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PARAMETRIC SYSTEM STUDIES OF CANDIDATE TF COIL SYSTEM OPTIONS FOR THE TOKAMAK FUSION CORE EXPERIMENT (TFCX)*

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Abstract: System studies were performed to determine the sensitivity of hybrid and superconducting toroidal field (TF) coil system options to maximum field at the TF coil and to field enhancement due to resistive insert coils. The studies were performed using Tokamak Fusion Core Experiment (TFCX) design assumptions, guidelines, and criteria and involved iterative execution of the Fusion Engineering Design Center (FEDC) systems code, magnetohydrodynamics (MHD) equilibrium code, and EFFI (a code to evaluate magnetic field strength). The results indicate that for TFCX with no minimum wall loading specified, a design point chosen solely on the basis of cost would likely be in the low-field region of design space where the cost advantage of hybrids is least apparent. However, as the desired neutron wall loading increases, the hybrid option suggests an increasing cost advantage over the all-superconducting option; this cost advantage is countered by increased complexity in design — particularly in assembly and maintenance.

Introduction

There are three generic TF coil options for the TFCX device: a superconducting coil option, a resistive coil option, and a hybrid option employing both superconducting and resistive coils. The focus of TFCX design efforts in FY1983 at the FEDC was developing configurations for the superconducting and hybrid options. Configuration concepts for the resistive option are currently being developed.

Superconducting devices represent the mainstream of "next step" reactor design studies. The motivation for the hybrid option is that by embedding resistive coils in the shield region, the field on-axis can be enhanced and/or the TF coil can be made thinner, resulting in reduced machine size and cost.

Configuration Concepts

The superconducting device configuration evolved from the Fusion Engineering Device/International Tokamak Reactor (FED/INTOR) design studies [1], [2]. An elevation view of a superconducting TFCX design is shown in Fig. 1. Key features include an open window area for radial extraction of sector modules, a common vacuum boundary between the plasma vacuum chamber and the superconducting coil cryostat, superconducting poloidal field (PF) coils located outside the TF bore, and a pumped limiter horizontally located below the plasma.

Several configuration concepts for the hybrid option were considered, all of which are variants of the superconducting device configuration. Plan views of the candidate options are shown in Fig. 2. The configuration concept selected for development of the design for the hybrid TFCX option features copper insert coils located in the shield region in the plane of the TF coil. The inboard shield of the hybrid option is not penalized due to neutronics considerations because the shielding effectiveness of copper is comparable to steel. Centering forces on the copper insert coils are reacted by wedging and overturning forces are reacted by intercoil structure.

An elevation view of the hybrid device configuration is shown in Fig. 3. Noteworthy distinctions from the superconducting device configuration are: (1) the additional space beneath the limiter pumping cavity required by the copper insert coil and (2) the additional clearance required between the shield region and outer TF coil leg to provide cooling lines and manifolding for the copper insert coil. The space required beneath the limiter pumping duct causes the PF systems to be asymmetric on the hybrid designs.

System Study Guidelines

To perform system studies on a self-consistent basis, it is necessary to have:

- well-defined, self-consistent configuration concepts,
- specified design criteria assumptions and guidelines from which design points can be derived, and
- reasonable models by which performance and operating characteristics can be assessed.

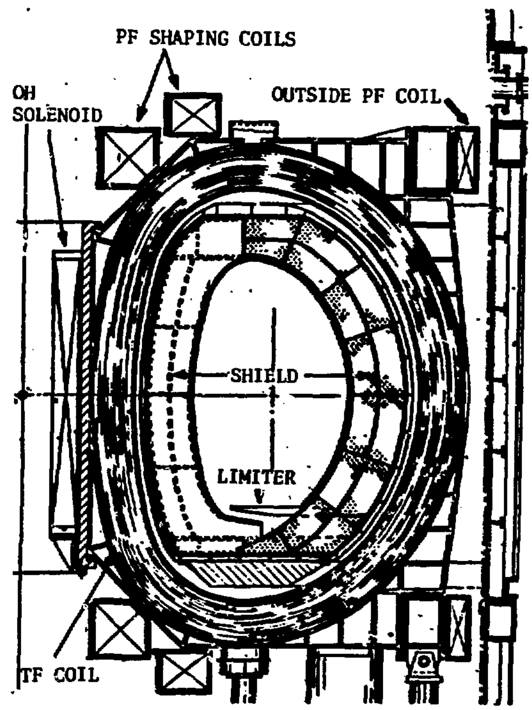

Fig. 1. TFCX superconducting design elevation.

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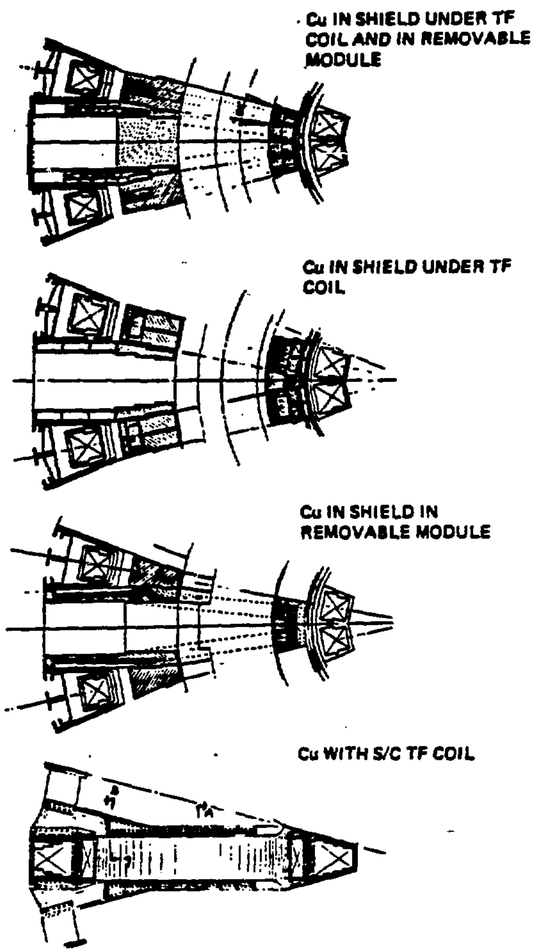

Fig. 2. TFCX hybrid design configuration options.

Table 1 lists the design parameters, assumptions, guidelines, and criteria commonly used in the study. Note that all cases assume the use of noninductive current drive during startup using Lower Hybrid Resonant Heating (LHRH). Each device is sized to provide inductive volt-seconds sufficient to achieve a 300-s burn pulse length. For comparing the superconducting and hybrid options, maximum fields of 8 T and 10 T at the superconductor winding were considered. The field enhancement on-axis due to the copper insert coils was varied from 0 to 1.6 T.

The FEDC systems code was used to calculate plasma performance, to determine machine size based on recognized engineering and configurational considerations, and to provide preliminary estimates of direct capital cost. Plasma performance is calculated with a zero-dimensional (0-D) model in which beta is proportional to

$$\langle\beta\rangle \propto \frac{(1+k^2)}{2}\,\frac{\varepsilon}{q} ,$$

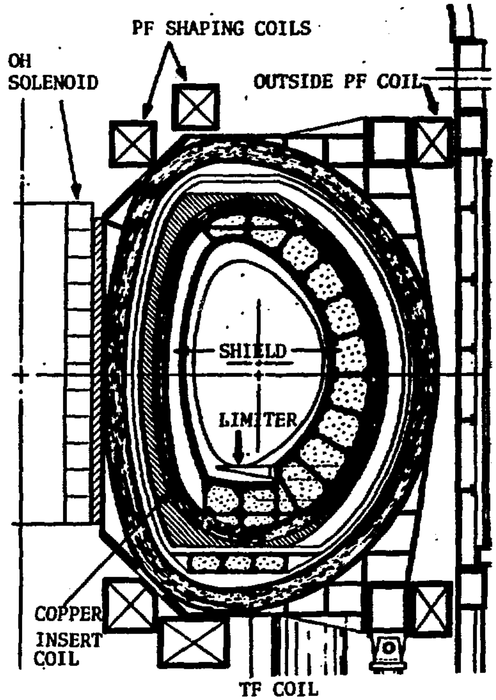

Fig. 3. TFCX hybrid design elevation.

Table 1. TFCX design criteria

Parameter	Value
Elongation	1.6
Triangularity	0.3
Safety factor	2.0
Ignition parameter	1.0
Maximum burn time[a], s	300
Cumulative burn time, s	2×10^5
Maximum TF ripple[b], %	1.5
Plasma temperature, keV	13
Startup current maintenance	LHRH
Maximum field at PF coils, T	8-10
Maximum field at TF coils, A/cm^2	2600-2000
Field enhancement on-axis, T	0-1.6
Allowable TF dose to insulator, rad	10^9
Allowable TF nuclear heating, mW/cm^3	
Inboard	1.00
Outboard	0.25
Shutdown dose rate, mR/h	1.0
Cooldown time, h	24

[a]Inductive driven.

[b]Judicious placement of iron for ripple reduction allowed.

and the energy confinement time is determined by

$$\tau_E \propto aI_p \ ,$$

where k is the plasma elongation, ε is the inverse aspect ratio, q is the safety factor at the plasma edge, a is the minor radius, and I_p is the plasma current.

The adequacy of the PF system (based on the constraints of plasma shape, burn time, maximum field at the PF coil, and configurational constraints) was determined by iterative execution of the FEDC systems code, an MHD equilibrium code, and EFFI (a code to evaluate magnetic field strength). Figure 4 is a flow diagram of the procedure.

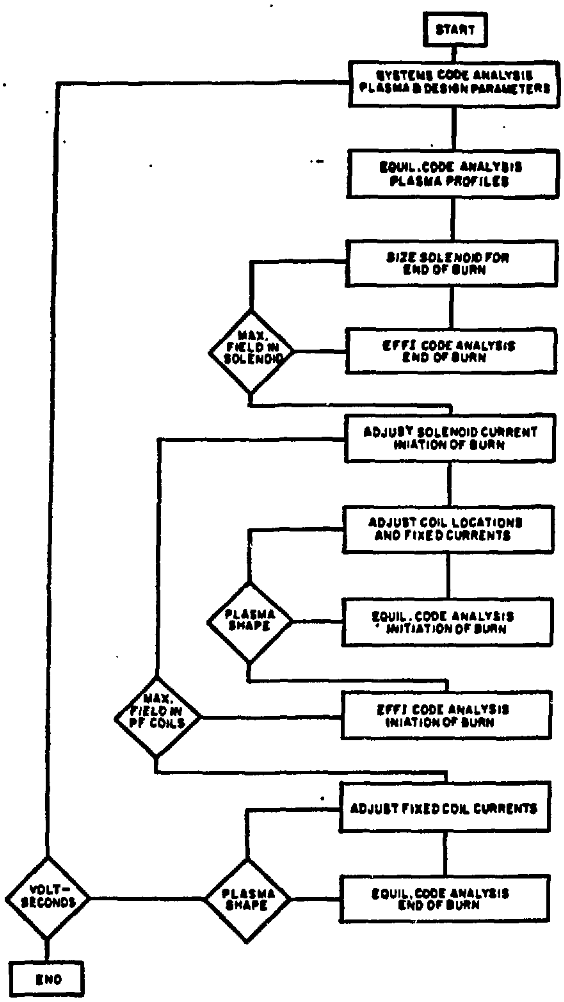

Fig. 4. Flow diagram of system study procedure.

System Study Results

Previous system studies [3] indicated that the optimum maximum field at the superconductor lies in the range of 8 to 10 T. Higher field superconducting ignition devices (B_{max} > 11 T) appear to be significantly more expensive. For these system studies, the 10-T superconducting design is arbitrarily used as the reference design point.

Sensitivity to B_{max} in Superconducting Designs

A system study was undertaken to assess the system ramifications of using 8-T superconducting coil technology instead of 10-T technology, as in the reference superconducting design. The use of 8-T coils is considered to be a lower risk option because the technology will have been demonstrated by the Large Coil Program (LCP). However, it is recognized that the 10-T coils would provide greater performance (neutron wall load and fusion power) and perhaps an environment more appropriate for engineering tests.

Table 2 lists parameters characterizing the 10-T (Case 1) and the 8-T (Case 3) design points. Note that although the plasma radius for the lower field case is larger than for the higher field case (to achieve ignition), the major radius of the 8-T device is actually smaller than for the reference 10-T device.

Table 2. Parameter comparison

Parameter		10 T		8 T		
	Case:	1	2	3	4	5
Plasma radius, m		1.07	0.82	1.45	1.05	0.97
Major radius, m		3.75	4.38	3.55	3.60	3.60
Aspect ratio		3.51	5.35	2.44	3.43	3.71
Field on-axis, T		4.34	7.10	2.62	4.34	4.84
Field on-axis due to CI coils, T		0	1.6	0	1.0	1.4
Beta		0.059	0.039	0.085	0.060	0.056
Plasma current, MA		7.7	5.8	10.8	7.8	7.2
Volt-seconds required, V-s		17.1	25.5	12.6	17.4	18.9
Electron density, $10^{20}/m^3$		1.0	1.8	0.5	1.0	1.2
Energy confinement time, s		1.97	1.14	3.75	1.95	1.68
Neutron wall load, MW/m^2		0.9	2.1	0.3	0.9	1.1
Fusion power, MW		230	490	110	220	250
ICRH power (startup), MW		21	37	13	19	21
TF MA-turns		81	121	46	60	63
PF MA-turns		79	85	68	77	78
Fractional OH current at beginning of burn, %		-83	+42	-91	-10	0
Combined scrapeoff, cm		~10	~13	~10	~10	~10

The larger plasma cross section of the 8-T device decreases the plasma resistance, resulting in a reduced loop voltage and volt-second requirement. The reduced volt-second requirement allows a smaller ohmic heating (OH) bore, which tends to reduce the overall machine size.

Compared to the 10-T device, the 8-T device also has a thinner radial build between the solenoid and the plasma. The centering forces on the bucking cylinder are less, so it becomes thinner. The 8-T TF coil is significantly thinner than its 10-T counterpart because of fewer MA-turns and higher allowable current density. The inboard shield on these low-fluence devices is sized to limit nuclear heating in the TF coil. Since the neutron wall load of the 8-T device is less than on the 10-T device, the inboard shield can be thinner. The radial builds of the two devices are listed in Table 3. The thinner bucking cylinder, TF coil, and inboard shield, coupled with the reduced volt-second requirement result in a smaller radial build for the 8-T device, which offsets the corresponding larger plasma radius.

Table 3. Radial build comparison (in meters)

Element	Case:	10 T		8 T		
		1	2	3	4	5
OH bore		0.45	1.18	0.33	0.62	0.68
Bucking cylinder		0.15	0.24	0.11	0.14	0.15
TF coil		0.67	0.62	0.37	0.36	0.36
Inboard shield		0.58	0.65	0.47	0.57	0.59
Plasma		1.07	0.82	1.45	1.05	0.97
Other (Gaps, dewar, solenoid, first wall, etc.)		0.83	0.87	0.82	0.86	0.85
Major radius		3.75	4.38	3.55	3.60	3.60

The direct capital cost of these devices was assessed with the FEDC systems code. The total capital cost is assumed to be related to the direct capital cost by a fixed percentage. Table 4 provides a breakdown of direct capital cost by system. The system costs are useful for identifying cost impacts of changes. Due to the large uncertainty associated with these costs, they should not be used for planning purposes, but rather solely for comparison with devices costed in a like manner.

Table 4. Direct capital cost comparison (in millions of dollars)

System	Case:	10 T		8 T		
		1	2	3	4	5
First wall/limiter		5.2	4.6	6.8	4.9	4.5
Shield		37.0	35.1	41.1	33.3	31.2
TF coils		58.0	79.0	27.1	31.6	32.0
CI coils			9.9		5.7	7.7
PF coils		41.3	58.4	36.5	41.9	42.0
TF/CI power supplies		7.6	17.7	7.3	13.9	15.3
PF power supplies		12.6	18.9	10.3	13.4	13.0
ECRH[a]		7.0	7.0	7.0	7.0	7.0
ICRH		38.7	58.7	26.3	37.0	39.6
LHRH[b]		38.6	38.6	38.6	38.6	38.6
Cryo-plant		14.3	12.0	14.1	9.5	8.6
Heat transport		20.6	37.3	13.6	21.6	23.8
Vacuum systems		33.5	46.0	34.8	31.2	31.6
Tritium systems		44.5	49.7	41.9	44.0	44.5
Instrumentation & Control		62.3	64.3	61.9	62.6	62.8
Remote maintenance		32.2	33.0	32.2	32.6	32.5
Electric plant		7.9	12.3	7.8	10.2	10.2
Facilities		80.2	83.1	79.7	79.2	78.7
		541	666	487	518	524
Relative direct capital cost		1.00	1.23	0.90	0.96	0.97

[a]Based on installed capacity of 1 MW.
[b]Based on installed capacity of 14 MW.

The 8-T design appears to be ~10% less costly than the 10-T reference design. The cost reduction can be attributed to more modest TF costs (fewer MA-turns, higher current density), ICRH costs (less heating required for startup), PF costs (easier plasma shaping), and heat transport costs (less fusion power).

Sensitivity to B_{max} in Hybrid Designs (Fixed B_t)

One motivation for investigating hybrid options is the idea that by transferring some of the TF MA-turns to copper insert coils in the shield region, the TF coils would become thinner and the major radius could be decreased. Cost advantages may arise from a reduction in TF costs and in system costs related to the reduced major radius. To explore this idea, an 8-T hybrid (Table 2, Case 4) was developed with the same field on-axis (B_t = 4.34 T) as the reference 10-T superconducting design (Table 2, Case 1).

As indicated in Table 2, since the field on-axis is the same, the other plasma parameters tend to be very similar as well. The major radius of the hybrid is 0.15 m less than for the reference superconducting design.

The hybrid configuration differs from the superconducting configuration in that sufficient space must be provided beneath the limiter pumping ducts to accommodate the copper insert coils. The minimum space must be increased from ~0.2 m for a superconducting design to ~0.7 m for a hybrid design. For a given field on-axis, the TF coils on a hybrid are thinner due to fewer MA-turns and a higher current density. This allows the upper PF coils to move closer to the plasma. However, the configurational requirement for space beneath the limiter pumping ducts tend to move the lower PF coils further away from the plasma.

On the 8-T hybrid, the lower PF coils are indeed further away from the plasma, thus rendering plasma shaping more difficult, because on the reference 10-T superconducting design, the shaping coils are already at 8 T (the maximum allowable field at the PF coils). At the beginning of burn, the OH swing must be more limited on the 8-T hybrid. To provide approximately the same volt-seconds, the OH bore on the 8-T hybrid must be larger. The radial build comparison is given in Table 3. Although the TF thickness is reduced by 0.31 m, the major radius decreases by only 0.15 m due to the larger OH bore. The idea that transferring some of the TF MA-turns to copper inserts results in a smaller machine appears sound. It is necessary to realize however that there is a step change in going from a superconducting to a hybrid configuration which may initially make shaping more difficult.

A comparison of direct capital costs by system between the 8-T hybrid and 10-T superconducting options in Table 4 indicates that the hybrid appears to have a modest cost advantage (~4%), which is primarily attributable to reduced TF costs.

Sensitivity to Field Enhancement (ΔB_t) in Hybrid Designs (Fixed B_{max})

Hybrids may also be perceived to be advantageous since the plasma radius is smaller than on a superconducting device employing the same TF coil technology. This idea was explored by developing two additional design points, an 8-T hybrid (Table 2, Case 5) with ΔB_t = 1.4 T and a 10-T hybrid (Table 2, Case 2) with ΔB_t = 1.6 T.

Examination of the radial build in Table 3 indicates that the decrease in radial build due to the reduced plasma radius tends to be offset by more subtle increases. Factors which tend to increase the radial build include the following.

- The higher field devices require more volt-seconds during burn due to a smaller plasma cross section which tends to enlarge the OH bore.
- The higher field devices feature thicker inboard shields due to higher wall loading.
- In the higher field devices that feature smaller plasma radii, the plasma edge is closer to the plasma center of current. Plasma shaping thus becomes more difficult requiring larger shaping coils. In order to accommodate larger shaping coils and keep the maximum field at the PF coils below 8 T, it may be necessary to limit the OH swing, which tends to enlarge the OH bore.

Summary of Results

In summary, for higher field devices, the higher volt-second requirement, increased shield thickness, and more limited OH swing can result in an increase in radial build sufficient to offset the corresponding reduction in plasma radius.

The results indicate that direct capital costs tend to increase with increasing field enhancement (for fixed B_{max}) and that this dependency appears stronger at higher values of B_{max}.

System study costs are plotted in Fig. 5 versus field enhancement and neutron wall load. It appears that

- for a given performance (neutron wall load), hybrid devices appear to be less expensive than all-superconducting devices;
- costs increase with increasing neutron wall load; and
- the cost advantage of hybrids appears to increase with increasing neutron wall load.

For a TFCX device with no specified minimum neutron wall load, a design point chosen on the basis of cost would likely be in the low field region of design space where the cost advantage of hybrids is least apparent. It is not clear that the indicated cost advantage derived from a hybrid design is sufficient to warrant the increase in complexity. On the other hand, if an aggressive performance level is specified (i.e., higher neutron wall loading), a hybrid design might be an attractive option.

Acknowledgment

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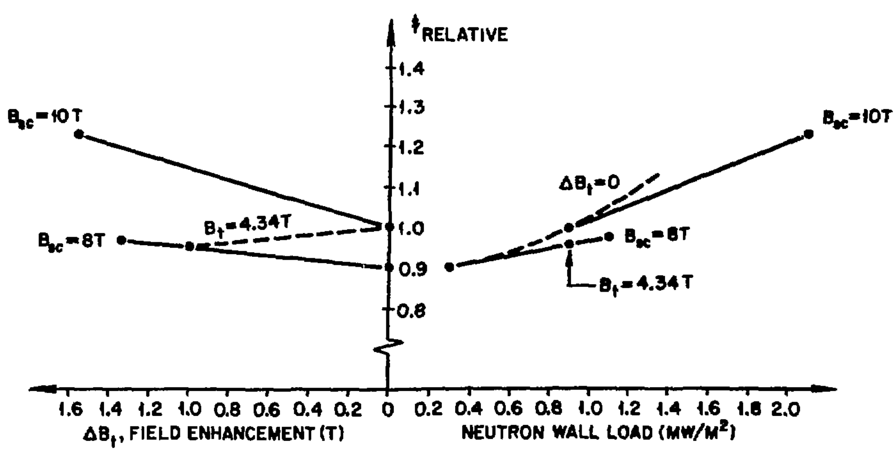

Fig. 5. Relative cost as a function of field enhancement and neutron wall load.

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