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U.S. Superconducting Magnet Data Base Assessment for INTOR

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M.I.T. Plasma Fusion Center Report PFC-RR-84-19

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Introduction

Because of its size, performance requirements and exposure to neutron and gamma irradiation , the superconducting magnet system for INTOR would represent a significant advance in superconducting magnet technology. U.S. programs such as LCP, MFTF-B and others provide a significant data base for the INTOR application. The assessment of the adequacy of the U.S. data base for the INTOR magnets is largely generic, and applies to the superonducting magnet systems for other magnetic confinement fusion reactors. Assessments of the data base generated by other national magnet technology programs are being prepared by the other INTOR participants.

1 Structure

1.1 Mechanical Characteristics

1.1.1 Static Characteristics

1.1.1.1 Stress-strain

A reasonable static characteristics data base exists for magnet cases and intercoil structural materials, through test programs at the United States ational Bureau of Standards [BA74] [FI78] and through the Mirror Fusion Test Facility Project (MFTF) at the Lawrence Livermore Laboratory (LLL). The data includes base metal and weld metal [VA78] [RE78] [WE77] [GO84].

A preliminary data base is available on the structural aspects of the internally-cooled cabled superconductor (ICCS) sheath materials [BO84] [GO80]. This conductor was the prime design choice for TF and PF conductor for the Toroidal Fusion Core Experiment (TFCX) design studies in 1984 [SC84C] [SR84].

1.1.1.2 Shear Stress

Specific shear stress-strain measurements are seldom performed on metals, since metal shear is seldom a limit on performance or can be reinterpreted in terms of principal stresses. However, bond and lamination shear strengths are important in designing with composite insulation structural materials. Some data base on G-10CR exists through the Magnetohydrodynamics (MHD) Magnet Program [HA83] [ER80A].

1.1.1.3 Friction Coefficients

A limited data base on typical insulation-insulation and insulation-metal friction coefficients exists through the MHD Magnet Program [KE80] [KE81] [MA82A] [MA82B] [IW79B]. Friction energy input is not considered important for ICCS conductors [IW79C], and will not be investigated further in the near-term United States program.

1.1.2 Fatigue Characteristics

A reasonable data base for cycles to failure exists for some cryogenic metals [FI78] [TO83]. There is some limited evidence, however, that these data have not been taken at sufficiently low strain rates to assure that the specific temperature remained at 4.2 K [DO83]. The materials may thus appear more ductile than they would be under realistic operating conditions.

1.1.3 Fracture Mechanics

A limited data base exists on fracture toughness and crack growth through the MFTF Project [HE81], and the background for that design [HE79C]. That data base has been used in the Fusion Engineering Device (FED) [HO81B], INTOR [HO81A] and TFCX designs.

1.1.4 Combined Stress

An extensive data base exists on the theory of combined stress failure in metals [AS80]. Data is more limited in composite insulated structures [HE79A].

1.2 Quality control Techniques

1.2.1 Detectable Flaw Size

A reasonable data base exists for flaw size determination limitations through the MFTF Project [HE80] [HE79B] [WO78] [HO80] and the background for that project [VA78]. Field experience in detecting flaws has been discussed at a meeting on structural standards for large superconducting magnets [DA80].

1.2.2 Flaw Detection during Operation

Present techniques for detection during operation (crack-detection wires, for example) have not been reliable. MFTF magnet tests indicated false signals due to debonding of the gages.

1.3 Radiation Effects on Structural Materials

There appears to be an adequate data base on low temperature steels from the Nuclear Engine and Rocket Program (NERVA) [NU75]. The data suggests that the effects will not be limiting at the location of the magnet systems. In any event, radiation doses to the magnet must be orders of magnitude less severe than that to first wall and blanket components. Data on insulating systems is limited.

2 Conductors

2.1 Critical Current Characteristics

A reasonable data base exists on basic characteristics of NbTi, NbTiTa and Nb_3Sn from projects in particle physics, fusion and MHD. Nb3Sn is the most subject to variation, due in part to the strong influence of critical current on the strain state of the Nb3Sn [EK79], due to the differential contraction with other components of the conductor, such as the bronze matrix or the ICCS sheath. Preliminary data suggests that by matching the differential contraction of the sheath and cable in ICCS conductors, a major gain can be made in the critical current. Quantitative knowledge of the energy margins and critical currents of these conductors, as a function of sheath design, are becoming available [HO83] [MI84] [ST84]. A limited data base is available on the effect of fatigue, which does not appear to be significant until the superconductor is close to structural failure [EK78].

2.1.1 Advanced Superconductors

Although the feasibility of INTOR does not require superconductors more advanced than those already available, the cost of superconducting magnets can be substantially reduced and the size of the overall reactor somewhat reduced by the qualification of more advanced superconductors. This is the approach currently being selected for the Superconducting Super Collider (SSC) [LI84] and the mirror program's high field choke coil development program [SC84A]. Advanced superconductors, with higher critical current or simplified manufacture, such as the elimination of intermediate anneals in the drawing of Nb_3Sn, require qualification for high current fusion applications, particularly for use in ICCS conductors. The most advanced, near-term technology is the internal tin Nb_3Sn conductor, developed by the Intermagnetics General Corporation (IGC) [ZE84]. Other possible optimizations of Nb_3Sn [SU84] [SM84] could develop an adequate data base on a time frame compatible with INTOR.

2.1.1 Recovery

Recovery of superconductivity, following a disturbance, has been achieved successfully, using several different methods. These include cryostability [KA65], cold end recovery [MA69], and critical current margin [IW79A]. There is also a data base supporting the design of ICCS conductors for energy margins comparable to the available enthalpy of the local helium envelope [MI80], independent of the helium flow rate [HO77] provided that critical current is sufficiently high to avoid a second stability regime [DR81] [LU80]. A more complex enthalpy stability criterion has been derived for superconductors cooled by superfluid helium [SC81].

2.2 Thermal and Electrical Characteristics

A reasonable data base exists on magnetoresistance, thermal conductivity and specific heat [JO60].

2.3 Heat Transfer Characteristics

2.3.1 Pool-cooling (4.2 K)

A substantial data base exists for static pool-cooling in controlled heat-transfer tests [IW78], in test coils, and in full scale coils. The LCP Project will soon add substantially to the full-scale data base. There is a more limited base for transient cooling. There is a limited data base for pool-cooled cable type conductors through the MHD Program. Heat transfer is seldom directly measured, but is inferred from recovery current measurements.

2.3.2 Forced-flow cooling

The data base for forced-flow cooling (specifically for the ICCS topology, for which transient cooling in stagnant helium is also of importance) is much more limited than for pool-cooling. Subscale conductor tests at ORNL and MIT provide the current data base. Simulations of these experiments have been made at the experimental laboratory, as well as at NBS and the Argonne National Laboratory (ANL). The Westinghouse LCP coil and the much smaller 12 Tesla coil [HO84A] for the High Field Test facility (HFTF) at LLL will provide a more extensive near term data base. Heat transfer is seldom measured directly, but is inferred from transient stability measurements.

2.3.3 Superfluid helium

There is a reasonable data base for heat transfer from flat surfaces in superfluid . There is a limited current data base for cooling from cable conductors [CH84A], and more will be generated in the General Atomic 12 T insert [AL84] for the HFTF facility. Heat transfer is inferred from recovery currents.

2.4 Analytical tools

2.4.1 Conductor AC losses

A considerable data base exists for the analysis of transverse field pulsed field losses [WA81]. The data base is much less extensive for longitudinal field losses [CA75]. Analysis of losses in cables with imperfect strand-to-strand insulation is beyon present abilities, without calibration of the specific cable configuration.

2.4.2 Stability analysis

Reasonable tools are available for predicting stability in pool-cooled conductors, although treatment of long helium passages at high vapor fractions are uncertain at best. One-dimensional transient analyses at fixed field exist for ICCS conductors.

2.4.2.1 Current transfer

Cabled conductors will not transfer all of the current from a normal strand to superconducting strands by the end of a quench/recovery event. Recent experiments seem to indicate that, while the amount of current transfer is quantitatively significant conservative design will dictate the assumption of no current transfer [MI84A], [MI84B] [TU84]. Design for large fractional strand-strand current transfers will require a larger data base.

2.4.3 Thermal Analysis

Available commercial thermal analysis codes appear adequate for the level of detail required for cool-down. Transient analysis of peak thermal stresses during and following a quench is beyond the capability of available finite element codes, although bounds can be put on the hot spot temperature excursion and magnet case thermal stresses. Purely thermal analysis of three-dimensional quench propagation in pool-boiling magnets are gradually becoming available [CH84B].

Thermohydraulic analysis of heat removal through internal cooling channels or in baths with some external pumping appears to be relatively well understood [MI79], although the effective hydraulic diameter of a complex winding pack, cooled by natural convection requires experimental verification [HE79B].

2.4.4 Mechanical Analysis

Available finite element codes are adequate for analysis of conductor mechanical performance. ICCS conductor conduit behavior under combined transverse and and longitudinal loads is currently under investigation using finite element analysis and experimental measurements.

2.4.5 Lead Design

Lead burnout is probably the most common failure in magnets. Up to a few thousand amperes, leads are available commercially. Design principles for leads are generally understood [HE68], but new features, such as combined high voltage and current or leads with thermal disconnects to reduce standby refrigeration [WI73] require development. The thermal performance of a lead design can be analyzed by finite difference techniques [PE84].

2.4.6 Joint Design

Electrical joints would have to be developed for the 50 kA INTOR conductor. There is an adequate data base for 20 kA joints with ICCS conductor from the 12 T program [ST82]. The general principles of joint design appear to be understood [RA75].

2.5 Manufacturing Techniques

There is an extensive manufacturing data base for conductors at the 8 tesla level, as represented by MFTF and LCP. There is a much more limited manufacturing data base for the Nb_3Sn

conductors, represented only by the Westinghouse LCP conductor and the much smaller MIT 12 tesla insert [HO84A] for HFTF.

2.6 Radiation effects

There is a limited data base on the effect of radiation on the critical current of NbTi and Nb_3Sn and on radiation-induced resistivity in stabilizers. It appears that damage to superconductors will not be limiting for machines of the INTOR class, although the data is not entirely unambiguous [WE83B], [UL75] [SN78] [HA83] [NA81] [WE82A] [WE832B] [SC77] [VA81]. Annealing of stabilizers through annual warm-ups to room temperature will probably be adequate [GU75] [GU83] [VA81] [BR80A] [CH82].

3 Insulation

3.1 Mechanical Properties

A very extensive data base exists on the degradation of polymer insulations as a result of gamma and/or neutron/gamma irradiation [SC83A] [SC83B] [SC83C] [IM79] . However, the interpretation of the data base remains controversial. A limited data base exists on polymer insulations irradiated at cryogenic temperatures [CO79A], [CO79B] [CO81] [EV81] [KA75] [VA77] [GU75] [LO79] [WE83A] [TA78] [TA83] [NI81] . Organic insulations such as G-10 CR suffer significant degradation of mechanical properties after a neutron-gamma irradiation comparable to that in the first layer of the INTOR TF coils. Polyimide insulations maintain the integrity of the bulk composite material up to another order of magnitude in irradiation [CO81]. Recent tests by Becker [ER82] [BE83], however, indicate that irradiated thin disks of organic insulations in compression do not fail up to irradiations several orders of magnitude higher than those being considered for INTOR. Since a magnet insulation is primarily in compression, but also includes cyclic effects of a delaminating shear, further extension of the data base is required to clarify the behaviour of cryogenic magnet insulations under irradiation.

3.2 Electrical Properties

A reasonable data base exists for G-10 CR type insulation under mechanical stress, including the effect of cyclical stress. The data base on low-temperature electrical insulation techniques for superconducting magnets has been reviewed recently by Schwenterly [SC84B], and has been reviewed previously for FED and INTOR [HU81].

Data on cyclical effects at low temperature of bonds and potting compounds is very limited and should be extended in simulated winding packs. The data base on strand-to-strand insulation in Nb_3Sn and NbTi ICCS conductors is almost nonexistent, and is now under investigation. The effect of radiation on electrical properties is less well characterized, but it appears that the limits on mechanical strength are more limiting for the INTOR application. The electrical properties of helium are degraded by radiation [PE83A] [PE83B], but may not be limiting, particularly for ICCS conductors which have no helium gap.

3.3 Thermal Properties

The strongest effect on thermal properties is probably debonding and cracking. Such thermal properties are not of primary importance to ICCS conductors [IW79C], which are internally cooled, and thus this data base is not being actively pursued in the United States Program.

4 Manufacturing Technology

A cost effective manufacturing technology for Nb_3Sn ICCS coils is to wind before reaction, with subsequent insulation and epoxy impregnation. A limited data base for this technique exists in the MIT 12 tesla insert [HO84A] for HFTF. There are also ceramic tapes [TH84] which may be suitable for application prior to windng and heat treatment, with only epoxy impregnation done after heat treatment. There is now no data base for coils impregnated by this method.

5 Refrigeration

An extensive data base exists for refrigeration through MFTF [ST79], LCP [RY79], the Energy Saver Tevatron at the Fermi National Laboratory [FE79], and the Colliding Beam Accelerator at the Brookhaven National Laboratory [BR80B] [BR80C] [BR81]. Some additional work on cold circulators and cold, low pressure compressors should prove cost effective [BE77]. There has been speculation that gas products produced by radiation will be released during warm-up, and then freeze out in the refrigerator. This can presumably be prevented by low temperature traps conventionally used with refrigeration systems.

6 Demonstration Coil Projects

This category has been included to emphasize the importance of integrated tests which combine all the previous data base considerations. these large-scale tests serve several purposes: (1) a data base is established on aspects which are scale dependent (passage length, realistic coil modulus, etc.); (2) manufacturing techniques are qualified prior to project production; (3) an integration discipline and project schedule focuses and drives research activities.

The current United States data base in superconducting magnet systems is represented by the LCP and MFTF Projects [KI84] [HA83], and the background that was developed for those 8 Tesla Projects. The United States Poloidal field Program [WE80] has been limited in recent years, in part because of the pressures of the LCP Project, and as a consequence, has a weak data base.

The high field mirror work has resulted in a 40 cm bore magnet at 12 tesla using monolithic Nb_3Sn conductors. Inserts for that magnet will also explore advanced Nb_3Sn internally cooled cabled superconductors (ICCS) and 1.8 K NbTiTa cabled conductors.

Conclusions

An adequate data base for tokamak superconducting magnets exists on the basis of existing programs, if design is restricted to moderate performance and light irradiation. However, performance at the level of INTOR requires expansion of the data base, depending on the topological options selected, in the specific categories described above.

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