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for the Radiation Environment**

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TF FUSION COIL CONDUCTOR PERFORMANCE OPTIMIZED FOR THE RADIATION ENVIRONMENT

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ABSTRACT:

A powerful computational tool, called *MagRad*, has been developed to optimize magnet design for operation in radiation fields. Specifically, *MagRad* has been used for the analysis and design modification of the cable-in-conduit conductors (CICCs) of the TF (Toroidal Field) magnets systems in fusion reactor designs. Since the TF magnets must operate in a radiation environment which damages the material components of the conductor, the optimization of conductor design must account not only for start-up magnet performance, but also just prior to shut-down. It was found that performance of superconducting magnets in all D-T (Deuterium-Tritium) reactor designs of significant power generation (ITER-class reactors and beyond) degrades significantly. This performance degradation consists primarily of three effects: reduced stability margin of the conductor; transition out of the well-cooled operating regime; and increased maximum quench temperature attained in the conductor. A new concept, the "goodness" of the design of the conductor, previously only applied to pool boiling magnets, has been redefined and applied to the CICC geometry. This goodness factor has been used to quantify performance degradation in TF conductors over the lifetime of a reactor. Upon addition of pure copper strands to the cable, the ITER CDA (Conceptual Design Activity) TF magnet design was found to be marginally acceptable, though much room for both performance improvement and cost reduction exists.

I. MAGNET PERFORMANCE:

A. Stability and Protection

Stability and protection are the two primary performance criteria for fusion magnets. [1-5]

Stability is a measure of the energy barrier encountered in the initiation of a thermal runaway situation, a quench, in the conductor. The most frequently used quantitative representation of stability is the stability margin, which is the minimum energy perturbation required to cause a length of conductor to transition irrecoverably from the superconducting state to the normal state.

Protection, on the other hand, is a measure of the potential for permanent damage to the coil in the event of a quench. The protection of the coil can be represented quantitatively by several criteria: maximum allowable hot spot temperature, maximum allowable voltage developed, and maximum allowable pressure rise in the event of a quench. [6] Ordinarily, the most demanding of these protection criteria is the maximum allowable hot spot temperature in the event of a quench, since this particular criteria is almost exclusively determined by the composition and geometry of the conductor itself.

Stability and protection (especially thermal protection) represent the performance of the magnet very well. A magnet with low stability is in danger of quenching often, and quenches have very high costs associated with them (i.e. cool-down costs and reactor down-time costs) even if the magnet is not damaged. [7] A magnet with poor protection runs the risk of becoming permanently damaged in the event of a quench, which, in turn, can impose exceedingly high cost penalties. [7]

As mentioned above, stability is usually quantified by the stability margin, which can be derived to be, [3]

$$\Delta E \approx \frac{f_{He}}{f_{co}} \cdot \left(1 - \frac{J_{op}}{J_c \cdot f_{sc}}\right) \cdot \rho_{He} \cdot C_{p,He} \cdot (T_c - T_{op}) \quad (1)$$

where ΔE is the energy (stability) margin, f_{He} is the strand region fraction of helium, f_{co} is the strand region fraction of conductor, f_{sc} is the strand region fraction of superconductor, J_{op} is the operating current density, J_c is the critical current density, ρ_{He} is the helium density, $C_{\text{p,He}}$ is the helium specific heat, T_c is the critical temperature, and T_{op} is the operating temperature. However, this equation for the approximate stability margin has been derived using the assumption that the conductor is operating in the well-cooled regime. For this assumption to hold, the following must be true,

$$f_{\text{Lim}} = \frac{J_{\text{op}}}{J_{\text{Lim}}} \leq 0.95 \quad (2)$$

where f_{Lim} is the ratio of the operating to the limiting current density and J_{Lim} is the limiting current density as iteratively calculated. Thus, for Eqn. 1 to hold, the satisfaction of Eqn. 2 is a necessary condition.

Additionally, designers use a third stability criterion which expresses only that the conductor current density should not exceed a certain fraction of the maximum current density attainable. It is as follows,

$$f_c = \frac{J_{\text{op}}}{J_c} \leq 0.6 \quad (3)$$

where f_c is the ratio of the operating to the critical current density in the conductor. This critical current fraction will behave very similarly with respect to fluence to the energy margin given in Eqn. 1.

The maximum hot spot temperature attained, T_{max} , in the event of a quench can be approximated in a number of ways. The three-phase quench model described elsewhere [7] gives very reliable results as compared to experiment, and is a general three-phase heat balance set of equations.

What is important to note is that these four criteria (ΔE , f_{Lim} , f_c , and T_{max}), the three for stability and the one for maximum allowable hot spot temperature, are fluence dependent. [8] This fact is quite important, since the three parameters are not dependent in the same way upon fluence, and thus must all be calculated independently. Fluence effects been largely ignored with respect to conductor performance. Nevertheless, at some

point in the lifetime of the conductor, one or more of these criteria may not be met, even though at start-up all may have been met with significant ease. In particular, it has been seen that f_{Lim} increases with fluence more rapidly than ΔE decreases with fluence. What this entails is that at some point in the lifetime of the conductor, there will be a transition from operation in the well-cooled regime to operation in the ill-cooled regime. The importance of this effect may be likened to the importance in structural designs using certain steels of the well known ductile to brittle transformation temperature (DBTT). Thus, at moderate fluences Eqn. 1 will fail to be valid, since the assumption upon which it is derived will no longer be valid. As will be shown later in this paper, this transition fluence occurs at moderate levels, such that even in near-term devices, such as ITER, the TF magnets would have become unstable well before the end of life of the reactor.

B. Conductor Analysis: *MagRad*

In order to predict the performance of a magnet at any fluence a code called *MagRad* has been developed and described in reference [2]. Full fluence effects are included for all of the material components of the magnet based upon radiation damage data. This allows for the accurate prediction of both stability and protection of the coil at any point in the reactor lifetime, with particular emphasis, of course, on the performance of the magnets just prior to the scheduled end of life of the reactor. The ultimate objective of *MagRad* is to give the magnet designer a powerful tool in the optimization of the operation of superconducting magnets in radiation environments.

Toward this end *MagRad* consists of a number of discrete modules, linked to a main algorithm. The modules include: conductor geometry specification; magnet shielding specification (B/S/VV materials and thicknesses); steady state heat transfer analysis (finite element); calculation of superconductor critical parameters (fluence-dependent); stability analysis; stabilizer annealing scheduling; protection analysis; superconductor annealing scheduling; and, finally, costing computations (including both

magnet specific and reactor level costings). *MagRad* also calculates the design goodness factor, as explained in the next section.

C. Conductor Optimization: The Goodness Factor

In recent years there have been several attempts to quantify what it means to develop an optimal conductor for fusion applications. Most recently, an optimization process has been qualitatively developed and put forward as a rational solution to the conductor optimization problem. [3] *MagRad* is particularly well suited to the implementation of such a systematic optimization process. Nevertheless, it would also be convenient for the magnet designer to have in hand some sort of figure of merit as to the "goodness" of the design in question. Goodness is here used in a qualitative sense, and would have to include both of the primary magnet performance criteria, stability and protection. As has been observed from *MagRad* calculations, the goodness of the design generally increases as the cost of the design increases. Thus, in general the magnet will be designed to operate at a nominally acceptable goodness, and overdesign will be minimized (and, thus, cost as well).

In the specific applications regarding pool boiling magnets, it has recently been proposed [9] that the magnet design be judged according to a goodness factor, representing the ratio of a stability parameter to a protection parameter. In particular, the goodness factor, G , has been defined as,

$$G \equiv E_{MPZ} / \theta_m \quad (4)$$

where E_{MPZ} is the energy required to initiate a minimum propagating zone and θ_m is the maximum attained hot spot temperature in the event of a quench.

This concept of a goodness factor and the subsequent definition is very useful as a sound figure of merit. However, the definition must be adapted in order to use the concept in forced flow applications (and specifically, CICC). As was mentioned above, stability actually entails two

mathematical criteria, the one being foundational to the assumptions used in deriving the second. With a suitable definition of the goodness factor, the concept of goodness acquires proper quantitative meaning for CICC designs. It is here proposed that for CICC applications the goodness factor be defined as,

$$G \equiv \frac{\sqrt[4]{(1-f_c)(1-f_{Lim})^2} \cdot \Delta E}{T_{Max}} \quad (5)$$

where f_{Lim} is the ratio of the operating current to the limiting current, f_c is the ratio of the operating current to the critical current, ΔE is the energy margin (assuming that the conductor is operating in the well-cooled regime), and T_{Max} is the maximum attained hot spot temperature in the event of a quench.

The significance of this definition (Eqn. 5) of the goodness factor is that it incorporates the often neglected fundamental stability criterion of f_{Lim} in a way that quantifies its fundamental importance as an overarching assumption (the well-cooled assumption). While designers almost always make reference to this criterion, the fact that it degrades more quickly with fluence than does the approximate energy margin has been quite neglected. Equal weight is given in the definition to stability and protection, as in Wilson's definition. [9] All four of these separate factors composing the goodness factor change with fluence. Thus, the goodness factor will give the designer a very reliable figure of merit with respect to the performance of the magnet at any fluence. The only question to be answered remains subjective: what should the minimum value of the goodness factor be, below which the magnet is considered to perform unacceptably?

II. DISCUSSION OF RESULTS

A full predictive characterization of the performance state of the conductor has been generated using *MagRad*. The performance criteria have been graphically represented under two different conditions (Figs. 1 and 2).

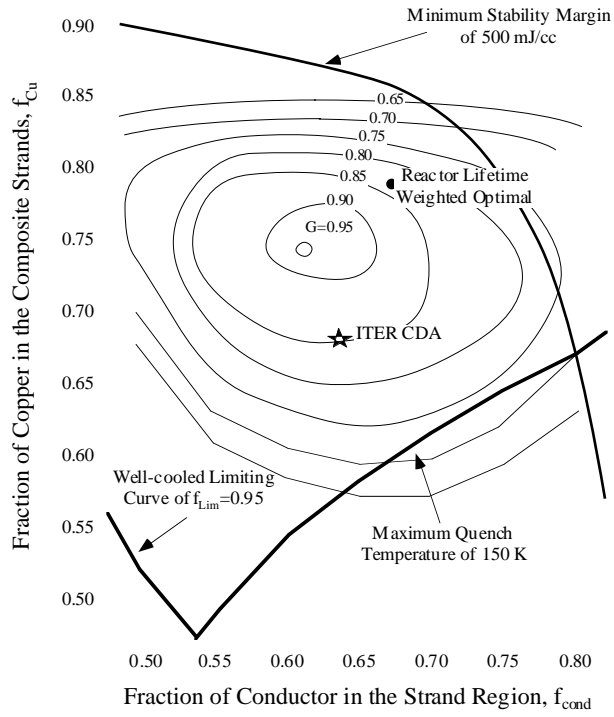


Fig. 1: Conductor variable space at start-up. Contours represent constant goodness factor (Eqn. 5).

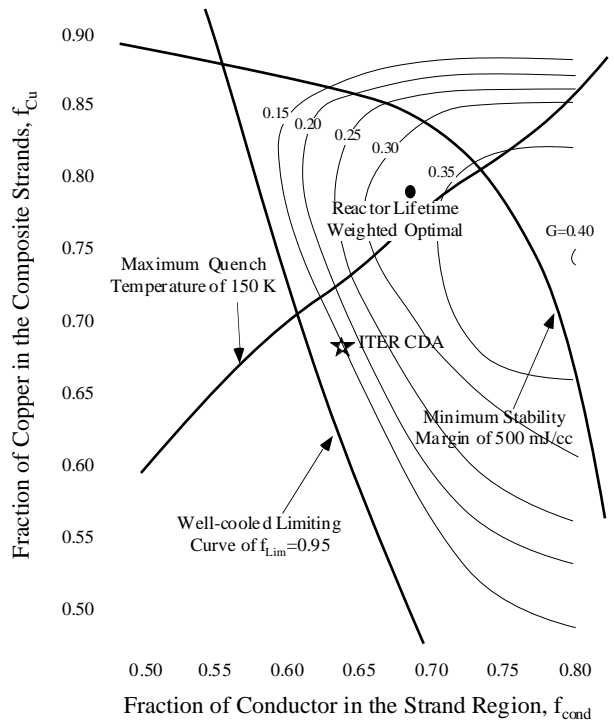


Fig. 2: Conductor variable space at 10^{19} n/cm^2 . Contours represent constant goodness factor (Eqn. 5).

The first condition represented is reactor start-up shown in Fig. 1, and the other condition is for a neutron fluence of 10^{19} n/cm² (which corresponds to reactor shut-down in the case of ITER CDA [10]) shown in Fig. 2. As is readily apparent, the performance states of the conductor at these two conditions are quite disparate.

Discussion of the performance of the conductor under these two specific operating conditions must start with the observation that the goodness (as well as the area of the acceptable design space) of the conductor is dramatically decreased by the time the reactor reaches shut-down conditions (e.g. Fig. 2). This decrease is, of course, of primary interest to the designer, since it implies that all conductors which operate in radiation fields must be designed specifically to tolerate the moderate fluence exposure (and corresponding performance degradation) characteristic of end-of-life.

The next most important observation is that the peak in the goodness factor (see contours in both figures) occurs at different primary conductor variable values depending upon the operating condition (i.e. neutron fluence). This shifting of optimal conductor design implies that the designer must not only take into account radiation induced performance degradation, but also be aware that a particular design optimized for start-up conditions will not, in general, be the optimized design for shut-down conditions. Thus, subjectively, the designer must choose to which point during the operation of the reactor to optimize the conductor design. Generally, the point which should be chosen to design to is shut-down, since it is at this point in the lifetime of the conductor that the lowest goodness occurs. In the case of ITER CDA it can be seen from Figs. 1 and 2 that, whereas the conductor design ($f_{Cu}=0.68$ and $f_{cond}=0.63$) is quite close to the optimal design with respect to start-up conditions, the base design (which includes 10% pure copper strands to enhance CDA performance in this regime) is not even in the acceptable range of parameters with respect to its shut-down conditions (10^{19} n/cm²).

A straightforward method of conductor design would be to overlay the goodness maps for both the start-up and shut-down conditions of

the given reactor. With the maps superimposed, the optimal design point will be the point which best weights the goodness factor over the reactor lifetime. In the case of a reactor with a lifetime corresponding to 10^{19} n/cm², this reactor lifetime weighted optimal design point is shown in Figs. 1 and 2. In this case, the design point corresponds to a goodness factor which remains fairly constant as a fraction of the highest goodness possible on the maps (in this case, the ratio of the reactor lifetime weighted optimal design point goodness to the highest achievable goodness is about 0.85).

By contrast, the ratio of design goodness to highest achievable goodness for a design point which is not weighted over the lifetime of the reactor decreases quite dramatically over the lifetime of the reactor. The ITER CDA design is an example of one such design, yielding a ratio of design goodness to highest achievable goodness of 0.90 at start-up and only 0.33 at shut-down. Obviously, in choosing the reactor lifetime weighted optimal design point care must be taken not to locate that design point on a steep goodness factor gradient for conservative design considerations. Additionally, it should be noted that the cost of the conductor design increases as one moves toward the lower left hand corner of the primary conductor space (since copper is being replaced by superconductor and the cable space cross-sectional area is increasing as the area of the helium is held constant). Thus, in the case shown in Figs. 1 and 2, the reactor lifetime weighted optimal conductor design point represents a less expensive conductor.

Also shown in the Figs. 1 and 2 are the usual limiting criteria mapped into primary conductor variable space. Certainly the most striking feature of these criteria curves is the degree of curve shifting which is involved due to radiation damage. For the ITER CDA design the range of acceptability (the intersection area between the three criteria curves) with respect to conductor design spans almost the entire mapped variable space at start-up. However, after 10^{19} n/cm² the range of acceptability has been significantly reduced. Thus, radiation damage puts severe constraints upon the boundaries of

acceptable conductor design. This fact has not widely been included into near-term designs.

As far as secondary conductor variables are concerned less significant effects have been predicted by *MagRad*. For example, by increasing the diameter of the strands the goodness of the conductor increases, as it does by increasing the number of the strands. In both cases, of course, the same helium fraction is maintained. The increase in goodness comes from the fact that there is now more conductor area, thus reducing the maximum quench temperature as well as reducing the operating current density. Moreover, the fraction of strands that are pure copper may also be varied. When the value of this secondary variable is increased, keeping the helium fraction constant, the goodness of the design increases as well (and the maximum quench temperature curve shifts downward). Therefore, some amount of alleviation of the radiation induced performance degradation can be achieved by varying these secondary conductor variables. Nevertheless, a cost penalty is encountered for either of these design modifications. It should further be noted that analysis of a secondary design parameter can be carried out in a very straightforward way by adding it as a third axis and mapping out the three-variable space, with contours of constant goodness replaced by shells of constant goodness.

III. CONCLUSIONS

It has been demonstrated through the use of the numerical optimization code, *MagRad*, that it is critical for magnets operating in radiation fields to be designed for end-of-life conditions (i.e. to the maximum neutron irradiation exposure level). Severe degradation in the performance of any CIC conductor should be expected at moderate fluences. A new concept, the "goodness" of the design of the conductor, previously only applied to pool boiling magnets, has been redefined and applied to the CICC geometry. This goodness factor has been used to quantify performance degradation in TF conductors over the lifetime of specific reactor designs. The ITER CDA conductor design, while being almost optimal when viewed from

start-up considerations, suffers an unacceptably high amount of performance degradation by its projected end-of-life. New designs of conductors operating in radiation fields will, in general, optimize at very different values of the primary conductor variables. Nevertheless, secondary variables may be varied in such a way to help compensate against the radiation induced degradation of performance.

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