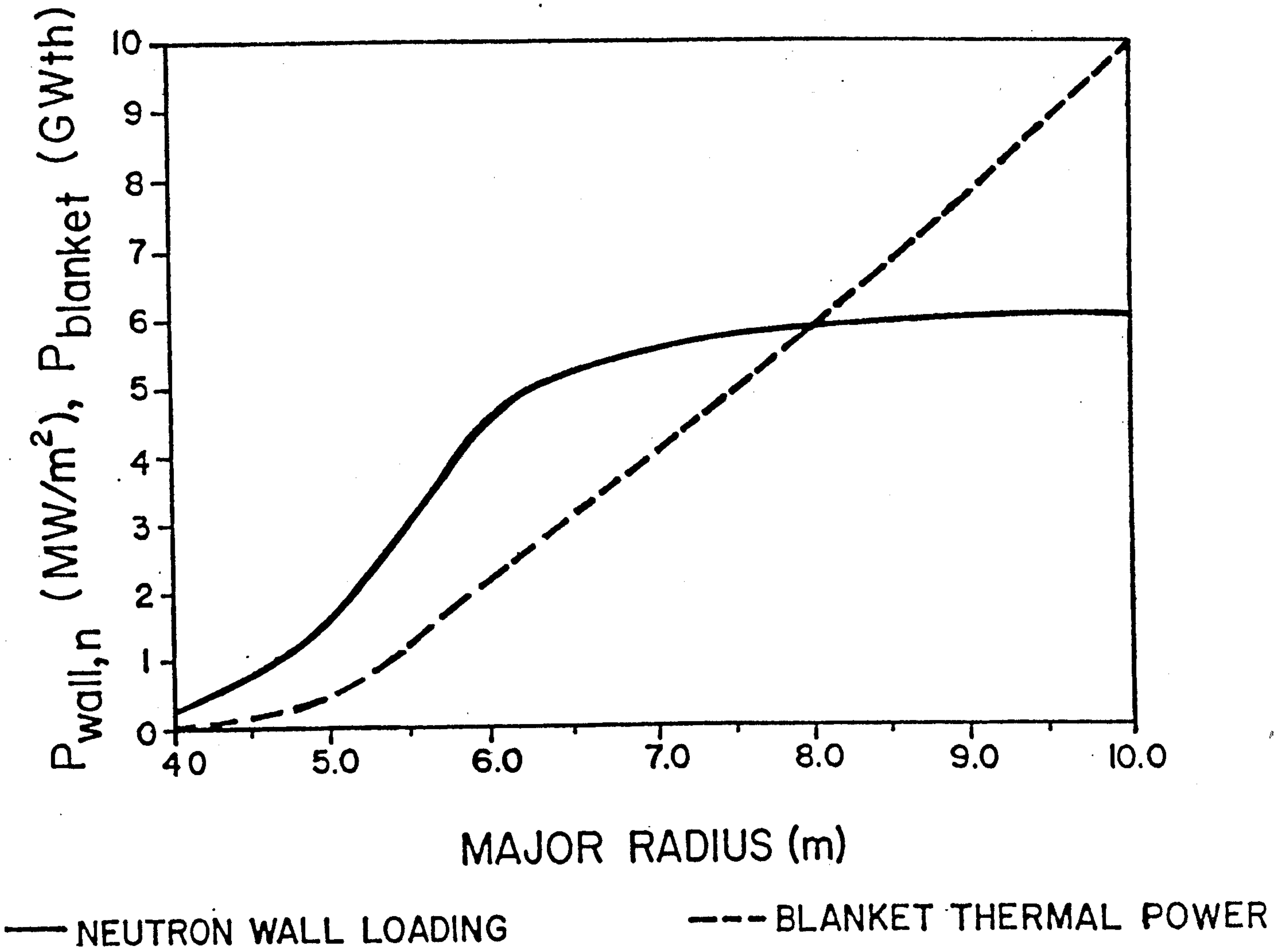

Optimum Field
Equivalent Tensile Stress=1.5GPa
Magnetic Field (T)
32
30
28
26
24
22
20
18
16
14
12
10
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Major Radius (m)
B plasma
B coil

FIGURE 2



BLANKET POWER AND NEUTRON WALL LOADING
EQUIVALENT TENSILE STRESS = 1.5 GPa
MAXIMUM DENSITY

FIGURE 3

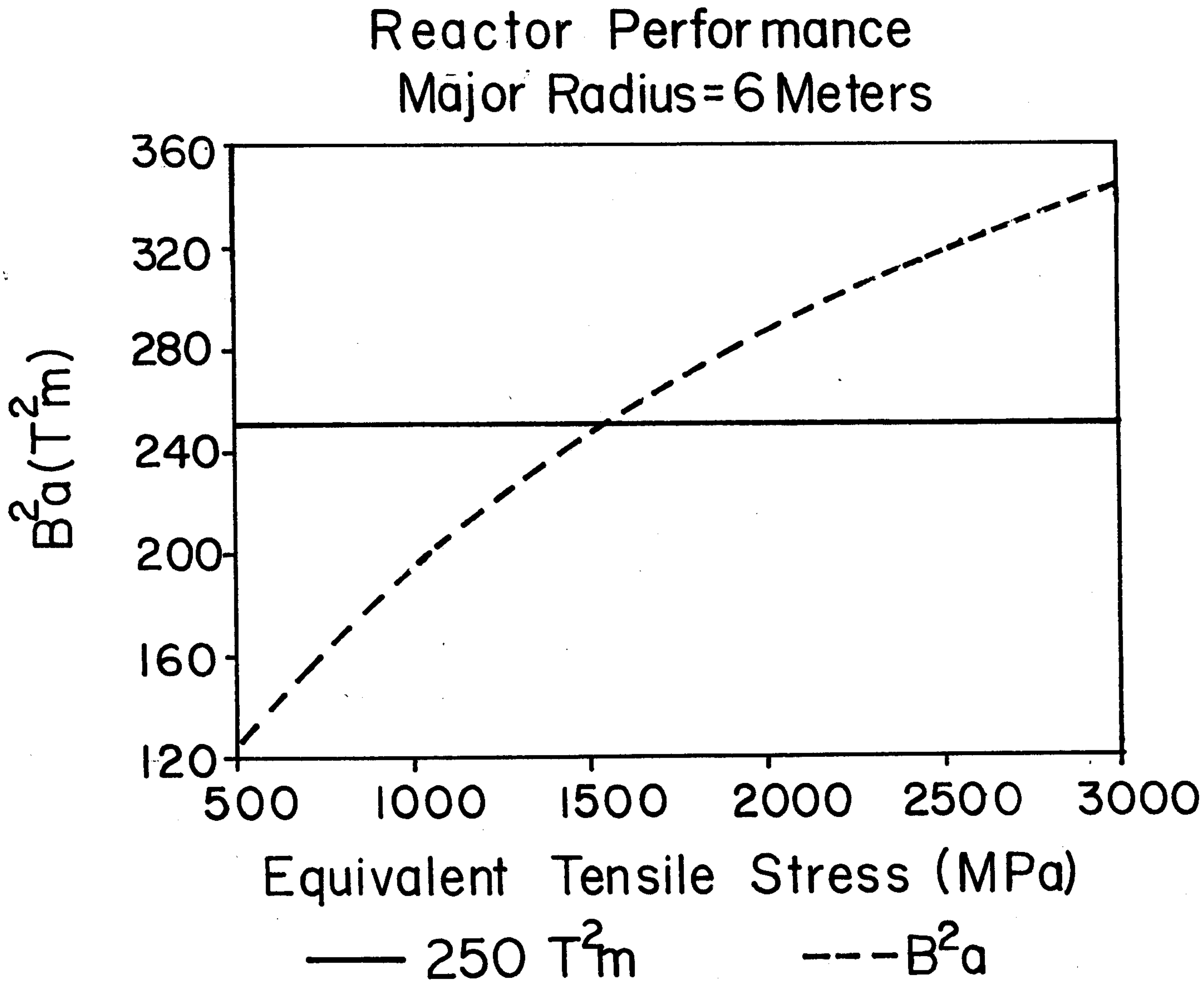

Reactor Performance
Major Radius=6 Meters
$B^2a(T^2m)$
360
320
280
240
200
160
120
500
1000
1500
2000
2500
3000
Equivalent Tensile Stress (MPa)
—— 250 T^2m
---B^2a

FIGURE 4

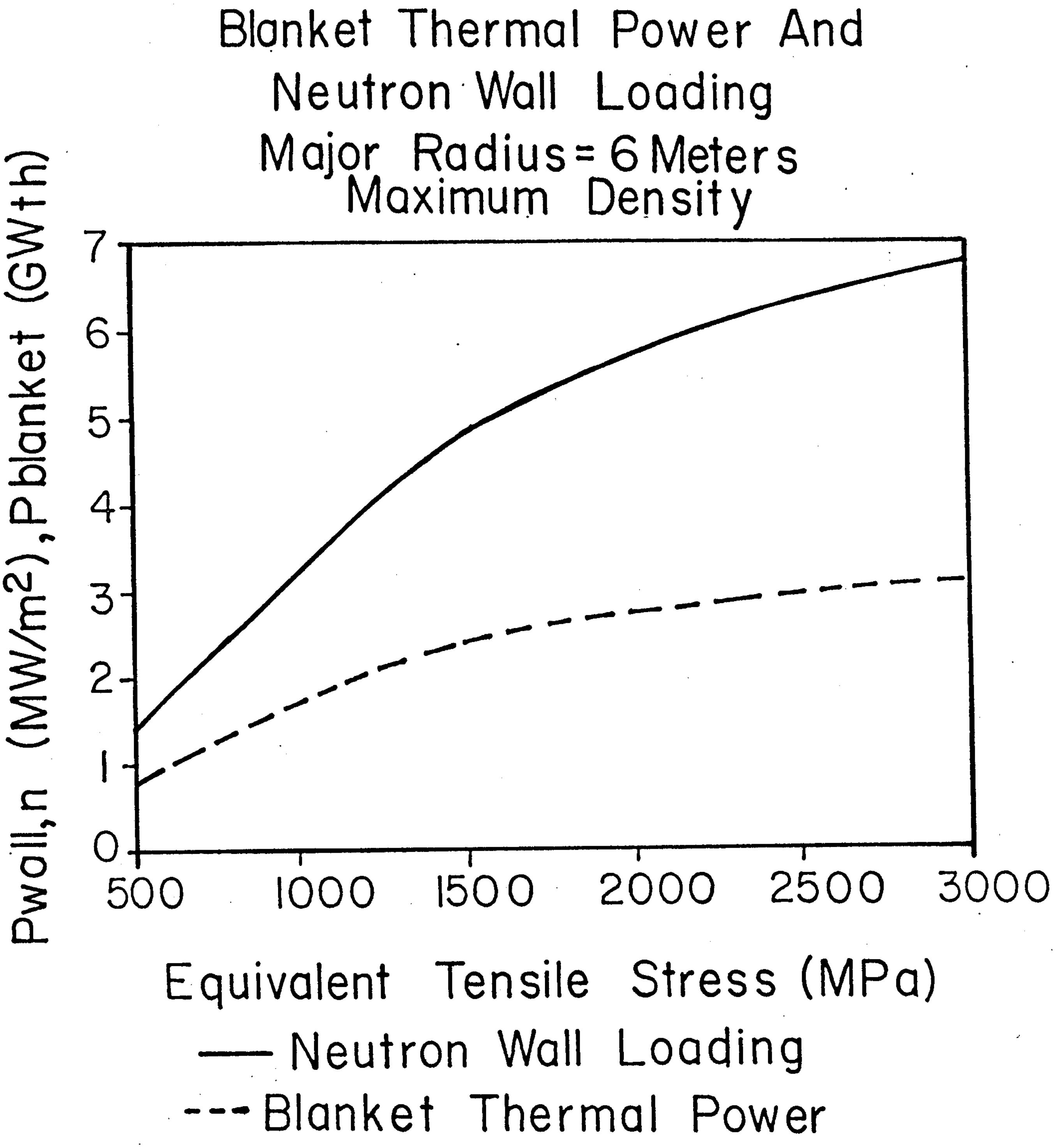

Blanket Thermal Power And
Neutron Wall Loading
Major Radius = 6 Meters
Maximum Density
Pwall,n (MW/m2), Pblanket (GWth)
0
1
2
3
4
5
6
7
500
1000
1500
2000
2500
3000
Equivalent Tensile Stress (MPa)
—— Neutron Wall Loading
- - - Blanket Thermal Power

FIGURE 5

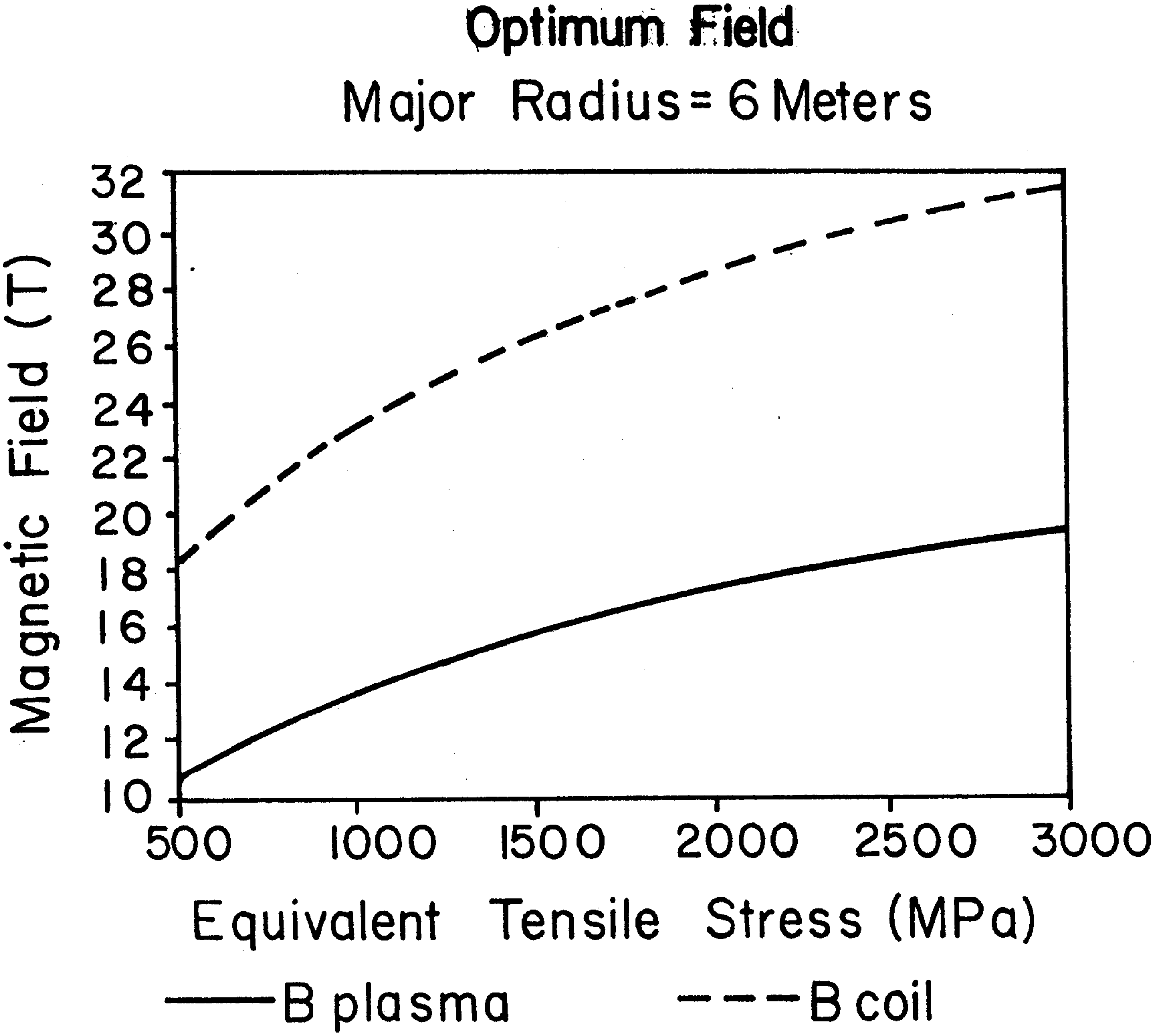

Optimum Field
Major Radius = 6 Meters
Magnetic Field (T)
10
12
14
16
18
20
22
24
26
28
30
32
500
1000
1500
2000
2500
3000
Equivalent Tensile Stress (MPa)
—— B plasma
- - - B coil

FIGURE 6

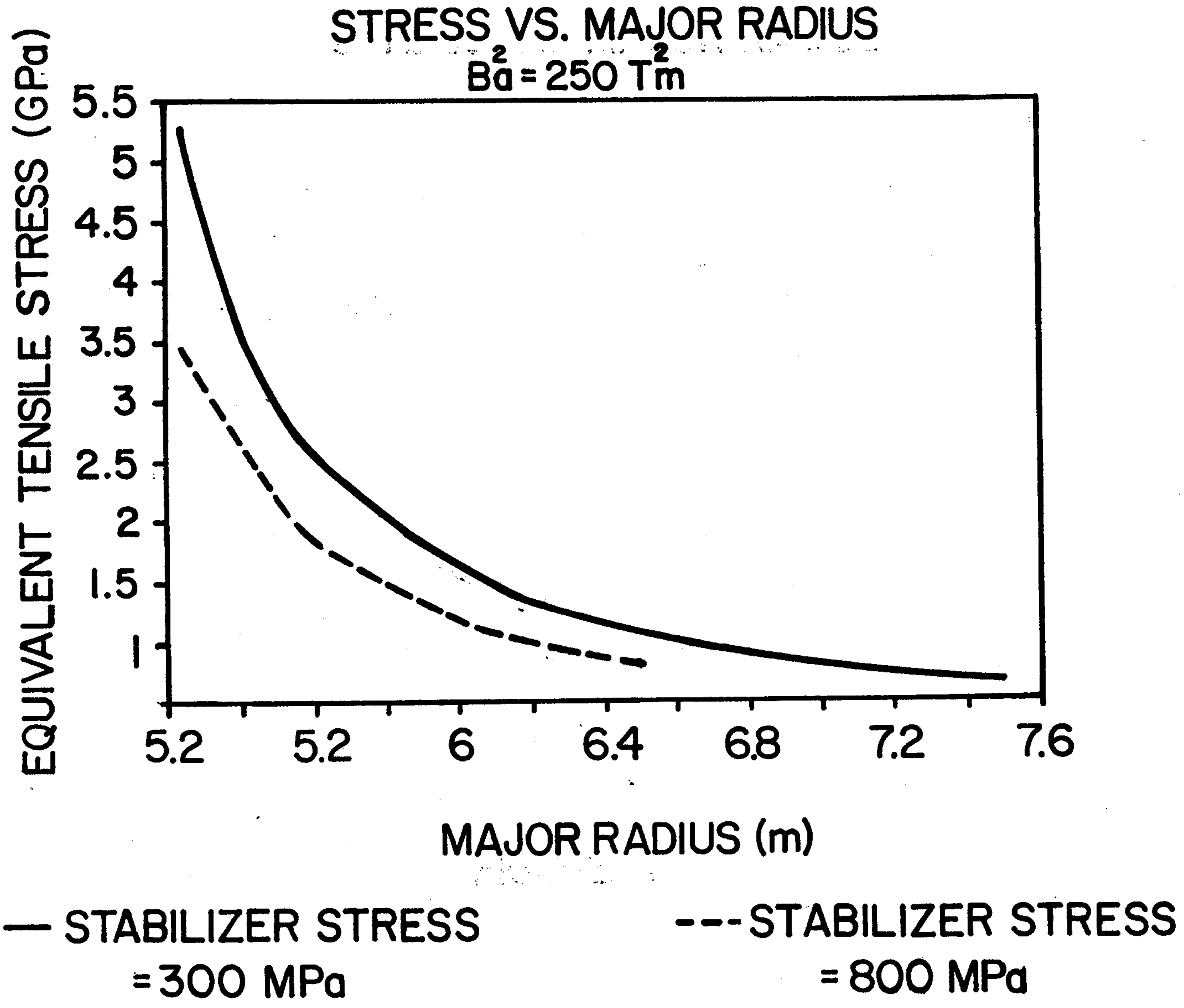
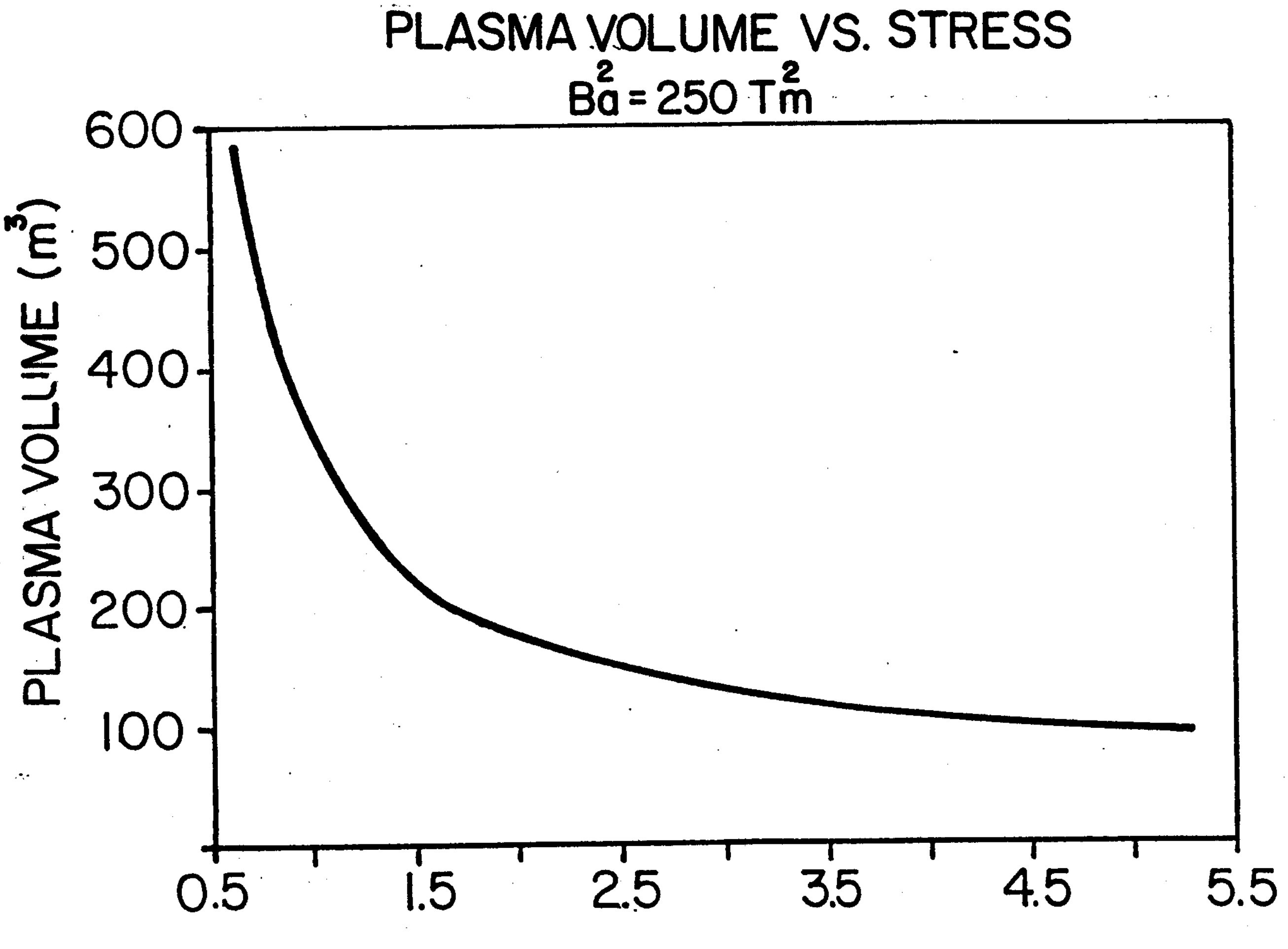

STRESS VS. MAJOR RADIUS
Ba² = 250 Tm²
EQUIVALENT TENSILE STRESS (GPa)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
5.2
5.2
6
6.4
6.8
7.2
7.6
MAJOR RADIUS (m)
— STABILIZER STRESS =300 MPa
--- STABILIZER STRESS =800 MPa

FIGURE 7



EQUIVALENT TENSILE STRESS (GPa)

FIGURE 8