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PERFORMANCE AND COST SENSITIVITIES ASSOCIATED WITH SUPERCONDUCTING DEVICES*

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Abstract: This paper describes the results of a study to explore the design space of superconducting ignition devices. Parametric studies were performed with the revised FEDC Tokamak Systems Code [1] to determine the sensitivity of performance and cost to variations in confinement model, aspect ratio, maximum field at the toroidal field (TF) coils, and plasma elongation. We discuss the methodology employed and the implication of the results obtained.

1. Introduction

One important design option for tokamak systems is the use of superconducting toroidal field magnets. The longer range planning of fusion energy systems, particularly for commercial applications, necessitates the examination of superconducting designs. In this study, we determine the impact of variations in plasma confinement model, maximum toroidal magnetic field, aspect ratio, and elongation on performance and cost. A description of the methodology utilized and a summary of the results are included in this paper.

2. Methodology of Analysis

The trade studies conducted for this paper used the FEDC Tokamak Systems Code. The specific constraints and assumptions imposed on the calculations are described below for the physics and engineering models.

The physics model, discussed in Ref. [2,3], performs a steady-state, two-fluid, power balance for the ions and electrons. Flexibility is provided to investigate the effects of different energy transport models and plasma profiles. Stability is characterized by limits on the maximum achievable value of beta and density and the minimum value of the safety factor on axis. All calculations for this study are consistent with a constant ignition margin of 1.5, a volume-averaged toroidal beta equal to the Troyon-Wesson beta limit [$\beta = 0.03I_p/(aB_t)$], an edge safety factor of 2.4, and a triangularity of 0.3. Three confinement models were utilized.

1. The electron confinement is described by neo-Alcator scaling ($0.07n_e aR^2q^*$), and the ions are treated with the Chang-Hinton neoclassical formulation [3] (with an anomaly factor of 1).
2. The electron confinement is described by Mirnov scaling ($0.15I_p a\kappa^{0.5}$) and the ions with neoclassical.
3. The global confinement (ion and electrons) is described by

$$\frac{1}{\tau_E^2} = \frac{1}{\tau_{AUX}^2} + \frac{1}{\tau_{OH}^2} ,$$

where

τ_{AUX} = Kaye-Goldston (L-mode or H-mode) confinement time,

τ_{OH} = Neo-Alcator confinement time.

More information on the specific formulation for this confinement model may be found in Ref. [3].

The engineering analysis and costing algorithms employed are consistent with the nominal performance superconducting design of the Tokamak Fusion Core Experiment (TFCX) [4]. Specifically, the operating scenario, radial build dimensions, and gaps for component clearance are based on this design, with the inboard shield thickness determined on the basis of a maximum TF coil nuclear heating rate of 5 mW/cm^3. Two types of superconductors are considered for toroidal field coil designs ranging from 8 to 12 T. The 8-T designs employed NbTi (pool boiling cooling) as the superconductor with a winding cost of 80 \$/kg and a conductor cost of 2.5 \$/kA-m-T. The 10- and 12-T designs employed Nb_3Sn (forced-flow cooling) with a winding cost of 120 \$/kg and a conductor cost of 3.0 \$/kA-m-T.

In this parametric survey of the superconducting design space, the calculations performed determined the major radius and field on axis that satisfied an ignition margin of 1.5 and a maximum field at the TF coil of 8, 10, or 12 T. Three confinement models, three aspect ratios (3.0, 4.0, and 5.0), and two values of elongation (1.6 and 2.0) were examined. The costs shown for the fixed performance designs essentially reflect variations in size and field. The costs associated with the RF heating and current drive, the poloidal field coil, and the power conversion systems are not precisely modeled; therefore, the direct capital costs are represented as relative values only.

3. Results

One interesting feature of superconducting designs is that a divertor may be required for operation. This issue was examined by comparing the major radius required to satisfy an ignition margin of 1.0 and a maximum field of 10 T for the Kaye-Goldston L-mode and H-mode confinement models. (An aspect ratio of 3.0 and an elongation of 1.6 were used for this

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comparison.) The resulting major radius for the L-mode design, 7.2 m, is approximately 57% larger than that for the H-mode design, 4.6 m, with a corresponding increase in the TF coil cost of approximately 162%. The economic advantages of operating in an H-mode regime imply the need for a divertor. In the remainder of this paper, the H-mode confinement is assumed for the Kaye-Goldston model, and a corresponding ignition margin of 1.5 is used.

Figures 1 and 2 show the variation of major radius with maximum field and aspect ratio for the three confinement models. Generally, the smallest sizes are associated with the neo-Alcator model, and the largest sizes are associated with the Kaye-Goldston model. Noteworthy features include the strong dependence on aspect ratio for the sizes predicted with the Mirnov model and the relatively weak aspect ratio dependence associated with the neo-Alcator model. Large aspect ratio systems are favored under the neo-Alcator model, while low aspect ratio systems are favored under the Mirnov model. For the Kaye-Goldston model, large aspect ratio systems are also favored, although not as strongly as under neo-Alcator. Furthermore, for a given aspect ratio, the reductions in size due to increasing field are the most significant under Kaye-Goldston.

The variation of volt-seconds required for plasma initiation is shown in Fig. 3 as a function of aspect ratio. It is interesting that the volt-second requirements decrease with increasing aspect ratio under the neo-Alcator and Kaye-Goldston models but increase under the Mirnov model. This increase is due to the fact that as the aspect ratio increases, the increase in major radius (and, hence, plasma self-inductance) is much stronger (Fig. 2) than the decrease in plasma current. The reverse is true for the other confinement models. Inductive startup is favored in systems having lower fields and larger aspect ratios. At a field of 12 T, aspect ratios greater than 5 are required, while at 8 T, inductive startup will occur for an aspect ratio of approximately 3.

The relative capital cost is shown in Fig. 4, normalized to the total direct cost associated ith a system having a field of 10 T and an spect ratio of 3 under the Mirnov confinement model. The curves for the neo-Alcator and Mirnov models show a shallow minimum in relative cost at 10 T and at an aspect ratio of 3. This agrees with results from previous studies [5,6], which arrived at similar conclusions. However, for the Kaye-Goldston model, the minimum occurs at a higher field of 12 T and an aspect ratio of 4. This is consistent with the conclusions above concerning the Kaye-Goldston systems. The shape of these curves can be attributed to two competing effects. As the field increases for a given aspect ratio, the major radius decreases, while the TF coil costs increase. For the Kaye-Goldston model, the increase in TF coil cost, in going from 10 to 12 T, approximately balances the decrease in size; whereas, for the other models, the increase in TF coil cost (from 10 to 12 T) dominates the decrease in system cost due to size reductions.

Finally, we investigated the impact on size and TF coil cost from increasing the elongation from 1.6 to 2.0 for a constant field of 10 T. The results are depicted in Figs. 5 and 6. For a given aspect ratio, increasing the elongation results in a 10-15% reduction in major radius under neo-Alcator and a 20-25% reduction under Mirnov and Kaye-Goldston. The corresponding decrease in TF coil cost is 25% under neo-Alcator and is 35-45% under Mirnov and Kaye-Goldston. (The largest reduction occurs for the Mirnov model.) Although this does not reflect any cost increments due to possible increased RF or power supply requirements, it may be postulated that enhanced plasma shaping (such as elongation) may have positive economic implications for the design of superconducting tokamak systems.

4. Conclusions

The results from an initial scoping study to explore the design space of superconducting tokamak systems are presented.

These results indicate that the most cost-effective systems predicted under the neo-Alcator and Mirnov confinement models are at a field of 10 T and an aspect ratio of approximately 3. However, the Kaye-Goldston model appears to favor a field of 12 T and an aspect ratio of 4. A further cost benefit may also accrue from increasing the plasma elongation.

References

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Confinement Models:
NA: Neo-Alcator; MV: Mirnov; KG: Kaye-Goldston

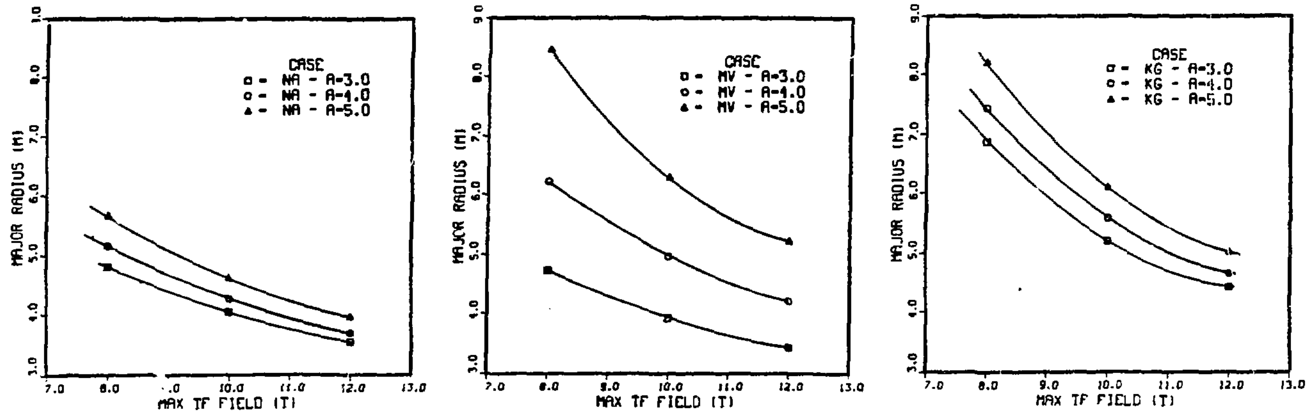

Fig. 1. Vari.*ion of major radius with maximum toroidal field and aspect ratio for 1.6 elongation.

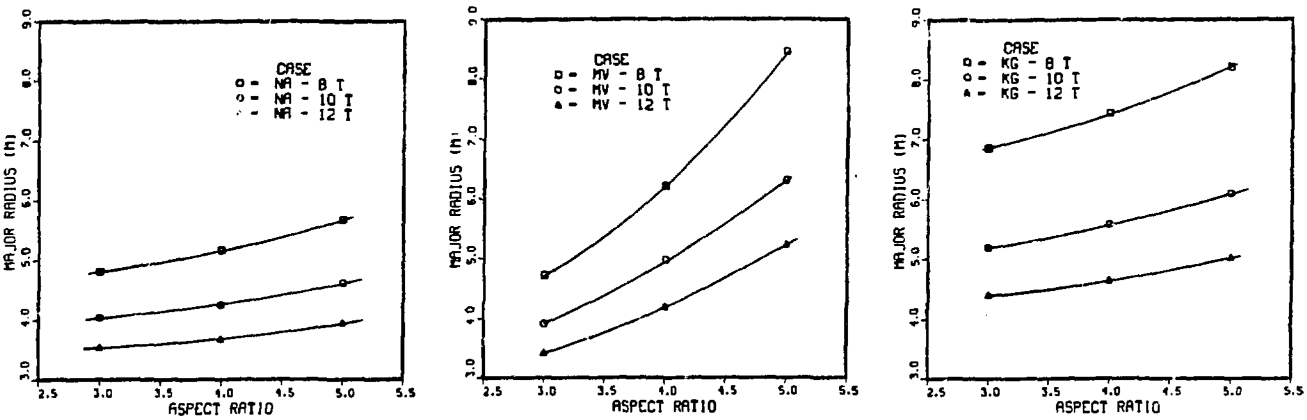

Fig. 2. Variation of major radius with aspect ratio and maximum toroidal field for 1.6 elongation.

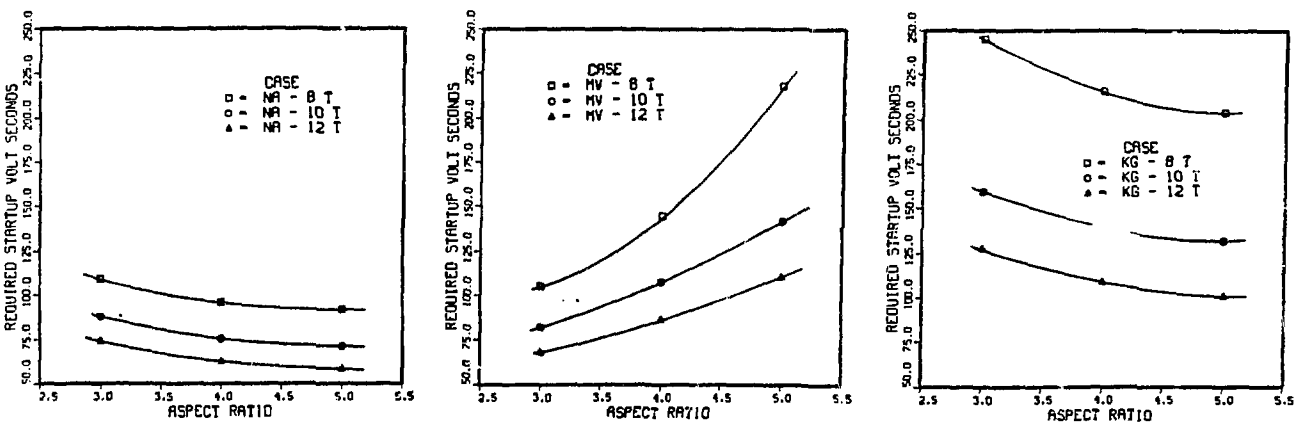

Fig. 3. Variation of required startup volt-seconds with aspect ratio and maximum toroidal field for 1.6 elongation.

Confinement Models:
NA: Neo-Alcator; MV: Mirnov; KG: Kaye-Goldston

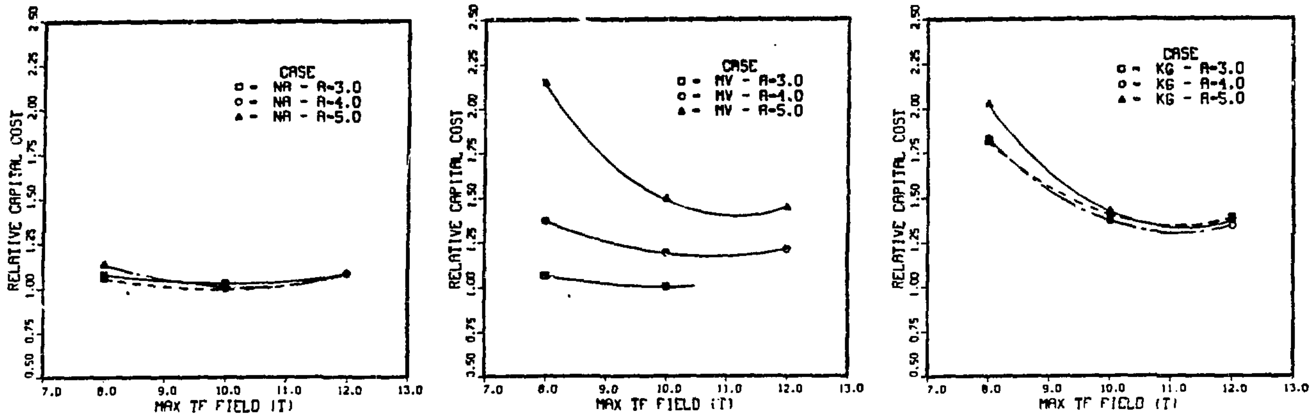

Fig. 4. Variation of relative capital cost with maximum toroidal field and aspect ratio for 1.6 elongation.

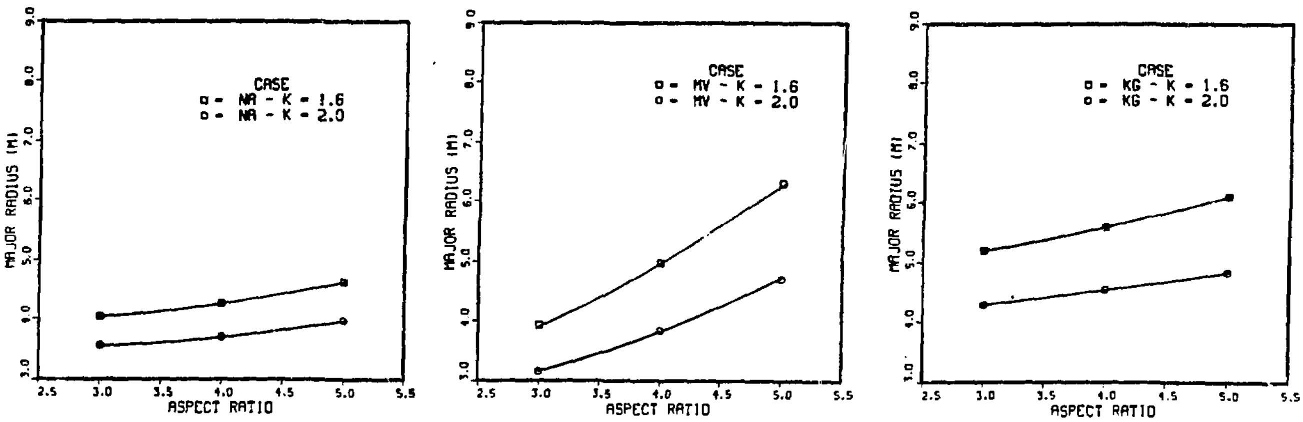

Fig. 5. Variation of major radius with aspect ratio and elongation for 10-T maximum toroidal field.

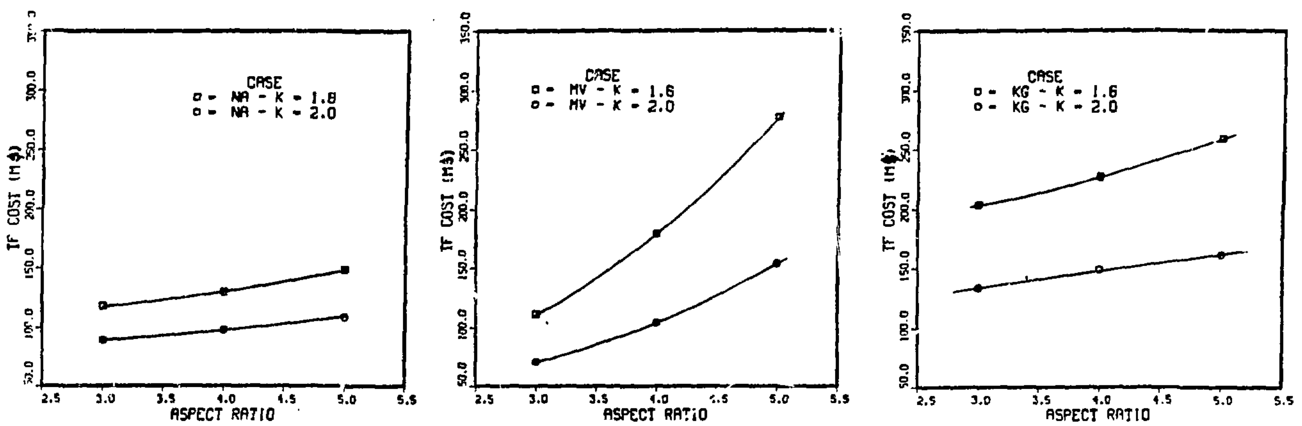

Fig. 6. Variation of toroidal field coil cost with aspect ratio and elongation for 10-T maximum toroidal field.