21
MASTER

UCRL- 84110
PREPRINT

CONF-800980--3

RELIABILITY OF LARGE SUPERCONDUCTING
MAGNETS THROUGH DESIGN

Carl D. Henning

This paper was prepared for submittal to the
Proceedings of the 1980 Applied Superconductivity
Conference, September 29 to October 2, 1980,
Santa Fe, NM

September 5, 1980

The logo for Lawrence Livermore Laboratory, featuring a stylized 'LL' symbol and the text 'Lawrence Livermore Laboratory' arranged in a triangular shape.

Lawrence
Livermore
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

RELIABILITY OF LARGE SUPERCONDUCTING MAGNETS THROUGH DESIGN*

Carl D. Henning
Lawrence Livermore National Laboratory, University of California
Livermore, CA 94550

As superconducting magnet systems grow larger and become the central component of major systems involving fusion, magnetohydrodynamics, and high-energy physics, their reliability must be commensurate with the enormous capital investment in the projects. Although the magnet may represent only 1% of the cost of a large system such as the Mirror Fusion Test Facility, its failure would be catastrophic to the entire investment. Effective quality control during construction is one method of ensuring success. However, if the design is unforgiving, even an inordinate amount of effort expended on quality control may be inadequate. Creative design is the most effective way of ensuring magnet reliability and providing a reasonable limit on the amount of quality control needed. For example, by subjecting the last drawing operation in superconductor manufacture to a stress larger than the magnet design stress, a 100% proof test is achieved; cabled conductors offer mechanical redundancy, as do some methods of conductor joining; cryogenic test data should be multilayered to prevent arcing and insulation and interlayer insulation spaced to be compatible with the self-extinguishing of arcs during quench voltages; electrical leads should be thermally protected; and guard vacuum spaces are incorporated to control helium leaks.

1. Introduction

Superconducting magnets have benefited from intense international development since the advent of type II, low-temperature superconductors in the early 1960's. Progress has been good, but the uncertainty that continues to limit magnet performance is incompatible with the large applications projected. Currently the U.S. magnetic fusion energy community, in collaboration with the International Energy Agency, is pursuing the Large Coil Program²; a major goal is to remove technical uncertainties and promote industrialization. Comparable development efforts are being pursued by groups working with magnetohydrodynamics³ and high-energy physics.⁴ For a large-scale superconducting magnets are expected to be major and expensive components of a still larger energy research construction project. Accordingly, the reliability of the magnet must be commensurate with the enormous capital investment and program objectives. No longer is it sufficient to expect higher performance; that performance must be guaranteed with some margin of safety.

There are several ways to ensure the success of a superconducting magnet system: Effective quality control during construction may be one method. However, if the basic design is unforgiving and overly optimistic, even an inordinate amount of effort expended on quality control may still be inadequate. Creative design is the most effective means of ensuring magnet reliability and placing a reasonable limit on the quality control effort needed. This may also be the most cost-effective method, because 100% quality inspection is not only difficult, but also expensive. Realistic safety margins must be incorporated. Who would fly an

airplane if the wing struts were made of chain with little safety margin, when each link of the chain was manufactured by a new and different technique, and no proof test was possible until the plane was flying? Reliable parallel load paths (cable) rather than series (chain) load paths must be incorporated. Even with the most careful quality control, standard design practices (eventually formulated into codes) must be followed to ensure success.

II. Modes of Magnet Failure

Despite the benefit of accurate statistics, we may place past magnet failures into categories. In our discussion, specific references will be omitted to protect the unfortunate or guilty, but those of long experience should agree with the following ordering of failures: thermo-electrical instabilities, electrical shorts and arcs, cryogenic/vacuum failure, and mechanical failure. After a brief discussion of each of these failure modes, we shall, in Sec. III, describe ways to avoid them.

Thermo-Electrical Instabilities

A large fraction of superconducting magnets fail to achieve the design specifications for the magnetic field. Rarely is this the result of insufficient critical current in the conductor; it more often results from thermo-electrical instabilities that cause the conductor to make the transition from superconducting to normal resistance. Magnetic diffusion (flux jumps), mechanical slippage, and inadequate heat transfer are the usual culprits.

Electrical Shorts and Arcs

Because of the open insulation in most magnets, electrical shorts are often encountered. These prevent the coil from charging because of large inductive currents in the shorted turns. There was even an instance in which the inner part of a coil was extruded from the magnet by diamagnetic currents in the shorted windings. Also, during quench, large overcurrents induced in shorted turns have led to damaging local temperatures.

Still worse have been the numerous examples of coil arcing. Usually this occurs between layers or between the coil and structures where voltages are higher. Because of the large stored energy in the magnet, the arc easily melts the conductor and causes severe damage. In future larger magnets, the arc may even progressively melt enough conductors to cause total mechanical failure.⁵

Cryogenic/Vacuum Failure

Beyond the known frailties of helium liquefiers, there have been examples of cryogenic failures within magnets because of vapor locking. Liquid helium has sufficient surface tension to allow the liquid level to form as much as a 10-degree angle with the horizontal. If the vapor exit is sufficiently remote, part of the magnet winding may be above the liquid-vapor interface.

Cryogenic electrical leads occasionally plug with ice, causing loss of helium flow, overheating, and interruption of the inductive circuit. All of the magnet energy is dissipated in an electrical arc, and the magnet may be severely damaged.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Frozen seals and subsequent vacuum leaks are common. Also, helium leaks into the plasma region of magnetic fusion experiments have been a difficulty because of time-consuming leak-hunting methods. Eventually the leaks have been found, but only after great effort.

Mechanical Failure

Brittle Nb₃Sn conductor regularly fractures in the high-stress regions of research magnets. Once fractured, magnet performance is degraded because of the early onset of resistance, when cracks open at any positive net strain on the Nb₃Sn instead of at the usual 0.2% tensile strain. Experience with multifilamentary Nb₃Sn is more limited, but similar performance can be expected. Conductor failure is also caused by joint delamination due to strain discontinuities.

Although structural failures are rare occurrences in magnets, some instances of excessive bore-tube deflections have been suspected as the cause of unstable performance. In the future, the use of very large, highly stressed magnet structures raises the specter of catastrophic brittle failure. More attention to fracture mechanics and cyclical crack growth phenomena will be necessary.

III. Reliable Design Methods

Failure can be best avoided if we use designs that use redundancy and have inherent simplicity. Although an extra margin of safety may cost more, the cost can be offset by reduced requirements for quality control and risk insurance. In the next paragraphs, we suggest methods by which appropriate design can be used to avoid the failure modes just discussed.

Stability

Although intrinsic conductor stability can now be achieved by using twisted, multifilamentary superconductor, magnetic stability still remains

uncertain because of thermo-mechanical heating of the windings.⁶ Sometimes the "cold-end-recovery" criterion is used with success.⁷ However, extensive normal regions can boil away the local helium faster than replenishment can prevent interlayer propagation and a magnet quench. High current density designs have worked, but are usually dependent upon technology that may not extrapolate to larger applications. For large magnets, unconditional stability, corresponding to a Stekley number greater than unity, is the only safe criterion.⁸ Even then, care must be taken to limit mechanical motion and friction characteristics, so that local frictional energy dissipation does not exceed the local heat capacity of the helium.

At Lawrence Livermore National Laboratory, our design called for controlling conductor slippage and friction in the Mirror Fusion Test Facility (MFTF) magnet by placing two layers of Mylar* film between the conductor pack and the structural pressure face (as in Fig. 1). Experimentally, friction coefficients were measured to be about 0.15, and no stick-slip phenomenon was observed.⁹ A conductor winding tension greater than 2500 R limited winding tolerances (Fig. 2) to less than 0.1 mm/turn, which should be squeezed out early in the magnet charging cycle at a magnetic pressure of about 30 atm (300 psi),¹⁰ as depicted in Fig. 3. Thus we expect no large, sudden motions at full field.

Of course, the use of unconditional stability penalizes current density. However, because surface heat flux varies with the square of the current density, with modest expense in copper and winding space, both adequate stability and desired current density can usually be obtained. In large coils, the cost of the additional copper seldom either exceeds the cost of extra quality control or merits the risk associated with marginal stability.

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Fig. 1. Mylar slip plane used to control friction in the magnet for MFTF.

Fig. 3. Winding the NTF magnet.

Fig. 3. Compaction of NTF conductor pack.

Insulation Design

The weakest dielectric in a superconducting magnet is usually assumed to be the liquid/gaseous helium, and Paschen curves (as in Fig. 4) are used for the design. However, typical failures usually result either from tracking along insulators or from the initiation of arcs due to conductor slivers or metal chips. Therefore, good design philosophy suggests that ground-plane insulation should include at least two layers of insulating film (so that pin holes will not align), and that, to prevent tracking during quench, the edges of the film be overlapped at least 1 cm/kV. Additional sacrificial layers may be included in anticipation of damage during winding. Even structures that are distributed in the windings can be insulated by coating the grounded structure with Formvar or Teflon. The probability of shorting to the grounded structure is then reduced by orders

Fig. 4. Arc initiation and extinguishment for helium at 20°C.

of magnitude, because pin holes in the coating are unlikely to align with any slivers in the windings.

Voltages between adjacent turns and layers of a magnet should be kept below the arc-extinguishing range. Because slivers or metal chips will probably be present in any open winding, a good design would be one in which an interlayer are established during magnet quench would self-extinguish before the conductor was damaged. Unfortunately, the arc-extinguishing voltages and characteristics under realistic conditions are unknown. Work must be done in this area, because the data are fundamental to magnet design. In the interim, a design providing 1-mm spacers and 30 V between layers seems safe.

There is a trade-off between quench voltage and maximum conductor temperature during magnet quench (Fig. 5). To limit peak conductor temperature, the magnet current must be decreased rapidly; unfortunately, the inductive voltage increases directly. As a criterion, the peak conductor temperature (including the heat capacities of the insulation and the helium gas) should not produce enough thermal strains to cause yielding of a warm conductor in a cold winding pack. If we use NTF as a typical example, this corresponds to a temperature of about 200 K and a quench voltage of 1000 V.¹¹

Fig. 5. Relationship between quench voltage, peak temperature, and strain.

Cryogenic/Vacuum Design

The dynamics of helium bubbles in magnets are poorly understood. Yet, if the insulation is permeable in all directions and has channels more than 1-mm deep, then the bubbles should move freely through the windings. In addition, a plenum chamber at the top of the magnet must be incorporated and no solid surface near the magnet may be inclined less than 10 degrees from the horizontal. Otherwise, the upper surface of the magnet may become vapor locked and magnet performance may be degraded.

Cryogenic transition leads can burn out if the helium flow is interrupted. For reliability, the lead voltage should be monitored to remain below 100 mV/lead and a bypass valve provided (shown in Fig. 6) to increase the flow if needed.¹² Also, thermal ballast (e.g., stainless steel) should be added to the transition leads to increase thermal inertia, thereby permitting rapid discharge of the magnet before thermal runaway of the lead can occur.¹³

Fig. 6. High-inertia electrical lead and control.

It is unusually difficult to hunt for helium leaks in a magnet because of the enormous surface area exposed by the conductor and insulation. Particularly bad is the cut epoxy-glass laminate used for insulation, because helium gas travels along the glass fibers, which act as a leak path. Vacuum pressures may never be low enough to enable attaching the magnet to a mass spectrometer, and the pressure of the helium background gas may be so large that leaks cannot be found in the usual way. A good magnet design either provides for leak-hunting the cryostat prior to its being assembled with the magnet, or it provides a guard vacuum space from which small leaks may be differentially pumped. In MFTF, such a space (shown in Fig. 7) also provides a passage for helium during cooldown to prevent excessive temperature gradients and stresses in the structure.

Mechanical Design

Mechanically and electrically testing both ends of a magnet conductor provides some assurance of quality. Yet, uniformity through the conductor

Fig. 7. MFTF coil assembly detail showing guard vacuum.

length is then still unknown. Building magnets with long lengths of such monolithic conductors is a unique game of Russian Roulette, especially when one notes the variability in strength exhibited by the MFTF conductor (Fig. 8). However, if the conductor is properly designed, a 100% tensile proof test can be obtained. This test is achieved by adjusting the final drawing operation so that the stress on the conductor wire at least equals the operating stress, when adjusted for low-temperature strengthening effects as in Fig. 9. Since copper is relatively soft, the ability of the conductor to withstand the drawing operation guarantees the uniform presence of the Nb-Ti. Accordingly, some assurance of superconducting ability is guaranteed as well.

Further assurance of conductor quality is provided by cabling the conductors. By placing potential flaws in parallel instead of in series, we can obtain an enormous increase in reliability. Also, better conductor economics are realized because cold-weld joints can be randomly spaced during manufacture of the desired-length conductors, as long as the safety margin exceeds the capability of at least one cable strand. Conversely, when large monolithic conductors are manufactured, no breaks are permitted from biller extrusion through the last drawing operation; the conductor must then be cut to the required length. Experience shows that because of manufacturing breaks and trimming, sometimes 25% of the conductor is wasted.

High-field superconductors are especially difficult to wind because of their brittle nature. Recent programs to improve the strain tolerance of Nb₃Sn by multifilamentation and *in situ* techniques have been only partially successful.^{14,15} Winding

DISCLAIMER

This document is prepared as an account of work sponsored by an agency of the United States Government. It is not to be distributed outside the agency, nor is it to be used for any other purpose without the express written permission of the agency. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Fig. 8. Tensile tests at 4 K of MFTF superconductor.

Fig. 9. Conductor proof test by wire drawing force.

conductors with about 0.6% strain-to-fracture capability presents an unacceptable quality control problem for large magnets. Who can be sure that at some time the winding crew has not accidentally overstrained the conductor? Certainly the present overbending and hammering techniques used to wind Nb-Ti are inappropriate. Instead, a wind-and-react technique should be pursued; then, the usual methods can be used for coil winding, and the 150-hour, 650°C reaction schedule for Nb₃Sn is credible for heat-treating large coils. This technique offers several advantages: the ceramic insulation needed because of the heat would better resist neutron damage in fusion magnets; the large reaction furnaces required would obviate those needed anyway for conductor manufacture; and the furnaces would cost less than the quality control otherwise required for the winding operation.

Conductor joints should be of 100% mechanical strength and have enhanced heat transfer for stability. In simple, soldered lap joints (see Fig. 10), a strain discontinuity occurs which starts to peel the solder bond at the end, no matter how long the joint overlap is made.¹⁶ For the MFTF joint in Fig. 11,

Fig. 10. Strain discontinuity in soldered lap joints.

we achieve 100% mechanical strength and full redundancy by first co d-welding the conductor ends and then soldering on a copper channel. The cold weld approaches 90% of the parent conductor strength, while the copper channel (even without the cold weld completed) achieves 100% strength. Tapered ears on the 1/2-hard copper channel are annealed at the ends to prevent strain discontinuity and peeling.

No code or standard guidance exists for the design of magnet structures. Instead, one usually either resorts to following a portion of various codes such as Secs. III or VIII of the ASME Boiler and Pressure Vessel Code or depends upon one's own intuitions and calculations. However, it is easy to show that blind obedience to existing codes can result in either excessively heavy or dangerously fracture-prone structures. For example, paragraph UA-500 of the ASME code recommends the lower of either 1/4 of the tensile strength or 5/8 of the yield strength of a metal be used for design. For some stainless steels (e.g., 304), the resulting design stress would be limited by yield strength and would be excessively conservative, considering the very high tensile strength and toughness of stainless steel at low temperatures. For other materials, criteria based on Charpy impact tests at 77 K are not at all representative of the toughness and crack growth properties at 4 K, so that insufficient fracture resistance might result in a magnet built to those standards.

Although it is premature to adopt a code, Table I summarizes some recommendations for the design of superconducting magnet structures.¹⁷ The criterion that results in the lowest stress should be used. Note that the design stresses are higher than

Fig. 11. MFT conductor joint with full redundancies.

those recommended in paragraph PA-500 for two reasons: (1) substantial electromagnetic computer codes can resolve the forces on magnetic structures, and the environment is benign and noncorrosive. More restrictive, however, is the design stress dependence upon fracture mechanics at 4.2°K due to the tendency of material to embrittle at low temperature in a neutron flux. Here, the plane-strain constant, K_{IC} , must be found and must be compatible with the permissible flaw size a_c . More difficult to obtain is the crack growth rate, but such data are critical during critical loading conditions. Linear elastic fracture can be used to predict cyclic life with crack growth data from compact fracture specimens.

Table 1. Design stress criteria for a magnetic structure.^a

1/3 yield strength (primarily tension and unbonded stresses)
1/100 yield strength (primarily bending)
1/2 tensile strength
1/2 E_{IC}/a_c
4 lifetime cycles

^aThe lowest stress criterion is chosen from among those listed.

Austenitic stainless steels are the most widely used structural materials in superconducting magnets, e.g., for the 304 LN structure for MFT shown in Fig. 12. These materials possess good strength and stiffness at cryogenic temperatures. However, attention must be paid to the decreasing fracture toughness (Fig. 13) as yield strength is increased. Even more important is the degradation of weld toughness (Fig. 14) whenever the welds are in the principal stress areas. Furthermore, these welds must have

Fig. 12. The MFT structure under test of 304 LN with 306 LN welding electrodes.

Fig. 13. Decline of fracture toughness with increasing yield strength for stainless steels.

Fig. 14. Fracture toughness of welds in stainless steel.

carefully controlled ferrite levels; as shown in Fig. 15, too little ferrite causes microfissuring of the weld, whereas too much ferrite causes loss of toughness. Careful control of welding technique and chemistry is mandatory.

IV. Summary

Many reliable design options are known to magnet designers. These options need to be documented and organized to produce a design guide. Eventually, standard procedures, safety factors, and design codes can lead to reliability in magnets comparable to that obtained in pressure vessels and other structures. Without such reliability, large-scale applications in major systems employing magnetic fusion energy, magnetohydrodynamics, or high-energy physics would present unacceptable economic risks.

Fig. 15. Effect of ferrite content on weld toughness.

References

1. International Energy Agency Implementing Agreement for a Programme of Research and Development on Superconducting Magnets for Fusion Power, IEA, Brussels (1978).
2. P. N. Haubenreich et al., "Procurement and Testing of Superconducting Toroidal Field Coils in the Large Coil Program," in *Proc. 7th Symp. Eng. Prob. Fusion Res.*, Knoxville, TN 1977 (IEEE, 1978).
3. P. Marston, "National DOE MID Program Magnet Requirements and Initial Design," presented at IEEE Region 6 Conference, San Diego, CA, February 1980.
4. A. D. McInturff et al., "ISABELLE Ring Magnets," *IEEE Trans. Magn.* **MAG-13**, 275 (1977).
5. F. Arendt, Lawrence Livermore National Laboratory, private communication (1980).
6. N. N. Wilson, "Filamentary Composite Superconductors for Pulsed Magnets," in *Proc. Applied Superconductivity Conference*, Annapolis, MD, 1972 (IEEE, 1972), p. 385.
7. B. J. Maddock, G. B. James, and W. T. Norris, "Superconductive Composites: Heat Transfer and Steady State Stabilization," *Cryogenics* **9** 261 (1969).
8. A. R. Kan'trowitz and Z. J. J. Stokly, "A New Principal for the Construction of Stabilized Superconducting Coils," *Appl. Phys. Lett.* **6**, 56 (1965).
9. C. D. Henning et al., *Mirror Fusion Test Facility Magnet System--Final Design Report*, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-52935 (in preparation).

10. J. A. Horvath, Mechanical Behavior of Mirror Fusion Test Facility, Superconducting Magnet Coils, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-84548 (1980).
11. C. D. Henning et al., "Mirror Fusion Test Facility Magnet," in Proc. 8th Symp. Eng. Prob. Fusion Res., San Francisco, CA, 1979 (IEEE, 1979), p. 740.
12. C. D. Henning, "Cryogenic Electrical Leads," in Proc. BNL Study on Superconducting Devices and Accelerators, Upton, NY, 1968 (BNL, 1968); also Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL-71150 (1968).
13. J. H. Van Sant, "MTF Magnet Cryoability," in Proc. 8th Symp. Eng. Prob. Fusion Res., San Francisco, CA, 1979 (IEEE, 1979), p. 1761.
14. J. W. Ekin, "Strain Dependence of the Critical Current and Critical Field in Multifilamentary Nb₃Sn Composites," IEEE Trans. Magn. MAG-15, 197 (1979).
15. S. Foner et al., "Mechanical Properties of In-Situ Multifilamentary Nb₃Sn Superconducting Wires," Appl. Phys. Lett. 34, 241 (1979).
16. P. H. Rackov and C. D. Henning, Superconductor Joining Methods for Large CTR Magnets, Intermagnetics General Corp., Guilderland, NY, Report 1071-1 (1975).
17. C. D. Henning and E. N. C. Dalder, "Structural Materials for Fusion Magnets," in Trans. 5th Intern. Conf. on Structural Mechanics in Reactor Technology, Berlin, Germany, 1979 (The Commission of the European Communities, Brussels, 1979), Vol. N.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.