MAGNET SYSTEMS FOR THE INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR*

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1. Introduction

The definition phase for the International Thermonuclear Experimental Reactor (ITER) has been nearly completed, thus beginning a three-year design effort by teams from the European Community (EC), Japan, U.S., and USSR. Preliminary parameters for the superconducting magnet system have been established to guide more detailed design work. Radiation tolerance of the superconductors and insulators has been important because it sets requirements for the neutron-shield dimension and sensitively influences reactor size. Major levels of mechanical stress appear in the structural cases of the inboard legs of the toroidal-field (TF) coils. The winding packs of the TF coils include significant fractions of steel that provide support against in-plane separating loads, but they offer little support against out-of-plane loads unless shear-bonding of the conductors can be maintained. Heat removal from nuclear and ac loads has not limited the fundamental design, but it has nonnegligible economic consequences.

2. Guidance to Design

An ITER Specialists Meeting was convened May 9-13, 1988, to gather data and prepare for the ITER magnet design. Data from existing superconducting tokamak magnet systems were reviewed to guide future design efforts. Table I lists the recent performance levels achieved. The Large Coil Task (LCT), T-15, and Tore-Supra are recent examples of superconducting tokamak magnet designs. The designations GE, GD, JA, CH, EU, and WH refer to the General Electric, General Dynamics, Japanese, Swiss, European, and Westinghouse large coils, respectively. Each used a different method of coil construction, and all worked. However, because field levels in ITER will be extended from 9 to 12 T or higher, forced-flow niobium-tin conductors are preferred. The achievable current density in niobium-tin superconductors was reviewed. The data in Fig. 1 can be adequately represented by the following design formulas for niobium-tin performance with zero intrinsic strain:

$$\begin{aligned} J_{cm}(B, T) &= J_{c0m} \left[1 - \frac{T}{T_{cm}(B)} \right], \\ T_{cm}(B) &= T_{c0m} \left(1 - \frac{B}{B_{c20m}} \right), \\ J_{c0m}(B) &= \frac{[111(1 - B/B_{c20m})]^2}{B^{1/2}}, \\ T_{c0m} &= 18 \text{ K}, \\ B_{c20m} &= 27.8 \text{ T}, \end{aligned}$$

where J is the current density in A/mm² over the non-copper fraction of the conductor, B is magnetic field, and T is temperature. The subscript c refers to the critical value; the subscript 0 on T_c refers to zero field; the subscript 0 on J_c and B_{c2} refers to zero temperature; and the subscript m refers to the maximum value of that parameter (i.e., at zero intrinsic strain). The curves in Fig. 1, from a survey by M. Suevaga (private communication, July 1988), show critical

current for wires with various compositions and manufacturing processes. The individual points represent samples taken from a large amount of conductor purchased by LLNL.

Several conductor systems applicable to ITER have been studied and developed. Although the configurations of the conductors are varied to accommodate structural and stability considerations, there is general agreement on the levels of current density that can be achieved with reasonable development. In the superconducting (non-copper) fraction of the conductor, about 800 A/mm² at 12 T and 4.2 K is considered reasonable. Also, structural materials could be designed to two-thirds of yield stress or half of the ultimate stress with a resulting value up to 800 MPa. Good advances have been made in such material properties in recent years, particularly in Japan, so that reliable cryogenic fabrications are possible. Table II lists some of the more advanced alloys from Japan and the USSR that are useful for the primary magnet structure. Table III lists alloys for a niobium-tin conductor conduit that must receive the reaction temperature heat treatment.

There has been considerable disagreement about radiation tolerance of insulators that will receive doses from 5×10^8 to 10^{10} rads. Some information exists on glass epoxies from compression and flexural tests; less information exists for polyimides (most tests have been on mixtures of epoxies and polyimides—not pure polyimides). No information exists on shear stress effects at doses ranging from 10^8 to 10^{10} rads. The results generally show decreases in strengths of 30-60% vs unirradiated values with doses approaching 10^{10} rads. With an optimization of the epoxy resins and the glass fibers, some data indicate that epoxies could be used up to 10^{10} rads. In particular, the data in Fig. 2, from a 1985 CERN report [1], show that certain epoxy resins can withstand close to 10^{10} rads and retain shear strength. Cleaning the fiberglass mat by heating to 400°C helps remove binders and impurities that cause degradation during irradiation.

Regarding superconductors, irradiation experiments using 14-MeV neutrons have been conducted on commercially available materials at room temperature and at 4.5 K with tests at 14 T (see Fig. 3) [2,3]. Neutron doses up to 1.4×10^{22} n/m² at 4.5 K and 2.5×10^{22} n/m² at room temperature were applied. The results show no degradation up to 2.5×10^{22} n/m². Critical current densities (non-copper) ranged from 250 to 500 A/mm². Because the actual neutron energy spectrum in the ITER magnets will be much softer than a 14-MeV source, the expected neutron dose in the magnet at which no degradation is expected is larger than 2.5×10^{22} n/m² (approaching 10^{23} n/m²); the actual dose will depend on the design of the inner shield and magnet.

3. Initial Engineering Design

Although the ITER definition phase is not complete, an initial engineering design was studied to assess the practicality of a 20-MA plasma current. Parameters for this example are listed in Table IV.

TF and poloidal field (PF) coils are being designed by each participant for comparison. Also, stress in the conductors, cases, and insulators is being evaluated to verify that the design envelope is credible. Eddy current losses could become important to the detailed design since the coils must withstand disruption conditions of 38 T/s at the inboard leg with the possibility of a continuous 0.3 Hz cycling of the PF coil to distribute the divertor heat flux.

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Table I: Field and current density (conductor + He) reached

NbTi:	LCT	9.2 T, 45.4 A/mm ² at 3.9 K
NbTi in HeII:	Tore-Supra (design)	9.0 T, 60 A/mm ² (approx.) at 1.8 K
Nb ₃ Sn:	LCT	9.0 T, 69.7 A/mm ² at 3.9 K
	T-15 (design)	9.2 T, 47.5 A/mm ²
	(single coil tests)	5.3 T, 58.6 A/mm ² at 4.5 K
Current densities in LCT coils at design point (8.0 T, 3.8-4.2 K)		
GE	GD	JA
25.0	28.2	26.1
15.7	15.3	16.0
CH	EU	WH
38.0	42.9	64.6
17.9	16.3	17.6
(conductor + He)		
(overall)

Figure 1: Critical current in Nb₃Sn.

Table II: Properties at 4.2 K of cryogenic steels.

Material	Yield stress (MPa)	Ultimate stress (MPa)	Fracture toughness (MPa√m)	Design stress (MPa)
C SUS-JWI	1250	1650	200	825
C SUS-JKA1	1200	1650	210	800
02×20H16A 6	1326	1834	180	700
03×13H9 19AM2	1530	2000	---	750

Table III: Properties of candidate materials for conductor conduit to be heat-treated at about 700°C

Material	Modulus (GPa)	Yield stress (MPa)	Ultimate stress (MPa)
JBK-75	207	1250	1750
A286	207	similar	similar
Incoloy 908	180	similar	similar

Material: Solventless epoxy resin No. 332.
Base DGEBA MNA other components reinforced with fiber-reinforced glass-cloth backing (type 3)

Type: Orllitherm-D insulation

Supplier: BBC Baden

Remarks: Magnet coil insulation application

Curve property Initial value

S Flexural strength at maximum load 324.0 MPa

D Deflection at maximum load 4.2 mm

M Modulus of elasticity 19,240.0 MPa

RI Radiation Index (10⁵ Gy/h) 8.0

Figure 2: Radiation damage to epoxy-glass.

Figure 3: Damage to superconductors.

Table IV: Tentative parameters for ITER.

Major radius	5.8 m
Minor radius	2.0 m
TF on axis/at conductor	5.1/11.3 T
Plasma current	20 MA
Fusion power	1 GW
Outer radius of central solenoid	2 m
Thickness of inboard TF coil region	0.75 m
Thermal isolation thickness	0.05 m
Shield/first-wall region thickness	0.8/0.85 m

4. Research and Development

The design effort for ITER is accompanied by a significant magnet R&D effort as summarized in Table V. This is needed because a large ignited/burning plasma as in ITER will require higher steady-state magnetic fields than previously achieved. TF coils of 12 T and large size require high-current niobium-tin superconductors to operate under conditions of high stress, cyclic loading, and nuclear heating. Ignition places large demands on the poloidal coil system because a large amount of energy is required to start up and burn the plasma. Accordingly, the conductors must operate near 40 kA and about 12 T or greater in the central solenoid.

If the TF magnets can be made more radiation tolerant, the neutron shielding may be reduced to permit a smaller tokamak or conversely a larger, higher current plasma to achieve ignition. Insulators such as polyimides, or advanced epoxy-glass with forced-flow conductors, capable of high neutron heat removal and good stability even with radiation-damaged copper stabilizers, are being studied to see if this goal can be achieved. Of course, large cryogenic components will be needed to remove the nuclear heat loads and pulsed field losses.

Task MT: Toroidal Coil. Three participants (EC, Japan, and USSR) offered to contribute TF conductor development, and the U.S. plans to develop TF conductor concepts through an integrated program emphasizing radiation-tolerant magnets. Three concepts have been proposed: react-and-wind by the EC, USSR, and Japan; wind-and-react by the U.S.; and the preformed armor technique discussed by Japan—an intermediate variant that allows special high-strength steels to be added as distributed structure to the conductor after reaction. Development of these different concepts provides options that would be lost if only one course were pursued. The cost of development of such pre-prototypical conductor models is small compared to the quantity and quality of information that can be obtained by fabricating and testing them.

Although all the teams have proposed developing and testing full-scale TF conductors, no participant possesses a test facility of sufficient size and field strength. The requirements for such test facilities (useful also for testing developmental PF conductors) can be roughly described as follows: high, transverse field exposure of at least 0.3 to 0.4 m of conductor (the conductor must be meters in length to allow joints outside the high-field region) to magnetic fields from 12–14 T, access for a conductor of about 50-mm lateral dimension; and application of current of about 40 kA. Critical current at the designed operating field and current can be determined by raising the temperature. Suggestions for such a test facility are being examined.

Task MP: Poloidal Coil. Development of conductors appropriate for the PF central solenoid has been proposed directly by the EC, in generic fashion by the U.S., and as part of a PF coil development by Japan. Both the U.S. and the EC (with vocal support from the USSR) favor wind-and-react, cable-in-conduit approaches to PF central solenoid fabrication and have chosen their conductor development paths accordingly. The approaches of these teams differ, however, in the fabrication techniques being investigated.

Table V: Participants in ITER magnet R&D.

Task	EC	U.S.	Japan	USSR
MT Toroidal coil	X		X	X
MP Poloidal coil	X		X	
MI Insulation material	X	X		X
MS Magnet structure material	X		X	
MA Radiation-tolerant magnets		X		
MC Cryogenics		X	X	

The Japanese preformed armor conductor, sometimes proposed by them as an PF central solenoid conductor candidate, offers alternatives for fabrication techniques and materials. Japan has been fabricating a coil (DPC-TJ) using this preformed armor cable-in-conduit conductor. The DPC-TJ is not a pulsed coil; however, it will verify the production feasibility of this new concept and mechanical advantages.

The PF central solenoid will be an extension of the state of the art; therefore, participants were encouraged to modify their development of plans to include the ITER PF central solenoid requirements (magnetic fields of 12 T and higher, currents near 40 kA, and ramp rates of about 1 T/s).

Task MI—Insulation Material. All participants have proposed work on irradiating and testing the magnet insulations. The U.S. plans to extend the testing to higher exposures (10^{10} rad) and to systems that do not rely on shear bonding. Some studies indicate that the insulation systems proposed by the EC will tolerate higher exposures than the 5×10^8 rads planned for their tests.

Task MS—Magnet Structure Material. For magnet cases, the Japanese and the USSR teams have emphasized developing cryogenic steels with dramatically improved properties. Particularly in Japan, reliable cryogenic steels (JCS) have been developed and are commercially available.

Task MA—Radiation-Tolerant Magnets. The U.S. has proposed an overall reduction in machine size and costs by simultaneously elevating the reliable performance levels of the superconducting magnet systems and designing them to accept higher radiation exposure. This integrated approach is one that both feeds and is fed by the developments of individual magnet system components, such as conductors, cryogenic components, insulation systems, and structural materials. The U.S. team believes this development approach is essential to significantly improve performance in these areas.

Task MC—Cryogenics. The cryogenic system of ITER must absorb approximately 100 kW at 4.5 K, corresponding to power consumption from the grid of several tons of MW. Japan and the USSR propose complementary approaches—the USSR emphasizing development of the largest components such as compressors, and Japan choosing to develop more sophisticated components such as turbo-expanders and helium pumps.

5. Conclusion

The ITER collaboration has already produced some convergence in magnet design criteria and a cohesive plan for R&D work. The definition phase will be completed in 1988. The design phase will continue through 1990, when the conceptual design report will be made.

References

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