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FOR FUSION APPLICATIONS

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HIGH FIELD SUPERCONDUCTING MAGNETS (12 T AND GREATER) FOR FUSION APPLICATIONS

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ABSTRACT

The technology for producing high fields in large superconducting magnets has increased greatly in recent years, but must increase still more in the future. In this paper, we examine the present state of the art vis-a-vis the needs of a next-generation fusion machine and outline a program to provide for those needs. We also highlight recent developments that suggest the program goals are within reach.

INTRODUCTION

Our ability to produce high magnetic fields over large regions for the confinement of fusion plasmas has grown dramatically in recent years. The coils in the International Fusion Superconducting Magnet Test Facility (IFSMTF) at Oak Ridge National Laboratory (ORNL) soon will have produced 8 T in a toroidal array of six Dee-shaped coils of 40 t each, appropriate for tokamak applications.¹ A Yin-Yang pair of 360 t for the Mirror Fusion Test Facility (MFTF) at LLNL has already produced 7.7 T,² and the entire 1200-t array of coils for MFTF-B has recently been tested with complete success, with fields in the "choke" coils exceeding 12 T.³

Several magnets built as technology demonstrations or as test facilities have approached or exceeded the 12-T level in coils of appreciable size in recent years. In fact, recent success in the development, design, and construction of large superconducting magnets warrants a reassessment of the state of the art and of what achievements in the near future might reasonably be expected.

SUPERCONDUCTING FUSION MAGNET TECHNOLOGY - STATE OF THE ART

As already mentioned, the tests in the IFSMTF under the Large Coil Task (LCT) constitute the best demonstration to date of large superconducting magnets appropriate for the toroidal field (TF) coils of a tokamak. Although each of these coils incorporates technological differences, they satisfy similar important

performance specifications. Table I lists the characteristics of the six-coil set pertinent to the present discussion.

Table I. LCT TF coil characteristics.

B _{max}	8 T
J _{pack}	25 A/mm ²
I _{total}	7 MA/coil
Bore dim.	2.5 m × 3.5 m
E _{stored}	170 MJ/coil
Coil mass	40 t/coil

The MFTF-B magnet system is pictured schematically in Fig. 1.⁴ MFTF-B is a fully operational fusion experiment that contains 1200 t of magnet mass in a linear array. The system performed flawlessly in tests conducted in February 1986.⁵ Possibly more than the rest of this set, the Yin-Yang pairs and high field axicells, A₂₀ + A₂₁, serve to advance the state of the art of fusion magnets - the Yin-Yang pairs for their shear mass and complex distribution of

Coils	Designation
12 solenoid coils (5m)	S1 through S6 (east & west)
4 transition coils	T1 and T2 (east & west)
4 axicell coils (NbTi)	A1 & A2 (east & west)
2 axicell insert coils (Nb ₃ Sn)	A21 inner (east & west)
2 Yin-Yang coil pairs	M1 & M2 (east & west)

Figure 1. Primary magnet system (MFTF-B) (trim coils deleted for clarity).

forces and the high field axicells for their production of fields to 12.7 T in an appreciable bore. A Yin-Yang pair reached 7.7 T during testing in 1982 in its original configuration.² Important features of superconducting magnet technology demonstrated in the tests of HFTF-B are listed in Table II.

Table II. HFTF-B magnet parameters.

Total length	55 m
Total mass	1200 t
Total refrig.	11 kW at 4.5 K

Yin-Yang
(Original Configuration)

$B_{\max}$	7.7 T
Coil mass	360 t/pair

Axicell
($A_{20} + A_{21}$)

$B_{\max}$	12.7 T
J _{pack}	20 A $\cdot$ m ⁻²
E _{stored}	75 MJ
Inner diameter	0.4 m
Outer diameter	2.5 m
Height	1.0 m
Coil mass	35 t

There have also been important demonstrations on a smaller scale, several laboratories having constructed relatively large coils producing magnetic fields in the neighborhood of 12 T. We have somewhat arbitrarily selected the facilities listed in Table III as representative.

Table III. Laboratory tests and facilities.

	HFTF	HOMER	SULTAN	TMC-I
$B_{\max}$	11.3 ^a	12.0	12.2 ^c	12.2
(I)	11.7 ^b			
J _{pack}	33 ^a	60	25	33
(A $\cdot$ m ⁻²)	35 ^b			
E _s	48 ^a	7.5	--	53
(MJ)	50 ^b			
I.D.	0.4	0.3	0.3	0.6

(m)

^aAlone

^bWith MIT "12 T" coil

^cNot yet tested

The High Field Test Facility (HFTF), from our own laboratory at Lawrence Livermore National Laboratory (LLNL), was constructed both as a demonstration of superconductor technology for mirror fusion applications and as a test facility for proving other coil concepts.³ It was used to test model coils from the Massachusetts Institute of Technology (MIT)⁴ and General Atomic

(GA)⁵ built under the U.S. 12-T program. HFTF consists of six bath-cooled coils; four use NbTi and two use Nb₃Sn conductors. The MIT module noted in the table was force-cooled Nb₃Sn.⁶ HOMER is a test facility for the development of candidate high field superconductors at Institut für Technische Physik, Kernforschungszentrum, Karlsruhe.⁷ The facility includes two cryostats using baths of subcooled He II at 1.8 K for improved superconductor performance; one contains the coil system and one encloses the test volume in the bore of the coil. SULTAN is a facility at the Swiss Institute for Nuclear Research resulting from a multinational collaboration of Switzerland, Italy, and the Netherlands.⁸ The 1-m i.d. background coils have been tested to 8 T. Three insert coils have been constructed to boost the field to 12.2 T. All coils use a variation of the force-cooled concept with NbTi, Nb₃Sn, and Nb₃Al as the superconductors. At the Japan Atomic Energy Research Institute, an asymmetric array of coils that gives some simulation of TF coil field and force distributions has been constructed.¹⁰ In a recent test, the field on the first test module coil (TMC-I) reached 12.2 T. The conductor in the TMC-I was an extended-surface, bath-cooled Nb₃Sn variety.¹¹

FUTURE REQUIREMENTS

Let us now examine the level of performance needed from superconducting magnet technology in the next generation of fusion machines. A tokamak design now being evolved, called TIBER II, provides good examples.¹² The TIBER-II design emphasizes compactness as a means to economy. High performance in the superconducting coil systems helps to achieve compactness. The high performance goal is exemplified by the requirements placed on the TF coils and on the central plasma shaping or "pusher" coil. These coils are indicated in the schematic of the TIBER II magnet system in Fig. 2.

Figure 2. The TIBER II magnet system.

The pusher coil will be about 1.1 m i.d. by 1.9 m o.d. and have an average winding pack current density of 40 A-mm^{-2} . The maximum field at the windings may be as high as 15 T. The stored energy will exceed 150 MJ. In the present machine design, the field will be steady, since rf current drive is envisaged.

The TF coil winding pack current density must also be 40 A-mm^{-2} , but the maximum field at the conductor will be less, 12 T. A clear bore of about $6.0 \text{ m} \times 3.8 \text{ m}$ is needed. However, these requirements should not necessarily be viewed as easier to achieve than those for the pusher coil. First, each of the 16 coils of the TF system will have approximately 380 MJ of stored energy. In addition, the TIBER II design calls for reduced shielding (also for compactness and reduced costs), which leads to peak nuclear heat loads in the TF coil windings on the order of 10 MW-cm^{-2} , neutron fluence to the conductor on the order of 10^{19} n/cm^2 , and radiation exposure to the insulating materials on the order of 10^{11} rad .

Clearly, vis-a-vis the performance that has been demonstrated in superconducting magnet systems to date, the goals established by the TIBER II design, are aggressive. However, these goals are fundamentally attainable within current technology. What is required is a careful coordination and optimization of the various subsystems comprising the superconducting magnet system for these applications.

A DEVELOPMENT PROGRAM TO MEET THE REQUIREMENTS

The LLNL high field superconducting magnet development program is undertaking an integrated approach toward advancing the state of superconducting magnet technology for fusion with the goals of the TIBER II design as a focus. The developments required to meet these goals will be useful for any future fusion application of superconducting magnet technology. The basic elements of our program are listed in Table IV. We have space to discuss only a few of these in relation to achieving the TIBER-II goals.

Superconductor Development.

Because of the near term focus of our program, we constrain our choices of superconductors to those for which some commercial fabrication experience exists. For the TIBER-II field and current density requirements, only variants of multifilamentary $\text{Nb-Nb}_3\text{Sn}$ are realistic choices, but under the general $\text{Nb-Nb}_3\text{Sn}$ heading are several choices of filament configuration and size and of conductor processing techniques, each appropriate for different operating conditions. Also, third element additions to the compound can be incorporated to improve the performance at higher fields.

Figure 3 is a compilation by M. Suenaga of recent critical current data for several $\text{Nb-Nb}_3\text{Sn}$

Table IV. Elements of the LLNL high-field coil development program.

Materials development
Superconductor development
Structural materials development
Insulation materials selection
Conductor system design and development
Coil design optimization techniques
Coil fabrication development
Cryogenic systems development
Concept verification

Figure 3. Recent critical current data for various $\text{Nb-Nb}_3\text{Sn}$ conductors at 4.2 K. Solid curves represent $(\text{NbTi})_3\text{Sn}$ and broken curves represent "pure" $\text{Nb-Nb}_3\text{Sn}$ variations.

conductors at 4.2 K.¹³ The solid curves represent variations of Nb_3Sn with Ti additions, i.e. $(\text{NbTi})_3\text{Sn}$; the particular data base used for the TIBER I study is highlighted.¹⁴ The broken curves represent variations of "pure" Nb_3Sn . Note that generally the $(\text{NbTi})_3\text{Sn}$ conductors show better performance at the higher fields and would, therefore, be our choice for the 15-T pusher coil. At 12 T and below, Nb_3Sn is almost as good or even better. However, when a comparison is made of the tolerances of pure and modified Nb_3Sn to high neutron fluence (see Fig. 4), the choice of pure Nb_3Sn for the TF coils becomes clear.¹⁵ Our present thrust is to establish that the level performance displayed in

Figure 4. Critical current vs neutron fluence. Data were taken using a 14.1-MeV neutron source. The lower horizontal axis accounts for the "softer" neutron energy spectrum expected in TIBER-II.

Fig. 3 can be maintained in a sizeable quantity of production wire. This wire will be used to complement our other conductor system design and development efforts.

Coil and Conductor System Design and Development.

Coil design begins with design of the conductor system. The conductor system must have provisions for handling mechanical loads, for strain control of the strain-sensitive Nb_3Sn superconductor, for providing stability sufficient for reliable operation, and for ensuring the protection of the coils. We are presently basing our development efforts on the cable-in-conduit conductor (CICC) system with forced-flow cooling for both the TF and pusher coils for TIBER II. The CICC offers real advantages for reliable heat removal, distributed structure, and high current density operation with adequate stability and protection.^{18,17,19}

The CICC also offers a high degree of design flexibility while retaining the basic features and fabrication techniques. The variations of the CICC under consideration for the TIBER II TF system (Fig. 5) provide a good illustration of this flexibility. The high field conductors (Fig. 5a) require more superconductor to attain the overall pack current density of 40 A-mm^{-2} with adequate current margin for stability. The

Figure 5. Variations of the CICC being considered for TIBER II: (a) the high-field grade (reduced structure and enhanced cooling and conductor space) and (b) the low-field grade (added structural unit for supporting high centering loads).

low field conductors (Fig. 5b) require less conductor cross section, but need a substantial and properly formed structural steel component to resist the crushing loads that build up through the winding pack due to the centering forces at the central straight leg of a TF coil. It can be seen that these conductors differ essentially only in the presence or absence of the added structural channel, with design and fabrication methodologies being the same for both.

A very important phase of CICC development is currently underway, namely an experimental program aimed at understanding superconductor strain determination and control.¹⁹ The strain in the Nb_3Sn filaments, and thus the critical current, at operating conditions is determined by the complex interaction of the CICC sheath and the cable inside during its history from formation at around 1000 K, through cooldown to the operating temperature around 4 K, to charging to full field and current, which results in high electromagnetic forces borne principally by the sheath. We hope to quantify this interaction through a series of electromechanical tests, which will allow this effect to be properly accounted for in the coil/conductor design.

We have completed one series of tests on model CICC's intended to measure the ratio of initial critical current of the CICC to maximum critical current as a function of void fraction. Nominally the critical current is at the maximum when the Nb_3Sn filaments inside are under minimum strain. We proceed by measuring critical current of the CICC vs axial load on the sheath, increasing the load by small increments until the measured critical current is observed to pass through a maximum. Our results to date are plotted in Fig. 6. Also plotted in Fig. 6 are other data from other sources.^{20,21,22} One of the points was obtained in the same way as were the present data.²¹ For the others, the ratio I_c/I_{c0} was inferred by assuming a direct correspondence of the high-void-fraction data to single-strand data and making the appropriate correction.^{20,22}

According to Ekin,²³ I_c/I is a direct indicator of strain. But also, axial strain in the filaments should be related to thermomechanical properties of the various conductor constituents according to a relation of the form:

$$\epsilon = \epsilon_{\text{init.}} + C \epsilon_{\text{sh}} \quad (2)$$

to predict strain at operating conditions in a coil.

$$\epsilon_{\text{init.}} = \frac{F(f_{\text{He}})E_{\text{sh}}A_{\text{sh}} \left[\left(\frac{\Delta L}{L} \right)_{\text{sh}} - \left(\frac{\Delta L}{L} \right)_{\text{fil}} \right] - (\sigma_{\text{Cu},y}A_{\text{Cu}} + \sigma_{\text{bz},y}A_{\text{bz}})}{F(f_{\text{He}})E_{\text{sh}}A_{\text{sh}} + E_{\text{fil}}A_{\text{fil}}} \quad (1)$$

Figure 6. Ratio of initial (unloaded) critical current of CICC samples to maximum critical current as a function of void or helium fraction inside the conduit.

where a factor $F(f_{\text{He}})$ multiplying the sheath modulus has been included to account for our observation that the greater the void fraction f_{He} , the less rigidly linked the conductor strands are to the compressive influence of the sheath during cooldown. Using Ekin's formalism²³ (illustrated graphically in Fig. 7) to convert I_c/I_0 to $\epsilon_{\text{init.}}$, Eq. (1) above can be used to empirically determine $F(f_{\text{He}})$. Figure 8 shows the results of this process for the data we have collected thus far and a curve of the form $F(f_{\text{He}}) = 0.17 \exp [-(f_{\text{He}}/0.4)^2]$ fit to the data. The curve does not fit all the data and we have some conjectures why, but we intend to clarify the situation with further testing. Hopefully, the outcome will be a universally applicable expression $F(f_{\text{He}}, x, y)$ that can be put into Eq. (1) to give $\epsilon_{\text{init.}}$. This strain value may then be put into an expression of the form

Figure 7. The effect of strain on critical current of a bronze-processed MF-Nb₃Sn conductor at 12 T, 4.2 K. The curve fitted to the data uses Ekin's formalism with $B_{\text{c2}}(0) = 22$ T and $T_{\text{c0}} = 18$ K.

In Eq. (2), ϵ_{sh} is the axial strain in the sheath determined from electromagnetic stresses, assuming the sheath bears all the conductor load, and C gives the relationship between sheath strain and filament strain. The factor C may also be a function of a number of things, such as cable twist pitch, void fraction, etc., but in our preliminary analyses, we are regarding it as a constant of order unity and are trying to verify its true dependences in our experimental program as well.

In the range of temperatures over which superconductors are usually operated, critical current density is essentially a linear function of temperature and can be accurately represented by the extrapolated intercepts $J_0(B, \epsilon)$ and $T_0(B, \epsilon)$. According to Ekin,²³ these have the functional forms

Figure 8. Data of Fig. 6 converted to values of $F(f_{He})$ using Eq. 1 and I_c/I_m as a measure of filament strain, as given in Fig. 7.

$$J_{c0}(B, \epsilon) = J_{c0m}(B)(1 - a|\epsilon|^{1.7})^{1/2}$$

$$\times \frac{\left[1 - \frac{B}{B_{c2m}(0)(1 - a|\epsilon|^{1.7})}\right]^2}{\left[1 - \frac{B}{B_{c2m}(0)}\right]^2}$$

$$T_c(B, \epsilon) = T_{cm}(B)(1 - a|\epsilon|^{1.7})^{1/3}$$

$$\times \frac{\left[1 - \frac{B}{B_{c2m}(0)(1 - a|\epsilon|^{1.7})}\right]^{1/2}}{\left[1 - \frac{B}{B_{c2m}(0)}\right]^{1/2}}$$

$$a = 900 \text{ for } \epsilon \leq 0,$$

$$a = 1250 \text{ for } \epsilon > 0.$$

These enter the stability parameter η^{25} according to

$$\eta = \frac{(1 - f_{cond})}{f_{cond}} \left\{ \frac{[T_c(B, \epsilon) - T_b]}{T_c(B, \epsilon)} - \frac{J}{f_{cond}(1 - f_{Cu}) J_{c0}(B, \epsilon)} \right\}$$

Inspection of this relation reveals that η is simply the product of the temperature margin $(T_c - T_b)/T_c$, the current margin $(I - I_c)/I_c$, and the ratio of helium to conductor in the CICC. The stability parameter is therefore a dimensionless parameter that varies monotonically with the actual stability so long as the interstitial helium is fully utilized. Figure 9

Figure 9. Contours of η in the (f_{cond}, f_{Cu}) plane with fixed J . Dashed contours ignore conductor strain effects. Solid contours account for strain as discussed in the text.

shows typical contours of constant stability mapped in the (f_{cond}, f_{Cu}) plane for a fixed value of cable-space current density J and points out the variation of these contours, depending upon whether the strain effects as discussed are included or not. The importance of verifying these effects is obvious because of the improvements they should afford to stability and because of their influence on the optimum CICC geometry.²⁵

Of course, a coil design cannot be based solely on stability. Many other constraints must be satisfied: the mechanical loads must be safely supported; the coil must survive a quench in good operating condition (for a coil using a CICC, this means both the maximum pressure and the maximum temperature must not exceed certain limits); and other operating parameters (e.g. dump voltages, operating current levels, required to

helium flow, etc.) consistent with these constraints must also be reasonably chosen. However, the design to be selected should provide the highest stability for a given J so long as all other constraints are satisfied.

The constraints on J we are currently using in design are as follows:

1. The limiting current density for full stability,

$$J \leq \left[\frac{r_{Cu} r_{cond}^3}{(1-r_{cond})} \right]^{1/2} \frac{[T_c(8,c) - T_b]^{1/2} k_H^{2/15}}{\rho_{Cu}^{1/2} T_H^{1/15} d_w} \quad (3)$$

This ensures that the heat capacity of the interstitial helium is fully utilized in absorbing the heat deposited by a disturbance even with stagnant or slowly flowing helium. Conditions of high steady flow may make this constraint unnecessary.

2. The constraint on J due to maximum allowable hot spot temperature during a quench,

$$J \leq \left\{ \frac{V_{Dop}}{E_s} \left[(1-r_{cond}) r_{cond} r_{Cu} I_1 + r_{Cu}^2 r_{cond}^2 I_2 + (1-r_{Cu}) r_{Cu} r_{cond}^2 I_3 \right] \right\}^{1/2} \quad (4)$$

where

$$I_1 = \int_{T_b}^{T_{max}} \frac{\nu_{He,init} C_{v,He}}{\rho_{Cu}} dT,$$

$$I_2 = \int_{T_b}^{T_{max}} \frac{\mu_{Cu} C_{Cu}}{\rho_{Cu}} dT,$$

$$I_3 = \int_{T_b}^{T_{max}} \frac{\mu_{Core} C_{Core}}{\rho_{Cu}} dT.$$

The use of $\nu_{He,init} C_{v,He}$ in I_1 to approximate the effective contribution of helium is intuitively based on the helium at the center of a long flow passage being effectively trapped for several seconds. The above appears conservative when compared to experiment.²⁶

3. The constraint on J due to maximum allowable pressure resulting from a quench,

$$J \leq \frac{6.59 \rho_{max}^{0.694} r_{Cu}^{1/2} r_{cond}^{1/4} (1-r_{cond})^{3/4} d_w^{1/4}}{L^{3/4} \rho_{Cu}^{1/2}} \quad (5)$$

We view this as a worst case. It corresponds to an entire flow path quenched instantaneously and held normal until the helium has vented.^{26, 27} But recent calculations indicate that other cases may result in pressures of the same order.²⁸ This criterion may be relaxed in designs where assurance is available that the condition is unrealistic. More experimental data are needed in this area.

4. The conduit contains sufficient material to support all loads to the conductor. This constraint essentially determines the relationship between winding J_{pack} and J.

Figure 10 is a typical contour map of the stability parameter with fixed J and some of the

Figure 10. Typical contours of η in the (r_{cond}, r_{Cu}) plane with fixed J and boundary curves embodying the constraints on J as discussed in the text: the curve labeled J_{lim} represents the constraint in Eq. (3), J_{OT} represents the constraint in Eq. (4), and J_{CP} represents the constraint in Eq. (5).

constraints overlaid. Generally, choices of $(r_{\text{cond}}, r_{\text{Cu}})$ must lie on or above the various constraint boundary curves. The choice of conductor geometry in this case giving the highest stability subject to these constraints is indicated by a "0." A more general optimization routine is under development that takes account of variations in sheath and insulation thicknesses and their interrelation with other conductor parameters in choosing the optimum configuration.

It must be remembered that many of the effects included here are approximations (albeit in many cases very good approximations). Therefore, as a conductor or coil design is tuned to a specific application, some iteration, more detailed calculation, and experimental verification will be required.

Concept Verification

Pursuant to the latter, we plan to use the existing HFTF coil set to maximum advantage in experimentally verifying our design concepts for a 15-T solenoid appropriate for the TIBER II machine. The HFTF coil set and its redesigned cryostat are shown schematically in Figure 11.

Figure 11. The HFTF coil set and cryostat. Separate cold spaces are provided for the background coils and the test volume. A schematic representation of the planned test insert 0.3 indicated inside the test well.

As a first step, we will produce a small insert that can be tested in the separate cryogenic environment (the test well) in the bore of the coil set. With the background field supplied by the HFTF, this insert will produce in excess of 14 T in a 0.15-m bore with an average $J_{\text{peak}} > 40 \text{ A-mm}^{-2}$. Tests of this insert will give valuable

information and experience on protection limits, cooling techniques, and conductor and coil fabrication techniques.

Subsequently, we will design and fabricate an insert to replace the Nb₃Sn coils of the HFTF set. Again maximum fields in excess of 14 T will be attained, but within a larger bore (0.4 m) and with higher stored energy (about 80 MJ). Following this demonstration, there are plans to combine the same insert with a higher field outsert produced by MIT as a part of the Multipurpose Coil Project, a joint venture between LLNL and MIT, to produce 16 T in the same bore. The developments leading up to and including the successful completion of these planned demonstrations will constitute sufficient verification of concept and of design and construction methodologies to allow reliable design, construction, and operation of the high-field solenoids needed for TIBER II. Many of the techniques of conductor design and application developed for the solenoids will transfer directly to use in the TF coils, and a central feature of the LLNL program is the desire to retain, as far as practical, the generic features of the CICC for coil design and fabrication.

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NOMENCLATURE

- A_{bz} = Total cross section of bronze in the CICC (m^2).
- A_{Cu} = Total cross section of copper stabilizer in the CICC (m^2).
- A_{fil} = Total cross section of Nb₃Sn filaments in the CICC (m^2).
- A_{sh} = Total cross section of sheath material in the CICC (m^2).
- B = Magnetic field at the conductor (T).
- $B_{\text{c2m}}(0)$ = Strain-free upper critical field at zero temperature (T).
- C_{core} = Specific heat of noncopper fraction of the composite superconductor. For MF-Nb₃Sn, this amounts to an average of the specific heats of CuSn-bronze and Nb₃Sn ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$).
- C_{Cu} = Specific heat of copper ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$).
- $C_{\text{v,He}}$ = Mean specific heat at constant volume for He, taken as $3100 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$.

d_w	- Diameter of a superconductor composite strand in the CICC (m).	V_D	- Terminal voltage resulting from a dump at full field (V).
E_{fil}	- Young's modulus of a Nb ₃ Sn filament (Pa).	$\left(\frac{\Delta L}{L}\right)_{fil}$	- Total relative thermal contraction of the Nb ₃ Sn filament from the conductor heat treatment temperature to operating temperature (i.e. from 1000 K to 4 K).
E_s	- Stored energy at full field (J).	$\left(\frac{\Delta L}{L}\right)_{sh}$	- Total relative thermal contraction of the sheath from the conductor heat treatment temperature to operating temperature (i.e. from 1000 K to 4 K).
E_{sh}	- Young's modulus of the CICC sheath (Pa).	ϵ	- Total axial strain in the superconductor filaments due to all effects.
f_{cond}	- Fraction of conductor inside the conduit of the CICC.	$\epsilon_{init.}$	- Initial axial strain in the superconducting filaments after cooldown to operating temperature.
f_{Cu}	- Fraction of stabilizing copper in the superconductor composite strands.	ϵ_{sh}	- Axial strain added to the sheath of the CICC under the action of electromagnetic forces.
f_{He}	- Fraction of helium inside the conduit of the CICC, $f_{He} = 1 - f_{cond}$	n	- Stability parameter.
I_c	- Critical current at operating field and temperature (A).	$\mu_{He,init.}$	- Density of the internal He in a CICC at the initial operating temperature and pressure (i.e. before a quench) (kg·m ⁻³).
I_{cm}	- Maximum I_c vs strain.	μ_{core}	- Density of the noncopper fraction of the composite superconductor (taken as 8920 kg·m ⁻³ for Nb ₃ Sn composites).
I_{op}	- Operating current at full field (A).	μ_{Cu}	- Density of copper (taken as 8940 kg·m ⁻³).
I_1, I_2, I_3	- Integral terms defined in text (A ² ·s ⁻¹ ·m ⁻⁴).	$\rho_{Cu(B)}$	- Resistivity of the stabilizing copper at operating field (Ω·m).
J	- Operating current density inside the conduit of a CICC (A·m ⁻²).	$\sigma_{Cu,y}$	- Yield stress of copper (Pa).
$J_{c0}(B, \epsilon)$	- Zero temperature critical current density over the noncopper fraction of a composite superconductor strand at field and strain (A·m ⁻²).	$\sigma_{bz,y}$	- Yield stress of bronze (Pa).
J_{c0m}	- Maximum of J_{c0} vs strain (A·m ⁻²).	τ_H	- Duration of a sudden heat impulse to the CICC (s).
L	- Length of CICC between helium flow connections (m).	REFERENCES	
l_H	- Length of CICC receiving a sudden heat impulse (m).		
p_{max}	- Maximum allowable, absolute pressure during a quench of the CICC (Pa).	1.	K. YASUKOCHI, "Large Coil Task of IEA in the Development of Superconducting Magnets for Fusion," <u>IEEE Trans. Magn.</u> MAG-17 , 1720 (1981).
s	- Saturation value of stabilizer residual resistivity due to radiation damage (nΩ·m).	2.	T. A. KOZMAN et al., "Magnets for the Mirror Fusion Test Facility: Testing of the First Yin-Yang and the Design and Development of Other Magnets," <u>IEEE Trans. Magn.</u> MAG-19 , 859 (1983).
T_b	- Bulk fluid temperature of the internal helium of a CICC at operating conditions (K).		
$T_c(B, \epsilon)$	- Critical temperature of the superconductor composite at a particular field and strain (K).		
T_{cm}	- Maximum of T_c vs strain (K).		

3. "MFTF-B Acceptance Test and Final Project Cost Report," K. Krause and T. A. Kozman, Eds., Lawrence Livermore National Laboratory, UCID report in preparation, 1986.
4. V. N. KARPENKO, "The Mirror Fusion Test Facility (MFTF-B): Status," Fusion Technol. **8**, 427 (1985).
5. J. P. ZBASNIK et al., "Construction and Testing of the Nb₃Sn Coils for the High Field Test Facility," Adv. Cryog. Eng. **29**, 95 (1984).
6. M. O. HOENIG et al., "Operation of the MIT 12-T Test Coil," 1985 Cryogenic Engineering Conference, 12-16 August 1985, Massachusetts Institute of Technology, Cambridge, MA.
7. The General Atomic (GA) 12-T test coil was tested in HFT in February 1986. A report is in preparation.
8. P. TUROWSKI et al., "A 12-T NbTi Solenoid at 1.8 K with a Clear Bore of 290-mm Diameter," 9th International Conference on Magnet Technology (MT-9), Zurich, Switzerland, 9-13 September 1985.
9. I. HORVATH et al., "Status Report on the Forced Flow High Field Test Facility SULTAN," IEEE Trans. Magn. **MAG-19**, 668 (1983).
10. T. ANDO et al., "Upgrading of the Cluster Test Facility and an Extended Test on the TMC-I," Proceedings of the Tenth International Cryogenic Engineering Conference, H. Collan, P. Berglund, and M. Krusius, Eds. (Butterworth & Co., Guilford, Surrey, UK, 1984), p. 173 and references cited therein.
11. T. ANDO, "TMC-I 12-T Experiment," U.S./Japan Workshop on Superconducting Magnet Requirements for Long Pulse Tokamaks, Naka, Japan, 29-30 October 1985.
12. C. D. HENNING et al., "TIBER-II: An Upgraded Tokamak Ignition/Burn Experimental Reactor," paper presented at this conference.
13. M. SUENAGA, private communication, July 1985.
14. C. D. HENNING et al., "TIBER: Tokamak Ignition/Burn Experimental Research Final Design Report," UCID-20589, Lawrence Livermore National Laboratory (1985).
15. R. FLUKIGER, W. MAURER, F. WEISS, P. A. HAHN, and M. W. GUINAN, private communication, March 1986.
16. J. R. MILLER and J. W. LUE, "Designing Internally Cooled Superconductors for Use in Large Magnets," Stability of Superconductors in He I and He II (International Institute of Refrigeration, Commission A 1/2, Paris, 1981), p. 247.
17. M. O. HOENIG, "Internally Cooled Superconductors," Cryogenics **20**, 373 (1980).
18. L. DRESNER, "Stability of Internally Cooled Superconductors: A Review," Cryogenics **20**, 558 (1980).
19. J. R. MILLER et al., "The Initial Filament Strain State of Cable-in-Conduit Superconductors and Its Relation to the Design of Large-Bore, High-Field Magnets," paper submitted for presentation at the 1986 Applied Superconductivity Conference, Baltimore, MD.
20. M. M. STEEVES et al., "Effects of Incoloy 903 and Tantalum Conduits on Critical Current in Nb₃Sn Cable-in-Conduit Conductors," Adv. Cryog. Eng. **30**, 883 (1982).
21. R. M. SCANLAN et al., "Mechanical Properties of High-Current Multifilamentary Nb₃Sn Conductors," Filamentary A15 Superconductors, M. Suenaga and A. F. Clark, Eds. (Plenum Press, New York, 1980) p. 221.
22. M. M. STEEVES, private communication, May 1986.
23. J. W. EKIN, "Strain Scaling Law for Flux Pinning in Practical Superconductors. Part 1: Basic Relationship and Application to Nb₃Sn Conductors," Cryogenics **20**, 611 (1980).
24. J. R. MILLER, "Design of Aggressive Superconducting TFCX Magnet Systems," Fusion Technology **8**, 829 (1985).
25. J. W. LUE and J. R. MILLER, "Heated Length Dependence of the Stability of an Internally Cooled Superconductor," Proceedings of the Ninth Symposium on Engineering Problems of Fusion Research (IEEE Pub. No. 81CH1715-2 NPS, IEEE Service Center, Piscataway, NJ, 1981), Vol. I, p. 52 and references cited therein.
26. J. R. MILLER et al., "Pressure Rise During the Quench of a Superconducting Magnet Using Internally Cooled Conductors," Proceedings of the Eighth International Cryogenic Engineering Conference, C. Rizzuto, Ed. (IPC Science and Technology Press, Guilford, UK, 1980), p. 321.
27. J. W. LUE et al., "Simulation of the Quenching of an Internally Cooled Superconducting Magnet," Proceedings of the Ninth International Cryogenic Engineering Conference, K. Yasukochi and E. Magano, Eds. (Butterworth & Co., Guilford, Surrey, UK, 1982), p. 814.
28. L. DRESNER, "The Growth of Normal Zones in Cable-in-Conduit Superconductors," 10th Symposium on Fusion Engineering Proceedings (IEEE Cat. No. 83CH1916-6 NPS, IEEE Service Center, Piscataway, NJ, 1983), Vol. 2, p. 2040.