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**THERMO-HYDRAULIC ANALYSIS
OF SUPERCONDUCTING TOROIDAL-FIELD MAGNETS
FOR THE TOKAMAK PHYSICS EXPERIMENT**

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ABSTRACT

The superconducting magnets in Fusion Reactors are subjected to pulsed, nuclear, and resistive heating. The thermo-hydraulic response of the helium forced-flow cooled conductors to the various heat sources is critical to magnet design and performance. Recently developed computer codes allow accurate modeling of conductor response and have been used as an aid to design of the toroidal field (TF) magnets for the Tokamak Physics Experiment (TPX). We present results of design studies that determine the trade-off between double- and single-pancake helium flow configurations, the minimum-temperature margin, and the stability against rapid heat input. The results guide the choice and design of the liquid helium refrigerator.

INTRODUCTION

The toroidal field (TF) coils for TPX use helium forced flow cooled superconducting cable-in-conduit conductor (CICC) to permit higher current densities and more compact magnets than is possible with conventional water cooled copper coils. These conductors are formed by enclosing the cabled superconducting wire strands inside a conduit and swaging the conduit to produce a void fraction of 35 to 40%, which serves as the flow path for supercritical helium. The advantage superconducting coils offer is that no Joule heating is generated during design operation. However to

maintain the superconducting characteristics of the Nb_3Sn ¹, the conductor must be operated at temperatures below the current sharing temperature. If the temperature rises above current sharing, current will flow in the parallel copper paths provided resulting in Joule heating.

TF COIL OPERATIONAL HEATING AND COOLING

The coils are designed to remain superconducting during operational heating, which consists of eddy current and hysteresis heating from the pulsed operation of the poloidal field (PF) coils, nuclear and gamma heating from plasma radiation, and eddy current heating induced by the vertical stabilization control coils.

Operational heating of the 16 coil TF set from various sources is listed in Table I.

Table I. Operational heat loading of TPX-TF coils

1. Direct CICC conductor heating from initial PF pulse=	248 kJ
2. Case heating diffusing into conductor from initial PF pulse=	350 kJ
3. Steady-state nuclear heat=	5 kW
4. Steady-state eddy current heat from vertical stabilization=	3 kW

Pulsed PF heating occurs during a 24 s initiation start-up sequence. Some of that heat is deposited directly into the conductor. The PF heat that is deposited into the case diffuses into the conductor over 500 s. The nuclear heating and the eddy current heating induced by the vertical stabilization coils are treated as steady state heat loads. We estimate that the coil absorbs 3.6 kW of the 8 kW steady state heat, with the remainder being intercepted by the auxiliary case cooling.

To remove this heat, the CICC conductor is cooled by force flowing supercritical (single phase) helium through the conductor. In a single-pancake flow configuration, helium flows outward from the bore through one pancake. In a double-pancake flow configuration, helium flows inward toward the bore through the first pancake; and outward through the second pancake (Fig. 1). Each conductor is electrically insulated with a G-10 epoxy impregnated wrap. The single-pancake flow geometry is thermodynamically preferable since the cold helium inlet is located at the magnet bore where the field is highest and the current sharing temperature is lowest. This maximizes the temperature margin (the difference between the current sharing temperature and the conductor temperature). The double-pancake flow configuration is preferred from a practical viewpoint since it allows all of the helium connections to be located at the outside of the coil, for possible access in case of repair. Twelve pancakes are stacked to form each of the 16 TF coils. Each pancake has seven turns.

¹M.N. Wilson, "Superconducting Magnets," Clarendon Press, Oxford (1983).

Fig. 1 Double pancake He flow geometry

TF Coil Operational Thermal Analysis

The response of the TF coils to operational heat input was determined using the computer program *CICC*². This program models the *CICC* conductor by numerically solving the one dimensional flow continuity, momentum, and energy equations in the helium, along with the axisymmetric heat conduction equations in the conductor, conduit, and insulation. *CICC* includes the superconductor critical current characteristics that allow the calculation of the current carrying capacity of the superconductor at any given field and temperature. We compared the temperature margins for double and single-pancake flow configurations.

Figure 1 presents the interpretation of the length coordinate used in program *CICC* for the double-pancake configuration. The length coordinate, x , is the length of the helium flow path, starting at $x=0$ at the helium inlet and ending at $x=L$ at the helium outlet. Each pancake consists of seven turns, each turn being 12.26 m long. For the double-pancake configuration $x=0$ is on the outside of the first pancake, and $x=L=172$ m is at the outside of the second pancake. The pancake-pancake transition occurs at $x=L/2=86$ m in the bore of the coil. A similar length coordinate exists for the single-pancake configuration with $x=0$ at the bore and $x=L=86$ m at the outside of the pancake. The model includes the pancake-pancake heat conduction in the double-pancake configuration, and the turn-turn conduction in the double and single-pancake configurations. Table 2 lists the conductor geometry, and Table 3 lists the helium and conductor parameters.

² R.L. Wong, "Program *CICC*, Flow and Heat Transfer in Cable-In-Conduit Conductors--Equations & Verification," Lawrence Livermore National Laboratory, rept. UCID-21733 (May 22 1989).

Table 2. CICC conductor geometry

1. Number of coils=	16
2. Number of pancakes/coil=	12
3. Number of turns/pancake=	7
4. Length per turn=	12.26 m
5. Helium flow area=	106 mm ²
6. Helium flow hydraulic radius=	0.513 mm
7. Conductor area=	194 mm ²
8. Conductor copper fraction=	0.778
9. Heat transfer perimeter=	992 mm
10. Conduit area=	193 mm ²
11. Conduit heat transfer perimeter=	80.1 mm
12. G-10 insulation thickness=	0.8 mm

Table 3. Problem input parameters

1. Total inlet helium flow=	400 g/s
2. Inlet temperature=	5 K
3. Outlet pressure=	4 atm
4. Maximum field=	7.63 T
5. Nb ₃ Sn current sharing temperature=	7.7 K
6. Nb ₃ Sn critical current density=	1384 A/mm ² (non-Cu)
7. Superconductor Cu RRR=	75
8. Operating current=	33.5 kA

Figures 2 and 3 are transient plots downstream of the bore (high field) turn, where the temperature margin is a minimum. Figure 2 shows the operational heat input and is a superposition of three different types of heat inputs. The initial 24-second-long high heat pulse is due to pulsed heating induced into the conductor by the initiation ramp of the PF coils. The 500-second-long intermediate level heat pulse is the diffusion of PF initiated eddy current structural heating into the coil, plus the steady-state nuclear and vertical stabilizer eddy current heating. The steady-state heating after 500 s is the nuclear and vertical stabilizer eddy current heating.

Figure 3 shows the transient temperature response of the double-pancake configuration to operational heating in Fig. 2. The plotted temperature is at the downstream end of the bore turn (inlet turn) of the second pancake. The temperatures of both the conductor and the outer edge of the G-10 insulation are shown in the figure. The conductor and helium are at the same temperature. The outer edge of the G-10 is the interface between turns. The temperature after 900 seconds of operation is 6.5 K, and will eventually reach a steady state value of 6.6 K. The conductor temperature is higher than the interface temperature, indicating that the heat is flowing out of the conductor. This is expected since the temperature plotted is located in the second pancake. Generally the heat flows from the second pancake to the first pancake. This is the undesirable counterflow heat exchanger effect of the double-pancake configuration that locates the maximum conductor temperature in the bore of the coil where the current sharing temperature is a minimum.

This counterflow heating effect is also evident in Figures 4, 5, and 6. These figures are plots along the conductor flow coordinate of the double-pancake configuration after 900 s of operation. Figure 4 shows the distribution of steady-state nuclear and vertical stabilizer heating along the entire flow length. This plot shows only the heat deposited directly into the conductor. Not shown is an equal amount of heat deposited into the sheath, which is also in thermal contact with the helium. The sawtooth pattern represents the conductor alternately spiraling into the low and high heating regions of the coil. The increase in heating toward the bore is due the nuclear heating decay through the coil with a characteristic decay length of 7 cm.

Figure 5 shows the net interface heat flow into the conductor vs flow length at 900 s. This plot gives additional insights into the characteristics and the importance of the pancake-pancake and turn-turn heat flow. The net interface heat flow plotted is generally the algebraic sum of three components: 1. heat conducted from the adjacent turn in the other pancake; 2. heat conducted from the inward adjacent turn in the same pancake, and; 3. heat conducted from the outward adjacent turn in the same pancake. The bore turns and outside turns have only two contributing components since there is only one adjacent turn in the same pancake. Heat flow into the conductor at any given location is positive. An indication of the importance of pancake-pancake and turn-turn heat flow can be seen by comparing of the magnitude of the conductor heating (Fig. 4) and the net interface heat flow (Fig. 5). Both the heating and the interface heat flow are generally of the same magnitude. However at the helium inlet, the interface heat flow is two orders of magnitude more than the heating at that location and one order of magnitude greater than the maximum heating anywhere in the conductor. The net interface heat flow is high for the first turn because the helium inlet is located there; but also because there is no heat flow out to an adjacent inner turn, and both the heat flow from the second pancake and from the outward adjacent turn are positive (into the conductor). The plot of the net interface heat flow masks the importance of the individual components of the interface heat flow. These individual components can be an order of magnitude greater than conductor nuclear and eddy current heating. This means that pancake-pancake and turn-turn heat flow, not the exact shape of the conductor nuclear and eddy current heating profile, dominates the shape of the temperature profile.

The temperature profile after 900 s is shown in Fig. 6. The peaking of the temperature in the bore, at the transition between the first and second pancakes, is a result of the conductor interface heat flow, particularly the heat flow from the second pancake to the first pancake. Without the inclusion of pancake-pancake heat flow, the temperature profile would peak near the helium outlet. The pancake-pancake heat flow is evident from the relative positions of the conductor temperature curve and the interface temperature curve (outside of G-10). In the first pancake the temperature of the interface is above the temperature of the conductor, indicating that the heat flow is into the conductor. In the second pancake the temperature of the interface is below the conductor temperature, indicating that the heat flow is out of the conductor.

The more favorable temperature profile of the single-pancake configuration is shown in Fig. 7. In this configuration the cold helium inlet turn is at the bore of the magnet. The conductor temperature continues to

increase from the inlet to the outlet at the outside of the magnet. However any increase in temperature past the first (bore) turn has no effect on the minimum temperature margin since the current sharing temperature increases even more rapidly than the conductor temperature. Note that outlet temperature is 6.0 K for the double and single-pancake designs, because each flow path for the double-pancake design has double the heating and double the flow of the single-pancake design. The turn length is 12.26 m so the minimum temperature margin occurs at $x=12.26$ m, the downstream end of the inlet turn. The temperature after 900 s is 5.8 K, and will reach 5.9 K at steady state. The temperature is 0.7 K lower than the bore temperature of the double-pancake configuration. The relative positions of the conductor and outside of G-10 plots indicates that there is considerable heat flow from the second turn to the bore turn.

Conclusions

The analyses above show that the maximum steady-state temperature in the bore for the more reliable double-pancake design is 6.6 K. This is 0.7 K higher than the 5.9 K temperature attained at the bore of the single-pancake design. Since the current sharing temperature is 7.7 K (at 7.63 T and 33.5 A/mm²) the temperature margin for the double-pancake design is 1.1 K, and that for the single pancake design is 1.8 K. With 5 kW of nuclear heating and 3 kW of vertical stabilization eddy current heating, both the double and single pancake designs meet the requirement of a 1 K temperature margin³. The penalty for the increased reliability of the double-pancake design is a 0.7 K decrease in temperature margin. With 400 g/s of total helium flow, the steady-state pressure drops for the double and single-pancake designs respectively are 2.2 and 0.4 atm. A stability analysis of the double-pancake design, beginning at the steady-state operating temperature of 6.6 K at the bore, shows that the energy stability margin is 375 mJ/cc. This meets the required energy margin of 300 mJ/cc³.

Fig. 2 Transient conductor heating at bore Double pancake geometry

³P.Heitzenroeder, ed., "TPX Structural and Cryogenic Design Criteria," Princeton Plasma Physics Laboratory (Sept. 23, 1992).

Fig 3 Maximum transient temperature at bore Double pancake geometry

Fig 4 Steady-state conductor heating profile Double pancake geometry

Fig 5 Net interface heat flow into conductor after 500 s
Double pancake geometry

Fig 6 Temperature profile after 900 s Double pancake geometry

Fig 7 Temperature profile after 900 s Single pancake geometry

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