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FOR FUSION APPLICATIONS

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SUPERCONDUCTING MAGNETS FOR FUSION APPLICATIONS*

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ABSTRACT

Fusion magnet technology has made spectacular advances in the past decade; to wit, the Mirror Fusion Test Facility and the Large Coil Project. However, further advances are still required for advanced economical fusion reactors. Higher fields to 14 T and radiation-hardened superconductors and insulators will be necessary. Coupled with high rates of nuclear heating and pulsed losses, the next-generation magnets will need still higher current density, better stability and quench protection. Cable-in-conduit conductors coupled with polyimide insulations and better steels seem to be the appropriate path. Neutron fluences up to 10^{19} neutrons/cm² in niobium tin are achievable. In the future, other amorphous superconductors could raise these limits further to extend reactor life or decrease the neutron shielding and corresponding reactor size.

INTRODUCTION

The application of superconducting magnets to fusion experiments has been limited, but increasing rapidly. Since 1970, when the Baseball II¹ and IMP² magnets at LLNL and ORNL respectively, were first used, the T-7 system³ at the Kurchatov (USSR) has been in operation. More recently, the MFTF magnet system⁴ at LLNL and the TriAM-1M in Japan⁶ have been completed. Soon the Tore Supra⁷ at Cadarache, France and the T-15⁸ at Kurchatov will be nearing completion. These fusion magnet systems represent significant advancements in magnet technology starting from small confinement experiments to near-reactor sizes. The Large Coil Project⁹ has further advanced the technology and enhanced an industrial base for magnet construction.

Now we are on the brink of nuclear application of fusion magnets. Currently, the U.S., U.S.S.R., Japan and the European Community are discussing the cooperative design of an International Thermonuclear Experimental Reactor (ITER). The impetus for this design effort came from a joint statement issued by President Reagan and Chairman Gorbachev at the November 1986 Geneva Summit Conference. These leaders called for the

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"...widest practical development of international cooperation (in fusion)." This statement resulted in a team from the Department of Energy meeting with representatives from the U.S.S.R. in April 1986. In October 1986, the U.S. formally proposed that the European communities, Japan, the U.S.S.R., and the U.S. collaborate in producing a detailed design for the next major device in fusion energy development. The final design will provide enough detail for the participating nations to make an informed decision on whether to construct and test the device. If the ITER is constructed, it could confirm the feasibility of fusion power by demonstrating physics and plasma performance as well as test components and materials under integrated reactor conditions.

Lawrence Livermore National Laboratory is leading the U.S. effort on the ITER. While compromises in design with other nations are expected, we can project some of the necessary conditions for superconducting magnet applications from the Tokamak Ignition/Burn Experimental Reactor Study (TIBER)¹⁰. This design (Figure 1) incorporates physics and engineering characteristics that could lead to a compact, steady-state, current-driven reactor to be used for testing components and materials in a nuclear environment similar to that expected in a power reactor. In fusion reactors, plasma cycling causes time-dependent changes in environmental testing conditions (for example, tritium-concentration profiles, eddy-current effects, thermal conditions, and failure or fracture modes). Because we are primarily interested in the effects of long-pulse reactor conditions on components, the often dominant short-pulse effects must be minimized so that testing results can be accurately extended to reactor conditions. For this reason, TIBER is designed with enough auxiliary current-drive power to maintain steady-state operations. A summary of the major parameters is given in Table 1.

Fig. 1. TIBER - a Tokamak Ignition/Burn Experimental Reactor

Table 1. TIBER Design Parameters

Fusion Power	314 MW
Major Radius	3.0 m
Minor Radius	.83 m
Elongation	2.4
Burn Time	Steady State
Average Neutron Wall Loading	1.3 MW/m ²
Peak Neutron Wall Loading	2.0 MW/m ²
Fluence Goal	>3 MW/m ²
Availability Goal (Testing Phase)	30%
Tritium Consumption (Testing Phase)	4.5 kg/yr
Surface Heat Flux	
First Wall (Uniform)	0.25 MW/m ²
Divertor (Peak)	2.2 MW/m ²
Test Area	
Frontal Area of Test Spaces	1.2 m x 2 m
Number of Test Spaces	8

ADVANCES IN MAGNET TECHNOLOGY

The size and cost of the next generation tokamak fusion experiments with ignited plasmas will be largely determined by the size characteristics of the center post region. Starting from the radial dimensions and current density of the central ohmic heating coil, the toroidal field coil current density and inner neutron shield control the tokamak inner plasma radius. Since plasma minor radius and aspect ratio are usually minimized (consistent with fusion power and physics scaling) the entire tokamak size is greatly influenced by the magnet current density, field, and radiation tolerance.

Current Density. The winding pack current density in the TIBER II design for both the poloidal and toroidal field coils was 4 KA/cm² at 14 T and 12 T respectively¹¹. This performance is above traditional standards, since cryogenically stable conductors have current densities about half of that projected for Cable In Conduit Conductors (CICC) as used in TIBER. Here the conductor stability is determined largely by the enthalpy of the trapped helium rather than the boiling heat transfer of liquid helium from the conductor surface. Not only does it result in high current density, but the conductor is much more radiation tolerant because it is not affected by copper resistance increases due to neutron damage.

CICC Coil operating experience has been bolstered tremendously by small scale test and development activities at a number of laboratories in the U.S., Japan, and Europe. Figure 2 gives some perspective of what has been achieved along with the goals of present development activities. Operating current density over the cable space, (i.e., inside the conduit of the CICC) is plotted versus the maximum field at the windings. The lower point shown for the ORNL Nb-T coil corresponds to a stability margin well in excess of 100 mJ/cm³. The solenoid also operated quite stably up to the critical current, where the stability margin was measured to be 56 mJ/cm³.

Other operating points for the Westinghouse LCT coil¹² are shown plus the demonstrated performance of the MIT 12 T coil, which was tested in the LLNL, High Field Test Facility (HFTF)¹³. The lower of the two MIT 12 T points represents the only point where stability of the coil was tested. The coil stably absorbed a pulse of >200 mJ/cm³ without consequence.

Fig. 2. Superconductor Stability - Higher conductor current densities through enthalpy stabilization in cable in conduit conductor are possible even with saturated neutron damage to the copper.

The upper enthalpy stabilization curve in Fig. 2 is a projection of the performance that is obtainable with state-of-art MF-Nb₃Sn in a CICC design. The projected improvement is possible because the performance of a CICC is tied directly to the increased current margin (or alternatively, increased temperature margin) provided by recent improvements in the critical currents of MF-Nb₃Sn wires. The middle curve takes account of the effects of radiation damage to the copper stabilizer in transforming the estimated performance boundary to one appropriate for the TIBER II TF coil environment, where shielding is much reduced.

Strain Effects. In a CICC conductor, the strain in the Nb₃Sn filaments, and thus the critical current at operating conditions, is determined by a complex interaction between the sheath and the cable inside from formation at around 1000 K, through cooldown to the operating temperature around 4 K, and charging to full field and current. An experimental program is in progress at LLNL to examine the conductor/sheath interaction through a series of electromechanical tests¹⁴. In the first series of tests, the critical currents of model CICC's were measured, with the axial load applied to the sheath increased by small increments until the measured critical current was observed to pass through a maximum. The ratio I_c/I_{cm} of initial or "no-load" critical current to maximum critical current was observed to vary with fraction of the internal space available for helium in otherwise identical specimens. These data are plotted in Fig. 3, along with other values for similar conductors inferred from data in the literature^{15,16}. A factor f_{He} has been plotted to account for the observation that, the greater the He fraction, the less rigidly linked are the conductor strands to the compressive influence of the sheath during cooldown.

An equally important factor in tokamak design is cyclic failure. In Fig. 4 the stress in the poloidal field coil sheath has been calculated to vary from 100 MPa to 420 MPa. The net 370 MPa cyclic stress amplitude then predicts a 50,000 cycle life limit (with a safety factor of two) for an initial 10 percent thickness flaw to propagate completely through the

Fig. 3. Ratio of initial (unloaded) critical current of CICC samples to maximum critical current as a function of void or helium fraction inside the conduit.

sheath. This does not constitute catastrophic failure, but only leaks helium into the magnet case as a warning of limited remaining magnet life.

Radiation Damage. Figure 5 is representative of the effects of high-energy neutron fluence on Nb_3Sn conductors, both pure and modified¹⁷. The samples tested were irradiated with 14.1-MeV neutrons at room temperature and then tested at 4.2 K. The lower horizontal axis in Fig. 5 accounts for the "softer" shielded neutron-energy spectrum calculated for TIBER II. Initial increases in current density are explained by the damage giving rise to increased normal-state resistivity of the superconductors, resulting in an increase in the upper critical field. In the modified materials, the upper critical field has already been optimized by additions of a third element to increase the normal-state resistivity. Therefore, any further increase due to damage might be expected to be small. Eventually, at high fluence a decrease in performance is caused by a drop in critical temperature with increased damage. For unmodified Nb_3Sn , it is clear that the conductor will retain its performance beyond the 10^{19} n/cm² fluence in TIBER II. Modified Nb_3Sn is useful for attaining the high field performance in the center poloidal field coils, where the high-field windings are essentially completely shielded by the TF system and the outer, lower field turns.

For radiation-hardened magnets the insulation must retain adequate strength and electrical properties after irradiation to end-of-life fluences above 10^{19} n/cm² and gamma dosages above 10^6 rads, especially in those portions of the magnet adjacent to shield-penetrations for diagnostics on plasma-heating systems. Irradiation-damage studies of organic materials are usually done using gamma (γ) irradiation alone, if possible, or in combination with neutron-fluences on the order of 10^{18} n/cm², which are thought to cause negligible additional damage¹⁸. High γ dosages cause breakage and/or rearrangement of bonds, so that scission, cross-limiting of adjacent long-chain polymers (with decreased ability to

Fig. 4. Cyclic lifetime of an initial crack in the conductor sheath is calculated from crack growth data for JBR-75 steel.

slide over each other under load), and creation of free radicals (fission fragments) and gases occurs.

For the load-bearing insulation in superconducting magnets, the two main classes of organic materials that have excelled are based on the use of a glass-fiber filament woven into a two-dimensional cloth, with layers of cloth being bonded together into a three-dimensional mass with either an "epoxy-type" or "polyimide type" binder. The details of the manufacture and basic materials science of such composites are described in Refs. 19 and 20, for example.

Much information on the response of these and other fiberglass-reinforced composites to γ irradiation to doses below 10^6 rads is available and is summarized in Refs. 21, 22, and 23. More recent work has concentrated on determination of the effects of higher γ dosages, in the range $10^6 - 10^7$ rads, on both the electrical properties (such as resistance and breakdown voltage and mechanical properties such as failure strengths under various static modes of loading such as bending, compression, tension²⁴⁻³⁰ and fatigue modes of loading³¹⁻³³. Usually,

Fig. 5. 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.

irradiation is done at 4-9 K; the specimens are warmed to room temperature during removal from the irradiation source and then are cooled to 77 K and tested. This procedure is not representative of real operation, where the radiation damage and mechanical loading occur simultaneously at 4-5 K but is useful for determination of generic behavior. Summarized in Table II are the results of cryogenic irradiations on various fiberglass-reinforced composites, as ratios of irradiated to unirradiated compressive and flexure strength as reported by Mauer et. al.

Table II. Neutron irradiation data for organic insulators (irradiated to 10^8 Gy or 10^{10} rad)

Material	Unirradiated strength		Irradiated strength	
	Compression	Flexure	Compression	Flexure
	(MPa)		(MPa)	
G-10	886	1100	65	95
G-10 BF		990		108
G-11	826	1113	62	110
Epikote 828 (epoxy)	513	165	125	25
Stycast 2850 (epoxy)	570	262	50	57
Spaulrad (polyimide)	680	990	400	640
Norplex (polyimide)	900	690	900	445
Vespal (polyimide)	250	320	255	320

The database on retention of electrical resistance and electrical breakdown voltage of composites is somewhat scattered^{22, 24, 34}, but the following trends emerge:

- o 300 K resistance data after 5 K irradiation to 10^{10} rads showed 30 to 80% degradation for four epoxy-bonded composites, but little change for polyimide-bonded composites. Dielectrical breakdown voltage was reduced about 30 to 50% for the epoxy materials and not reduced for the polyimide bonded materials.
- o Irradiation at ~ 60 K to about 3.2×10^9 rads resulted in 10^9 reductions in 300 K electrical-resistances of about 10^3 to 10^4 for five epoxy-bonded composites, but only a six-fold reduction in this quantity for polyimide bonding composite.

Nuclear Heating. With an optimized neutron shield of about 50 cm, the neutron heating in a toroidal field coil can be limited to 5 mW/cm^2 . This rate is compatible with niobium tin receiving a fluence of 10^{19} n/cm^2 corresponding to 10^6 seconds of lifetime. Higher heating rates up to 100 mW/cm^2 are possible, but the reactor lifetime would be correspondingly reduced. For TIBER II the 5 mW/cm^2 heating rate at the inside turns is low enough that a full pancake can be cooled without intermediate helium connections.

Perhaps contrary to intuition, the cold helium in this scheme is injected into the windings at the outermost turns (one inlet at the outer end of each half-pancake). The helium from both halves is exhausted at the same opening on the innermost and most highly heated turn of the pancake. The exhaust port can be located along the outer leg of the "Dee" where space is available. With the helium injected at relatively low pressures, there is significant Joule-Thompson expansion that gives some added cooling and stabilization of temperature in the more highly heated portions of the windings. This can be seen in the path traced out on the TS diagram for the 72 kW total heat load case shown in Fig. 6. The numbers on the curve represent conditions in particular turns of the winding, counting in from the outside.

With temperature distribution in the flow path determined, the conductor can be designed to give the desired performance, i.e., stability margin at the desired current density, in the region of the windings where conditions are most severe, i.e., the highest fluid temperature and field. For the heat loads expected in TIBER II, there are options that hold the fluid temperature in the 12 T region of the TF coils to 5.3 K or less.

CONCLUSION

The advancement toward fusion energy has brought new requirements on superconducting magnet technology. Not only does performance (field and current density) need to be improved, but nuclear effects must be accommodated. Neutron damage and nuclear heating will be prime considerations in the next generation of fusion experiments.

Fig. 6. Thermodynamic path taken by the helium in a TIBER II TF coil corresponding to a total radiation heat load of 72 kW to all coils. The numbers on the curve are turn numbers, helium is injected at the outside (Turn 1) at 4.5 K, 5 atm, and $3000 \text{ g} \cdot \text{s}^{-1}$.

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