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SUPERCONDUCTING FIELD WINDING STUDIES
Magnet Field Winding System for 30 Megawatt Ship Propulsion
Superconducting Motor Solenoid Using Internally Cooled Cabled Superconductor (ICCS)

Prepared for
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FOREWORD

This report is issued by the Superconducting Magnet Development Group of the Plasma Fusion Center (PFC), Massachusetts Institute of Technology (MIT).

Mitchell O. Hoenig, Principal Investigator

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TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.0 DESIGN SUMMARY</td>
<td>2</td>
</tr>
<tr>
<td>3.0 RESPONSE TO SPECIFIC QUESTIONS IN CUSTOMERS WORK STATEMENT</td>
<td>6</td>
</tr>
<tr>
<td>4.0 ICCS DESIGN</td>
<td>11</td>
</tr>
<tr>
<td>4.1 Conductor Design</td>
<td>13</td>
</tr>
<tr>
<td>4.2 Selection of Wire Diameter</td>
<td>16</td>
</tr>
<tr>
<td>4.3 Calculation of ICCS Sheath Thickness</td>
<td>17</td>
</tr>
<tr>
<td>5.0 COIL DESIGN</td>
<td>24</td>
</tr>
<tr>
<td>6.0 ICCS SUPERCONDUCTING STABILITY</td>
<td>34</td>
</tr>
<tr>
<td>7.0 EMERGENCY OPERATION</td>
<td>42</td>
</tr>
<tr>
<td>8.0 PROTECTION</td>
<td>50</td>
</tr>
<tr>
<td>9.0 RECOMMENDATIONS FOR FURTHER WORK</td>
<td>56</td>
</tr>
<tr>
<td>10.0 PUBLICATIONS</td>
<td>58</td>
</tr>
</tbody>
</table>
ABSTRACT

Design studies of a (nominally) 100 cm diameter, 150 cm long superconducting solenoid are described. Calculations reflect 5 and 6 T central fields. The conductor is an internally cooled, cabled superconductor (ICCS) with NbTi. The 2 x 2 cm stainless steel sheathed conductor consists of 19 coaxially cabled 1,000 amp bundles, which are insulated from each other by means of braided fiberglass. Coil current is 1,000 A. Conductor design has been optimized for (1) superconducting operation using single phase (supercritical) helium in the interstitial cable space; (2) under emergency conditions the coil will provide "Take Home Capability" at 10% current level operating resistively at essentially room temperature with forced water cooling through the interstitial cable space.

INTRODUCTION

The object of this study is to provide the U.S. Navy with a highly stable superconducting solenoid, free of training quenches and able to be operated as a resistive magnet under emergency conditions, conceivably encountered out at sea, far from home port. This has been done by using our internally cooled cabled superconductor technology,* developed in the last 10 years under the sponsorship of the U.S. - DOE for nuclear fusion.

* See Section 10 Publications
2.0 DESIGN SUMMARY

The recommended coil and conductor design is shown in Fig. 2.1. Figure 2.2 is a photograph of the conductor (less sheath). It consists of three (3) identical, coaxial subcoils, all contained in one liquid helium filled cryostat. Each subcoil is made up from 12 identical double pancakes each consisting of eleven (11) turns. The double pancakes are individually vacuum-epoxy potted and on assembly are separated by a 1 mm gap, generated by vertical G10 strips. These strips accomplish two objectives: (1) provide liquid helium access to each face of a double pancake and (2) provide additional electrical insulation between double pancakes.

The selected design accomplishes the following features:

<table>
<thead>
<tr>
<th>FIELD</th>
<th>(1) Central plane, on axis field (Boo) of 5 or 6 T.</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRESS</td>
<td>(2) ICCS sheath thickness with a mean tensile stress of 34 ksi.</td>
</tr>
<tr>
<td>CURRENT (S/C)</td>
<td>(3) Operating current of approximately 1,000 A in the coil's superconducting mode and 100 A in its emergency, resistive mode.</td>
</tr>
<tr>
<td>CURRENT DENSITY (S/C)</td>
<td>(4) Superconducting operation at 64% to 70% of the NbTi's critical current density (2331 A/mm² at 5.25 T, 4.2 K). Alternatively 57 to 71% for 6 T design.</td>
</tr>
<tr>
<td>INTERSTITIAL HELIUM HEAT CAPACITY</td>
<td>(5) Superconducting stability with a current sharing temperature of 4.9 K. Interstitial helium heat capacity to absorb 631.6 mj per cm³ of wire (0.6 j/cm of ICCS) below current sharing temperature.</td>
</tr>
<tr>
<td>TRANSIENT STABILITY</td>
<td>(6) Transient superconducting heat capacity to absorb an energy impulse of 168 mj per cm² of wire (0.16 j/cm of ICCS), absorb joule heating during current sharing post-impulse recovery and recover without quench.</td>
</tr>
</tbody>
</table>
Hydraulic design has been arranged in order to minimize helium pressure in case of quench. Peak pressure based on a simultaneous quench along the full length of a double pancake is 500 psig at the 827 A basic current (and 667 psig, 4.7 MPa at 1,000 A).

In terms of protection, the selected coil with its three (subcoils) has a total number of 7524 turns and an inductance of 22.6 henries. Coupled to a 3.4 ohm resistor it can be discharged with peak discharge voltage of 2.6 kV and a time constant of 7.3 seconds with an operating current of 827 A. At 1,000 A, discharge voltage will be 4.5 kV, the time constant 5s and dump resistor rating 4.5 ohms. These criteria are based on a 300 K hot spot temperature.

In its normal (superconducting) mode the coil could be operated in two ways:

A. Placed in a tight fitting liquid helium cryostat the coil will need no helium flow. The interstitial cable space must simply be purged and pressurized to 2.5 atm of helium. In this manner the interstitial helium will protect the conductor from transient heating, such as "training" and transient energy pulses up to 16 joules per meter (512 joules per double pancake). Secondary, steady-state heating will be accomplished by lateral heat transfer, on one face of each pancake, to the liquid bath.

B. The coil could be simply installed in a vacuum chamber without cryostat. Transient heat transfer will be unchanged. Secondary, steady-state cooling will be accomplished by means of helium circulated at a nominal velocity of approximately 20 cm/s. At this velocity, volume flow per double pancake would be 22.8 cm³/s., mass flow 3
Under emergency conditions the coil could be brought to room temperature and operated at 100 amps using a closed cycle water cooling system. As under superconducting conditions current (100 A) will flow in series through the 19 bundles of each double pancake, while cooling water will flow through the ICCS' 19 bundles in parallel (in one path).

A. Maximum voltage between any two points within one ICCS double pancake is 305 V. Voltage between two adjacent bundles is 16 V. If the three (3) subcoils are wired in parallel, power supply requirements will be: 300 A, 3.7 kV, 1.1 MW.

B. Cooling water will have to be distilled, deionized, closed cycle. See Fig. 3.1. With flow through all subcoils and each double pancake in parallel, total flow will be 38.6 gpm (59.9 g/s per ICCS); pressure drop 137.4 psi, temperature rise 140°F, net pumping power 3.3 kW. A 1.1 MW heat exchange will be required to remove the resistive heat load from the cooling water.
Fig. 2.1 Overall coil and conductor dimensions.
Fig. 2.2 Photographs of Model ICCS

(a) 19 bundle ending
(b) section through ICCS
3.0 SPECIFIC RESPONSE TO CUSTOMER "WORK STATEMENT" REQUIREMENTS

3.1 Magnet System Stability

Basic stability is inherent in the ICCS conductor. The superconducting magnet could be charged up to its full operating current (approximately 1,000 amps) in one (1) minute without quench if a 500 V power supply were available. No training quenches would be required even if the magnet is charged at this faster rate, though transient voltages may appear.

Transient stability is a function of transient energy input, interstitial helium heat capacity and secondary, steady-state heat removal. Calculations (See Section 6) indicate that the conductor will recover from an instantaneous pulsed energy input of 168.3 mj per cm$^3$ volume of wire. This is equivalent to a 16 j/m length of conductor. Since the interstitial helium heat capacity is 60 j/m of conductor, such pulses could be repeated four (4) times in the same location without any steady-state heat removal.

3.2 Magnet system emergency operation in the normal conducting mode in the event of liquid helium supply system failure.

In order to place the magnet in its "Emergency Operating" mode the following procedure must be followed:

(a) Remove all liquid helium from dewar and bring coil and dewar up to room temperature.

(b) Connect the three (3) subcoils in parallel electrically.

(c) Evacuate ICCS helium system (See Fig. 3.1), open normally closed water valves (N/C), fill ICCS with water from special deionized, distilled water tank, pressurize water tank to 10 psig and start water pump.
The emergency, resistive operation at 300 A will require the removal of 1.1 MW of heat from the emergency H\textsubscript{2}O cooled heat exchanger.

3.3 Magnet system, machine personnel protection in the event of a magnet quench with helium filled conductors.

Should a quench occur, 11.3 MJ of energy will have to be discharged from the coil. This will happen automatically in the following sequence:

In case of quench either a pressure transducer or voltage sensitive actuator will open the main contactor between the magnet and its power supply. The magnet, will now be in series with its room temperature dump resistor (Fig. 8.1 page 55). The bulk of the coils energy will be discharged in the dump resistor. Conductor hot spot temperature will not exceed 300 K.

Helium pressure, normally 30 to 40 psig will rapidly rise to a maximum of 400 to 500 psig. Pressure relief valves, set at 150 psig will relieve system pressure to a safe vent.

Personnel located in the vicinity of the coil will not be exposed to any hazard, though there will be a peak discharge voltage of 4.5 kV across both the coil and the dump resistor.

3.4 Magnet, Cryogenic Liquid Supply System and Refrigeration Requirements

The cooldown mass of the fully potted coil is approximately 3.5 tonnes. Steady-state refrigeration heat load will be minimal, essentially dominated by the two (2) 1,000 A current leads.

3.5 Magnet system electrical current supply requirements for both superconductive and normal conducting operations.

Power supply requirements are as follows:

(a) Superconductive: In order to achieve a charging time of 10 minutes a 1,000 A, 50 V DC power supply will be required. Until the coil has been charged to approximately 990 A, 11 amps will also flow (in parallel) through the dump resistor. The coil can also operate on a 1,000 A, 5 V DC power supply. Charging time will be close to 2 hours.
(b) Emergency: 300 A at 3.7 kV - DC. The dump resistor will be disconnected during the emergency operation of the magnet.

Steady-state power requirement is 1.1 MW.

3.6 Magnet cooldown time for room temperature to superconducting operating temperature

A nominal cooldown time of 30 hours is expected. This could be accelerated by 12 hours by providing cooldown by means of the interstitial helium system.

3.7 Magnet current charge time from 0 to 100% of operating current. Magnet current discharge time from 100 to 0% of operating current

Normal current charging as well as discharging times of 10 minutes are possible with a 50 V power supply. Under emergency conditions the bulk of the coil's energy (11.3 MJ) can be discharged into the coil's dump resistor ($R = 4.5 \ \Omega$) with a terminal self generated voltage (4.5 kV) and a time constant of 5s.

3.8 Magnet system operating and performance monitoring instrumentation

Instrumentation for an operating production system should include:

(a) Abnormal voltage indicators
(b) Excess pressure indicator (s)
(c) Low liquid level alarm
(d) Current indicator

For emergency operation there should also be excess temperature indicators on the cooling system.
### 3.9 Estimated full scale magnet system construction cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of conductor, ready to wind (34 m per double pancake 36 double pancakes) at $14/kA - m = $ K 326*</td>
<td></td>
</tr>
<tr>
<td>Cost of winding 36 double pancakes (labor intensive)</td>
<td>72</td>
</tr>
<tr>
<td>Cost of potting</td>
<td>36</td>
</tr>
<tr>
<td>Cost of terminations (labor intensive)</td>
<td>50</td>
</tr>
<tr>
<td>Cost of casing and assembly</td>
<td>50</td>
</tr>
<tr>
<td>Contingency (10%)</td>
<td>50</td>
</tr>
<tr>
<td>Engineering, Supervision, Q/c etc.</td>
<td>100</td>
</tr>
<tr>
<td><strong>TOTAL ESTIMATED 1984 COST</strong></td>
<td><strong>$684</strong></td>
</tr>
</tbody>
</table>

*Includes $191 K for wire, $37 K for cabling and $52 K for sheathing labor, $46 K for steel sheath.*
Fig. 3.1 Hydraulic schematic for superconducting and emergency operations.
4.0 ICCS DESIGN

The following table provides a step by step ICCS design, which has been optimized to satisfy all known critical constraints. Primary constraints include the following:

(a) Use of a maximum current of 1,000 A (Line 7).*

(b) Selection of concentric bundle transposition in order to protect bundle-to-bundle insulation. Options are 7, 19 or 37 bundles (Line 21).

(c) The relatively high (54.55%) coolant cross-section was selected primarily to minimize coolant (water) temperature rise under steady-state (100 Amp) emergency operations (Line 15).

(d) Insulation between bundles (Line 8) is needed because the 1,000 A (superconducting) or 100 A (emergency) current is to be carried in series from bundle-to-bundle. The insulation is provided in the form of a porous braid in order to permit transverse coolant mixing between bundles.

(e) In addition to bundle-to-bundle insulation, the 19 bundles are insulated from the steel sheath. Bundle-to-bundle as well as bundle to sheath insulation thickness is identical. In order to protect the sheath from becoming a ground short, it too has been insulated. This, external insulation will be epoxy filled and will add to the strength of the potted coil structure.

(f) The copper to superconductor ratio ($R_{Cu} = 8$), (Line 9) was selected to satisfy:

(i) An acceptable current discharge time constant on quench ($\tau = 5s$).

(ii) Acceptable peak pressure on quench ($P_{max} = 682$ psi).

(iii) Sufficient copper cross section to minimize steady-state joule heating (1.1 MW for three (3) 50 cm long coils) at a 100 A emergency operating current.

(iv) $R_{Cu}$ must be limited in order to preserve a reasonable overall current density ($j_A$, Line 37).

*See Section 4.1 Conductor Design (Line 7).
(g) Sheath thickness was selected in order to satisfy conductor structural requirements. A decrease in the sheath thickness (Item 28) would increase \( j \lambda \), but would necessitate a substantial support ring around each coil. The selected thickness in a fully potted coil will support coil against Lorentz forces.

A chart illustrating the ICCS conductor fabrication is shown in Fig. 4.1.
### 4.1 Conductor Design

Geometry Development, Calculation of Overall Current Density and Determination of Conductor Weight.

- **(1)** Select superconductor
  - S/C
  - NbTi

- **(2)** Available S/C current density
  - \( J_c(5 \text{ T, } 4.2 \text{ K}) \)
  - 2,400 A/mm\(^2\)

- **(3)** Select desirable ratio of operating to critical current density
  - \( J_{\text{op}} / J_c \)
  - 75 %

- **(4)** Hence operating current density
  - \( J_{\text{op}} \)
  - 1,800 A/mm\(^2\)

- **(5)** Critical temperature at 5 T
  - \( T_c \)
  - 6.9 K

- **(6)** Current sharing temperature @ 5 T, where \( J_{\text{op}} = J_c \)
  - \( (5 \text{ T, } T_c / s) \)
  - \( T_c / s \)
  - 4.9 K

- **(7)** Operating current carried by individual bundle (b)
  - \( I_{\text{op}} \)
  - 1,000 A

- **(8)** Cross sectional area of NbTi per bundle
  - \( (A_{\text{NbTi}})_b \)
  - 0.5556 mm\(^2\)

- **(9)** Select stabilizing copper to S/C ratio
  - \( R_{\text{Cu}} \)
  - 8

- **(10)** Hence cross sectional area of stabilizing copper
  - \( (A_{\text{Cu}})_b \)
  - 4.445 mm\(^2\)

- **(11)** Cross sectional area of wire per bundle (carrying \( I_{\text{op}} \))
  - \( (A_w)_b \)
  - 5.0 mm\(^2\)

- **(12)** Select coolant to wire cross sectional area ratio \( (A_{\text{Cool}} / A_w) \)
  - \( R_{\text{Cool}} \)
  - 1.2

- **(13)** Coolant area
  - \( (A_{\text{Cool}})_b \)
  - 6.0 mm\(^2\)

- **(14)** Cable space area within bundle
  - \( A_b \)
  - 11.0 mm\(^2\)

- **(15)** Bundle compaction ( uninsulated)
  - \( (\text{Comp})_b \)
  - 45.45 %

Bundle void fraction ( uninsulated)
- \( (\text{Void})_b \)
- 54.55 %
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Diameter of uninsulated bundle assumed circular</td>
<td>$\text{Dia}(u/i)_b$</td>
<td>3.74</td>
</tr>
<tr>
<td>17</td>
<td>Bundle periphery</td>
<td>$\text{Perif}(u/i)_b$</td>
<td>11.76</td>
</tr>
<tr>
<td>18</td>
<td>Thickness of braided insulation around bundle</td>
<td>$t_{i(b)}$</td>
<td>0.254</td>
</tr>
<tr>
<td>19</td>
<td>Cross sectional area of bundle insulation</td>
<td>$(A_i)_b$</td>
<td>2.986</td>
</tr>
<tr>
<td>20</td>
<td>Cross sectional area of insulated bundle</td>
<td>$(A_b)_i$</td>
<td>13.986</td>
</tr>
<tr>
<td>21</td>
<td>Number of bundles per ICCS</td>
<td>$N_b$</td>
<td>19</td>
</tr>
<tr>
<td>22</td>
<td>Cross sectional area ICCS cable space excluding insulation wrap</td>
<td>$(A_{c/s})_{u/i}$</td>
<td>265.73</td>
</tr>
<tr>
<td>23</td>
<td>Cable space width $(WR_{\text{Rad}} = WA_{\text{Axial}}$ allowing for corner loss, where corner Rad = W/4</td>
<td>$W_{c/s}$</td>
<td>16.76</td>
</tr>
<tr>
<td>24</td>
<td>Cable overwrap (o/w) insulation thickness</td>
<td>$(t_{i})_{o/w}$</td>
<td>0.254</td>
</tr>
<tr>
<td>25</td>
<td>Width of squared cable with overwrap</td>
<td>$(W_{c/s})_{i}$</td>
<td>17.268</td>
</tr>
<tr>
<td>26</td>
<td>Cross sectional area of cable with overwrap (i) incl sharp corners</td>
<td>$(A_{c/s})_{i}$</td>
<td>298.19</td>
</tr>
<tr>
<td></td>
<td>(ii) rounded corners</td>
<td></td>
<td>282.09</td>
</tr>
<tr>
<td>27</td>
<td>Cross sectional area of overwrap insulation</td>
<td>$(A_{i})_{o/w}$</td>
<td>16.36</td>
</tr>
<tr>
<td>28</td>
<td>Select sheath thickness</td>
<td>$t_w$</td>
<td>1.5</td>
</tr>
<tr>
<td>29</td>
<td>Sheath external width $(WR_{\text{Rad}} = WA_{\text{Axial})}$</td>
<td>$(W_{sh})_{u/i}$</td>
<td>20.268</td>
</tr>
<tr>
<td>30</td>
<td>Cross sectional area of sheath and contents (externally uninsulated) (i) with sharp corners</td>
<td>$(A_{sh})_{u/i}$</td>
<td>410.79</td>
</tr>
<tr>
<td></td>
<td>(ii) rounded corners</td>
<td></td>
<td>388.61</td>
</tr>
<tr>
<td>31</td>
<td>Cross sectional area of sheath</td>
<td></td>
<td>106.52</td>
</tr>
</tbody>
</table>
(32) External insulation thickness \((t_i)_{\text{ex}}\) 0.254 mm

(33) Overall width of ICCS conductor (for \(W_{\text{Rad}} = W_{\text{Axial}}\)) \(W_{\text{ICCS}}\) 20.778 mm

(34) Cross sectional area of insulated ICCS (i) including corners \(A_{\text{ICCS}}\) 431.64 mm² (ii) excluding corners \(A_{\text{ICCS}}\) 408.33 mm²

(35) Cross sectional area of external insulation \((A_i)_{\text{ex}}\) 19.72 mm²

(36) Cross sectional area of epoxy filled corners 23.31 mm²

(37) Overall current density of ICCS operating at 19 x 1,000 amps \(J_{\lambda_{\text{ICCS}}}\) 4402 A/cm²

(38) Volume fraction of ICCS constituents

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Volume/Unit Length (mm³/mm)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) NbTi superconductor</td>
<td>10.556</td>
<td>2.45</td>
</tr>
<tr>
<td>(b) Stabilizing copper</td>
<td>84.451</td>
<td>19.57</td>
</tr>
<tr>
<td>(c) Coolant space</td>
<td>114.008</td>
<td>26.41</td>
</tr>
<tr>
<td>(d) Bundle insulation</td>
<td>56.734</td>
<td>13.14</td>
</tr>
<tr>
<td>(e) Cable overwrap</td>
<td>16.360</td>
<td>3.79</td>
</tr>
<tr>
<td>(f) Sheath</td>
<td>106.520</td>
<td>24.68</td>
</tr>
<tr>
<td>(g) ICCS insulation</td>
<td>19.720</td>
<td>4.57</td>
</tr>
<tr>
<td>(h) Corner epoxy fill</td>
<td>23.310</td>
<td>5.40</td>
</tr>
<tr>
<td>Total Volume ICCS/Unit Length</td>
<td>431.64</td>
<td>100.0</td>
</tr>
</tbody>
</table>

(39) Approximate weight of insulated and epoxy filled ICCS 2.7 Kg/m
4.2 Selection of Wire Diameter

The following table shows the effect of various wire diameter selections on critical coil design criteria.

**CONSTANT PARAMETERS:**

\[
R_{Cu} = 8 \quad (A_{w})_b = 5 \text{ mm}^2 \quad G = 50 \text{ g/cm}^2\text{s (H}_2\text{O)}
\]

\[
R_{Cool} = 1.2 \quad (A_{Cool})_b = 6 \text{ mm}^2
\]

\[
N_B = 19 \quad (\text{Perif})_b = 11.76 \text{ mm}
\]

**VARIABLE PARAMETERS:**

<table>
<thead>
<tr>
<th>(d_w)</th>
<th>.841</th>
<th>.595</th>
<th>.486</th>
<th>.343</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>((N_w)_b)</td>
<td>9</td>
<td>18</td>
<td>27</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>(D_H)</td>
<td>.068</td>
<td>.053</td>
<td>.045</td>
<td>.034</td>
<td>cm</td>
</tr>
<tr>
<td>((A_{HT})^*)_b</td>
<td>1.0</td>
<td>1.42</td>
<td>1.73</td>
<td>2.45</td>
<td>-</td>
</tr>
<tr>
<td>((A_p)^*)_{H_2O}</td>
<td>1.0</td>
<td>1.35</td>
<td>1.65</td>
<td>2.31</td>
<td></td>
</tr>
<tr>
<td>((\text{Pump Power})_{H_2O})</td>
<td>1.0</td>
<td>1.35</td>
<td>1.65</td>
<td>2.32</td>
<td></td>
</tr>
</tbody>
</table>

* Selected

* Normalized
4.3 Calculation of ICCS Sheath Thickness

The intent is to provide a sheath thickness sufficient to withstand tensile Lorentz forces in a fully potted coil. Since the tensile load is maximum at the coil's inner radius and decreases with increasing radius, the tensile load will be shared between the turns. A relatively thin band must be provided around the coil periphery though there must be some growth in the outer turn. It is assumed that the outer band will carry some of the load.

Maximum tensile stress \( \sigma_t \) max is given by:

\[
\sigma_t = \frac{BIR}{A_{SH}} \quad \text{(Kg/cm}^2\text{)}
\]

where

- \( B \) is field in gauss (50,000)
- \( I \) is current in amps (19,000)
- \( R \) is coil inner radius - cm (40)
- \( A_{SH} \) is sheath cross-sectional area (cm\(^2\))

for the selected design with a sheath thickness of 1.5 mm, \( A_{SH} = 1.065 \text{ cm}^2 \).

Hence at \( R = 40 \text{ cm} \), \( \sigma_t \) (max) = 3,739 Kg/cm\(^2\) or 53,200 psi.

Tensile stress in the sheath as a function of coil radius is as follows for the design geometry:

<table>
<thead>
<tr>
<th>R(cm)</th>
<th>40</th>
<th>42</th>
<th>44</th>
<th>46</th>
<th>48</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_t / \sigma_t ) (max)</td>
<td>1.0</td>
<td>.97</td>
<td>.76</td>
<td>.58</td>
<td>.35</td>
<td>.15</td>
</tr>
</tbody>
</table>

This leads to an average value of tensile stress \( \sigma_t \) (avg.) = 34,000 psi.

More complex stress analysis will be required in order to allow for axial stresses on the coil, forces and stresses between subcoils as well as radial stresses on the ICCS sheath in its transfer of force from turn to turn.
The above analysis is designed to show that a 1.5 mm thick sheath is optimum. An increase in sheath thickness to 2 mm would reduce the average tensile load by 26.9% from 34 Ksi to less than 25 Ksi. The resultant decrease in overall current density would be close to 10% and would lead to a 5% increase in the coil build.
0.486 mm DIA. 1. Single strand
1.0 mm DIA. 2. Triplet
2.26 mm DIA. 3. Set of 9
4.9 mm DIA. 4. 27 strand bundle

4.4 mm DIA. UNINSULATED
4.9 mm DIA. INSULATED 5. Reduced bundle diameter
to 4.4 mm and insulate with 0.254 mm thick fiberglass
braid.

Fig. 4.1 ICCS conductor fabrication. (Approximate scale 5 x full size) (Distortion on compaction not shown).

(5 Sheets)
6. Cable 12 around first 7 bundles.

7. Cable 12 around first 7 bundles.

24.5 mm OUTSIDE DIAMETER
8. Insulate by wrapping .254 mm thick fiberglass braid around cable.

25.0 mm OUTSIDE DIA.

9. Encapsulate in s/s tube, 1.5 mm wall thickness, forming 24 mm OD; weld using continuous TIG process.

28.0 mm OUTSIDE DIA.
10. Draw down to 23.6 mm tube OD.

11. Square-off to square or rectangular form with rounded corners (10 & 11 have same periphery).
19 BUNDLES OF 27 STRANDS OF 0.5 mm DIA. WIRE EACH. EACH BUNDLE IS BRAID INSULATED AS A COMPLETE CABLE

12. Insulate using 0.254 mm thick fiberglass layer.
5.0 COIL DESIGN

The basic premise calls for the following characteristics:

(a) Coil ID 80 cm
(b) Coil OD 100 cm
(c) Coil length 150 cm
(d) On axis central plane field 5 (6 teslas)

On the basis of a 1.5 mm sheath thickness (ICCS Design, Line 28) and a field of 5 (6 teslas) the cross-sectional area of the insulated ICCS is 4.32 (4.8) cm$^2$ (Line 34). If the conductor is square, its insulated width is 2.1 (2.2) cm.

In order to be able to place three (3) identical coaxial subcoils close together, each subcoil should be composed of 12 identical double pancakes, with external, radial terminations (as shown in Fig. 2.1). In order to permit liquid helium access (for secondary cooling) to both outside surfaces of each double pancake a 1 mm gap is provided between all double pancakes.

Superconductor selected is commercially available NbTi with a critical current density $J_c(5\ T,\ 4.2\ K) = 2,400\ \text{A/mm}^2$. Rather than selecting a fixed Cu:NbTi ($R_{Cu}$) the normal stabilizing copper current density ($J_{Cu}$) has been fixed at 22.5 kA/cm$^2$. For the nominal 5 T ICCS design this corresponds to an $R_{Cu}$ of 8* (Line 9) for superconducting operation and 2.25 kA/cm$^2$ for emergency operation. For 6 T the $J_{Cu}$ values remains the same and $R_{Cu}$ (6 T) = 5.9.

In calculating the effective field ($B_{eo}$) the following conditions must be satisfied:

(a) A double pancake, allowing for its cross-over turn can only have an odd number of complete turns, namely 7, 9, 11, 13 etc.

*Where $R_{Cu} = \text{area of cross-section of copper/NbTi}$
The ratio of operating/critical current (at the superconductor) must be less 100%, optimally 60 to 70%.

An optimum must be found in the number of turns (n_{dp}) per double pancake. The larger n_{dp} is the lower will be the safety ratio \( I_{op}/I_c \). On the other hand an increase in n_{dp} represents a significant increase in: weight and cost of coil; length of conductor per double pancake and hence increase in pressure drop, Joule heating and peak pressure.

5.1 Optimum Design

The optimum coil design characteristics are given below for 5 and 6 tesla coils. A cross-sectional view of a double pancake is shown in Figs. 5.1 and 5.2.

<table>
<thead>
<tr>
<th>Boo</th>
<th>5</th>
<th>6</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_{dp} Primary Characteristics</td>
<td>11</td>
<td>11</td>
<td>(Turns/dbl pancake)</td>
</tr>
<tr>
<td>Coil OD</td>
<td>105.6</td>
<td>108.4</td>
<td>cm</td>
</tr>
<tr>
<td>Coil ID</td>
<td>80</td>
<td>80</td>
<td>cm</td>
</tr>
<tr>
<td>Coil Length</td>
<td>150</td>
<td>150</td>
<td>cm</td>
</tr>
<tr>
<td>I_{op}/I_c</td>
<td>70.1</td>
<td>71.2</td>
<td>%</td>
</tr>
</tbody>
</table>

| N_{dp} Secondary Characteristics | 36 | 36 | (Double pancakes) |
| L_{dp} | 32.1 | 32.6 | m (length of each ICCS) |
| Insulated ICCS Dimensions | 2.03 x 2.13 | 2.03 x 2.36 | cm |
| Approx. coil weigh (36 double pancakes) | 3.1 | 3.5 | Tonnes |
| Overall coil current density (jX) required | 3.7 | 3.8 | kA/cm² |
The effect on $I_{op}/I_c$ is shown in Fig. 5.2 in terms of $n_{dp}$. By reducing $n_{dp}$ from 11 to 9, the $I_{op}/I_c$ ratio rises from 70.1 to an excessive 85.2 (86.4% for 6 T). An increase in $n_{dp}$ from 11 to 13, on the other hand, represents a reduction in $I_{op}/I_c$ from 70% to 60 or 61%, which is desirable, but a 4% increase in coil diameter with a corresponding 20% increase in conductor length, weight and potential cost.

Net weight of superconductor (NbTi plus copper), the dominant cost factor, is 753 kg for the 5 T coil and 848 kg for the corresponding 6 T coil. At a nominal $225 per kg cost of composite wire this represents a basic outlay of $170 K and $191 K respectively.

5.2 Effect of Coil Geometry

A comparison has been made to evaluate the effect of a fixed coil OD (100 cm) on the $I_{op}/I_c$ ratio as well as on corresponding factors such as coil weight and length of conductor per double pancake. A plot of $I_{op}/I_c$ as a function of number of turns ($n_{dp}$) per double pancake is given in Fig. 5.2

Thus for a 5 T (6 T) coil with an OD = 100 cm, $n_{dp} = 11$, coil ID is reduced from 80 to 76.4 cm (71.6 cm), $I_{op}/I_c$ is reduced from 70.1 to 64.2% for 5 T (and 71.2 to 57.3% for 6 T); length of ICCS conductor per double pancake ($L_{dp}$) from 32.1 to 31.5 m (32.6 to 29.7 for 6 T); coil weight from 3.1 to 3.0 tonnes (3.8 to 3.5 tonnes for 6 T). The corresponding reduction in the required overall current density ($jX$) for the 5 T (6 T) coil is 3.7 to 3.4 kA/cm² (4.0 to 4.5 kA/cm²).

5.3 Method of Calculation

The calculation procedure is shown below for a sampling of cases considered and is tabulated in Section 5.4 for 5 T and Section 5.5 for 6 T.

(a) Pick $B_{oo}$: 5 or 6 T

* Reference is made to Sections 5.4 and 5.5 "Calculation of Operating Margin" (for 5 & 6 T coils resp.)
(b) Pick coil length $L_C = 150$ cm

(c) Pick coil ID or coil OD

(d) Pick $A_{ICCS}$ (insulated) from ICCS design, Line 34 for 5 T design ($4.32 \text{ cm}^2$). For the 6 T design the corresponding value of $A_{ICCS}$ (insulated) is $4.8 \text{ cm}^2$, based on an increase of NbTi only.

(e) Axial length of insulated ICCS ($x_{ICCS}$) is given by:
$$[L_C - (N_{dp} + 1) 0.1]/(2 N_{dp})$$
For $N_{dp} = 36$ and $L_C = 150$ cm, $x_{ICCS} = 2.03 \text{ cm}$

(f) To accommodate the axial ICCS length to fit the given coil length the ICCS will no longer be square. The radial width ($W_{ICCS}$) is given by:
$$A_{ICCS}/x_{ICCS} = W_{ICCS}$$

(g) Coil build, $\Delta R$ is given by:
$$\Delta R = (n_{dp} + 1)/2 \times x_{ICCS}$$

(h) The coil OD ($D_0$) is given by:
$$D_0 = D_i + 2\Delta R$$

(i) If the coil OD is fixed (i.e., at 100 cm)
then
$$D_i = D_0 - 2\Delta R$$

(j) The on center, central plane field ($B_{oo}$)* is given by
$$B_{oo} = j_{\lambda req.} \left( F(\alpha, \beta) \right) \frac{D_i}{2} \times \frac{1}{10^4} \text{ -- T}$$

where $j_{\lambda req.}$ is overall current density ($A/cm^2$)

and $F(\alpha, \beta) = \frac{4\pi\beta}{\ln \frac{\alpha^2 + \beta^2}{\beta^2 + 1}}^{1/2} + \alpha$

where $\alpha = \frac{D_0}{D_1}$

$\beta = \frac{L_0}{D_1}$

Thus for a given Boo, $\alpha$, $\beta$, $D_0$ and $D_1$ the required $j_{\lambda \text{req.}}$ can be calculated (Line 14)

(k) The overall current density for the ICCS ($j_{\lambda \text{ICCS}}$) is given by

$$j_{\lambda \text{ICCS}} = j_{\lambda \text{req.}} \times \frac{ndp + 1}{2}$$

(Line 15)

(l) Operating current ($I_{op}$) is given by

$$I_{op} = \frac{j_{\lambda \text{ICCS}} \times A_{\text{ICCS}}}{19}$$

(Line 16)

where the number of bundles for the ICCS is 19.

(m) The peak field at superconductor ($B_{\text{max}}$) can be obtained from Table of the reference (Line 17)

(n) $J_c (B_{\text{max}}, 4.2 \text{ K})$ is given by

$$J_c (B_{\text{max}}) = \frac{5 + 22 (10 - B_{\text{max}})}{5 + 22 (10 - B_{\text{oo}})} \times J(B_{\text{oo}})$$

(Line 18)

(o) $J_{op}$ is given by

$$J_{op} = \frac{I_{op}}{A_{\text{NbTi}}}$$

(Line 20)

where $A_{\text{NbTi}}$ is given by Line 19

(p) The operating margin $I_{op}/I_c$ is given by

$$\frac{I_{op}}{I_c} = \frac{J_{op}}{J_c (B_{\text{max}})}$$

(Line 21)
5.4 Calculation of Operating Margin at 5 T

<table>
<thead>
<tr>
<th>Description</th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
<th>(D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) On axis central plane field</td>
<td>$B_{oo}$</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>(2) Coils length</td>
<td>$L_c$</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>(3) Coils ID</td>
<td>$D_i$</td>
<td>80</td>
<td>74.44</td>
<td>80</td>
</tr>
<tr>
<td>(4) Cross-sectional area of insulated ICCS</td>
<td>$A_{ICCS}$</td>
<td>4.32</td>
<td>4.32</td>
<td>4.32</td>
</tr>
<tr>
<td>(5) Axial length of insulated ICCS</td>
<td>$L_{ICCS}$</td>
<td>2.03</td>
<td>2.03</td>
<td>2.03</td>
</tr>
<tr>
<td>(6) Radial width of insulated ICCS</td>
<td>$W_{ICCS}$</td>
<td>2.13</td>
<td>2.13</td>
<td>2.13</td>
</tr>
<tr>
<td>(7) No. turns per double pancake</td>
<td>$n_{dp}$</td>
<td>11</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>(8) No. double pancakes</td>
<td>$N_{dp}$</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>(9) Coils build</td>
<td>$\Delta R$</td>
<td>12.78</td>
<td>12.78</td>
<td>14.91</td>
</tr>
<tr>
<td>(10) Coils OD</td>
<td>$D_0$</td>
<td>105.56</td>
<td>100</td>
<td>109.8</td>
</tr>
<tr>
<td>(11) $D_0/D_i$</td>
<td>$\alpha$</td>
<td>1.320</td>
<td>1.343</td>
<td>1.373</td>
</tr>
<tr>
<td>(12) $L/D_i$</td>
<td>$\beta$</td>
<td>1.875</td>
<td>2.015</td>
<td>1.875</td>
</tr>
<tr>
<td>(13) $F(\alpha, \beta)$</td>
<td>-</td>
<td>.342</td>
<td>.373</td>
<td>.396</td>
</tr>
<tr>
<td>(14) Req. $\lambda$</td>
<td>$J_\lambda$(req.)</td>
<td>3665</td>
<td>3355</td>
<td>3160</td>
</tr>
<tr>
<td>(15) Req. $\lambda$(ICCS)</td>
<td>$J_\lambda$(ICCS)</td>
<td>3998</td>
<td>3660</td>
<td>3403</td>
</tr>
<tr>
<td>(16) Req. current</td>
<td>$I_{op}$</td>
<td>909</td>
<td>832</td>
<td>774</td>
</tr>
<tr>
<td>(17) $B_{max}$</td>
<td>$B_{max}$</td>
<td>5.25</td>
<td>5.25</td>
<td>5.25</td>
</tr>
<tr>
<td>(18) $J_c$ ($B_{max}$, 4.2 K)</td>
<td>$J_c$ (NbTi)</td>
<td>2331</td>
<td>2331</td>
<td>2331</td>
</tr>
<tr>
<td>(19) Cross-sectional area of NbTi per bundle</td>
<td>$A$ (NbTi)</td>
<td>.556</td>
<td>.556</td>
<td>.556</td>
</tr>
<tr>
<td>(20) $J_{op}$ (B, 4.2 K)</td>
<td>$J_{op}$ (NbTi)</td>
<td>1635</td>
<td>1497</td>
<td>1392</td>
</tr>
<tr>
<td>(21) Operating Margin</td>
<td>$I_{op}/I_c$</td>
<td>70.1</td>
<td>64.2</td>
<td>59.7</td>
</tr>
</tbody>
</table>
### 5.5 Calculation of Operating Margin

**Operating/Critical Currents at 6 Teslas**

<table>
<thead>
<tr>
<th>(1) On axis central plane field</th>
<th>$B_{00}$</th>
<th>6</th>
<th>6</th>
<th>6</th>
<th>6</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Coil length</td>
<td>$L_c$</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>cm</td>
</tr>
<tr>
<td>(3) Coil ID</td>
<td>$D_i$</td>
<td>80</td>
<td>71.63</td>
<td>80</td>
<td>80</td>
<td>cm</td>
</tr>
<tr>
<td>(4) Cross-sectional area of insulated ICCS</td>
<td>$A_{ICCS}$</td>
<td>4.80</td>
<td>4.80</td>
<td>4.80</td>
<td>4.80</td>
<td>cm²</td>
</tr>
<tr>
<td>(5) Axial length of insulated ICCS</td>
<td>$L_{ICCS}$</td>
<td>2.03</td>
<td>2.03</td>
<td>2.03</td>
<td>2.03</td>
<td>cm</td>
</tr>
<tr>
<td>(6) Radial width of insulated ICCS</td>
<td>$W_{ICCS}$</td>
<td>2.365</td>
<td>2.365</td>
<td>2.365</td>
<td>2.365</td>
<td>cm</td>
</tr>
<tr>
<td>(7) No. turns per double pancake</td>
<td>$n_{dp}$</td>
<td>11</td>
<td>11</td>
<td>13</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>(8) No. double pancakes</td>
<td>$N_{dp}$</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>(9) Coil build</td>
<td>$\Delta R$</td>
<td>14.19</td>
<td>14.19</td>
<td>16.42</td>
<td>11.82</td>
<td>cm</td>
</tr>
<tr>
<td>(10) Coil OD</td>
<td>$D_o$</td>
<td>108.37</td>
<td>100</td>
<td>112.84</td>
<td>103.64</td>
<td>cm</td>
</tr>
<tr>
<td>(11) $D_o/D_i$</td>
<td>$\alpha$</td>
<td>1.355</td>
<td>1.396</td>
<td>1.41</td>
<td>1.30</td>
<td>-</td>
</tr>
<tr>
<td>(12) $L/D_i$</td>
<td>$\beta$</td>
<td>1.875</td>
<td>2.094</td>
<td>1.875</td>
<td>1.875</td>
<td>-</td>
</tr>
<tr>
<td>(13) $F(\alpha, \beta)$</td>
<td>-</td>
<td>.377</td>
<td>.432</td>
<td>.434</td>
<td>.317</td>
<td>-</td>
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<tr>
<td>(14) Req. $j^\lambda$</td>
<td>$j^\lambda_{(req.)}$</td>
<td>3975</td>
<td>3475</td>
<td>3460</td>
<td>4740</td>
<td>A/cm²</td>
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<tr>
<td>(15) Req. $j^\lambda_{(ICCS)}$</td>
<td>$j^\lambda_{(ICCS)}$</td>
<td>4336</td>
<td>3791</td>
<td>3726</td>
<td>5267</td>
<td>A/cm²</td>
</tr>
<tr>
<td>(16) Req. current</td>
<td>$I_{op}$</td>
<td>1096</td>
<td>958</td>
<td>942</td>
<td>1331</td>
<td>A</td>
</tr>
<tr>
<td>(17) $B_{max}$</td>
<td>$B_{max}$</td>
<td>6.25</td>
<td>6.25</td>
<td>6.25</td>
<td>6.25</td>
<td>T</td>
</tr>
<tr>
<td>(18) $J_c$ ($B_{max}$, 4.2 K)</td>
<td>$J_c$ (NbTi)</td>
<td>1885</td>
<td>1885</td>
<td>1885</td>
<td>1885</td>
<td>A/cm²</td>
</tr>
<tr>
<td>(19) Cross-sectional area of NbTi per bundle</td>
<td>$A$ (NbTi)</td>
<td>.817</td>
<td>.817</td>
<td>.817</td>
<td>.817</td>
<td>mm²</td>
</tr>
<tr>
<td>(20) $J_{op}$ (B, 4.2 K)</td>
<td>$J_{op}$ (NbTi)</td>
<td>1341</td>
<td>1173</td>
<td>1153</td>
<td>1629</td>
<td>A/mm²</td>
</tr>
<tr>
<td>(21) Operating Margin</td>
<td>$I_{op}/I_c$</td>
<td>71.2</td>
<td>62.2</td>
<td>61.2</td>
<td>86.4</td>
<td>%</td>
</tr>
</tbody>
</table>
Fig. 5.1 ICCS coil double pancake (D/P) (12 D/Ps make one (1) 50 cm subcoil) (3 subcoils make one (1) 150 cm coil).
Fig. 5.1a Cross-section of double pancake.
Fig. 5.2 Plot of operating over critical current ($I_{op}/I_c$) as a function of number of turns per double pancake. With a fixed coil ID of 80 cm, coil ODs are 101.3, 105.6 and 109.8 cm resp. for 5 T and $n_{dp} = 9$, 11, and 13 for 5 T. For 6 T coil ODs are 103.6, 108.4 and 112.8 cm resp. for $n_{dp} = 9$, 11, and 13.
6.0 ICCS SUPERCONDUCTING STABILITY

6.1 Geometry
Consider one bundle with the following characteristics (19 bundles per ICCS):

- \( R_{Cu} = 8 \left( A_{Cu}/A_{NbTi} \right) \)
- \( R_{Cool} = 1.2 \left( A_{Coolant}/A_{Wire} \right) \)
- Void fraction = 54.5%
- \( (N_w)_b = 27 \) (Number strands per bundle)
- \( I = 1,000 \) A
- \( d_w = 0.486 \) mm (wire diameter)
- \( D_H = 0.046 \) cm (hydraulic diameter)
- \( (A_{HT})_b = 4.122 \) cm\(^2/cm\) (heat transfer surface area) for one bundle

6.2 Interstitial Helium Heat Capacity

- Volume He space = 0.060 cm\(^3/cm\) per bundle, 1.140 cm\(^3/cm\) for the ICCS
- Current sharing temperature \( (T_{cs}) = 4.9 \) K
- Critical temperature \( (T_c) = 6.9 \) K

Below \( T_{cs} \) current is in superconductor only.

Above \( T_c \) current is in stabilizing copper only.

Between \( T_{cs} \) and \( T_c \) current is shared

\( \Delta H_{He} (4.9-4.2 \) K) = 3.9 j/g = 0.527 j/cm\(^3\) = 0.03159 j/cm (bundle) = 0.6008 j/cm (ICCS)

Volume of wire per 32 m length of ICCS (one double pancake) = 3,040 cm\(^3\)
Mass of wire (one double pancake) = 27.36 Kg

Energy which can be absorbed by interstitial helium is

\[ 0.6008 \times 3200 = 1922.6 \text{ j/double pancake.} \]

Specific energy is

\[ \frac{1,922.6}{27,360} = 0.0702 \text{ j/g wire} \]

Thus \( \Delta Q_{\text{He}} \)

\[ = 70.2 \text{ mj/g wire} \]
or \[ 631.6 \text{ mj/cm}^3 \text{ wire} \]
or \[ 0.6 \text{ j/cm ICCS} \]

6.3 COOLING POWER

(Heat transfer to interstitial helium)

It can be shown that \( h \), the heat transfer coefficient for single phase (supercritical) helium is given (approximately) by the following relationships.

\[ \text{Nu} = \frac{hD_H}{K} \quad \text{(1)} \]

\[ \text{Nu} = 0.023 \text{ Re}^{-0.8} \text{Pr}^{-0.4} \quad \text{(2)} \]

\[ \text{Re} = \frac{D_H G}{\mu} \quad \text{(3)} \]

\[ \text{Pr} = \frac{C_p \mu}{K} \quad \text{(4)} \]

\[ G = \rho v \quad \text{(5)} \]

\[ D_H = \frac{4 \text{ AHe}}{\text{w.p.}} \quad \text{(6)} \]

\[ \text{AHe} = \text{ACool} = \text{coolant cross sectional area} \]

\[ \text{w.p.} = \text{Wetted perimeter of heat transfer surface.} \]

Heat transfer between wire and interstitial helium is then given by:

\[ \dot{Q}_C = hA_{HT}\Delta T \quad \text{(7)} \]

\( A_{HT} \) is area of cooling heat transfer

\( \Delta T \) is temperature differential between the wire and helium.
Thus if \( v = 20 \) (30) cm/s
\[
\begin{align*}
T_{\text{He}} & = 4.2 \text{ K} \\
P_{\text{He}} & = 2.5 \text{ atm} \\
\rho_{\text{He}} & = 0.131 \text{ g/cm}^3 \\
G & = 2.62 \text{ g/cm}^2 \text{ s} \ (3.93) \\
A_{\text{He}} & = 0.06 \text{ cm}^2 \text{ per bundle} \\
D_H & = 0.058 \text{ cm} \\
Re & = 4237 \ (6356) \\
Pr & = 0.7 \\
Nu & = 15.9 \ (22.0) \\
h & = 0.057 \ (.079) \text{ w/cm}^2 \text{ K}
\end{align*}
\]

Since \( A_{HT} \) for the above geometry is 4.122 cm\(^2\)/cm of bundle:
\[
\dot{Q}_c = \frac{0.236 \text{ w/K cm for a bundle (.327)}}{\Delta T} \ 4.5 \text{ w/K cm for the ICCS (6.2)}
\]

This is cooling power (\( \dot{Q}_c \)) available to remove heat from a wire to surrounding helium.

6.4 Heating Power (\( \dot{Q}_H \))

Heating power is zero as long as \( T_W < T_{CS} \) (\( T_W \) is wire temperature)

Thus \( \dot{Q}_H = IJ \rho_R f \) \hfill (8)

where
\[
\begin{align*}
I & \text{ is current} \quad 1,000 \text{ A} \\
J & \text{ is normal (Cu) current density} \\
J & = \frac{I}{A_{\text{Cu}}} \ (A/cm^2) = \frac{1000}{0.0445} = 22,461 \text{ A/cm}^2 \\
\rho_R & \text{ is magneto resistance of copper at given field} \\
\rho_R & = 4E-8 \ \Omega \text{cm}
\end{align*}
\]

hence \( \dot{Q}_H = 0.90 \ f \text{ (w/cm)} \) -- bundle \( = 17.1 \ f \text{ (w/cm)} \) -- ICCS

where
\[
\begin{align*}
f & = 0 @ T_W < 4.9 \text{ K (T_{CS})} \\
f & = 1 @ T_W > 6.9 \text{ K (T_{C})}
\end{align*}
\]

Between \( T_{CS} \) and \( T_{C} \) \( f = \frac{(T - T_{CS})}{(T_{C} - T_{CS})} = \frac{(T - 4.9)}{2.0} \)
The heating power $\dot{Q}_H = 0.9 \, f \, \text{watts per cm of a bundle or } 17.1 \, f \, \text{watts per cm of the ICCS.}$

6.5 Net Cooling Power

In the absence of any external heat source net cooling power is given by:

$$\dot{Q}_{\text{net}} = \dot{Q}_H - \dot{Q}_C \, (W) \quad \text{(9)}$$

6.6 Stability Criteria

If the wire is subject to a transient heating pulse of $Q_{\text{imp}} \, (j)$ at time $t_0$ its temperature will rise instantaneously to a relatively high level.

Thus if $Q_{\text{imp}} = 50 \, \text{mj/g}$, the instantaneous wire temperature will rise from 4.2 to 22 K. Since this is greater than $T_C$, $f = 1$ and $Q_H$ will be equal to 17.1 W/cm ICCS. $Q_C$ will be given by

$$Q_C = h A H \Delta T = 4.5 \times (22-4.2) = 80.1 \, W/cm \text{ for } v = 20 \, \text{cm/s} \quad \text{(or } 110.4 \, W/cm \text{ for } v = 30 \, \text{cm/s})$$

Hence net cooling power is given by

$$\dot{Q}_{\text{net}} = 17.1-80.1 \quad = \quad -63 \, W/cm @ 20 \, \text{cm/s}$$

or

$$17.1-110.4 \quad = \quad -93.3 \, W/cm @ 30 \, \text{cm/s}$$

After the wire has been cooled down to a lower temperature (but $T_W > T_C$) the joule heating rate $\dot{Q}_H$ remains essentially constant, though $Q_C$ will diminish (due to reduced $\Delta T$, since not only has $T_W$ fallen, but $T_{He}$ will have increased to close to $T_{CS}$, i.e., 4.9 K). Once $T_W$ has dropped below $T_C$, $Q_H$ will diminish more rapidly than $Q_C$.

If $\dot{Q}_H > \dot{Q}_C \, \dot{Q}_{\text{net}}$ will be positive and the wire will never cool below $T_{CS}$, will heat up again and go into a quench.

If the coolant temperature exceeds current sharing, i.e., $T_{He} > T_{CS}$ (4.9 K for the given geometry and current) there will again be no recovery since $T_W > T_{CS}$ and again a quench will result.

6.7 Effect of Joule Heating ($\dot{Q}_H$) on Maximum Energy Input ($Q_{\text{imp}}$)

If $\Sigma \dot{Q}_H \Delta t$ is the integrated joule heating energy in mj/cm ICCS and $\Delta Q_{He}$ is the energy (mj/g) required to raise the temperature of helium from $T_0$ (4.2 K) to $T_{SC}$ (4.9 K), then if $M_w$ is the mass of wire per unit length, allowable $Q_{\text{imp}}$ will be given by:

$$Q_{\text{imp}} \geq \frac{\Delta Q_{He} - \Sigma \dot{Q}_H \Delta t}{M_w} \quad \text{(mj/g)} \quad \text{(10)}$$
6.8 Second Limitation to $Q_{imp}$

As $T_w$ approaches $T_{CS}$, $T_{He}$ will also approach $T_{CS}$. At a high $Q_H$, a minimum $\Delta T$, $(T_w - T_{He})$ is needed to keep $Q_{net}$ negative (cooling). There is consequently a maximum helium temperature ($T_{He}$ max) which will support recovery, where $T_{He}$ max < $T_{CS}$.

6.9 Method of Calculation

An iterative calculation has been used to check stability (recovery) for the following conditions, using the above design geometry for an ICCS conductor section (19 bundles).

\[
\begin{align*}
I &= 19,000 \text{ A} \\
T_{CS} &= 4.9 \text{ K} \\
T_C &= 6.9 \text{ K} \\
\nu &= 30 \text{ cm/s} \\
T_w \text{ (max)} &= 24 \text{ K} \\
Q_{imp} &= 17.1 \text{ W/cm} @ T_w > T_C
\end{align*}
\]

Each step of the calculation (see § 6.12) assumes an interval ($\Delta t$) and a wire temperature $T'_w$ at the end of the interval. The interval is reduced if $(T_w - T'_w)$ is excessive. A new value of $T'_w$ (for the particular step) is taken until the heat balance confirms $T'_w$. As the cooldown progresses $Q_{net}$ is evaluated. When $Q_{net}$ ceases to be negative (signifying heating rather than net cooling) $T_{He}$ (max) must be decreased in order to keep $Q_{net}$ negative. Results of the calculation are shown in Fig. 6.1.

As Section 6.12 shows, when $T_{He}$ (max) is 4.6 K, the system recovers with $T'_w < T_{CS}$.

Since $\Delta Q_{He} = 0.6 \text{ j/cm for } T_{He}$ (max) = 4.9 K

acceptable $\Delta Q_{He} = 0.343 \text{ j/cm for } T_{He}$ (max) = 4.6 K

and since $\Sigma Q_H\Delta t = 0.183 \text{ j/cm}$,

maximum $Q_{imp} = 0.16 \text{ j/cm or } 18.7 \text{ mj/g wire or } 168.3 \text{ mj/cm}^3 \text{ wire}$

6.10 Conclusion on Stability Analysis

The above calculations show that the design has adequate stability based on a fluid velocity of 30 cm/s, or a heat transfer coefficient of $h = 0.079 \text{ W/cm}^2 \text{ K}$. Since heat transfer coefficients of this order are obtained under conditions of self stability with no bulk flow, the design can be considered adequate.

6.11 Comments

Options are available to increase the product $h A_{HT}$, if desired:
( i) Velocity could be increased in case of bulk flow. \( h \) would then increase. A negative aspect is an increase in pressure drop for forced flow.

(ii) The heat transfer coefficient \((h)\) for self stability could be increased by the use of a lower void fraction. With a lower void fraction helium pressure at the heated point will increase, causing higher local velocity. To decrease the void fraction of the subject design would have a derogatory effect on water cooled "Emergency Operation". A decrease in void fraction will also decrease helium content and hence \( \Delta Q_{He} \).

(iii) Heat transfer area \( (A_{HT}) \) can be increased by a decrease in wire diameter and an increase in number of strands per bundle. This would however have a derogatory effect by generating a correspondingly (proportionately) lower \( D_H \) (hydraulic diameter). Thus a factor of 2 reduction in \( d_w \) will generate a factor of 2 reduction in \( D_H \), a 15\% increase in \( h \) but a 52\% increase in pressure drop (for both He and water flow).

\( Q_{net} \) (cooling) can also be increased by an increase in copper area \( (R_{Cu}) \), thus lowering \( J_{Cu} \). This action will decrease overall current density \((j\lambda)\) and hence effective on-axis field and for the same field will necessitate a bulkier coil.

The above analysis is only indicative, though useful for the selection of variables. Before a coil is built a section of it must be tested under representative conditions.
### 6.12 Stability Analysis

<table>
<thead>
<tr>
<th>$t$ (ms)</th>
<th>$t'$ (ms)</th>
<th>$\dot{Q}_H$ (W/cm)</th>
<th>$\dot{Q}_C$ (W/cm)</th>
<th>$\dot{Q}_{net}$ (W/cm)</th>
<th>$T_W$ ($K$)</th>
<th>$T_W'$ ($K$)</th>
<th>$T_W''$ ($K$)</th>
<th>$T_{mean}$ ($K$)</th>
<th>$H'$</th>
<th>$T_w$ (K/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>-131.84</td>
<td>-13.58</td>
<td>24.0-22.4</td>
<td>2.0</td>
<td>23.2</td>
<td>56.6</td>
<td>22.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>-123.38</td>
<td>-12.43</td>
<td>22.4-21.2</td>
<td>1.2</td>
<td>21.8</td>
<td>44.2</td>
<td>21.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-114.56</td>
<td>-11.4</td>
<td>21.2-20.0</td>
<td>1.2</td>
<td>20.6</td>
<td>32.8</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-104.34</td>
<td>-10.2</td>
<td>20.0-18.4</td>
<td>1.6</td>
<td>19.4</td>
<td>22.6</td>
<td>18.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>-90.95</td>
<td>-8.64</td>
<td>18.4-16.3</td>
<td>2.1</td>
<td>17.35</td>
<td>13.96</td>
<td>16.3</td>
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<tr>
<td>5</td>
<td>6</td>
<td>-74.38</td>
<td>-6.7</td>
<td>16.3-13.8</td>
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<td>15.05</td>
<td>7.26</td>
<td>13.8</td>
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</tr>
<tr>
<td>7</td>
<td>8</td>
<td>-52.88</td>
<td>-4.20</td>
<td>13.8-10.3</td>
<td>3.5</td>
<td>12.05</td>
<td>3.08</td>
<td>10.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>-32.78</td>
<td>-1.83</td>
<td>10.3-8.3</td>
<td>2.0</td>
<td>9.3</td>
<td>1.25</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>17.1</td>
<td>-21.86</td>
<td>-0.556</td>
<td>8.3-7.2</td>
<td>0.8</td>
<td>7.8</td>
<td>6.94</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>17.1</td>
<td>-16.92</td>
<td>+0.02</td>
<td>7.2-6.9</td>
<td>T_{He} (max) = 4.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.3</td>
<td>11.0</td>
<td>8.55</td>
<td>-10.75</td>
<td>-0.18</td>
<td>6.95-5.3</td>
<td>2.35</td>
<td>6.13</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.0</td>
<td>11.3</td>
<td>3.42</td>
<td>-7.23</td>
<td>-0.134</td>
<td>5.3-4.6</td>
<td>2.67</td>
<td>4.9</td>
<td>.366</td>
<td>4.6</td>
<td></td>
</tr>
</tbody>
</table>

where $t$ is time at beginning

$t'$ is time at end of period

$\dot{Q}_H$ is heating rate

$\dot{Q}_C$ is cooling rate

$\dot{Q}_{net}$ is net cooling rate if negative or net heating rate if positive

$T_W$ is wire temperature at start of period

$T_W'$ is wire temperature at end of period (assumed)

$T_W''$ is wire temperature at end of period (computed)

$\dot{T}$ is temperature gradient

$H'$ is enthalpy at end of period

The above calculation results have been plotted in Fig. 6.1.
Fig. 6.1 Calculated plot of wire temperature ($T_w$) and helium temperature ($T_{He}$) as a result of energy pulse ($Q_{imp}$) delivered between $t=-1$ and $1$ ms.
7.0 EMERGENCY OPERATION AT ROOM TEMPERATURE

The proposed concept envisions that in the event of a major vacuum, cryogenic or other failure at sea, the superconducting magnet system would have the following "Take Home Capability":

(i) Warm up system to room temperature.
(ii) Fill cable interstitial (helium) space with deionized, distilled water.
(iii) Circulate water through solenoid in an externally cooled loop as shown in Fig. 7.1.
(iv) Operate solenoid at 10% of superconducting current, normally at 100 A. See electrical diagram, Fig. 7.2.

7.1 Summary of Optimized Operating Conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Operating current (I)</td>
<td>= 100 A</td>
</tr>
<tr>
<td>(2) Current per ICCS</td>
<td>= 1900 A</td>
</tr>
<tr>
<td>(3) Operating temperature:</td>
<td>360 F maximum</td>
</tr>
<tr>
<td>(4) Number of parallel flow paths (double pancakes)</td>
<td>= 36</td>
</tr>
<tr>
<td>(5) Temperature rise in cooling water</td>
<td>= 140 F</td>
</tr>
<tr>
<td>(6) Flow per double pancake</td>
<td>= 59.9 g/s (1.1 gallons per min.)</td>
</tr>
<tr>
<td>(7) Total flow (36 circuits)</td>
<td>= 38.6 gpm</td>
</tr>
<tr>
<td>(7a) Pressure drop</td>
<td>= 137.3 psi</td>
</tr>
<tr>
<td>(8) Net pumping power</td>
<td>= 1.2 kW</td>
</tr>
<tr>
<td>(9) Steady-state heat load</td>
<td>= 1.1 MW</td>
</tr>
<tr>
<td>(10) Voltage drop per bundle</td>
<td>= 16 V</td>
</tr>
<tr>
<td>(11) Voltage drop per double pancake (19 circuits in series)</td>
<td>= 305 V</td>
</tr>
</tbody>
</table>
(12) Maximum voltage between any two points in a double pancake -- 305 V

(13) Power supply requirements for system assuming the three (3) subcoils are wired in parallel for the emergency operation -- 300 A, 3.7 kV, 1.1 MW-DC

7.2 Heating Power \((Q_H)\)

Steady-state heating is given by:

\[
Q_H = IJP_R \quad -- \quad (1)
\]

\(I\) is current -- 100 A

\(J\) is current density in copper

\[
J = \frac{I}{A_{Cu}} \quad (A/cm^2)
\]

\[
= \frac{100}{0.0445} = 2,246 \text{ A/cm}^2
\]

\(\rho_R\) is electrical resistivity at operating temperature, assumed to be 2.23E-6 \(\Omega\)cm

Hence \(Q_H\)

\[
= 0.5 \text{ w/cm (bundle)}
\]

\[
= 0.5 \times 19 = 9.52 \text{ w/cm ICCS}
\]

7.3 Cooling Power \((Q_C)\)

Heat transfer characteristics are given by the following relationships:

\[
Nu = h \frac{D_H}{K} \quad -- \quad (2)
\]

\[
Nu = 0.023 \Re^{0.8} \Pr^4 \quad -- \quad (3) \text{ for } \Re > 3,000 \quad (*)
\]

\[
Nu = 3.65 \quad -- \quad (3a) \text{ for } \Re < 2,300 \quad (*)
\]

\[
Re = \frac{D_H G}{\mu} \quad -- \quad (4)
\]

\[
Pr = \frac{c_p \mu}{K} \quad -- \quad (5)
\]

\[
G = \rho \frac{D^4}{V} \quad -- \quad (6)
\]

* Ref: Cryogenic Systems, Barron P 134 and 135 (McGraw Hill)
\[ D_H = 4 \frac{A_c}{w.p.} \quad -- (7) \]

\( D_H \) is hydraulic diameter  
\( w.p. \) is wetted perimeter  
\( A_c \) is coolant (H\(_2\)O) cross-sectional area.

7.4 Steady-State Cooling Requirement

\[
\dot{Q}_c = \dot{Q}_H 
\quad -- (8)
\]

where

\[
\dot{Q}_c = h A_{HT} \Delta T_{HT} 
\quad -- (9)
\]

\( A_{HT} \) is wire surface area in contact with coolant  
\( \Delta T_{HT} = T_w - T_c \quad -- (10) \)

where  
\( T_w \) is wire temperature  
\( T_c \) is coolant temperature

7.5 Local Heat Transfer

Assume  

\[ G = 75 \text{ (g/cm}^2\text{s)} \]

\[ \nu = 84.8 \text{ (cm/s)} \]

at  

\[ R_{cool} = 1.2 \text{ and } R_{cu} = 8 \]

mass flow per bundle (\( m_b \)) is

\[ m_b = 4.5 \text{ g/s} \]

and

\[ m_{MICCS} = 85.5 \text{ g/s (19 bundles)} \]

\[ A_{cu} = 0.06 \text{ cm}^2 \text{ (1 bundle)} \]

\[ D_H = .058 \text{ cm} \]

\[ \mu = .0013 \text{ g/s cm (viscosity)} \]

\[ Re = 3345 \text{ ie } Re > 3000 \]

in

\[ Nu = 14.8 \]

\[ K = .0065 \text{ w/cm K (thermal conductivity of water at 100 C)} \]

\[ h = 1.66 \text{ w/cm}^2 \text{ K} \]
since \( Q_c \) = \( 0.5 \) w/cm (required per bundle) and \( A_{HT} \) = 4.122 cm\(^2\)/cm (bundle) from Eq. (9) \( \Delta T_{HT} \) (required) = 0.073 K Even for the laminar \( Nu = 3.65 \), the required \( \Delta T_{HT} = 0.3 \) K

7.6 Temperature Rise in Cooling Water

\[ \dot{Q}_H = G A_c C_p \Delta T_c \quad -- \quad (11) \]

where \( A_c = 0.06 \times 19 = 1.14 \) cm\(^2\) for the 19 bundle ICCS and \( C_p = 4.66 \) j/gK - specific heat of water and \( \dot{Q}_H = 0.5 \times 19 = 9.5 \) w/cm for the 19 bundle ICCS

Since length of a single ICCS conductor (one double pancake) is 32 m,

\[ \Sigma \Delta T_c = 77.3 \) K (or 140 F)\]

While this is a relatively large temperature rise it is necessary due to the constrained geometry.

7.7 Pressure Drop and Pumping Power Requirements

Pressure drop through a tubular conduit is given by:

\[ \frac{\Delta p}{L} = \frac{fG^2}{2g_c \rho_D D_H} \quad -- \quad \text{dynes/cm}^3 \]

where \( L \) is length -- 3200 cm \( G \) is given by Eq. 6 -- 75 g/cm\(^2\)s \( \rho_D \) is density -- 0.885 g/cm\(^3\) \( D_H \) is hydraulic diameter (Eq. 7) (cm) \( f \) is friction factor
where $f = \frac{64}{Re}$ for $Re < 2300$

$$= 0.0056 + Re^{-0.32} \enspace \text{for} \enspace Re > 3000$$

The hydraulic diameter for pressure drop purposes must allow for the wetted perimeter of wires as well as the bundle wrap.

hence $D_H = 0.046 \text{ cm}$

for $G = 75 \text{ g/cm}^2 \text{ s}$

$Re = 3345$

and $f = 0.043$

and $\Delta P/L = 2970 \text{ dynes/cm}^3$

= $4.29 \text{ psi/m}$

hence for $L = 32 \text{ m}$ $\Delta p = 137.4 \text{ psi}$

Total pumping power ($P_p$) is given by

$$P_p = \sum m \times \Delta p / \rho_D \quad \text{(dyne cm/s)}$$

where $m$ is in g/s (36 parallel conductors)

$m = 3078 \text{ g/s}$

$\Delta p = 2970 \times 3200$

= $9.5 \times 10^6 \text{ dynes/cm}^2$

$\rho_D = 0.883 \text{ g/cm}^3$

$P_p = 3.3 \times 10^10 \text{ dynes cm/s}$

= $3.3 \text{ KW (4.4 HP)}$
7.8 Comments

The pressure drop is relatively high, though pump power is reasonable. Due to the compact cable geometry the above friction factor \( f \) could be optimistic. If \( f \) is 100% higher, \( \Delta p \) would increase two-fold to 275 psi, pump power to 8.8 HP. In order to keep the pressure drop from exceeding 150 psi, \( G \) should be reduced by 30% to 52.5 g/cm²s. Resultant net power load would be 6.7 HP. By reducing flow by 30%, \( \Delta T_c \) (temperature rise in H₂O) will also be increased by 30%, from 140 F to 182 F. The actual pressure drop will have to be determined experimentally.
Fig. 7.1 Water cooling diagram for emergency operation of solenoid at 100 A.
Fig. 7.2 Electrical diagram for emergency operation of solenoid at 100 A.
8.0 PROTECTION

Superconducting magnets store substantial energy. In case of quench this energy must be safely discharged. As described below, this can be done by (i) early detection of a quench followed by automatic switching and (ii) discharge of energy in a series connected dump resistor. See Fig. 8.1

A second consideration is the maximum (initial) discharge voltage. Electrical insulation must be adequate at all points.

For an ICCS conductor there is a third consideration. Due to a tight cable compaction there is a potential for a high helium quench pressure.

8.1 Dump Resistor Sizing and Energy Release

An ICCS conductor is not subject to training quenches. It is also able to sustain repeated rapid cycling of current. It should be possible to charge the coil from zero to 1,000 amps in several seconds without quench.

For safe operation, nevertheless, protection against a spontaneous quench must be provided. Two quench sensing devices are recommended. These are:

(i) A pressure transducer for each (of 3) subcoil, which would trigger a switch, disconnecting the power supply and allowing the coil to discharge its energy in a room temperature dump resistor.

(ii) Voltage taps across each double pancake protected by a bridge circuit. The power supply would again be automatically disconnected should the voltage across any double pancake register a minimal voltage (order of 0.5 to 1.0 mV). The purpose of the bridge circuit is to act as an override during planned charging or discharging of the coil.
In order to provide proper protection one must consider local generation of a normal (nonsuperconducting) zone of minimal length and its propagation. In the multi-bundle ICCS, a quench will propagate both along the wire as well as transeversly from bundle-to-bundle by means of interstitial helium heating. Thus a unit length of a bundle, when fully normal will raise the temperature of surrounding bundles. The ICCS, around the "seed" bundle will be normal in 0.25s. Helium expansion should then cause the total length of ICCS (32 m) to be normal in about 0.5s. The danger of a static hot spot with everincreasing temperature is thus negligible.

In order to provide conservative protection to the coil one must nevertheless consider so called "Hot Spot Temperature". It can be shown that

if $T_F$ is a hot spot temperature
assume $T_F$ at 300 K,
if a function, $z(T_F) > 12.7E8 \text{ (A}^2\text{s/cm}^4\text{)}$
where $z(T_F)$ is the integral of the ratio
of instantenous joule heating/cable heat capacity.

$z(T_F) = J_{Cu}^2 \tau/2,$
where $\tau$ is the time constant of current decay
for $I = 1000 \text{ A and } A_{Cu} = .044 \text{ cm}^2 \text{ per bundle,}$
$J_{Cu} = 22.501 \text{ A/cm}^2 \text{ and } \tau = 5s$

The current must thus be discharged to its time constant value (of 1000/e) 368 A in 5s. With a total coil inductance of $L = 22.6 \text{ h}$, the discharge voltage ($V_D = IL/\tau$) will be 4.5 kV. This can be achieved by placing a 4.5 ohm resistor in series with the coil.
The dump resistor must be able to absorb Coil Energy \((E_C)\), which is given by
\[
E_C = \frac{1}{2} LI^2 = 11.3 \text{ MJ}
\]

8.2 Discharge Voltage on Quench

As noted above, the discharge voltage on quench will be a maximum of 4,500 volts. Voltage difference between two adjacent double pancakes will be 125 volts, as will be the maximum voltage difference between any two bundles. Voltage drop across each bundle will be a maximum of 6.6 volts. Internal insulation within an ICCS should be more than adequate (.020 inches of fiberglass braid). Orbital rather than crossed transposition has also been selected in order not to abrade insulation during cabling. Insulation thickness between conductor and sheath is also 0.020 inches as is sheath-to-sheath insulation. The latter will be epoxy filled. Electrical stress from the layer of one double pancake to the adjacent one will be a maximum of 6.3 volts per mill of insulation.

Care will have to be taken in the placement and insulation of current leads and dump resistor terminals because of the high potential between them.

8.3 Peak Helium Pressure on Quench

Measurements of peak pressure have been made by J. Miller et al., at ORNL for a solenoid in which a quench was simultaneously universally initiated. This represents the worst case. The following formula, based on the ORNL tests was developed by L. Dresner (also of ORNL):
\[ P_{\text{max}} \text{ (Pa)} = 75.81 \left( Q_{\text{He}}^2 L^3 D_H^{-1}\right)^{.36} \]

where

\[ Q_{\text{He}} = \frac{I^2 P_R}{A_{\text{Cu}} A_{\text{He}}} \quad \text{(j/cm}^3\text{)} \]

\[ L = \text{Half length (cm)} \]

\[ D_H = \text{Hydraulic diameter} \]

\[ = \frac{4 A_{\text{He}}}{\pi d_w N_w + 4a} \quad \text{(cm)} \]

\[ d_w = \text{wire diameter} \quad \text{(cm)} \]

\[ N_w = \text{number of strands per ICCS} \]

\[ a = \text{internal width of ICCS} \quad \text{(cm)} \]

\[ A_{\text{He}} = \text{cross-sectional coolant area of the ICCS} \quad \text{(cm}^2\text{)} \]

\[ A_{\text{Cu}} = \text{cross-sectional copper area of ICCS} \quad \text{(cm}^2\text{)} \]

\[ I = \text{current carried by ICCS} \quad (19 \times 1,000 \text{ amps}) \]

\[ \rho_R = \text{magneto resistivity at 5 teslas} \quad \text{(ohm-cm)} \]

Thus for the subject design:

\[ Q_{\text{He}} = (19,000)^2 4E-8/\left(0.8444 \times 1.14\right) = 15 \text{ j/cm}^3 \]

and

\[ P_{\text{max}} = 75.81 \left[ 15^2 \times \left(\frac{3200}{2}\right)^3 \times (0.045)^{-1}\right]^{.36} = 4.7 \text{ MPa or 622 psi}. \]

Experiments performed at Rutherford Labs., U.K., were similar, except that quench was initiated at one end of a 200 m long conductor. Peak pressures were an order of magnitude lower.
It can be concluded that the "worst case" peak pressure of 682 psi (46 atm) is not excessive. Compression tests at MIT of fully potted coils have shown:

(i) minor elastic deformations with no epoxy cracking under stresses of 7,000 psi

(ii) noncatastrophic deformations at stresses in excess of 20,000 psi.
Fig. 8.1 Electrical and control wiring schematic for 1,000 A superconducting operation.

C - Controller - Voltage & Pressure Control

P/S - DC Power Supply
1,000 amp
5 KVA

R_D - Dump Resistor
4.5 ohms

S - Switch (contactor), normally open, energized if P/s is energized and Controller is satisfied (no quench in progress).
9.0 RECOMMENDATIONS FOR FURTHER WORK

The subject design study indicates that a Magnet Field Winding System for the Navy's 30 MW Ship Propulsion Superconducting Motor Solenoid using ICCS Technology is feasible and advantageous.

In order to advance the state-of-the-art of this program the following developmental steps are recommended:

A. (1) Build 2-3 test coils using 20 ft length of the full size, 19 bundle, 1,000 amp cable. The conductor would be thinly sheathed and would be wound into rectangular grooves machined in a 20 cm OD phenolic cylinder. See Fig. 9.1.

The 3 proposed conductors would be identical except for their helium content, which would range from 40 to 60 percent of bundle space.

(2) Operate the test coil in the 10 inch warm bore 0 to 8 tesla Bitter magnet. The test coil, as shown in Fig. 9.1 would include a pulse heater to facilitate inductive heating and hence stability testing.

(3) After exhaustive tests at 1,000 A in the superconductive mode, the test coils would be subject to 100 A operation at room temperature using water cooling.

(4) Develop and test ICCS conductor terminations for the 19 bundle, 1,000 A x 19 ICCS conductor.

B. (1) Build one or more double pancakes. These would then be tested in a ± 7 tesla rapid cycling split pair magnet at Argonne National Laboratory.

We recommend that Phase A of the above program be pursued in FY 1984 and FY 1985. Phase B could be started in FY 1985 and completed in FY 1986.
Fig. 9.1 Test coil for experimental evaluation of superconducting and emergency characteristics.
The following list of publications represents the state-of-the-art of the Internally Cooled Cabled Conductor (ICCS).


