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SAFETY SYSTEMS AND STRUCTURAL ASPECTS
OF SUPERCONDUCTING MAGNETS FOR FUSION POWER REACTORS*

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ABSTRACT

Potential safety systems are examined for superconducting magnets in fusion power reactors. Because of current and voltage limitations, energy removal systems do not appear practical for dumping significant amounts of energy external to the magnet for designs currently envisioned. Some type of Temperature Equalization System appears necessary to minimize temperature inhomogeneities if energy is dumped internally during a quench or other accident situation since inhomogeneities may cause electrical breakdown and/or structural damage. Large detection nets appear necessary to detect potential "hot spots" before they can damage the magnet. Qualitative fault/event trees have been developed for some potential accident pathways; however, many years will be required before quantitative risk assessment studies can be made.

In general, existing large superconducting (SC) magnet systems have operated safely and reliably. However, future SC magnet systems for fusion power reactors will represent a very large extrapolation over existing SC systems, in terms of size, stored energy, effects of pulsed force loadings (in the case of Tokamak fusion reactors) and operating time. Complex and reliable safety systems will be incorporated in fusion SC magnets to ensure that failure rates are at the very low levels required of nuclear power plants. Safety systems for present SC magnets are far less developed and complex than those that will be required for fusion SC magnets. Fusion magnet designs have generally been conceptual in nature, and relatively little attention has been paid to their associated safety systems. It is appropriate to examine safety considerations at this early stage, however, since they can strongly affect the directions that magnet designs will take. Retrofitting safety systems to detailed magnet designs that have evolved without early consideration of such safety systems could involve considerable delays and expense.

Figure 1 shows the overall pattern likely to be followed in safety analyses of SC fusion magnets, based on the pattern that has developed for fission reactors. Tasks in the C Level Boundary, involving quantitative estimates of the probabilities for various possible accident pathways are being carried out in LWR fission reactor safety studies.¹ To reach this point in magnet safety studies will probably require several decades of development and extensive experiments to determine component failure data. Present safety studies for fusion magnets are still at an early stage inside the A Level Boundary.² A number of possible accident sequences and initiating events have been identified for some conceptual fusion magnet designs. It will be several years before fusion magnet designs are detailed enough that one can begin to work

inside the B Level Boundary, that is, the qualitative identification of all accident sequences common mode failures, and integrated safety systems for a complete self-consistent magnet design.

Figure 2 schematically illustrates the inter-relationships between the various safety systems that are likely for fusion SC magnets. A wide variety of detection systems (DS) will be necessary to sense the pressure, temperature, voltage, etc., characteristics of all parts of the magnet. Fission reactors typically require several hundred sensors. It is likely that fusion magnets will need a considerably greater number. The most difficult detection task, and the one requiring the most sensors, is probably the detection of "hot spots" in the SC winding. A single UWMK-I TF coil,³ for example, has ~ 130 km of 10 KA conductor, and it is possible for a relatively short section, e.g., ~ 1 meter in length, of conductor to undergo a non-recovering transition to the normal state by a number of processes such as coolant channel blockage (spacer cracking, impurity plugging), conductor degradation, etc., and then monotonically increase in temperature. If this condition is not detected fairly quickly, the conductor could melt or break causing an arc, which then could spread to adjacent portions of the winding. To unequivocally detect small hot spots in the presence of background noise from pulsed fields, coil motion, etc., will require many detection locations. For a UWMK-I magnet system, for example, at least two detection locations for each disc seem necessary (~ 4 km of conductor per disc). This corresponds to ~ 1000 detection locations for the complete TF magnet system. In order that detector failure does not cause the safety system to miss a hot spot, several redundant detectors will be required per location. Also, to prevent excessive spurious magnet scrams, coincidence between two or more detectors at a given location would be required to activate a safety response. For typical nuclear instrumentation reliability values of $\sim 10^{-6}$ failures/hour, with performance goals of 1 spurious scram/year and $\sim 10^{-4}$ events/year where a hot spot was not detected before arcing could be prevented an arrangement of 5 redundant detectors at each location and a coincidence agreement between any two of the redundant detectors would be required.

The massive volume of information from the DS network will have to be processed by computer, with appropriate discrimination criteria for display. Scram decisions will also have to be made by computer, with human decisions only permitted for auxiliary initiations of scrams, and not to override automatic decisions. Studies indicate that in high stress emergency situations, the human error rate, where a decision worsens the situation, is large, on the order of 30%.¹ Appropriate data and

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computer tests will have to be carried out and the system shut down if serious malfunction occurs.

The active safety systems in Figure 2 are grouped into 3 categories: Temperature Equalization (TES), Energy Dispersion (EDS), and Energy Removal (ERS). If significant amounts of magnet energy will be dumped as heat in the coil during a quench or accident situation, the TES drives the conductors normal at all points at an early stage, in order to minimize subsequent temperature inhomogeneities. These can cause severe problems and will be discussed later. The best candidates for a TES appear to be either a net of auxiliary non-inductive heating wires wound with the conductor or a rapid He dump followed by repressurization with warm He gas. The function of an EDS would be to prevent an excessive concentration of energy at any given point by dispersion of the energy deposited in the coil. If an arc should start at a given point, for example, by breaking of a conductor, the large local rate of energy release (e.g., several hundred KW in a UWMAK-I TF coil, which would melt one kg of coil per second) would quickly involve adjacent conductors. A spreading cascade of secondary arcs could then locally deposit enough energy to cause serious weakening of the coil with potential risk of coil disruption. An EDS that created secondary arcs in a widely distributed pattern in the coil after a primary arc occurred could prevent serious local concentration of deposited energy. Such an EDS could easily be provided by incorporating a net of small, pulsed HV cables to cause breakdown leading to distributed secondary arcs.

Dumping of the magnet's energy external to the coil by an ERS is very desirable, since it reduces the chances of coil damage. Unfortunately, for the fusion SC magnet designs considered so far, an ERS does not appear to be feasible in quenches or accident situations, since the voltage across the magnet leads required to remove a significant part of the coil energy in the time scale dictated in a quench or accident would probably result in electrical breakdown. For example, if the necessary time scale for energy removal is on the order of 100 seconds, a voltage of $\sim 10,000$ volts across leads would be necessary to remove energy from a UWMAK-I TF coil. For this magnet, the allowable voltage will probably be only a few hundred volts, so that a meaningful ERS would require either a much higher conductor current (e.g., $>10^5$ amp instead of 10^4 amp) or a high degree of coil segmentation, e.g., a pair of leads for each of the 30 discs in each TF coil. Several factors contribute to the low voltage capability: release of H_2 from radiolytic decomposition of organic insulators and glues, which causes a Penning effect in He gas leading to low dielectric strength in quenches [≤ 3 volt/cm torr (std.)], large background ionization generation by radiation from activated blanket and shield components, and electric stress intensification caused by coil reinforcement structures. For example, Figure 3 shows some of the potential breakdown paths in a UWMAK-I TF coil. The stainless steel discs form equipotential surfaces, and breakdown can occur between widely separated conductors by arcs from one conductor through a small He gap (~ 0.1 cm) to the disc and through another small He gap (0.1 cm) to another conductor somewhere on the disc. Even more serious, the aluminum bolts (not shown) passing transversely through and tying together the assembly of 30 discs form ready breakdown paths for conductors on opposite sides of the TF coil.

Even if an ERS is not used and there is no voltage across the magnet leads, internal IR voltages can appear if there are temperature inhomogeneities in the SC winding. [In the UWMAK-I design, IR voltages will appear

even if the temperature is uniform, since outer conductor turns have considerably less copper/amp than inner turns. This can be remedied by a constant copper/amp ratio.] However, even for a constant copper/amp ratio, figure 4 shows that relatively small temperature inhomogeneities during a quench in a UWMAK-I TF coil can cause electrical breakdown. For example, if 10% of the coil is only $40^\circ K$ hotter ($T=T_1$) than the rest of the coil ($T=T_0$) the developed IR voltage will exceed 1000 volts. The estimated breakdown voltage is at most ~ 1000 volts, not allowing for electric stress intensification. A more realistic breakdown voltage would probably be only a few hundred volts. It will be very difficult to achieve the degree of temperature homogeneity required to prevent breakdown during quenches.

Figure 5 shows a sample event tree assuming that a conductor break occurs. It is considerably simpler than the event tree that would be drawn for a detailed magnet design, since many possible branching routes reflecting behavior of safety system components are not shown. Other event trees have been developed, and in general, there appear to be hundreds of potential accident pathways. Quantitative analysis of accident probabilities will probably involve considerably more effort than with the simpler fission reactor systems, and is not possible to carry out at this time. Even a relatively complete qualitative accounting of potential pathways will involve a considerably greater safety analysis effort than has been attempted to date.

Figure 6 shows a sample fault tree for the routes leading up to a given event, i.e., a conductor break. Again, many fault trees can be drawn for other accidents and the one shown is considerably simplified from that appropriate to a detailed magnet design. Fault trees show pathways leading to a given event and are considerably more difficult to construct than event trees which show the various events following an assumed initial accident initiator.

A number of heat transfer analyses have been made of the UWMAK-I TF coil, using the 2D version of the finite difference heat transfer code, Heating-3. Detailed results are given in the annual report.² In general, because of the large physical scale of the TF coil, and the good cryostatic stability of the conductor, if a quench zone appears (due to partial blockage of some coolant channels or other causes), it will either spread very slowly or remain localized, so that a TES or rapid energy dump by an ERS is mandatory if unacceptable damage to the coil is to be avoided. Temperature inhomogeneities are very severe in the direction normal to the plane of 30 discs making up the TF coil.

A variety of structural safety analyses have been carried out on the UWMAK-I TF coil. One aspect of this study has been the examination of the effect of temperature inhomogeneities as the structural integrity of the TF coil, using 2D elastic and 2D elastic-plastic large capacity (~ 2000 elements) finite element structural codes.

Figure 7 shows results of one of a number of analyses with the elastic-plastic code of the effects of a circular quench zone with parabolic temperature distribution over a portion of the radial thickness of the TF coil. Considerable plastic deformation of the steel reinforcement and conductors occurs with relatively modest temperature inhomogeneities, i.e., the hottest point is only $\sim 300^\circ K$ above the rest of the coil. The coil is damaged enough that attempt of further operation could lead to subsequent accidents, through "hot spots", conductor failure, etc. Even more worrisome are small temperature inhomogeneities between discs. If one (or a few) disc(s) in the 30 disc assembly is at

a slightly higher temperature, i.e., $\sim 100^\circ\text{K}$, than the rest, the relatively greater radial expansion of the hotter disc(s) will cause yielding and/or rupture of the outer bolts holding the assembly together, followed by a "zippering" effect as the zone of damage to the bolts moves inwards to the center of the assembly. The coil would then be too damaged for further operation, even if it could be safely shut down. Another potentially worrisome condition is that substantial temperature inhomogeneities will exist between the conductors and the UWMAK-I discs even if the TES works and all conductors go normal at approximately the same time in a quench or accident situation, because of the high thermal resistance caused by the epoxy glue layer present between the conductors and their steel reinforcement discs. Structural analyses indicate large stresses on the order of tens of ksi will occur, resulting in potential plastic deformation of conductors and/or reinforcement and fracture of glue and/or mica spacers between discs, with subsequent possible blockage of coolant channels and excessive conductor movement.

A number of structural analyses have also been carried out on the effects of failed regions in the UWMAK-I TF coil. As an example, figure 8 shows the stress distributions and zones of yielding around a failed region that extends from the outer edge to 10% of the 93 cm radial thickness of the coil. These analyses were made using a 2D elastic-plastic finite element code, with coil material properties represented by average homogeneous values. [The degree of heterogeneity associated with conductors, insulators, etc., is much too great to allow exact modeling of the actual coil structure.] The analyses indicate that, to the limits imposed by the model approximations, that substantial failed regions, i.e., up to at least 30% of the radial thickness of the coil can be present without resultant coil disruption, though some local plastic yielding can take place. However, these analyses do not allow for progressive yielding and failure of individual conductors in the zone around the tip of the failed region, which then might result in a zippering action. That is, as conductors fail, causing local arcs, the high stress zone then could shift to the adjacent conductors, causing them to progressively fail, till enough of the coil cross section failed to cause coil disruption. Failure analysis of this accident mode requires much more sophisticated structural analysis codes than presently exist, and meaningful conclusions as to the chances of failure cannot be drawn until such analyses have been carried out.

Three-dimensional structural analyses have been carried out of the effects of earthquakes on the UWMAK-I TF magnet structure, using standard earthquake spectrum input (e.g., 50% of the 1940 El Centro earthquake). Peak structural due to the earthquake are quite low, i.e., ~ 4000 psi, in the structure even with minimal external support for the TF coils (i.e., at the inner and outer edges of the coil), and no safety problem appears to exist, at least as regards to gross structural stress. Individual problems may occur due to localized coolant channel blockage (i.e., from a fractured spacer) or excessive localized conductor movement, however.

References

1. Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400, USAEC, (August 1974).
2. Aspects of Safety and Reliability for Fusion Magnet Systems - First Annual Report: Magnet Safety Studies Group (January 15, 1976).

3. UWMAK-I "A Wisconsin Toroidal Fusion Reactor Design", UWFD-68, (November 1973).

Fig. 1 Tasks involved in magnet safety analyses.

Fig. 2 Hierarchy of operating magnet safety systems.

Fig. 3 Potential electrical breakdown paths in disc type TF coil construction.

Fig. 4 Effect of temperature inhomogeneities in UWMak-1 TF coil on internal voltage during quenches.

Fig. 5 Simplified event tree for consequences of conductor break.

Fig. 6 Simplified fault tree for conductor break.

Fig. 7 Circular quench near outside radius.

Fig. 8 Stress distribution and zone of yielding around 10% failed region in UWMMAK-I TF coil.