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Aspects of Safety and Reliability of Superconducting
Magnet Systems for Fusion Power Reactors*

by

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ABSTRACT

Existing superconducting (SC) systems are shown to be inadequate for predicting successful performance of fusion magnets, since they have simpler geometry, much smaller size and simpler safety systems, less complex loading conditions and cyclical variations in loads, and are not exposed to radiation. Even so, a number of mechanical and electrical failures have occurred in existing magnet systems. Using the UWMAK and various EPR SC magnet designs as starting points, a number of potential safety and reliability problems are analyzed for future Tokamak TF coil systems. The voltage withstand capability of TF coils appears to be only a few hundred volts during quenches because of release of H_2 from organic glues and insulators to form Penning mixtures with helium, ionization of He by gamma rays, and use of equipotential magnet structures. It appears impossible to remove any large fraction of the TF coil energy during a quench or other accident situation unless much larger conductor currents are used or a considerable degree of segmentation is employed for the TF coils. Substantial temperature inhomogeneities may be generated during quenches unless active safety systems are used. Elastic-plastic finite element analyses indicate that local plastic deformation of the reinforcement and conductors appears probable if moderate temperature inhomogeneities are generated in the coil. Electrical breakdown of the coil also appears likely with moderate temperature inhomogeneities. A number of highly reliable active and passive safety systems will be required. A large detector net (~1000 detection points) will be required to monitor the TF coil system for coolant channel blockages or other cooling failures which would cause a local region to monotonically increase in temperature while the rest of the coil remains superconducting. This will be very difficult to detect because of the ~100km long conductor lengths involved. Redundant detectors are necessary; to avoid false scram signals, coincidence between two or more detectors is probably required. A temperature equilization system (TES) to drive all conductors normal at an early stage of a quench or accident to minimize temperature inhomogeneities appears necessary.

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1. INTRODUCTION

A summary of operating experience on existing superconducting (SC) magnets[1] shows that a large fraction have had accidents resulting from various causes, such as inadequate lead cooling, electrical breakdown of insulation, coolant channel blockage, conductor movement, etc. In general, experience with existing SC magnets does not appear adequate for predicting the performance of SC magnet systems for fusion power reactors. Existing SC magnets tend to be built as part of experimental devices, and often cannot depend on extensive previous engineering experience. In contrast, commercial fusion SC magnets will undergo many evolutionary steps. On the other hand, however, existing SC magnets typically are much simpler than fusion SC magnets will be, since they have simpler geometry, smaller size, fewer safety systems, less complex loading conditions, and do not have background radiation.

A study of the safety and reliability aspects of fusion SC magnets has been initiated at BNL. Using the UWMAK and various EPR SC magnet designs as starting points, a number of potential problems for the TF coils have been analyzed, and possible safety systems requirements projected [2]. Such analyses are exploratory since detailed fusion magnet designs have not been developed, and knowledge of material behavior and analytical methodology is very limited.

As a focus for safety and reliability studies, magnet performance goals should be specified. For our purposes, four illustrative accident classes have been assumed. A class one accident would leave the TF coil (and reactor) inoperable, with replacement required, but no radioactive material would be released to containment. A class 2 accident would involve disruption of a TF coil with subsequent release of tritium and activated structure from the blanket and coolant system to containment, but not to the environment. Classes 3 and 4 would involve various amounts of radioactive release to the environment. A lower bound to the probability of a class one accident would appear to be $\sim 3 \times 10^{-2}$ to 10^{-2} per reactor year. The primary consequences would be economic with a long shutdown required for magnet replacement or repair. A lower bound to a class 2 accident would appear to be $\sim 10^{-4}$ per reactor year, which is comparable to the estimated probability for core melt-down in a LWR fission reactor [3]. Class 3 and 4 accident probabilities would have to be one to two orders of magnitude below these for class 2. Since class 3 and 4 situations would primarily depend on non-magnet safety system response, however, they are not further considered here.

These performance goals imply much longer mean time between failures (MTBF) than the total accumulated operating time on existing SC magnets. The longest accumulated time is only 2 years (on the ANL bubble chamber magnet [1]), compared to the desired 30 to 100 years for a class 1 and 10^4 years for a class 2 accident.

Figure 1 illustrates the analysis tasks involved in fusion magnet safety studies. Quantitative estimation of accident probabilities and risk assessment of the type now carried out for nuclear reactors [3] involves tasks inside the C level. For fusion magnets, work has only just started on tasks inside the A level, involving only qualitative identifications of important potential problems. It will be several years before B level tasks involving integrated magnet safety systems can be carried out, and much longer to C level tasks.

Various types of magnet safety systems are possible: detection systems (DS) to provide information on conditions (temperature, pressure, etc.) in the SC magnet; temperature

equalization systems (TES), to drive all regions of the SC winding normal at the same time, so as to minimize temperature differences; energy dispersion systems (EDS), to minimize energy deposition differences in the SC winding; energy removal systems (ERS), to dump magnetic energy external to the magnet, and containment systems (CS), to contain SC magnets in the event of failure of a portion of them.

Figure 2 illustrates an operating hierarchy of magnet safety systems. The volume of sensor information will be far too great to handle manually, and a computer processing/discrimination/decision system will be required with mandatory shutdown for certain conditions. Human decisions can be incorporated for additional decisions to shutdown, but human error rates are probably too great [3] to permit negation of automatic shutdown decisions. Appropriate interlocks and system malfunction tests will form part of the overall hierarchy.

2. POTENTIAL ACCIDENT INITIATORS AND PATHWAYS

Many accident initiators and pathways can be visualized for fusion SC magnet systems; in general, magnet safety analyses appear more complex than those for fission reactors. The same basic techniques can be applied, however. In an event tree (Figure 3), possible pathways leading from a given initiating event (i.e., a break of a superconductor) are laid out. Depending on safety system response, the accident pathways lead to various possible consequences. In a fault tree (Figure 4), the possible pathways leading to a given event (i.e., a conductor break) are laid out. Both examples shown are greatly simplified from the actual processes in a real case, and only depict principal events.

A variety of electrical, heat transfer (using the Heating-3 code), and structural (using 2 dimensional elastic and elastic-plastic finite element codes) have been carried out for the UWMAK-I and various EPR TF coil designs [2]. Among the conclusions are: coil breakdown voltage is probably well below 1000 volts, due to breakdown through helium; helium forms Penning mixtures of very low dielectric strength (less than $3 \text{ volt cm}^{-1} \text{ mmHg}^{-1}$) with H_2 released from irradiated organic insulations and glues; irradiation by activated components produces high levels of volume ionization in insulators, including helium; electrical breakdown can readily occur between widely separated conductors through equipotential reinforcement structures (e.g., the steel discs (Figure 5) in the UWMAK-I TF coils and aluminum bolts holding the discs together, and the welded steel conduits in the ORNL EPR design); relatively small temperature differences between different regions in a coil during a quench can produce sufficient voltages to cause electrical breakdown (Figure 6), and can also cause localized plastic yielding of the conductor and/or reinforcement (Figure 7) due to uneven distribution of structural stresses; only a small fraction of the stored magnetic energy can be dumped external during a quench or accident situation, because of voltage breakdown limitations; heat transfer rates are very slow, because of the large coil size and degree of cooling available with the cryogenic helium in the coil, and large temperature differences (Figure 8) will be generated in the coil during quenches, unless suitable active safety systems can be devised; if coolant channels are blocked by fracture of spacers and/or insulators, small localized conductor regions may monotonically increase in temperature until they fail, unless such regions are detected in time to shut the coil down safely; detection of such small "hot" zones, on the order of a meter or so in length, will probably be difficult, because of the long conductor lengths involved (130km in a UWMAK-I coil) and the presence of background coil motions and time varying magnetic fields; and internal arcs due to electrical breakdown

or conductor failure will spread across the coil winding as a result of the large dissipative power, tending to generate secondary arcs and localized failure in the neighborhood of the original arc.

3. MAGNET SAFETY SYSTEMS

Various safety systems can be incorporated to prevent failures arising from initiators of the types summarized above. Here we consider in more detail the types of safety systems discussed briefly earlier.

For the detection system (DS), detectors should monitor temperatures, lead coolant flow and temperature, helium level, pressure and/or flow to the SC windings, and periodically check for electrical shorts. On the order of 100 detectors would probably be required for such monitoring. The principal detection problem, however, will probably be the early detection of local "hot" spots in the SC winding where blocked or inadequate cooling is causing a small region to monotonically increase in temperature with time. Unless such a region is detected and the coil is shutdown, the conductor could fail at this point, causing internal arcing and destruction of part of the coil. As an example, if the UWMAK-I TF coils had two "hot" spot detectors per disc, approximately 1000 detectors would be required for the entire TF coil assembly. The conductor length monitored by each detector location would be ~2 kilometers, and the voltage signal from a 1 meter long "hot" spot in this interval would only be a few tens of millivolts. Very small motions of the disc or conductor (e.g., an additional slow increase in strain of $\sim 10^{-7}$ per second) would generate spurious voltage signals comparable to that generated by "hot" spots. The signal to noise ratio of such detectors will be low even with 1000 detection points. Further, each detection location will have to have multiple detectors, so that the probability of missing "hot" spot accident initiator would be less than 10^{-4} /year with achievable instrumentation reliability, approximately 5 redundant detectors are required per detection location, with coincidence agreement between any two to reduce the false scram signal rate to acceptable levels, i.e., one per year.

In a UWMAK-I TF coil, an upper limit to the allowable voltage across the coil leads during a quench is probably on the order of 500 volts, because of breakdown paths through helium at the disc-conductor or bolt-conductor interfaces with 10,000 Amp design conductor current, several thousand seconds would be required to externally dump the magnetic energy of the coil, compared to the ~200 second time required to dump energy internally as heat after the coil goes normal. [Magnetic coupling to adjacent SC coils will transfer some coil energy, but most will remain in the quenched coil.] As a result, if a local "hot" spot is detected, the safest course is probably to dump coil magnetic energy internally in the SC winding, since the long time for external dump may result in conductor failure. Accordingly, Energy Removal Systems (ERS) do not appear practical for quench or accident situations in the TF coils as designed and much higher conductor currents ($\sim 10^5$ Amp) or extensive coil segmentation (i.e., each of the 30 UWMAK-I discs in a TF coil might have its own external leads for energy removal) must be employed if ERS's are to be used.

Since heat transfer is in general not adequate to ensure uniform temperature distributions in the coil if the magnetic energy is dumped internally during quenches or accidents, some safety system must be present to minimize temperature inhomogeneities. Temperature differences on the order of 100°K may lead to localized yielding of the reinforcement and/or conductors, and may also lead to electrical breakdown due to differential voltages in the

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winding. Both Temperature Equalization Systems (TES) and Energy Dispersion Systems (EDS) are potentially possible modes for minimizing temperature differences. A TES would function to minimize differences in energy deposition rates throughout the coil, by driving the coil normal everywhere as soon as a situation was detected that could lead to a local conductor and/or reinforcement failure if shutdown did not occur. There are several methods of accomplishing this. The two most promising ones appear to be either auxiliary heater wires, or rapid dump of the liquid or supercritical helium coolant, followed by rapid injection of warm helium gas. Whatever temperature inhomogeneity existed when the TES was activated would tend to persist, but would not tend to grow, as it would if shutdown did not occur. An EDS would in general not appear very useful, since it is difficult to smooth out non-uniform energy deposition distributions by conduction or convection in large TF coils. An EDS appears very attractive if an arc occurs in a coil, however. Since the coil will not be subsequently reusable, an EDS that generated widely distributed secondary arcs by electrical breakdown (e.g., by HV cable) would prevent coil disruption caused by excess local energy dump.

Finally, a containment system (CS) of close fitting coil cases for TF coils may be desirable. These cases could be designed to contain the SC and reinforcement even if complete failure occurred. The case could be at room temperature, and since it could undergo some yielding if loaded, need not be an expensive, massive structure. If constructed of aluminum, it could also function as a partial transformer coupled ERS during accidents or quenches.

- [1] HSIEH, S.Y., et al., "Summary of Existing Superconducting Magnet Experience and its Relevance to the Safety of Fusion Magnets", Proc. of 6th Symposium on Engineering Problems of Fusion Research, p. 116, San Diego, California, Nov. 18-21, 1976.
- [2] POWELL, J.R.(Ed.), "Aspects of Safety and Reliability for Fusion Magnet Systems, First Annual Report: Magnet Safety Studies" Group, BNL Report (in preparation).
- [3] "Reactor Safety Study, An Assessment of Accident Risks in US Commercial Nuclear Power Plants," WASH-1400, U.S. AEC, 1974.

Fig. 1 Analysis Tasks for Fusion Magnet Safety Studies

Fig. 2 Operating Hierarchy of Magnet Safety Systems

Fig. 3 Event Tree for Accident Pathways Following Conductor Break

Fig. 4 Fault Tree for Pathways Leading to Conductor Break

Fig. 5 Electrical Breakdown Paths in UWMAK-1 TF Coil Structure

Fig. 6 Electrical Voltage Produced in UWMAK-1 TF Coil with Temperature Inhomogeneities

Fig. 7 Plastic Deformation Zones in UWMAK-1 TF Coil with Temperature Inhomogeneities

Fig. 8 Temperature Inhomogeneities in Direction Normal to UWMAK-1 TF Coil Discs During Magnet Quench

FIGURE II.1.2

A LEVEL - QUALITATIVE IDENTIFICATION OF IMPORTANT POTENTIAL ACCIDENT SEQUENCES AND ENGINEER SAFETY FEATURES

B LEVEL - QUALITATIVE DEFINITION OF INTEGRATED SAFETY SYSTEMS FOR MAGNETS

C LEVEL - QUANTITATIVE ESTIMATE OF RELIABILITY OF INTEGRATED MAGNET SAFETY SYSTEMS AND RISK ASSESS

HIERARCHY OF OPERATING MAGNET SAFETY SYSTEMS

FIGURE II.1.3

SIMPLIFIED EVENT TREE - INITIATOR IS CONDUCTOR BREAK

(NO EXTERNAL CASE FOR COIL)

SIMPLIFIED FAULT TREE FOR CONDUCTOR BREAK
(NO EXTERNAL CASE FOR COIL)

FIGURE IV.7.2
POTENTIAL ELECTRICAL BREAKDOWN PATHS IN
DISC TYPE TF COIL CONSTRUCTION

FIGURE IV.7.11

EFFECT OF TEMPERATURE INHOMOGENEITIES
IN UWMAK-1 TF COIL ON
INTERNAL VOLTAGE DURING QUENCHES

CIRCULAR QUENCH NEAR OUTSIDE RADIUS

TRANSIENT TEMPERATURE PROFILE OF UWMAK MAGNET DISC
 (CALCULATION BASED ON 12 DISCS WITH HELIUM COOLANT AND MICARTA INSULATION BETWEEN THE DISCS)