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**Magnet Design for the ARIES-I High Field
Tokamak Reactor**

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MAGNET DESIGN FOR THE ARIES-I HIGH FIELD TOKAMAK REACTOR*

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A design has been developed for a high field magnet for the ARIES-I reactor design. The toroidal field magnet produces 21 T at the coil. It uses a tertiary Nb₃Sn conductor. The combination of a high aspect ratio design, advanced magnet design, and a bucking cylinder structural design reduces toroidal field coil stress levels to ~700 MPa. The stress level could be handled in a steady-state reactor by industrially available steels.

1. INTRODUCTION

A major feature of the ARIES-I reactor is the use of high field [1]. As such, design and feasibility issues of the 21-Tesla toroidal field magnet system are critical. We have developed a high field magnet design that could reasonably be extrapolated from present technology. The design uses powder metallurgy Nb₃Sn superconducting cables. The stress levels are kept at ~700 MPa by use of a high aspect ratio configuration and a bucking cylinder configuration. We have been guided in part by earlier design work on high field tokamak power reactors [2,3].

2. DESIGN APPROACH

The design approach winds the conductor into grooves within a plate in a manner similar to the Westinghouse LCP [4]. A group of such plates are made of a high strength steel alloy. Figure 1 shows a cross-section of the toroidal field coil. Each coil consists of 22 plates. Instead of winding all of the material in the magnet, only the conductor requires winding. This approach eases the fabrication by eliminating the stiffest material from the winding process.

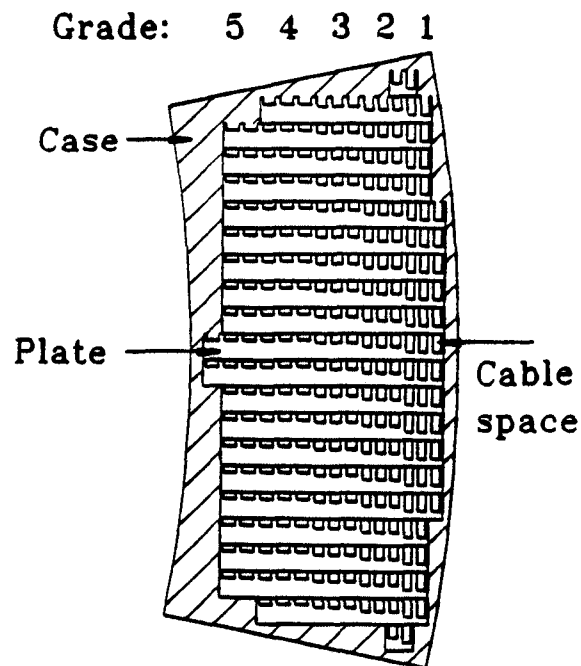


FIGURE 1
TF coil cross-section.

Currently available Nb₃Sn alloys [5] are capable of producing fields up to about 21 Tesla. Other superconductors exist in the laboratory for

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use at higher field levels, but there is not full-scale manufacturing experience. We concluded that fields higher than 21 T, although feasible, would require tape conductors. In particular, the best results obtained with Nb₃(Al,Ge) have been in tapes [6]. The sensitivity of the tapes to pulse losses would lead to magnet quenching in the event of a disruption.

The conductor in each toroidal field coil is graded with Nb₃Sn used for the intermediate and high field (≥ 6 T) regions and NbTi used for the low field (< 6 T). The stabilizer is high strength Cu-Nb [7].

The TF coils are supported against radial forces by a bucking cylinder. Two structural shell caps, located above and below the bucking cylinder, support the out-of-plane loads on the outer legs of the magnets as shown in Figure 2. These caps are continuous in the toroidal direction and have access ports to the divertor targets both above and below the midplane. The cap, the toroidal field coils, and the poloidal field coils that are supported by the cap are all in a common dewar. For maintenance, these caps can be removed in one piece by relatively simple lift operations. The cap shells are connected to the bucking cylinder by a set of radial keys. There is no transfer of vertical loads from the cap shells to the bucking cylinder.

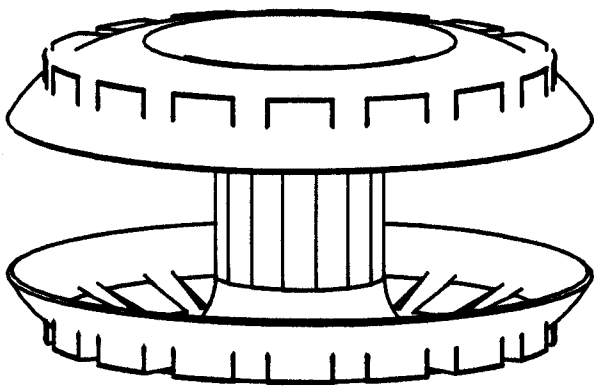


FIGURE 2
Schematic diagram of the TF coil external support structure (bucking cylinder and cap shells).

The coils were designed subject to the following constraints: superconductor stability; quench protection; superconductor strain (including thermal); stress and strain limits in the structure; and fabricability. Five grades of conductor winding pack are employed. The parameters of the TF magnet are summarized in Table 1.

3. STRUCTURAL DESIGN

A relatively low stress for a 21-T magnet is made possible by some unique aspects of the ARIES-I design. First, the high aspect ratio increases the area over which the large Lorentz forces are distributed. The ratio of the field at the plasma to the field at the coil is also increased. Second, the stress levels are reduced by using a bucking cylinder and two structural caps. Third, the use of plates facilitates the ability to use the conductor (superconductor, stabilizer, and sheath) as part of the structural material.

The coils are supported against radial loads by a thick bucking cylinder, the thickness of which is determined by the radial loads. The out-of-plane loads generated in the inner leg of the magnet are also supported by the bucking cylinder. The shell caps support the out-of-plane loads generated.

Finite element models (FEM) were constructed to analyze the ARIES-I magnets. The first analyzes global loads while the second analyzes the behavior of the magnet cross-section. Results from the global model are shown in Figures 3 and 4. Figure 3 shows the von-Mises stresses in the coil, while Figure 4 shows the stresses in the support structure (bucking cylinder and cap shell). Detailed finite-element analyses of the magnet yield a maximum von-Mises stress of ~700 MPa averaged over the midplane cross-section. This takes into account the partial transfer via friction of vertical loads from the toroidal field coil to the bucking cylinder. The stresses in the structure are ~850 MPa. This level of stress can be handled in a steady-state reactor by the industrially available steels [8,9] or Incoloy 908 [10,11]. This material has been considered for the ITER magnets.

The stresses in the outer leg of the TF magnet are larger than in the inboard leg, especially in

Table 1
ARIES-I Conductor Design Parameters

Magnetic field (T)	21.04
Pack current (kA)	100
Maximum voltage (kV)	20
Number of coils	16
Ripple on axis (%)	0.15
Ripple on edge (%)	1.49

Thermal contraction (293 K to 4 K):

Superconductor	2.0×10^{-3}
Stabilizer	2.9×10^{-3}
Plate	2.0×10^{-3}
Case	3.0×10^{-3}
Insulation	2.0×10^{-3}

Conductor detail:

Grade	1	2	3	4	5
Maximum field (T)	21.1	18.	14.	9.	4.
Critical current density (10^8A/m^2)	24	4.98	12.5	35.5	46.5
Critical temperature (K)	4.6	6.5	9.1	12.4	6.6
Radial build (cm)	3.8	4.0	4.4	5.0	5.1
Plate thickness (cm)	1.85	3.28	4.30	4.84	4.96
Conductor height (cm)	2.10	2.30	2.70	3.30	3.41
Superconductor fraction	0.433	0.269	0.128	0.032	0.038

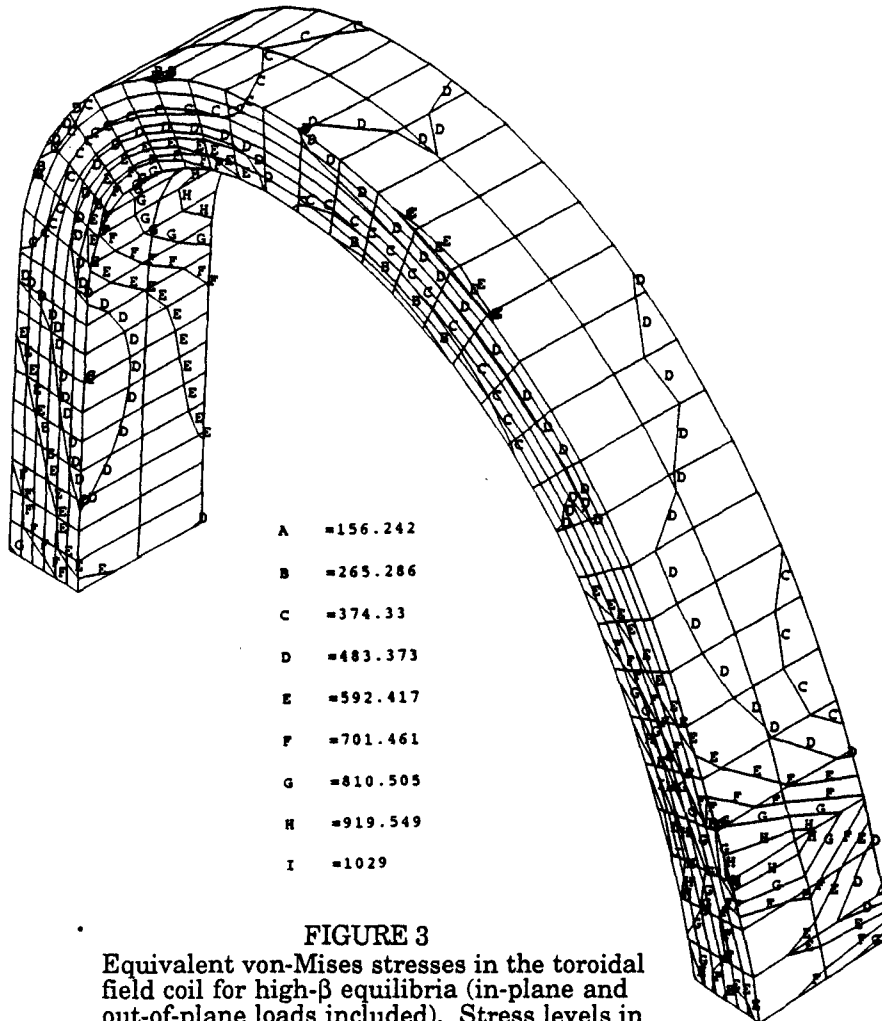


FIGURE 3
 Equivalent von-Mises stresses in the toroidal field coil for high- β equilibria (in-plane and out-of-plane loads included). Stress levels in MPa.

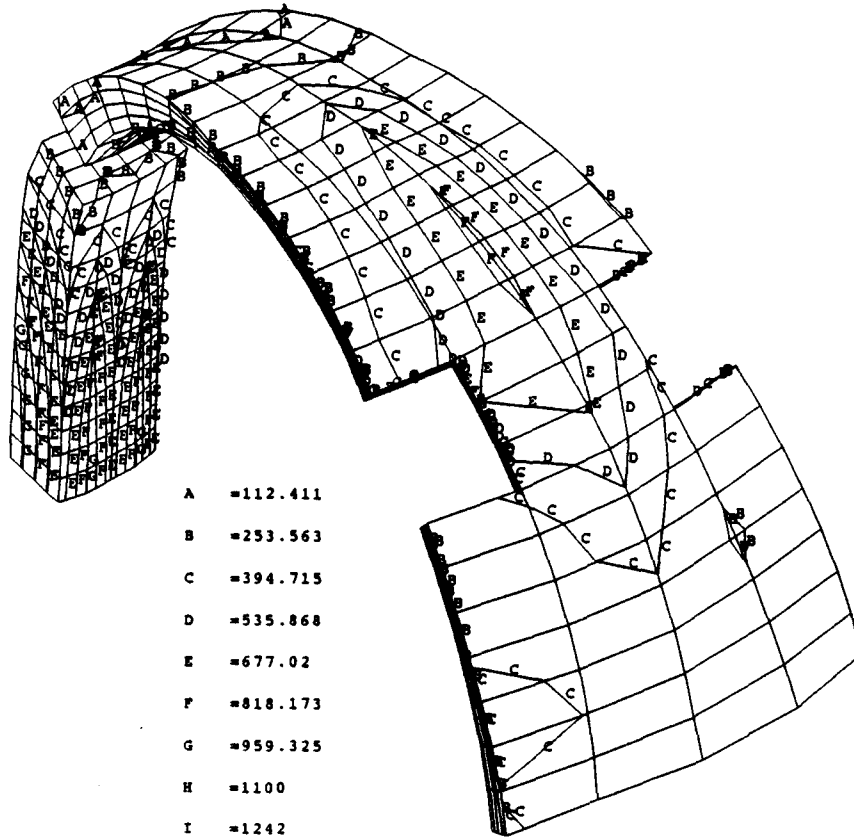


FIGURE 4
Same as Figure 3 but for the external support structure.

the region that is not supported by the cap shell. In this region, space is not at a premium. This region should be reinforced to bring the stresses down.

The shear stresses from the out-of-plane loads have a maximum of ~150 MPa assuming that the cap shell is 0.20 m thick. In order to minimize the weight of the cap shell, we have iterated the thickness of the cap so that the stresses are approximately 600 MPa everywhere. It may be possible to decrease the weight even further by making the cap shell as a shear truss.

4. CONDUCTOR

Figure 5 shows the upper critical magnetic field, H_{c2} , as a function of temperature for various low temperature superconductors [12]. Only two of these superconducting materials are available commercially today: NbTi and Nb₃Sn. Other materials, however, have much higher $H_{c2}(T)$ and may be attractive for high field tokamaks in the long term. The most promising of these materials are Nb₃Al and Nb₃(Al,Ge).

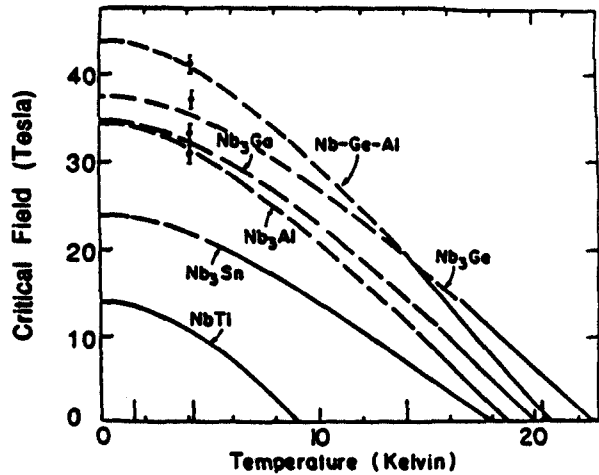


FIGURE 5
Critical field versus critical temperature for several low temperature superconductors.

The conductor in the highest field region of the ARIES-I magnet is multifilamentary Nb₃Sn. Numerous techniques exist for producing binary and ternary Nb₃Sn. In general, each technique attempts to provide good mixing between the Nb and the Sn, and high temperature (~700° C) heat

treatment for growth of the superconducting phase. The best high field Nb₃Sn-based superconductor has been produced by powder metallurgy (P/M) processing [5].

5. PULSED LOSSES, STABILITY, AND QUENCH PROTECTION

Pulse losses in the TF system are dominated by hysteretic mechanisms. The total pulse loss energy in the TF system during a full scenario (startup, burn, and shutdown) is 1.1 MJ. This energy can be absorbed adiabatically and is easily removed during the burn or shutdown periods.

The fraction of the conductor envelope of the helium in the high field grade is 7%, and while the bulk of the magnet is at a bath temperature of 4.2 K, the inlet helium temperature of the first row is subcooled to 3.8 K. The lowest energy margin is 140 mJ/cm³, a value that while not conservative is sufficient for stability. The energy dissipated in a disruption at the location of the minimum energy margin is 30 mJ/cm³. Everywhere else in the magnet the difference between the energy margin and the energy dissipated in a disruption is larger. Therefore, the toroidal field magnet will not quench in a disruption. The energy dissipated in the toroidal field coil in a current-conserving disruption is ~1 MJ (during the flattop).

The stabilizer requirements are dictated by quench protection and not by stability. In the ARIES-I magnet, the allowed stabilizer current density is increased by two mechanisms: increasing winding pack current which becomes feasible in the plate geometry; and halving the effective stored energy per coil by adding an extra layer of electrical insulation between the center plates in each coil. Each half-coil is then driven by a separate power supply and current lead. Thus, although there are 16 coils mechanically, there are 32 coils electromagnetically.

6. POLOIDAL FIELD DESIGN

The design of the PF magnet system does not share the feasibility and development issues of the TF system. The PF conductor in ARIES-I is an internally cooled, ternary Nb₃Sn.

The total pulse energy loss in the PF system is 1.6 MJ for a normal scenario. It was found that

the temperature margin of the PF system is everywhere greater than 0.5 K, and the energy margin exceeds 0.5 J/cm³. The total energy dissipated in the PF during either a flux-conserving or current-conserving disruption is \leq 300 kJ. Similarly to the TF coil, the PF system will not quench with a disruption.

7. CONCLUSION

We have analyzed the difficulties associated with construction in a high field magnet. We conclude that using present-day materials that exist in the laboratory (both structure and superconductor), it is possible to design the magnets for a 21 T superconducting tokamak reactor.

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