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**SAFETY OF SUPERCONDUCTING FUSION MAGNETS:
TWELVE PROBLEM AREAS**

by

Larry R. Turner

Prepared for EG&G Idaho, Inc. and the
U. S. Department of Energy Idaho Operations Office
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FUSION POWER PROGRAM

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ABSTRACT

Twelve problem areas of superconducting magnets for fusion reaction are described. These are: Quench Detection and Energy Dump, Stationary Normal Region of Conductor, Current Leads, Electrical Arcing, Electrical Shorts, Conductor Joints, Forces from Unequal Currents, Eddy Current Effects, Cryostat Rupture, Vacuum Failure, Fringing Field and Instrumentation for Safety. Each is described under the five categories: Identification and Definition, Possible Safety Effects, Current Practice, Adequacy of Current Practice for Fusion Magnets and Areas Requiring Further Analytical and Experimental Study. Priorities among these areas are suggested; application is made to the Large Coil Project at Oak Ridge National Laboratory.

1.0 INTRODUCTION

The purpose of this report is to call attention to twelve areas requiring further study for the safety of fusion magnets. It is based largely on the experience of the ANL Superconducting Magnet Group. The discussion deals directly with tokamak toroidal field (TF) coils, cryostable, cooled by pool boiling helium, with NbTi superconductor and copper stabilizer. Most of the remarks, however, apply more generally; in some cases applications to differently designed magnets are pointed out explicitly.

Two areas with important safety implications have been deliberately omitted from this report, structural stability and the achievement of cryo-stability. These two areas are central to all aspects of the magnet design, not to safety alone. Moreover, they are widely discussed in the literature, and any meaningful discussion here would require a much longer report.

Each of the twelve areas is discussed under the five subheadings: Identification and Definition, Possible Effects on Safety, Current Practice, Adequacy of Current Practice for Fusion Magnets, and Areas Requiring Further Analytical or Experimental Study. Under "Possible Effects of Safety," consequences have been followed as far as the breaking or melting of the current path, excessive thermal stresses, or overpressurization of the cryostat. Subsequent accident trees are beyond the scope of this report; some preliminary work on them has been reported.⁽¹⁻³⁾

"Current Practice" refers to current practice as the author is aware of it at Argonne and elsewhere; there has been no extensive literature search or questioning of colleagues at other institutions.

Discussion on current practice is limited to experience with large cryo-stable magnets. Most superconducting magnets are small, intrinsically-stable magnets with current densities an order of magnitude larger than those of the magnets being considered for fusion research. Moreover, many of them have been built with a philosophy that views a magnet failure as part of the learning process. Intrinsically-stable magnets are stable against quenches induced by flux jumps, but not against those induced by mechanical perturbations; cryo-stable magnets are stable against both.

The Large Coil Project (LCP), centered at Oak Ridge National Laboratory plays a unique role in superconducting magnets for fusion; these coils are the

only superconducting TF coils being built in this country. Consequently, there should be extensive dialogue between the LCP and the fusion magnet safety studies. Originally it was intended to include the appropriate LCP specifications under the "Current Practice" subsection of each area, but it now seems more useful to include a separate section on the LCP.

Finally, priorities for the recommended experimental and analytical studies are discussed.

2.0 QUENCH DETECTION AND ENERGY DUMP

2.1 Identification and Definition

A superconducting magnet is said to quench when a section of conductor goes from the superconducting state to the normal state, the normal region generates heat, the heat drives more conductor normal, and the normal region propagates until a large part of the conductor is normal and the current has decayed. Quench analysis is a particularly difficult part of magnet safety for a large cryostable magnet. On the one hand, such a magnet is designed so that it cannot quench; cryostability requires that there be sufficient cooling and stabilizer available that a normal region will shrink and disappear rather than grow. On the other hand, there are fault conditions that could quench a magnet, and large cryostable magnets have been known to quench.

A quench must be detected early, and the energy of the magnet dumped into an external dump resistor. The discharge voltage is the product of the magnet current and dump resistance, although the highest potential to ground can be reduced to half this voltage if the center of the dump resistor is grounded. If the discharge voltage is too high, there is danger of electrical arcing. If it is too low, the dump will last too long; and the conductor can rise to too high a temperature.

Choice of discharge voltage is not the only aspect of a dump with safety implications, however. The quench detection system must be sensitive enough to detect a quench early, but not so sensitive as to dump the magnet unnecessarily. The switching circuitry must switch the magnet to the dump resistor quickly and reliably and disconnect the power supply. The dump resistor must be ready to operate after long periods of standing by and must be capable of dissipating the magnet energy quickly and safely.

Nearly all of the tokamak reactor studies have addressed the problems of quench detection and energy dump; quite properly, it is the safety topic which has received the most attention.

2.2 Possible Safety Effects

A high discharge voltage can lead to electrical arcing, discussed below in Section 5. A slow dump can cause excessive heating of parts of the coil, leading to unacceptable thermal stresses. It can also cause extensive helium boiling, leading to cryostat overpressurization. A very slow dump or an undetected quench may allow the conductor to heat until it melts or until it decomposes the electrical insulation and arcs over. Okrent, et al.⁽³⁾ show an event tree for a quench.

2.3 Current Practice

A quench analysis, for quenches initiated by various fault conditions, will determine what discharge voltage is required for an acceptable temperature. The coil is designed for that temperature rise and that voltage.

To detect a quench, the voltages across two halves of a magnet, which should be equal by the symmetry of the halves, are compared. If they differ by an amount corresponding to the voltage drop across a specified length of normal conductor, the magnet is discharged.

As the normal region grows, more and more liquid helium is vaporized. The pressure in the cryostat increases until the pressure relief valve opens, emptying helium from the cryostat. Thereafter the quench propagates more rapidly. Powell⁽⁴⁾ recommends subsequent repressurization with warm helium gas to avoid the poor dielectric strength of low pressure helium gas, but much the same benefit can be achieved with a pressure relief valve which maintains a higher pressure.

The dump resistor should be permanently connected across the magnet terminals. In case of a quench, the power supply is disconnected and the magnet discharges into the dump resistor; thus there is no question of switches between the magnet and dump resistor failing to close. The power dissipated in the dump resistor during normal operation is negligible because the operating voltage is so low.

The dump resistor may consist of long lengths of stainless steel ribbon submerged in a tank of water.⁽⁵⁾ It should be of such a size that discharging the magnet may heat the water appreciably, but should not cause it to boil.

When the completed magnet is tested, it is discharged into the dump resistor several times, from progressively higher currents, to ensure that the dump circuitry is working correctly and that the dump resistor is sized adequately.

The superconducting coils of the T-7 Tokamak⁽⁶⁾ in Moscow quenched a number of times during its initial tests, presumably due to spurious inductive signals from coil motion. When the triggering threshold was raised to 5 V and 0.2 s duration, the spurious quenches stopped.

Powell⁽⁷⁾ gives reference to other methods of detecting quenches and extracting the energy from magnets.

2.4 Adequacy of Current Practice for Fusion Magnets

The methods currently used should be adequate, but the means of implementing those methods must be thought out. For example, the protection scheme must assure that the energy of all the TF coils is not dumped in the one coil which quenches. Clee and Trowbridge⁽⁸⁾ discuss the circuitry needed to achieve that. Moreover, the choice of discharge voltage continues to be a compromise between high voltages and high temperatures; but it may be that a safe compromise exists only for high currents, 50,000 A or higher. A quench analysis must be done to choose that compromise, but existing computer programs for quench analysis are decidedly inadequate.

Similarly, the quench analysis should determine how quickly a quench should be detected and the discharge started. This information in turn would set the requirements for the quench detection system. If it turns out that the method mentioned above, comparing voltage across two identical halves, is adequate, it could be used in any situation where there are identical halves, e.g. between the two pancakes of each TF coil in the ANL Experimental Power Reactor (EPR) design.⁽⁹⁾ It may be that a comparison of the supposedly equal voltages across all the TF coils may be sufficient to detect a quench early enough.

Likewise the principles involved in designing a dump resistor apply, but because of the much larger amounts of energy to be dumped (tens of gigajoules), the dump resistor itself may be much different.

Many alternate schemes for coil protection have also been considered. Yeh⁽¹⁰⁾ considers several and favors active switching of groups of coils with dump resistors. Boom, Moses and Young⁽¹¹⁾ propose that the non-quenching coils be switched to persistent mode and the energy from the quenching be fed back into the power supply.

2.5 Areas Requiring Further Analytical and Experimental Study

A general computer program for quench analysis should be developed for cryostable magnets; no such program exists today. The program should be sufficiently general that the properties of any particular magnet design could be readily inserted into it. Solution by backward difference methods would allow much larger time steps than are possible with forward difference methods.

Quench detection, switching, and dump resistor design depend on the actual coil design, and must await the choice of a design.

3.0 STATIONARY NORMAL REGION OF CONDUCTOR

3.1 Identification and Definition

The previous section explored the consequences of a propagating normal region of conductor. Here we examine a normal region which does not propagate. In a cryostable magnet, a stationary normal region can arise only from a failure of cooling of that region. With forced-flow cooling, it could result from blockage of the cooling passages to one region of conductor, while the remainder of the conductor continues to be cooled by cooling passages in parallel with the blocked one. For cooling by pool-boiling, it could result either from a massive blockage of the cooling passage or network of passages to the normal region or from the liquid level falling below the conductor region. In each case the region is characterized by good cooling at each end of the region, preventing its further growth, but poor cooling within the region.

3.2 Possible Safety Effects

The consequences of the stationary normal region depend on the temperature difference required to conduct the joule heating of the normal region to the cold end regions. If that temperature difference is only a few kelvin, there may be operational consequences (e.g. increased refrigeration load); but there will be no safety consequences. If the temperature difference is hundreds of kelvin, the electrical insulation can be damaged, permitting turn-to-turn and turn-to-ground electrical shorts, and possibly an overpressurization of the helium vessel. For intermediate temperature differences, thermal stresses can result leading to possible mechanical damage, structure weakening, or insulation destruction.

3.3 Current Practice

It is possible to create a stationary normal zone in a length of conductor operating near its cryostability limit in an experiment using a heater; potential taps and thermocouples are attached to detect the region; but there are no recorded instances of a stable normal region being observed in an operating cryostable magnet. Magnet designs prevent such regions by preventing uncooled regions, i.e. by preventing the liquid level falling below the top of the

coils and by providing a network of cooling channels to prevent massive blockage.

3.4 Adequacy of Current Practice for Fusion Magnets

The large size of the TF magnets and their orientation in a vertical plane makes the potential problems from stationary normal regions much more serious than those with existing magnets. Even experience with the large MHD dipole magnets, existing and under construction, cannot be extrapolated to the large TF coils.

3.5 Areas Requiring Further Analytical and Experimental Study

The credible length for a normal region is not known; it should be established both for force-cooled conductors and for those cooled by pool boiling. Willig and Moses⁽¹²⁾ discuss the critical length but do not estimate it; Powell et al.⁽¹³⁾ estimate it at 1 m.

Meanwhile an analysis should be done to determine the consequences of an uncooled length, for lengths up to a half turn. An example of such an analysis is shown in the Appendix.

4.0 CURRENT LEADS

4.1 Identification and Definition

Probably current leads have been responsible for more superconducting magnet failures than any other cause; some examples are given by Hsieh, et al. (14) Each lead generally consists of two parts: a normal lead from room temperature to liquid helium temperature, and a superconducting lead from the normal lead to the magnet itself. The leads experience the magnetic field of the magnet and so undergo a force, but their location makes them difficult to support. Because of their location outside the coil, they are also subject to excessive heat input and to arcing.

4.2 Possible Safety Effects

Failure of a current lead means a discontinuity of current, with all the safety consequences that entails. There will be high voltages and possible arcing, both at the lead that failed and throughout the magnet system. Large transient forces and eddy current heating are likely. High thermal stresses, overpressurization, and magnet destruction may occur.

4.3 Current Practice

The normal, gas-cooled leads are typically procured commercially. These are available with current capacities up to 20 kA or so. Beyond careful installation and insulation, the principal safety practice is to monitor the temperature of the leads, the voltage drop across them, and the gas flow through them, and to dump the magnet if these exceed prescribed limits. The leads must have sufficient excess capacity that if the gas flow stops, they can safely carry the magnet current throughout the magnet dump.

Safety practice for the superconducting lead is to secure it wherever possible, thus preventing motion, and to monitor the lead temperature via thermocouples or potential taps. It is common to use a double thickness or more of conductor in the lead in order to improve its thermal recovery. Use of Nb₃Sn leads in a NbTi magnet has been proposed for the same purpose.

4.4 Adequacy of Current Practice for Fusion Magnets

There are three areas in which the adequacy of current practice might be questioned. First, the support of both the gas-cooled and the superconducting leads may be more difficult because of the higher fields and more complex geometry of TF coils. Second, the much greater stored energy of a TF coil system may require a longer dump time; and the leads must survive this longer dump. Third, currents of 50 kA and higher have been proposed for TF coils; but gas-cooled leads of this capacity are not well developed. Thomas, Purcell, and Boom have recently reviewed the design of high-current leads.⁽¹⁵⁾ The first of these problems can probably be solved with careful design and engineering, but the other two require development effort.

4.5 Areas Requiring Further Analytical and Experimental Study

An experimental program should be undertaken on high-current (50,000 A or more) leads with sufficient excess capacity to survive a long discharge. Fortunately, such leads are largely independent of the magnet design.

5.0 ELECTRICAL ARCING

5.1 Identification and Definition

Electrical arcing is another frequent cause of superconducting magnet failure. (14,16) Arcing may occur between the current leads or between a lead and a grounded component, especially where the intermediate space is filled with helium vapor, which has a very low dielectric strength. It may also occur between turns, where the intervening insulation exhibits imperfections or has been damaged by overheating, overstressing, or radiation.

5.2 Possible Safety Effects

The safety effects of arcing are severe; it can lead to the destruction of the coil. Even if it does not, it may lead to shorted turns, with the effects described in Section 6. If arcing shorts out an entire coil, it will lead to the force imbalance described in Section 6.

5.3 Current Practice

Arcing is avoided by using insulating material with appropriate low temperature properties, and by ensuring that there are no chips or sharp edges that can break through the insulation. Where there is a potential difference across a helium-filled space, the gap must be wide enough; and the conductor must be mounted firmly to avoid deflections which narrow the gap.

After the magnet is assembled, it is checked against arcs to ground with a high voltage insulation breakdown tester. During that test, the cryostat contains helium gas at low pressure.

5.4 Adequacy of Current Practice for Fusion Magnets

Insulating materials, including helium, are not as well understood as they should be at liquid helium temperature. Moreover, radiation effects on insulation, characteristic of fusion reactor magnets, are even less well understood.

There have been recent measurements⁽¹⁷⁻¹⁹⁾ of the dielectric strength of helium liquid and vapor. There have also been measurements of the mechanical, but not the dielectric, properties of organic^(20,21) insulation at cryogenic temperatures; Nishijima and Okada⁽²²⁾ report the combined effects of low temperatures and irradiation on the mechanical properties of organic insulators. The GA-ANL TNS report⁽²³⁾ describes radiation effects on the electrical, mechanical, thermophysical, and dimensional properties of insulators, but only at room temperature and above.

5.5 Areas Requiring Further Analytical or Experimental Study

Insulating material must be studied in a simulated fusion reactor environment, including radiation. A number of kinds of insulating materials with potentially favorable properties should be included in the tests. Helium liquid and vapor should be studied in that environment as well.

6.0 ELECTRICAL SHORTS

6.1 Identification and Definition

Electrical shorts can be caused by arcing, but they can also be caused by point, line, and area contact between conductors. Both turn-to-turn and turn-to-ground shorts can occur. Turn-to-ground shorts are less likely to happen because there is much less conductor exposed to grounded surfaces than to other conductors and because providing thick, tough insulation between the coil and grounded surfaces imposed much less of a space penalty than would providing it between all turns. A single turn-to-ground short is not serious if the coil is otherwise ungrounded or grounded only through a fuse. The remainder of this section deals only with turn-to-turn shorts.

6.2 Possible Effect on Safety

Contact shorts have little effect on a superconducting magnet during steady state operation. The short resistance is much greater than the resistance of a turn of stabilizer, not to mention the zero resistance of the superconductor. The contact resistance of a short is found⁽²⁴⁾ to be essentially independent of temperature, while the resistance of the stabilizing copper decreases with decreasing temperature.

However, during the charging or discharging of the magnet, the shorted turn can have a large current induced in it by transformer action from the changing flux through it. This current can drive the turn from the superconducting state to the normal state, and cause overheating of the conductor.

With contact shorts, overheating may or may not occur, but with dead shorts from arcing, it almost certainly will.

6.3 Current Practice

During winding, a magnet coil can be checked for shorts by both eddy-current and resistance methods, but some shorts do not show up until the magnet is assembled and more difficult to check. In fact, some shorts may not show up until the magnet is cooled down or even until it is energized.

6.4 Adequacy of Current Practice for Fusion Magnets

Whether current practice is adequate depends on how serious the consequences of a short will be, and that can only be determined by analysis and experiment.

6.5 Areas Requiring Further Analytical or Experimental Study

An analytical study must be performed for a particular magnet design to determine what the consequences of a contact short would be. Experiments should then be carried out to check the analytical predictions.

7.0 CONDUCTOR JOINTS

7.1 Identification and Definition

Conductor joints are always potentially a safety concern in a superconducting magnet. If they are not well made, they are in danger of mechanical failure, as well as serving as a large heat input through their resistance. Even if they are well made, they are mechanically an irregularity in the coil structure and necessarily a source of heating.

Two kinds of joints are to be distinguished: Intra-coil joints, which are performed during coil winding, and inter-coil joints, which are performed during coil assembly. Intra-coil joints include joints between different grades of conductor and joints required if a length of conductor sufficient to wind a whole coil cannot be manufactured or spooled in one continuous piece. Inter-coil joints include joints between coils, or between pre-assembled portions of coils, e.g. pancakes. The distinction is useful because intra-coil joints can be made under almost ideal conditions in the winding line, with whatever space is needed for forming and inspecting the joints; while inter-coil joints must be made and inspected in the process of assembling the coils.

There are differences between joining monolithic conductor and joining cables. Also, joining forced-flow conductor requires a vacuum-tight joint of the coolant passage as well as a good electrical and mechanical joint. Nonetheless, it is sensible to discuss joints in general, but keeping these differences in mind.

7.2 Possible Effects on Safety

A poorly bonded joint or a joint in which one side protrudes out of the coil and can be sheared off when the coil is energized can lead to a current discontinuity. A joint with good mechanical strength but high electrical resistance causes heating and may produce a magnet quench.

7.3 Current Practice

Techniques by which safe joints can be made include: soldering,^(25,26) cold welding,^(25,27) resistance welding,⁽²⁵⁾ ultrasonic welding,⁽²⁸⁾ explosive welding,^(26,29) and electron-beam^(25,26) welding. Any of these could be

incorporated in the winding operation for intra-coil joints, but space limitations may preclude some of them for the inter-coil joints.

Inspection methods include ultrasonic and X-ray. In addition, resistance measurements can be made of completed joints. Acceptable joints must meet the criteria of having an electrical resistance less than a specific value determined by the allowable I^2R heating and a mechanical strength greater than a specified value, e.g. stronger than the parent material.

7.4 Adequacy of Current Practice for Fusion Magnets

Because of the high current capacity and novel design of conductors for fusion magnets, it is by no means clear which technique of making joints is most likely to produce safe, reliable joints. An extensive development program is required.

7.5 Areas Requiring Further Analytical or Experimental Study

Once a conductor concept, or a small number of different conductor concepts, is chosen, development work should begin on determining the best way to make safe intra-coil joints. Subsequently, work should be done to adapt that method to inter-coil joints or, failing that, to find a method that can make safe inter-coil joints.

8.0 FORCES FROM UNEQUAL CURRENTS

8.1 Identification and Definitions

If the TF coils of a tokamak are perfectly aligned, and all carrying the same current, they exert only a centering force on each other, pulling them toward the torus axis; the central support cylinder is made to support this force. The misalignment of the coils expected in assembly introduces out-of-plane forces on each coil, but these forces have been found⁽⁹⁾ to be relatively small, in fact to be smaller than the out-of-plane forces due to the pulsed poloidal field.

However, a large current imbalance among the TF coils would lead to very large out-of-plane forces which tend to pull the coils together like an accordeon.

8.2 Possible Effects on Safety

It is hard to imagine a worse accident in a tokamak reactor than the TF coils collapsing together. Cryostat rupture, vacuum failure, electrical discontinuity, all would result, with all their subsequent dangers.

8.3 Current Practice

As no superconducting TF coils now exist, it is more accurate to speak of current planning rather than current practice. Two approaches may be taken to this problem. One is to provide an outer structural shell connecting the TF coils and sufficiently strong to withstand the forces produced by any combination of currents in the coils. The other is to operate the coils in series; operating in series, the coils must carry equal currents, and there is no force problem.

Boom, Moses, and Young⁽¹¹⁾ describe the advantages and disadvantages of non-series operation. Yeh⁽¹⁰⁾ describes both, plus an intermediate case of several loops.

8.4 Adequacy of Current Practice for Fusion Magnet

The outer structural shell imposes a severe burden in cost and accessibility to the tokamak. If it were considered absolutely safe, the series current approach would be very advantageous. In fact, it is safe provided

there is no possibility of current arcing across an entire coil or many turns of a coil, bypassing the coil and providing field imbalance among the coils. The improbability of such an occurrence is described in the interim status report⁽³⁰⁾ for the GA-ANL TNS design study.

8.5 Areas Requiring Further Analytical and Experimental Study

A careful analytical study should be carried out to see if it is possible to design and build a coil which is not subject to shorting out. Such a study might then define some key experimental questions which must be answered before the choice can finally be made between the two approaches to forces from unequal currents.

9.0 EDDY CURRENT EFFECTS

9.1 Identification and Definition

Eddy currents are produced by the pulsed poloidal field coils and by the normal charging and discharging of the TF coils. More severe eddy current problems will be produced by any rapid unscheduled interruption of the toroidal field, poloidal field or field from the plasma. Eddy current effects occur not only in the magnets themselves, but also in the support structure, cryostats, and other systems of the reactor such as the blanket and shield. Yeh and Lue⁽³¹⁾ have studied the interaction between TF and PF coils during normal and abnormal operation.

9.2 Possible Safety Effects

Eddy currents can cause heating, forces and torques both in the magnet system and in other systems of the reactor. In the coils and elsewhere within the cryostat, the heating is a significant problem as it could vaporize helium and overpressurize the cryostat or could quench the magnet. The forces and torques are a problem both inside the cryostat (e.g. the liquid nitrogen-cooled heat shield) and outside (e.g. the blanket and shield).

9.3 Current Practice

Where changing fluxes occur, non-conducting or poorly-conducting materials prevent eddy current effects. If a conducting material is required, it can be segmented to limit eddy current paths. For example, the nitrogen shield can be made from multiple segments.

9.4 Adequacy of Current Practice for Fusion Magnets

The field from the fusion magnets engulfs the entire reactor. Thus eddy current effects can occur throughout the reactor. The design of all systems of the reactor must take eddy current effects into account. For example, a computer code was developed⁽³²⁾ to guide the segmenting of the blanket and shield to reduce eddy current effects; all parts of the reactor must be studied similarly.

9.5 Areas Requiring Further Analytical or Experimental Study

Eddy currents occur in many parts of the reactor, and differ from system to system and from one reactor design to another. To analyze them, one of the general purpose eddy current programs, such as those under development at the Rutherford Laboratory^(33,34) and Argonne^(35,36) should be adapted to fusion magnets.

10.0 CRYOSTAT RUPTURE

10.1 Identification and Definition

Obviously a cryostat should not rupture; but a cryostat rupture is conceivable through overpressurization, excessive mechanical stress, penetration by an object or the shearing off of tubing to the cryostat.

Cryostat rupture and vacuum failure are interrelated; either can cause the other. In order to be specific, this section will concern a failure between the helium vessel and the vacuum space, and the following section will concern a failure between the vacuum space and the atmosphere.

10.2 Possible Safety Effects

A rupture which allows helium into the vacuum can result in rapid heat transfer from the outer cryostat wall to the inner or helium temperature wall. The pressure in the helium space and vacuum space will rise, and the magnet may quench, which in turn will result in more heating and pressurization. A dangerous failure of the magnet system is possible.

10.3 Current Practice

Both the helium vessel and the vacuum space must be equipped with pressure relief valves or rupture disks to prevent overpressurization. These must lead to vent piping sized so that a low pressure gradient can empty the vessel quickly.

10.4 Adequacy of Present Practice for Fusion Magnets

The helium vessel is larger and more complex for the fusion magnets than for any existing magnets. Only a thorough analysis can determine what must be done to prevent serious consequences from a cryostat failure.

It may be necessary to provide separate helium vessels for each coil, although this would greatly complicate the support of the coils against their centering force and would certainly increase the heat load of the system.

10.5 Areas Requiring Further Analytical and Experimental Study

Analysis of heat transfer and pressure buildup and relief should be carried out for the helium vessel and vacuum space for a typical fusion reactor design. This should determine whether a common helium system for all coils is acceptable.

All potential causes of cryostat rupture should be studied as well.

11.0 VACUUM FAILURE

11.1 Identification and Definition

As described in the previous section, this section concerns a failure between the vacuum space and the atmosphere. Such a failure could occur for any of the reasons listed above.

11.2 Possible Safety Effects

Air in the vacuum space is even worse than helium, because the air can liquify on the helium vessel, transferring heat much more rapidly than the helium gas can transfer it.

11.3 Current Practice

The remarks of Section 10.3 apply.

11.4 Adequacy of Current Practice for Fusion Magnets

The choice of a common vacuum space for all coils or a separate vacuum for each must be made. It is possible to have common vacuum with separate helium vessels, but the opposite cannot be done.

11.5 Areas Requiring Further Analytical or Experimental Study

An analysis similar to that referred to in Section 10.5 should be carried out; it will impact the choice of common or separate vacuum space and common or separate helium vessel.

All potential causes of vacuum failure should be studied as well.

12.0 FRINGING FIELD

12.1 Identification and Definition

The TF coils will produce a weak fringing field, but one extending far from the magnets. The pulsed field from the PF coils will be even higher.

12.2 Possible Effects on Safety

There are three possible effects on safety: disturbance of instrumentation with consequent malfunction, attraction of iron objects to the magnets with possible penetration of the cryostat, and effects on personnel. The first two of these are readily dealt with in a straightforward manner, but the effects on personnel are hard to specify, because there is so little evidence of biological effects from low fields. S. J. St. Lorant⁽³⁷⁾ in his extensive review on biomagnetic effects concludes that magnetic effects are fully reversible and that there are no data which indicate a cumulative effect.

12.3 Present Practice

St. Lorant reports safety standards adopted in American and Soviet laboratories; these appear in Tables 1 and 2 (1 mT = 10 gauss).

Table 1. Safety Standards for Magnetic Fields Recommended by the Stanford Linear Accelerator Center

	Extended Periods (hours)	Short Periods (minutes)
Whole body or head	20 mT	200 mT
Arms and hands	200 mT	2 T

Table 2. Safety Standards for Magnetic Fields Recommended by A. M. Vyalov

	Field	Gradient
Whole Body	30 mT	50-200 mT/m
Hands	70 mT	100-200 mT/m

To prevent accidents from iron objects, the checklist for magnet charge should include a thorough check for iron objects each time the magnets are charged; all objects within a predetermined distance should be securely attached or removed.

12.4 Adequacy of Present Practice for Fusion Magnets

In the absence of new data, the present practice provisionally can be considered adequate.

Any fusion reactor design should include a map of the fringe field from the TF and PF coils.

12.5 Areas Requiring Further Analytical or Experimental Study

The fusion magnet program, perhaps together with the magnet programs for MHD and energy storage, should carry out a thorough literature search and analysis to find all that is appropriate to biomagnetic effects on personnel. Following that, an experimental program should be commissioned to find the needed data that do not yet exist.

13.0 INSTRUMENTATION FOR SAFETY

13.1 Identification and Definition

Proper instrumentation is required to monitor and respond to the safety concerns discussed in the previous sections. Temperature sensors, potential leads, strain gauges, liquid level indicators, and instrumentation for the leads must all be chosen so that any fault condition can be detected quickly, analyzed, and informed action taken.

13.2 Possible Safety Effects

Problems such as abnormal forces between coils, a propagating or stationary normal length, an uncooled length, an overheated or uncooled lead, an electrical short, high pressure in the cryostat, or a poor vacuum cannot be corrected without sufficient reliable instrumentation to inform the operator what is happening. The choice of instrumentation is an important safety consideration.

13.3 Current Practice

Existing large cryostable magnets are extensively instrumented for safety. Temperature sensors and potential leads are located in the coil region. Strain gauges are located in the coil and in the structure where high or anomalous stresses may occur. Liquid level indicators tell when the level is in danger of falling below the top of the coil. The leads are checked for temperature, voltage drop, and gas flow.

On the basis of this information, appropriate action is taken. In case of a severe problem, the magnet is discharged. For some situations, such as liquid level below the top of the coil, discharging the magnet may aggravate the problem by causing a magnet quench. In these cases and in case of some external problems such as power supply problems, the magnet is switched to a "free-wheeling" state in which the magnet terminals are connected together, the power supply is disconnected, and the magnet continues to operate but with a very slowly decreasing current. For less severe problems, a visible and audible warning is given so that the problem will be noticed and corrected.

13.4 Adequacy of Current Practice for Fusion Magnets

The current philosophy of instrumentation for safety seems adequate, but the choice of sensors will be unique to the fusion reactor. The magnets are so closely located to the rest of the reactor that the magnet must be made to respond to problems in the other systems and vice versa. In addition to other instrumentation, it may be desired to monitor radiation dosage at the coil.

13.5 Areas Requiring Further Analytical and Experimental Study

An analysis of the instrumentation requirements for fusion magnets should be made; such a study would be only slightly design dependent. The object of such a study would be to find areas in which existing sensors are inadequate. Suitable ones must then be developed and evaluated.

14.0 SPECIFICATIONS OF THE LARGE COIL PROJECT

The large coil project and the fusion magnet safety program can benefit each other; the LCP can serve as a touchstone for the analysis of the safety studies and can at the same time make use of the ideas developed by those studies. As an aid to this interchange, the specifications of the LCP related to the safety problem areas described above are discussed here. (38,39,40)

14.1 Quench Detection and Energy Dump

The choice of discharge voltage is up to the manufacturer, but can be no higher than 2000 V. The voltage of the acceptance tests is determined by the discharge voltage selected. The coil temperature upon quenching should not exceed 80 K under normal operating conditions or 100 K under extended conditions. Exceptions to these temperature specifications can be made if they can be shown to lead to no damage to the coil.

14.2 Stationary Normal Length of Conductor

There are no specifications about an uncooled length. Cryostability specifications require that the coil recover from the worst credible event, and in particular, that it recover from a half turn going normal.

14.3 Current Leads

The leads are supplied by Oak Ridge National Laboratory. They must operate for several minutes with no gas flow.

14.4 Electrical Arcing

In the acceptance tests, the coils are tested to a higher voltage than they will experience in operation. There are also other specifications on the insulation.

14.5 Electrical Shorts

There should be no shorts, but there is no specification about shorts per se.

14.6 Conductor Joints

Choice of joint methods is left to the manufacturer. There are requirements on total heat load and on the provision of voltage taps which will monitor joints.

14.7 Forces Between TF Coils

The coils will be tested individually and in various groupings, as well as all six together carrying equal currents. Consequently, the coils must withstand force conditions that would not occur in a reactor. Specifications include a number of coil current combinations which the coils must withstand.

14.8 Eddy Current Effects

The coils are designed for the forces and losses from pulsed coils simulating the poloidal field coils.

14.9 Cryostat Rupture and Vacuum Failure

The support structure and cryostat are designed to less than two-thirds yield stress under normal conditions and less than yield stress under extended (fault) conditions. The pressure rise under an air leak and a magnet dump is calculated. A rupture disk will be incorporated, and pressure tests will exceed the disk rating by a few atmospheres.

14.10 Fringing Field

There are no specifications for fringing field. However, Walstrom and Domm⁽⁴¹⁾ have pointed out that the compact torus has a lower fringe field than any of the other concepts for the toroidal simulation tests.

14.11 Instrumentation and Safety

Potential taps and temperature sensors are to be located in the coils for quench protection. Other instrumentation is provided by Oak Ridge.

15.0 CONCLUSIONS AND PRIORITIES

The above list of safety concerns is by no means complete, but it does include those that have been of concern to the Superconducting Magnet Group at Argonne.

Considerations of structural strength, along with cryostability, have deliberately been omitted from this report. However, it is appropriate to remark here that the choice of stress criteria for structural materials, welds, conductor, and conductor joints should be based on cyclic load, because the coils experience cyclic forces from the poloidal fields.

The highest priority should be attached to those areas which are very important, need to be determined early, and are virtually design independent.

1. The development of a computer program for the quench analysis of cryostable fusion magnets.
2. Development of a general purpose program for eddy current calculations applied to fusion magnets.
3. Analysis of series-connected TF coils, to determine if a credible accident could cause them to carry unequal currents.
4. An experimental program to develop current leads of capacity above 50 kA.
5. An experimental study of the behavior of electrical insulation under radiation at cryogenic temperatures.

Second priority should go to problems that are very important, but that are somewhat design dependent or for which the answers are not needed immediately. These include:

1. The analysis of the consequences of an uncooled length of conductor, plus an analytical determination of the greatest credible length for an uncooled region of conductor.
2. An experimental program on making safe joints in the conductors of fusion magnets, particularly high-current conductors.

Third priority should go to those which are both design dependent and not immediately needed or to those which are not of so high an importance. These include:

1. An analysis of electrical contact shorts and their effect on a large magnet, particularly during charging or discharging.
2. Analysis of the instrumentation needs of fusion magnets.
3. Analysis of possible vacuum failure, its consequences, and the adequacy of a common vacuum.
4. Analysis of possible cryostat failure, its consequences, and the adequacy of a common helium vessel.
5. Determination of acceptable fringing field exposure.

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APPENDIX A

Calculated Temperature of a Stationary Normal Length of Conductor: an Example

As an example of the consequence of an uncooled length of conductor, as described in Section 3, a calculation has been made of the central temperature of such a length, subjected to an initial perturbing heat pulse. The calculation has been performed with the program BACKSAFE, now under development at ANL. Assumptions include that the length is cooled by neither liquid or vapor helium, but that the adjacent conductor at both ends is cooled by liquid helium at 4.2 K. The results, shown in Fig. A-1, should be viewed as illustrative rather than definitive. For lengths of 0.9 m and above, the temperature rises to 500 K in two to five minutes, either for an undetected region or for a quench with discharge voltage of 2000 V. The temperature rise in fact is the same for all lengths between 1.8 m and 18 m. The temperature of an uncooled length of 0.36 m, however rises to only 52 K and remains at the temperature if not detected. With a 2000 V discharge, it rises to 44 K in 55 s and then drops. The magnets and conductor were assumed to have the properties described in the 1976 and 1977 ANL EPR designs.

A more complete analysis should consider the effects of varying the discharge voltage and time, as well as other parameters.

Figure A-1. Temperature rise in an uncooled length of conductor: peak temperature vs. time with lengths of 0.36 m, 0.9 m, and 1.8 to 18.0 m, for undetected (UD) and for a discharge with a 2000 V discharge voltage.

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