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Abstract

The toroidal field (TF) coils in the International Thermonuclear Experimental Reactor (ITER) will operate with varying heat loads generated by ac losses and nuclear heating. The total heat load is estimated to be 2 kW per TF coil under normal operation and can be higher for different operating scenarios. AC losses are caused by ramping the poloidal field (PF) for plasma initiation, burn, and shutdown; nuclear heating results from neutrons that penetrate into the coil past the shield. Present methods to reduce or eliminate these losses lead to larger and more expensive machines, which are unacceptable with today's budget constraints. A suitable solution is to design superconductors that operate with high heat loads. The cable-in-conduit conductor (CICC) can operate with high heat loads. One CICC design is analyzed for its thermal performance using two computer codes developed at LLNL. One code calculates the steady state flow conditions along the flow path, while the other calculates the transient conditions in the flow. We have used these codes to analyze the superconductor performance during the burn phase of the ITER plasma. The results of these analysis give insight to the choice of flow rate on superconductor performance.

Introduction

The superconducting TF coils for ITER will operate with relatively high ac and nuclear heat loads that will increase the temperatures in the CICC. The CICC temperature also increases because of the Joule-Thompson (JT) effect in the helium flow. The heat transfer area in a CICC between the conductor, helium, and conduit is large, so these components are at the same temperature. The maximum temperature along the flow path in the CICC must be less than the local current-sharing temperature (T_{cs}) to prevent a magnet quench. As a design guideline, the ITER magnet design team has specified that the local temperature margin, defined by T_{cs} minus the local helium bulk-fluid temperature (T_b), be greater than 0.5 K.[1]

TF conductor designs must be checked to determine if they meet this design guideline. Both T_{cs} and T_b must be calculated along the flow path. As a first step, we determined T_b along the flow path for a candidate CICC during the burn phase of an operating scenario for ITER. This analysis was performed using an equilibrium[2] and transient[3] computer codes developed at LLNL. The results of this study show how the local bulk-fluid temperature is dependent on the pressure drop, flow rate, and heat pulse.

Helium Flow and Heat Loads

Calculating local temperature margins in the TF coils depends on the flow-path length, the magnetic field, heat pulse, and CICC design. The TF coil shape can be described as a "D," in which the straight leg is near the axis of the machine (Fig. 1). A typical winding pack design (Fig. 2) will be made up of several pancakes which are stacked together. Helium coolant is introduced into the coil on the crossover turn which is located inside the torus on the curved section of the "D" near the midplane. This inlet provides coolant to each side of the pancake. The helium flows from the inner turns radially outward. The flow-path length of one CICC coolant channel for the TF coil in Fig. 1 is 448 m.

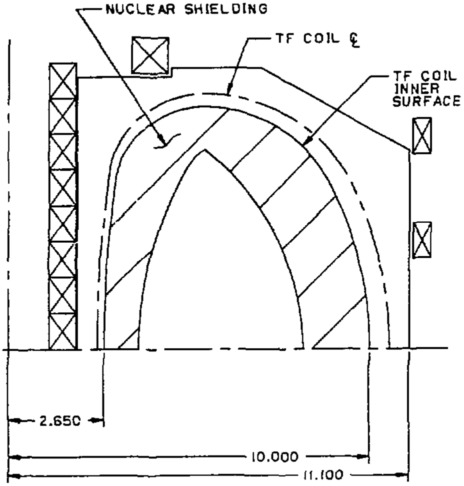

Figure 1. ITER 5.5 m TF and PF conductor set. The TF coil centerline and coil case inner surface are shown. The nuclear shielding is not shown in detail.

The current-sharing temperature along the flow path is a function of the magnetic field. The superconductor in the CICC generates a non-uniform magnetic field (B) along its length. The non-uniformity occurs because the B-field inside the torus varies inversely with the radius measured from the axis. The field decreases through the coil pack and approaches zero outside the torus. The highest field which produces the lowest T_{cs} (5.8 K) in the TF coil is located on the inner turns of the straight leg of the "D".

The heating inside the coolant channel is also a function of position and of time. Each burn cycle is accompanied by plasma startup, shutdown, and a "recocking" time in which the magnets are brought to

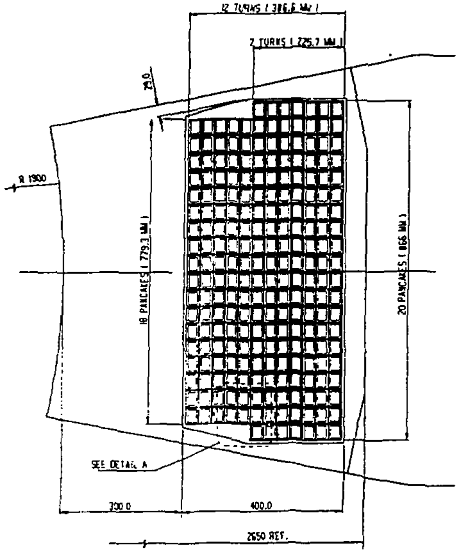

Figure 2. Candidate TF coil winding pack design located at the midplane of the straight leg. This design was proposed by the European group of the ITER Design Team.

their pre-startup conditions. A candidate operating scenario could have a 90 s startup, 100 s burn, 70 s shutdown, followed by 100 s for "recocking." The heat loads for this operating scenario are shown in Fig. 3. The background heating is assumed to be spatially uniform and consists of thermal conduction and radiation and joint losses. AC heating, generated by the PF fields interacting with the TF coil currents, varies along the flow path. We have assumed a uniform-spatial ac-heating distribution during the burn phase because the magnitude of the ac heating during the burn is low compared to the nuclear heat load.

The nuclear heating also varies along the flow path for several reasons. First, the nuclear shielding thickness around the inside of the torus (Fig. 1) is non-uniform. The shielding thickness along the straight leg is thin compared to the thickness on the outer leg. The nuclear heating is therefore higher on the inner straight leg of the "D." The other reason is that nuclear radiation and heating decay exponentially, with a 6.5 cm decay length, through the coil. From these observations, we conclude that the highest nuclear heating occurs on the inner turns of straight leg of the TF coil; the same location where T_{cs} is lowest.

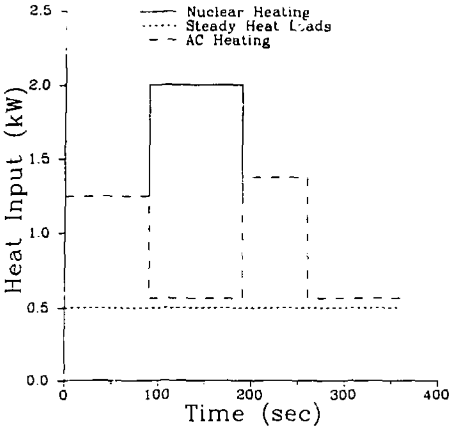

Figure 3. Heat loads into a TF coil for ITER as a function of time for an operating scenario.

CICC Parameters

Typical candidate CICC designs for the TF coils in ITER are rectangular. For this study we have chosen a CICC design which has cable space dimensions of 22.17 mm by 32.35 mm. The conduit is 4 mm thick and there is 1 mm of insulation around the conduit. The conductor fraction in the cable space is 60 %. The corresponding helium flow area is 276 mm^2 with a wetted perimeter of 1.72 m, giving a hydraulic diameter of 0.643 mm. The copper fraction in the superconductor is 66.7 %.

Mass Flow Analysis

The mass flow rate ($\dot{m}$) through the coil is determined by the allowable pressure drop, friction, and heat load. We can specify the inlet temperature (T_{in}) and pressure P_{in} along with $\dot{m}$ for the equilibrium code or P_{out} for the transient code. The inlet temperature is set at 4.5 K. A maximum value for P_{in} of 2 MPa and a minimum value for P_{out} of 0.1 MPa are specified by the ITER design team.[4] In our design, we limit P_{out} to be greater than 0.25 MPa and add a margin of 0.25 MPa for 10 % uncertainties in the friction factor and heat load. In the analysis, P_{in} and $\dot{m}$ are adjusted to obtain P_{out} of 0.5 MPa.

The choice of $\dot{m}$ and P_{in} for the ITER design depends on T_b which, when combined with T_{cs}, must satisfy the design temperature margin. The bulk helium temperature increases because of the JT effect and heating. An illustration of the magnitude of these effects is shown in Fig. 4, where the external heating is limited to 100 W per cooling channel or 2 kW for the coil. In this figure, the solid line represents a low flow rate (.013 kg/s, P_{in} approx. 1 MPa) and the dashed line is a high flow rate (.023 kg/s, P_{in} approx. 2 MPa). The lowest solid and dashed lines show temperature increases due to the JT effect. This result means that at low or no heat loads, the lower flow rates with low pressure drops are desirable. For uniform heating, the choice between low or high $\dot{m}$ becomes more complicated, and other factors like refrigeration costs could impact the decision. When the heat load is peaked on the inner turns, like it is for nuclear heating, T_b for low $\dot{m}$ increases faster than for high $\dot{m}$. Nuclear heating will

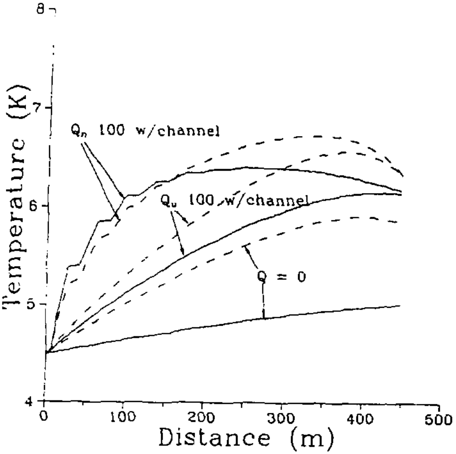

Figure 4. Steady-state-temperature profiles as a function of mass flow rate and inlet pressure. Solid line is for .013 kg/s at 1 MPa inlet pressure. Dashed line is for .023 kg/s at 2 MPa inlet pressure. The exit pressure is fixed at 0.5 MPa and the inlet temperature is 4.5 K.

force CICC designers to consider high flow rates through the TF coils; this implies large pressure drops for the long flow-path lengths.

Transient Flow Analysis

The time required to establish a steady state flow through the ITER TF coil depends on the mass flow. For example, a helium particle in the previous high flow analysis traveling through the 448 m long CICC flow path during the plasma burn of Fig. 3 would take approximately 411 s. This is longer than the total operating scenario and more than four times longer than the plasma burn. A particle in the low flow case would take 1.8 times larger to travel through the coil. Steady state flow for a constant plasma burn is established in 1300 s. This result emphasizes the fact that the operating scenario, individual heat pulses, and the characteristic flow time through the coil are the same order of magnitude. Therefore, true steady state flow conditions cannot be established in the CICC TF coils for ITER. Because of this we expect the outlet temperature and pressure from the coils to continuously vary as a function of time. The ITER refrigeration design requires knowledge of the helium exit temperatures and pressures from the TF coils. A detailed thermal analysis of the TF coil heating during several operating scenarios is needed to establish the helium exit parameters.

We have taken a first step in performing this thermal analysis by concentrating on the 100 s plasma burn. The transient response the the combined uniform and nuclear heat load using $\dot{m}$ of .023 kg/s is shown in Fig. 5. The lowest and highest curve are the steady state temperature profiles for zero heat input and for a long plasma burn of Fig. 3. These two curves would represent temperature boundaries through the CICC if the only heating occurred during the burn. The temperatures in the CICC increase as a function of time during the plasma burn. At 100 s into the burn the first turn of the TF coil has reached its steady state temperature value. At this time the burn ends and if no other heating occurred this heat pulse would continue to propagate down the CICC flow path and reach the exit some 300 s later.

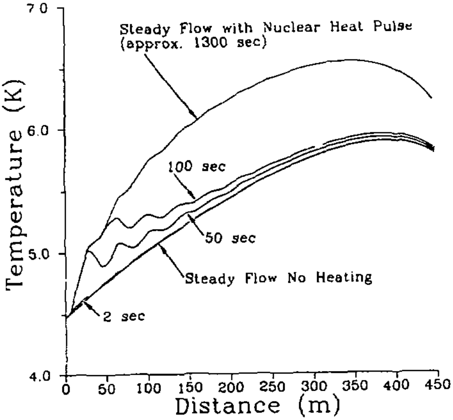

Figure 5. Transient helium temperature response to the plasma burn shown in Fig. 3. Steady state temperature profiles are shown for zero heat input and for an infinite burn time.

Conclusions

We have used two thermal analysis design codes to study the thermal response in a CICC conductor for the ITER TF coils. The first result of this analysis verifies that the mass flow rate through the coils affects the temperature margin. Secondly, we determined that a true steady state flow is not established in the ITER coils for the flow rates and operating conditions expected for ITER. Finally, we have taken a first step in determining the helium exit conditions during a normal operating scenario by studying the transient response of the helium to a 100 s plasma burn.

Acknowledgments

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