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Cable-In-Conduit Conductors for Fusion
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NUMERICAL SIMULATION OF THE STABILITY IN LONG CABLE-IN-CONDUIT CONDUCTORS FOR FUSION MAGNETS

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ABSTRACT

The stability phenomenon is investigated numerically for a quench initiating in a cable-in-conduit conductor (CICC) at a significant distance from the ends. The thermo-hydraulic computer program, CICC, was used. The geometry chosen for this study is a toroidal field (TF) coil for the conceptual design activity (CDA) of the International Thermonuclear Experimental Reactor (ITER). Previous studies of short conductors have shown that convective helium flows, induced by the initiating heat pulse, control the stability of the conductor. The present study of a long conductor exhibits reduced energy margins and the absence of a transition region between the well-cooled and ill-cooled stability regions because the initiating heat pulse has difficulty sustaining a convective flow. The effect of heat-pulse duration and heated length were considered. For short, high-energy heat pulses, high convective and conductive heat-transfer coefficients can only be maintained for 10 ms. If the heat-pulse energy is spread over 100 ms, the steady-state heat-transfer coefficient is sufficient to stabilize the conductor. Pulse durations between 10 and 100 ms cause a decrease in energy margin. On the other hand, the conductor length heated was found to have only a small effect on stability.

I. INTRODUCTION

Figure 1 shows the previously calculated stability margin for the stability of a short conductor from Ref. 1 [United States Demonstration Poloidal Coil (US-DPC)]. These calculations are made using the computer code CICC (Ref. 2). They compare favorably with test data and with theoretical predictions for the limiting current, I_{lim} , given in Eqns. 1 and 2 by Dresner (Ref. 3)

$$J_{lim} \propto \left[\frac{f_{Cu}(1-f_{Co})}{f_{Co}} \right]^{1/2} \left[\frac{(T_{cr} - T)^{1/2} \ell^{2/5}}{\rho^{1/2} D_h \tau^{1/5}} \right] \quad (1)$$

or

$$I_{lim} \propto [R_{Cu} R_{He}]^{1/2} \left[\frac{(T_{cr} - T)^{1/2} \ell^{2/5}}{\rho^{1/2} D_h \tau^{1/5}} \right] \quad (2)$$

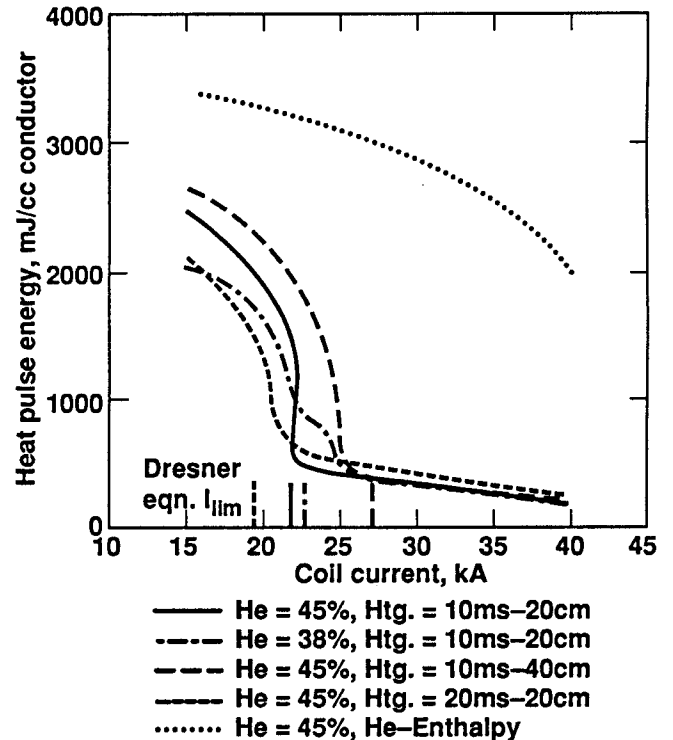


Fig. 1. The numerically calculated stability curve of the US-DPC experiment ("short" conductor).

where:

- J_{lim} = Limiting current density in the conductor, A/m²
= I_{lim}/A_{co}
- A_{Cu} = Cross-sectional area of the copper, m²
- A_{co} = Cross-sectional area of the conductor, m²
- A_{He} = Cross-sectional area of the helium, m²
- f_{Cu} = Volume fraction of copper in the conductor
- f_{co} = Volume fraction of conductor in cable space
= $1-f_{He}$
- f_{He} = Volume fraction of helium in cable space
- T_{cr} = Critical temperature of the conductor, K
- T = Helium temperature, K
- ρ = Resistivity of the copper, Ωm
- τ = Heat-pulse duration, s
- l = Heated zone length, m
- D_h = Hydraulic diameter, m.

The quench is initiated in the middle of the 1.637-m-long inlet turn. The stability curves exhibit three stability regions: a well-cooled region at low conductor currents, an ill-cooled region at high currents, and a transition region. Sustained helium convection during the initiating heat pulse is important in the well-cooled region, while sustained helium convection during and after the initiating heat pulse is important in the transition region.

II. STABILITY ANALYSIS OF THE ITER-TF COIL

Figure 2 shows the calculated stability curves for the ITER/CDA-TF coil. The conductor is a CICC design similar to that used in the US-DPC experiment. The quench is initiated in the middle of the inlet first turn where the maximum field and temperature occur during the operating cycle. In contrast to the US-DPC, the inlet ITER-TF turn is

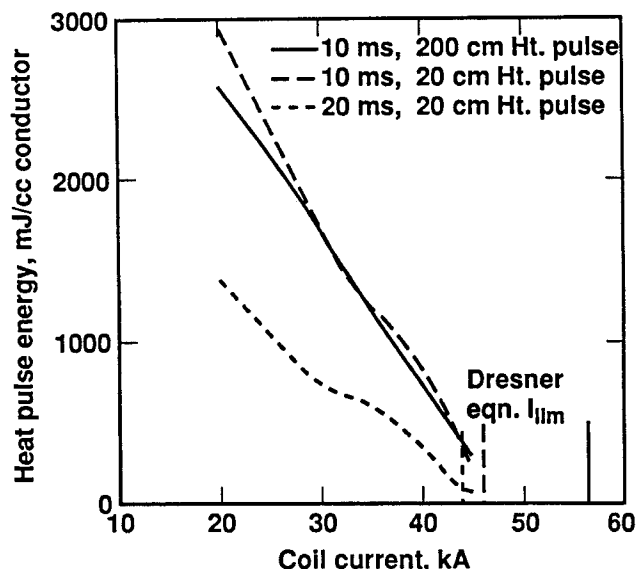


Fig. 2. The numerically calculated stability curve of the ITER/CDA TF coil ("long" conductor).

40-m long, so the quench does not "see" the end of the coil during the initial 100-ms period significant in determining stability. Vertical lines in figures 1 and 2 also show I_{lim} as calculated using Dresner's equation (Eqs. 1 and 2). These values of I_{lim} are calculated using helium and conductor properties and geometry (the original 1/5 and 2/5 powers of the pulse length, τ , and conductor heated length, l , are used). Stability curves are calculated for heated lengths of 20 and 200 cm, and for pulse lengths of 10 and 20 ms.

Figure 2 shows that increasing the pulse heated length from 20 cm to 200 cm decreases the stability slightly. This is in contrast to the US-DPC stability curve (Fig. 1) which shows an increase in stability due to increasing the heated length from 20 cm to 40 cm. The long coil length of the ITER-TF suppresses the induced convective helium cooling. Dresner predicts a large increase in I_{lim} when increasing the heated length from 20 to 200 cm (Fig. 2), but this equation assumes that there is no pressure rise in the heated helium.

The stability curves in Fig. 2 show that an increase in pulse duration from 10 ms to 20 ms causes a large decrease in energy margin. The US-DPC curves in Fig. 1 show a much smaller decrease. At high-energy pulses, the long ITER-TF coil length allows high heat-transfer coefficients to be maintained to only about 10 ms. There is no coil end available to relieve the helium pressure pulse, so the induced helium flows decrease after 10 ms. Also, the transient, conductive heat-transfer

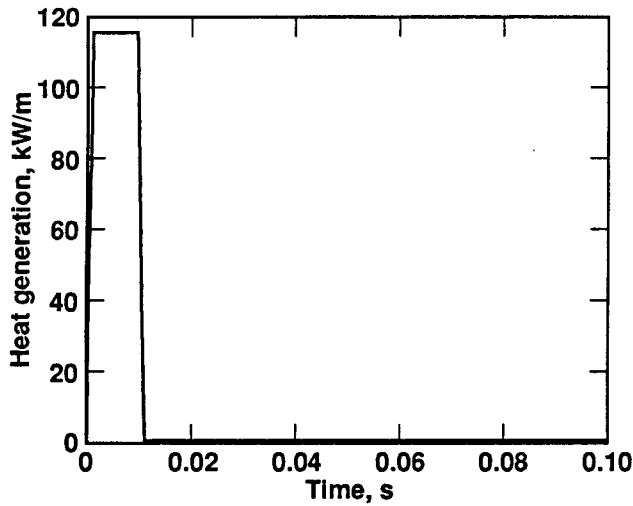


Fig. 3. Heat generation versus time for a 10-ms, 20-cm pulse resulting in a marginal quench for the ITER TF coil.

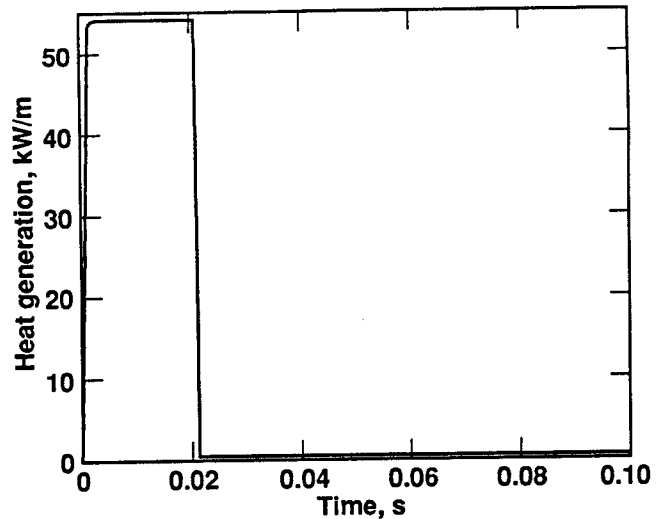


Fig. 5. Heat generation versus time for a 20-ms, 20-cm pulse resulting in a marginal quench for the ITER TF coil.

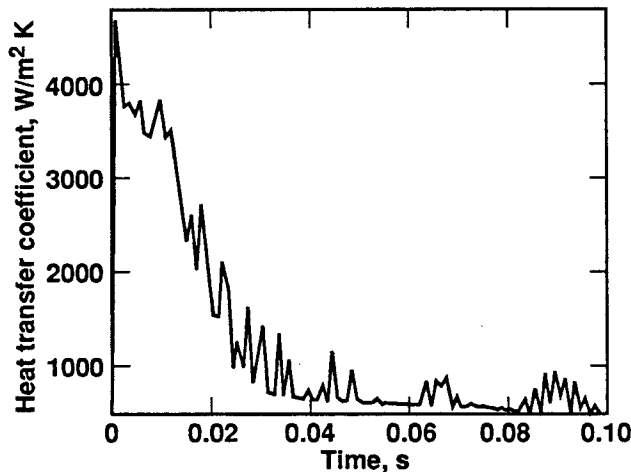


Fig. 4. Heat transfer coefficient versus time for a 10-ms, 20-cm pulse resulting in a marginal quench for the ITER TF coil.

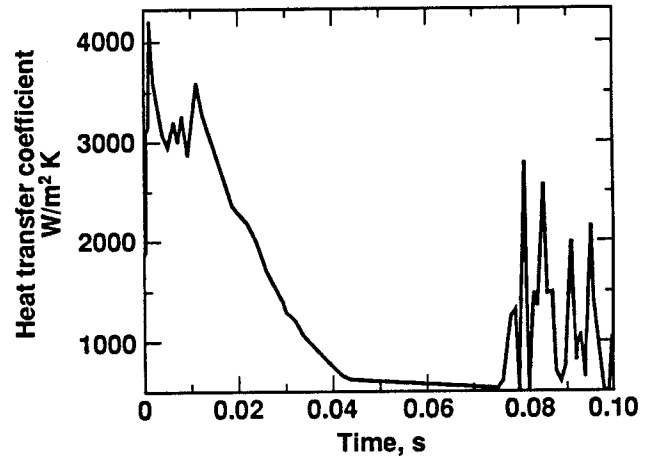


Fig. 6. Heat transfer coefficient versus time for a 20-ms, 20-cm pulse resulting in a marginal quench for the ITER TF coil.

coefficient vanishes after 10 ms. Figures 3 and 4 show the heat generation and the heat-transfer coefficient with a 10-ms, 20-cm pulse for a marginal quench at the location of quench initiation. Figures 5 and 6 are for a 20-ms, 20-cm pulse. The heat-transfer coefficient remains high for the duration of the 10-ms pulse, but it decreases after 10 ms for the 20-ms pulse.

Since the long ITER-TF coil inhibits the sustaining of helium convection after the heat pulse, the stability curve (Fig. 2) does not have separate well-cooled, ill-cooled, and transition stability regions, as found in the US-DPC coil (Fig. 1). As discussed in Ref. 1, helium convection

after the heat pulse is necessary for the formation of the transition region. The heat-transfer phenomenon exhibited by the ITER-TF coil is that of the well-cooled region at all currents less than the limiting current. The well-cooled region is characterized by being well-cooled during the heat pulse, allowing efficient transfer of heat from the conductor to the helium. The quench is then initiated after the heat pulse as the heated helium and the low heat-transfer coefficients cause increased conductor temperatures. Typically, quench initiation occurs near the ends of the heated length because the highest helium temperatures occur there.

Due to the high field (11.2 T at the 37.89 kA design current) and the 3.6 K temperature margin, the ill-cooled region for the ITER-TF coil is almost non-existent. The limiting current, I_{lim} , at the beginning of the ill-cooled region occurs when the initiating pulse-heating rate equals the electrical-resistance-heating rate (Refs. 1 and 3). For the 20-cm heated length, the value of I_{lim} agrees with that calculated by Dresner's equation (Eqs. 1 and 2). The calculation of I_{lim} for the 200-cm heated length does not agree, due to the fraction-suppressed helium flow.

III. MAGNET DESIGN CONSIDERATIONS

The calculations show that the ITER-TF conductor experiences reduced energy margins for heat pulses with a duration of between 10 and 100 ms. The coil should be designed to avoid exposing the conductor to heat-pulse disturbances of this time duration. Disturbances caused by flux jumping are in the millisecond range. Long-duration frictional heating can be eliminated by coil designs that minimize conductor movement. An electromagnet quench can result in heating in the critical range of tens of milliseconds. However, some of this heat can be removed and the duration increased to 100 ms or longer by carefully designing the first wall, blanket, and magnet cases. First-wall ablation and active blanket cooling will remove some of the heat. Magnet cases absorb electromagnetic energy in the form of eddy currents, so increasing the case thickness will increase the duration of the heat pulse experienced by the conductor. Additional heat removal can be accomplished by active magnet case cooling.

Cooling is improved by conductor designs allowing increased induced convection. Design considerations favoring increased convection are those that lessen the flow frictional resistance: short-flow length from a quench location to a vent, increased hydraulic diameter, and increased helium fraction. Design trade-offs are clearly required, since shortening the flow length may be difficult, and increasing the hydraulic diameter and the helium fraction may be contrary to what is required by heat-transfer and heat-capacity considerations.

IV. CONCLUSIONS

The stability of long conductors is decreased due to the difficulty of sustaining an induced

convective helium flow if a conductor end is not close enough to relieve the helium pressures generated by the initiating heat pulse. Well-cooled stability is decreased if the heat-transfer coefficient decreases before the end of the heat pulse. The transition region is nonexistent due to the decreased helium convection after the heat pulse. For the ITER-TF coil, the energy margin is 1000 mJ/cc at the 37.89-kA operating point if the initiating heat pulse is 10 ms. If the heat pulse is 20 ms, the energy margin decreases to 500 mJ/cc. If the energy of the heat pulse is spread over 100 ms or longer, the energy margin increases because the steady-state convective heat transfer can handle the heat load. The heated coil length has little effect on the stability of long conductors. Optimizing a coil design for transient stability requires trade-offs that consider the complex interactions between all of the thermofluid phenomena: fluid friction, heat transfer, and heat capacity.

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