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CONCEPTUAL DESIGN OF A 20 MJ SUPERCONDUCTING FORCED COOLED OHMIC HEATING COIL*

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INTRODUCTION

Conceptual design of a 20 MJ superconducting coil is described which was developed to demonstrate the feasibility of an ohmic-heating system. The superconductor material was Nb_3Sn for a 9 tesla maximum field. Cabled and braided conductors were investigated and the braided conductors were identified as the best alternates due to their high operating current densities and because of its porosity. The coil was designed to be cryostable for bipolar operation from +9 tesla to -9 tesla maximum field within 1 second. The forced cooled design described in the paper utilizes cross flow cooling. The coil was designed to generate the flux swing while simultaneously meeting the limitations imposed by cooling, insulation, current density and stresses in the materials.

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DESIGN CONSIDERATIONS

The superconducting ohmic-heating coil described in this paper required an energy store of 20 MJ at a current of 50 kA. The coil structure was to withstand the forces resulting from plasma collapse fault mode. The required coil inductance was 16 millihenries resulting in a terminal voltage of 1600 volts for a resistive discharge and 2500 votls for a capacitive discharge. Bipolar operation from +9 to -9 tesla maximum field on the conductor, and bipolar half cycle sinusoidal operation from full positive field to full negative field within one second. The hold time between field reversal was to range from 10 seconds to 100 seconds at full field. The coil was to be cryostable and the coil was not to go normal during bipolar operation. The superconductor material was Nb_3Sn for a peak field of 9 tesla.

Because of the stored energy requirement, high operating current density and the desire for a fully ventilated coil, it was decided to adopt a multilayer helically wound coil design. The resulting design utilized a lattice braided conductor in a ten-layer configuration. The major design parameters are shown in Table I.

CONDUCTOR DESIGN

Several[1] conductors were designed for potential application in a forced-cooled ohmic-heating coil. The superconducting material considered was Nb_3Sn. A cabled conductor with 504 strands was also considered. All conductors were designed to be cryostable, i.e., the heat generation rate when all of the current is in the stabilization material is less than the heat removal rate. The copper to non-copper ratio and the strand diameter were selected to give an operating current density to critical current density ratio approximately equal to 50%.

Table I

Coil Design Parameters

Energy Storage Rating at 50 kA	20 MJ
Peak Field	9 tesla
Inductance	16 mH
Insulating Rating	10 kV
Type of Cooling	Forced
Type of Conductor	Braid
Superconductor Material	Nb_3Sn
Coil Length	139.7 cm
Coil Diameter	149.4 cm
Coil Bore	33.0 cm
Number of Turns	240
Number of Layers	10

Because the lattice braided conductors were found to be superior to the cabled conductors in current density and porosity characteristics, they were selected for the ohmic-heating coil application[4].

AC LOSSES

The ac losses in the ohmic heating coil conductors have been calculated assuming a nonoptimized superconductor configuration. Table II summarizes these calculations and the reference conductor characteristics. In all cases, the predominant ac loss is eddy current loss in the copper stabilizer. This loss can be lowered by incorporating resistive webbing. However, because the surface heat flux during the field pulses is between two and fourteen times smaller than the surface heat flux required for cryostability, this loss reduction has been ignored at this time.

MECHANICAL DESIGN

The structural design and analysis were based on the 300 kJ coil[2] that has been successfully tested at LASL when subjected to an ohmic-heating cycle[3]. The pulsed operating cycle requires minimization of electrically conducting structures to minimize eddy current losses during the operating cycle. For this reason fiber reinforced composites were used wherever possible in the coil structure. The structural design was developed using the following design codes.

- The maximum strain in the Nb_3Sn superconductor should be limited to 0.1%
- The primary stress intensity in the structure should be less than two-thirds material yield stress or 40% of ultimate whichever is less

Table II

Reference 50 kA Conductor Characteristics

Peak Field, tesla	9
Type of Cooling	Forced
Type of Conductor	Braid
Material	Nb_3Sn
Number of Strands	503
Bare Strand Diameter, inches	0.038
Insulated Strand Diameter, inches	0.040
Number of Filaments	6,328
Filament Outside Diameter, microns	3.5
Filament Inside Diameter, microns	1.5
Filament Twist Length, cm	1.0
J to J_c Ratio	0.500
Cu-to-Non Cu Ratio	3.069
Packing Factor	0.41
Conductor Width, inches	1.378
Conductor Thickness, inches	1.126
Conductor Current Density, kA/cm^2	5.00
Matrix Conductivity, σ_m, mho/m	5.9×10^8
Transverse Conductivity, $\sigma_\perp$, mho/m	1.2×10^9
Sheath Conductivity, σ, mho/m	1.7×10^9
Peak AC Loss per Pulse, J/cc	1.66
Peak Field Pulse Heat Flux, mW/cm^2	58.0
Cryostability Recovery Heat Flux, mW/cm^2	448

- The maximum stress theory will be used for composite structures.

The coil structural design will address the following areas:

- Distribution of structure for maximum utilization of material properties
- Structural materials to be used in pulsed field environment

The design concept for the coil is shown in Figure 1. The concept uses teeth to support axial forces and stainless steel bands for radial support. The axial and radial forces vary within the coil cross section.

The structural design considers three areas, the tooth thickness, the banding thickness and the former thickness. The tooth thickness calculations are based on a cantilever beam with uniform loading in the axial direction. The tooth width can be decreased from its maximum value at the coil ends toward the center as the axial force decreases.

The banding concept uses an overwind of metal band on the conductor outside surface. The thickness of the band is varied to limit the strain in the conductor to prevent degradation of its current carrying capacity. The band is fastened at each end on each layer. This will enable tension to be developed within the band.

The former thickness is sized to achieve the required prestress during cooldown to minimize conductor motion. When the coil is energized, the compression is relieved as the magnetic force in the conductor increases. This results in a relatively constant tension in the banding until the magnetic forces exceed the preload forces. This concept was used successfully in the 300 kJ coil[1]. The prestress in both the band and former are dependent upon the physical and mechanical properties of the two subassemblies. The technique assumes an infinitely rigid conductor. The concept also assumes that each layer acts independently.

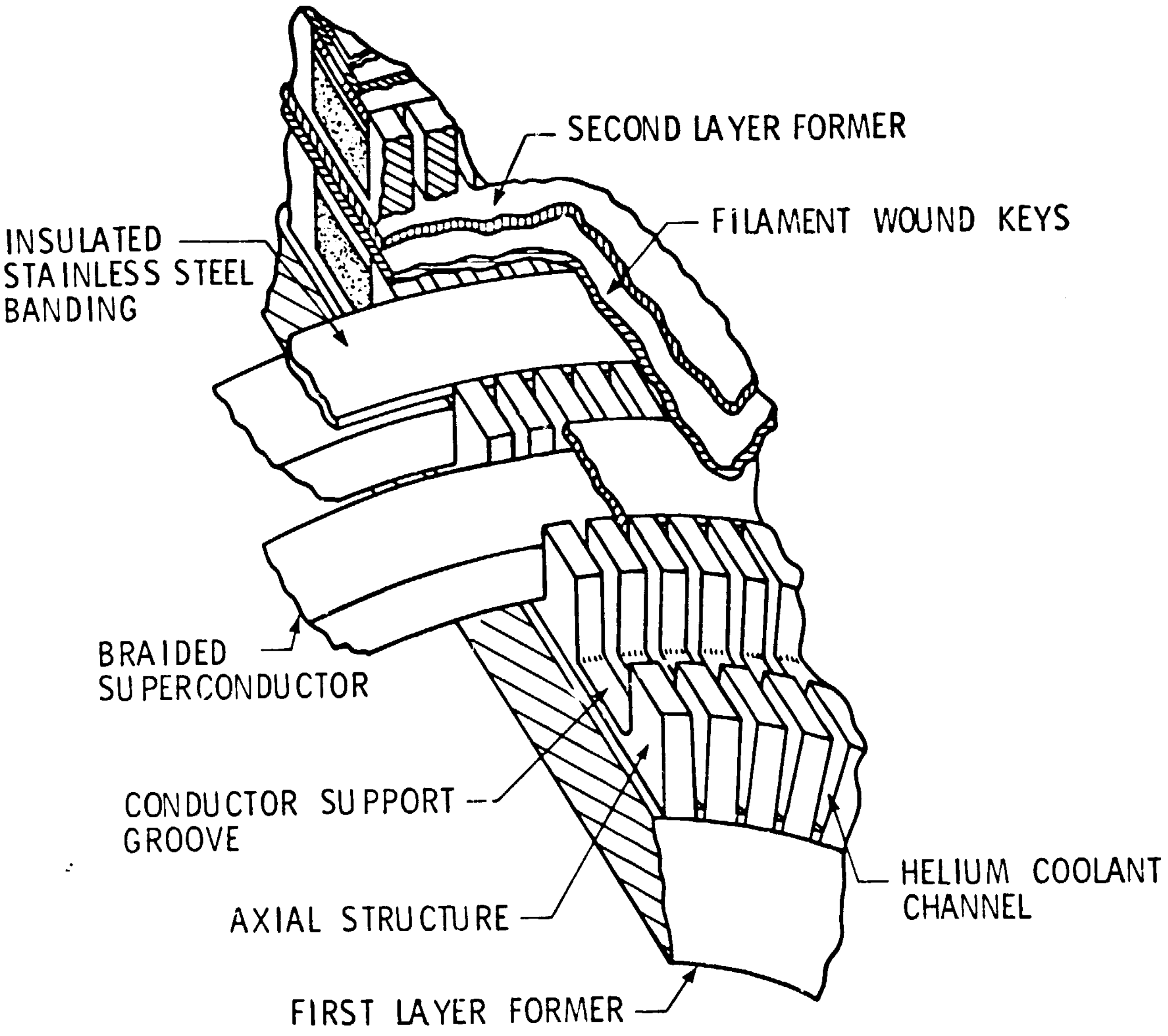


Figure 1 Cross Section of a Layered Wound Coil

The former thickness can be structurally graded for each layer, however for the conceptual design, a constant thickness was chosen for every layer.

The materials selected for the structural component include G-10[2] for the axial structure and spacers, KEVLAR for the former and 304L[2] stainless steel for the banding.

Using a maximum bending stress of 38.6 MPa (40% of 96.5 MPa), assuming an axial alignment of fibers, the tooth thickness was calculated at 1.96 cm. The shear stress was calculated to be 5.8 MPa which is 12% of the allowable value of 48.2 MPa.

The radial strain was limited to .1% for Nb_3Sn superconductors. This resulted in band hoop stress of 201 MPa. The variation of bending thickness with radius was calculated and the results are shown in Figure 2. Using these banding thicknesses and a former thickness of 1.07 cm, the banding prestress due to cooldown was calculated and the results are shown in Figure 2.

The axial structures are bonded to the formers using polyurethane adhesion. Polyurethane adhesives are the most appropriate for use at cryogenic temperature[1]. This is so because they share the least embrittlement at very low temperatures compared to other classes of adhesives. They can be cured at room temperatures and do not need much pressure during cure.

Thermohydraulic Analysis and Design

The forced cooled design is very similar to the pool cooled 300 kJ coil design[1] except that there are no bypass channels around the conductor and the conductor is cooled by crossflowing helium. Crossflow was selected for this coil on the following bases:

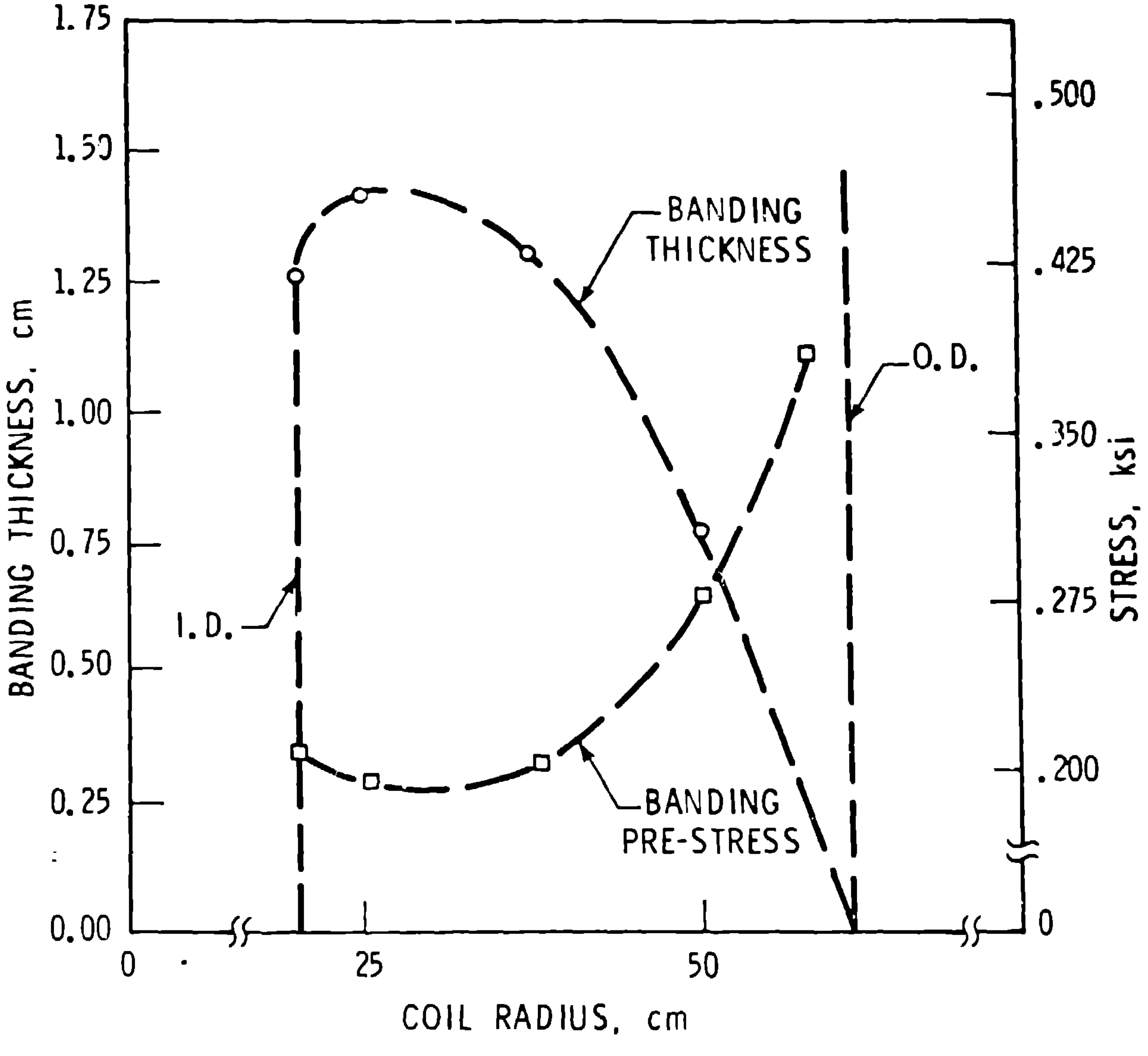


Figure 2 Variation of Banding Thickness and Stress with Radius

- **A sheathed cable could not be reliably bent around the small radii**
- **Headering of the coil would be difficult because of its compactness**
- **Since the crossflow pressure drop is inversely proportional to temperature, a minimum additional flow over the basic stabilization value is required to maintain adequate flow to a normalized, elevated temperature section**
- Heat transfer coefficients are high for small strands of conductor in crossflow
- The helium expansion effect occurring during a normalization has a minimal effect on the flow field in crossflow cooling

The leads from the coil to room temperature are cooled by supercritical helium flow which is controlled by a critical orifice at room temperature. Again the large flow rate of the lead precludes any significant rise in pressure in the expansion of the coolant due to absorption of energy during a quench The operating thermodynamic state of the coolant is selected as six atmospheres and 4.2 K based on adequate thermodynamic-fluid dynamic stability of the coolant channels and adequate dewar strength.

A supercritical flow circuit is shown in Figure 3. The helium pump and downstream heat exchangers are located in a dewar filled with helium by the refrigerator. The refrigerator capacity is matched to the dewar load by the previously identified heat leak pool depth type relation. By applying this method of forced circulation, the refrigerator is decoupled from the coil, coil dewar and lead load. Figure 3 also shows a cold pressurized line used to make up the leak flow and to control the pressure in the forced cooled circuit.

The conductors are transverse to the axial flow of coolant in the coil. Flow enters the coil on the centerline and flows to a distribution header on the opposite

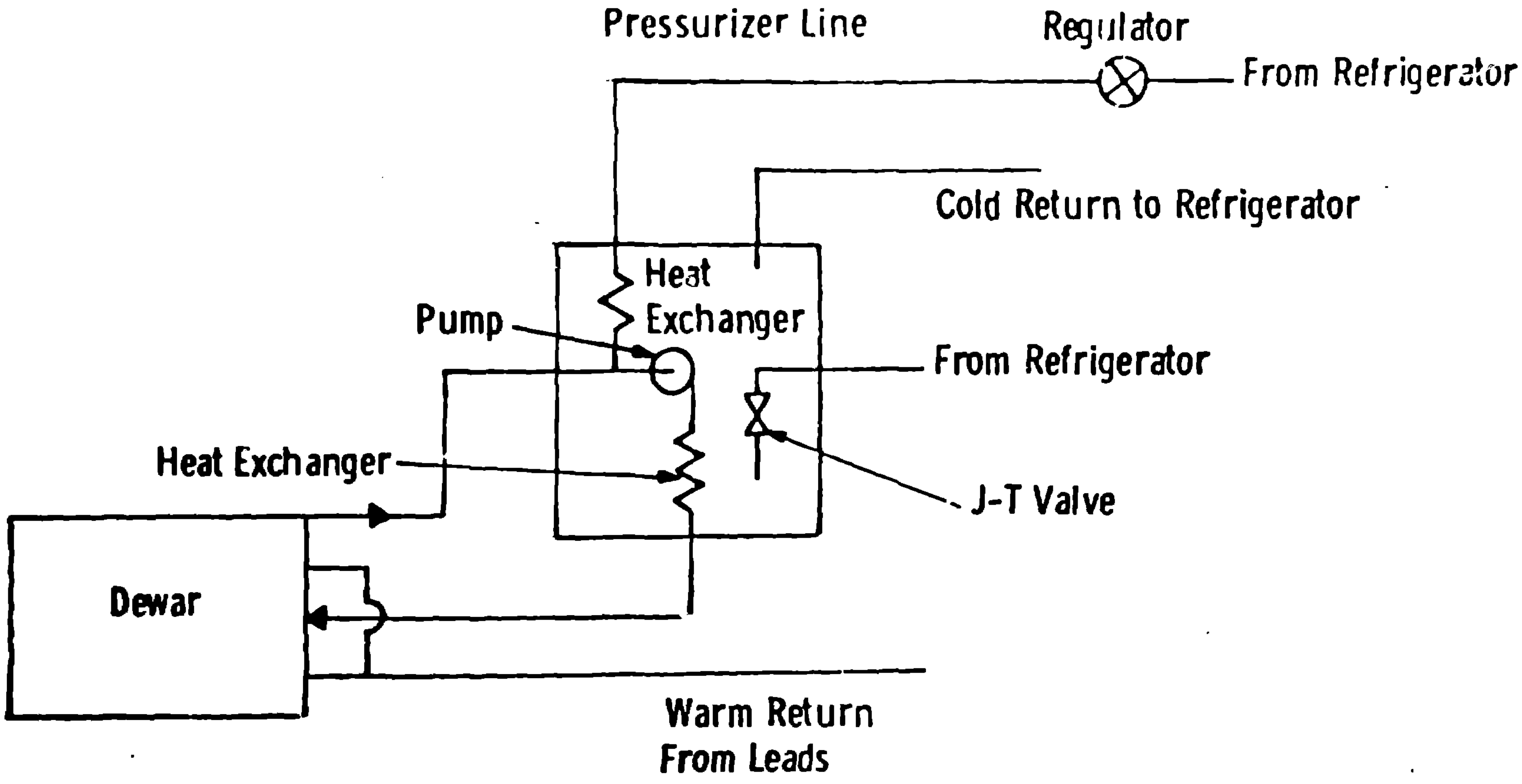


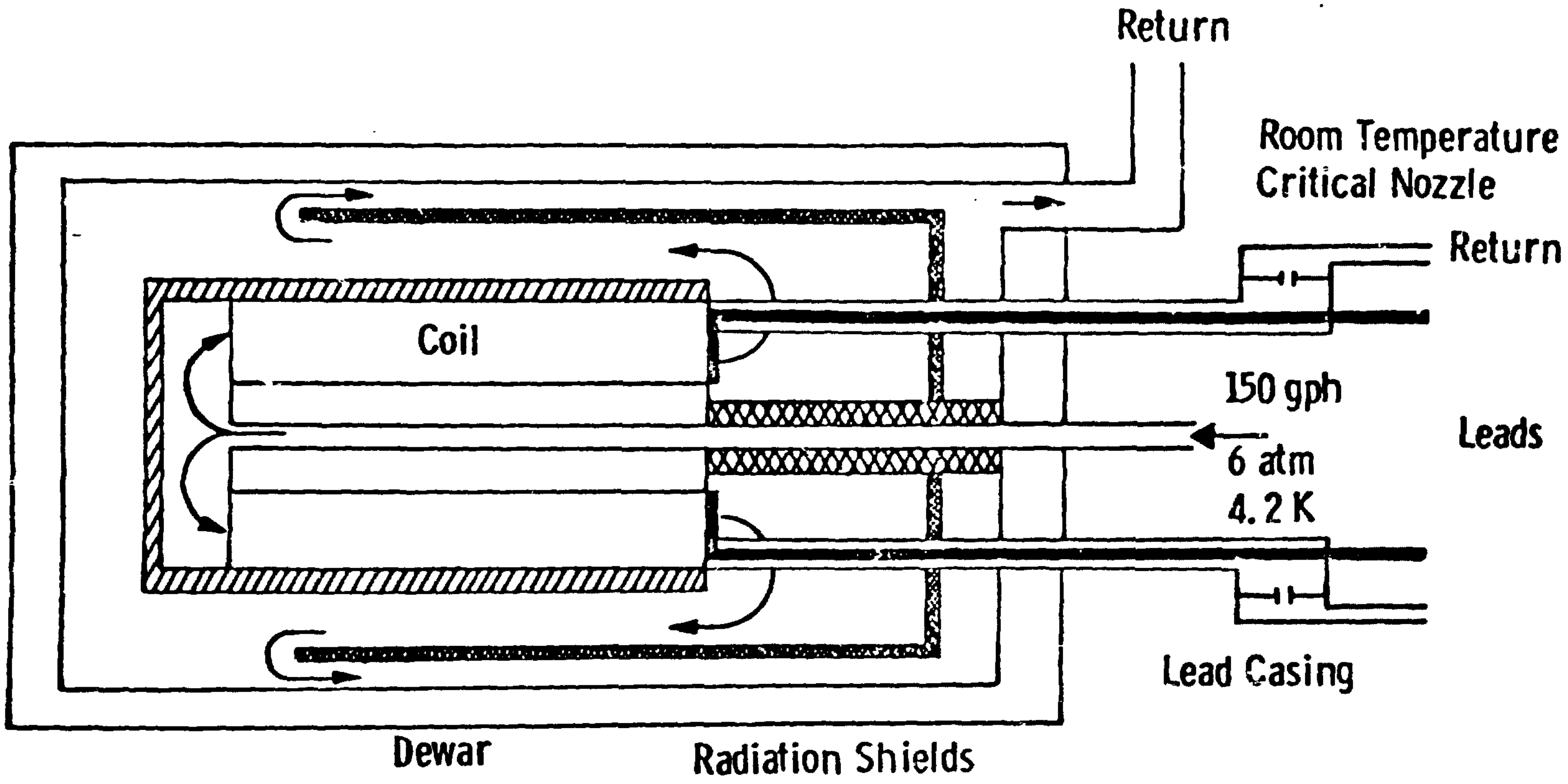
Figure 3. Forced Cooled Coil Flow Schematic

end as shown in Figure 4. The flow proceeds to the opposite end where an insulating shroud returns the flow over the coil surface eliminating any possibility of heat leak to the conductor from a stratified dewar. The flow then turns to flow upward along the dewar walls to carry away any heat leak from ambient and to return to the pump. This system prevents dewar stratification and the recirculation of any temperature spikes introduced into the coolant by pulsed operation.

Stability Analysis

In the initial design phase it was determined that for the conductors and geometries that are practical for this coil, a forced convection coefficient of 0.07 W/cm^2-K is appropriate. Because a strand-to-strand insulation has not been identified for Nb_3Sn, a representative value of $k/ = 1.0$ W/cm^2-s was used in conjunction with the critical temperature for $j/j_c = 0.50$ to determine that heat transfer coefficient of 0.2 W/cm^2-K is required. An insulation having a k/δ of 1.0 could be a polyamide, polyethylene or nylon 1 mm thick or glass 10 mm thick.

The peak losses in the forced cooled design result in a surface heat flux of 0.058 W/cm^2 or a local peak temperature of the conductor of 6.0 K. This is well below the current sharing temperature, 6.9 K. The average heat generation per cycle will not exceed 0.83 J/cc of conductor or 0.577 J/cc of helium in the conductor. If the heat is stored locally in static coolant the temperature will rise to 5.3 K. In a one second cycle the helium will be 50% replenished so that satisfactory performance is assured. The residence time of helium in the coil is approximately 26 s. Depending on the exact space-time averaging of the ac losses, the flow velocity could stand a 10-15% increase for safety margin. The need for additional margin is not demonstrated by this analysis.



Cooled Lead and Coil Flow Schematic

The forced cooled conductor stability is described in terms of a steady and transient criteria. Whereas the steady state minimum propagating zone criteria for pool cooling is satisfied by a simple choice of conservative surface heat flux, the force cooled conductor average surface heat flux is lower, leading to a design minimum propagating zone that specifies the cooling system pumping power.

The transient stability of the conductor is described in terms of recovery from an instantaneous, adiabatic, 20 K conductor temperature rise with the surrounding helium at 4.2 K. The half turn criterion is of sufficient length that axial conduction can be neglected. Cooldown is then given by simultaneous solution of Equations 1 and 2.

$$(T - t - \dot{q}''' A_{cu}/U\ p)/(T_o - t - \dot{q}''' A_{cu}/U\ p) = \exp \quad - \frac{Up}{c_v p} (\tau - \tau_o) \qquad (1)$$

$$\frac{t - t_o}{T - t} = \frac{U\ p}{M'\ c_p} (\tau - \tau_o) \qquad (2)$$

This simplistic method of solution is adequate because the temperature rise of the helium is less than 2 K. The temperature of the conductor is found by marching forward in small time steps and is conservative because the conductor-fluid temperature difference is written in terms of the fluid temperature at the end of the time step, not the average as is customary. The transient heat transfer coefficient is given as

$$h = 2 \quad \frac{\rho c_p\ k}{\pi(\tau - \tau_o)} \qquad (3)$$

which decays to the steady value given by

$$j_h = 0.91\, R_e^{-0.51}\, \psi \qquad R_e \le 54.6 \tag{4}$$

$$j_h = 0.61\, R_e^{-0.4}\, \psi \qquad R_e \ge 54.6 \tag{5}$$

$$j_h = \frac{h}{c_p G_o} (P_r)^{2/3} \tag{6}$$

$$\psi = 0.91 \tag{7}$$

The overall U is determined as a series impedance of the Kapitza resistance (taken here as 2.5 cm^2-K/W), insulation resistance (δ/K = 1.0 cm^2-K/W) and convection impedance (1/h). This reasonable formulation can be verified by the heat transmission time constants for the conductor, insulation and helium which are respectively approximately: 1 μs, 0.1 ms, and 0.2 s.

Solving Equations (1) and (2) yields a recovery time of 2.4 ms and the required steady state heat transfer coefficient is much less than the minimum propagating zone (MPZ) value. In this case the transient stability criterion does not set the minimum flow rate. The forced convection cooled coil is designed so that the Stekly energy balance criterion is exceeded in the cooling channels and the steady state minimum propagating zone for a cross flow cooled conductor.

$$\zeta \le 2 \left(\frac{kA}{Up}\right)^{1/2} \tanh^{-1} \left(\frac{1}{\frac{\rho_e J^2 A_{cu}}{Up(T_c - t)} - 1}\right) \tag{8}$$

For the values in Table III the minimum propagating zone is 1.79 cm which is larger than the repeat length of the structure.

Table III

Parameters Used to Determine the Minimum Propagating Zone (Equation 12)

Parameter	Value
$U = (2/3 \times 0.003 + 1/3 \times 0.09)$	0.0320 W/cm^2-K
A_{cu}	2.775 cm^2
p	144.9 cm
$\rho_e\ J^2$	24.59 W/cm^3
ρ_e @ 9 T	7.575×10^{-8} -cm
$T_c - t$	6.4 K
k_{Cu} @ 9 T	1.3 W/cm-K

From Equation (5), the mass velocity required to obtain the space averaged heat transfer coefficient of 0.032 W/cm^2-K is 0.782 gm/cm^2-s. The total flow area of the coil is 2.835×10^3 cm^2 for a total flow rate of 2.217 kgm/s. The pressure drop is given by the Burke-Plummer equation (Equation 9) for a Reynolds number of 8000.

$$\left.\frac{\Delta p}{L}\right|_f = \frac{3.5}{D_p}\ \frac{1}{2}\ \frac{G_o^{\ 2}}{\rho}\ \frac{1 - \varepsilon}{G^3} \qquad (9)$$

The expansion and contraction losses per meter are

$$\left.\frac{\Delta P}{L}\right|_X = \frac{\left[(1 - \varepsilon)^2 + \left(\frac{1.0}{\varepsilon}\right)^2\right] \frac{G_o^{\ 2}}{2\ \rho}}{L} \qquad (10)$$

For a coil length of 1.57 m the total pressure drop is 0.947 kPA. Pump work is given by Equation (11).

$$W_p = \frac{(\dot{m}/\rho)\Delta P}{\eta_{th}} \qquad (11)$$

For a pump thermal efficiency of 50% the cold refrigeration load due to pumping is 29.9 W.

The quench analysis of a coil is solely concerned with survivability of the coil and dewar. A conventional quench of the coil with the protection circuit and dump resistor operation results in 0.03 J/cc heat addition to the conductor. This is less than a conventional bipolar swing.

NOTATION

A_{cu}	area copper
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D_w	diameter wire
G	mass velocity
G_o	superficial mass velocity
h	heat transfer coefficient
j_h	Colburn "j" factor
J	current density
k	thermal conductivity
L	length
M'	mass helium per unit length
$\dot{m}$	mass flow rate
p	perimeter, pressure
Pr	Prandtl number
$\dot{q}'''$	heat energy per unit volume
Re	Reynolds number
t, T	temperature, coolant, metal
U	unit thermal surface conductance

W_p	pump work
δ	radiation shield thickness
ε	void fraction
η_{th}	thermal efficiency
ρ	density
ρ_e	resistivity
τ	time
ζ	minimum propagating zone

Subscripts

c	critical
o	outlet, outside

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