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CONCEPTUAL DESIGN OF A HOLLOW CABLE CONDUCTOR FOR THE LARGE COIL PROGRAM *

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INTRODUCTION

Westinghouse selected forced flow, supercritical helium-cooled Nb_3Sn hollow cable conductors for the Large Coil Porgram (LCP)[1]. A number of requirements and constraints were specified for the design of the model coil. Those that have direct and indirect impacts on the conductor design were: 1) The conductor must recover spontaneously to the superconducting state when half a turn is driven normal initially; 2) Total refrigeration load must be less than 550 W when the coil is operating with the full current; 3) Total refrigeration load must be less then 100 W when the coil is operating at 80% of the full current; 4) The peak magnetic field is to be 8 teslas; and 5) The maximum conductor current is 16,000 A. The conceptual TF coil is a pancake-wound device where each pancake of aluminum contains a number of conductor slots. Each slot accommodates 5 parallel turns. Details are described elsewhere[2].

The basic conductor concept selected consists of cabled triplexes, initially enclosed in a round pipe stainless steel jacket and then compacted to a square configuration with the desired void fraction[3]. Examination of a typical conductor cross section (See the figure below) suggested a number of uncertainties that affect the conductor design. They are: The uniformity of helium flow in the interstices of the twisted strands, the uniformity of current flow among the strands during conductor recovery, the load-bearing capability of the conductor, the heat transfer coefficients and the friction factors for twisted-strands compacted hollow cable conductors. These uncertainties and the lack of prior experience in the design of superconducting devices with hollow cabled conductors suggested that conservative assumptions be used. This paper discusses the design approach and the selection of a reference design.

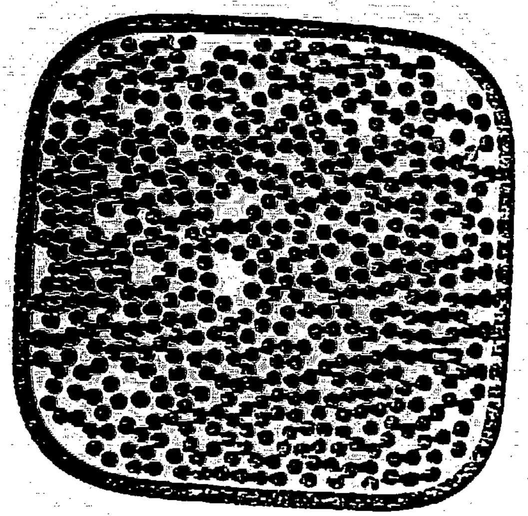

Figure 1. Cross Section of a Prototypical LCP Forced Cooled Conductor (567 Strands).

DESIGN APPROACH AND REFERENCE CONCEPT

The design of a conductor-cooling concept to meet the specified requirements and constraints of the LCP is essentially a transient heat transfer problem where the conductor selected must meet simultaneously the stability criteria and the refrigeration load constraints. The approach to the conceptual design was to perform initial scoping calculations based on simplified models and conservative assumptions. A reference concept was then selected from the results. This was followed by detailed transient conductor cooldown analysis to verify the stability of the conductor.

It can be shown that a conservative conductor design criterion can be derived from the equation of energy of the conductor such that the overall heat transfer coefficient required for stability is given by the relation:

$$U \geq \frac{J_{nc}\, I\, \rho_{cu}}{\psi\, p_c\, (T_c - T_f)} \qquad (1)$$

where J_{nc} is the current density in the non-copper portion of the conductor strands, I is the transport current, ρ_{cu} is the maximum electrical resistivity of the copper stabilizer (irradiated), T_c is the maximum critical temperature, T_f is the bulk fluid temperature, ρ_{cu} and T_c occur at the location of the peak magnetic field. ψ is the copper to non-copper ratio, p_c is the heat transfer perimeter of the conductor strands, assumed to be 75% of the total perimeter. The overall heat transfer coefficient is related to the film coefficient h, the insulation thickness δ and the thermal conductivity of the insulation k_{in}:

$$h = \frac{1}{\frac{1}{U} - \frac{\delta}{k_{in}}} \qquad (2)$$

The film heat transfer coefficient h can be related to the helium mass velocity G, through a heat transfer correlation. The helium mass velocity determines the pressure drop in the conductor, the helium pump work and finally the helium refrigeration load due to the pump work. To minimize the helium pump work, the overall heat transfer coefficient must be minimized while simultaneously satisfying the stability criterion. In the absence of a heat transfer correlation specifically applicable to hollow cable conductors, the one developed by Giarratano[4] for forced convective supercritical helium based on data obtained for turbulent flow in smooth tubes was assumed with a multiplicative factor of 1.5 (in the scoping calculations) to take into account the anticipated better heat transfer in the twisted strands when compared to smooth tubes.

Conductor Design Variables

The criterion given in Equation 1 contains the conductor design parameters ψ, Jnc, and Pc, which are in turn dependent on a number of other design variables such as the conductor cross-sectional area, the helium (void) fraction, the number and the size of the conductor strands, the cabling configuration selected, and the insulation thickness. To minimize helium pump work, it is desirable to maximize the conductor cross-sectional area. However, considerations of structural requirements and the total number of conductor turns resulted in a maximum conductor area not to exceed 4 cm^2 for the helium plus the conductor strand cross-sectional areas. The number of conductor strands and the strand diameter depends on the type of cabling configuration considered. The selection of a cabling configuration was based on considerations of the void, the void size distributions and the desire for total transposition of the strands (to minimize AC losses). Some possible cabling configurations and the corresponding total number of strands are the following:

CABLING CONFIGURATION	NO. OF STRANDS	FRACTION OF ACTIVE STRANDS FOR TOTAL TRANSPOSITION
3 x 3 x 3 x 7	189	0.86
3 x 3 x 3 x 3 x 3	243	1.0
3 x 3 x 7 x 7	441	0.73
3 x 3 x 3 x 3 x 7	567	0.86

Cabling operations ending in 4 groups of conductors were not considered because this configuration tends to yield excessively large voids. The larger the number of groups of strands in the cabling configuration, the better is the void and void size distributions.

Parametric Analyses

It becomes evident that there are a number of possible trade-offs which can be elucidated through parametric analysis. Because of the large number of design variables involved, a number of the conductor parameters were fixed for the parametric analysis. The current density in the non-copper portion of the conductor was set at 25,000 A/cm^2. The current density in the superconductor was fixed at 100,000 A/cm^2 (20% of short sample value at 8.3 T and 50% of short sample value at 11 T). The conductor (helium plus conductor strand) area was taken to be 4 cm^2. The helium void fraction was selected to be 0.4, the insulation thickness was 10 μ, the thermal conductivity of the insulation was assumed to be 1.3×10^{-3} W/cm - K, the transport current was set at 15,000 A for the preliminary scoping calculations, and the friction factor was assumed to be 20% greater than those obtained by Hoenig for a 57 strand round pipe hollow cable conductor[5].

It was postulated that because of the nonuniformity of the void sizes, conductor strands in contact with the highest helium flow velocities would recover first. The strands would then carry a greater current than the average, resulting in a "cascaded recovery" process[6]. The strands recovering last are in contact with the minimum flow velocity. The strands in contact with the minimum mass velocity, G_{min}, thus control the recovery of the conductor. The ratio of the nominal to minimum mass velocities was assumed to be three, based on a preliminary correlation of Hoenig's friction factor data. The nominal mass velocity, G_{nom}, is needed to establish the pressure drop and the helium pump work. The relation between G_{min} and G_{nom} is discussed in more detail in a companion paper[6].

The effects of the cabling configuration and the number of strands on the strand diameter, total heat transfer surface area and the coppper-to-non-copper ratio are shown in Table 1. Based on the preliminary calculations on various heat losses and the resultant refrigeration loads, a tentative limit of 300 watts was [illegible] refrigeration load for helium pump work. For a pump efficiency

TABLE 1

PRELIMINARY PARAMETRIC ANALYSIS

EFFECT OF CONDUCTOR DESIGN PARAMETERS ON REFRIGERAION LOADS 15,000 A CONDUCTOR

TYPE OF CONDUCTOR	TRANSPOSITION	NO. OF STRANDS	FRACTION OF ACTIVE STRANDS	STRAND DIAMETER, cm	COPPER TO NON-COPPER RATIO	REFRIGERATION FOR He PUMP WORK, W
CABLED	FULLY TRANSPOSED (DUMMY STRANDS)	189*	0.86	0.127	2.44	2114
		567†	0.86	0.073	2.44	305
CABLED	NOT FULLY TRANSPOSED (NO DUMMY STRANDS)	189*	1.0	0.127	3.0	437
		567†	1.0	0.073	3.0	79
LATTICE BRAID	FULLY TRANSPOSED UNIFORM VOID SIZES	189*	1.0	0.127	3.0	56
		567†	1.0	0.073	3.0	10

*3 x 3 x 3 x 7 = 189 INITIAL VOID = 0.79 COMPACTED TO 0.4

†3 x 3 x 3 x 3 x 7 = 567 INITIAL VOID = 0.86 COMPACTED TO 0.4

of 50%, the maximum pump work allowed is 150 watts. The helium pump work calculated for the various cabling configurations showed that among the cables investigated only the 567 strand, 7×3^4 cable can meet the stability criteria and this pump work goal. Obviously, a cable with greater than 567 strands can also meet this goal; however, it would compromise other design goals/considerations. For example, the next potentially attractive cables are 1539 strands (9×3^4), 1701 strands (7×3^5), etc. However, these would result in appreciably smaller strand diameters and higher manufacturing costs. In addition, the sub-channel sizes would be considerably smaller. The 567 strand cable was therefore selected as the reference cable conductor. A lattice braided conductor was calculated for a comparison. This conductor can achieve significant reductions in the helium pump work and the refrigeration load because full transposition can be attained without incorporating any dummy strands.

The specifications of the reference conductor concept are given in Table 2 below.

TABLE 2

SPECIFICATIONS FOR THE REFERENCE CONDUCTOR CONCEPT

CONDUCTOR DIMENSIONS INSIDE THE STAINLESS STEEL JACKET	2 cm x 2 cm
CONDUCTOR CURRENT	16,000 A
NUMBER OF CONDUCTOR STRANDS	567
NUMBER OF INACTIVE STRANDS	81
STRAND DIAMETER	0.0734 cm
INSULATION THICKNESS	17 microns
WIRE DIAMETER	0.07 cm
COPPER TO NON-COPPER RATIO	1.92
HELIUM (VOID) FRACTION	0.40
Cu Sn to Nb RATIO	3 to 1

Verification of Conductor Stability

Verification of the stability of the conductor was carried out by transient recovery analysis of the reference conductor using zero-dimensional and one-dimensional models and the TAP-B computer code. The code solves simultaneously the equation of energy of the conductor and the equations of energy, motion, continuity and state of the fluid by finite difference analysis. Three models were used in the analysis. The zero-dimension model adopted the peak local magnetic field of 8.3 T, while the 1/2 turn (one-dimension model) assumed a field distribution in a region where the magnetic fields are the highest. The third model is essentially the same as the second model. The basic difference is that only 25 cm of the half turn was assumed to be driven normal initially. The analyses were performed by driving the conductor normal initially with a given amount of energy input. The recoverability of the conductor was then analyzed by varying the helium flowrate based on minimum subchannel mass velocities and the total conductor flow area. The details of the analyses will not be given here, but the results are summarized in Figure 2. The helium flowrate limited by the refrigeration constraint is shown on the figure. The starred point corresponds to the hand-calculated conditions.

It becomes apparent from Figure 2 that the basic stability criteria used for the scoping analysis compares well with the computer analysis and that the zero-dimension model provides a conservative design. The transient analyses show that the conductor can recover to the superconducting state (within the refrigeration constraint) with the conductor initially driven to 21 K. This corresponds to an adiabatic energy input of some 650 mJ/cm^3 (strand volume).

CONCLUSIONS AND RECOMMENDATIONS

The good agreement between the "steady-state" criterion (Equation 1) and the "zero-dimension" transient model merely suggests that consistent assumptions were used in both sets of analysis. The uncertainties delineated earlier remains to be resolved. Their resolution may permit [illegible] ation of the conservative design assumptions made. In particular, press[illegible] p, heat transfer and stability data for twisted-strand, compacted cable co[illegible] are urgently needed.

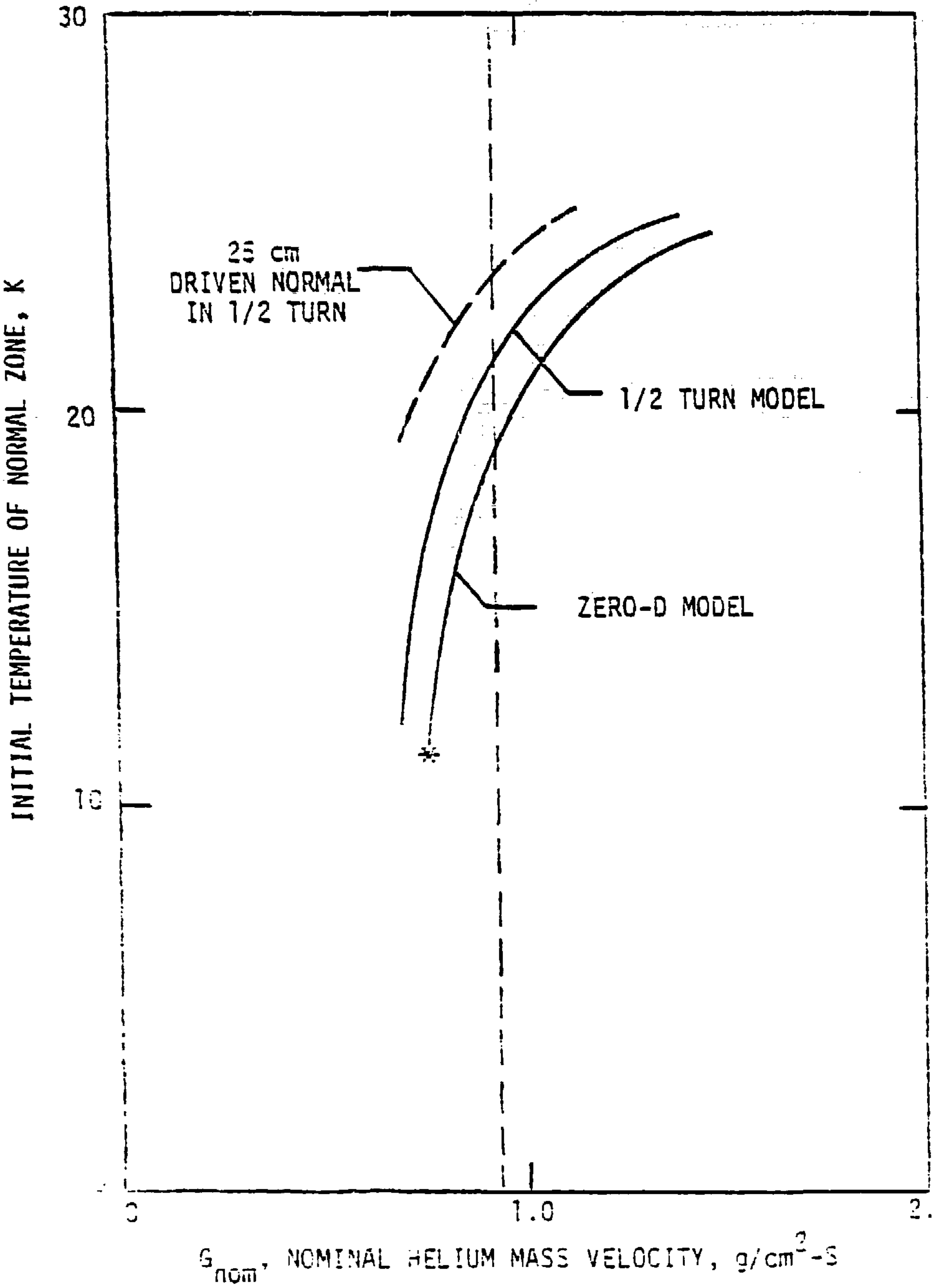

Figure 2. Comparison of the Stability Maps of the Reference Conductor.

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